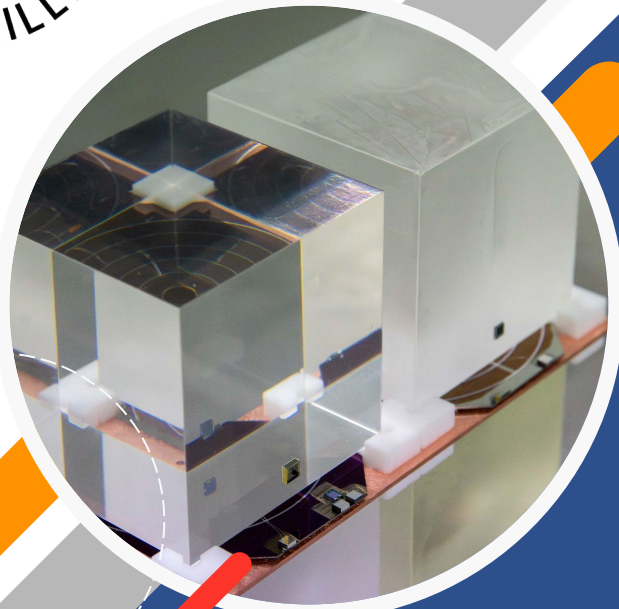
CUPID

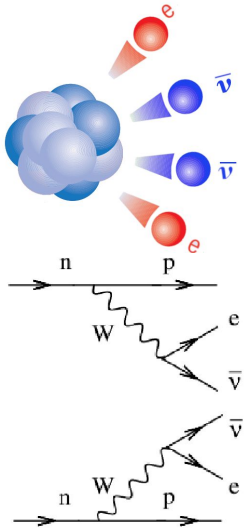
The next generation $0\nu\beta\beta$ bolometric experiment

Mathieu Pageot for the CUPID collaboration

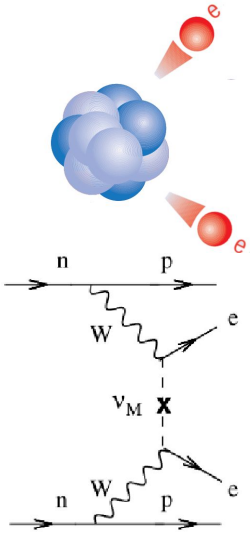


The $0\nu\beta\beta$ decay

$2\nu2\beta$



$0\nu2\beta$



Allowed By Standard Model

Needs Beyond Standard Model Physics !

$\Delta L = 2$

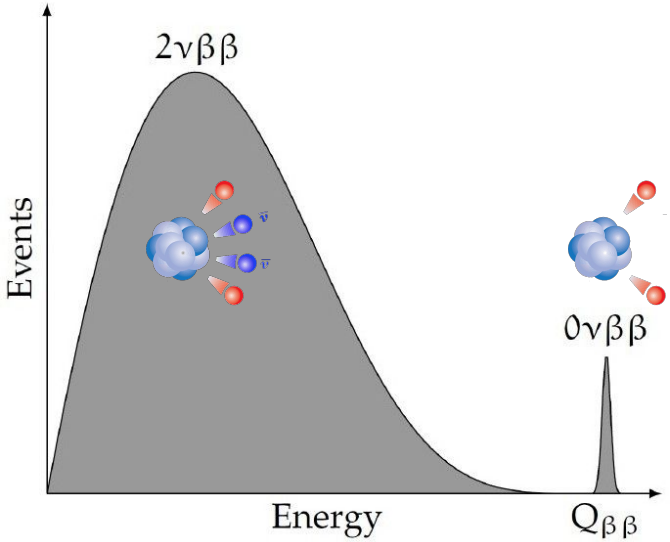
Lepton Number Violation

$\nu = \bar{\nu}$

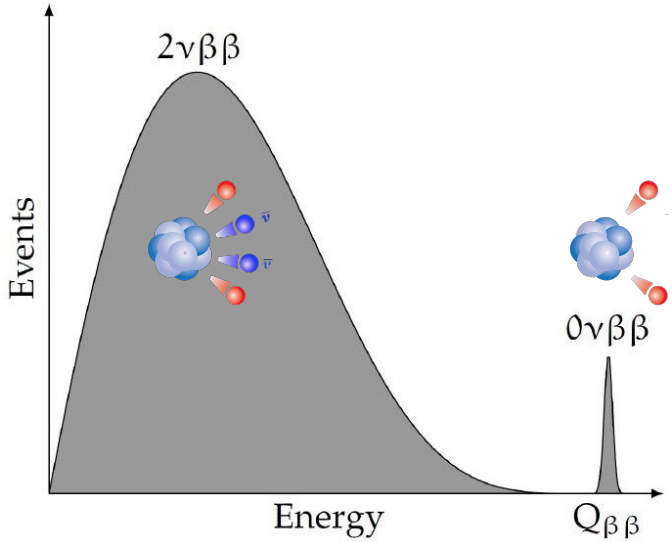
Majorana Particle

Detect $0\nu\beta\beta$

Main signature of the $0\nu\beta\beta$: peak at the Q-value of the reaction



Detect $0\nu\beta\beta$ with cryogenic calorimeters



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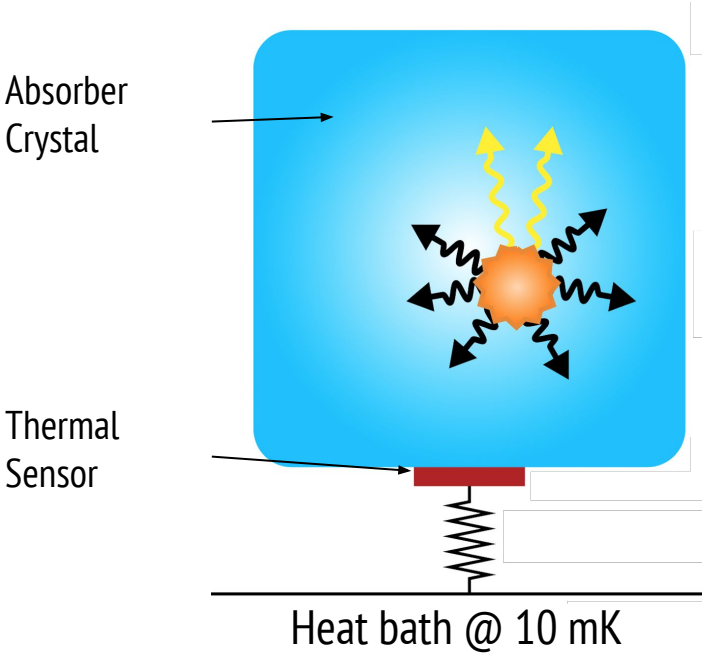


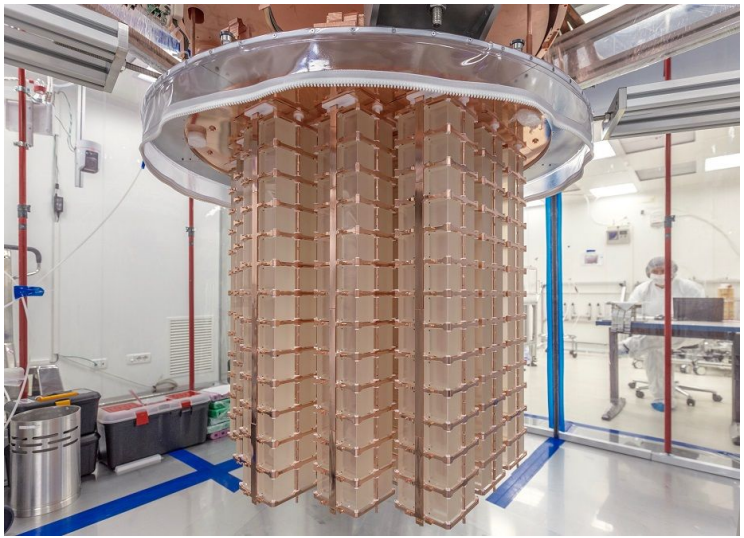
Cryogenic calorimeters

- High detection efficiency : $\beta\beta$ emitter embedded in the detector
- Flexible in isotope choice
- Excellent energy resolution ⟶ narrow $0\nu\beta\beta$ peak
- Cost efficient
- Scalable as array of O(1000) crystals (100g - 1kg each)

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 7.3(2) keV FWHM (0.3% relative resolution) [arXiv:2404.04453]



