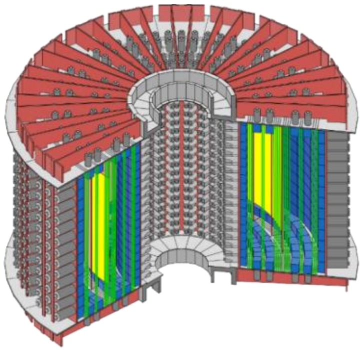


supernemo collaboration

Recent results from NEMO-3 and status of SuperNEMO

Cristóvão Vilela, for the NEMO-3 and SuperNEMO collaborations
cristovao.vilela@stonybrook.edu

2010 – 2015: UCL

Currently at: Stony Brook University

International workshop on double-β decay and underground Science

Osaka University, November 8th 2016

Outline

- Neutrinoless double-β decay
- The NEMO-3 experiment
- Latest results from NEMO-3
- Status of the SuperNEMO Demonstrator

SuperNEMO collaboration, Aussois 2015

Neutrinoless double-β decay

- **Lepton number violating** process
  - ΔL= 2
- Several underlying mechanisms can contribute:
  - Exchange of **light Majorana neutrinos**
  - Right-handed currents, R-parity violating supersymmetry, etc

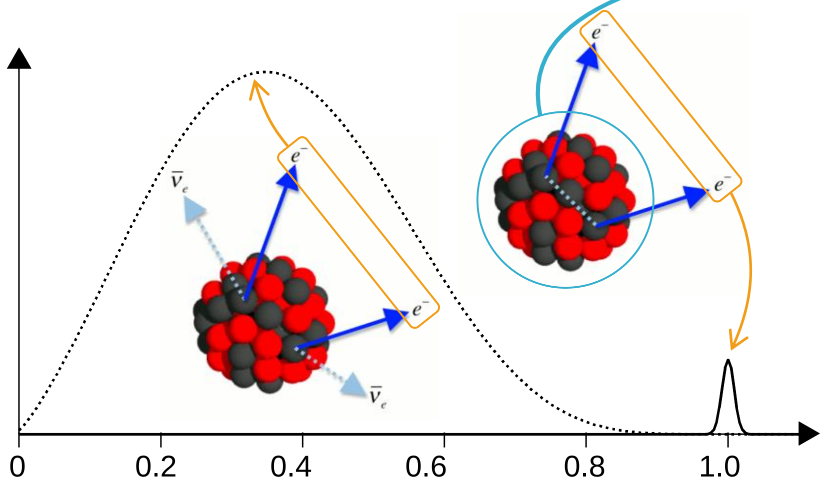
Measure!

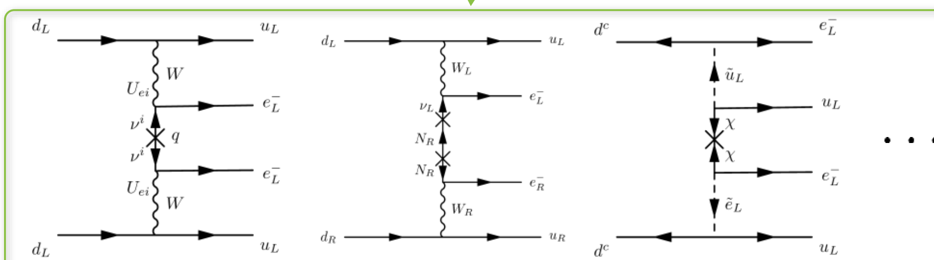
Nuclear matrix element

Large theory uncertainty

Phase-space ∝ $Q_{\beta\beta}^5$

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



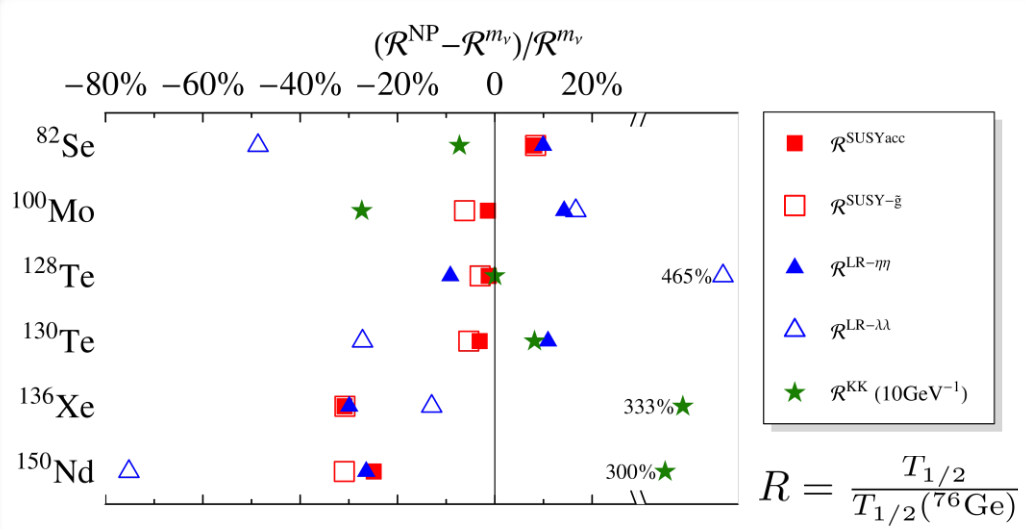


Mass mechanism	Right-handed currents	R-parity violating SUSY
$m_{\beta\beta} = \lvert\sum_i U^2_{ei}\, m_i\rvert$	$\lambda,\ \eta$	$\lambda_{111,\ldots}$

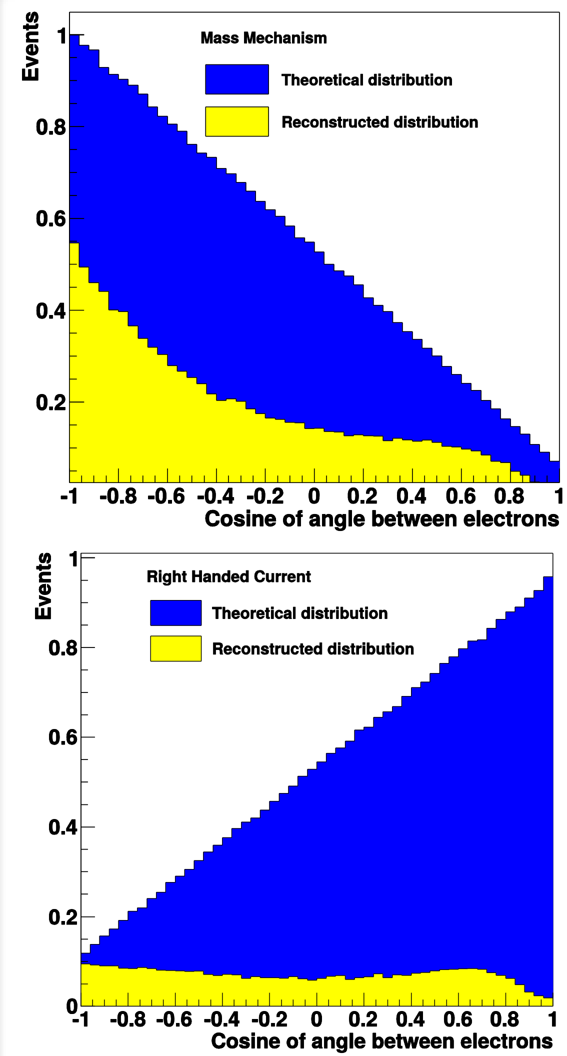
New J. Phys. 17 (2015) no.11, 115010

Neutrinoless double-β decay

- Summed energy peak is **not the full story**
- To distinguish between the mechanisms want:
    - Measurements of electron kinematics
    - Measurements of multiple isotopes
- Equivalent measurements of **two-neutrino** modes help constrain nuclear theory



