Search for 0νββ decay and measurement of 2νββ with the NEMO-3 experiment

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- ββ-Decay & NEMO
- The NEMO Technique
- NEMO-3 Results
- Summary & Outlook

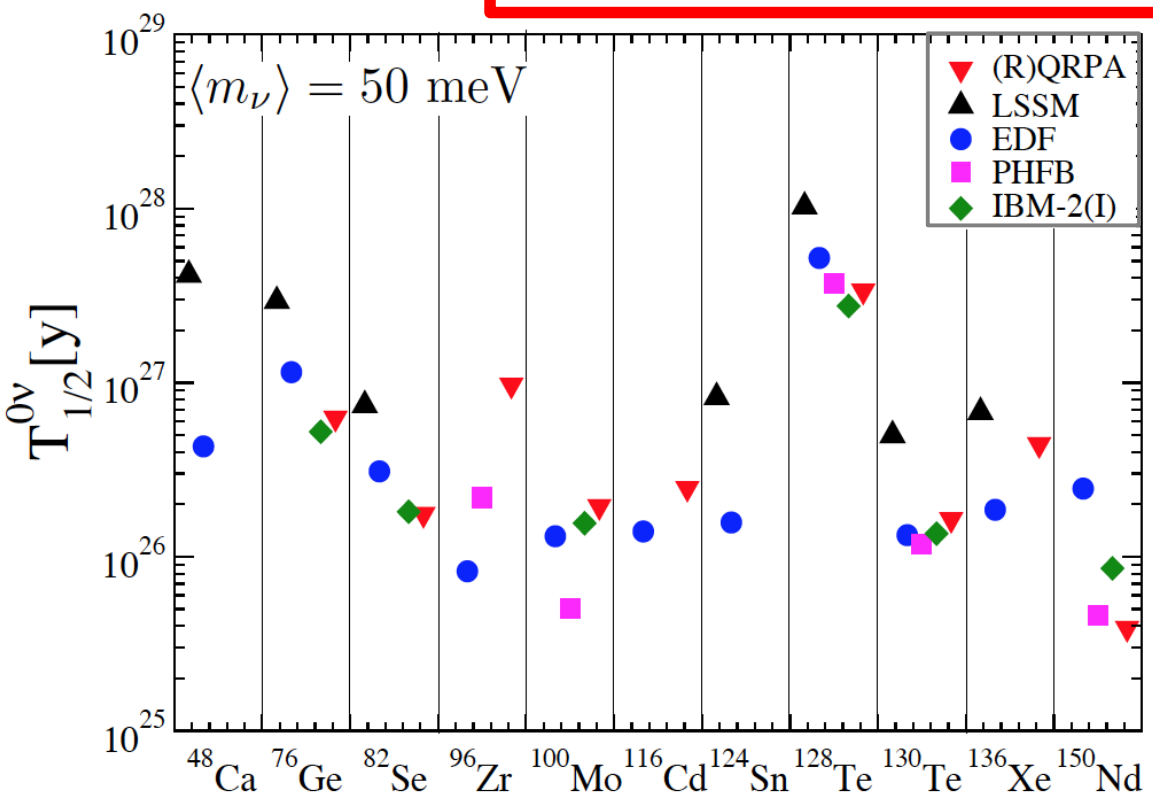
Double Beta Decay

Well known phase-space factor

Effective neutrino mass

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

Difficult to calculate **N**uclear **M**atrix **E**lement (NME)



Vergados et al. 2012

- NEMO-3 is **uniquely** suited to provide theorists with many SM measurements:
  - 2νββ half-lives for **various isotopes**
  - Decays to **excited states**
  - **Dynamics** of the decay

Double Beta Decay

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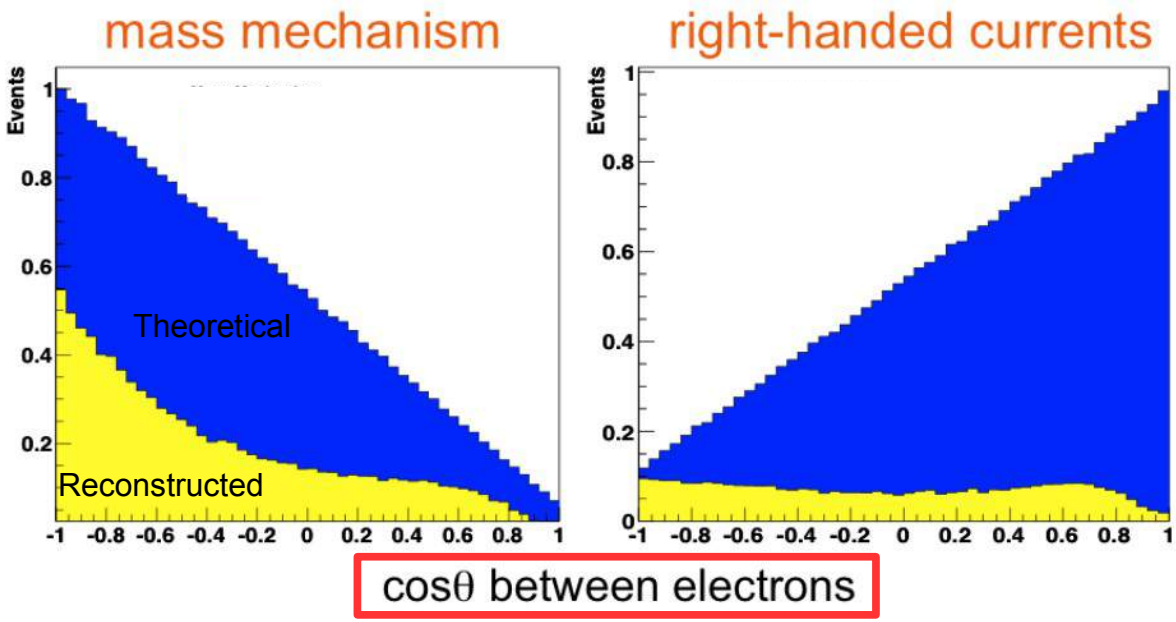
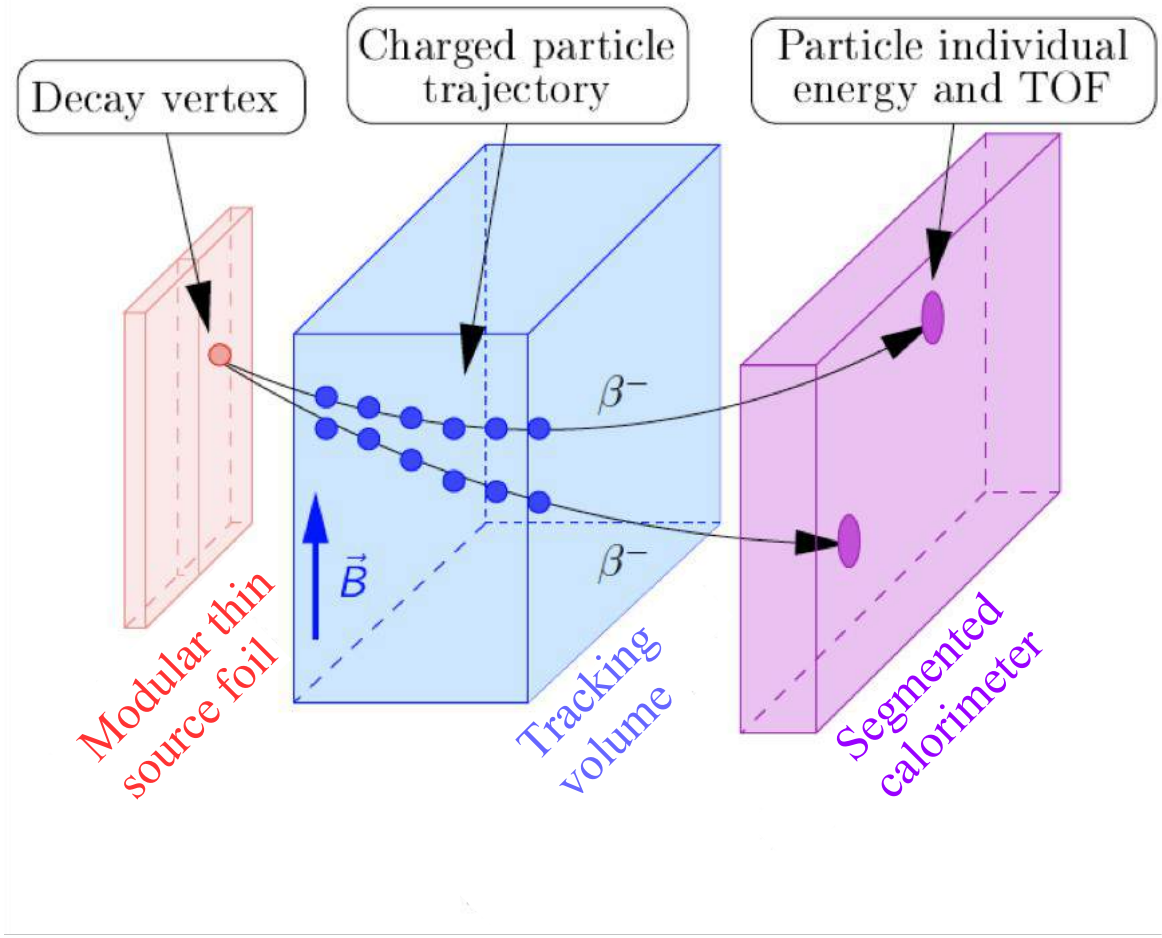


- NEMO-3 can also **probe the underlying 0νββ physics** via kinematic decay variables
  - Mass mechanism, right hand currents, majoron emission, SUSY, etc.

The NEMO-3 Technique

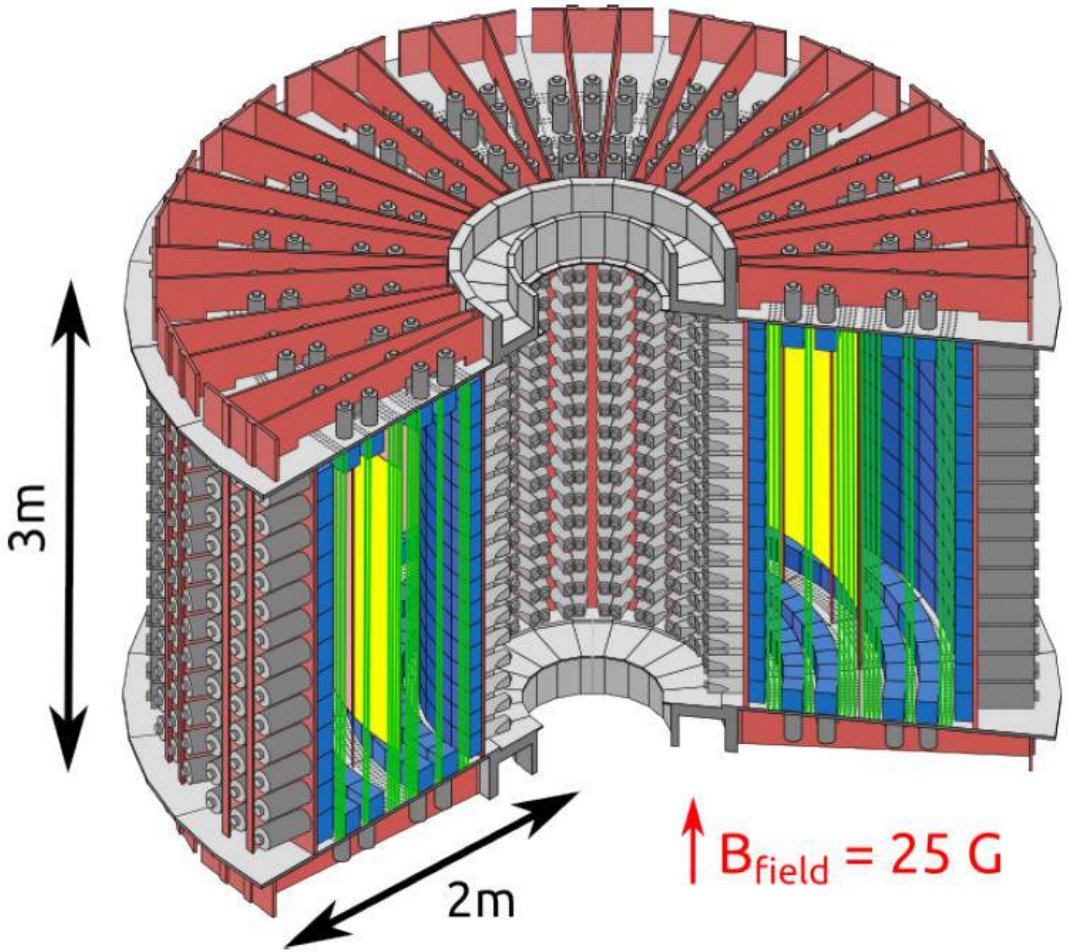
The multi-isotope, multi-observable 0νββ search

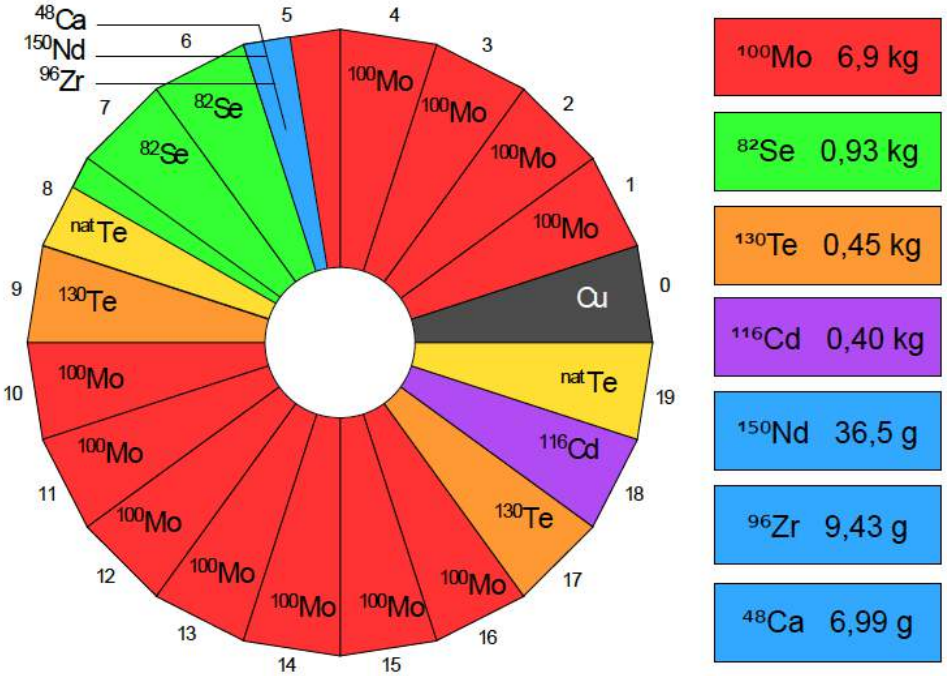
- **Heterogenous (source ≠ detector)** vs Homogenous (source = detector)
  - Full decay kinematics reconstruction
    - Individual electron energies (E_1,E_2)
    - Timing (T_1,T_2)
    - Track lengths (L_1,L_2)
    - Curvature (+,-)
    - Opening angle (cosθ)
    - Emission vertex
  - Identification of e^-, e^+, α, and γ
  - High degree of background suppression



The NEMO-3 Detector

- Source + Tracking + Calorimetry
  - 7 different isotopes in thin source foils
  - Drift wire cells operating in Geiger mode
  - Plastic scintillator blocks coupled to low radioactivity 3” and 5” PMTs

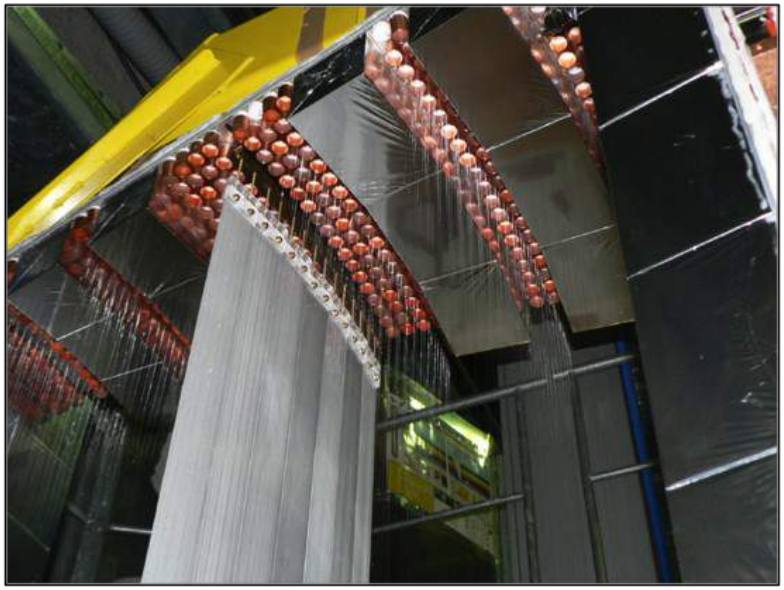




- 25 Gauss magnetic field aids in PID
- External iron, wood, and borated water shielding for (γ,n) flux
- Anti-radon enclosure surrounds detector
  - Phase 1 (pre-enclosure): Feb 2003 – Sep 2004
  - Phase 2 (post-enclosure): Oct 2004 – Jan 2011
- Located in the Laboratoire Souterrain de Modane (LSM) at 4800 m.w.e.

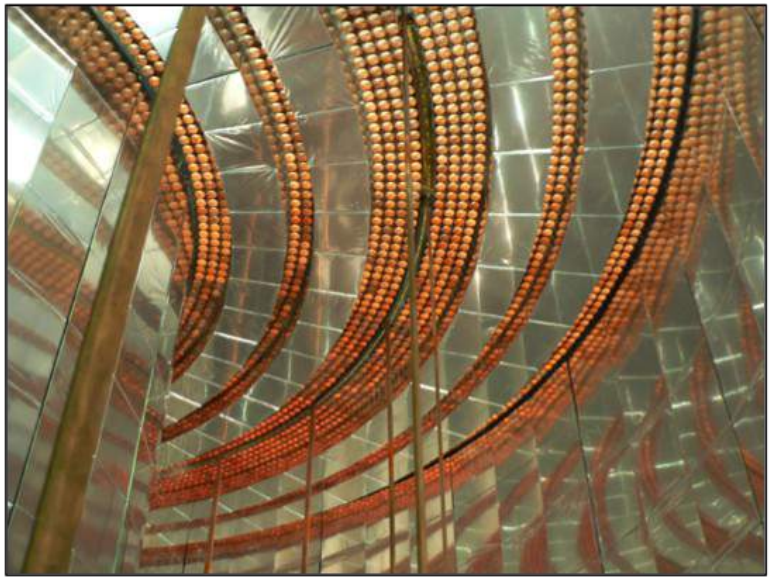
The NEMO-3 Detector

NEMO-3 construction



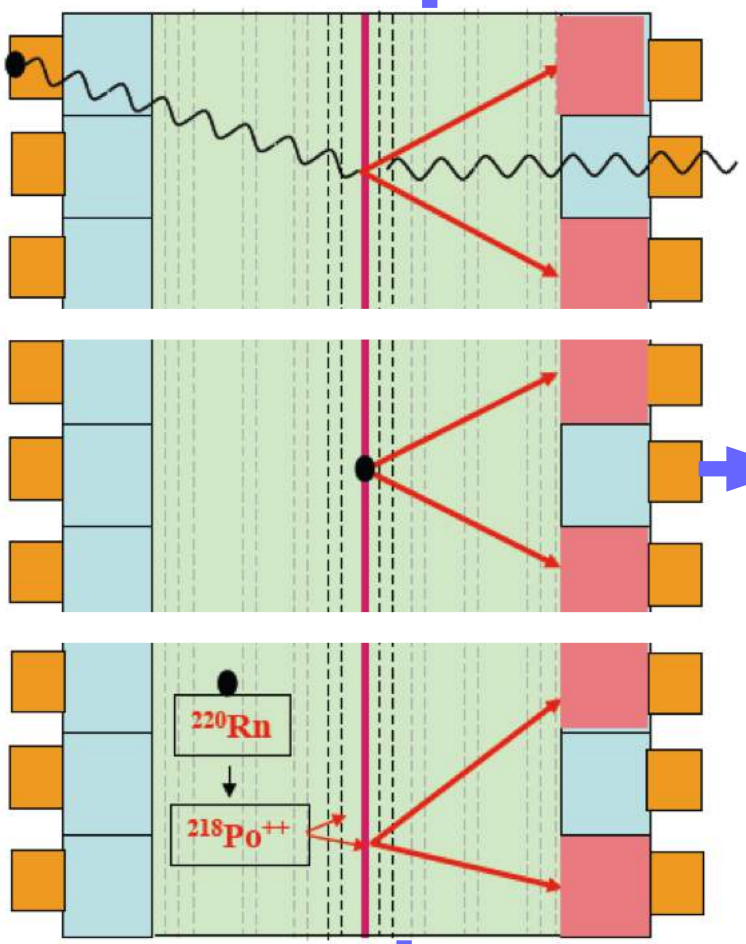
Inside a sector, source + tracker + calorimeter

Installation of anti-radon enclosure



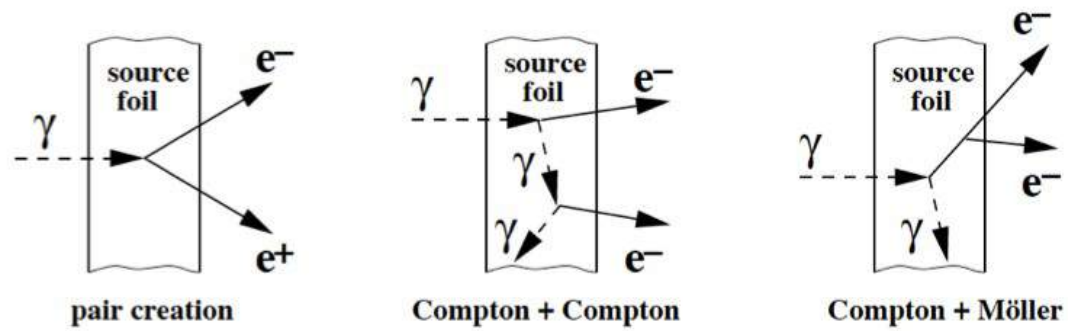
Decommissioning, no source foils

NEMO-3 Backgrounds



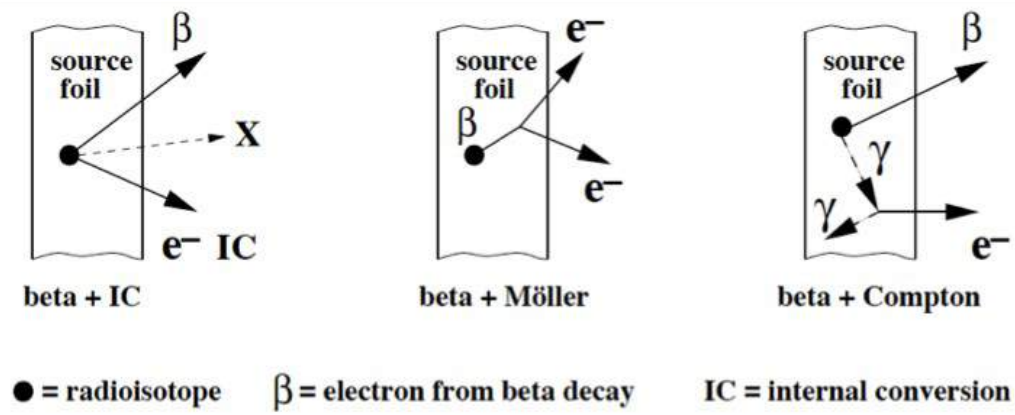
External Backgrounds:

