Status of the SuperNEMO Experiment

Alessandro Minotti (LAPP)

On Behalf of the SuperNEMO Collaboration

CNNP 2020

Outline

- What is the $0\nu\beta\beta$ and how we look for it with SuperNEMO?
- We are making a Demonstrator! With 6.3 kg ^{82}Se
- It builds on and enhances the NEMO technology
- Is under commissioning!
- It will search for the $0\nu\beta\beta$ and study the $2\nu\beta\beta$ of ^{82}Se

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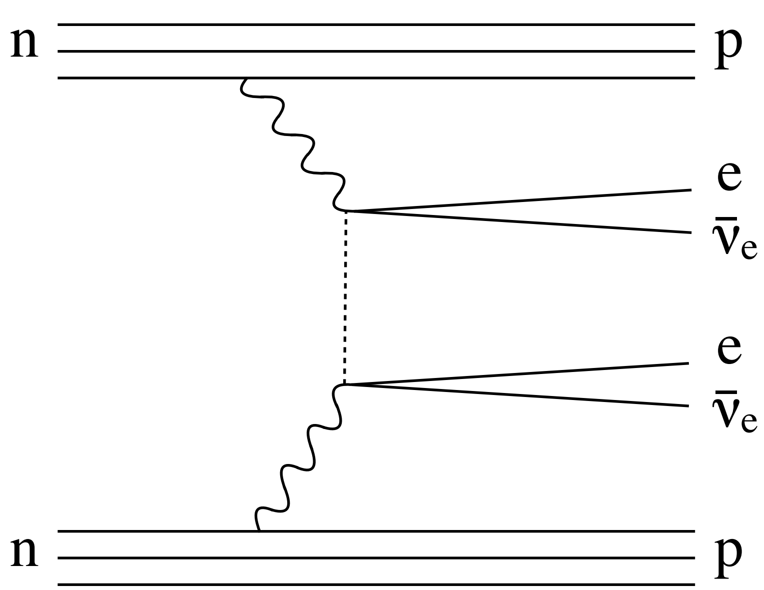
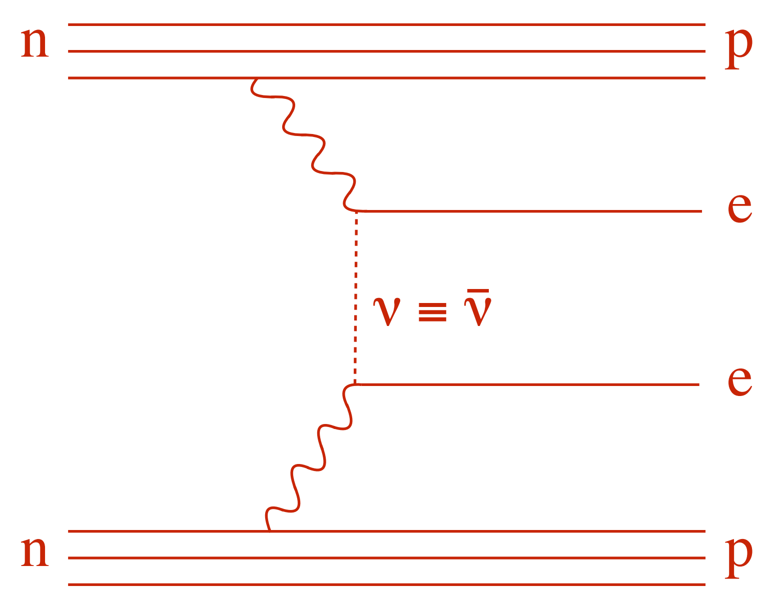
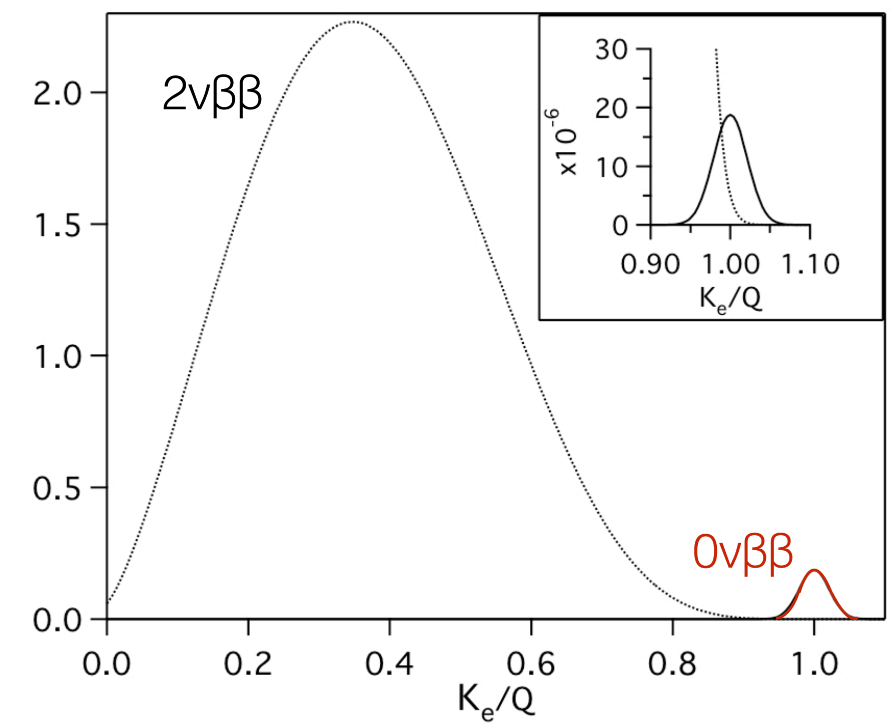
Neutrinoless Double Beta Decay

- Nuclear decay where matter is created, and the conservation of total lepton number violated
  - Requires **Majorana neutrinos** ($\nu \equiv \bar{\nu}$)
  - Is a gateway toward **Physics beyond the Standard Model**
  - Can help answering a number of open questions in particle Physics and cosmology (mass scale, baryon-antibaryon asymmetry)







$2\nu\beta\beta$

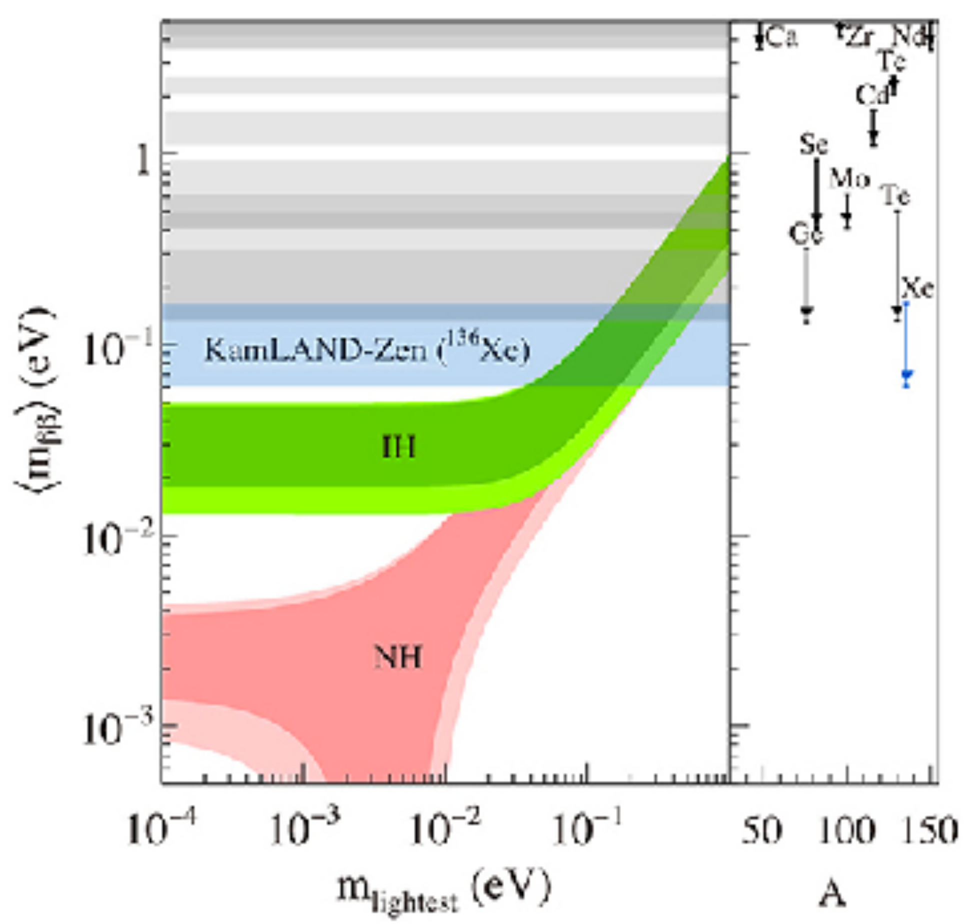
- Observed in 14 even-even isotopes for which β decay is suppressed
- Continuous β-like energy distribution

$0\nu\beta\beta$

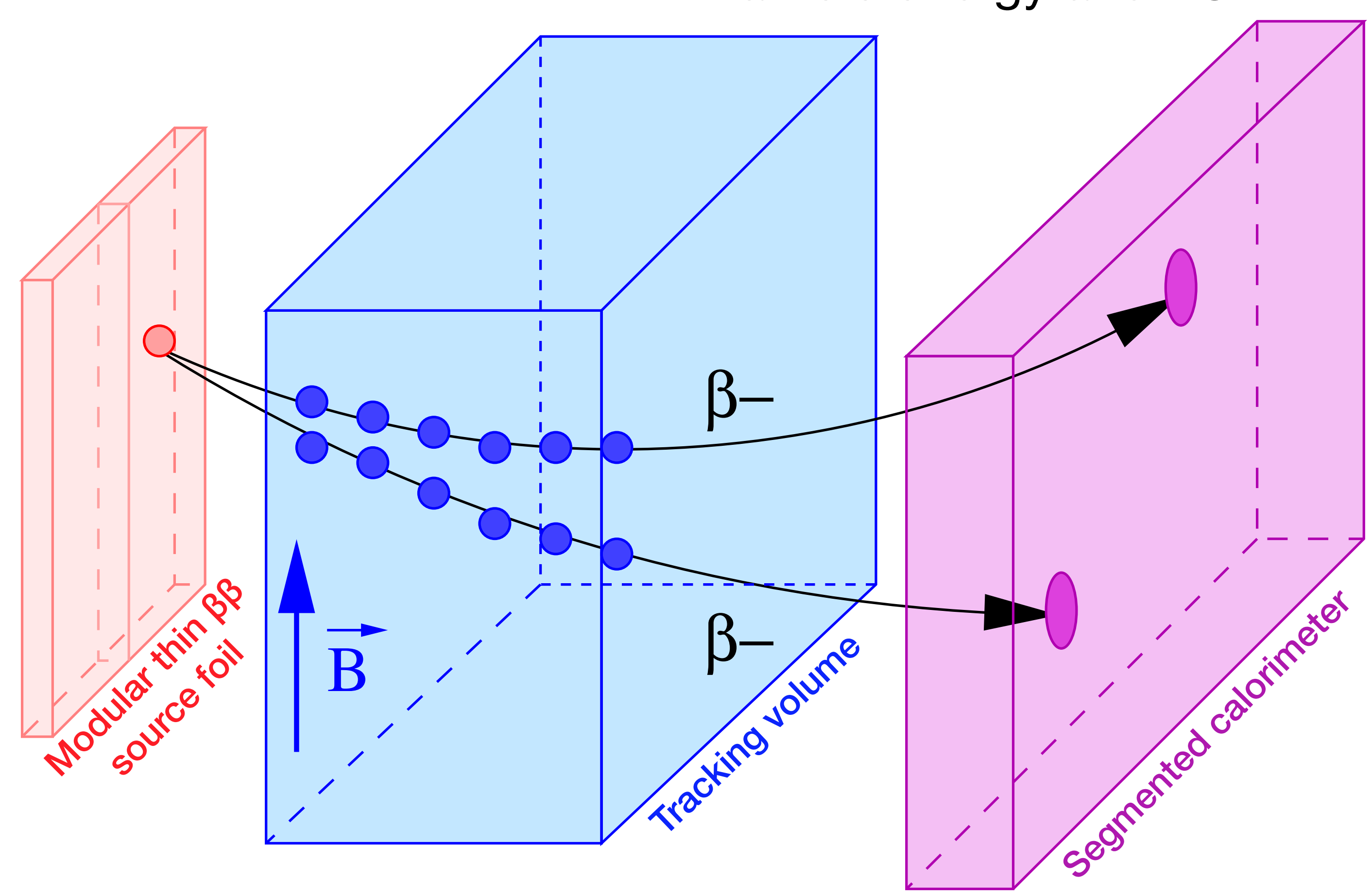
- Forbidden in the Standard Model
- Signature: energy peak at Q-value

SuperNEMO and the Hunt for 0νββ

- A large number of projects worldwide is seeking 0νββ with different isotopes/techniques
- **SuperNEMO** employs a **tracking-calorimetry** detection technique
  - Source decoupled from detector → modular, can change isotope
  - Full event topology reconstruction → PID, background rejection, **distinguish between ββ mechanisms**



- Decay vertex
- Charged particle trajectory
- Particle energy and TOF



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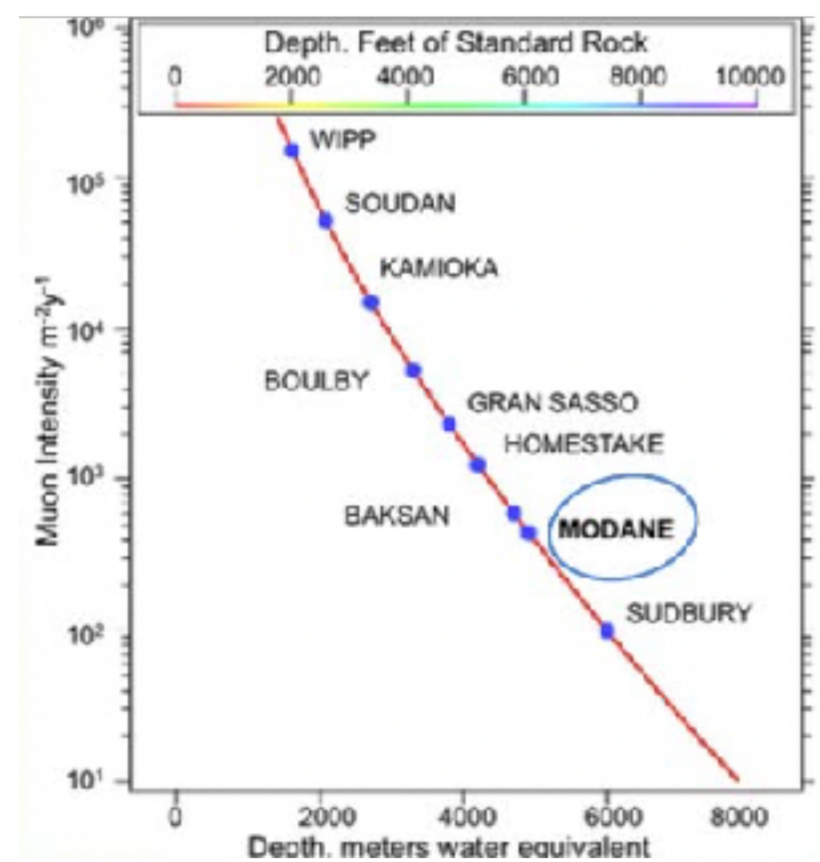
LSM - Home of SuperNEMO

- The SuperNEMO Demonstrator is hosted in the Modane Underground Laboratory (LSM)

- In the Frejus road tunnel

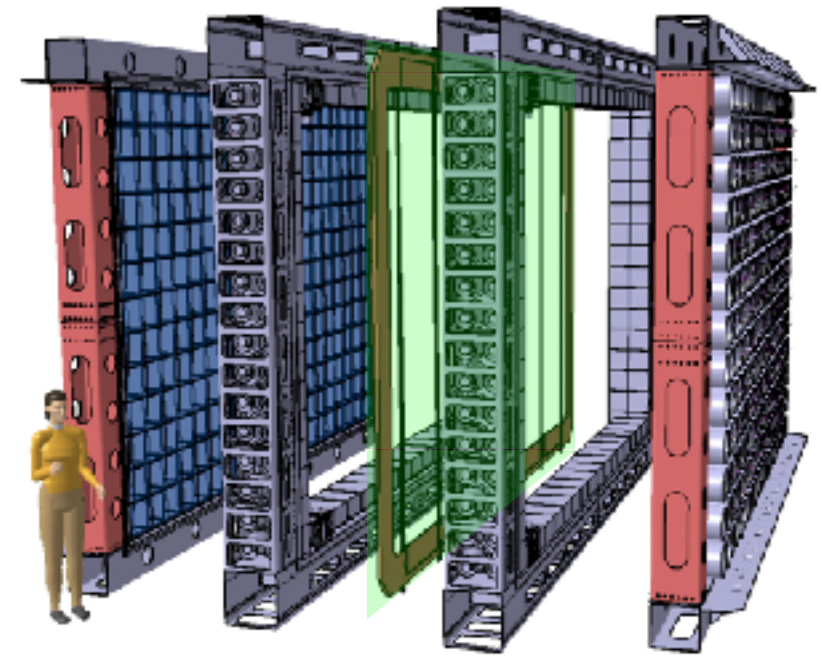
- 4800 m water-equivalent cosmic rays shielding

