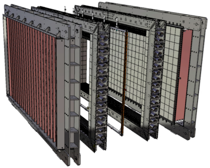
The SuperNEMO double-beta-decay experiment

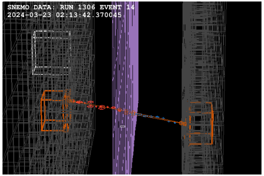
Emmanuel Chauveau on behalf of SuperNEMO collaboration

24th International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

Place des Arts, Downtown Sudbury – October 2nd, 2025

supernemo collaboration





- **Introduction on $0\nu\beta\beta$ physics and SuperNEMO**
- **Status of SuperNEMO as a technology demonstrator**
- **Physics goal of SuperNEMO demonstrator**

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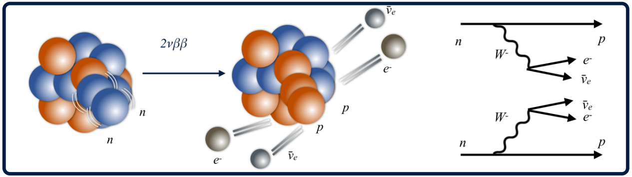
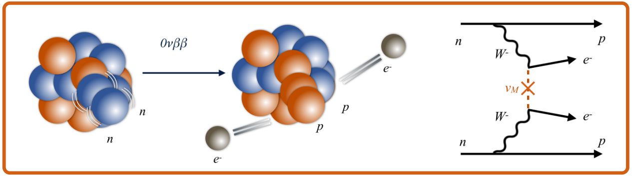
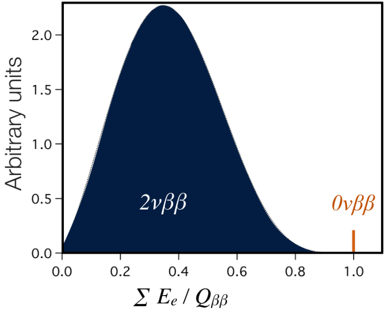
Neutrinoless double beta research

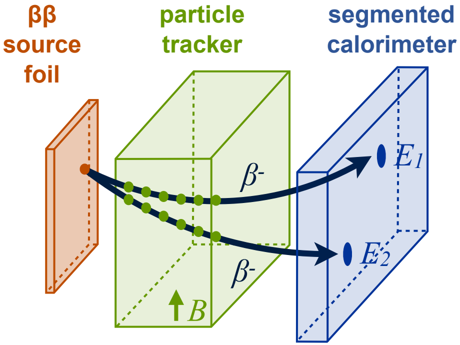




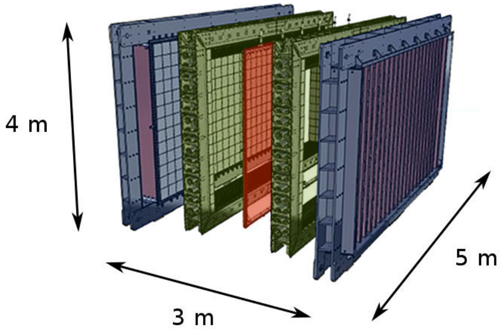


- $0\nu\beta\beta$ search to probe Majorana neutrino and absolute mass scale of neutrinos
- Signature of $0\nu\beta\beta$ is 2 electrons with summed energy $= Q_{\beta\beta}$
- $T^{0\nu}_{1/2} > 10^{26}$ years $\rightarrow$ ultra low background experiment required

Neutrinoless double beta research with SuperNEMO demonstrator



SuperNEMO demonstrator



SOURCE
~ 300 μm thick
6.11 kg of ^{82}Se
($Q_{\beta\beta}$ = 2.99 MeV)

TRACKER
helium chamber
2034 drift cells
in Geiger mode

CALORIMETER
712 Optical Modules (OMs)
1 OM = polystyrene
scintillator + 8" or 5" PMT

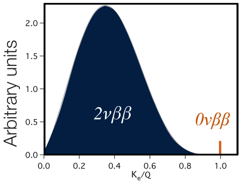
- SuperNEMO approach = thin $\beta\beta$ source foil + tracker + segmented calorimeter

What makes NEMO super ?

