Basic Applications in Fundamental Research – Neutrino Physics

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Outline

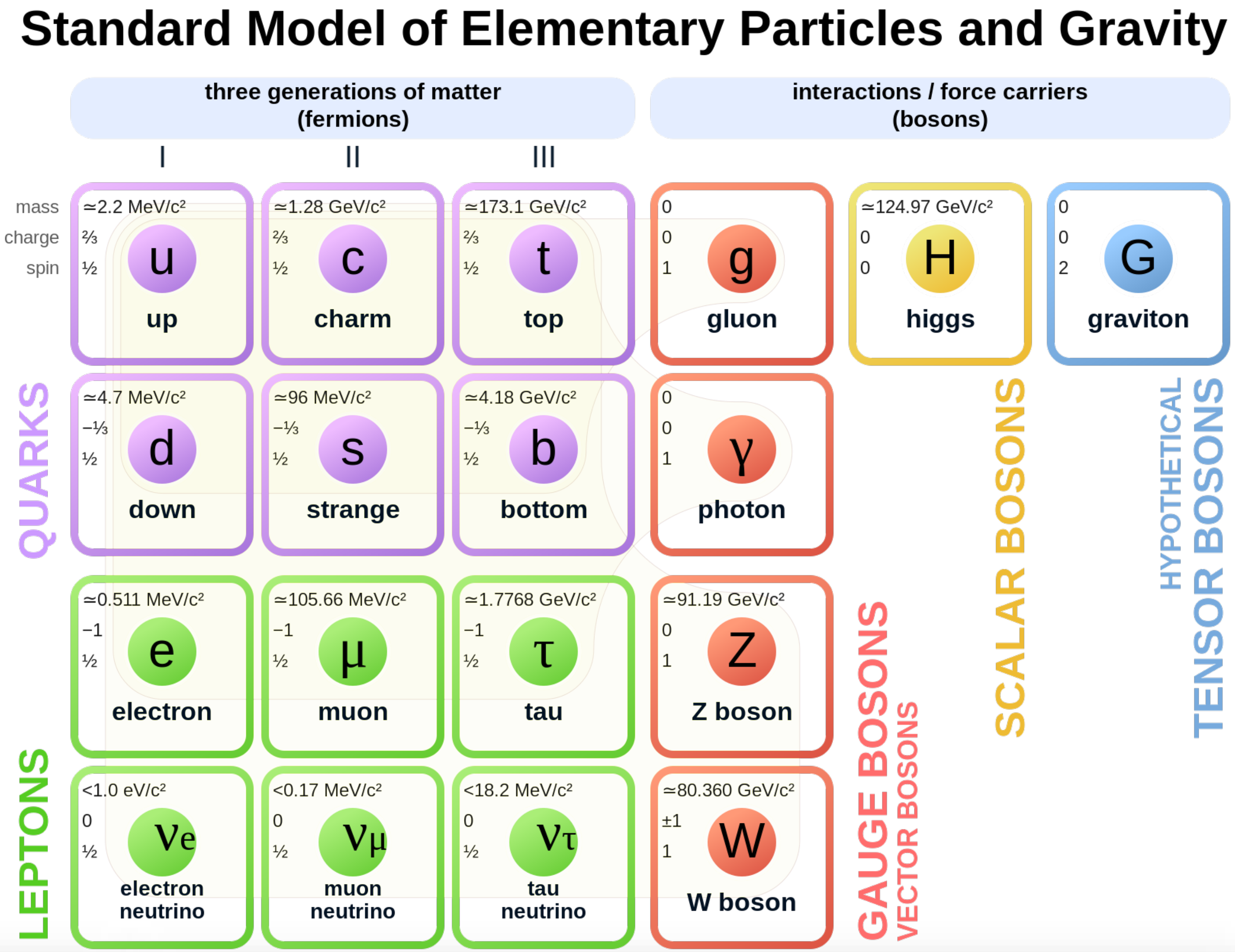
- Neutrino - general introduction
- Double beta decay
- SuperNEMO experiment
- Modane Underground Laboratory (LSM)

Neutrino - general introduction

The Standard Model of Particle Physics → is a comprehensive theory describing the fundamental particles and their interactions via the electromagnetic, weak, and strong forces, excluding gravity.

Neutrinos are:

- Fundamental - part of the Standard Model
- Electrically neutral – no charge
- Small but non-zero magnetic moment
- Elusive → only weak interaction and gravity = extremely low cross sections
- Oscillating - three types and flavours (e, μ, τ)
- Lightweight - still unknown non-zero masses
- Diverse - different sources spanning orders of energies and rates
- Mysterious - masses not produced by the Higgs mechanism
- Very mysterious - sterile neutrinos???
- Ultra mysterious - their own antiparticles???



Neutrinos – one of the most important and abundant structural constituents of the Universe
– 330 neutrinos/cm^3 → 10^{87} neutrinos per flavor in the visible Universe

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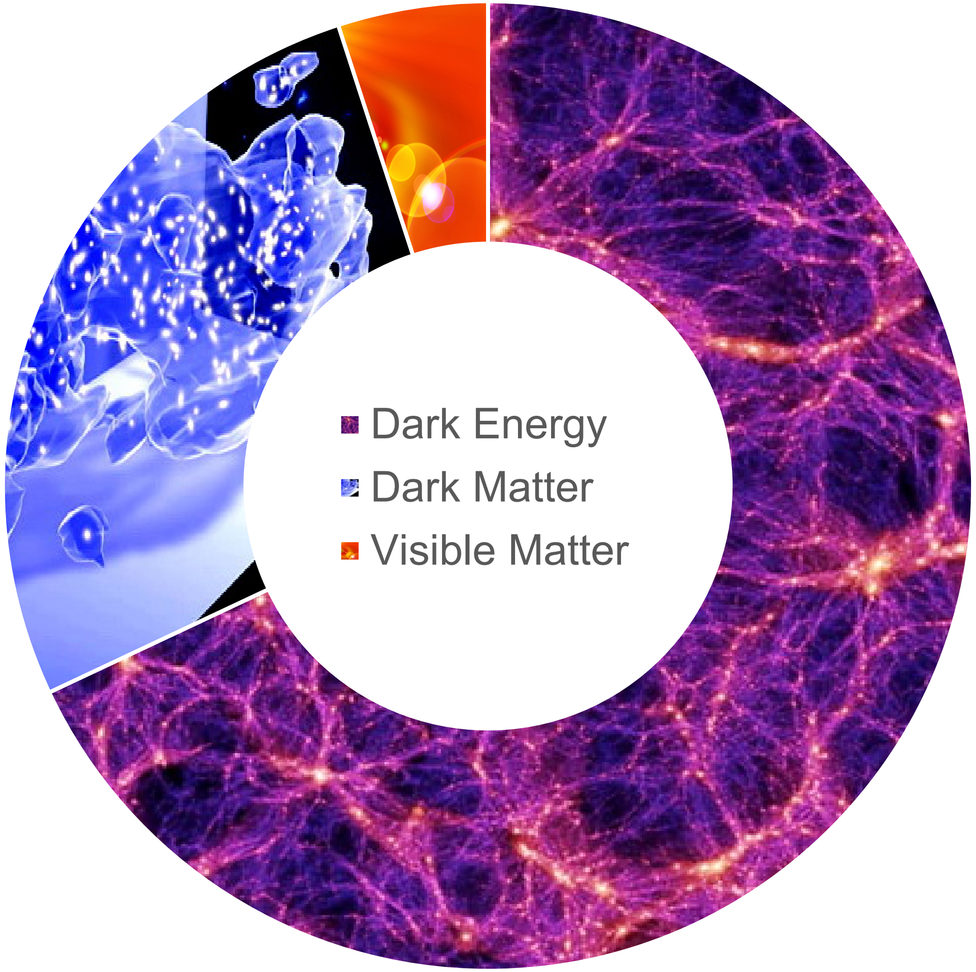
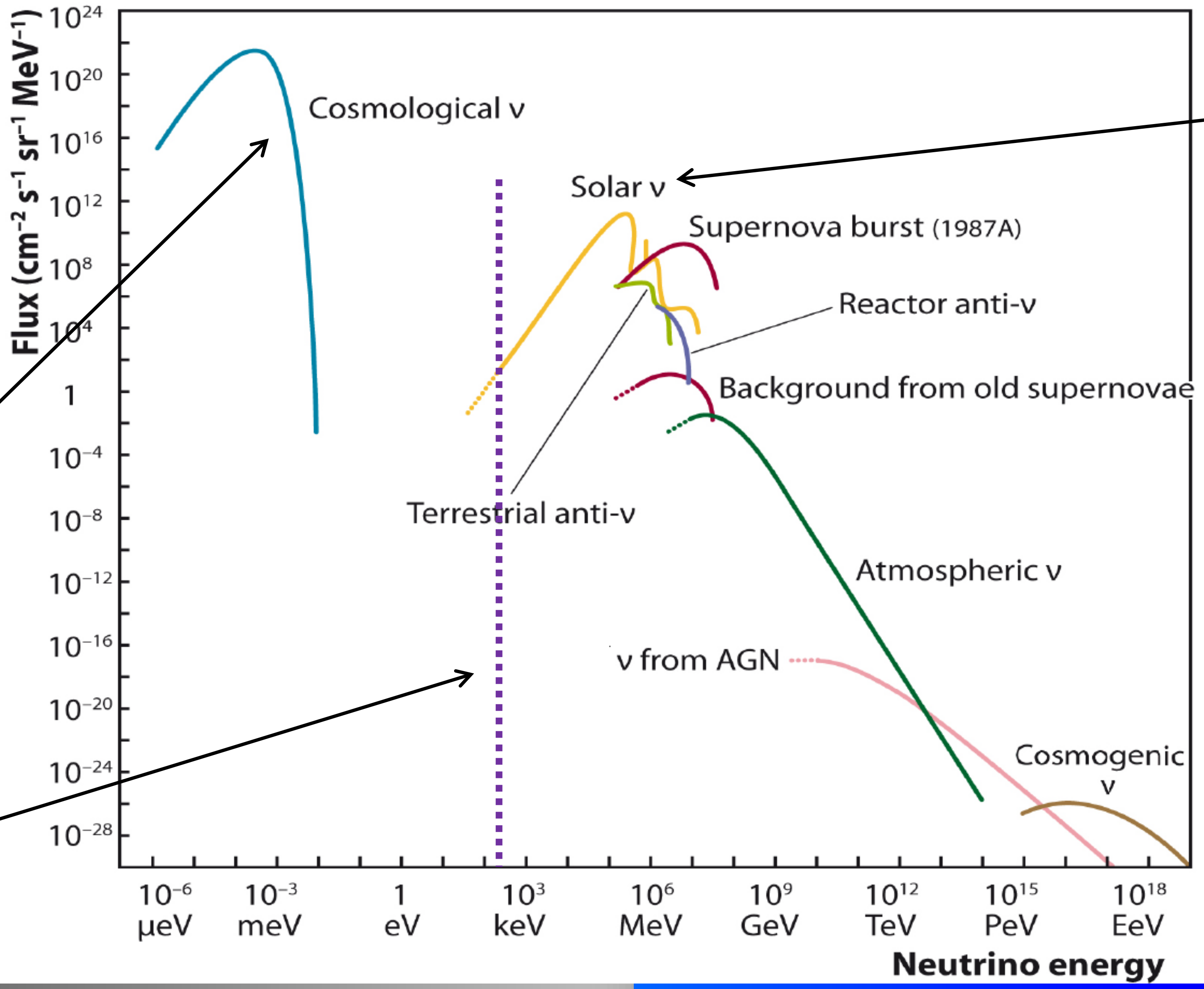


Component	%
Dark energy	68
Dark matter	27
Free H and He	4
Stars	0.5
Neutrinos	0.3
Heavy elements	0.03

K. Nakamura et al. (Particle Data Group Coll.), J. Phys. G: Nucl. Part. Phys. 37 (2010) 075021

Neutrino sources → Flux of neutrinos on Earth from different sources as a function of energy



About 100 billion solar neutrinos pass through your thumbnail every second.

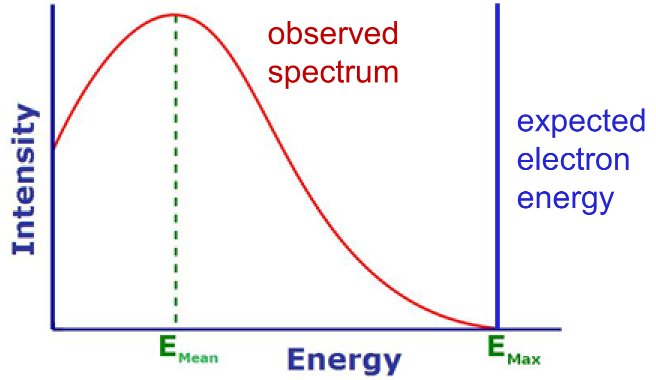
Abundant but challenging detection.

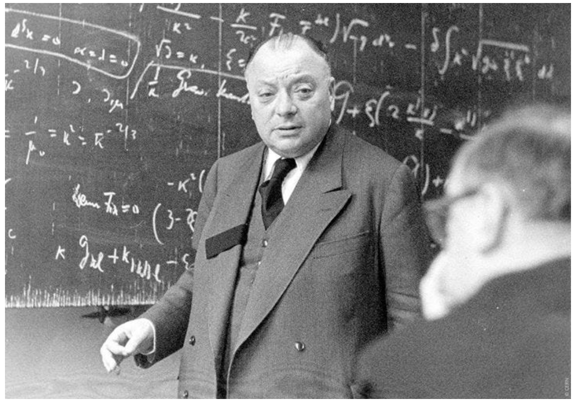
Below detection threshold of current experiments.

Argüelles, C.A. et al., Rep. Prog. Phys. 83 (2020) 124201

Brief history of neutrinos

- 1930 → W. Pauli postulated existence of new neutral particle „neutron“ (spin ½ and m < $0.01m_p$), to explain the missing energy in beta decay (continuous β-spectrum).

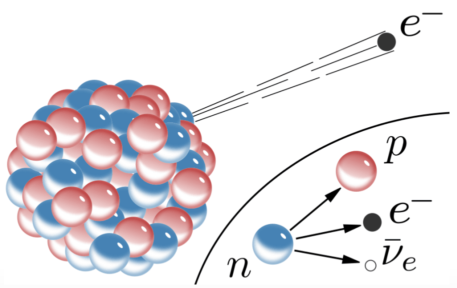


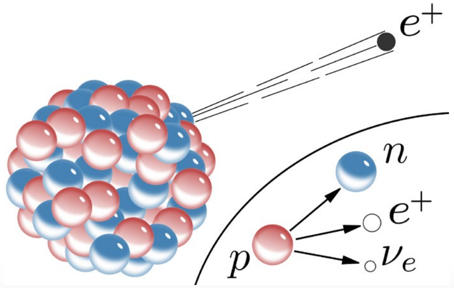

Wolfgang Ernst Pauli

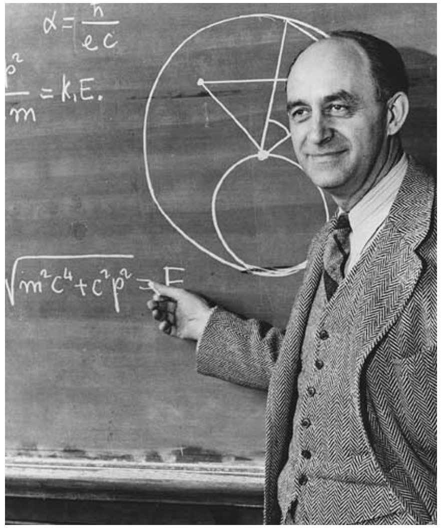
- 1932 → James Chadwick discovered neutron ($m_n \approx m_p$).
- 1934 → Enrico Fermi renamed Pauli's new particle, „neutrino” (Italian for „little neutron”).
  → formulation of the theory of β-decay.

$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

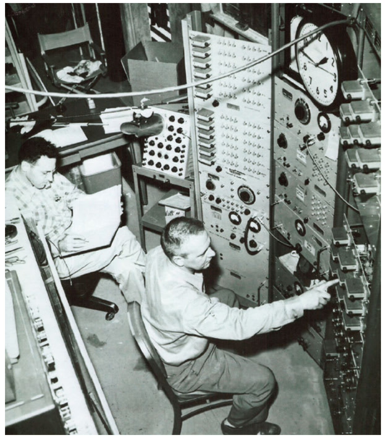
$$(A, Z) \rightarrow (A, Z-1) + e^+ + \nu_e$$



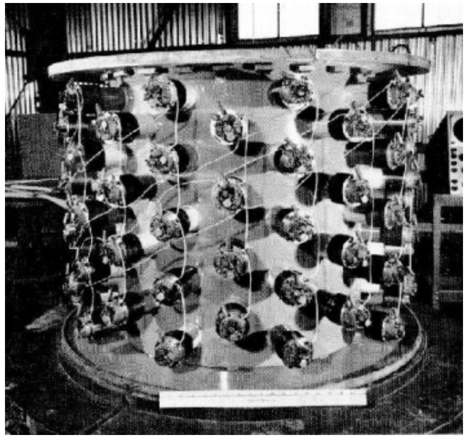



Enrico Fermi

- 1956 → Clyde Cowan and Frederick Reines confirm the existence of neutrinos through the detection of antineutrinos from a nuclear reactor (Savannah River Plant, South Carolina (USA)) → earning the 1995 Nobel Prize in Physics.



Fred Reines (left) and Clyde Cowan



Neutrino detector

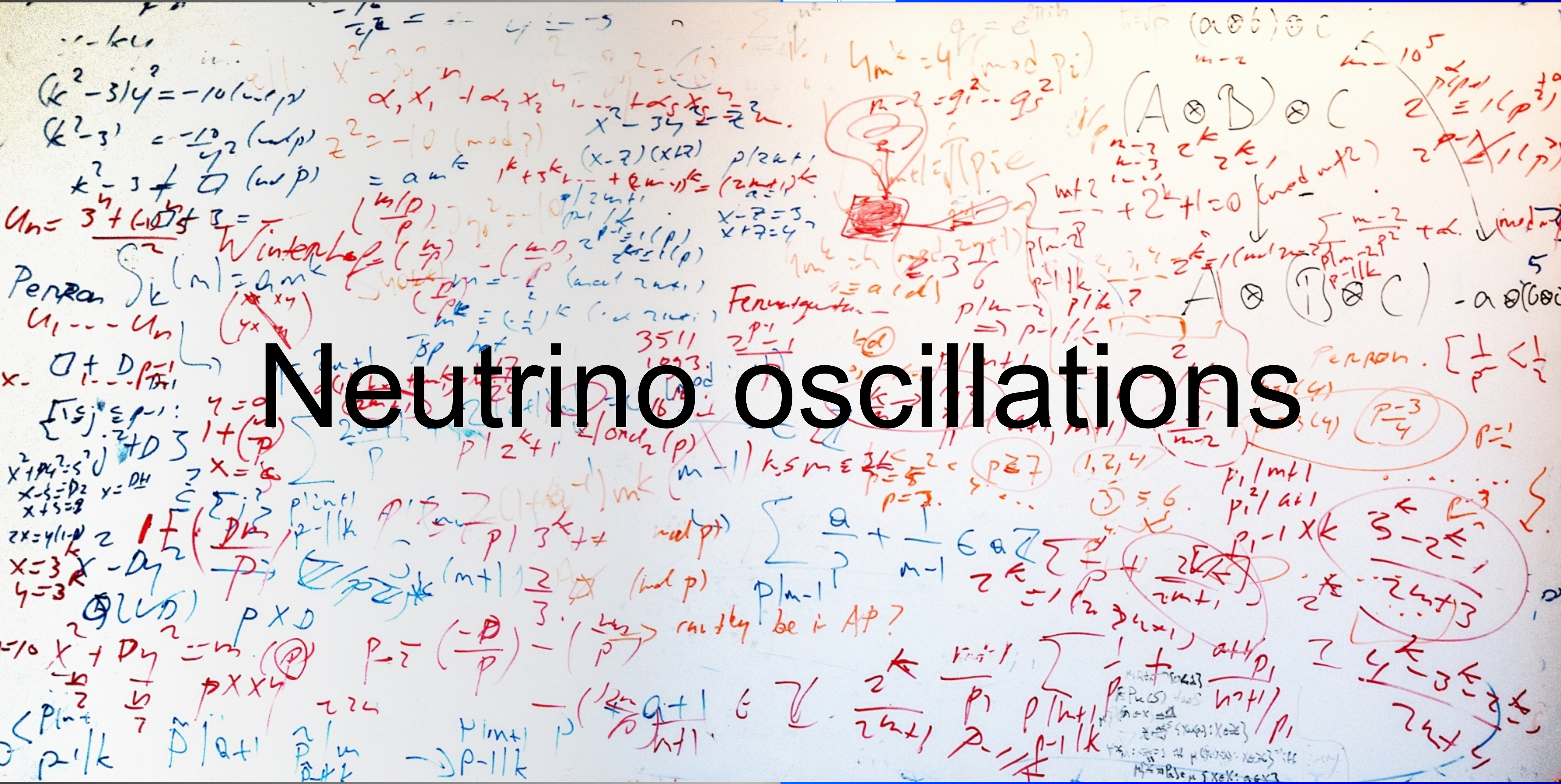
- 1962 → Leon Lederman, Melvin Schwartz, and Jack Steinberger discover the muon neutrino in an accelerator experiment at the Brookhaven National Laboratory, showing that there are at least two types of neutrinos, winning the 1988 Nobel Prize in Physics.