- Impurities in detector materials and detector environment



Internal Backgrounds:

- Impurities in source foils (^{208}Tl - Q_β=5.0 MeV & ^{214}Bi - Q_β=3.3 MeV)



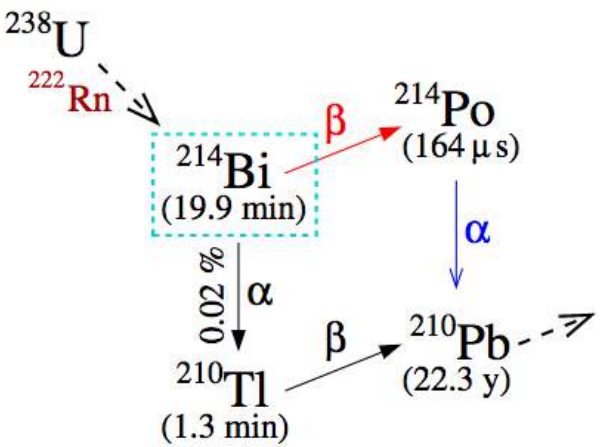
Radon Backgrounds: (^{214}Bi)

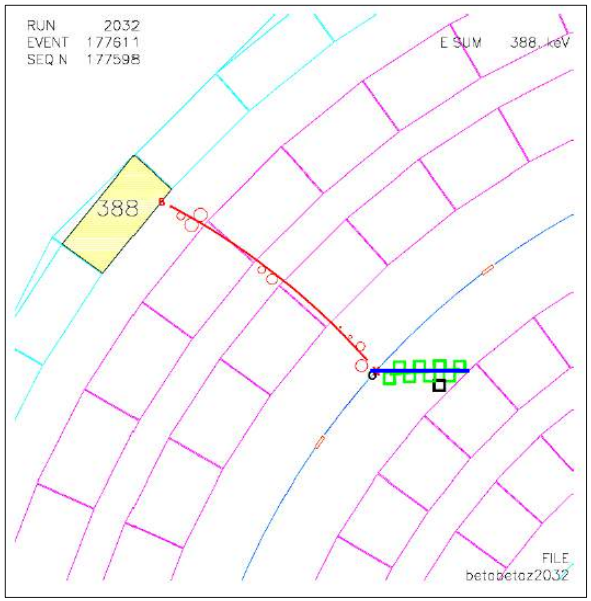
- Radon from surroundings permeates into detector depositing daughters on foil surface, drift wires, etc.

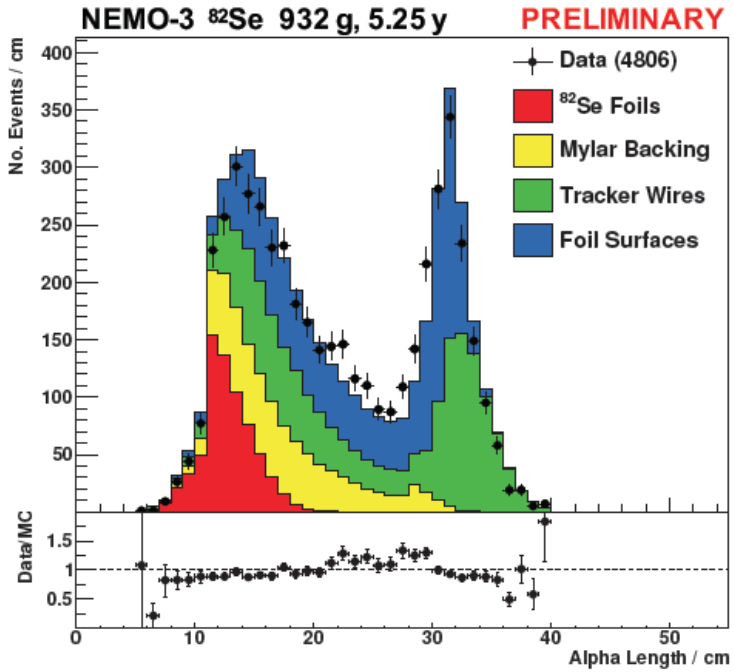
Background Measurements

- NEMO-3 is **uniquely** suited to measure its own backgrounds

Example: ^{214}Bi



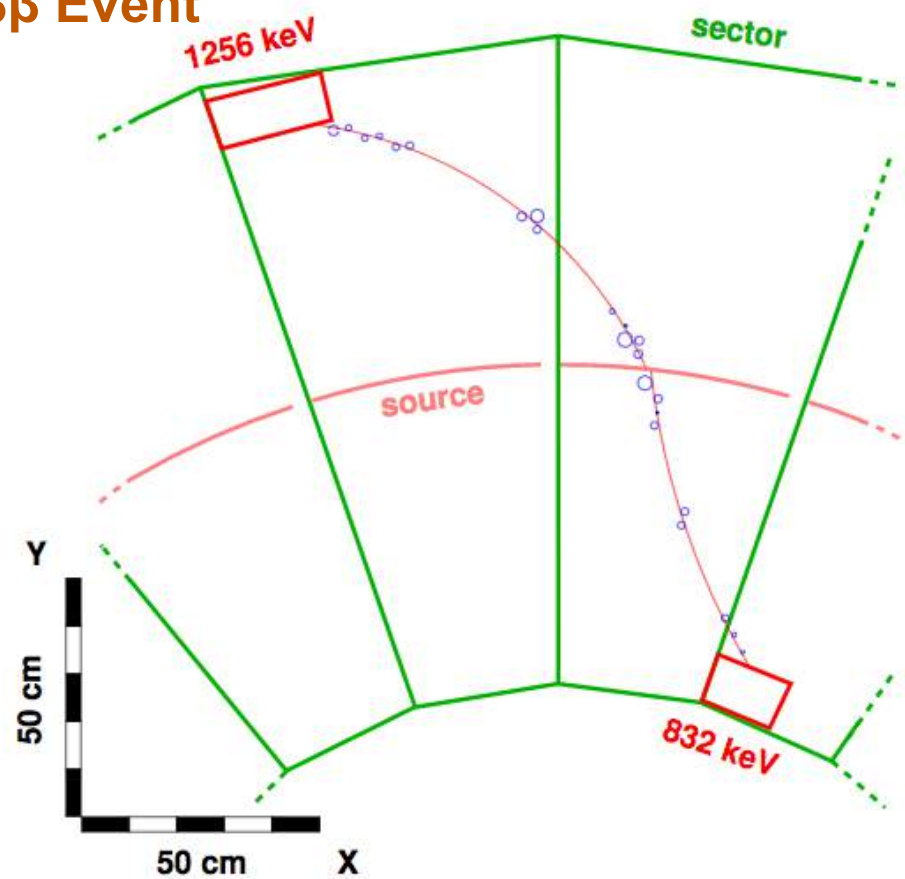


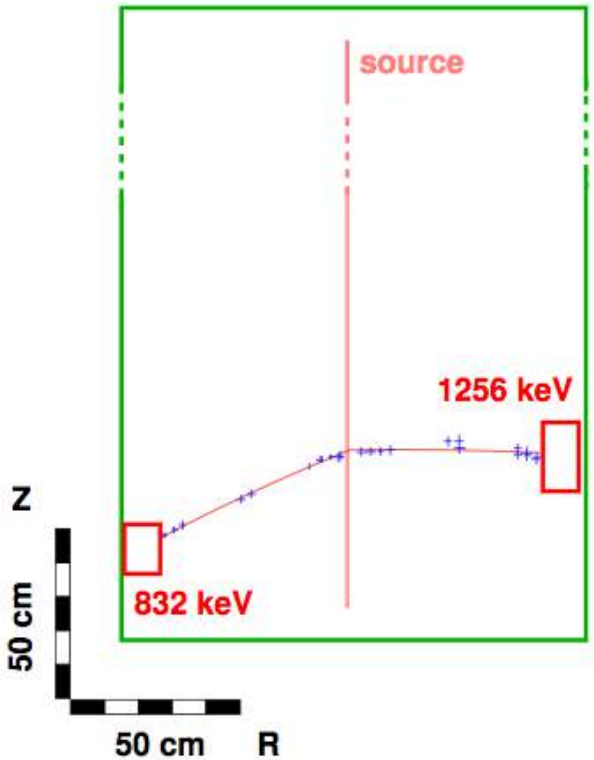


- Specific topologies indicate various background contributions
- Observables can be fitted to measure and constrain background activities

Signal Channel

^{100}Mo ββ Event

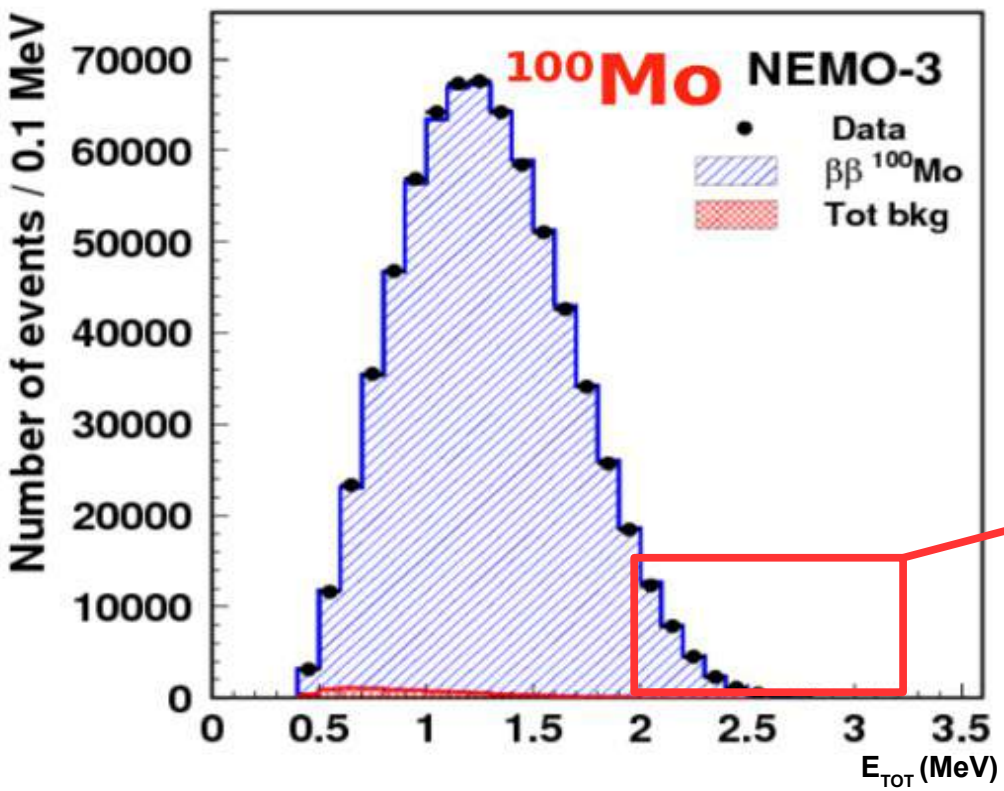


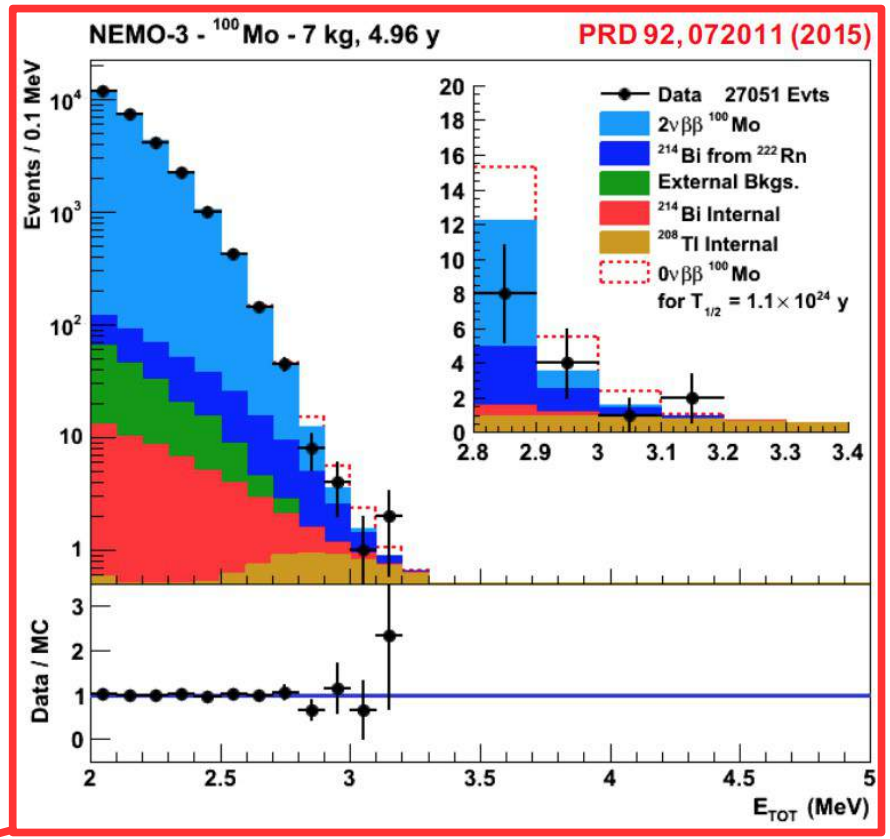


- **Clear** signature of a ββ event originating in the ^{100}Mo foils
- **Full decay kinematics** captured
- **No other interactions** present

Final Results: ^{100}Mo

- $Q_{\beta\beta}$ = 3.034 MeV, 6.9 kg
- High background suppression → **S/B = 76**





- 0νββ searched in the [2 - 3.2] MeV region

- Mass mechanism limit:

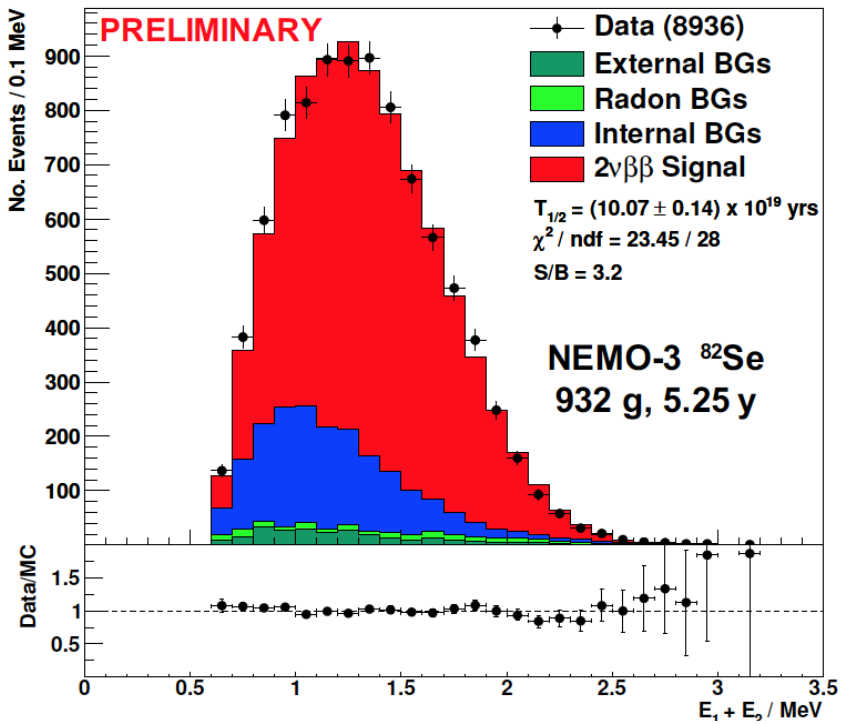
$$T^{0\nu}_{1/2} > 1.1\times10^{24}\,\mathrm{y}\ (90\%\ \mathrm{C.L.})$$
$$\langle m_{\beta\beta}\rangle < 0.3-0.6\,\mathrm{eV}$$

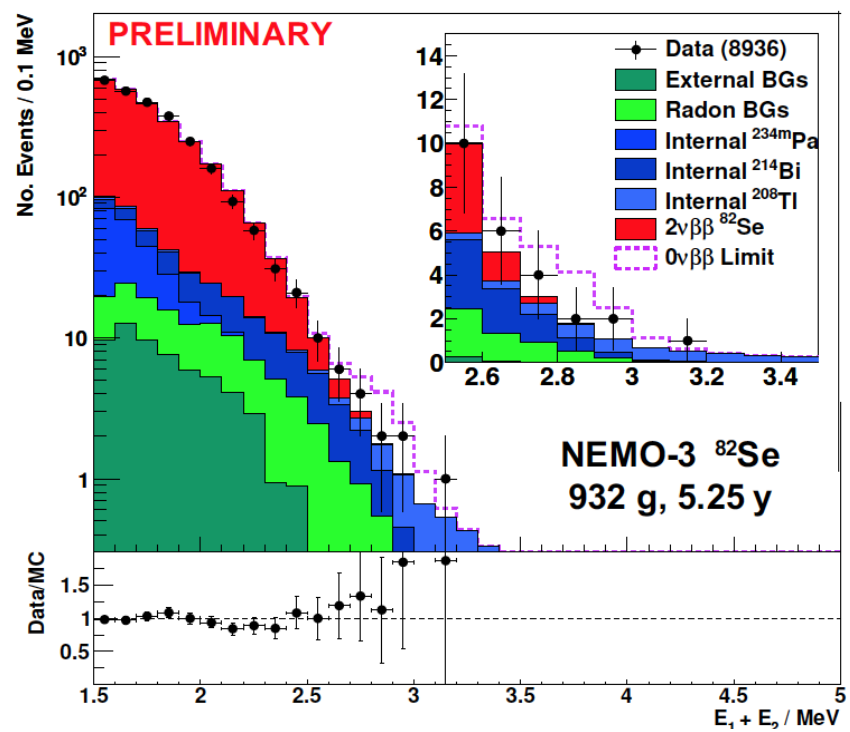
- No events above 3.2 MeV for full 47 kg·y
  - **Background free for high $Q_{\beta\beta}$ isotopes!**

Final Results: ^{82}Se

Poster #721

- $Q_{\beta\beta}$ = 2.995 MeV, 0.93 kg
- SuperNEMO baseline isotope
- Longer $T_{1/2}^{2\nu}$ reduces contributions to 0νββ search from the irreducible 2νββ tail





$$T_{1/2}^{2\nu} = [10.07 \pm 0.14(\text{stat.}) \pm 0.54(\text{syst.})] \times 10^{19}\,\text{y}$$

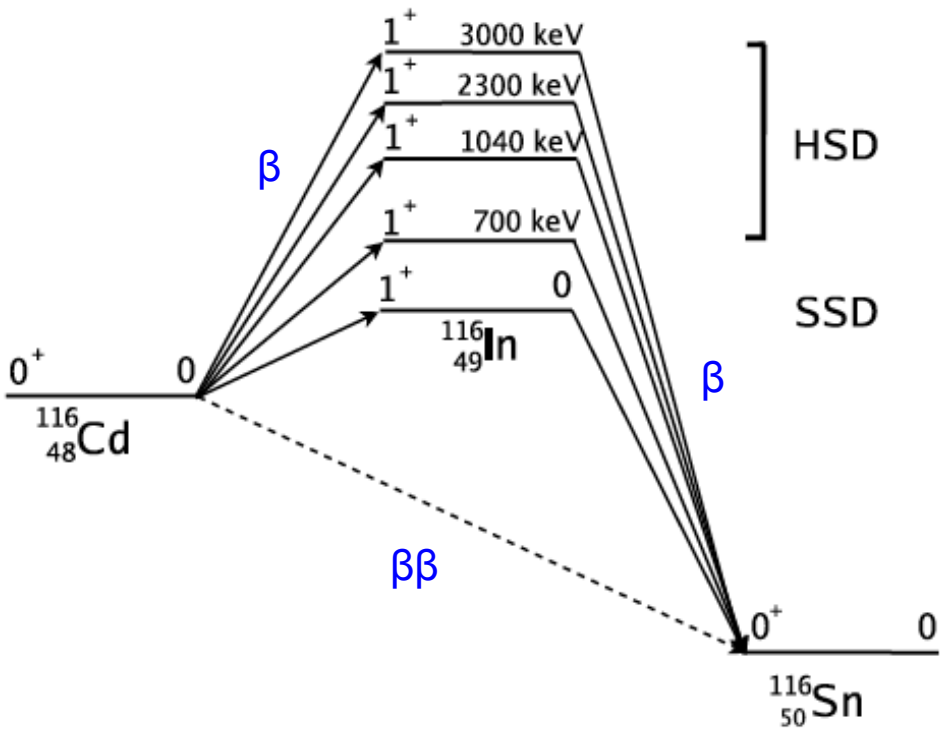
$$T_{1/2}^{0\nu} > 2.5 \times 10^{23}\,\text{y (90\% C.L.)}$$