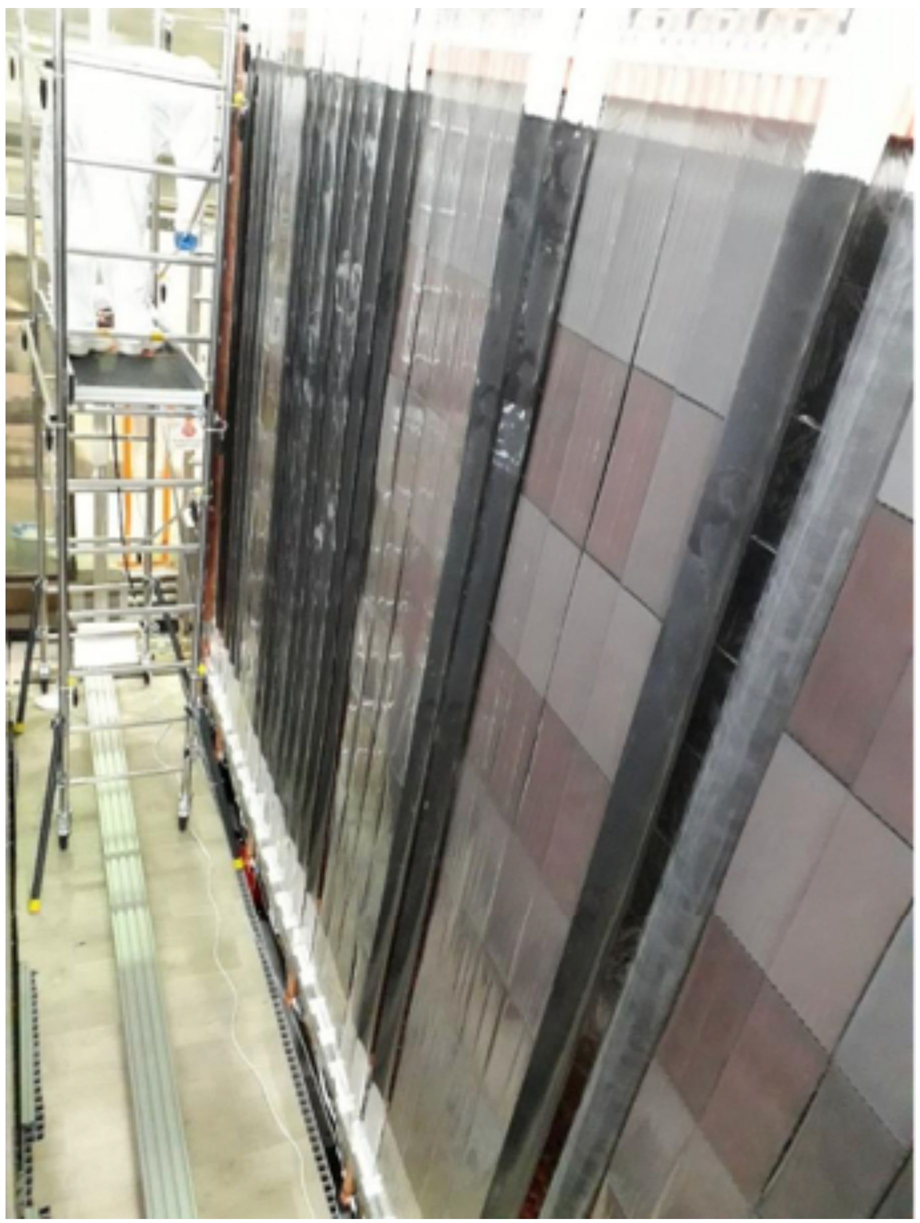


The SuperNEMO Demonstrator

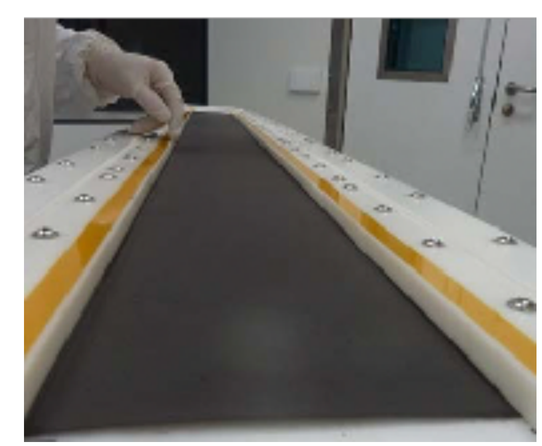
ββ source	^{82}Se foils (~ 50 mg/cm^2)

- 34 source foils for **6.3 kg ^{82}Se ($Q_{\beta\beta}$ = 2997.9 keV)**
- Total surface 13.1 m^2



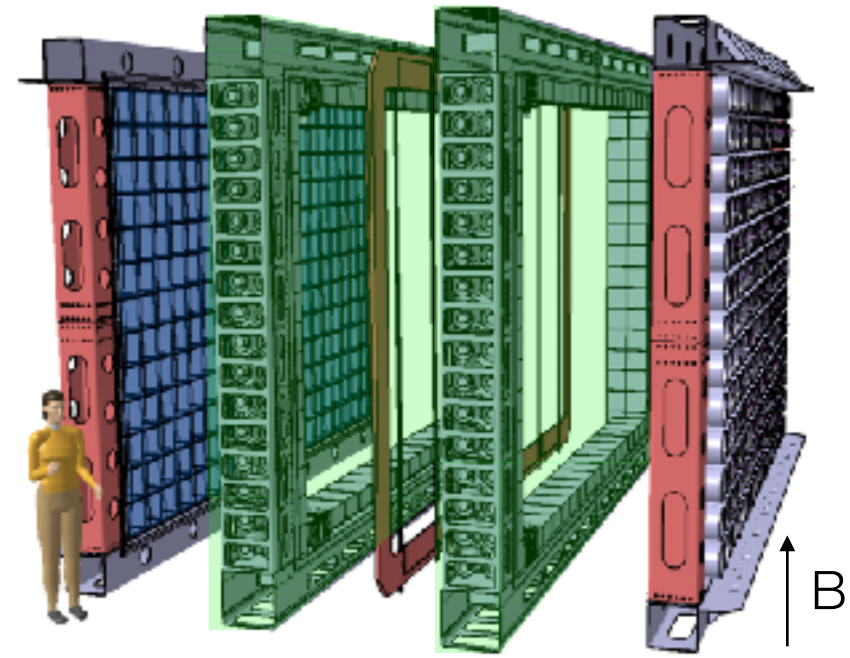


- Different purification techniques (distillation, chromatography, chemical precipitation)
- Enriched ^{82}Se powder mixed with PVA and poured/wrapped in Mylar

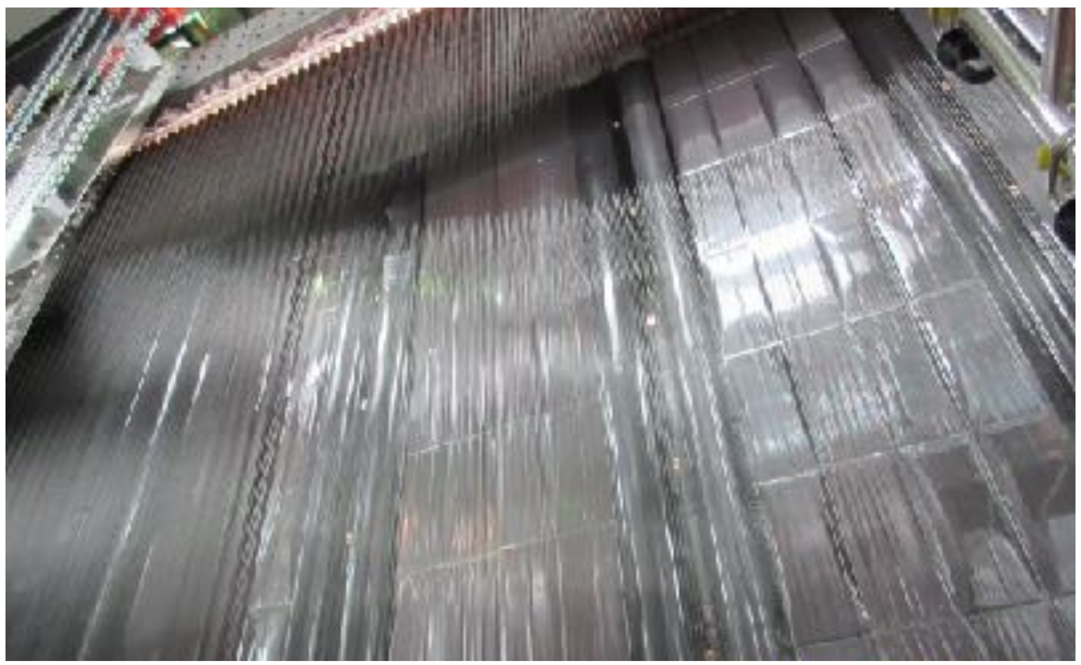


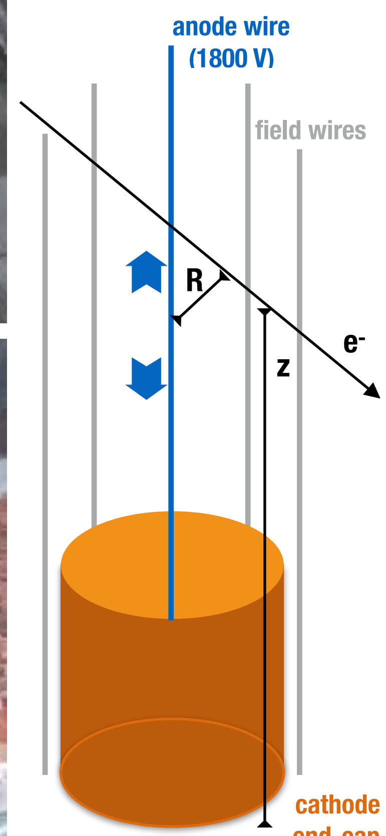
The SuperNEMO Demonstrator

ββ source	^{82}Se foils (~ 50 mg/cm^2)
Tracker	2034 geiger cells drift chamber in B field (25 G)

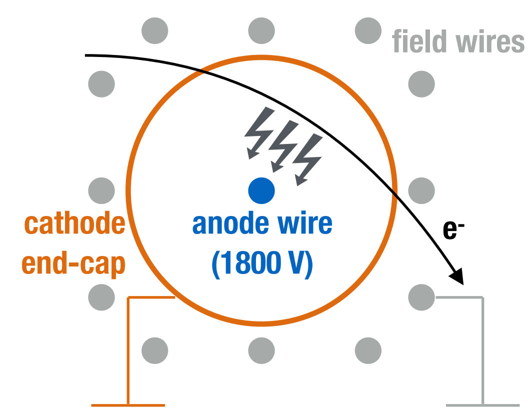


- 113 rows of 9 cells on each side (~13000 wires)
- 25 G magnetic field for PID (α / e^+ / e^-)





- Charged particle ionises gas (He_2) and the resulting e^- avalanche drifts towards anode
  - Drift time gives distance from anode R
  - Difference in signal on wire ends gives z



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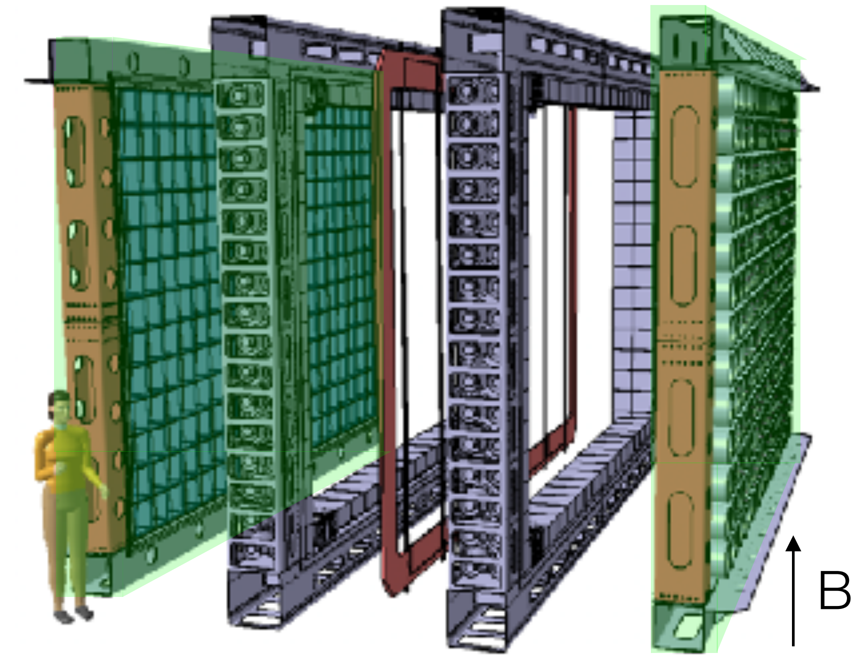
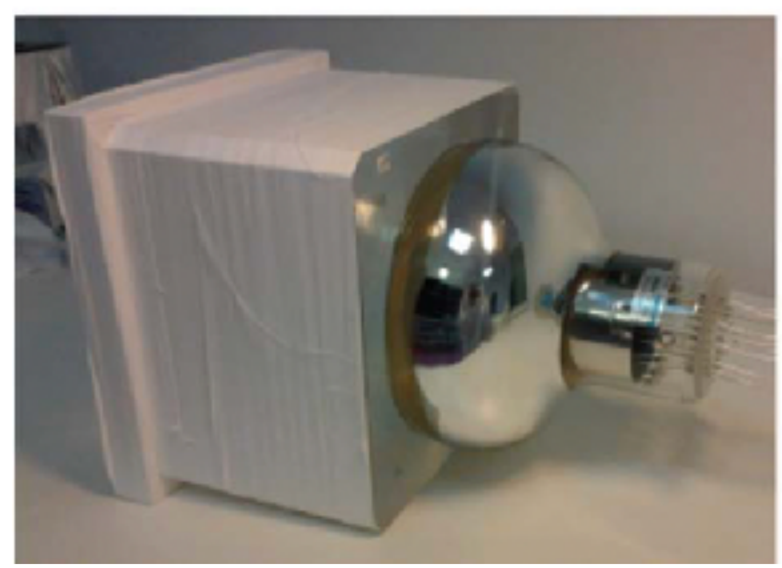
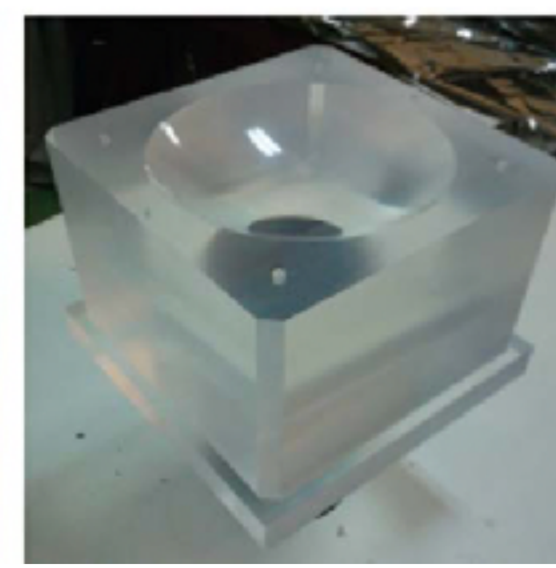
Calorimeter	712 optical modules (PS coupled with PMT)



- Main walls: 20 × 13 optical modules
- X-walls (sides): 4 × 16 optical modules
- γ-veto (top/bottom): 2 × 16 optical modules

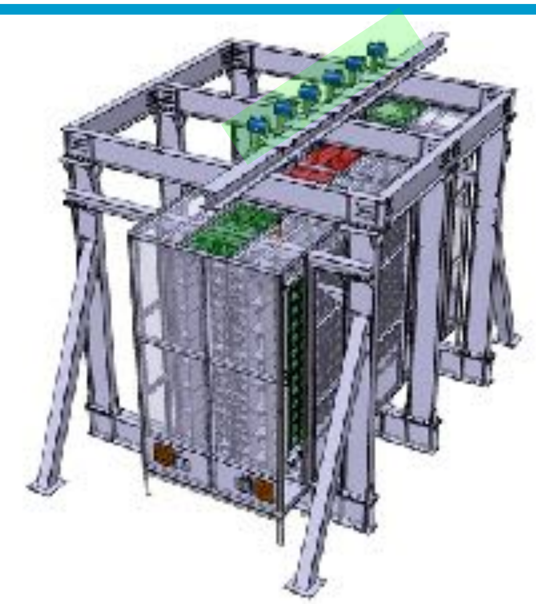
- **Optical module**: 8”(5”) Hamamatsu photomultiplier directly coupled with plastic scintillator block
  - Individual magnetic shield
  - teflon/mylar wrapping for optical insulation