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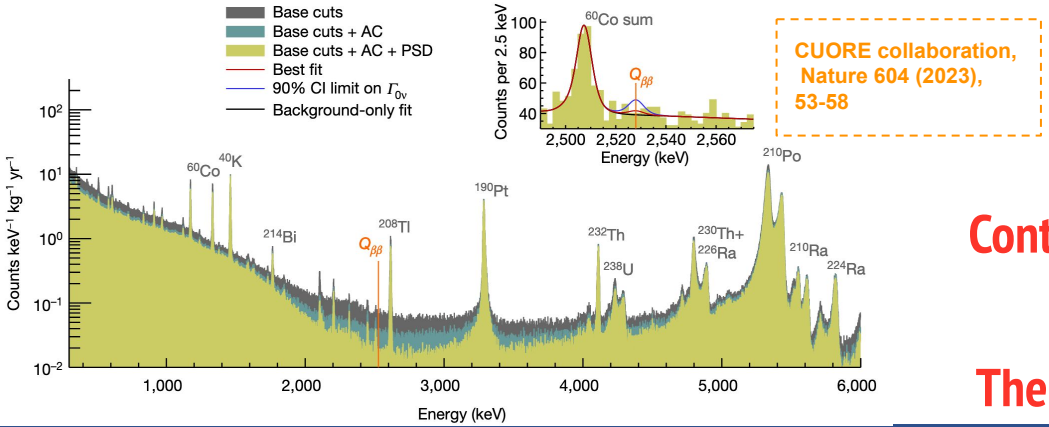
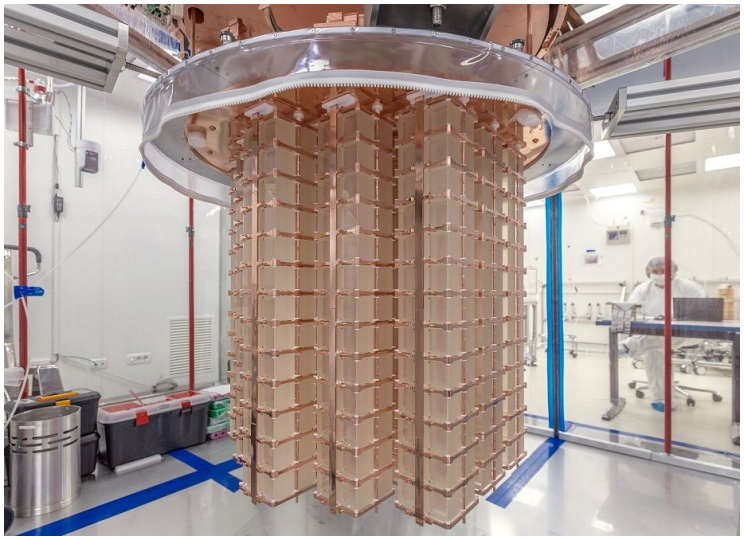


CUORE collaboration, Nature 604 (2023), 53-58

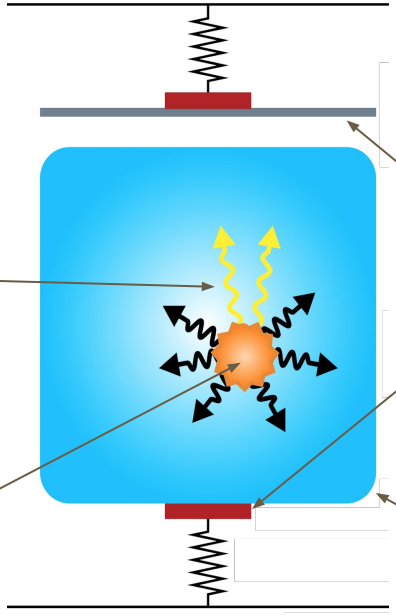


Continuous & efficient operation of ton-scale cryogenic calorimeter over >7 years!

The α background is now the limiting factor.

CUPID

CUORE Upgrade with Particle IDentification



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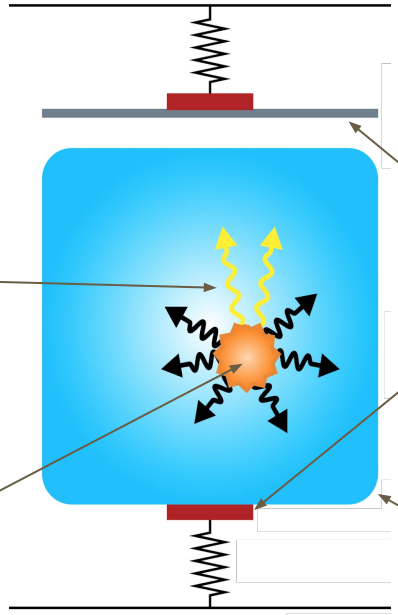


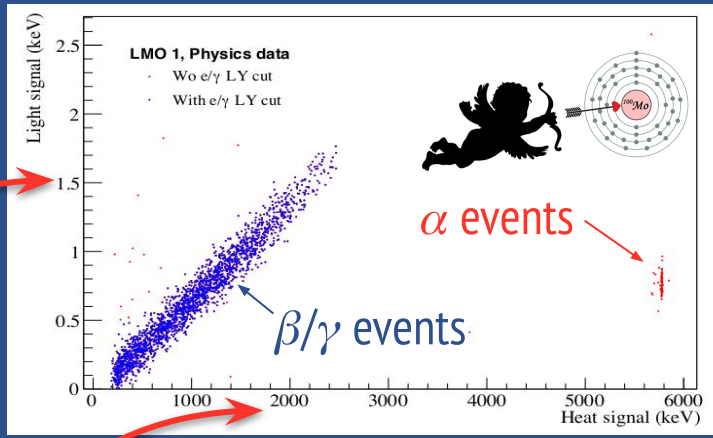
Light Detector

Light

Thermal Sensor

Energy Release (phonons)

Absorber scintillating Crystal (Li_2**Mo**O_4)



CUPID Mo: EPJ C arXiv:1909.02994

Particle Identification with light detector to discriminate between α from β/γ

CUPID

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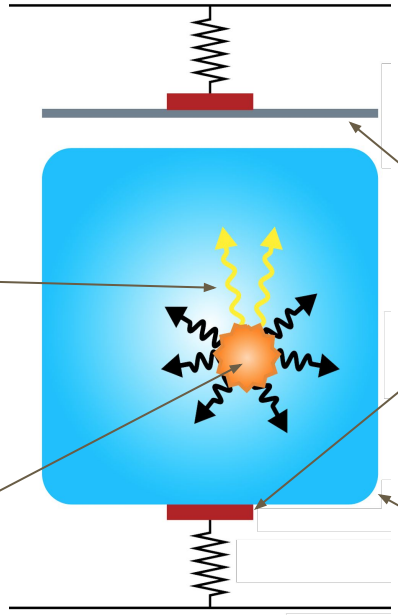

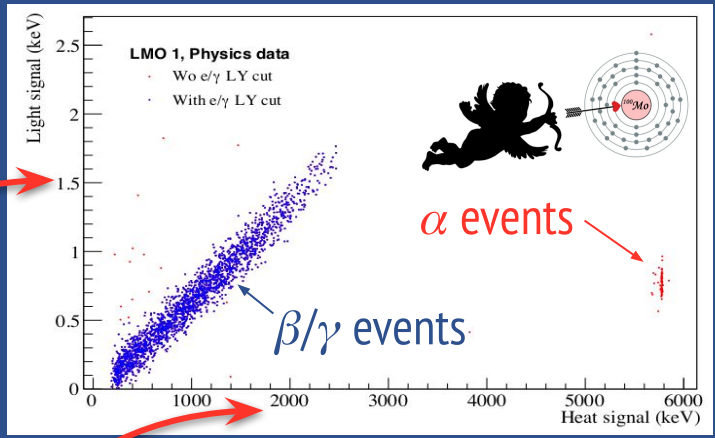

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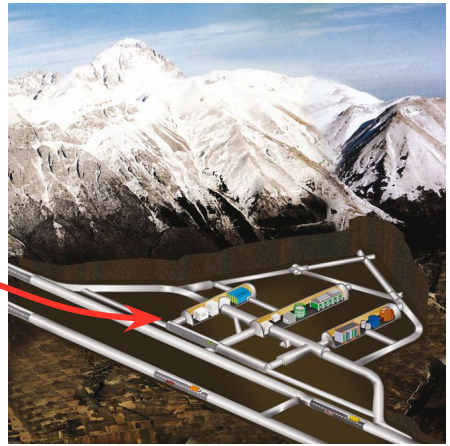
Particle Identification with light detector to discriminate between α from β/γ

