Evolution of underground science in LSM

Laboratoire Souterrain de Modane

From digging to modern experiments

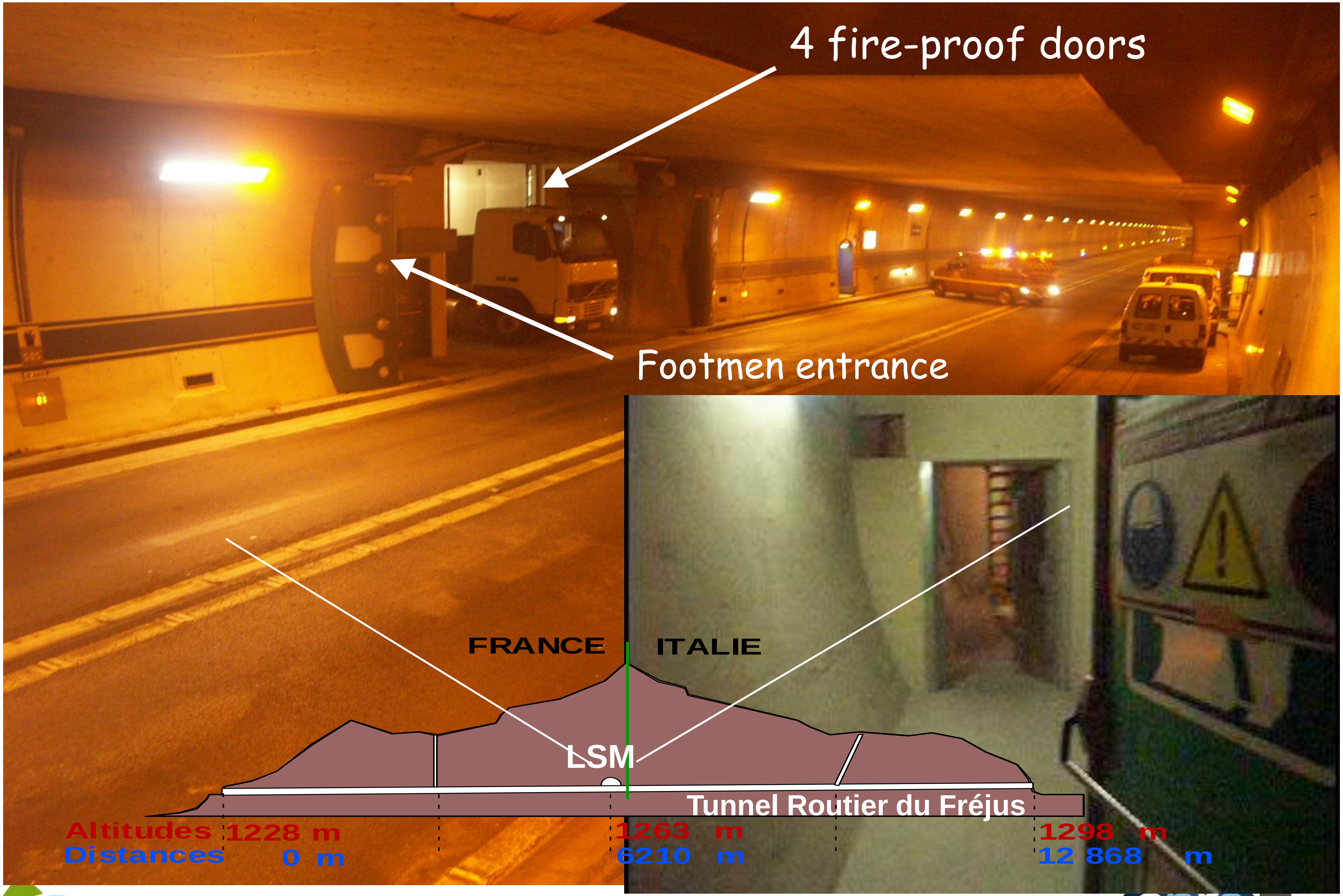
Laboratoire Souterrain de Modane

- Located in Modane,France
- Middle of Fréjus tunnel
- Part of LPSC; Lab in Grenoble
- National facility for underground science
- 1000 visitors days per year
- Wide range of interdisciplinary topics
- Astroparticles, nuclear physic, environment, electronics, radioactivity measurement, biology

Laboratoire Souterrain de Modane

- Merger with Laboratoire de Physique Subatomique & Cosmologie (LPSC-IN2P3) in Grenoble
  - 70 researchers, 90 Engineers & technicians
  - Covering fields in particle & nuclear physics, astroparticle and cosmology
- LSM now becomes a « national facility » as labelled by the CNRS
  - National facility for IN2P3 / CNRS
- LSM as a national experimental facility for :
  - Fundamental Physics
    - Neutrino property determination
    - Direct Dark matter search
  - Gamma spectrometry measurement
    - 14 detectors measuring continuously
    - Open to geosciences, materials, biology and medecine
      - Actually 1000 samples measured per year
    - PARTAGe project to automatize measurments
      - Increase significantly the scope of the LSM

Location and access



Guillaume Warot

History of LSM

1979 - 1981 | **1982- 1990** | **1990- 2000** | **2000 - ….**

Digging | **Proton decay** | **Prototypes** → **Experiments**

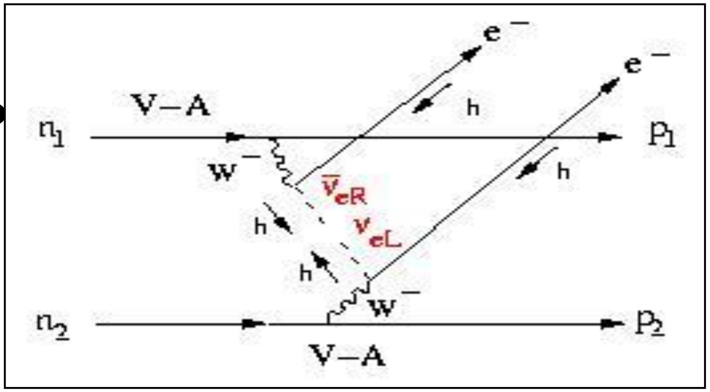
- 2.10^{-6} n/cm^2.S
- 4 µ/m^2.d
- 3500m^3
- 400m^2

- 15Bq/m^3 Rn in air
- Radonless air 125m^3/h
  15mBq/m^3

Guillaume Warot

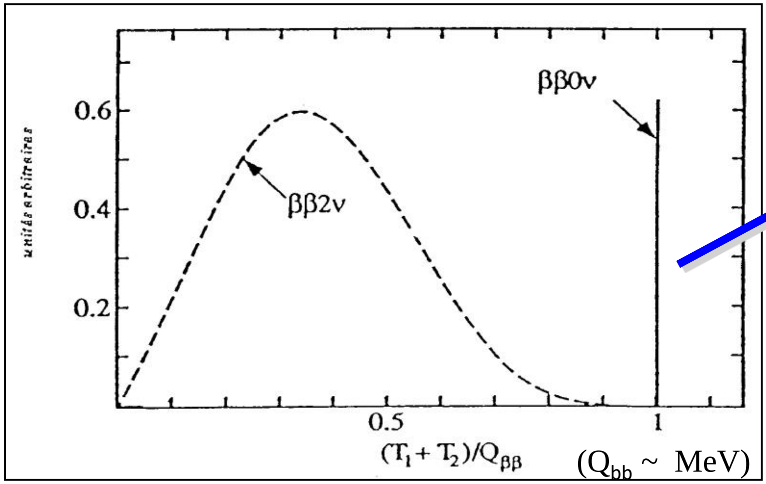
Double beta decay

bb0n : (A,Z) $\rightarrow$ (A,Z+2)+2e$^-$



$\Leftrightarrow$
$$\begin{cases} DL = 2 \\ n = \bar{n} \\ m_n \neq 0 \end{cases}$$
Majorana's neutrino