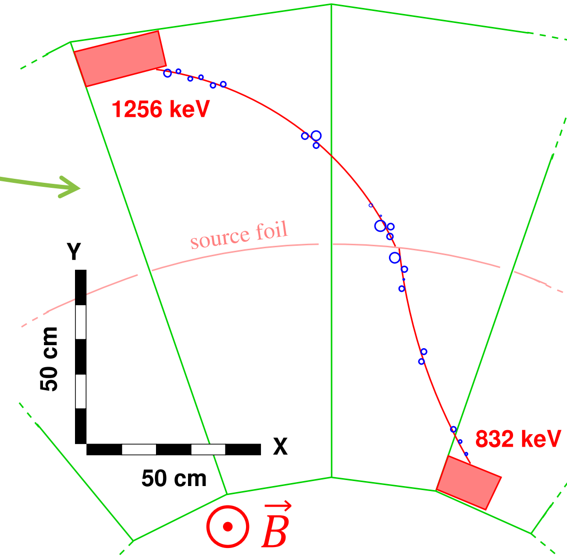
Phys. Rev. Lett. 98 (2007) 232501



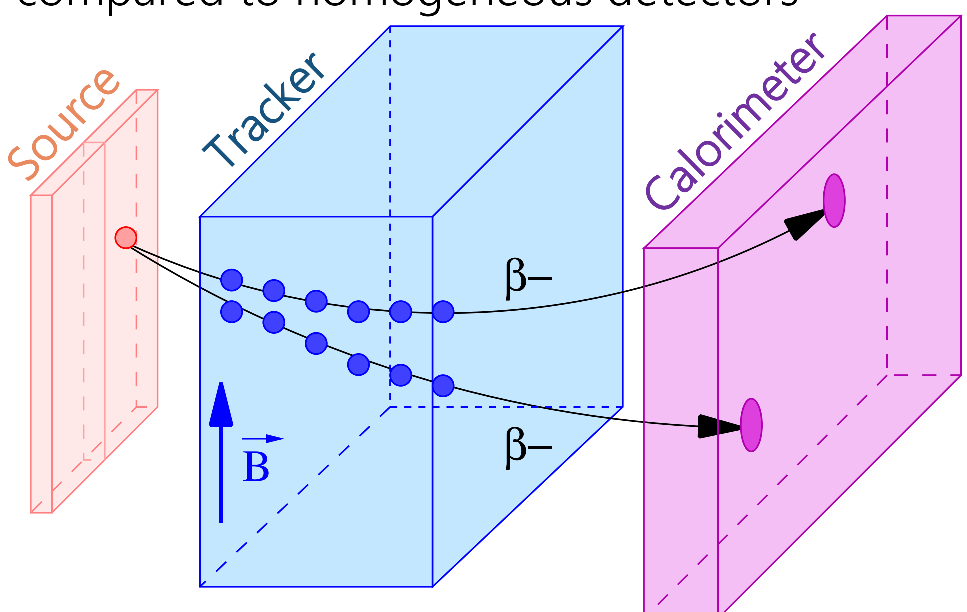
Eur. Phys. J. C 70 (2010) 927

Tracker & calorimeter technique

- The tracker and calorimeter approach has two main advantages:
  - Event topology is fully reconstructed
    - Powerful background suppression
    - Control samples for background measurement
    - Measurement of individual electron kinematics
  - Source and detector are independent
    - (nearly) Free choice of isotope
- The main disadvantage is worse energy resolution compared to homogeneous detectors



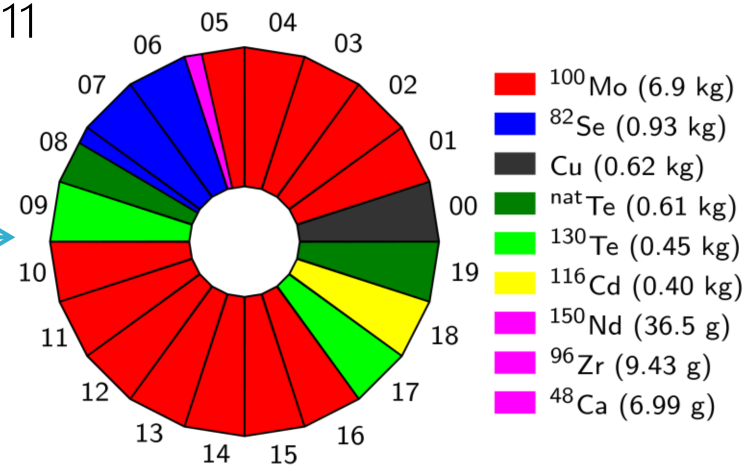
Double-β decay event in NEMO-3

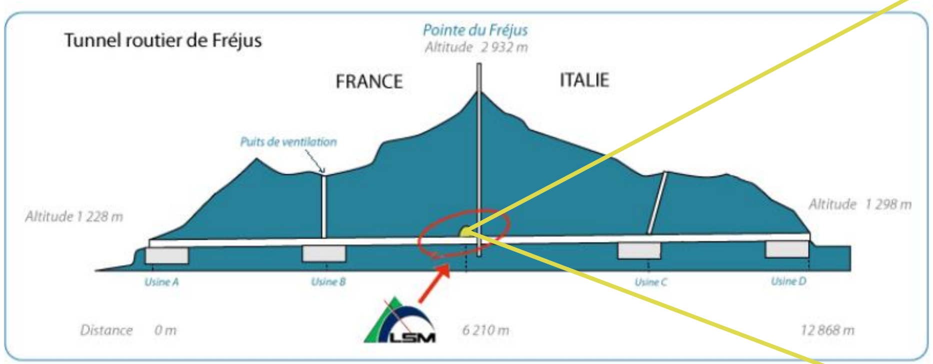


- Use tracker signature to identify:
  - e^-/e^+
  - α from ^{214}Bi-^{214}Po decays
  - γ
- Calorimeter **timing** used to distinguish between events with **internal** and **external** origin to the source

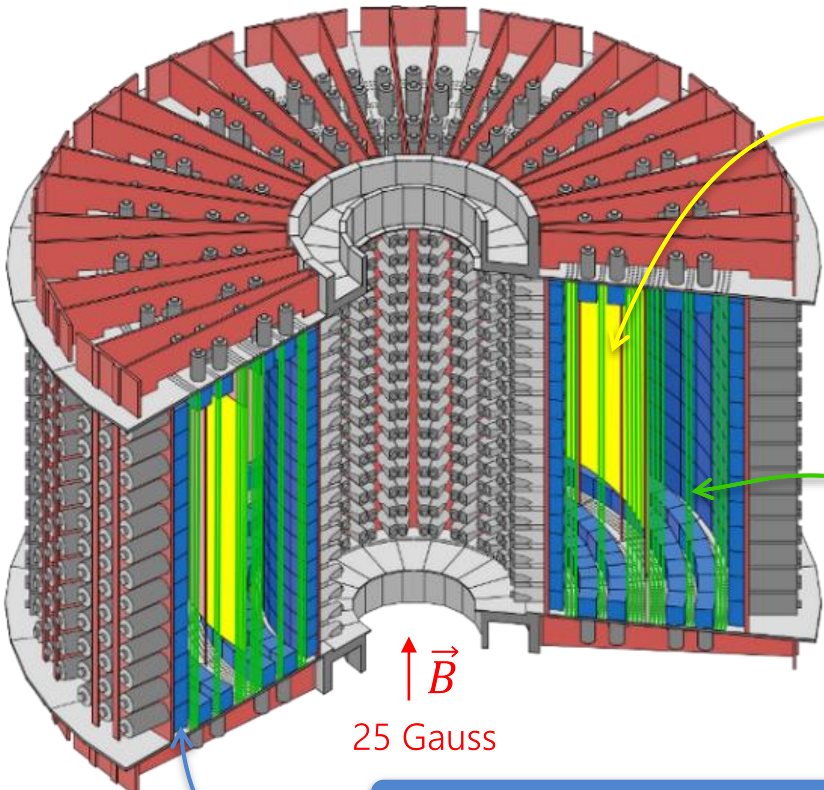
The NEMO-3 experiment

- Operated from February 2003 to January 2011
- In the **L**aboratoire **S**outerrain de **M**odane
  - **4800 m.w.e.** overbuden
- Hosted **10 kg** of double-β decay **sources**
  - Seven different isotopes
    - Mostly ^{100}**Mo**
- **Cu structure** surrounded by **Fe shielding**
- Paraffin, wood, borated water for neutron moderation and absorption
- Tent flushed with ^{222}**Rn-free air** installed in 2004



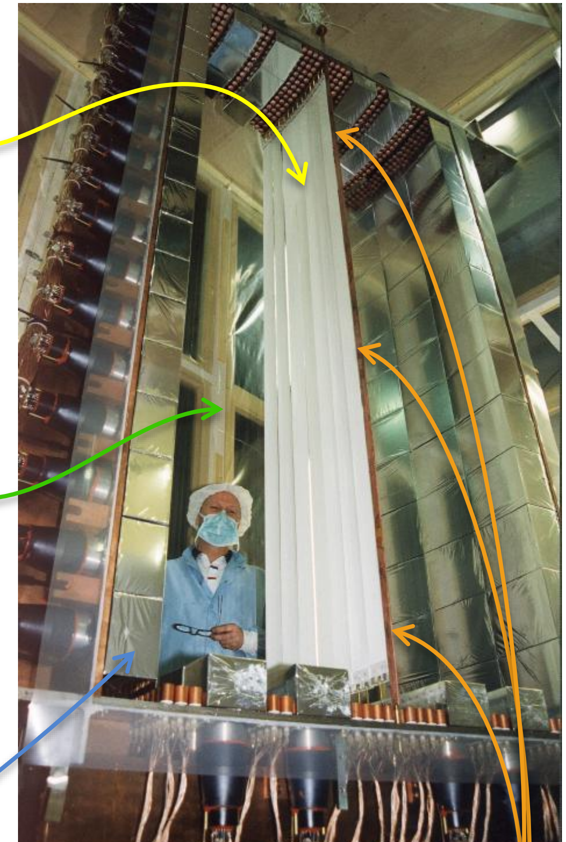


The NEMO-3 detector



Source
- 60 mg/cm^2 strips
- Metallic or composite structure

Tracker
- He-based gas mix
- 6180 cells
- Geiger mode
- σ_{xy} ~ 3 mm
- σ_z ~ 10 mm



Calorimeter
- Polystyrene scintillator blocks
- 3″ and 5″ low activity PMTs
- 1940 modules
- $FWHM_E$ = 14% @ 1 MeV
- σ_t ~ 250 ps