- 2000 → The tau neutrino was directly observed by the DONUT experiment at Fermilab (USA).

- 1957 → Bruno Pontecorvo – concept of neutrino-antineutrino oscillations (first signature of “Physics Beyond the Standard Model”).

Bruno Pontecorvo

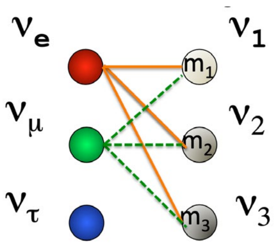
- 1968 – 2001 → Solar Neutrino Problem observed; fewer neutrinos detected from the Sun than predicted.
- 1998 → The Super-Kamiokande experiment in Japan provides experimental evidence for neutrino oscillation (showing atmospheric muon neutrinos oscillate into tau neutrinos), implying that neutrinos have mass.
- 2001 → The SNO (Sudbury Neutrino Observatory) experiment confirms that solar electron neutrinos oscillate into other flavors, resolving the Solar Neutrino Problem and providing further evidence of neutrino mass.
- Current → Experiments like IceCube, DUNE, and JUNO aim to measure neutrino properties more precisely.



Neutrino oscillations

Neutrino oscillations → neutrino mixing

- Neutrino oscillation arises from mixing between the flavour (ν_e, ν_μ, ν_τ) and mass eigenstates (ν_1, ν_2, ν_3) of neutrinos.
- Neutrinos are created and detected as flavor eigenstates. They propagate as mass eigenstates.
- Principle of neutrino mixing→ each flavour is a superposition of different masses.
- The relationship is given by the PMNS mixing matrix (Pontecorvo-Maki-Nakagawa-Sakata).

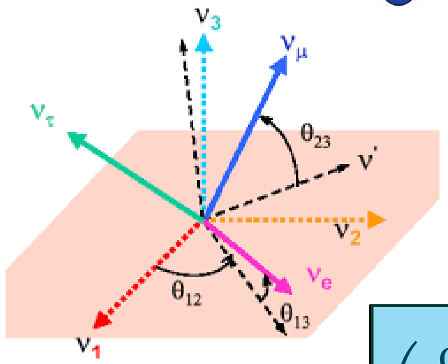


$$\nu_l(x) = \sum_{i=1}^{3} U_{li}\, \nu_i(x)$$

flavor eigenstates — mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS mixing matrix



Dirac phase ⟨0, 2π⟩ in oscillation experiments

Majorana phases ⟨0, 2π⟩ in 0νββ experiments

Parametrization:

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Solar, reactor — Reactor, accelerator — Atmospheric, accelerator

Parameters: 3 mixing angles (θ_{12}, θ_{23} and θ_{13}), 3 CP phases: 1 Dirac and 2 Majorana, 3 masses (m_1, m_2 and m_3)

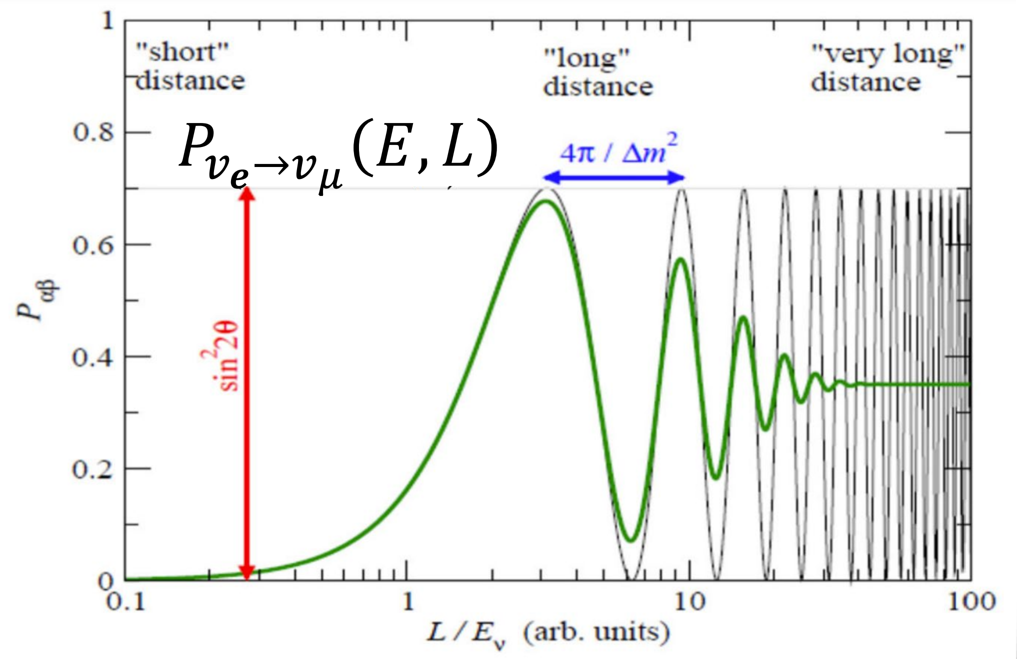
Neutrino oscillation experiments

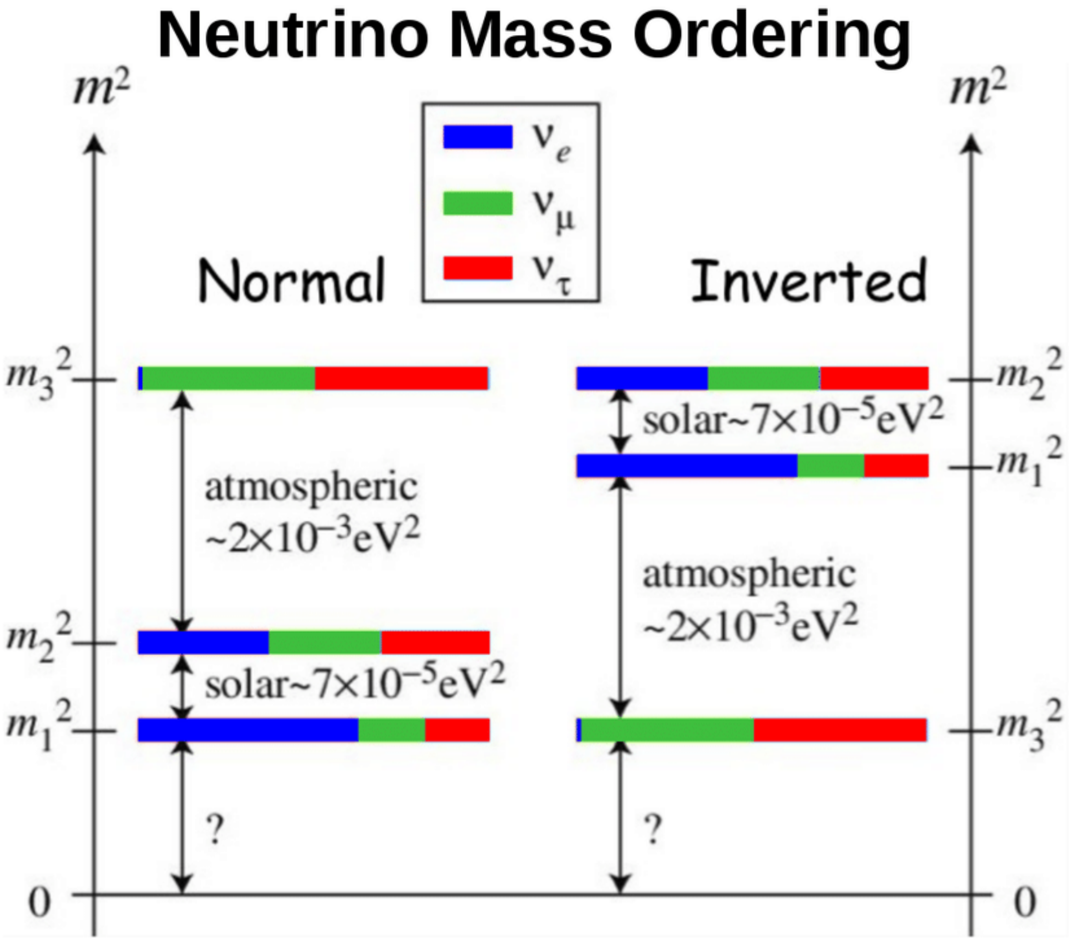
- Neutrino oscillation is a function of the ratio L/E, where L is the distance traveled and E is the neutrino energy.
- Transition probability for two neutrino flavours in a vacuum:

P. Fernández, SciPost Phys. Proc. 1 (2019) 029

$$P_{\nu_e\to\nu_\mu}(E,L) \approx \sin^2 2\boldsymbol{\theta} \, \sin^2\left(1.27\,\frac{\Delta m^2[eV^2]\,L[m]}{E[MeV]}\right)$$

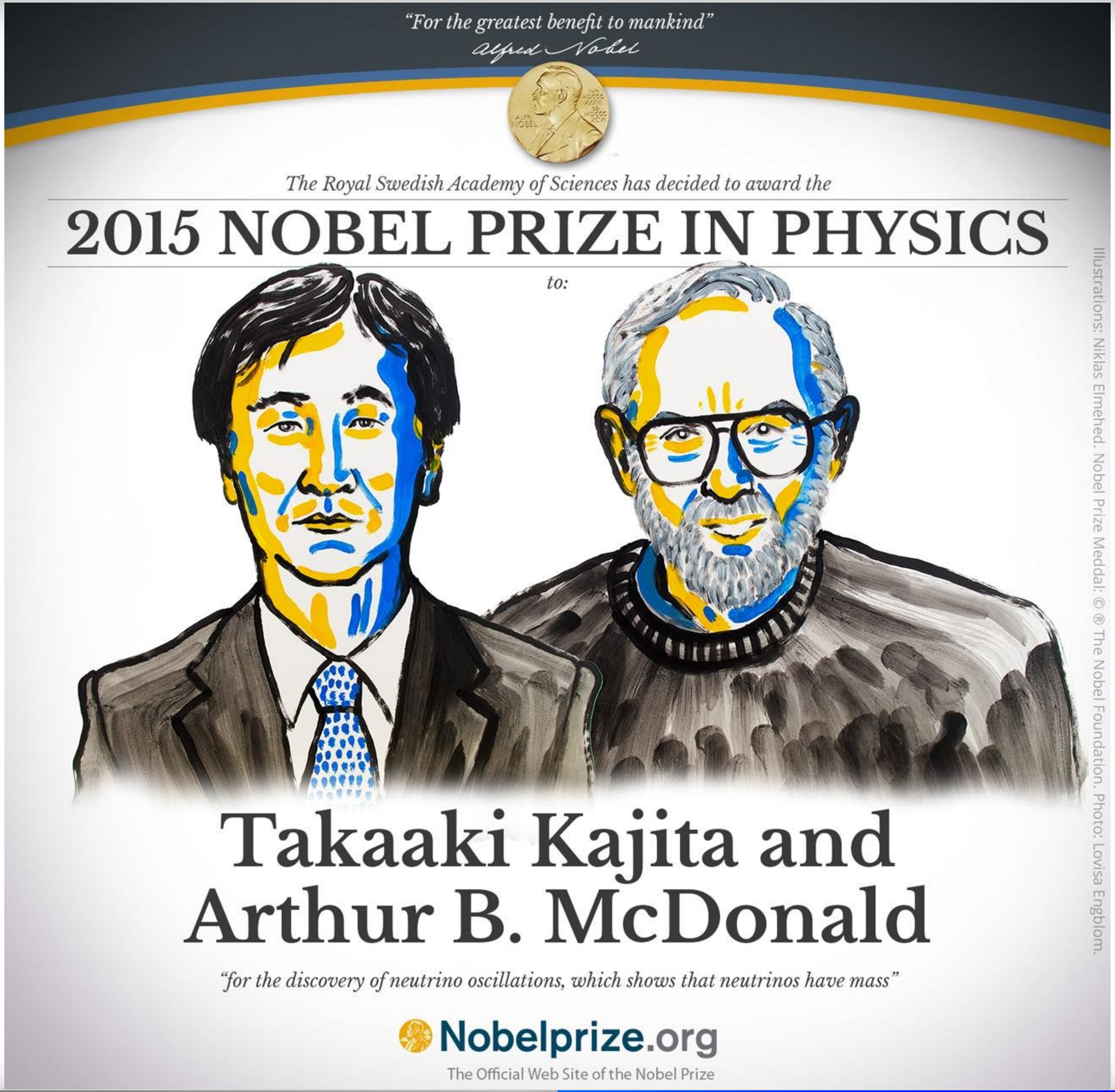
θ is neutrino mixing angle
Δm^2 is the mass-squared difference between eigenstates





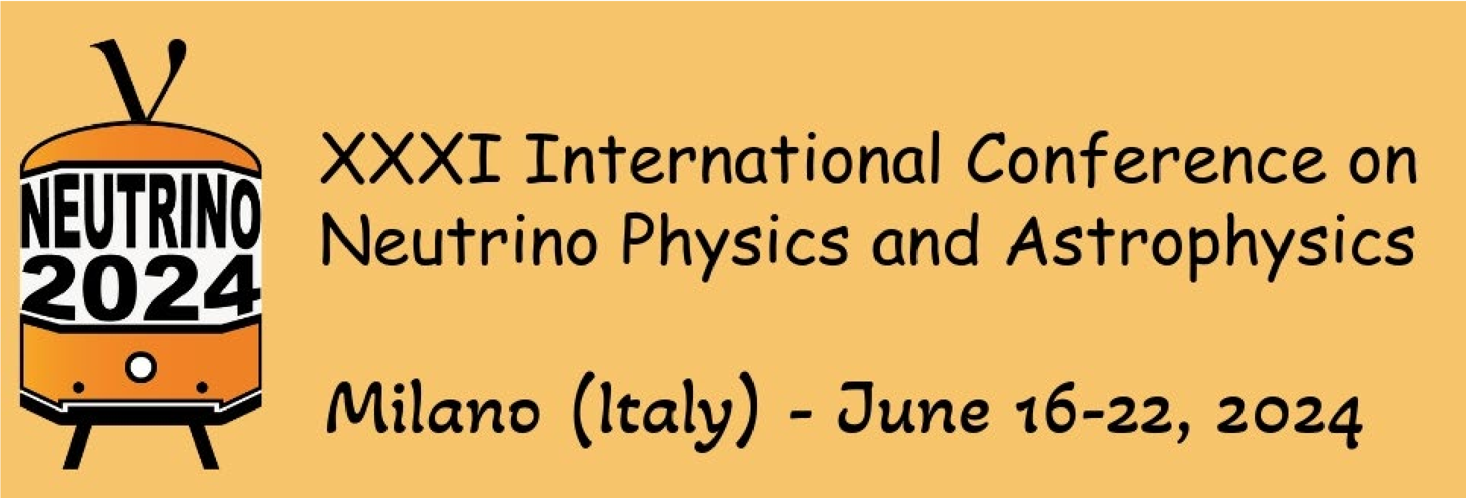
$m_3 > m_2 \sim m_1$

$m_2 \sim m_1 > m_3$


"For the greatest benefit to mankind"
Alfred Nobel
The Royal Swedish Academy of Sciences has decided to award the
2015 NOBEL PRIZE IN PHYSICS
to:
Takaaki Kajita and
Arthur B. McDonald
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"
Nobelprize.org
The Official Web Site of the Nobel Prize
Illustrations: Niklas Elmehed. Nobel Prize Meddal: © ® The Nobel Foundation. Photo: Lovisa Engblom.

- Open questions
  - absolute neutrino mass?
  - neutrino mass and hierarchy?
  - nature of neutrinos (Dirac or Majorana)?
  - existence of lepton number violation?
  - sterile neutrino hint?

https://www.particlezoo.net/



https://neutrino2024.org/

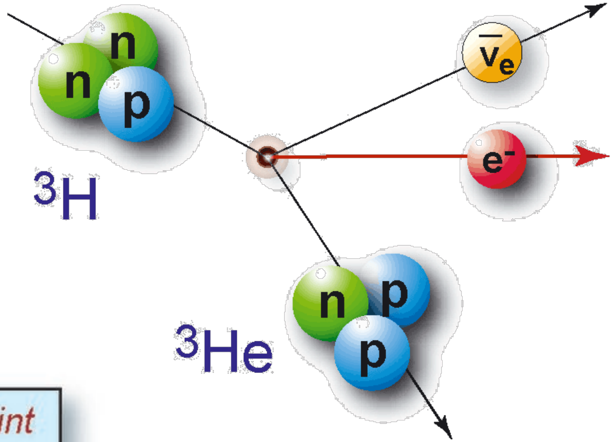
Beta decay

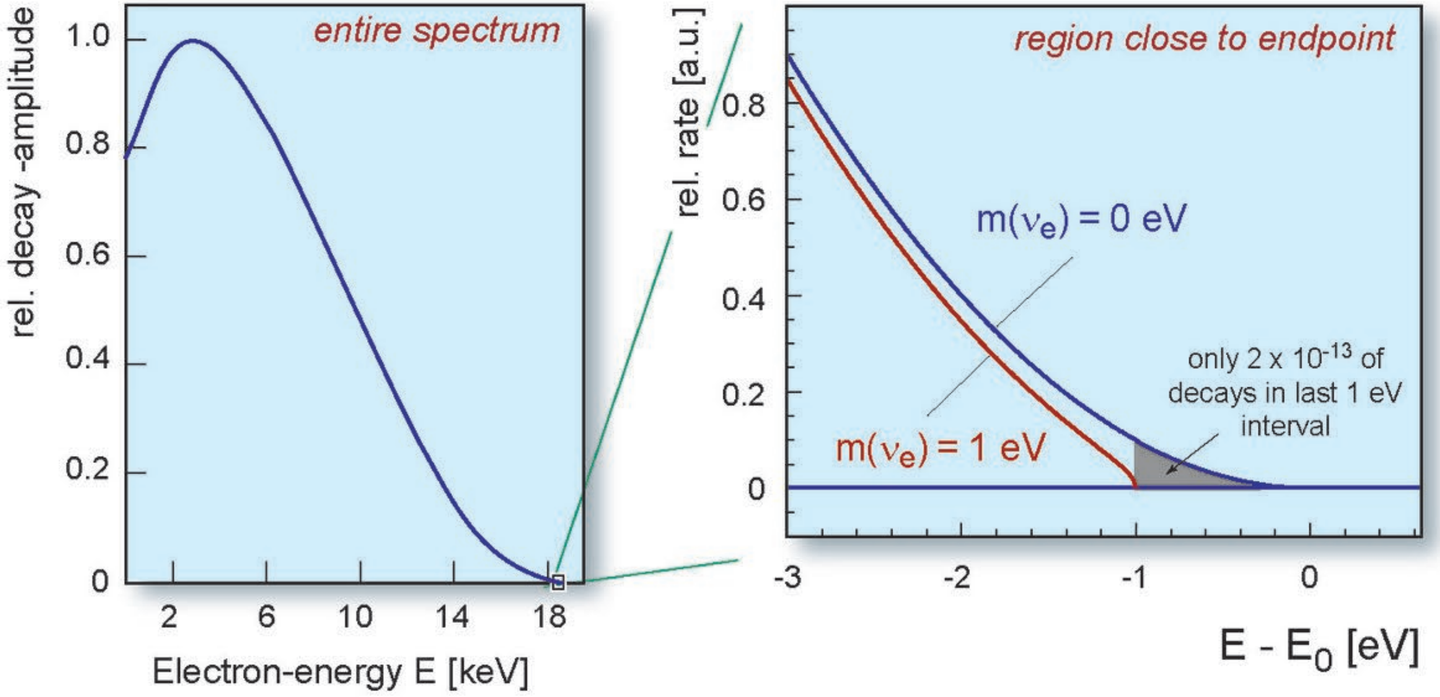
model-independent

$$m_\nu = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

$$m_\nu < 0.45\ eV\ c^{-2}\ (90\ \%\ C.L.)$$

The KATRIN Coll. 2024, arXiv:2406.13516v1





https://www.katrin.kit.edu/

Cosmology

model-dependent
(multi-parameter fits)