Measure



Full electron energy

$$(T^{0\nu}_{1/2})^{-1} = C\,(Q^5_{bb})\; M^2 \; \langle m_n \rangle^2$$

C : phase space factor

M : nuclear matrix element

$\langle m_n \rangle$: effective neutrino mass

$\langle m_n \rangle \Rightarrow$ mass hierarchy

Laboratoire Souterrain de Modane

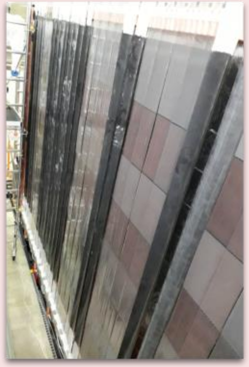
Guillaume Warot

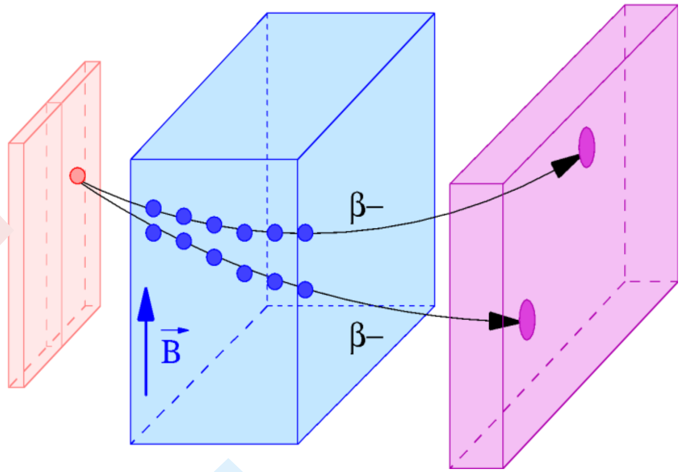
SuperNemo experiment

Unique tracker-calorimeter technology

Source foil

^{82}Se or **any $\beta\beta$ isotope**





Segmented calorimeter

Individual e^- & γ energies

Tracker

Identification of e^-, e^+, γ and α

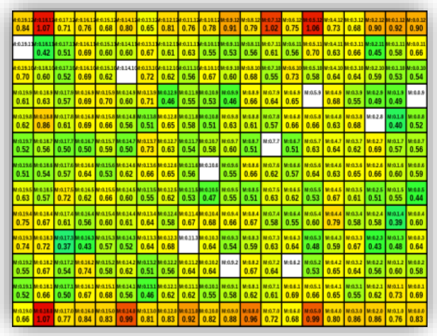
Full $\beta\beta$ **kinematics** & topology

- Excellent background rejection
- Disentangle $0\nu\beta\beta$ mechanisms: V+A, SUSY…
- Nuclear physics: constrain g_A in $2\nu\beta\beta$
- e-γ separation probes decays to excited states

SuperNemo experiment

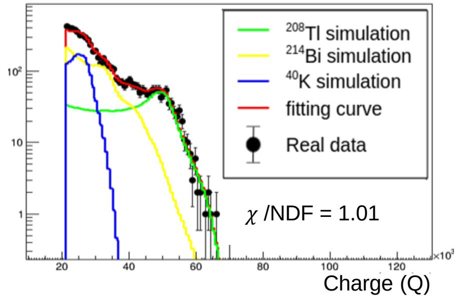
Magnetic coil
for particle ID
(Installed Sept 21)

Energy and timing calibration



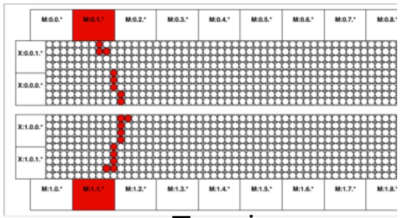
Timing resolution (main calorimeter)
with ^{60}Co γ coincidences

Energy calibration (each optical module)
with background spectrum

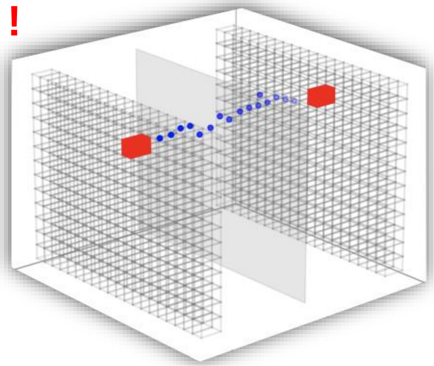


Tracker + calorimeter commissioning: First $\beta\beta$-like event !

- Tracker-calorimeter coincidences
- Full event tracking



Top view



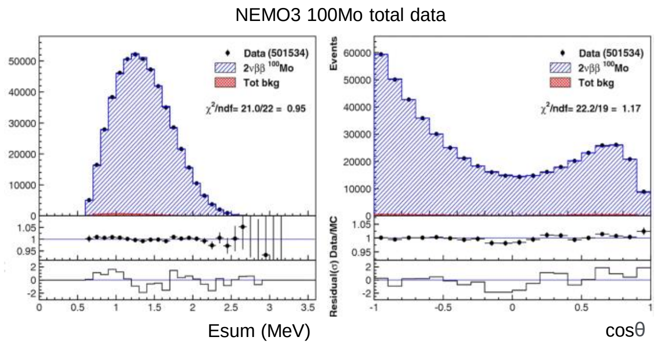
Guillaume Warot

SuperNemo experiment

Full kinematics and precision measurements of $2\nu\beta\beta$

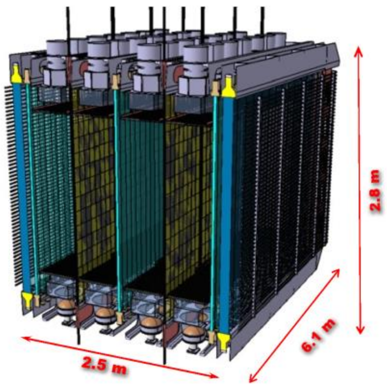
- Nuclear model constraints
- g_A quenching constraints

(NEMO-3 analysis in preparation)



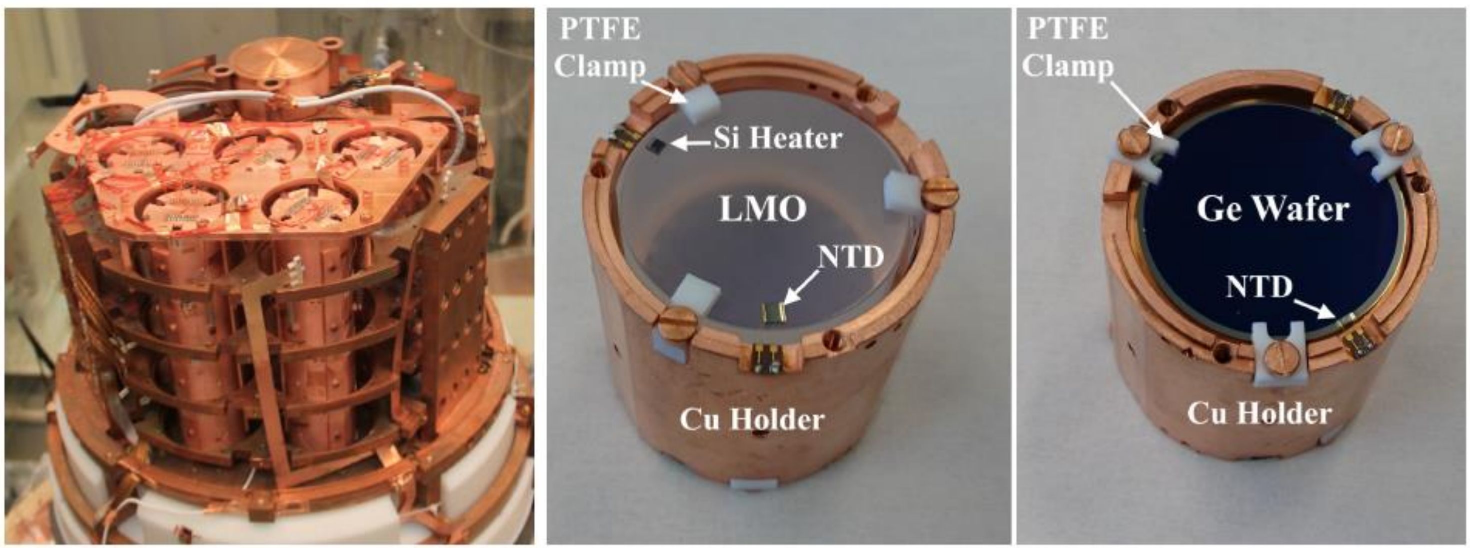
Understanding the Ultimate Reach of the Tracker-Calorimeter Technique

- Can the technique be used to confirm & probe a signal found in the next generation of $0\nu\beta\beta$ experiments?
- Explore alternative tracker-calorimeter technologies & different isotopes



CupiD -Mo

- Demonstrator for CUPID, a next generation tonne scale $0\nu\beta\beta$ experiment
- Consists of 20 Lithium Molybdate bolometers and 20 Ge Light detectors
- Operated in LSM in 2019-2020
- Showed performance very close to CUPID goals
  - Radiopurity
  - Energy resolution
  - Detection efficiency

