An Apparatus to Search for Neutrinoless Double Beta Decay

Benton Pahlka

Fermi National Accelerator Laboratory

On behalf of the NEMO Collaboration

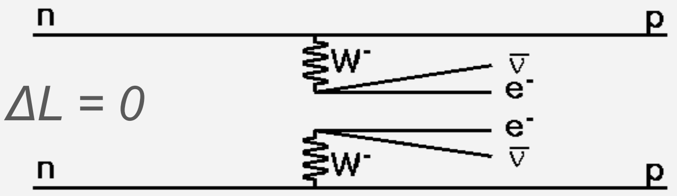
Outline:

◆ Physics motivation for $0\nu\beta\beta$ and practical factors
◆ The NEMO-3 Experiment
◆ Results from NEMO-3
◆ R&D for SuperNEMO
◆ SuperNEMO status

Phenomenology of Double Beta Decay

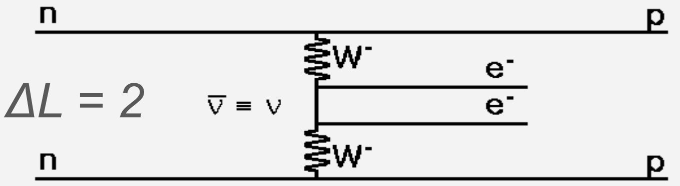
- ➢ What is the absolute neutrino mass scale?
- ➢ What is the neutrino mass ordering (“mass hierarchy”)?
- ➢ Are neutrinos Majorana or Dirac particles?

$$(Z, A) \rightarrow (Z, A+2) + 2e^- + 2\overline{\nu_e}$$

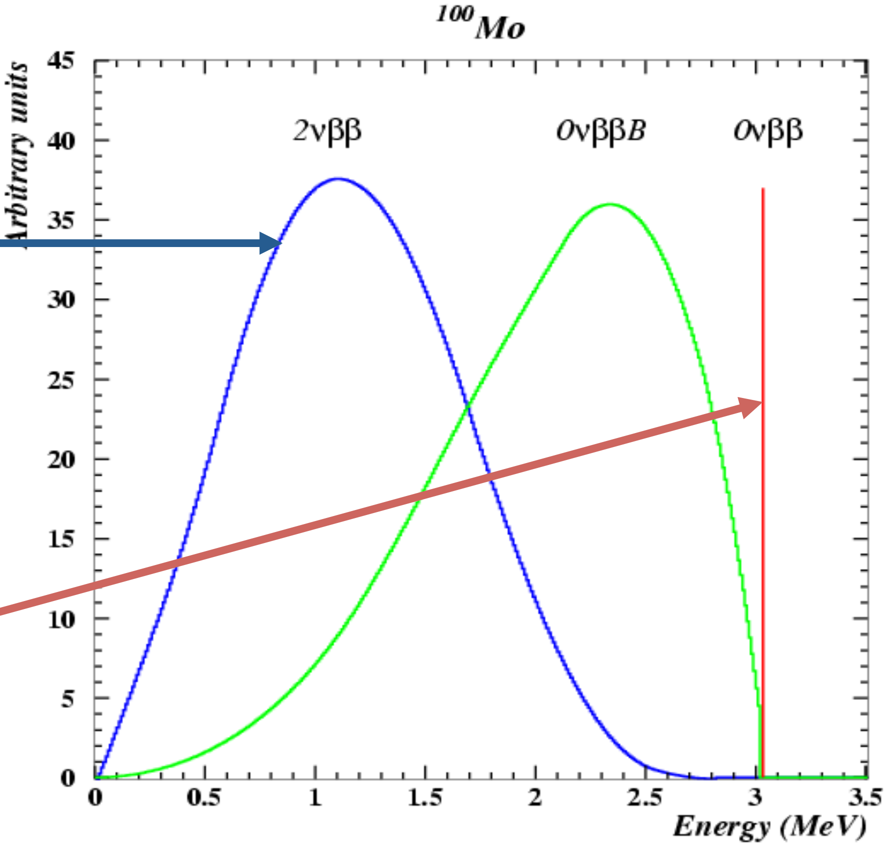


Allowed in the Standard Model

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



Beyond the Standard Model



$0\nu\beta\beta$ only possible if neutrinos are massive Majorana particles!

NEMO-3 Experimental Technique

Based on Calorimetry and Tracking

Observables of the final state:

Tracking:

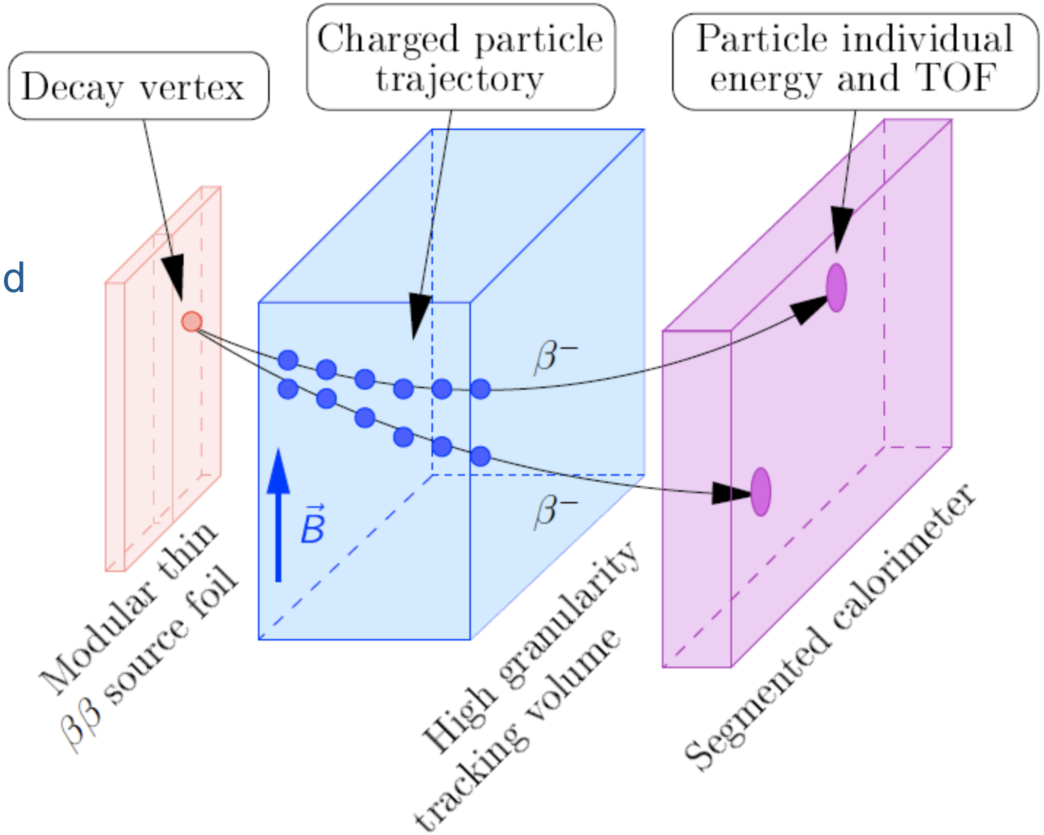
- Vertex location
- Trajectory of each electron
- Track curvature from magnetic field
- Angular distribution

Calorimetry:

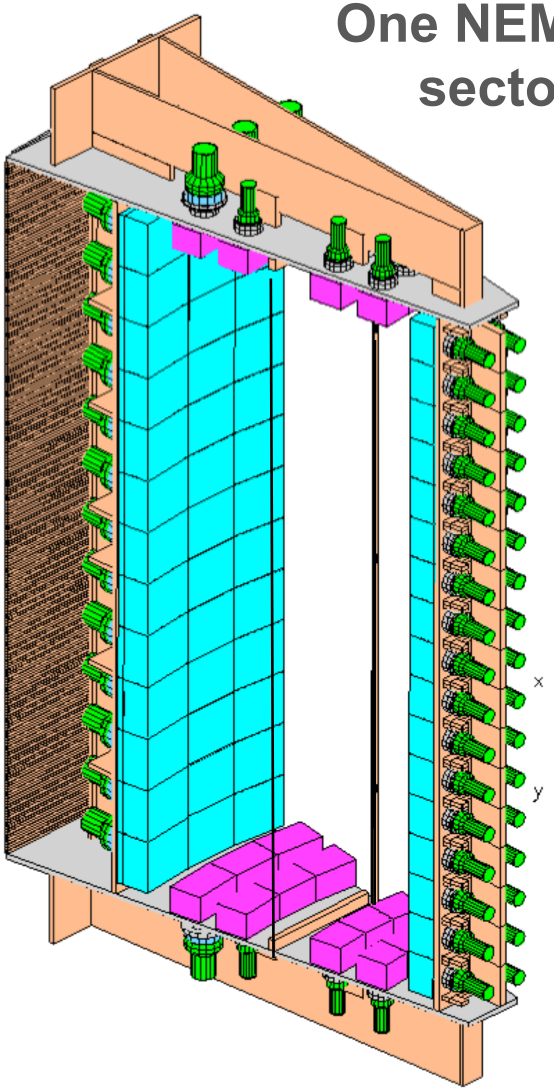
- Energy of each electron
- Time coincidence

Background rejection through:

- PID: identify e^+, e^-, γ, α
- event topology
- particle energy



The NEMO-3 Detector



One NEMO-3 sector

Thin source foils:
10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

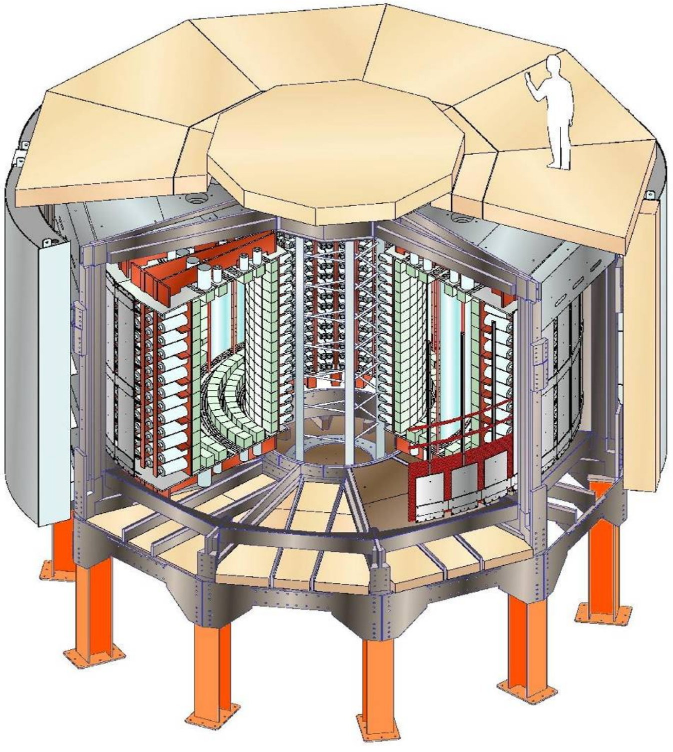
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

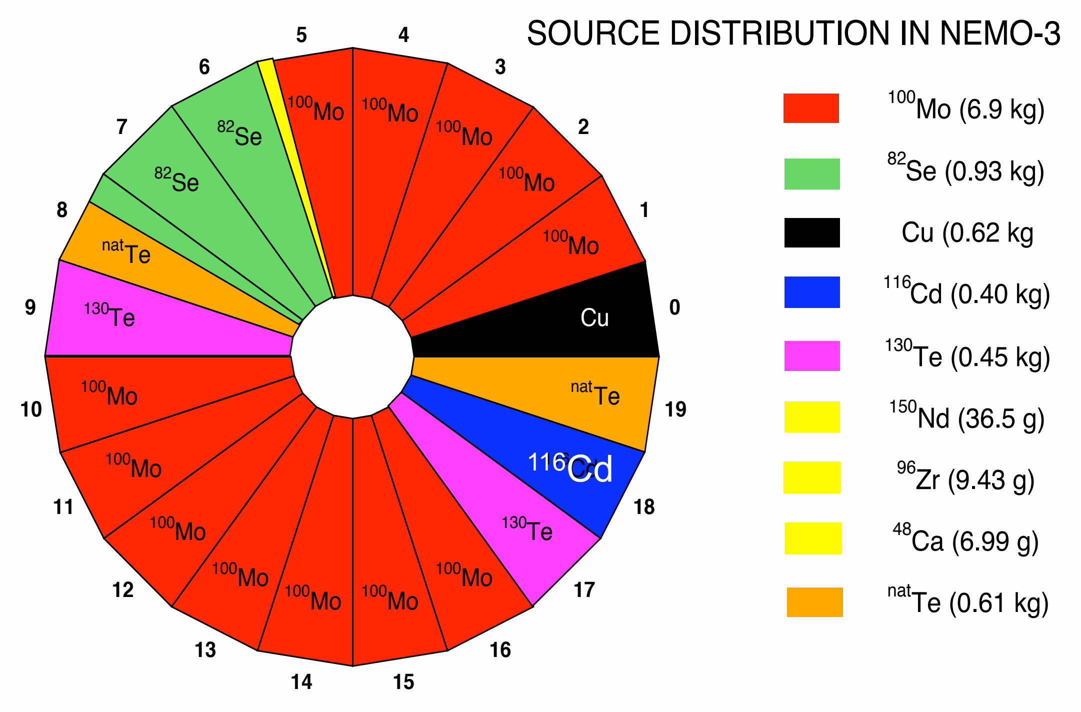
Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water
+ Wood

Radon-free air around the detector
Phase One: Feb 2003 – Oct 2004: high radon
Phase Two: Dec 2004 – today: low radon

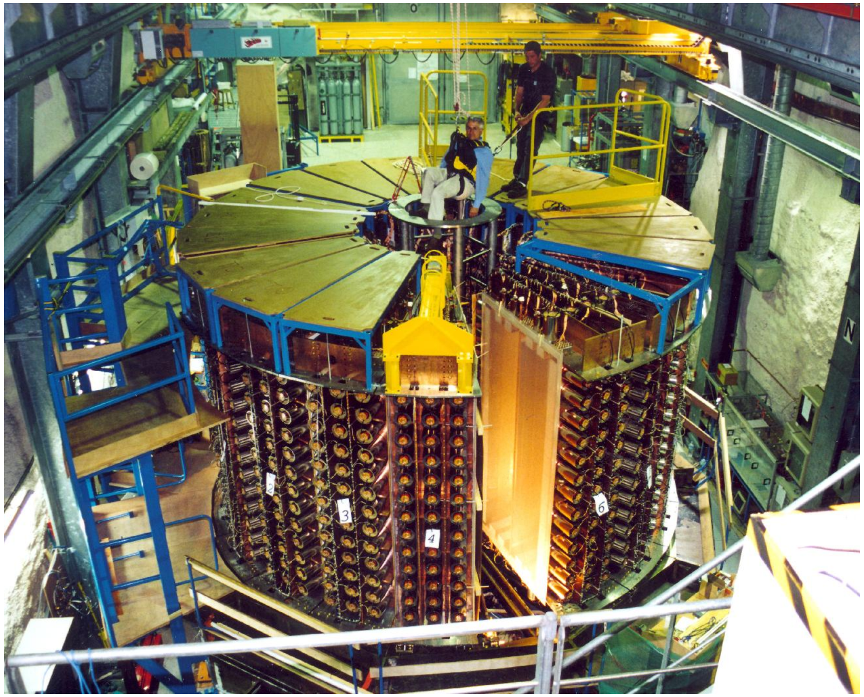
NEMO-3 Isotopic Sources

- Twenty sectors
- Seven double beta decay isotopes
- Cu and ^{nat}Te used to study background

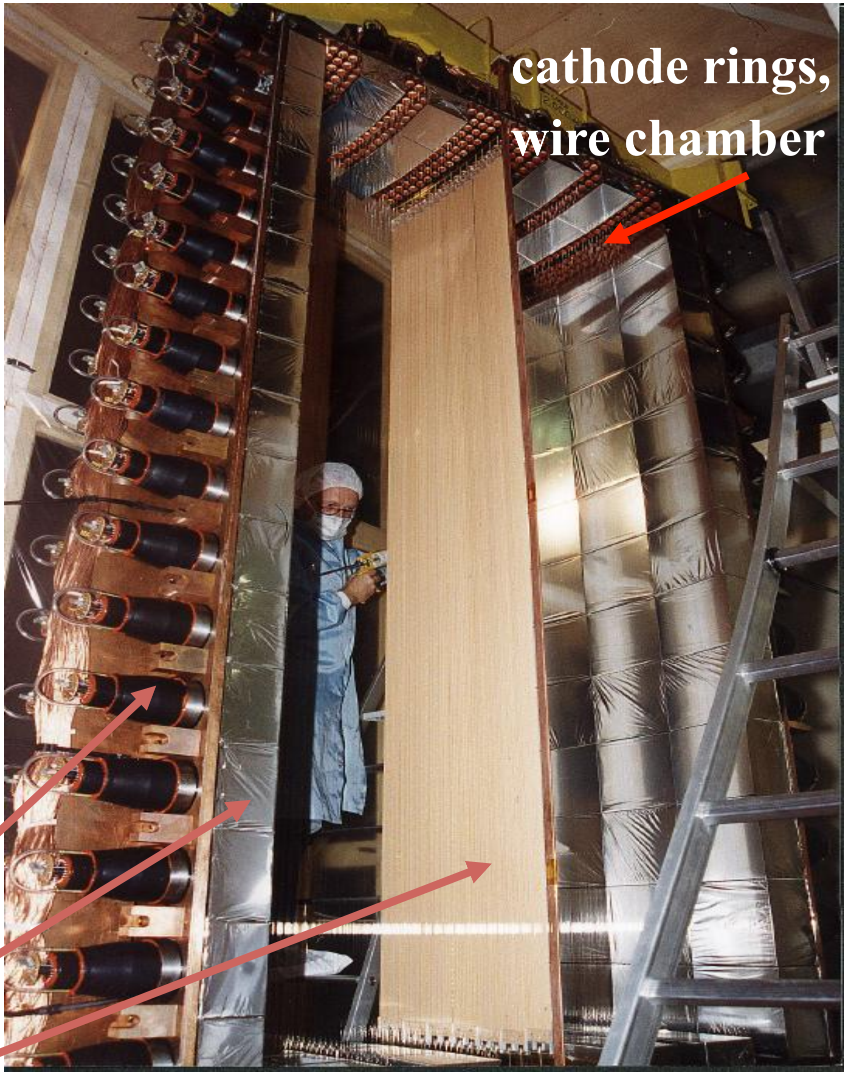




The NEMO-3 Detector



NEMO-3 Installation (2001)



PMTs

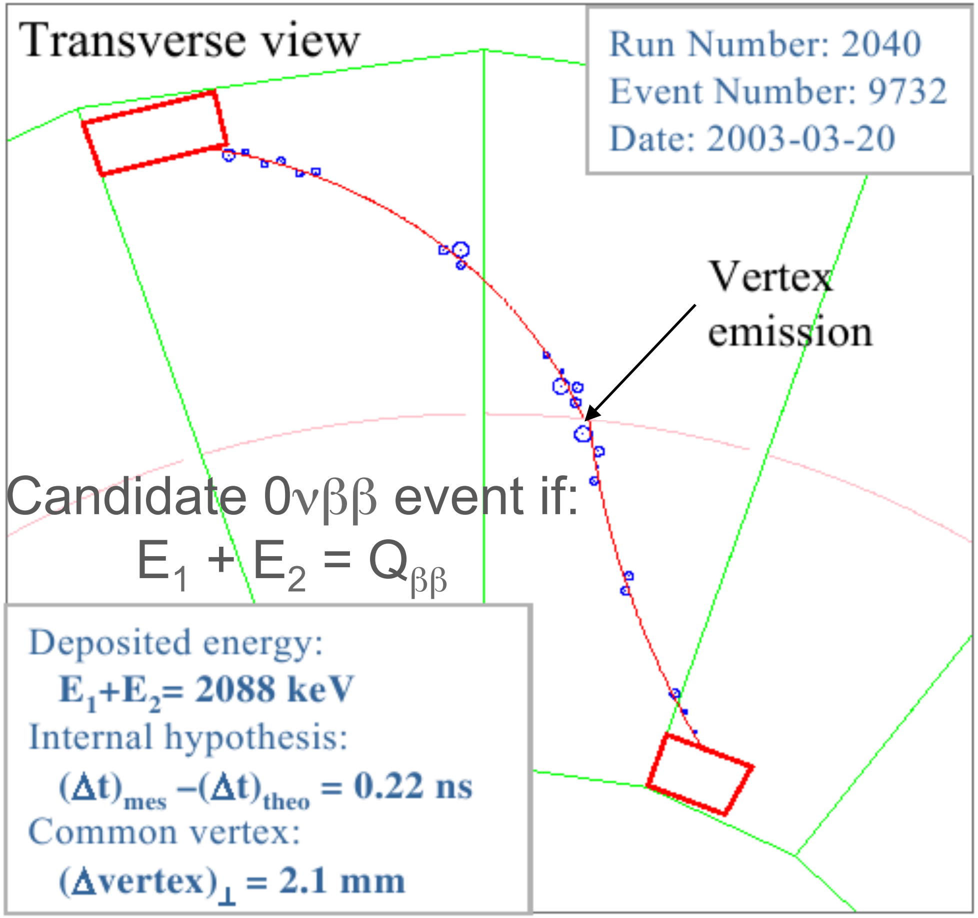
scintillators

ββ isotope foils

NEMO-3 Kinematics

Goal: Reconstruct two electrons in the final state

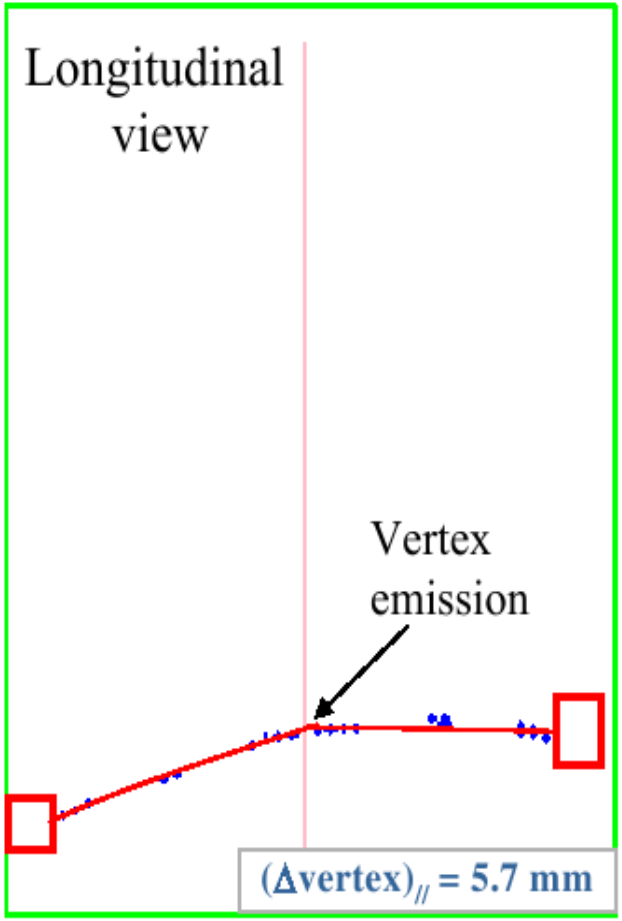
Particle Physics – like approach



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

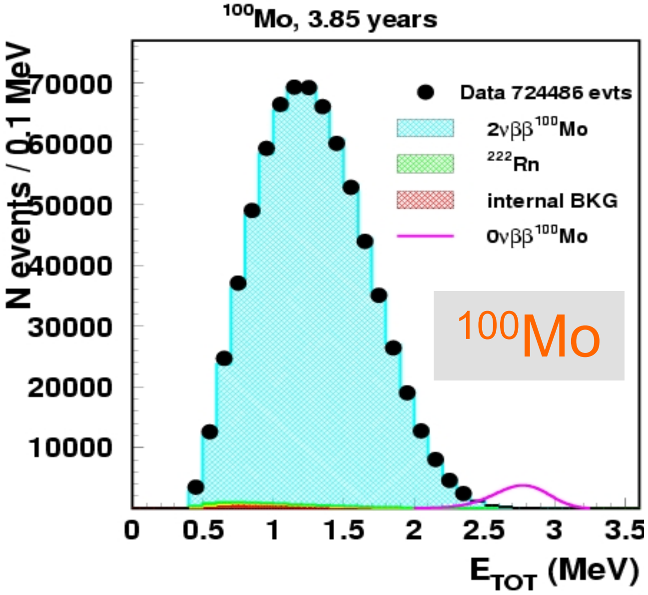
Deposited energy:
$E_1+E_2= 2088$ keV
Internal hypothesis:
$(\Delta t)_{mes} -(\Delta t)_{theo} = 0.22$ ns
Common vertex:
$(\Delta \text{vertex})_\perp = 2.1$ mm

Candidate $0\nu\beta\beta$ event if:
$E_1 + E_2 = Q_{\beta\beta}$

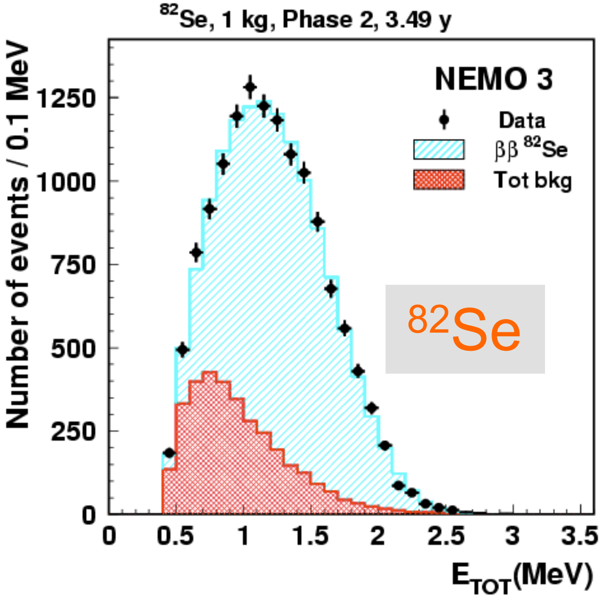


$(\Delta \text{vertex})_{//} = 5.7$ mm

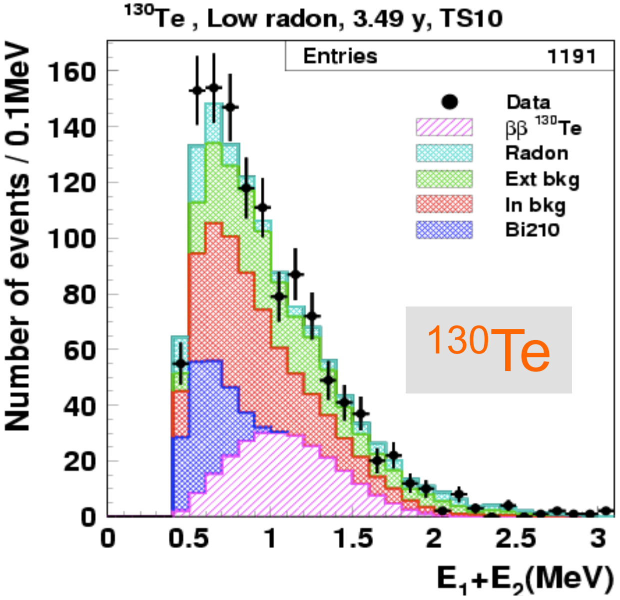
ββ-decay Measurements



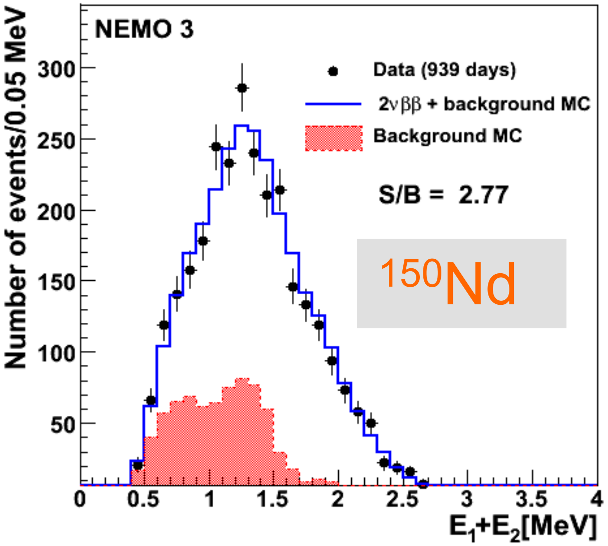
(7.17 ± 0.01(stat) ± 0.54(syst))·10^{18} y