Calibration
- Cu tubes for source deployment
- Windows at three z positions

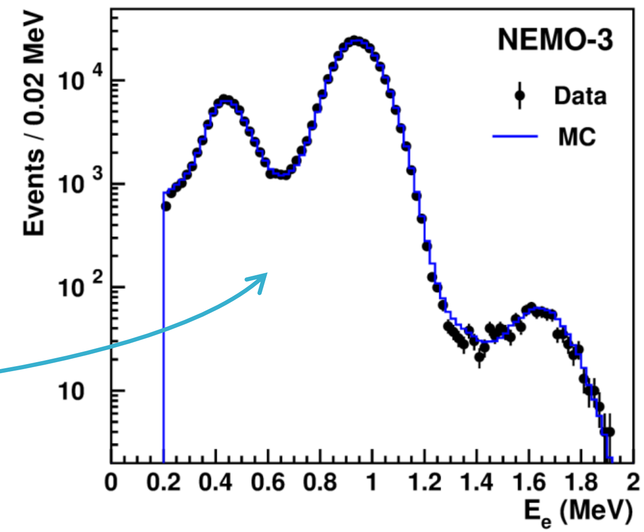
NEMO-3 calibration

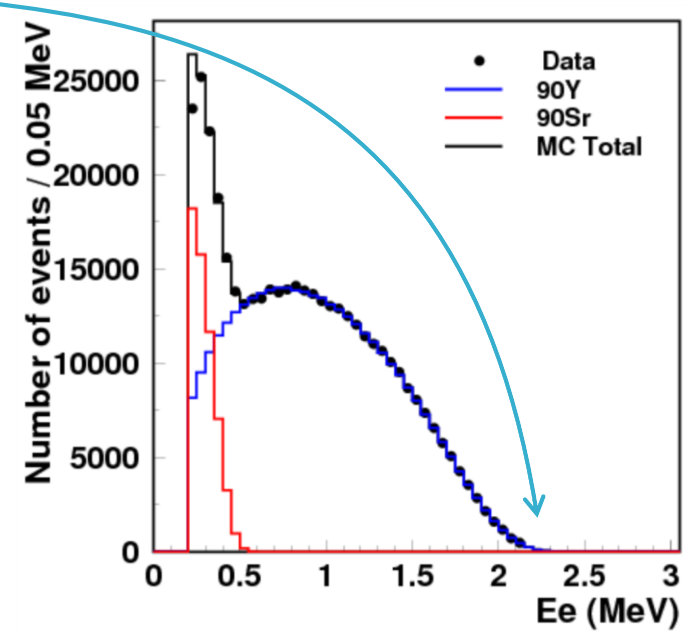
Radioactive sources

- ^{207}Bi and $^{90}Sr/^{90}Y$ sources inserted in detector for calibration every 2 – 3 weeks
- Energy scale constrained by:
  - ^{207}Bi to ^{207}Pb electron capture internal conversion electrons
    - 482, 976 and 1682 keV
  - ^{90}Y β-decay end-point
    - Q_{β} = 2280 keV
- Two-electron reconstruction efficiency:
  - ^{207}Bi source with well-known activity

Laser injection system

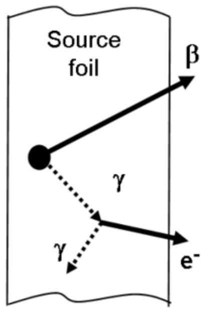
- Optical fibres inject laser light into all scintillator blocks and reference modules
  - Laser source can be attenuated with an optical filter
- Calibrate calorimeter stability and linearity two times a day





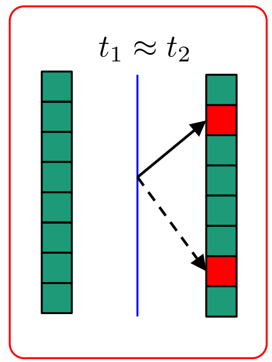
Backgrounds in NEMO-3

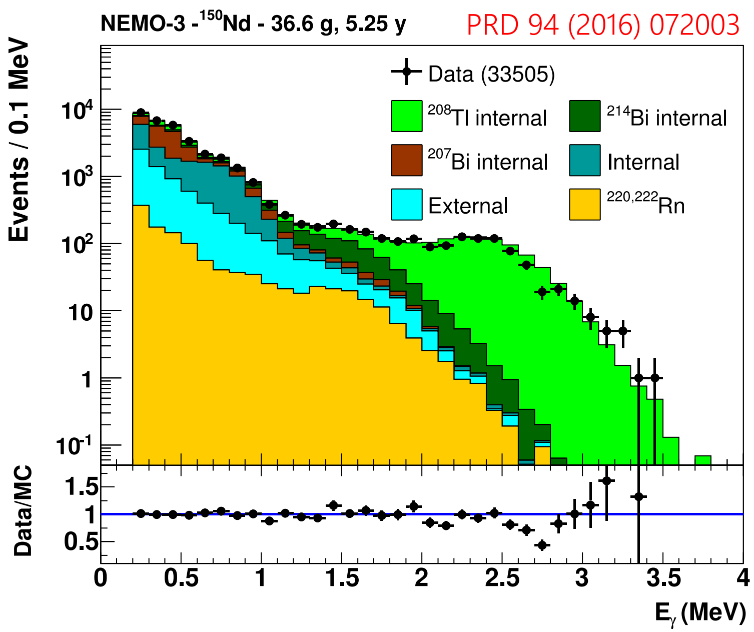
Internal



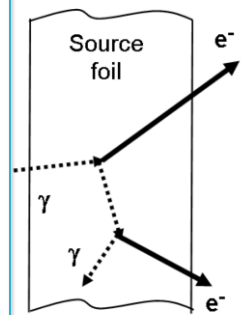
Source contaminants
- E.g.: ^{214}Bi, ^{208}Tl

Measure in **internal** samples:
- single e$^-$
- 1e1γ (internal TOF)
- 1e2γ (internal TOF)



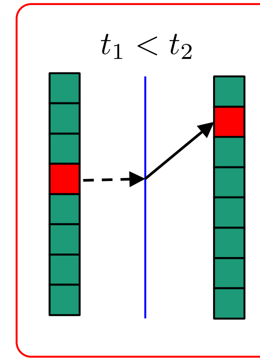


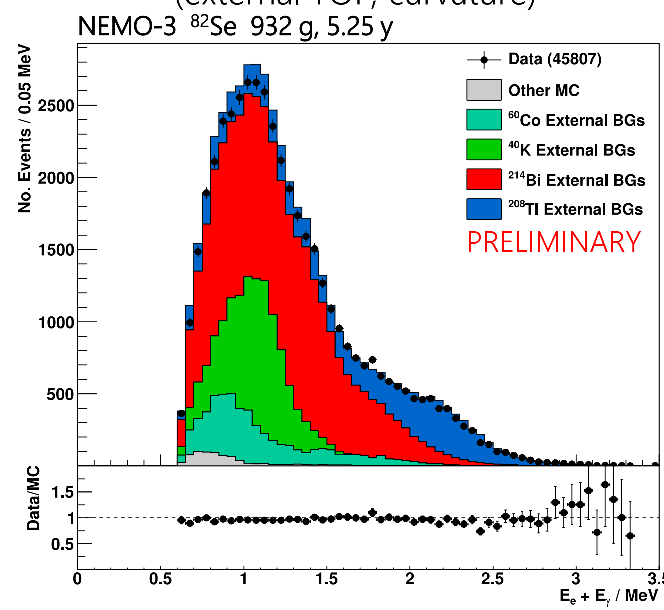
External



Detector materials contamination
- E.g.: ^{214}Bi, ^{208}Tl, ^{60}Co in PMTs, scintillator

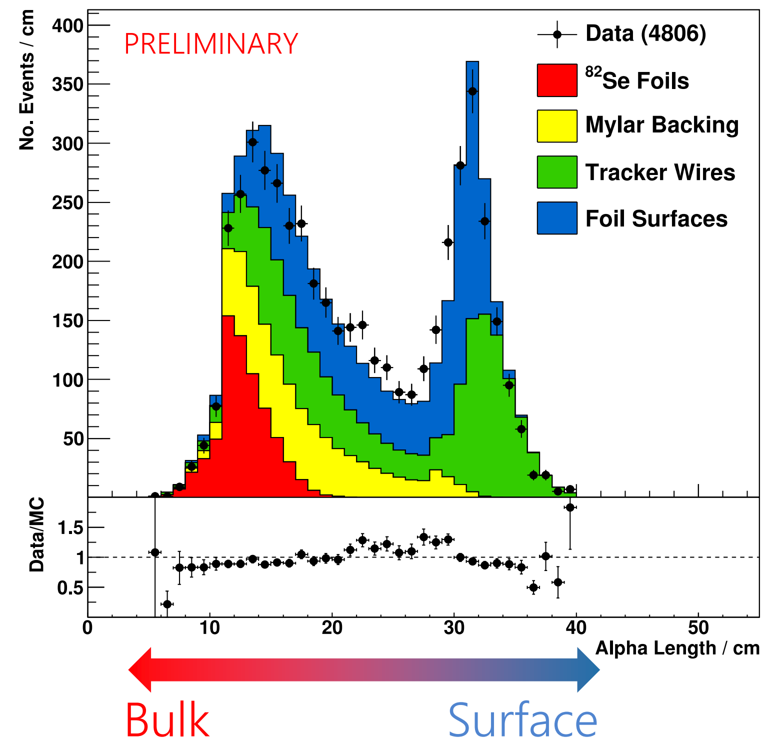
Measure in **external** samples:
- 1e1γ (external TOF)
- crossing electron (external TOF, curvature)