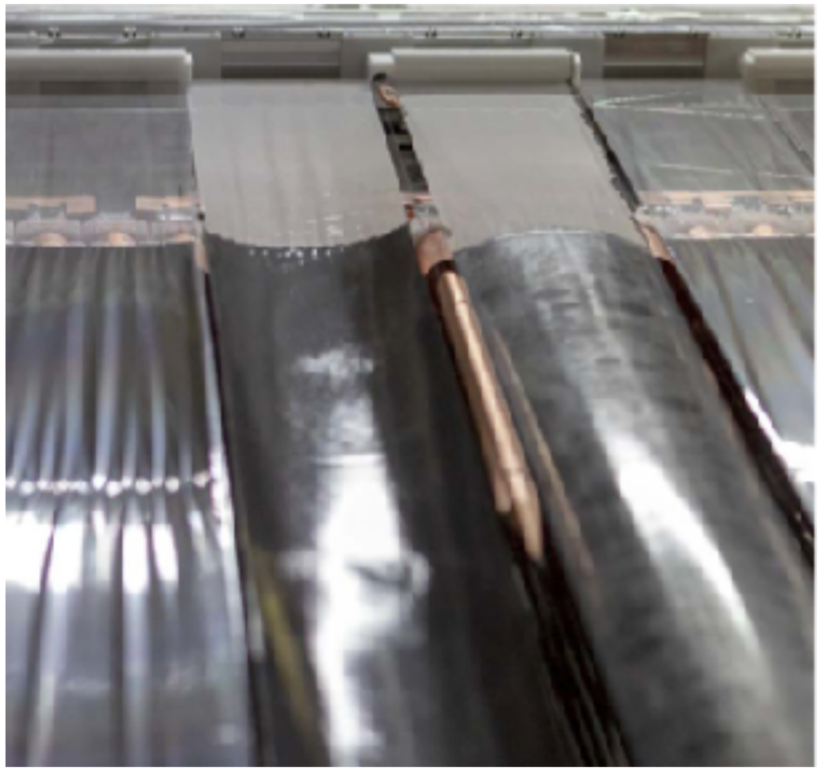


The SuperNEMO Demonstrator

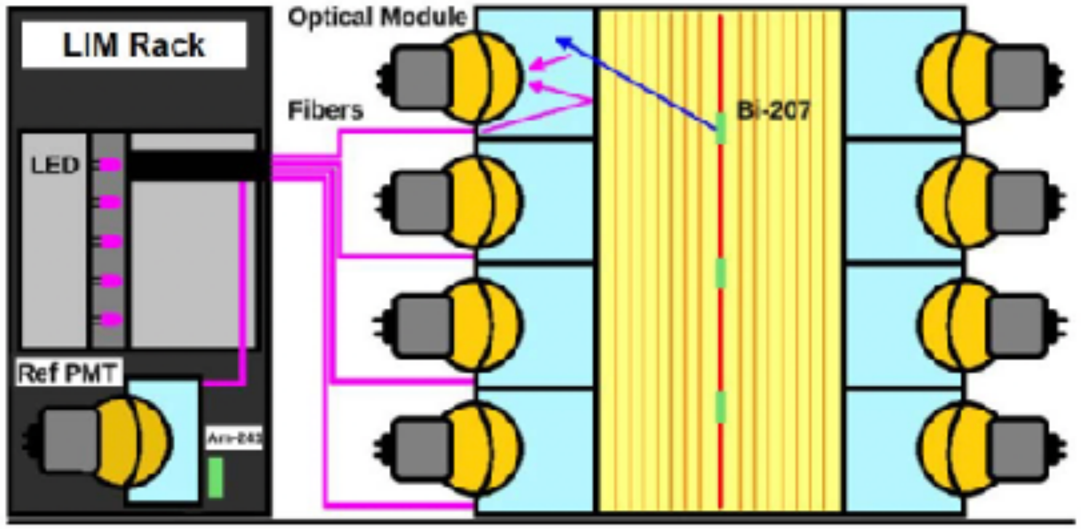
ββ source	^{82}Se foils (~ 50 mg/cm²)
Tracker	2034 geiger cells drift chamber in B field (25 G)
Calorimeter	712 optical modules (PS coupled with PMT)
Calibration Systems	Source Deployment, Light Injection



- Absolute energy calibration & background studies
  - Rn-tight automatised **deployment system** of calibration sources (γ, n)
  - Calibration on on weekly basis (~15 hours)



- Relative time/energy calibration
  - UV **light injection system** (20 pulsed LED + fibres)
  - Reference PMT for stability monitoring



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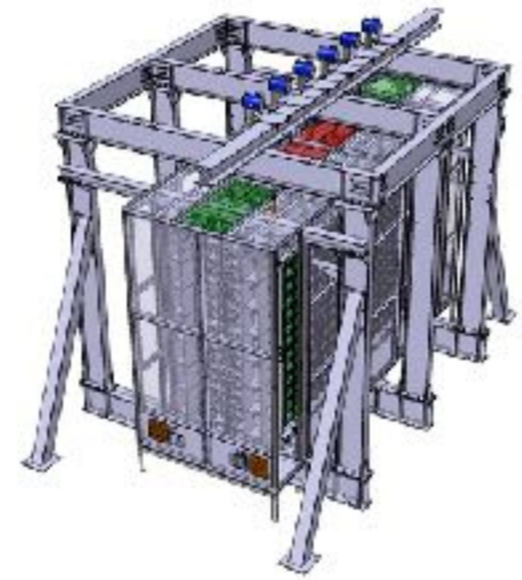
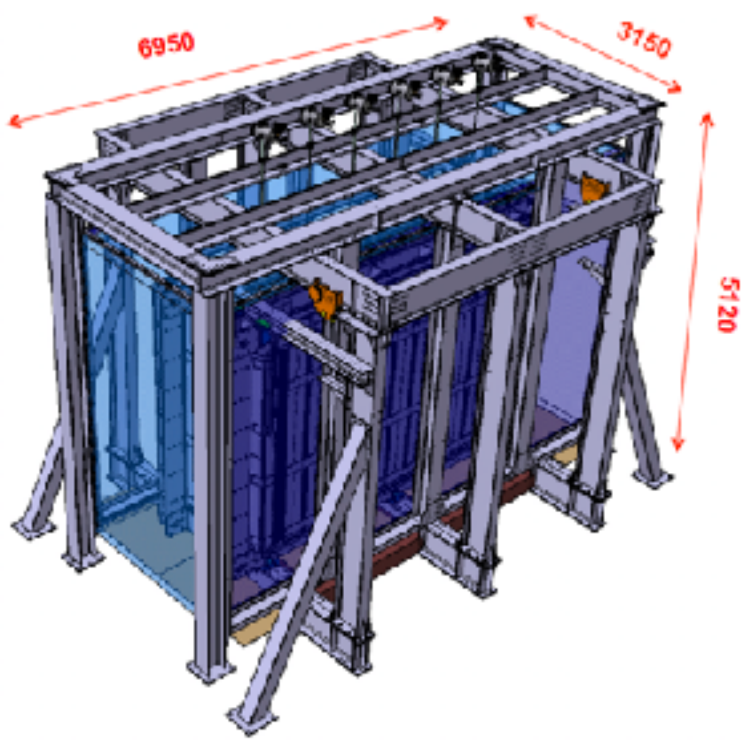
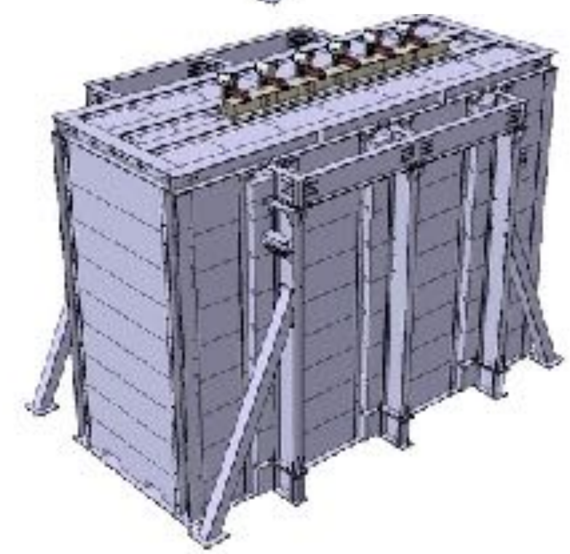
Calibration Systems	Source Deployment, Light Injection
Background Mitigation	Passive shielding (Fe, PE, H_2O), anti-Rn system

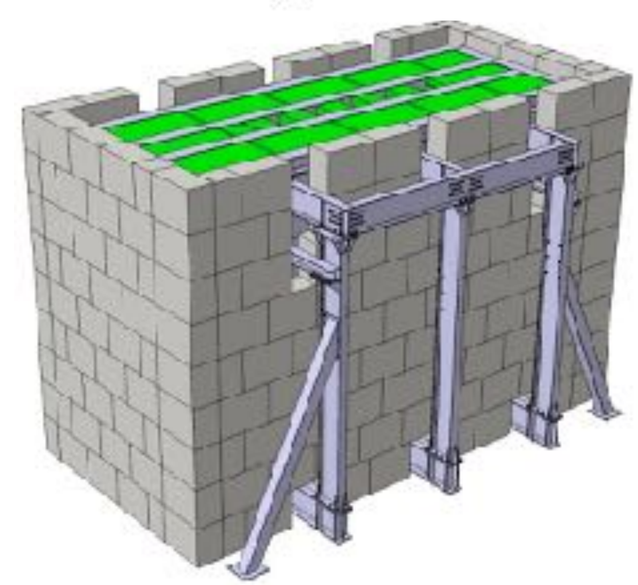


- Anti-radon system
  - Black polycarbonate tent
  - Flushed air purified with Rn cold-C trap



- Multi-purpose shielding
  - 20 mm PE
  - 180 mm Fe
  - 300 mm H_2O enriched with B





SuperNEMO Papers

- Technical papers published and under preparation for SuperNEMO

Development of methods for the preparation of radiopure ^{82}Se sources for the SuperNEMO neutrinoless double-beta decay experiment

Alimardon V. Rakhimov / A. S. Barabash / A. Basharina-Freshville / S. Blot / M. Bongrand / Ch. Bourgeois / D. Breton / R. Breier / E. Birdsall / V. B. Brudanin / H. Burešova / J. Busto / S. Calvez / M. Cascella / C. Cerna / J. P. Cesar / E. Chauveau / A. Chopra / G. Claverie / S. De Capua / F. Delalee / D. Duchesneau / V. G. Egorov / G. Eurin / J. J. Evans / L. Fajt / D. V. Filosofov / R. Flack / X. Garrido / H. Gomez / B. Guillon / P. Guzowski / R. Hodák / K. Holý / A. Huber / C. Hugon / A. Jeremie / S. Jullian / D. V. Karaivanov / M. Kauer / A. A. Klimenko / O. I. Kochetov / S. I. Konovalov / V. Kovalenko / K. Lang / Y. Lemière / T. Le Noblet / Z. Liptak / X. R. Liu / P. Loaiza / G. Lutter / J. Maalmi / M. Macko / F. Mamedov / C. Marquet / F. Mauger / A. Minotti / A. A. Mirsagatova / N. A. Mirzayev / I. Moreau / B. Morgan / J. Mott /

Radiochimica Acta (2019) 108.2 (2019): 87-97

- ^{82}Se source papers
  - Radiopurity paper published
  - Source foils preparation paper under preparation

- Other technical papers under preparation
  - Tracker paper
  - Calorimeter paper

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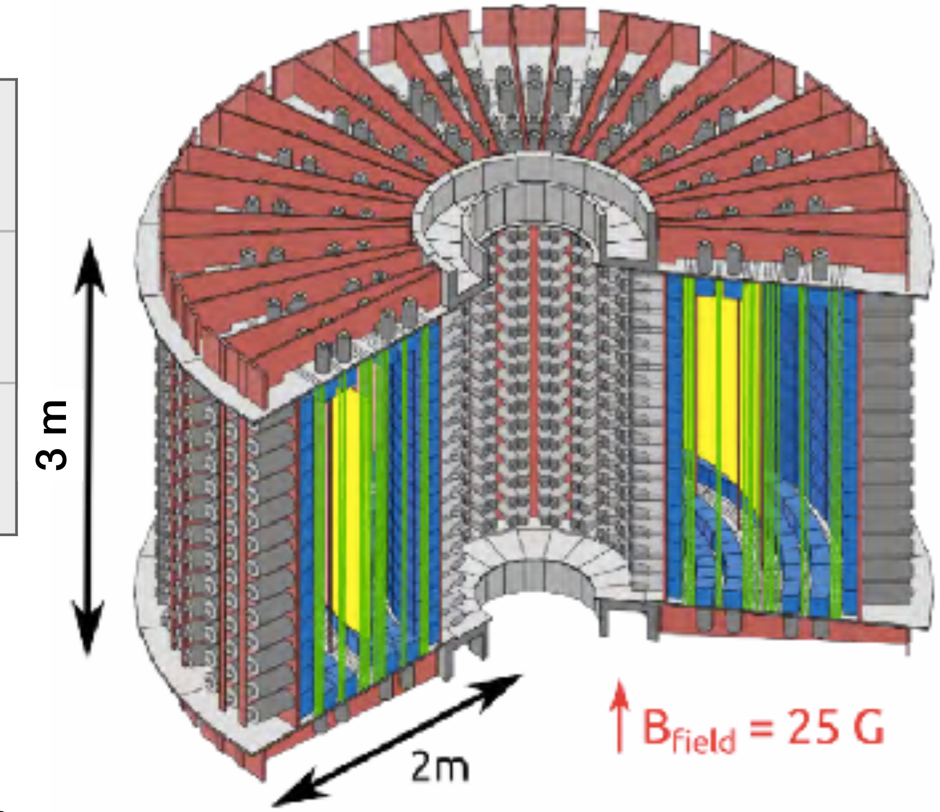
The NEMO-3 Experience

- SuperNEMO builds on the successful NEMO-3 experiment

ββ source	^{100}Mo (6.9 kg), ^{82}Se (0.93 kg), ^{130}Te (0.45 kg), ^{116}Cd (0.40 kg) foils (60 mg/cm2)
Tracker	6180 geiger cells drift chamber in B field (25 G)
Calorimeter	1940 optical modules (PS coupled with 3/5" PMT)



- Several world-best limits ($T_{0\nu\beta\beta}$) and measurements ($T_{2\nu\beta\beta}$) on a variety of isotopes
  - **^{100}Mo** (Eur. Phys. J. C (2019) 79:440) $T_{1/2}^{2\nu\beta\beta}$ = [7.11 ± 0.02 (stat) ± 0.54 (sys)] × 10^{18} y
  - **^{48}Ca** (Phys. Rev. D 93, 112008) $T_{1/2}^{2\nu\beta\beta}$ = [$6.4^{+0.7}_{-0.6}$ (stat) $^{+1.2}_{-0.9}$ (sys)] × 10^{19} y
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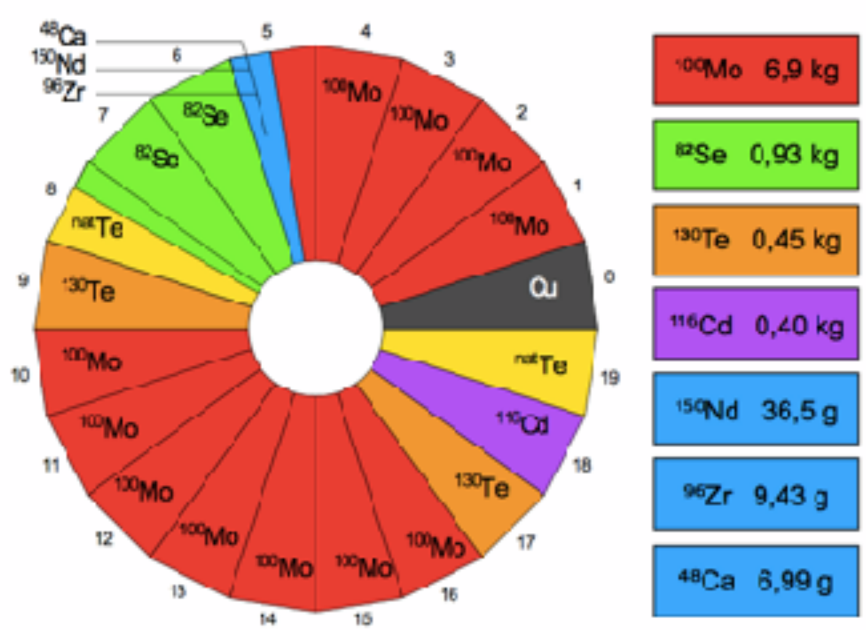
  - **^{96}Zr** (Nucl.Phys.A847:168-179) $T_{1/2}^{2\nu\beta\beta}$ = [2.35 ± 0.14 (stat) ± 0.16 (sys)] × 10^{19} y
  - **0v4β** (Phys. Rev. Lett. 119, 041801) $T_{1/2}^{0\nu4\beta}$ > 1.1 × 10^{21} y

NEMO-3 "camembert" (source top view)