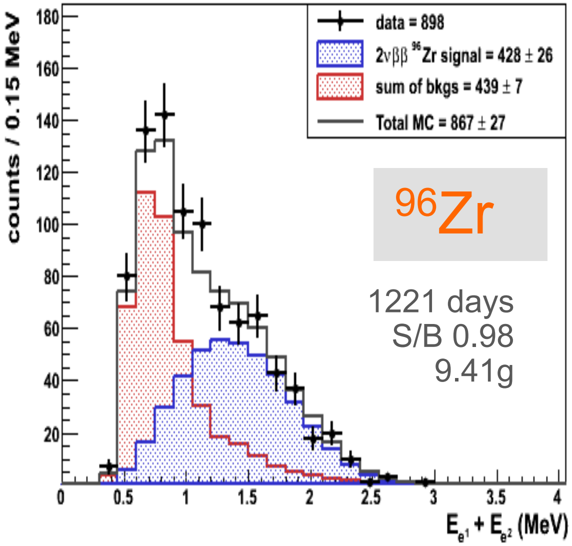
[9.6 ± 0.1 (stat) ± 1.0 (sys)] x 10^{19} y



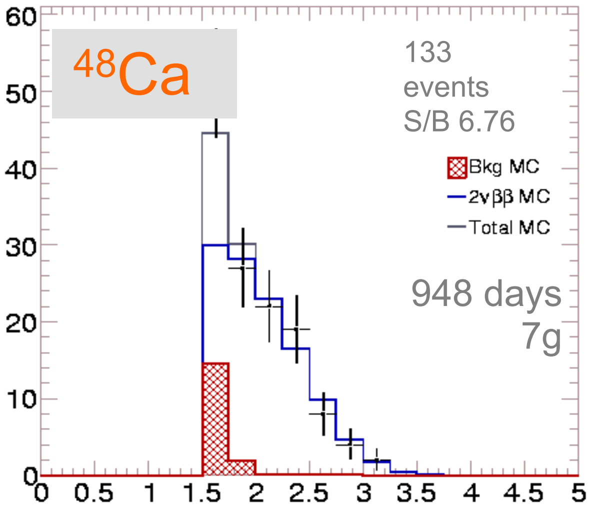
[7.0 $^{+1.0}_{-0.8}$ (stat) $^{+1.1}_{-0.9}$ (sys)] x 10^{20} y



[9.20 ± 0.25 (stat) ± 0.63 (sys)] x 10^{18} y



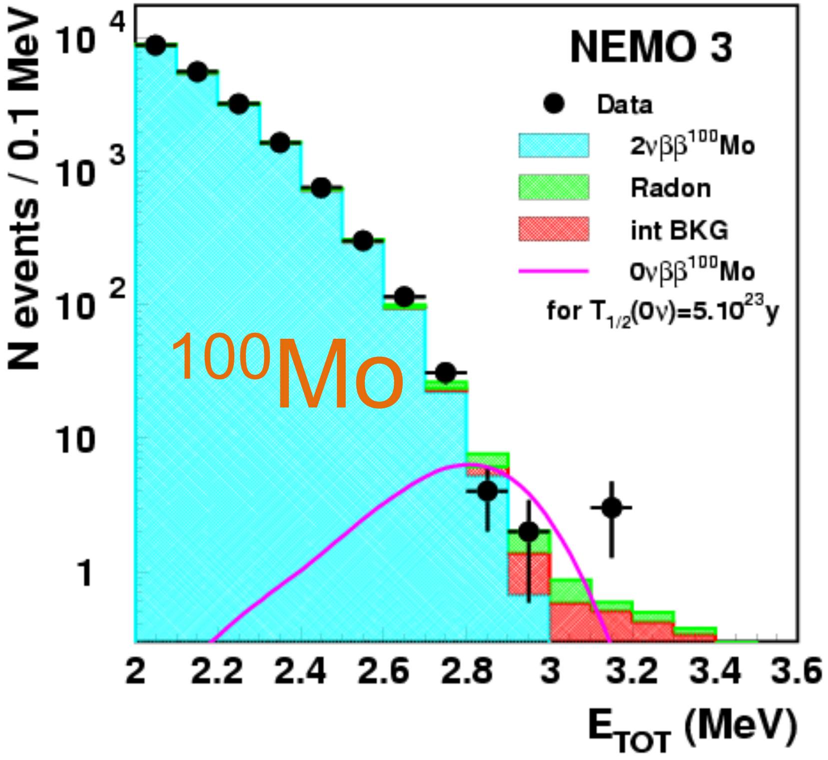
[2.35 ± 0.14 (stat) ± 0.16 (sys)] x 10^{19} y

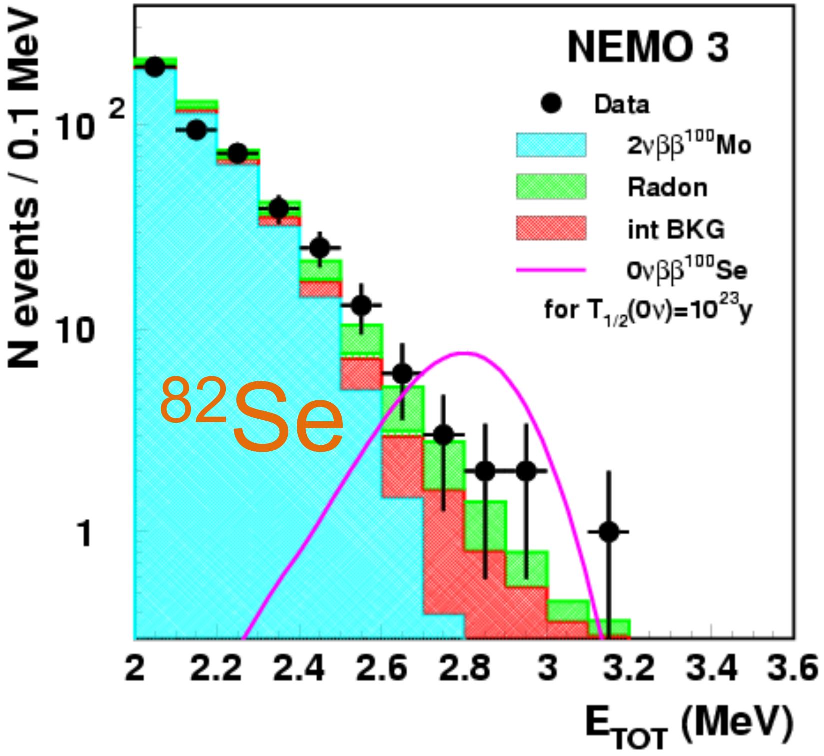


[4.4 $^{+0.5}_{-0.4}$ (stat)± 0.4 (sys)] x 10^{19} y

0νββ: ^{100}Mo and ^{82}Se (Phase 1+2)

End-point energy spectrum





$T_{1/2}$ (0νββ) > 1.0 x 10^{24} y @ 90% C.L.

<m_ν> < 0.47 – 0.96 eV

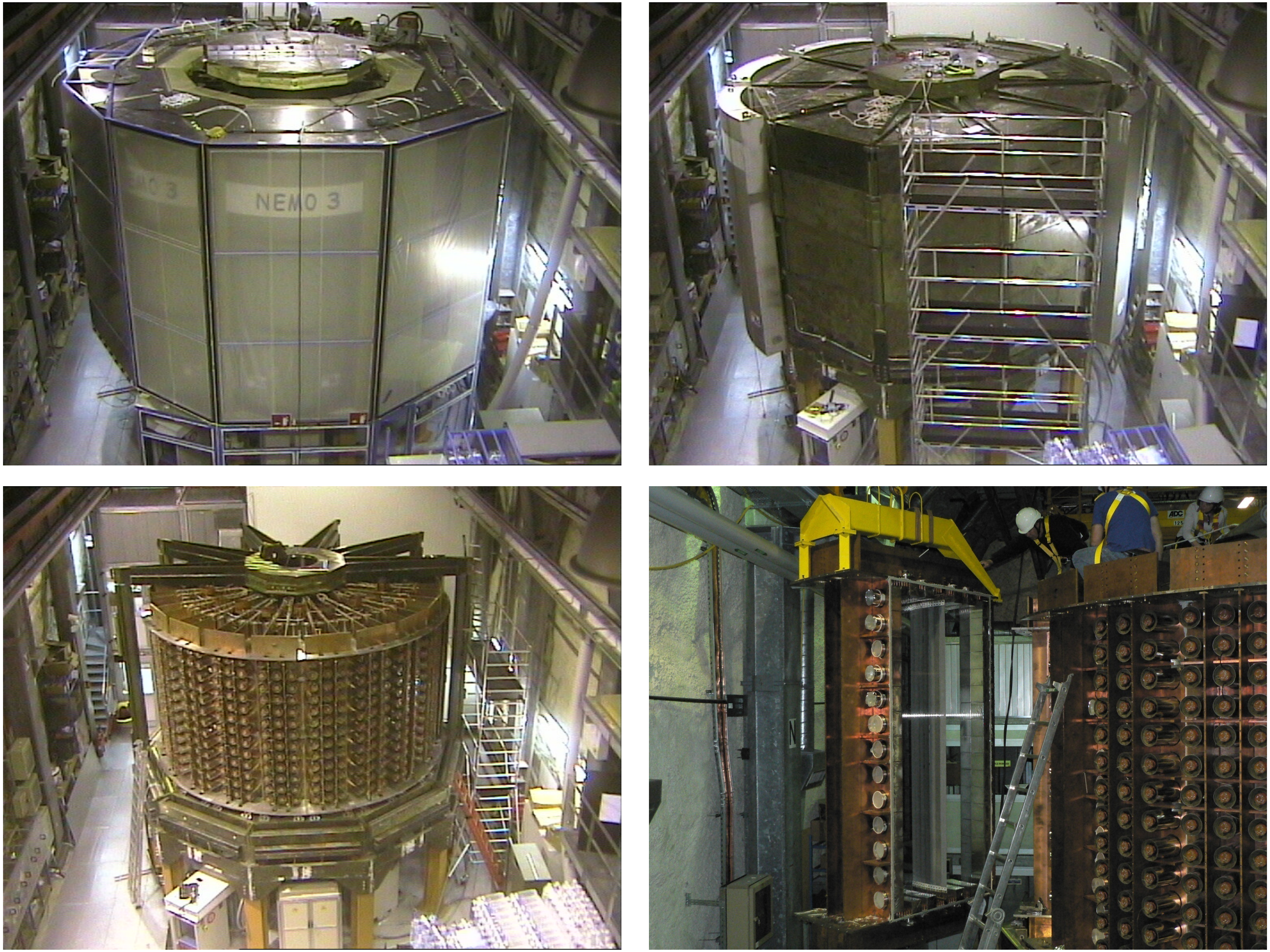
Phase 1+2 exposure: 4.51y*6.914 kg = **31.18 kg*y**

$T_{1/2}$ (0νββ) > 3.2 x 10^{23} y @ 90% C.L.

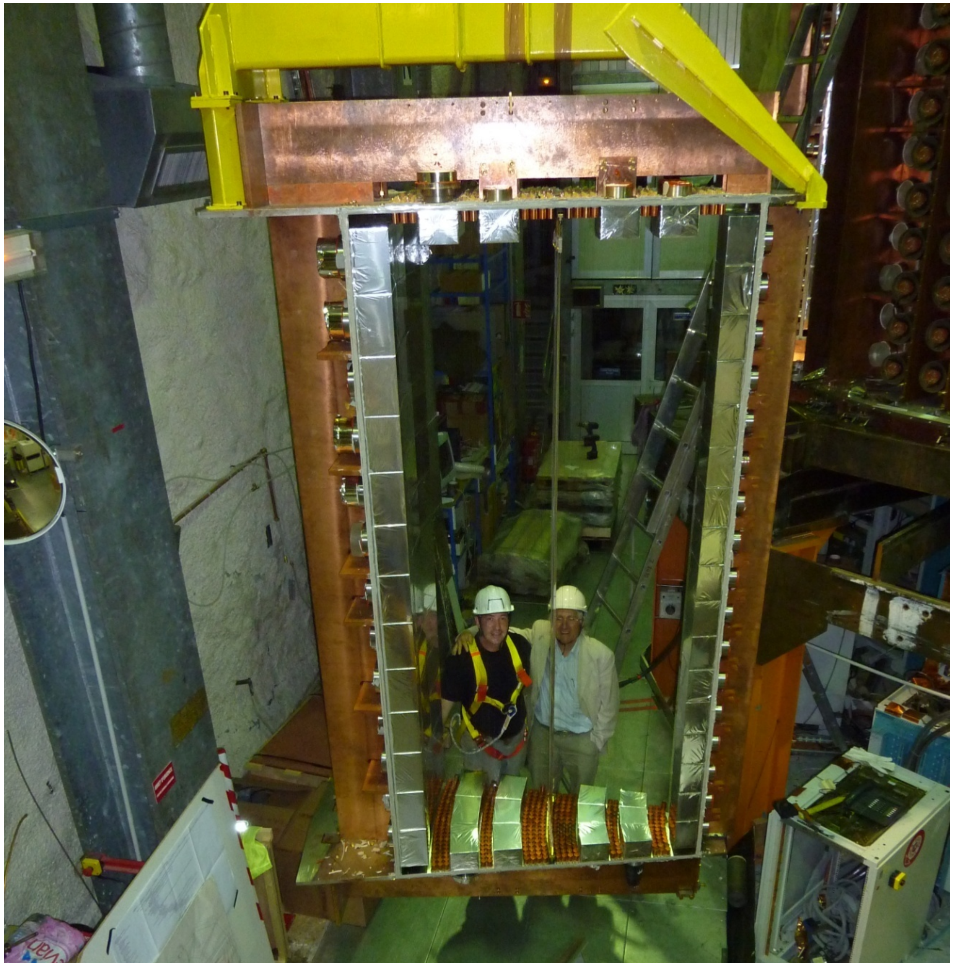
<m_ν> < 0.9 – 2.5 eV

Phase 1+2 exposure: 4.51y*0.932 kg = **4.20 kg*y**

NEMO-3 Dismantling



NEMO-3 Dismantling

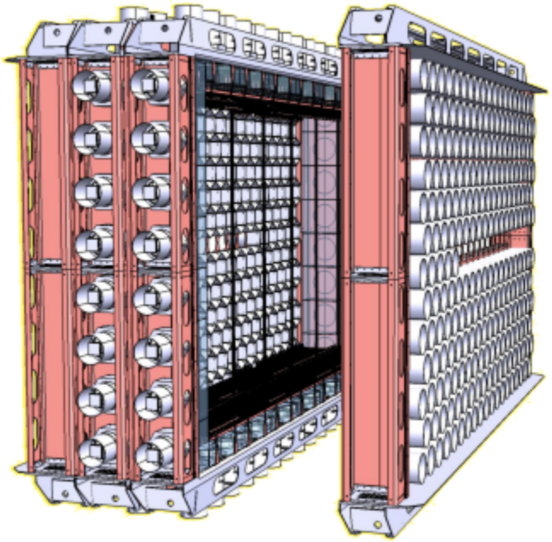


NEMO-3 to SuperNEMO

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

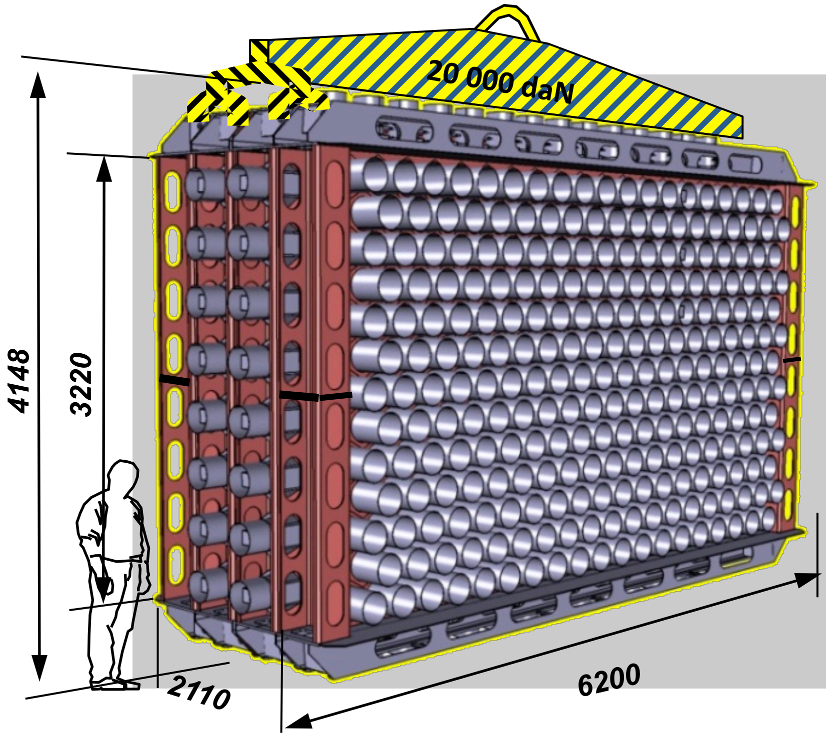
n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source

M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts $(\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{y})$
ΔE – energy resolution (keV)



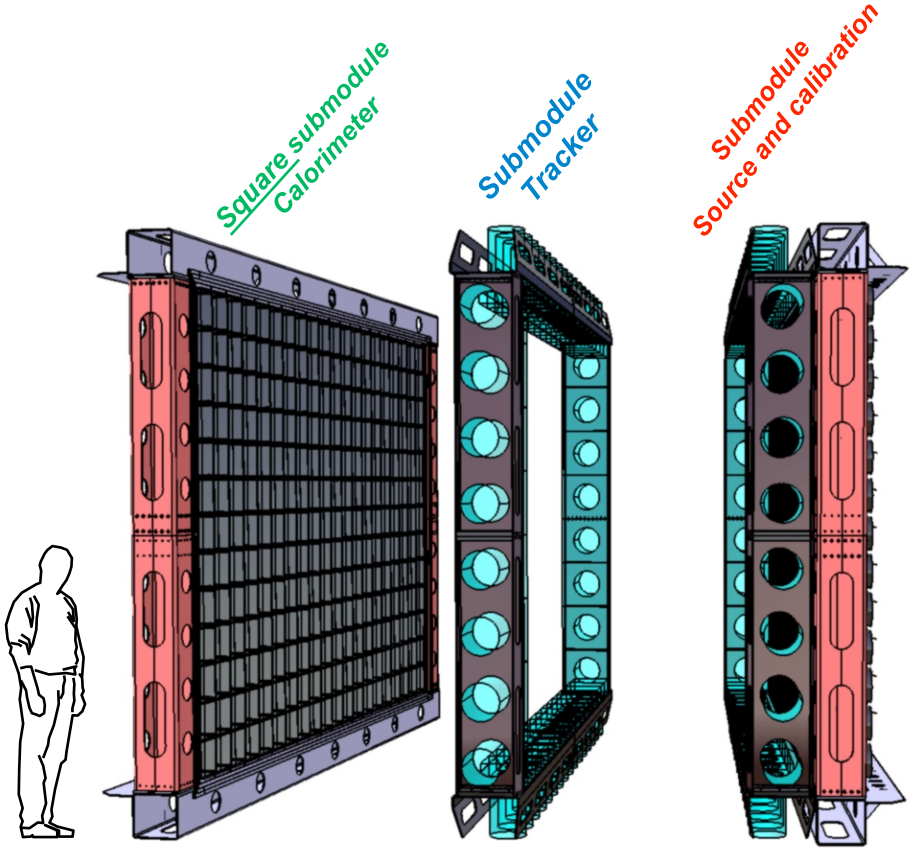
NEMO-3	R&D since 2005	SuperNEMO
^{100}Mo	isotope	^{82}Se (maybe also ^{150}Nd or ^{48}Ca)
7 kg	mass	100 kg
A(^{208}Tl) < 20 μBq/kg A(^{214}Bi) < 300 μBq/kg Rn ~ 5-6 mBq/m^3	Radio-purity of the foil Radon in the tracker	A(^{208}Tl) < 2 μBq/kg A(^{214}Bi) < 10 μBq/kg Rn < 0.1 mBq/m^3
18%	efficiency	30%
8% FWHM @ 3 MeV	Energy resolution	4% FWHM @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 1.4 \times 10^{24}$ y $\langle m_n \rangle < 390 – 810$ meV	sensitivity	$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{26}$ y $\langle m_n \rangle < 40 – 140$ meV
1 module	modularity	>20 modules (new lab)

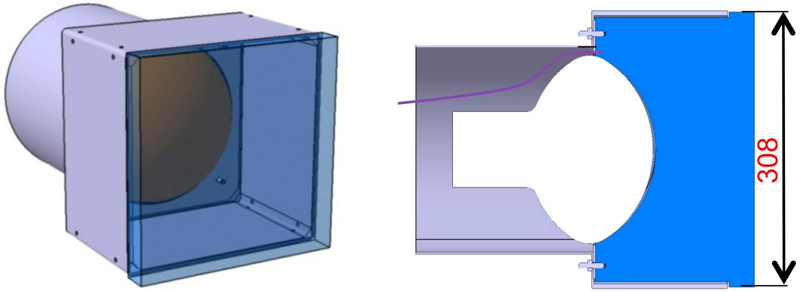
SuperNEMO Demonstrator Module



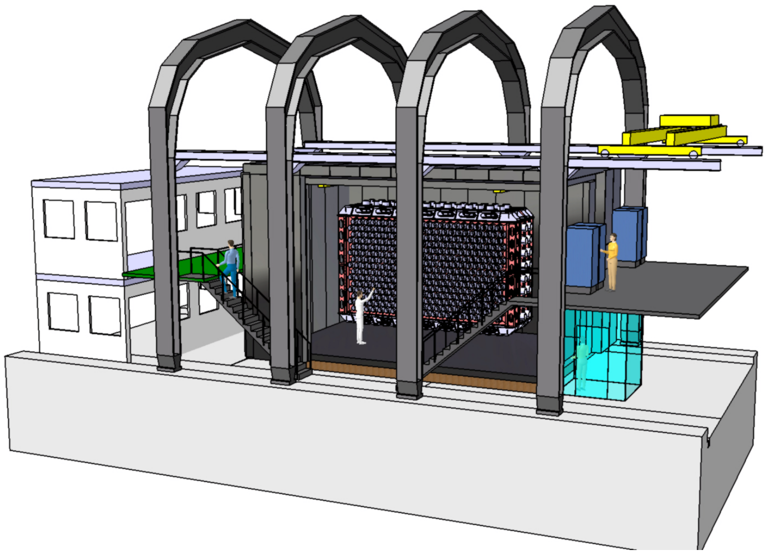
20 modules for 100 kg

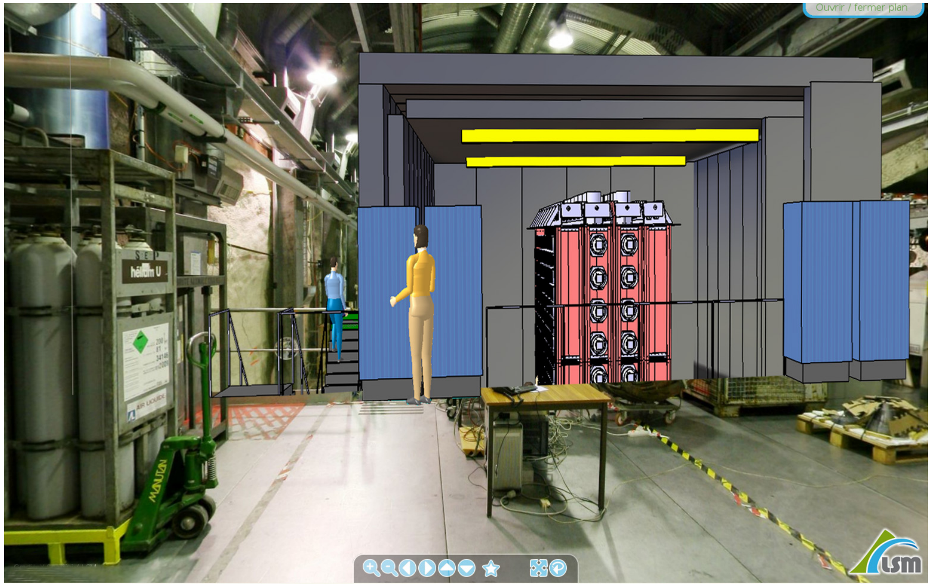
Source: ~ 6.3 kg Se (40 mg/cm^2, 12m^2)
Tracking: ~ 2,100 drift cells
Calorimeter: ~ 600 blocks