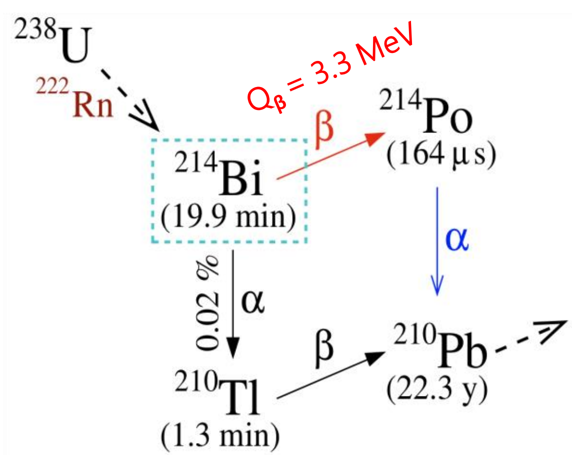


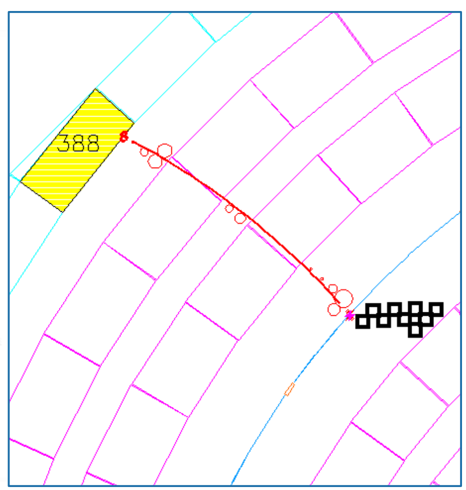


Radon backgrounds in NEMO-3

- The **β-decay of ^{214}Bi** is a significant background in NEMO-3 analyses
- Arises from:
    - **Internal** ^{238}U chain contamination of the source
    - **Emanation of ^{222}Rn** into the tracking volume and deposition of progeny on detector **surfaces**
        - Greatly **reduced** by surrounding the detector with **^{222}Rn-free air**







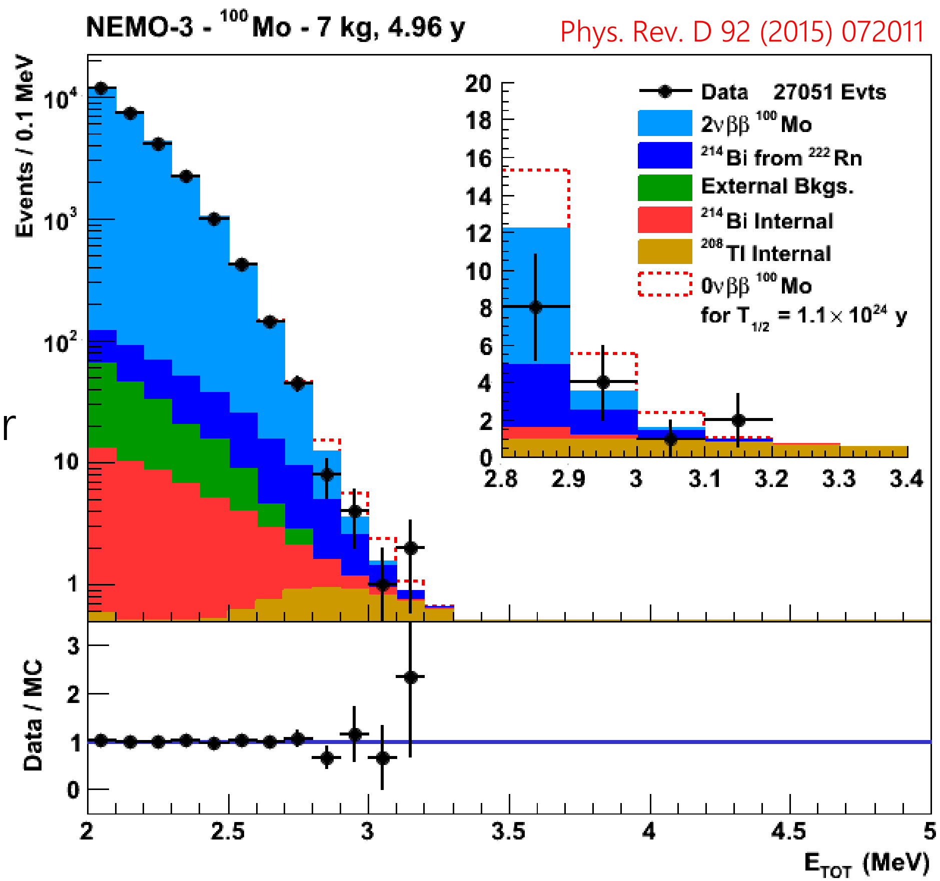
- **^{222}Rn activity** measured by selecting events with an e$^-$ and a **delayed α** track
- Length of α track used to discriminate between **bulk** and **surface** contamination

Search for $0\nu\beta\beta$ in ^{100}Mo

- Backgrounds constrained in control and signal channels
- Limit on Majorana mass **competitive** with best limits in the field
  - With only **7 kg** of isotope

- **No events** observed above 3.2 MeV for full 34 kg yr exposure

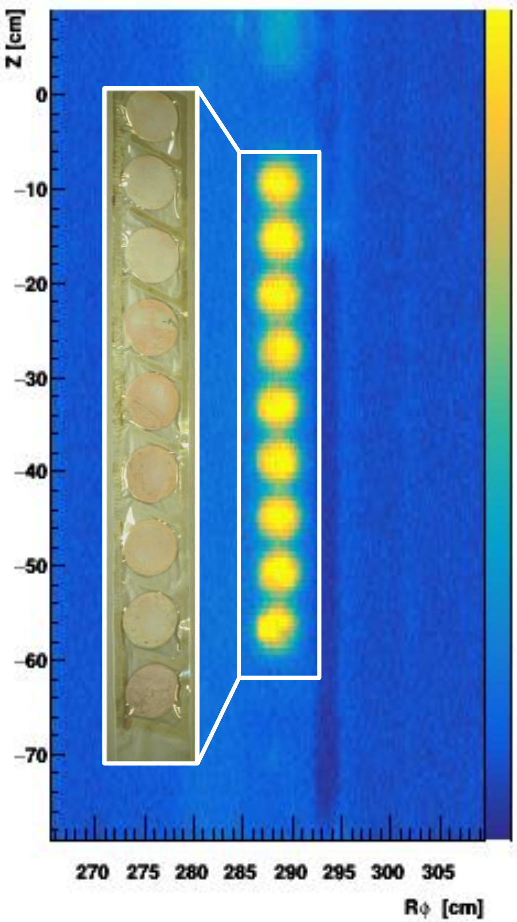
- Competitive limits also placed on:
  - R-parity violating couplings
  - Right handed current couplings
  - Majoron ν coupling



$$T_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ yr } (90\% \text{ CL})$$
$$\langle m_{\beta\beta} \rangle < 0.3 - 0.6 \text{ eV}$$

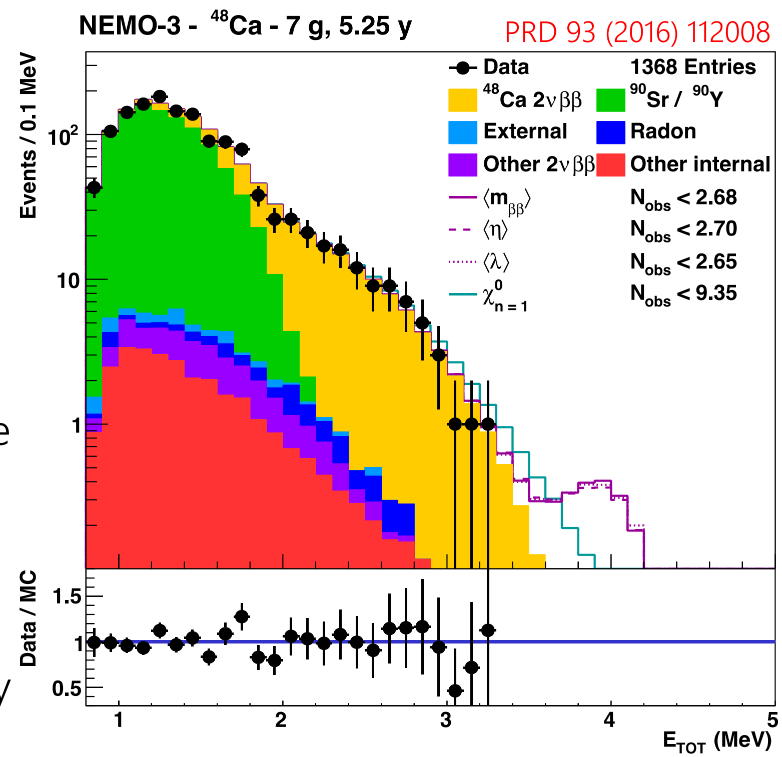
Double-β decay of ^{48}Ca

- **Highest $Q_{\beta\beta}$** of all 0νββ isotopes at 4.3 MeV
  - Above all naturally occurring β emissions
- Doubly magic and low Z: lends itself to precise **nuclear shell model calculations**



In **NEMO-3**:

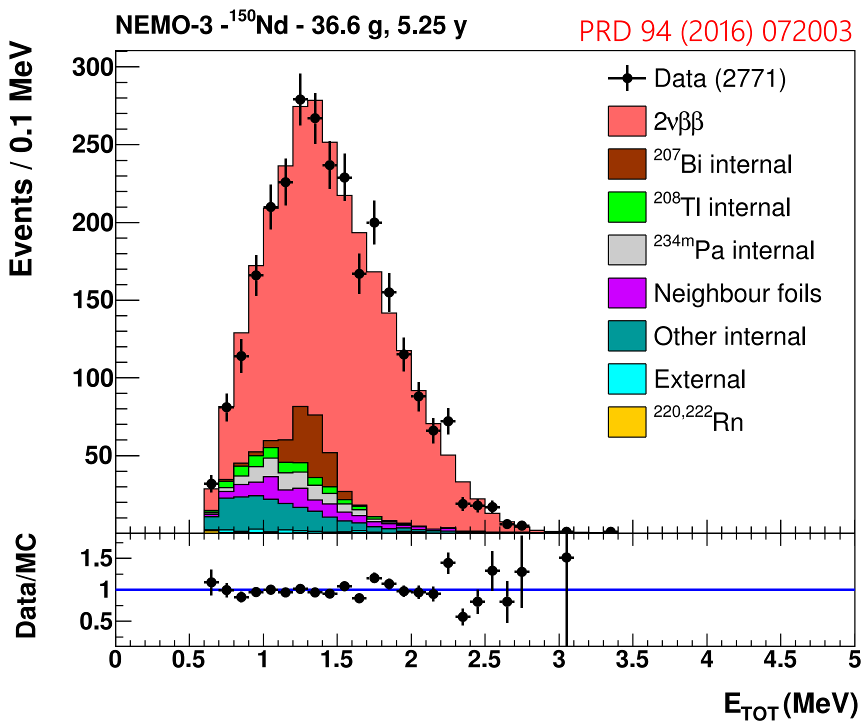
- Nine disks of compressed CaF_2 powder
- **Enriched** by electromagnetic separation to 73.2%
  - **7 g** of ^{48}Ca
- Clearest 2νββ signal to date
  - **300 observed events**
- **Most precise** measurement of the 2νββ half-life
- In slight tension with theory prediction of ~ 4 x 10^{19} yr