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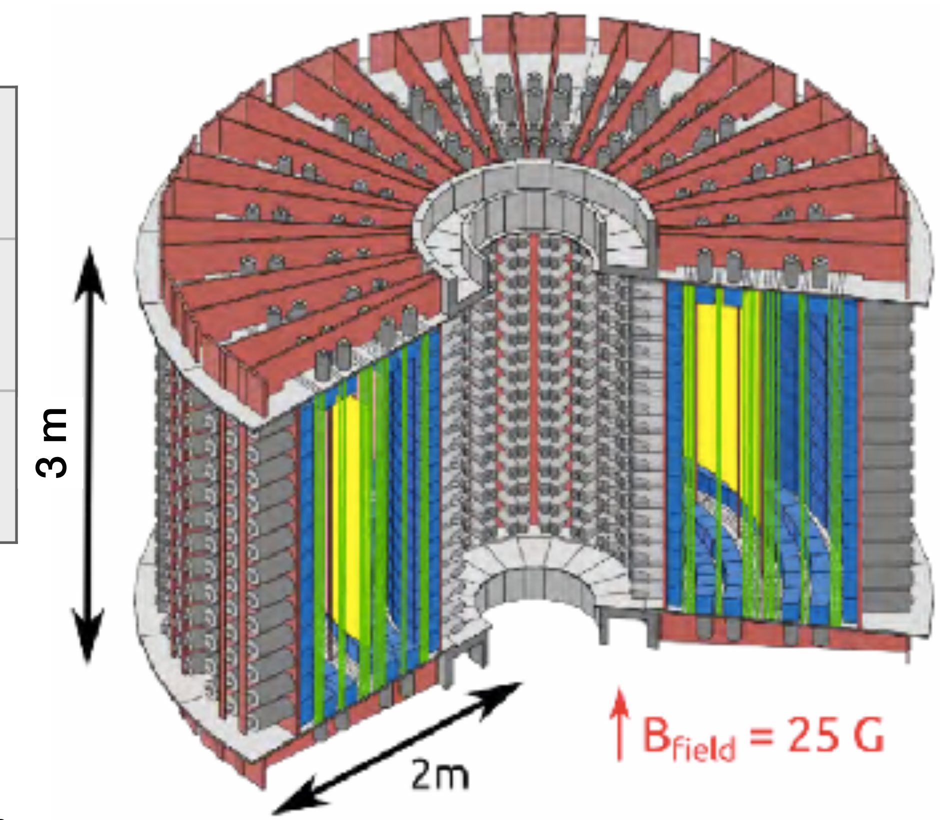

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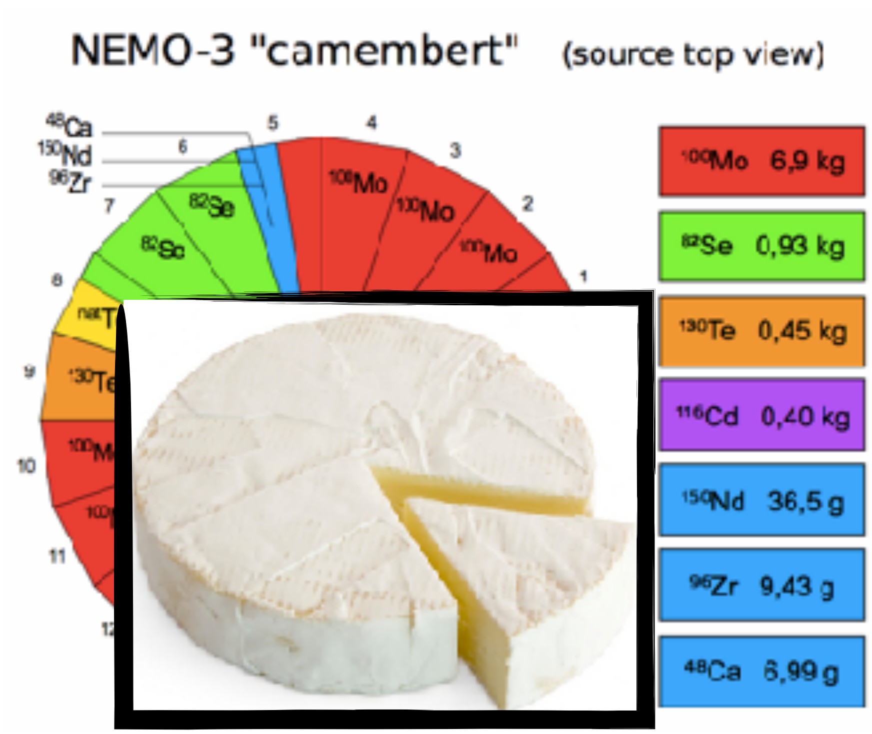
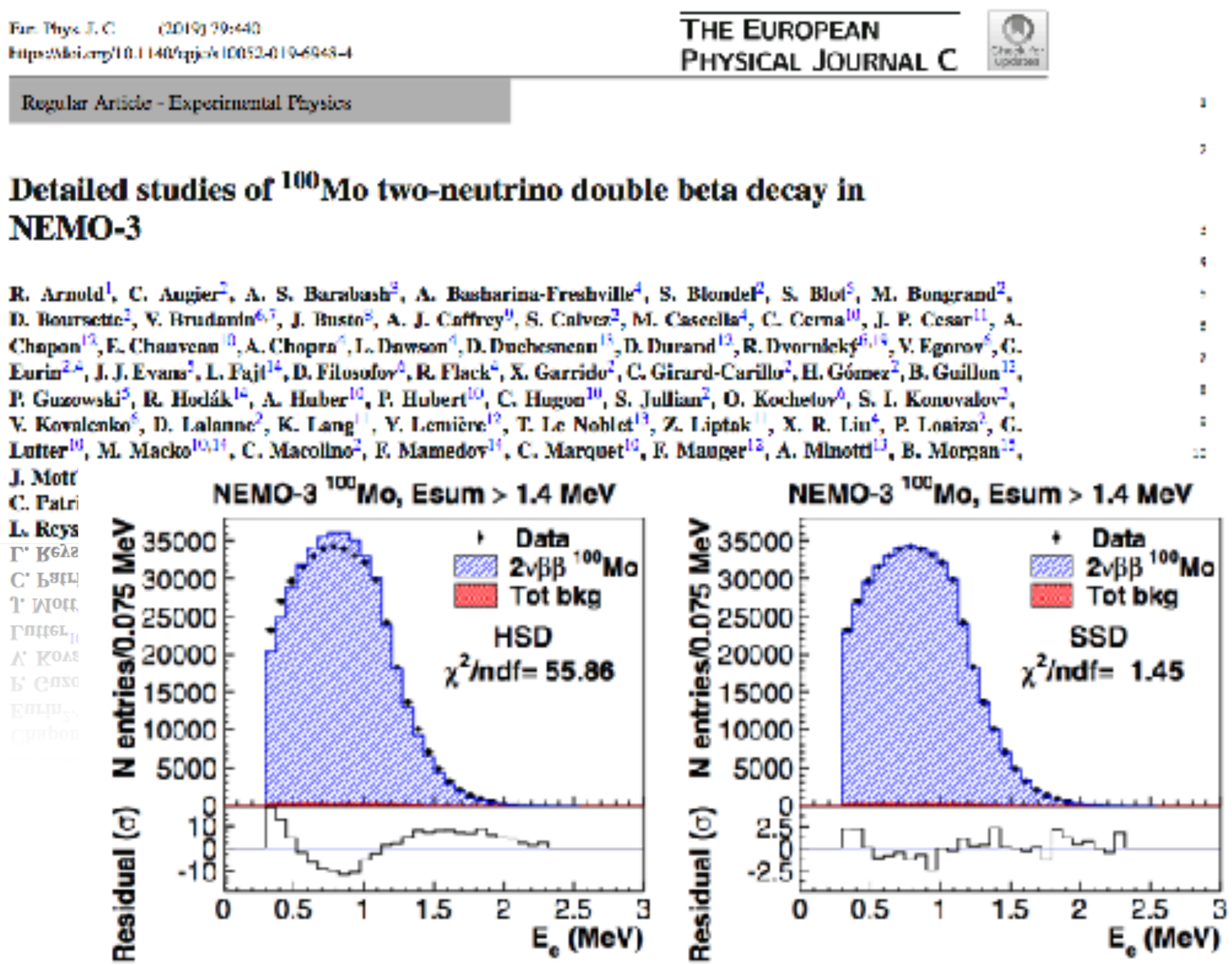
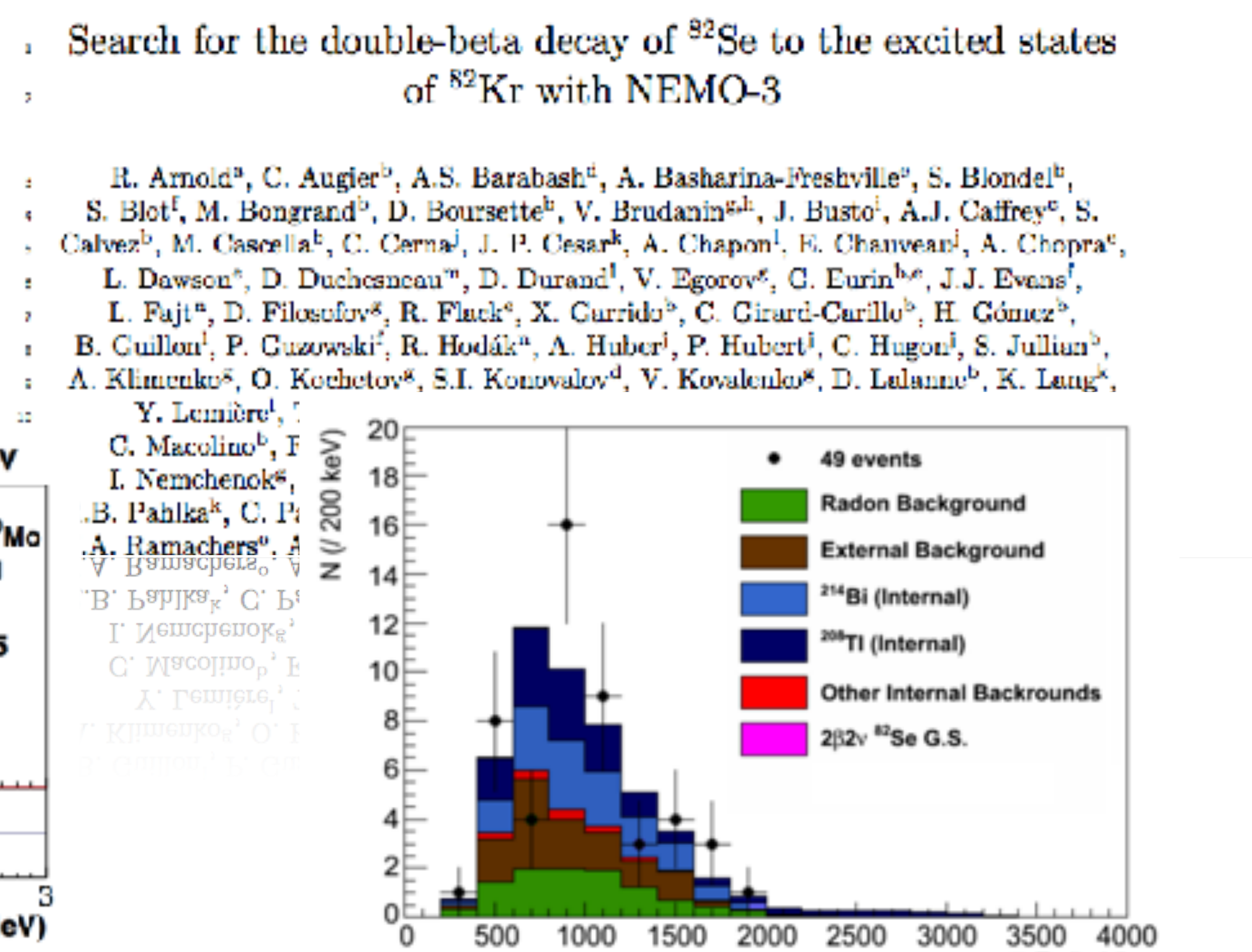


The NEMO-3 Experience

- Recent NEMO-3 results on ^{100}Mo and ^{82}Se



Nuclear Physics A (2020) 996 121701



The European Physical Journal C (2019) 79(5) 440

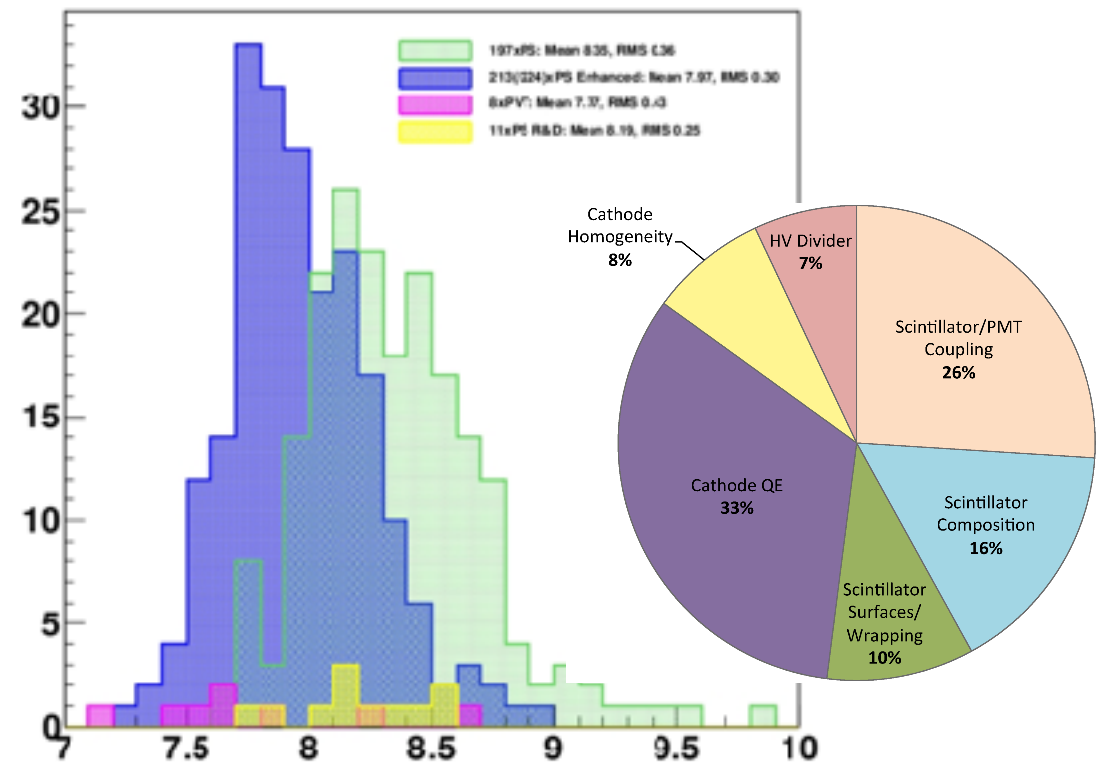
- New spectral analysis of ^{100}Mo 2νββ
  - Single-state dominance strongly favoured
  - Exotic searches with spectral analysis
- New limits on ^{82}Se → ^{82}Kr* ββ
  - $T^{2\nu}_{1/2}$ (^{82}Se, 0^+_{gs} → 0^+_1) > 1.3 × 10^{21} y
  - $T^{0\nu}_{1/2}$ (^{82}Se, 0^+_{gs} → 0^+_1) > 2.3 × 10^{22} y

From NEMO-3 to SuperNEMO

- The SuperNEMO demonstrator upgrades the NEMO-3 technique
  - Improved energy resolution in high-granularity calorimeter

	NEMO-3	SuperNEMO Demonstrator
Source Isotope **Main Isotope** **Mass**	^{100}Mo 7 kg	^{82}Se 7 kg
Energy Resolution **FWHM @ 1 MeV** **FWHM @ 3 MeV**	15 % 8 %	8 % 4 %
Source Radiopurity **A(^{208}Tl)** **A(^{214}Bi)**	~ 100 µBq/kg < 300 µBq/kg	< 2 µBq/kg < 10 µBq/kg
Gaseous Radon **A(^{222}Rn)**	~ 5 mBq/m^3	< 0.15 mBq/m^3
$0\nu\beta\beta$ Sensitivity	$T_{1/2} > 10^{24}$ y (5y)	$T_{1/2} > 6 \times 10^{24}$ y (2.5y)

- OMs tested individually
  - 7.8 % FWHM @ 1 MeV
  - Time resolution 400 ps



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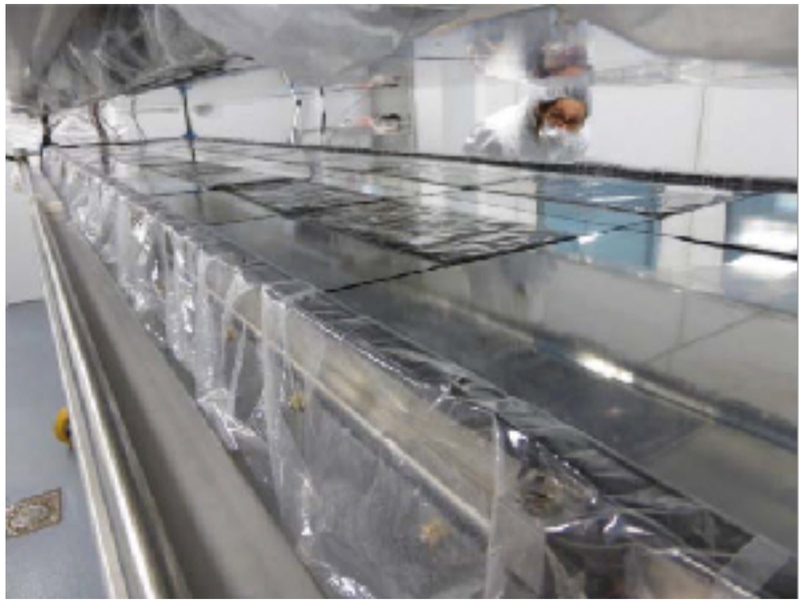
- Source foil contaminations investigated with dedicated BiPo setup
  - 10μBq/kg target A for ^{214}Bi
  - 2 μBq/kg target A for ^{208}Tl