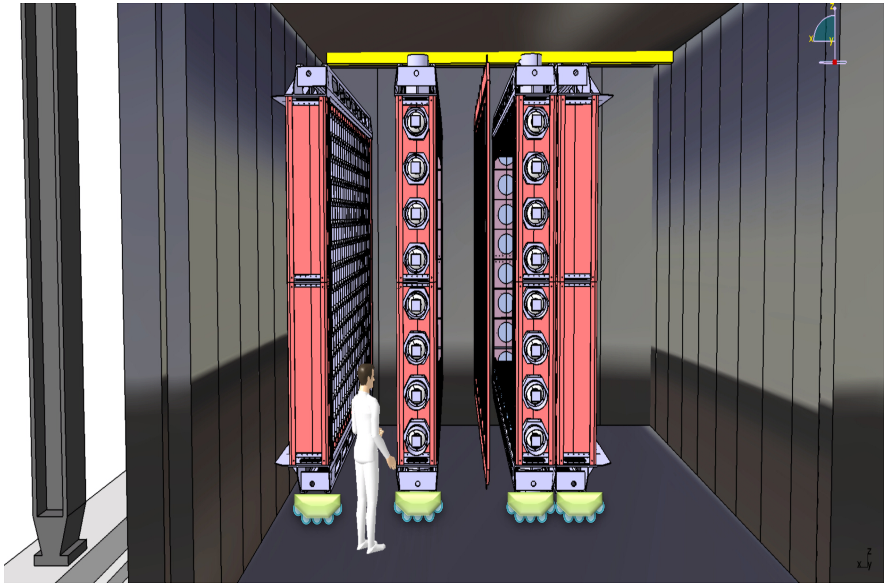




Demonstrator in LSM

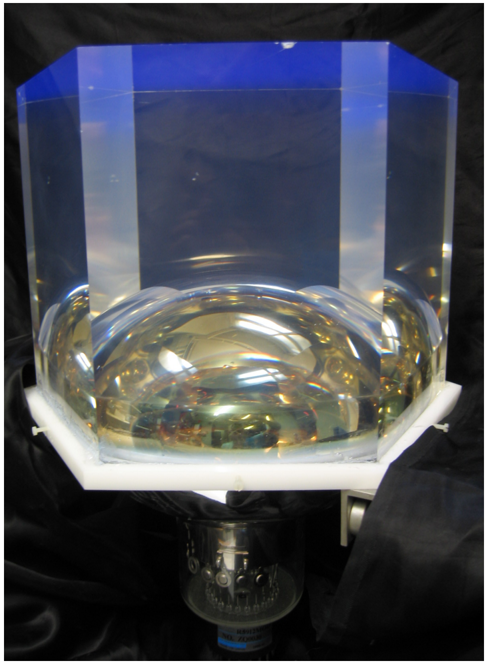




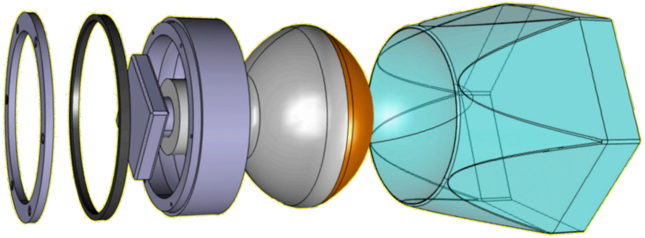


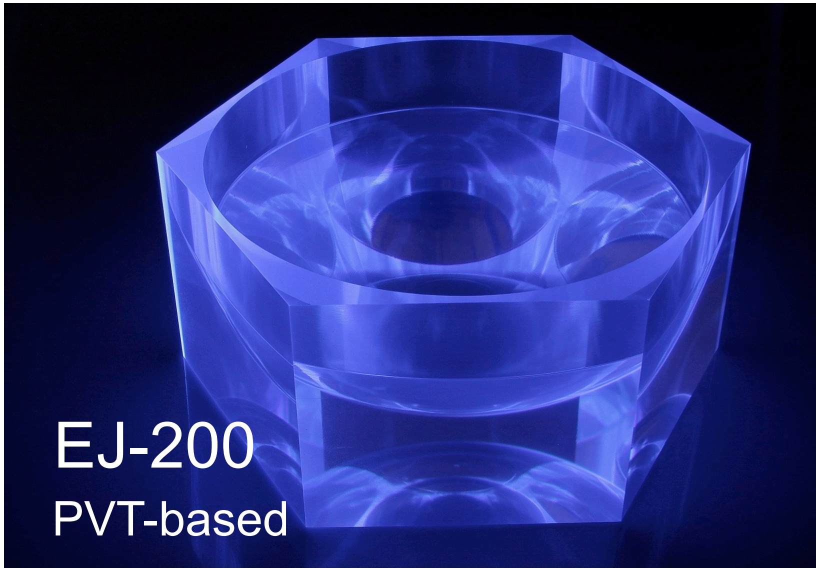
SuperNEMO Calorimeter R&D

Measurements of hexagonal blocks give excellent energy resolution



8” Hamamatsu R5912-MOD Super-Bialkali PMT with 276 mm Ø block

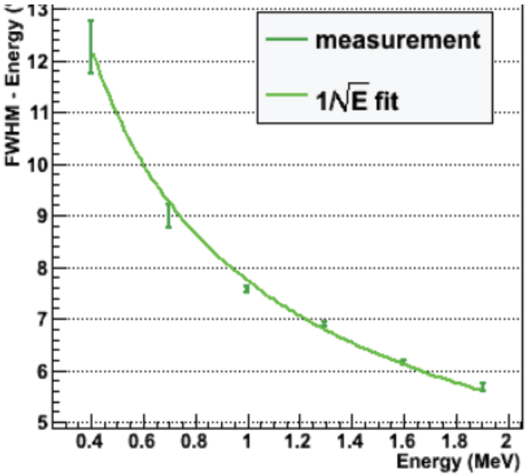




EJ-200

PVT-based

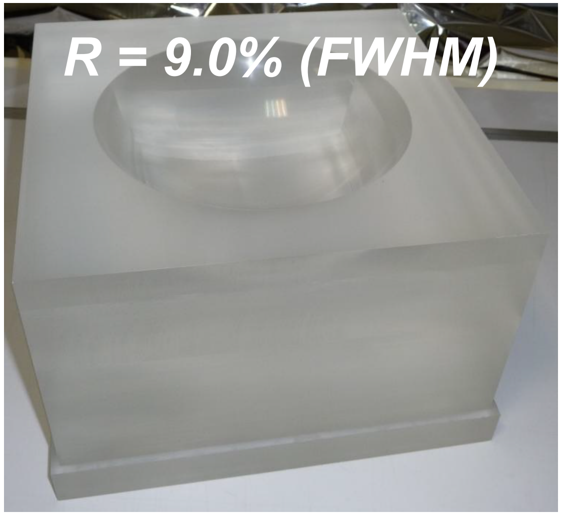
ΔE/E ~ 7.2% (FWHM) at 1 MeV



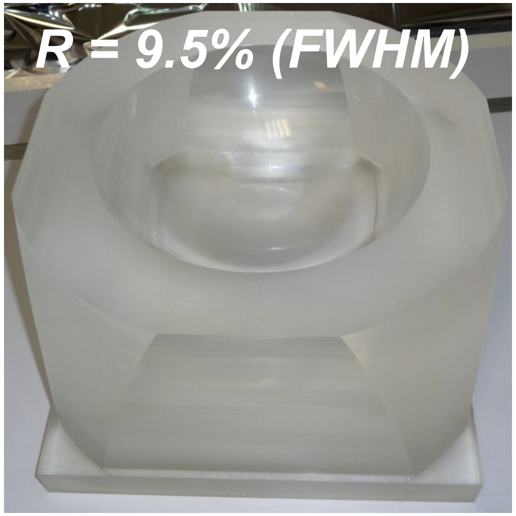
Courtesy of: J.FORGET & C.BOURGEOIS (SuperNEMO Collaboration)

SuperNEMO Calorimeter R&D

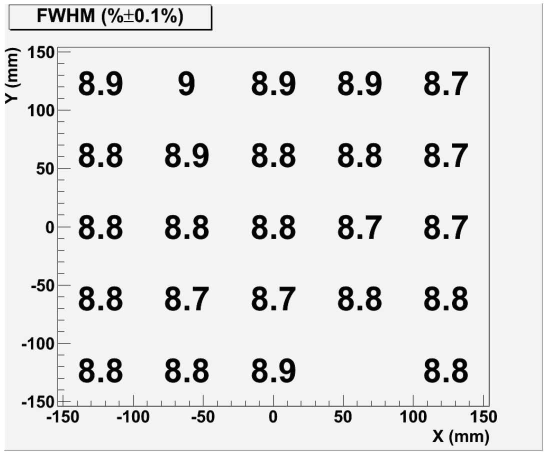
Measurements of wall blocks: Small degradation in resolution with tapering



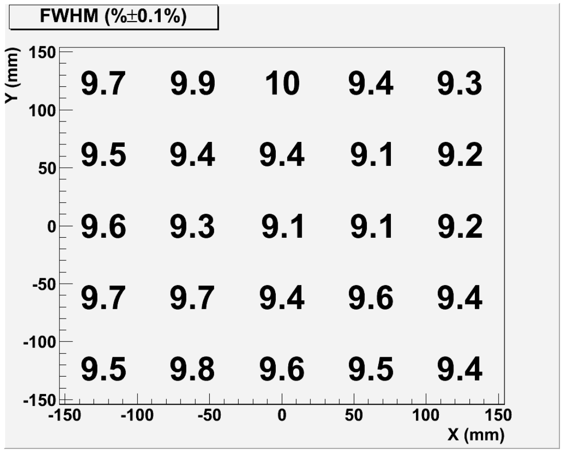
Cubic Side Wall Block



Cubic Tapered Side Wall Block



8.9	9	8.9	8.9	8.7
8.8	8.9	8.8	8.8	8.7
8.8	8.8	8.8	8.7	8.7
8.8	8.7	8.7	8.8	8.8
8.8	8.8	8.9		8.8

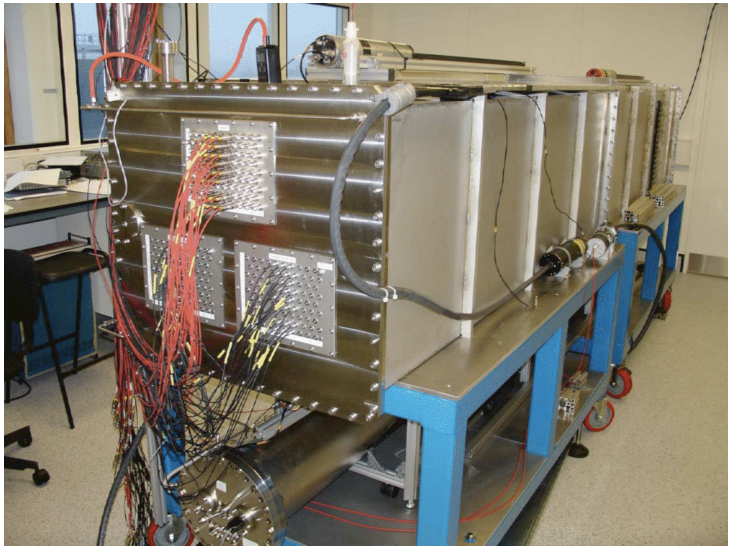


9.7	9.9	10	9.4	9.3
9.5	9.4	9.4	9.1	9.2
9.6	9.3	9.1	9.1	9.2
9.7	9.7	9.4	9.6	9.4
9.5	9.8	9.6	9.5	9.4

Optical simulations predict +0.7% degradation. Compare to +0.5%

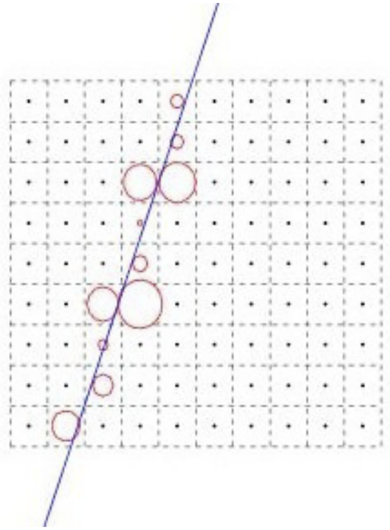
SuperNEMO Tracker R&D

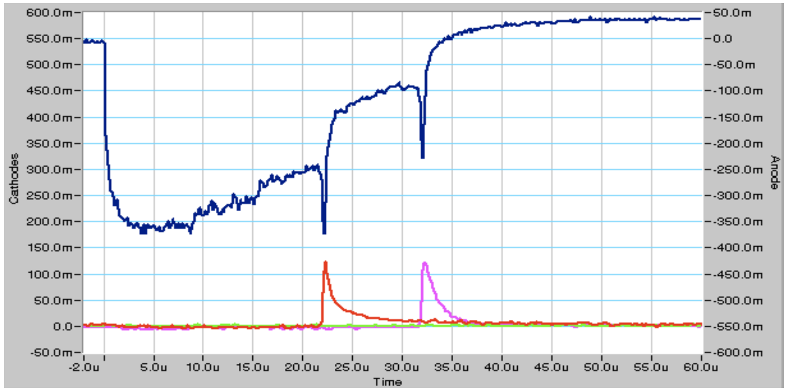
- Optimize length, wire material and diameter, read-out, gas mix
- Several 1-cell and two 9-cell prototypes built and tested
- 90-cell prototype:



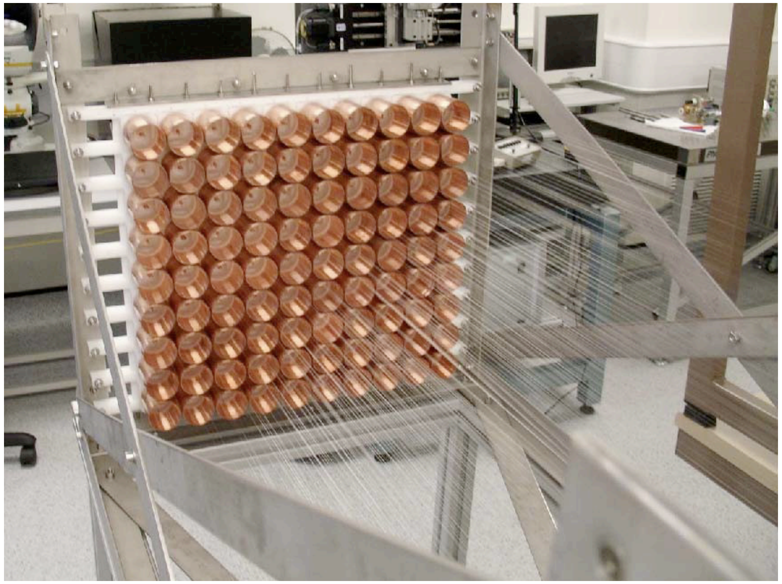
r – resolution 0.7 mm

z – resolution 1.3 cm





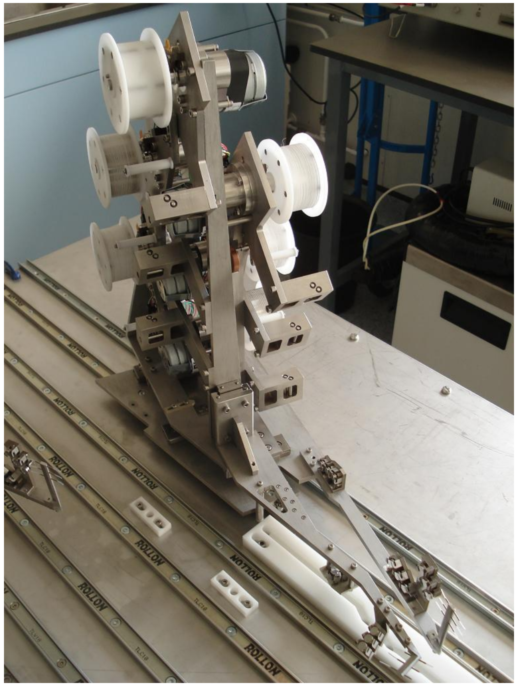
90-cell prototype in Manchester



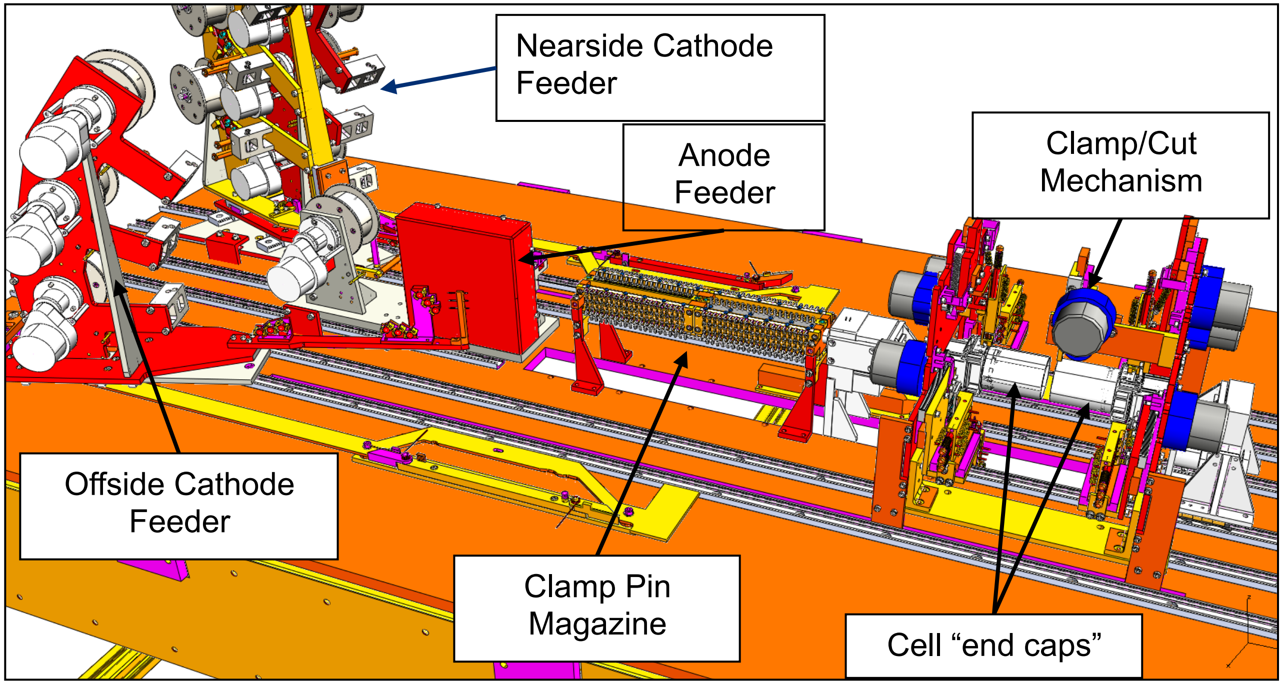
SuperNEMO Tracker R&D: Wiring Robot

Provide automation of tracker cell wiring: uniform tension and repeatability

Cathode feed mechanism



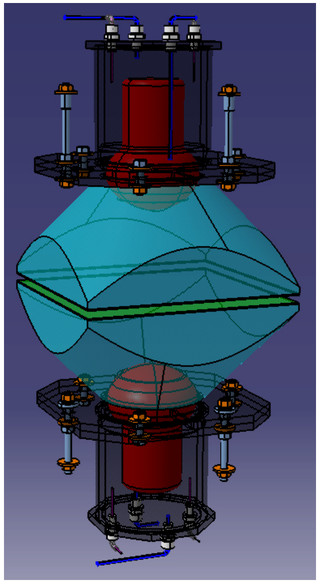
Complete wiring robot setup

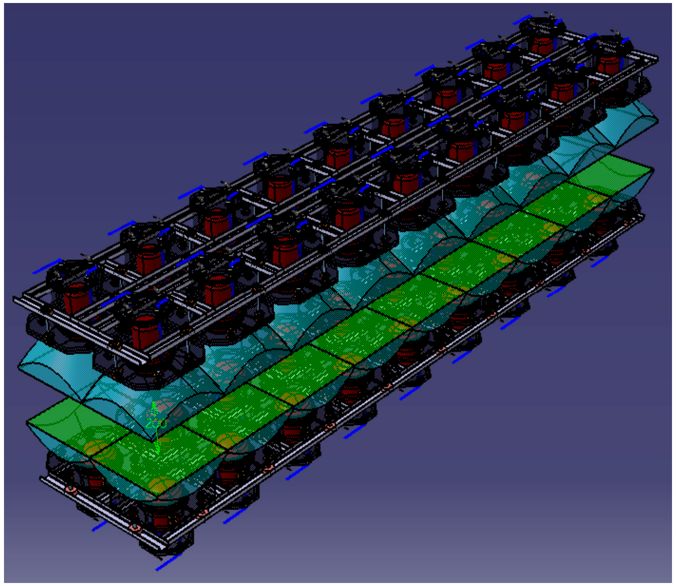


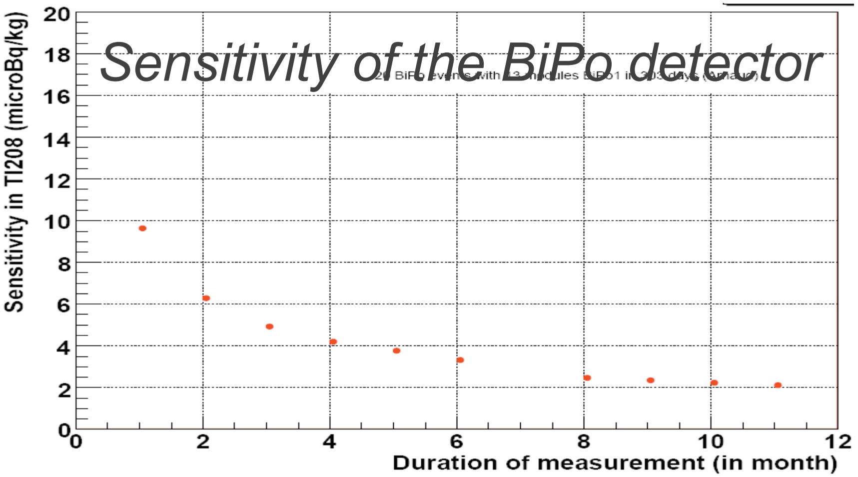
Most modules complete. The rest will be ready this month.

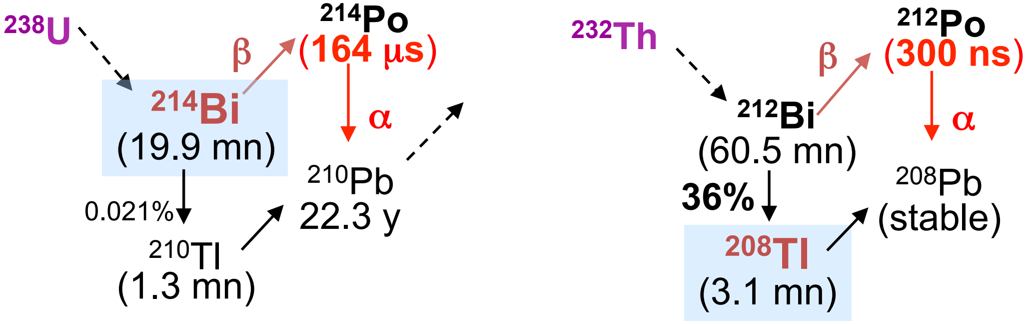
BiPo R&D for Source Purity

Measure ^{208}Tl < 2 mBq/kg & ^{214}Bi < 10 mBq/kg in $\beta\beta$ source foil









^{238}**U**

^{214}**Bi**
(19.9 mn)

β

^{214}**Po**
(164 μs)

α

^{210}Pb
22.3 y

0.021%

^{210}Tl
(1.3 mn)

^{232}**Th**

^{212}**Bi**
(60.5 mn)

β

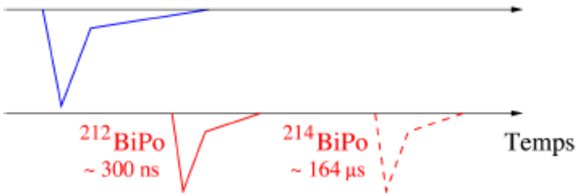
^{212}**Po**
(300 ns)

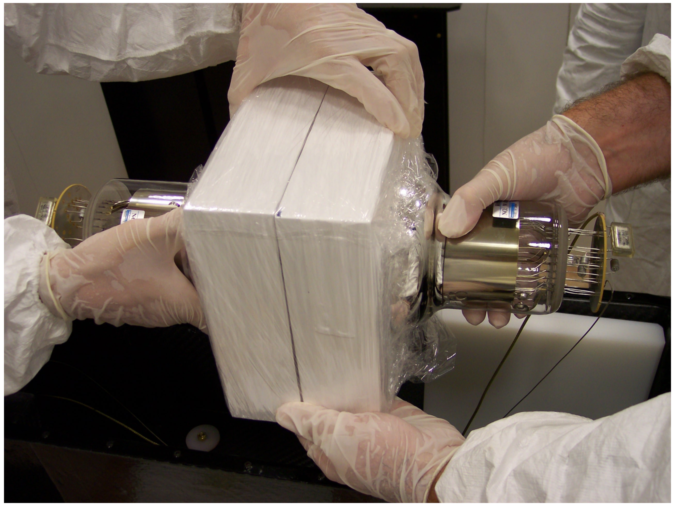
α

36%

^{208}**Tl**
(3.1 mn)

^{208}Pb
(stable)

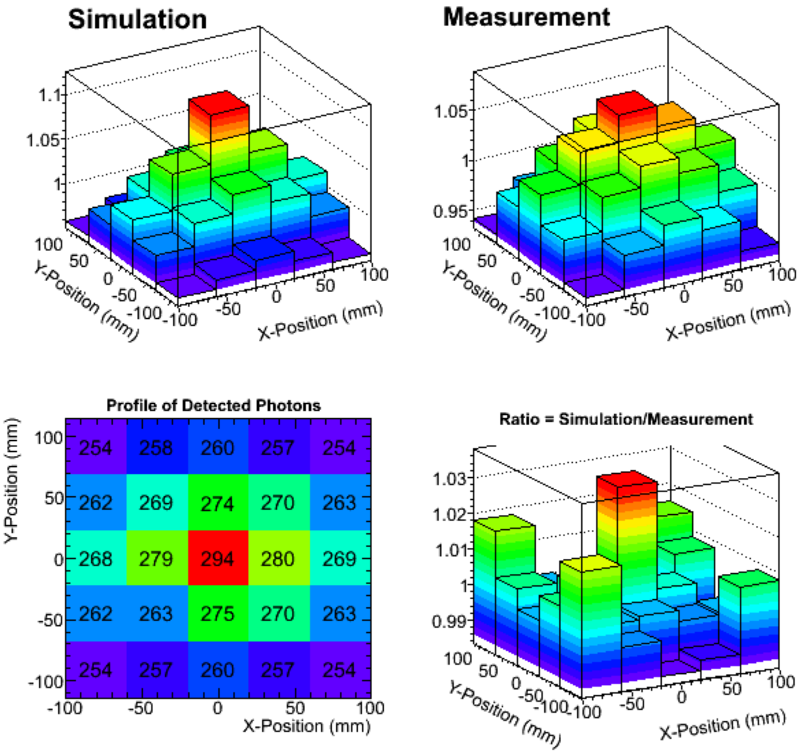




NEMO-3 Optical Simulations

Simulations of large NEMO-3 scintillators agree with measurements

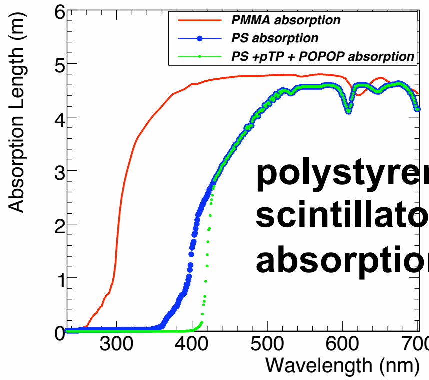
1 MeV electrons on the block face



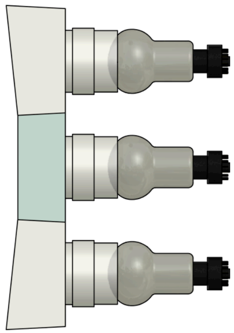
Profile of Detected Photons

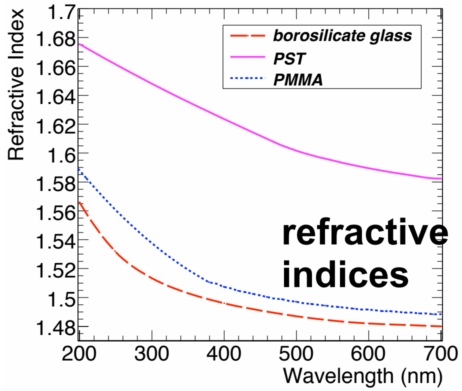
Y-Position (mm) \ X-Position (mm)	-100	-50	0	50	100
100	254	258	260	257	254
50	262	269	274	270	263
0	268	279	294	280	269
-50	262	263	275	270	263
-100	254	257	260	257	254

Comparison of measurement and simulation for a NEMO-3 external wall block.