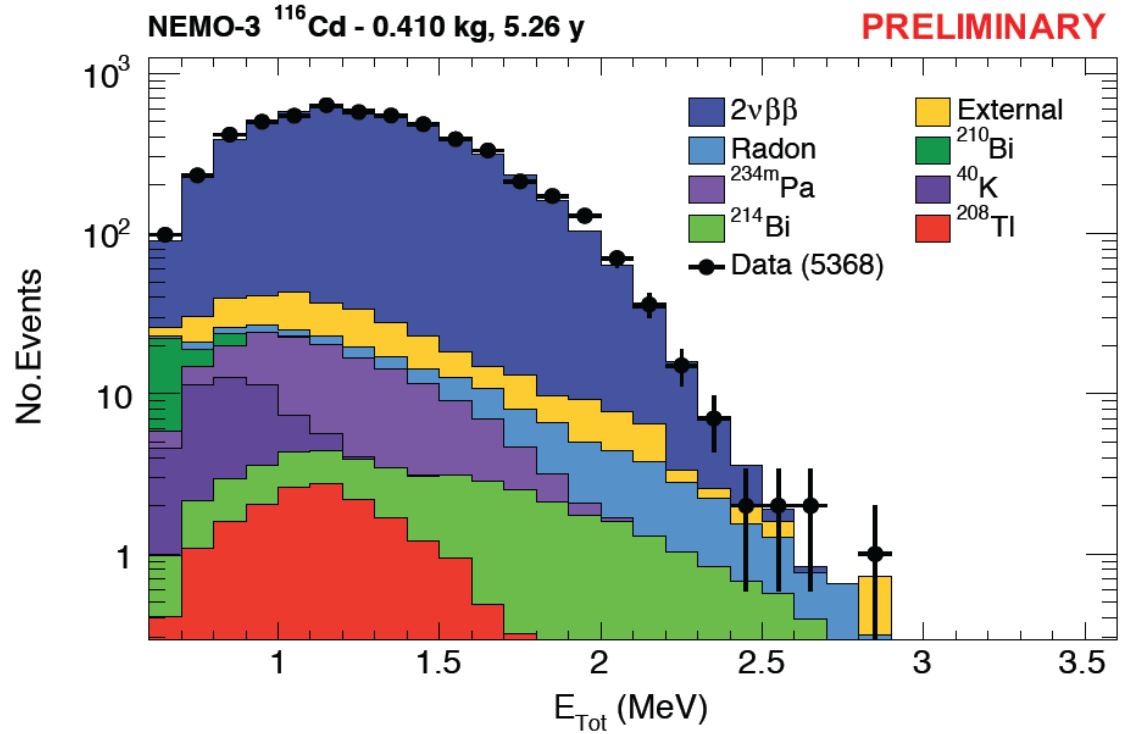
$$\langle m_{\beta\beta} \rangle < 1.2 - 3.0\,\text{eV}$$

➢ **More precise than (and consistent with) previous world-average value**

Final Results: ^{116}Cd

- $Q_{\beta\beta}$ = 2.804 MeV, 410 g
- **Opportunity to test single versus higher states dominance** hypotheses (SSD vs HSD)
- Single electron energy used for discriminating these
  - **Results favor SSD but don't exclude HSD**

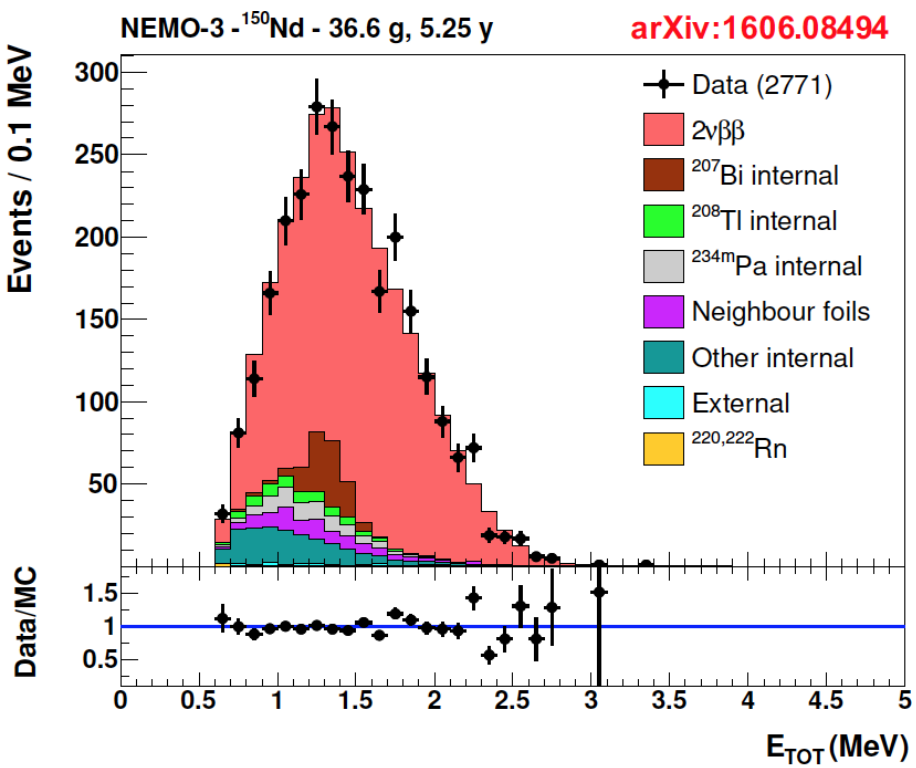


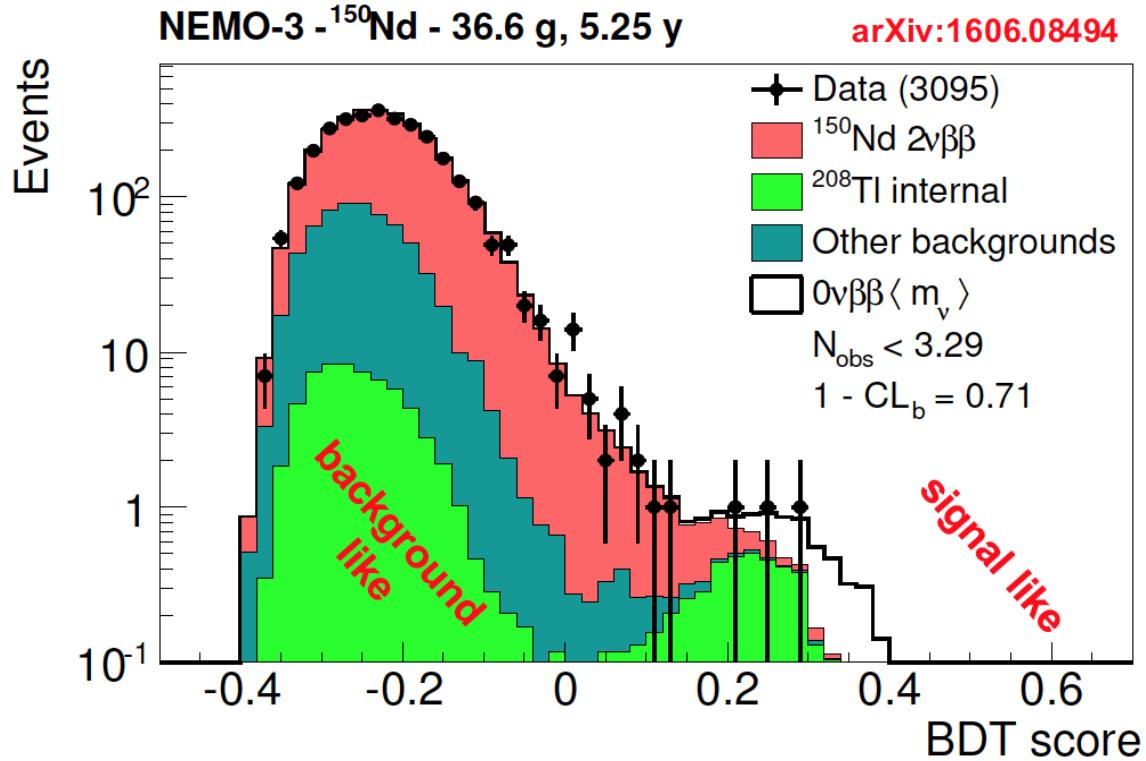


$$T^{2\nu}_{1/2} = [2.74 \pm 0.04(\text{stat.}) \pm 0.18(\text{syst.})] \times 10^{19}\,\text{y}$$

Final Results: ^{150}Nd

- $Q_{\beta\beta}$ = 3.368 MeV, 36.5 g
- Full decay kinematics provided by **NEMO-3 allows multivariate approach to 0νββ search**
  - Boosted Decision Tree (BDT) was used with 10 kinematic/detector variables





$$T^{2\nu}_{1/2} = [9.34 \pm 0.22(\text{stat.})^{+0.62}_{-0.60}(\text{syst.})] \times 10^{18}\,\text{y}$$

- **Most precise half-life measurement for this isotope**

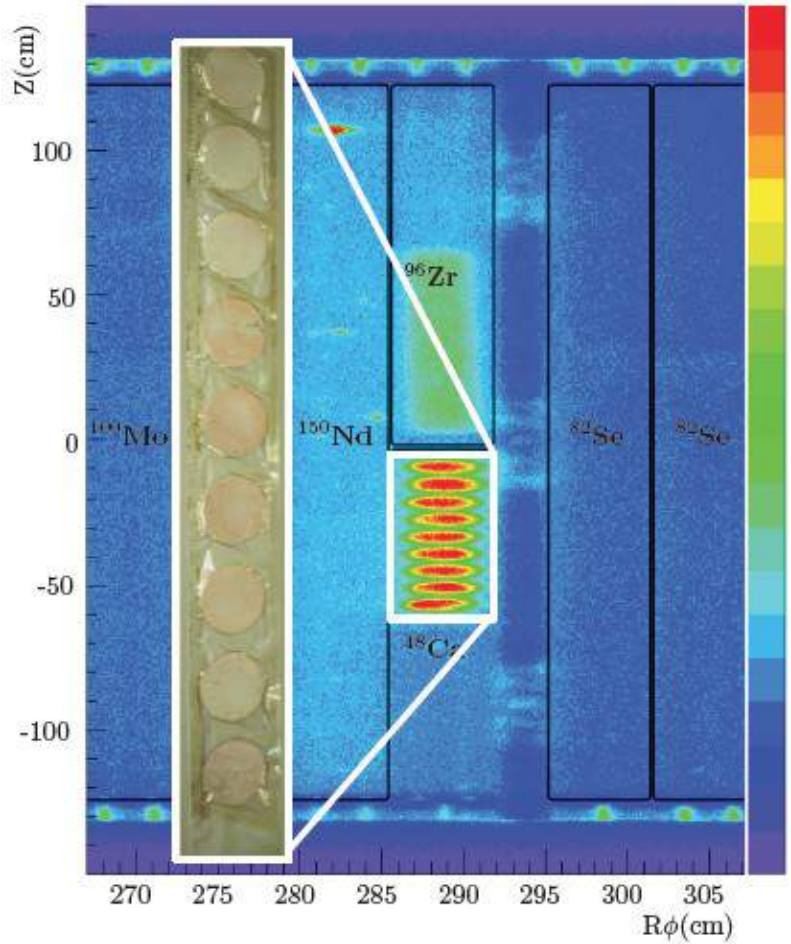
$$T^{0\nu}_{1/2} > 2.0 \times 10^{22}\,\text{y (90\% C.L.)}$$
$$\langle m_{\beta\beta} \rangle < 1.6 - 5.3\,\text{eV}$$

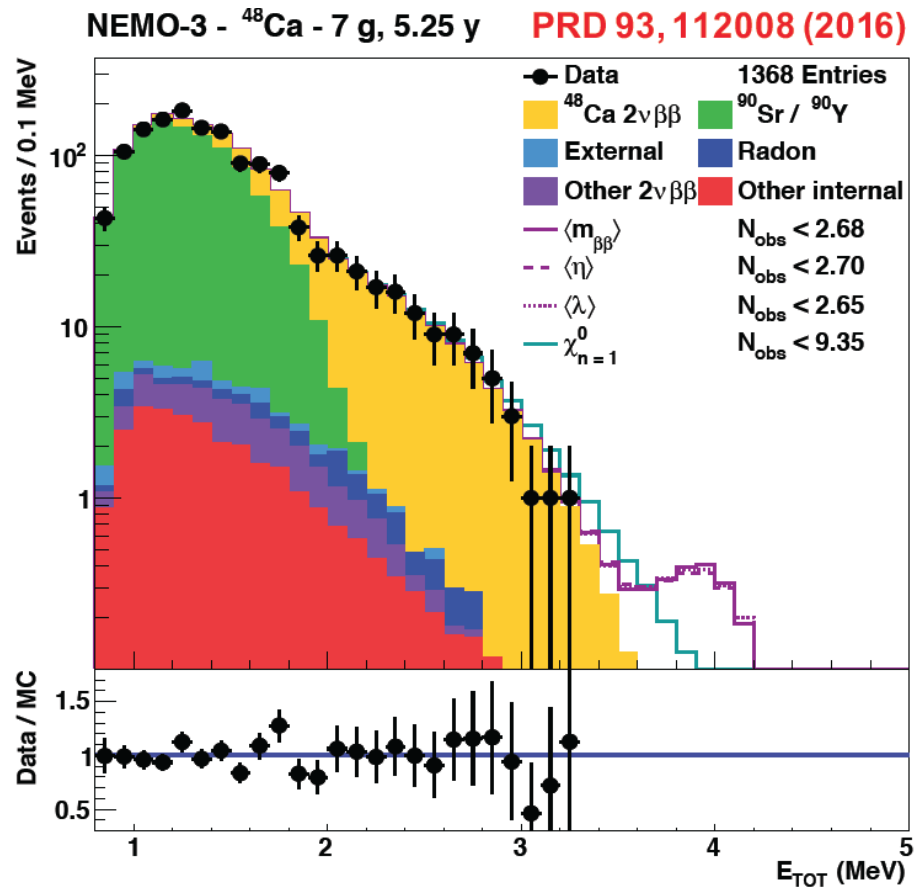
- Expected (observed) limit is 11% (34%) better than using E_{TOT} variable alone

Final Results: ^{48}Ca

Poster #534

- $Q_{\beta\beta}$ = 4.276 MeV → Highest decay energy of any candidate isotope
  - Above nearly all backgrounds
- **Most difficult to amass** → 6.99 g in NEMO-3 one of world's largest agglomerations!





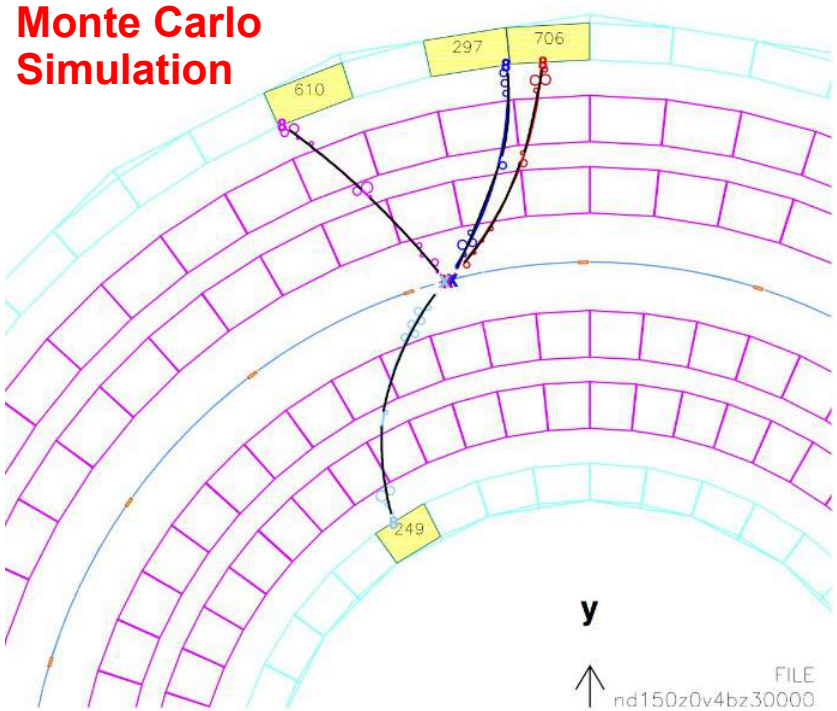
➢ **Most precise 2νββ half-life determination to date:**

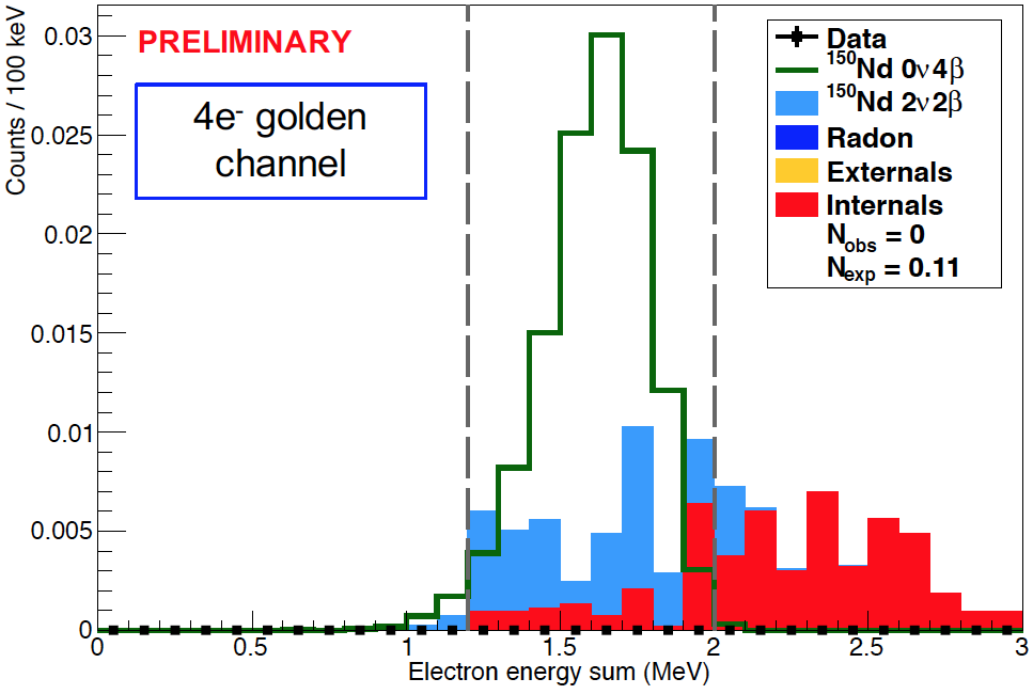
$$T^{2\nu}_{1/2} = [6.4^{+0.7}_{-0.6}(\text{stat.})^{+1.2}_{-0.9}(\text{syst.})] \times 10^{19}\,\text{y}$$

Final Results: Unique Physics

- Neutrinoless quadruple beta decay (0ν4β) is a proposed process allowing for Dirac neutrinos
  - (Heeck & Rodejohann 2013)
- **Best candidate is ^{150}Nd** → ^{150}Gd + 4e$^-$ due to highest $Q_{4\beta}$ = 2.08 MeV
- NEMO-3 uniquely suited since it can reconstruct full kinematics in the 4e "golden channel"

Monte Carlo Simulation





- Expected half-life: 4.3 x 10^{21} y

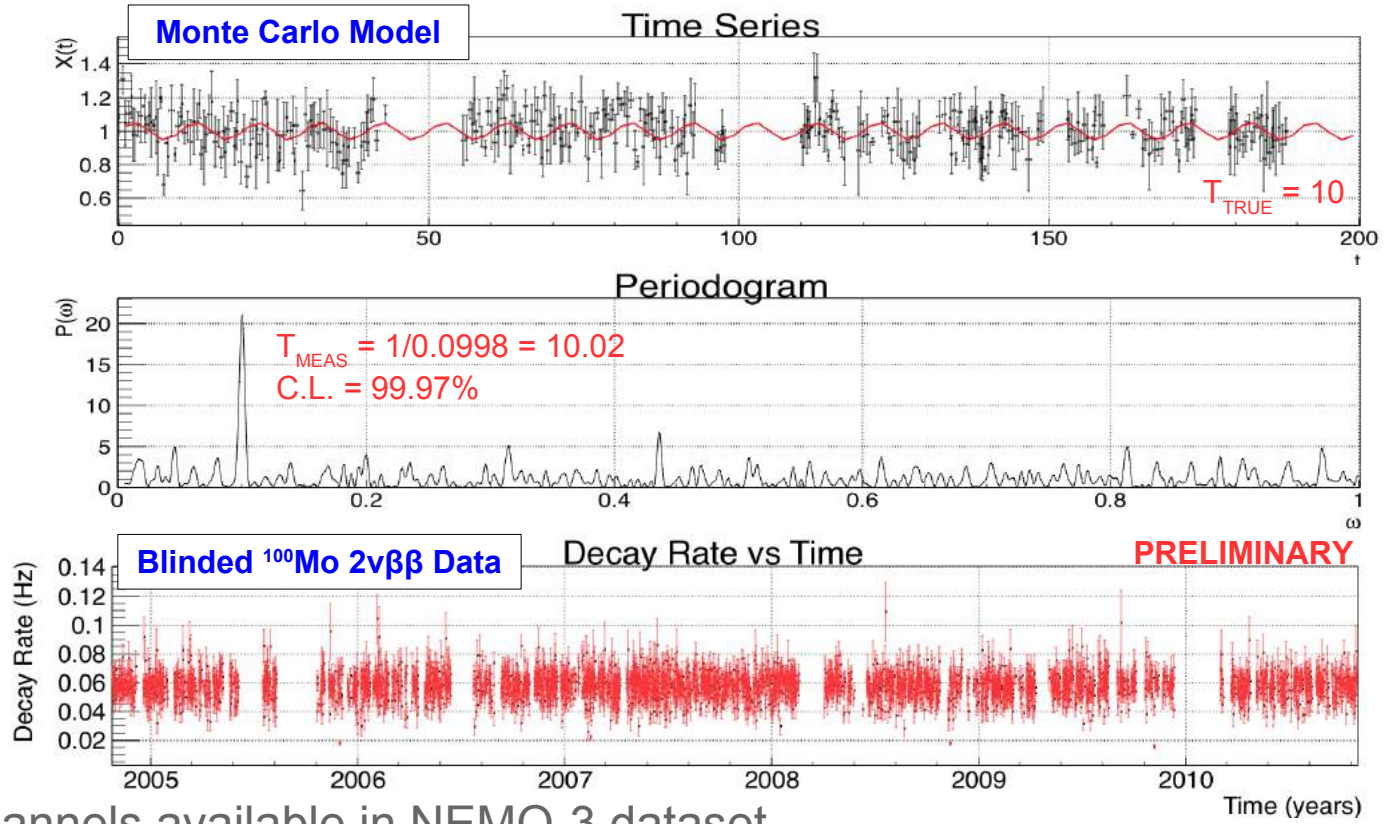
$$T_{1/2}^{0\nu 4\beta} > 2.6 \times 10^{21}\ \text{y (90\% C.L.)}$$

First ever limit!