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- Careful screening of materials using HPGe detectors
  - Measured activities 0.1-1 mBq/kg

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  - Improved source radio purity thanks to novel source foil production technique
  - Better insulation and gas purification to reduce ^{222}Rn

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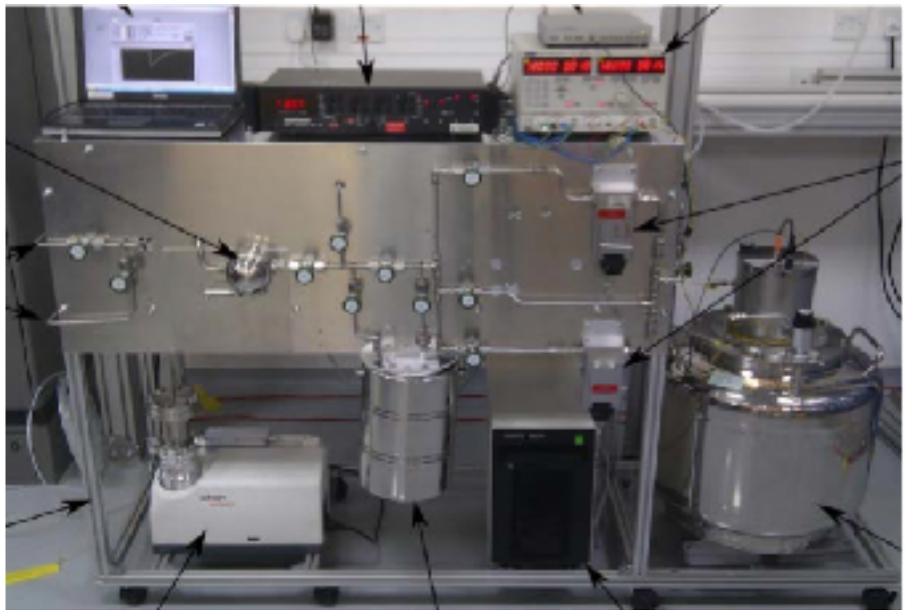
- Tracker flushed with He mixture (2 m^3 / h) through Rn trap
  - A(Rn): 2.7 mBq/m^3 ⇒ 0.15 mBq/m^3
  - Measured with Rn concentration line

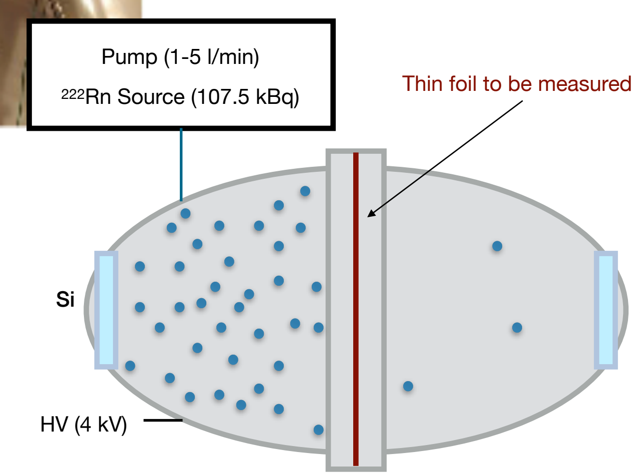


From NEMO-3 to SuperNEMO

- The SuperNEMO demonstrator upgrades the NEMO-3 technique
  - Improved energy resolution in high-granularity calorimeter
  - Improved source radio purity thanks to novel source foil production technique
  - Better insulation and gas purification to reduce ^{222}Rn

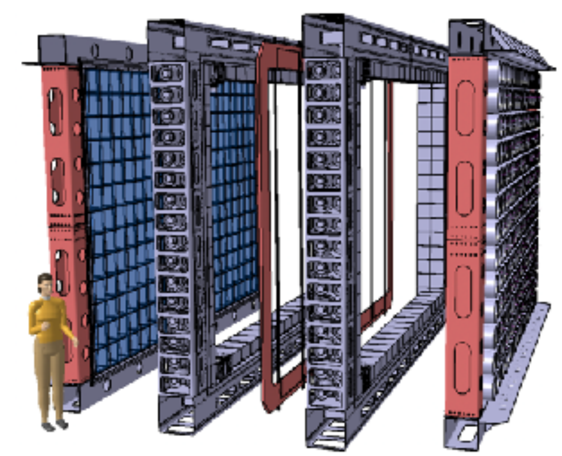
	NEMO-3	SuperNEMO Demonstrator
Source Isotope **Main Isotope** **Mass**	^{100}Mo 7 kg	^{82}Se 7 kg
Energy Resolution **FWHM @ 1 MeV** **FWHM @ 3 MeV**	15 % 8 %	8 % 4 %
Source Radiopurity **A(^{208}Tl)** **A(^{214}Bi)**	~ 100 µBq/kg < 300 µBq/kg	< 2 µBq/kg < 10 µBq/kg
Gaseous Radon **A(^{222}Rn)**	~ 5 mBq/m^3	< 0.15 mBq/m^3
0νββ Sensitivity	$T_{1/2} > 10^{24}$ y (5y)	$T_{1/2} > 6 \times 10^{24}$ y (2.5y)

- Materials carefully scrutinised
  - Rn emanation chamber
  - Rn permeability system

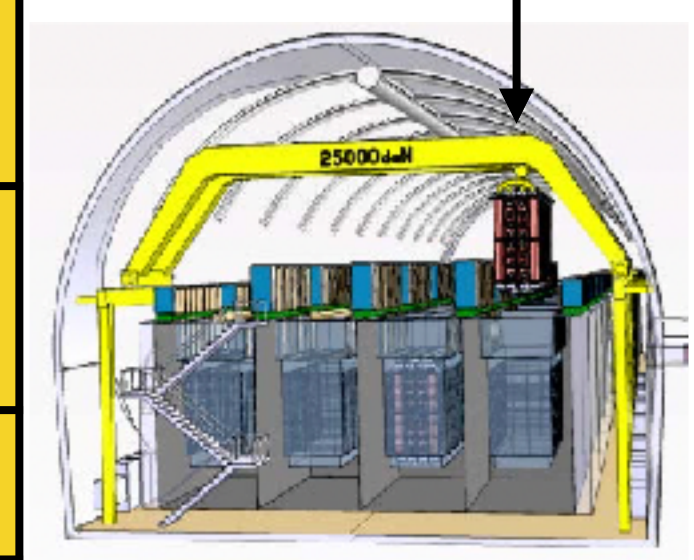


From NEMO-3 to SuperNEMO

- The SuperNEMO demonstrator upgrades the NEMO-3 technique
  - Improved energy resolution in high-granularity calorimeter
  - Improved source radio purity thanks to novel source foil production technique
  - Better insulation and gas purification to reduce ^{222}Rn
- Acts as a proof of principle for the SuperNEMO full project



x 20 modules



	NEMO-3	SuperNEMO Demonstrator	SuperNEMO
Source Isotope **Main Isotope** **Mass**	^{100}Mo 7 kg	^{82}Se 7 kg	**^{82}Se** **~100 kg**
Energy Resolution **FWHM @ 1 MeV** **FWHM @ 3 MeV**	15 % 8 %	8 % 4 %	
Source Radiopurity **A(^{208}Tl)** **A(^{214}Bi)**	~ 100 μBq/kg < 300 μBq/kg	< 2 μBq/kg < 10 μBq/kg	
Gaseous Radon **A(^{222}Rn)**	~ 5 mBq/m³	< 0.15 mBq/m³	
0νββ Sensitivity	$T_{1/2} > 10^{24}$ y (5y)	$T_{1/2} > 6\times10^{24}$ y (2.5y)	**$T_{1/2} > 10^{26}$ y (5y)**

Detector Assembly Milestones

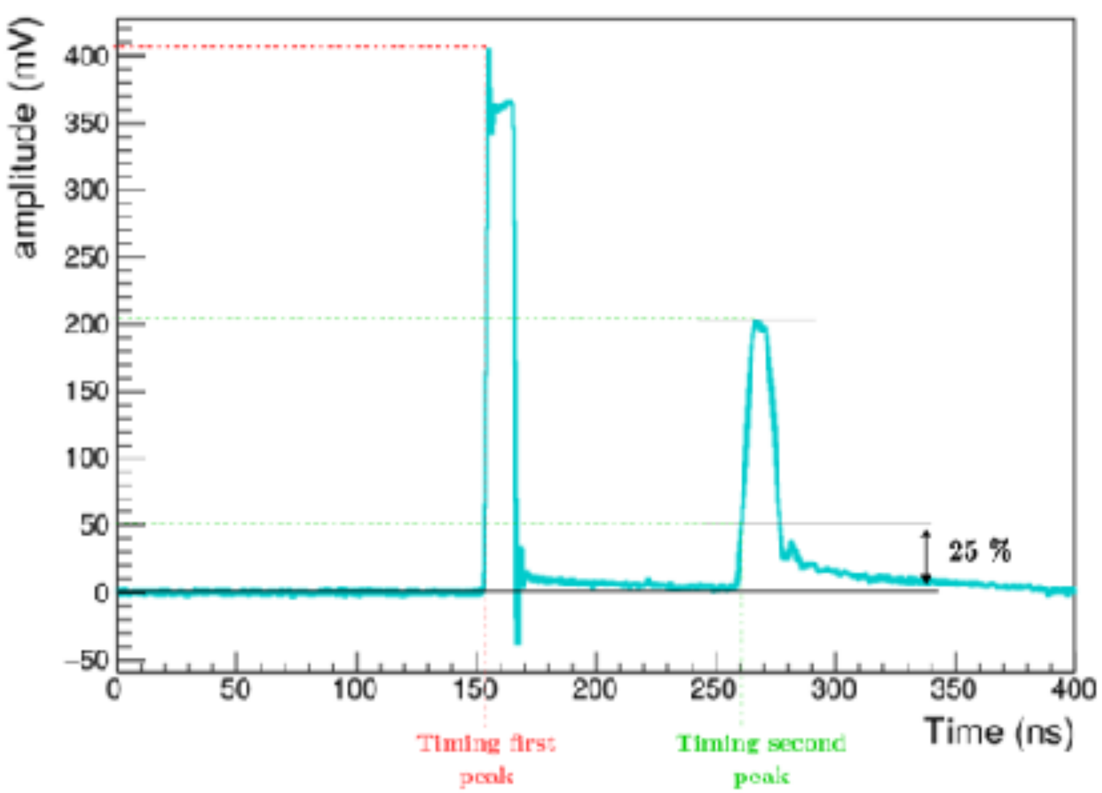
- Half-detector commissioning with Argon in March-June 2018
- **Detector closing in November 2018**
- **Calorimeter fully functional** (cabled, electronics, DAq) beginning of 2019, commissioning data collected since then
- Detector sealing operations, now reached overpressure in the tracker
- Currently finalising tracker cabling and electronics installation
- Coil and shielding installation in 2020
- **First data with fully shielded detector by 2020**

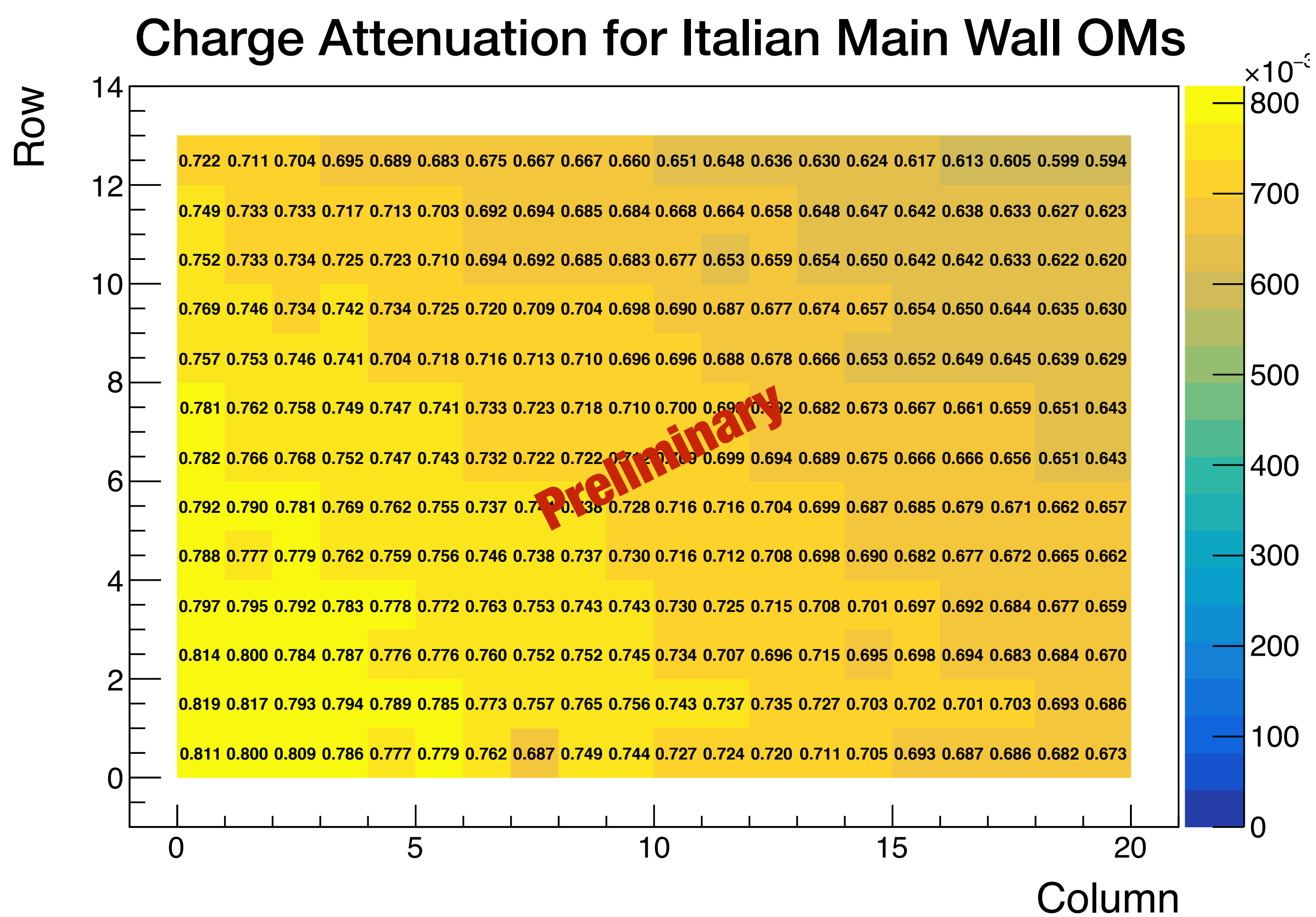
Outline

- What is the $0\nu\beta\beta$ and how we look for it with SuperNEMO?
- We are making a Demonstrator! With 6.3 kg ^{82}Se
- It builds on and enhances the NEMO technology
- **Is under commissioning!**
- It will search for the $0\nu\beta\beta$ and study the $2\nu\beta\beta$ of ^{82}Se

Detector Commissioning

- Since November 2018, we have been collecting data with the calorimeter, with different conditions (w/ or w/o ^{207}Bi source, single- vs multi-PMT trigger, light injection runs)
- Reflectometry: measure the reflection of a pulse on an OM to verify the cable length