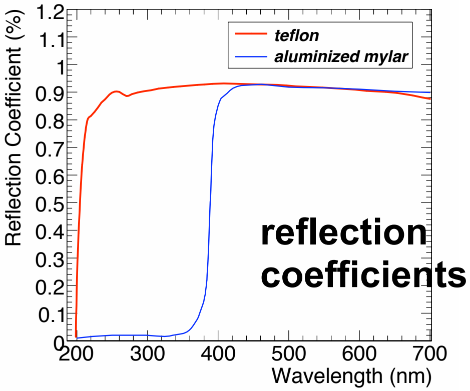


polystyrene and scintillator absorption





refractive indices



reflection coefficients

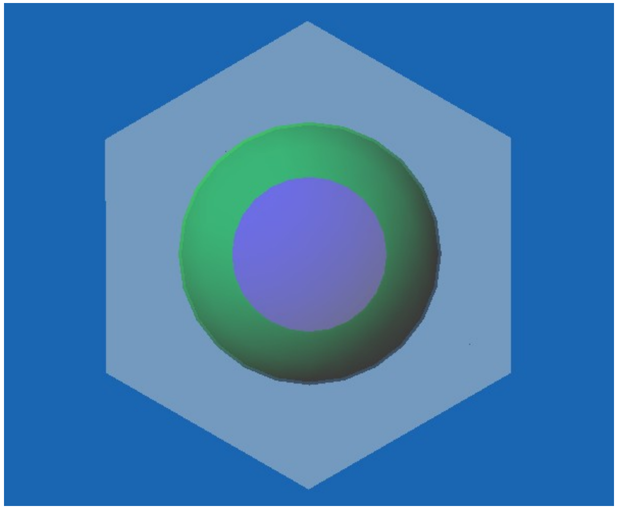
(Published NIM A (625) 2011, 20-28)

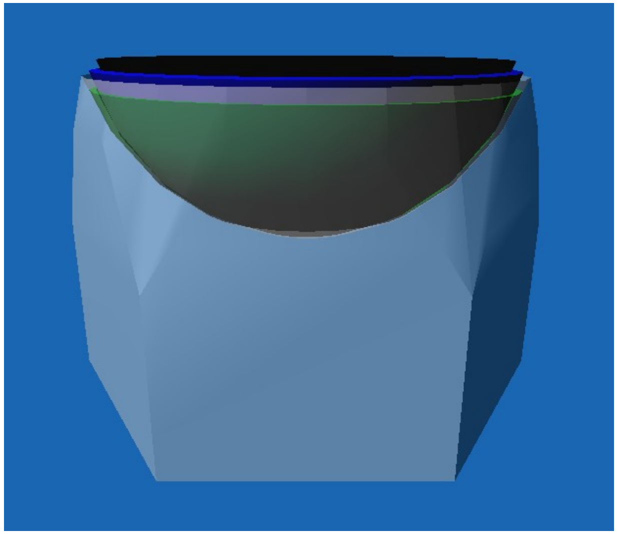
Results: 14.4% FWHM @ 1 MeV simulation
13.8% FWHM @ 1 MeV measurement

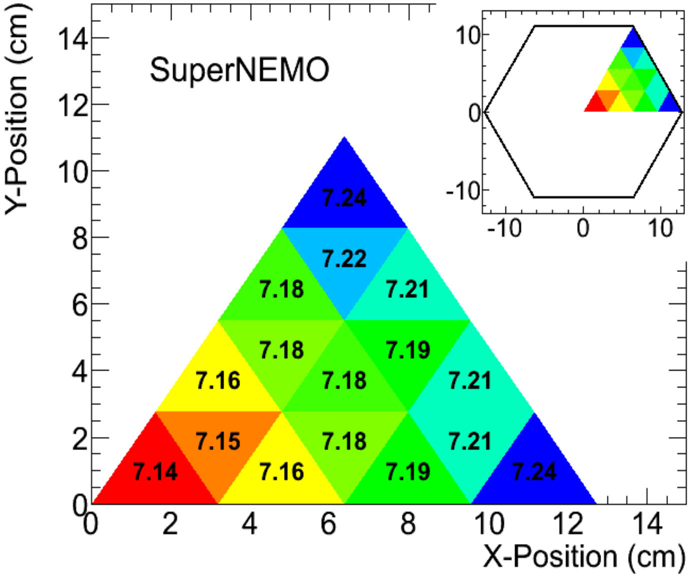
See poster #18 by B. Pahlka

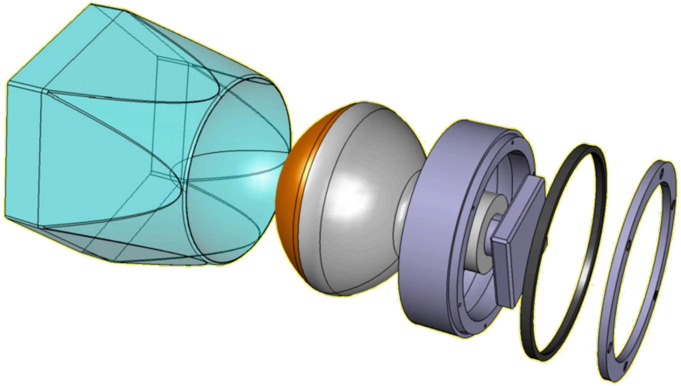
SuperNEMO Optical Simulations

Simulations of SuperNEMO prototype blocks agree with measurements







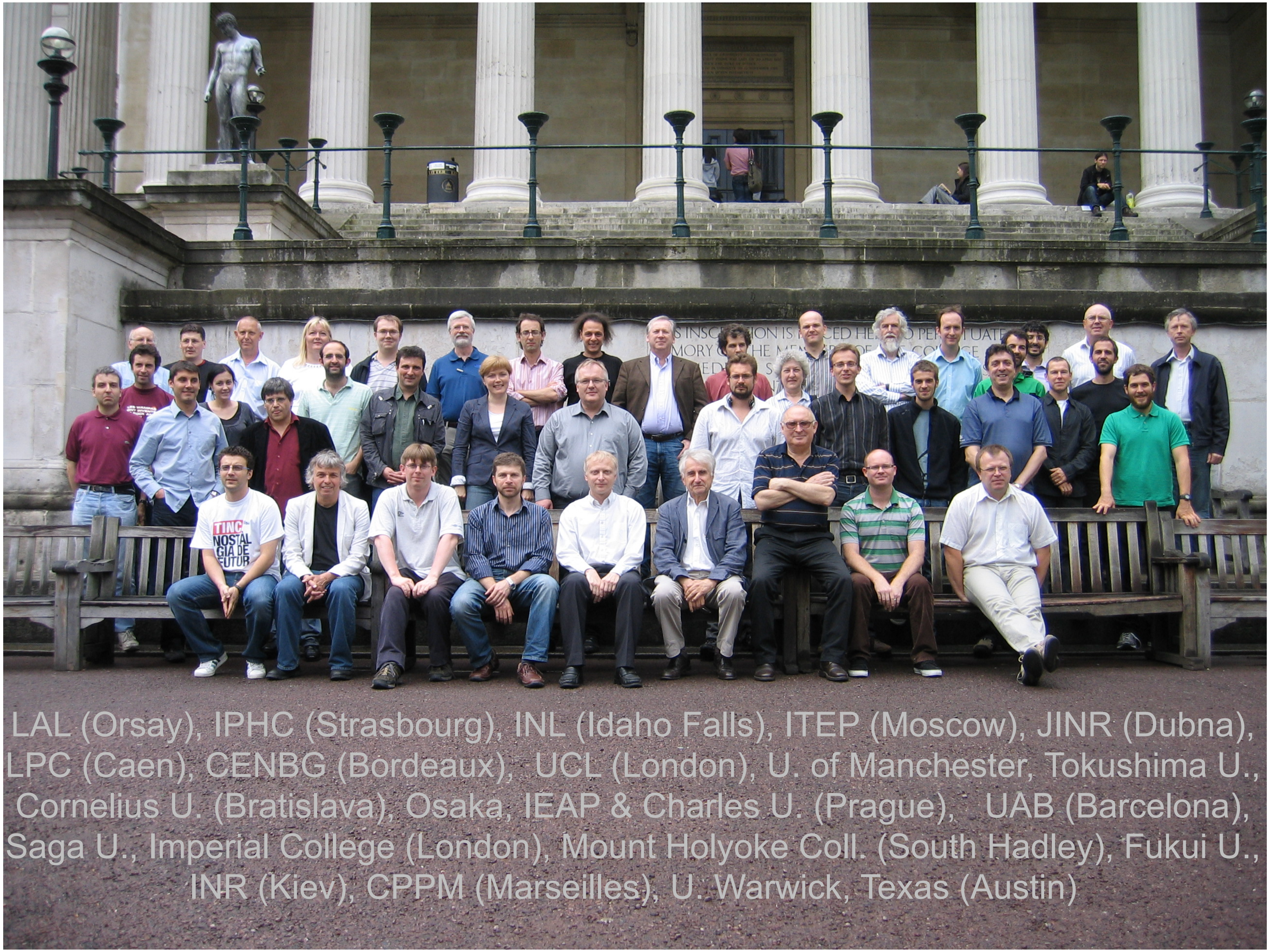


Summary

- NEMO-3 finished running at the end of 2010
- NEMO-3 established a low background technique (with strong BG rejection)
- NEMO-3 allows measurement of many observables
  - Energy
  - Topology
  - Timing
- SuperNEMO is a next generation experiment based on NEMO-3 success
- SuperNEMO further improves the technique
- SuperNEMO extends the half-life sensitivity by a factor of 100

Stay tuned for news from the SuperNEMO Demonstrator!

NEMO-3 and SuperNEMO Collaboration



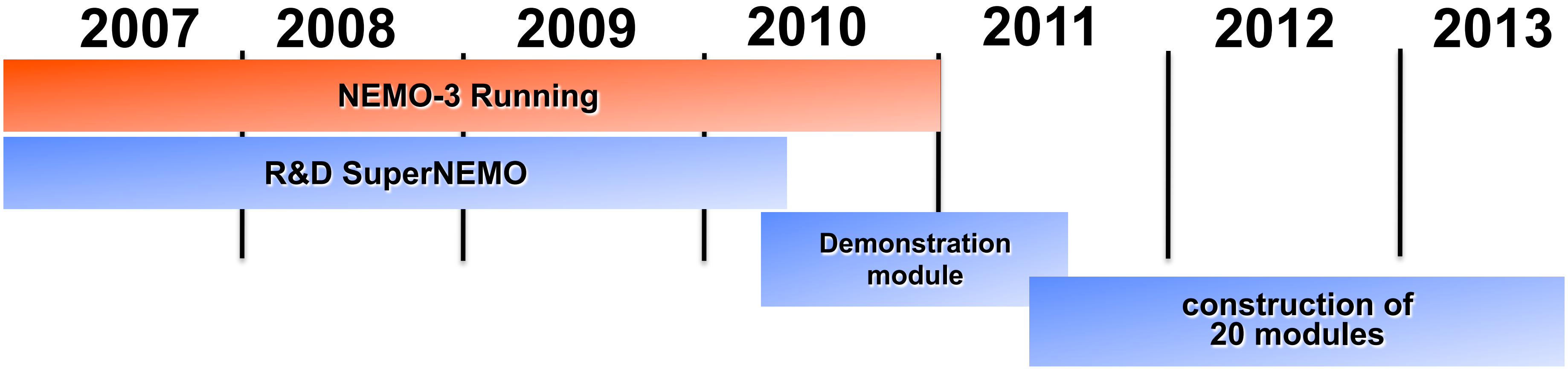
LAL (Orsay), IPHC (Strasbourg), INL (Idaho Falls), ITEP (Moscow), JINR (Dubna), LPC (Caen), CENBG (Bordeaux), UCL (London), U. of Manchester, Tokushima U., Cornelius U. (Bratislava), Osaka, IEAP & Charles U. (Prague), UAB (Barcelona), Saga U., Imperial College (London), Mount Holyoke Coll. (South Hadley),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

Backup Slides

Future Prospects

- ◆ NEMO-3 finalized running at the end of 2010
- ◆ Analyzing data now, should expect improved results

- ◆ A next generation experiment, SuperNEMO is being developed
- ◆ ^{82}Se sensitivity $T_{1/2}(0\nu)$ = (1-2) × 10^{26} y (500 kg*y exposure)
  $\langle m_\nu \rangle \leq$ 40 – 140 meV (NME uncertainty)

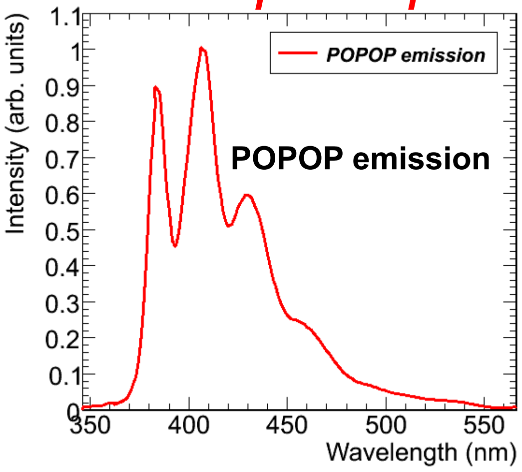


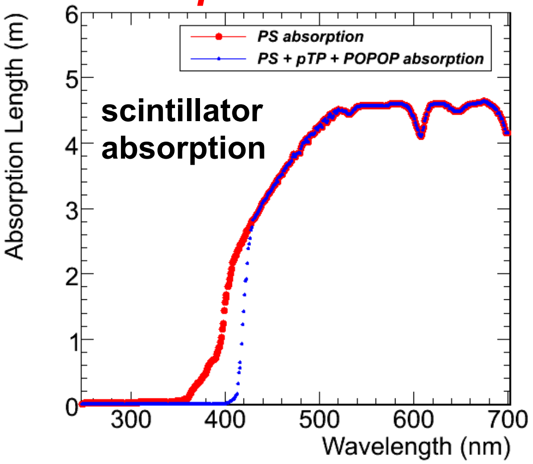
Optical Photon Model Ingredients

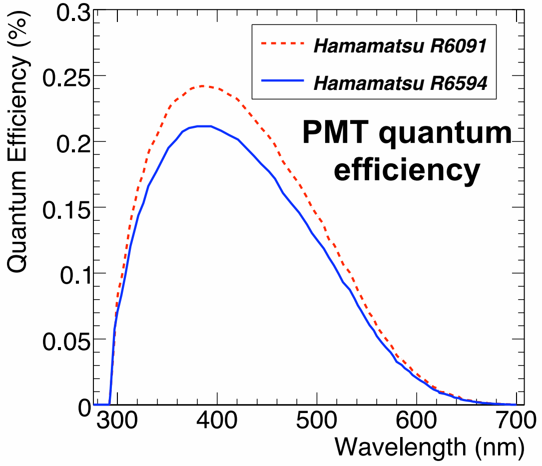
- Emission and absorption spectra
  - base scintillator
  - primary and secondary fluors
  - Stokes shifting and fluorescent quantum yield
- Spectral reflectivity of all relevant materials
- Spectral indices of refraction
- Spectral QE of photodetector

GEANT4 + ROOT
framework

Example input data for optical simulations:



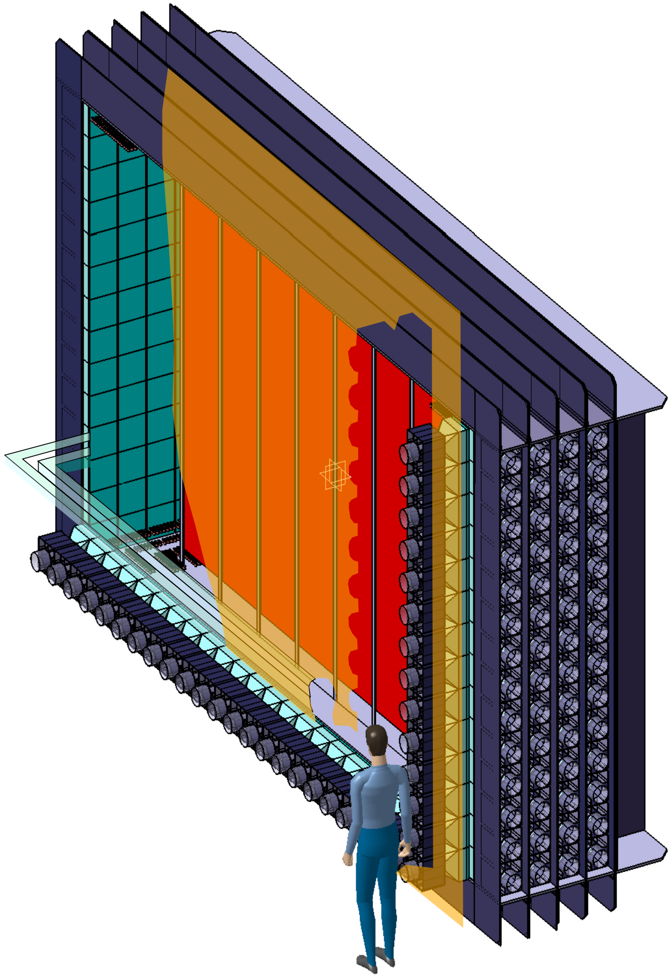


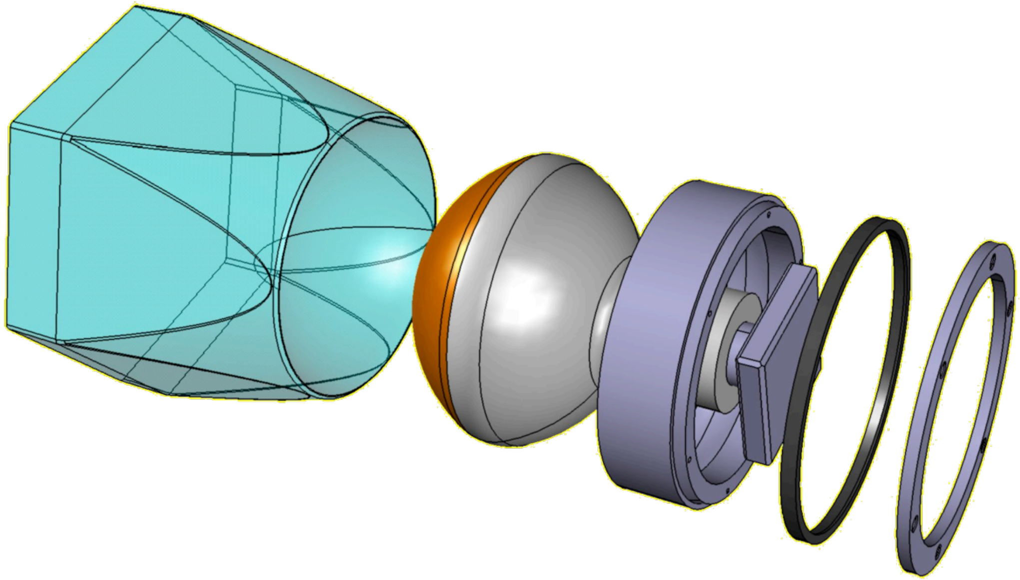


SuperNEMO Design

20 modules for 100 kg

Source: ~ 5kg (40 mg/cm^2, 12m^2)
Tracking: ~2,100 drift cells).
Calorimeter: ~600 blocks

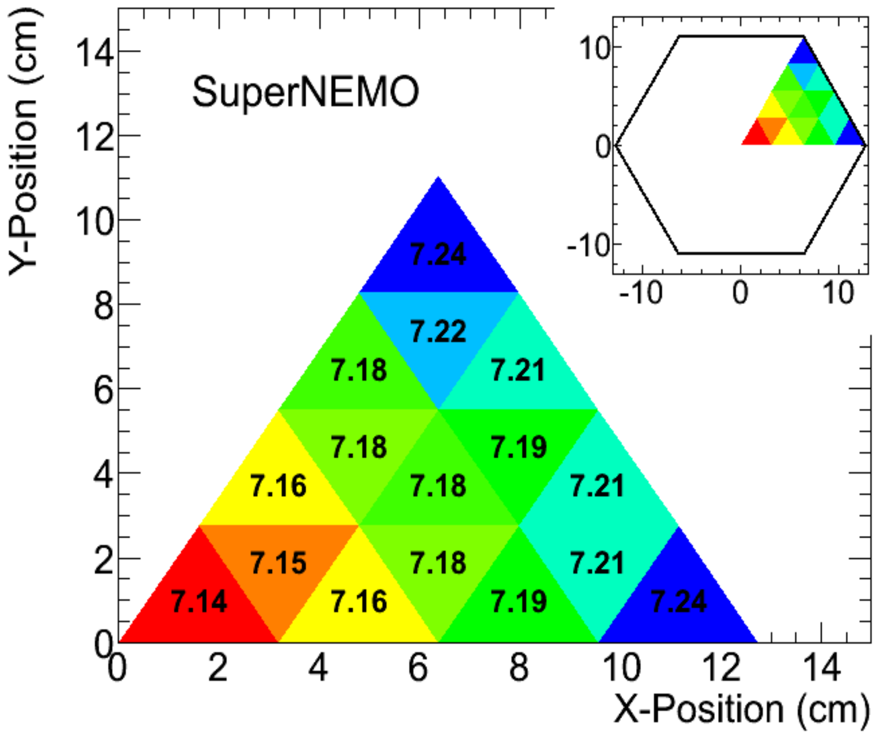


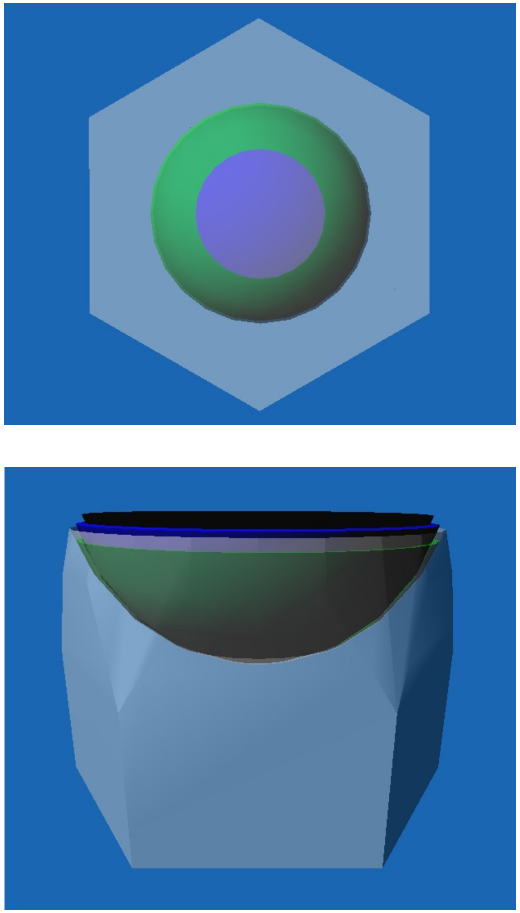


Courtesy of: J.FORGET & C.BOURGEOIS (SuperNEMO Collaboration)

SuperNEMO Block Simulations

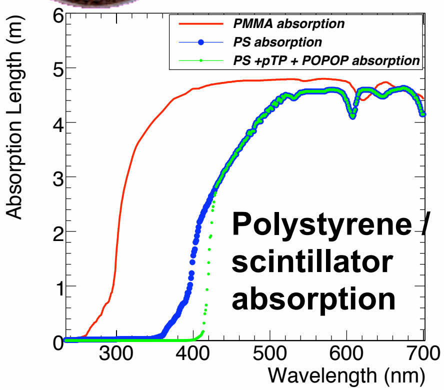
Simulations of large hexagonal scintillators agree with measurements

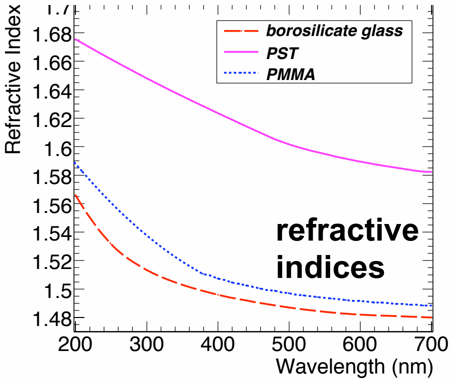


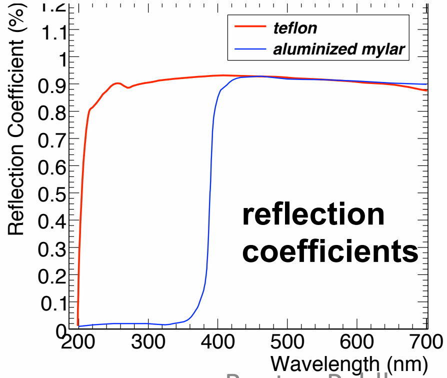


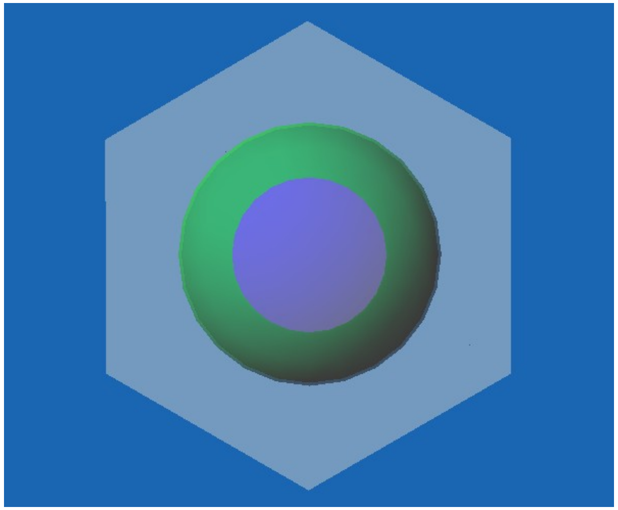
Simulations of a large hexagonal prototype block coupled to an 8” PMT to be used for SuperNEMO. Measurements of 7.5 ± 0.5% FWHM @ 1 MeV have recently been obtained.

