MANCHESTER 1824

The University of Manchester

Double Beta Decay with NEMO and SuperNEMO

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University of Manchester

Fermilab Joint Experimental-Theory Seminar
12 September 2008

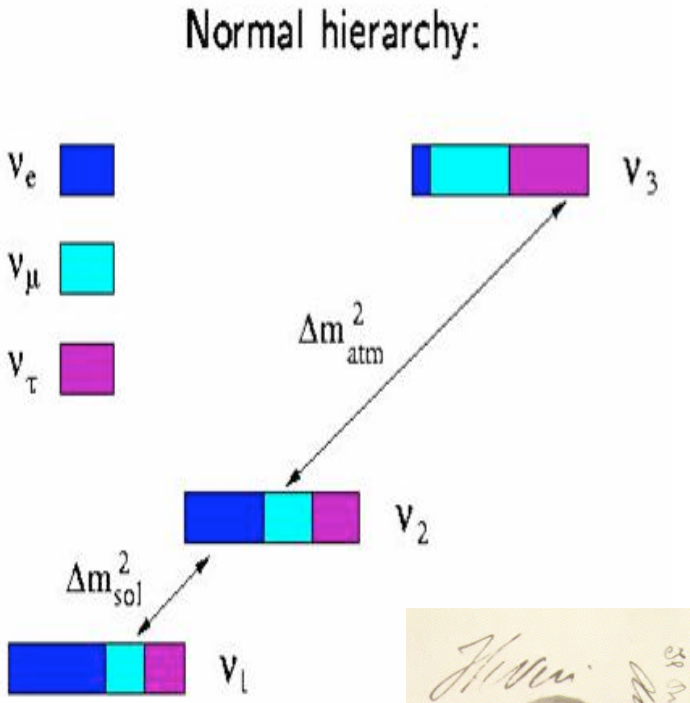
What do we know about neutrino masses ?

We know that neutrinos
have masses from oscillations:

$$(\Delta m_{23})^2 \approx (50\ \mathrm{meV})^2$$
$$(\Delta m_{12})^2 \approx (9\ \mathrm{meV})^2$$

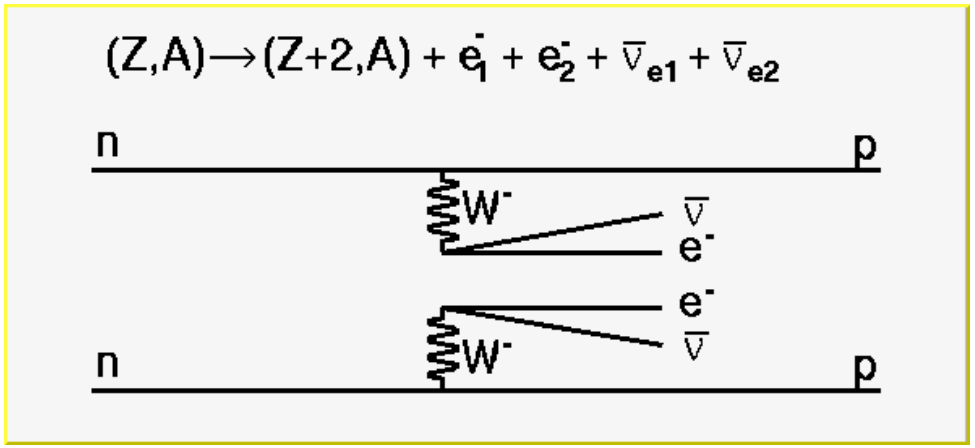
$m_{1,2,3}$ = mass eigenstates

Neutrinos can be (m>0)
- Dirac ($\upsilon \neq \bar{\upsilon}$)
- Majorana ($\upsilon = \bar{\upsilon}$)



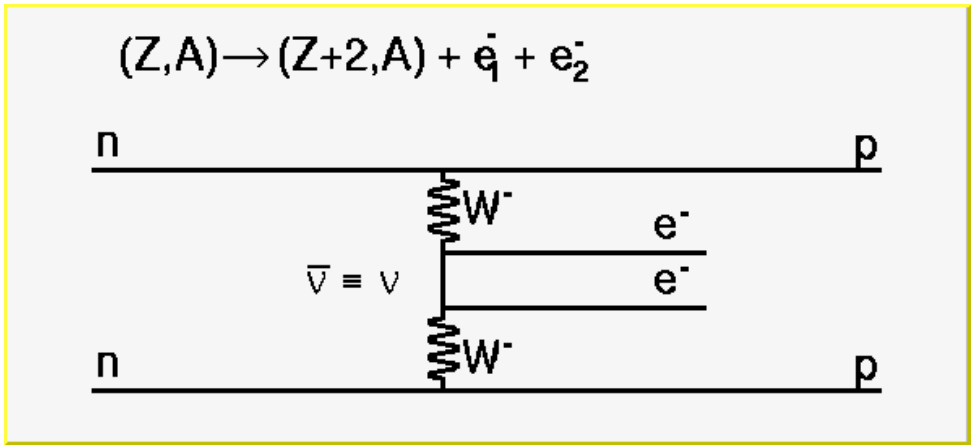
Majorana terms in Lagrangian:
- explain small neutrino masses through see-saw mechanism
- violate lepton number

Double Beta Decay



$$\frac{1}{T^{2\nu}_{1/2}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

predicted in 1935 by
Maria Goeppert-Mayer

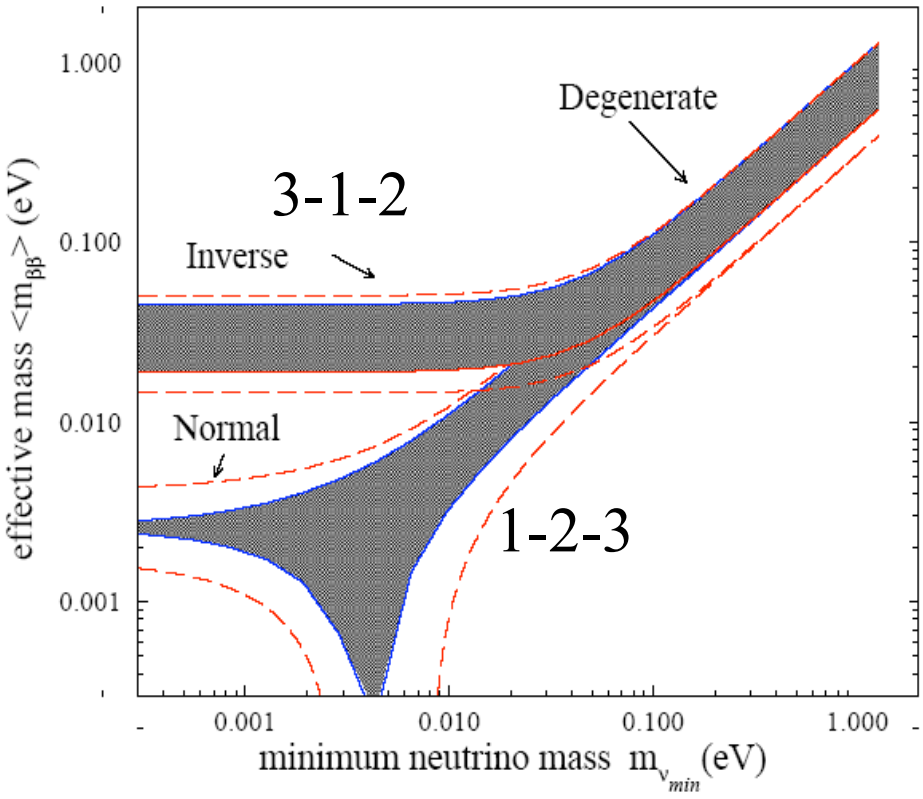


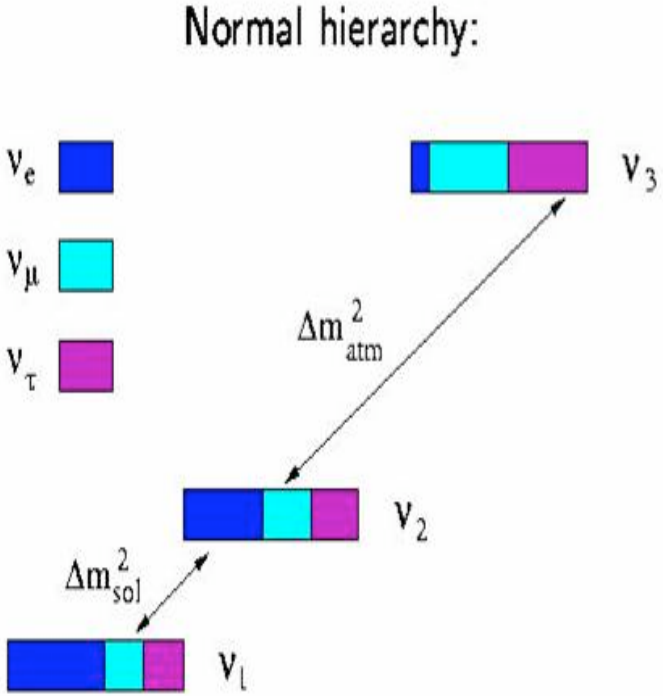
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

$\Delta L = 2$ - only possible for
Majorana neutrinos with mass > 0

Beyond the SM:
Lepton Number Violation !

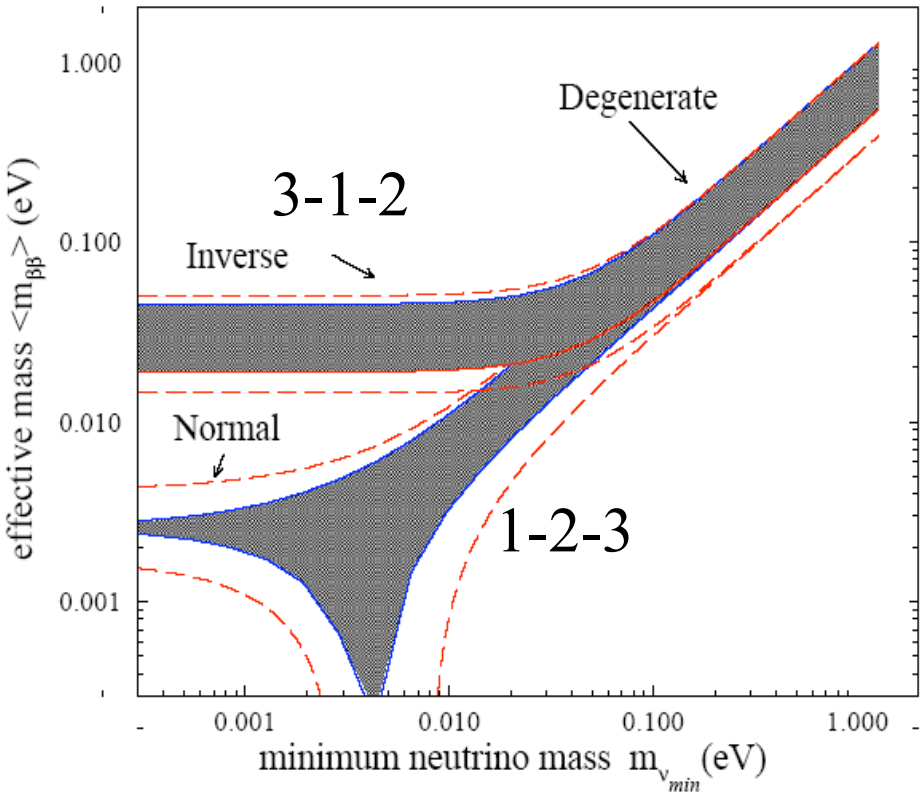
$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_i|^2$$

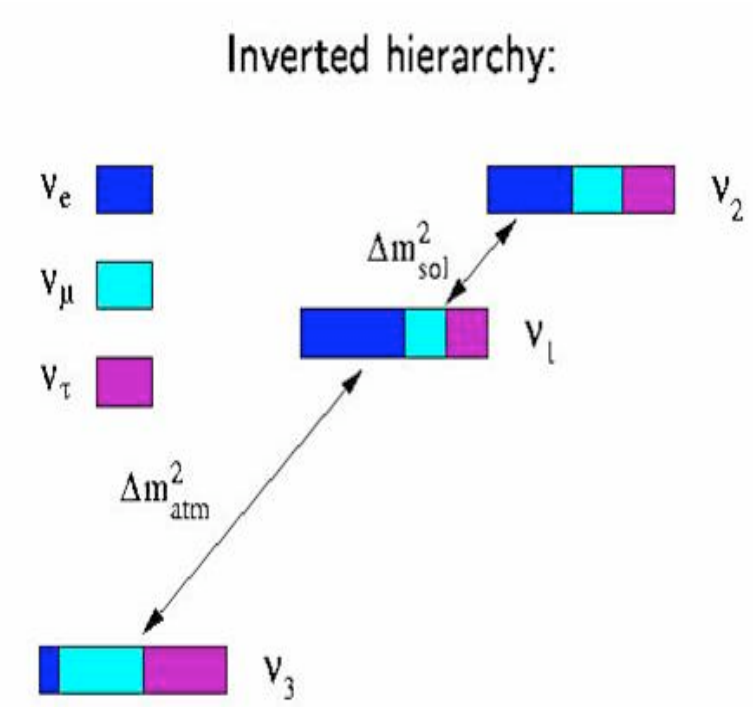




from oscillation fits

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_i|^2$$





from oscillation fits

The observation of double beta decay can answer many questions:

1) Existence of Lepton Number Violation

2) Nature of neutrino: Dirac versus Majorana

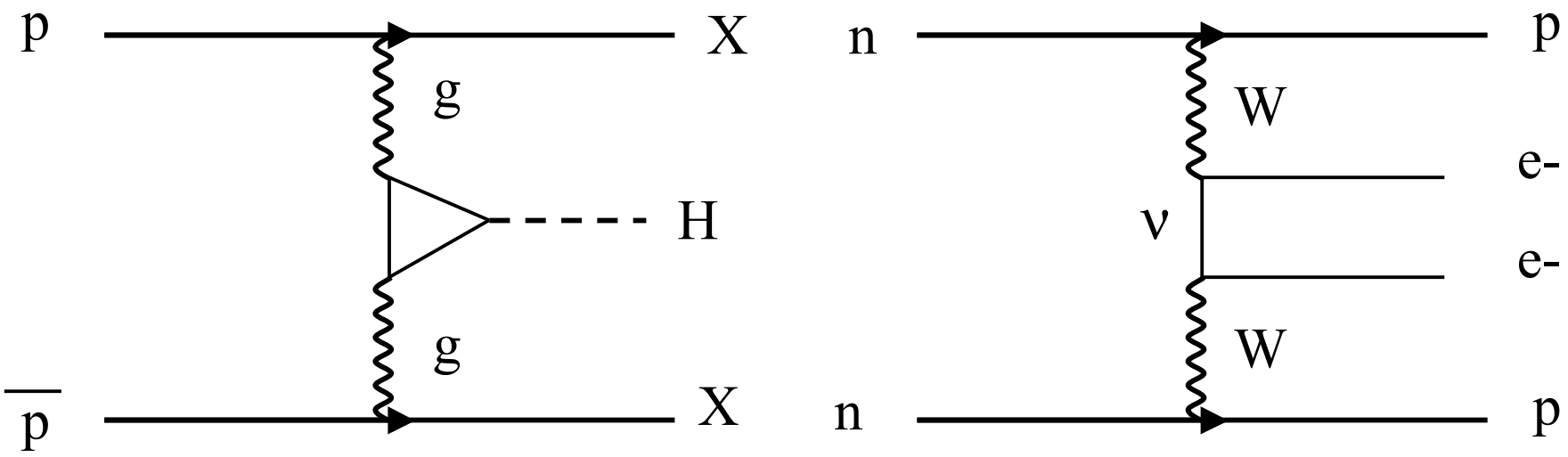
3) Absolute neutrino mass scale (SBD: sensitivity about 0.2 eV)

4) Type of neutrino mass hierarchy

5) CP violation (measurement of Majorana CP violating phases)

6) Existence of new physics (V+A, SUSY…)

Two needles in a haystack



$p_p \approx 1$ TeV

neutrons at rest
(in nucleus)