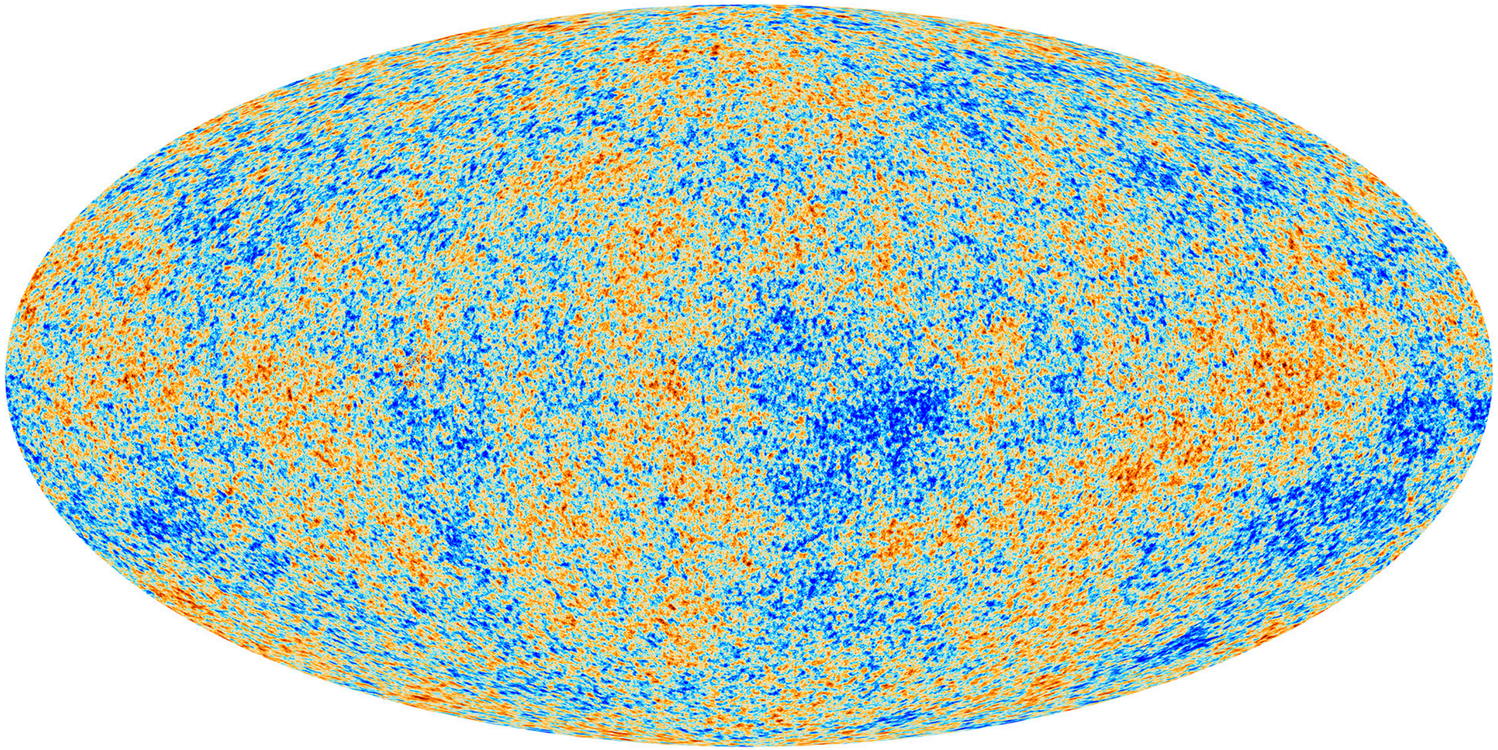
$$\boldsymbol{m_\nu^{cosm}} = \sum_{i=1}^{3} m_i$$

$m_\nu^{cosm} < 0.072\ eV\ (95\ \%\ C.L.)$

DESI Collaboration 2024, arXiv:2404.03002v2

$m_\nu^{cosm} < 0.043\ eV\ (95\ \%\ C.L.)$

Wang et al. 2024, arXiv:2405.03368v1



https://www.cosmos.esa.int/web/planck/planck-collaboration

0νββ decay

model-dependent
(Majorana CP-phases, NME)

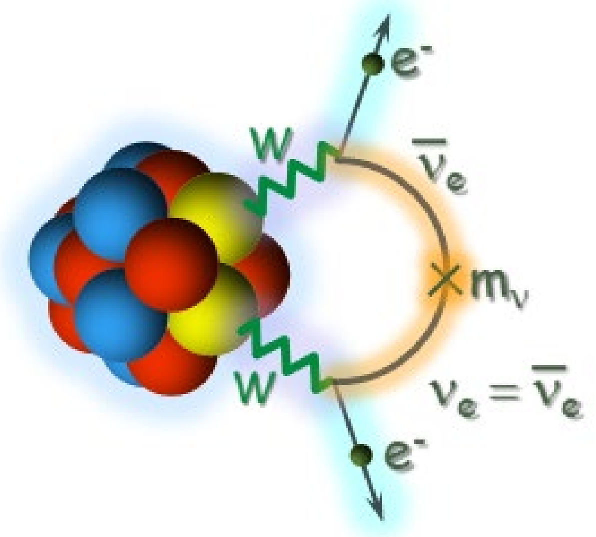
$$\left\langle m_{\nu}^{\beta\beta} \right\rangle = \sum_{i=1}^{3} |U_{ei}|^2 e^{i\alpha_i}\, m_i$$

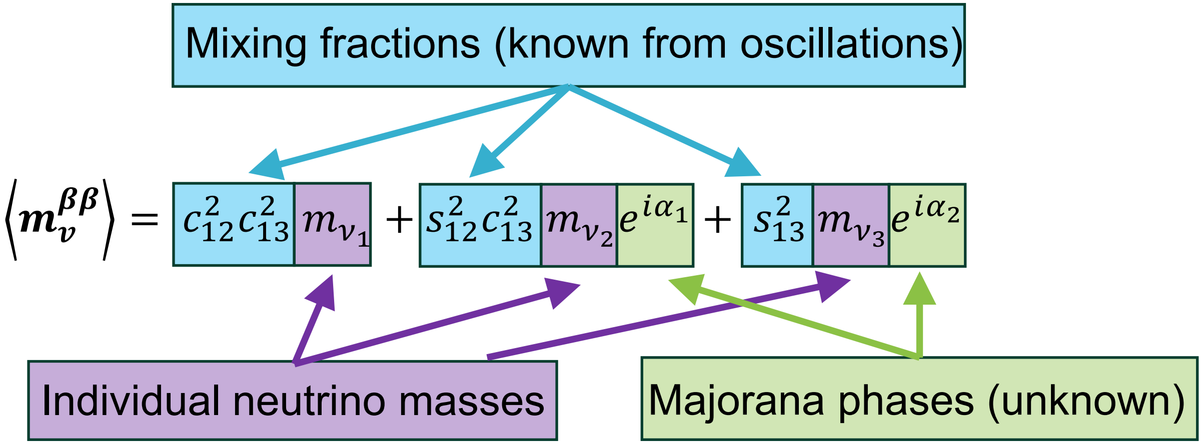
$$^{76}Ge:\ \left\langle m_{\nu}^{\beta\beta} \right\rangle < 0.079 - 0.18\ eV\ (90\ \%\ C.L.)$$

M. Agostini et al. (GERDA Coll.), Phys. Rev. Lett. 125 (2020) 252502

$$^{136}Xe:\ \left\langle m_{\nu}^{\beta\beta} \right\rangle < 0.028 - 0.122\ eV\ (90\ \%\ C.L.)$$

The KamLAND-Zen Coll. 2024, arXiv:2406.11438v1





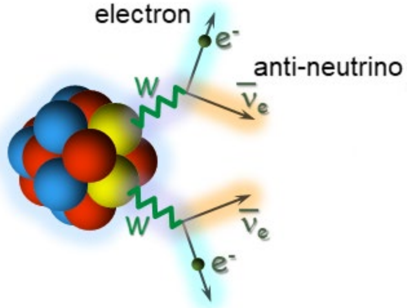
https://legend-exp.org/
http://kamland.stanford.edu/

Double beta decay

The double beta decay (DBD) processes

→ two-neutrino (2νββ) DBD process allowed in the SM of electroweak interactions (proposed by Maria G. Mayer in 1935).

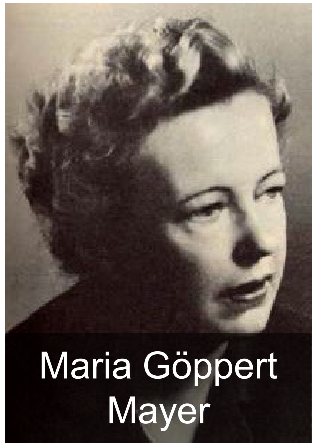
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$



- $\Delta L = 0$
- $\upsilon \neq \bar{\upsilon}$ (Dirac)
- $(T_{½}^{2\upsilon})^{-1} = G^{2\nu}(Q,Z)\,|M^{2\upsilon}|^2$
- $T_{½}^{2\upsilon} \approx 10^{18} - 10^{21}$ years

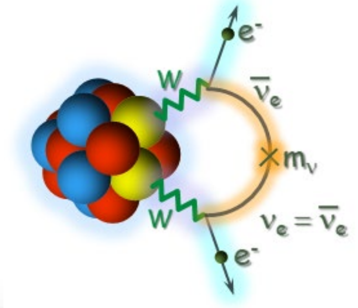
Nuclear matrix elements (Nuclear structure effects of the parent, daughter, and intermediate nuclei)

Phase space factor (Coulomb effects of nucleus on emitted electrons. Fairly well understood. Increases with atomic number Z, $Q_{\beta\beta}^5$)


Maria Göppert Mayer

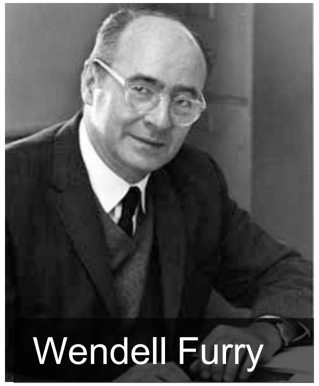
→ neutrinoless (0νββ) DBD process - extremely rare, lepton-number-violating nuclear transition (first proposed by Wendel Furry in 1939).

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



- $\Delta L = 2$
- $\upsilon \equiv \bar{\upsilon}$ (Majorana)
- $(T_{½}^{0\upsilon})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\upsilon}|^2 \left\langle m_\upsilon^{\beta\beta}\right\rangle^2$
- $T_{½}^{0\upsilon} \gtrsim 10^{24}$ years ($10^{14} \times$ age of the Universe)

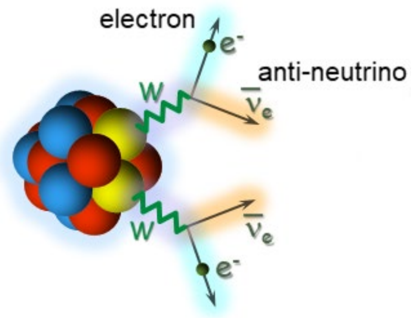
Effective neutrino mass


Wendell Furry

The double beta decay (DBD) processes

→ two-neutrino (2νββ) DBD process allowed in the SM of electroweak interactions.

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\upsilon}_e$$

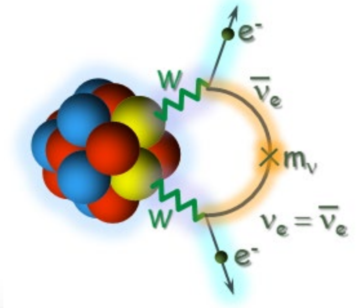


- $\Delta L = 0$
- $\upsilon \neq \bar{\upsilon}$ *(Dirac)*
- $(T_{1/2}^{2\upsilon})^{-1} = G^{2\upsilon}(Q,Z)\,|M^{2\upsilon}|^2$
- $T_{1/2}^{2\upsilon} \approx 10^{18} - 10^{21}$ *years*

Experimentally observed on:
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{128}Te, ^{130}Te, ^{150}Nd, and ^{238}U.

→ neutrinoless (0νββ) DBD process - extremely rare, lepton-number-violating nuclear transition.

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



- $\Delta L = 2$
- $\upsilon \equiv \bar{\upsilon}$ *(Majorana)*
- $(T_{1/2}^{0\upsilon})^{-1} = G^{0\upsilon}(Q,Z)\,|M^{0\upsilon}|^2 \left\langle m_\upsilon^{\beta\beta} \right\rangle^2$
- $T_{1/2}^{0\upsilon} \gtrsim 10^{24}$ *years* ($10^{14} \times$ *age of the Universe*)

NOT OBSERVED!

Nuclear matrix elements (NMEs)

$$\Gamma_{0\nu} \approx (T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\, |M^{0\nu}|^2 \left\langle m^{\beta\beta}_{\nu} \right\rangle^2$$

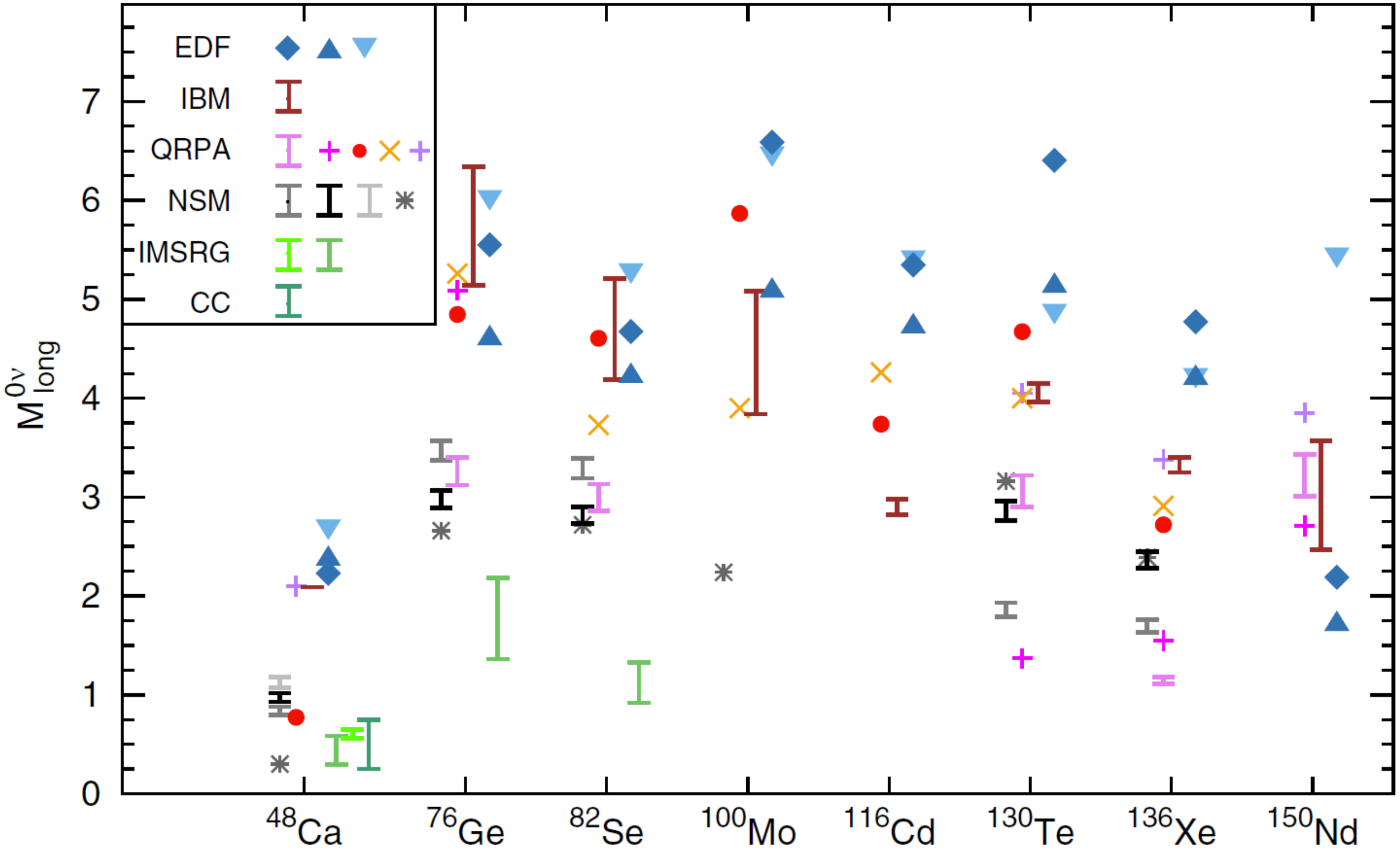
- The rate of 0νββ is proportional to the nuclear response, which is quantified by the square of the absolute value of the NME (describe the transition from the initial nuclear state to the final nuclear state).

- Different many-body methods

- Large difference in NME calculations $\rightarrow$ factor ~ 3 (leads to order-of-magnitude variation in $T_{1/2}$).

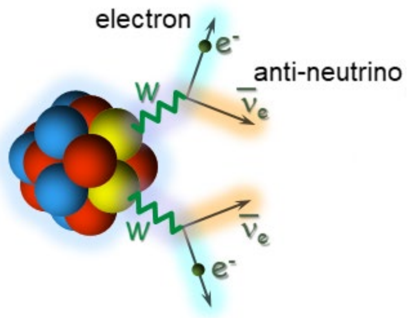
- There is a significant effort underway to improve nuclear models for various isotopes, as the precision in determining $m_{\beta\beta}$ from the measured $T_{1/2}$ relies on the accuracy of the NMEs.

Agostini, M. et al., Rev. Mod. Phys. **95** (2023)



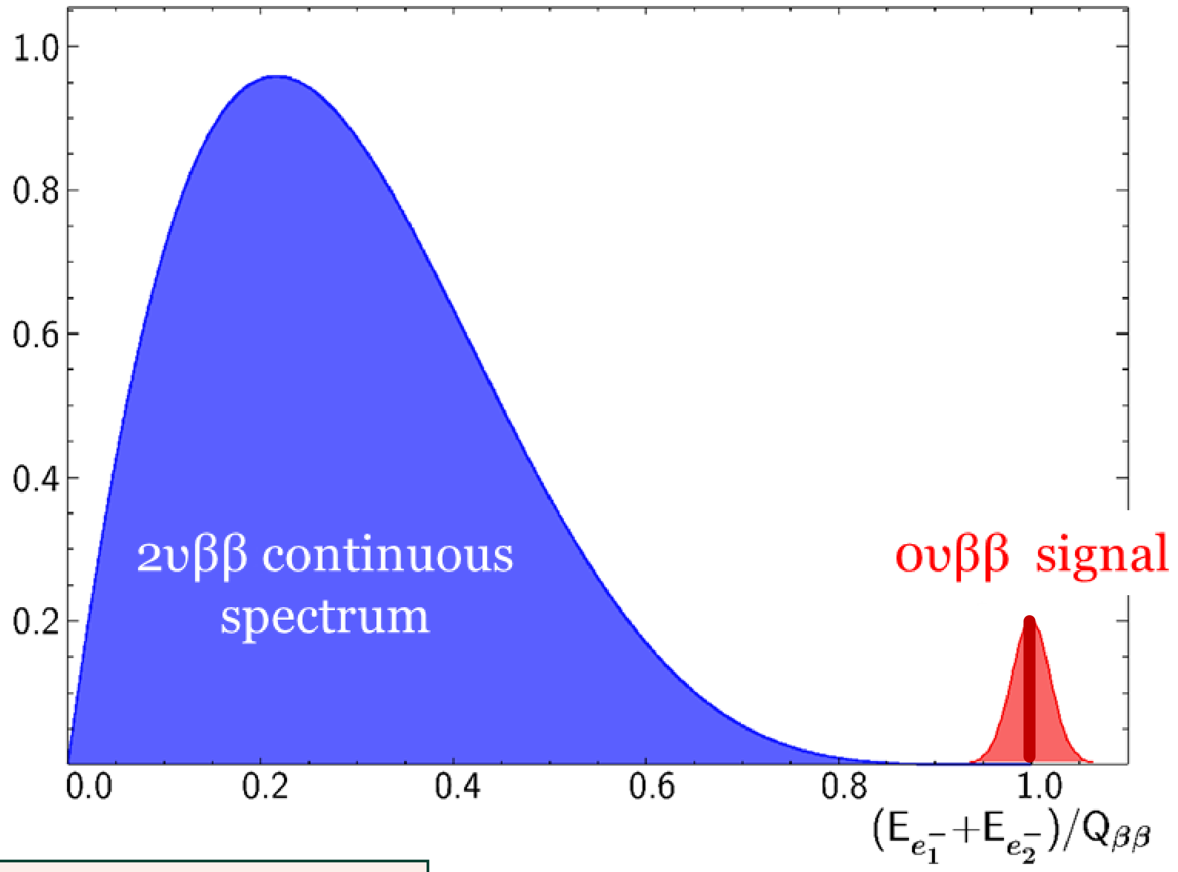
Experimental signature → measurement of the summed electron energy.