Final Results: Unique Physics

Poster #482

- NEMO-3 was an observatory running for 7+ years
  - Opportunity to search for new physics → time variation of fundamental constants/processes
- 2νββ decay rate of ^{100}Mo → **First search for variations in a 2nd-order weak decay**
- Employing periodogram technique to search for periodicities with a range of frequencies



- Multiple channels available in NEMO-3 dataset
  - 2νββ rates in other isotopes
  - Single β emitters (backgrounds) for higher statistics

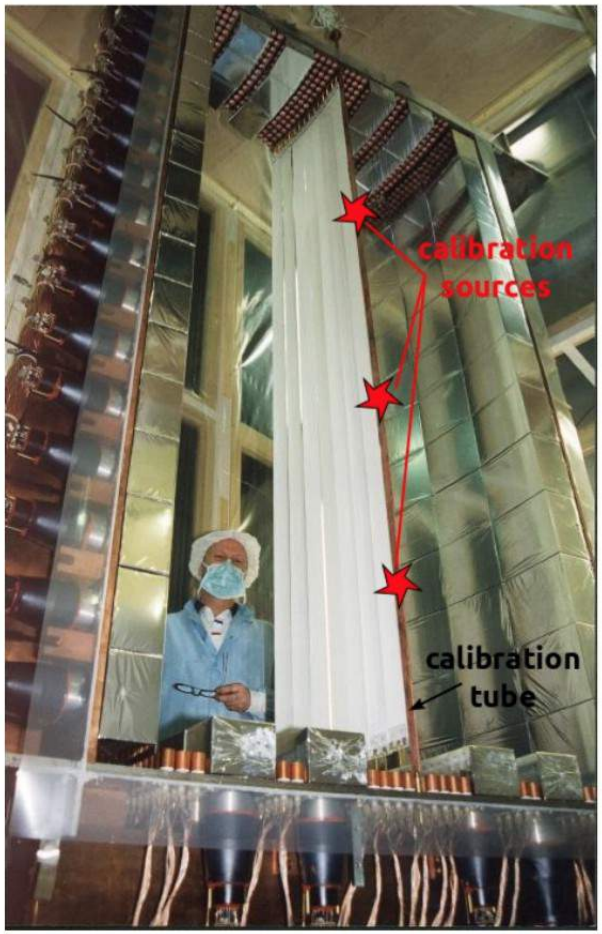
Summary and Outlook

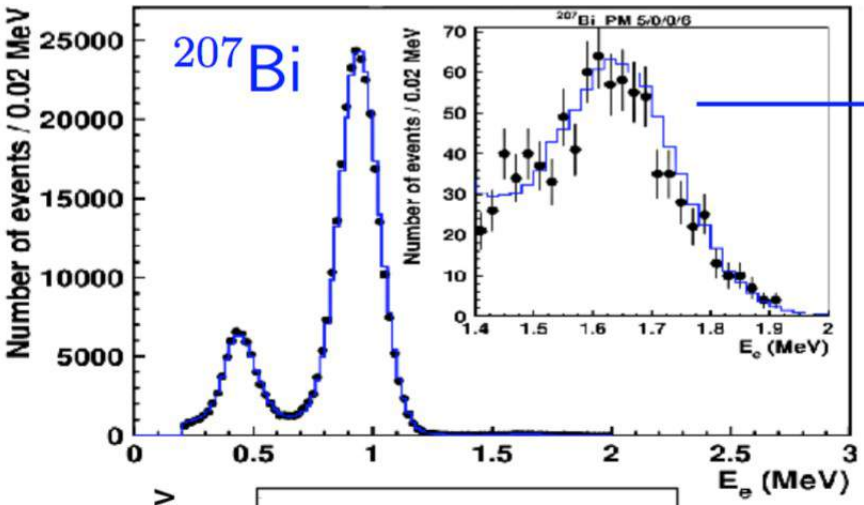
- The NEMO-3 advantage
  - No events > 3.2 MeV in 47 kg·y in ^{100}Mo search → $\langle m_{\beta\beta} \rangle < 0.3 - 0.6\,\mathrm{eV}$
  - Multi-isotope + multi-observables
- NEMO-3 continues producing a unique spectrum of results
  - World-leading 2νββ measurements and probing of 0νββ mechanics
  - Varying nuclear decay rates, 0ν4β decay, etc.

Backup Slides

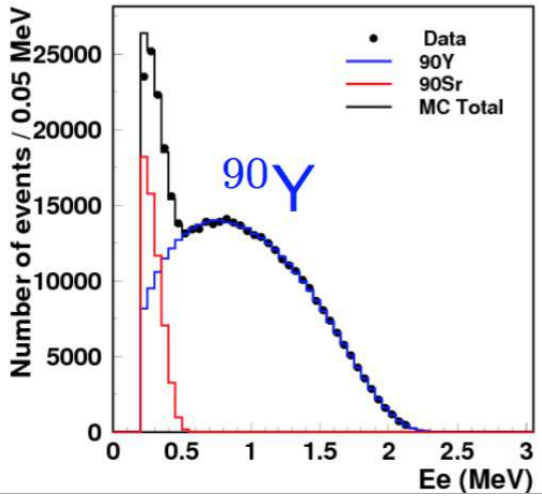
Energy Calibrations

- 20 calibration tubes close to foils for sources at 3 vertical positions:
  - reconstruction of the $1e^-$ events from the source to the calorimeter
  - ^{207}Bi: 482 and 976 keV conversion electrons every 2-3 weeks
  - ^{90}Sr-^{90}Y: β-decay end-point $Q_\beta = 2280$ MeV
  - ^{207}Bi: 1682 keV conversion electrons $\rightarrow$ test the energy scale





99 % PMTs
Data/MC < 0.2 %

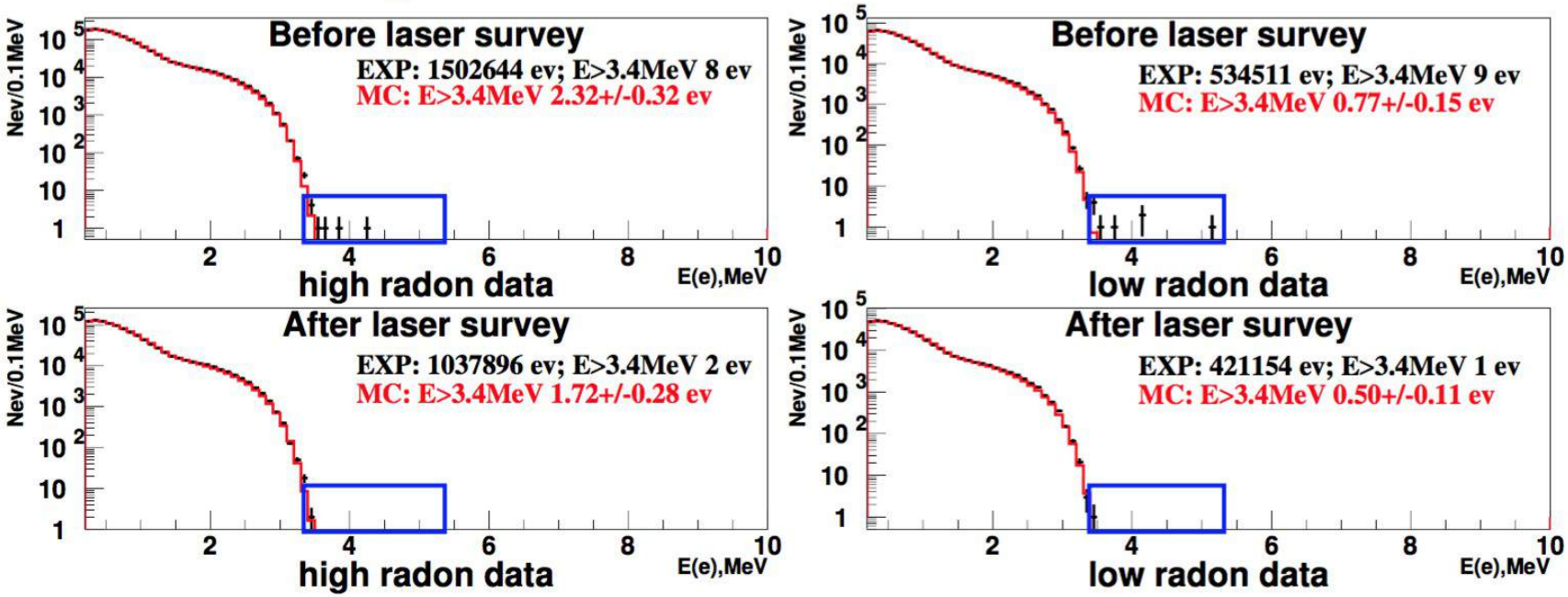


Laser Energy Survey

- Light injection into each calorimeter block through optical fibers:
  - linearity better than 1 % between 0 and 4 MeV
  - PMT gain and timing survey twice a day (82 % PMTs < 5 %)
- ^{214}Bi β-decay end-point ($\mathcal{Q}_\beta = 3.27$ MeV) to validate PMT stability:
  - reconstruction of the BiPo $e^-\alpha_{\text{delayed}}$ events from radon (background-free channel)

Phase 1: high radon data

Phase 2: low radon data



Half Life Limits

maximise efficiency (ε) & isotope abundance (*a*)

maximise exposure = mass (*M*) × time (*t*)

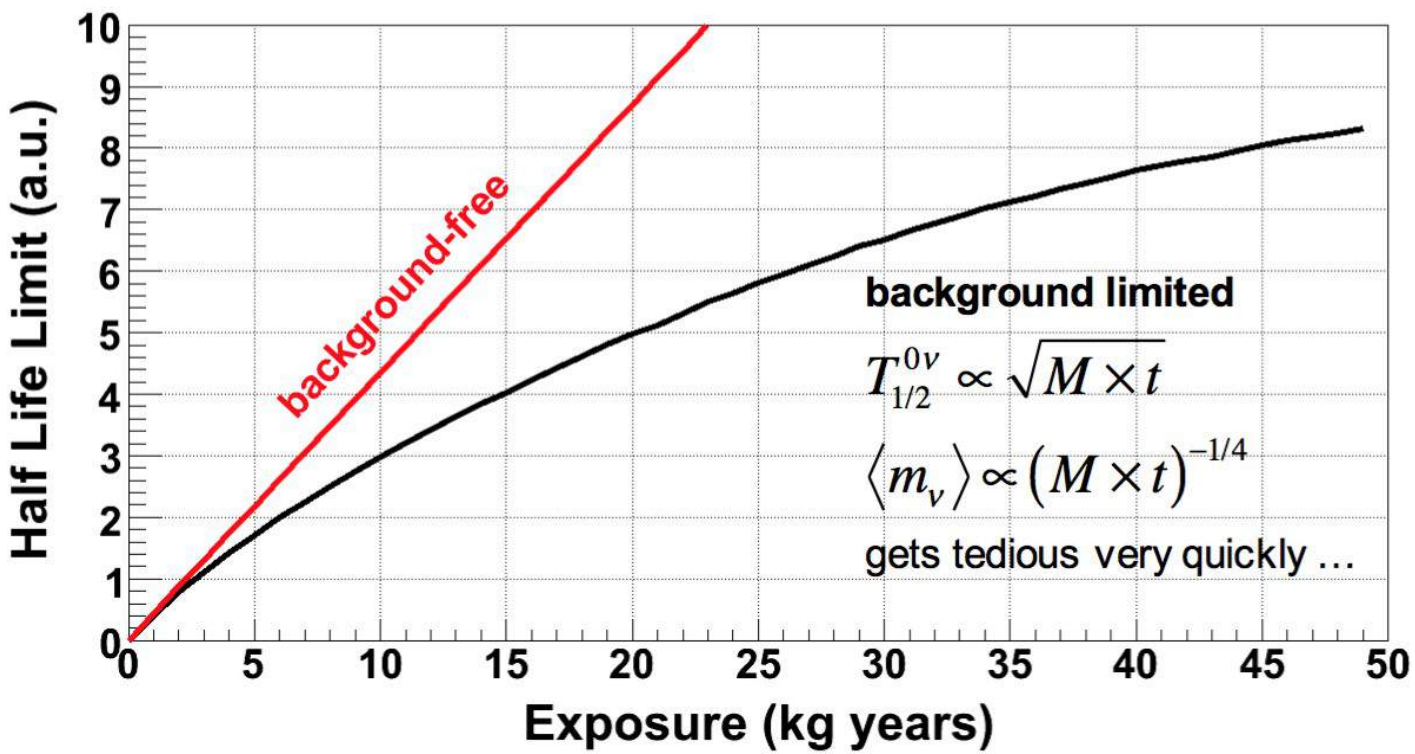
$$T_{1/2}^{0\nu}(90\%\ \text{C.L.}) = 2.54\times10^{26}\,\text{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

W = atomic weight

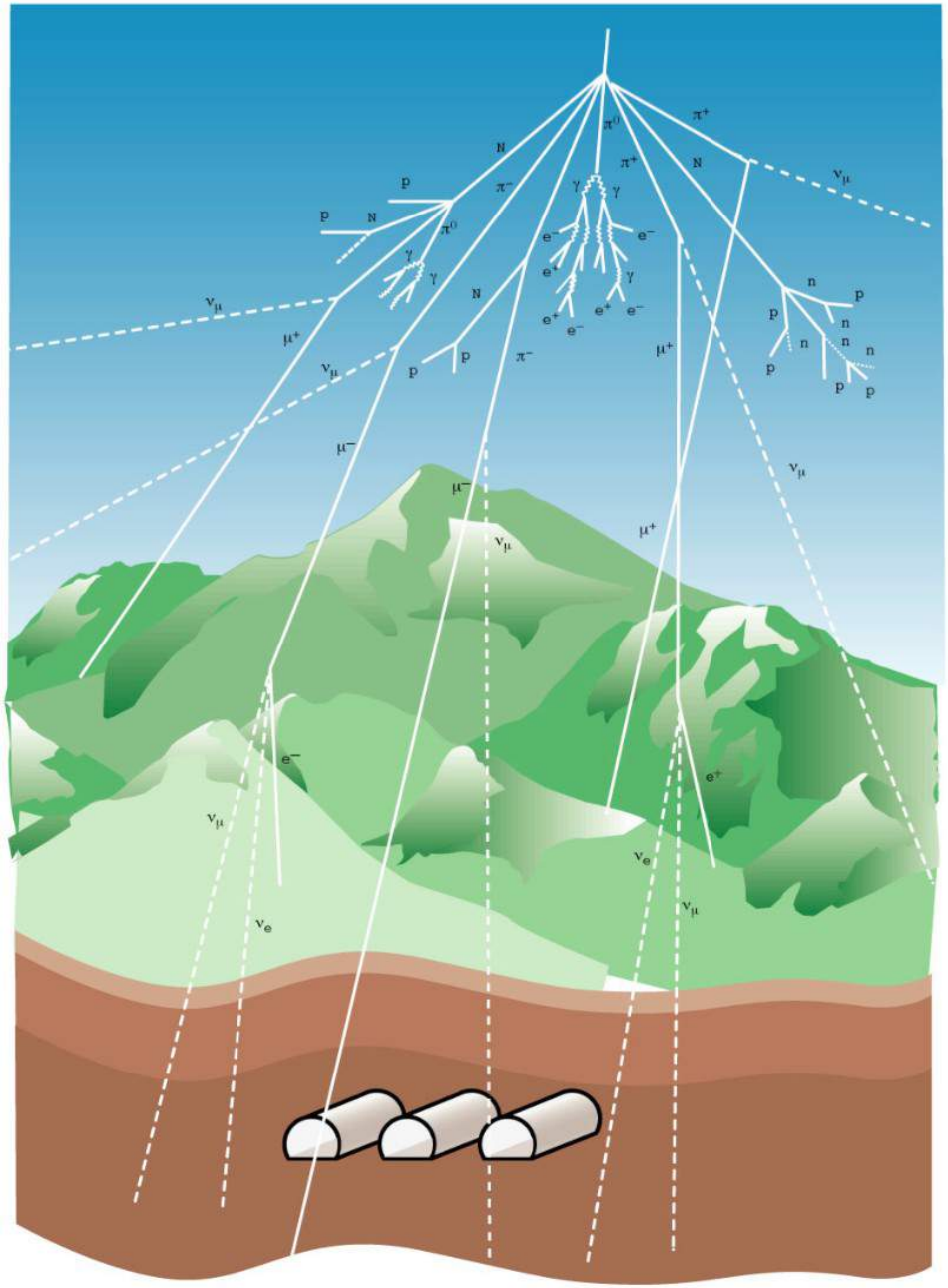
minimise background (*b*) & energy resolution (Δ*E*)

GERDA (^{76}Ge): $b\times\Delta E \sim 0.01\times 4$ keV = 0.04

SuperNEMO (^{82}Se): $b\times\Delta E \sim 0.0001\times 120$ keV = 0.012

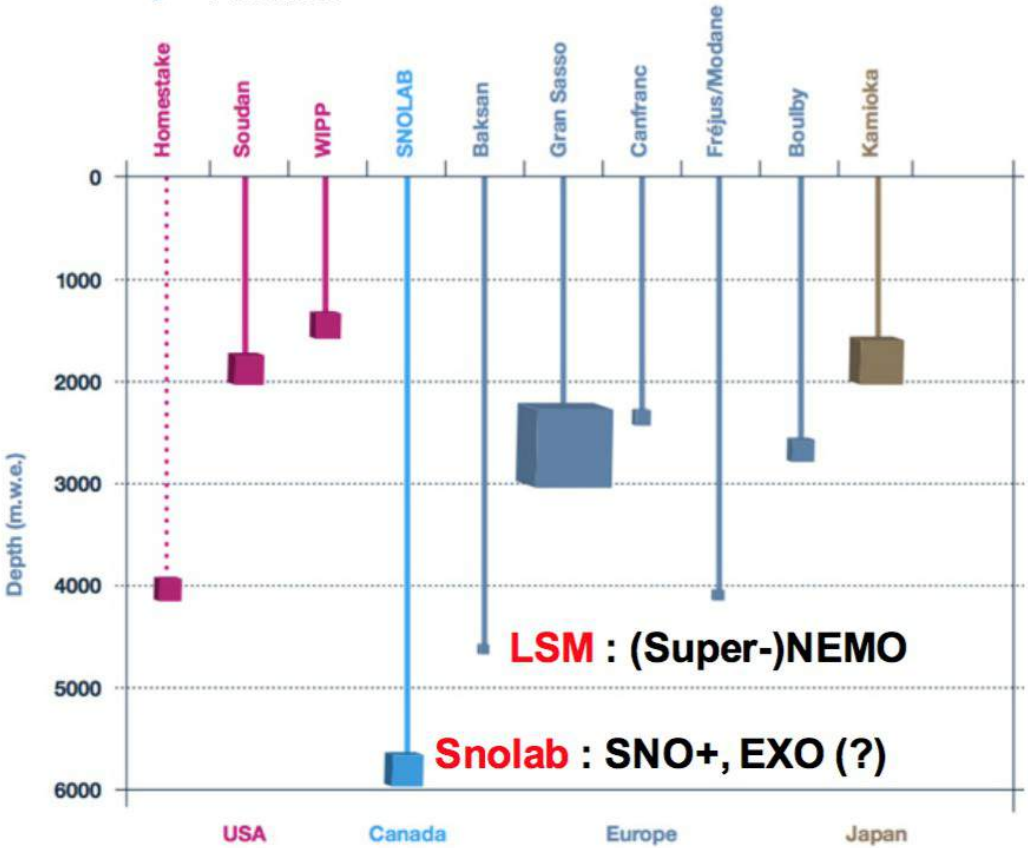


Underground Laboratories



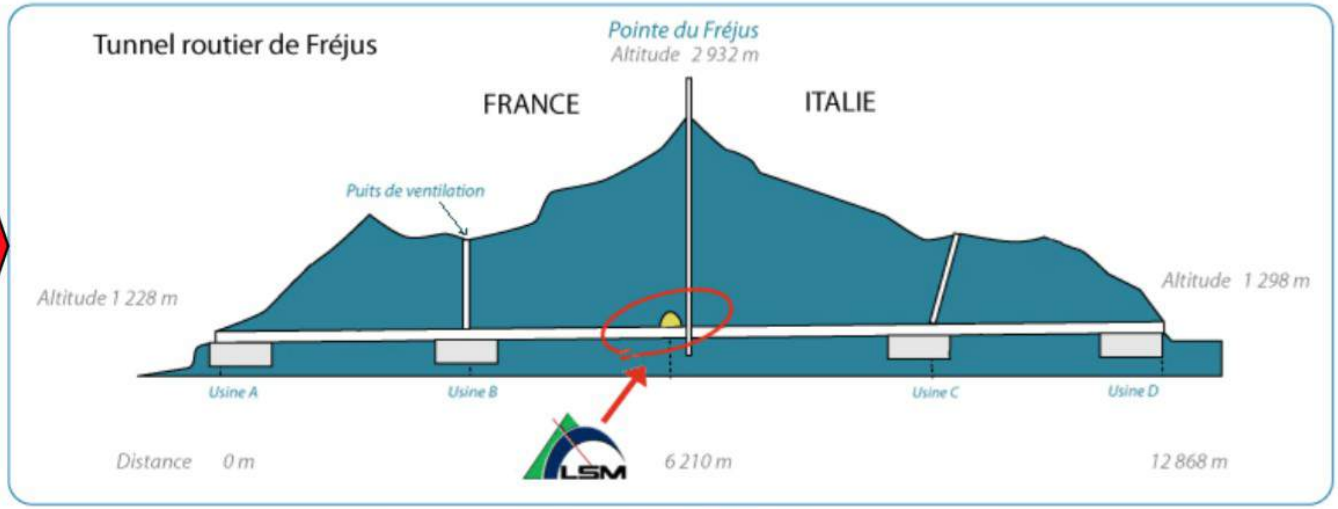
Essential to go deep underground

- Cosmic ray muon flux reduced by 10^{-6}
- Other important backgrounds are a function of depth and local geology :
  - Neutrons
  - γ's
  - Radon



NEMO-3 at the LSM

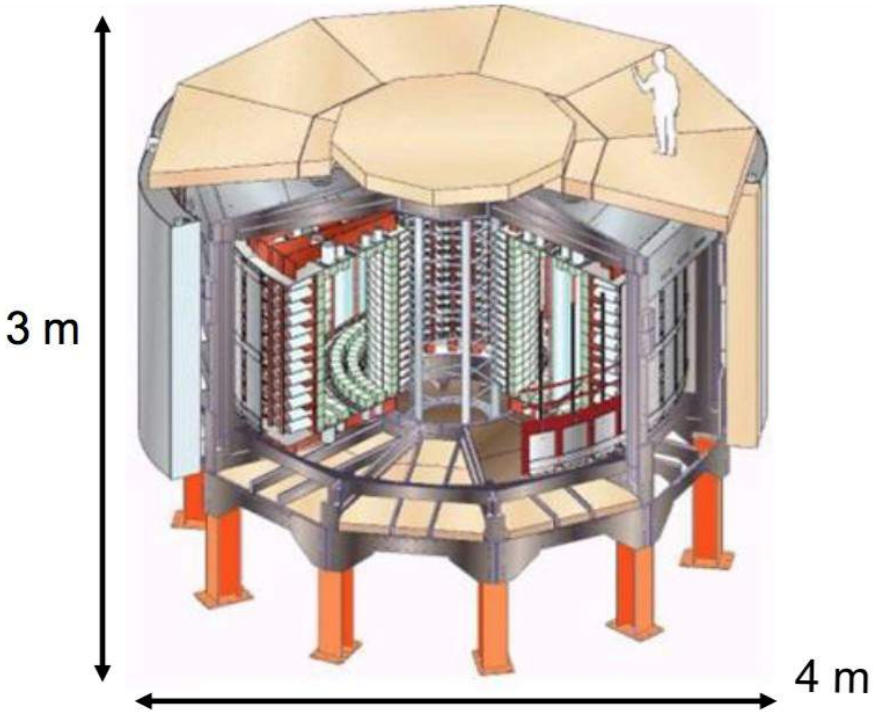
Laboratoire Souterrain de Modane (LSM) : 4800 M.W.E.