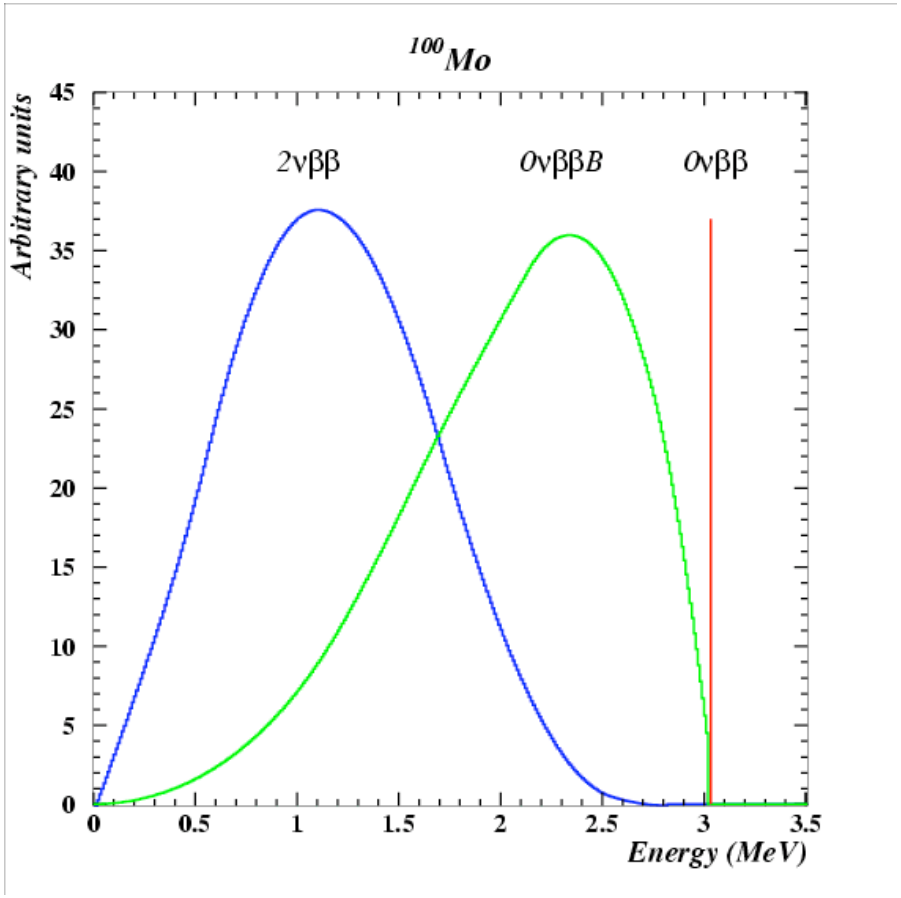
$m_H \approx 100$ - 200 GeV

$Q_{\beta\beta} \approx 3$ MeV

$\sigma_H/\sigma_{tot} \approx 10^{-12}$

$T_{1/2}^{0\nu\beta\beta}/T_{1/2}^{nat} \approx 10^{-17}$

energy sum of two electron



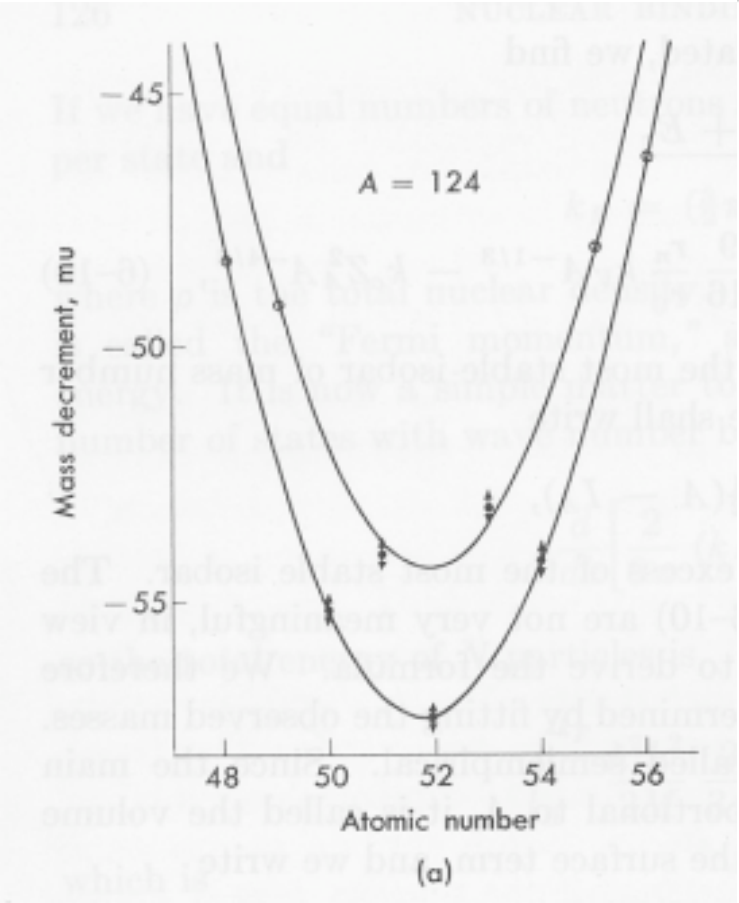
In many even-even nuclei, 'single' β decay is highly suppressed, leaving only ββ decay.

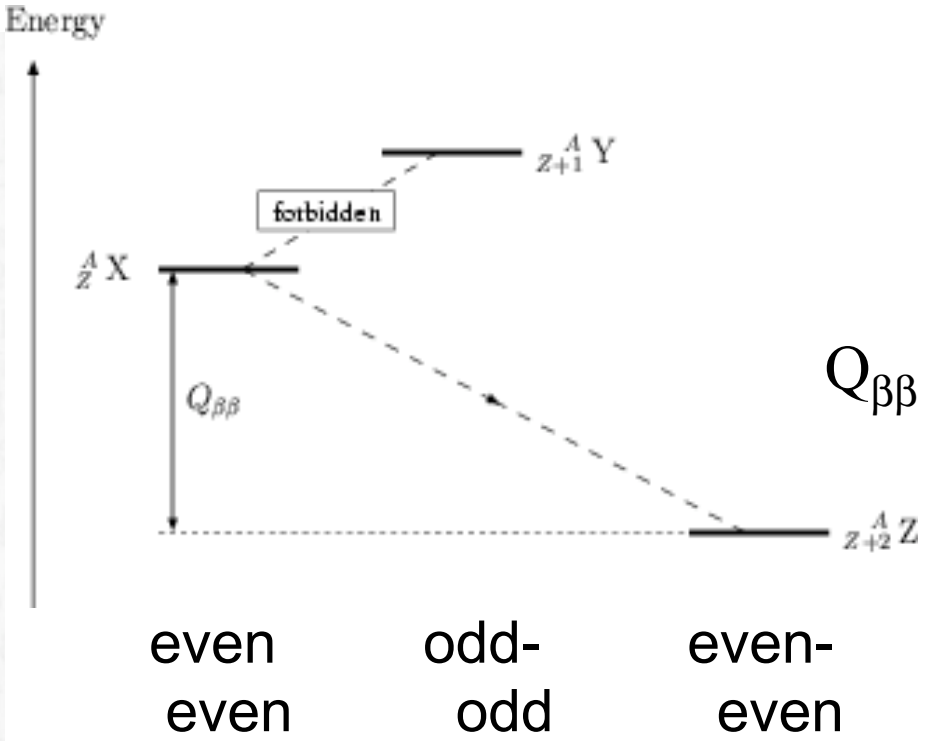
Only about ten isotopes can be used to search for double beta decay.

Most of them measured by NEMO

..some nuclear physics:

48-Ca, 76-Ge, 82-Se, 96-Zr, 100-Mo, 116-Cd, 128-Te, 130-Te, 150-Nd, and 238-U.

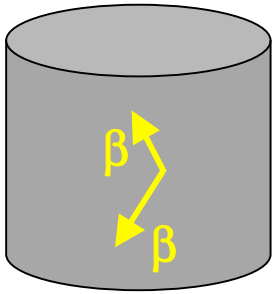




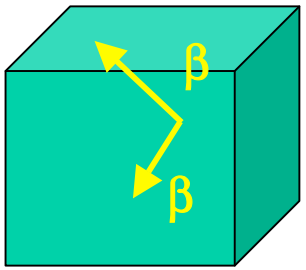
even even — odd-odd — even-even

Experimental Techniques

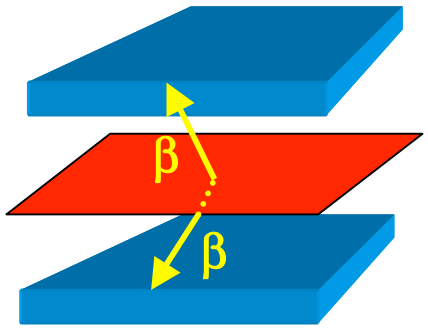
Calorimeter
Semi-conductors
Source = detector



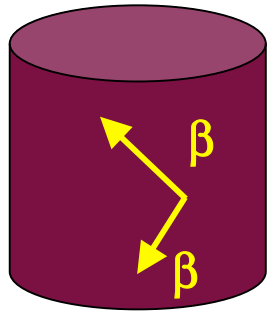
Calorimeter
Loaded Scintillator
Source = detector



Tracking + Calorimeter
Source ≠ detector



Xe TPC
Source = detector

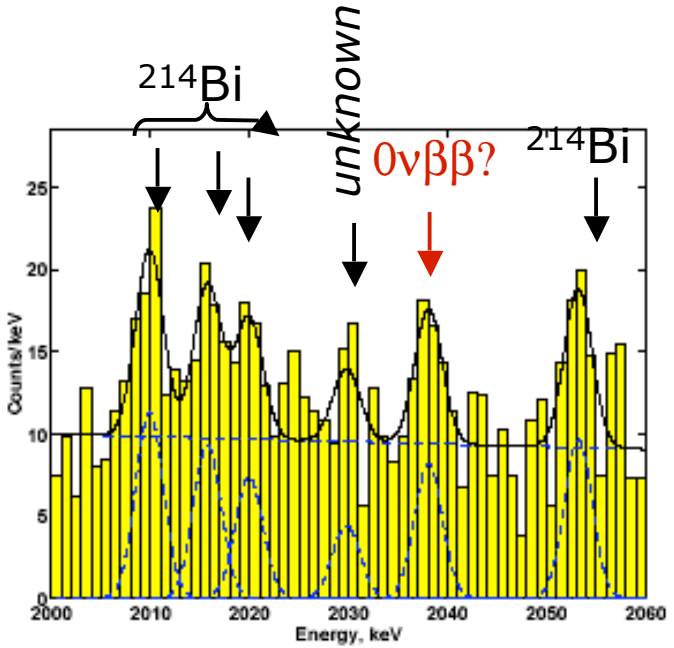


NEMO 3:

- Source separated from the detector
  - isotope choice flexibility.
- Calorimetry plus tracking technique.
- Background rejection through particle identification: e^-, e^+, γ, α particles

Heidelberg-Moscow Experiment in Gran Sasso

(Klapdor-Kleingrothaus et al.)



- 11 kg, 86% ^{76}Ge
- ΔE/E ~ 0.2%
- >10 years of data

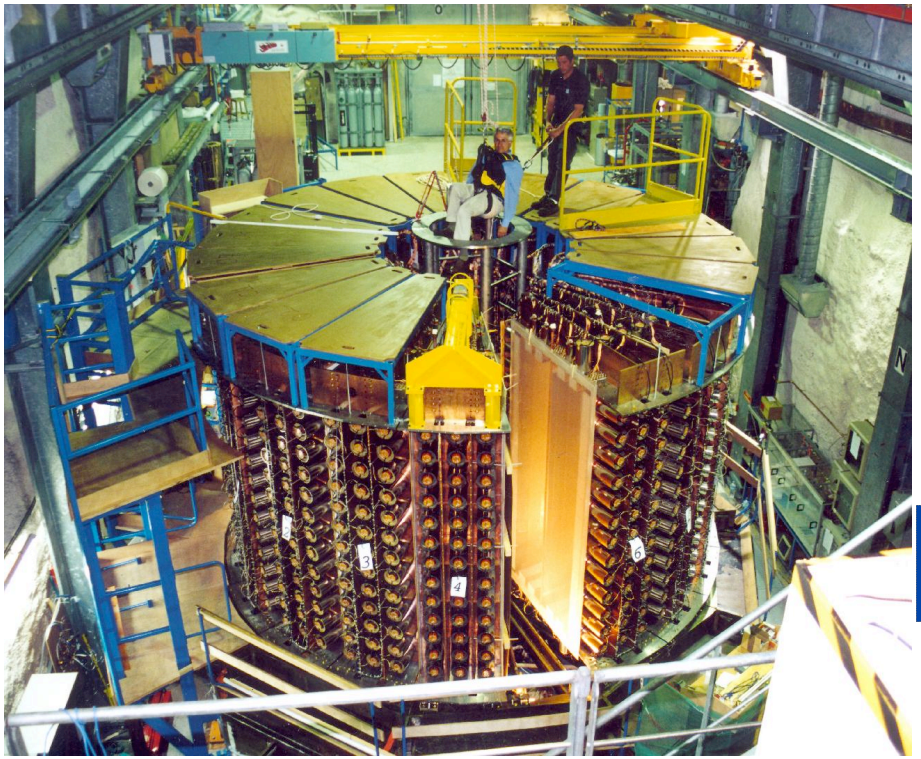
$$< m_\nu >^2 = \left| \sum_i^N U_{ei}^2 m_i \right|^2 = \left| \sum_i^N |U_{ei}|^2 e^{\alpha_i} m_i \right|^2$$

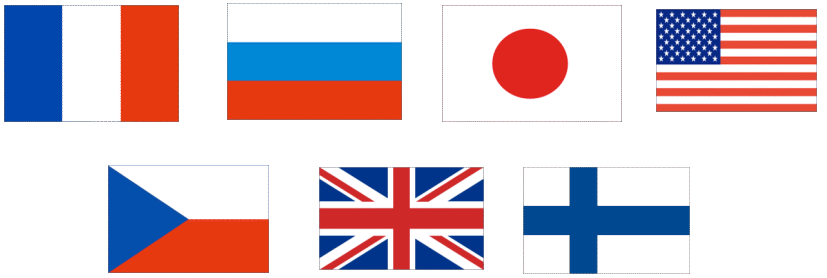
$$< m_\nu >= 0.1 - 0.9\,\text{eV (KDHK, 2004)}$$

disputed

NEMO 3: Neutrino Ettore Majorana Observatory

Modane – Frejus tunnel
at 1800 m (4800 m.w.e)

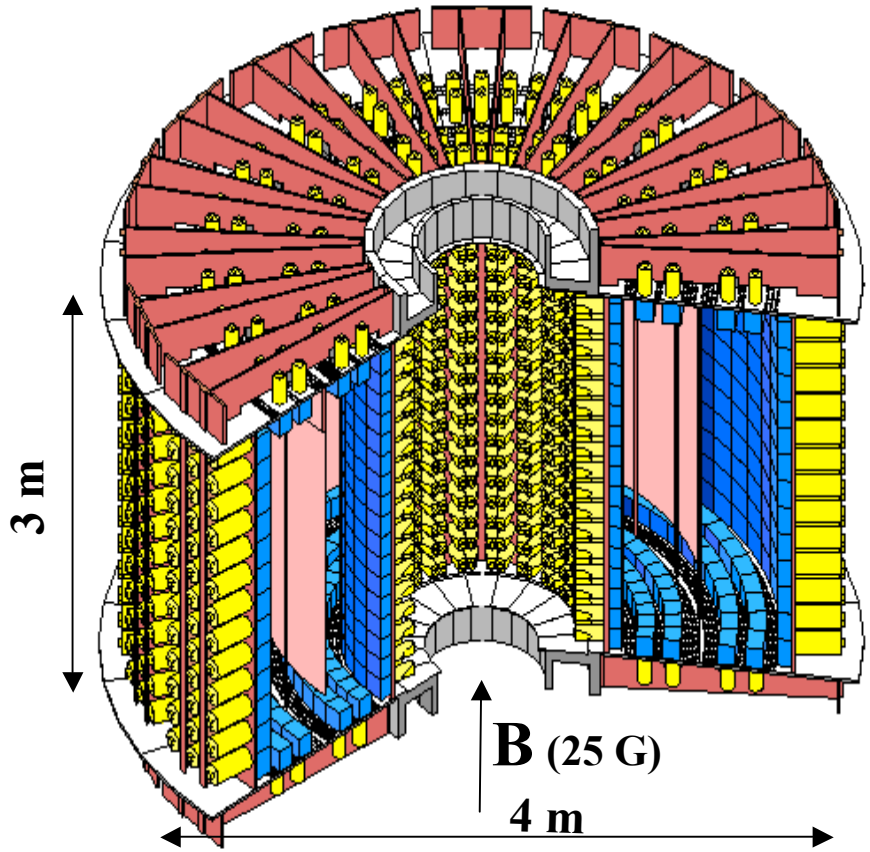




NEMO - 3

Fréjus Underground Laboratory : 4800 m.w.e.

20 sectors



Source: ~10 kg of ββ isotopes

cylindrical, surface = 20 m^2, 60 mg/cm^2

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

$\sigma_\perp$ = 5 mm, σ_z = 1 cm (vertex)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

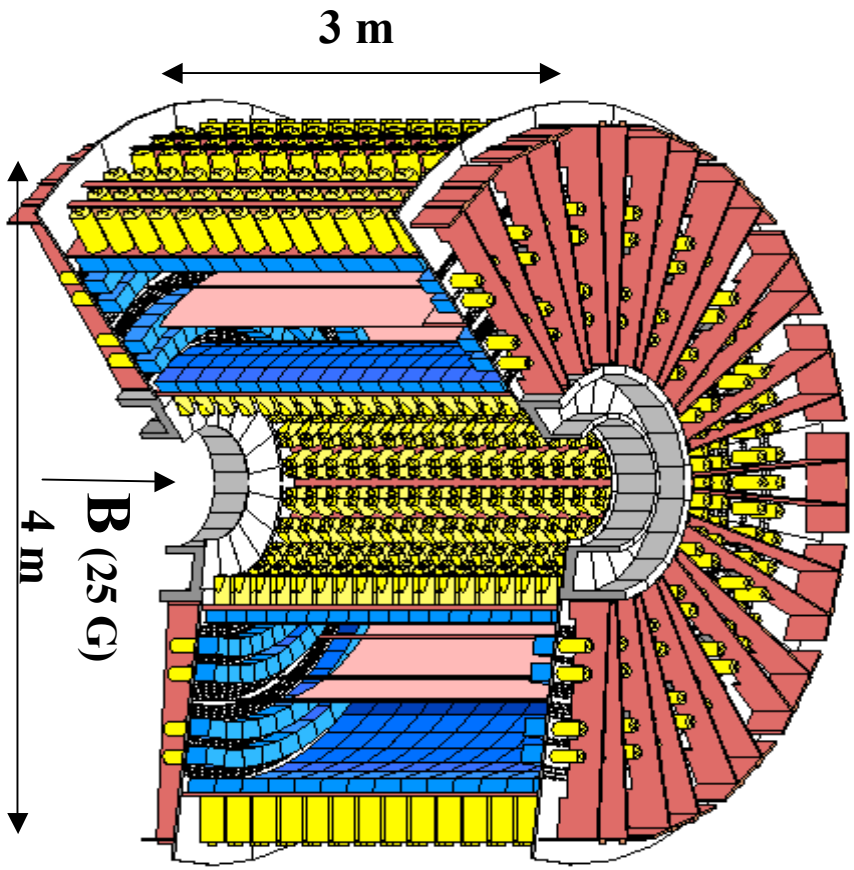
Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

time of flight σ = 250 ps

NEMO - 3

Fréjus Underground Laboratory : 4800 m.w.e.



