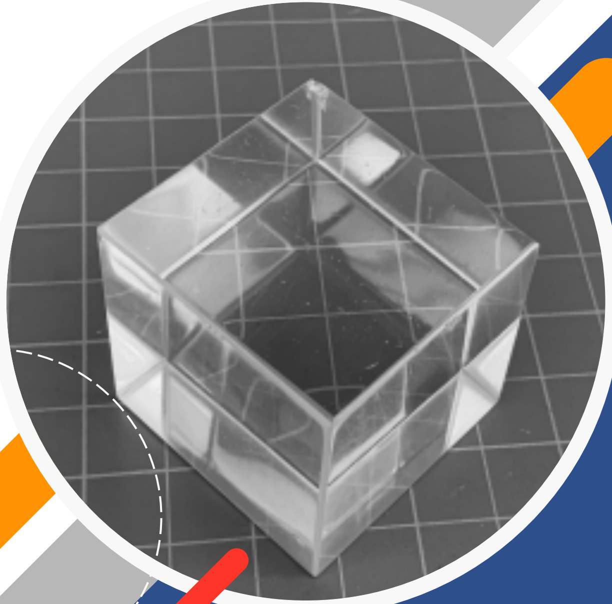
XIII International Conference on New Frontiers in Physics

CUPID

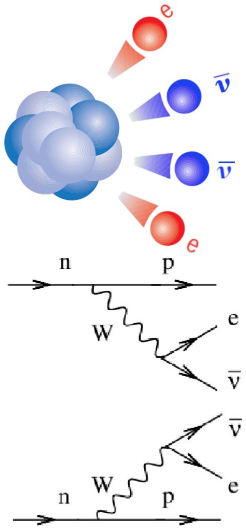
A next generation $0\nu2\beta$ bolometric experiment



Mathieu Pageot for the CUPID collaboration

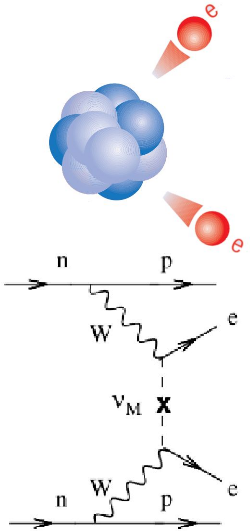
The neutrinoless double beta decay
What is it ?

$2\nu2\beta$



Allowed By Standard Model

$0\nu2\beta$



Needs Beyond Standard Model Physics !

$$\Delta L = 2$$

Lepton Number Violation

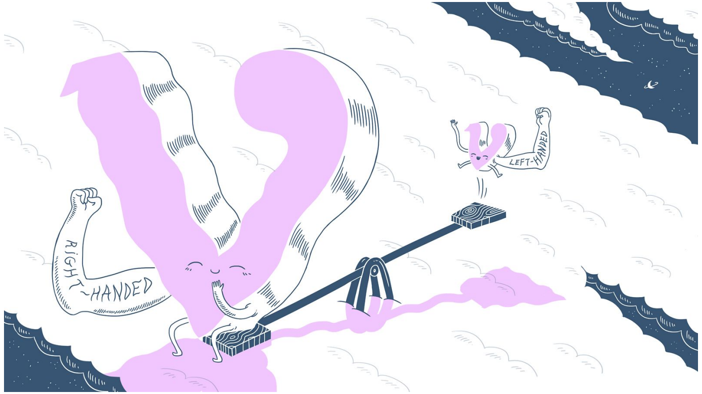
$$\nu = \bar{\nu}$$

Majorana Particle

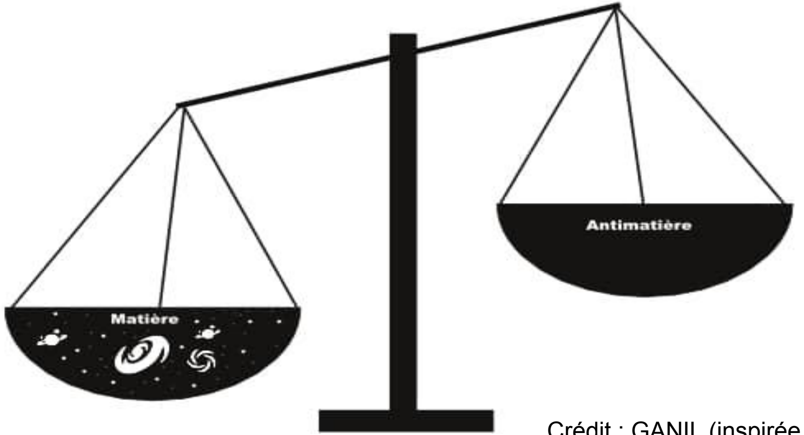
The neutrinoless double beta decay
What does it imply ?

CP violation

This discovery could help us understand why the Universe is matter-dominated by finding a matter-creating process.