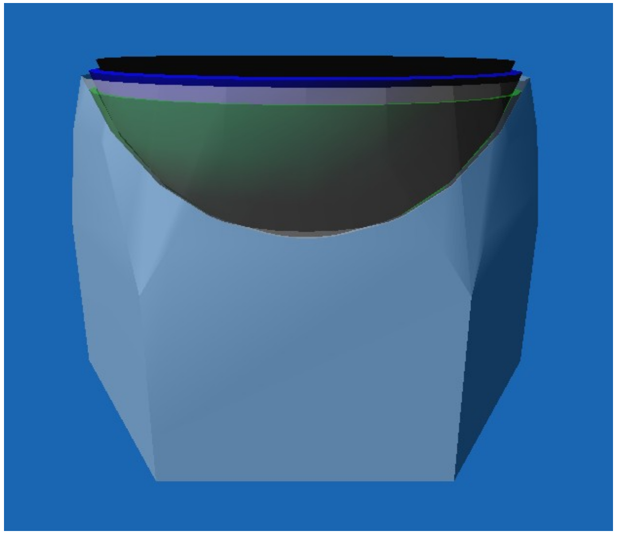
NEMO-3 Optical Simulations

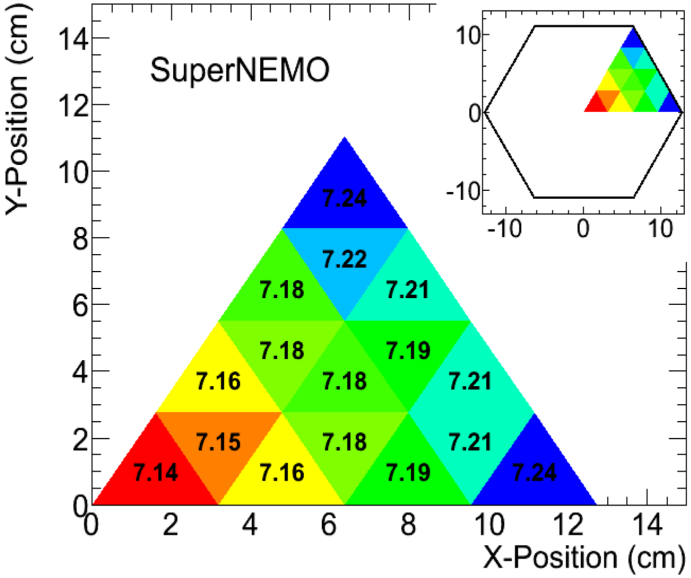


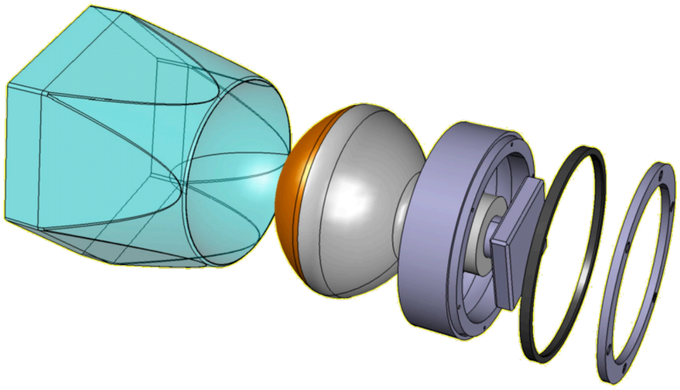




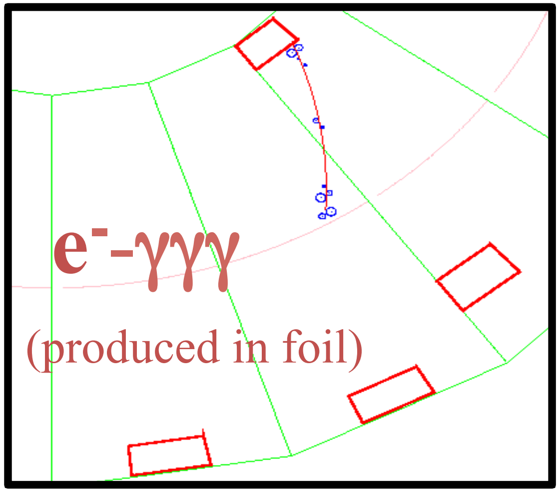




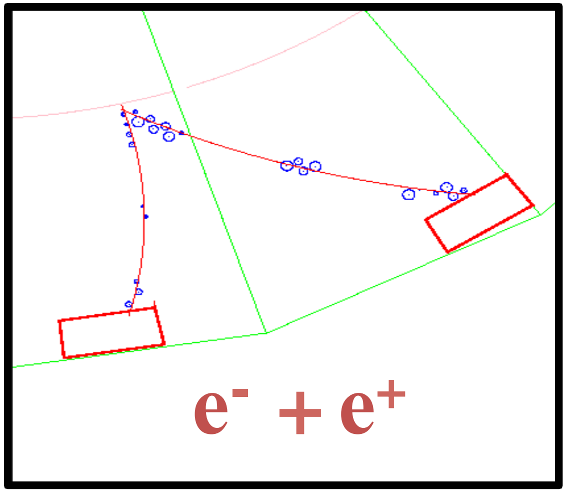




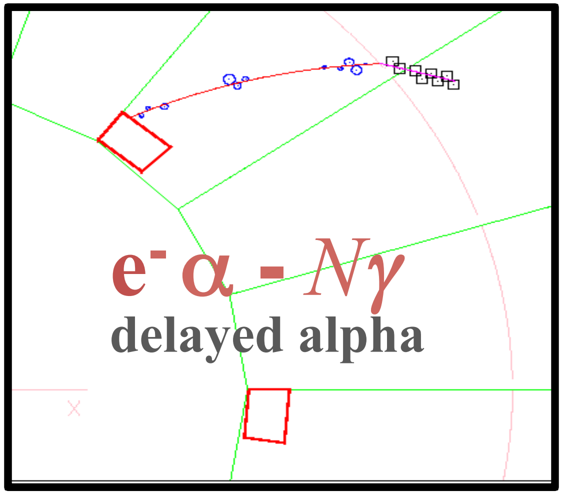
Background Signatures



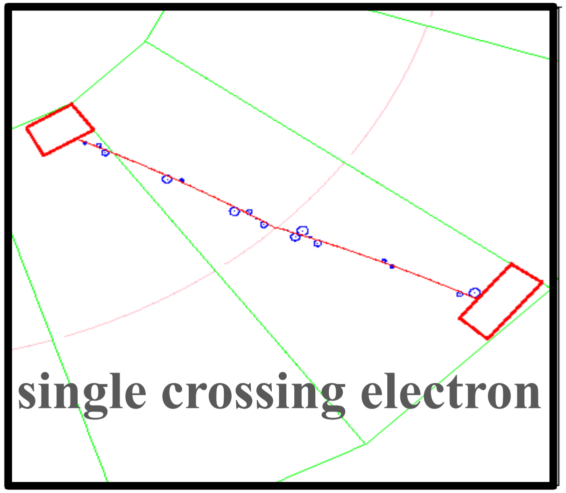
Candidate ^{208}Tl decay



Candidate ^{40}K decay



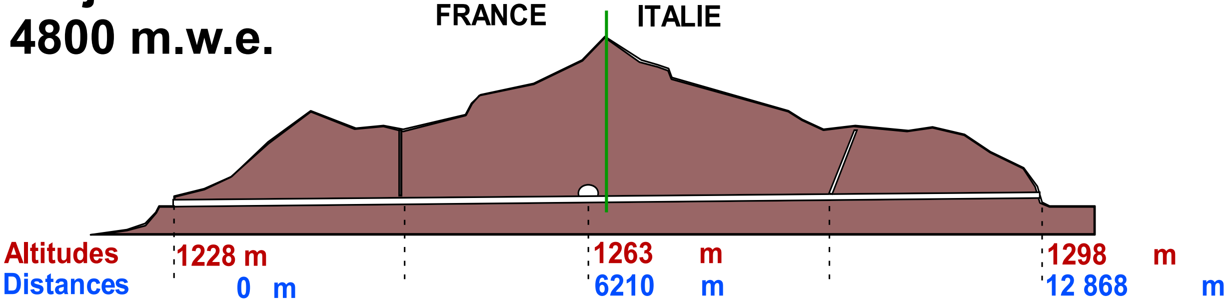
Candidate ^{214}Bi decay



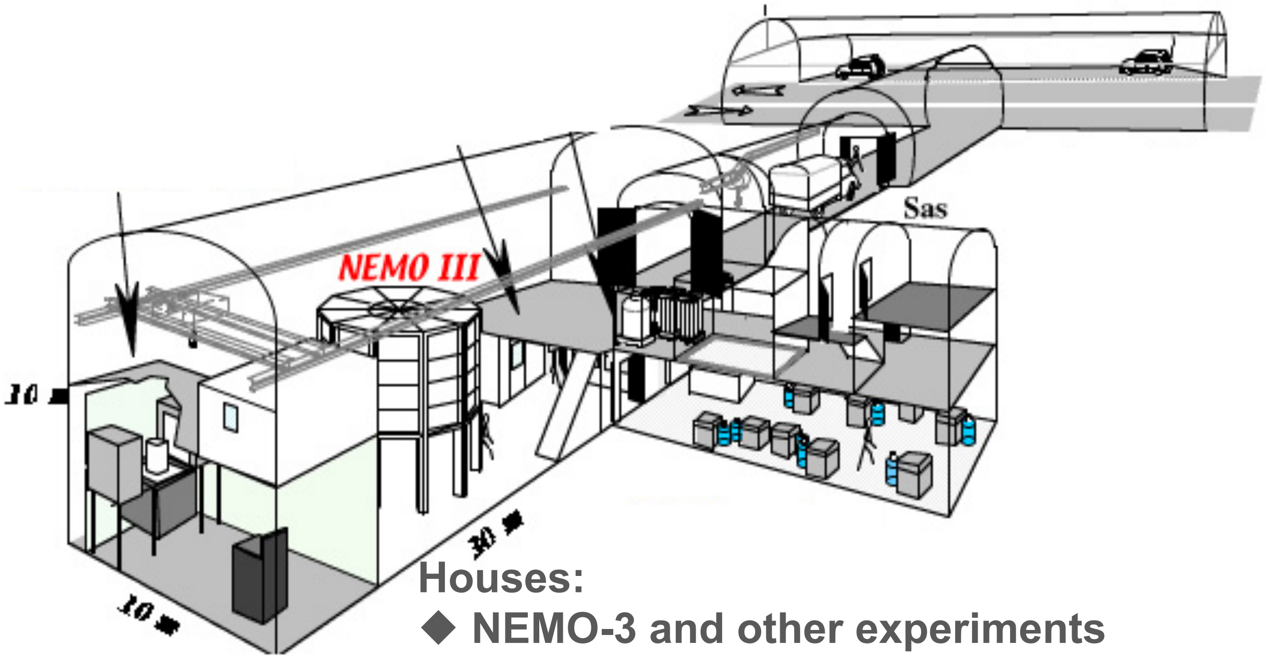
Candidate external event

Laboratoire Souterrain de Modane

Fréjus Tunnel:
4800 m.w.e.




Fréjus Tunnel



Houses:
- ◆ NEMO-3 and other experiments
- ◆ High Purity Germanium (HPGe) Detectors

Modane, France

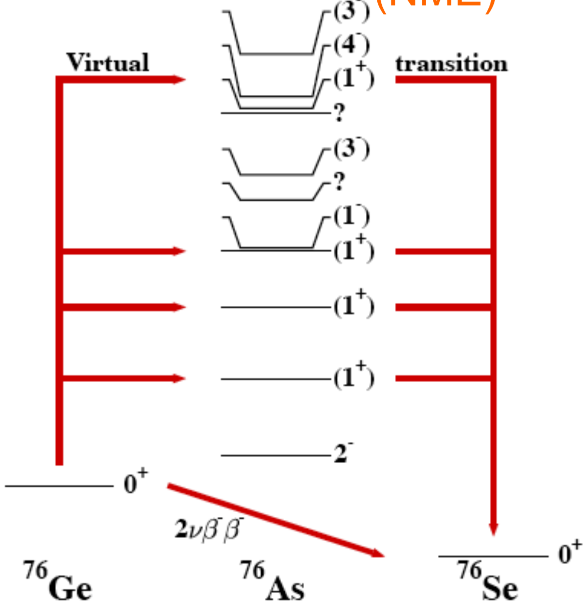
Double Beta Decay Half-life

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

Phase Space factor

Nuclear matrix element (NME)

$2\nu\beta\beta$

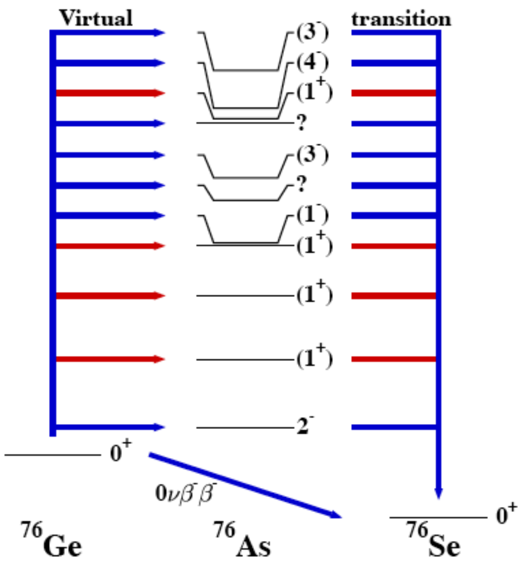


$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left|M_{0\nu}\right|^2 \bullet \left\langle m_{\beta\beta} \right\rangle^2$$

Phase Space factor

Nuclear matrix element (NME)

$0\nu\beta\beta$



$$\langle m_{\beta\beta} \rangle = \sum_k m_k |U_{ek}^2| e^{i\alpha k}$$

U_{ek} = *PMNS matrix elements*

$e^{i\alpha k}$ = Majorana CP violating phases

Some Aspects of Neutrino Mass

- ◆ Neutrino oscillations can probe the Δm^2 mass splittings
- ◆ Cannot probe the absolute neutrino mass scale

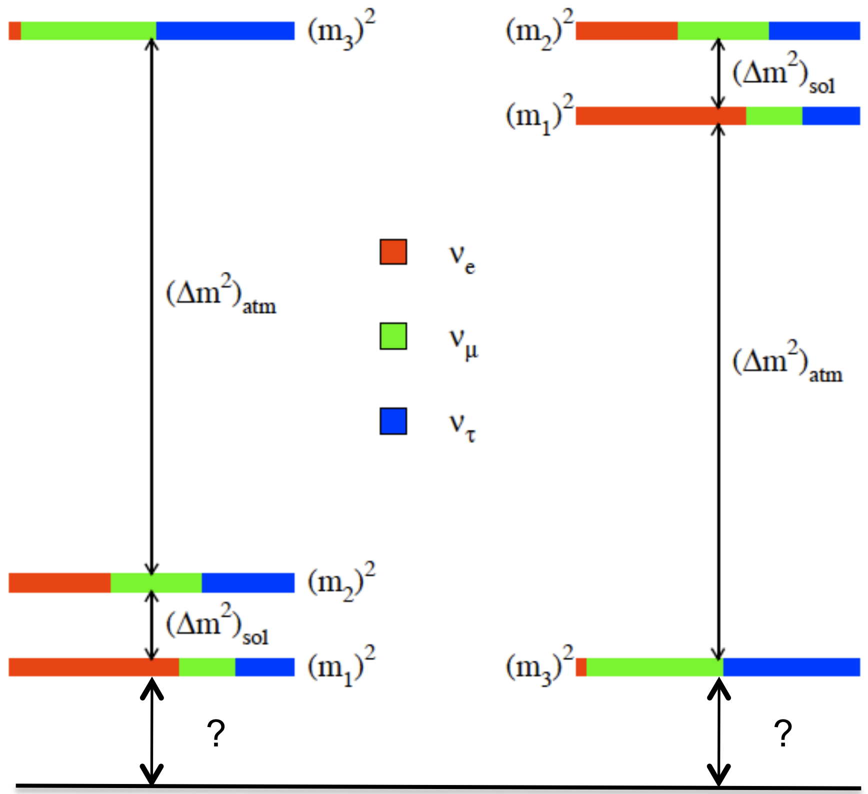
Mass eigenstates (ν_1, ν_2, ν_3)

flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$

$$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i}|\nu_\alpha\rangle$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix

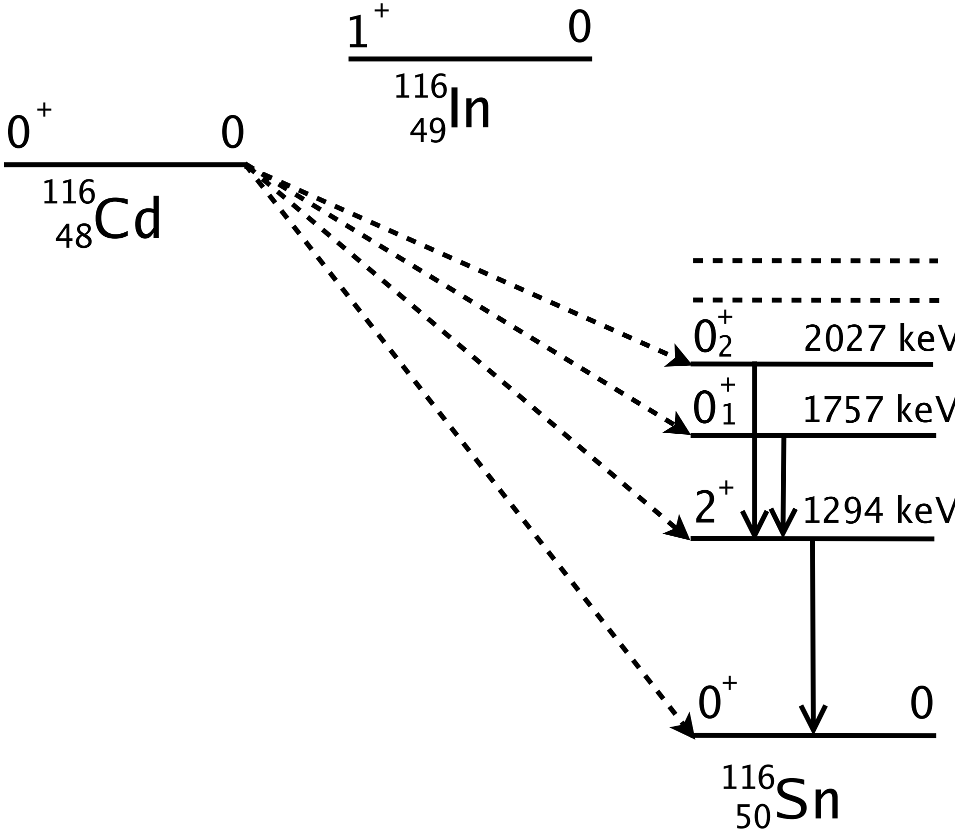


Normal hierarchy
$(m_3)^2 >> (m_2)^2 \sim (m_1)^2$

Inverted hierarchy
$(m_2)^2 \sim (m_1)^2 >> (m_3)^2$

Phenomenology of Double Beta Decay

- Nucleon pairing in even-even nuclei more bound than odd-odd
- ^{116}Cd stable against β decay but unstable against ββ decay



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

Choice of Isotope

Choice of isotope:

- $Q_{\beta\beta}$
- Isotopic abundance
- Phase space factor ($G_{0\nu}$)
- Nuclear matrix elements ($M_{0\nu}$)
- Background at the $Q_{\beta\beta}$ value

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

$$\langle m_{\beta\beta} \rangle = \sum_k m_k |U_{ek}^2| e^{i\alpha k}$$

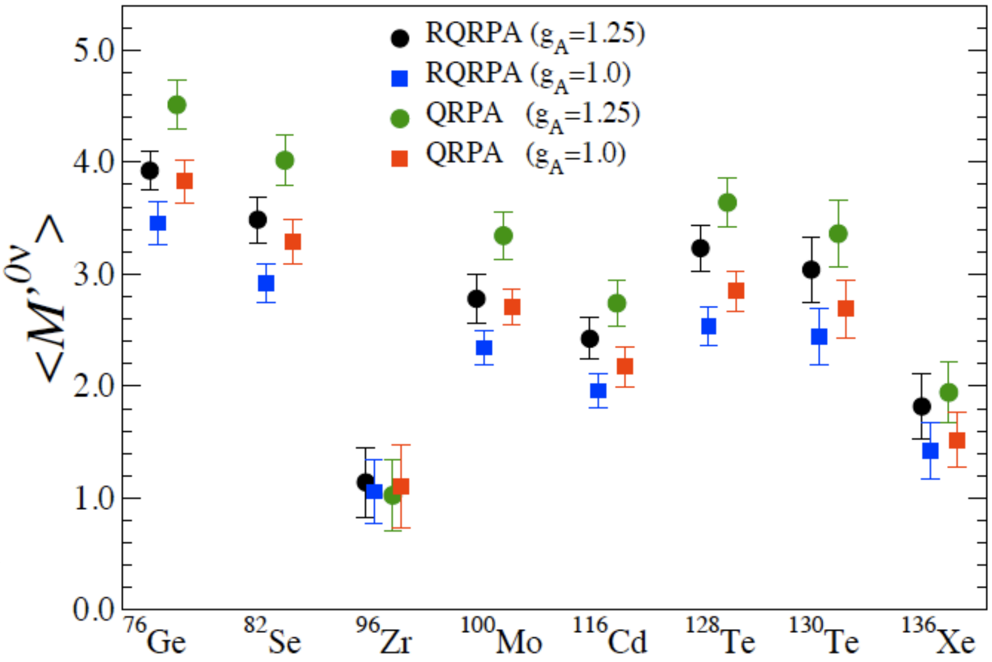
Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic Abundance (%)	$G_{0\nu}$ x 10^{-25} (y^{-1})
^{48}Ca	4.271	0.187	2.44
^{76}Ge	2.040	7.8	0.24
^{82}Se	2.995	9.2	1.08
^{96}Zr	3.350	2.8	2.24
^{100}Mo	3.034	9.6	1.75
^{116}Cd	2.804	7.5	1.89
^{130}Te	2.528	33.8	1.70
^{136}Xe	2.479	8.9	1.81
^{150}Nd	3.367	5.6	8.00

Choice of Isotope (2)

Choice of isotope:

- $Q_{\beta\beta}$
- Isotopic abundance
- Phase space factor (*G*)
- Nuclear matrix elements (*M*)
- Background at the *Q* value

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q^5_{\beta\beta}, Z) \bullet \left| M^{GT}_{0\nu} \right|^2 \bullet \left\langle m_{\beta\beta} \right\rangle^2$$



Calculating NMEs is a complex task:

- Heavy open shell nuclei have complicated nuclear structure
- Must have complete set of states for intermediate nucleus
- Many-body problem requires good approximations

Choice of Isotope (3)

Choice of isotope:

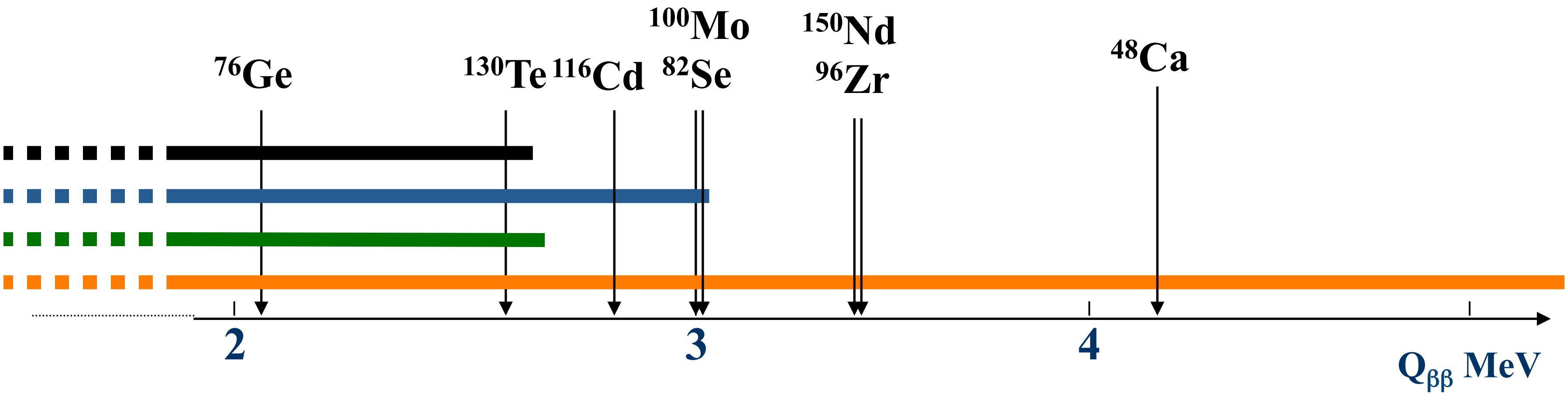
- ◆ $Q_{\beta\beta}$
- ◆ Isotopic abundance
- ◆ Phase space factor (*G*)
- ◆ Nuclear matrix elements (*M*)
- ◆ Background at the *Q* value

▬ **^{40}K, ^{60}Co, ^{137}Cs**

▬ **^{214}Bi and other radon progeny**

▬ **^{208}Tl (2.6 MeV gamma line) and other thorium progeny**

▬ **γ from (n,γ) reaction and cosmic ray muon bremstrahlung**



+ tail of 2νββ distribution

Experimental Techniques

$0\nu\beta\beta$ half-life sensitivity

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

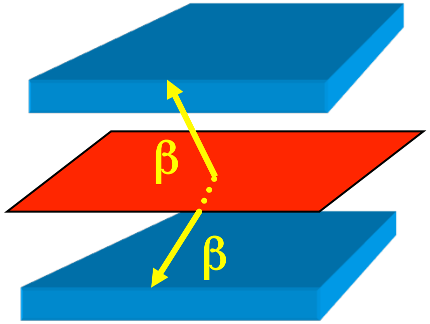
n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source
M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts $(\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{y})$
ΔE – energy resolution (keV)

Different technologies exploit different physical parameters

Experiments	Isotopes	Techniques
NEMO3	**^{100}Mo, ^{82}Se**	**Tracking + calorimeter**
Cuoricino	**^{130}Te**	**Bolometers**
GERDA	**^{76}Ge**	**Ge diodes**
COBRA	**^{130}Te, ^{116}Cd**	**ZnCdTe semi-conductors**
CANDLES	**^{48}Ca**	**CaF$_2$ scintillating crystals**
SNO++	**^{150}Nd**	**Nd loaded liquid scintillator**

Tracking-calorimetry

Source ≠ detector



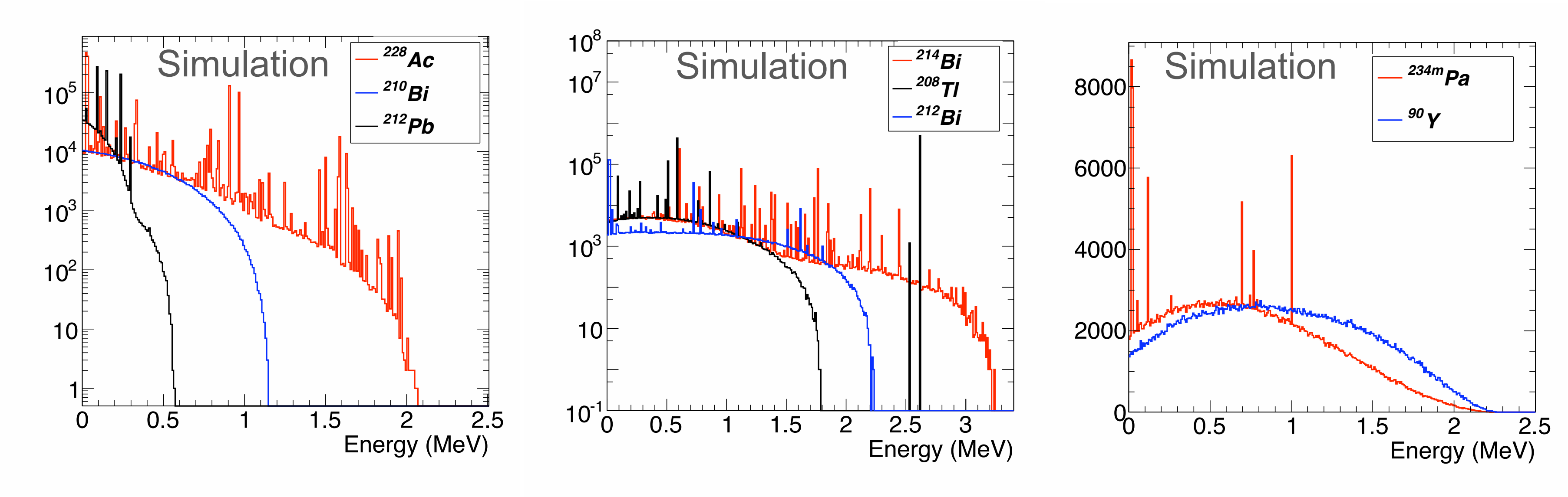
Strengths: Efficiency, Resolution, mass

N_{Bckg}, isotope choice flexibility

Background Considerations

Backgrounds contribute to the $2\nu\beta\beta$ and $0\nu\beta\beta$ energy spectra

- ^{210}Bi and ^{90}Y are pure beta emitters
- ^{214}Bi, ^{208}Tl and others emit betas and gammas
- Plots show gamma rays and beta rays together

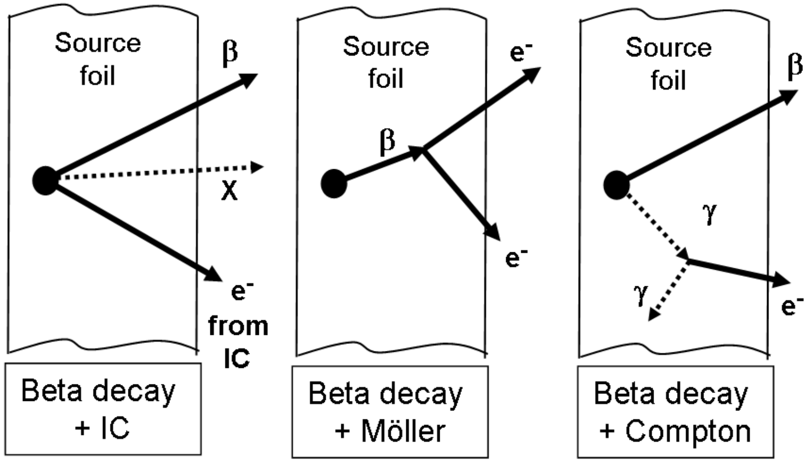


Simulated energy spectra for several isotopes showing gamma ray spikes overlayed on top of continuous beta spectra.