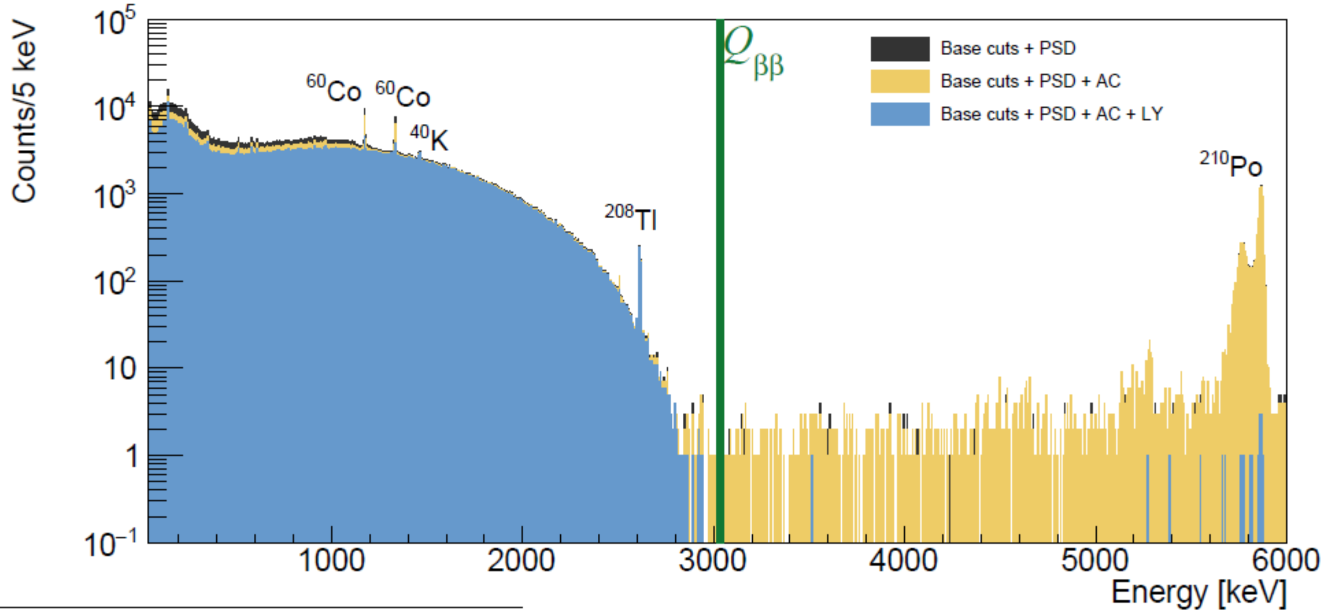


Cupid Mo

- **Not just a demonstrator but an experiment in its own right**
- New leading limits on $0\nu\beta\beta$ [1] and beta decays to excited states

$$\boxed{T_{1/2}^{0\nu} > 1.8 \times 10^{24}\,\mathrm{yrs}}$$

- Novel analysis techniques developed (delayed coincidence, pulse shape, light cuts)
- Background model and other analyses nearing completion



[1] arXiv:2202.08716

Guillaume Warot

Bingo

- BINGO will set the grounds for a large scale bolometric experiment searching for neutrinoless double-beta decay (0v2β) using revolutionary technologies
- It aims to reduce dramatically the background in the region of interest, through:

A revolutionary detector assembly:

- Reduce the Cu material seen by the main absorber → reduction of the total surface radioactivity contribution
- Having a compact assembly → anticoincidence cuts

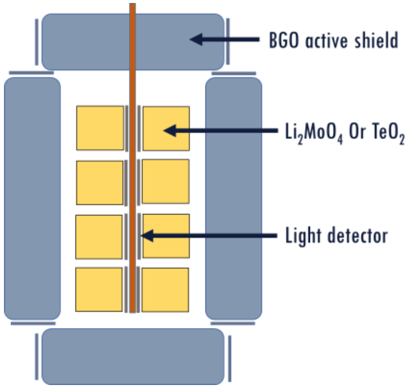
Neganov-Luke light detectors:

- Amplification of the tiny Cherenkov signal (TeO_2) → suppress alphas
- Higher sensitivity, lower energy threshold → suppress external γ background using the active shield

An active shield based on BGO or $ZnWO_4$ scintillators:

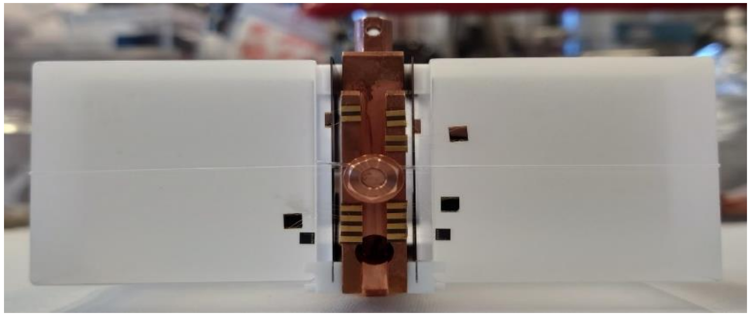
- Suppress the external gamma background (specifically essential for TeO_2)

Bi-Isotopic approach: observation in 2 candidates → discovery + confirmation



Bingo Nylon wire assembly

- Two 45mm cubic Li_2MoO_4 crystals fixed against PTFE pieces using nylon wire
- The PTFE pieces sandwich also Ge light detectors
- The test successfully validated the nylon wire assembly in terms of bolometric performance



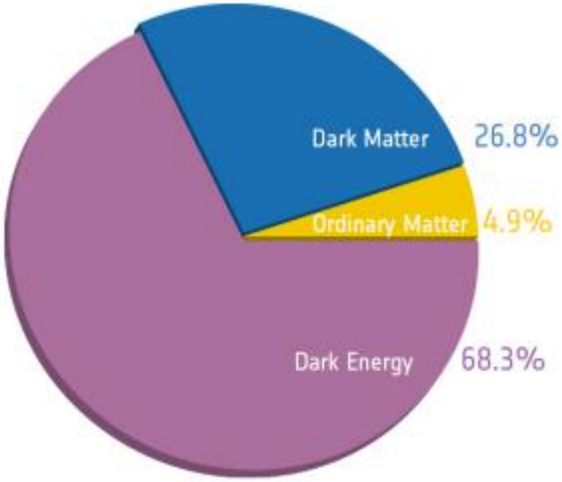
Performances	S (nV/keV)	FWHM bsln (keV)	FWHM @ 609 keV
LMO	58	4.9	7.2

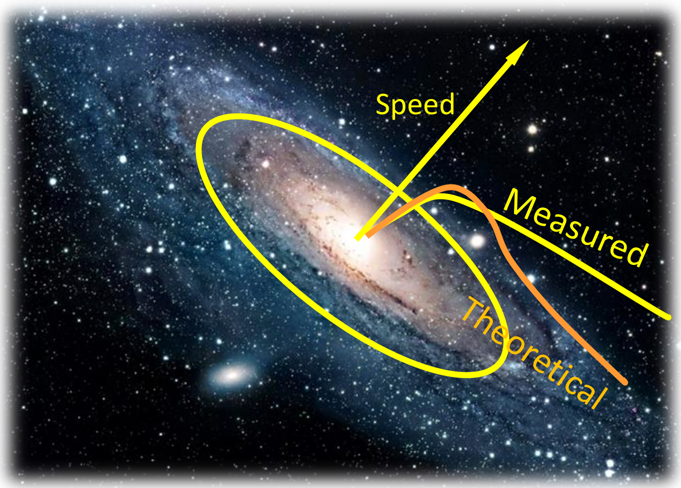
The bolometric performance was promising. 2 detectors modules (4 Li_2MoO_4) will be tested underground before moving to **MINI-BINGO**:

- new low-background cryogenic infrastructure at LSM
- 6 modules of Li_2MoO_4 and 6 modules of TeO_2 to be tested at **LSM** starting in 2023
- The physics volume is surrounded by 16 scintillating crystals on the lateral, 4 on the top and 4 on the bottom acting as an active shield
- 1-year run starting in 2024 to reach $b=10^{-4}$ c/keV/kg/y

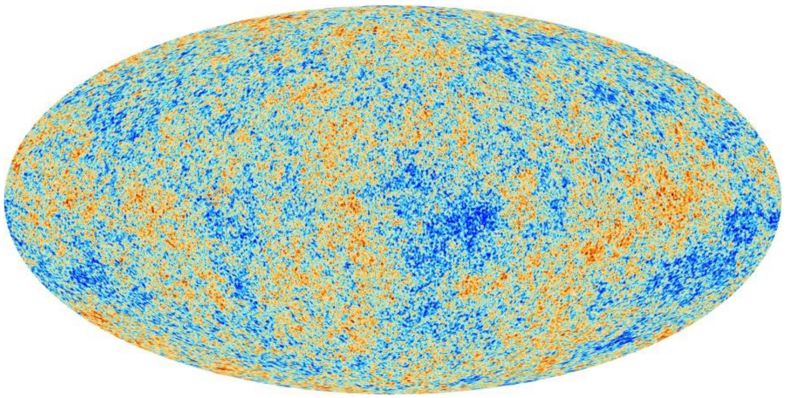
Dark matter search

- Major physics goal
- Direct detection would answer to a lot of question
- WIMP candidate is a target for underground detection