New isotope : ^{100}**Mo** with a Q-value at 3.034 MeV above natural γ radioactivity present below 2.6 MeV

CUPID at the LNGS[(1)] Underground Laboratory

(1) National Laboratory of Gran Sasso

CUPID at the LNGS[(1)] Underground Laboratory



Existing CUORE Infrastructure located LNGS

- Dry cryostat T~10 mK for a ton-scale detector
- Established and well understood infrastructure and environment.
- Underground Laboratory (1.4km of rock) shielding the experiment from cosmogenic particules

New scintillating detector array

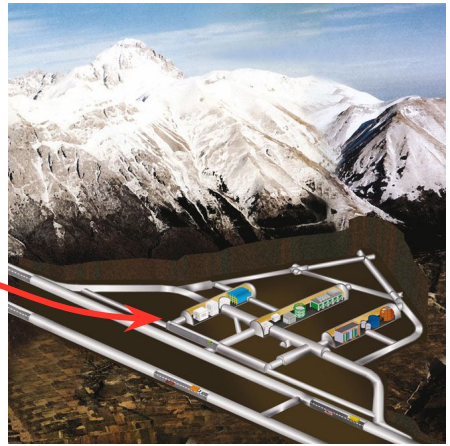
- 1596 Li_2MoO_4 crystals (240 kg of ^{100}Mo)
- 1710 Ge light detectors

With upgrades

- New pulse tubes
- New muon vetos
- Additional PE shielding

(1) National Laboratory of Gran Sasso

CUPID at the LNGS[(1)] Underground Laboratory



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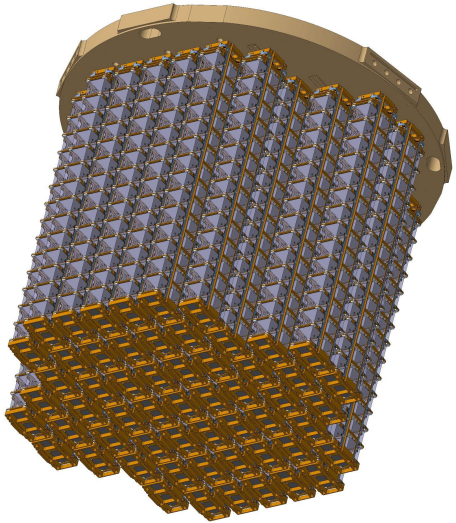

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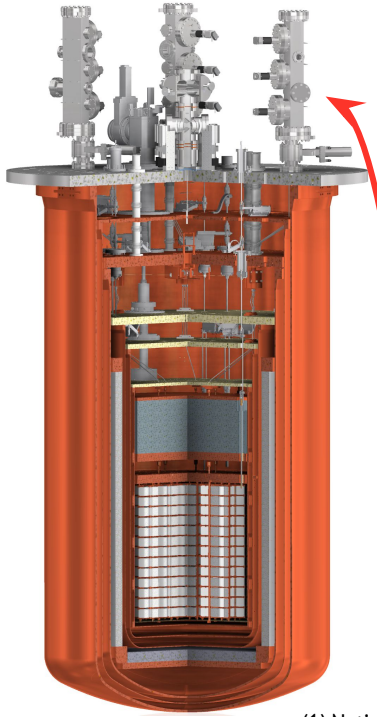

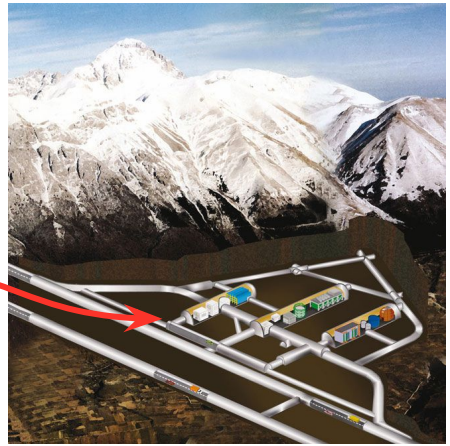

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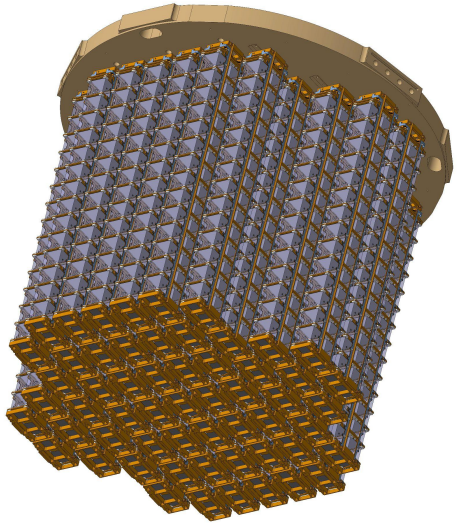

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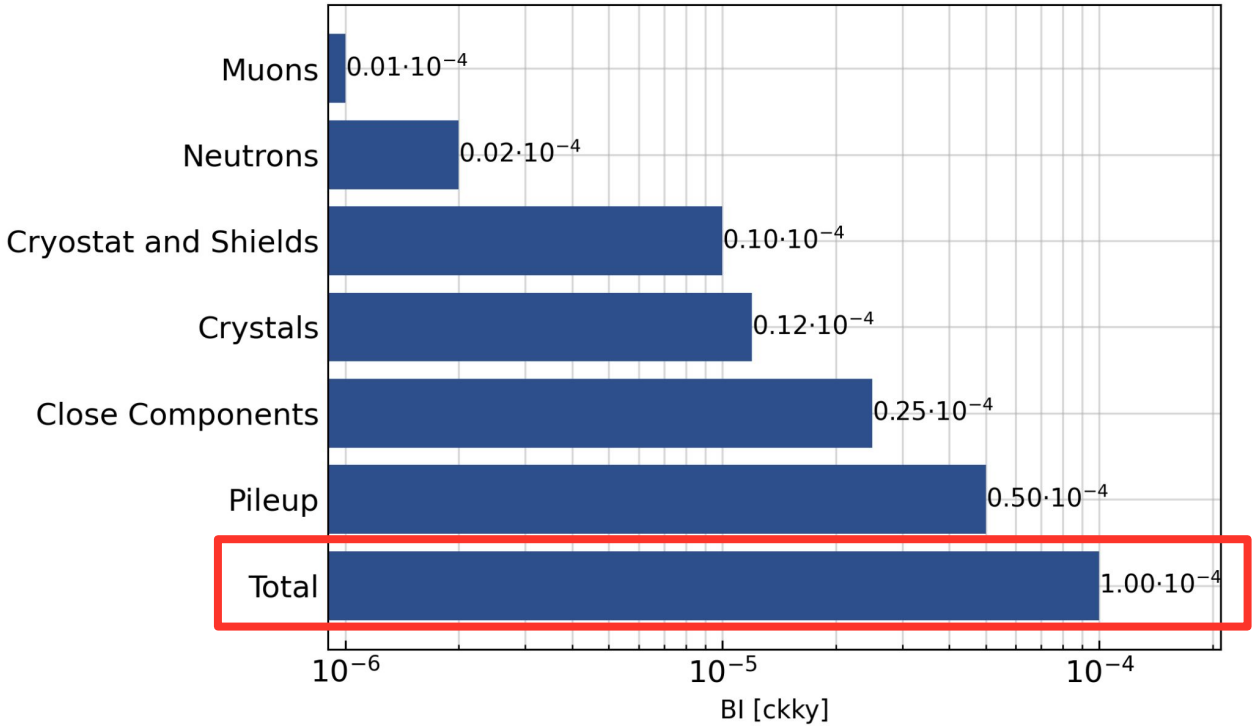
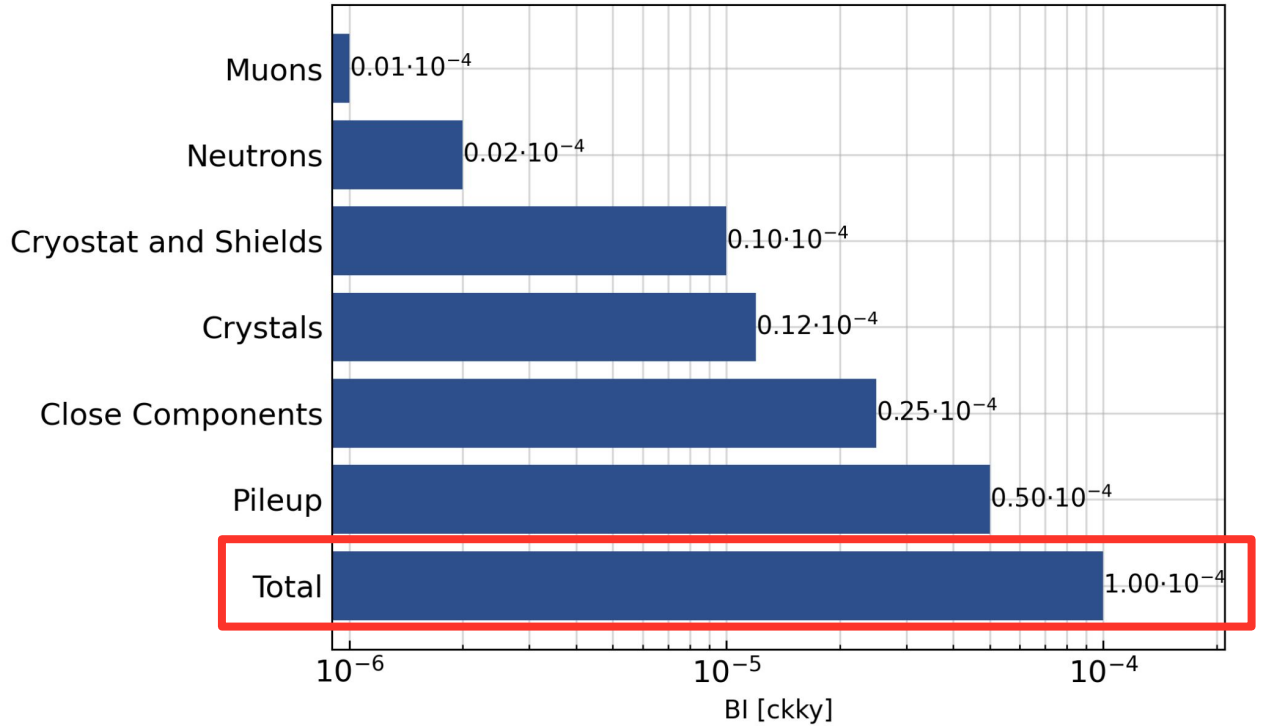
Background projection
Background budget