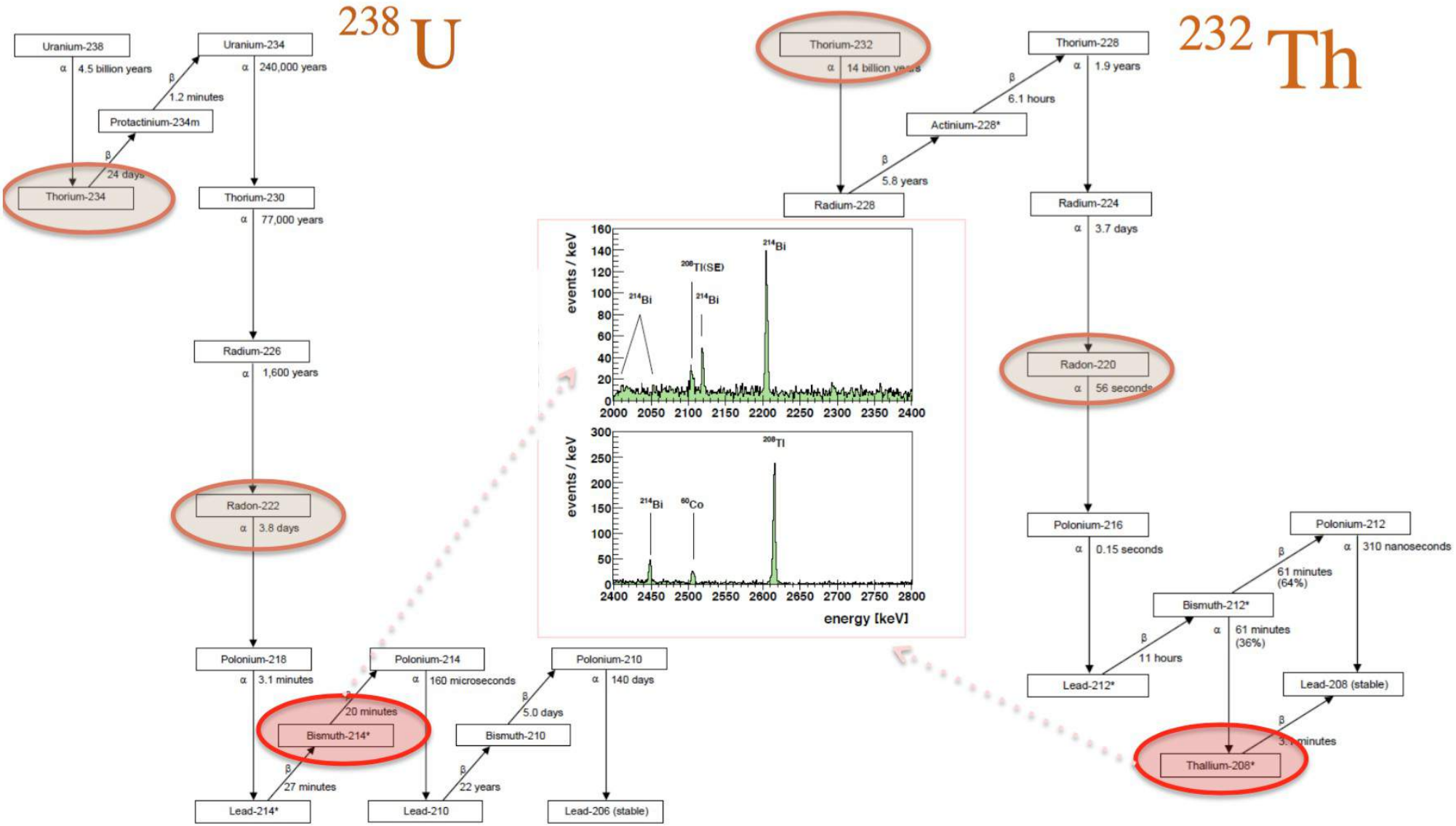
NEMO-3

The world's biggest and cleanest Geiger counter

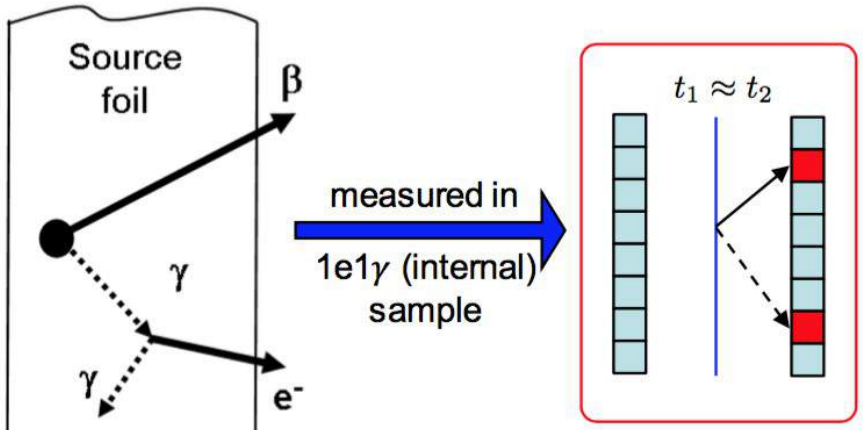
Ran from Feb. 2003 to Jan. 2011

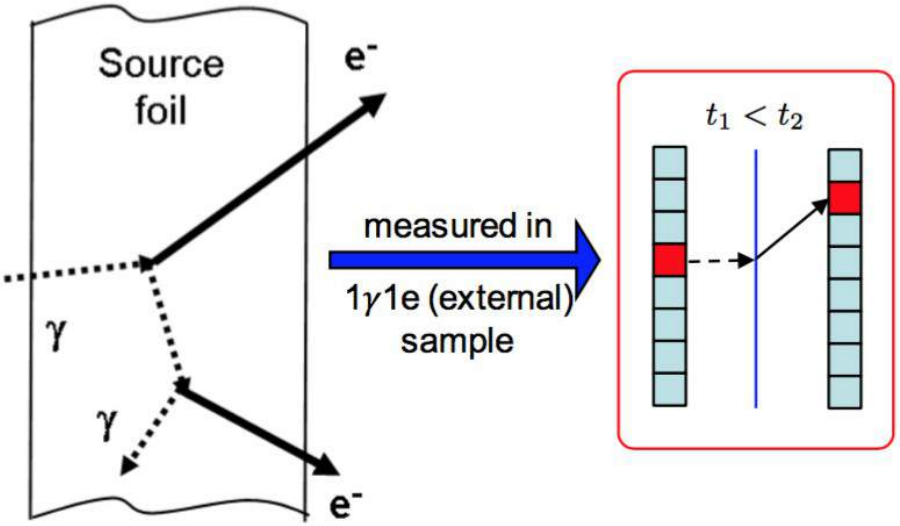


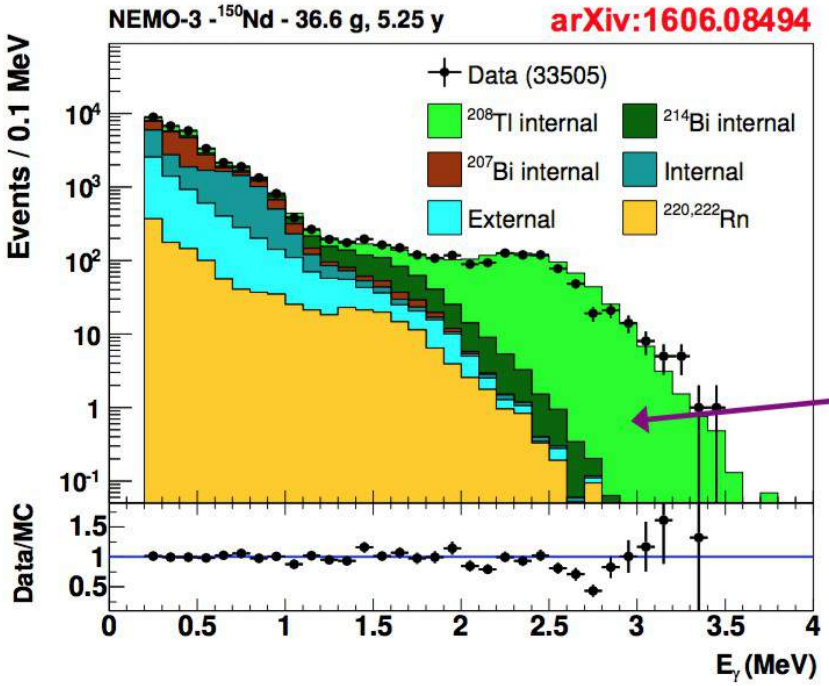
^{238}U and ^{232}Th Chains



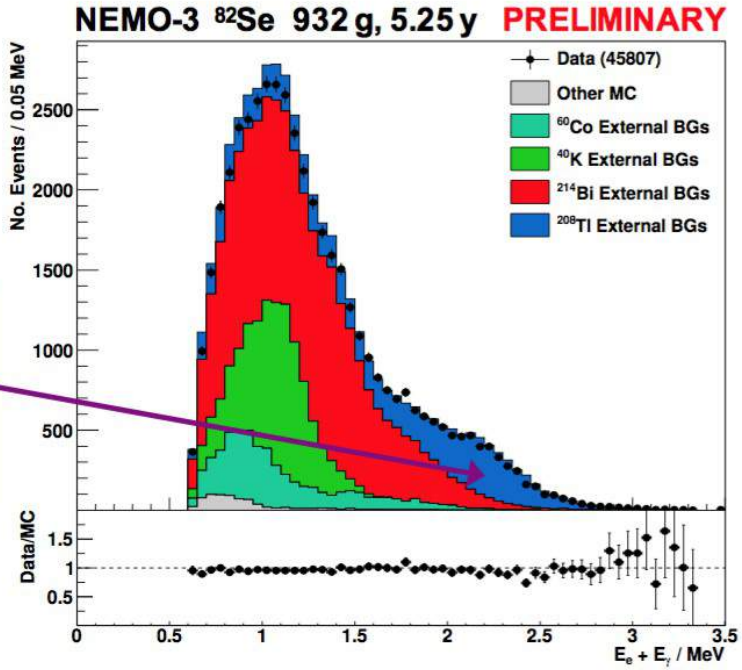
NEMO-3 Backgrounds





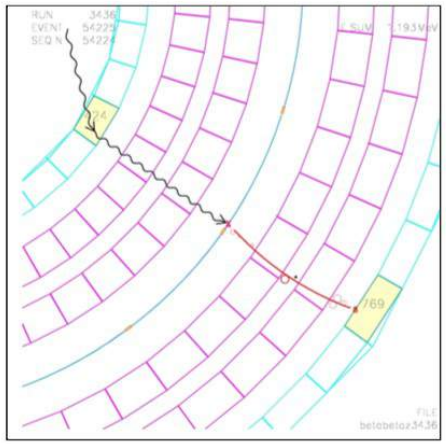


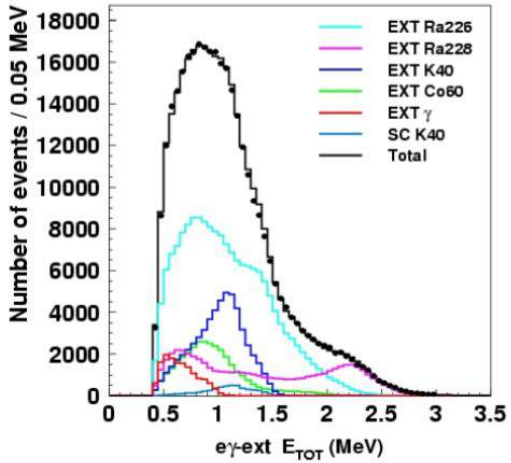
^{208}Tl :
- Internal
- External (e.g. PMTs)

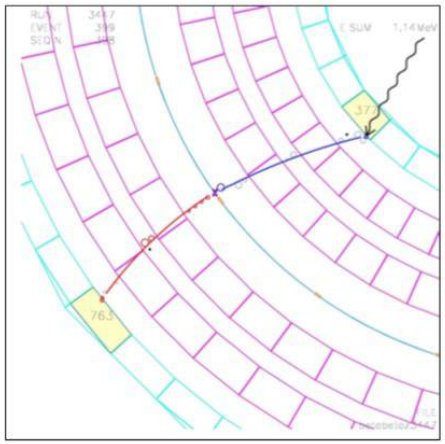


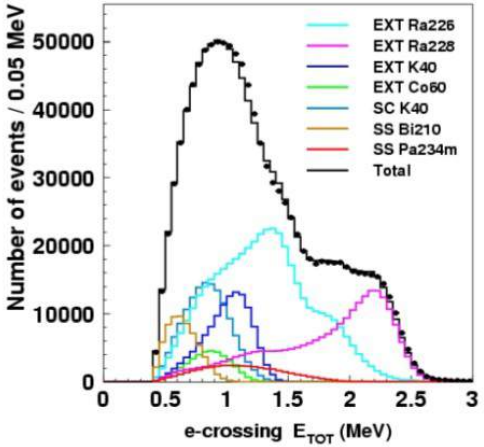
NEMO-3 Backgrounds

External background: eγ-external and e-crossing events

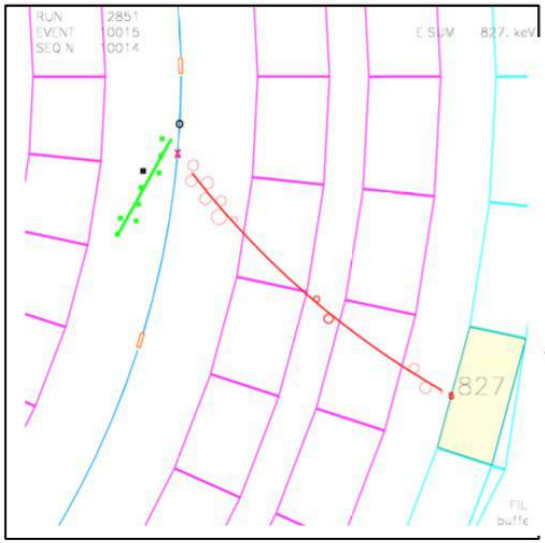


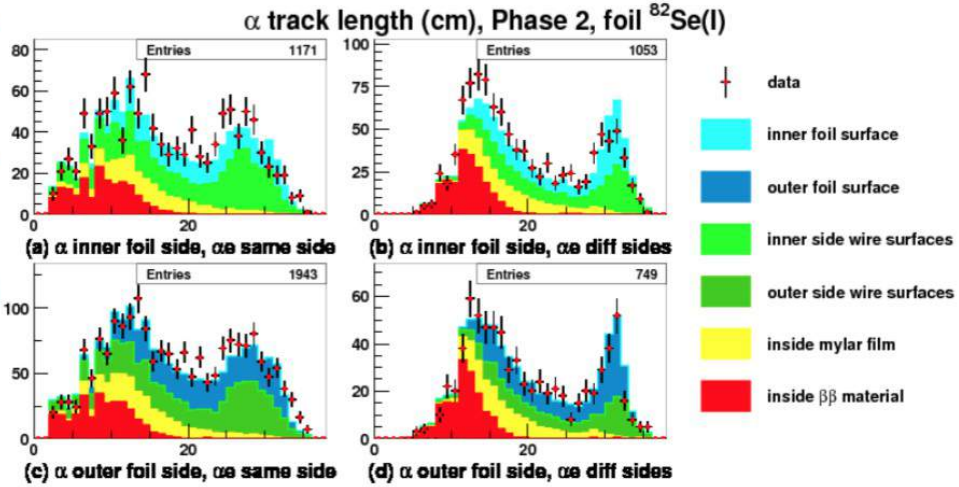




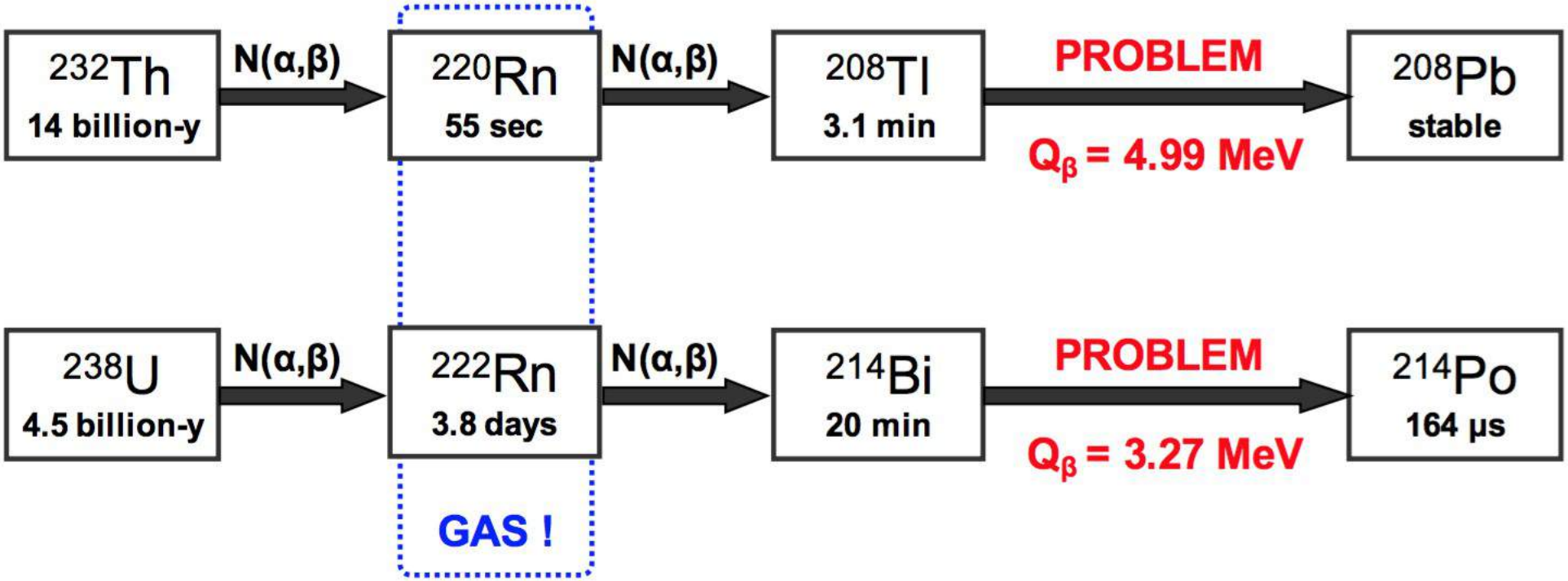


Internal ^{214}Bi : eα(γ)-events from foil





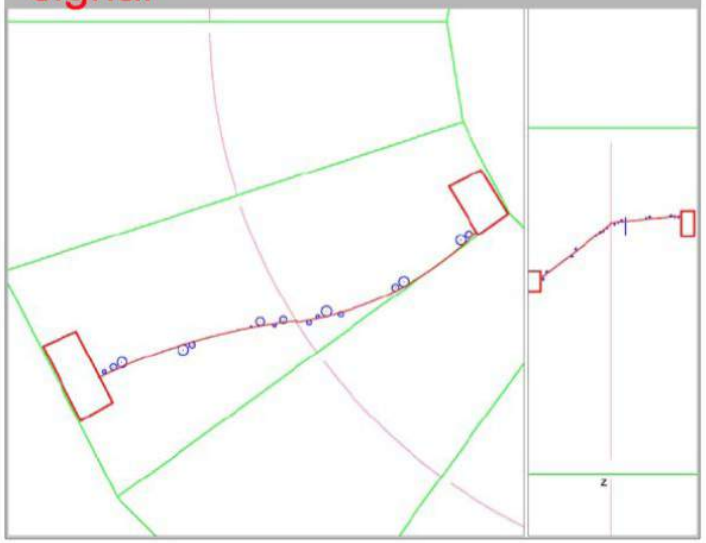
Radon/Thoron Backgrounds



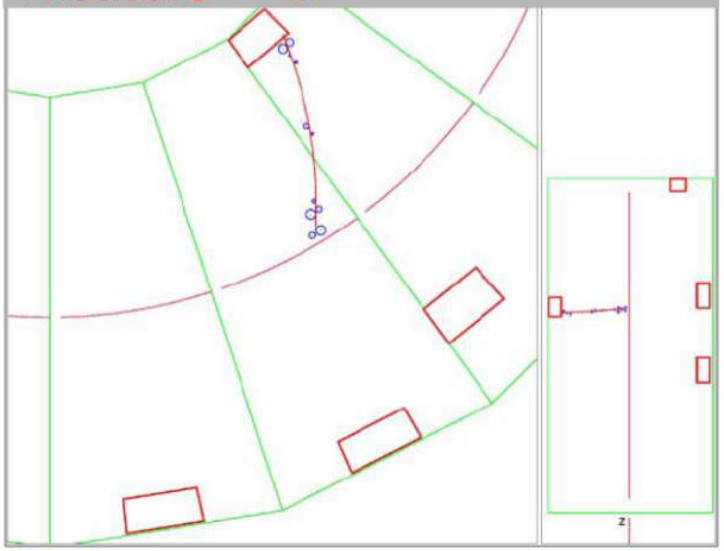
- Most troublesome are ^{214}Bi and ^{208}Tl → High single beta Q values
- Can enter detector from highly diffusive radon gas
- Or can be present in detector and source foil materials
- Background minimization:
  - Material screening and purification
  - Vetoes and active shielding
  - Radon barriers
  - Background identification *in situ*