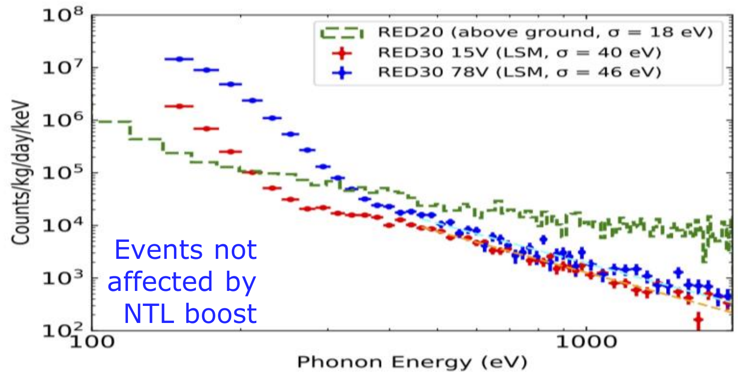


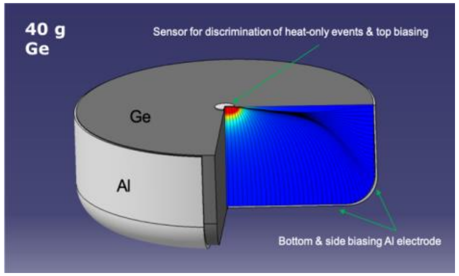
CMB anisotropy



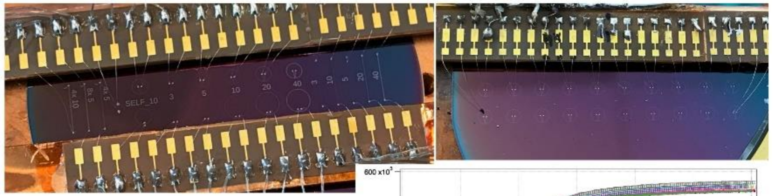
EdeLWEISS Status

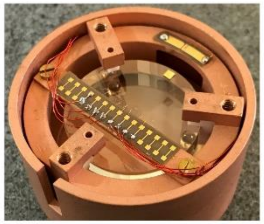
- *Study of low-energy events not associated with charge: dominant "Heat-Only" background at HV.* (arXiv:2112.05467, and EXCESS2021 arXiv:2202.05097)
- ***New CRYOSEL R&D*** *(CRYOSEL ANR, 2022-2024)*: ***single electron tag using NbSi microwire*** to trigger on athermal NTL phonons produced in small acceleration region just below the sensor
- ***Physics run @LSM in 2023-2024 in Bingo cryostat*** *(BINGO ERC, 2020-2025)*

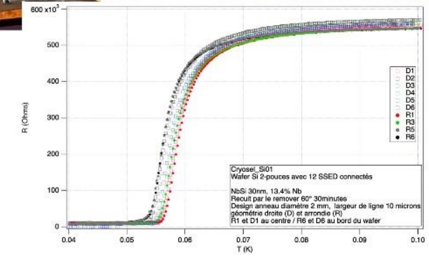


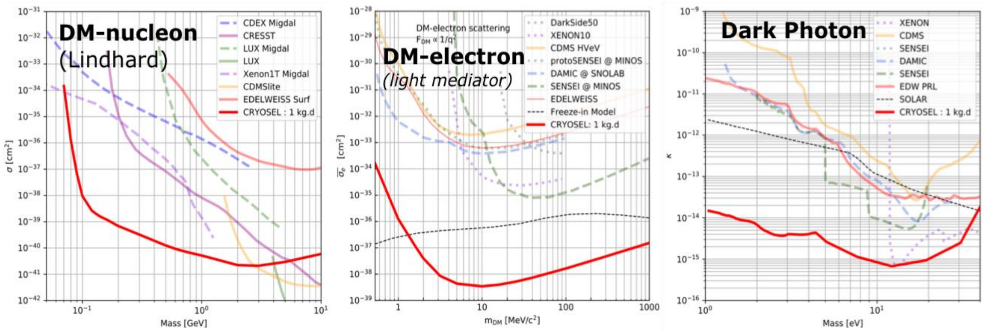


CRYOSEL detector scheme + first NbSi microwire SSEDs @IJCLAB







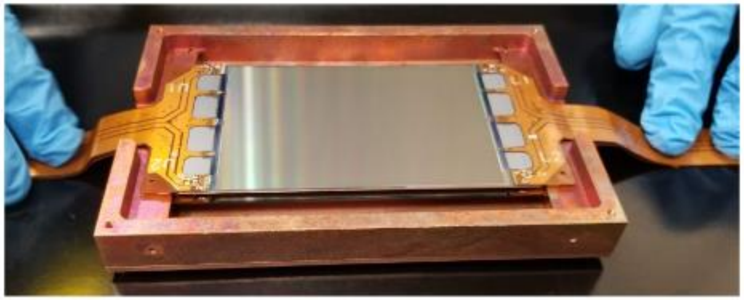


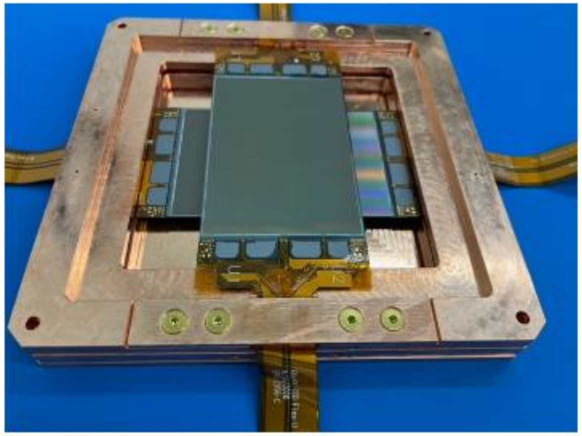
CRYOSEL: physics reach of LSM run of 40g detector x 1 month, with single-electron tag

Damic-M

- CCDs for direct dark matter search.
- Multi-CCD array operating at SNOLAB since 2012.
- 50x more sensitive DAMIC-M will start operations at LSM in 2024.

- **DM-e⁻ interactions:**
  - First DM search results from ~eV ionization signals: **PRL 118 (2017) 141803**
  - Latest DM-e⁻ scattering results: **PRL 123 181802 (2019)**
- **WIMP search:** **PRL 125 (2020) 241803** **Full details:** **PRD 105 (2022) 062003**
  - 11 kg-day of data from seven-CCD array.
  - First full background model in CCDs.



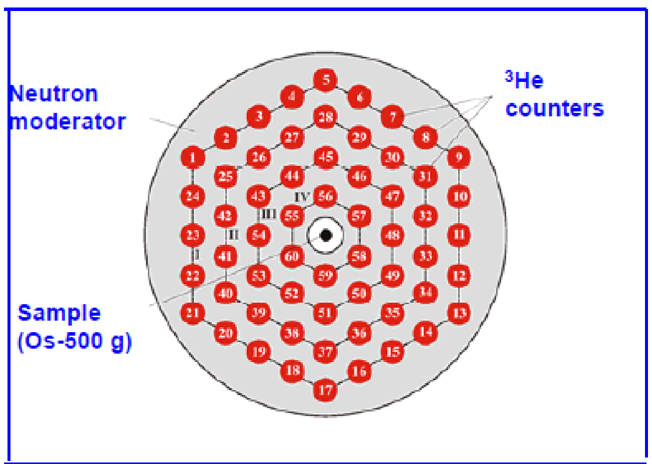


SHIN

- Super heavy element with half life $>^{238}U$
- Z=108 targeted with self fission producing >5n

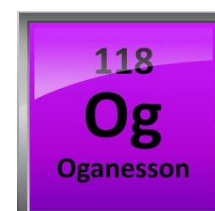
Nuclear physics
Super Heavy Element In nature
SHIN (osmium ore surrounded by 3He neutron detectors)

Events	Single	Double	Triple	Quadruple
Measured 550g Os	1 ev/ minute	1 ev./ 10days	2 events	1 event
Random events (100µs)		2 ev/ year	0 ev/ year	0 ev./ year



From these results, we can deduce an upper limit of 10^{-14} g/g for the concentration of EKA-Os super-heavy element in Osmium (with a sample of 550 g sample of Os and assuming a half-life of ~ 10^9 years for this EKA-Os)

This leads to a limit of the mean concentration of EKA-Os of 10^{-22} g/g in the earth crust