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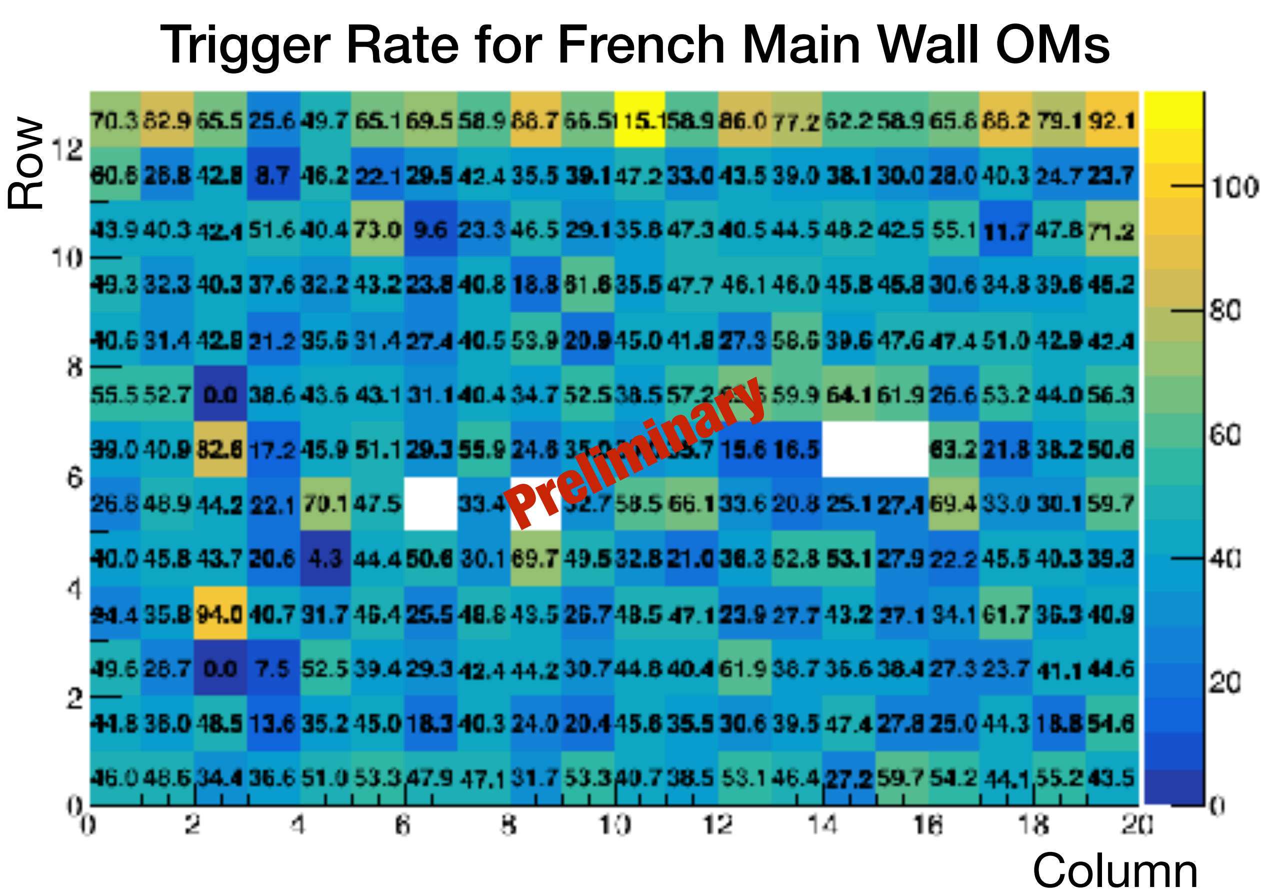
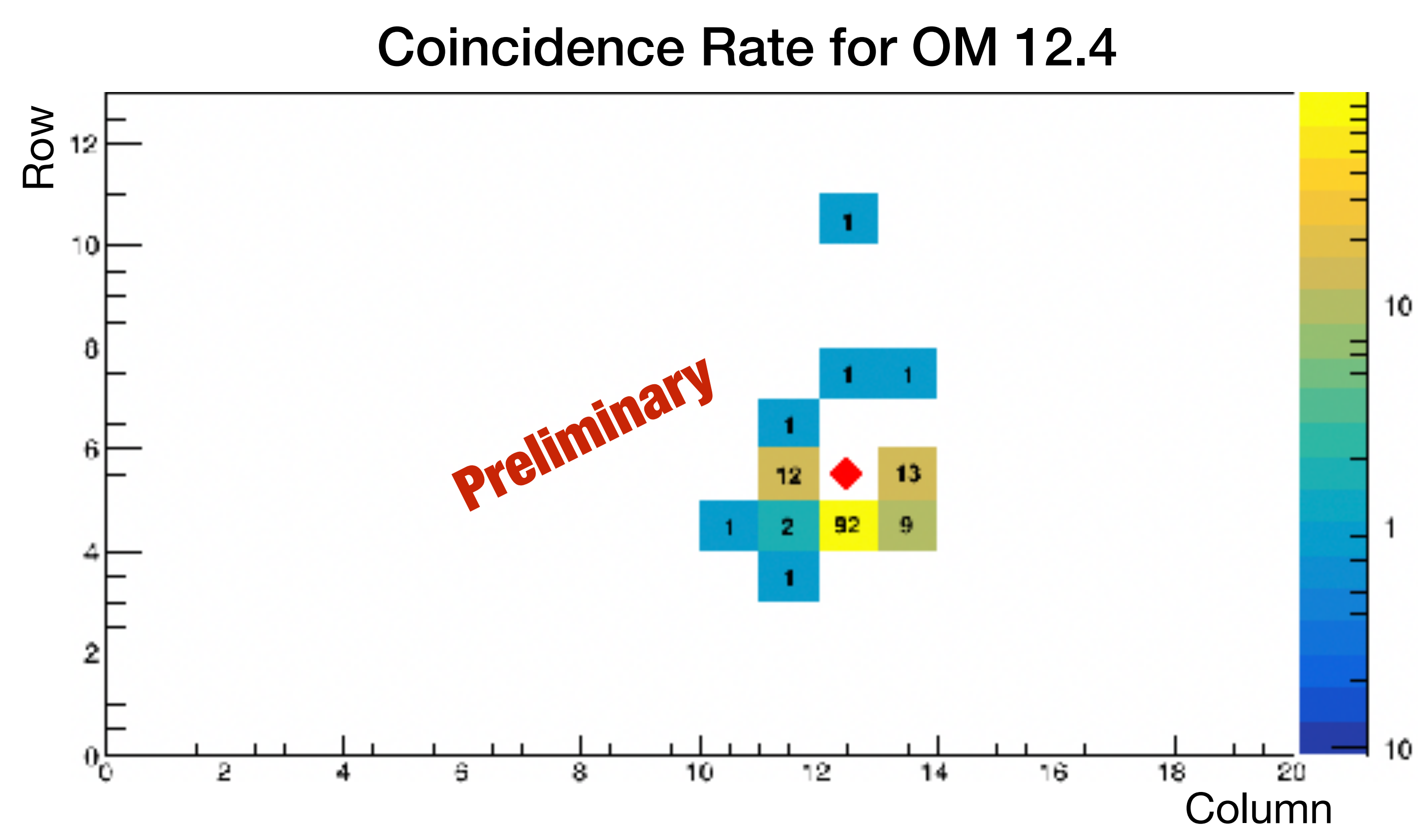
- PMT trigger rates and event time coincidence (cross-talk)





Detector Commissioning

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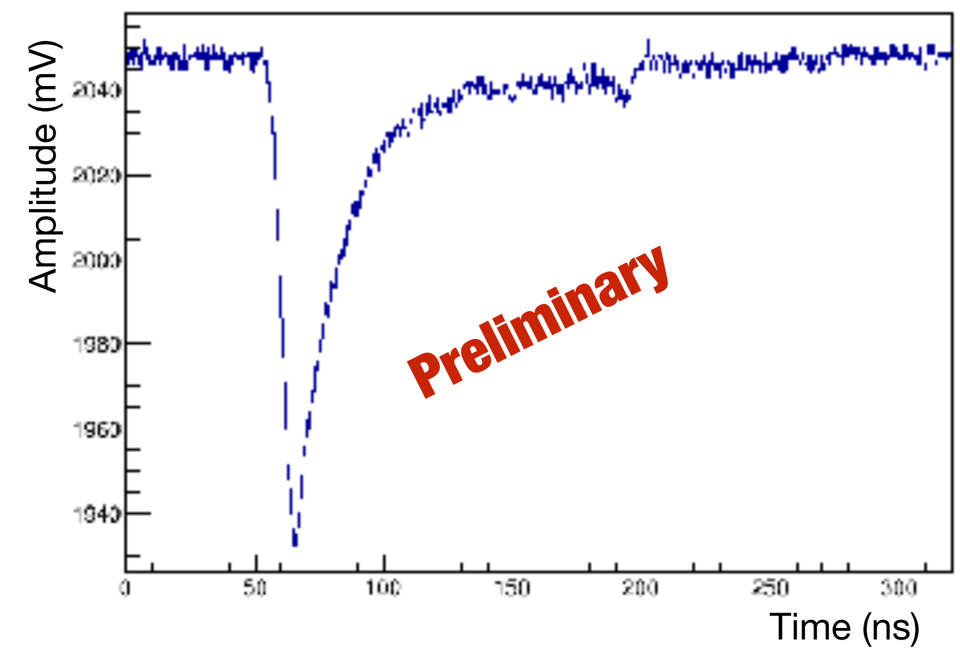
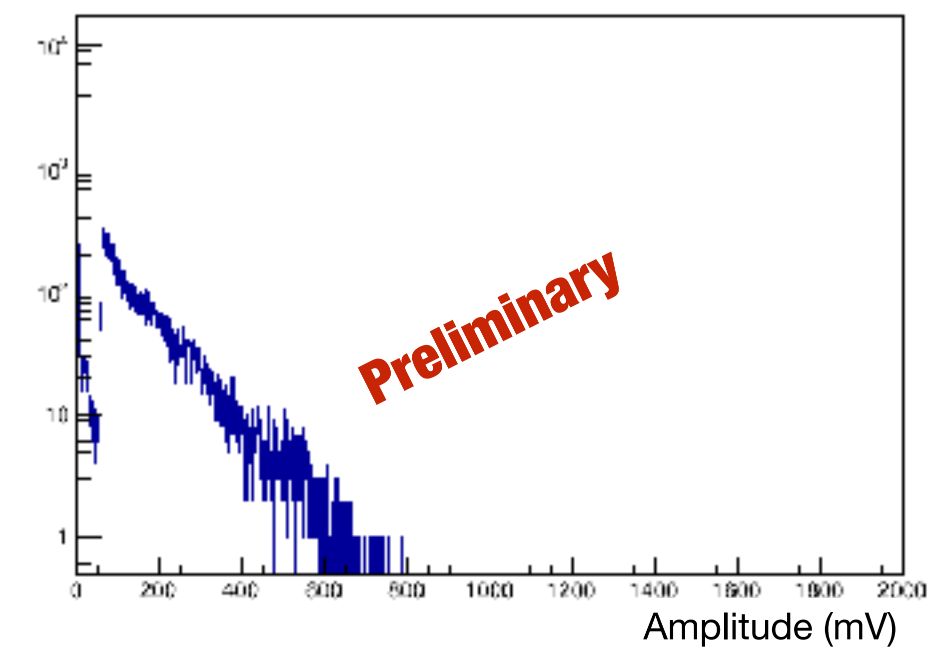
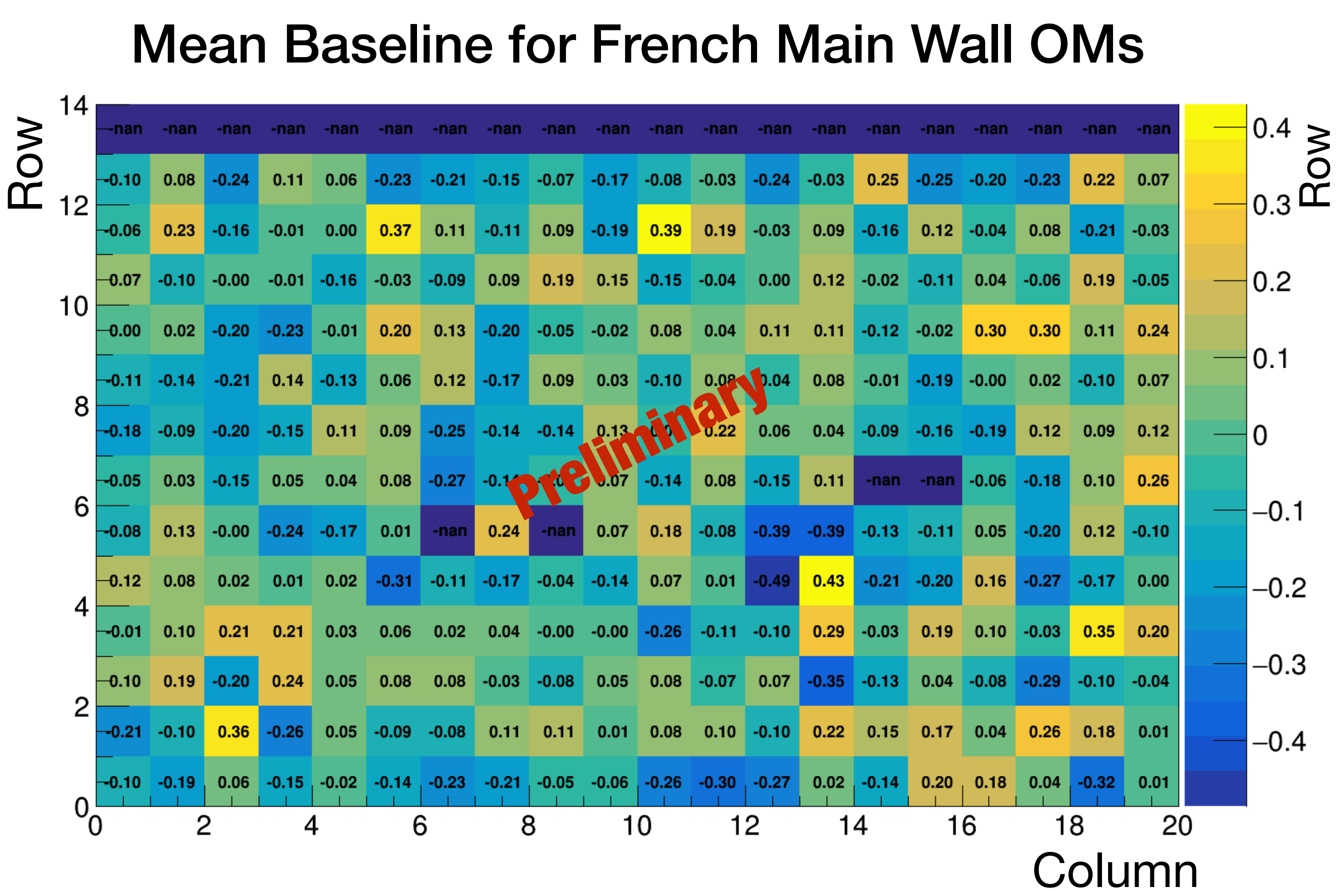
- Reflectometry: measure the reflection of a pulse on an OM to verify the cable length
- PMT trigger rates and event time coincidence (cross-talk)
- Waveform and baseline studies





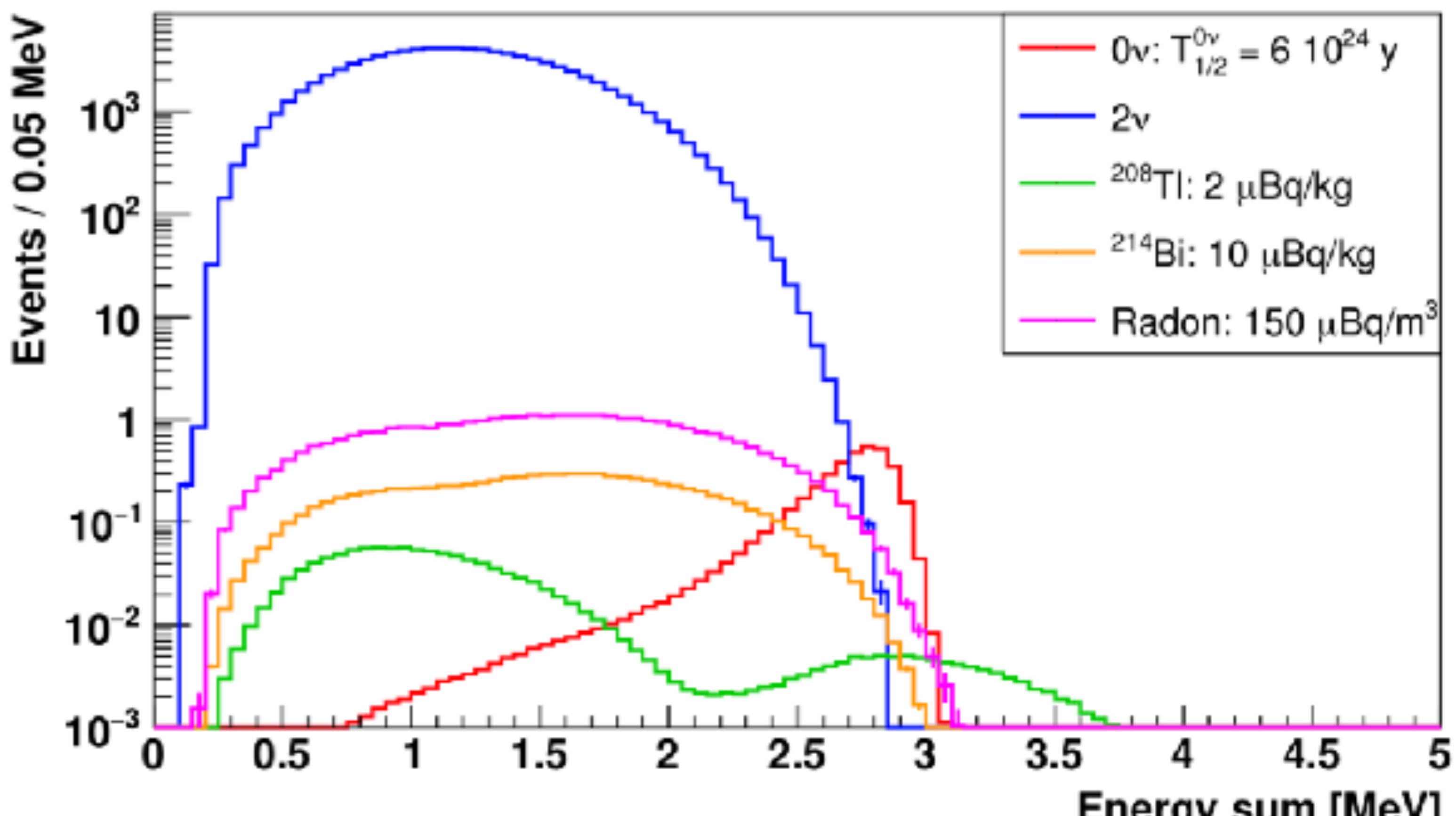


Outline

- What is the $0\nu\beta\beta$ and how we look for it with SuperNEMO?
- We are making a Demonstrator! With 6.3 kg ^{82}Se
- It builds on and enhances the NEMO technology
- Is under commissioning!
- **It will search for the $0\nu\beta\beta$ and study the $2\nu\beta\beta$ of ^{82}Se**