Processes that mimic ββ-decay

Internal Backgrounds from:

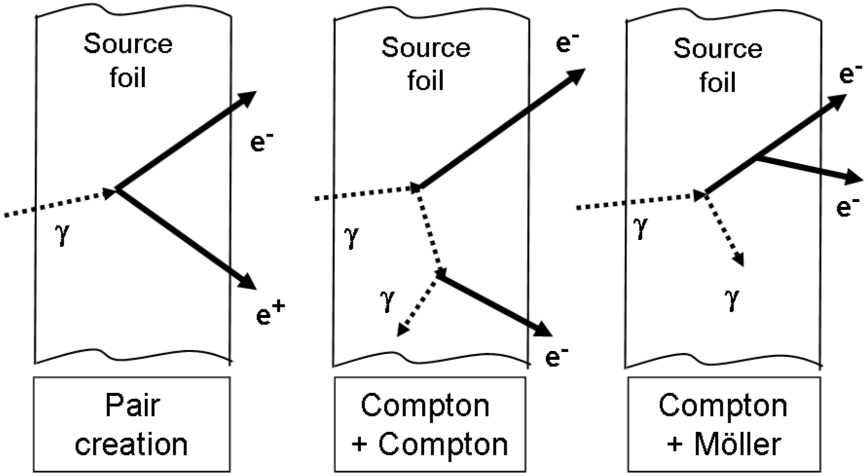
- impurities in isotopic foil
- 2νββ background of 0νββ



Internal processes yielding 2 e^- events

External Backgrounds from:

- PMTs (glass, shielding)
- iron / water shielding
- tracking chamber wires
- copper support structure
- outside the detector



External processes yielding 2 e^- events

Steps Towards a ββ Analysis

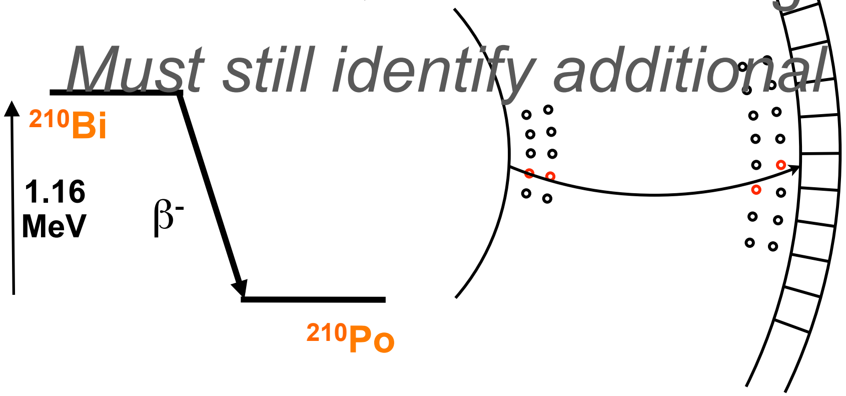
Key is identifying ALL background contaminations
NEMO-3 Advantage: Backgrounds are measured *in situ!*

Recent publication in NIM A606 (2009) 449-465

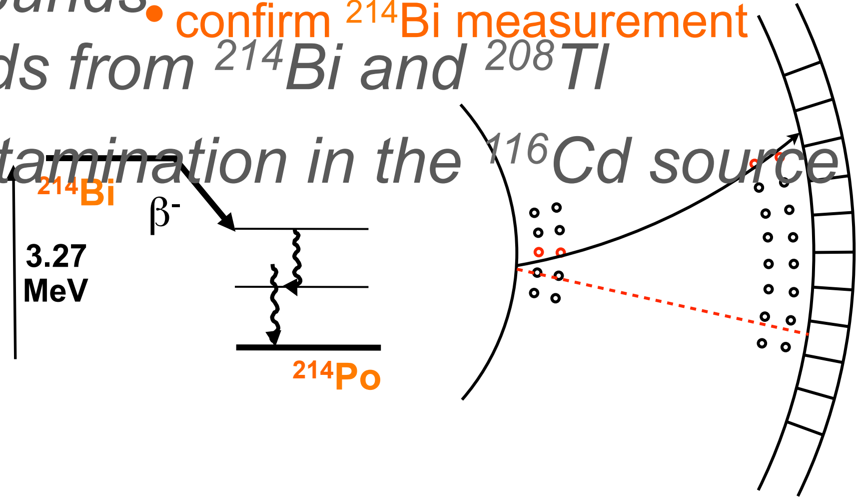
- *all external backgrounds*
- *internal backgrounds from ^{214}Bi and ^{208}Tl*

Must still identify additional contamination in the ^{116}Cd source

- Measure single β-emitters in ^{116}Cd source foil:
  - ^{40}K, ^{234m}Pa, ^{210}Bi



- Measure single β-emitters with gamma transition in ^{116}Cd source foil:
  - confirm ^{214}Bi measurement



- Other backgrounds measured with:
  - High Purity Germanium detectors
  - single electron ejection with alpha emission (e-α)
  - electrons originating in tracking chamber that interact with the foil
- Use activity model to study 2νββ and 0νββ half-lives

Single Electron Selection Criteria

To select single electron events in the foil, we require:

1) TRACKING REQUIREMENTS

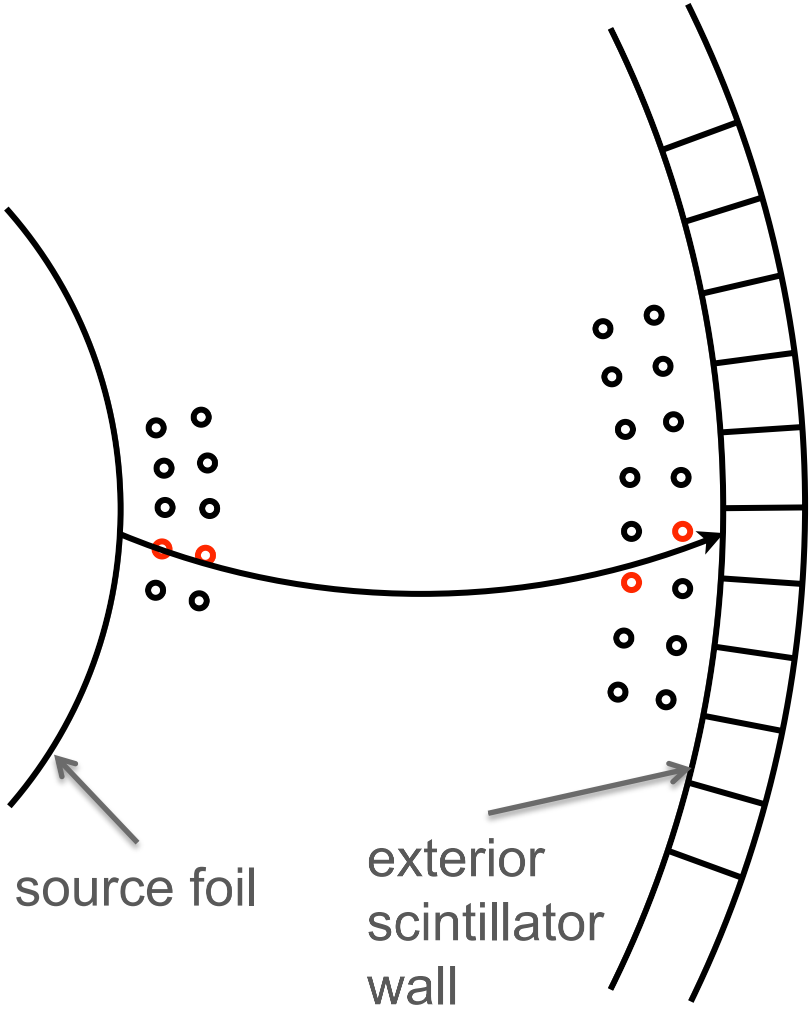
- One track with “negative” curvature
- At least one of the first two Geiger planes near the foil are fired
- At least one of the first two Geiger planes near the wall are fired
- Electron track length > 50 cm

2) CALORIMETER REQUIREMENTS

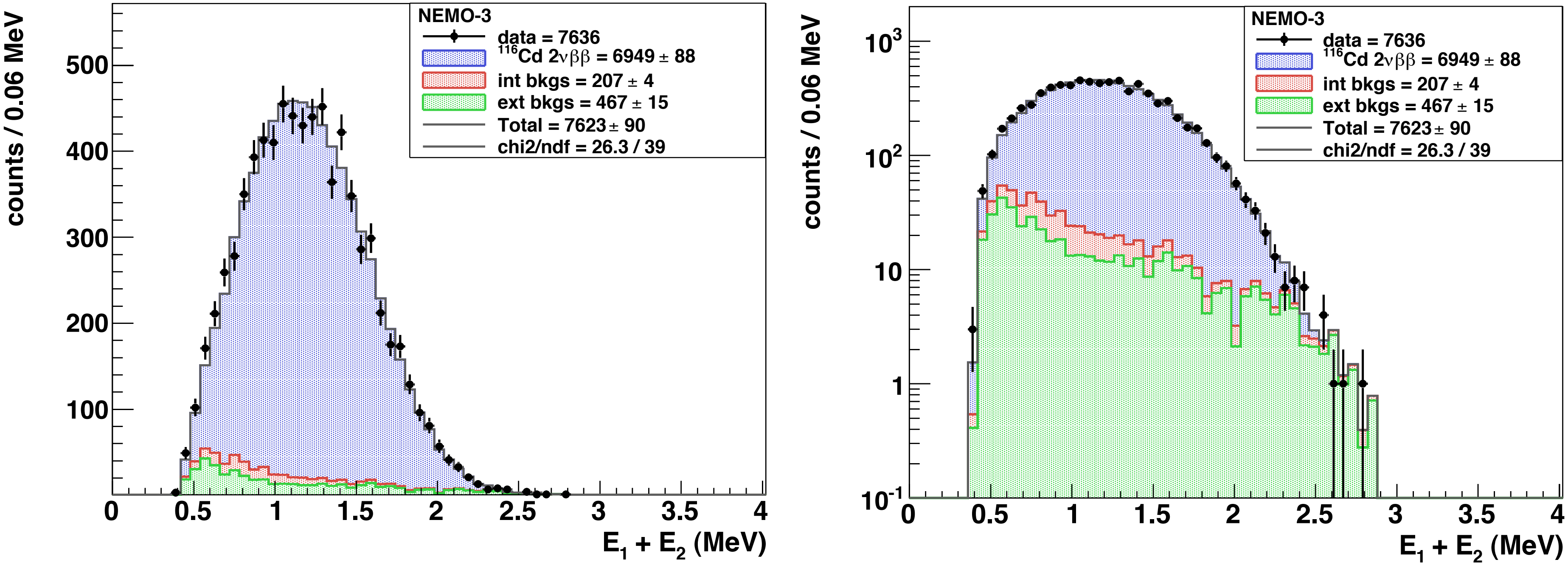
- Only one isolated scintillator to be fired
- The track is associated to the scintillator
- Minimum electron energy > 200 keV

3) FOIL VERTEX REQUIREMENTS

- Track is reconstructed in cadmium foil
- No alpha particles in event



^{116}Cd 2νββ Results



Results	
Data	7636 ± 87
Background	674 ± 15
Signal	6949 ± 88
Total time	1471 days
Mass	410.4 grams
Efficiency	3.6%

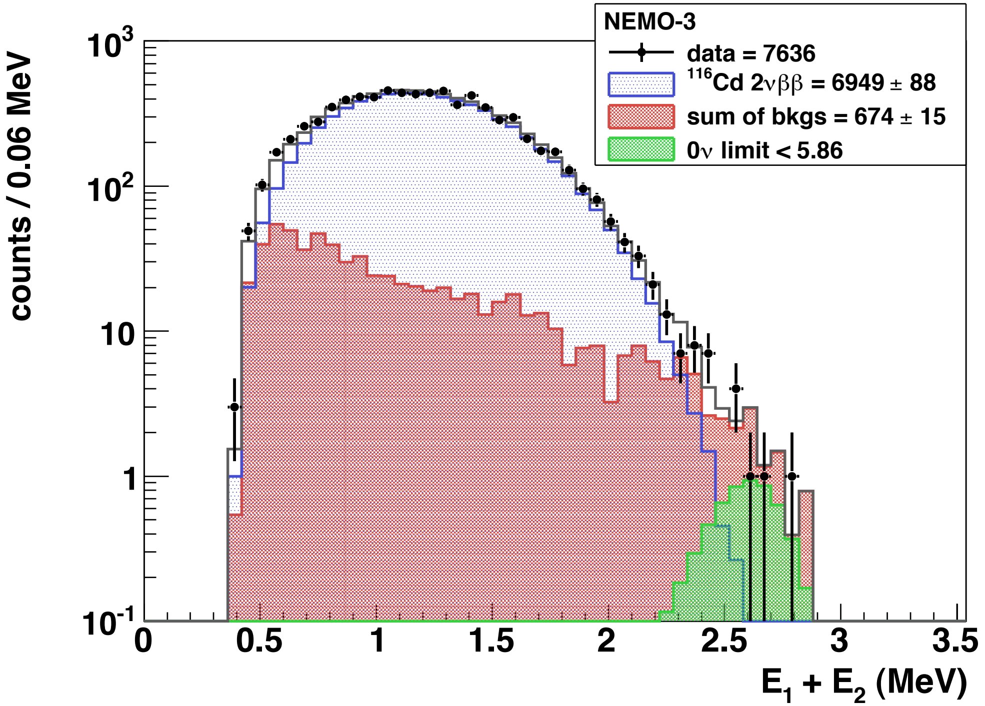
$$T_{1/2} = \epsilon \frac{N_A \ \ln(2)}{N_{obs}} \left(\frac{m}{M}\right) t$$

$T_{1/2}^{2\beta2\nu} = (2.88 \pm 0.04_{stat} \pm 0.16_{syst}) \times 10^{19}$ y

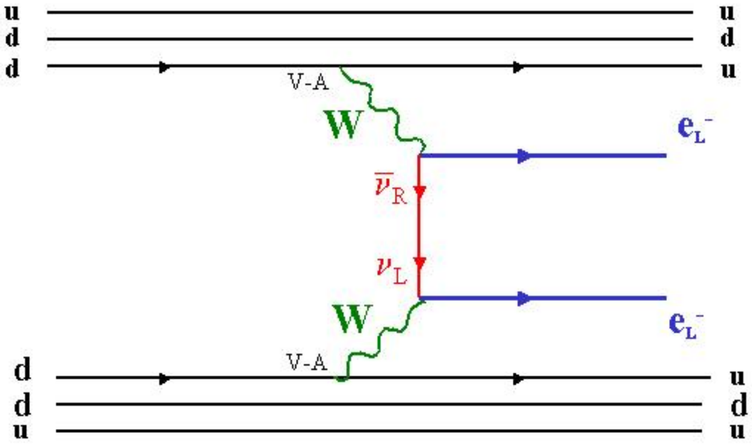
$T_{1/2}^{2\beta2\nu} = (2.90 \pm 0.06_{stat} \pm 0.3_{syst}) \times 10^{19}$ y

Danevich, F. *et al.* Phys. Rev. C, 68, 035501, (2003) (Solotvina)

^{116}Cd 0νββ Results (V-A)



Combined Results	
Data	7636
Exp. Background	7623
Exp. 0νββ Signal	< 5.86
0νββ efficiency	12.74%



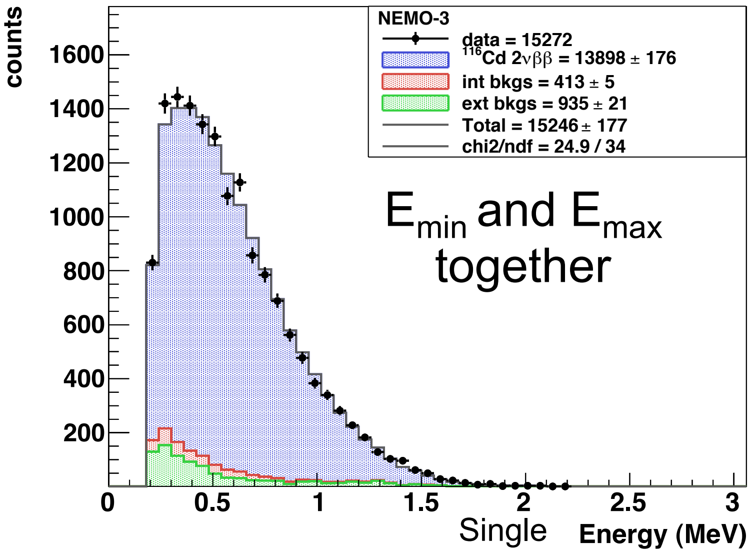
$T_{1/2}^{0\nu\beta\beta} > 1.29 \times 10^{23}$ y (90% C.L.)

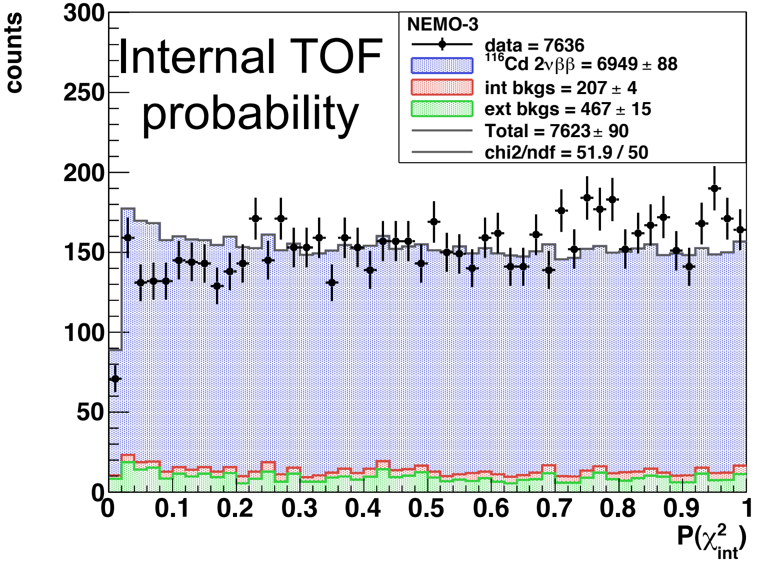
$T_{1/2}^{0\nu\beta\beta} > 1.7 \times 10^{23}$ y (90% C.L.)

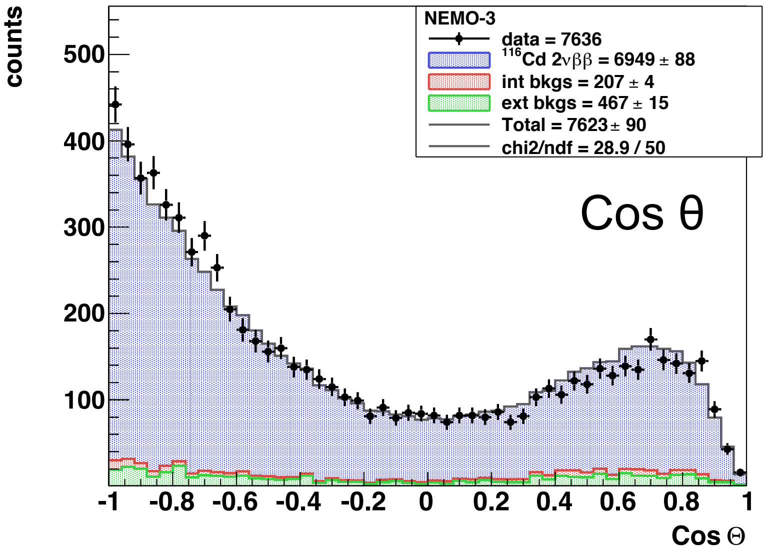
Danevich, F. *et al.* Phys. Rev. C, 68, 035501, (2003) (Solotvina)

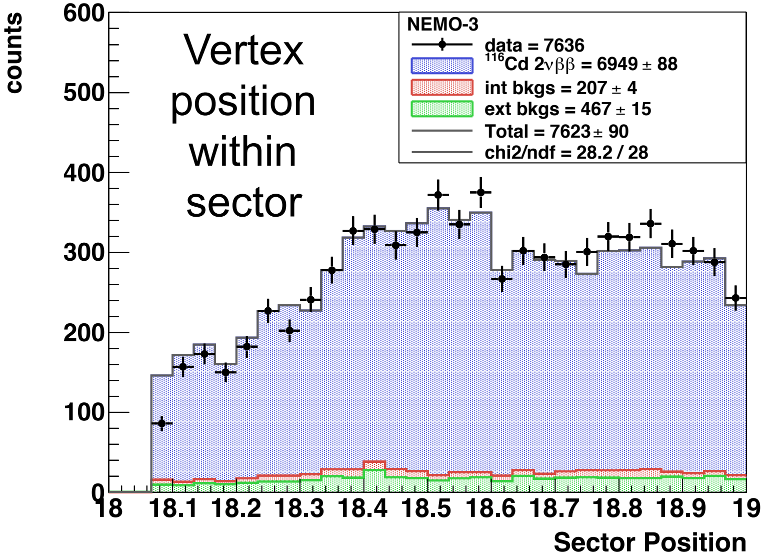
$G = 1.89 \times 10^{-25}\ \text{y}^{-1}$ $M = 1.83 – 2.93\ \text{eV}^{-1}$ $\langle m_{\beta\beta} \rangle < 2.2 – 3.5$ eV

^{116}Cd $2\nu\beta\beta$ Results
Other Observables



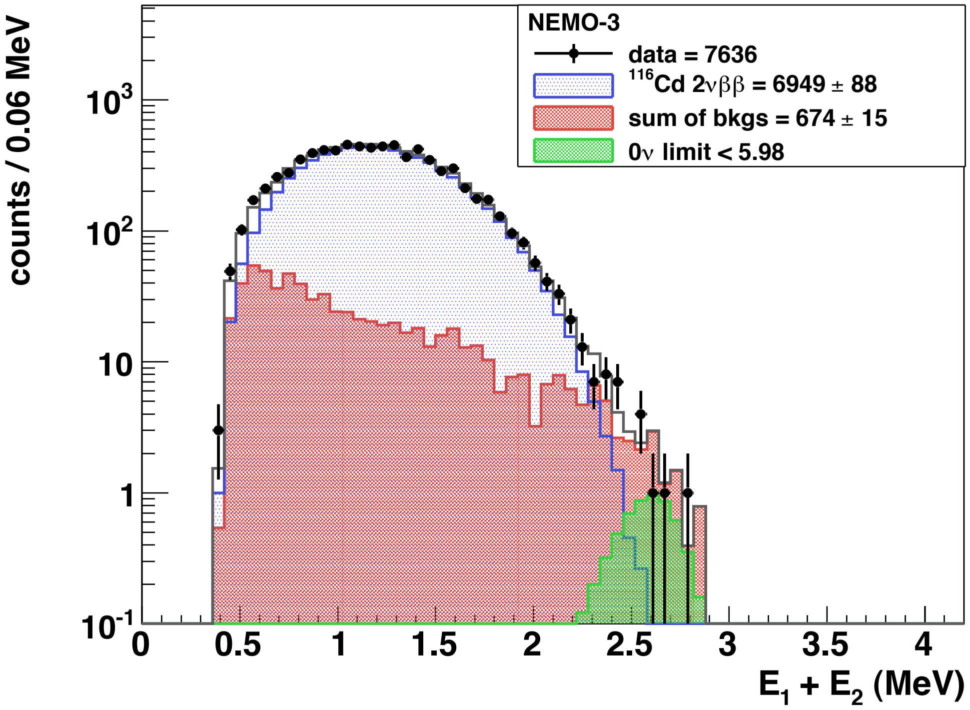




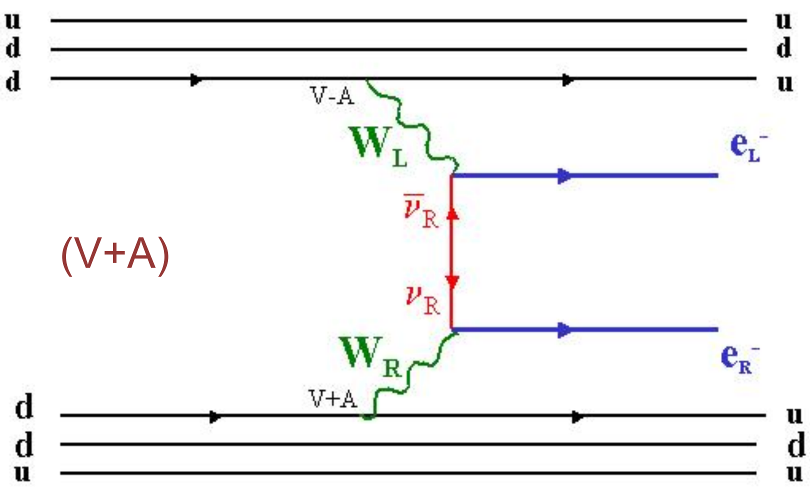


^{116}Cd 0νββ Results (V+A)

Models exist that contain neutrino couplings to right-handed leptons (V+A)



Combined Results	
Data	7636
Exp. Background	7623
Exp. 0νββ Signal	< 5.98
0νββ efficiency	6.92%



(V+A)

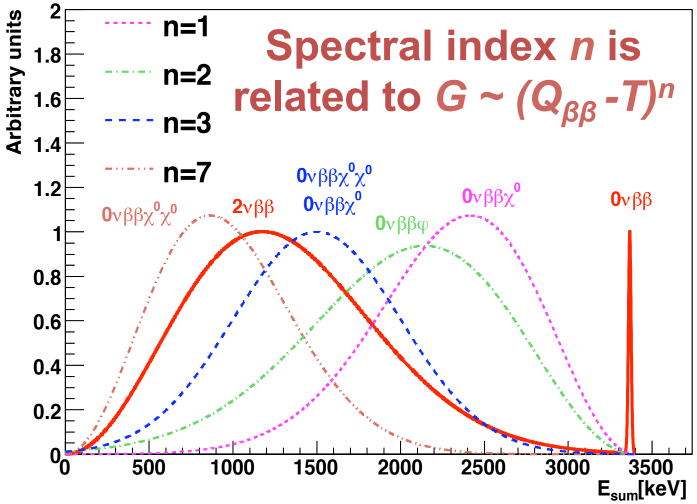
$T_{½}^{0\nu\beta\beta} > 6.88 \times 10^{22}$ y (90% C.L.)

$T_{½}^{0\nu\beta\beta} > 1.2 \times 10^{21}$ y (90% C.L.)

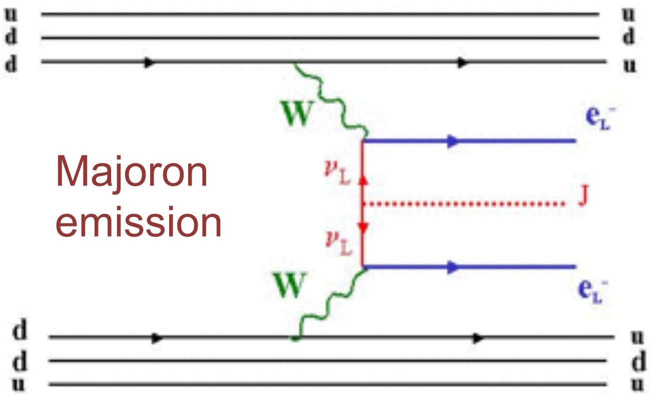
Arnold, A. *et al*. Nucl. Phys. A, 678, 341-352, (2000) (NEMO-2)

0νββ-decay (Majoron Emission)

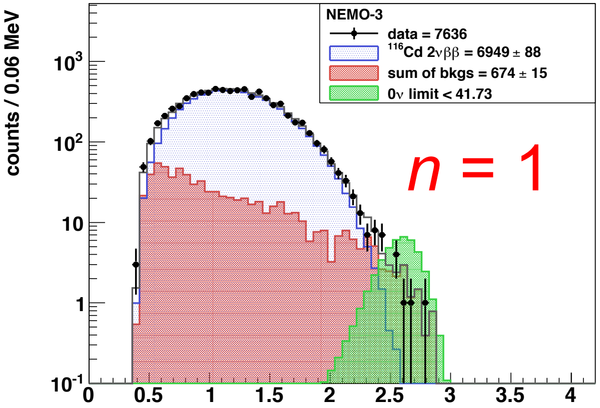
Models exist where the global baryon-lepton symmetry is broken predicting a boson (Majoron) which can couple to the neutrino.



