Status of the SuperNEMO demonstrator, a double-beta-decay experiment

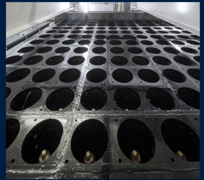
TAUP 2025

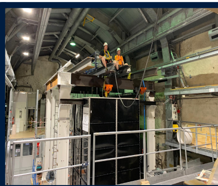
Xalbat Aguerre University of Edinburgh, on behalf of the SuperNEMO collaboration







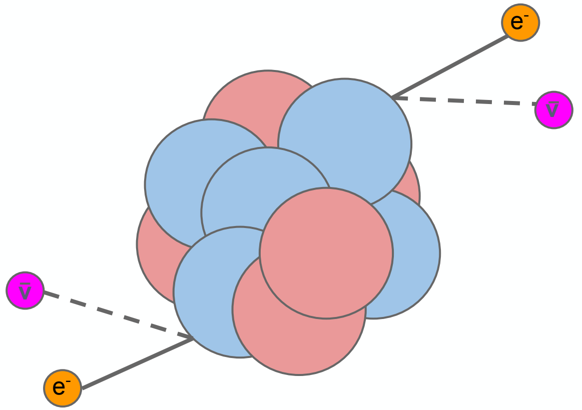




Double beta decay

Standard Model double beta decay

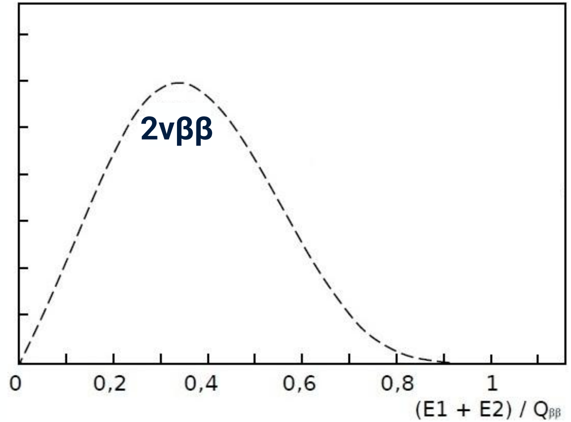
$(A,Z) \Rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ **2νββ**



Only possible when **β decay is forbidden** for energetic reasons
Experimentally observed
Very long half-life = 10^{18-21} yrs

Q value (~MeV) shared between electrons and neutrinos
➔ Summed electron energies form a **continuous spectrum**

2νββ decay electrons energy spectrum

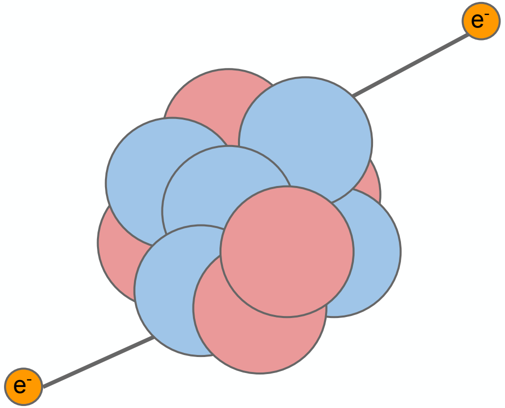


Double beta decay

Neutrinoless double beta decay

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

0νββ



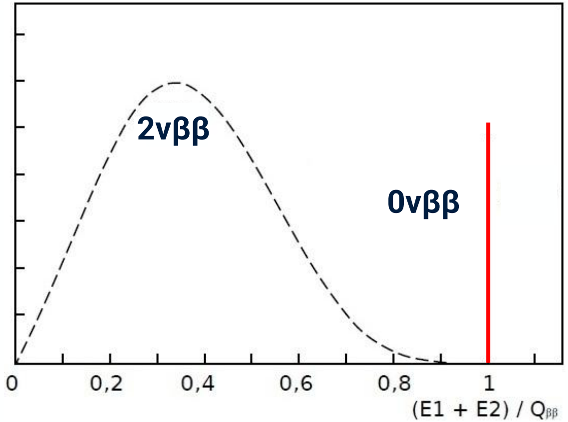
Forbidden by the Standard Model (Lepton number violation)

Virtual neutrino exchange

➔ Only **two e⁻** as outcome that share all the decay energy

➔ Forms **a monoenergetic peak**

2/0νββ decay electrons energy spectrum

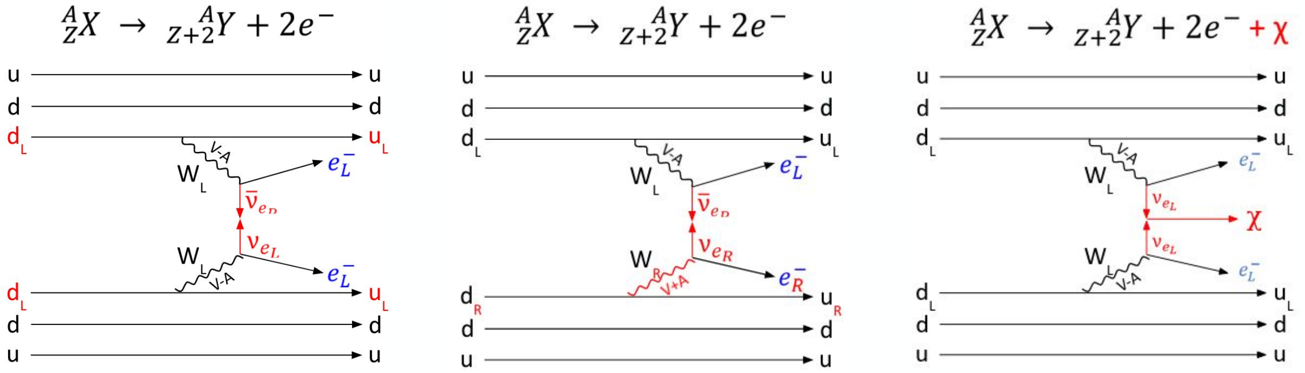


If observed ⇒ proof of the **Majorana nature** of neutrinos

Very high half life (> 10^{26} y for ^{136}Xe)

New Physics with SuperNEMO

0νββ mechanism discrimination



V-A current

V+A current

Majoron emission

...

Mechanisms distinguishable by:

- e^- individual energy
- e^- angular distribution

SuperNEMO is the only experiment fully able to study these mechanisms!

R. Arnold et al. "Probing New Physics Models of Neutrinoless Double Beta Decay with SuperNEMO" [Eur. Phys. J. C70:927-943, 2010]

SuperNEMO collaboration

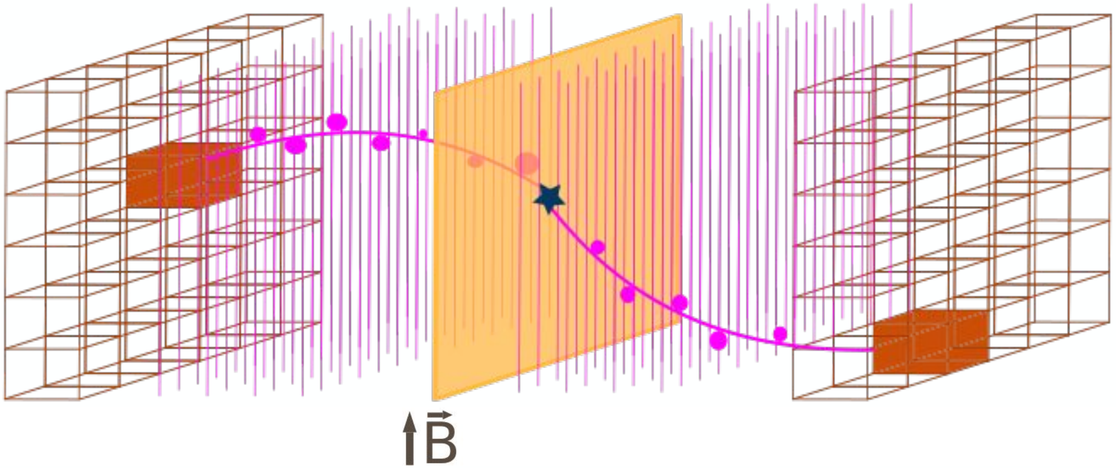
~100 collaborators over 8 countries

Collaboration meeting in Marseille last year

Collaboration meeting in Edinburgh two years ago

SuperNEMO double beta decay experiment

Unique tracker/calorimeter approach



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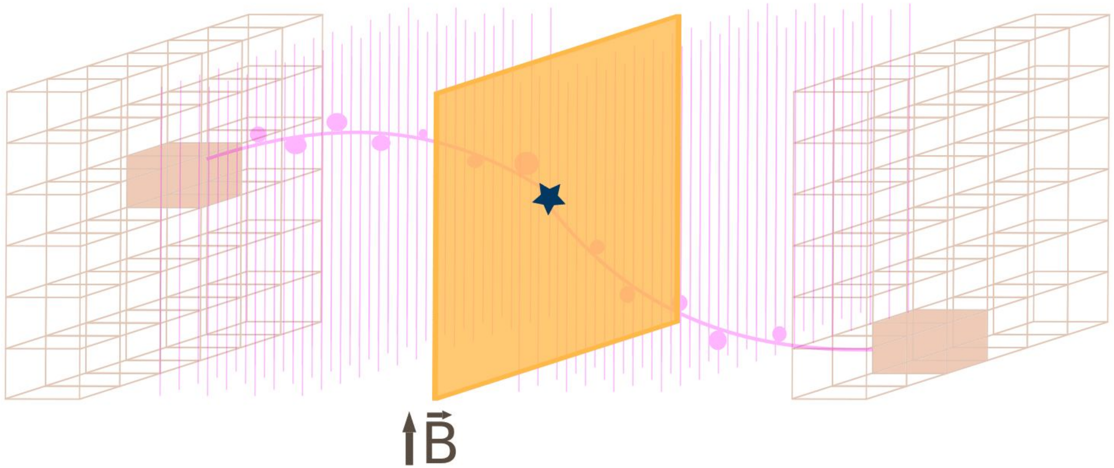