Laboratoire Souterrain de Modane

Guillaume Warot

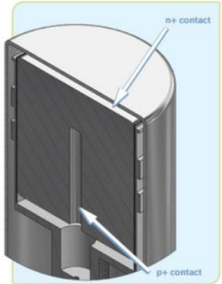
Low radioactivity constraints

- Requirement on material below mBq
- Strong pressure on analytical capabilities
- Increased number of pieces and longer time
- Main measurement performed by gamma ray spectrometry
- Constant effort took place in LSM to develop ultra low background germanium
- Hosting 22 HPGe by 2020

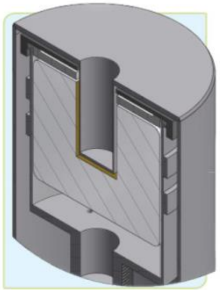
High purity germanium

- Semi conductor crystal cooled down to 77 K
- Sample at room temperature
- Sensitive to gammas from 20keV up to 3MeV
- Non destructive measurement
- Sensitive to muons and cosmic activation
- Different detectors adapted to samples shape

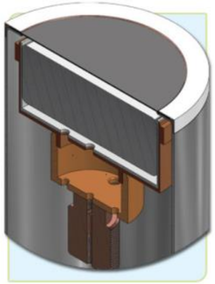
Coax

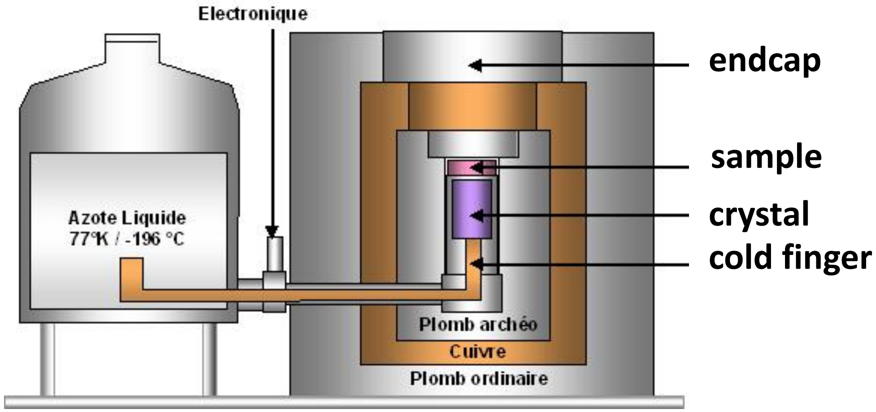


Well



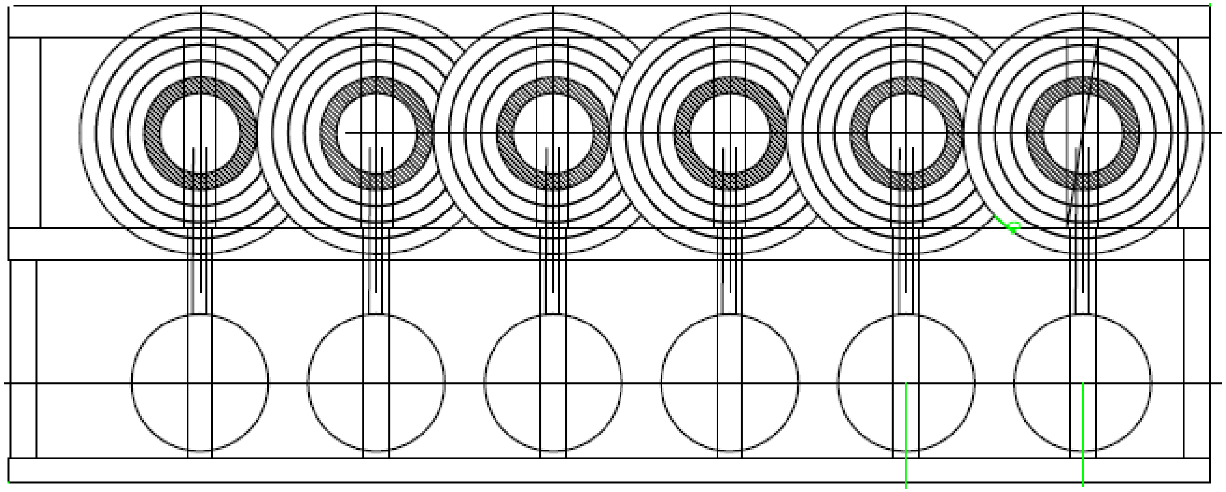
Planar





Future of measurement at LSM

- PARTAGe project
  - Combining shields in common walls



- Robotisation
- Optimisation of measurement time based on the radiopurity objectives

Shielding in progress

Guillaume Warot

Germanium facility

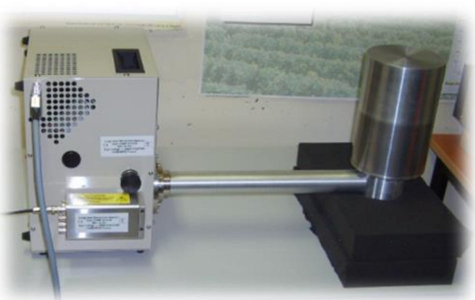
- Example of detection limits

Mafalda : (our swiss army knife)

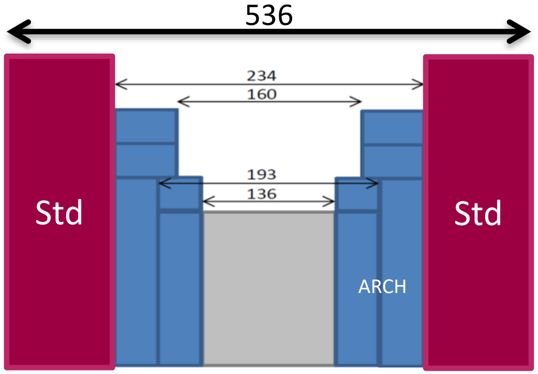
- Size 150 cc – 43,1%
  - Φ 80mm h 31,7mm
- Resolution
  - 122 keV 920 eV
  - 1,33MeV 1,97keV
- Background
  - Integral 115±3,5 count/day
  - 133 c/kg
  - Peaks
  - 46,5 keV 1,49 ± 0,37 c/d [210Pb]
  - 75 keV 3,6 ± 0,62c/d [Pb]

$$\text{limit (Bq)} = \frac{1{,}43 + 2{,}36\sqrt{1{,}36 + bdf \times t}}{\varepsilon(m)\, m\, t}$$

$$\varepsilon = \frac{detected}{emitted}$$



Shielding



Silicon wafer measurement
700 000s 650g

Nucleide		Bq/kg
210Pb	<	1,58E-02
^{226}Ra	<	1,27E-03
238U	<	6,27E-03
228Ra	<	3,82E-03
228Th	<	8,66E-04

Germanium facility

- Improving detection limit :
  - Imply choices :

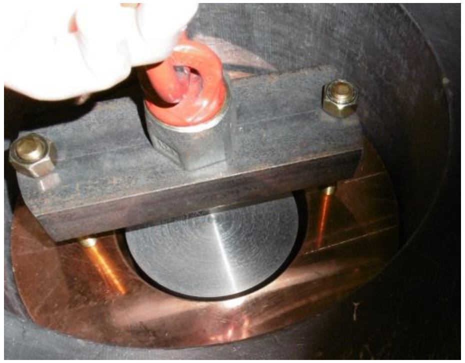
This detector can welcome much bigger sample but the low energy gamma are stopped by the dead layer around the detector.