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

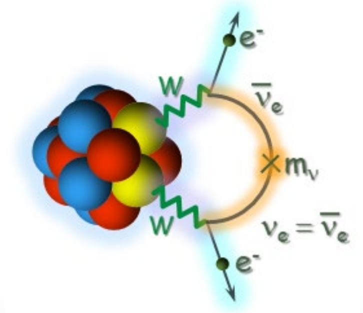


Energy spectrum of emitted electron is continuous

(E1+E2) ∈ [0, $Q_{\beta\beta}$]



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



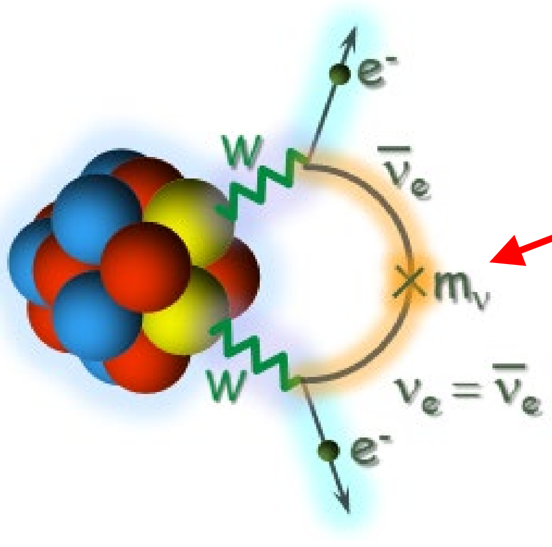
Two electrons carry away all the decay energy.

(E1+E2) / $Q_{\beta\beta}$ ≈ 1 [× energy resolution of the detector]

The neutrinoless double beta decay

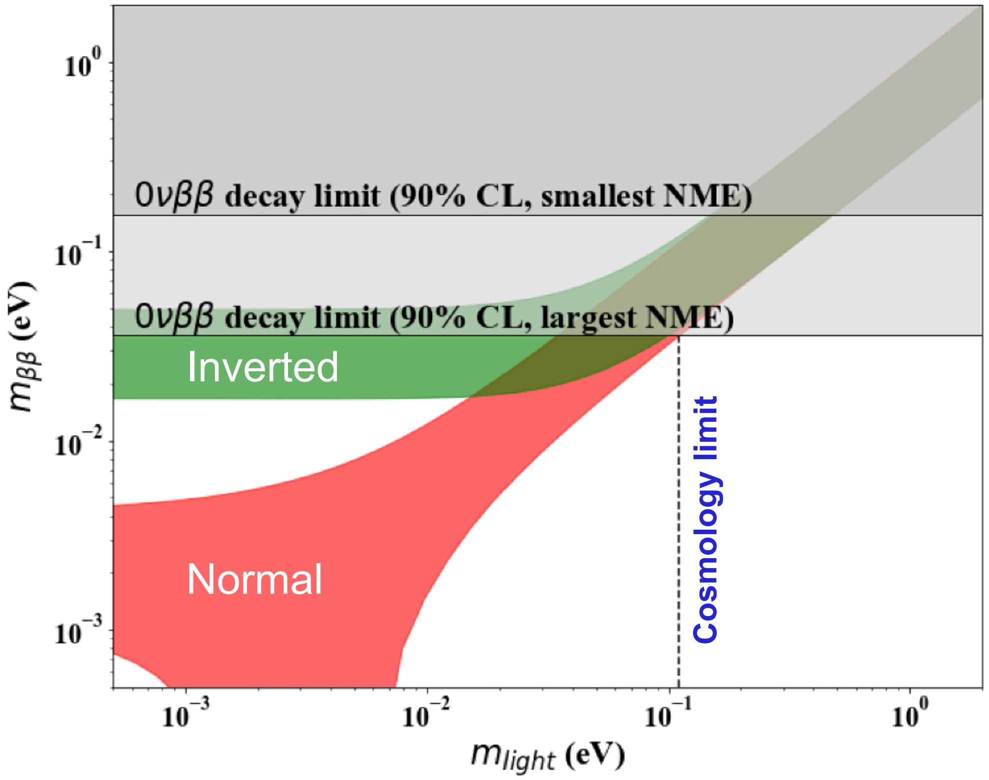
- $0\nu\beta\beta$ half-life of a nucleus is directly connected with the effective neutrino mass

Gómez-Cadenas, J.J. et al., *Riv. Nuovo Cim.* 46 (2023) 619.



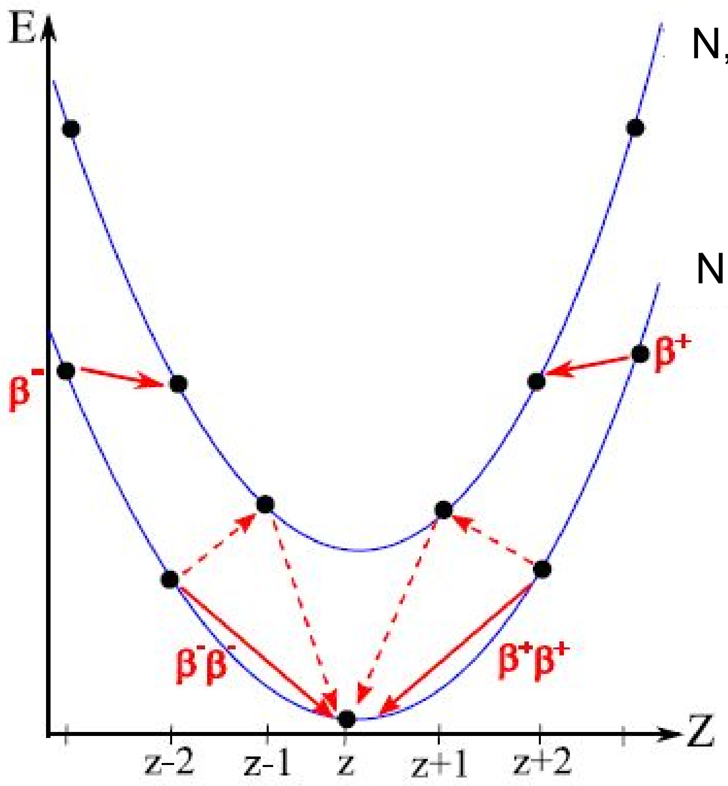
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m^{\beta\beta}_{\nu}\rangle^2$$

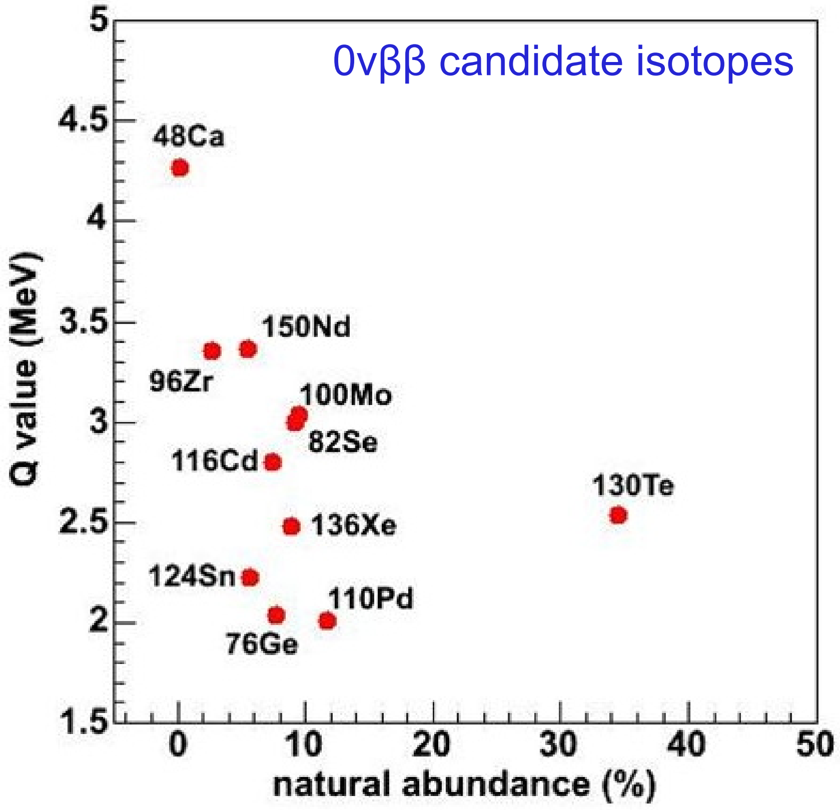
virtual process (QFT)
→ light Majorana neutrino exchange



- Observation would have fundamental implications for neutrino physics, theories beyond the SM and cosmology:
  - → Lepton number violation
  - → Presence of a Majorana mass term for the neutrino mass
  - → Constraints on neutrino mass hierarchy and scale
  - → Hint on origin of matter/anti-matter asymmetry in the Universe

- Isotope source → criteria





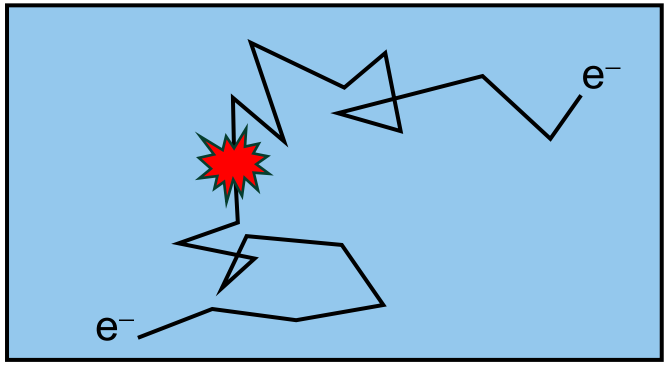
- Mass parabola: single β decay energetically forbidden → ββ decay

- Higher Q value means smaller radioactive background in ROI and faster decay rate.
- Large natural abundance makes the experiment cheaper.

Double beta decay experiment

- Detector parts should be radiopure (radioactive contamination as low as possible) = contribution to the background.
- Excellent energy resolution to distinguish between signal / background.
- High efficiency and high isotopic abundance.
- Large mass of the ββ isotope and lots of time for the measurement (exposure).
- Background suppression (gamma and neutron shielding, underground laboratories).

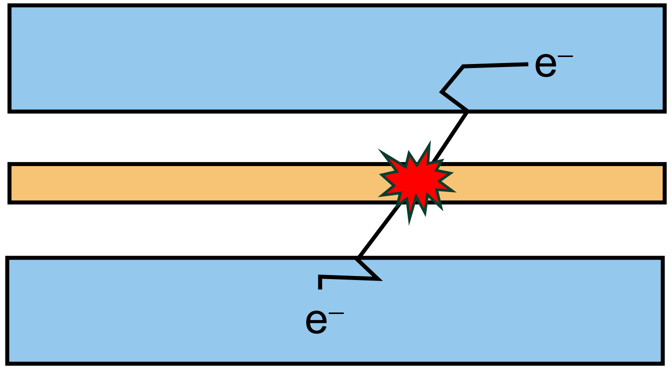
Experimental approaches



detector = source

detector

source



detector

Experimental sensitivity on the 0νββ half-life

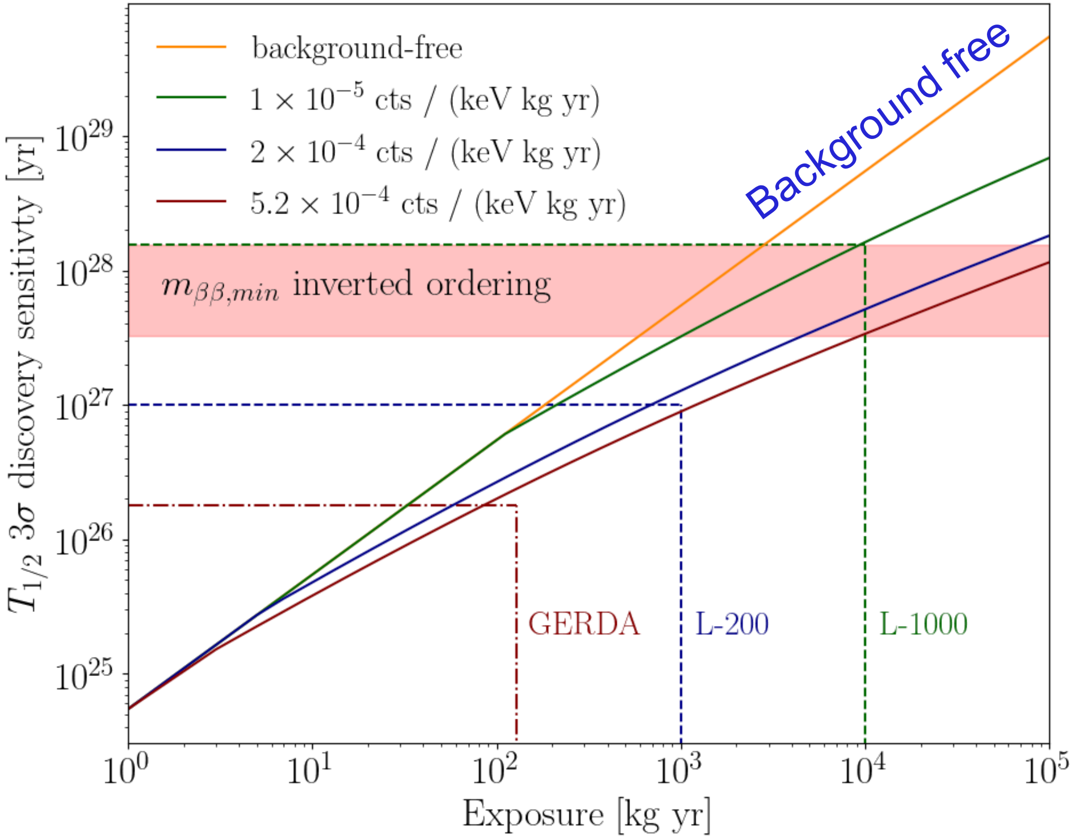
F. T. Avignone III et al., Rev. Mod. Phys. 80 (2008) 481

$$T^{0\nu}_{1/2} \geq \frac{ln(2)\,.\,N_A}{n_\sigma}\,\frac{\varepsilon\,.\,a}{W}\sqrt{\frac{M\,.\,t}{B\,.\,\Delta E}}$$

- Maximize efficiency and isotopic abundance
- Maximize exposure
- "Minimize" energy resolution
- Minimize background

- ***M*** is total mass of ββ source [kg]
- ***t*** is total exposure time [yr]
- ***B*** is expected background rate [$cnts.keV^{-1}.kg^{-1}.yr^{-1}$]
- ***ΔE*** is energy resolution
- N_A is Avogadro number
- n_σ is constant depending on the chosen CL
- ***ε*** is signal efficiency
- ***a*** is isotopic abundance
- ***W*** is molecular weight

https://legend-exp.org/



Background levels in ROI [$cnts.keV^{-1}.kg^{-1}.yr^{-1}$]

B. Schwingenheuer, Ann. Phys. 525 (2013) 269

KamLAND-Zen2	→ B ≈ 0.01×10^{-3}	CUORE	→ B ≈ 10×10^{-3}
GERDA-II	→ B ≈ 1×10^{-3}	NEMO-3	→ B = 1.2×10^{-3}
EXO-200	→ B ≈ 1.5×10^{-3}	SuperNEMO	→ B ≈ 0.1×10^{-3}
Majorana-Dem.	→ B ≈ 1×10^{-3}	SNO+	→ B ≈ 0.0002×10^{-3}

- **Background source**: Any radioactivity source that deposits energy near the $Q_{\beta\beta}$ –value of the nuclear reaction

→Natural radioactivity: Primarily U and Th decay chain products which are present in all materials

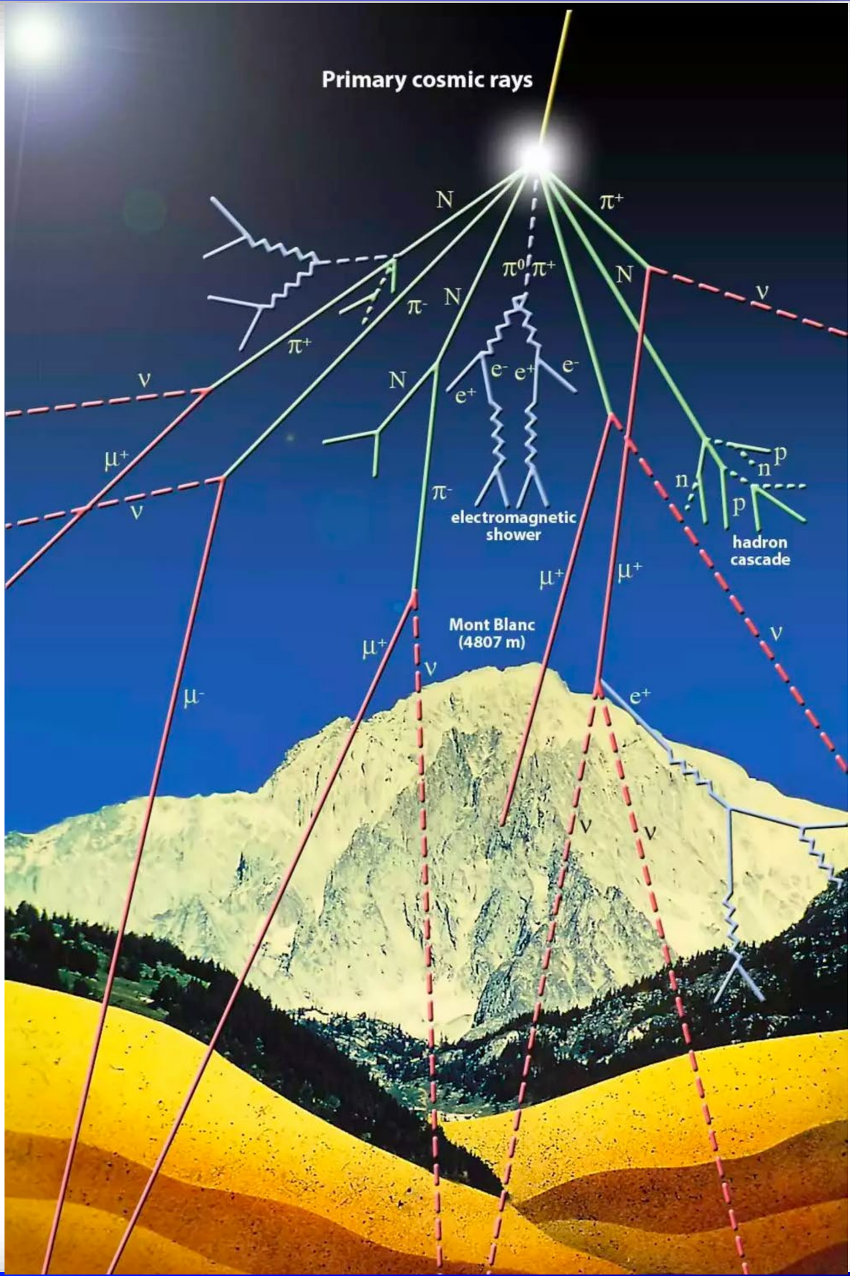
→Cosmic ray induced background

- **Background suppression**

→Natural radioactivity
  - material selection and purification techniques
  - barriers against radon penetration
  - vetos and active shielding
  - passive shielding
  - background tagging/cuts → identification techniques

→Cosmic ray induced background: Experiments are located deep underground: ~ thousands meter of rock → water equivalent)

→For 0νββ it is 2νββ, therefore → excellent resolution and isotope choice

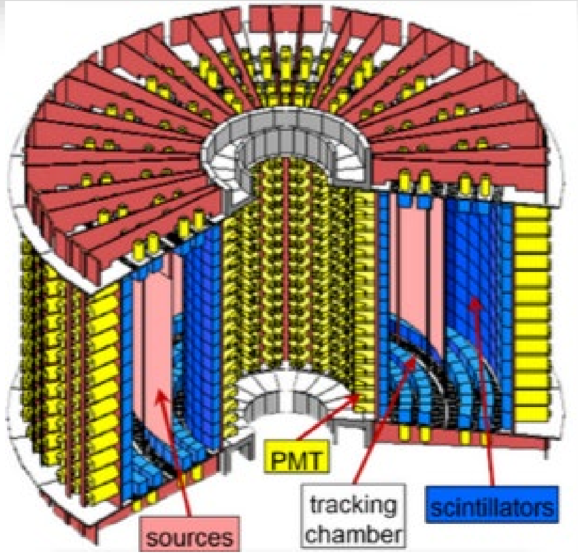


SuperNEMO experiment

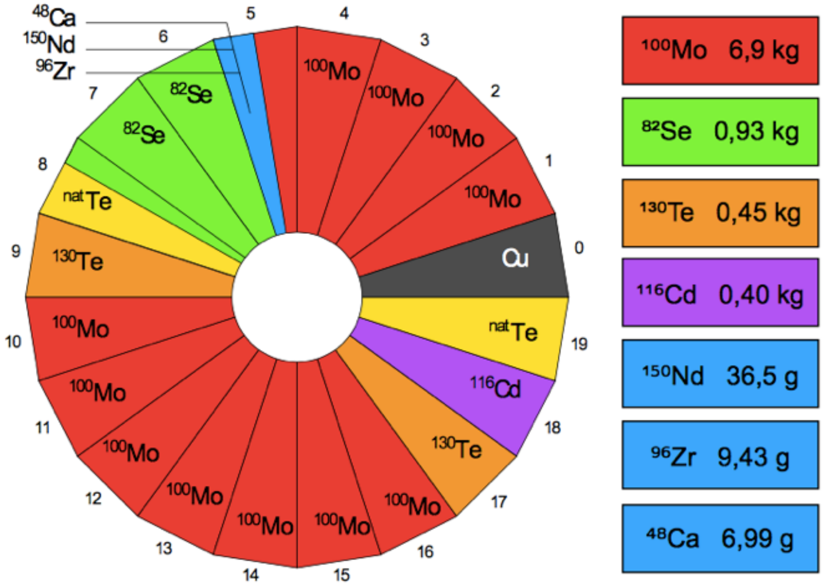
NEMO-3 (Neutrino Ettore Majorana Observatory) → 2003 – 2011