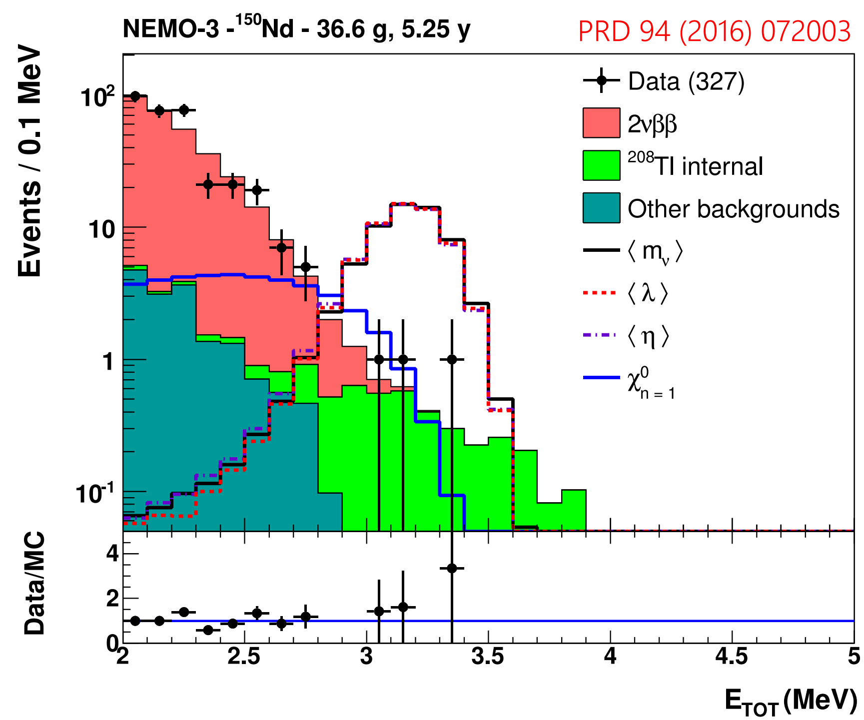


$$T^{2\nu}_{1/2} = [6.4\,^{+0.7}_{-0.6}(\text{stat.})\,^{+1.2}_{-0.9}(\text{syst.})] \times 10^{19}\,\text{yr}$$

Double-β decay of ^{150}Nd

- **Largest phase space factor** of any 0νββ candidate isotopes
- High $Q_{\beta\beta}$ at 3.4 MeV



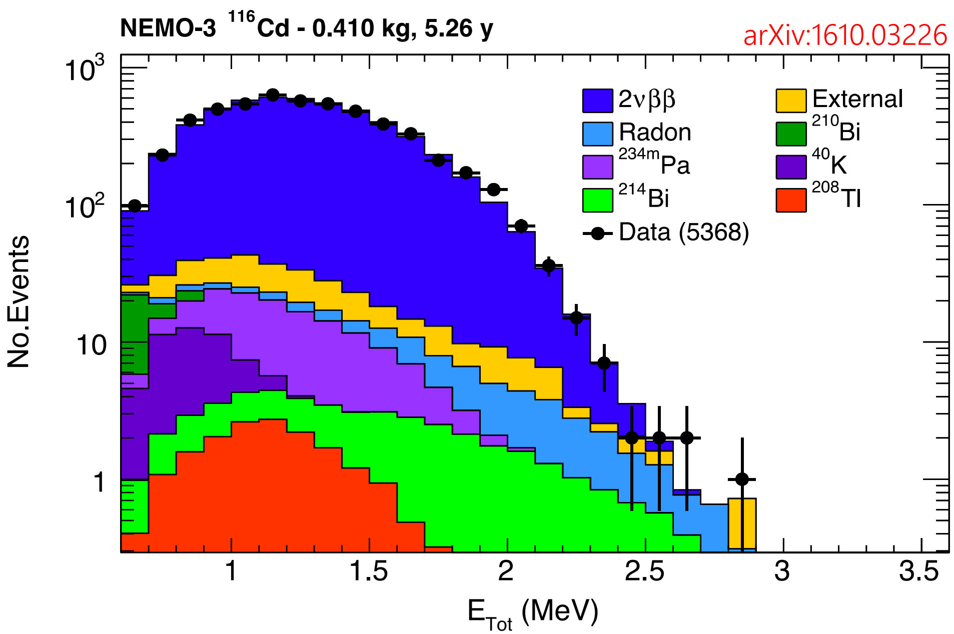


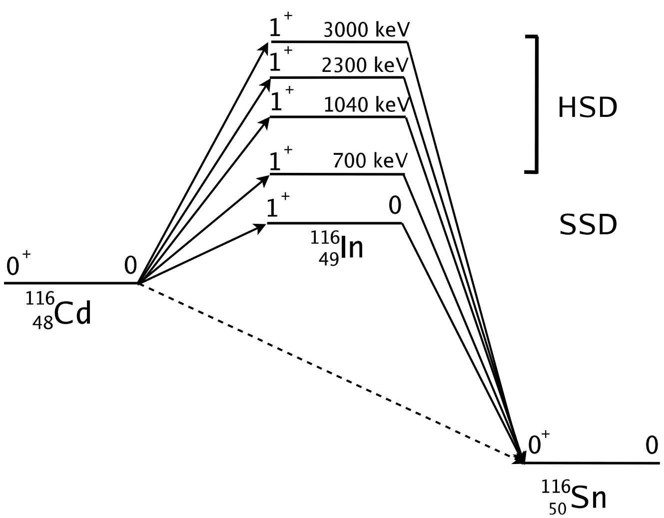
- **Most precise** measurement of 2νββ to date

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

Double-β decay of ^{116}Cd

- Isotope of interest for **future experiments** (pixelated CdZnTe)
- $Q_{\beta\beta}$ = 2.8 MeV
- Can test **H**igher **S**tates **D**ominance vs **S**ingle **S**tate **D**ominance