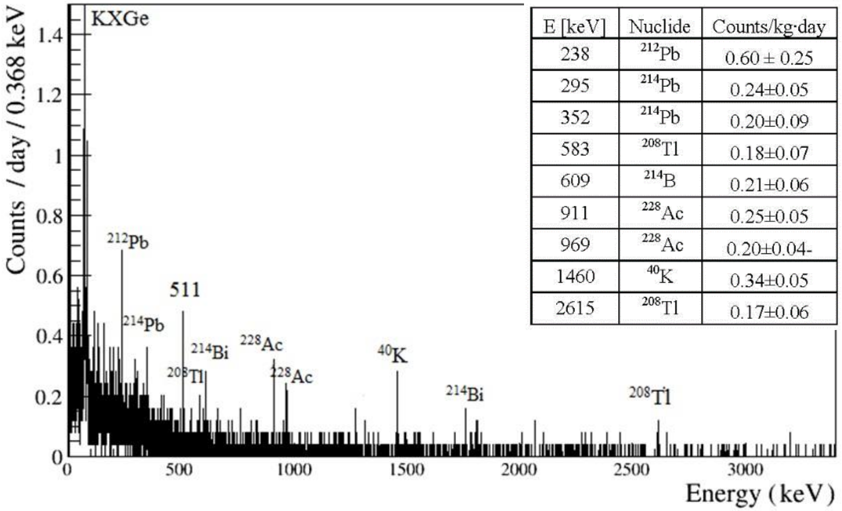
Theoretical sample of 1kg for 500000s

Nucleide		Bq/kg
210Pb		NA
^{226}Ra	<	4,96E-4
238U		NA
228Ra	<	1,78E-03
228Th	<	4,37E-04

Obélix :

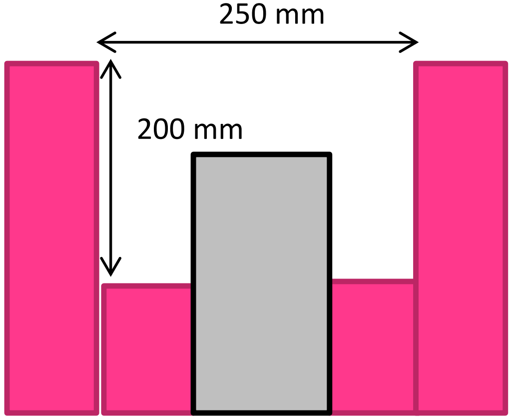
- Size
  - 600cc-160%
- Background
  - 95 counts/kg.d
- Resolution
  - 122 keV 1,1 keV
  - 1,33MeV 2keV





E [keV]	Nuclide	Counts/kg·day
238	^{212}Pb	0.60 ± 0.25
295	^{214}Pb	0.24±0.05
352	^{214}Pb	0.20±0.09
583	^{208}Tl	0.18±0.07
609	^{214}B	0.21±0.06
911	^{228}Ac	0.25±0.05
969	^{228}Ac	0.20±0.04-
1460	^{40}K	0.34±0.05
2615	^{208}Tl	0.17±0.06

Sample Chamber

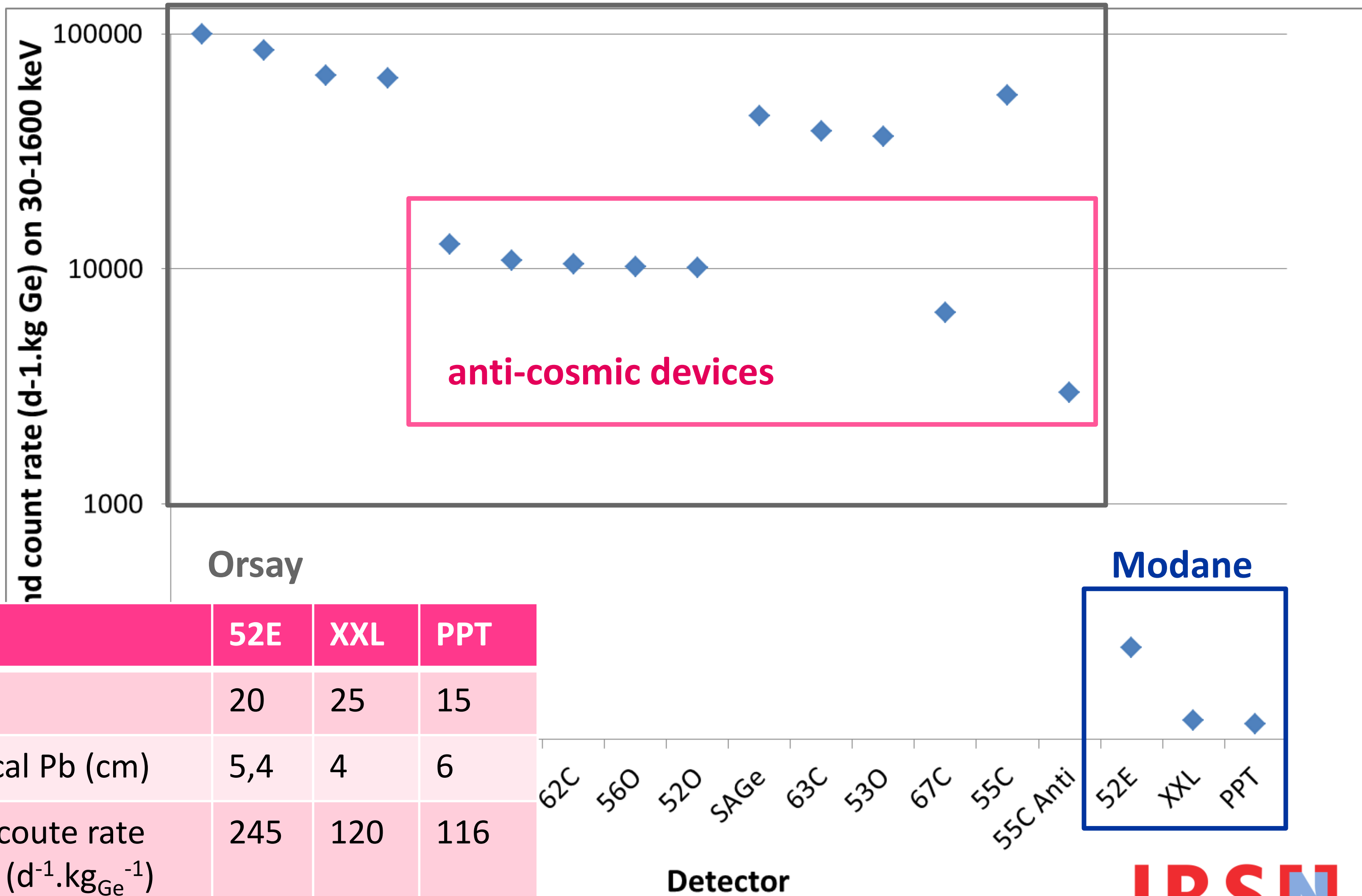


Nickel measurement

Decay mode	Final state or Decay transition	$T_{1/2}$, (90% CL)	Previous limits, $T_{1/2}$
β^+EC	g.s.	1.7×10^{22} y	7.0×10^{20} y (68%CL)*
β^+EC	811 keV	2.3×10^{22} y	4.0×10^{20} y (68%CL)*
EC/EC	811 keV	3.3×10^{22} y	4.0×10^{19} y (90%CL)**
EC/EC	1675 keV	3.4×10^{22} y	4.0×10^{19} y (90%CL)**
0νEC/EC resonant	Radiative 1918 keV	4.1×10^{22} y	2.1×10^{21} y (90%CL)***

*S.I. Vasil'ev et al., JETP Lett. 57 (1993) 631.
**E. Bellotti et al., Lett. Nuovo Cim. 33 (1982) 273.
***B. Lehnert et al., J. Phys. G: Nucl. Part. Phys. 43 (2016) 065201

N.I.Rukhadze (JINR, Dubna)

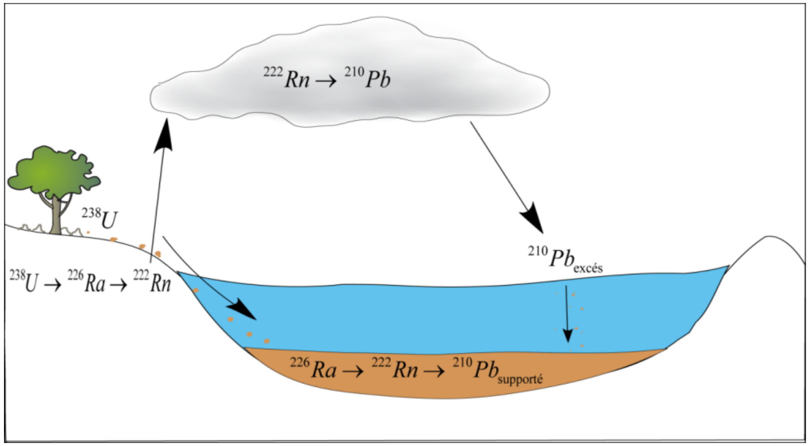


	52E	XXL	PPT
Pb (cm)	20	25	15
Archeologiocal Pb (cm)	5,4	4	6
Background coute rate 30-1600 keV ($d^{-1}.kg_{Ge}^{-1}$)	245	120	116

Analitycal power for interdiciplinarity

- Possibility to measure a wide range of nucleides
- Used in many environmental datation