ALL ββ EXPERIMENTS

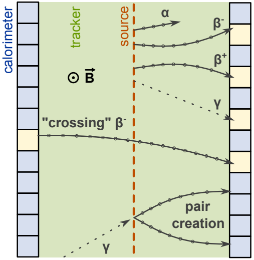
ONLY SUPERNEMO

Total Energy



$\sum E_e / Q_{\beta\beta}$

Topological signature of events

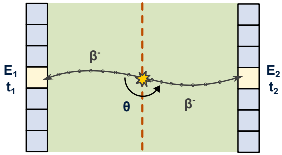


Full kinematic of ββ events

Individual electron energy

Angular correlation

Total electron energy

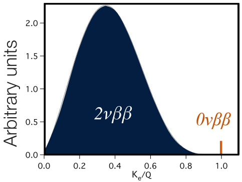


- Excellent background rejection
- Background measurement
- Usage of any solid isotope
- $\beta\beta$ kinematics: electron's individual energy + angular correlation
- Investigate models of new physics for $0\nu\beta\beta$ mechanisms
- Detailed study of $2\nu\beta\beta$, excited states, g_A quenching, etc.

What makes NEMO super ?

ALL ββ EXPERIMENTS

Total Energy



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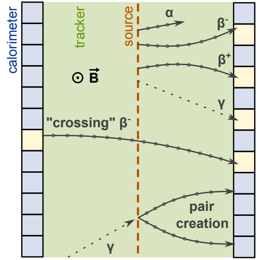

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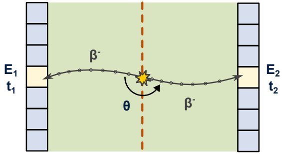

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- Usage of any solid isotope

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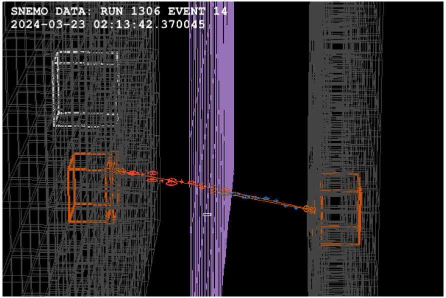
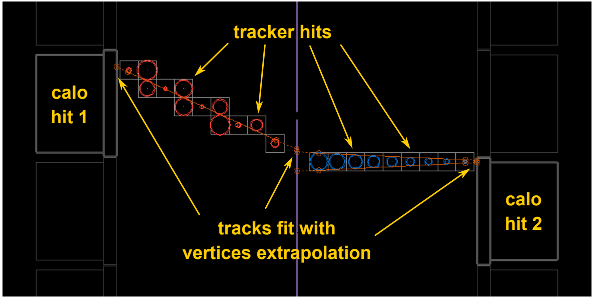
NB: What makes NEMO *not* super ? low $\beta\beta$ mass, low $0\nu\beta\beta$ efficiency ($\leq$ 20% @ ROI), moderate energy resolution ... to be fair !

Example of $\beta\beta$ event

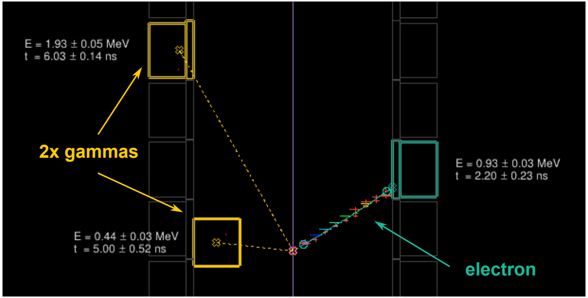
Measured 2-track event (March 2024)



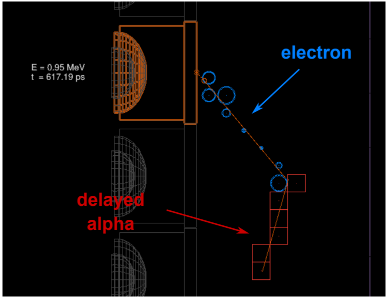
side view



top view



^{208}Tl in source foil (top view)



BiPo cascade from Rn

The SuperNEMO collaboration

20 Institutions

9 Countries

Plus contributions from Russian colleagues (Russian institutions no longer members)

SuperNEMO demonstrator currently in LSM

SuperNEMO status

- Construction of a demonstrator module completed in LSM
- $\beta\beta$ running since 2025 April 10th

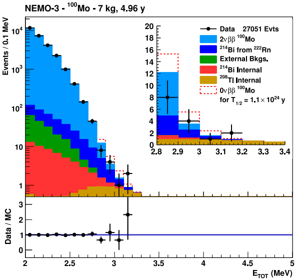
Demonstrator main purposes

- **Technology demonstration**
  - only way to study $0\nu\beta\beta$ mechanism (APPEC 2019 recommendation)
  - which scaling of full SuperNEMO will be required to confirm a hypothetical future signal by another experiment?
- **Competitive physics results**
  - $0\nu\beta\beta$ search in multiple modes
  - nuclear physics of $2\nu\beta\beta$
  - search for BSM $2\nu\beta\beta$ decays