1. **ββ source foil:** free choice of solid **isotopes**

SuperNEMO double beta decay experiment

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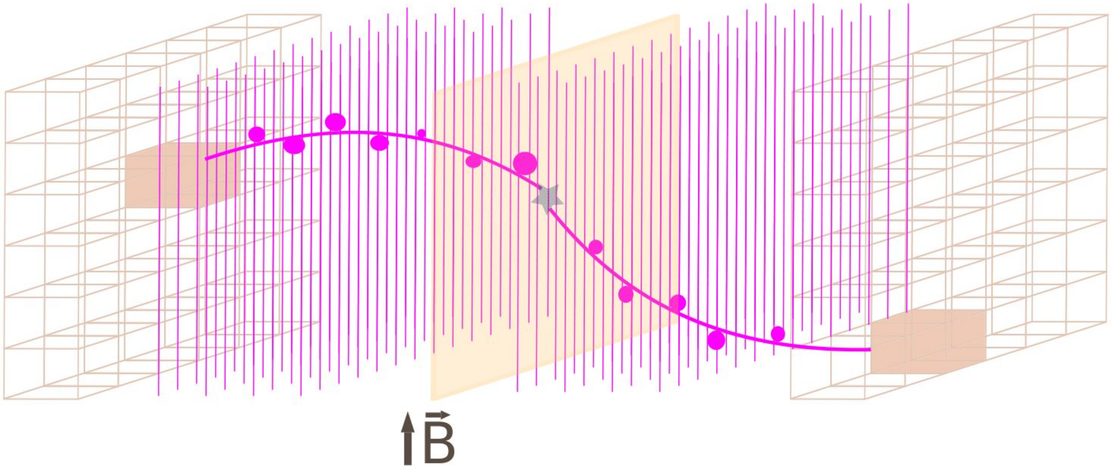

1. **ββ source foil:** free choice of solid **isotopes**
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SuperNEMO double beta decay experiment

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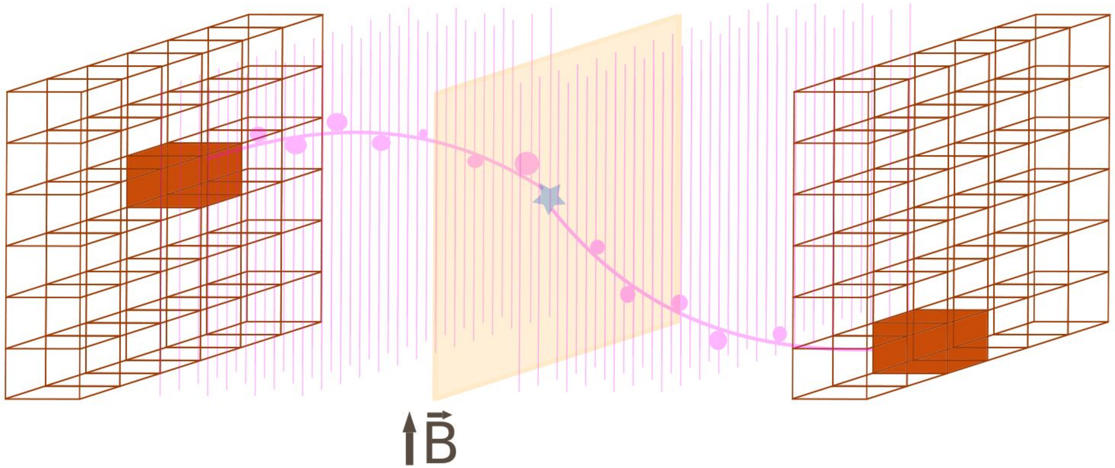

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SuperNEMO double beta decay experiment

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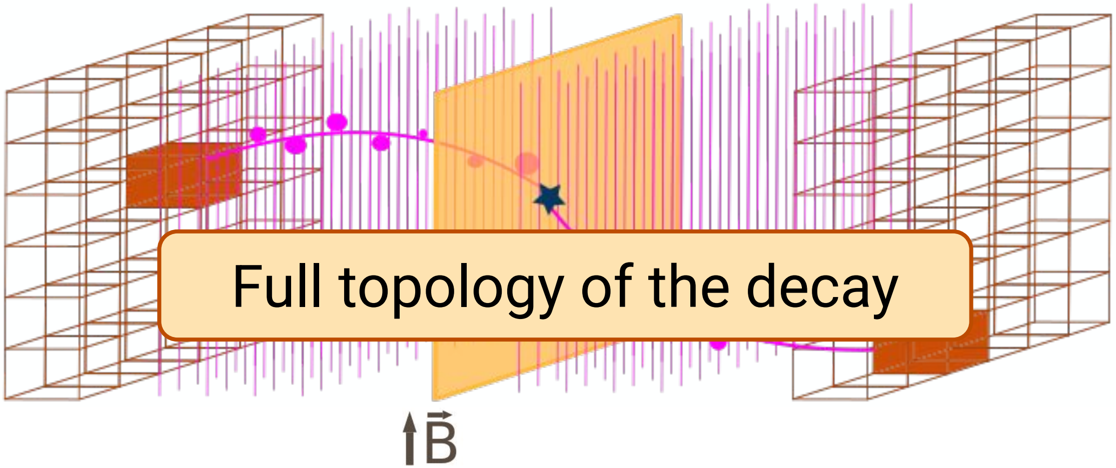

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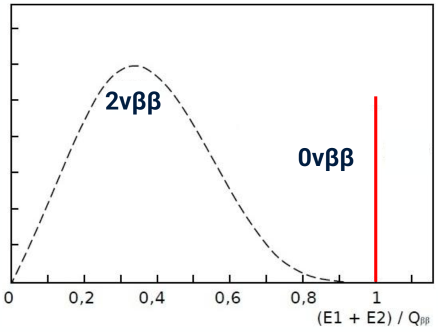
SuperNEMO strengths

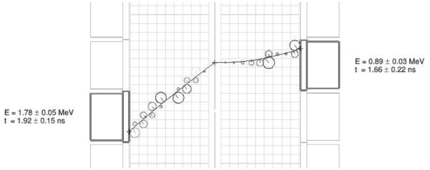
All experiments

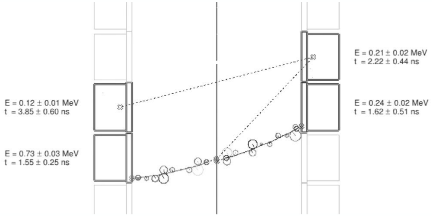


Total energy

SuperNEMO only

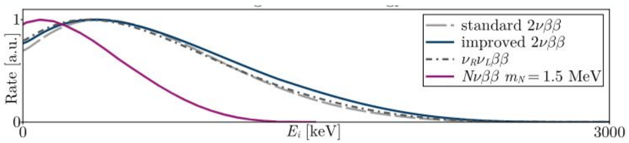
0νββ Golden event



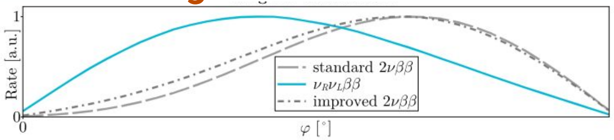


Background rejection by event identification

Individual e⁻ energy



Angular distribution



Free-isotope choice

SuperNEMO demonstrator

Demonstrator built in Modane Underground laboratory (LSM), France, 4800 m.w.e

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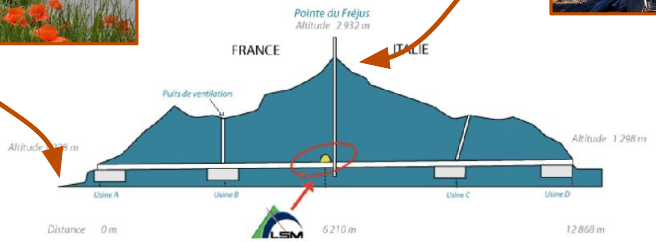
Demonstrator built in Modane Underground laboratory (LSM), France, 4800 m.w.e

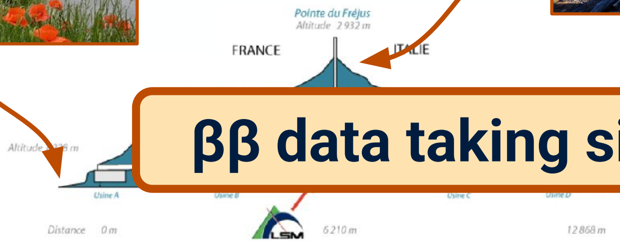


Successor to NEMO-3, who obtained numerous world leading results
Demonstrator **objectives**:

- Demonstrate the capability of tracker/calorimeter approach
- **Scalability** for a future large-scale detector
- Precision measurement of the **2νββ decay kinematics**
- 0νββ search background-free in the ROI (~ 3 MeV)

SuperNEMO demonstrator

Demonstrator built in Modane Underground laboratory (LSM), France, 4800 m.w.e



ββ data taking since April 10, 2025 !!!