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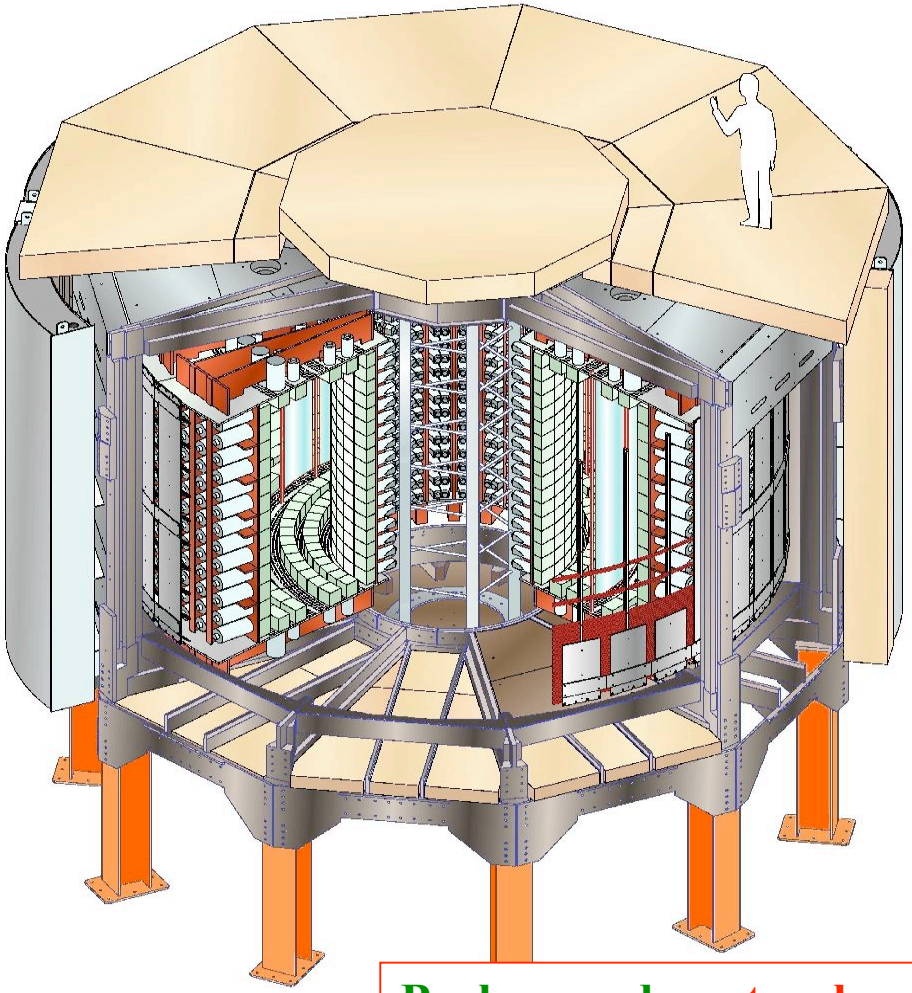
‘Particle Physics Approach’

NEMO - 3

Fréjus Underground Laboratory : 4800 m.w.e.



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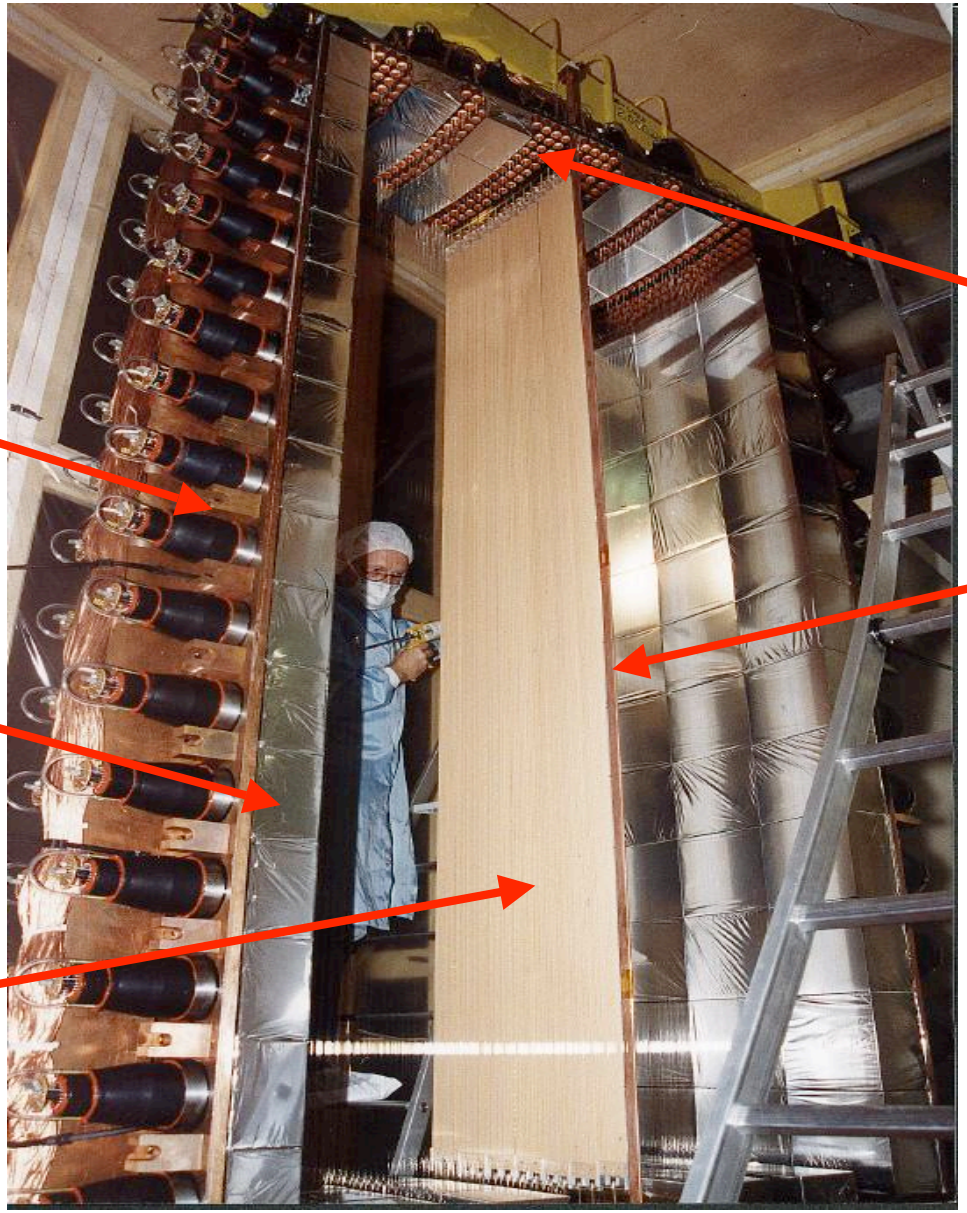
$\sigma_\perp = 5$ mm, $\sigma_z = 1$ cm (vertex)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs
time of flight $\sigma = 250$ ps

Magnetic field: 25 Gauss
Gamma shield: pure Iron (18 cm)
Neutron shield: borated water, wood

Background: natural radioactivity, mainly ^{214}Bi and ^{208}Tl
Radon, neutrons (n,γ), muons, ββ2ν

Sector Interior View



Finished detector

The NEMO experimental approach

Calorimetry plus tracking
(source ≠ detector)

Detection of both electrons: reject unknown nuclear gamma line

Three kinematic observables: study underlying physics mechanism

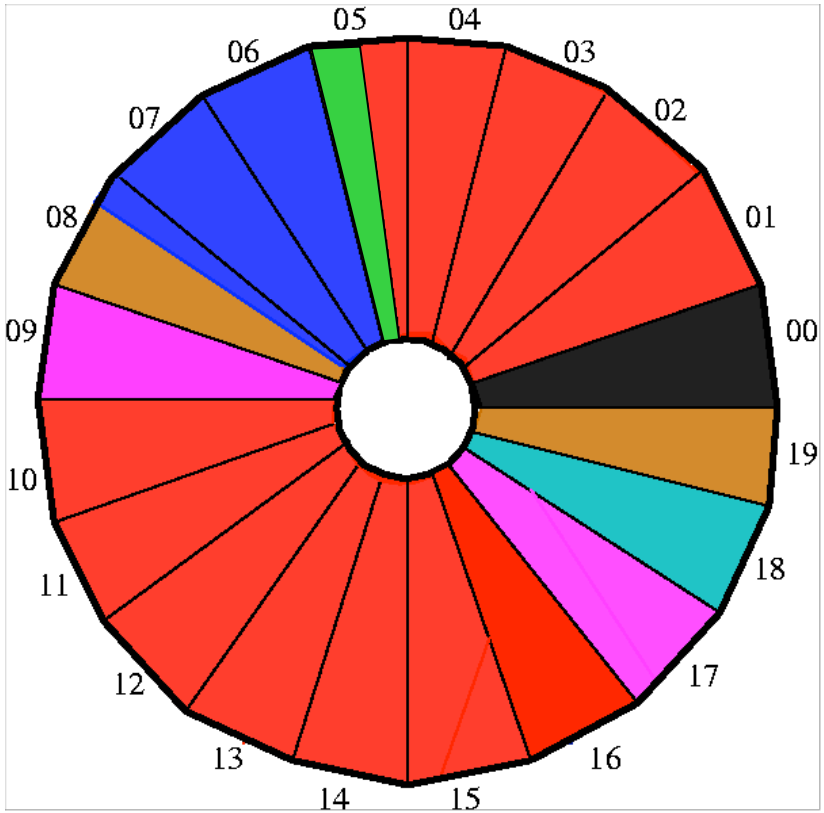
(i) individual electron energies
(ii) angular correlation
(iii) energy sum

Sources separated from the detector: measure $T_{1/2}$ for several isotopes

Background rejection through particle identification: e^-, e^+, γ, α particles

unique and complementary to source = detector experiments

ββ decay isotopes in NEMO-3 detector



ββ2ν measurement

- ^{116}Cd 405 g, $Q_{\beta\beta}$ = 2805 keV
- ^{96}Zr 9.4 g, $Q_{\beta\beta}$ = 3350 keV
- ^{150}Nd 37.0 g, $Q_{\beta\beta}$ = 3367 keV
- ^{48}Ca 7.0 g, $Q_{\beta\beta}$ = 4272 keV
- ^{130}Te 454 g, $Q_{\beta\beta}$ = 2529 keV
- ^{nat}Te 491 g
- Cu 621 g

External bkg measurement

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

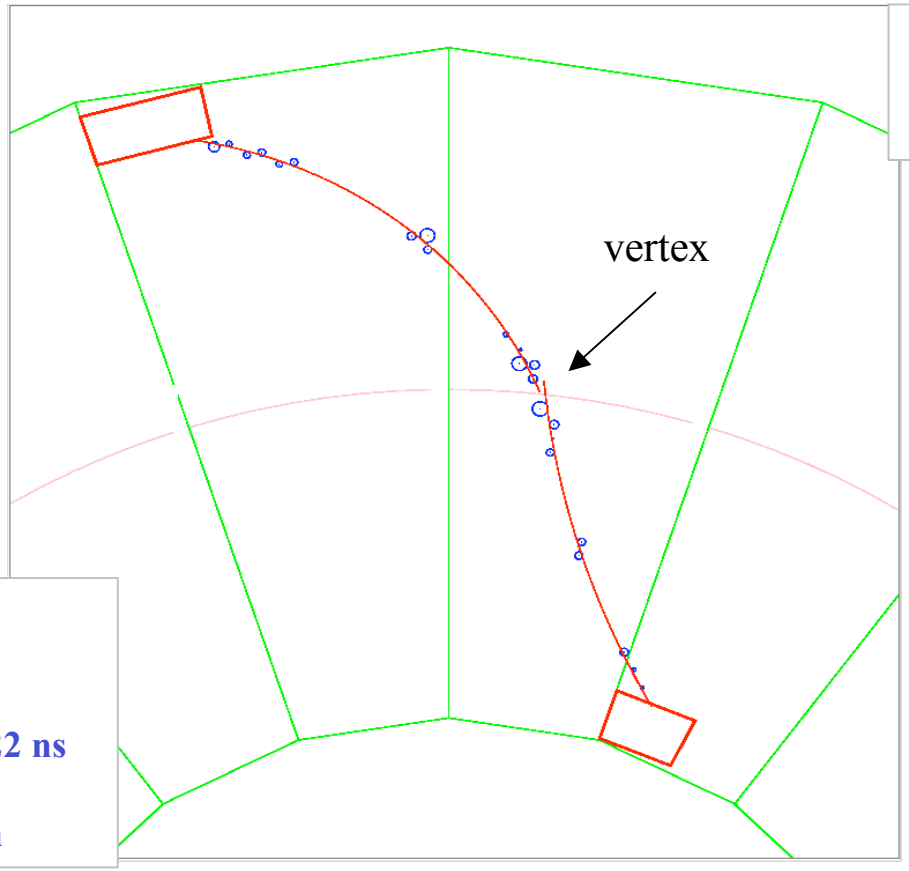
^{82}Se 0.932 kg, $Q_{\beta\beta}$ = 2995 keV

ββ0ν search

(All enriched isotopes produced in Russia)

Typical ββ2ν event observed in ^{100}Mo

Transverse view



Run Number: 2040
Event Number: 9732
Date: 2003-03-20

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

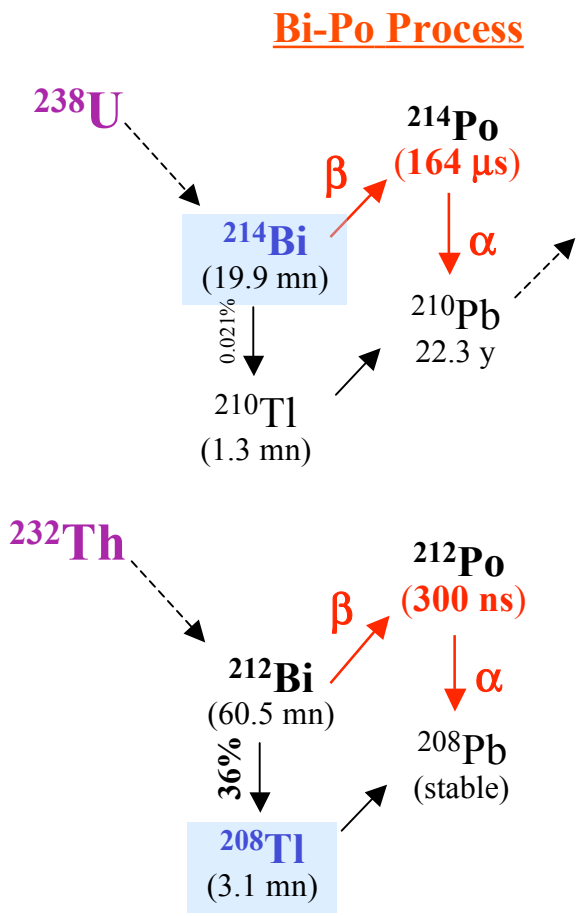
Trigger: **at least 1 PMT > 150 keV**

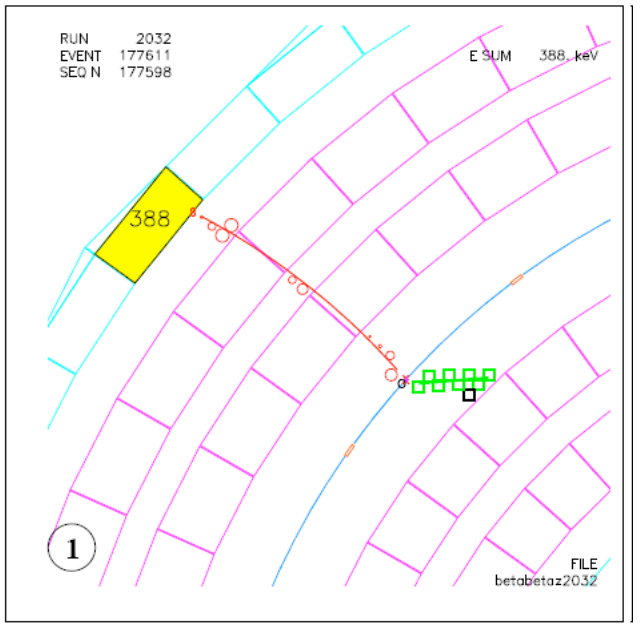
≥3 Geiger hits (2 neighbouring layers+1)

Trigger rate = 7 Hz

25 ββ events per hour

Backgrounds

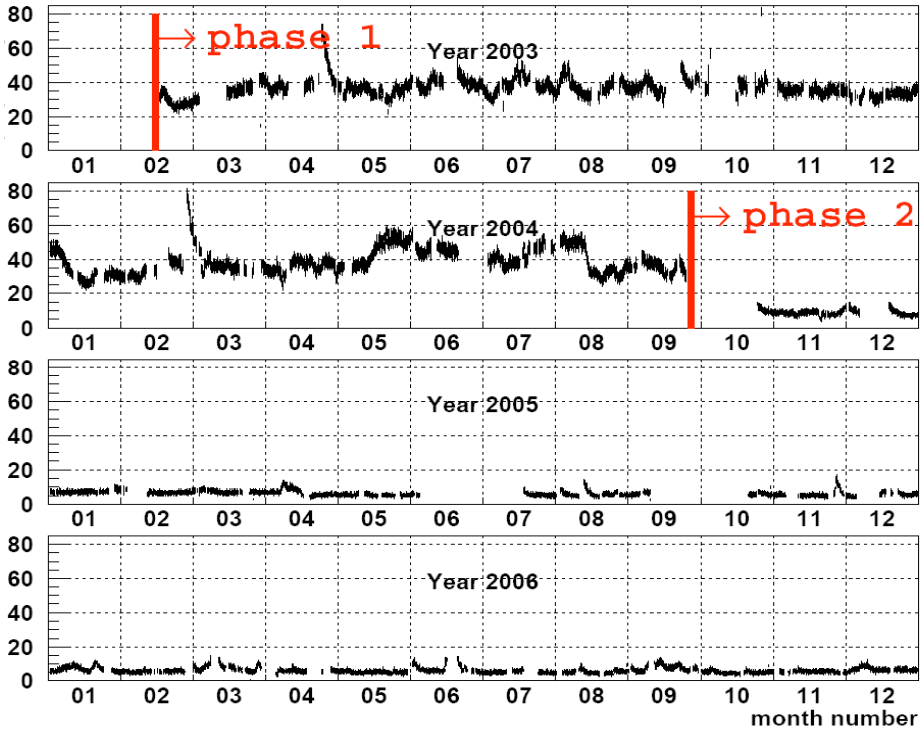




NEMO measures
each component of its background

Radon Trapping Facility

- Radon trapping facility installed in September 2004.
- The trapping time in activated charcoal longer than ^{222}Rn half-life of 3.8 days.
- Radon level reduced by almost factor of 10 by installing radon trapping facility