Background projection
Background budget

Coming from outside the detector structure :
mitigate by shielding and vetos



Background projection
Background budget

Coming from outside the detector structure :
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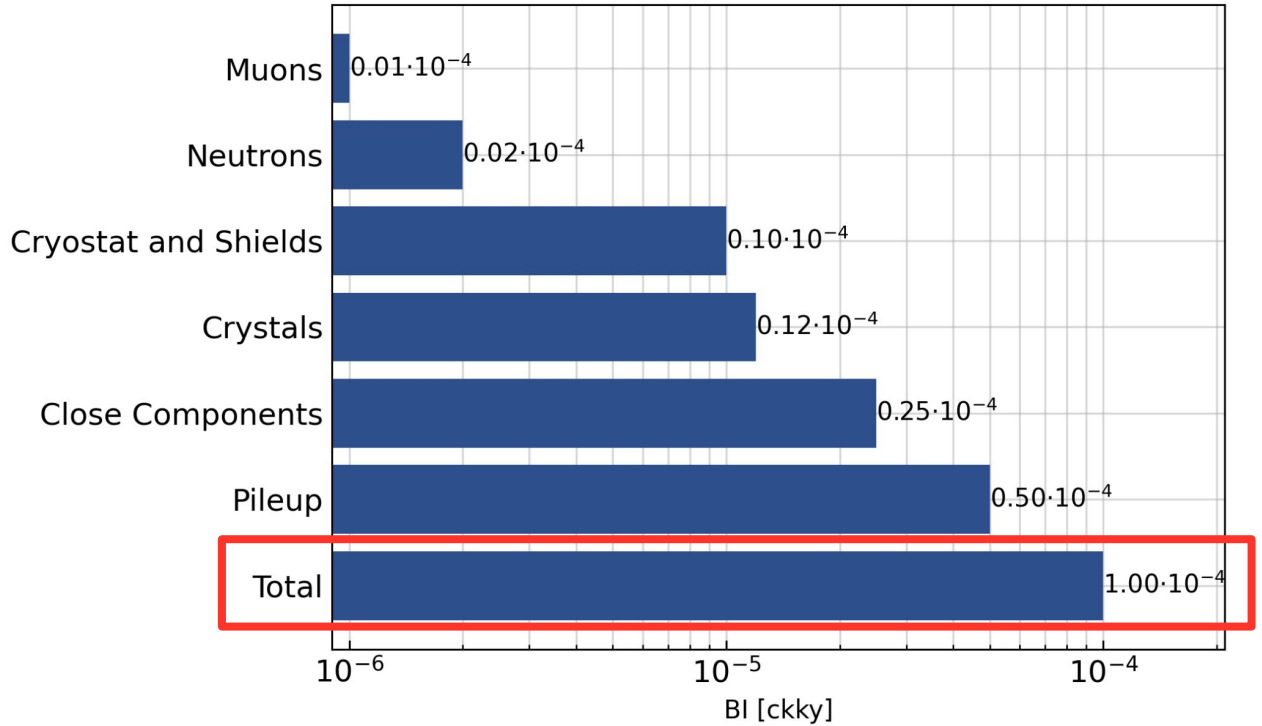
Mainly due to surface contamination:
mitigated by a clean assembly and coincidence between crystals



Background projection
Background budget

Coming from outside the detector structure :
mitigate by shielding and vetos

Mainly due to surface contamination:
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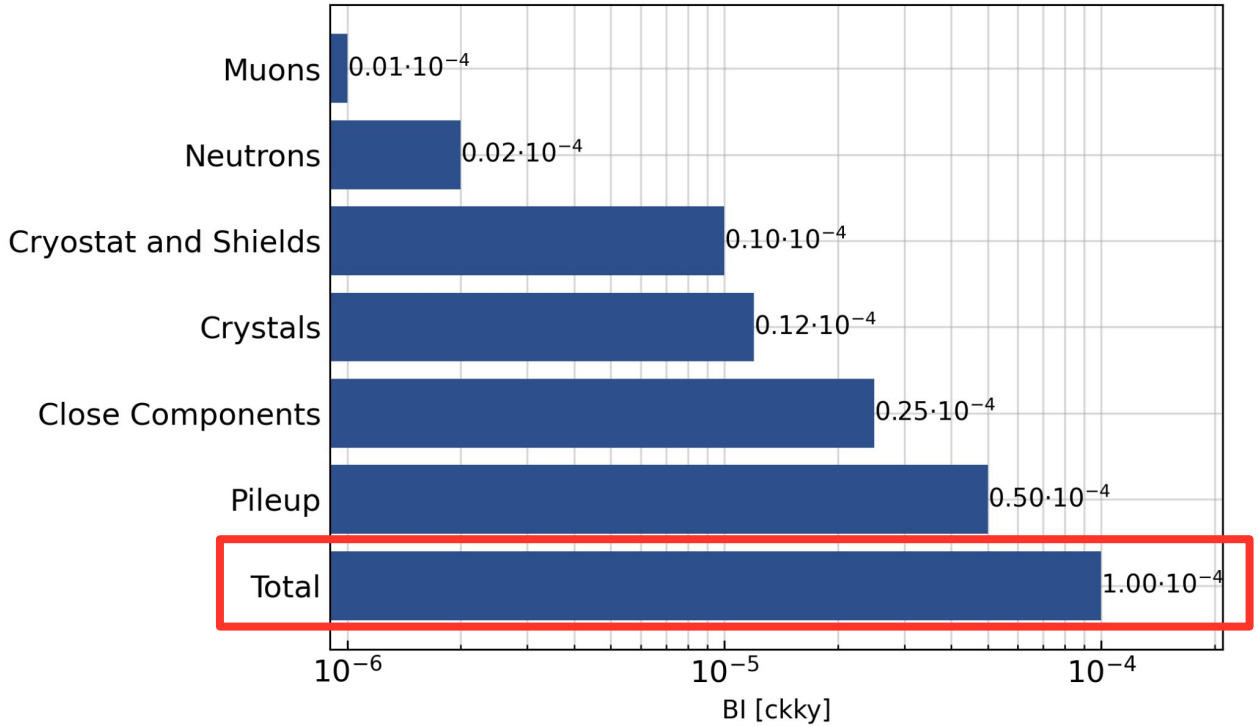
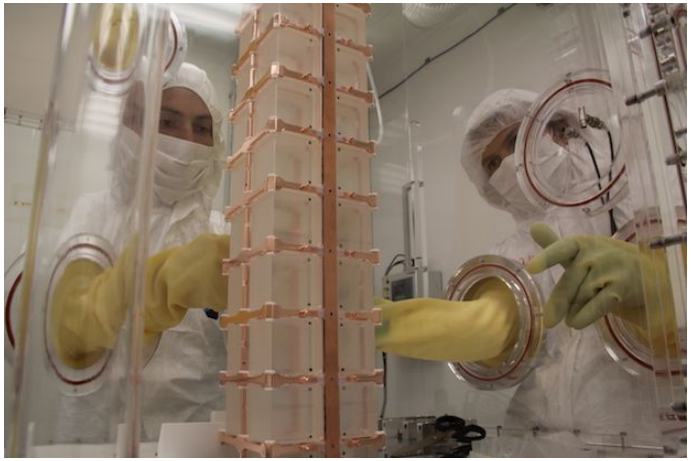
Two $2\nu\beta\beta$ events occurring simultaneously which sum of energy ends up in the ROI:
mitigate by using the fast light channel



