Neutrinoless Double Beta Decay Search with CUPID

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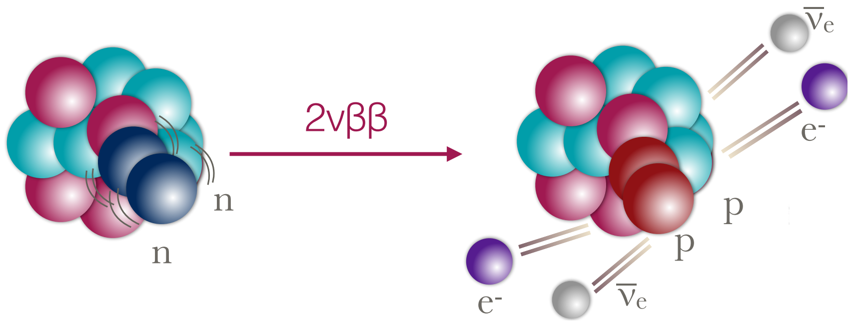
Double Beta Decay

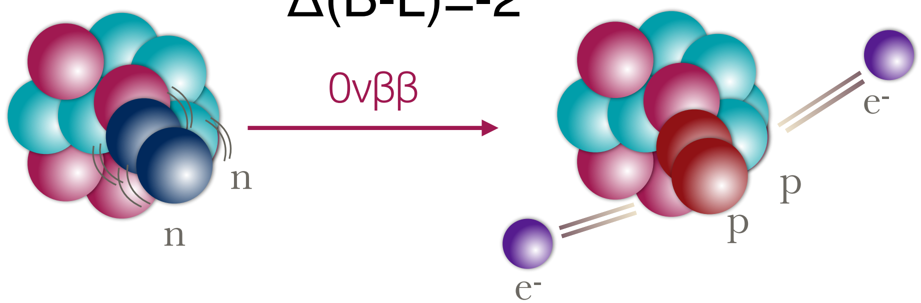
- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}$
  - 2^{nd} order weak process in SM,
  - Measured at a few % precision
  - $t^{2\nu}_{1/2} \gtrsim 10^{18}$ yr



- $(A,Z) \rightarrow (A,Z+2) + 2e^-$
  - Forbidden in SM, L and B-L violated
  - Matter creation in LAB (could explain barion asymmetry in the universe)
  - Many non SM diagrams can contribute
  - Simplest and plausible model foresees exchange light-mass Majorana neutrinos $\rightarrow m_\nu \neq 0$ and $\Psi \equiv \Psi^C$
  - $t^{0\nu}_{1/2} \gtrsim 10^{25\text{-}26}$yr