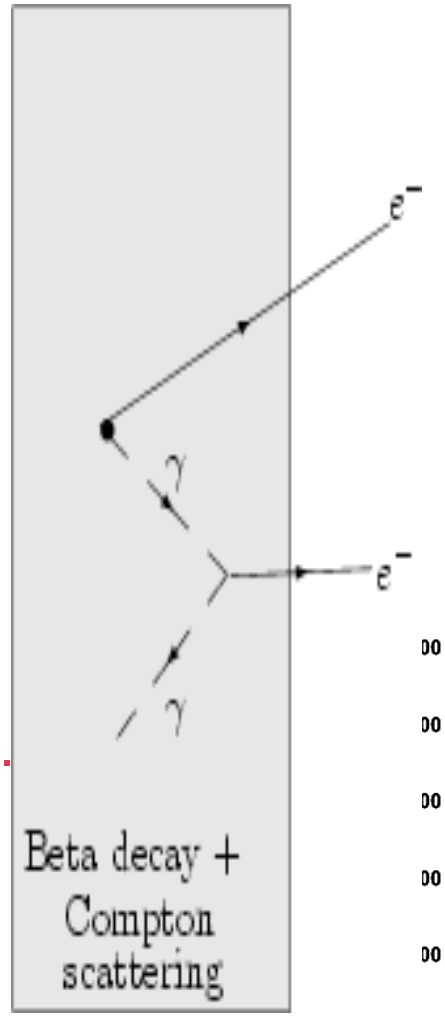
Adsorption unit @-50°C

Input: A(^{222}Rn) 15 Bq/m^3

Output: A(^{222}Rn) < 15 mBq/m^3 !! reduction factor of 1000

Control Channels

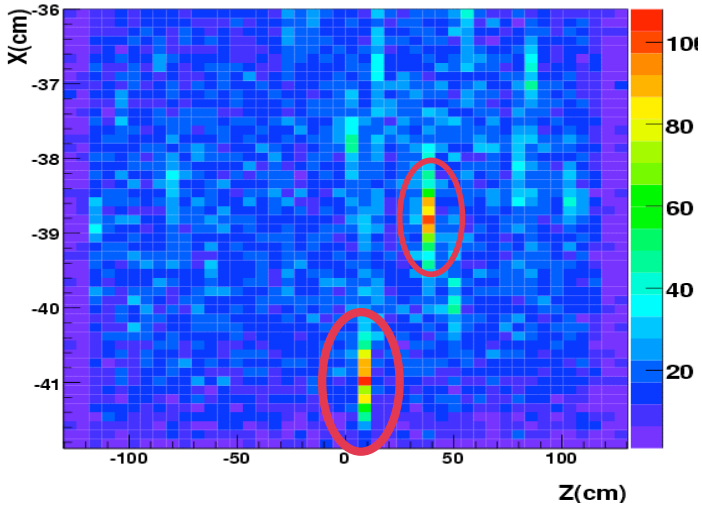
internal bg



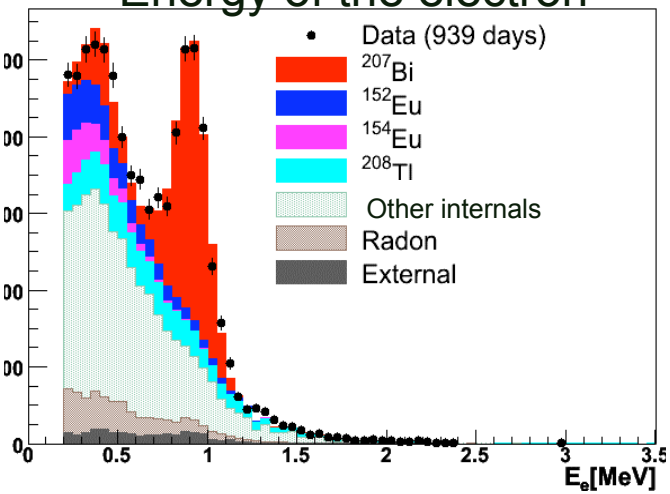
Example:

eγ control channel

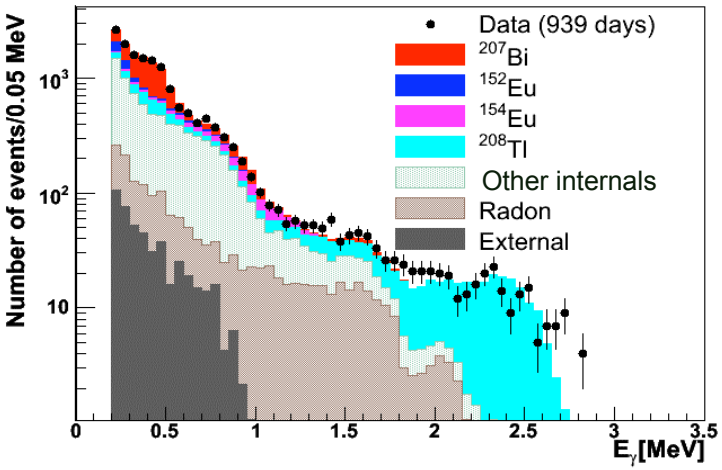
150-Nd foil



Energy of the electron



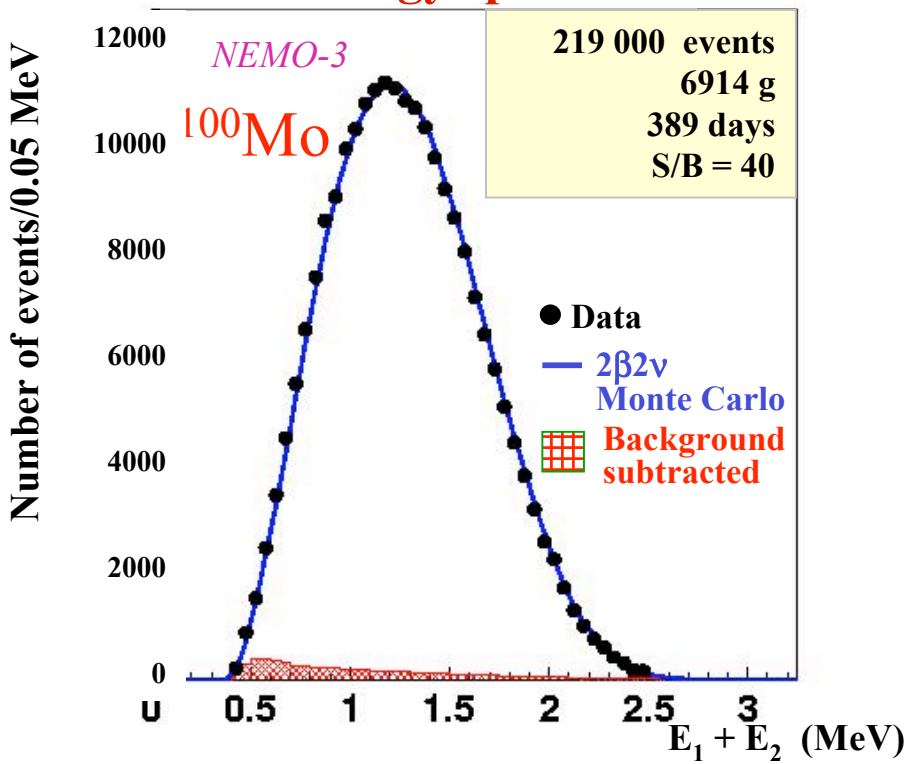
Energy of the photon



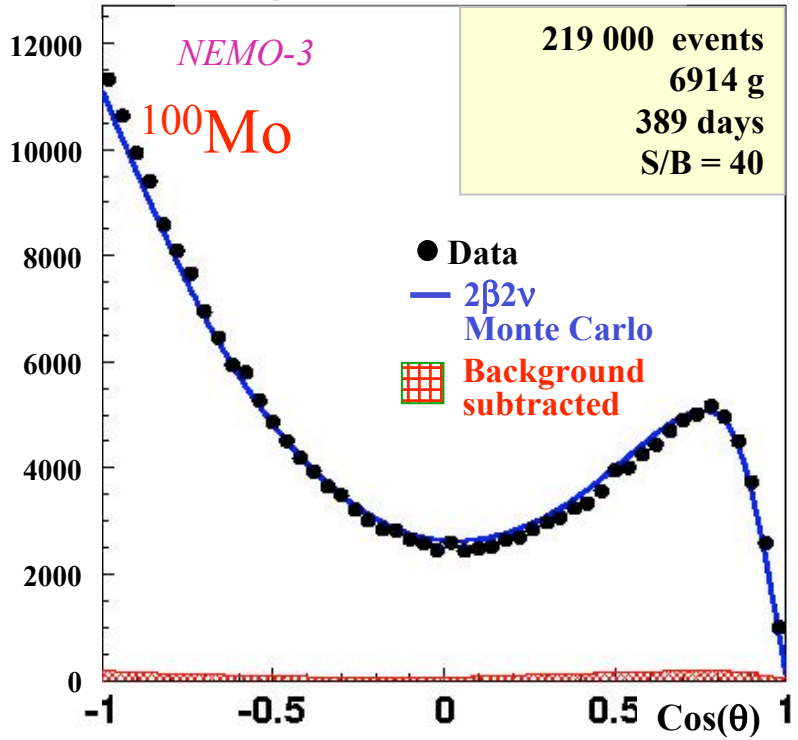
^{100}Mo ββ2ν results

Phase 1 Feb. 2003 – Dec. 2004 WITH RADON

Sum energy spectrum



Angular distribution



$T_{1/2}(\beta\beta2\nu) = 7.11 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ years

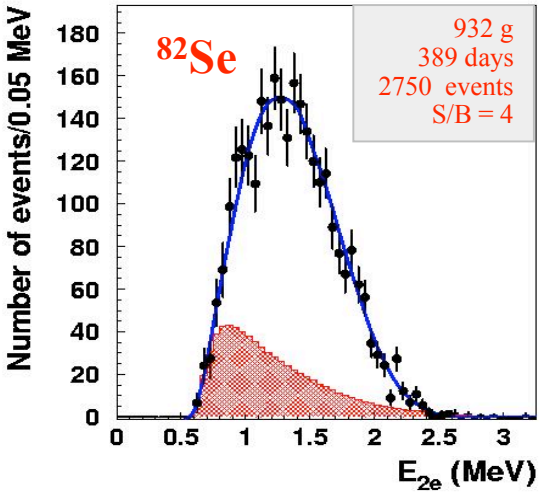
Phys. Rev. Lett. 95 182302 (2005)

«ββ factory» → tool for precision test

3.5 more years of data

ββ2ν results with other nuclei

Background subtracted



Preliminary results for ~360 d Phase I data. Additional statistics are being analysed and to be published soon.

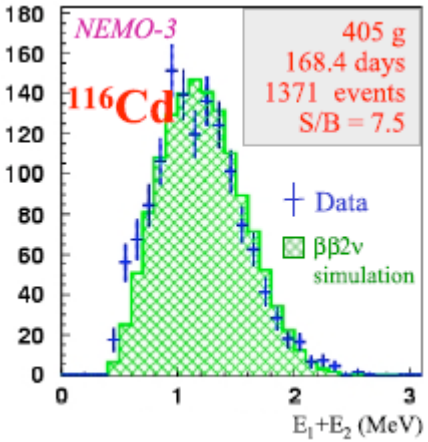
^{82}Se $T_{1/2} = 9.6 \pm 0.3\ (stat) \pm 1.0\ (syst) \times 10^{19}$ y

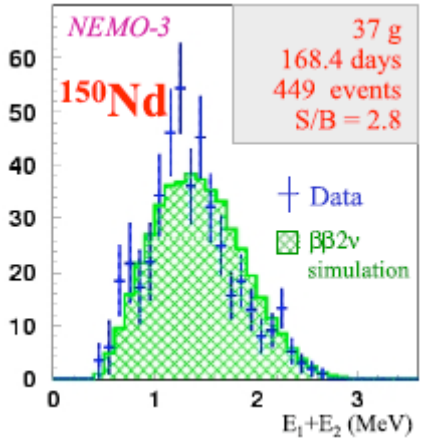
^{116}Cd $T_{1/2} = 2.8 \pm 0.1\ (stat) \pm 0.3\ (syst) \times 10^{19}$ y

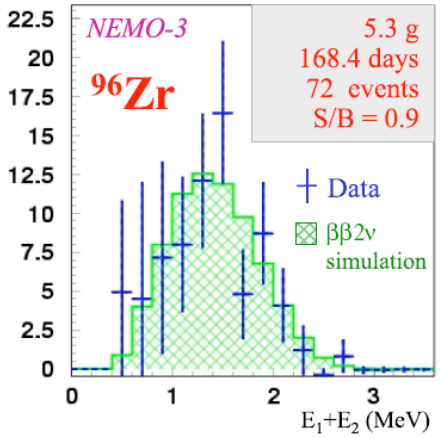
^{150}Nd $T_{1/2} = 9.7 \pm 0.7\ (stat) \pm 1.0\ (syst) \times 10^{18}$ y

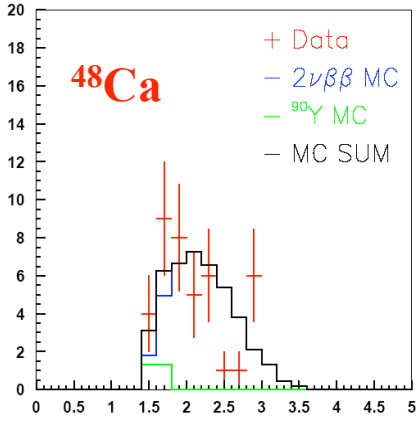
^{96}Zr $T_{1/2} = 2.0 \pm 0.3\ (stat) \pm 0.2\ (syst) \times 10^{19}$ y

^{48}Ca $T_{1/2} = 3.9 \pm 0.7\ (stat) \pm 0.6\ (syst) \times 10^{19}$ y





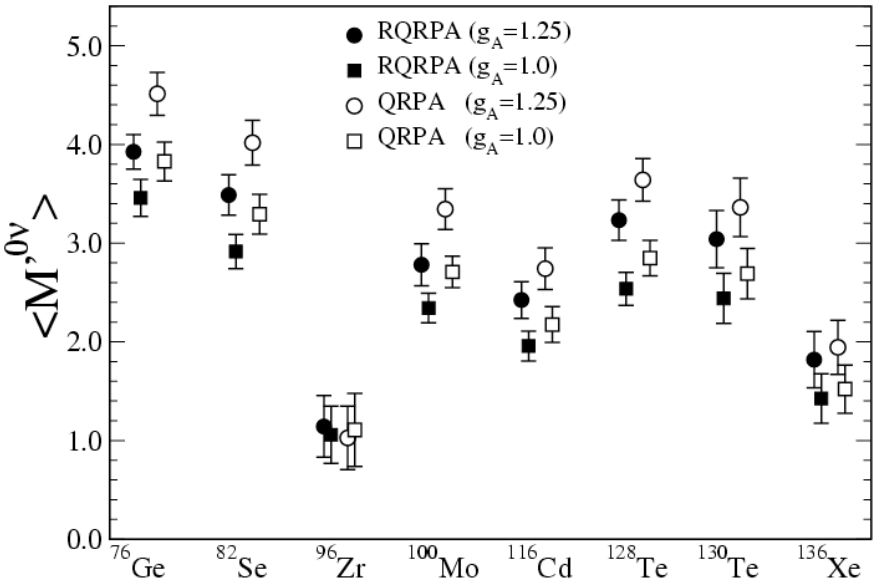




..ultimate irreducible background for ββ0ν search.

Nuclear Matrix Elements

V.A. Rodin et al., Nucl. Phys. A 766, 107 (2006) - Erratum



g_{pp} fixed from *experimentally* measured $M^{2\nu}$

Error bars are from experimental errors on $T_{1/2}^{2\nu}$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

NMEs source of largest uncertainty

ββ2ν half-life of ^{130}Te

The ββ2ν half-life of ^{130}Te has been a long-standing mystery:

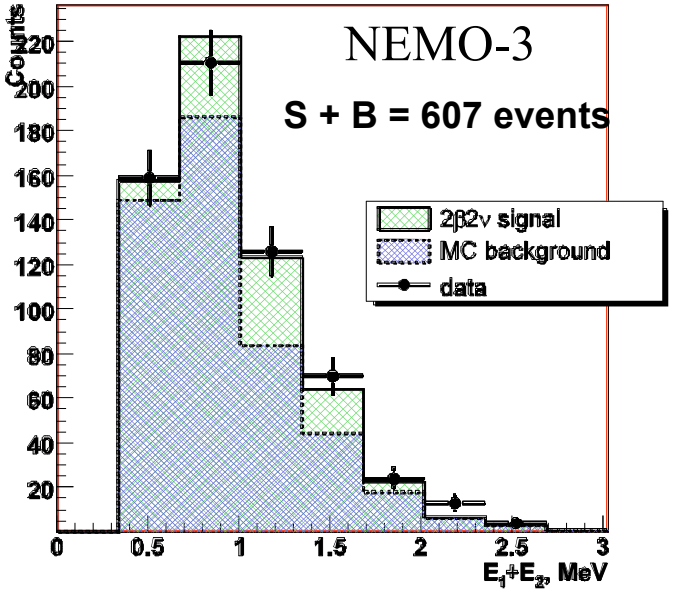
~1 billion years

~100 million years

Geochemical (^{130}Te → ^{130}Xe):
- (25 ± 2) x 10^{20} years (Kirsten 83)
- (27 ± 2) x 10^{20} years (Bernatowicz 93)
- (7.9 ± 1) x 10^{20} years (Takaoka 96)
- ~8 x 10^{20} years (Manuel 91)

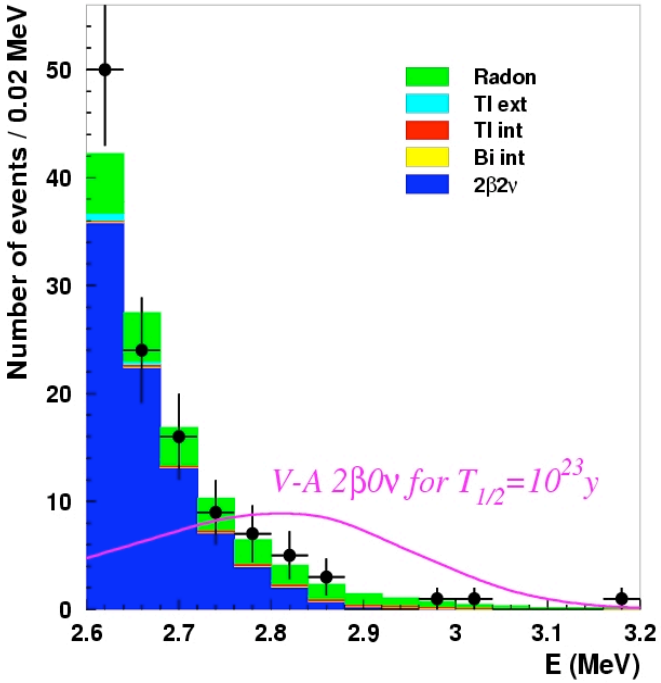
Difference between 'old' and 'young' ores due to time dependence of G_F..?