- Introduction on $0\nu\beta\beta$ physics and SuperNEMO
- **Status of SuperNEMO as a technology demonstrator**
- Physics goal of SuperNEMO demonstrator

SuperNEMO = Successor of NEMO-3

NEMO-3 (2003-2011 at LSM)



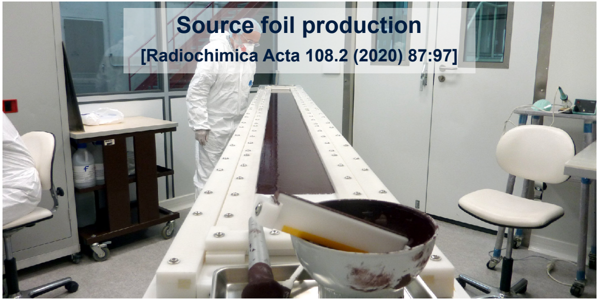
0vββ search with NEMO-3

[Phys. Rev. D89, 111101 (2014)]

- NEMO-3 still has 20 world's-best $0\nu\beta\beta$ and $2\nu\beta\beta$ results [PDG 2025]
- 0 background event above $0\nu\beta\beta$ region (with 7 kg x 5 years of ^{100}Mo)
- SuperNEMO improves NEMO-3 design for next-generation sensitivities:

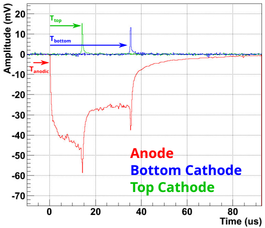
  initial goal $= T^{0\nu}_{1/2} > 10^{26}$ year with 100 kg of ^{82}Se (NEMO-3: $T^{0\nu}_{1/2} > 1.1 \times 10^{24}$ year)

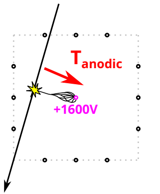
Technology demonstrator: source foil radiopurity



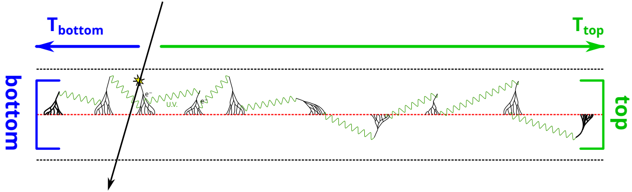
- 6.11 kg of ^{82}Se (96-99 % enriched) over 34 source foils
- Radiopurity goal: A(^{208}Tl) < 2 μBq/kg and A(^{214}Bi) < 10 μBq/kg
- Tested different powder-production, purification technique and foil geometries
- Final validation of technique(s) can be done only by the analysis of SuperNEMO data..
- Enrichment possibility demonstrated for ^{96}Zr* (attempts with ^{150}Nd* too)

* in terms of $m_{\beta\beta}$ sensitivity, 1 ton of ^{76}Ge would be equivalent to 74 kg (145 kg) of ^{150}Nd (^{96}Zr)





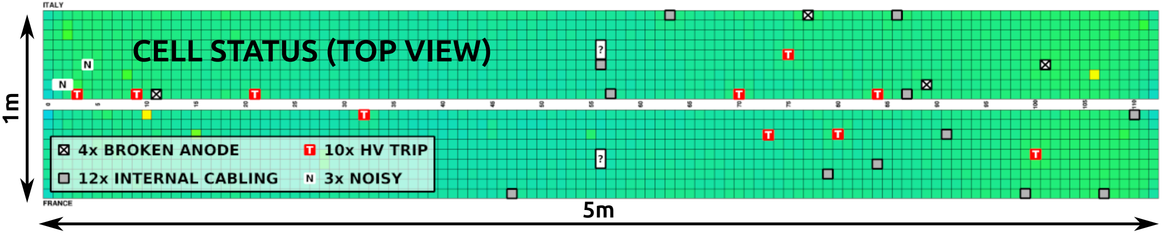
transverse view



longitudinal view

- 2034 drift cells (14970 wires) operating in Geiger regime
- Improved geometry: larger and taller cells (more transparent) with same performances as NEMO-3
- Gas-mixture optimisation: 95.5% He + 3.5% ethanol + 1% Argon

Technology demonstrator: tracker operation



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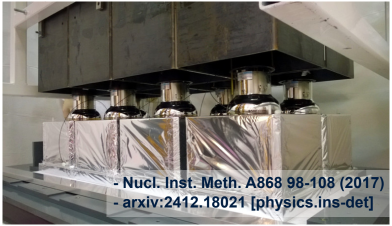
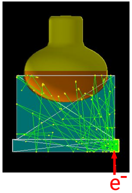
- 98.4 % of cells operational