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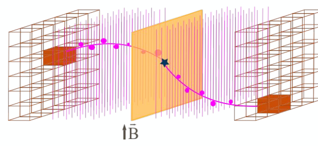
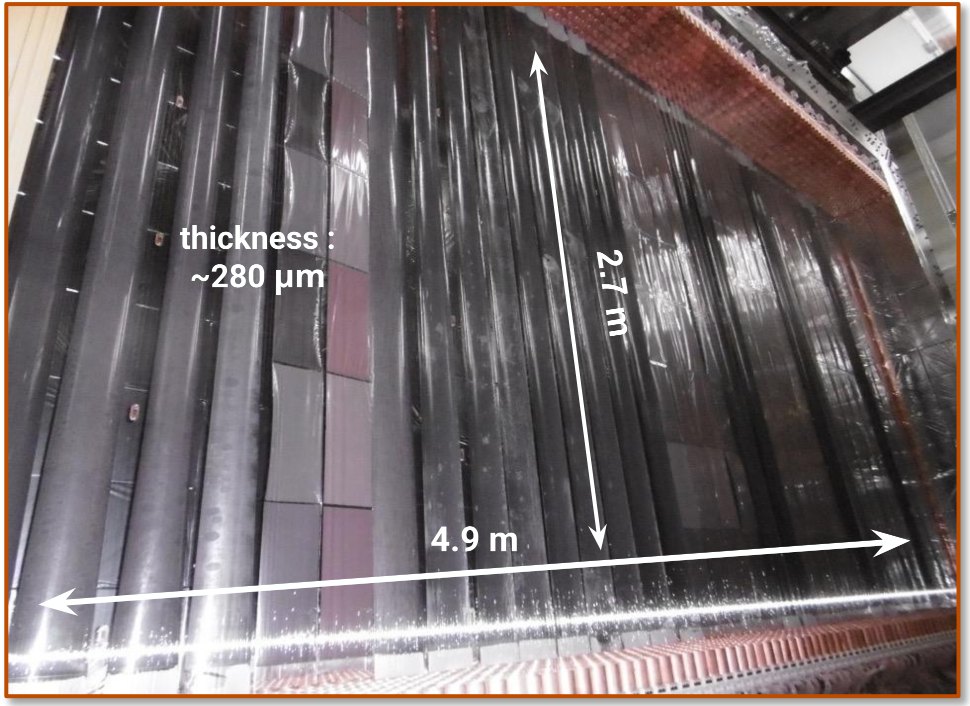
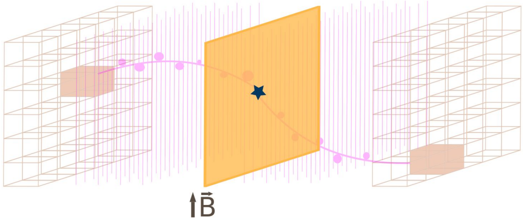
SuperNEMO as technology demonstrator



^{82}Se source foils





34 ^{82}**Se** foils, i.e **6.11 kg** (96-99% enriched)

- High $Q_{\beta\beta}$ = 2.998 MeV
- High $T^{2\nu}_{1/2}$ = 9.4 x 10^{19} years

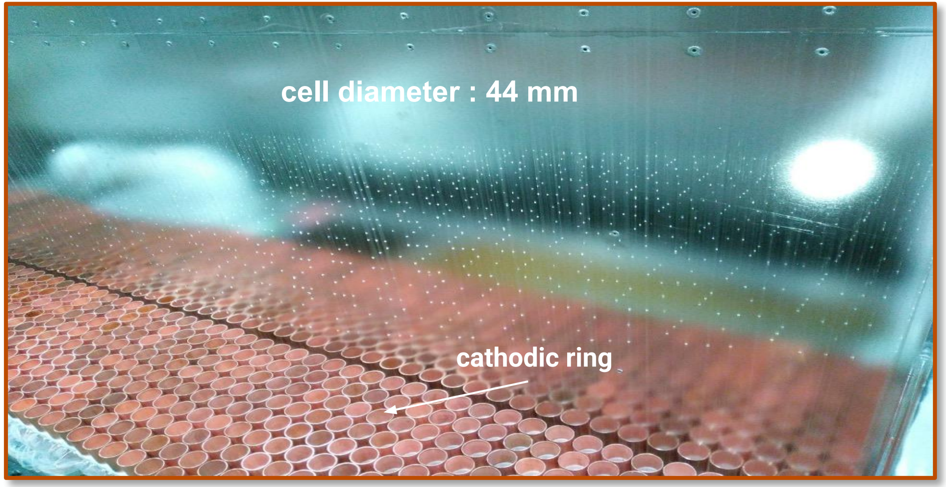
Technology demonstrator:

- Foils geometry
- ββ emitting powder production
- Purification

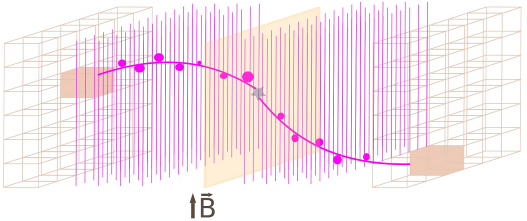
(target: 2 µBq/kg ^{208}Tl; 10 µBq/kg ^{214}Bi)

Radiochimica Acta, 108 (2020) 11

Tracker



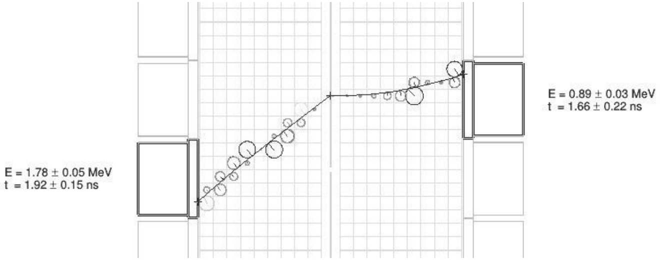
2034 cells (14970 wires) in Geiger mode (98.4% working)
3D track reconstruction:
Tracker gas ionisation, plasma creation and propagation
Scalable geometry



Gas mixture optimisation:

- 95% He (low energy losses)
- 1% Ar (low ionisation)
- 4% ethanol (quencher)

3D track reconstruction example



Tracker - Anti-radon technique

SuperNEMO goal: 150µBq/m^3
Measured 10-15 mBq/m^3 before anti-radon strategies (2024)

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Diffusion from the laboratory's air

- Anti radon tent
- Filled with radon-reduced air (active charcoal)

Anti-radon tent

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Tracker gas

- Gas de-radonisation with charcoal
- Constant gas flushing (5 - 20 L/min)

-80°C
6X500 cm^3 charcoal
⇨ radon capture
⇨ Very pure gas needed

-50°C
2X500 cm^3 charcoal
⇨ pre-cooling the gas
⇨ capture trace of vapour

Radon capture system

Anti-radon tent

Tracker - He recycling system

Poster # 197

He consumption: 5-20 L/min

Recycling:
- High global helium prices
- Environmental concerns
- Scalability to large systems