Direct measurements:
(6.1 ± 3.5) x 10^{20} years (Arnaboldi 2003)
(7.6 ± 1.7) x 10^{20} years (NEMO-3)



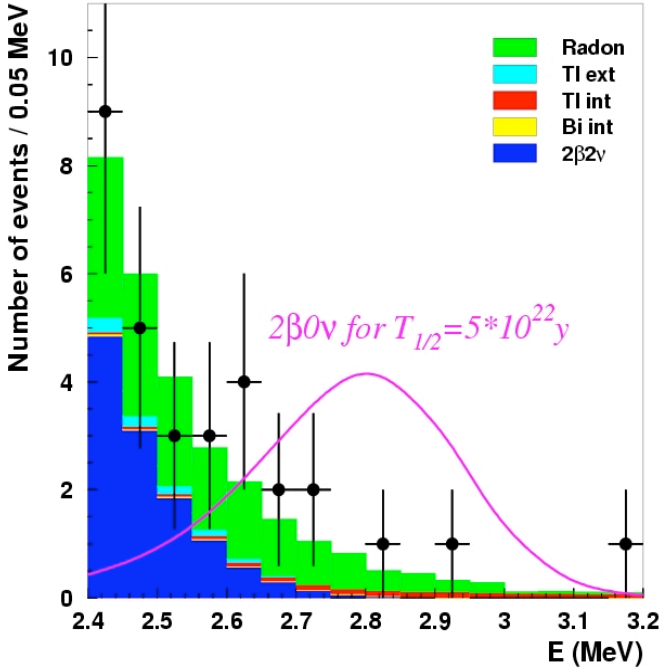
ββ0ν search

^{100}Mo, Phase I + II, 693 days



$T_{1/2}^{\beta\beta0\nu} > 5.8 \times 10^{23}$ (90 % CL)
$\langle m_\nu \rangle < 0.8 - 1.3$ eV

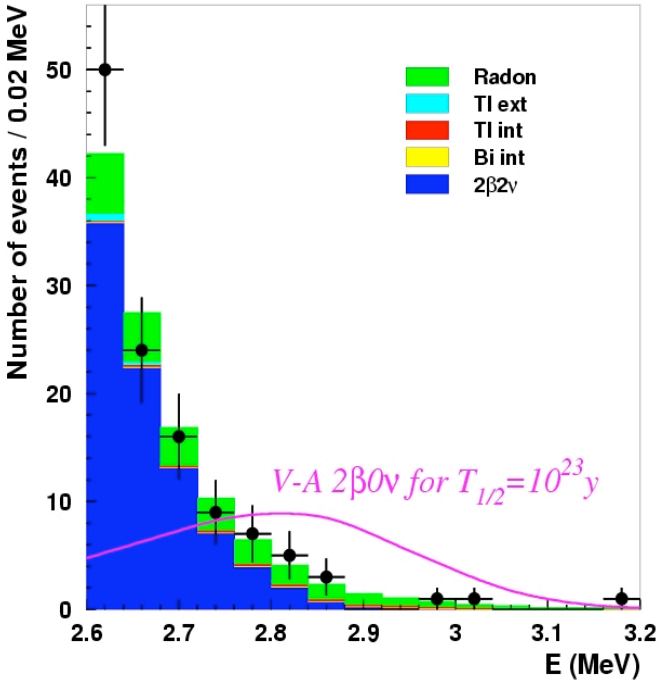
^{82}Se ,Phase I + II, 693 days



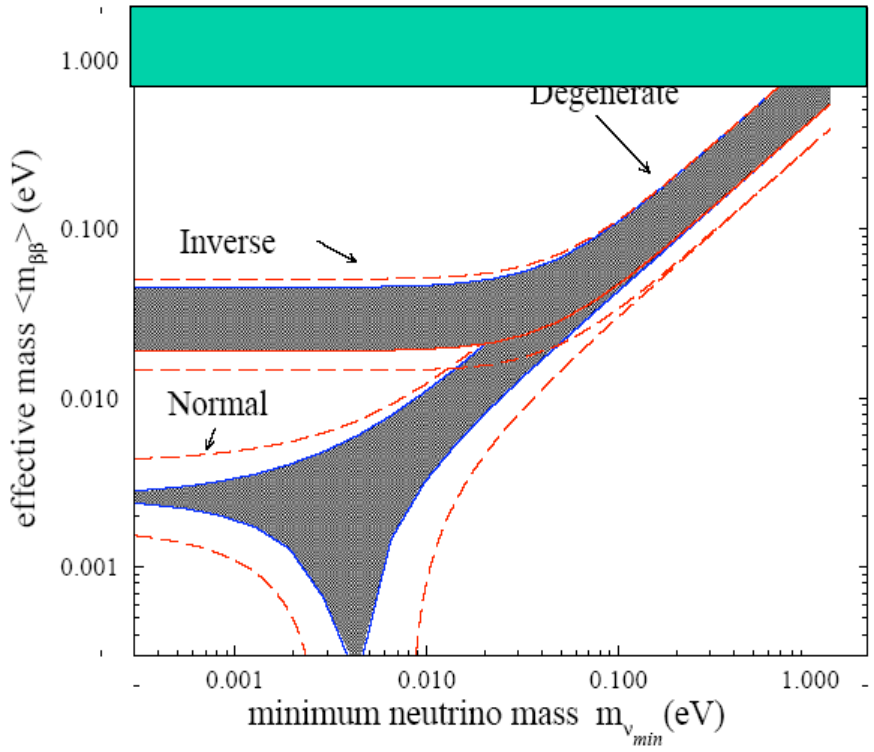
$T_{1/2}^{\beta\beta0\nu} > 2.1 \times 10^{23}$ (90 % CL)
$\langle m_\nu \rangle < 1.4\text{-}2.2$ eV

ββ0ν search

^{100}Mo, 4782 kg days



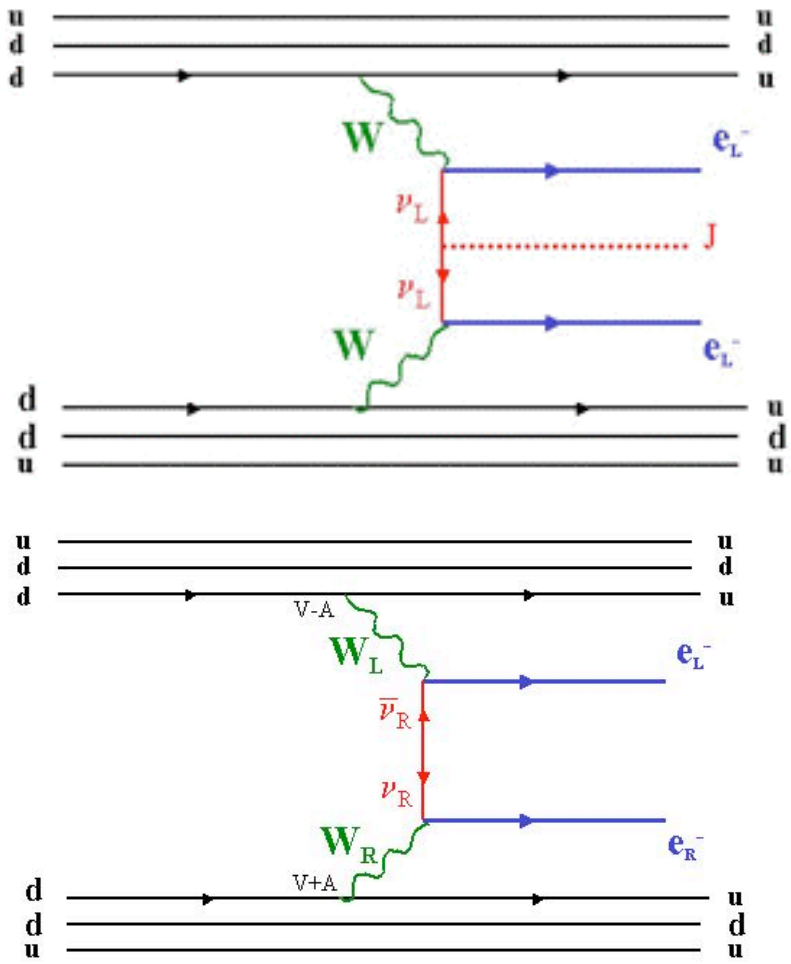
$T_{1/2}^{\beta\beta0\nu} > 5.8 \times 10^{23}$ (90 % CL)
$\langle m_\nu \rangle < 0.8 - 1.3$ eV



expected in 2009: $T_{1/2}^{\beta\beta0\nu} > 2 \times 10^{24}$ (90 % CL)
$\langle m_\nu \rangle < 0.3 - 0.6$ eV

analysis now blinded, will open box in 2009 and once more later

Majorons and V+A currents

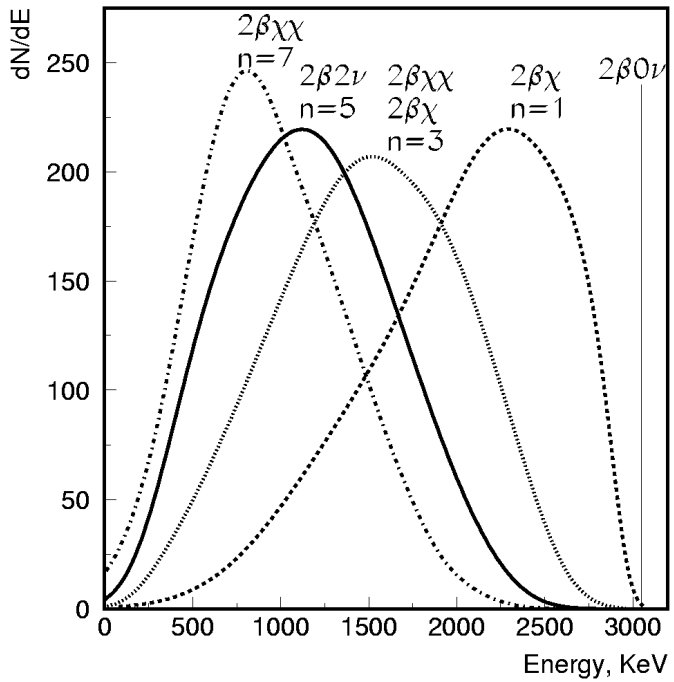


- Majorons χ with coupling to neutrinos
- Goldstone boson due to B-L symmetry breaking
- also used as generic term for a large number of models

- V+A, right handed currents

Majorons and V+A currents

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



$\sim (Q\text{-}E_{12})^n$

world's best limits

	V+A *	n=1 **	n=2 **	n=3 **	n=7 **
Mo	**$>3.2\cdot10^{23}$** $\lambda<1.8\cdot10^{-6}$	**$>2.7\cdot10^{22}$** $g_{ee}<(0.4\text{-}1.8)\cdot10^{-4}$	**$>1.7\cdot10^{22}$**	**$>1.0\cdot10^{22}$**	**$>7\cdot10^{19}$**
Se	**$>1.2\cdot10^{23}$** $\lambda<2.8\cdot10^{-6}$	**$>1.5\cdot10^{22}$** $g_{ee}<(0.7\text{-}1.9)\cdot10^{-4}$	**$>6.0\cdot10^{21}$**	**$>3.1\cdot10^{21}$**	**$>5.0\cdot10^{20}$**

n: spectral index, limits on half-life in years

* PI+PII data

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

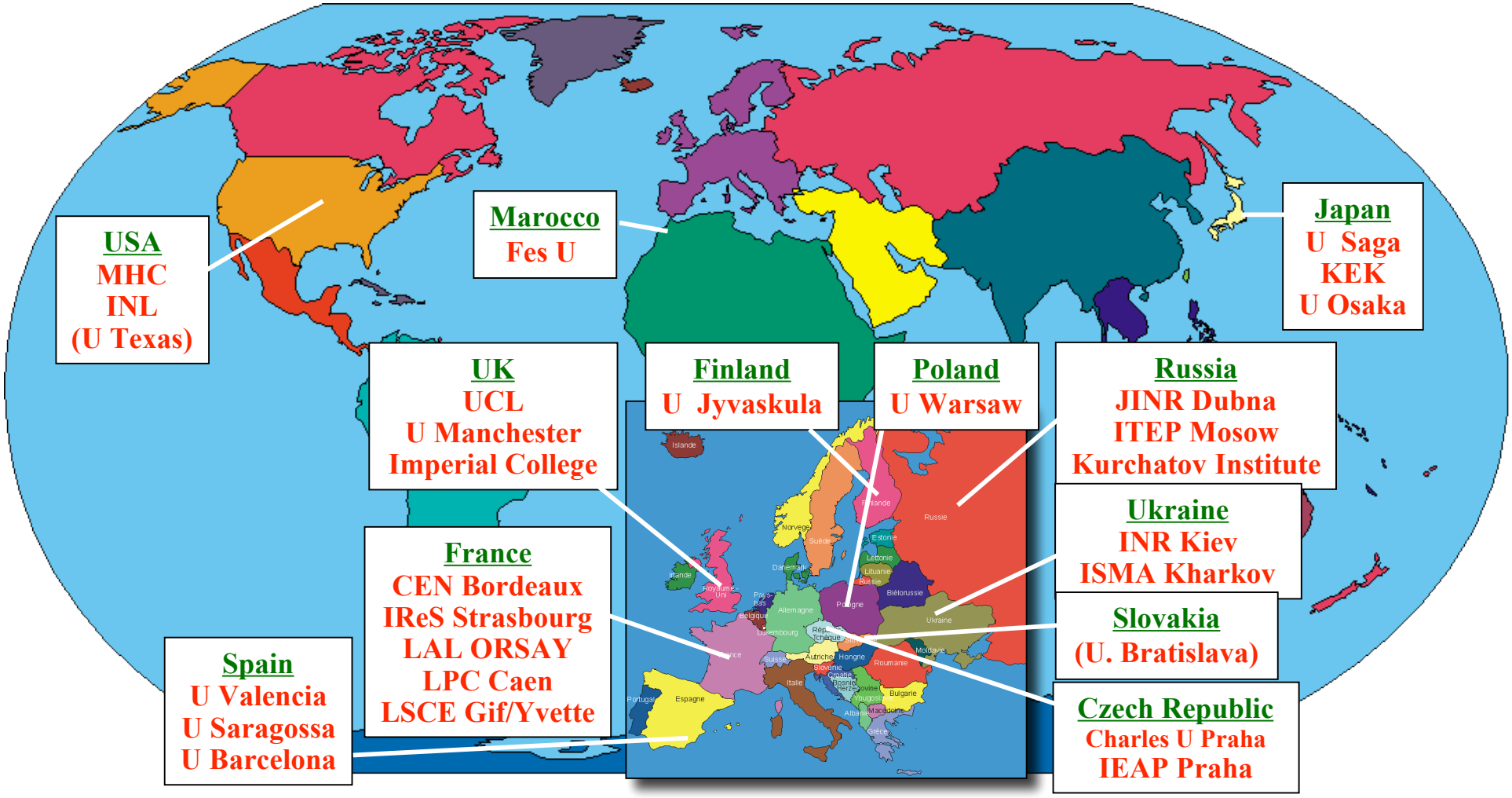
From NEMO-3 to SuperNEMO… challenges

$$T_{1/2}(\beta\beta 0\nu) > \ln 2 \times \frac{N_A}{A} \times \frac{M \times \varepsilon \times T_{obs}}{N_{90}}$$

NEMO-3		SuperNEMO
^{100}Mo	isotope	^{150}Nd or ^{82}Se
7 kg	isotope mass M	100-200 kg
8 %	efficiency ε	~ 30 %
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	internal contaminations ^{208}Tl and ^{214}Bi in the ββ foil	^{208}Tl < 2 μBq/kg *if ^{82}Se*: ^{214}Bi < 10 μBq/kg
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(\beta\beta 0\nu) > 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 - 0.9$ eV		$T_{1/2}(\beta\beta 0\nu) > 2 \times 10^{26}$ y $\langle m_\nu \rangle < 40\text{-}110$ meV

SuperNEMO Collaboration

~ 60 physicists, 12 countries, 27 laboratories



2006 – 2009

- Approved in UK, France and Spain. Similar proposals under consideration in Russia, Czech Republic, Japan
- Main tasks and deliverables
  - R&D on critical components
    - Calorimeter energy resolution of 4% at 3 MeV
    - Optimisation of tracking detector and construction (incl. robot)
    - Better background rejection (e.g. extra veto counters)
    - Ultrapure source production and purity control
    - Simulations and geometry optimisation
  - Experimental site selection (Frejus, Canfranc, Gran Sasso, Boulby)

SuperNEMO preliminary design

Planar geometry. 20 modules for 100+ kg

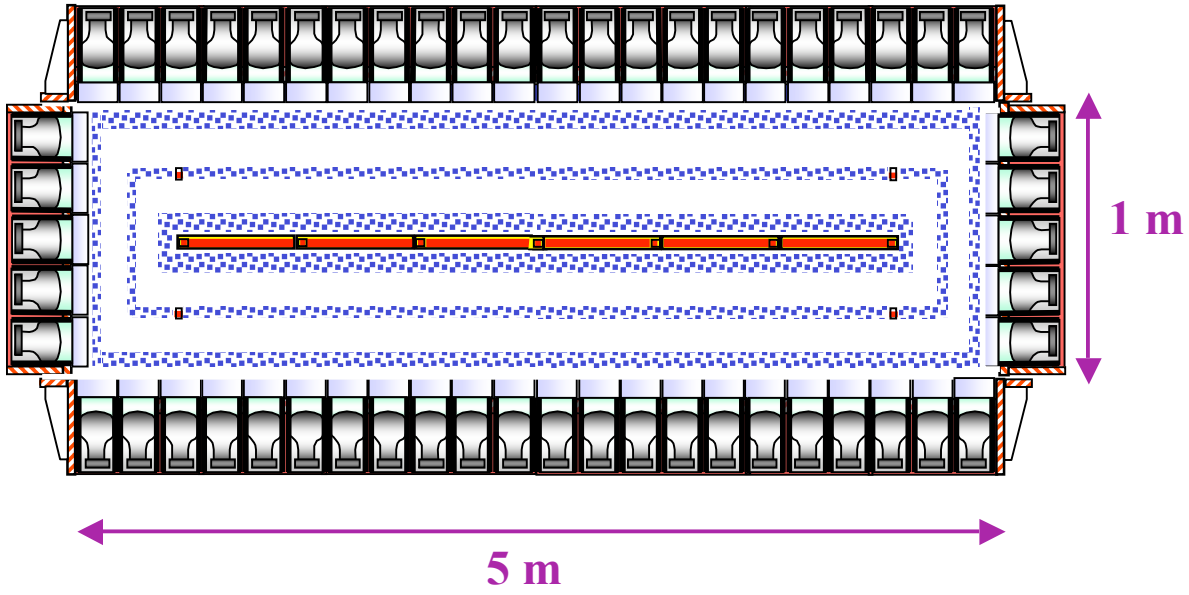
Single model (baseline design)