NEMO-3 Event Displays

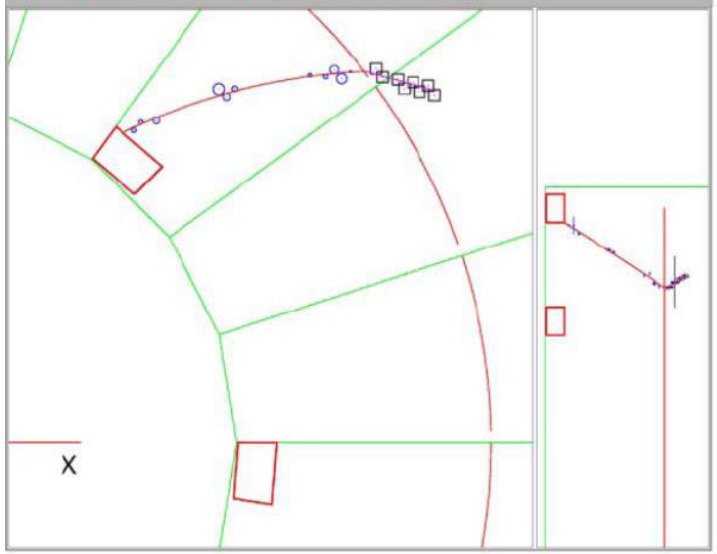
$2e^-$ event
signal



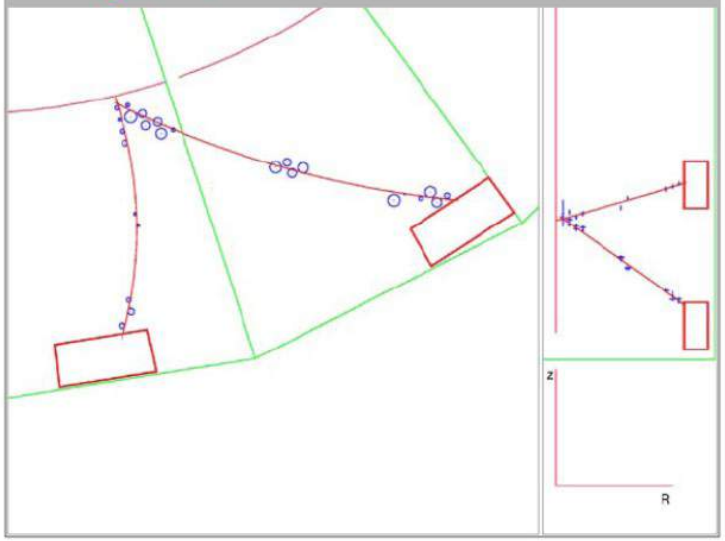
e^- $\gamma\gamma\gamma$ event
measure ^{208}Tl



β - α (delay track) event
$^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$

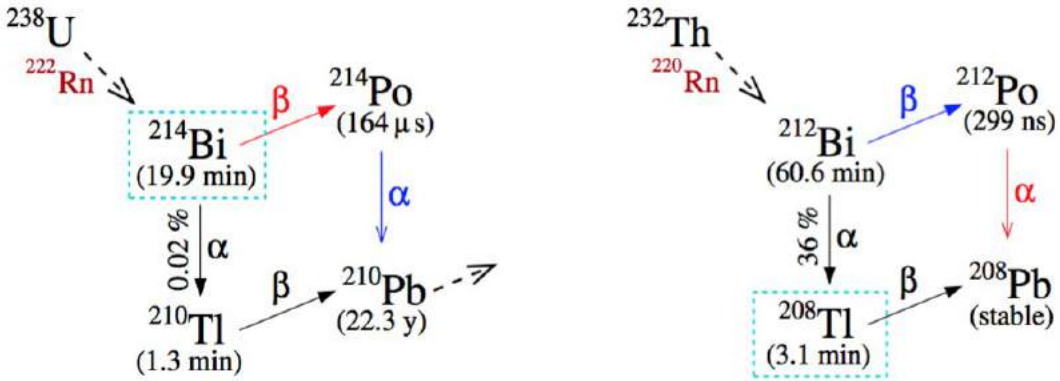


$e^+ - e^-$ pair event
B rejection

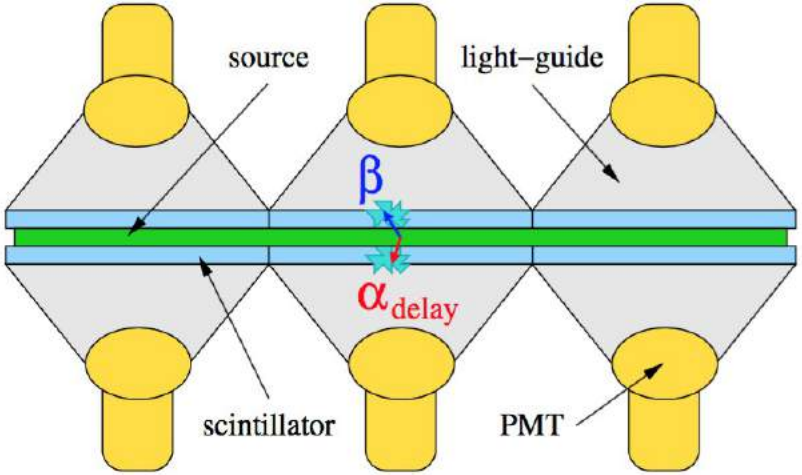


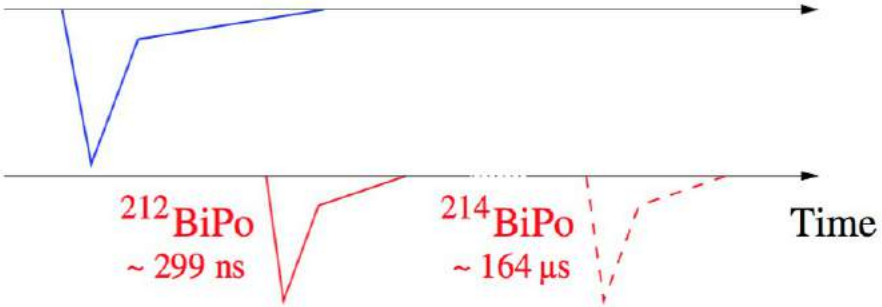
Source Foil Background Measurement

- HPGe γ spectroscopy not sufficient to reach few μBq/kg today (factor 50 improvement needed for thin foils)
- Main contaminations for $0\nu2\beta$ search (^{214}Bi and ^{208}Tl) measured through BiPo processes from natural radioactivity chains:



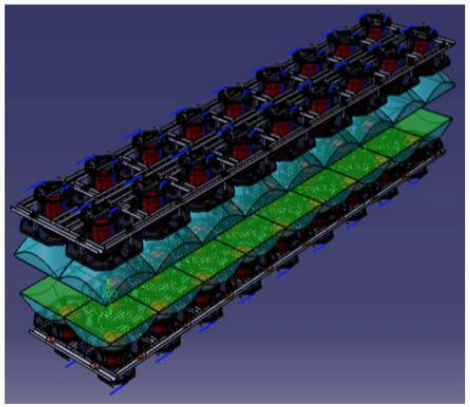
- β and α particles detected by thin radiopure plastic scintillators coupled to light-guides and low radioactivity PMTs:

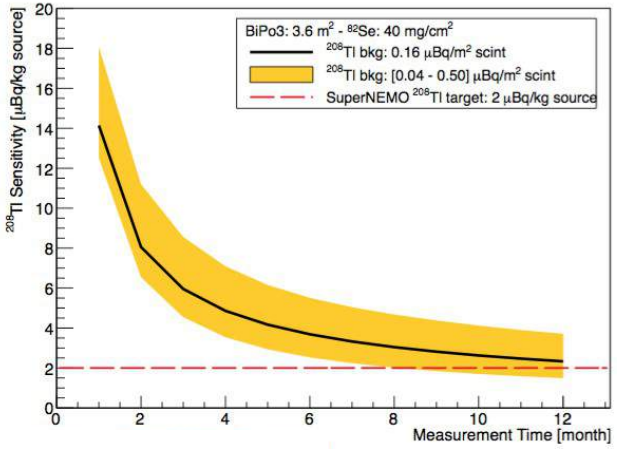


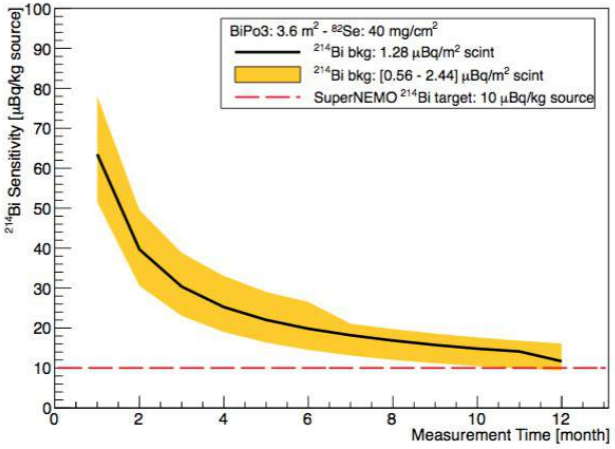


The BiPo Detector

- 2 modules of 3.0x0.6 m^2 can measure 1.4 kg of ^{82}Se foil (40 mg/cm^2)
- 2 mm thick aluminized polystyrene scintillators, PMMA light guides and 5" Hamamatsu low radioactivity PMTs
- PMT pulses digitized by MatAcq boards and dedicated trigger board
- Running since 2012 in Canfranc Underground Lab (LSC, Spain)
- Sensitivity: ^{208}Tl $< 2\ \mu$Bq/kg and ^{214}Bi $< 10\ \mu$Bq/kg

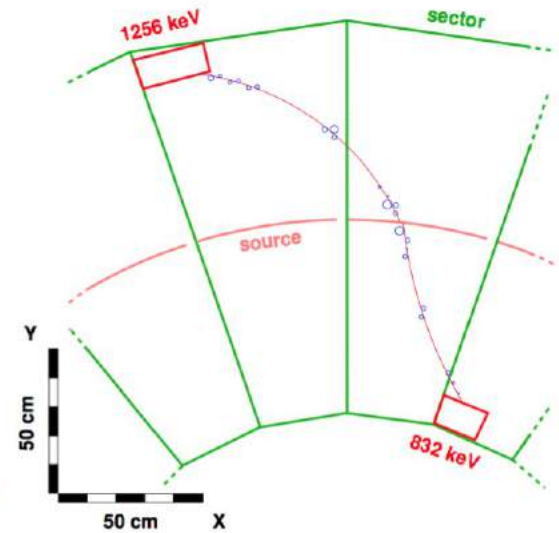


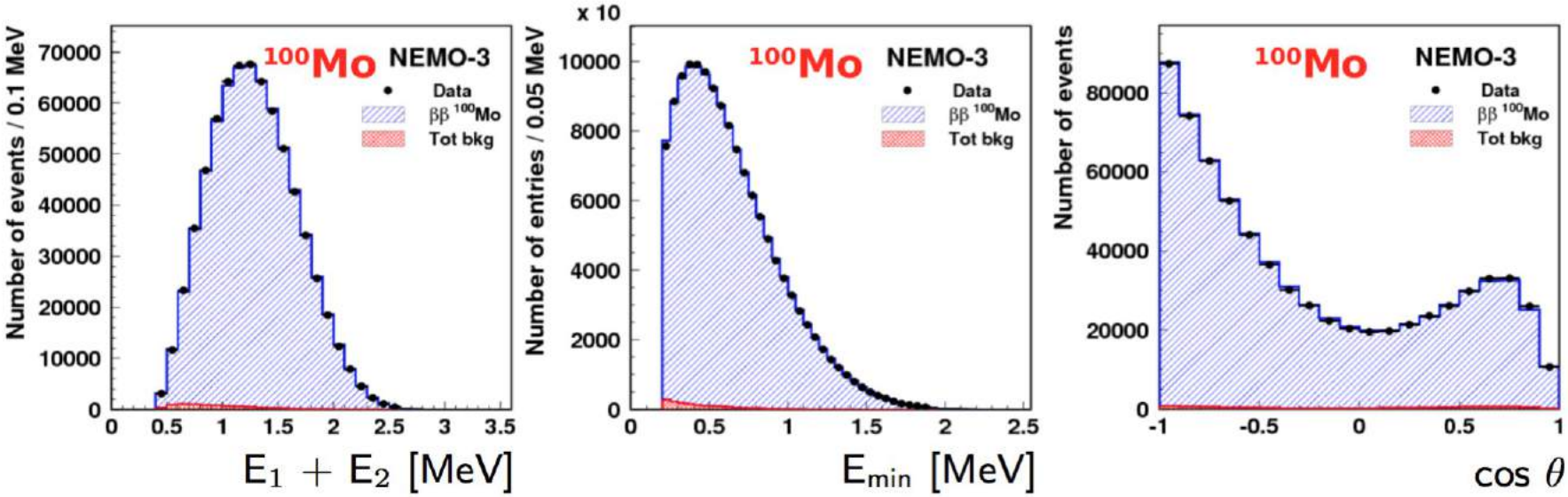




NEMO-3 ^{100}Mo 2νββ Results

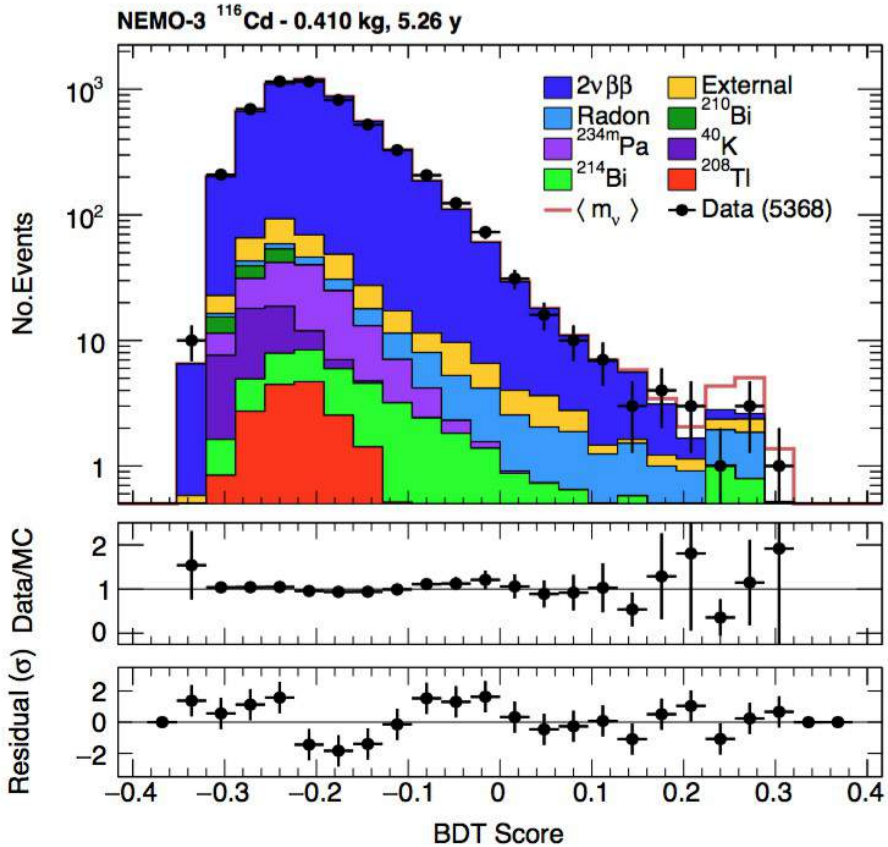
- 6.9 kg of ^{100}Mo
- ~700 000 $2\nu2\beta$ events collected
- Efficiency $\mathcal{E}_{2\nu} = 4.3$ %
- Signal to background ratio S/B = 76
- Preliminary half-life:
  $\mathcal{T}^{2\nu}_{1/2} = 7.16 \pm 0.01$ (stat) ± 0.54 (syst) 10^{18} y
  compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]

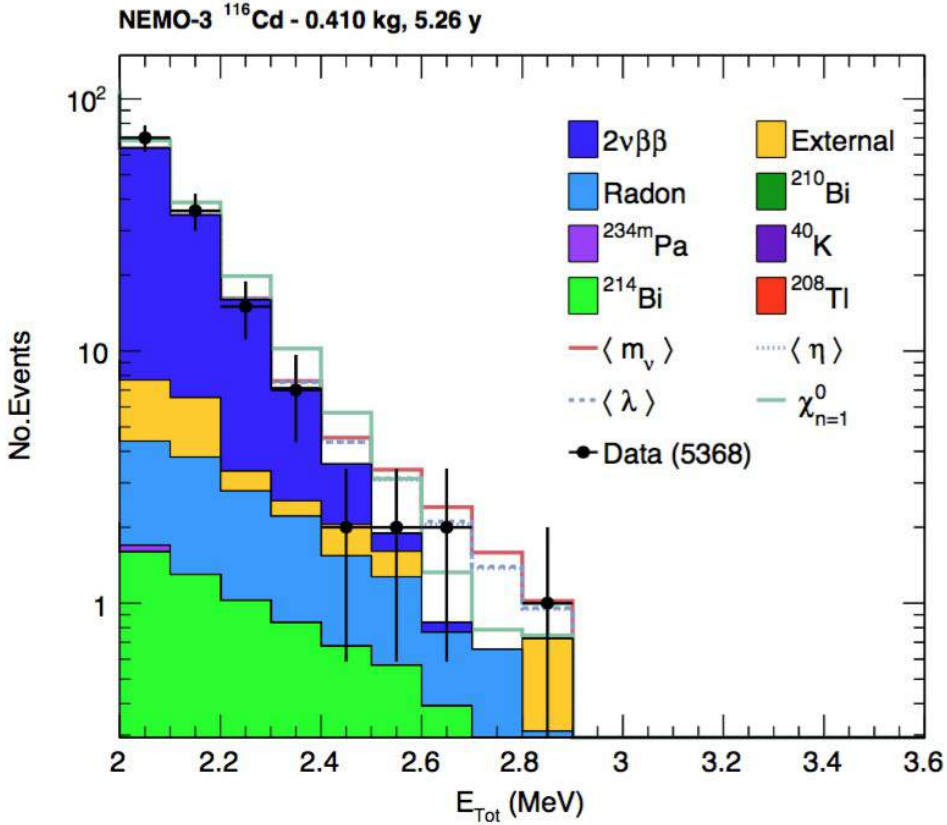




- 0.7 % systematical uncertainty on the $2\nu2\beta$ efficiency above 2 MeV

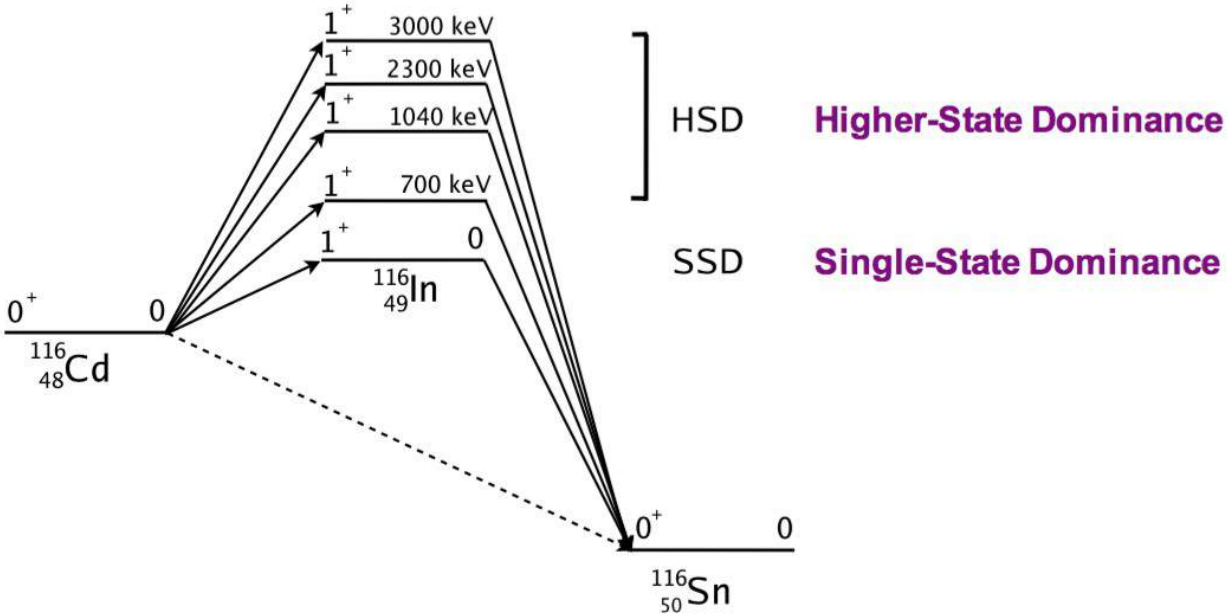
NEMO-3 ^{116}Cd 0νββ Limits





Mechanism	Obs. $T^{0\nu}_{1/2}$ limit	$(\times 10^{23}$ yr$)$
$\langle m_{\beta\beta}\rangle$	≥ 1.0	$< (1.4 - 2.5)$ eV
λ'_{111}		$< 0.1 \times f$
$\langle \eta \rangle$	≥ 1.1	$< (2.5 - 11.9) \times 10^{-8}$
$\langle \lambda \rangle$	≥ 0.6	$< (3.6 - 43.0) \times 10^{-6}$
$\langle g_{\chi^0} \rangle$	≥ 0.085	$< (5.2 - 9.2) \times 10^{-5}$

NEMO-3 ^{116}Cd SSD vs HSD Studies



SSD

Observable	KS Test	χ^2/ndf Test	P(χ^2)
E_{Tot}	0.949	0.53	0.992
E	0.999	0.79	0.784
E_{Min}	0.974	0.70	0.767
E_{Max}	0.893	0.72	0.878

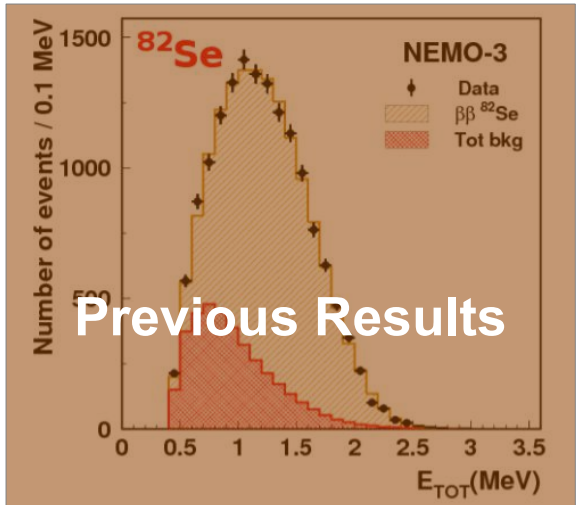
HSD

Observable	KS Test	χ^2/ndf Test	P(χ^2)
E_{Tot}	0.871	0.59	0.976
E	0.691	1.27	0.140
E_{Min}	0.262	0.92	0.534
E_{Max}	0.376	1.13	0.279

NEMO-3 2νββ Results

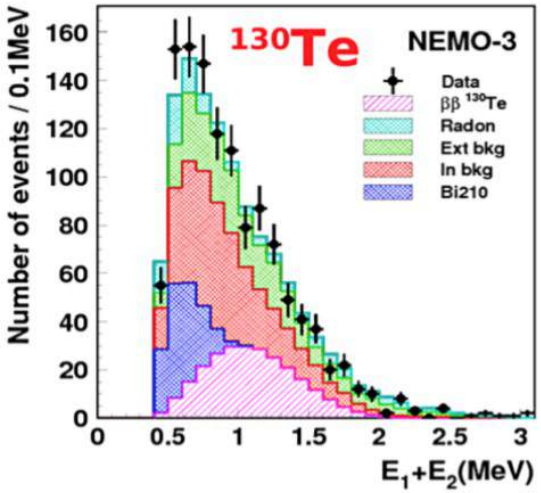
Isotope	mass, g	$Q_{\beta\beta}$ (keV)	$T_{1/2}$ (10^{19} yrs)	Comments
^{100}Mo	6914	3034	0.71 ± 0.05	World's Best !
^{82}Se	932	2996	10.07 ± 0.56	World's Best !
^{96}Zr	9.4	3350	2.35 ± 0.21	World's First (N2) & Best !
^{48}Ca	7	4272	6.4 ± 1.4	World's Best !
^{116}Cd	410	2814	2.74 ± 0.18	World's Best !
^{130}Te	454	2528	70 ± 14	World's Best & First (Direct) !
^{150}Nd	37	3371	0.934 ± 0.066	World's Best !