- Precise measurement of $2\nu\beta\beta$ and several world-best limits on $0\nu\beta\beta$ for ^{100}Mo, ^{150}Nd, ^{82}Se, ^{116}Cd, ^{48}Ca, ^{96}Zr, ^{130}Te, + excited states

- NEMO collaboration (since 1989) – France, UK, CR, Russia, USA, Slovakia, Japan, Ukraine



NEMO-3 "camembert" (source top view)

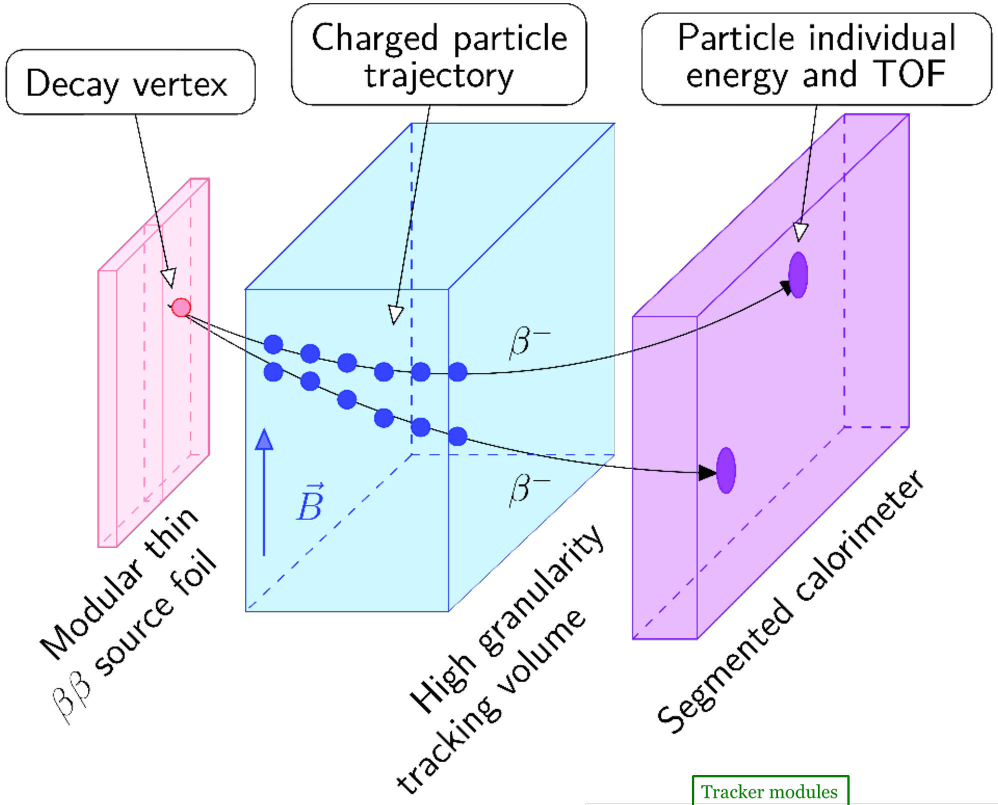


	$T_{1/2}^{2\nu\beta\beta}$ $[yr]$	$T_{1/2}^{0\nu\beta\beta}$ $[yr]$ $(90\%\ C.L.)$	$\langle m_\nu \rangle$ $[eV]$
^{100}Mo	$(6.93 \pm 0.04(stat)) \times 10^{18}$	$> 1.1 \times 10^{24}$	< 0.33 – 0.62
^{150}Nd	$(9.34 \pm 0.22(stat)^{+0.62}_{-0.60}(syst)) \times 10^{18}$	$> 2.0 \times 10^{22}$	< 1.6 – 5.3
^{82}Se	$(9.39 \pm 0.17(stat) \pm 0.58(syst)) \times 10^{19}$	$> 2.5 \times 10^{23}$	< 1.2 – 3.0
^{116}Cd	$(2.74 \pm 0.04(stat) \pm 0.18(syst)) \times 10^{19}$	$> 1.0 \times 10^{23}$	< 1.4 – 2.5
^{48}Ca	$(6.4^{+0.7}_{-0.6}(stat)^{+1.2}_{-0.9}(syst)) \times 10^{19}$	$> 2.0 \times 10^{22}$	< 6.0 – 26
^{96}Zr	$(2.35 \pm 0.14(stat) \pm 0.16(syst)) \times 10^{19}$	$> 9.2 \times 10^{21}$	< 7.2 – 19.5
^{130}Te	$(7.0 \pm 0.9(stat) \pm 1.1(syst)) \times 10^{20}$	$> 1.3 \times 10^{23}$	< 1.4 – 3.5

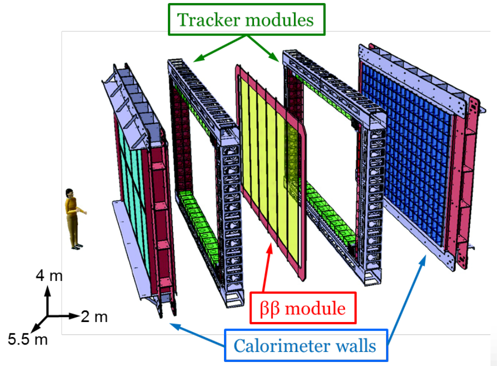
SuperNEMO → installation 2017-2018 → commissioning 2019-2024 → ββ data taking after summer 2024

- Measurement of 0νββ for ^{82}Se
- Detection technique remains the same – calorimetry and tracking
- Modular design to test scalability

NEMO-3		SuperNEMO
^{100}Mo		^{82}Se (^{150}Nd or ^{48}Ca)
7 kg	isotope mass	100+ kg
18 %	signal efficiency	> 30 %
^{208}Tl ~ 20 μBq/kg ^{214}Bi < 300 μBq/kg Rn ~ 5 mBq/kg	contaminations in the source foil Rn in the tracker	^{208}Tl ~ 2 μBq/kg ^{214}Bi < 10 μBq/kg Rn ≤ 0.2 mBq/kg
~ 15 % @ 1 MeV	Calorimeter FWHM	~ 8 % @ 1 MeV
$T_{1/2}(0\nu\beta\beta) > 2\times10^{24}$ yr $\langle m_\nu\rangle < (0.3 - 0.9)$ eV	half-life sensitivity effective neutrino mass	$T_{1/2}(0\nu\beta\beta) > 1\times10^{26}$ yr $\langle m_\nu\rangle < (0.04 - 0.11)$ eV



- ββ source foil is separated from the detector → possibility to measure several ββ isotopes
- Kinematics of the decay → individual electron energies $E_{e_1^-}, E_{e_2^-}$, angular distribution $cos\theta$
- Particle identification → e⁻, e⁺, γ, α
- Background rejection → internal (^{208}Tl, ^{214}Bi and radon) and external background (neutrons, gammas)



- ***Demonstrator location***
  → Modane Underground Laboratory

- ***ββ source** foils* (6.11 kg; ~ 50 mg/cm^2)
  → prime: ^{82}Se (96 - 99% enrichment, high $Q_{\beta\beta}$ ~ *3 MeV*)
  → ^{150}Nd, ^{48}Ca + any ββ isotope

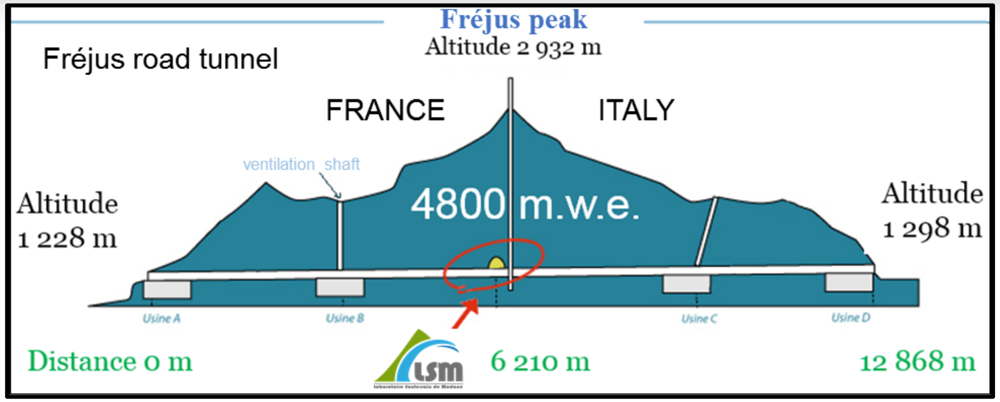
- ***Tracking detector***
  → drift wire chamber - 2034 cells in Geiger mode (+ 25 G magnetic field)
  → 95 % He + 4 % ethanol (C_2H_5OH) + 1 % Ar

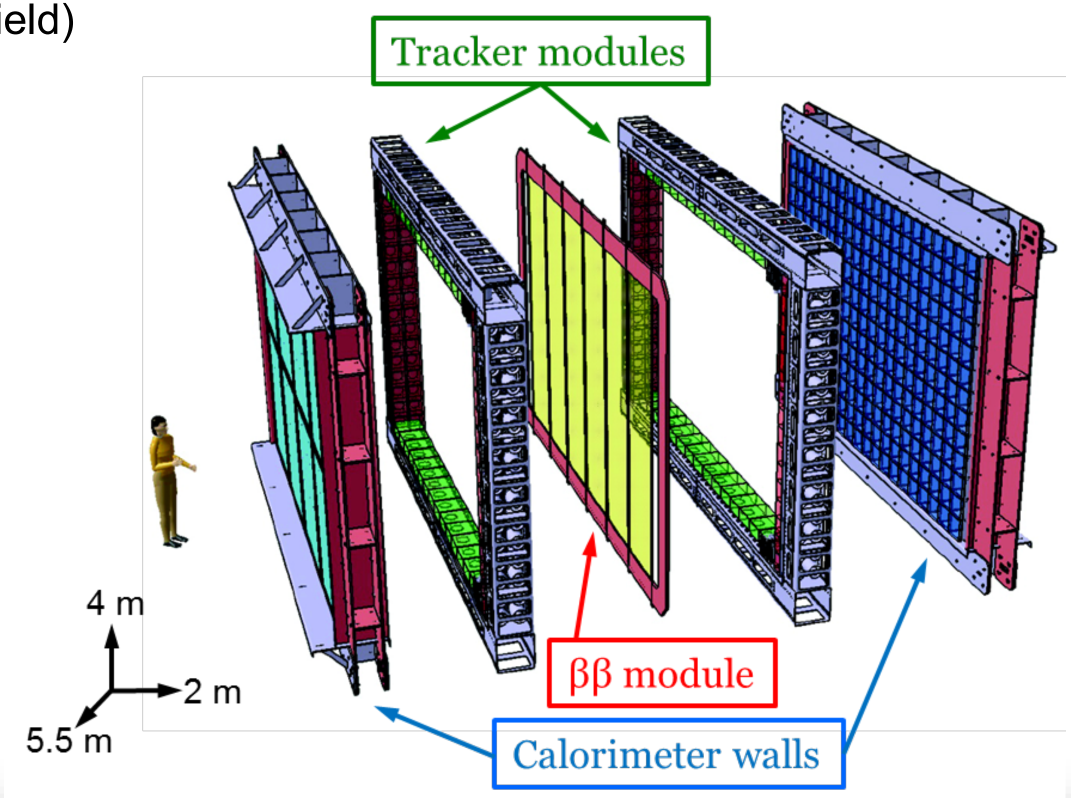
- ***Calorimeter***
  → 712 PMTs + PS scintillators
  (main walls, X-walls and gamma veto)

- ***Calibration system***
  → LED light injection, ^{207}Bi source deployment

- ***Passive shielding***
  → iron + PE + Water tanks

- ***Air flushing system***
  → radon activity - reduction factor of 10^3





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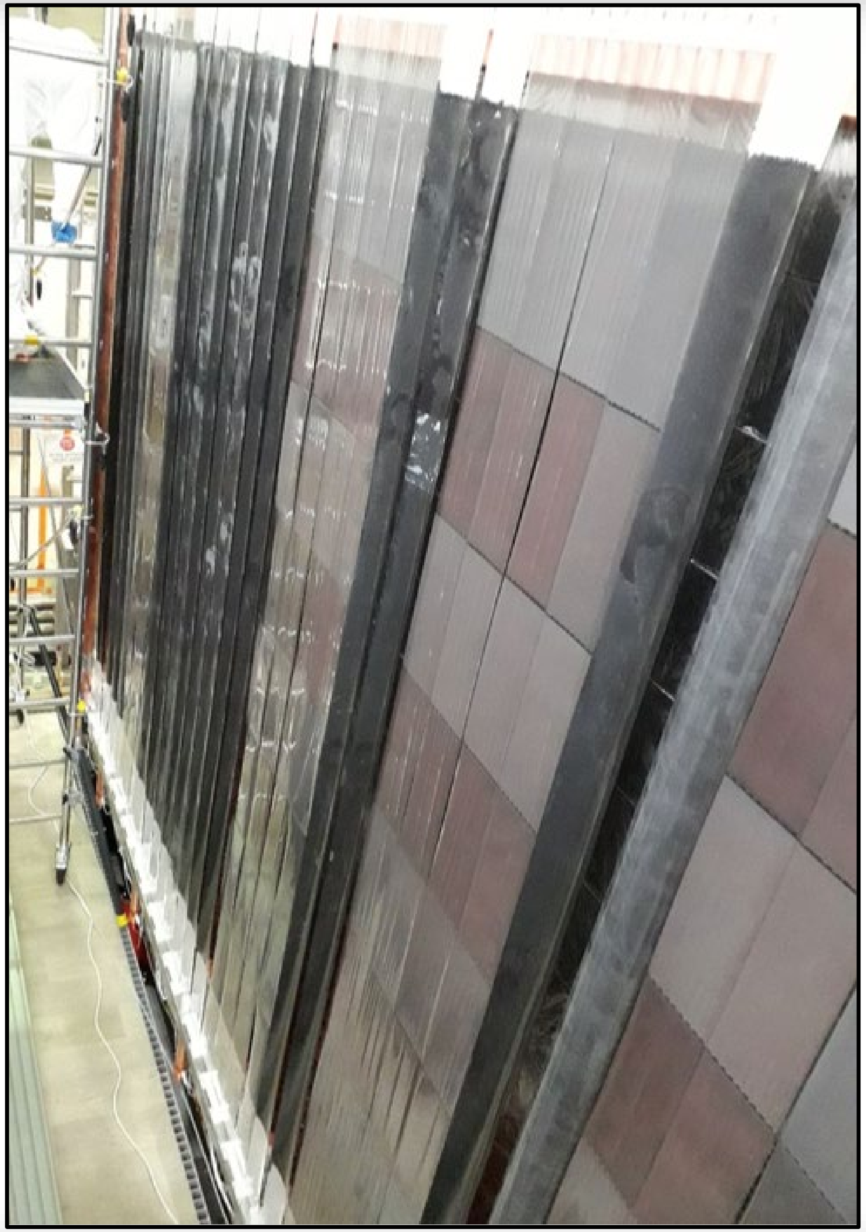

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  → radon activity - reduction factor of 10^3


Gas system

- ***Demonstrator location***
  → Modane Underground Laboratory

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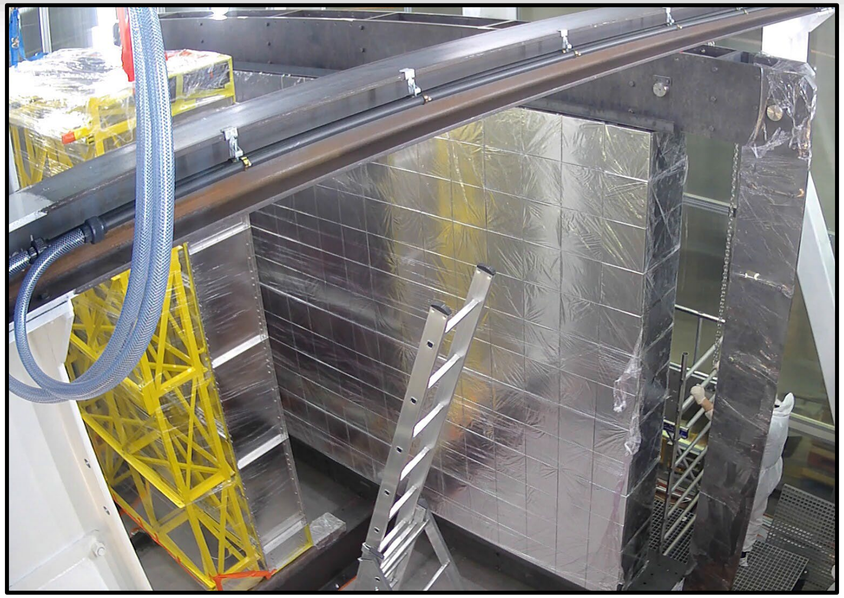
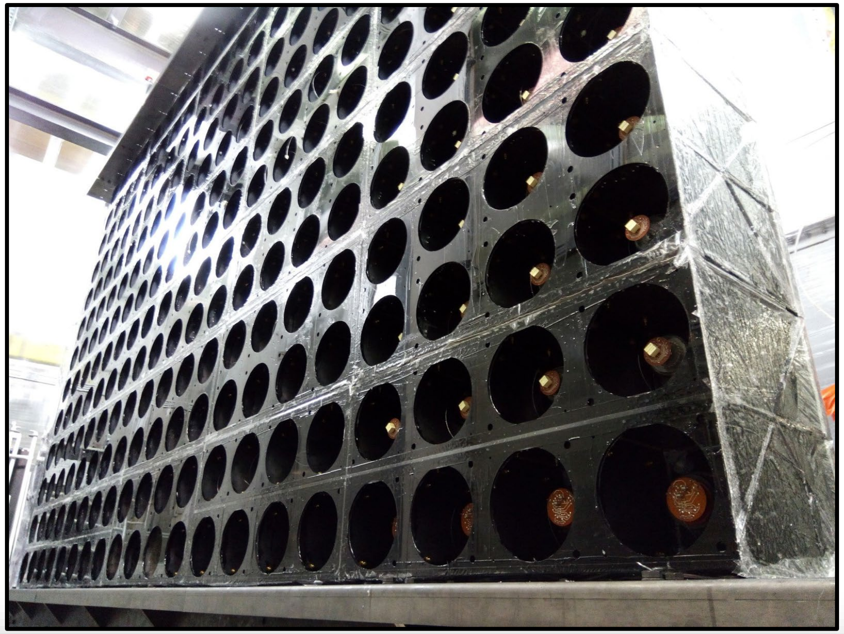