Symmetry Magazine

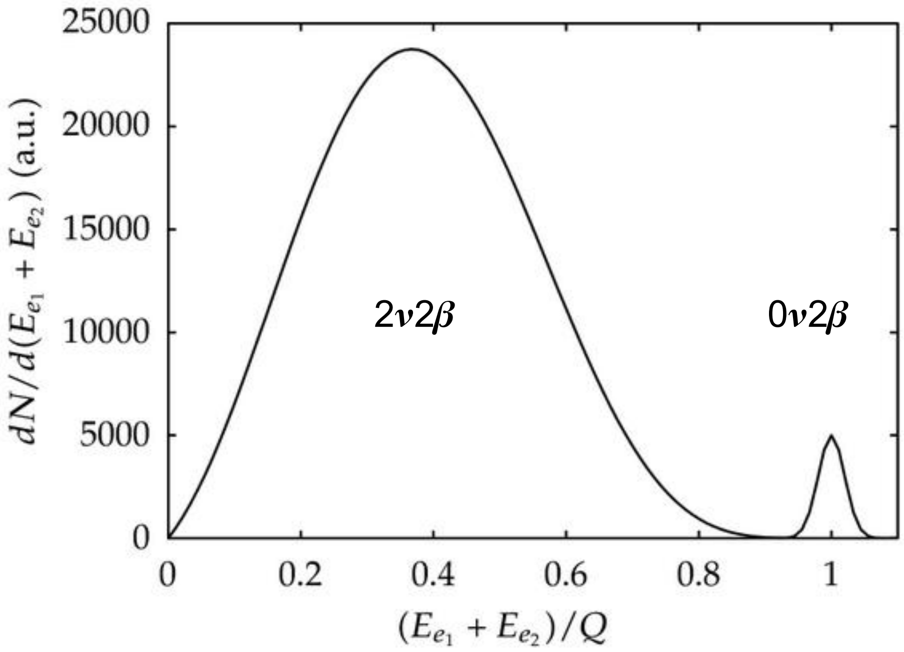


Crédit : GANIL (inspirée de https://www.quantumdiaries.org/2011/11/14/what-exactly-is-cp-violation/)

See-Saw mechanism

Heavy right-handed Majorana neutrinos can provide a natural explanation of the smallness of neutrino masses via the See-Saw mechanism.

The neutrinoless double beta decay
How do we find it ?



Lifetime

$$T_{1/2} \propto a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

$$T_{1/2} > 10^{25} - 10^{26} yr$$

Critical components:

- Large exposure (M·T)
- Large Isotopic abundance or enrichment (a)
- Excellent energy resolution (ΔE)
- High detection efficiency (ε)
- Low background (b)

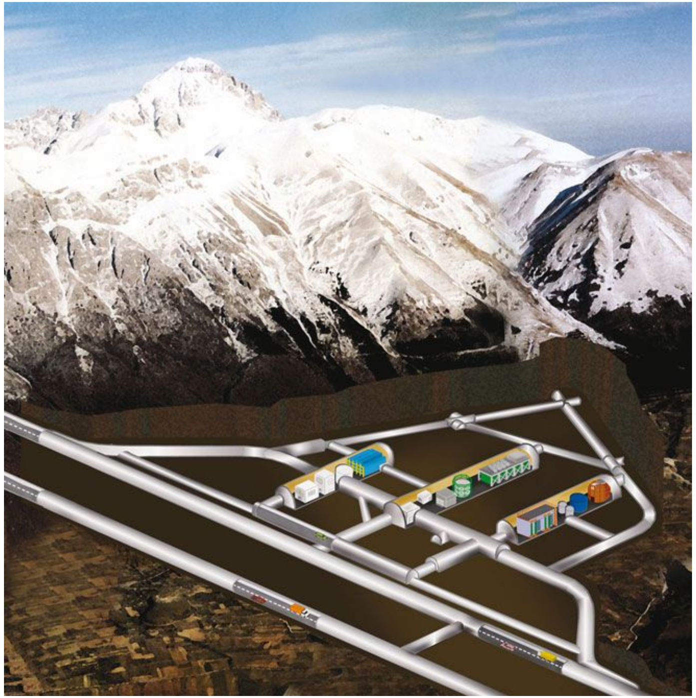
(~1 event/ tonne.yr exposure)

The neutrinoless double beta decay
Where ?

Reduce background from **cosmic particles**.

Underground Facilities

- Gran Sasso National Laboratory (LNGS)
- Laboratoire souterrain de Modane (LSM)
- Laboratorio Subterráneo de Canfranc (LSC)



https://www.appec.org/news/hands-on-experimental-underground-physics-at-lngs/

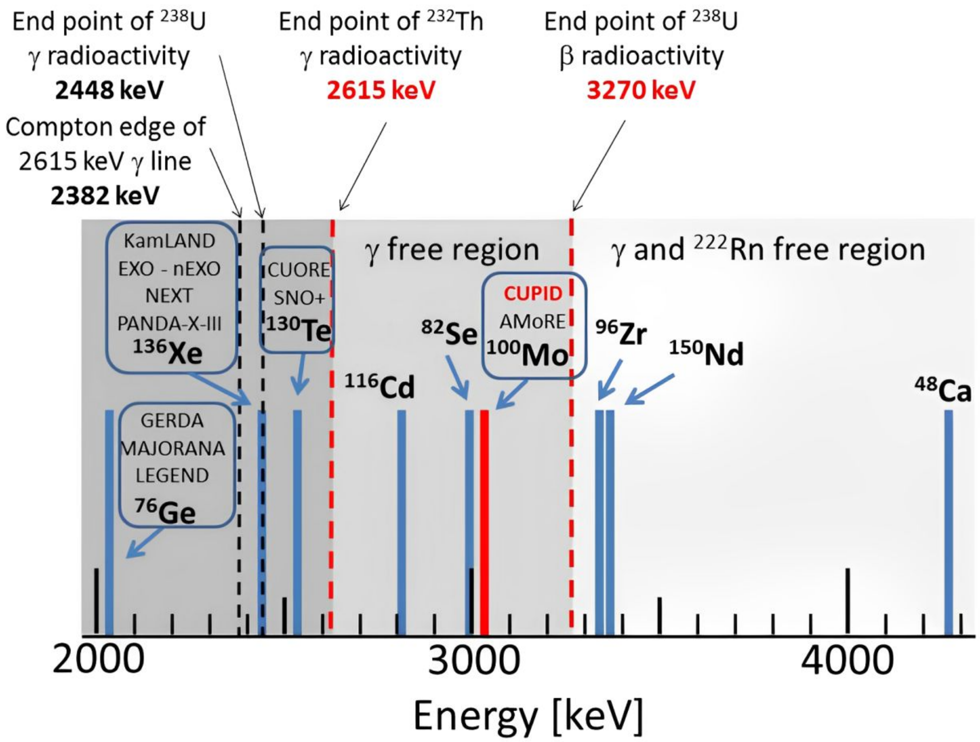
The neutrinoless double beta decay
Which are the candidates ?