Physics Scope

- **^{82}Se 0νββ search, sensitivity goal: $T_{1/2} > 6 \times 10^{24}$ y ; $\langle m_\nu \rangle < 140$-$400$ meV**
- Single-state vs higher-state dominated 2νββ discrimination @ 5σ
- **Constraining of g_A**
- Search for exotic 0νββ mechanisms
- Possibility to extend to other isotopes (^{150}Nd, ^{48}Ca) to test 0νββ, 0ν4β



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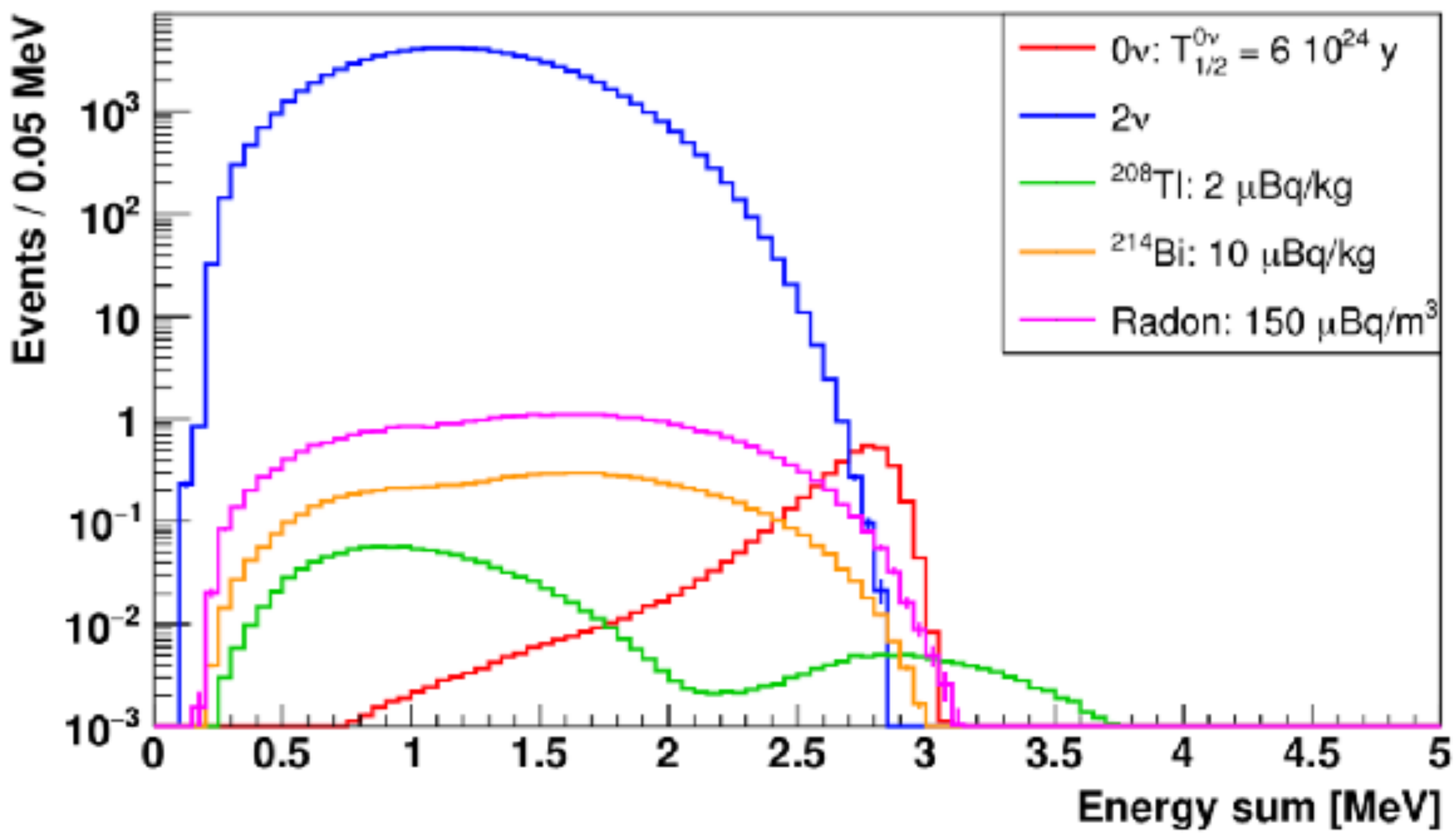
Profit from full ββ topology reconstruction

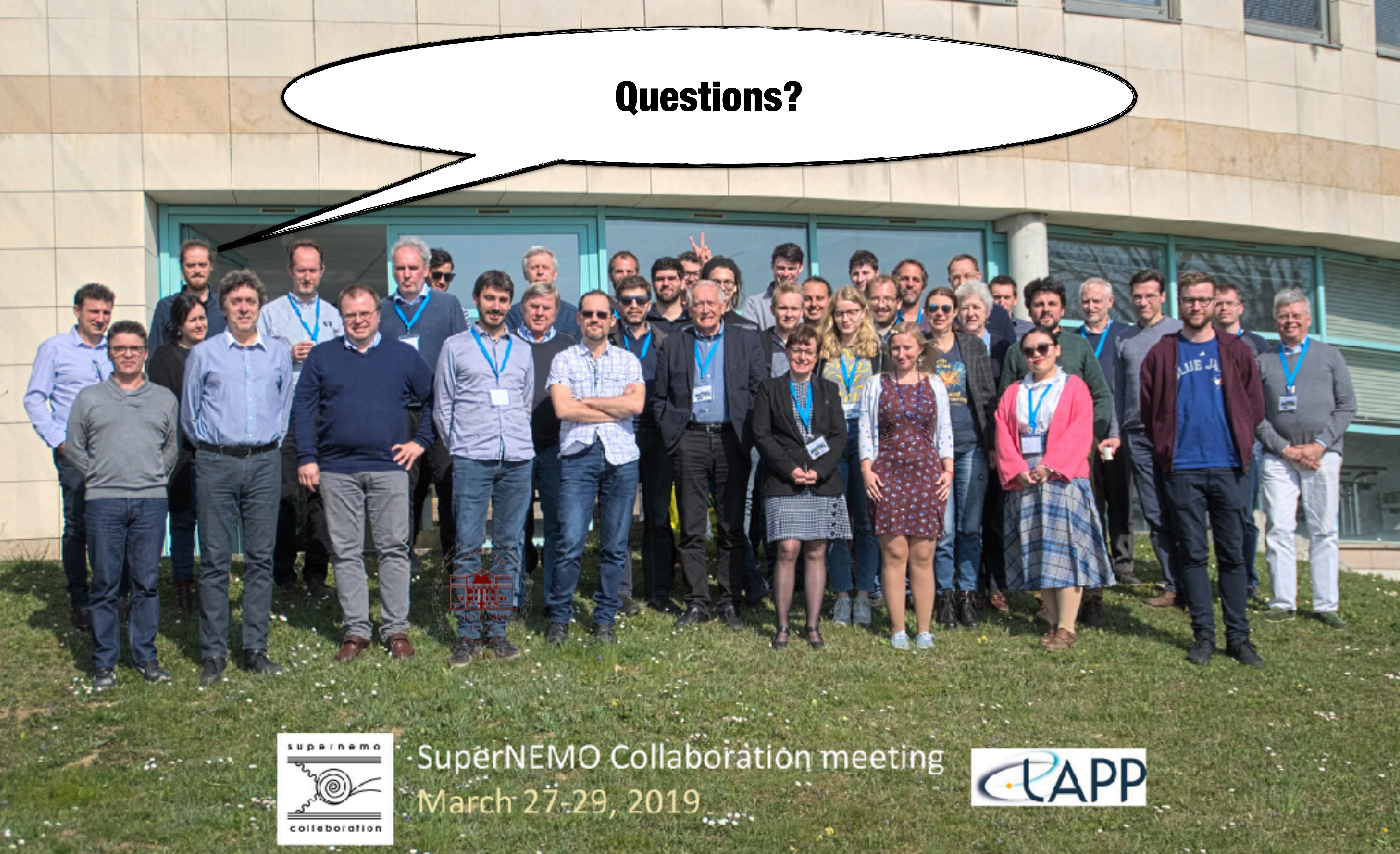
- Possibility to extend to other isotopes (^{150}Nd, ^{48}Ca) to test 0νββ, 0ν4β — Profit from modularity



Summary

- The SuperNEMO demonstrator is undergoing its final integration phase and commissioning at LSM
- First data with full detector in 2020! Stay tuned!
- It builds on the success of the NEMO tracking-calorimetric technique, and aims to improve the sensitivity to $0\nu\beta\beta$ thanks to a better background mitigation and event detection
- With 6.3 kg of ^{82}Se, we aim at reaching a sensitivity of $T_{1/2} > 6 \times 10^{24}$ y
- The scientific scope includes single-state vs higher-state dominance discrimination, the constraining of g_A, and the search for $0\nu4\beta$
- The demonstrator acts as a proof of principle of a full scale 100 kg multi-module detector, whose sensitivity will scratch into the inverted hierarchy region

CENBG
LSM
Imperial College London
Czech Technical University in Prague
INL Idaho National Laboratory
CPPM
LPC Caen
LAL Laboratoire de l'Accélérateur Linéaire
UCL
MANCHESTER 1824 The University of Manchester
TEXAS The University of Texas at Austin



CENBG
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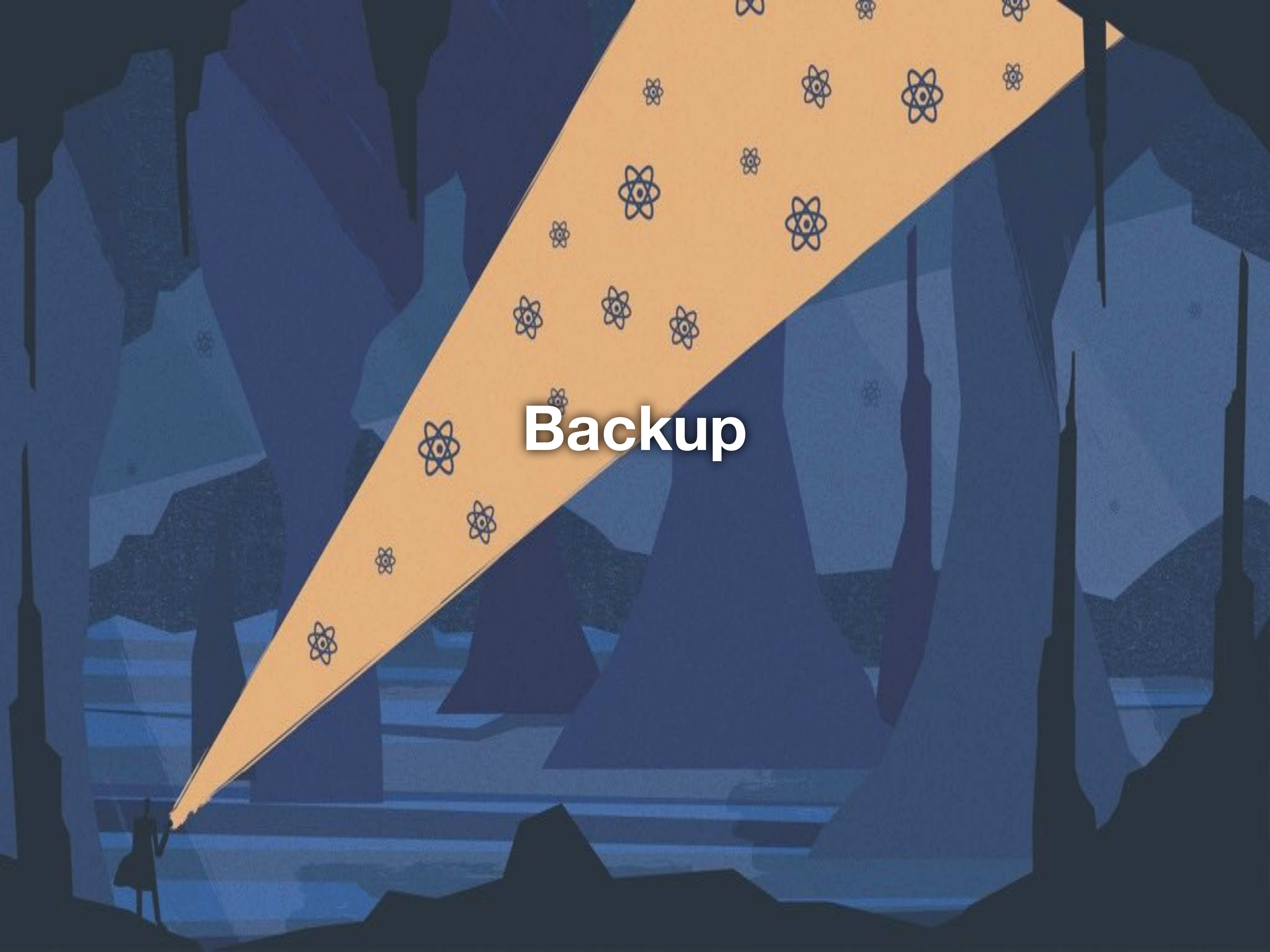
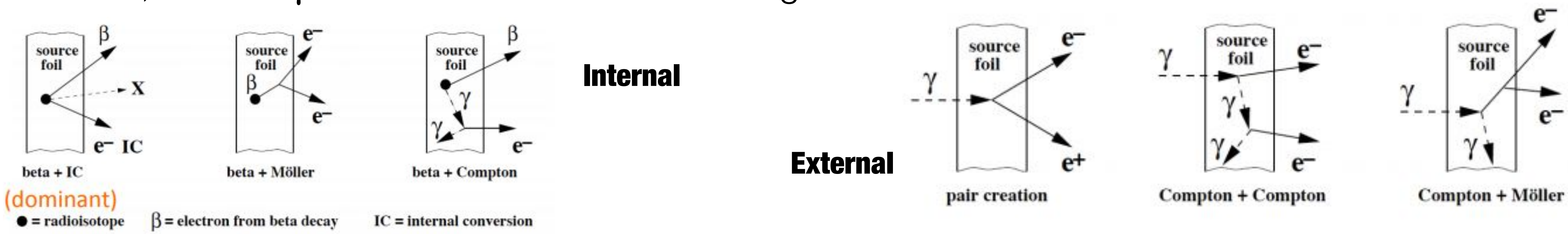

Backup

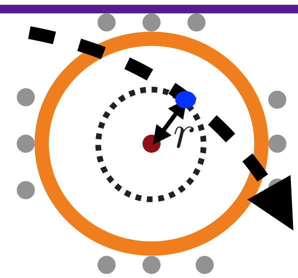
Event Selection

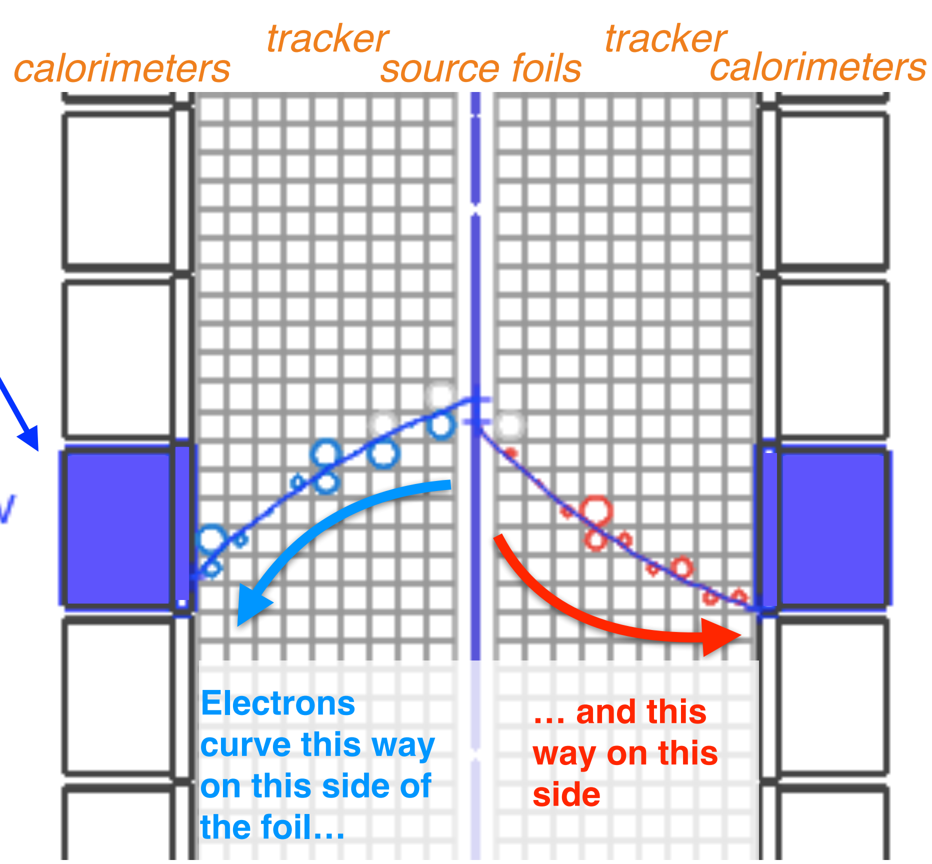
- Electrons, α's and γ's are reconstructed combining the tracker and calorimeter signals



e⁻

Tracker hits appear as circles (radius depends on drift time)