Source (40 mg/cm^2) 12m^2

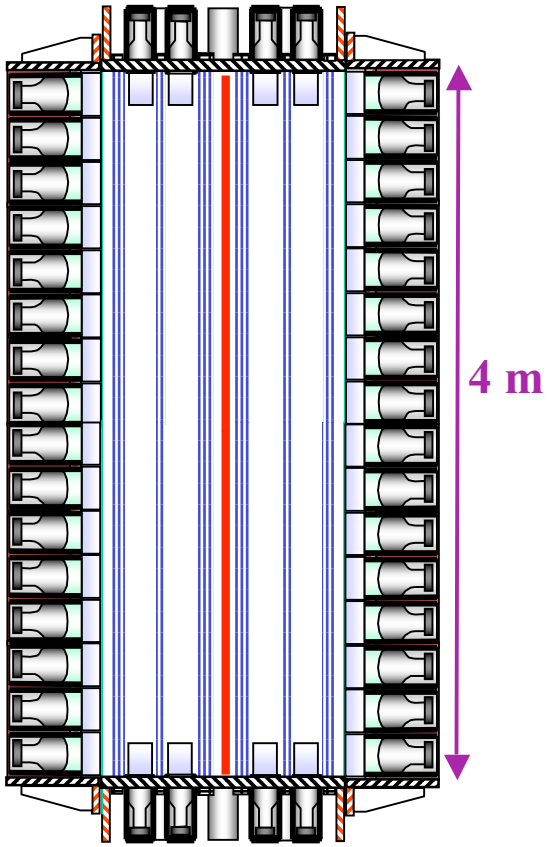
Total:

~ 40-60k Geiger channels for tracking

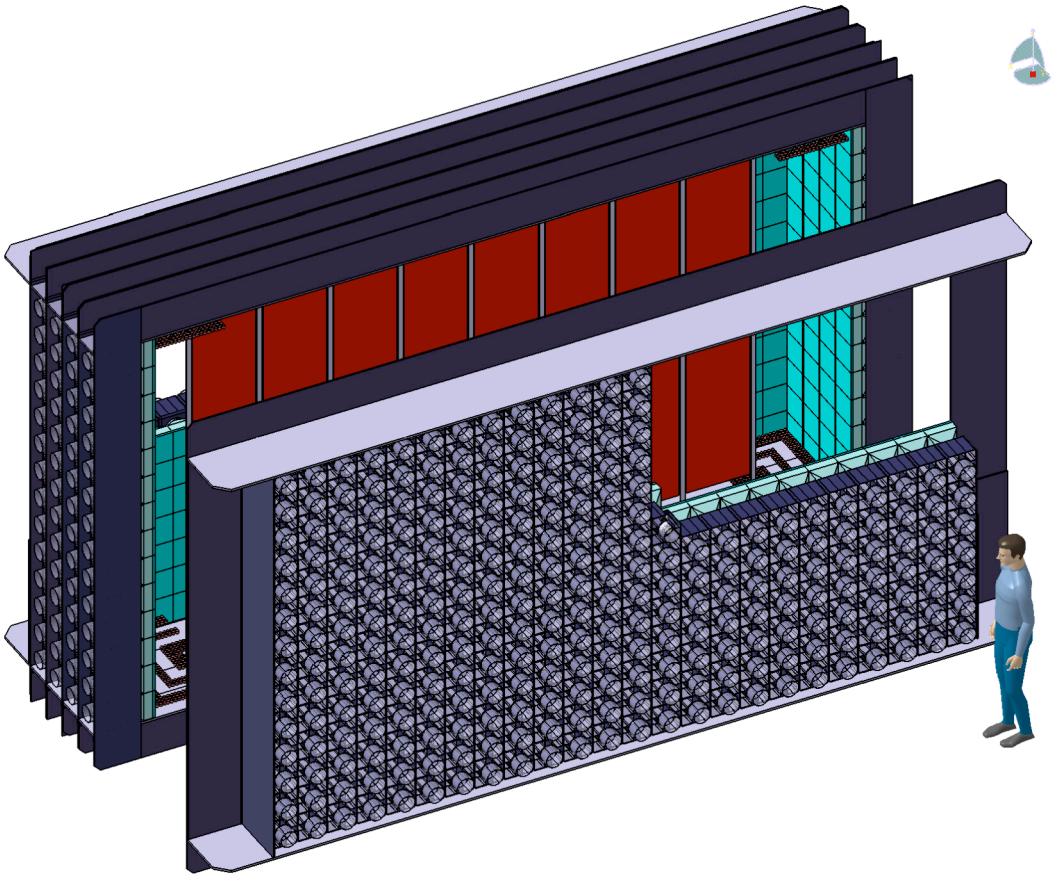
~ 10-20k PMTs (3k if scintillator bars design)

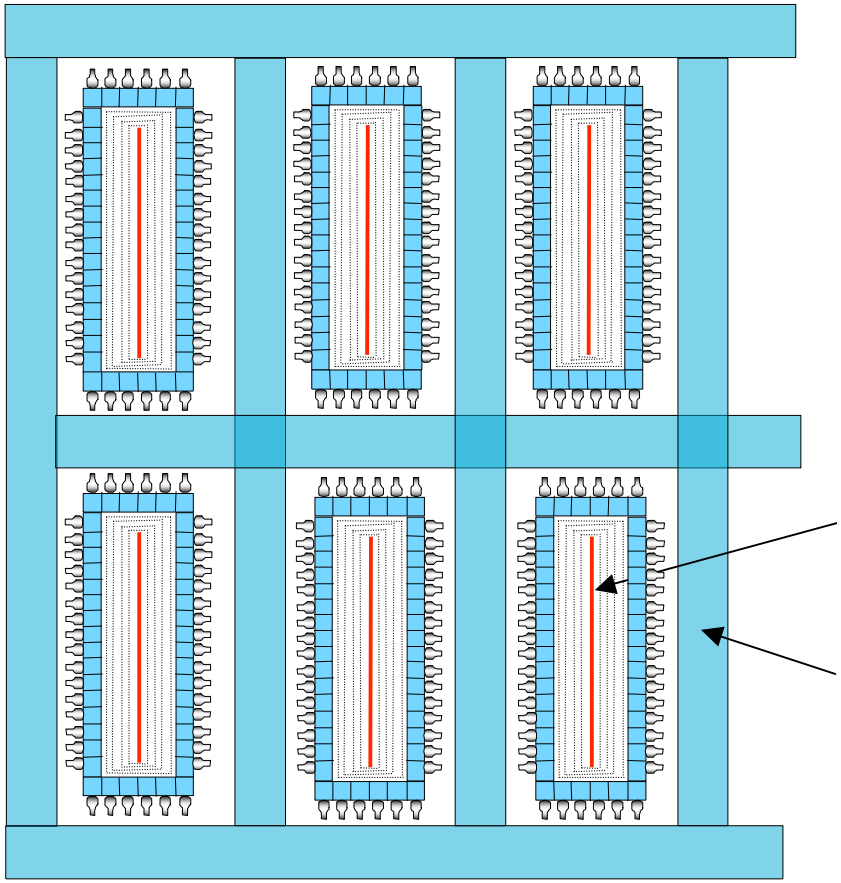


Top view



Side view



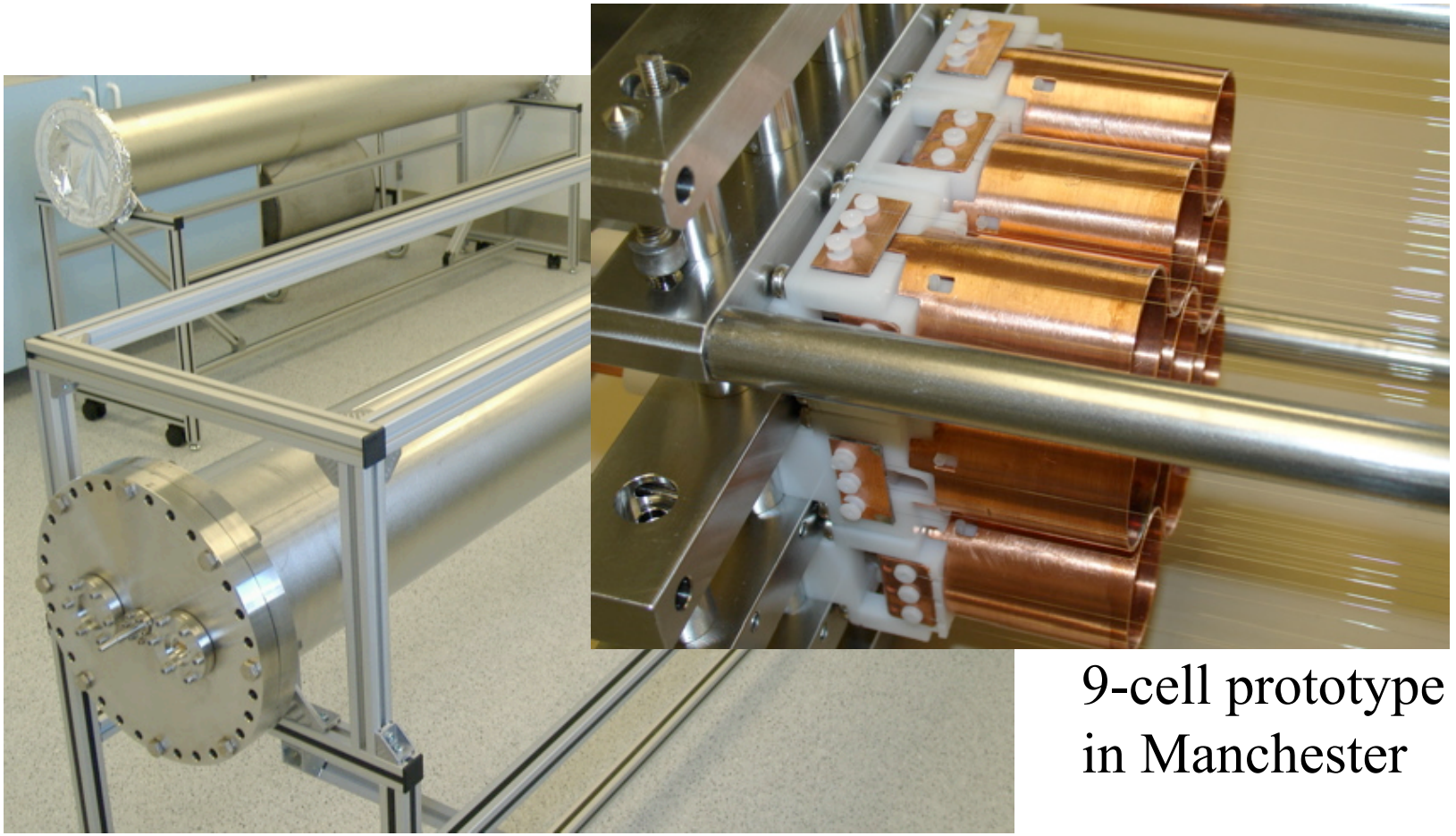


Single sub-module with ~5-7 kg of isotope

~20 sub-modules for 100+ kg of isotope surrounded by water shielding

Tracker

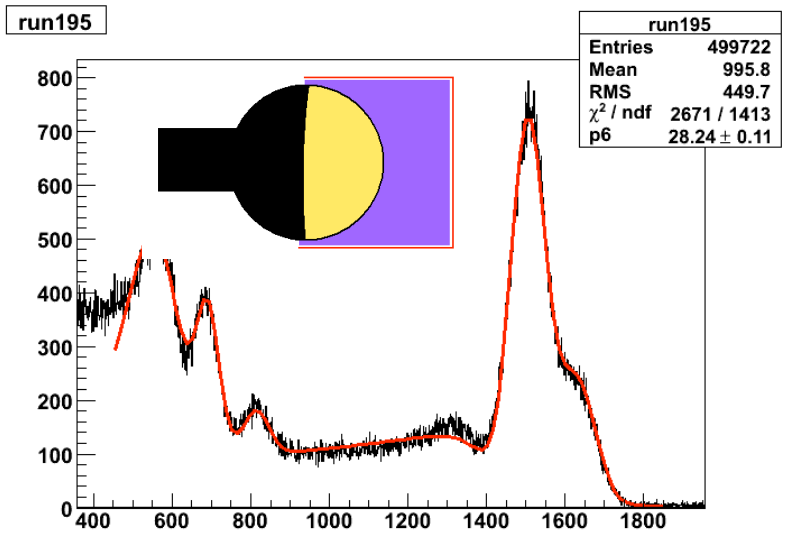
Optimize length, wire material and diameter, read-out, gas mixture etc
Several small prototypes built and successfully tested, robot development
100-cell prototypes to be finished by autumn 2008



9-cell prototype in Manchester

Calorimeter

- **Goal: FWHM ≈ 7-8%/√E ⇒ 4% at 3 MeV (Currently 14-16%/√E in NEMO3)**
- **A combination of energy losses in the foil and calorimeter resolution**
- **Studies**
  - **Organic (plastic and liquid),**
  - **Shape, size, coating**
  - **PMTs (Photonis, Hamamatsu, ETL)**
  - **Light guides, optical contact**
  - **Chemistry**



High QE Hamamatsu tube (8 in)+PVT

ΔE/E = 7.5-8% at 1 MeV
⇓
4% at 3 MeV if 1/√E

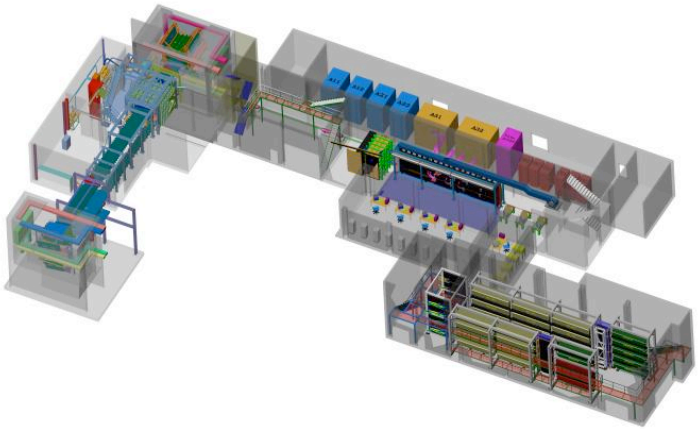
Choice of isotope/enrichment/purification

major cost factor

- 4 kg of ^{82}Se funded by ILIAS have been delivered from Russia.
- purification at ILN (Idaho)
- enrichment of Nd possible in France (MENPHIS, currently mothballed)

Choice of nucleus depends on:

- enrichment possibilities
- high $Q_{\beta\beta}$ value
  - → larger phase space
  - → lower non-ββ background
  - → increase in ββ2ν small



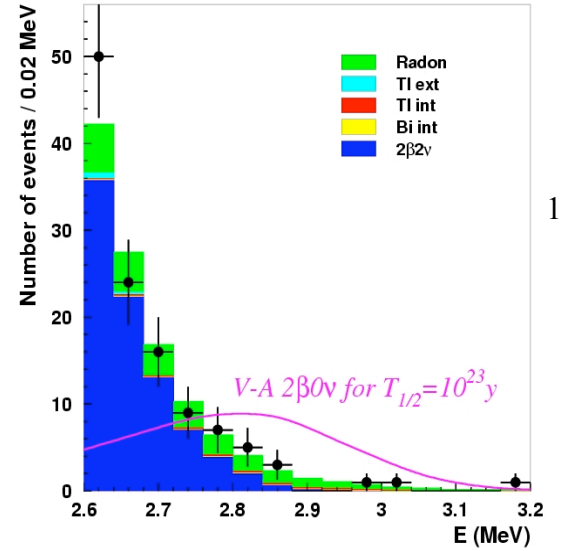
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

Two main options:

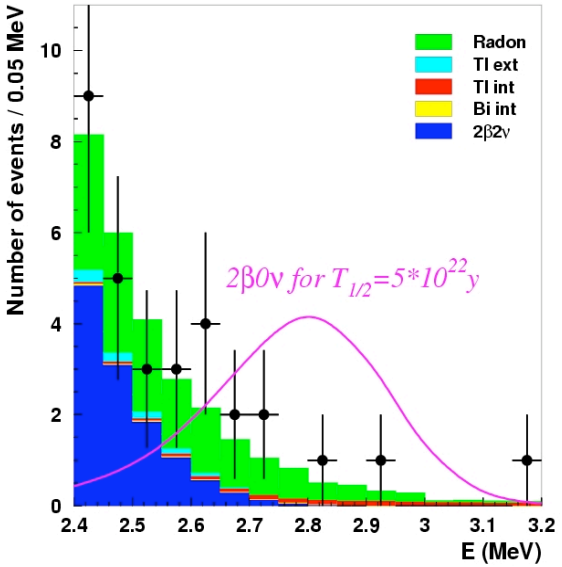
	^{150}Nd	^{82}Se
Q(MeV)	3.367	2.995
$G^{0\nu}(y^{-1}eV^{-2})$	8E-25	1E-25

150-Nd

- candidate for SNO++
- problem: deformed nucleus, NME ?