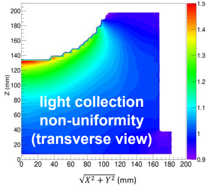
Technology demonstrator: calorimeter performance

- 712 plastic scintillator coupled to 8" PMTs (x440) and 5" PMTs (x272)
- Target energy resolution 8% FWHM/$\sqrt{E}$ (was 14 % in NEMO-3)
- Time resolution measured to 250 ps for 1 MeV electrons
- Spectral modeling with optical simulation (energy non-linearity and photoelectron collection non-uniformity in scintillators)
- 97.4% of calorimeter channels operational

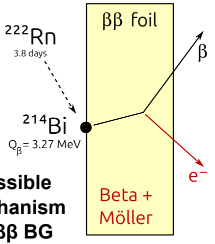


Optical simulations of scintillation light

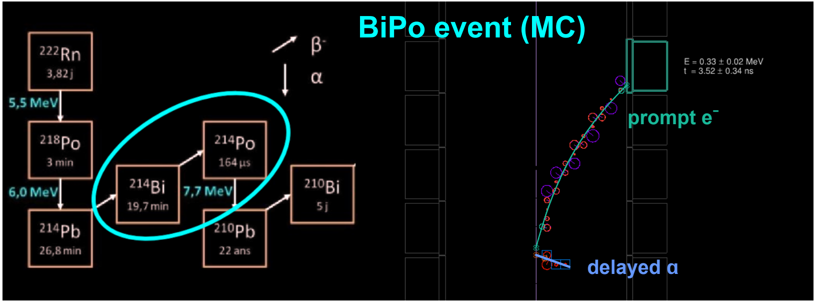




Technology demonstrator: radon contamination level



possible mechanism of ββ BG



- Emanation/diffusion of ^{222}Rn can introduce continuous deposit of ^{214}Bi on source foils
- ^{222}Rn background level measured/monitored through dedicated channel ("BiPo")
- Strategies: material selection, tracker sealing, gas purification, anti-radon tent, LSM radon-free air facility
- SuperNEMO target < 150 uBq/m^3 (≈ 20 mBq/m^3 measured **without** radon trap and radon-free air)

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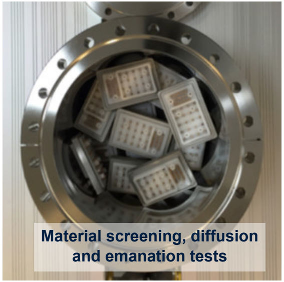

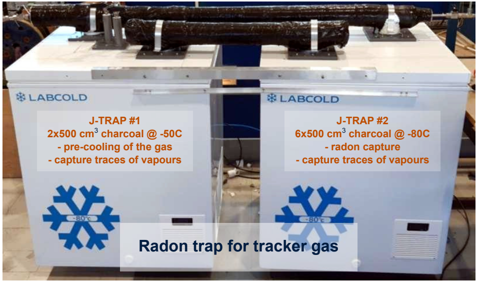

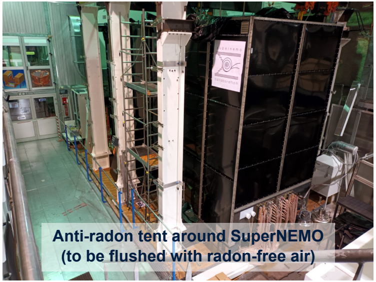

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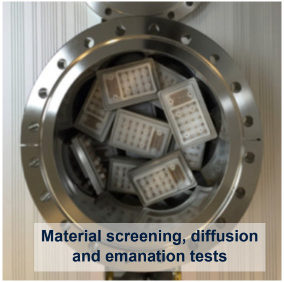

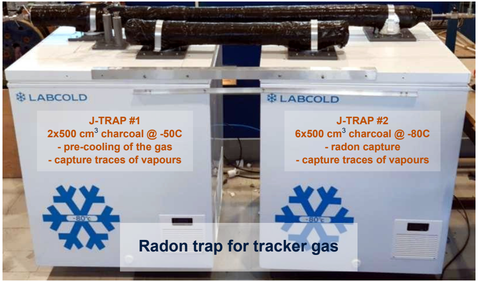

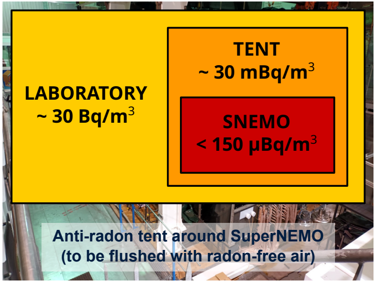

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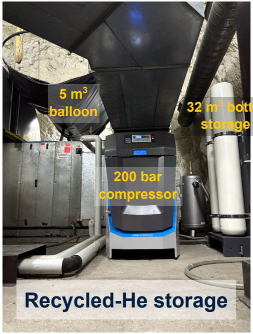
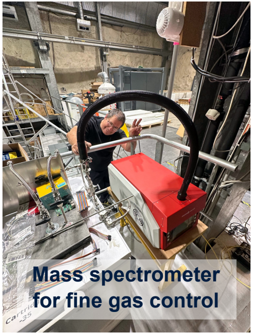
Technology demonstrator: helium recycling system