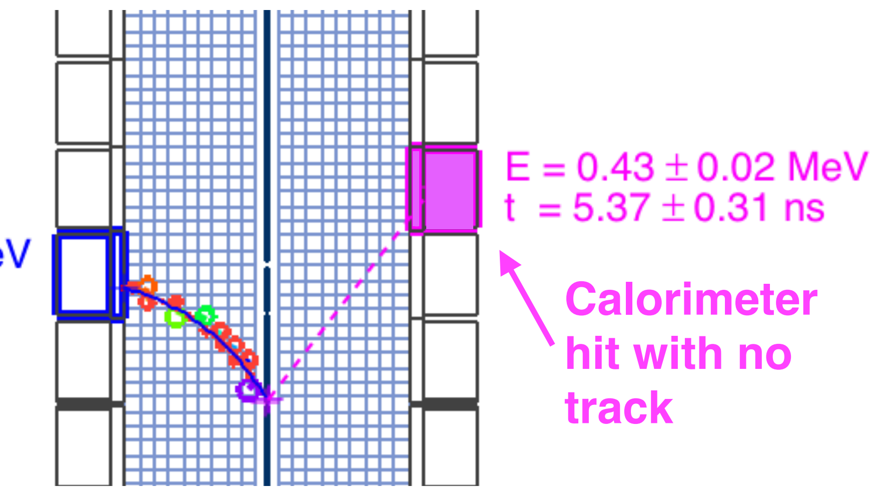


Individual electron energy and time

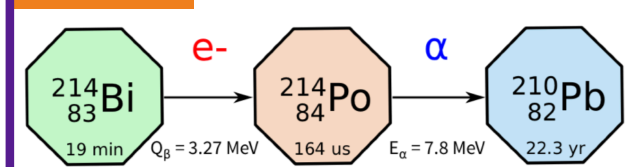
= 2.01 ± 0.05 MeV
= 2.02 ± 0.14 ns

Plan view (partial)

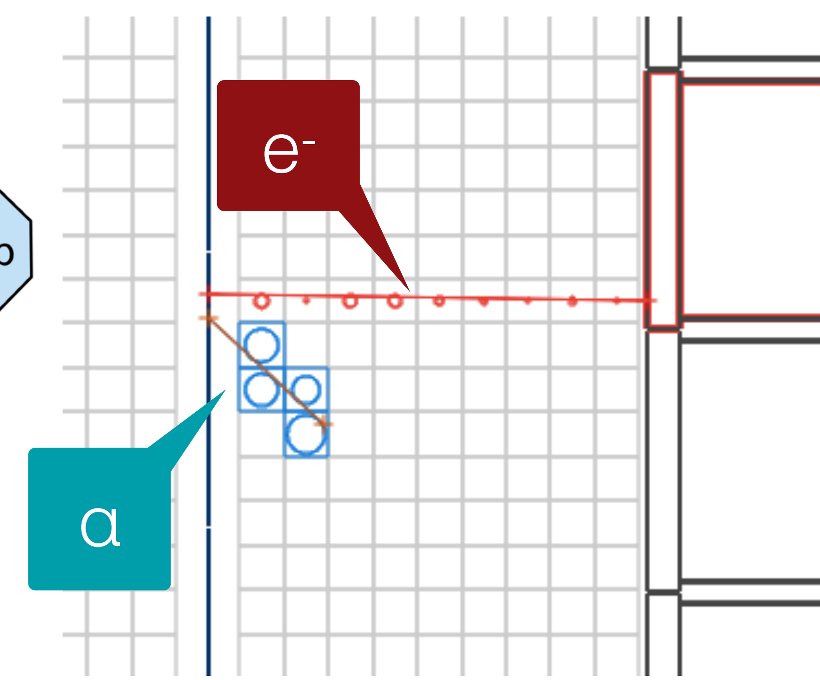
γ



α



Short, straight tracks a few μs **after an electron** are characteristic of **alpha particles** from ^{214}Bi-^{214}Po decays



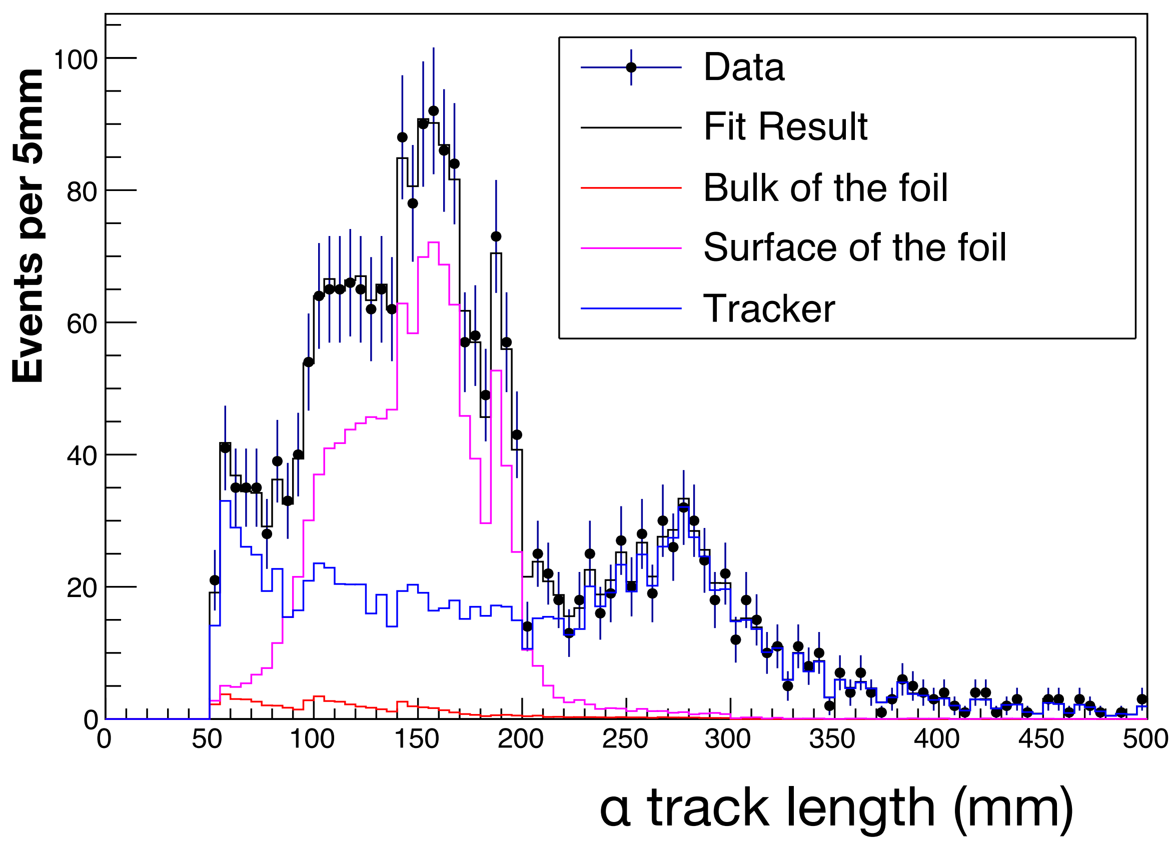
$0\nu\beta\beta$ Sensitivity Estimation

- ^{214}Bi background from Rn gas or ^{238}U chain is estimated using Bi-Po coincidence and α tracks
- ^{208}Tl background is estimated using energy of γ's

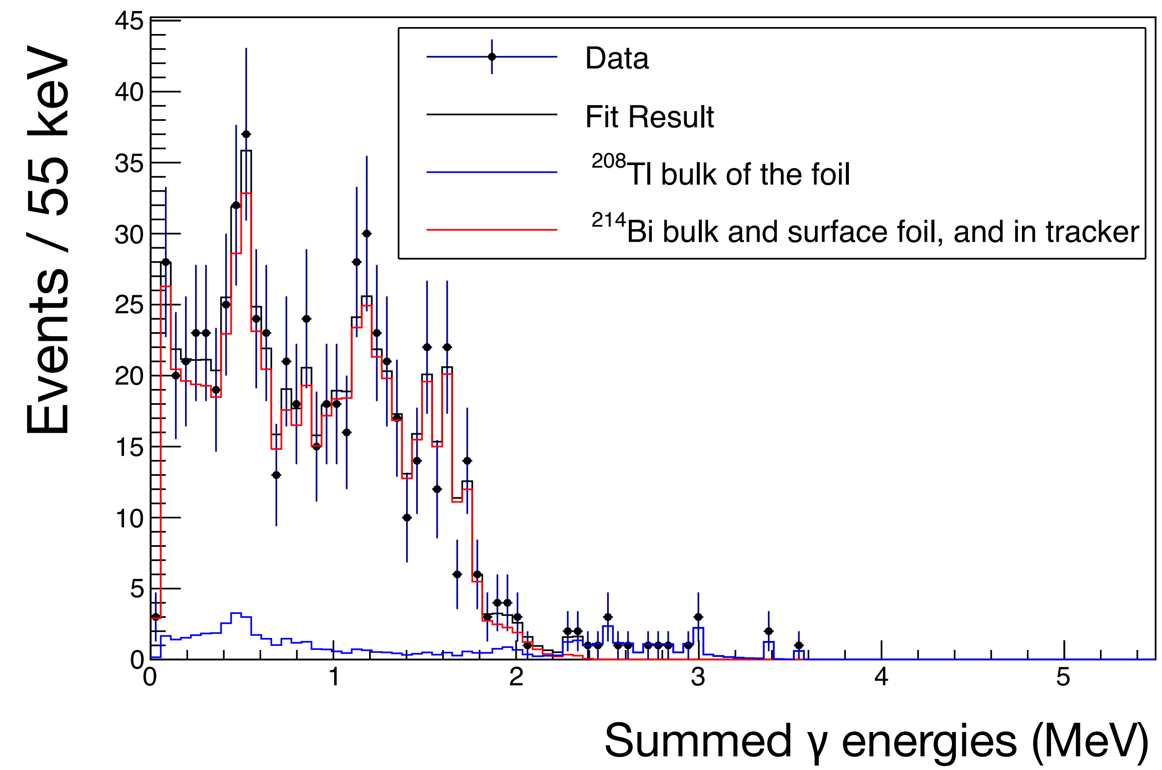
$$^{214}_{83}Bi \rightarrow ^{214}_{84}Po + \beta \rightarrow ^{210}_{82}Pb + \alpha$$

$T_{1/2}=164\mu s$

Fitted ^{214}Bi activities: after 675 days



Fitted ^{208}Tl and ^{214}Bi activities: after 200 days



Measuring g_A in NEMO

New **KamLAND-Zen** paper investigates g_A quenching for $2\nu\beta\beta$ in ^{136}Xe *Phys Rev Lett 122, 192501 (2019)*

$$\left(T^{2\nu}_{1/2}\right)^{-1} \simeq \left(g_A^{\rm eff}\right)^4 \left|M^{2\nu}_{\rm GT}\right|^2 G^{2\nu}_0$$

Phys Rev C 97. 034315 (2018)

$$\left(T^{2\nu}_{1/2}\right)^{-1} \simeq \left(g_A^{\rm eff}\right)^4 \left|\left(M^{2\nu}_{GT}\right)^2 G^{2\nu}_0 + M^{2\nu}_{GT} M^{2\nu}_{GT-3} G^{2\nu}_2\right|$$

$$= \left(g_A^{\rm eff}\right)^4 \left|M^{2\nu}_{GT-3}\right|^2 \frac{1}{\left|\xi^{2\nu}_{31}\right|^2} \left|G^{2\nu}_0 + \xi^{2\nu}_{31} G^{2\nu}_2\right|$$

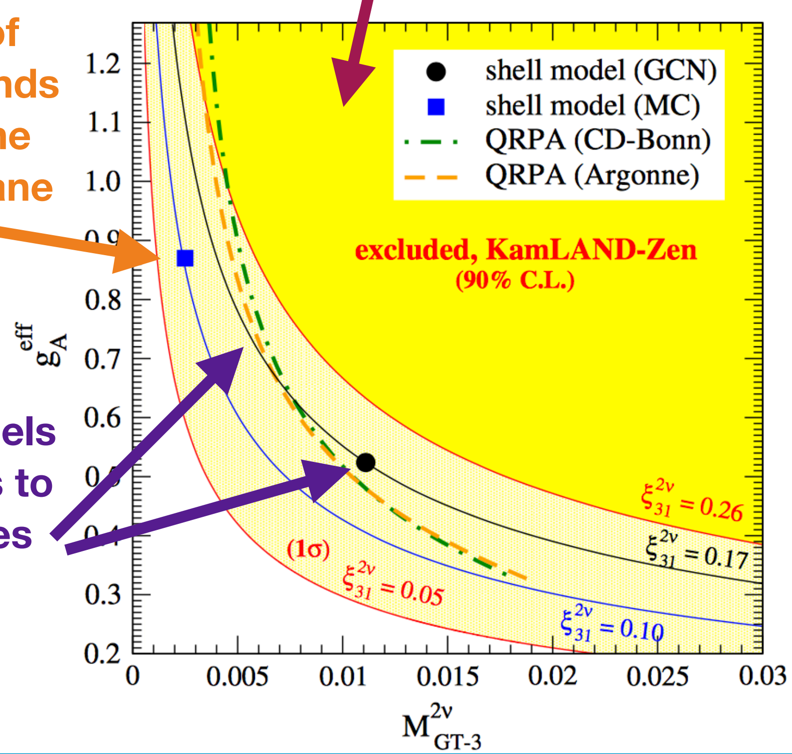
Only sensitive to lower-lying states (easier to calculate)

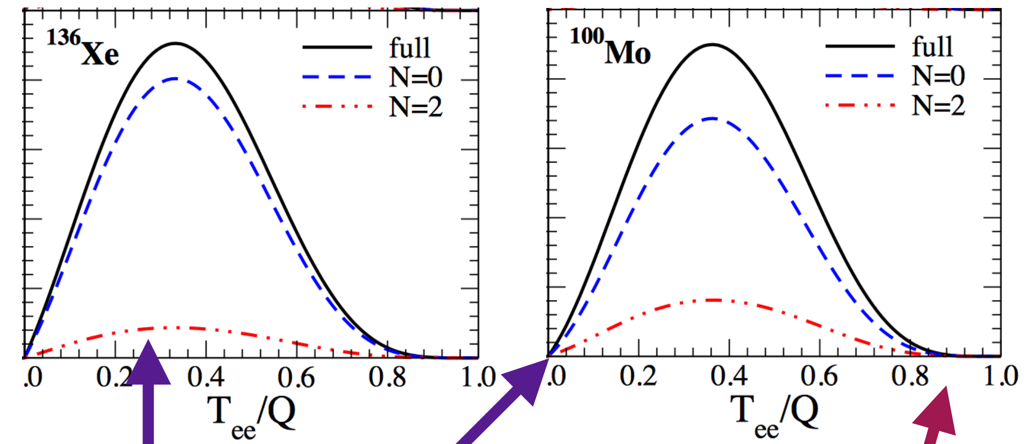
Ratio of matrix elements

KamLAND-Zen excludes ξ_{31} >0.26

Each value of ξ_{31} corresponds to a line in the g_A / M_{GT-3} plane

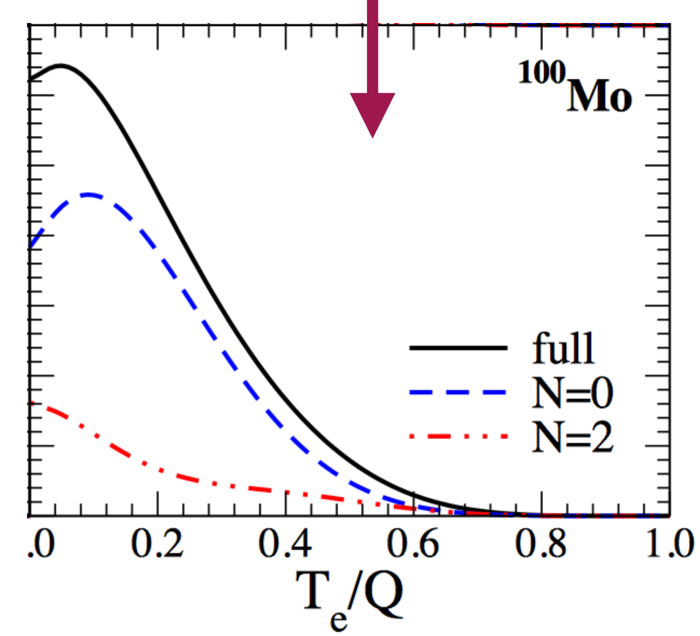
Different nuclear models corresponds to points or lines in the plane





Contribution from second term is larger in ^{100}Mo than ^{136}Xe

Individual electron spectrum has better shape differentiation than 2-electron spectrum



Courtesy of C Patrick, UCL