Isotopes :

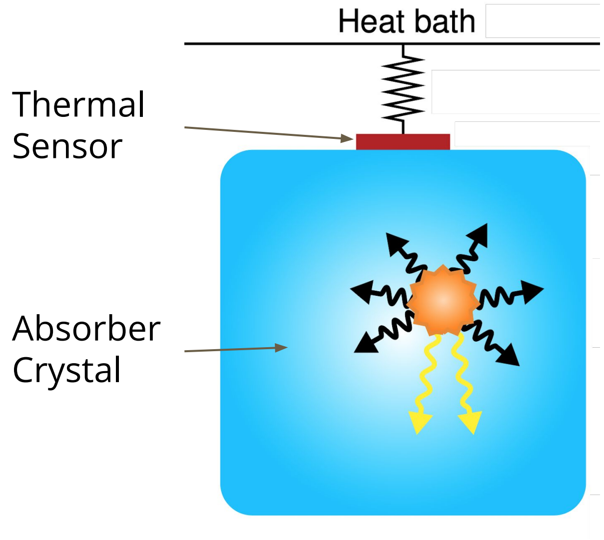
- 35 naturally occurring isotopes capable of double beta decay.
- 9 different candidates are being considered in experiments.

Selection Criteria :

- high **Q value** above natural β/γ radioactivity .
- High natural abundance.
- Compatibility with the detection technique.



Cryogenic calorimeters / Bolometers



Key features

- Measure the temperature increase of an absorber crystal: $\Delta T = E/C$
- Need very low base temperature: ~10 mK
- Several thermal sensors can be used: NTD, TES, etc.

Pros

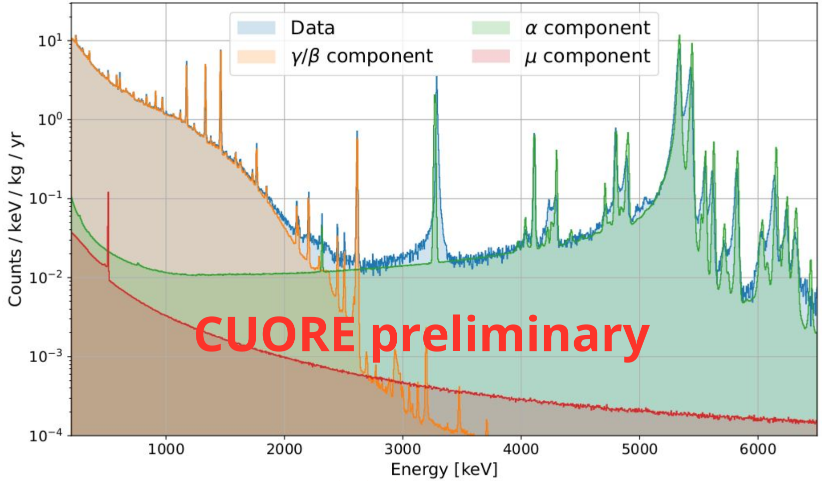
- The emitter of the 2β is also the absorber (high detection and analysis efficiency)
- Superior energy resolution
- Very low radioactive contamination
- Flexibility on the Isotope choice

Cons

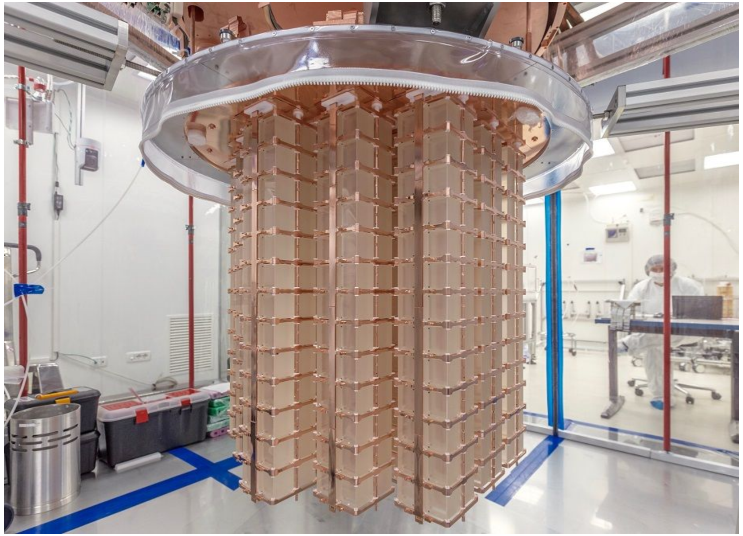
- Cryogenic calorimeters are intrinsically slow
- A complex cryogenic infrastructure is necessary, operated for very long time

CUORE
(Cryogenic Underground Observatory for Rare Events)

- Uses ^{130}Te ($Q_{\beta\beta}$ = 2527 keV)
- 988 TeO_2 cryogenic calorimeters (206 kg ^{130}Te)
- Stringent radiopurity control on materials and assembly
- Energy Resolution at $Q\beta\beta$ is 7.32 keV FWHM (0.3% relative resolution)