Optical module



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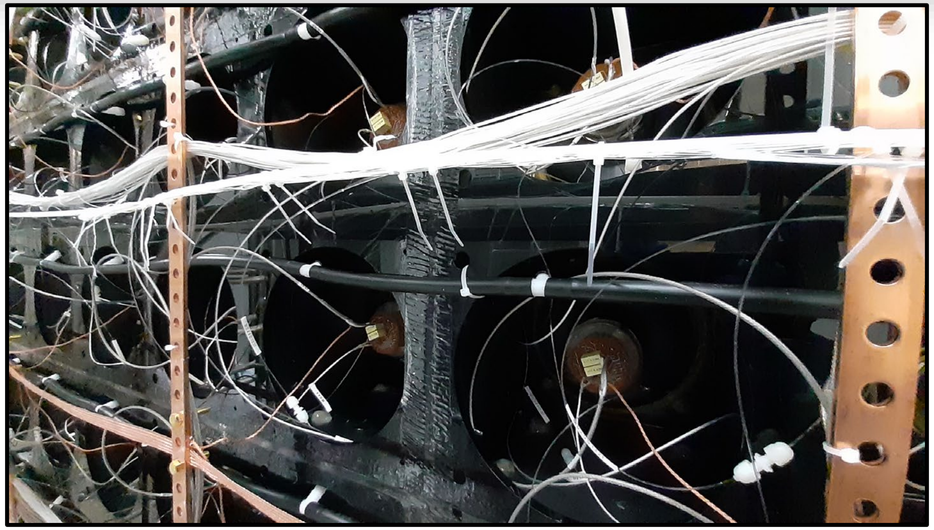
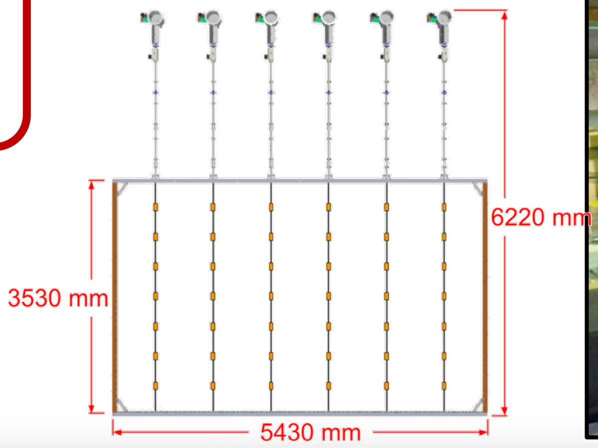
  → radon activity - reduction factor of 10^3



optical fibres

42 sources



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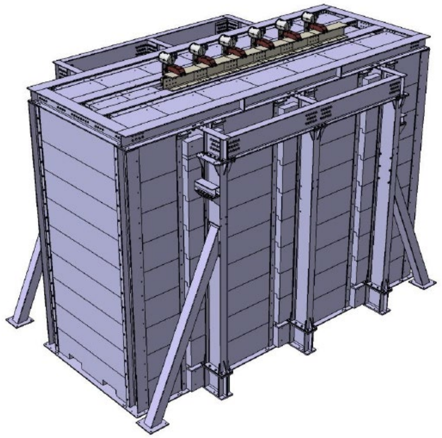
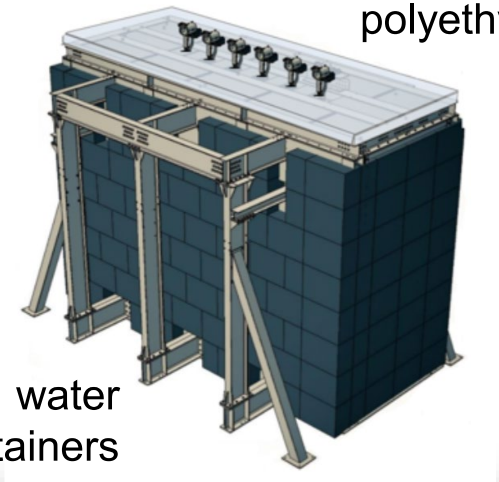

iron shielding


polyethylene
water containers

- ***Demonstrator location***
  → Modane Underground Laboratory

- ***ββ source** foils* (6.11 kg; ~ 50 mg/cm^2)
  → prime: ^{82}Se (96 - 99% enrichment, high $Q_{\beta\beta}$ *~ 3 MeV*)
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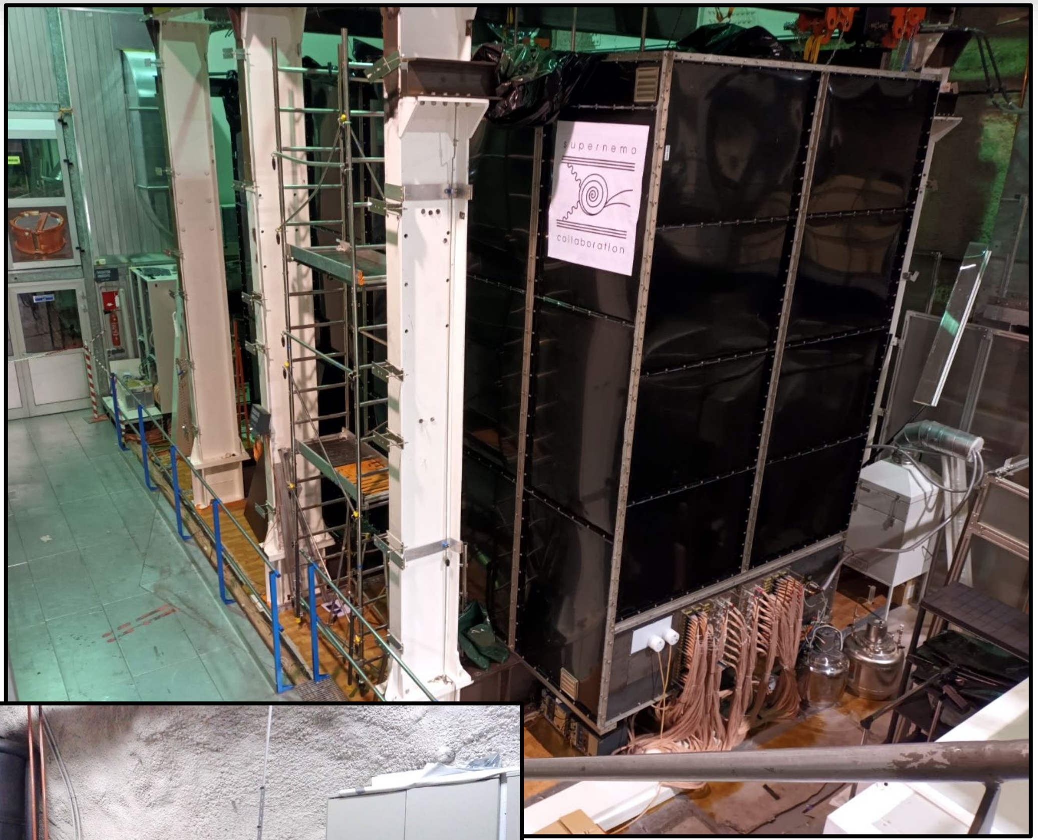
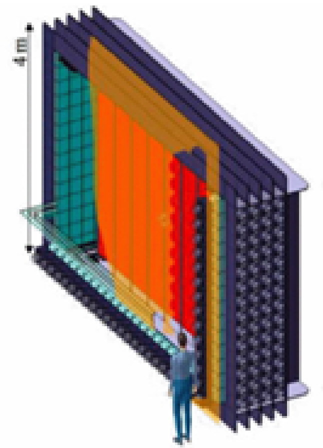


Anti-radon tent

Anti-radon facility

Background reduction and rejection



=

= 100 Bq

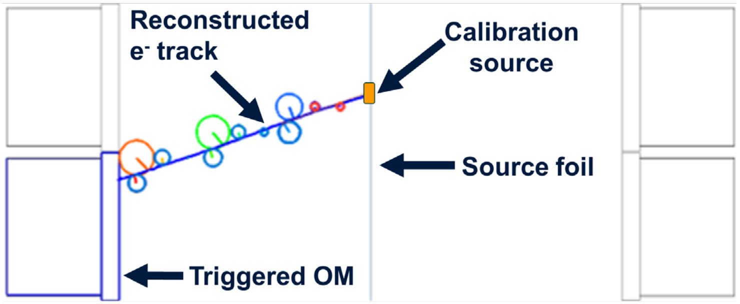
SuperNEMO
Demonstrator Module
35 tons

1 kg of bananas

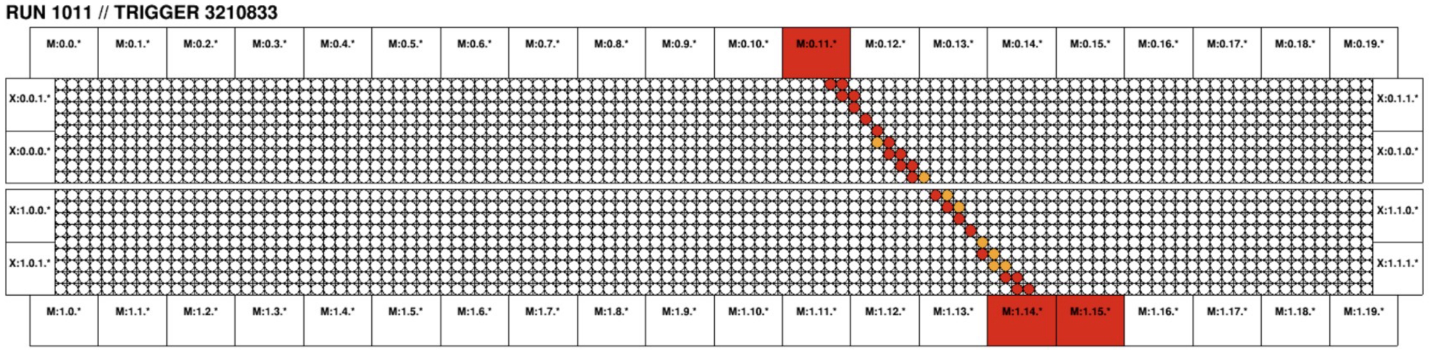
Commissioning + background & calibration data (courtesy of IEAP team)

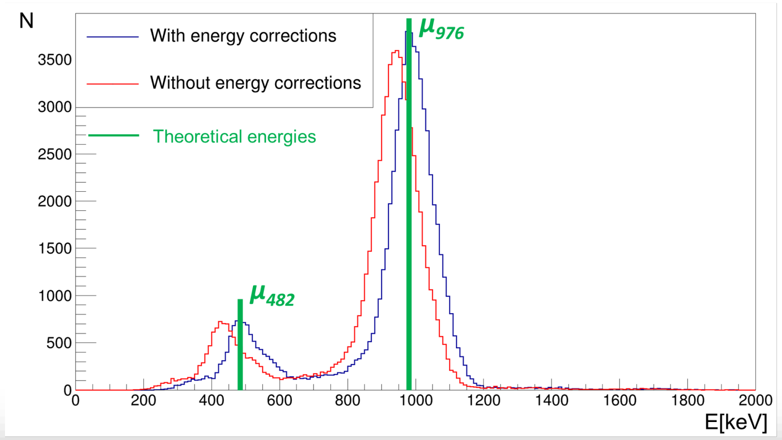
- Unique calibration and tracking algorithms are being developed and tested with this first data.
- Energy calibration is performed using 42 ^{207}Bi electron sources, which can be automatically deployed between the source foils.
- Reconstructing particle energies from measured charges and track topologies $\rightarrow$ model has been developed to estimate the energy losses that electrons experience as they pass through the tracker before reaching the OM.

Calibration event (top view)



Track and events reconstruction (top view)





Full detector is operational and taking background & calibration data:
99% of tracker and 98% of calorimeter channels live!

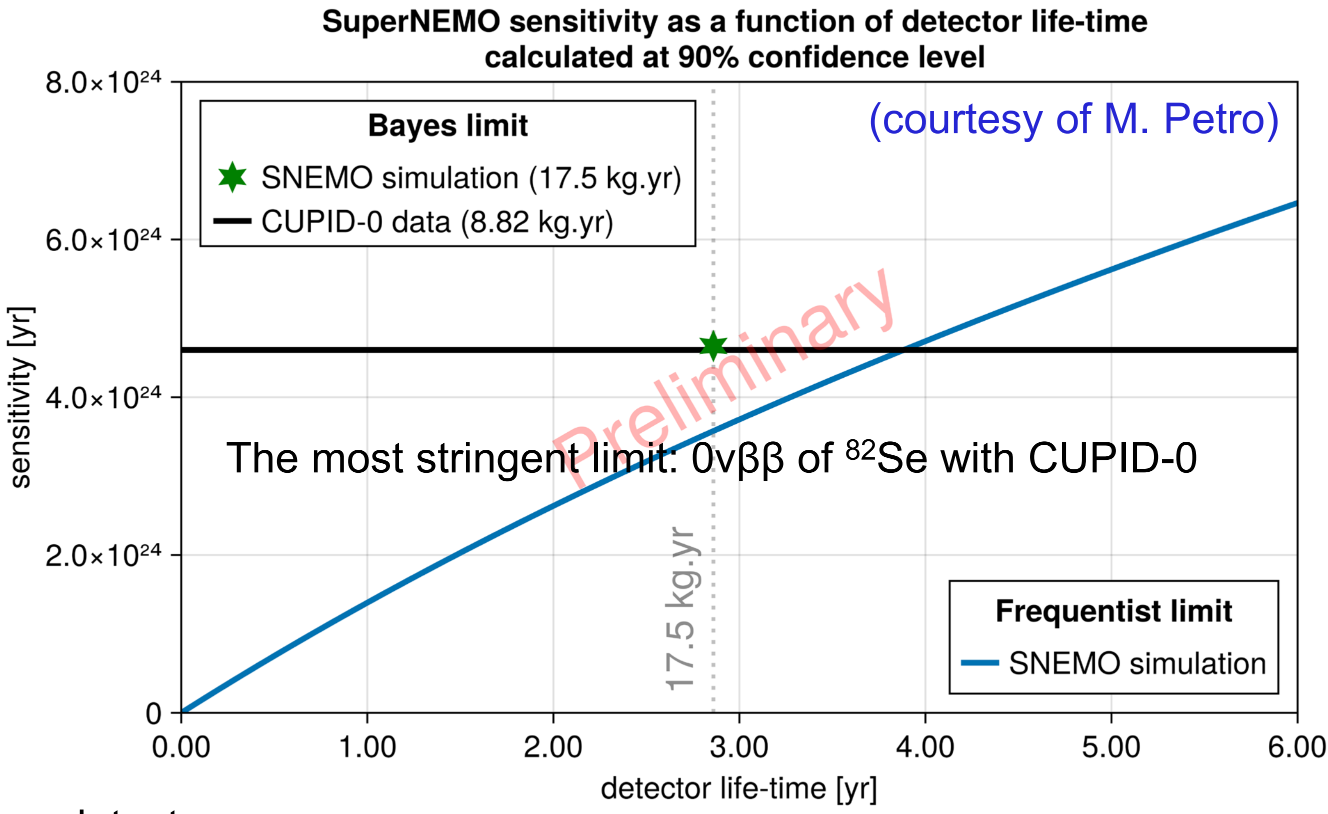
SuperNEMO demonstrator → physics goals

- Nuclear structure effects (single-state vs. higher-state dominance)
- Nuclear physics probes (measuring the axial vector coupling constant, g_A)
- Decays to excited states
- Exotic decay searches (2νββ / 0νββ mechanisms)
- Precision 2νββ measurements can reveal beyond SM effects (right-handed neutrinos)

Estimated number of 2νββ events:
~ 10^4 – 10^5

Expected bkg. in 0νββ ROI:
10^{-4} keV.kg.yr

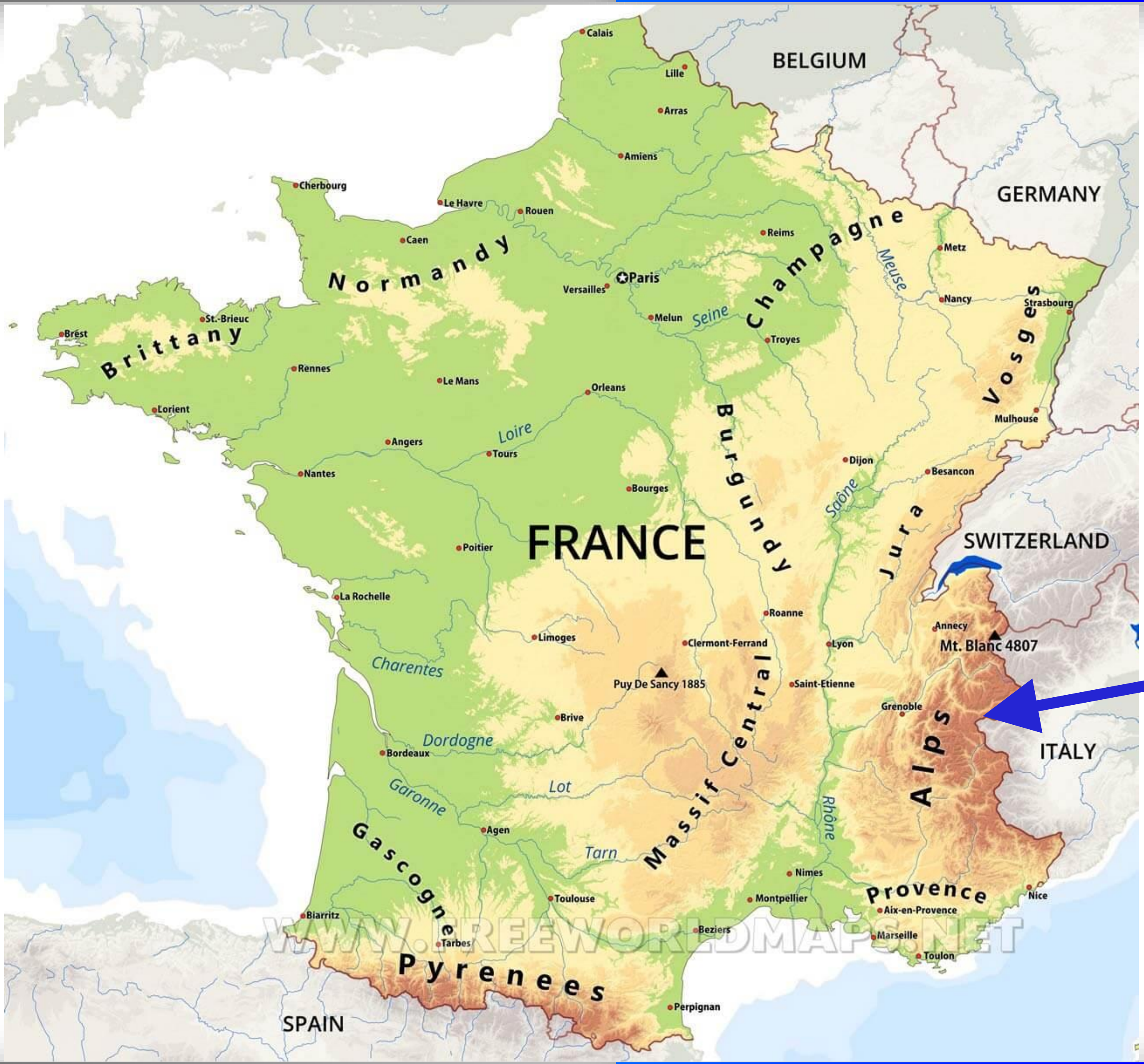
Expected sensitivity to 0νββ decay:
> 4.6 ×10^{24} yr (Bayes limit, at 90% C.L.)