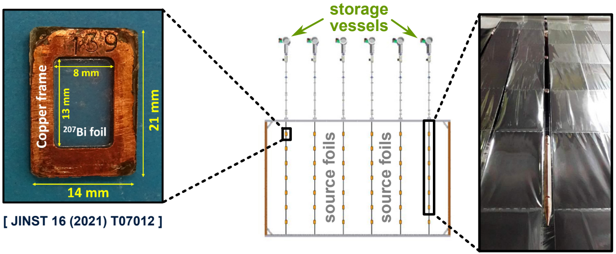
- Motivated by: high He prices*, environmental concerns (finite He supply), scalability to large system
  * SuperNEMO consumption range 7–30 m^3/day ⇒ 0.3–1.2 keuros/day without recycling
- Home made system: ethanol condensation → gas control with mass spectrometer → temporary balloon storage → compression → 200-bars storage → re-mixing with fresh gas





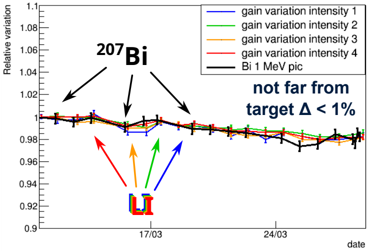
Technology demonstrator: calibration systems

- Absolute calibration ($\sim$ weekly): automated deployment system with 42x ^{207}Bi calibration sources
- Relative calibration ($\sim$ daily): Light Injection system (LI) $=$ flashing LEDs $+$ optical fibers



[JINST 16 (2021) T07012]

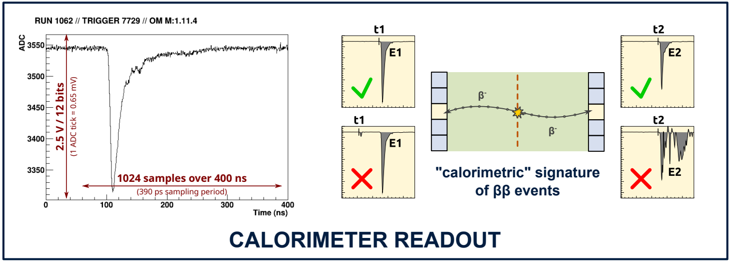
ABSOLUTE CALIBRATION SYSTEM (^{207}Bi)

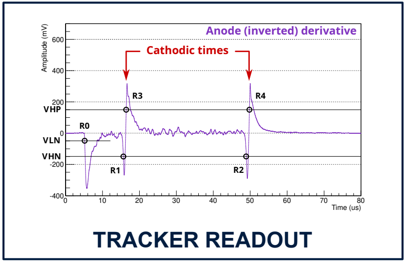


ABSOLUTE VS RELATIVE CALIBRATION

Technology demonstrator: novel electronics

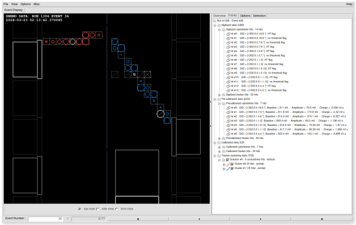
- Calorimeter (712 channels): PMT waveform digitisation using 52x Wavecatcher boards
- Tracker (6102 channels): reconstruct cathode activation time from anode signal (-33% channels)
- Trigger: live pattern recognition to record only useful data (electron, delayed α identification)



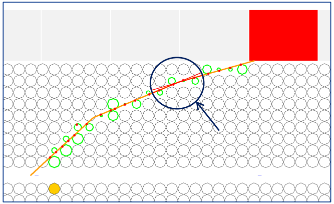


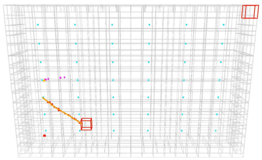
Technology demonstrator: new software

- *Falaise* = main software for simulation, reconstruction and analysis of SuperNEMO data
  https://github.com/SuperNEMO-DBD/Falaise
- *Falaise* based on generic library *Bayeux* providing a coherent framework for any HEP data analysis
  https://github.com/BxCppDev/Bayeux
- new tracking (Legendre transform + polyline fit) recently developed to enhance signal efficiency