Relative datation



$$(^{210}Pb)^{t}_{ex} = (^{210}Pb)^{0}_{ex} \times e^{-\lambda t}$$

$$Ln(^{210}Pb)^{t}_{ex} = -\lambda \frac{z}{V} + Ln(^{210}Pb)^{0}_{ex}$$

Absolute datation

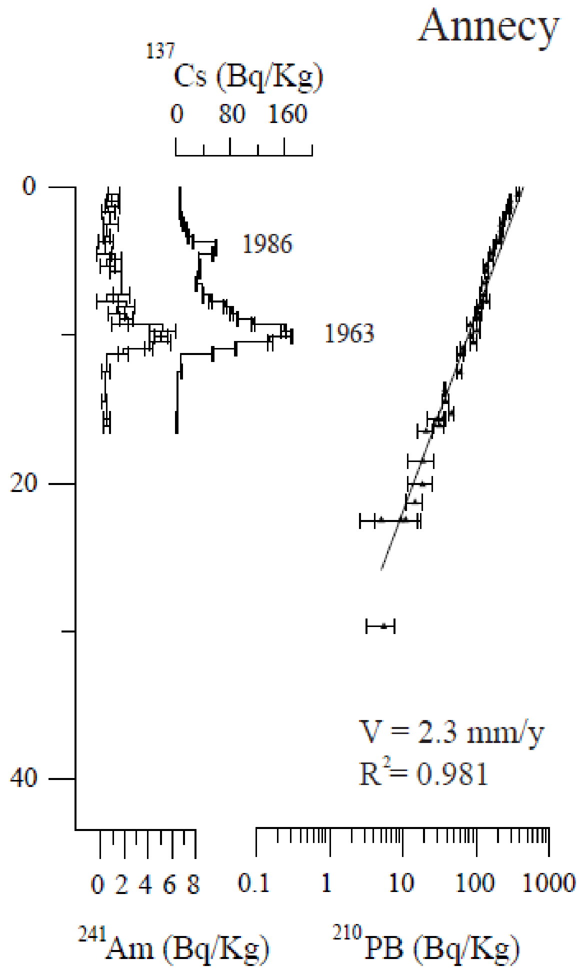
^{137}Cs + ^{241}Am
1963

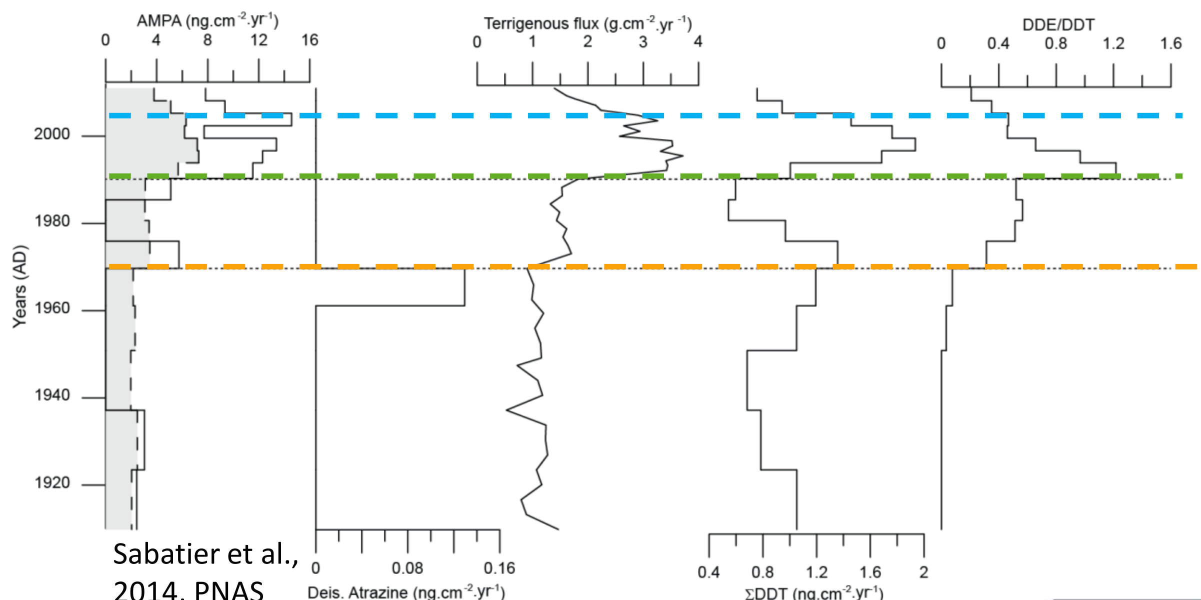
^{137}Cs only
1986

Guillaume Warot

Lake survey

- 210Pb gives the sedimentation rate
- tificials nucleides
- nstruct the history of a lake without archives



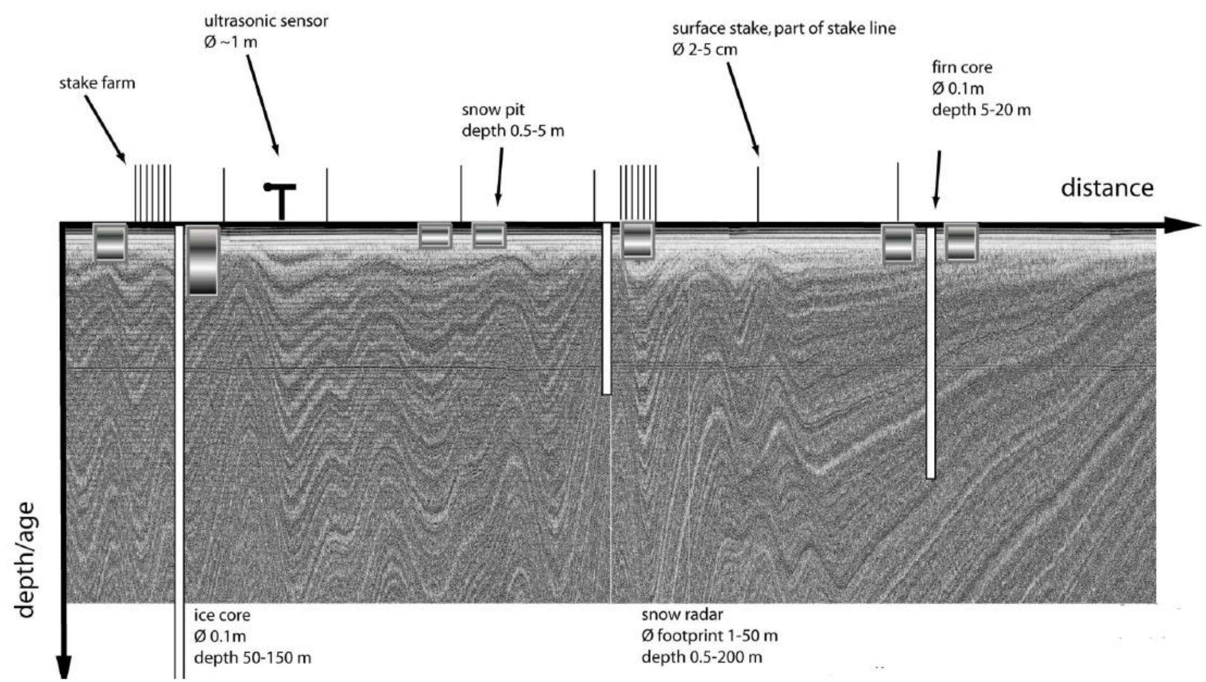


Sabatier et al., 2014, PNAS

Guillaume Warot

Ice survey

- Datation of ice core in antartica
- Calibration of radar
- Temporal marker for climate change
- 2 days measure needed in underground lab