Assembly

- High purity assembly under a controlled N_2 atmosphere at all time to avoid surface contamination



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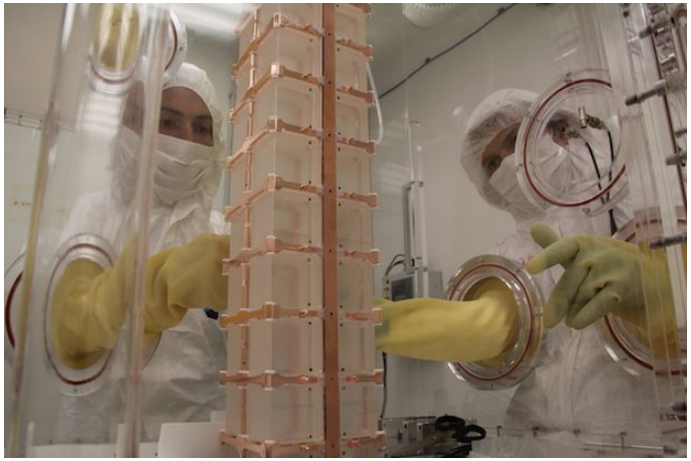
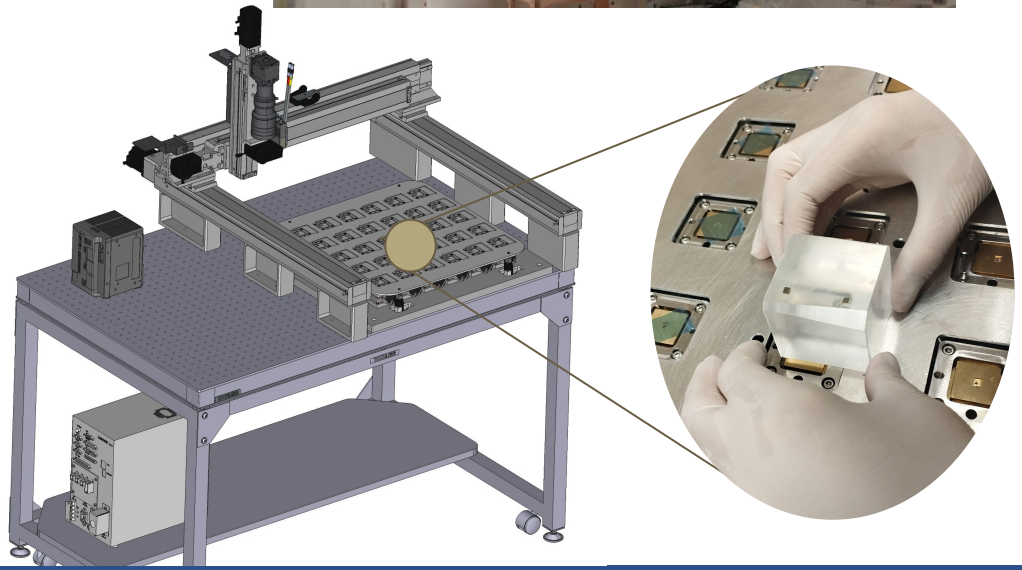


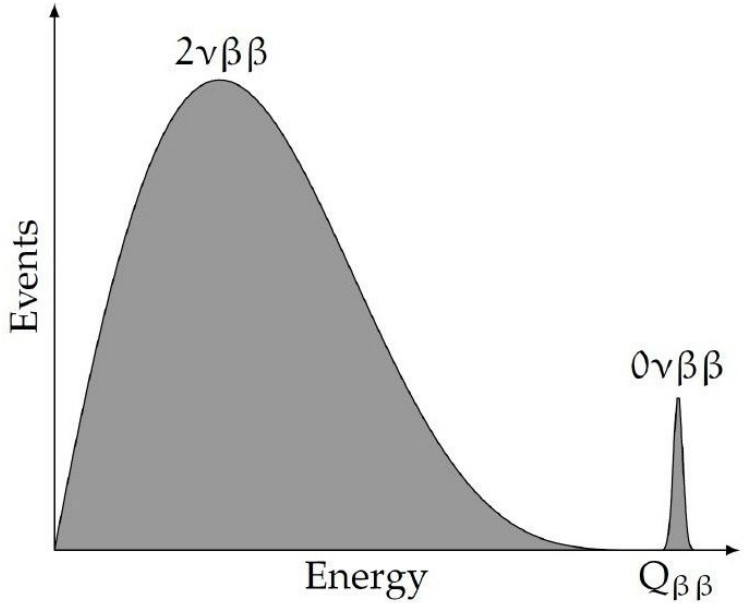
- High purity assembly under a controlled N_2 atmosphere at all time to avoid surface contamination

- Gluing Robot @ CEA for semi-automatized instrumentation of the 1596 crystals and 1710 light detectors with high reproducibility and quality control



$2\nu\beta\beta$ pile-up

- ^{100}Mo has a higher rate of $2\nu\beta\beta$ than ^{130}Te.
- Two $2\nu\beta\beta$ events close enough in time that are not resolved, but **reconstructed** as a single event



→ Extended background at high energy (Q-value and beyond)

- Parameters that determine the ability to identify pile-up events: rise time and signal-to-noise ratio (SNR)

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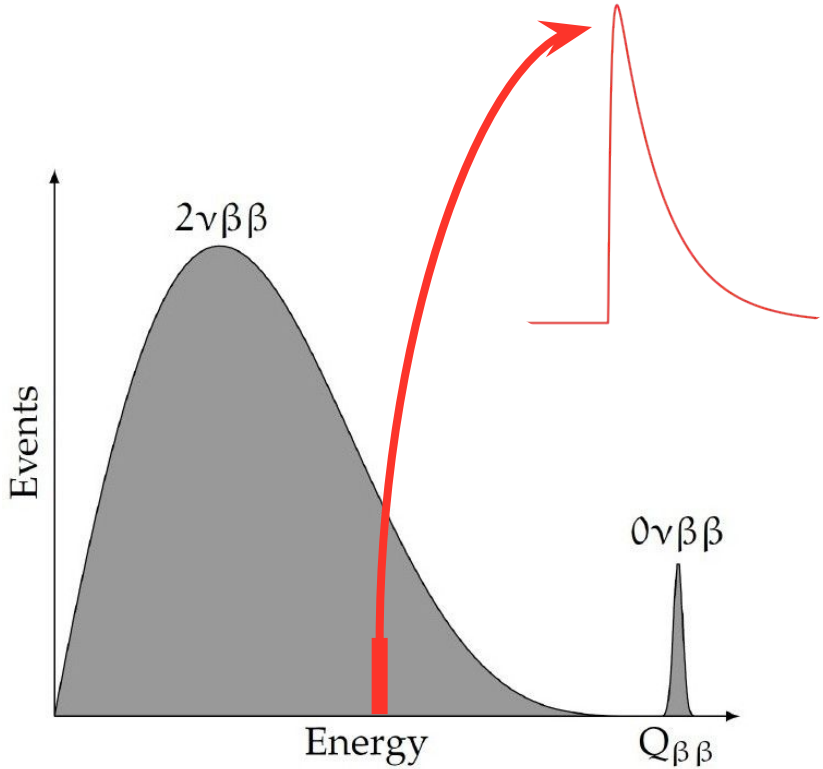