EVENT BROWSER (FALAISE)



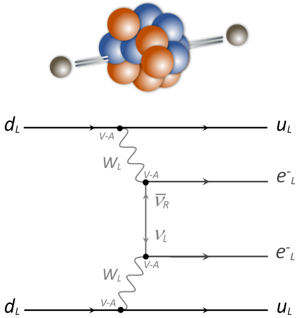


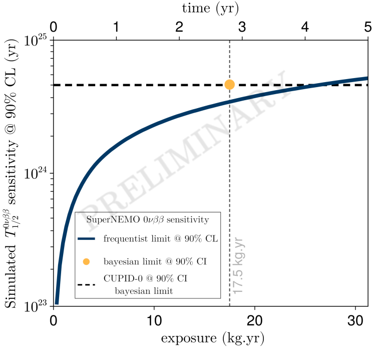
Run 974 | Event 80

TRACKING ALGORITHM RECONSTRUCTING "KINKED TRACKS"

- Introduction on $0\nu\beta\beta$ physics and SuperNEMO
- Status of SuperNEMO as a technology demonstrator
- **Physics goal of SuperNEMO demonstrator**

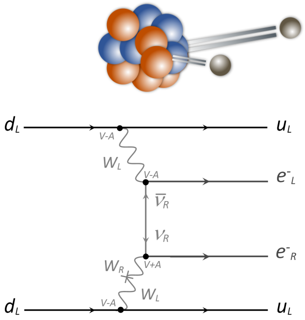
$0\nu\beta\beta$ with light neutrino exchange (V-A current)

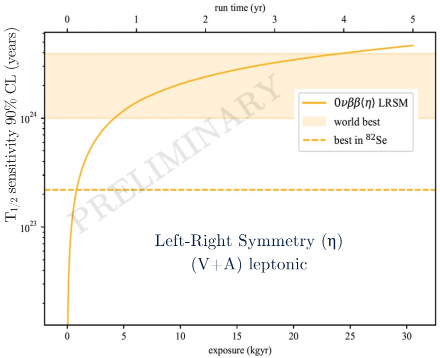




- V-A current: model assumed by most experiments
- Expected background index in ROI = 2.7 x 10^{-4} event/kev/kg/year
  $\rightarrow$ can reach best limit with sufficient runtime

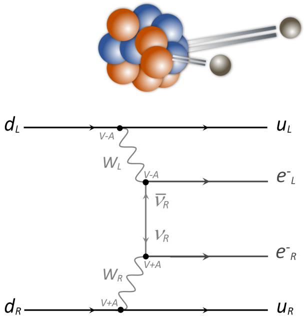
$0\nu\beta\beta$ with light neutrino exchange (V+A current)

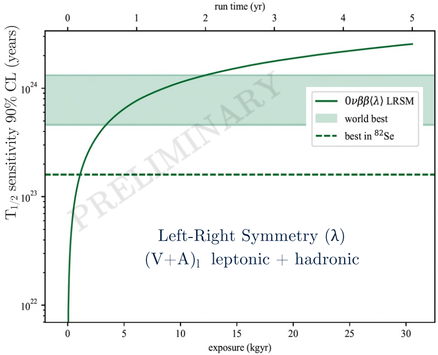




- Letonic (η) and leptonic+hadronic (λ) V+A gives one electron with right-handed helicity:
  V+A favors **asymmetric** electron energies with **small angle** (while V-A favors **similar** energies and **back-to back**)
  $\rightarrow$ only SuperNEMO can identify both of these differences
- World's best limits reached within few months (^{82}Se) or in 2–4 years (all isotopes)

$0\nu\beta\beta$ with light neutrino exchange (V+A current)





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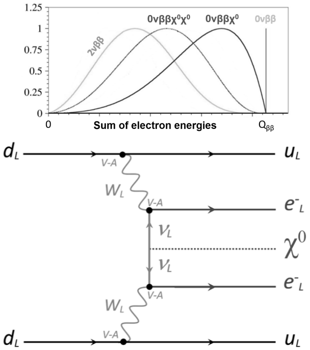
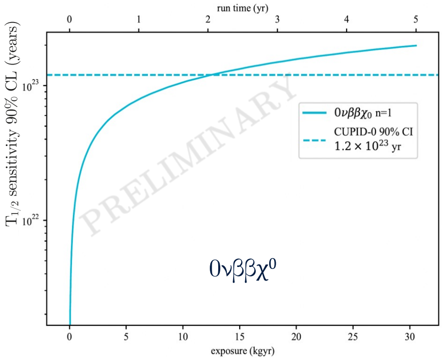
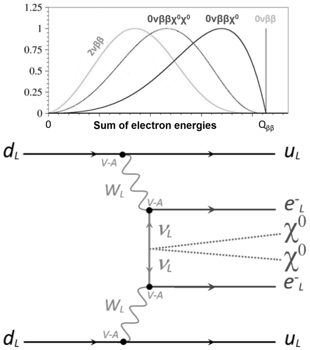
$0\nu\beta\beta$ with Majoron(s) emission