Guillaume Warot

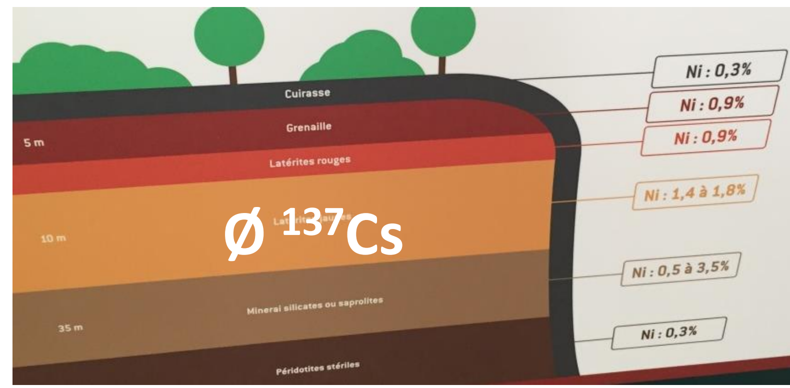
Erosion survey

Sources of sediment in mining catchments of New Caledonia

Two main sources of sediment to the main river

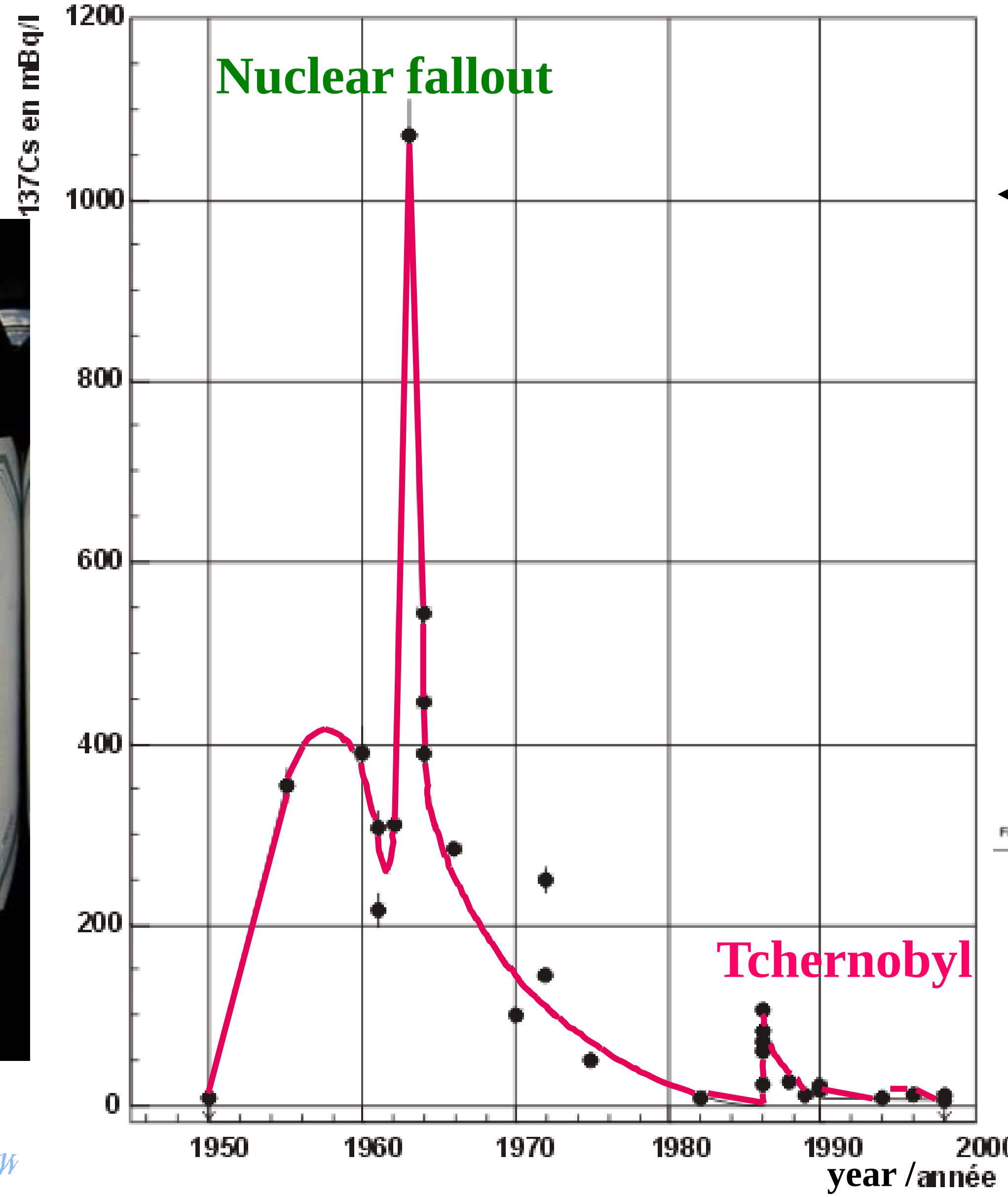
Non-mining tributaries

Mining tributaries



- Discrimination of contributions of both types of tributaries based on their activities in natural/artificial radionuclides
- Quantification using mixing models
- Analysis of sediment cores collected in the delta to reconstruct changes in source contributions with time

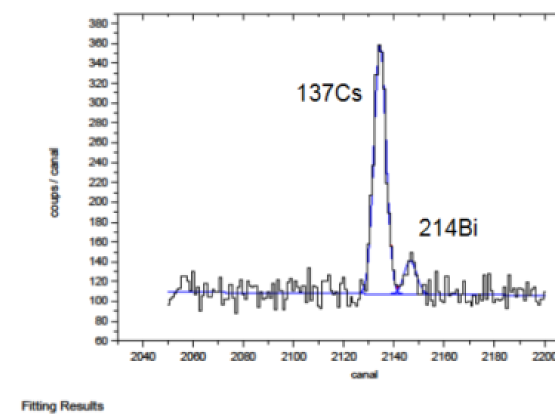
Millesime identification



← **1 Bq/l**

Margaux 1900

?

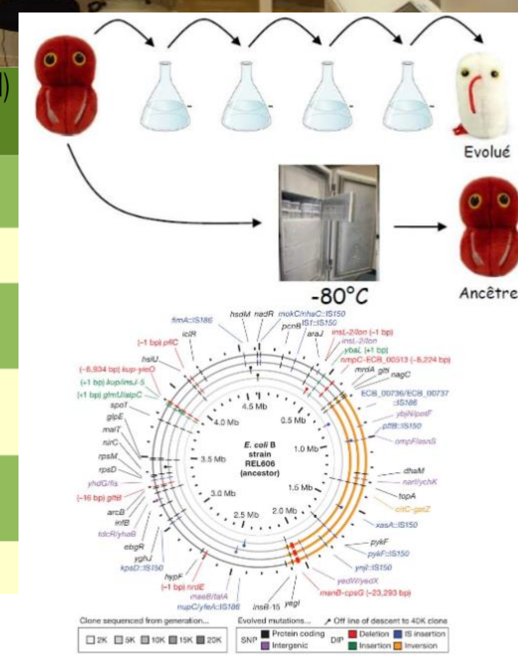


Guillaume W

Biology at LSM

- Evolution driven by radiation
- Comparison between surface and underground bacteria culture 800 generations harvested

Source	Measurement Method	LPC Clermont (nGy/day)	Modane (nGy/day)	Modane (shielded) (nGy/day)
γ background	Dosimeter measurement (rate varied by 10%)	2400	480	15
Muon flux	From theory	460	0	0
Potassium-40 (γ)	Simulations based on concentration	0.4	0.4	0.4
Potassium-40 (β)	Simulations based on concentration	74.4	74.4	74.4
Carbon-14 (β)	Simulations based on concentration	0.02	0.02	0.02
Total		2935	555	90

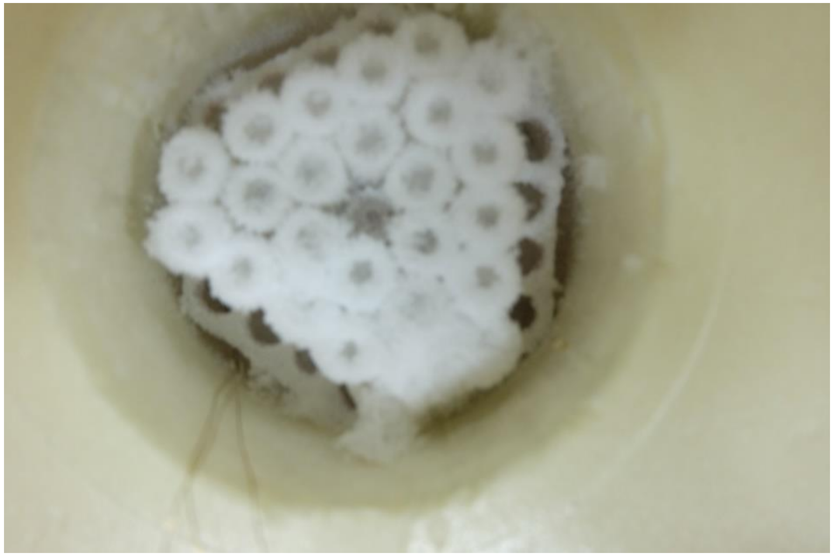


Laboratoire Souterrain de Modane

Guillaume Warot

Stem cell storage

- LSM-pasteur institute collaboration
- Funded by interdisciplanary mission from CNRS
- Allowed to test a stem cell storage shielded from natural radioactivity and terrestrial cosmic rays
- Patented solution
- Publication in progress
- P. ROCHETEAU, G. WAROT, M. CHAPELLIER, M. ZAMPAOLO, F. CHRETIEN et F. PIQUEMAL – Cryopreserved Stem Cells Incur Damages Due to Terrestrial Cosmic Rays Impairing their Integrity Upon Long-Term Storage, Cell Transplantation, 2022.



Laboratoire Souterrain de Modane

Guillaume Warot

Institut Pasteur

Conclusion

- Underground labs are designed for large scale fundamental physics
- Unique environment find always a use sometimes unforeseen at digging
- Leaves room for interdisciplinary program at moderate cost
- New fields and discoveries made possible by the access to low level radiation environment