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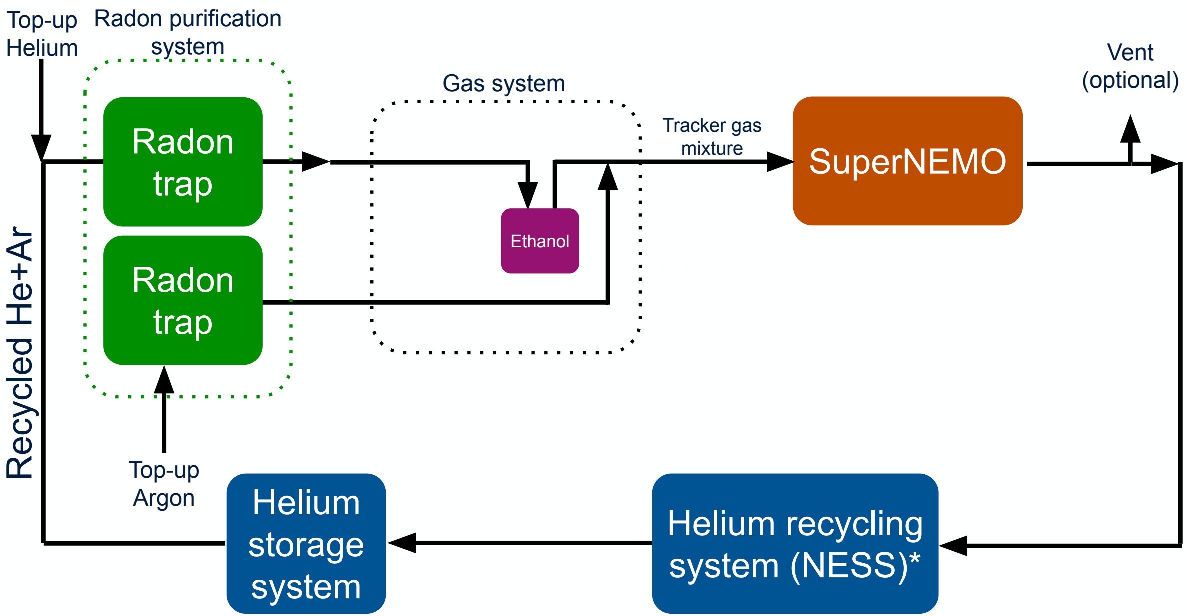
Low **radon activity** needed

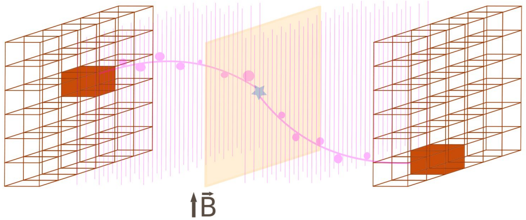
Radon trap: **no ethanol!**

Gas recycling: remove ethanol



Calorimeter

712 Optical Modules
(scintillator + photomultiplier)



Time resolution:
- Gammas, 615 ps measured
- Electrons, 250 ps goal at 1 MeV

Energy resolution:
- Target 8 % FWHM at 1 MeV

(measurements ongoing)

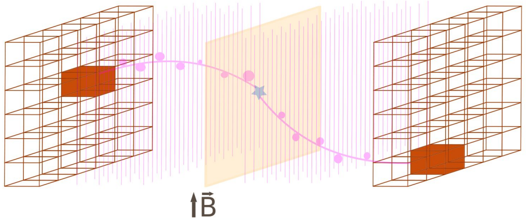
Nonlinearity corrections implemented

One of the calorimeter walls prior to the detector's closure

Nucl.Inst.Meth. A 868 98-108 (2017): arXiv:2501.13755 JINST accepted

Calorimeter - energy calibration

Calibration goal: 1% precision (measurements ongoing)



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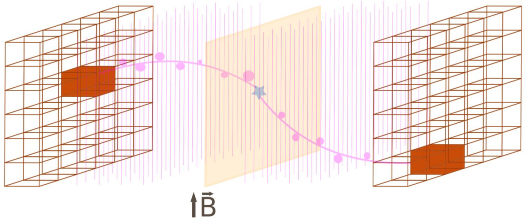
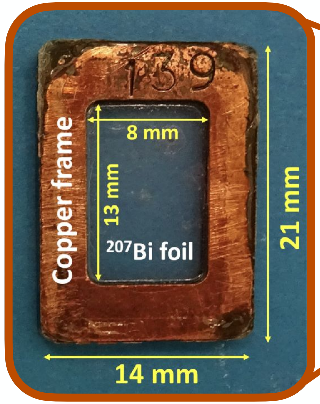
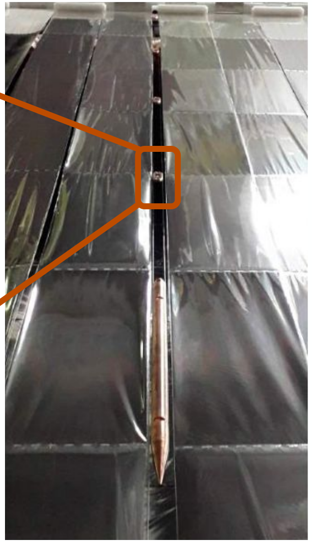


Absolute ^{207}Bi calibration

- Automatic deployment system
- 42 sources at ~120 Bq
- Weekly 6h calibration





^{207}Bi sources /
automatic deployment system

Calorimeter - energy calibration

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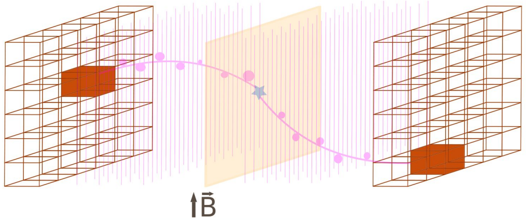

Absolute ^{207}Bi calibration

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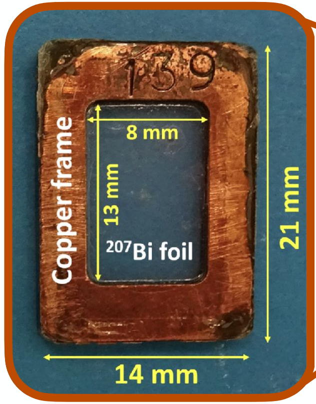
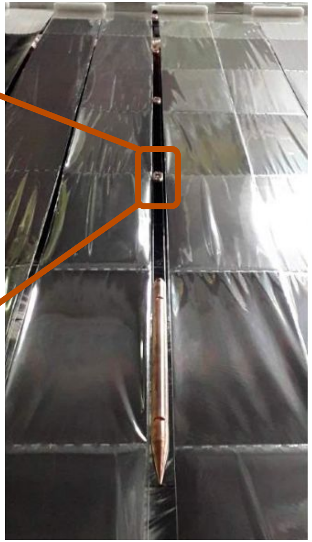
Relative Light Injection calibration

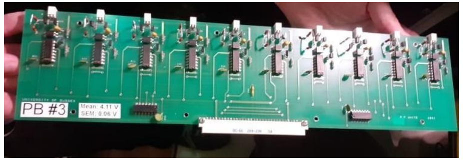
- LED system to flash all optical modules
- LED calibrated by external optical modules
- Daily ~15 min relative calibration





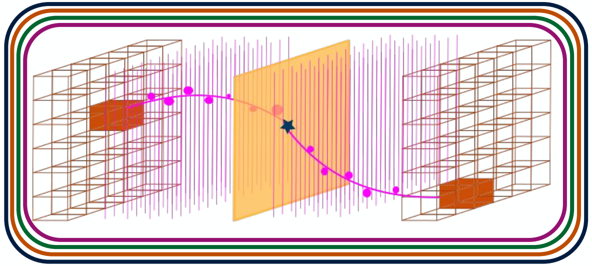
^{207}Bi sources / automatic deployment system

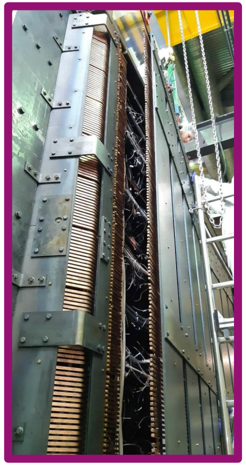
10 calibration LED



Shielding

Goal: ~ 1 event in 3 years in 0νββ ROI

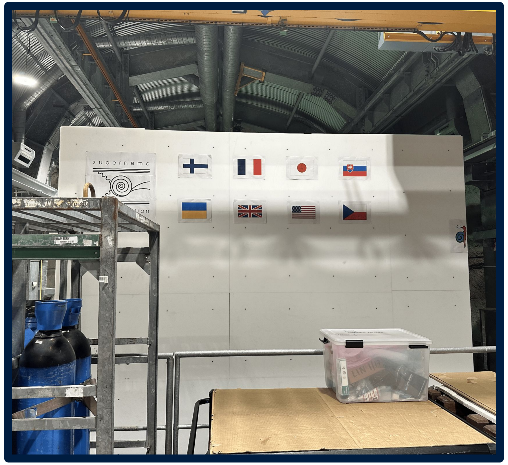




Magnetic coil (25G)
pair creation

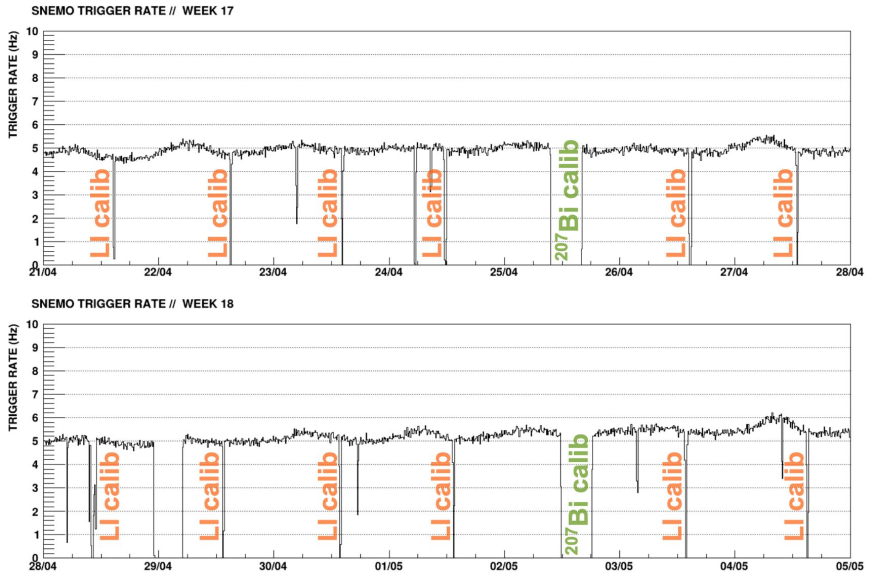
Anti-radon tent
external radon

Iron shielding (18 cm)
ambient gamma



Polyethylene shielding (24cm)
ambient neutron

ββ data taking ongoing



Typical two weeks duty cycle

Average duty cycle:

- **92% in ββ mode**
- 4.8% weekly ^{207}Bi calibration
- 1.2% daily light-injection calibration

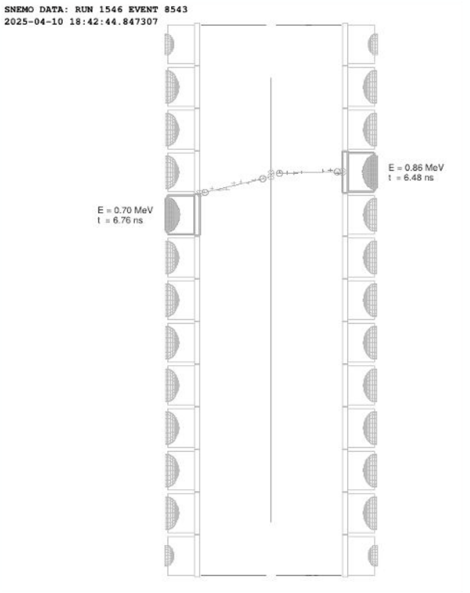
~2.5 kg/y data collected since April

First ββ candidate!

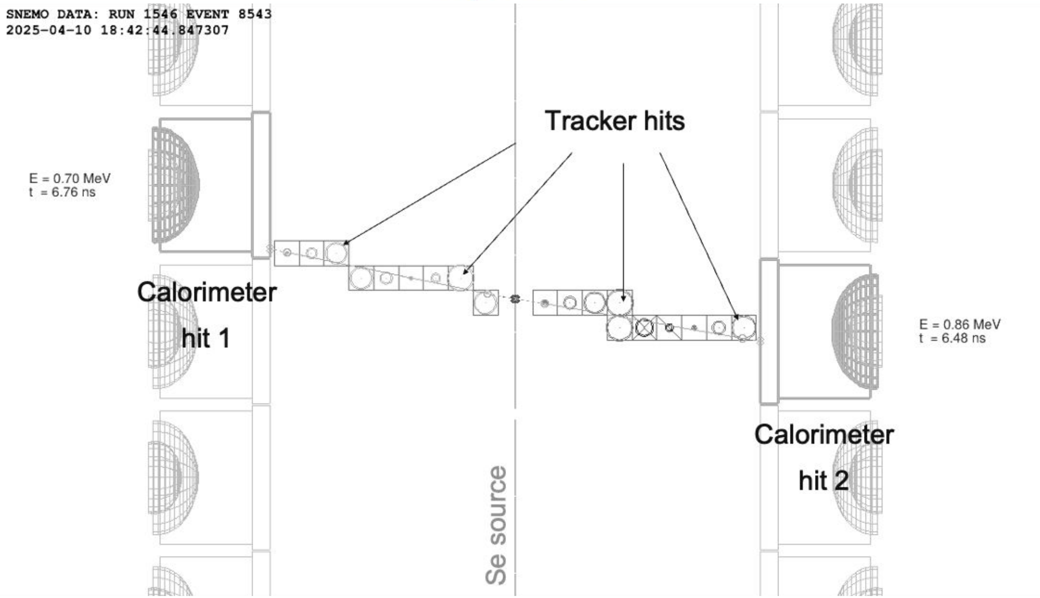
10 April 2025 18:42:44

$E_{e1}+E_{e2} \sim 1.56$ MeV

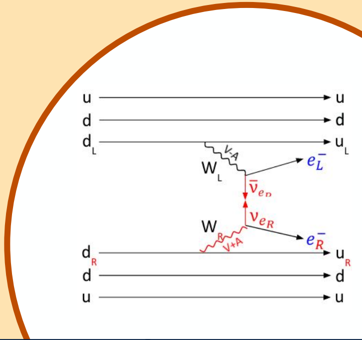
Side view



Top view

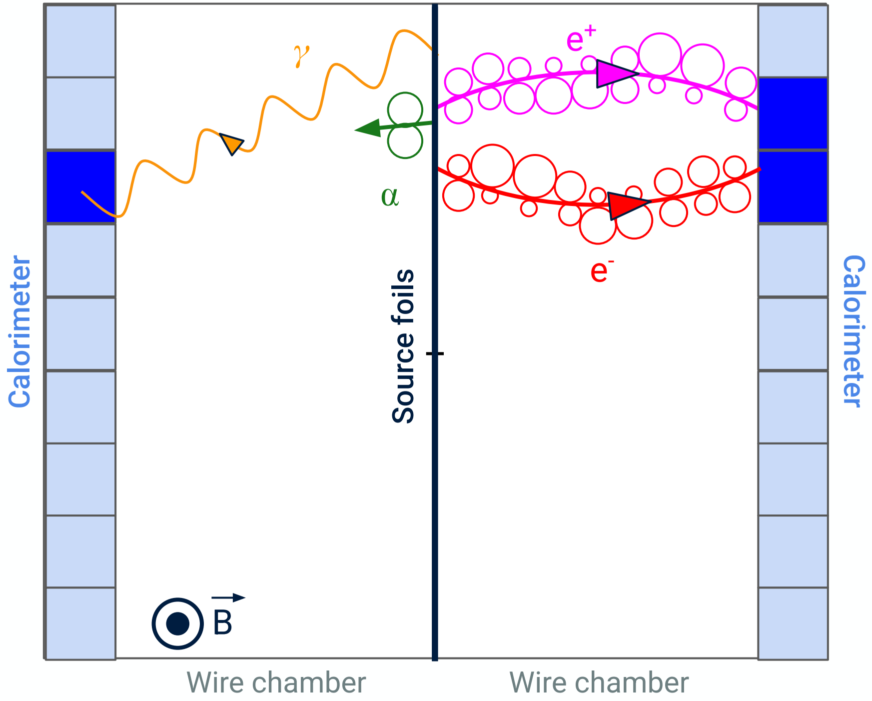


SuperNEMO's physics prospects



Event identification

Magnetic field can identify pair production background



γ : **no track**, only calo hit

α : **short track**, no calo hit

e^- and e^+ : **track and calo hit,** distinction by magnetic field

Event identification

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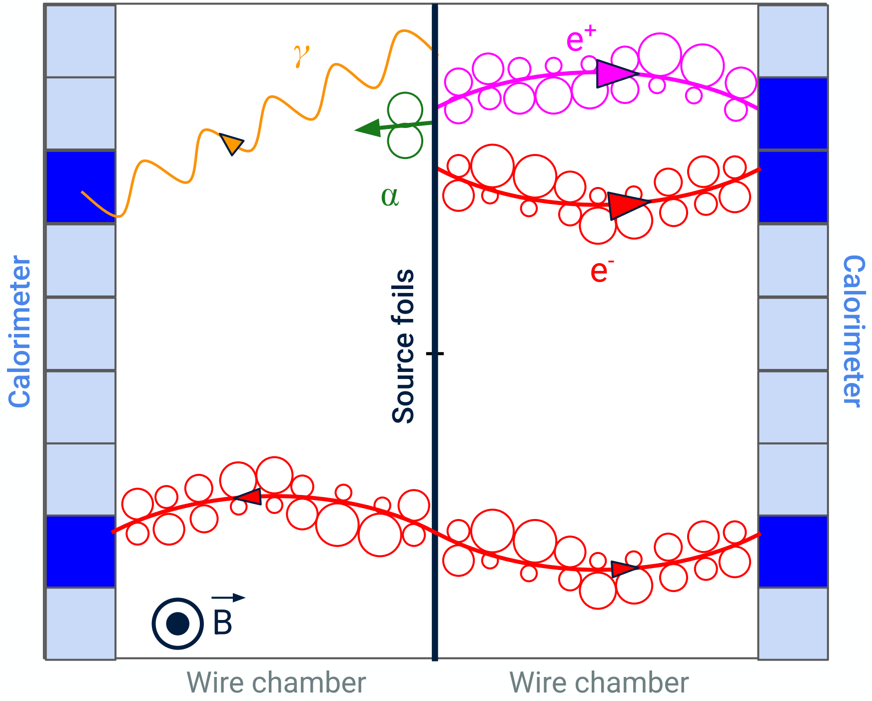