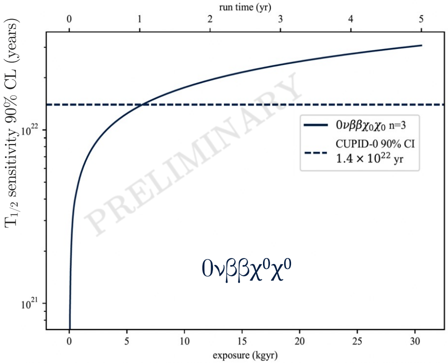




- Some $0\nu\beta\beta$ theories involves emission of one, or more, Majorons (Goldstone bosons χ^0)
- SuperNEMO expect to surpass ^{82}Se world's best limits in $\approx$ 2 years ($0\nu\beta\beta\chi^0$) and $\approx$ 1 year ($0\nu\beta\beta\chi^0\chi^0$)

$0\nu\beta\beta$ with Majoron(s) emission





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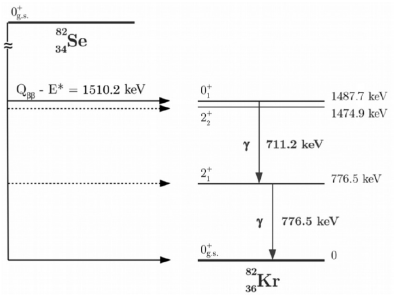
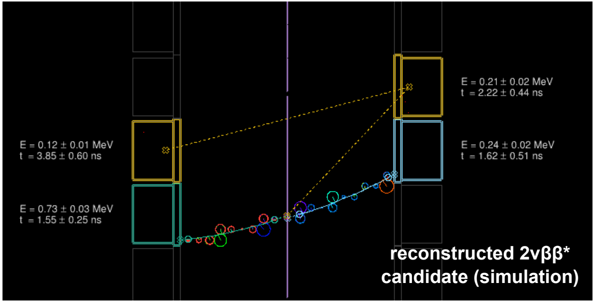
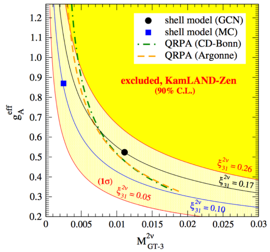
$\beta\beta$ decay to excited states





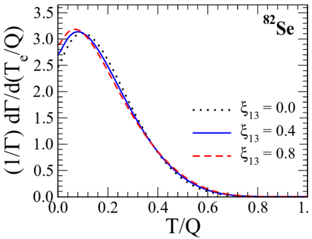
- Unique ability to see each individual electron and to perform gamma tracking
- Preliminary study: demonstrator can surpass world's best limit for $2\nu\beta\beta$ to 2^+_2 state of ^{82}Kr with a sensitivity on half-life of 1.9 x 10^{22} years (90% CL) for a 17.5 kg.y exposure

$2\nu\beta\beta$ vectoriel axial coupling constant g_A

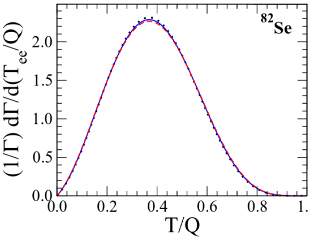


g_A constraint with ξ_{31} parameter

[Phys. Rev. Lett. 122, 192501 (2019)]



Single-electron spectrum (only SuperNEMO)

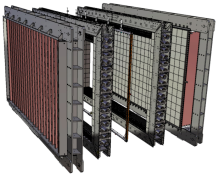


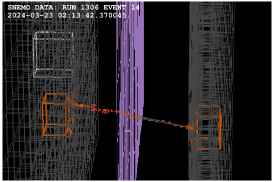
Summed energy spectrum (all ββ experiments)

- (Mis)knowledge of g_A impacts interpretation of $m_{\beta\beta}$: $(T^{0\nu}_{1/2})^{-1} = g_A^4\ G^{0\nu}\ |M^{0\nu}|\ |m_{\beta\beta}|^2$
- Shape of $2\nu\beta\beta$ spectrum can be used to constraint quenching of g_A [Phys. Rev. C 97, 034315 (2018)]
- Effect is stronger in individual energy spectrum, and only SuperNEMO can see this !
- Sensitivity will depend on background level at low energy and energy scale systematics (under estimation)
  $\Rightarrow$ SuperNEMO demonstrator will record $\approx$ 35k $2\nu\beta\beta$/year