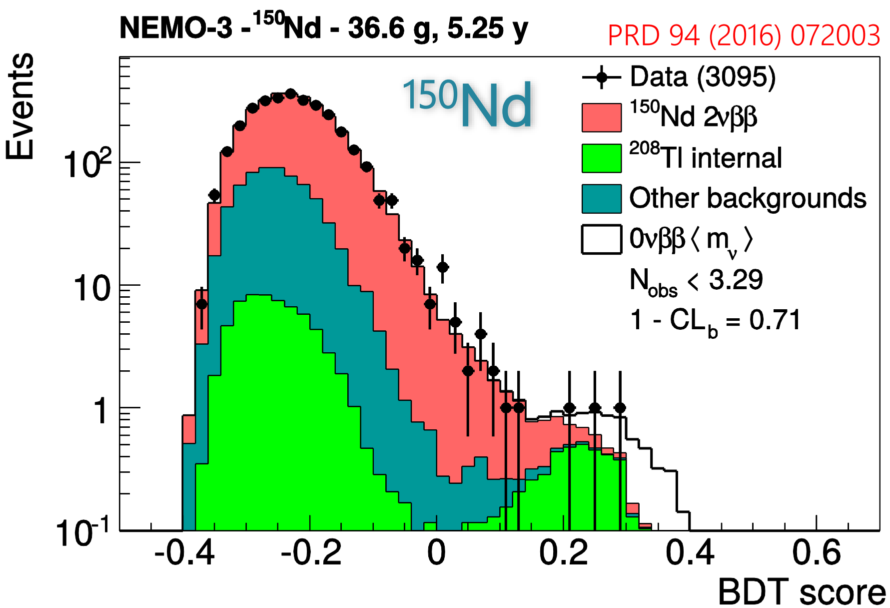


- Single electron kinematics favour SSD but do not exclude HSD

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

Multivariate analyses

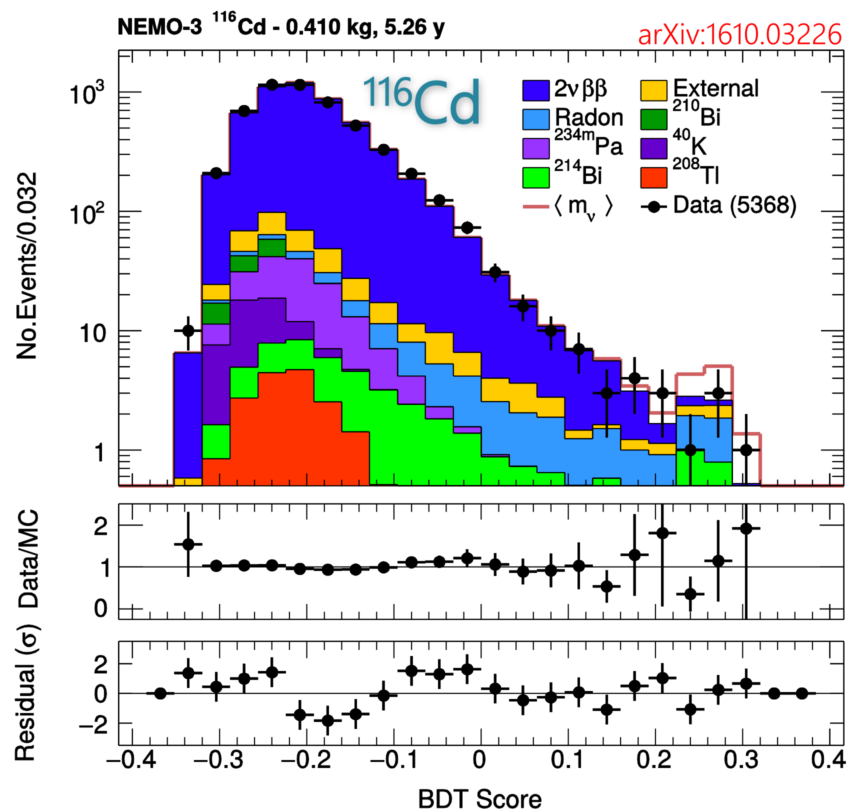
- **World's first** 0νββ searches using **multivariate** analysis methods
- **B**oosted **D**ecision **T**rees used with 10 kinematic variables



Background-like
Signal-like

- BDT **improves** 0νββ sensitivity by **11%**
- **Most stringent** limit on **^{150}Nd 0νββ**

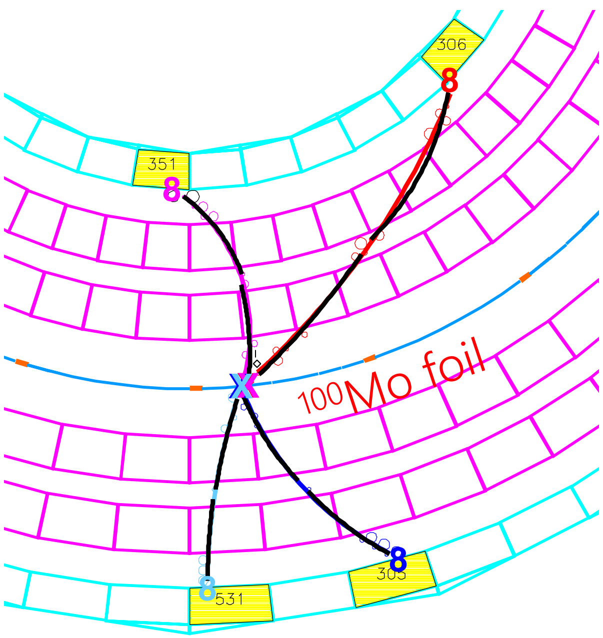
$$T^{0\nu}_{1/2} > 2.0 \times 10^{22} \text{ yr } (90\% \text{ CL})$$

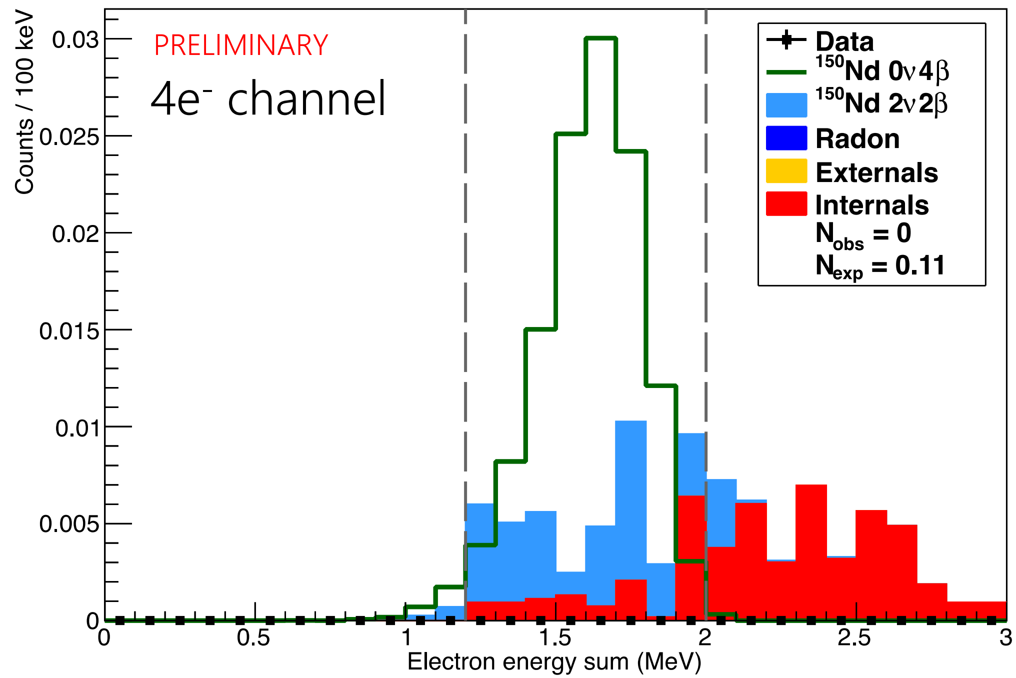


$$T^{0\nu}_{1/2} > 1.0 \times 10^{23} \text{ yr } (90\% \text{ CL})$$

Quadruple-β decay of ^{150}Nd

- Heeck & Rodejohann pointed out that $\Delta L = 4$ processes are possible with **Dirac** neutrinos EPL 103 (2013) 32001
- One of these processes is **quadruple**-β decay
  - The best candidate is $^{150}\text{Nd} \rightarrow {}^{150}\text{Gd} + 4e^-$ with $Q_{4\beta} = 2.08$ MeV





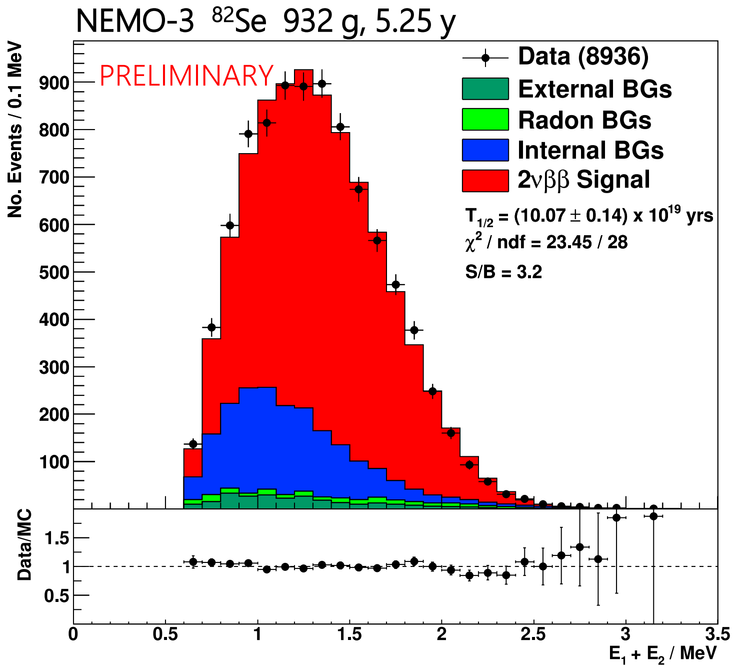
- Combination with other channels yields world's first limit on this process:

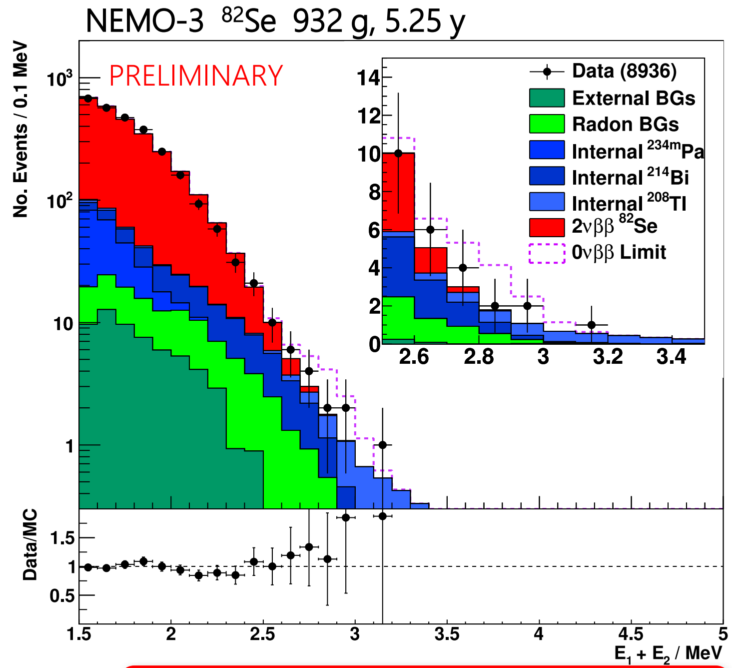
$$\boxed{T_{1/2}^{0\nu 4\beta} > 2.6 \times 10^{21} \text{ yr (90\% CL)}}$$

4.3×10^{21} yr expected

Double-β decay of ^{82}Se

- ^{82}Se has a significantly **longer 2νββ half-life** compared to ^{100}Mo
- $Q_{\beta\beta}$ = 3.0 MeV
- Baseline isotope choice for **SuperNEMO**