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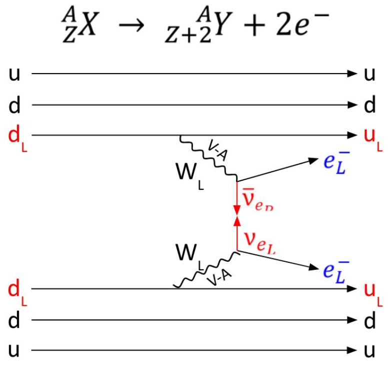
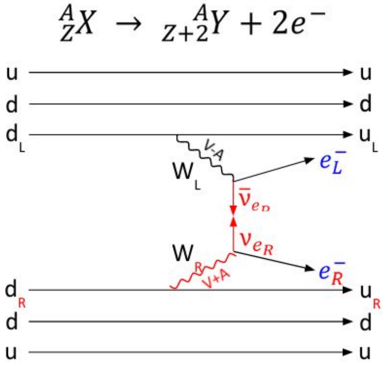
Golden ββ event

0νββ mechanisms



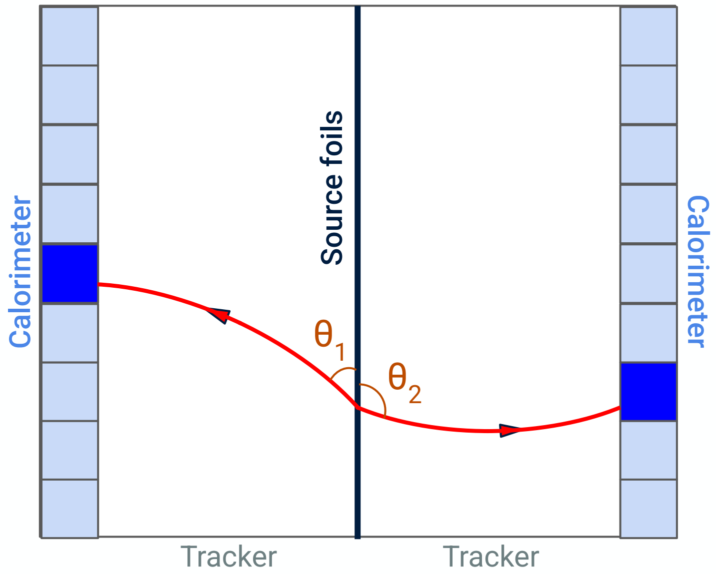
V-A



V+A

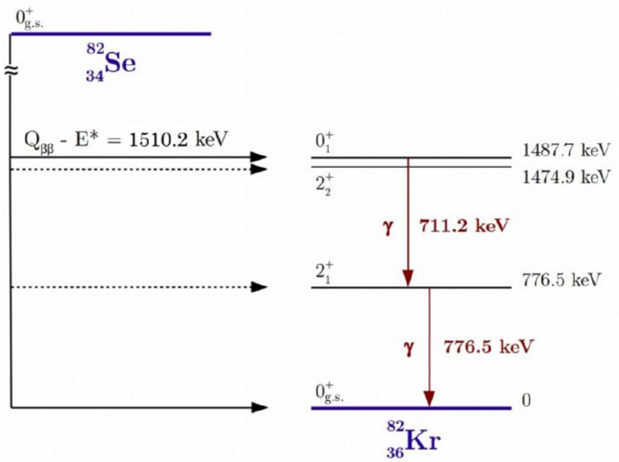
Mechanisms could be distinguished by:

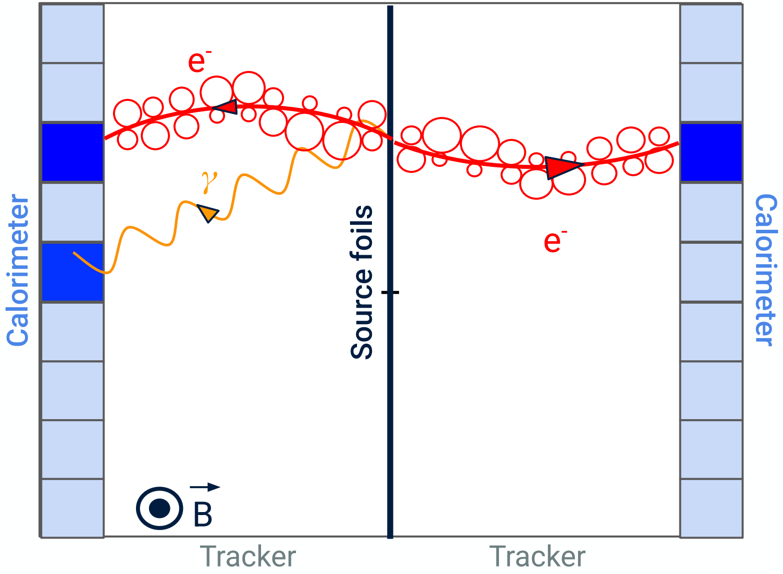
- e^- individual energy
- e^- angular distribution



New Physics with SuperNEMO

Standard and exotic 2νββ: decay into excited states

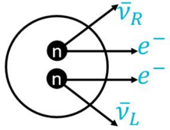




Need an efficient way to measure γ and e⁻ in coincidence, which SuperNEMO is very efficient at

Frank F. Deppisch et al., Phys.Rev.Lett. 125 (2020) 171801

Standard and exotic 2νββ

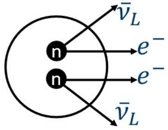


Decay with right-handed neutrino

- $\nu_R\nu_L\beta\beta$
- Constrains on the RH neutrino interactions $(V+A)$[2]

Where to look:

- **Angular distribution**

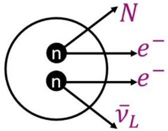


Improved description of $2\nu\beta\beta$ spectrum shape

- Precise shape analysis can constrain g_A[1]
- Shape parameters: ξ_{31}, ξ_{51}

Where to look:

- **Single-electron energy spectrum**

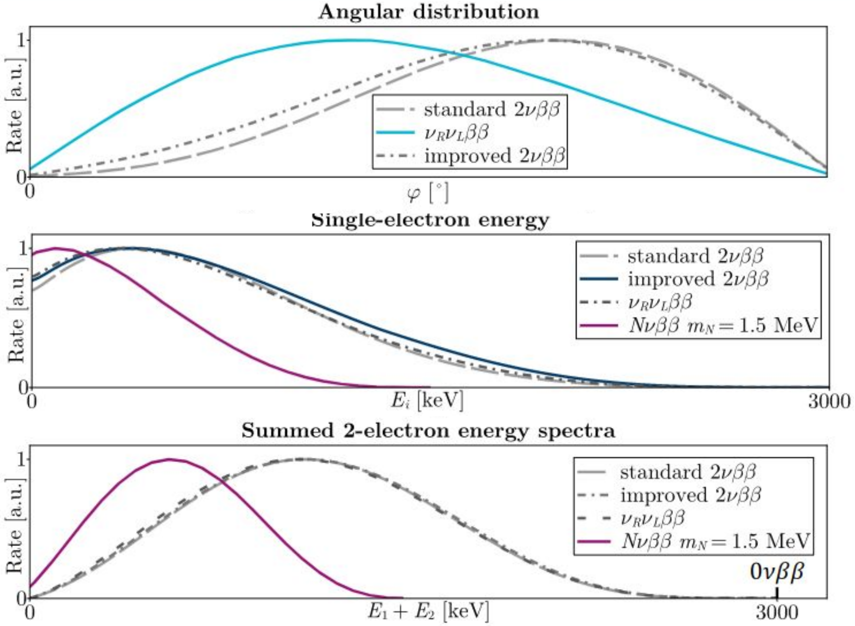


Decay with sterile neutrino

- $N\nu\beta\beta$
- Shape depends on m_N[3]

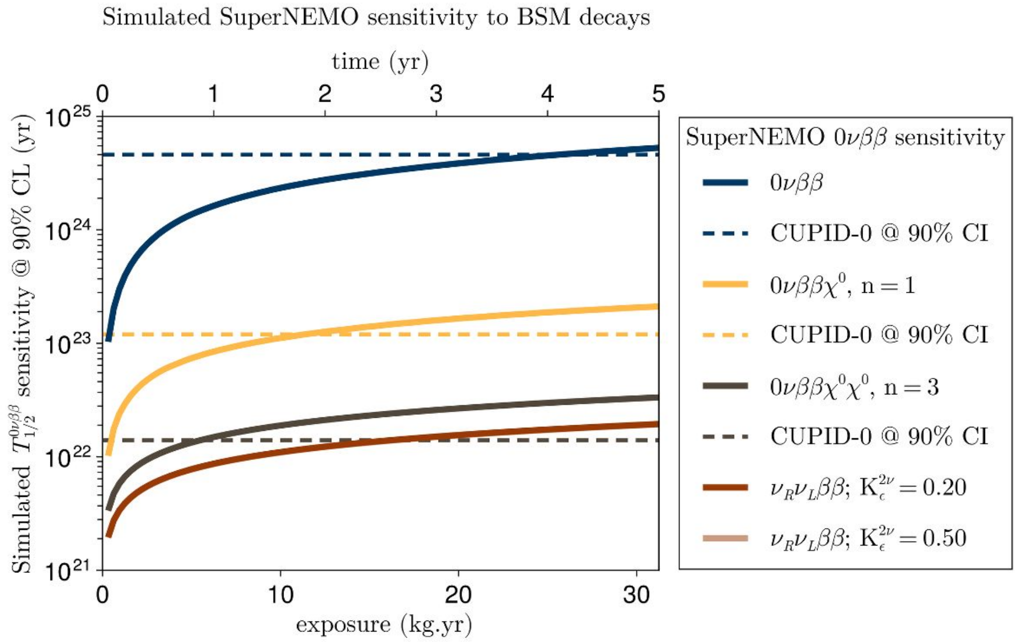
Where to look:

- **Single-electron energy and Summed energy spectra**



New Physics with SuperNEMO

Some simulated SuperNEMO sensitivities



Conclusion

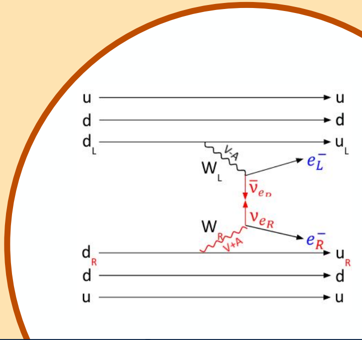
ββ data taking since April 10, 2025 **!!!**

SuperNEMO is a unique ββ tracker/calorimeter experiment:

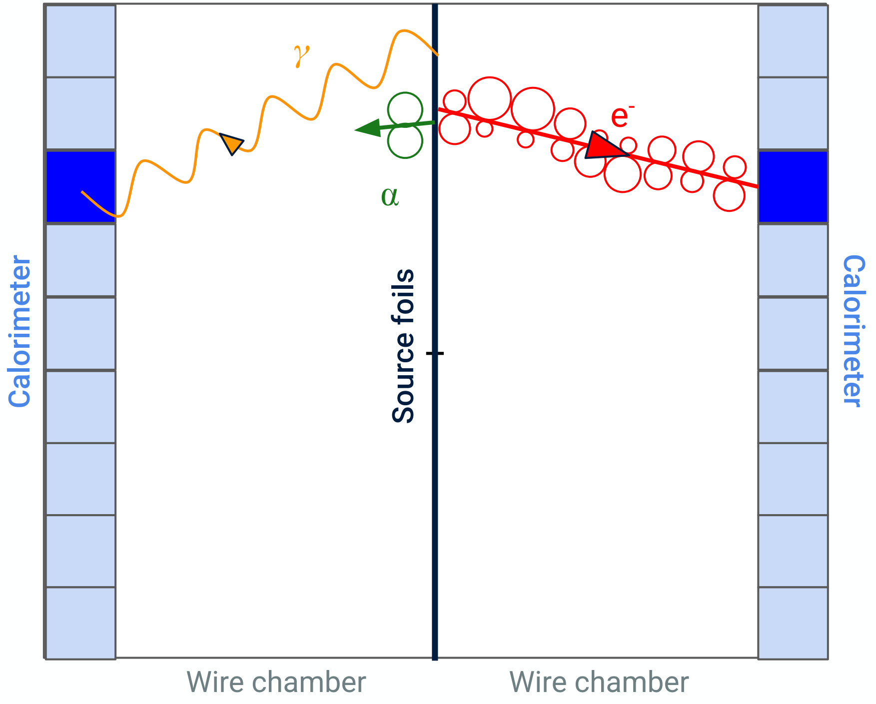
- ➔ Unique study of **0νββ mechanisms**
- ➔ Unique probes of **BSM with 2νββ** as well as nuclear physics
- ➔ **Technology optimisation** for a scaled-up detector