- SuperNEMO demonstrator presents a proof of concept for future detectors
- Possibility to extend to alternative isotopes (^{150}Nd, ^{48}Ca) to test 0νββ or eventually 0ν4β

Modane Underground Laboratory (LSM)

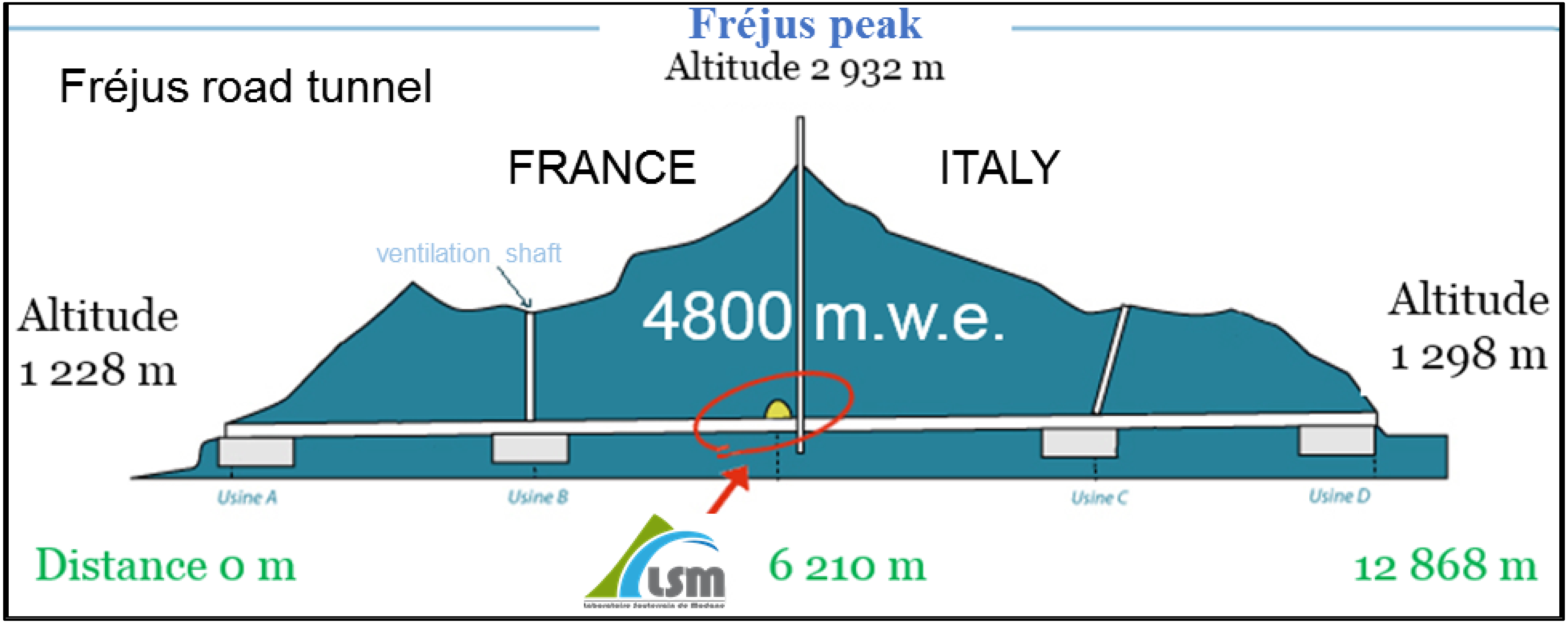
Aldo Lanni, J. Phys.: Conf. Ser. 1342 (2020) 012003



SAVOIE

Laboratoire Souterrain de Modane

- Fréjus road tunnel – two-way traffic tunnel opened in 1980 (construction started in 1974)
  – 12.868 km long



Fréjus peak
Altitude 2 932 m
Fréjus road tunnel
FRANCE
ITALY
ventilation shaft
4800 m.w.e.
Altitude
1 228 m
Altitude
1 298 m
Usine A
Usine B
Usine C
Usine D
LSM
Distance 0 m
6 210 m
12 868 m

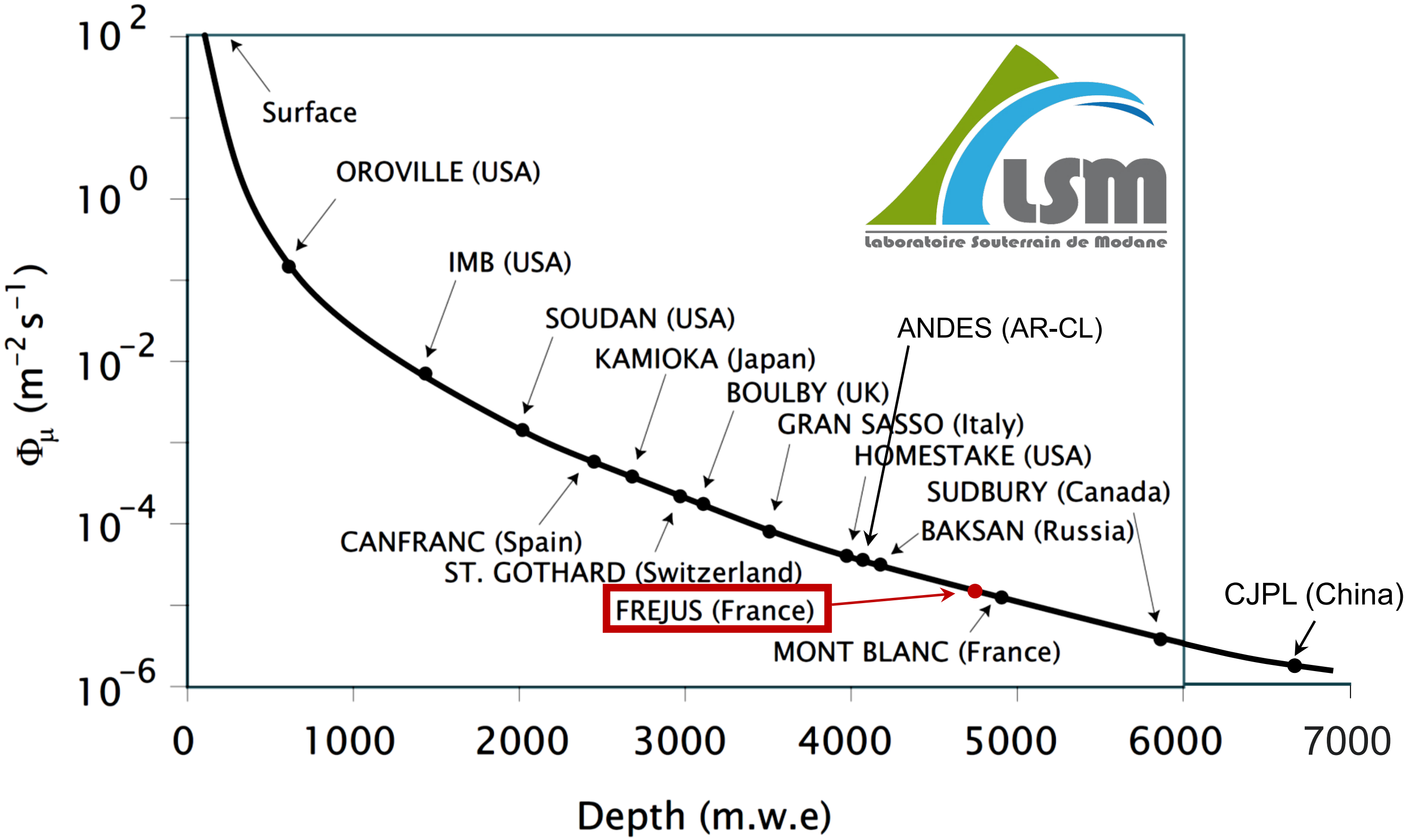

70

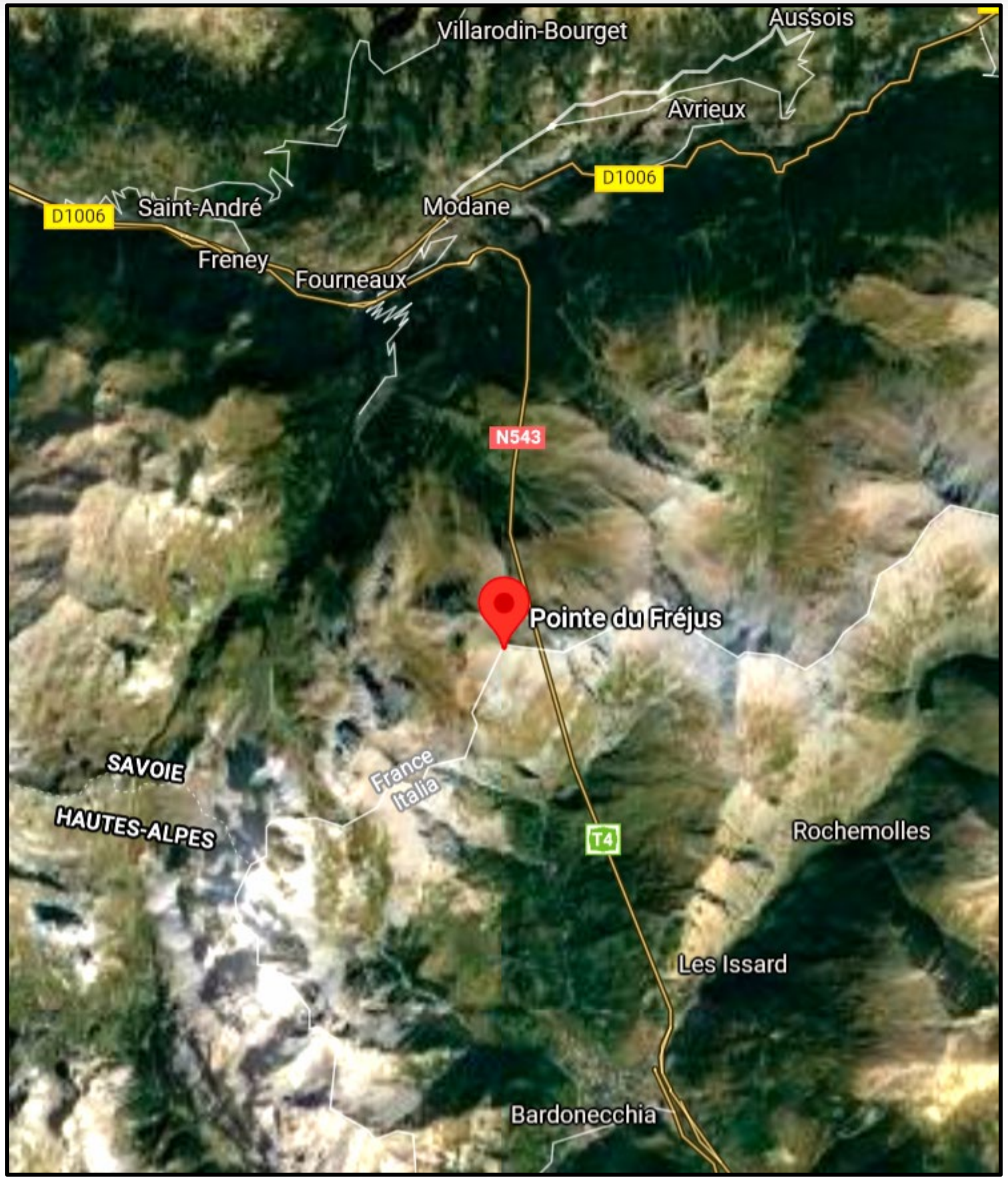
LSM – view from Fréjus tunnel

- LSM
  - the deepest underground laboratory in Europe (horizontal access)
  - was established in 1982 as a common utility of the CNRS and CEA directly controlled by IN2P3 (National Institute of Nuclear and Particle Physics)
  - since 2019 national research platform attached to the Laboratory of Subatomic Physics & Cosmology (LPSC), a joint CNRS and Université Grenoble Alpes (UGA) research unit
  - multi-disciplinary platform for experiments requiring unique ultra-low radioactive environment (few mBq/m^3) in particle, astroparticle and nuclear physics but also for environmental sciences, biology, applications and industrial test benches.

  - external facility (offices, workshops, outreach space and guest rooms) & underground laboratory

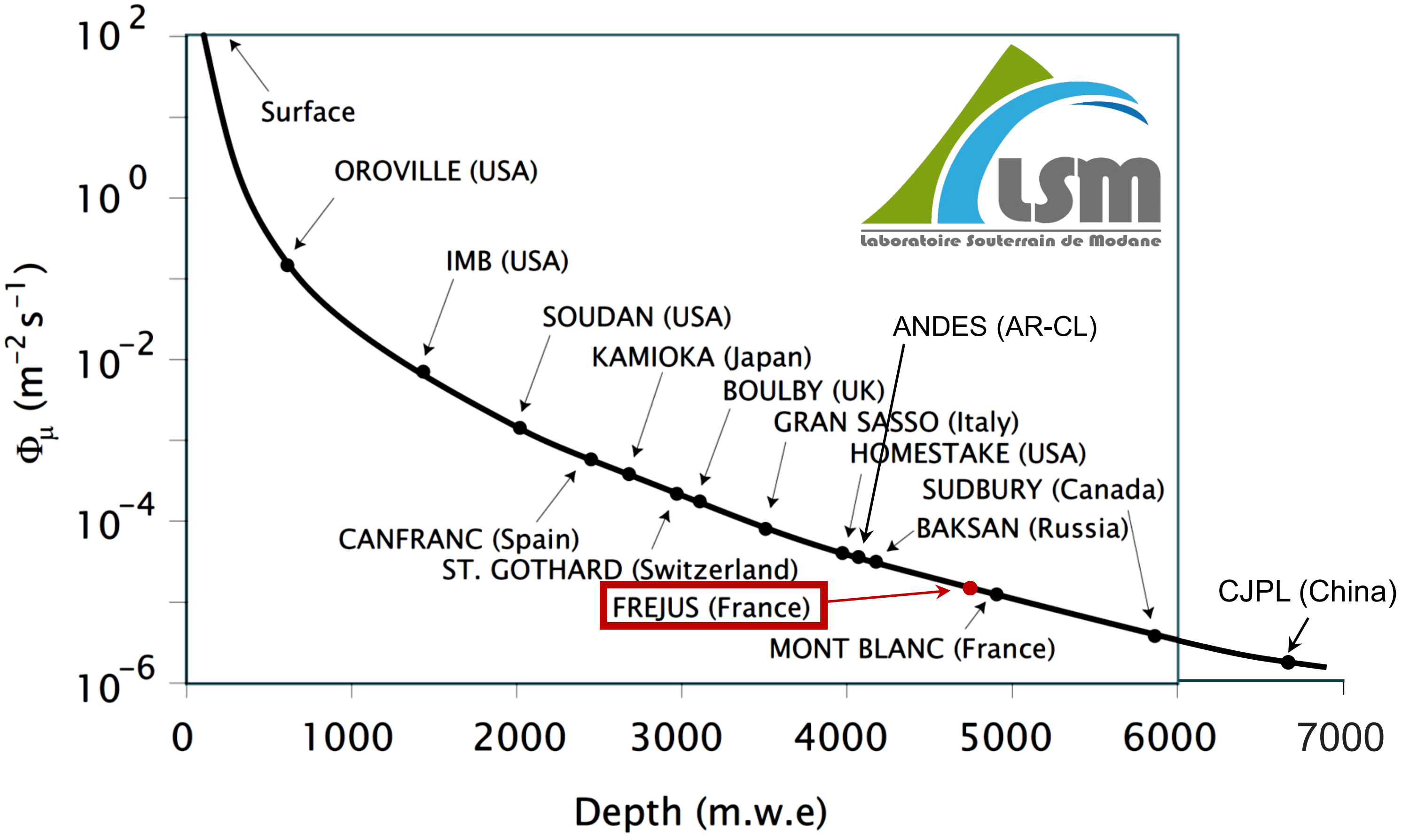
• Depth of ~ 4 800 m.w.e.

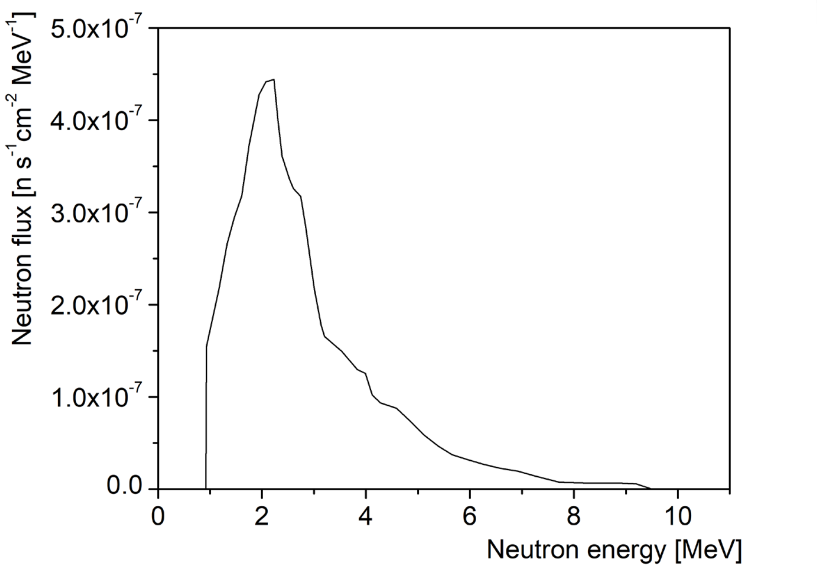


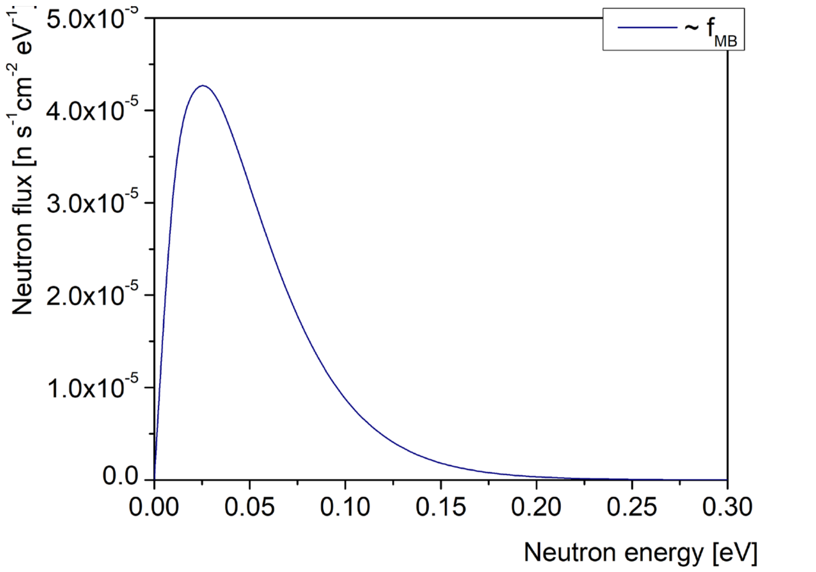


• Muon flux: 4×10^{-5} $\mu.m^{-2}.s^{-1}$ (muon suppression ~ 10^6)
• Neutron flux: 4×10^{-2} $n.m^{-2}.s^{-1}$ (fast);
1.6×10^{-2} $n.m^{-2}.s^{-1}$ (thermal)
• Radon in air: (5 – 20) $Bq.m^{-3}$

- Depth of ~ 4 800 m.w.e.







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Chazal V. et al., Astroparticle Physics 9 (1998) 163

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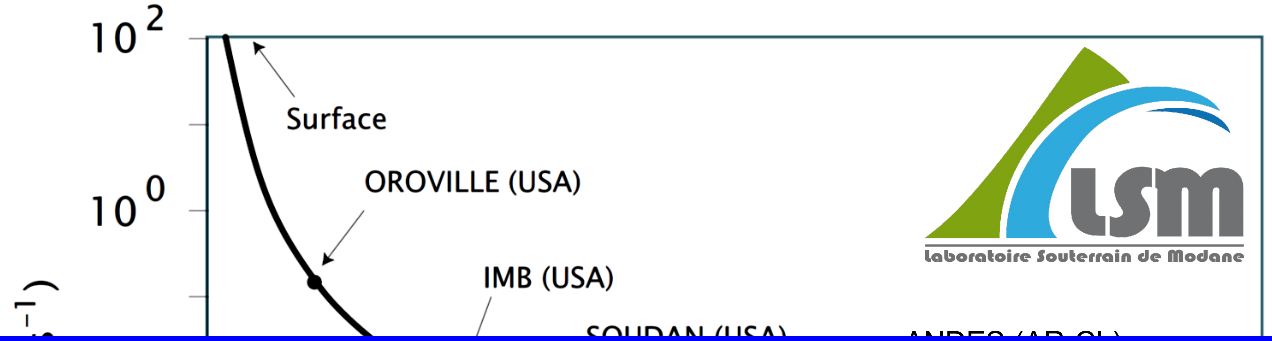