Spectral index *n* is related to $G \sim (Q_{\beta\beta} - T)^n$



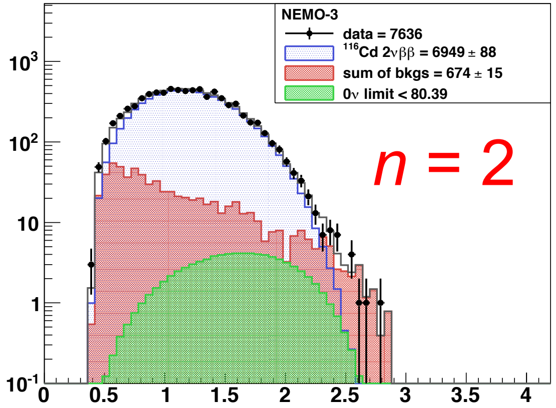
Majoron emission



***n* = 1**

$T_{1/2}^{0\nu\beta\beta\chi0} > 1.3 \times 10^{22}$ y

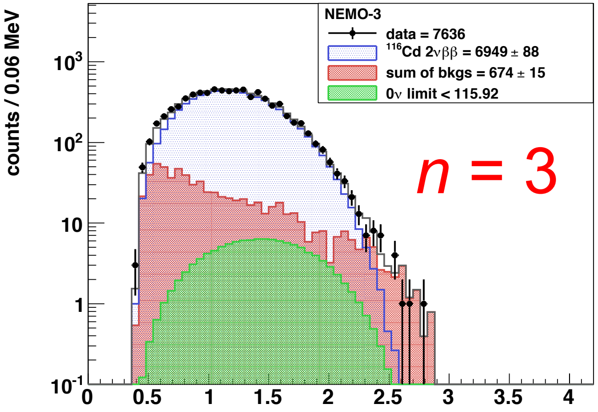
$T_{1/2}^{0\nu\beta\beta\chi0} > 0.8 \times 10^{22}$ y



***n* = 2**

$T_{1/2}^{0\nu\beta\beta\chi0} > 5.4 \times 10^{21}$ y

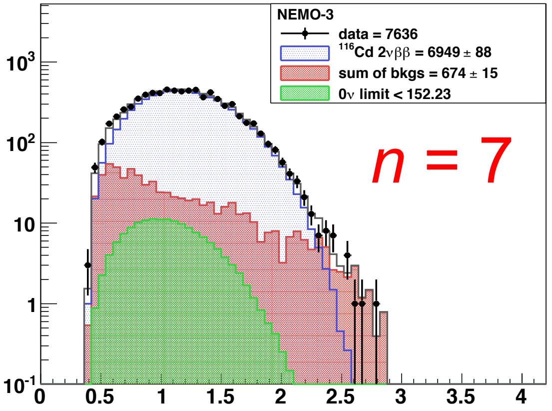
$T_{1/2}^{0\nu\beta\beta\chi0} > 1.7 \times 10^{21}$ y



***n* = 3**

$T_{1/2}^{0\nu\beta\beta\chi0} > 3.0 \times 10^{21}$ y

$T_{1/2}^{0\nu\beta\beta\chi0} > 0.8 \times 10^{21}$ y



***n* = 7**

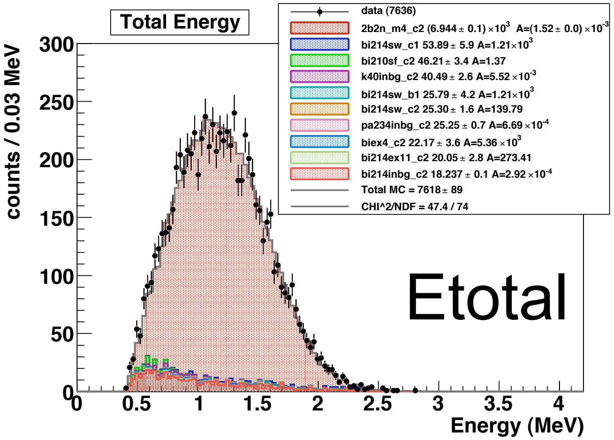
$T_{1/2}^{0\nu\beta\beta\chi0} > 8.4 \times 10^{20}$ y

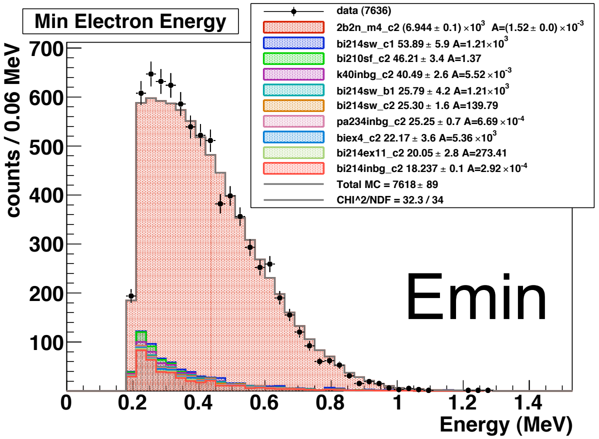
$T_{1/2}^{0\nu\beta\beta\chi0} > 4.1 \times 10^{19}$ y

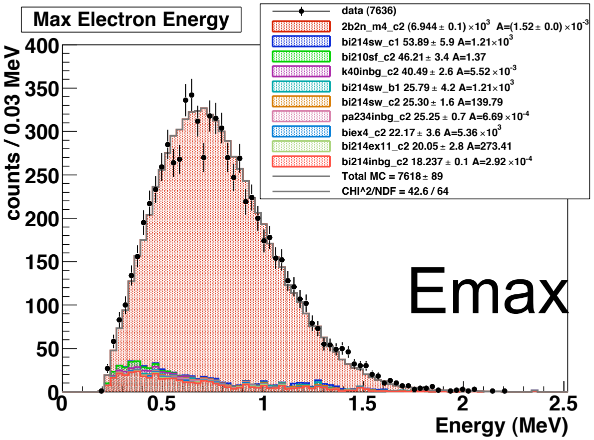
Overview of the Field

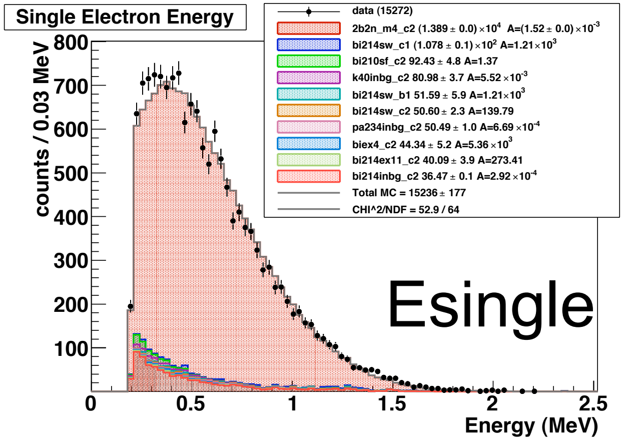
Experiments	Isotopes	Techniques	Main caracteristics
NEMO3	^{100}Mo,^{82}Se	Tracking + calorimeter	Bckg rejection, isotope choice
SuperNEMO	^{82}Se, ^{150}Nd	Tracking + calorimeter	Bckg rejection, isotope choice
Cuoricino	^{130}Te	Bolometers	Energy resolution, efficiency
CUORE	^{130}Te	Bolometers	Energy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

Higher States Dominance





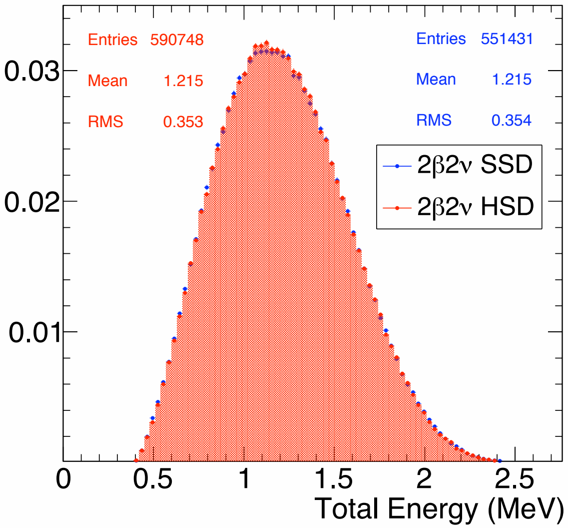


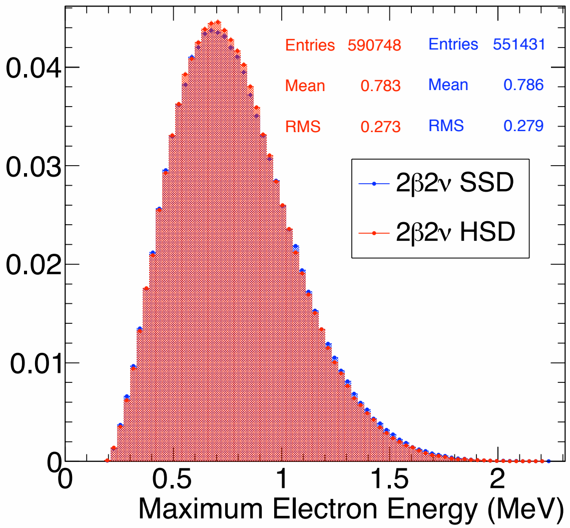


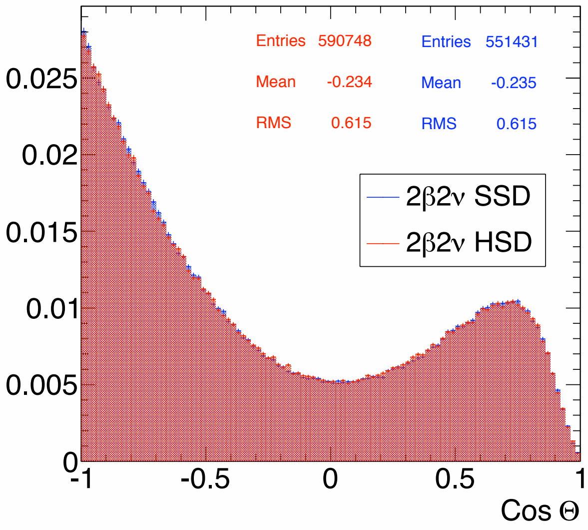
Combined Results	
Data	7636 ± 87
Background	674 ± 15
Signal	6944 ± 89
S/B	10.3
Efficiency	0.036
T1/2 (2b2n)	$3.08 \pm 0.04 \times 10^{19}$ y

SSD vs HSD

Monte Carlo distributions for the total energy, maximum electron energy and the cosine of the angle show no difference between SSD and HSD.







Final 2e Selection Criteria

1) TRACKING REQUIREMENTS

- Only two tracks identified and reconstructed
- Each track corresponds to a particle with negative charge
- The first Geiger plane near the foil are fired (layer 0)
- Reject petal scintillator near foils
- For petal events near the wall, there must be a Geiger hit in layer 5 or 6
- At least one of the first two Geiger planes near the scintillator are fired (7 or 8)
- Sum of electron tracks > 60 cm
- Less than 2 (no more than one) fast Geiger hits, not associated to any track with distance to event vertex in XY plane < 15 cm
- If both tracks belong to one part of the detector, there are no fast GG hits on the other part with distance to event vertex in XY plane < 15 cm

2) CALORIMETER REQUIREMENTS

- Only two isolated scintillators to be fired
- Scintillator and track to be associated (track/scintillator correlation)
- gain < 6 and account for dead PMTs in data/MC
- $E_{min} > 200$ keV and $E_{tot} > 400$ keV

3) FOIL REQUIREMENTS

- Event must be reconstructed in cadmium foil
- Distance between track/foil vertices in XY plane < 2 cm
- Distance between track/foil vertices in Z plane < 4 cm

4) TIME OF FLIGHT REQUIREMENTS

- Internal TOF probability > 1%
- External TOF probability < 1%

Latest NEMO-3 Results

- No evidence for non conservation of lepton number as of June 2010
- Current limits on 0νββ (at 90% C.L.):

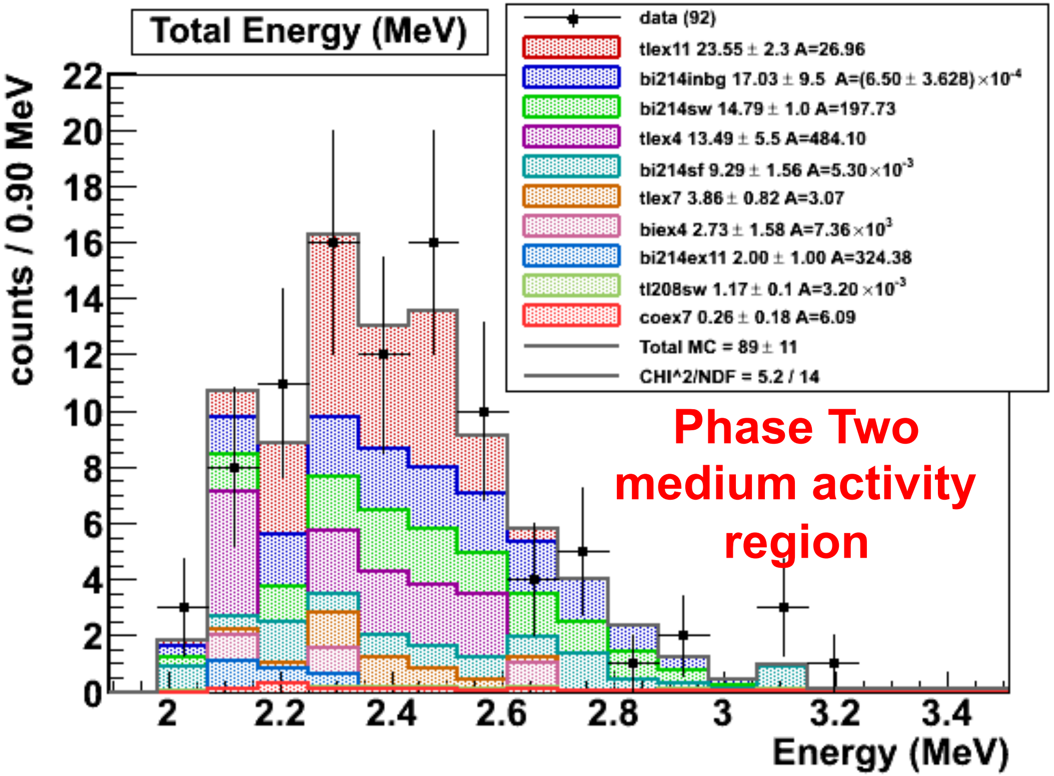
Isotope	**Exposure (kg·y)**	**$T_{1/2}(0\nu\beta\beta)$, y**	**$\langle m_\nu \rangle$, eV [NME ref.]**
^{100}Mo	26.6	$> 1.0 \cdot 10^{24}$	$< 0.47 - 0.96$ [1-3]
^{82}Se	3.6	$> 3.6 \cdot 10^{23}$	$< 0.94 - 1.6$ [1-3]; < 2.5 [7]
^{150}Nd	0.095	$> 1.8 \cdot 10^{22}$	$< 1.7 - 2.4$ [4,5] ;$< 4.8 - 7.6$ [6]
^{130}Te	1.4	$> 9.8 \cdot 10^{22}$	$< 1.6 - 3.1$ [2,3]
^{96}Zr	0.031	$> 9.2 \cdot 10^{21}$	$< 7.2 - 19.5$ [2,3]
^{48}Ca	0.017	$> 1.3 \cdot 10^{22}$	< 29.6 [7]

- NME references:

[1] M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
[2] M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
[3] F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
[4] V.A. Rodin et al. Nucl.Phys. A 793 (2007) 213
[5] V.A. Rodin et al. Nucl.Phys. A 766(2006) 107
[6] J.H.Hirsh et al. Nucl.Phys. A 582(1995) 124
[7] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

Electron-gamma: E_{total} > 2.0 MeV

All background activities are fixed except ^{214}Bi in the foil . We measure the activity of ^{214}Bi in the foil using Phase Two data in the medium activity region:



Phase Two medium activity region

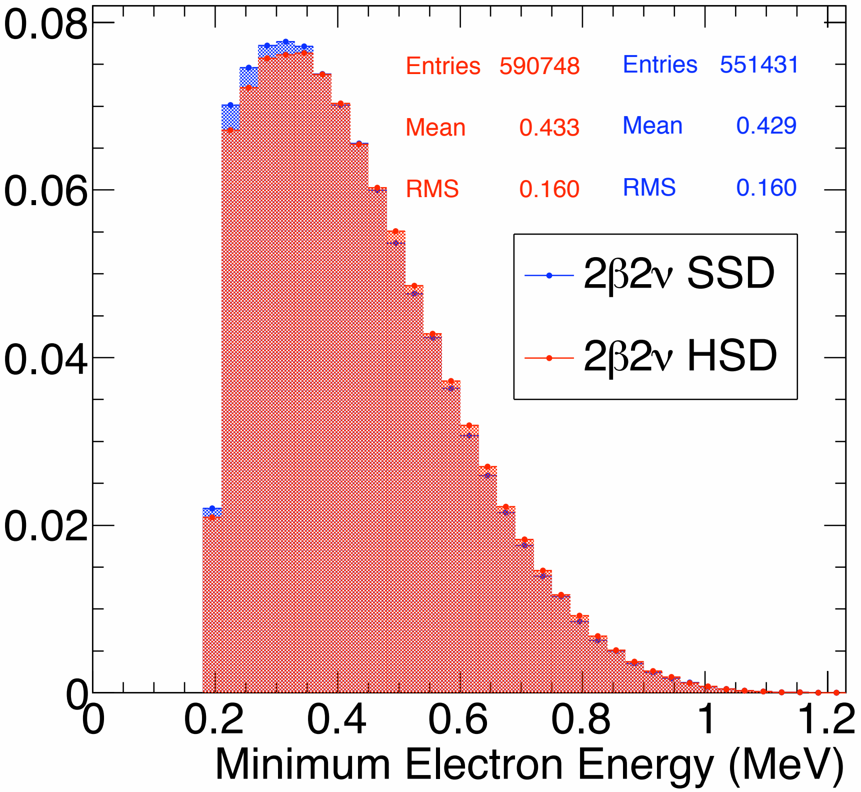
Distribution of the energy sum of the electron and gamma-ray.

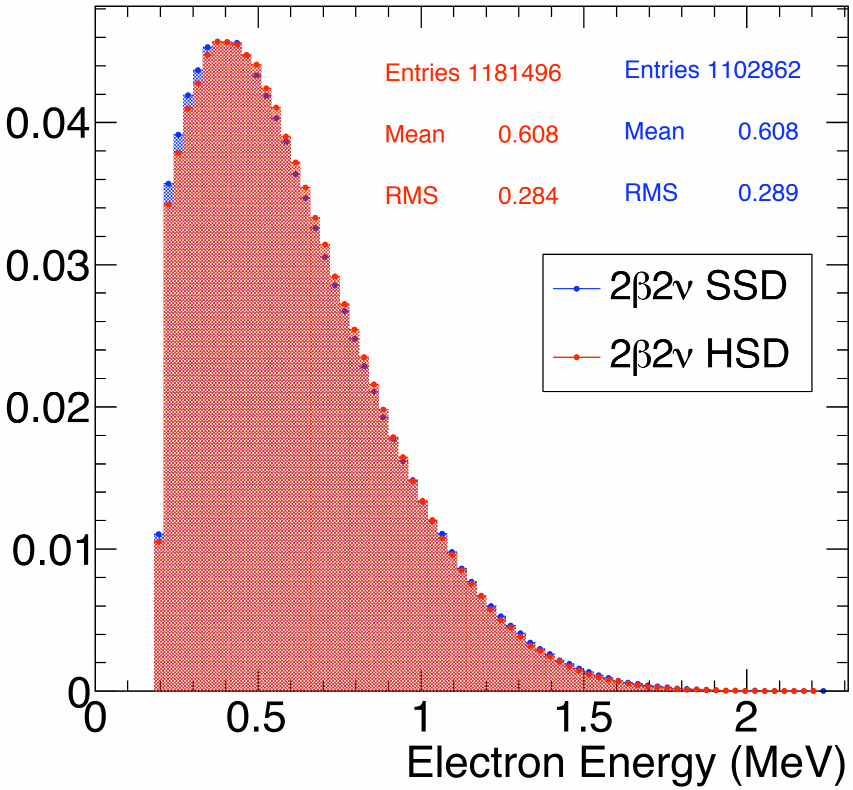
Isotope in Med Activity Region	Activity (mBq)
^{214}Bi (e-gamma)	0.65 ± 0.36
^{214}Bi (e-alpha)	0.39 ± 0.04

This analysis is not sensitive enough to provide precise values.

SSD and HSD Monte Carlo Distributions

Monte Carlo distributions for the minimum electron energy and the single electron energy show very slight difference between SSD and HSD.





0νββ-decay with Majoron Emission

Calculate the results for the neutrino-Majoron coupling constant $<g_{ee}>$*:*

- Phase space factor and NME are known for n =1, 3, and 7

Spectral Index *n*	**Phase Space Factor**	**NME**	**This work $T_{1/2}\ (2\nu\beta\beta\chi^0)$ (y)**	**Best Previous Limit $T_{1/2}\ (2\nu\beta\beta\chi^0)$ (y)**	**This work $<g_{ee}>$**
$n = 1$	1.75×10^{-15}	3.29	**$> 1.3 \times 10^{22}$**	$> 0.8 \times 10^{22}$ [1,3]	**$< 6.4 \times 10^{-5}$**
$n = 2$			**$> 5.4 \times 10^{21}$**	$> 1.7 \times 10^{21}$[3]	
$n = 3$	6.95×10^{-18}	3.29	**$> 3.0 \times 10^{21}$**	$> 3.5 \times 10^{20}$ [2] $> 0.8 \times 10^{21}$ [3]	**$< 2.1 \times 10^{-3}$**
$n = 7$	1.03×10^{-16}	3.29	**$> 8.4 \times 10^{20}$**	$> 4.1 \times 10^{19}$ [2]	**$< 3.2 \times 10^{-2}$**

Electron-Gamma Analysis

Analysis details:

- Phase Two data used (runs 3395 – 7920)
- Try to measure internal ^{214}Bi with events containing electrons and gammas
- Second attempt with $E_e > 0.5$ MeV and $E_\gamma > 0.5$ MeV

Initial activity values:

Isotope	Activity (mBq/kg)
^{214}Bi internal	0.63 ± 0.14

Derived values from previous measurements and HPGe:

Isotope	Medium Activity Region Activity (mBq)	Low Activity Region Activity (mBq)
^{214}Bi internal	0.153 ± 0.040	0.062 ± 0.014
^{214}Bi mylar (HPGe)	< 0.24	< 0.10
^{214}Bi (int + mylar)		

Can we measure ^{214}Bi with better precision than this? →

Electron-gamma Selection Criteria

1) TRACKING REQUIREMENTS

- One track with “negative” curvature
- At least one of the first and last two Geiger planes near the foil are fired
- Less than 2 fast Geiger hits, not associated to any track with distance to event vertex in XY plane < 15 cm
- If track belong to one part of the detector, there are no fast GG hits on the other part with distance to event vertex in XY plane < 15 cm
- Electron track length > 50 cm

2) CALORIMETER REQUIREMENTS

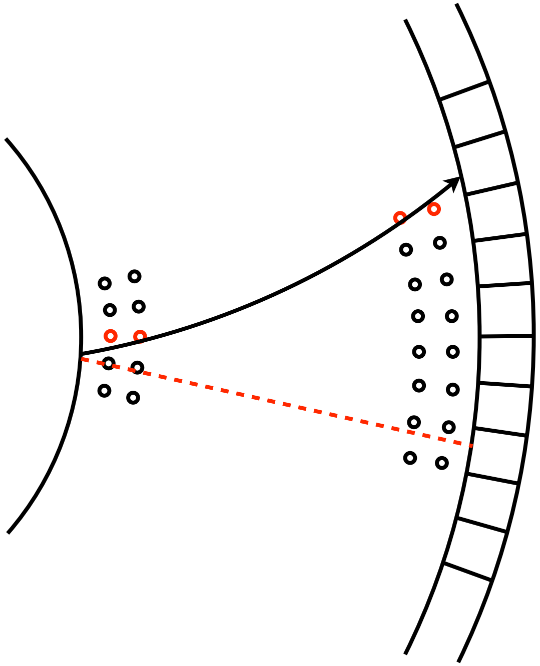
- Two isolated scintillators registered
- Scintillator and track are associated
- $E_e > 500$ keV and $E_\gamma > 500$ keV
- $E_{total} > 1000$ keV

3) FOIL REQUIREMENTS

- Track is reconstructed in cadmium foil
- High activity region rejected
- No alpha particles in event

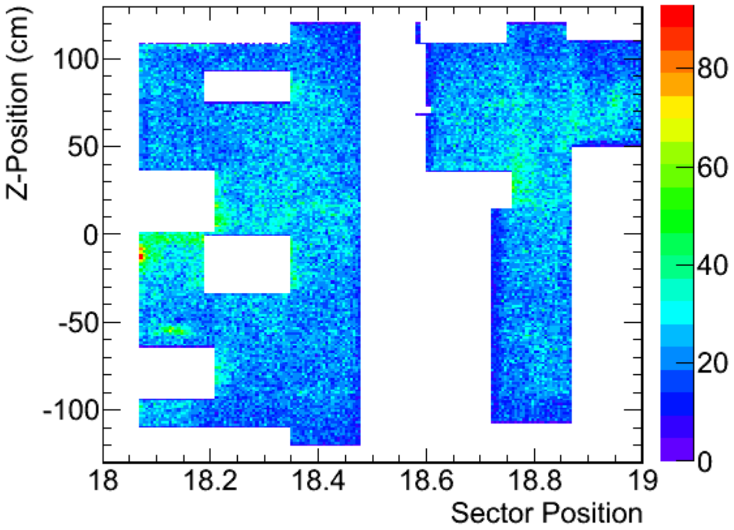
4) TIME OF FLIGHT REQUIREMENTS

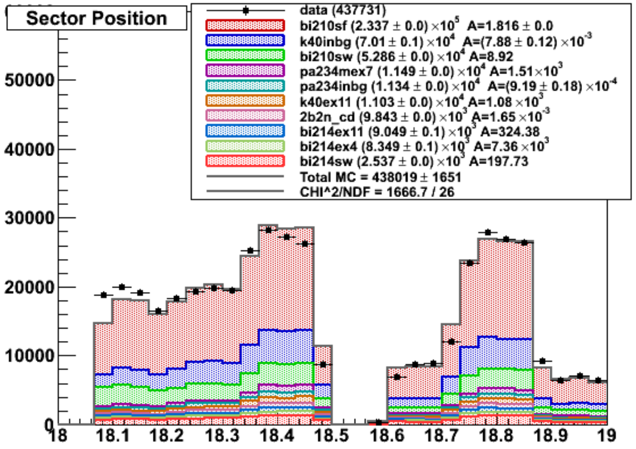
- TOF probability for internal decay > 4%
- TOF probability for external OCE < 1%

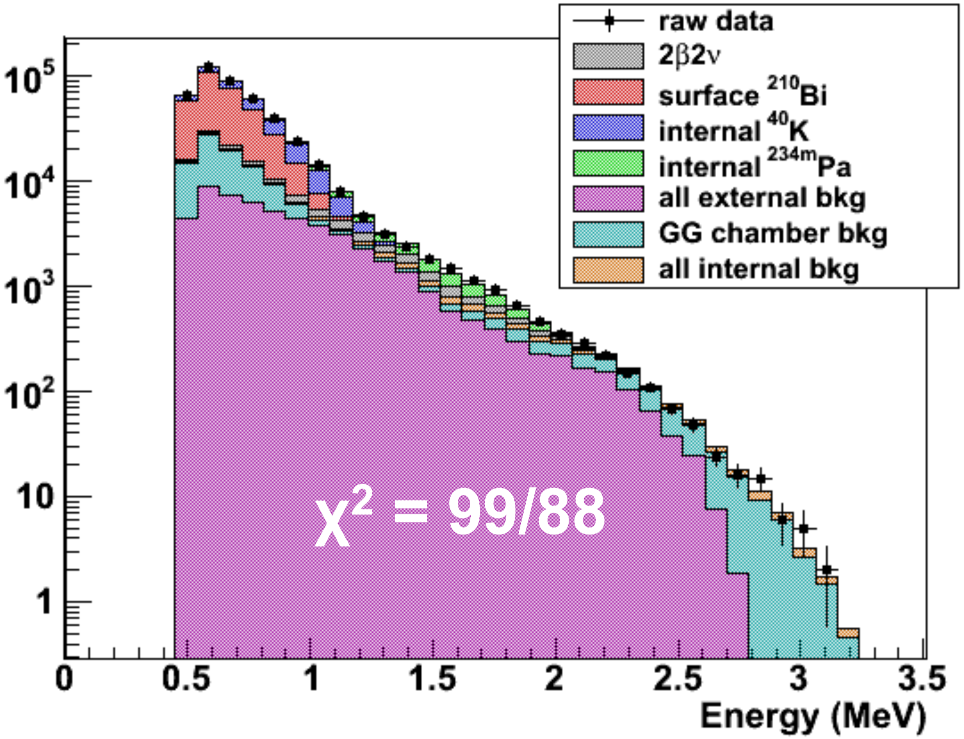


Single Electron Analysis
Medium Activity Region

Medium activity region modeled better. Radon in tail represented well.