SuperNEMO is **key to understand 0νββ**

Backup



Event identification

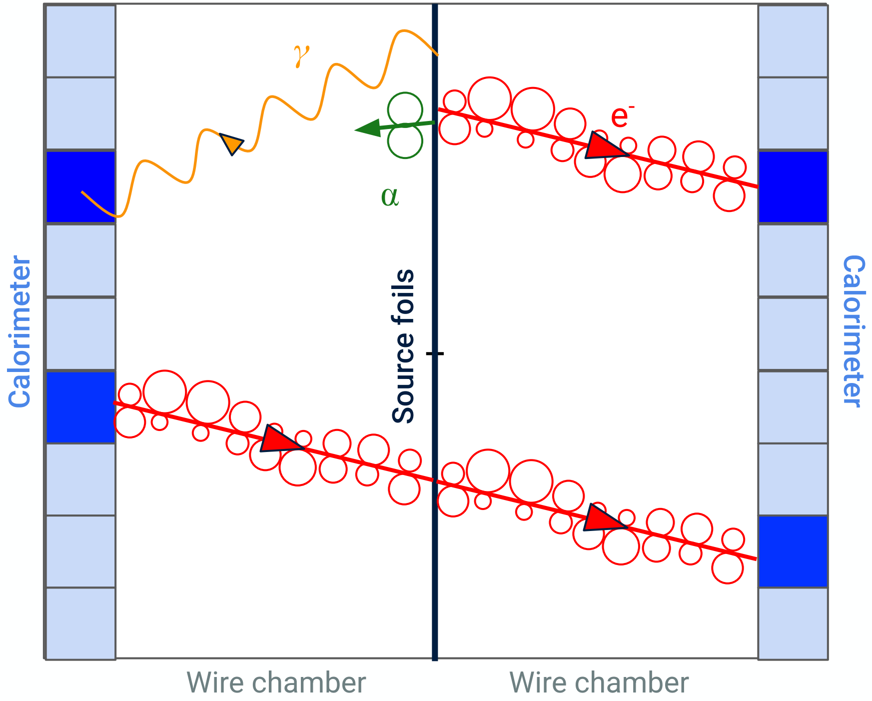


γ : **no track**, only calo hit

α : **short track**, no calo hit

e^- : **track and calo hit**

Event identification



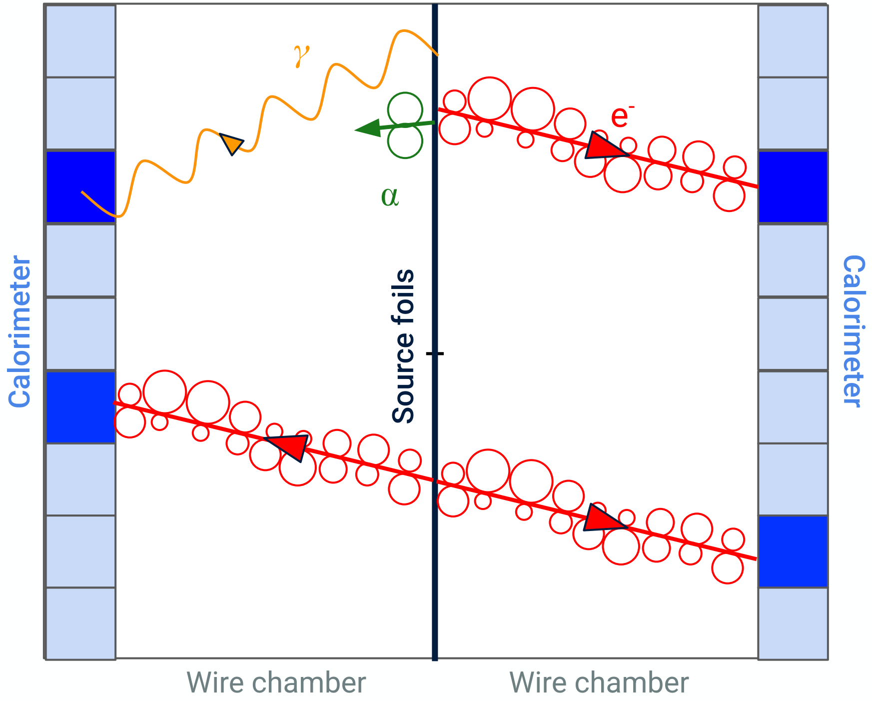
γ : **no track**, only calo hit

α : **short track**, no calo hit

e^- : **track and calo hit**

Crossing electron distinguishable by time of flight

Event identification



γ : **no track**, only calo hit

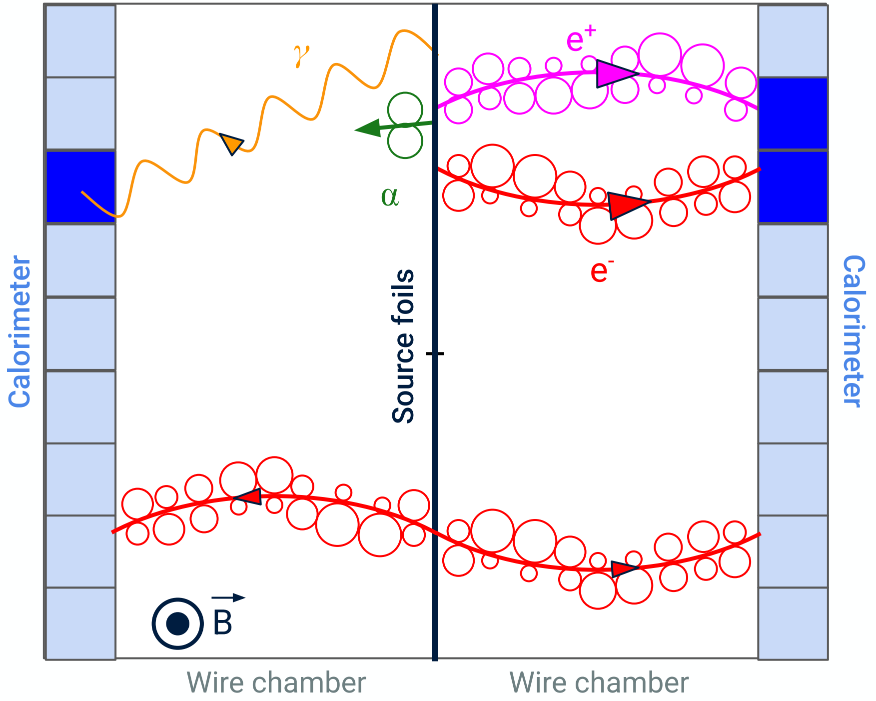
α : **short track**, no calo hit

e^- : **track and calo hit**

Keep event from the **same vertex with time of flight**

Event identification

Magnetic field can identify pair production background

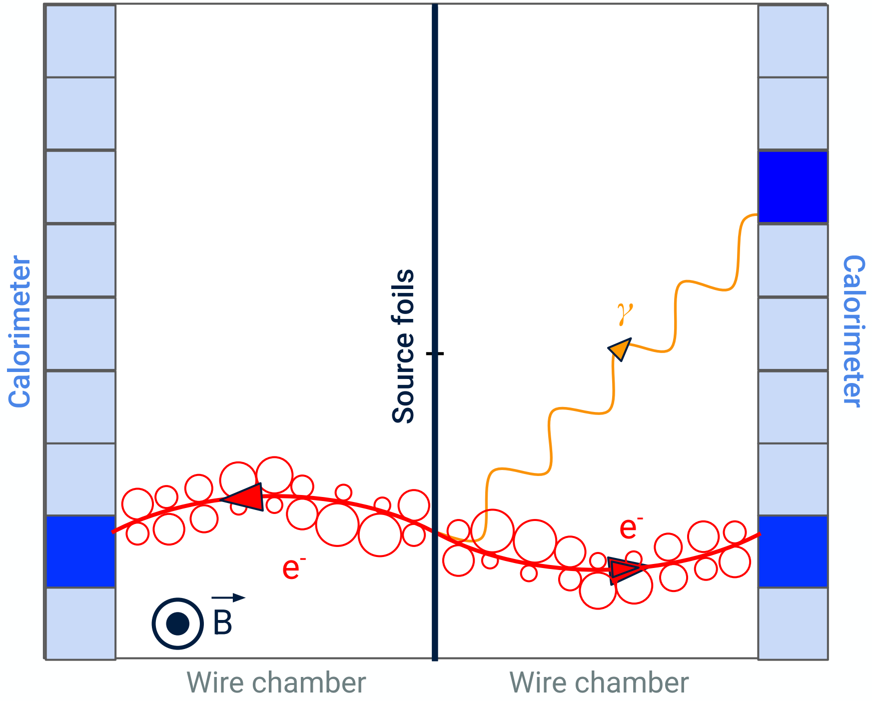


γ : **no track**, only calo hit

α : **short track**, no calo hit

e^- and e^+ : **track and calo hit,** distinction by magnetic field

Event identification



γ : **no track**, only calo hit

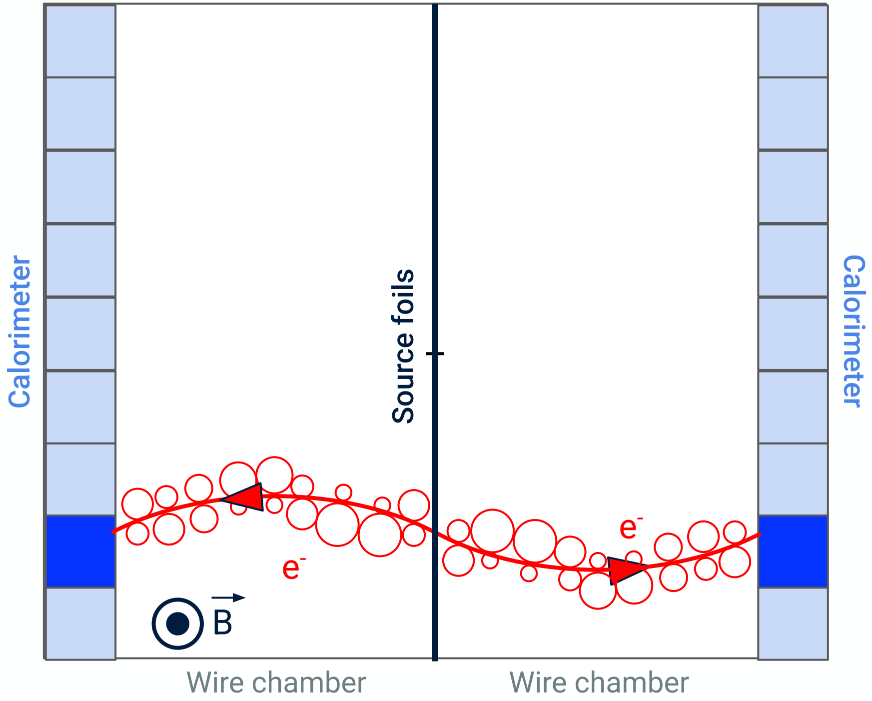
α : **short track**, no calo hit

e^- and e^+ : **track and calo hit,** distinction by magnetic field

Keep event from the **same vertex with time of flight**

Identify $2e^-n\gamma$ events with time of flight

Event identification



γ : **no track**, only calo hit

α : **short track**, no calo hit

e^- and e^+ : **track and calo hit,** distinction by magnetic field

Keep event from the **same vertex with time of flight**

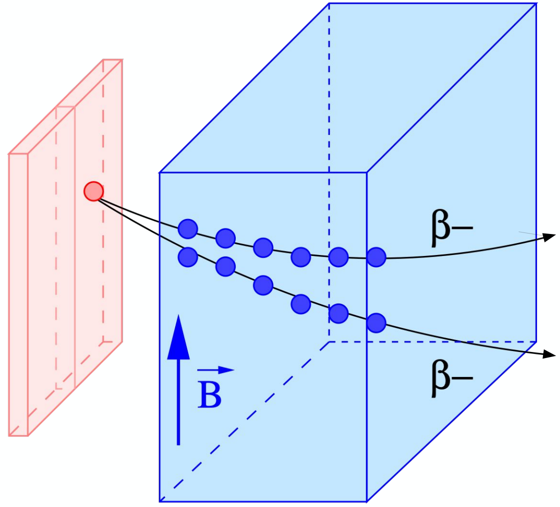
Identify $2e^-n\gamma$ events with time of flight

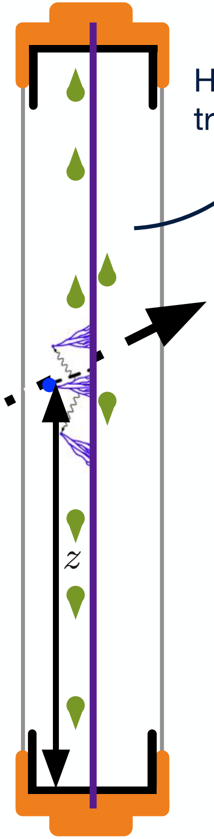
Golden ββ event

How the tracker works

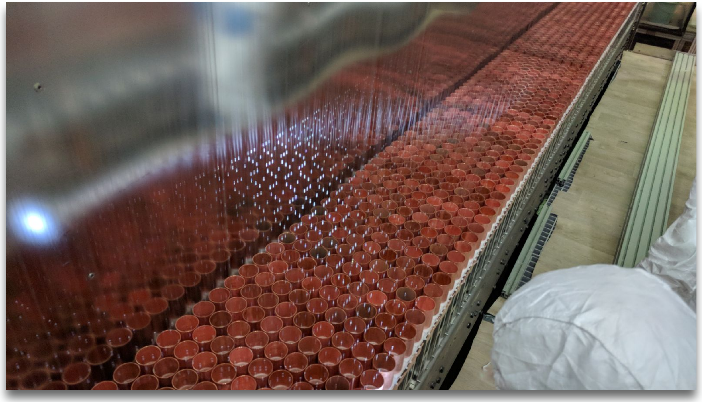
$\beta\beta$ source

High-granularity tracker





Helium based tracker gas



Electron avalanche