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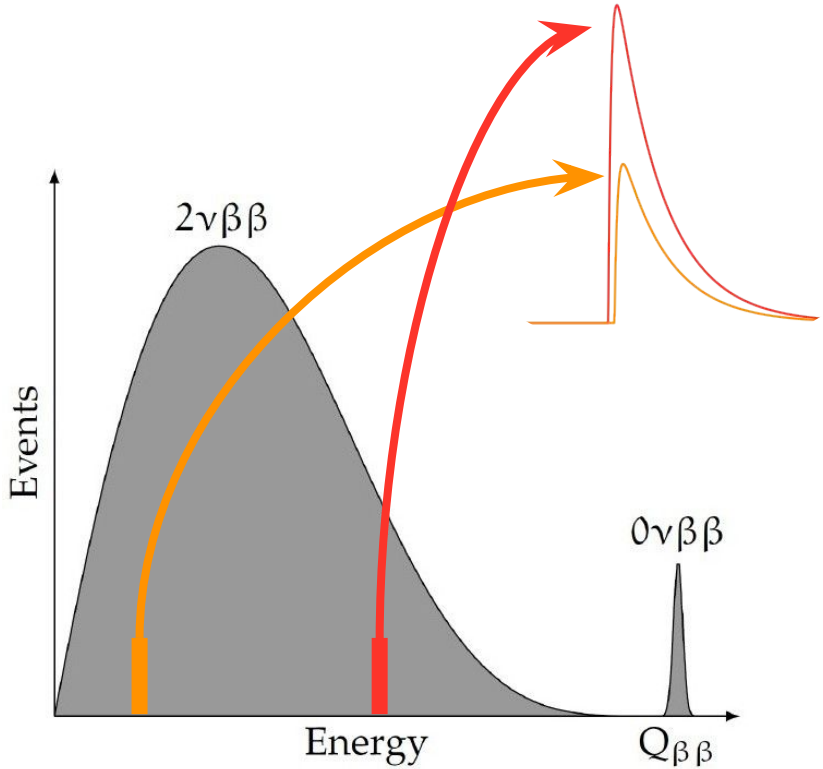

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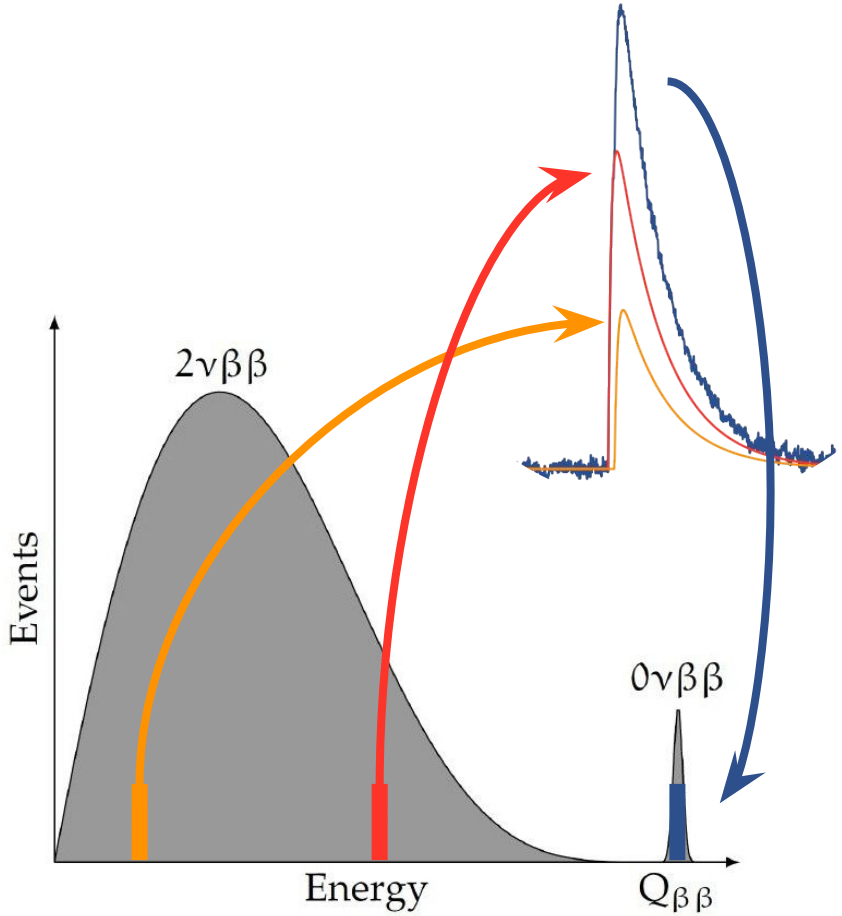
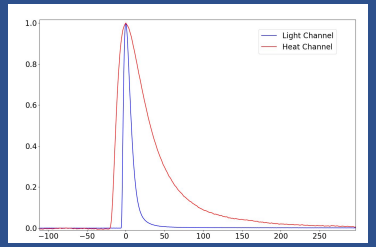


Light Detector Optimization

Light Detector Optimization

Pileups

- Fast signal response is essential
- Use the Light Channel for its faster pulse
- Improving SNR enhances pileup rejection



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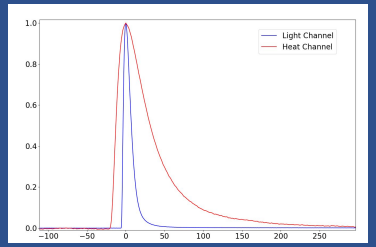
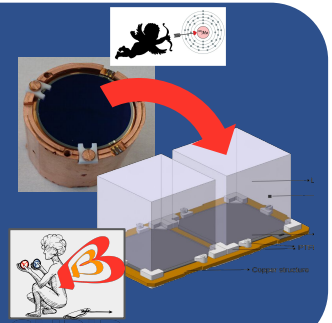


Change of structure

⊕ More densely packed array
⊕ Less passive materials
⇒ More coincidence information results in lower background
⊖ Lower light yield



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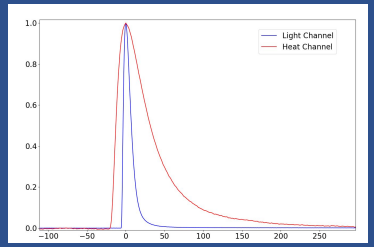

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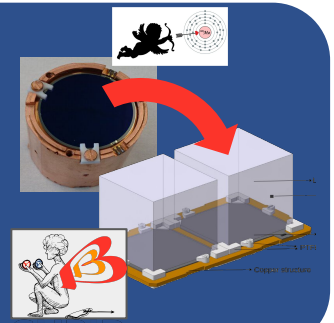
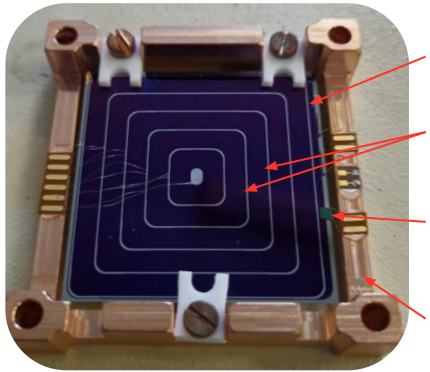




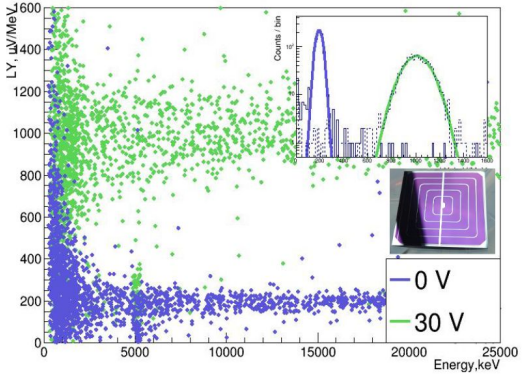
Light Detector Electrodes

Thermal Sensor

Cu Holder

Neganov-Trofimov-Luke (NTL) amplification

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



Test Towers
GBPT and VSTT

GBPT(1) [arXiv:2503.04481]