NEMO-3 Previous Results



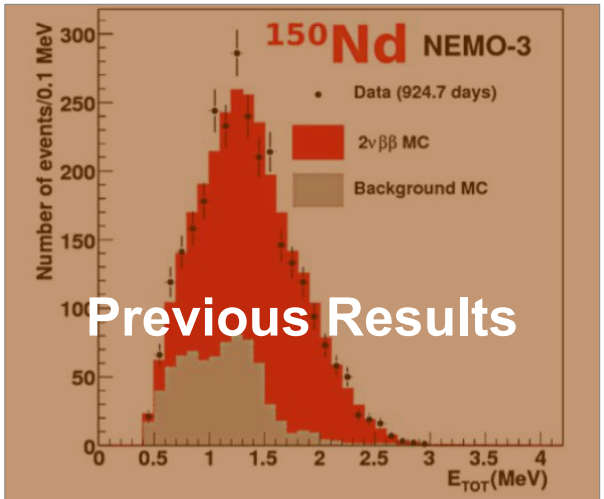
$\mathcal{T}_{1/2} = 9.6 \pm 1.0\ 10^{19}$ y

PRL 95, 182302 (2005)



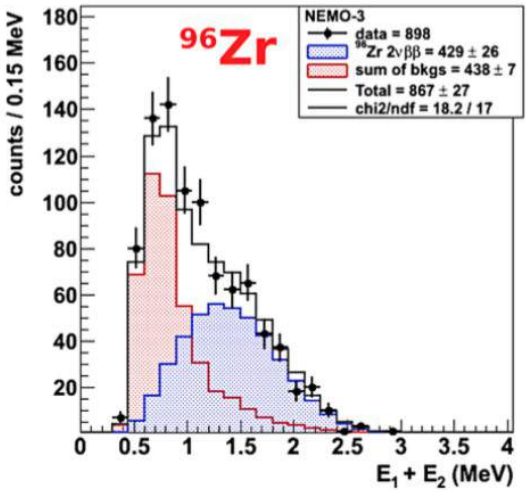
$\mathcal{T}_{1/2} = 7.0 \pm 1.4\ 10^{20}$ y

PRL 107, 062504 (2011)



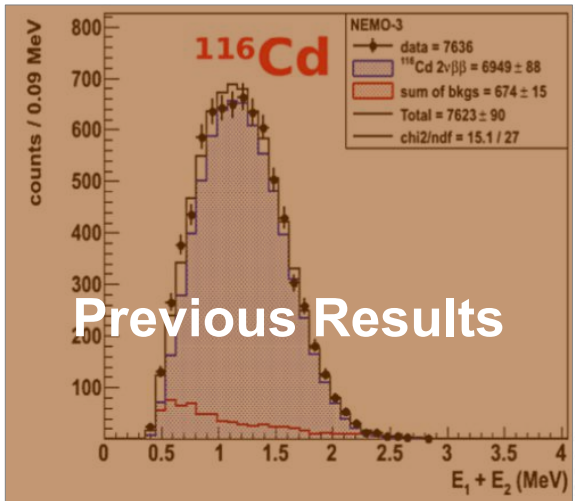
$\mathcal{T}_{1/2} = 9.1 \pm 0.7\ 10^{18}$ y

Phys. Rev. C 80, 032501 (2009)



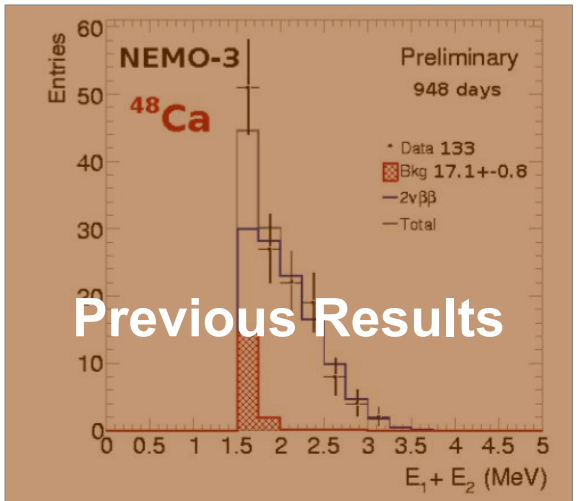
$\mathcal{T}_{1/2} = 2.35 \pm 0.21\ 10^{19}$ y

Nucl. Phys. A 847, 168 (2010)



$\mathcal{T}_{1/2} = 2.9 \pm 0.3\ 10^{19}$ y

To be published



$\mathcal{T}_{1/2} = 4.4 \pm 0.6\ 10^{19}$ y

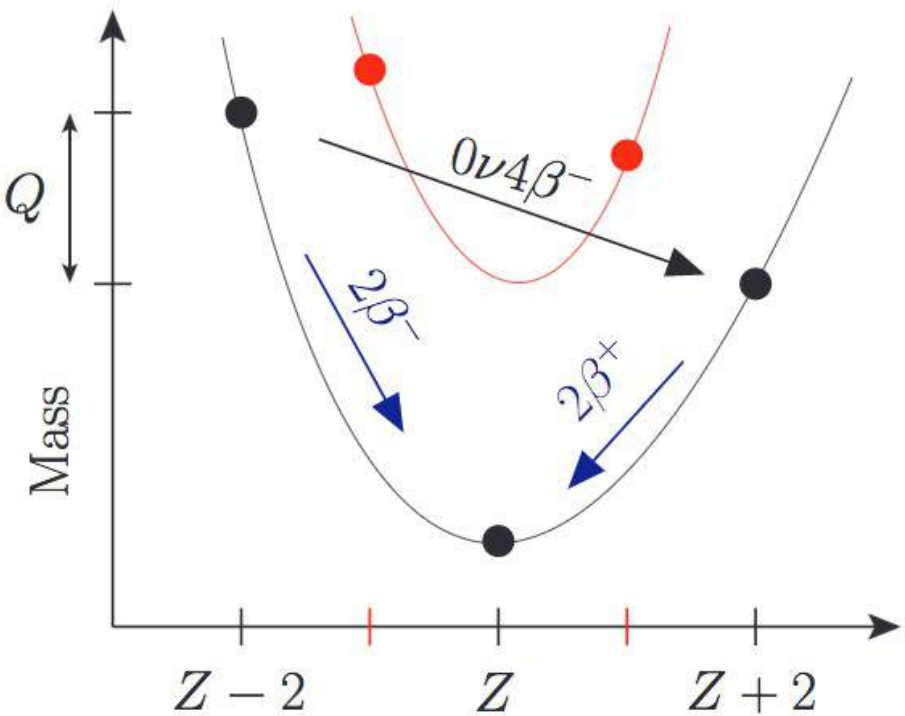
Systematics under study

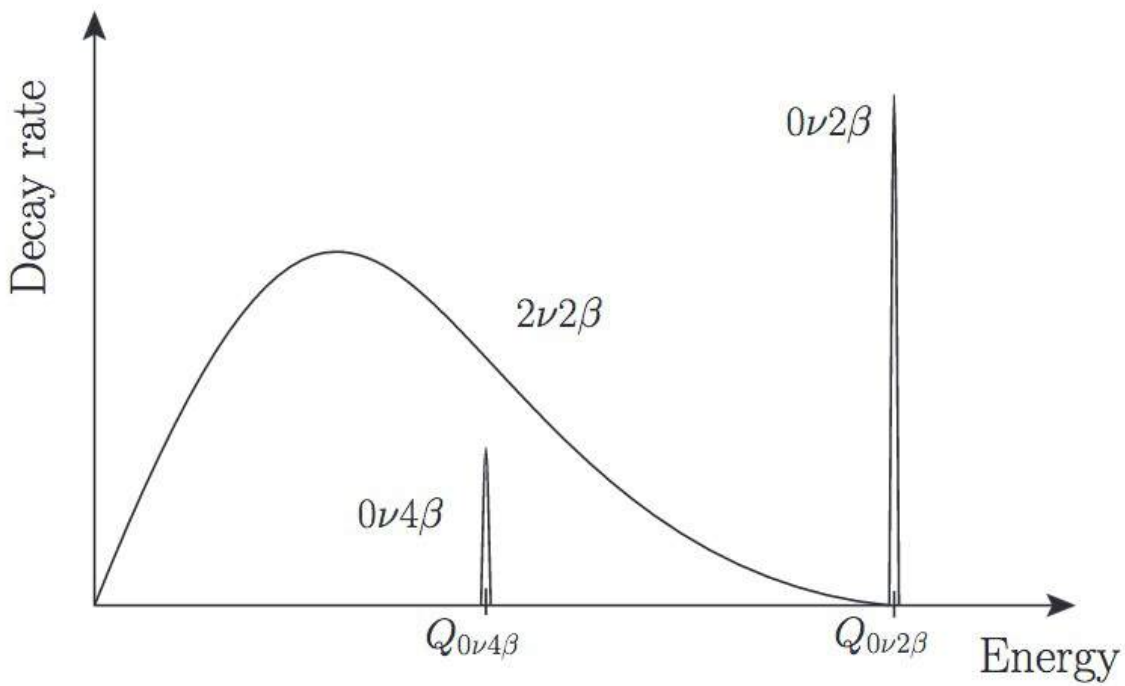
NEMO-3 ^{150}Nd 0ν4β

	$Q_{0\nu4\beta}$	Other decays	NA
$^{96}_{40}\mathrm{Zr} \rightarrow ^{96}_{44}\mathrm{Ru}$	0.629	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
$^{136}_{54}\mathrm{Xe} \rightarrow ^{136}_{58}\mathrm{Ce}$	0.044	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
$^{150}_{60}\mathrm{Nd} \rightarrow ^{150}_{64}\mathrm{Gd}$	2.079	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6

- NEMO-3 contains both ^{150}Nd & ^{96}Zr
- Only ^{150}Nd has a significant $Q_{4\beta}$ value
- 4v4β? → suppressed by phase space needed for 8-particle decay
- 0v4β model postulates v's are Dirac particles and 0v2β is forbidden

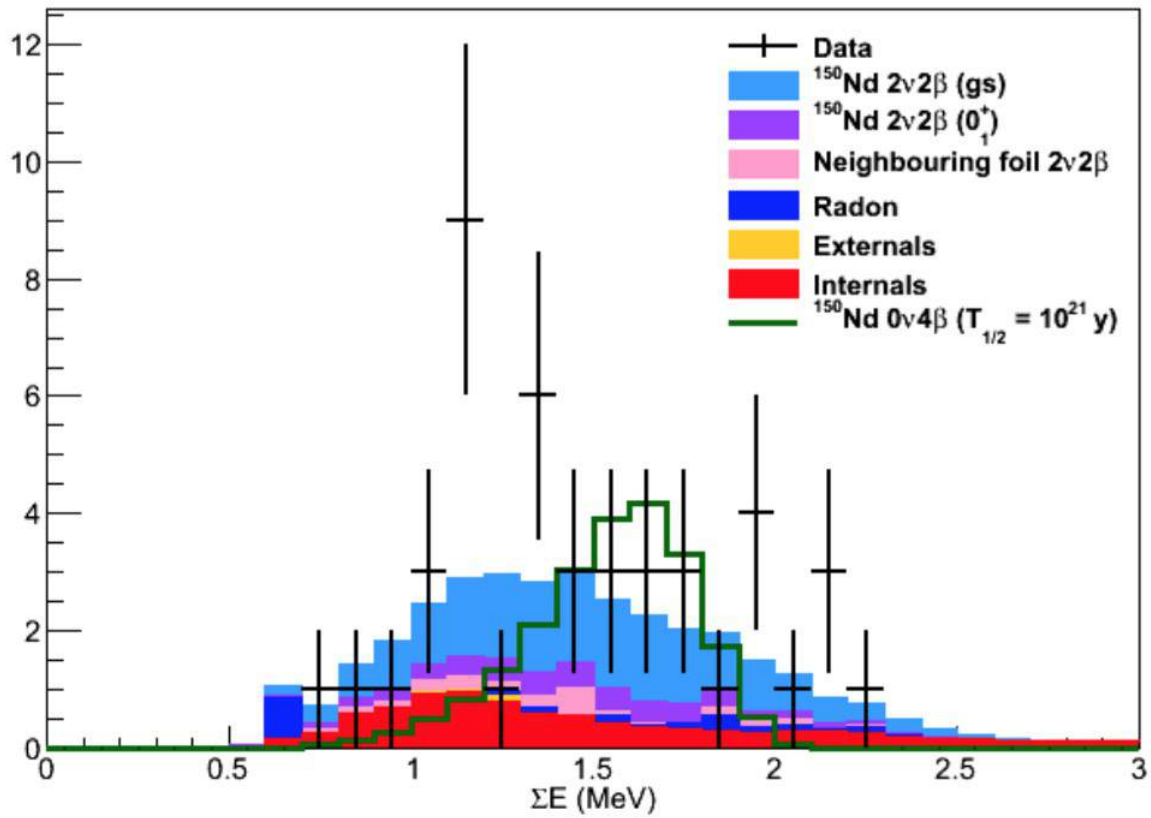
ArXiv:1306.0580v2

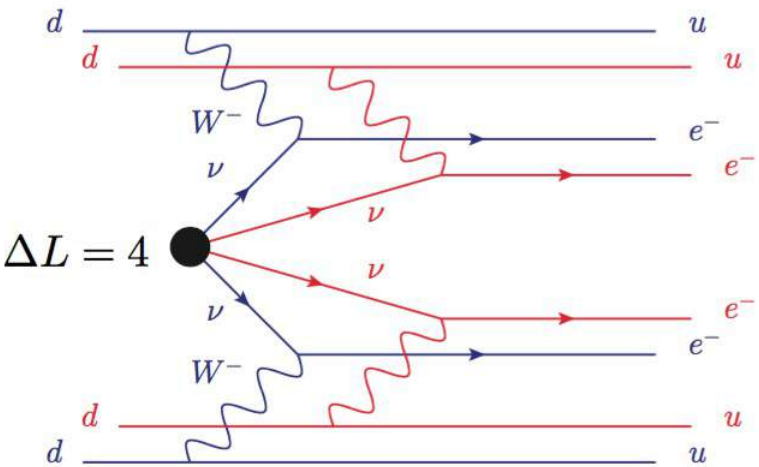




NEMO-3 ^{150}Nd 0ν4β

- Increase sensitivity by looking in 3-electron channel:





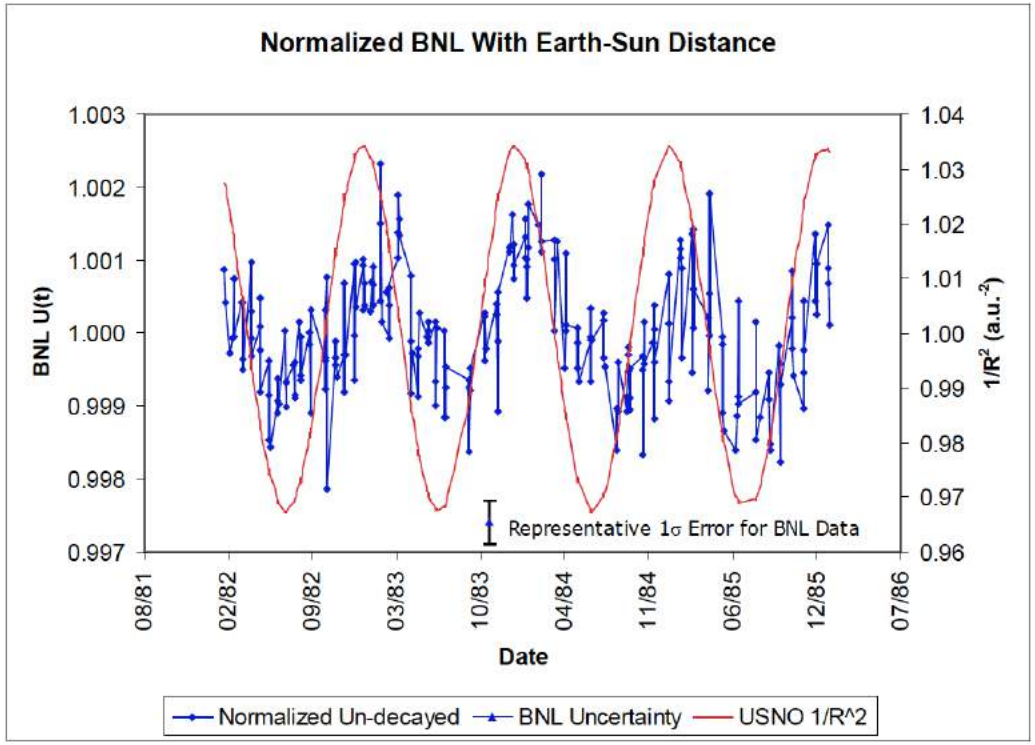
- Lifetime estimate :

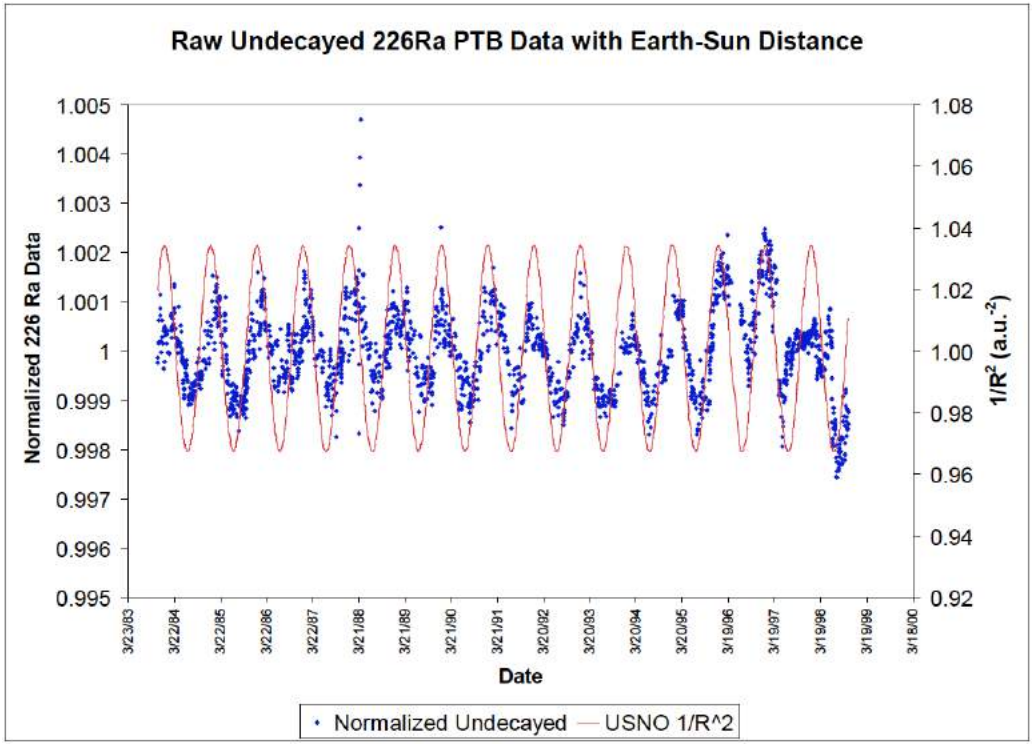
$$\frac{\tau_{0\nu4\beta}}{\tau_{2\nu2\beta}} \simeq 10^{46} \left(\frac{\Lambda}{\mathrm{TeV}}\right)^4$$

- But :
  - Very uncertain.
  - Little phenomenology yet in the literature.