Summary

supernemo collaboration





- SuperNEMO demonstrator is running after almost 20 years of R&D, construction and commissioning
- Expected leading results on wide range of $\beta\beta$ processes:
  – $0\nu\beta\beta$ V+A , $0\nu\beta\beta\chi^0$, $0\nu\beta\beta\chi^0\chi^0$
  – $2\nu\beta\beta$ detailed nuclear structure insights: NME and g_A
  – other BSM process searches: massive sterile neutrino, bosonic neutrinos, Lorentz violation, ...
- Key technology to understand a possible future $0\nu\beta\beta$ signal

Thanks a lot for listening ... and see you may be ~~inside~~ above LSM ?

MONT D'AMBIN 3378M

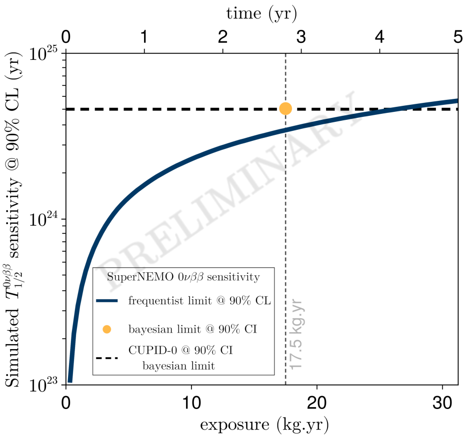
GRANDE SASSIÈRE 3747M

RATEAU D'AUSSOIS 3128M

DENT PARRACHÉE 3697M

Backup slides

$0\nu\beta\beta$ background budget of SuperNEMO demonstrator



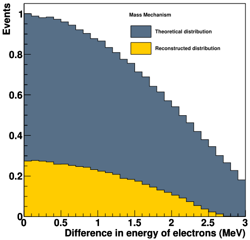
Background	Events for 17.5 kg.year
$2\nu\beta\beta$	0.98 ± 0.13
^{208}Tl	0.04 ± 0.01
^{214}Bi	0.09 ± 0.01
radon	0.23 ± 0.04
neutrons	0.60 ± 0.30
total	1.9 ± 0.4

$0\nu\beta\beta$ efficiency	16.5 %

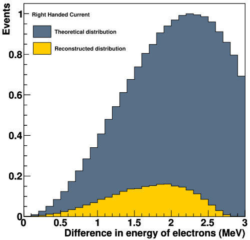
in ROI = [2.7-3.1] MeV

- Expected background index in ROI = 2.7 x 10^{-4} event/kev/kg/year (NEMO-3 ^{100}Mo: 10^{-3} event/kev/kg/year)

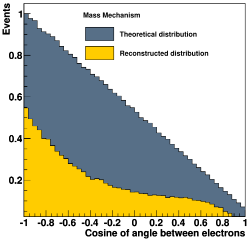
$0\nu\beta\beta$ V-A vs V+A kinematics



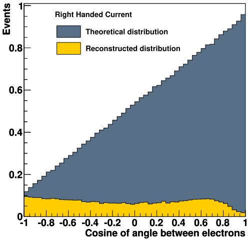
V-A 0νββ



V+A(λ) 0νββ



V-A 0νββ



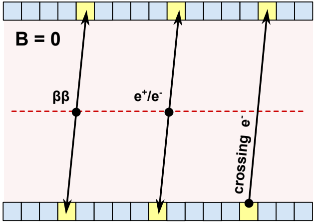
V+A(λ) 0νββ

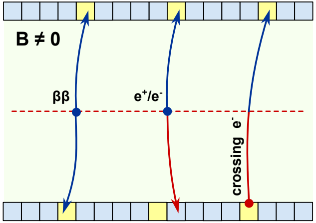
Energy asymetry ΔE

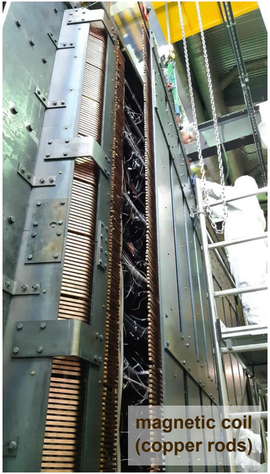
Angular distribution cos(θ)

Eur. Phys. J. C 70, 927–943 (2010)

Magnetic field or not ?







- Magnetic coil as an optional extra protection to neutron background
  pros: particle's charge identification for extra background rejection
  cons: reduce also detection/reconstruction efficiency on $\beta\beta$ signal
- Turning ON is irreversible (magnetisation of demonstrator's metals)
- Balanced decision to be taken depending of neutron background level