First test tower for CUPID

Revolutionary gravity based design

Detector close to CUPID requirements

To do : mitigate LD noise and demonstrate 2νββ pile-up rejection capability

(1): Gravity Based Prototype tower
(2): Vertical slice test tower

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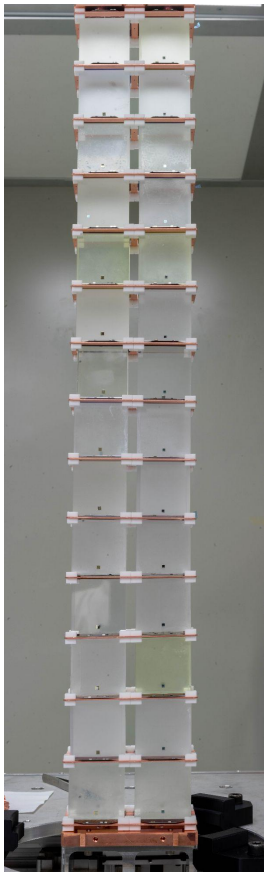
VSTT(2)

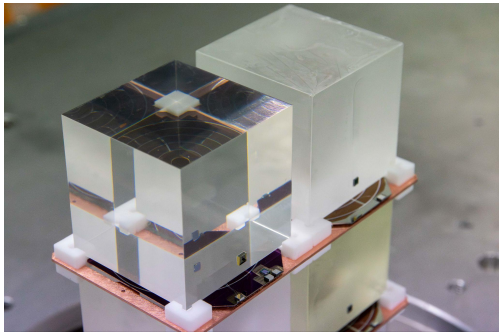


Build upon GBPT design, now with :

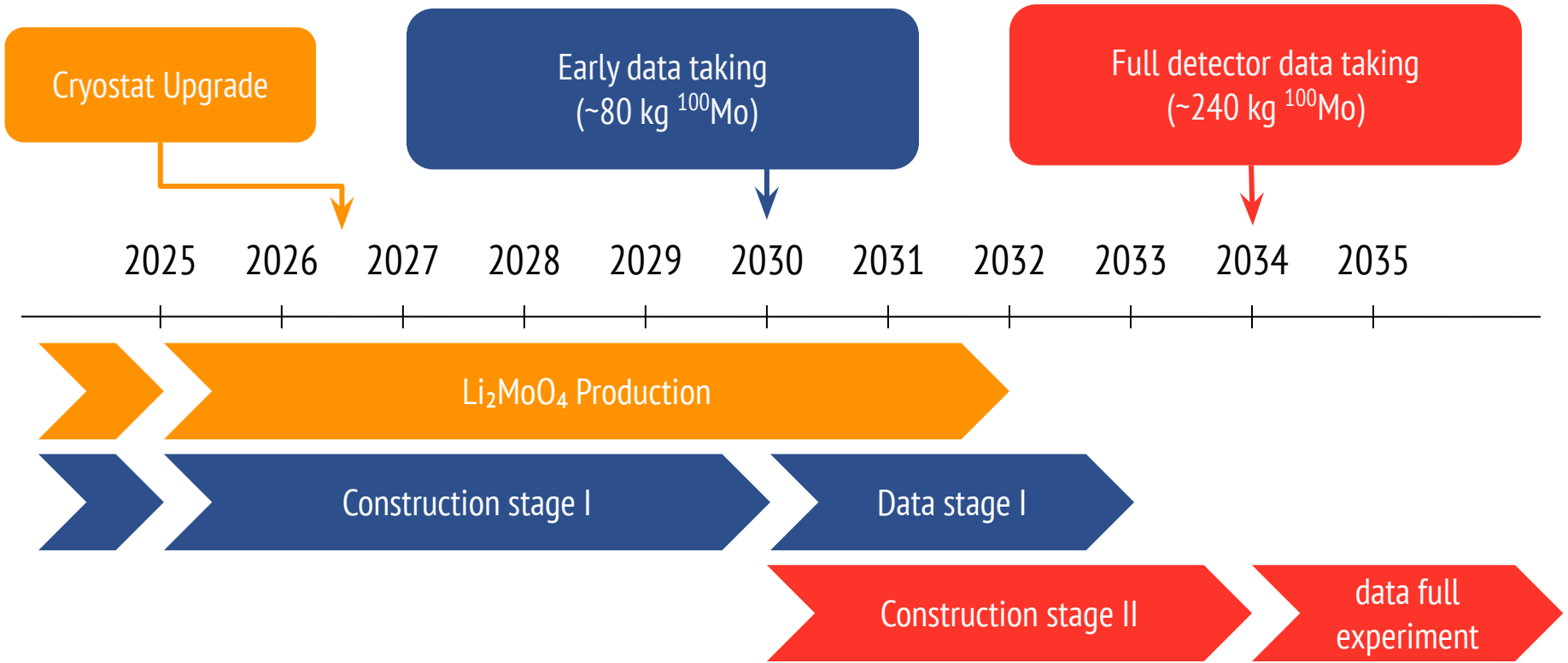
- NTL amplification light detectors
- Refined LD holders
- Gluing of the thermal sensor done with gluing robot

Assembly ongoing at LNGS

Cooldown and validation of performance by summer 2025



Timeline from CUORE upgrade to CUPID
Staged detector deployment



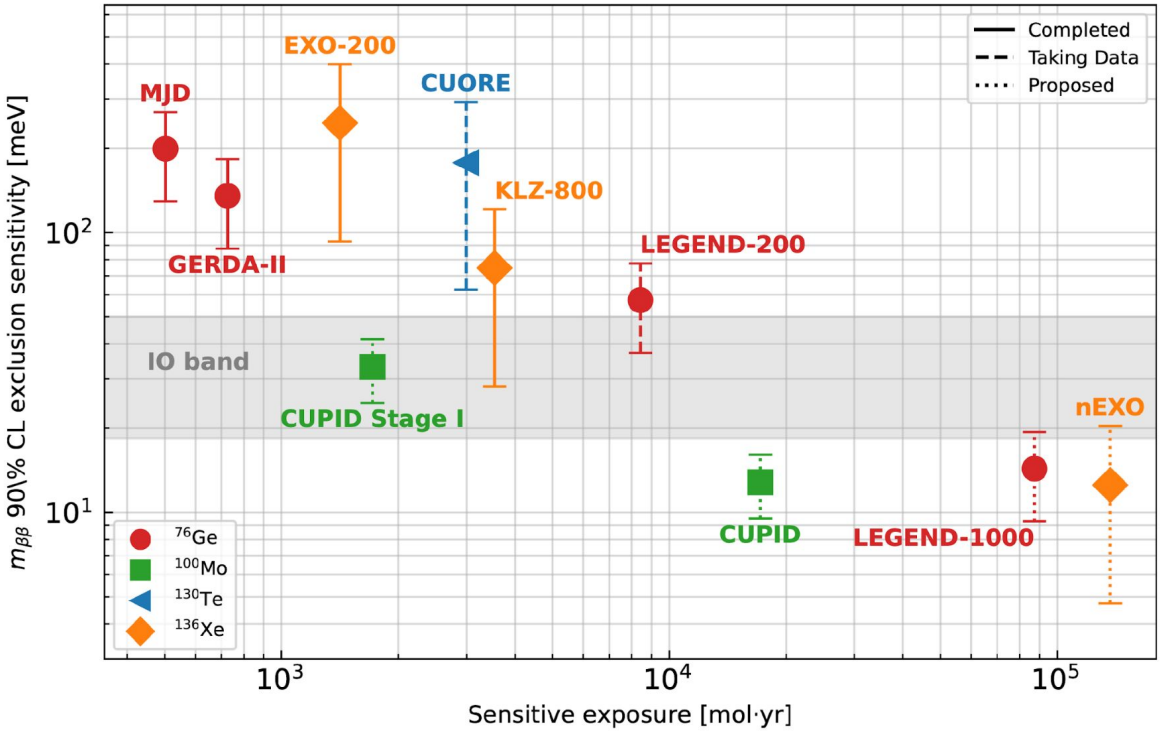
CUPID Sensitivity

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

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

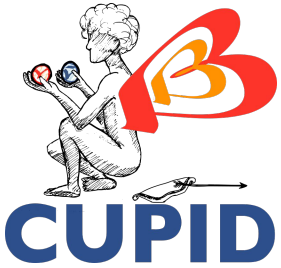
CUPID goal:

- highly competitive sensitivity after **stage I**
- full coverage of the inverse order of the neutrino masses with the **stage II**