CUORE supplemental material: arXiv:2405.17937 / arXiv:2404.04453v1

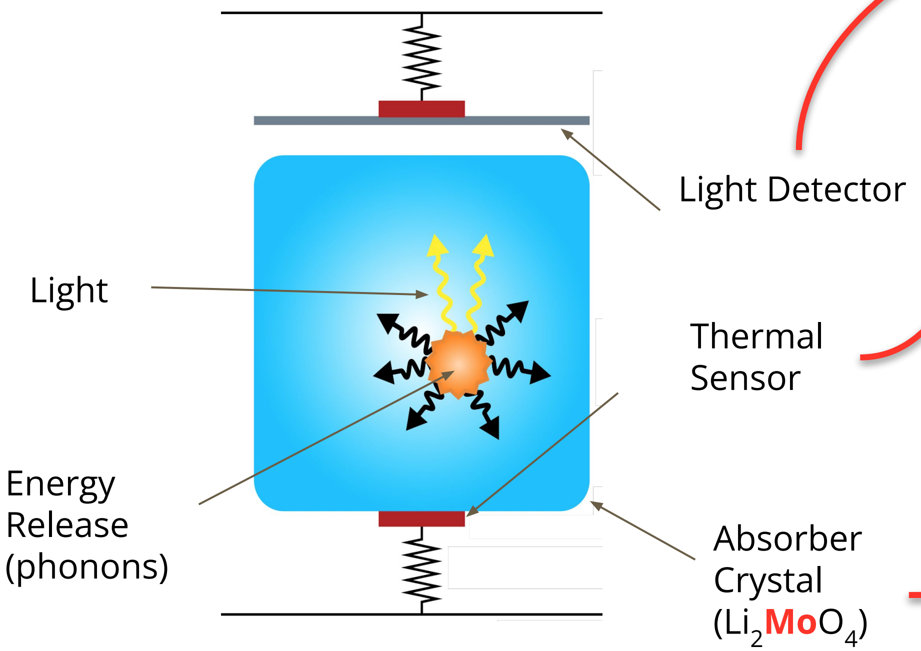


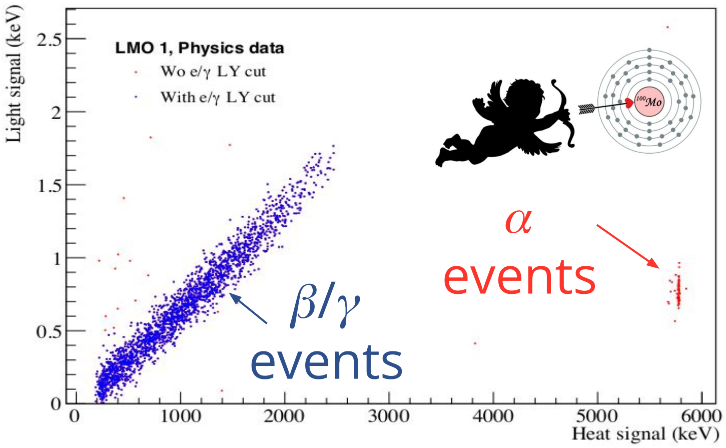
Manage to accomplish the complexe challenge of a large scale cryogenic experiment.

The α background is now the limiting factor.