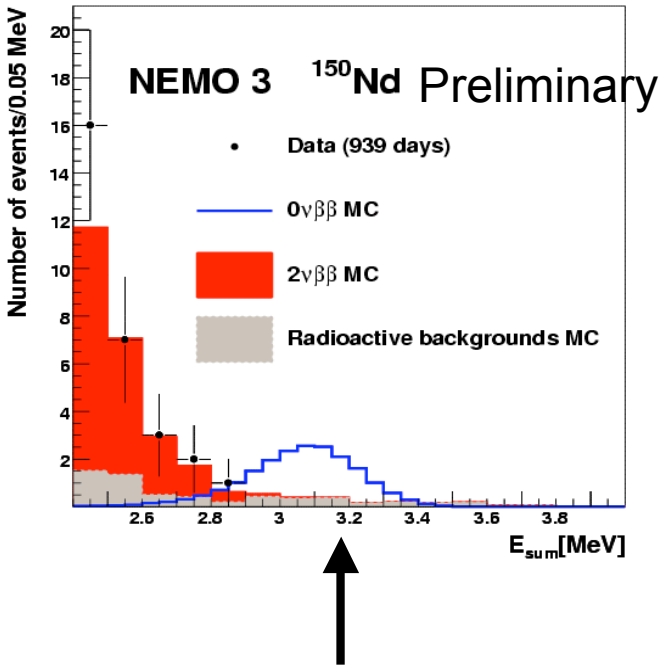


^{100}Mo, 4782 kg days



^{82}Se, 646 kg ays

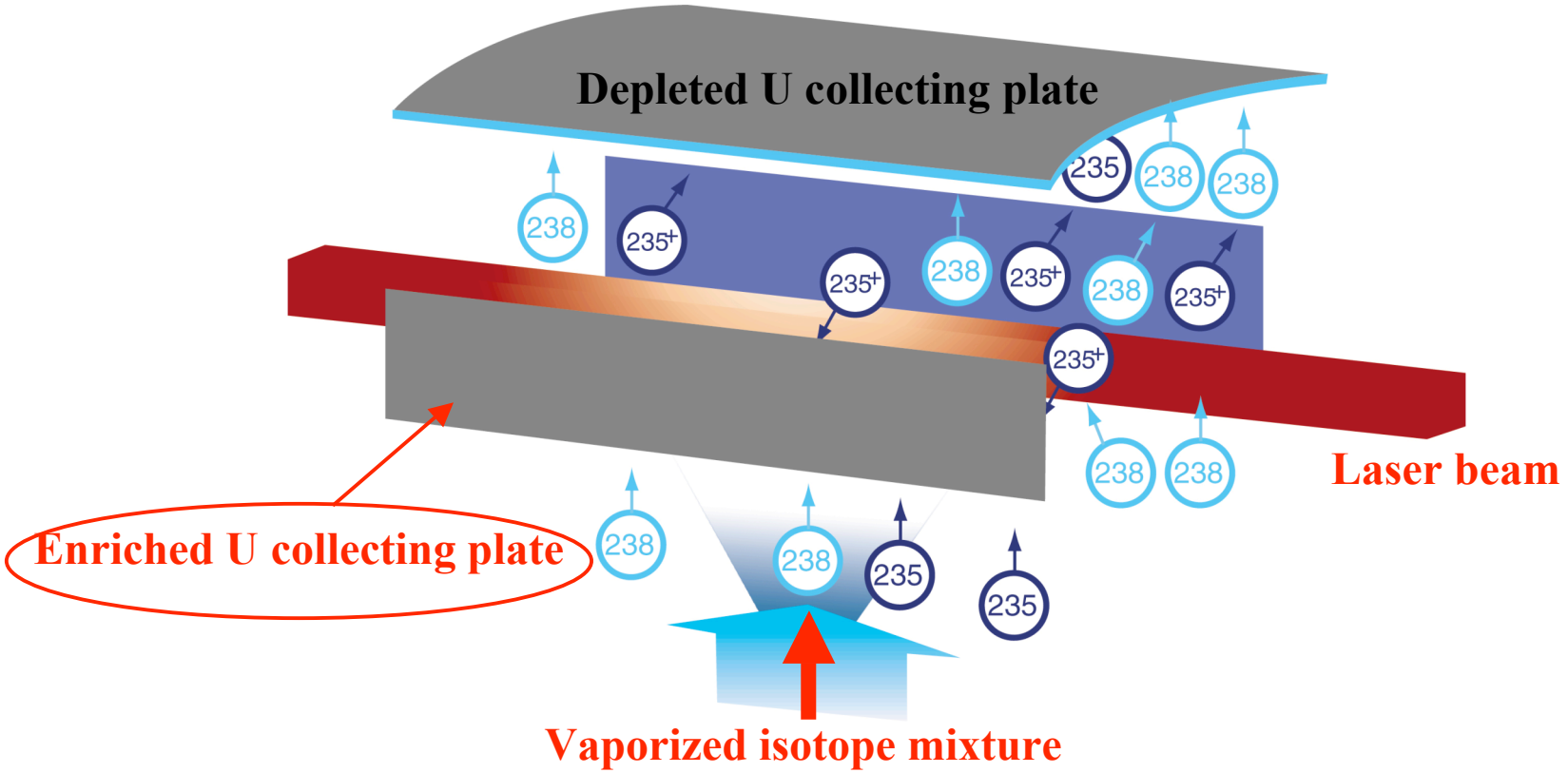
^{150}Nd, 35 kg days



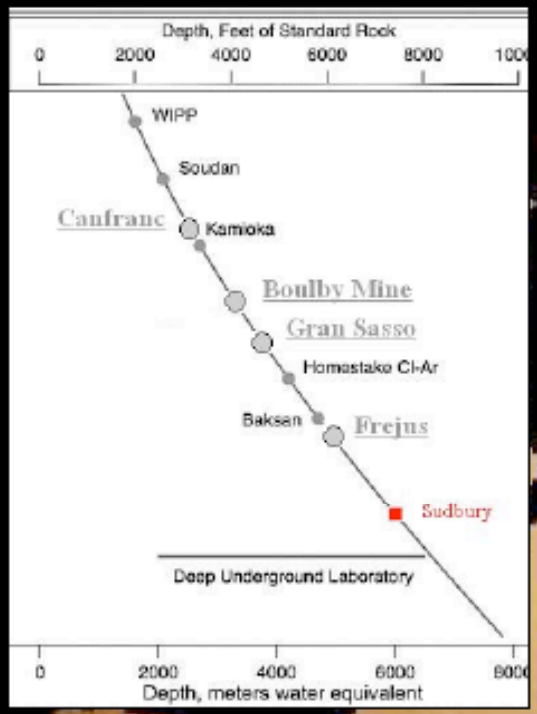
^{150}Nd enrichment using lasers (AVLIS)

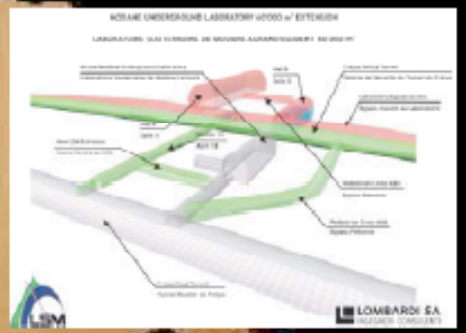
AVLIS: Atomic Vapor Laser Isotope Separation

Selective photoionization based on :
isotope shifts in the atomic absorption optical spectra
U + 3 selective photons → $^{235}U^{+}$ + e^{-}



Possible location for SuperNEMO

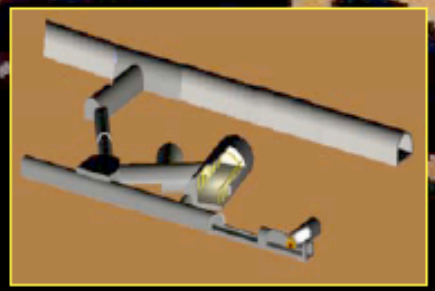




Modane (Frejus) (France)

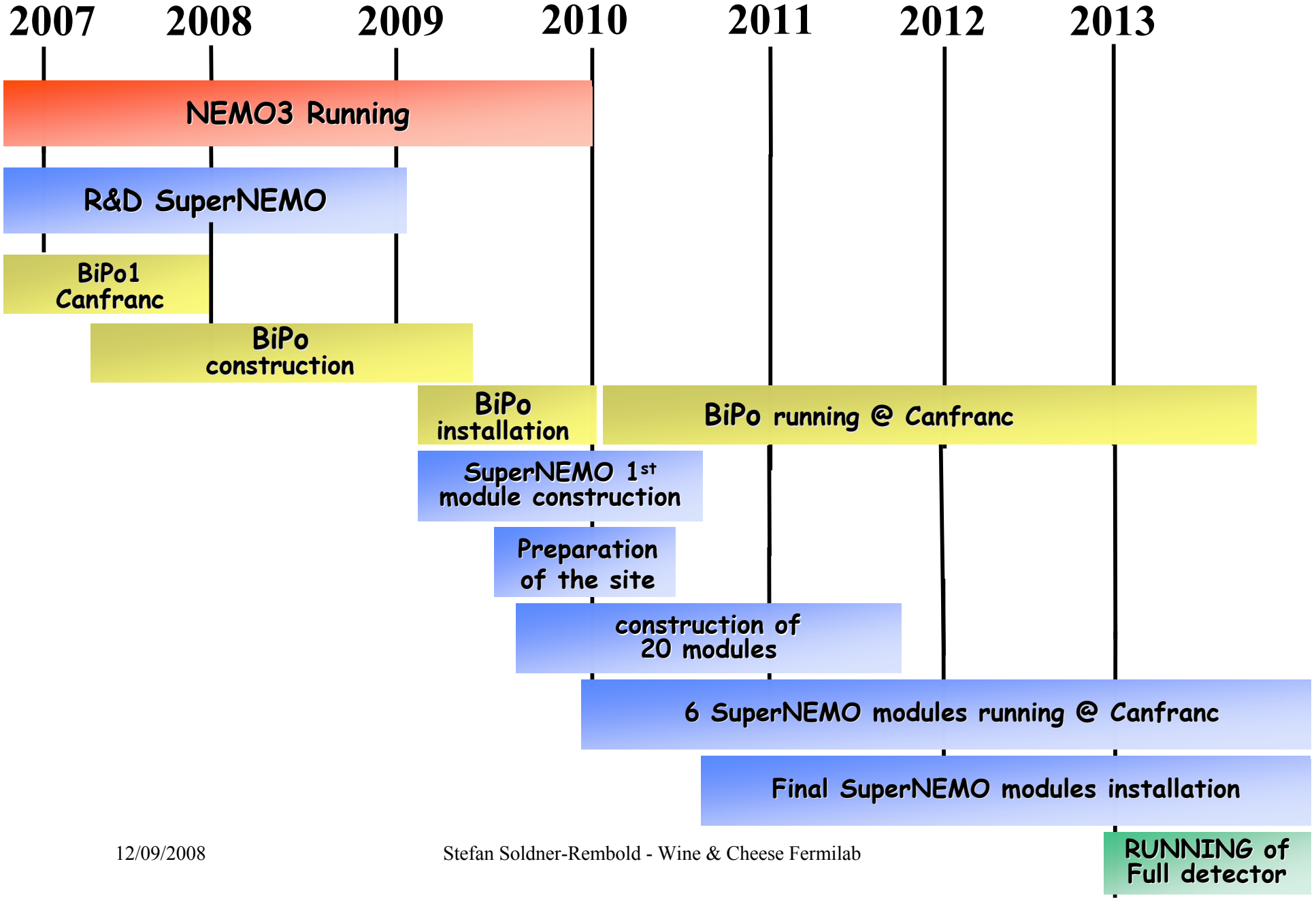
Phase II
100- 200 kg

BiPo
Phase I
20 kg

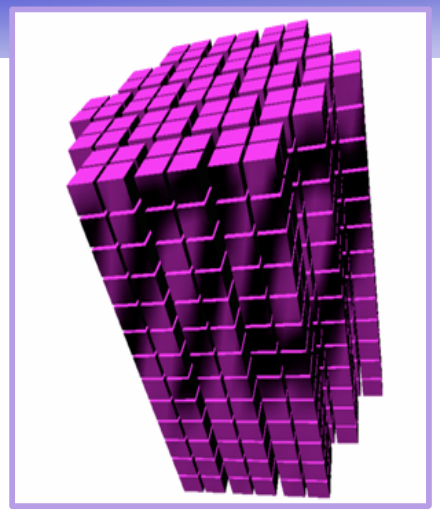


Canfranc (Spain)

Schedule Summary



Cuore/Cuoricino



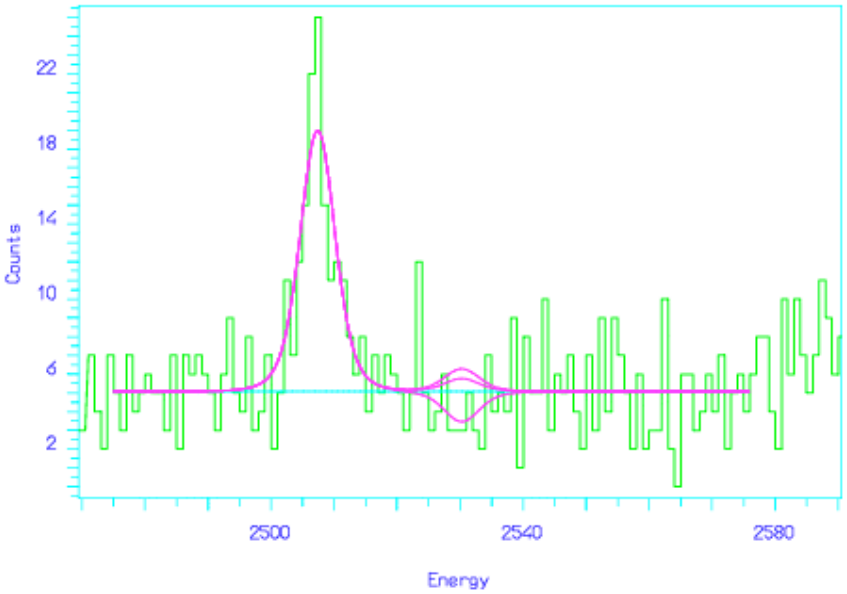
40.2 kg of TeO_2
(=11 kg ^{130}Te)

read-out with
thermal sensors

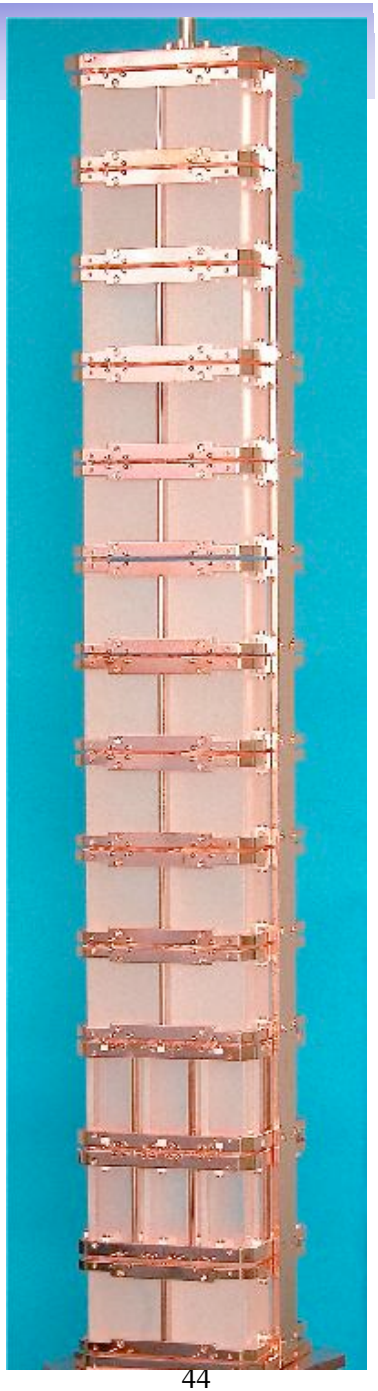
resolution (FWHM)
~ 8-10 keV

Prototype
for Cuore

^{130}Te: 8.38 kg years (2006)