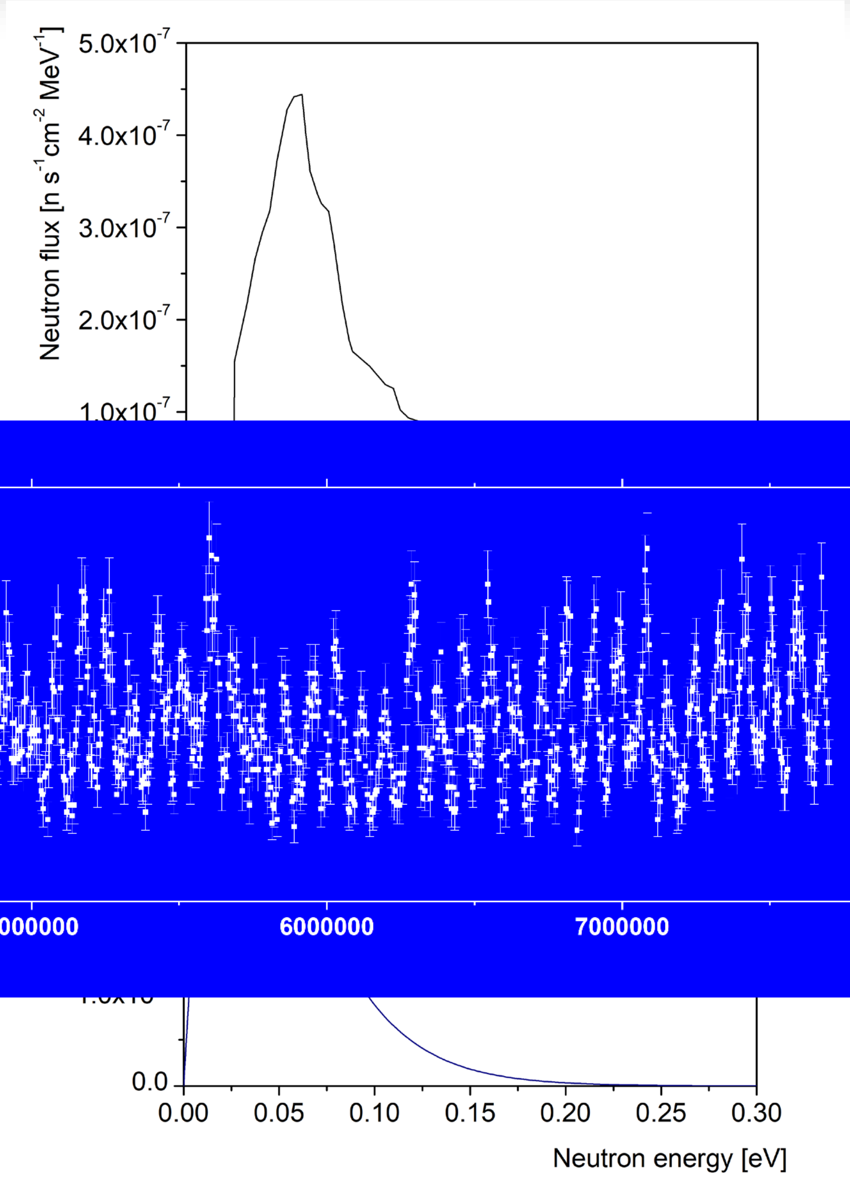

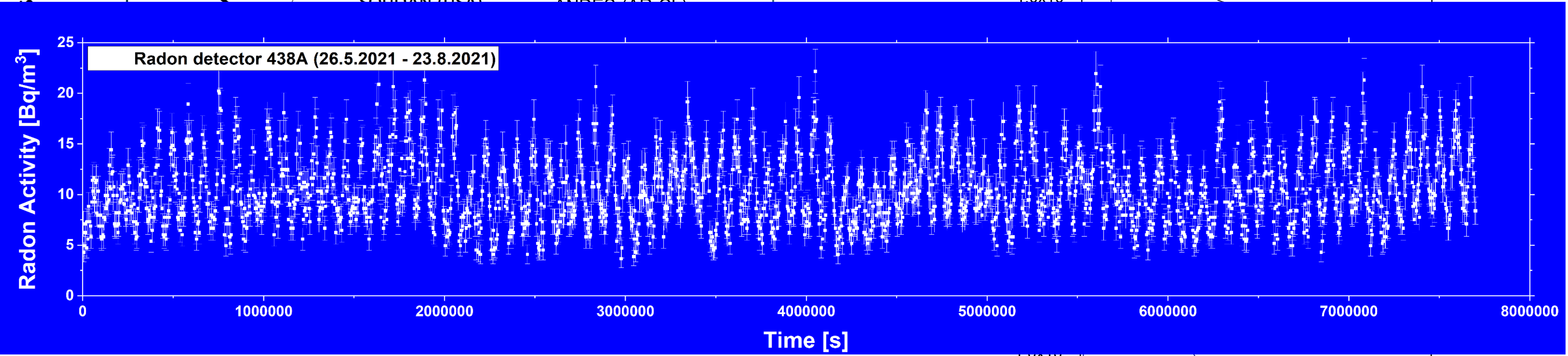

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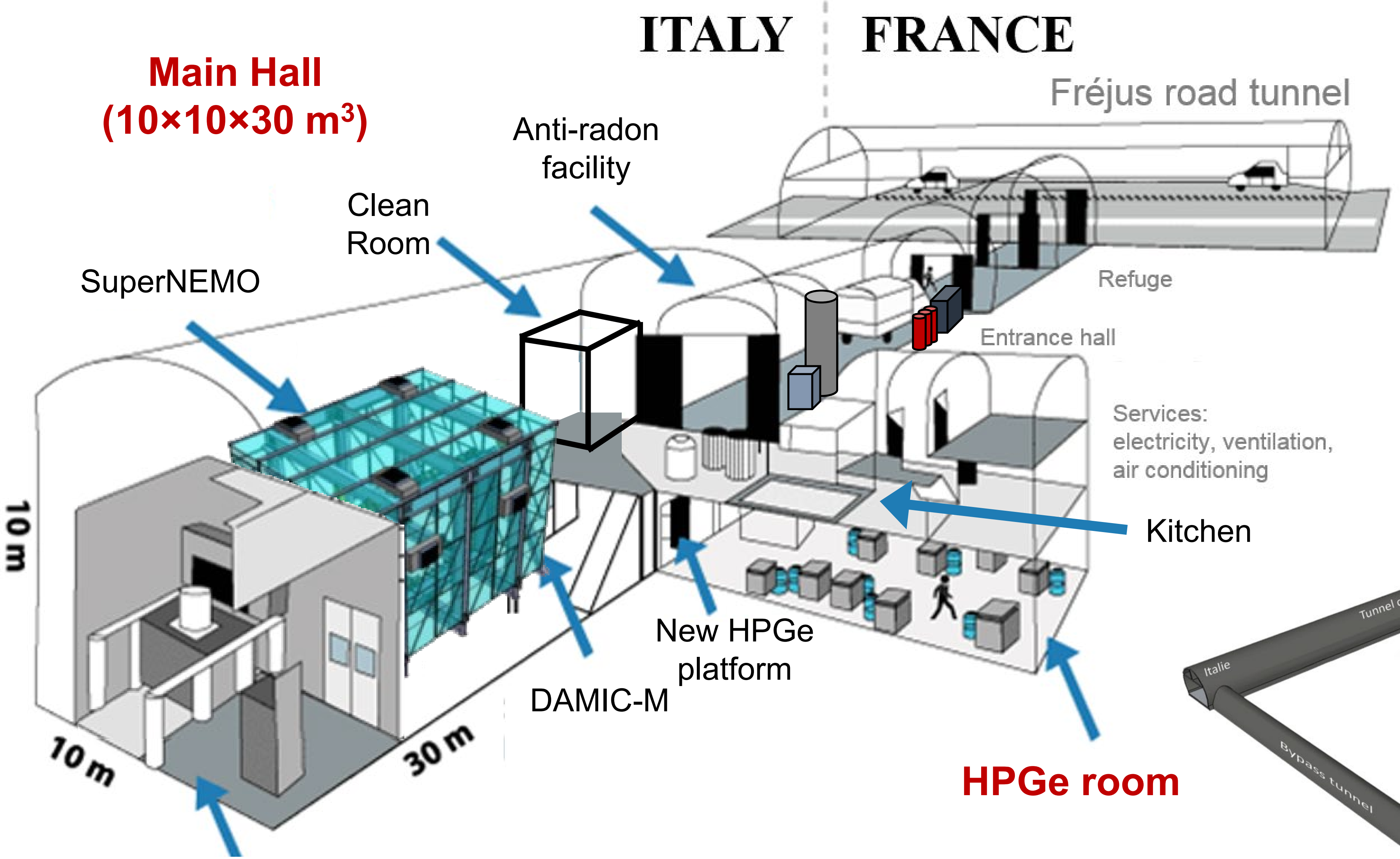
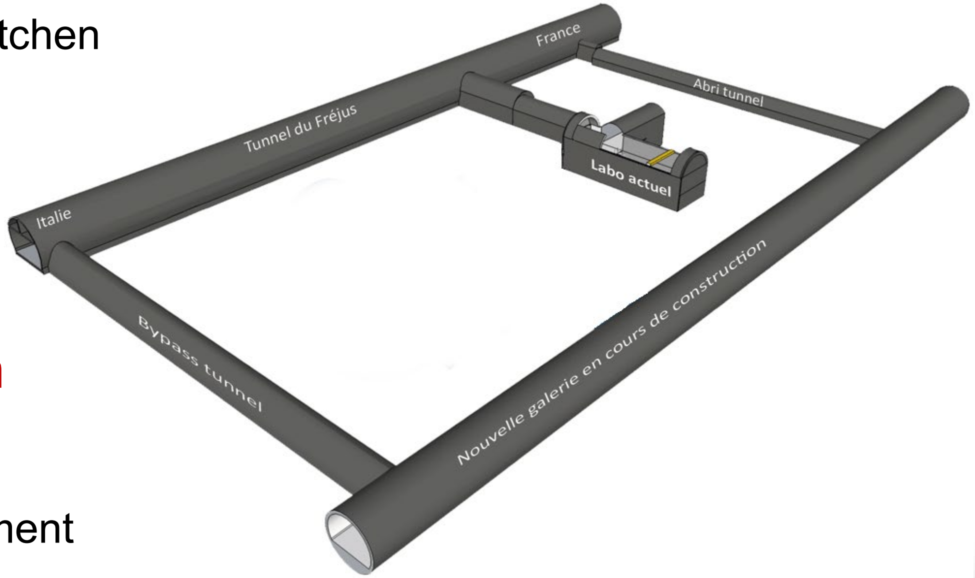




EDELWEISS (finished – currently being dismantled) → BINGO experiment

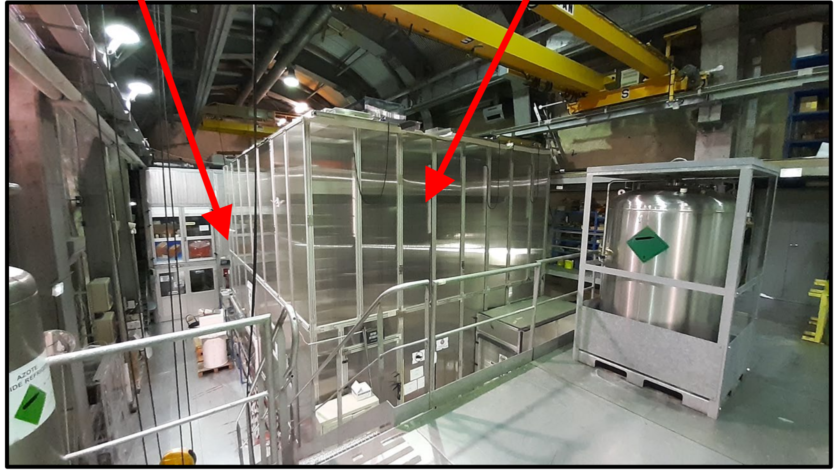
SEDINE (Spherical Detection of Neutron)

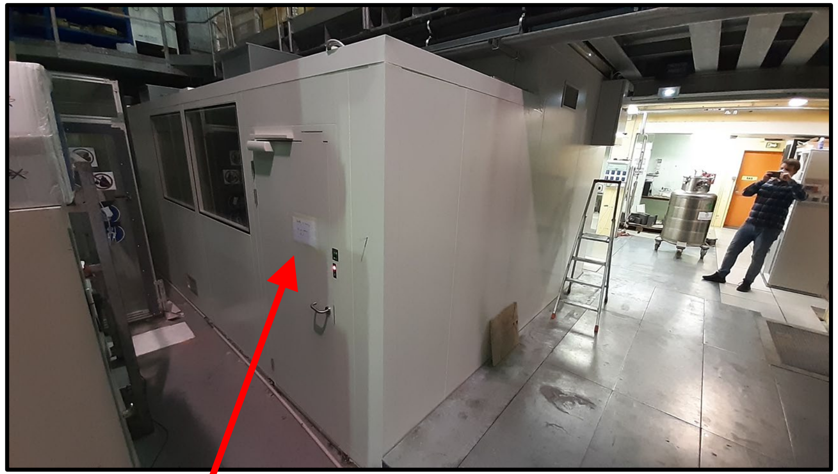
SPT (Silicon Pixel Telescope)

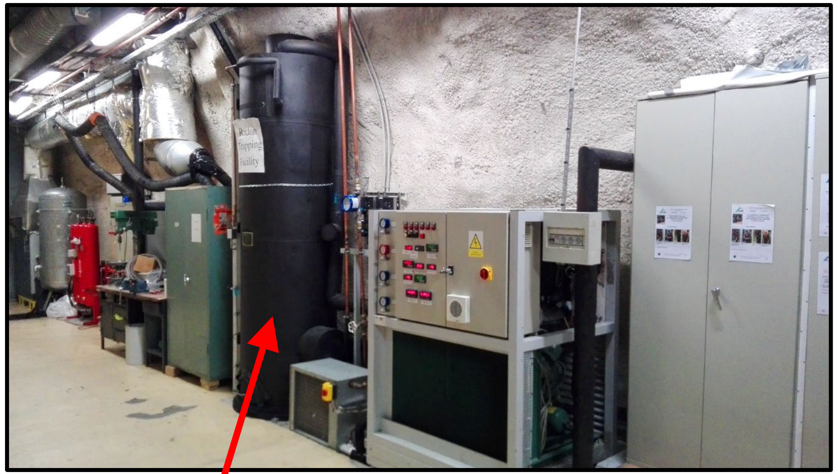
Lab air-conditioning system (25 °C)

SuperNEMO demonstrator

BINGO





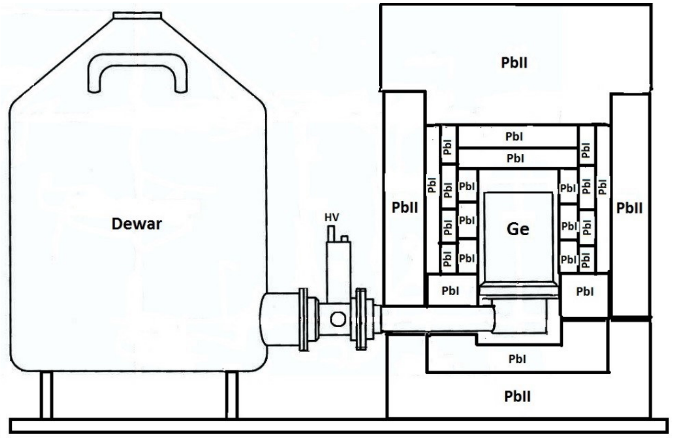


DAMIC-M (DArk Matter In CCDs)

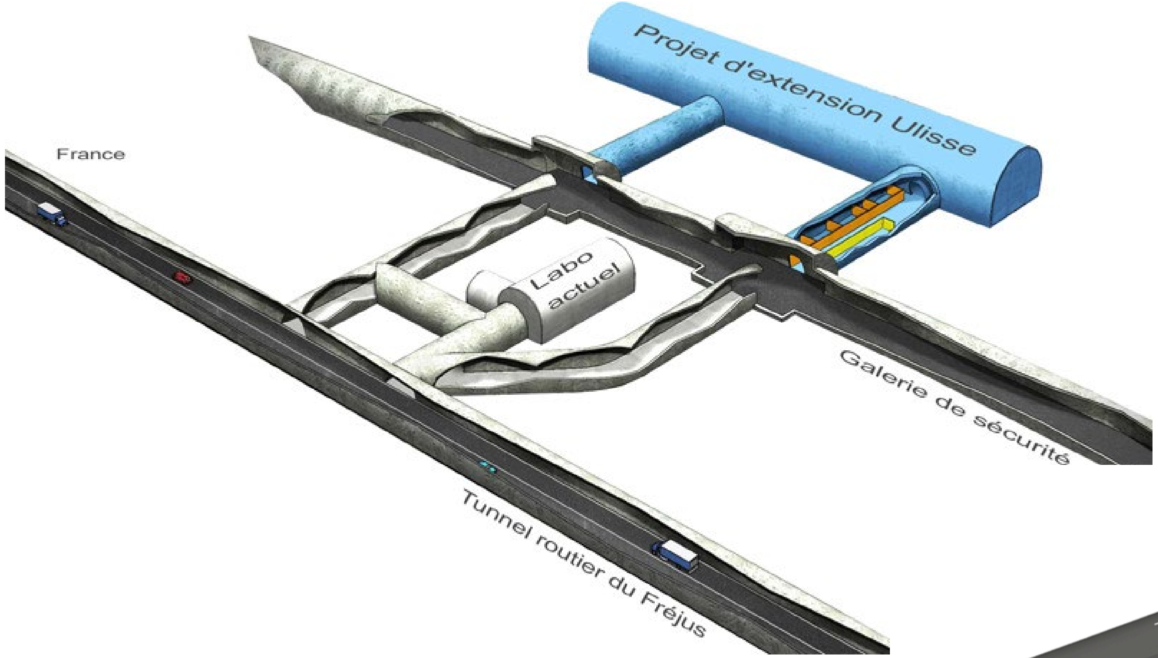
New platform for HPGe detectors

Anti-radon facility

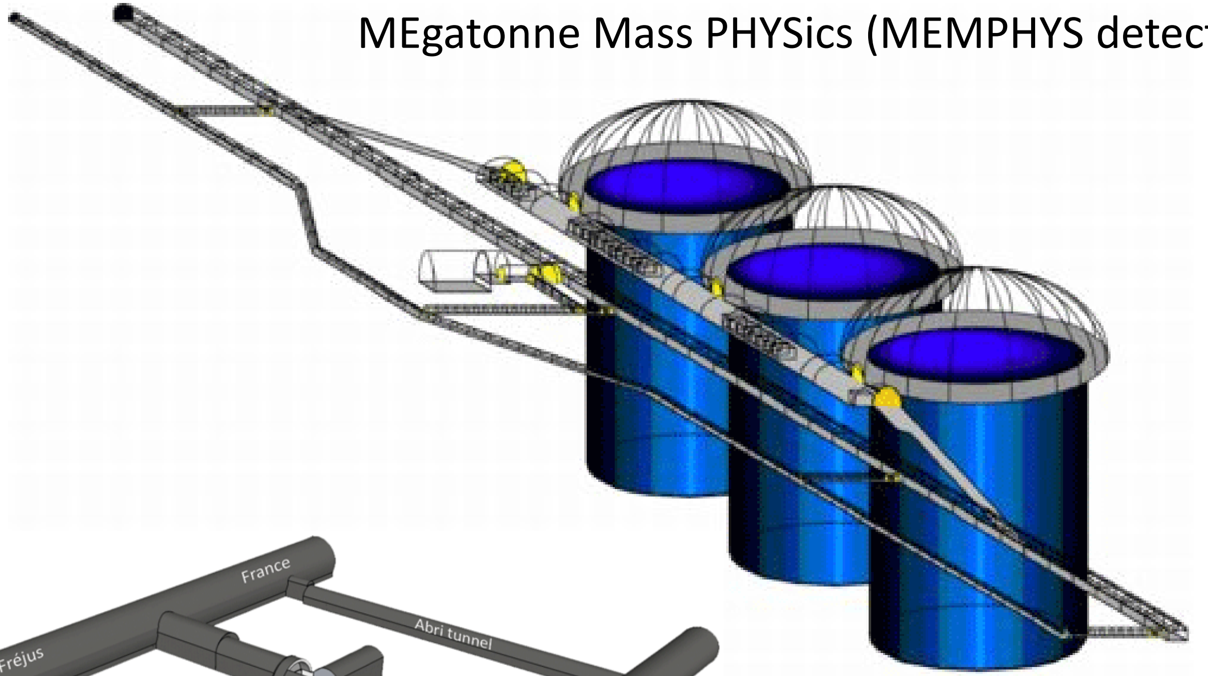
OBELIX HPGe detector (rel. eff. ~ 160 %)

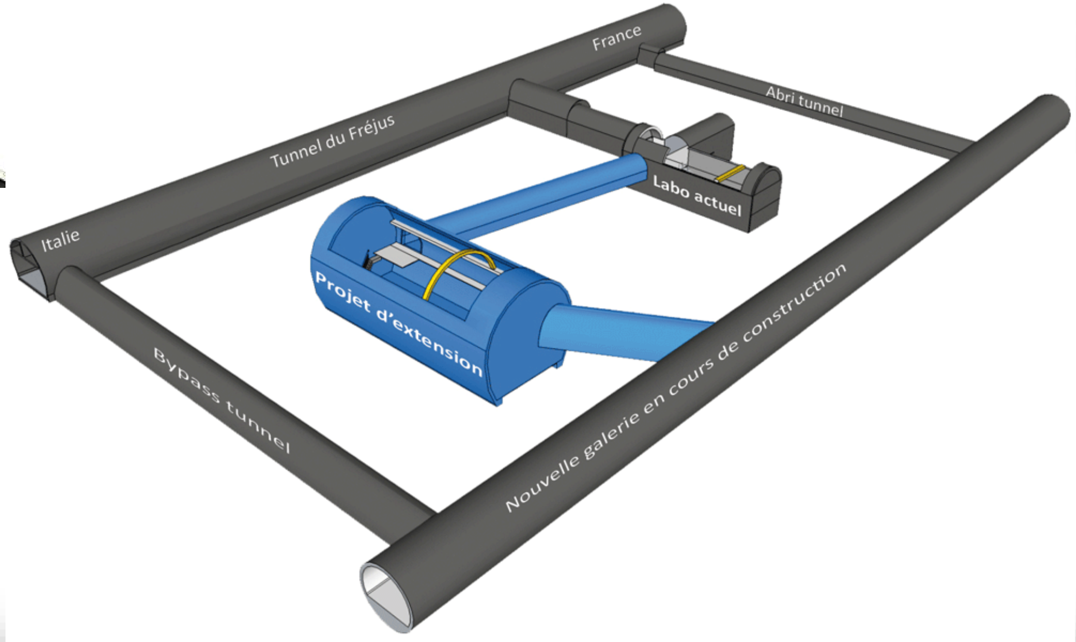


- LSM unsuccessful extension plans



MEgatonne Mass PHYSics (MEMPHYS detector)





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Thank you for attention!