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

- **More precise** than the previous world average

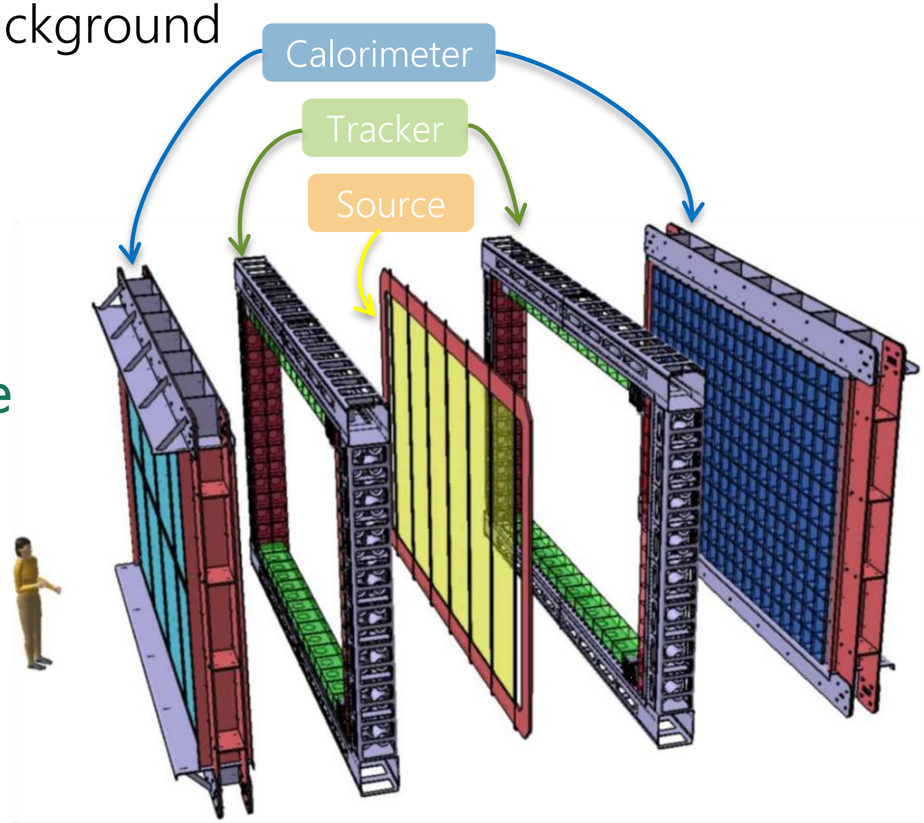
$$T_{1/2}^{0\nu} > 2.5 \times 10^{23}\ \text{yr (90\% CL)}$$
$$\langle m_{\beta\beta} \rangle < 1.2 - 3.0\ \text{eV}$$

- Only 4 times worse than ^{100}Mo with <15% of the mass

The SuperNEMO Demonstrator

- Build on the **tracking and calorimetry technique** honed in NEMO-3
- **Modular design** with planar geometry
- Much **stricter radiopurity** constraints
- Much better **energy resolution**
- ^{82}**Se** source to reduce the $2\nu\beta\beta$ background

- First stage is to prove radiopurity requirements can be achieved by building the Demonstrator module
    - 7 kg of isotope
    - Reach $T_{1/2} > 6.5 \times 10^{24}$ yr in 2.5 yr



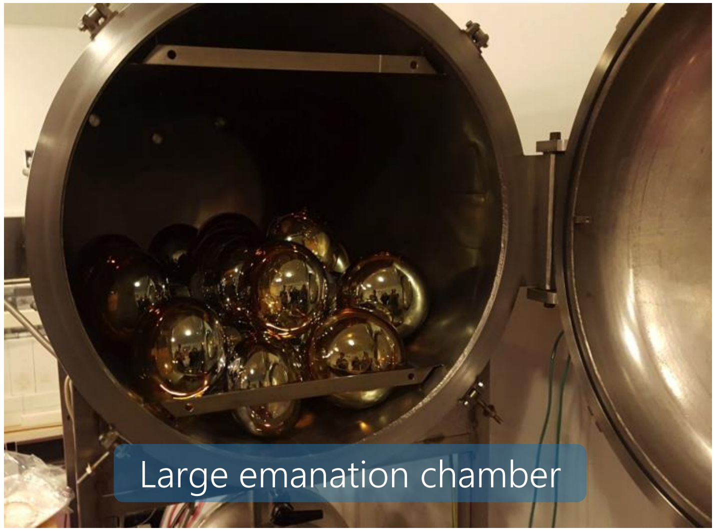
Tracker construction

- **Geiger-mode** multi-wire drift chamber
- Restricted set of materials:
  - Cu, steel, duracon
- **Robotic construction** of 2034 tracker cells
  - ~15000 wires
- **Radiopure** gas delivery system
- **Radon** sealing
- **Ultra-clean** construction, assembly and testing conditions

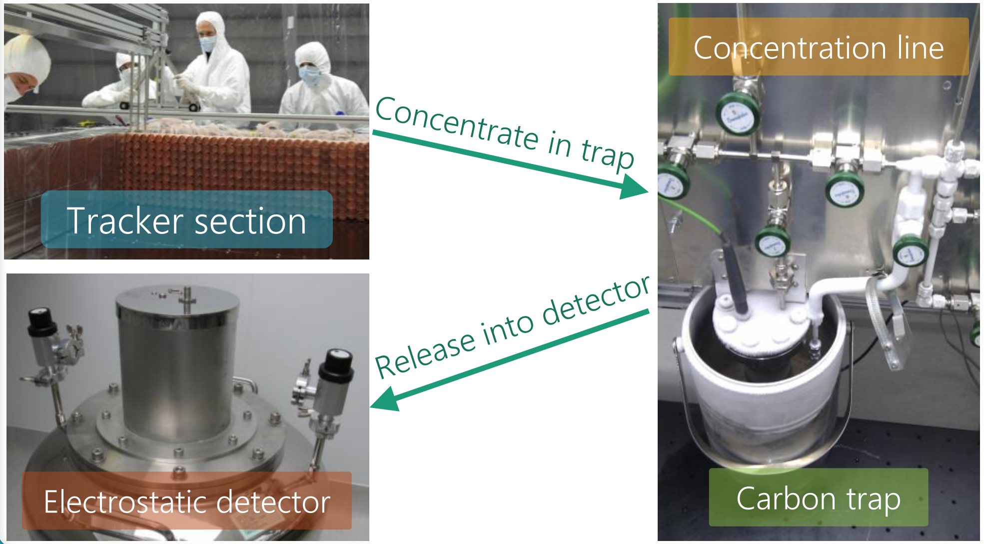
Cell production complete
Dead channel rate ~1% (most recoverable)

Radon mitigation

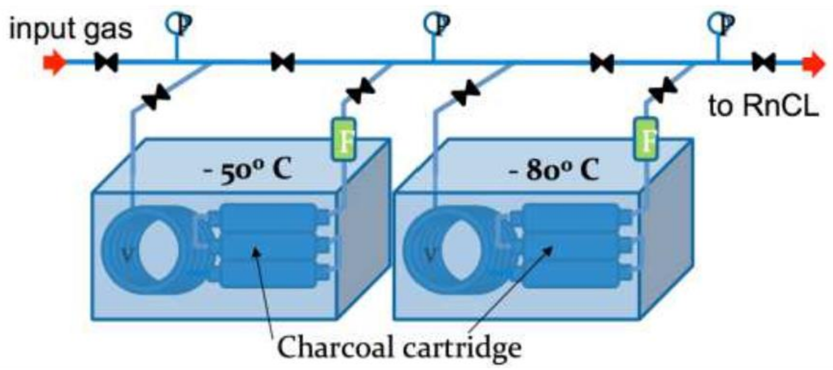
Measure materials and components



Measure assembled tracker sections



Trap ^{222}Rn on gas input



Flush ^{222}Rn out before it decays

- At reasonable rates achieve

$$A(^{222}\mathrm{Rn}) = 150\,\mu\mathrm{Bq/m}^3$$

- ~**70** ^{222}Rn atoms / m^3
- 30 times better than NEMO-3

Source foil production

- The **source** is composed of 36 **strips**
  - Each 2.7 m x 13 cm
- Yielding a **total** of **7 kg** of ^{82}Se

- The foils are made of a mixture of enriched **Se powder** and **PVA**

- Source foil support structure includes **automatic deployment** system for **calibration sources**

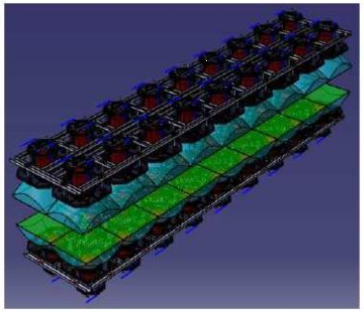
- Source foil **production** is **ongoing**

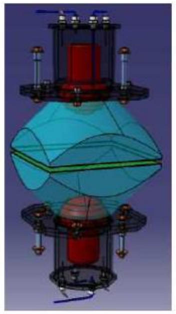
- Strips are measured in parallel with production in **BiPo-3**

Finish production and installation in early 2017

BiPo-3

- Measure ^{232}Th and ^{238}U chains contamination with e^--α delayed coincidence
- ^{212}Bi-^{212}Po (^{208}Tl):
  - 2 µBq / kg
- ^{214}Bi-^{214}Po:
  - 10 µBq / kg