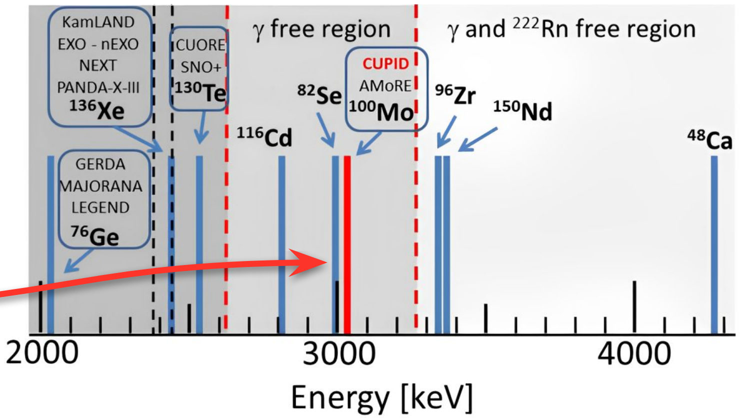
From CUORE to CUPID

CUORE Upgrade with Particle IDentification

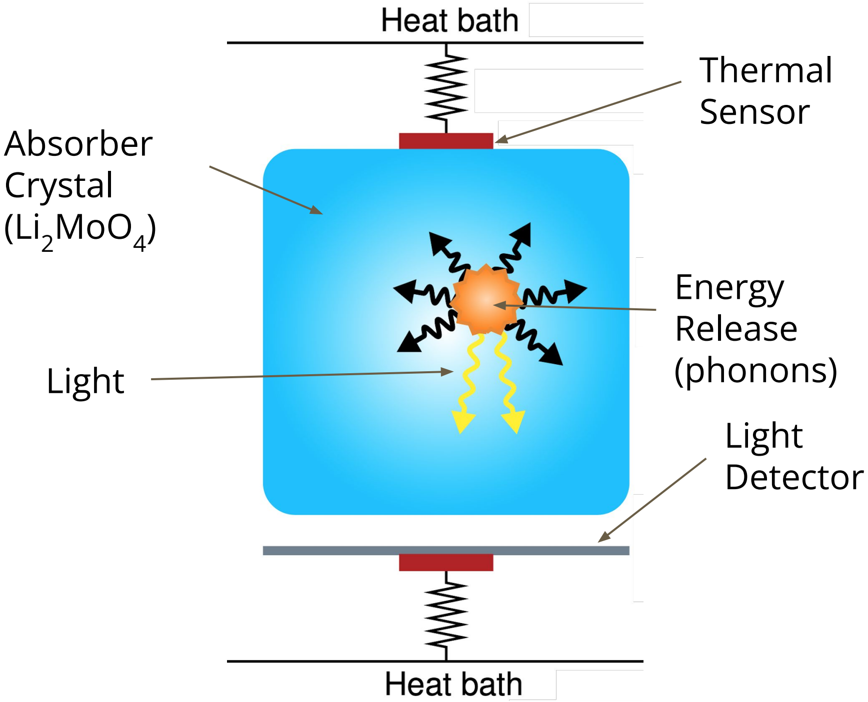




CUPID Mo: EPJ C arXiv:1909.02994



CUPID (CUORE Upgrade with Particle IDentification) Baseline Design



1596 Li_2MoO_4 crystals

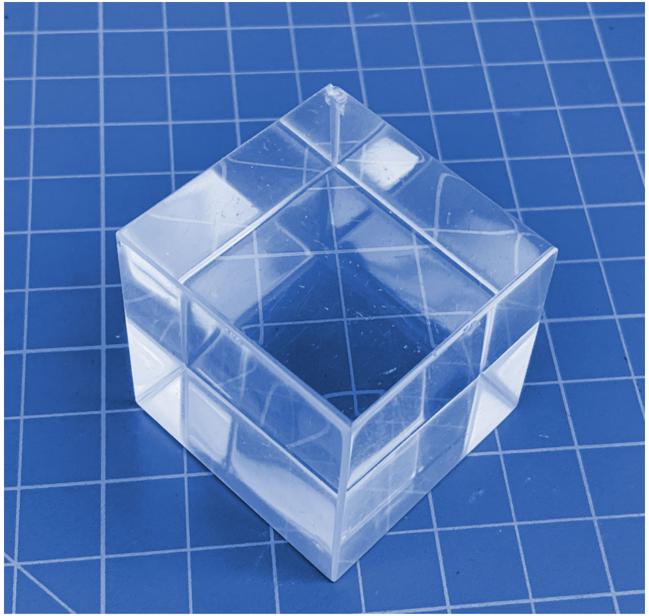
- Crystal mass: **280 g**
- 450 kg of Li_2MoO_4
- 95% enrichment in ^{100}Mo: **240 kg of ^{100}Mo**
- Aims for 5 keV Energy Resolution at $Q\beta\beta$

1710 Ge light detectors with SiO anti-reflective coating

- Simple Bolometer
- Each crystal has top and bottom light detectors
- Open structure to maximize anti-coincidence cut effectiveness

Additional PE based neutron shielding and and active muon veto

Assembly
Enriched crystals procurement

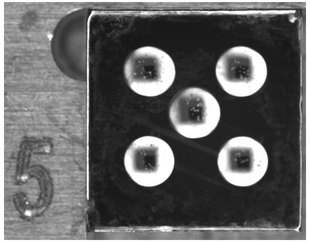


CUPID has established a Crystal procurement chain

- Producing 1596 Li_2MoO_4, crystals grown with **~95% enriched ^{100}Mo** by SICCAS*.
- Pre-production is on-going , funded by INFN (Italy) and CNRS (France).
- Sequential crystal tests at LNGS CUPID facility.

* SICCAS produced the 988 TeO_2 crystals used by CUORE that have a radiopurity similar to CUPID requirements for LMO.

Assembly Instrumentation

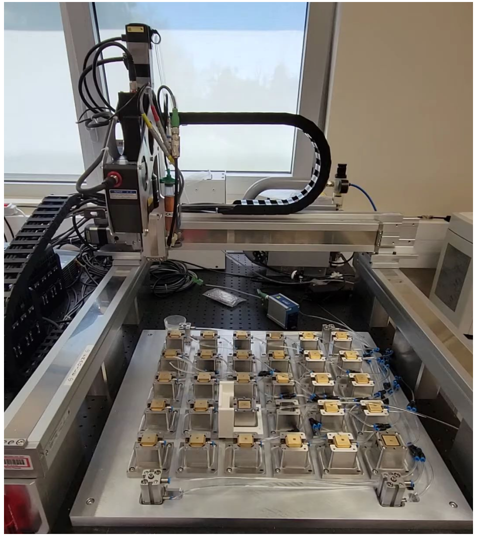


During Detector Assembly:

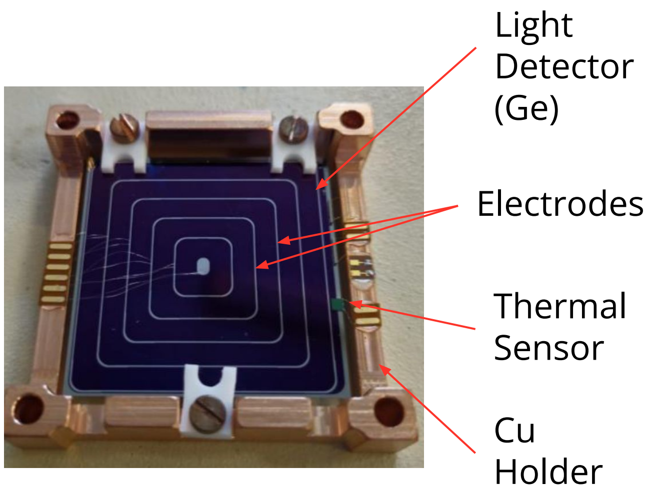
- Rigorous Radiopurity Control:
  - Ensuring both the infrastructure and all components maintain high radiopurity standards.
- High Reproducibility:
  - Achieving consistent, high performance across all detectors.

Techniques Employed:

- Nitrogen Atmosphere:
  - All assembly processes are conducted under a nitrogen (N_2) atmosphere to prevent surface contamination.
- Robotic Instrumentation:
  - A specialized robot has been developed for precise gluing of the sensors to various detectors, including crystals and light detectors.



Pile-up Rejection
Neganov Trofimov Luke Effect

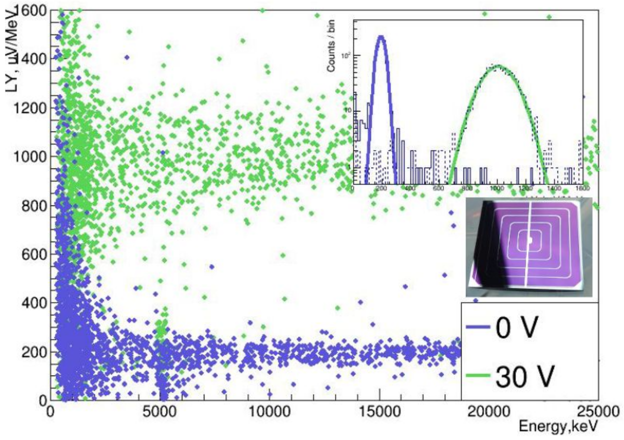


Pile-Up:

- ^{100}Mo has a higher rate of 2νββ than ^{130} Te.
- Risk of 2νββ Pile-up.