$T_{1/2} > 3.\ 10^{24}$ yr (90% CL)
$<m_\nu> < 0.2 – 1$ eV

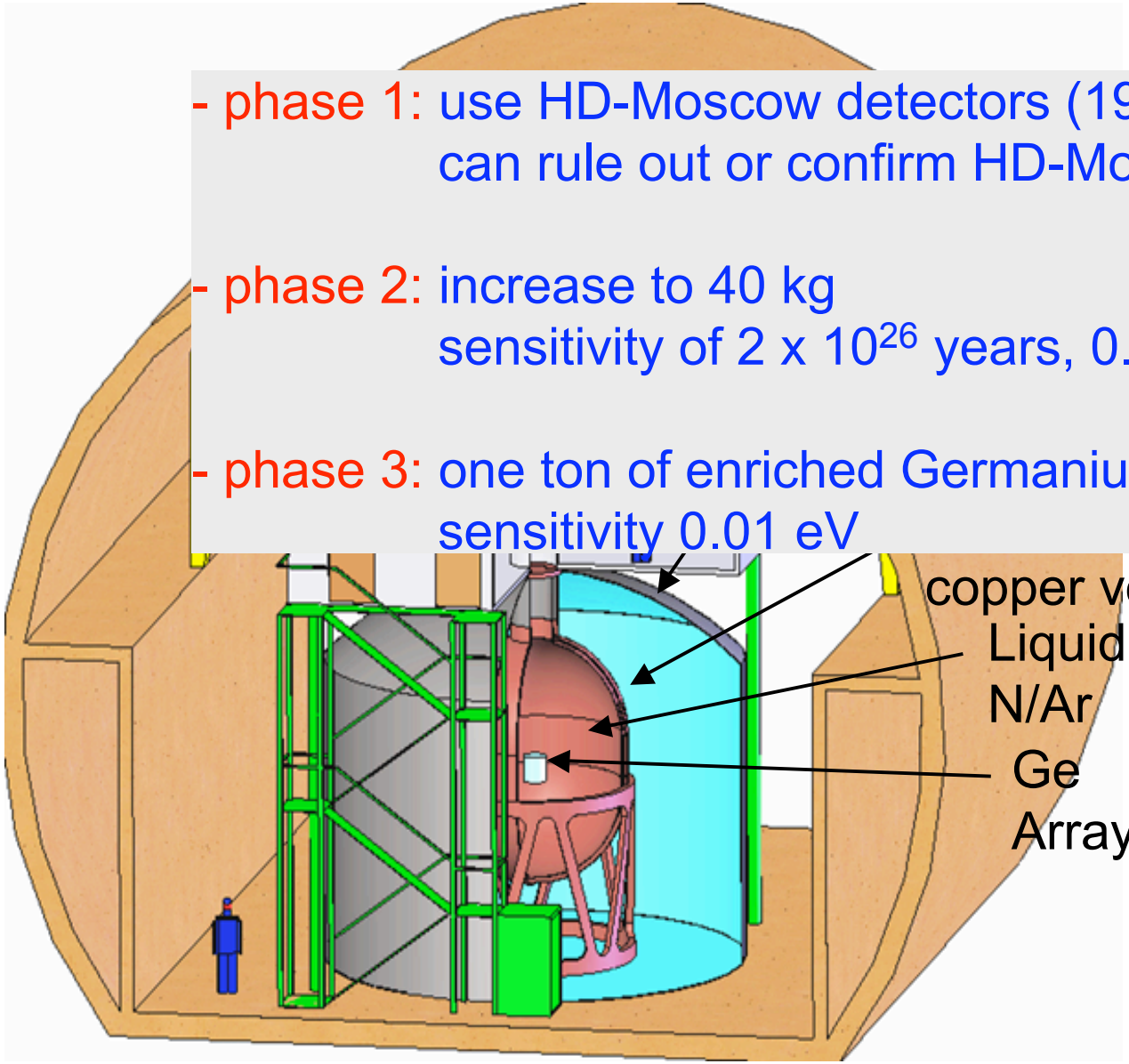


GERDA

- phase 1: use HD-Moscow detectors (19 kg)
  can rule out or confirm HD-Moscow

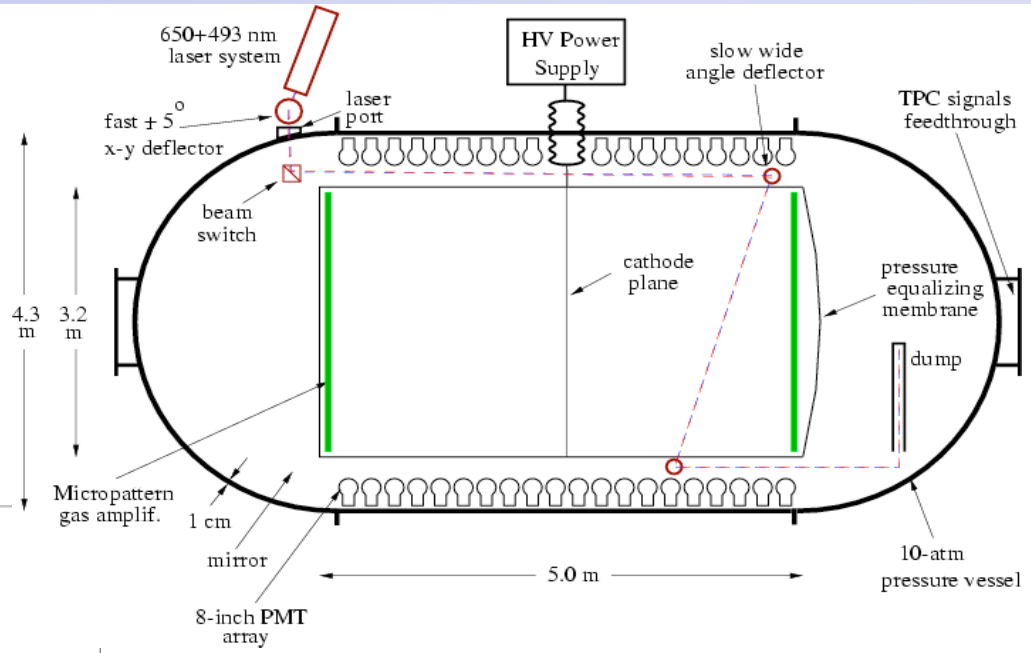
- phase 2: increase to 40 kg
  sensitivity of 2 x 10^{26} years, 0.09-0.29 eV

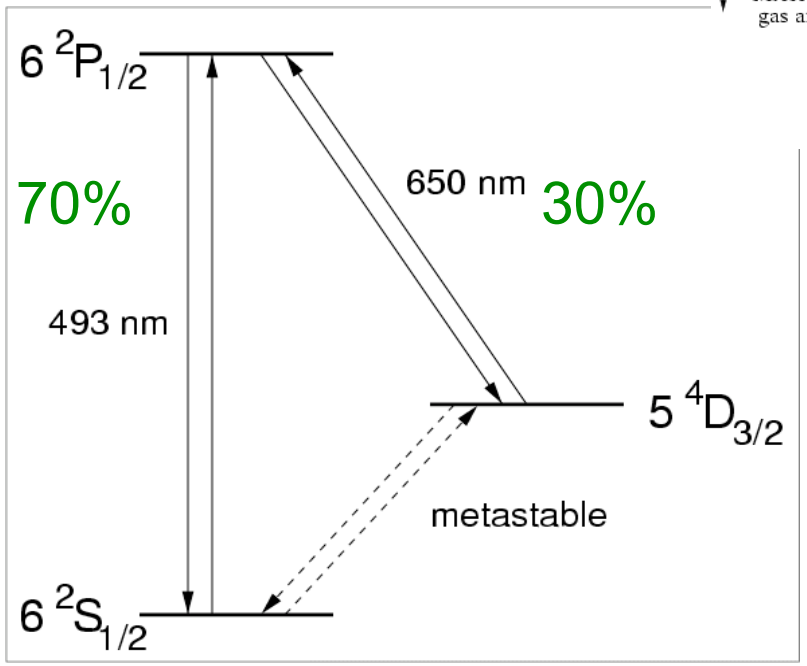
- phase 3: one ton of enriched Germanium
  sensitivity 0.01 eV



Exo

1-10 tons of 80% enriched ^{136}Xe



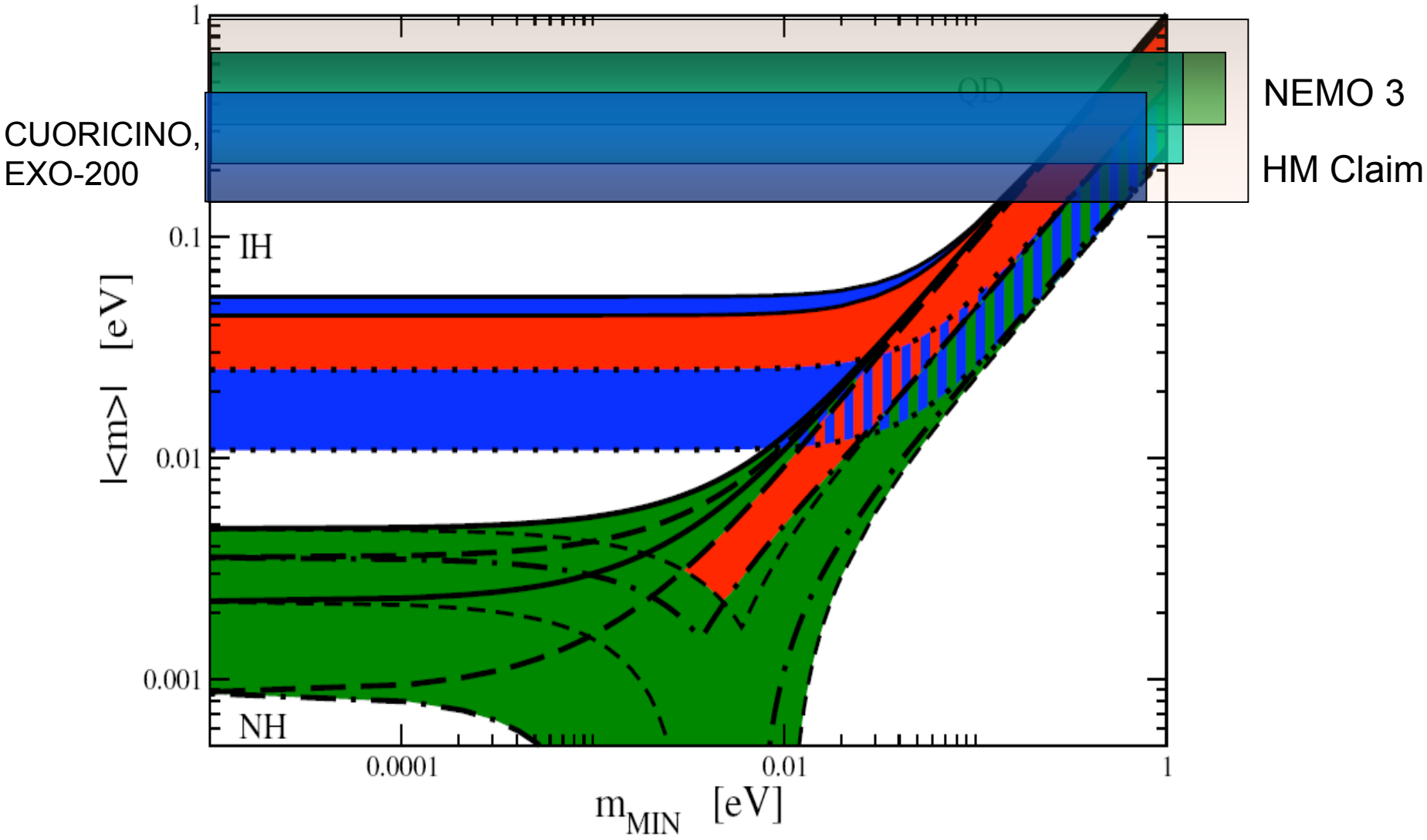


- high pressure gas TPC
- extract Ba^+ ions produced in $\beta\beta$ decay (electrostatic probe)
- identify ^{136}Ba using lasers
- EXO-200 prototype installation

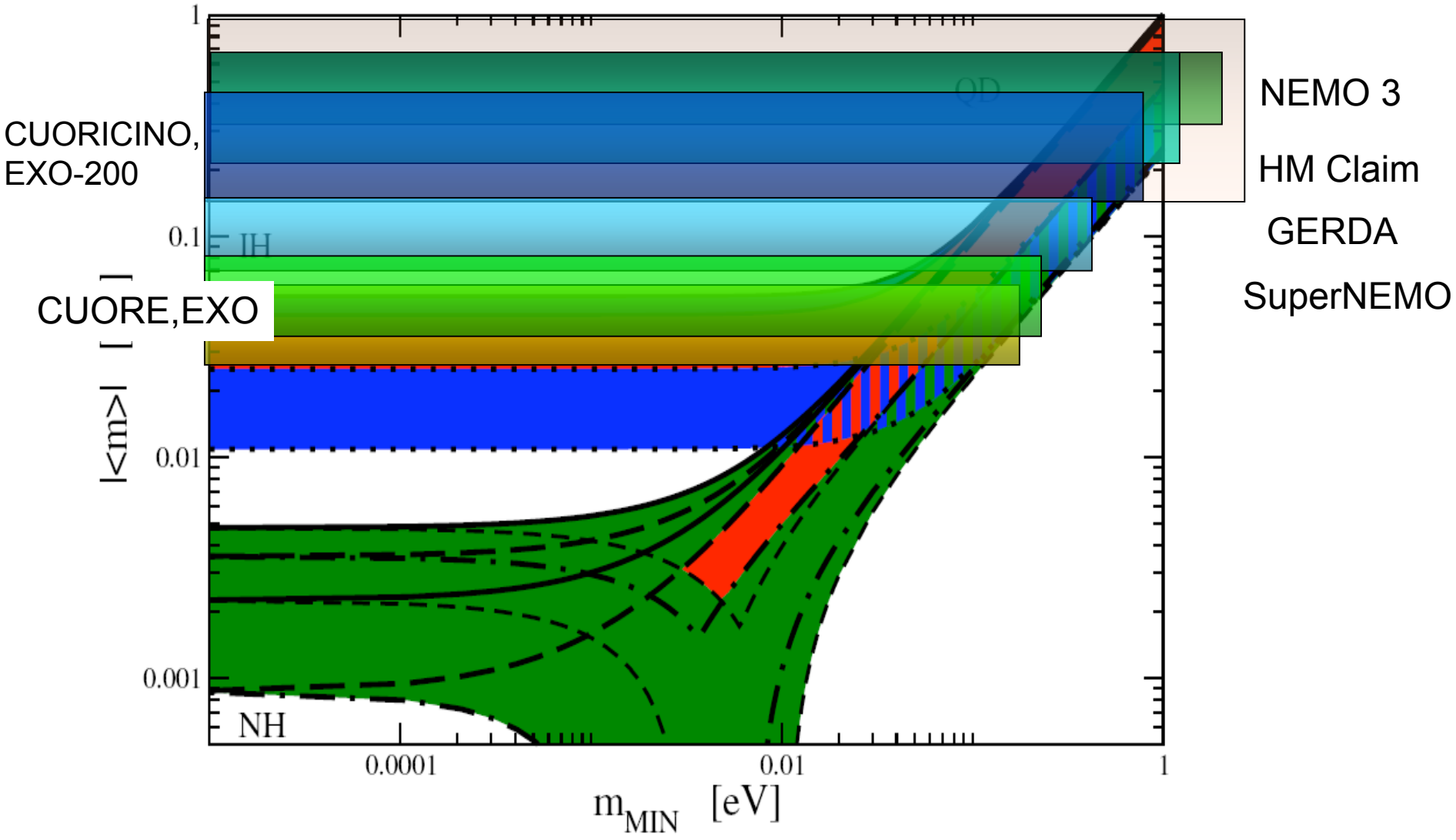
0νββ experiments overview F. Piquemal, LP07

Experiment	Isotope	Enriched isotope mass (kg)	$T_{1/2}$ (yr)	$\langle m_\nu \rangle$ (eV)	Start	Status
CUORE	^{130}Te	203	$2.1\ 10^{26}$	0.03 - 0.07*	2011	Funded
GERDA phase I phase II	^{76}Ge	17.9 40	$3.\ 10^{25}$ $2.\ 10^{26}$	0.2 – 0.5* 0.07 – 0.2*	2009 2011	Funded Funded
Majorana	^{76}Ge	30 - 60	1.10^{26}	0.1 – 0.3*	2011	Funded
EXO-200	^{136}Xe	200	$6.4\ 10^{25}$	0.2 - 0.7*	2008	Funded
SuperNEMO	^{82}Se ^{150}Nd	100 100	$2.\ 10^{26}$ 10^{26}	0.05- 0.09* 0.07	2011	R&D
CANDLES	^{48}Ca	0.5		~0.5	2008	Funded
MOON II	^{100}Mo	120		0.09 – 0.13	?	R&D
DCBA	^{150}Nd	20			?	R&D
SNO++	^{150}Nd	500				R&D
COBRA	116Cd, ^{130}Te	420				R&D

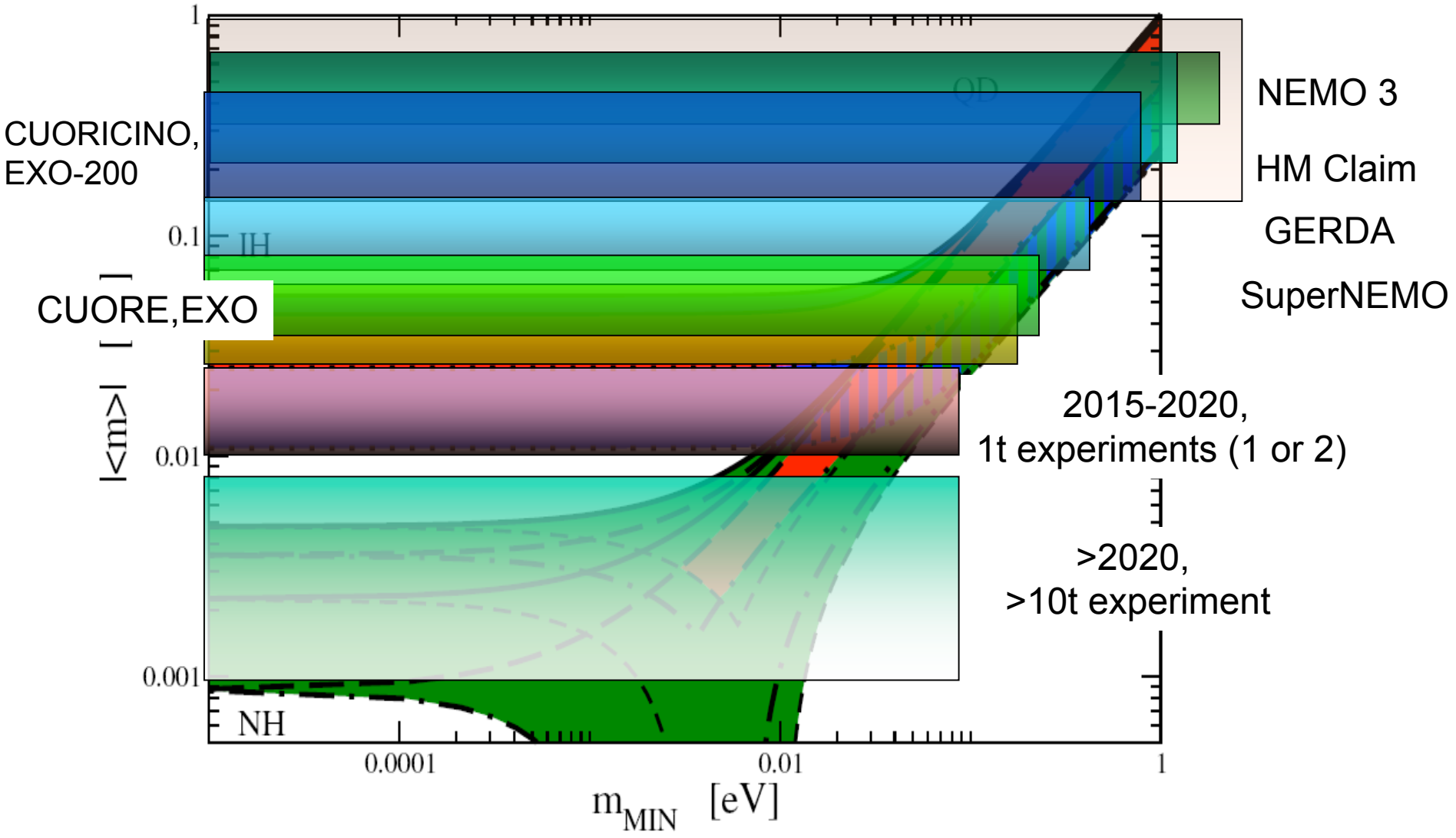
* Calculation with NME from Rodim et al., Suhonen et al., Caurier et al. PMN07



S. Pascoli, S.T.P., 2006



S. Pascoli, S.T.P., 2006



S. Pascoli, S.T.P., 2006

Summary

- NEMO and SuperNEMO follow a unique experimental approach where detector and source are kept separate

- Lower energy resolution, but many advantages:
  - electron identification
  - measurement of the kinematics
  - choice of isotopes
  - particle id and background rejection

- This will not only allow us to discover neutrinoless double beta decay, but also to understand its mechanism once it has been discovered.