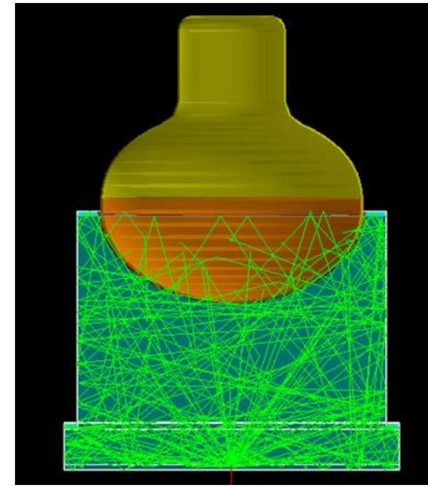


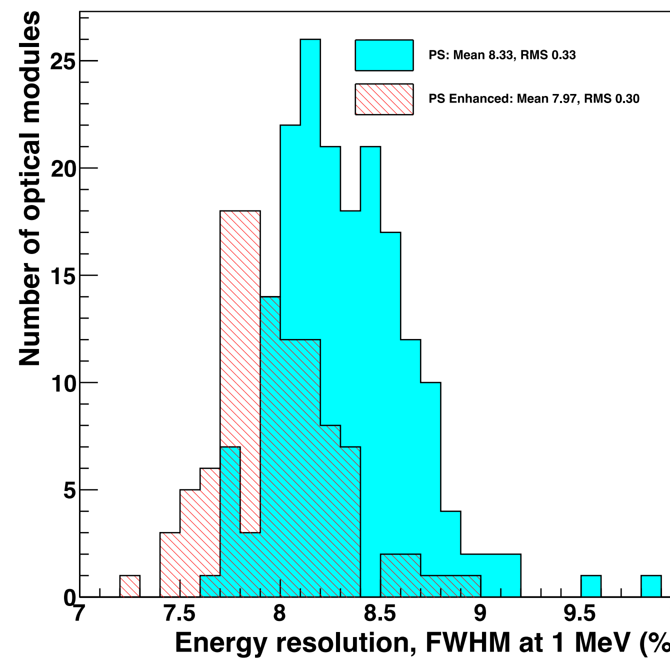


Operating in Canfranc since 2013

Calorimeter construction

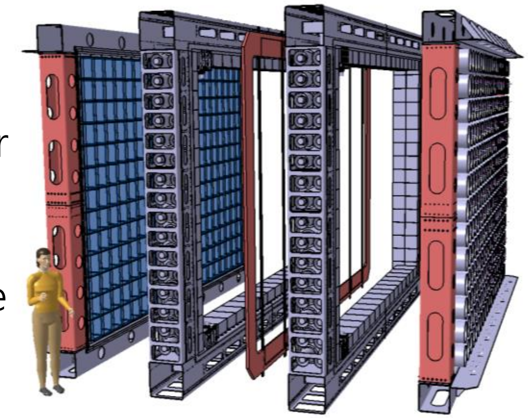
- Main calorimeter comprises **520 modules**
- **Polystyrene** scintillator blocks
- 8″ high QE radiopure PMTs
- FWHM_E = 8.0 – 8.3 % @ 1 MeV
  4.6 % @ ^{82}Se $Q_{\beta\beta}$
- σ_t = **400 ps** @ 1 MeV
- **Calibration** systems maintain stability to **better than 1%**
- Validation with detailed **optical simulations**

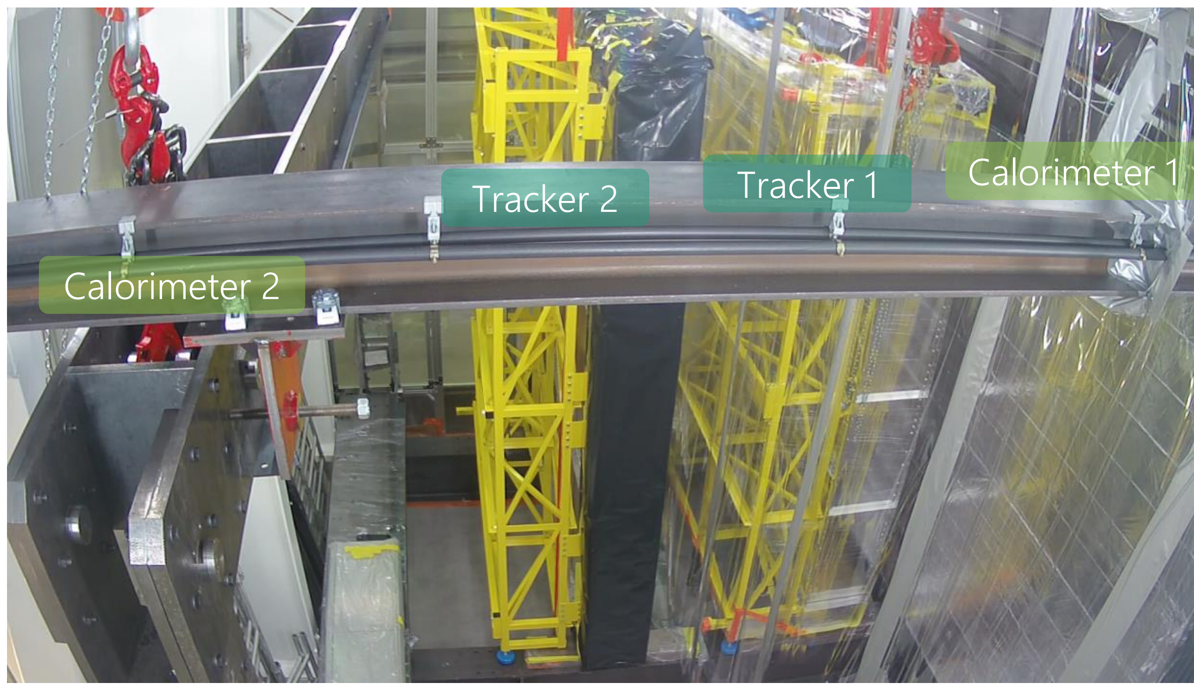




Demonstrator integration

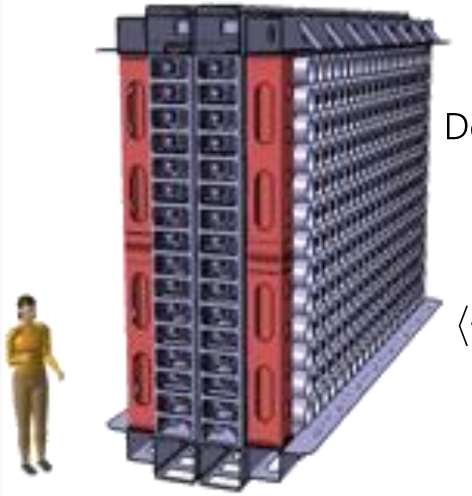
- Half of the detector is **in place** at LSM
- Remaining components of the detector will be delivered over the **next few months**
- Demonstrator module will be complete by **early 2017**





SuperNEMO sensitivity

NEMO-3		SuperNEMO	Status
^{100}Mo	isotope	^{82}Se (or other, e.g. ^{150}Nd)	✓ (7 kg)
7 kg	isotope mass	7 ➔ 100 kg	✓
5 mBq/m^3	radon	0.15 mBq/m^3	✓
^{208}Tl: 100 μBq/kg ^{214}Bi: 300 μBq/kg	internal contamination	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg	in progress
14% @ 1 MeV	FWHM	8% @ 1 MeV	✓



Demonstrator Module

17.5 kg.yr :

$$T^{0\nu}_{1/2} > 6.5 \times 10^{24} \text{ yr}$$

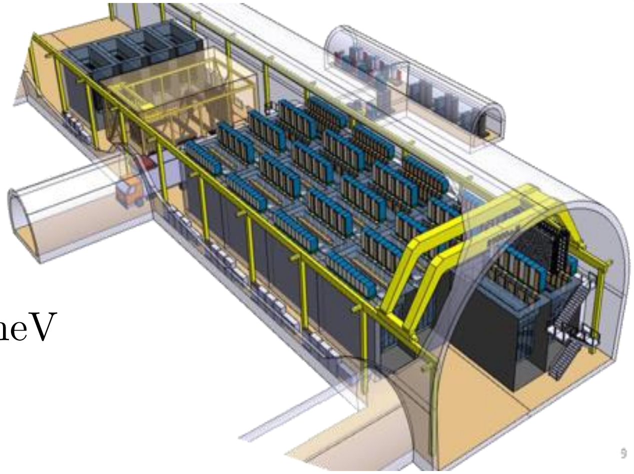
$$\langle m_\nu \rangle < 0.20 - 0.40 \text{ eV}$$

Full SuperNEMO

500 kg.yr :

$$T^{0\nu}_{1/2} > 10^{26} \text{ yr}$$

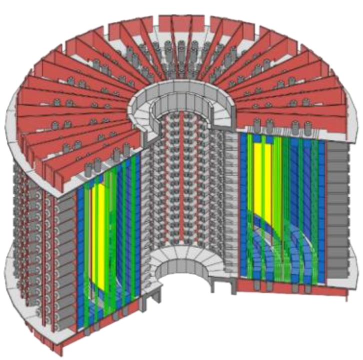
$$\langle m_\nu \rangle < 50 - 100 \text{ meV}$$



Summary

- The NEMO-3 experiment has produced a wealth of physics results, with data analysis still ongoing
  - Competitive 0νββ limit with the ^{100}Mo source: $\langle m_{\beta\beta} \rangle < 0.3 - 0.6$ eV
  - Most of the world's best measurements of 2νββ half-lives
  - Unique physics, such as the 0ν4β search
  - Advanced analysis techniques, such as the first use of multivariate methods in 0νββ searches

- The SuperNEMO Demonstrator construction is close to completion
  - On track to achieve the strict radiopurity goals



Thank you

supernemo collaboration