NTL effect principle

- Drift electron/hole pair by applying a voltage on the Light detector to generate an additional heat signal.



Goals:

- Increase in signal to noise ratio to use the light channel (fast) for pileup rejection (main background contribution).

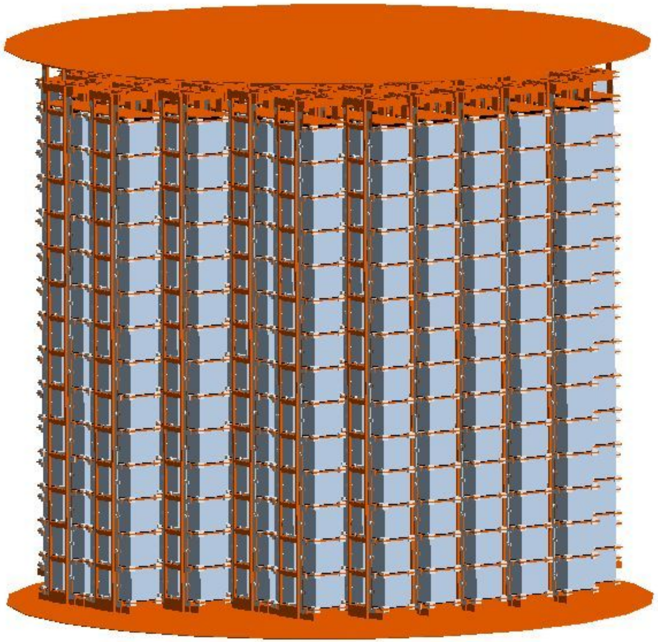
Background projection Simulation

CUPID background simulations are based on results from precursor experiments :

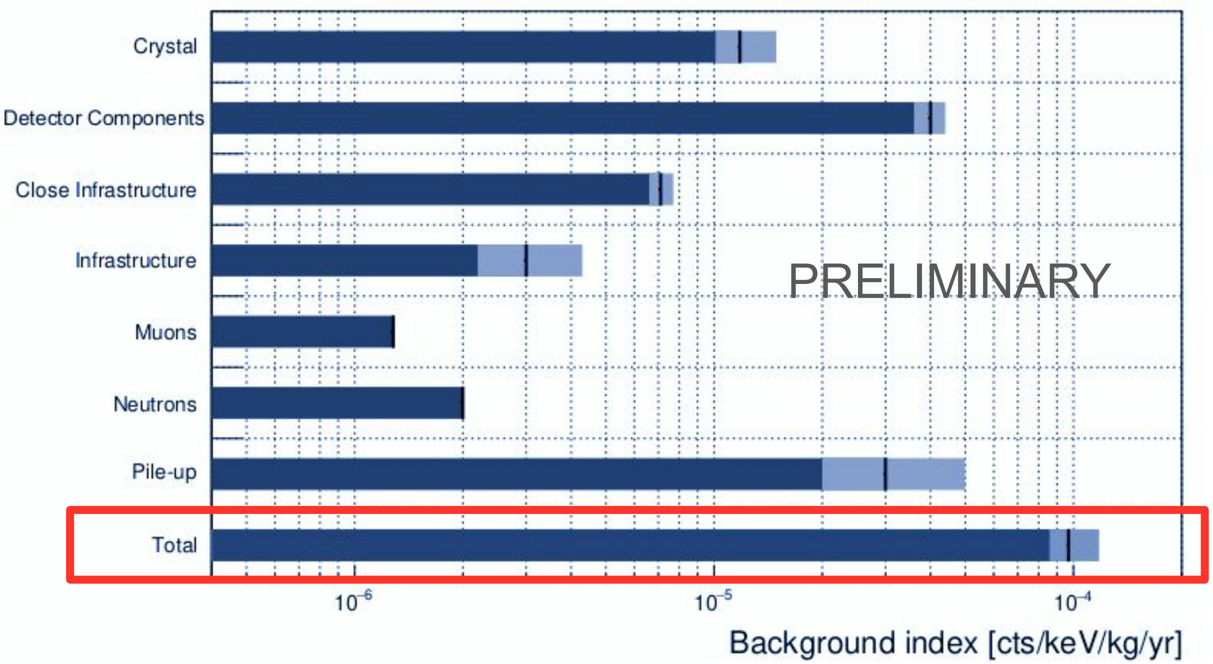
- **CUORE** : arXiv:2405.17937
- **CUPID-0** : Phys. Rev. Lett. 131, 222501 2023
- **CUPID-Mo** : *EPJ C* arXiv:2305.01402

Detailed Implementation of the geometry base on the BDPT (Baseline Design Prototype Tower).

Software : Geant4



Background projection
Background budget



Sources of Background in CUPID

- LMO ^{100}Mo pile-up: demonstrated performance on baseline NTL detectors
- Detector components: surface driven
- LMO contaminants: surface driven
- Cryostat & shields: bulk
- Muons and neutrons

Simulations shows this budget as reachable !