Conclusion

- Builds on the success of the **CUORE** experiment
- Supported by a well-established infrastructure ready to host **CUPID**
- Informed by a clear understanding of backgrounds
- Employs innovative techniques to mitigate background
- Follows a clear, staged deployment timeline to enable early data-taking


CUPID


cea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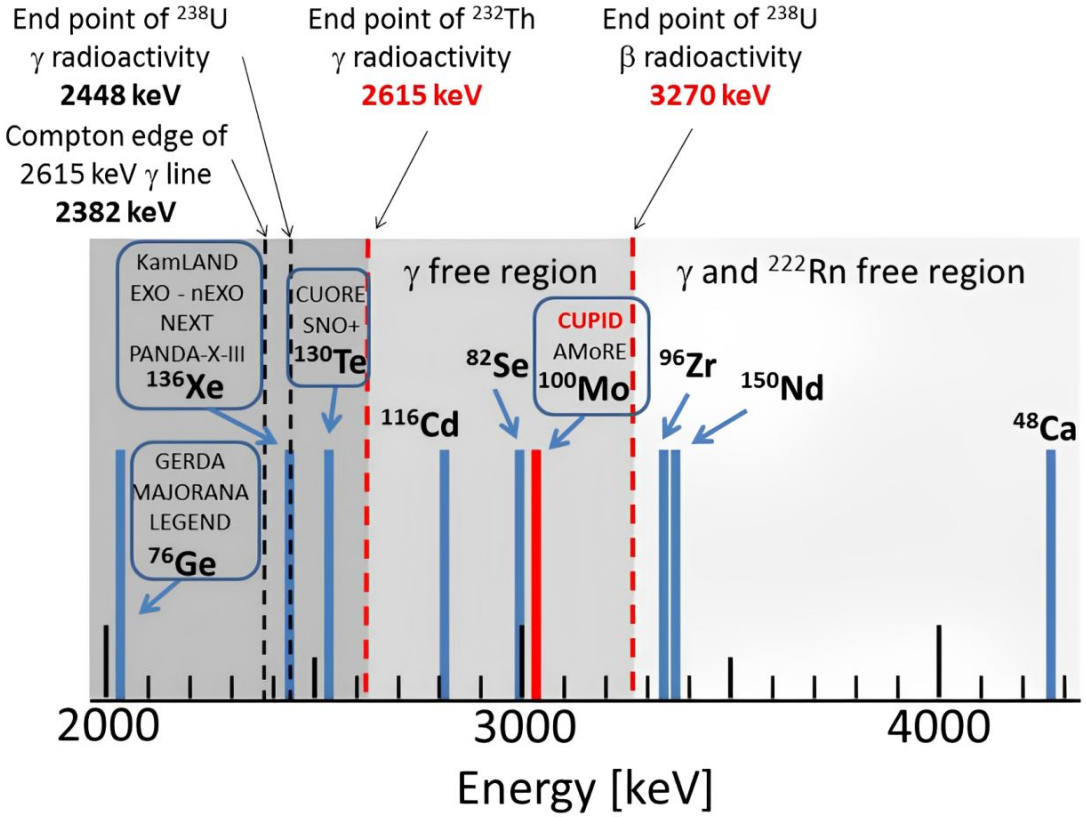
MARSEILLE

Thank you !

Q-values of the different $\beta\beta$ isotopes



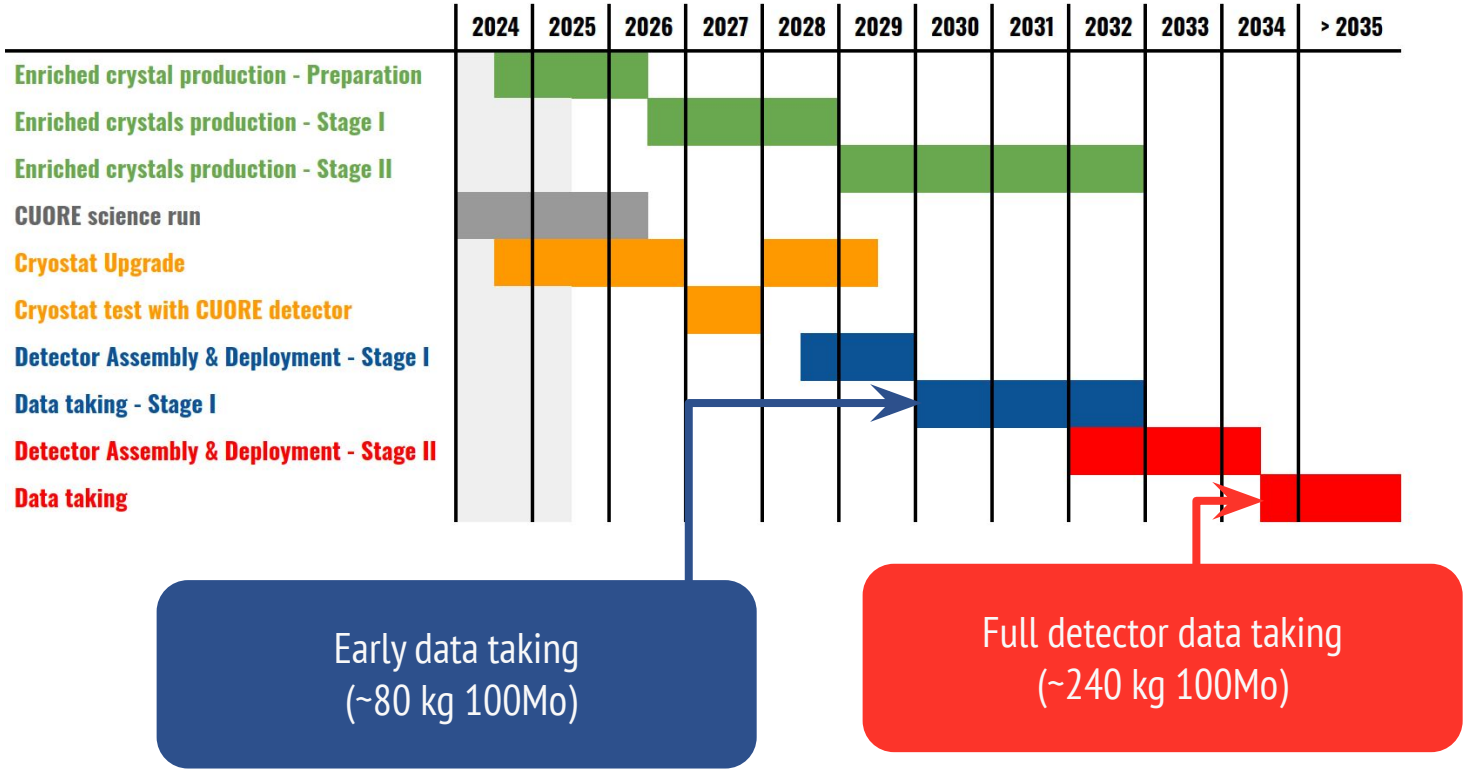
Enriched crystals procurement

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.

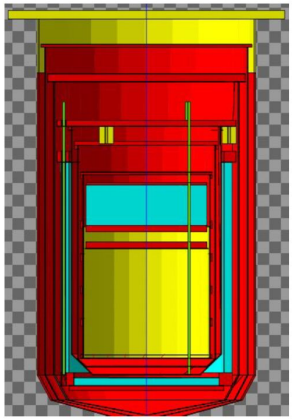
* SICCAS produced the 988 TeO_2 crystals used by CUORE that have a radiopurity similar to CUPID requirements for LMO.

CUPID Timeline



Futur and Mass Scaling

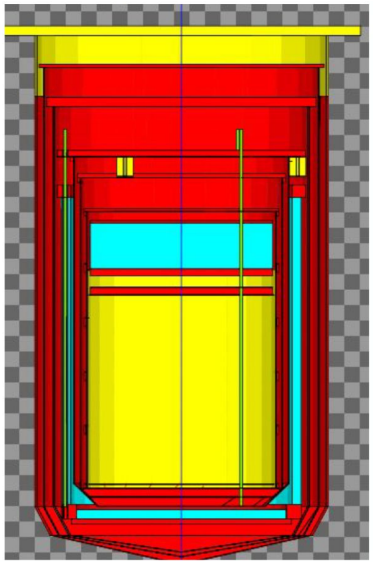
CUPID Baseline



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

Technically ready

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