Nuclear Decay Rate Variations

- Variations in nuclear decay rates have been claimed previously
  - Decay of ^{32}Si and ^{226}Ra fron BNL and PTB respectively
  - Postulated to correlate with solar activity and the Earth-Sun distance





J.H. Jenkins, et al., "Evidence of Correlations Between Nuclear Decay Rates and Earth-Sun Distance."Astroparticle Physics, 2009. 32(1): p. 42-46.[doi:10.1016/j.astropartphys.2009.05.004]

The Periodogram Approach

- Is a common technique for detecting periodic signals hidden in noise
  - It has very well known statistical behavior
  - It's equivalent to least squares fitting of sinusoids to data
  - It's time translation invariant
- Consider an arbitrary time series:

$$X(t_i), i = 1, 2, \ldots N$$

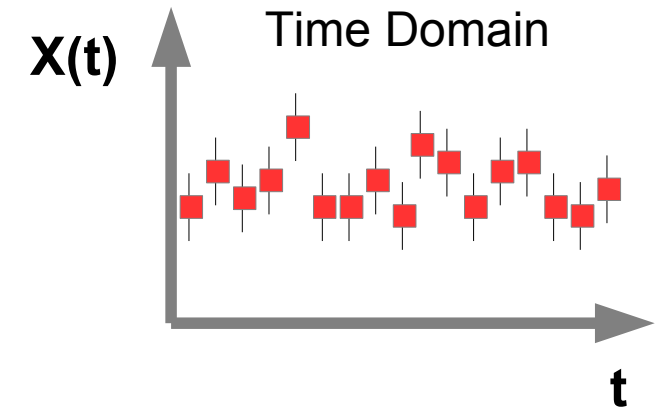
- The Discrete Fourier Transform (DFT) is then:

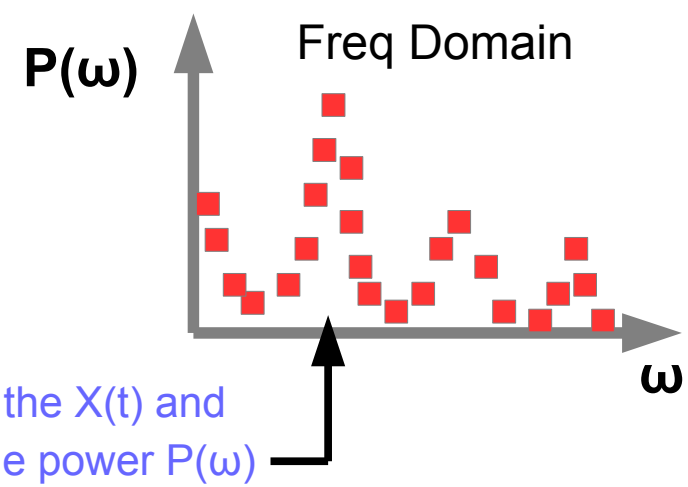
$$FT_X(\omega) = \sum_{j=1}^{N} X(t_j) \exp(-i\omega t_j)$$

- The **classical** periodgram is then defined by:

$$P_X(\omega) = \frac{1}{N} \left| FT_x(\omega) \right|^2$$

$$= \frac{1}{N} \left[\left(\sum_j X_j \cos(\omega t_j) \right)^2 + \left(\sum_j X_j \sin(\omega t_j) \right)^2 \right]$$





If X(t) contains a sinusoidal component of frequency ω_0 then at $\omega=\omega_0$, the X(t) and exp(-iωt) are in phase and make a large contribution to the sum → large power P(ω)

The Generalized Lomb-Scargle Periodogram

- Extends the periodogram technique:
  - Can be used on unevenly sample data (Δt ≠ const. Or presence of gaps)
  - Accounts for data weights and offset
- Power calculation is replaced by →

$$P_{GLS}(\omega)=\frac{1}{\sum w_i(X_i-\bar{X})^2}\left\{\frac{\left[\sum_j w_i(X_j-\bar{X})\cos\omega(t_j-\tau)\right]^2}{\sum_j w_i\cos^2\omega(t_j-\tau)-[\sum_j w_i\cos\omega(t-\tau)]^2}+\frac{\left[\sum_j w_i(X_j-\bar{X})\sin\omega(t_j-\tau)\right]^2}{\sum_j w_i\sin^2\omega(t_j-\tau)-[\sum_j w_i\sin\omega(t-\tau)]^2}\right\}$$

$$\tan(2\omega\tau)=\frac{\sum_j w_i\sin(2\omega t_j)-2\sum_j w_i\cos(\omega t_j)\sum_j w_i\sin(\omega t_j)}{\sum_j w_i\cos(2\omega t_j)-[(\sum_j w_i\cos(\omega t_j))^2-(\sum_j w_i\sin(\omega t_j))^2]}$$

- Powers follow exponential distribution → easily calculable false alarm probability on C.L.s

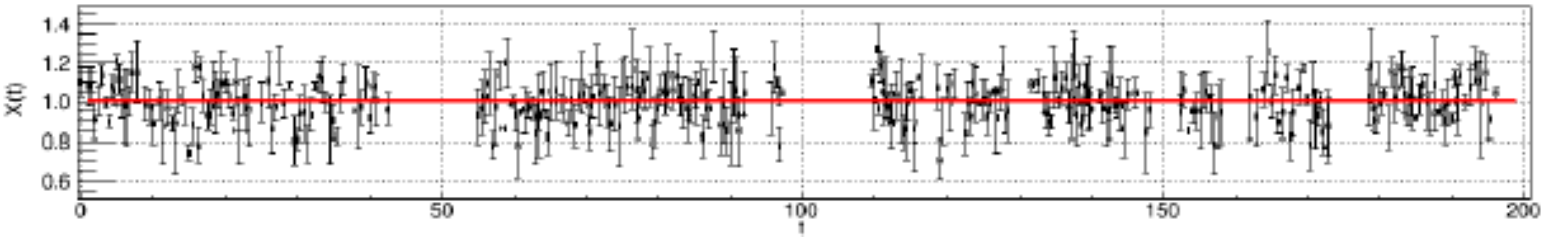
$$Prob\{P_{LS}>p\}=1-(1-e^{-P_{LS}})^N$$

$$C.L.=100\times(1-e^{-P_{LS}})^N$$

The Generalized Lomb-Scargle Periodogram

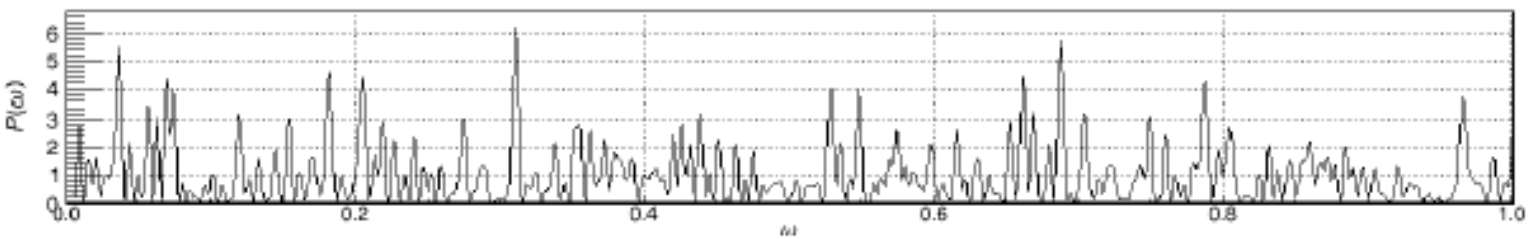
- Example application of the technique to pure noise and modulated data

Monte Carlo



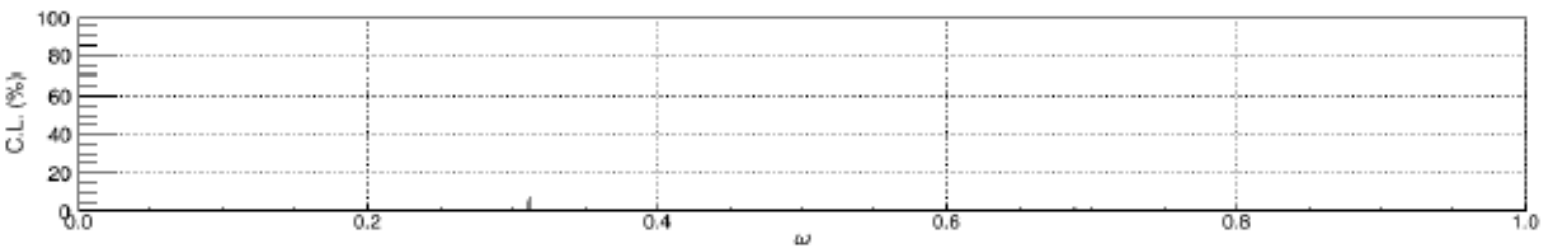
(a) Example Time Series

Monte Carlo



(b) Example Power Spectrum Distribution (PSD)

Monte Carlo



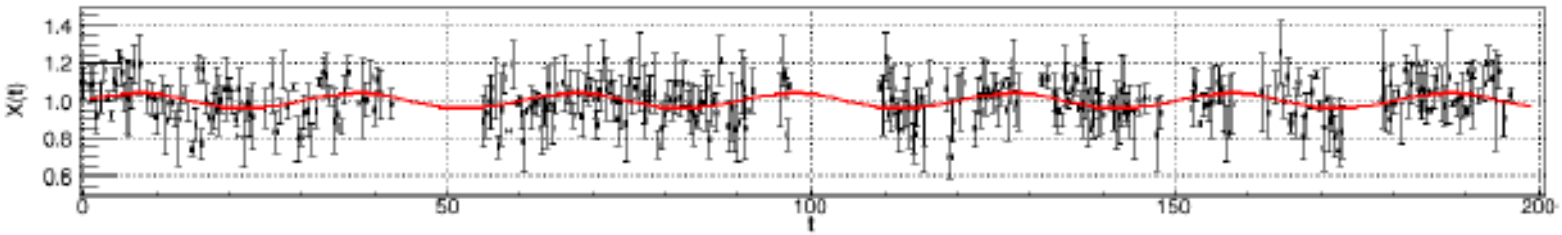
(c) Example C.L. Distribution

1. Randomly generated Gaussian noise time series
2. Lomb power P_{LS} is calculated at each sample frequency
3. Powers follow exponential distribution allowing for simple calculation of false alarm probability and C.L. No significant powers detected in pure noise

The Generalized Lomb-Scargle Periodogram

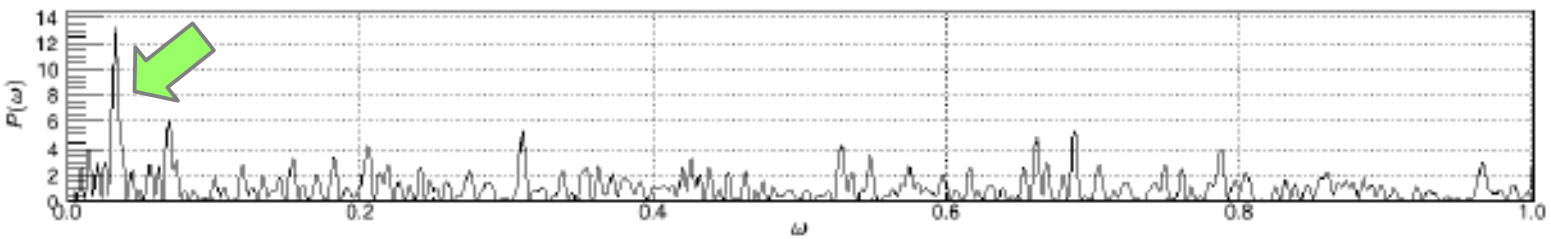
- Example application of the technique to pure noise and modulated data

Monte Carlo



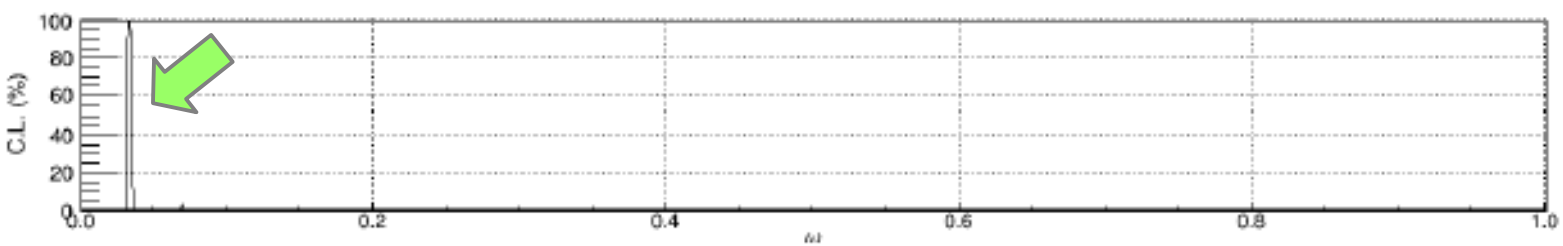
(a) Example Modulated Time Series

Monte Carlo



(b) Example Modulated Power Spectrum Distribution (PSD)

Monte Carlo



(c) Example Modulated C.L. Distribution

1. Modulation is applied:

$$X'(t_i) = X(t_i) \times (1 + A \sin(2\pi t_i f))$$

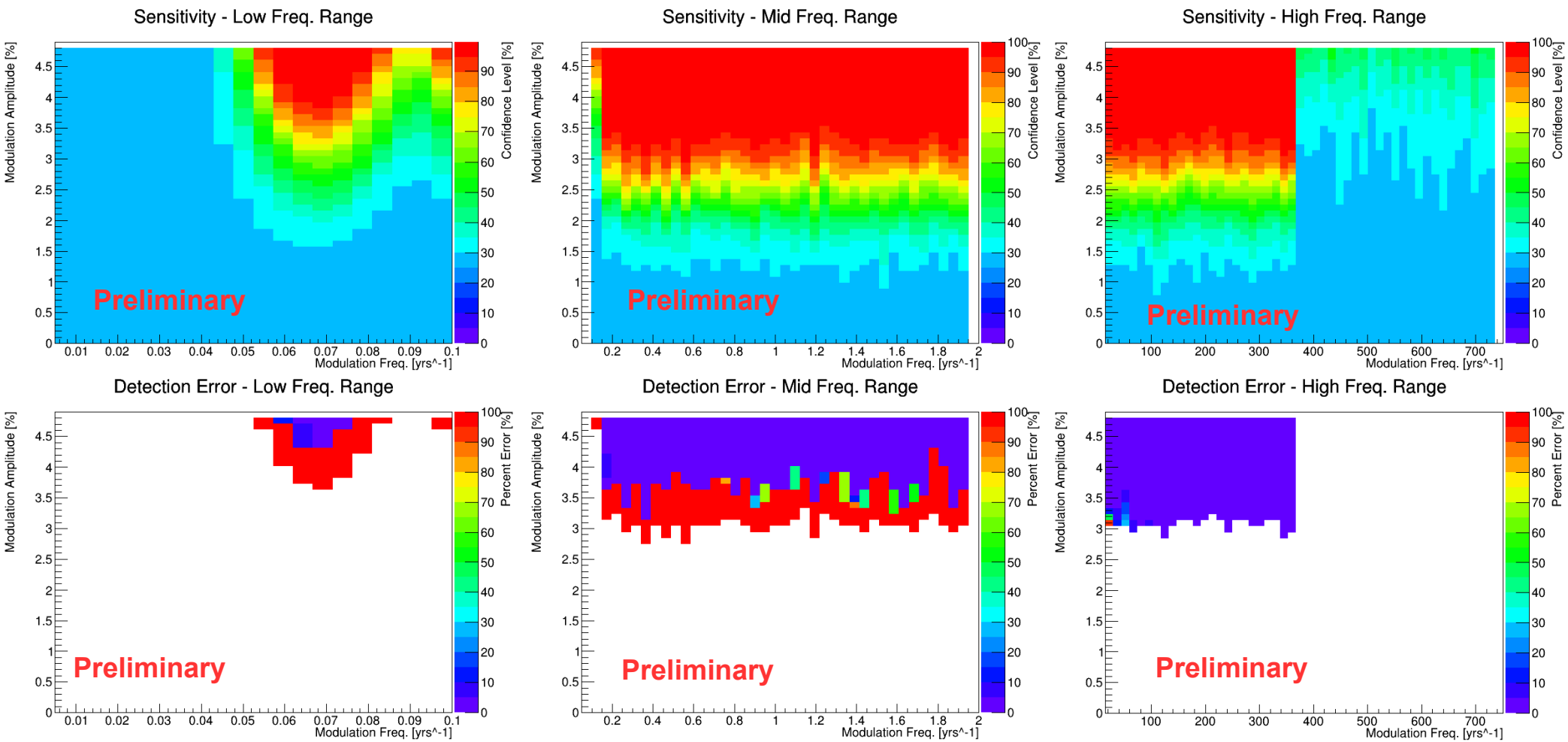
with f = 0.03

2. Large Lomb power P_{LS} appears at the corresponding value of f

3. Correspondingly large C.L. for that peak

Rate Modulation Sensitivity

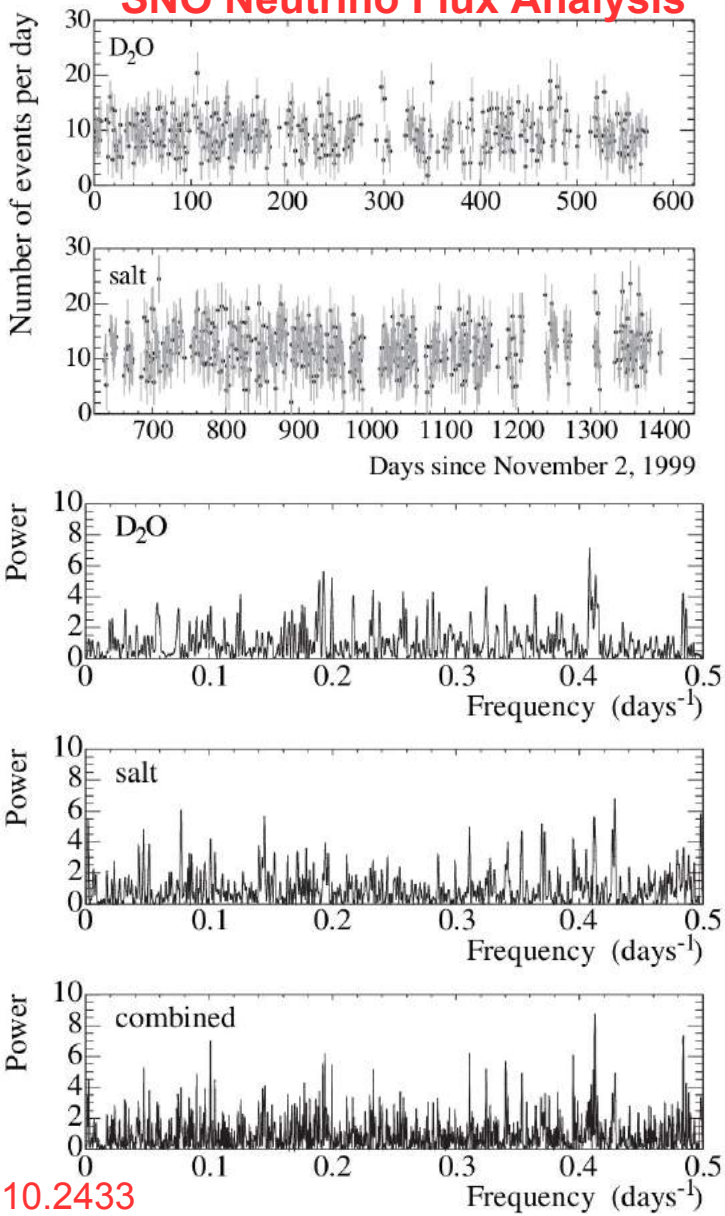
- Pseudo-data MC is generated to mimic NEMO-3 decay rate data
- Data is then modulated with sinwave of different parameters (amplitude, freq)
- Periodogram technique applied to each data set → largest peak/C.L. are output



Periodogram Applications

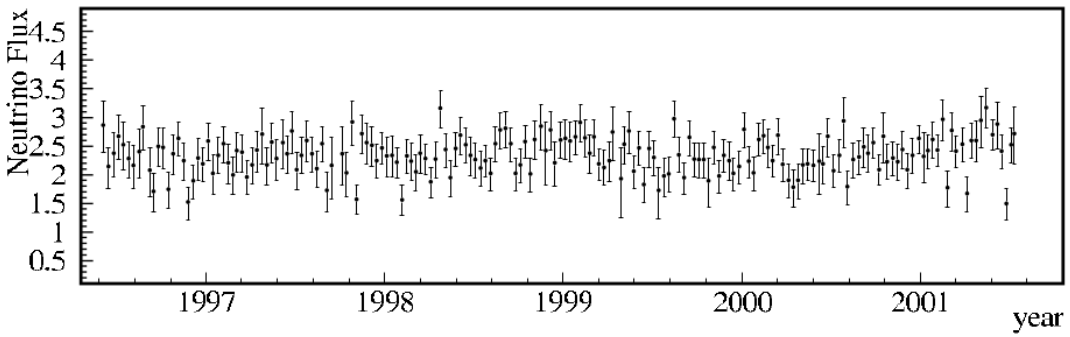
- Has been used to probe for variations on other experiments

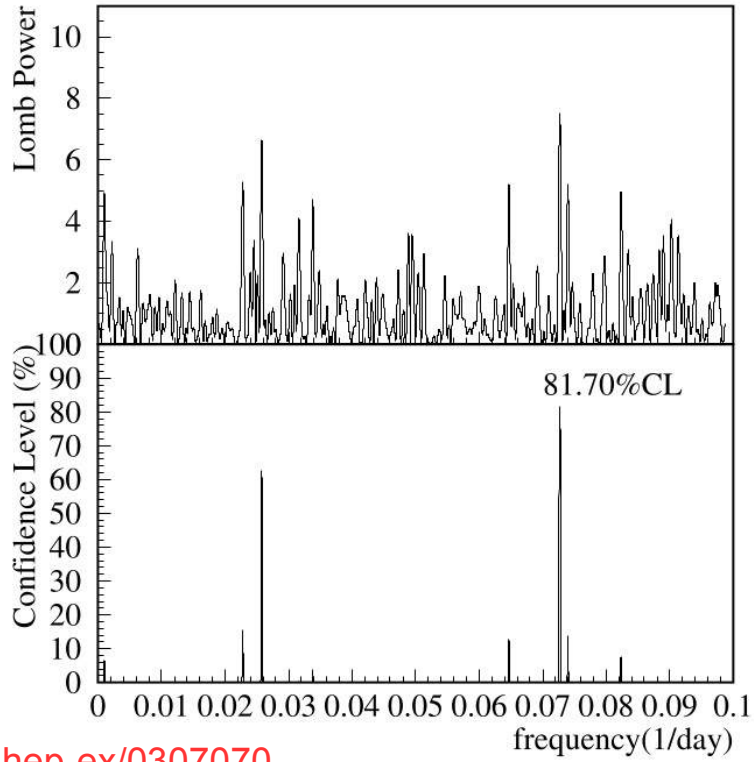
SNO Neutrino Flux Analysis



arXiv:0910.2433

SuperKamiokande Neutrino Flux Analysis





arXiv:hep-ex/0307070

NEMO-3 to SuperNEMO

	NEMO-3	SuperNEMO
Mass	6.9 kg	100 kg
Isotopes	^{100}Mo	^{82}Se
	7 isotopes	^{150}Nd, ^{48}Ca
Energy resolution (σ | FWHM)		
@ 3 MeV	3.4 | 8 %	1.7 | 4 %
Radon in tracker		
$\mathcal{A}(^{222}\text{Rn})$	5.0 mBq/m^3	0.15 mBq/m^3
Sources contaminations		
$\mathcal{A}(^{208}\text{Tl})$	$\sim$ 100 μBq/kg	$<$ 2 μBq/kg
$\mathcal{A}(^{214}\text{Bi})$	60 - 300 μBq/kg	$<$ 10 μBq/kg
Total background		
cts·keV^{-1}·kg^{-1}·y^{-1}	1.3×10^{-3}	5×10^{-5}
Sensitivity (90 % CL)		
$\mathcal{T}^{0\nu}_{1/2}$	$> 1.1 \times 10^{24}$ y	$> 1 \times 10^{26}$ y
$\langle m_\nu \rangle$	$<$ 0.33 - 0.87 eV	$<$ 0.04 - 0.10 eV