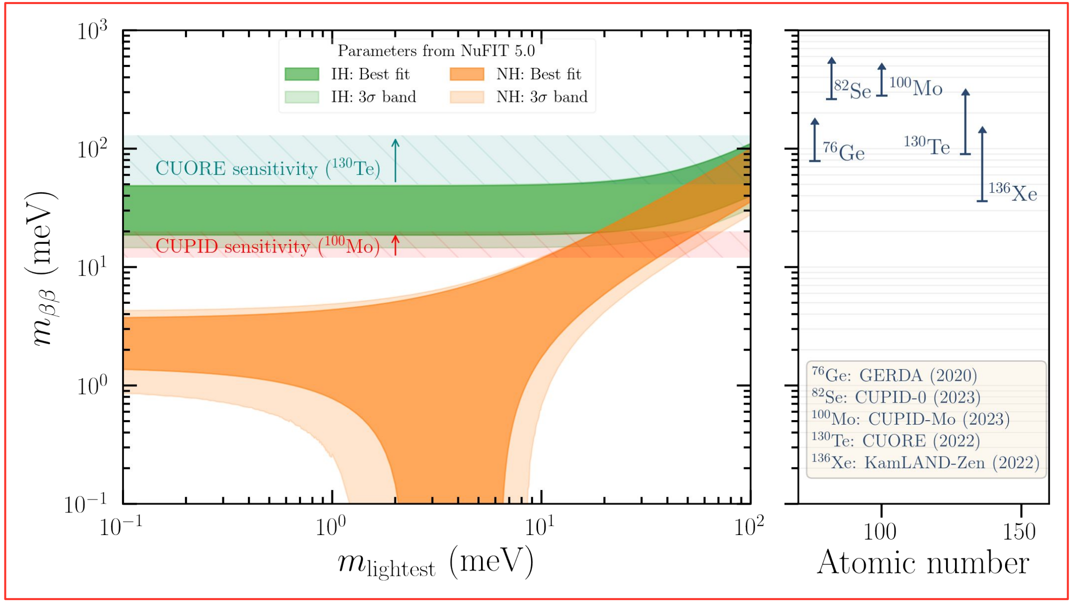
CUPID Sensitivity

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

$$|m_{\beta\beta}| = |\sum_{i=0}^{3} U_{ei}^2 m_i|$$

Goal :

- Fully probe the “Inverted Hierarchy” region. Improve sensitivity to $m_{\beta\beta}$ by **factor of ~5** relative to CUORE

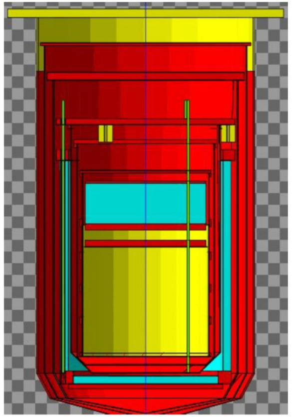


Improved Sensitivity from Background Reduction

- Particle identification
- Muon veto
- Neutron shielding
- Increased **Q value** for reduced γ/β backgrounds
- Pileup rejection

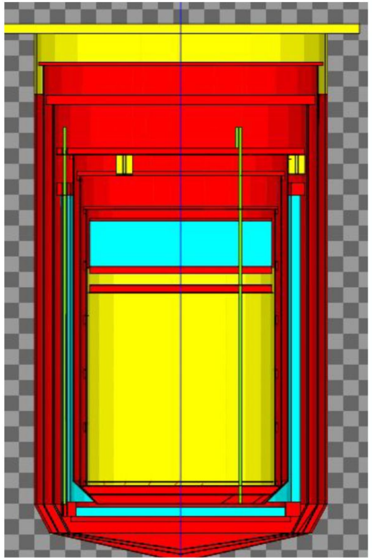
CUPID Sensitivity
Futur and Mass Scaling

CUPID Baseline



- 240 Kg ^{100}Mo
- CUORE Cryostat
- b ~ 10^{-4} ckky
- $T_{1/2}$ > 1.10^{27} yr
- $m_{\beta\beta}$~ [13-21] meV

CUPID 1Ton



- **1000 Kg ^{100}Mo**
- **New Cryostat**
- b ~ 5.10^{-6} ckky
- $T_{1/2}$ > 9.10^{27} yr
- $m_{\beta\beta}$~ [4-7] meV

Technically ready

Conclusion

$0\nu2\beta$ is a **key process** to explore beyond Standard Model physics

CUPID is a **next generation $0\nu2\beta$ experiment** which fully probe the "Inverted Hierarchy" region

Cryogenic calorimeters present huge advantages : **cost effective,low radioactivity, isotope choice.**

A robust background model shows b~10^{-4} counts/keV/kg/yr as reachable.

Ready to move ahead with **CUPID Baseline.**

CUPID

cea

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Thank you !

See-Saw mechanism (type I)
One flavor case

- $\left(\overline{(\nu_L)^c},\ \overline{N_R}\right)\begin{pmatrix}0 & m\\ m & M\end{pmatrix}\begin{pmatrix}\nu_L\\ (N_R)^c\end{pmatrix} + \left(\overline{\nu_L},\ \overline{(N_R)^c}\right)\begin{pmatrix}0 & m\\ m & M\end{pmatrix}\begin{pmatrix}(\nu_L)^c\\ N_R\end{pmatrix}$

- $\begin{pmatrix}0 & m\\ m & M\end{pmatrix} = \begin{pmatrix}c_\theta & -s_\theta\\ s_\theta & c_\theta\end{pmatrix}\begin{pmatrix}\lambda_- & 0\\ 0 & \lambda_+\end{pmatrix}\begin{pmatrix}c_\theta & s_\theta\\ -s_\theta & c_\theta\end{pmatrix}$

- $\lambda_\pm \equiv \frac{M}{2} \pm \sqrt{\left(\frac{M}{2}\right)^2 + m^2}$

- $\lambda_- \sim m^2/M\,,\ \lambda_+ \sim M$ for $m \ll M$
  - Ex.) $M \sim 10^{11}$ GeV for $m^2/M \sim \sqrt{\Delta m^2} \sim 10^{-2}$ eV, $m \sim 1$ GeV

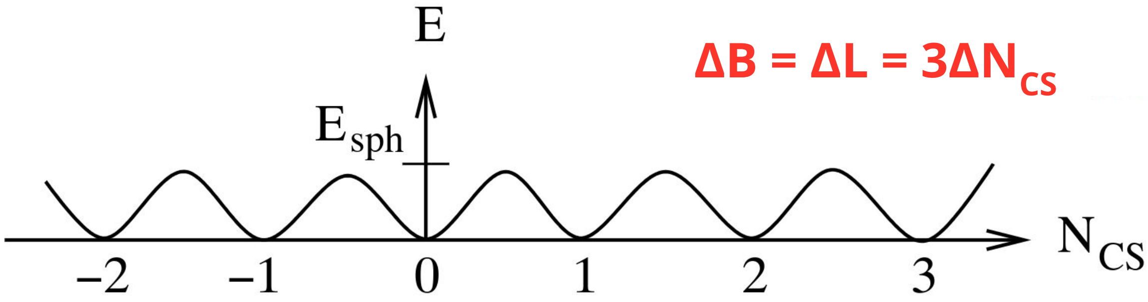
Baryogenesis via Leptogenesis
Sphaleron and instanton-like process

There are **non perturbative solutions** to the electroweak field equations. Those solution are called **instanton-like** process when the system must tunnel through electroweak potential or **Sphaleron** process when the energy is high enough to classically cross over the barrier.