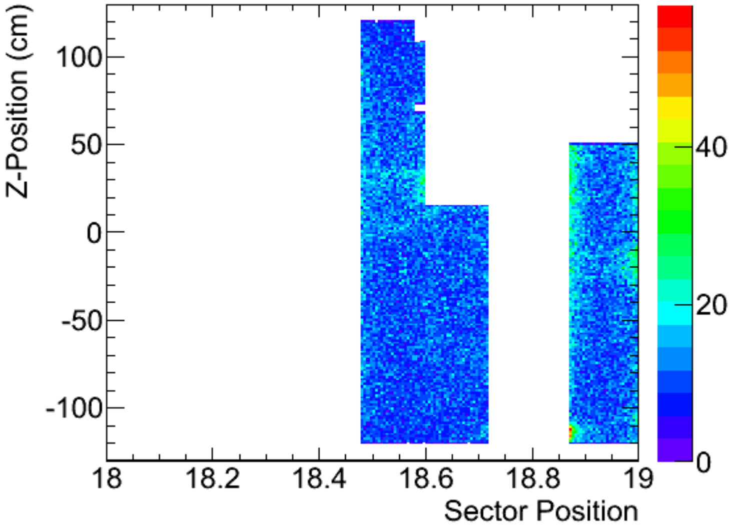


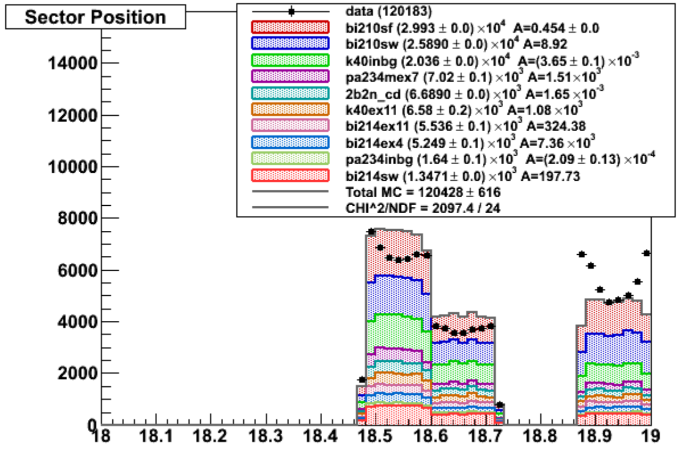
$\chi^2 = 99/88$

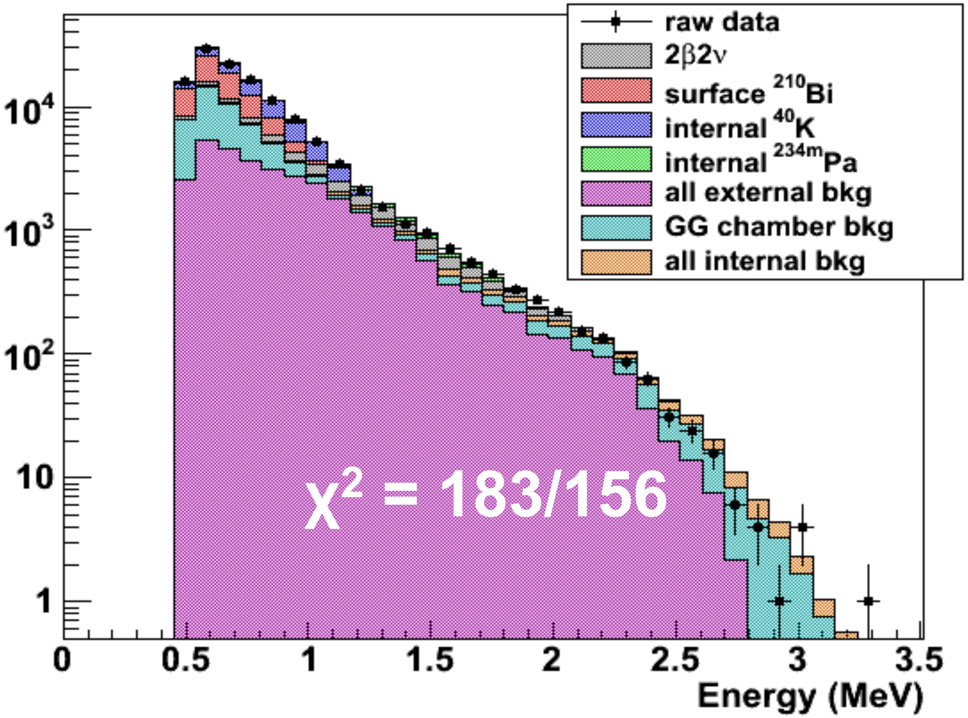
Isotope	Activity (mBq)
^{40}K	7.98 ± 0.11
^{234m}Pa	0.89 ± 0.02
^{210}Bi (surf)	1810 ± 20

Single Electron Analysis
Low Activity Region

Low activity region modeled better. Radon in tail represented well.



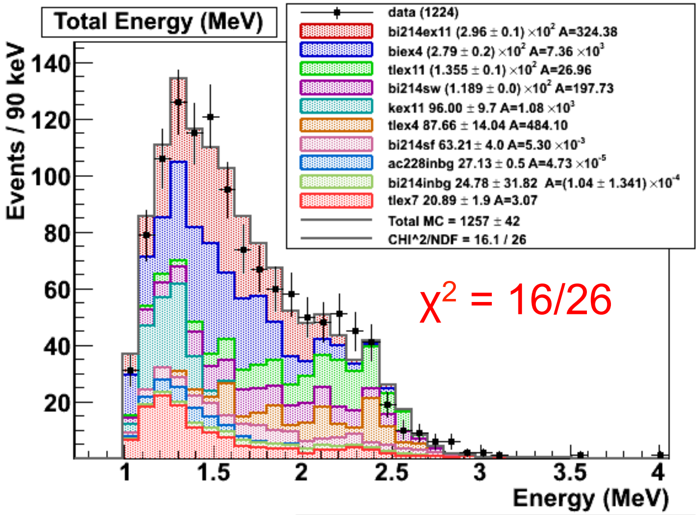


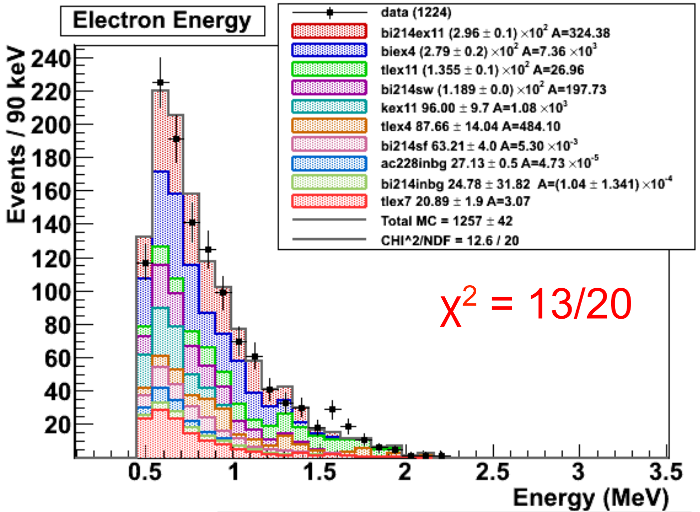


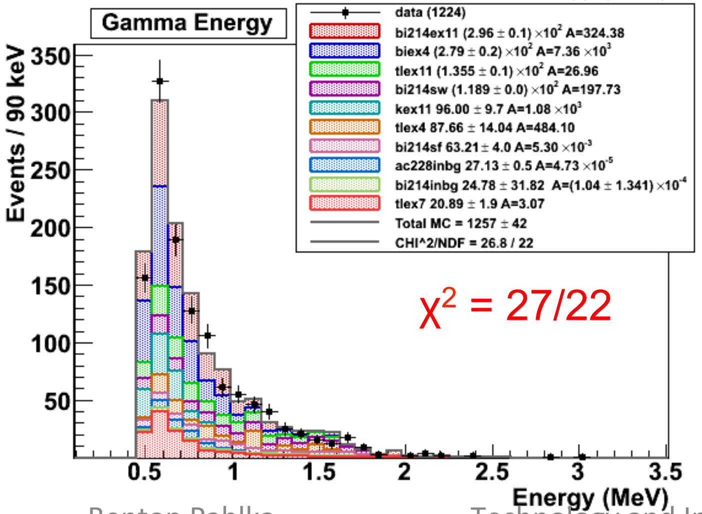
Isotope	Activity (mBq)
^{40}K	3.66 ± 0.10
^{234m}Pa	0.26 ± 0.01
^{210}Bi (surf)	454 ± 5

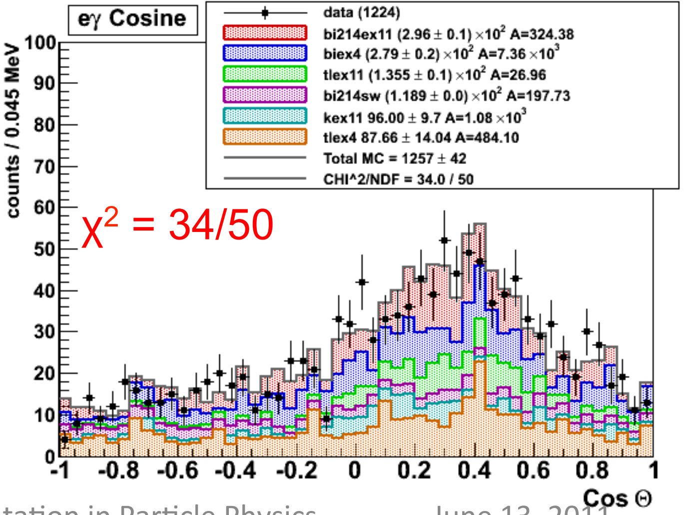
Electron-gamma Analysis
Low Activity Region

Require E_e > 0.5 MeV, E_γ > 0.5 MeV, and E_{total} > 1.0 MeV:









Event Reconstruction and Analysis

Goal: Select data events characteristic of a given topology

RAW data/MC
(ADC and TDC)

~ 3 TB

track reconstruction

RECO data/MC
(event tracks)

~ 5 TB

topology skimming
and calibration

SKIMMED
data/MC

~ 500 MB

final selection
criteria

FINAL
data/MC

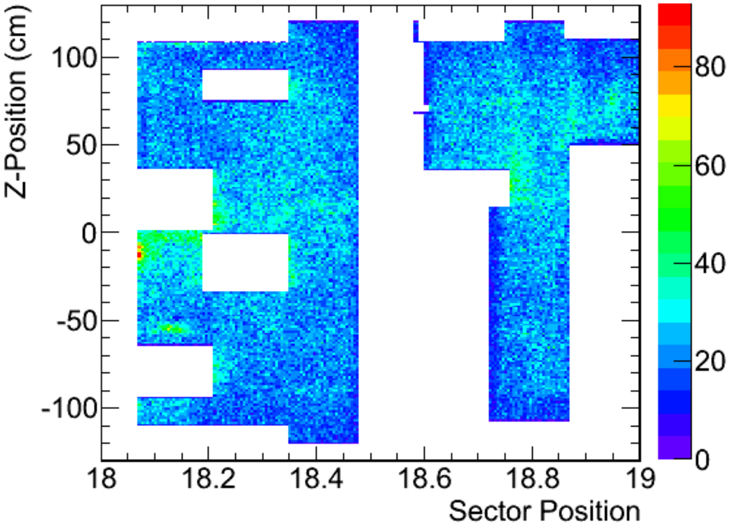
~ 5 MB

MC = Monte Carlo simulated data
generated using *DECAY0*
(e.g. backgrounds, $2\nu\beta\beta$, etc)

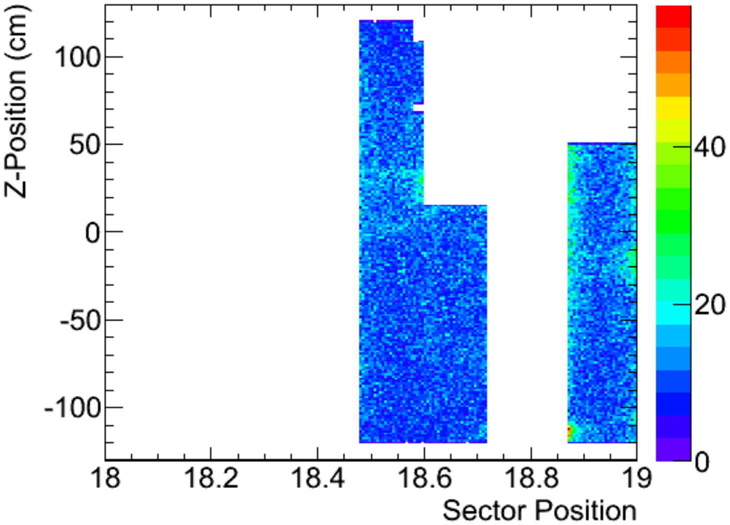
Trigger rate ~ 7 Hz
$\beta\beta$ rate ~ 1 event / 2.5 minutes

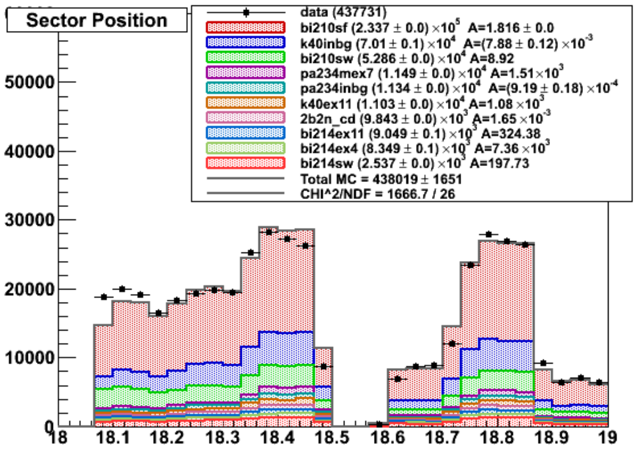
Single Electron Analysis
Medium and Low Activity Regions

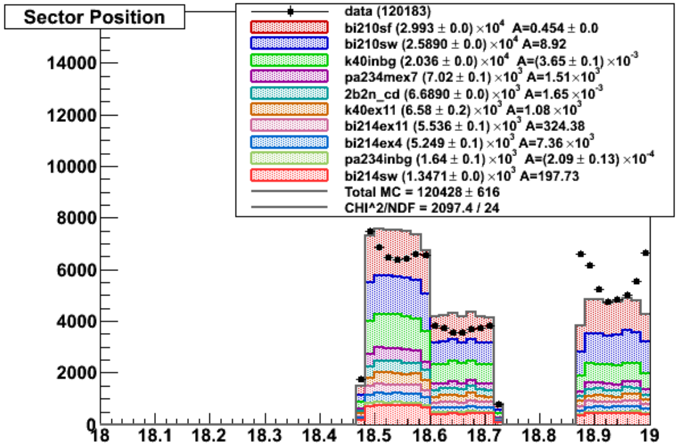
MEDIUM ACTIVITY REGION



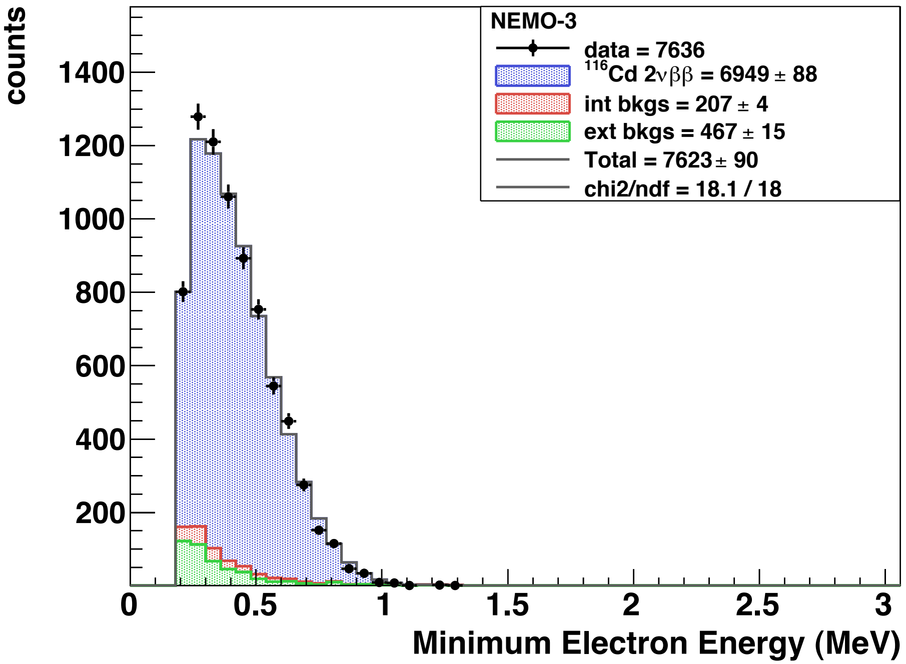
LOW ACTIVITY REGION

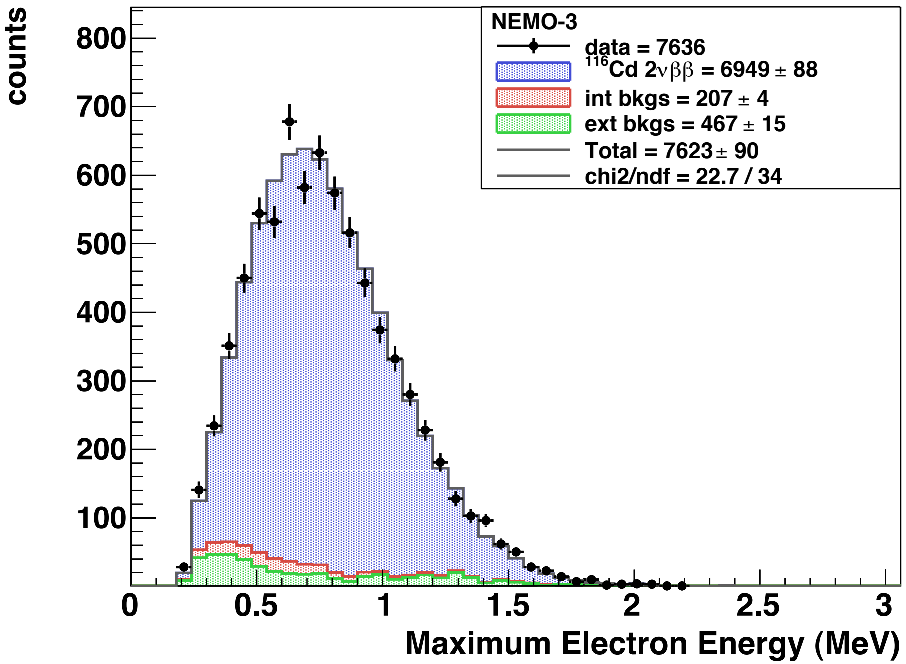






^{116}Cd 2νββ Results
Minimum and Maximum Energies





Event Reconstruction Chain

Goal: Select data events characteristic of a given topology

Trigger rate ~ 7 Hz
$\beta\beta$ rate ~ 1 event / 2.5 minutes

RAW data
(ADC and TDC)

~ 3 TB

track reconstruction

RECO data
(event tracks)

~ 5 TB

topology skimming
and calibration

SKIMMED
data

~ 500 MB

final selection
criteria

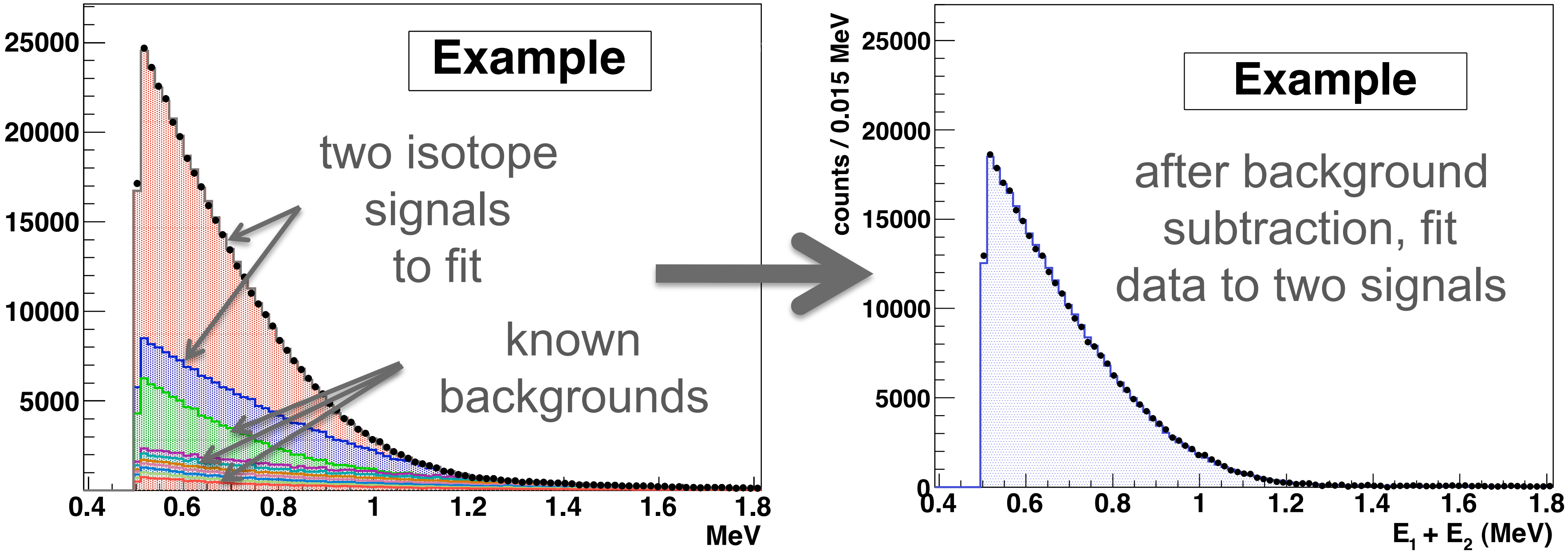
FINAL
data set

~ 5 MB

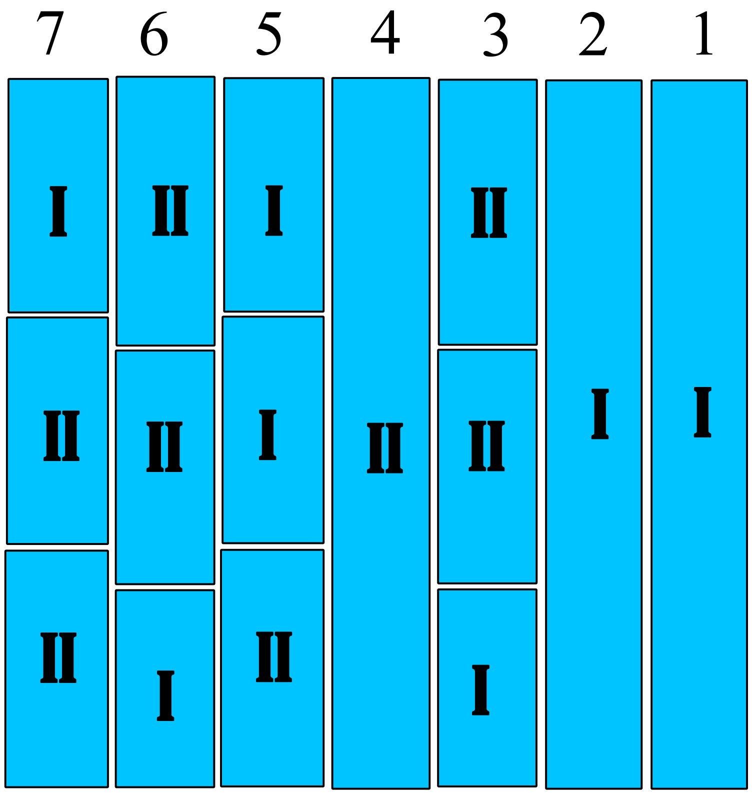
Fitting the Signal

Compare data to Monte Carlo with known activity estimates

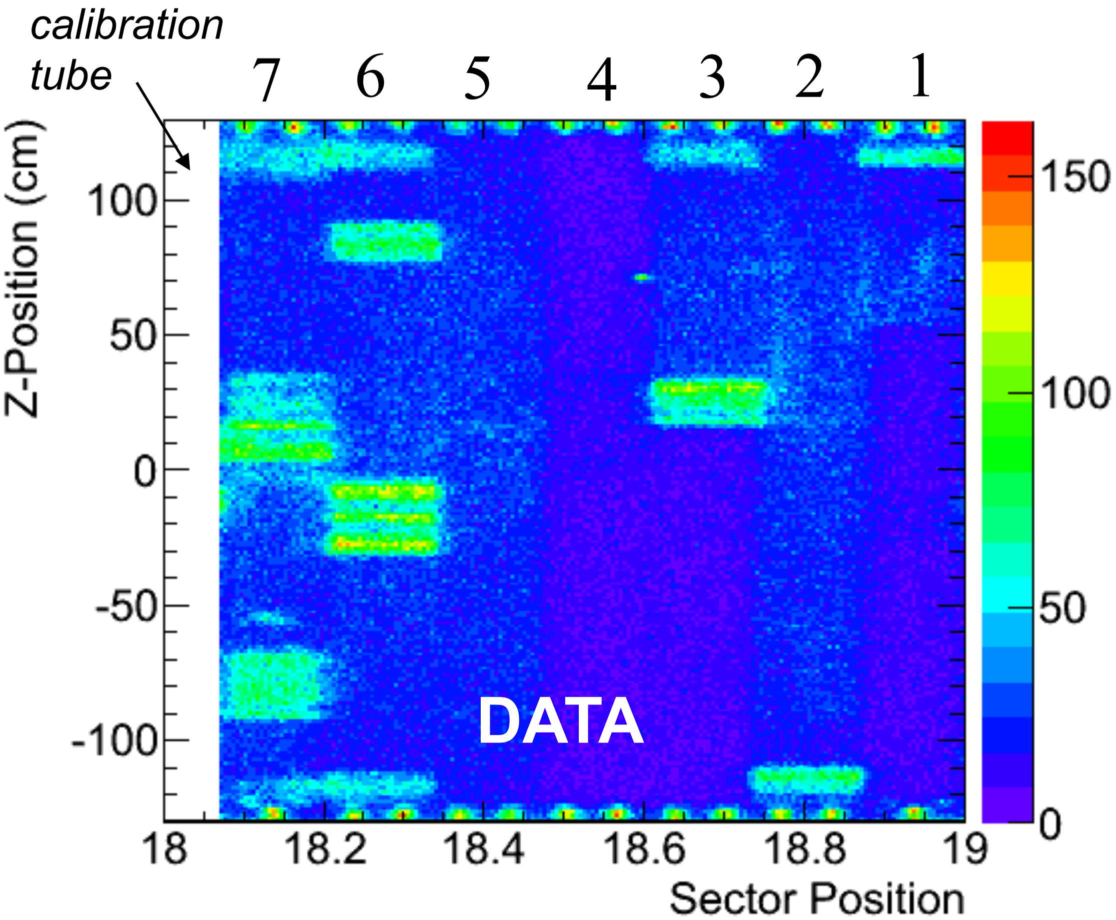
- Fix backgrounds to measured activities
- Subtract background
- Fit data to one (or more) signals to get activity



Single Electron Results



Arrangement of foil segments. Two types of enrichment are used, (I) and (II). 93.2% enrichment (chemical/gas centrifuge)



Results of selecting single electron events in the cadmium foil. The two different types of enriched cadmium and the contaminated clips are visible.

Results

$2\nu\beta\beta$ Results	This work $T_{1/2}(2\nu\beta\beta)$ (y)	Best Previous Measurement $T_{1/2}(2\nu\beta\beta)$ (y)
SSD	2.88 ± 0.04 (stat)$\pm$ 0.16 (syst) x 10^{19} y	2.9 ± 0.06 (stat) $^{+0.4}_{-0.3}$ (syst) x 10^{19} y
HSD	3.08 ± 0.04 (stat) $\pm$ 0.16 (syst) x 10^{19} y	

$0\nu\beta\beta$ Results	This work $T_{1/2}(0\nu\beta\beta)$ (y)	Best Previous Limit $T_{1/2}(0\nu\beta\beta)$ (y)	This work $\langle m_{\beta\beta}\rangle$ (eV)	Best Previous Limit $\langle m_{\beta\beta}\rangle$ (eV)
Light Majorana exchange (V-A)	$> 1.29 \times 10^{23}$	$> 1.7 \times 10^{23}$	< 2.2 -3.5	< 1.7
Right-handed current (V+A)	$> 6.88 \times 10^{22}$	$> 1.2 \times 10^{21}$		

Spectral Index *n*	This work $T_{1/2}(0\nu\beta\beta\chi^0)$ (y)	Best Previous Limit $T_{1/2}(0\nu\beta\beta\chi^0)$ (y)	This work $\langle g_{ee}\rangle$
$n = 1$	**$> 1.3 \times 10^{22}$**	$> 0.8 \times 10^{22}$ [1,3]	**$< 6.4 \times 10^{-5}$**
$n = 2$	**$> 5.4 \times 10^{21}$**	$> 1.7 \times 10^{21}$[3]	
$n = 3$	**$> 3.0 \times 10^{21}$**	$> 0.8 \times 10^{21}$ [3]	**$< 2.1 \times 10^{-3}$**
$n = 7$	**$> 8.4 \times 10^{20}$**	$> 4.1 \times 10^{19}$ [2]	**$< 3.2 \times 10^{-2}$**

[1] Danevich, F. *et al.* Nucl. Phys. A, 643, 317-328, (1998) (Solotvina)
[2] Arnold, A. *et al*. Nucl. Phys. A, 678, 341-352, (2000) (NEMO-2)
[3] Danevich, F. *et al.* Phys. Rev. C, 68, 035501, (2003) (Solotvina)