Those process can convert three leptons into three antibaryons.

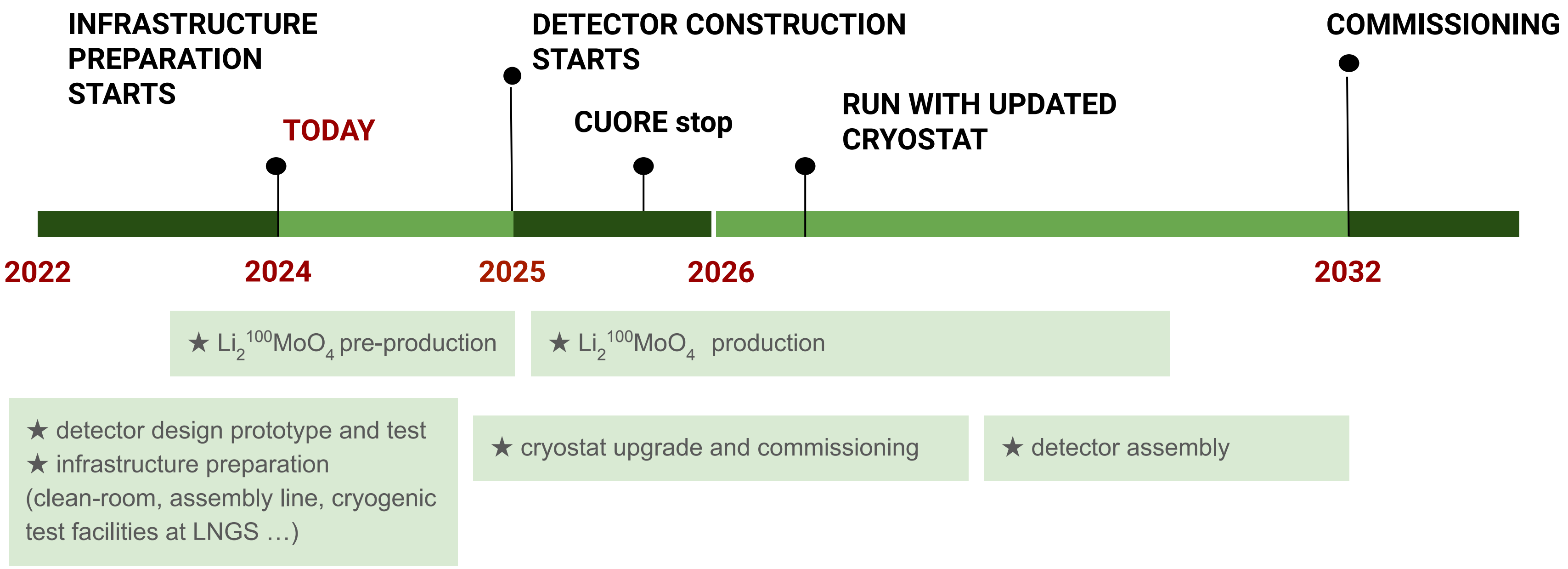
So if lepton number is generated through the Majorana mass term it can be transformed into the baryon number due to **Sphaleron or instanton-like** process not suppressed in early universe.

$$\Delta B = \Delta L = 3\Delta N_{CS}$$

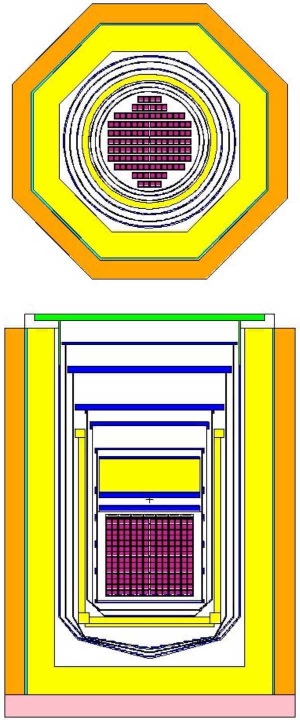


https://irfu.cea.fr/Phocea/file.php?file=Seminaires/3075/Lavignac_SPP.pdf

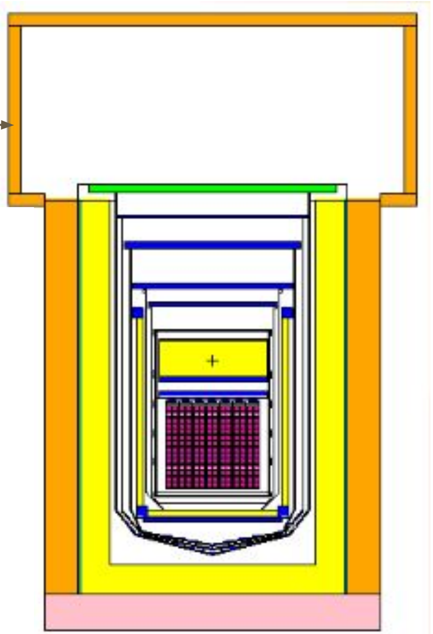
CUPID Timeline



Neutron Shield



Closed polyethylene
neutron shield



- Green: stainless steel
- Yellow: lead
- Orange: PE
- Azure: boric acid
- Pink: borated PE