$\Delta L=2$

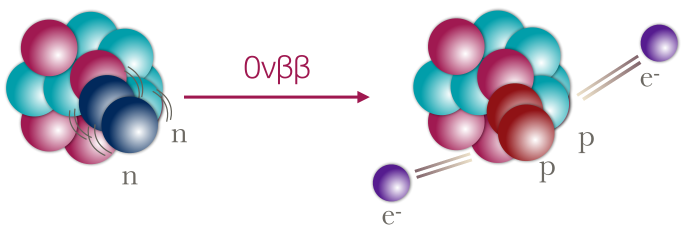
$\Delta(B\text{-}L)=-2$



0ν Double Beta Decay

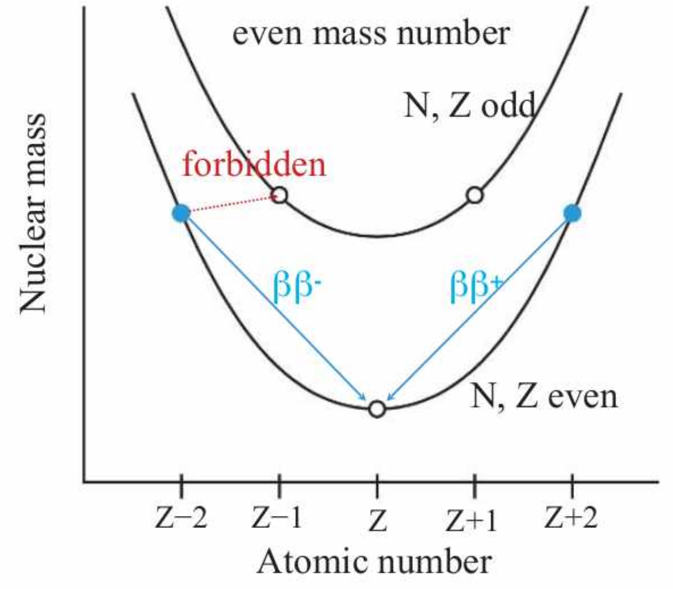
Experimental signature

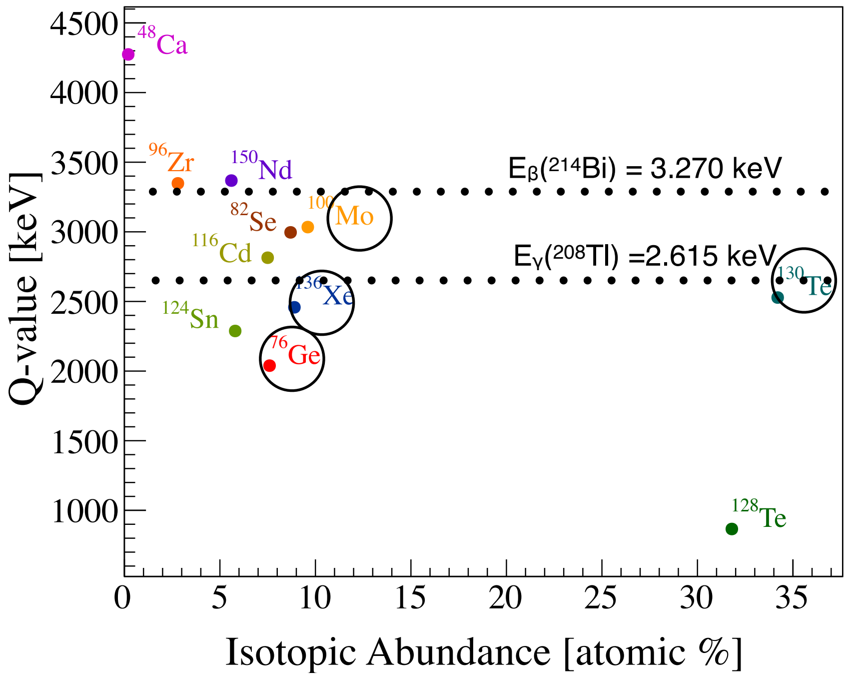
$K_{e-}+K_{e-}$: line at $Q_{\beta\beta}$ (~2-3 MeV)



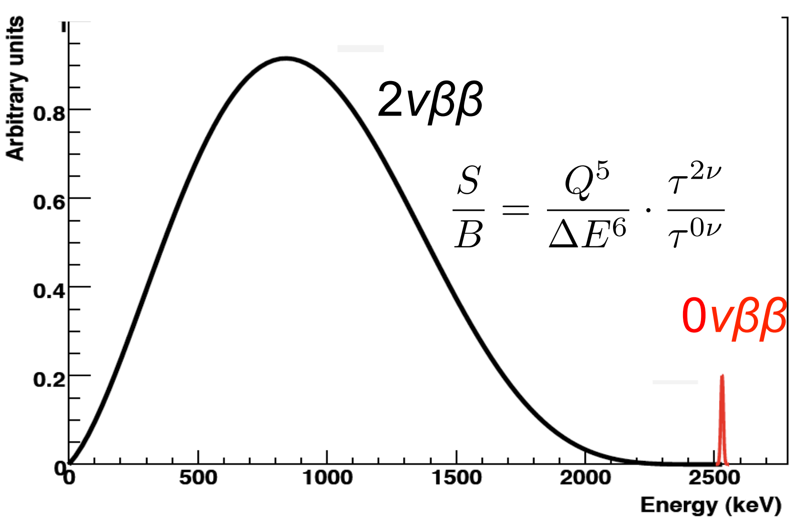
Single Beta decay must be forbidden

^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd





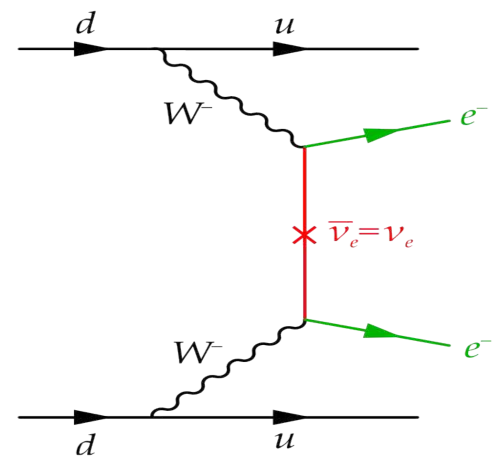
One Irreducible background



$$\frac{S}{B} = \frac{Q^5}{\Delta E^6} \cdot \frac{\tau^{2\nu}}{\tau^{0\nu}}$$

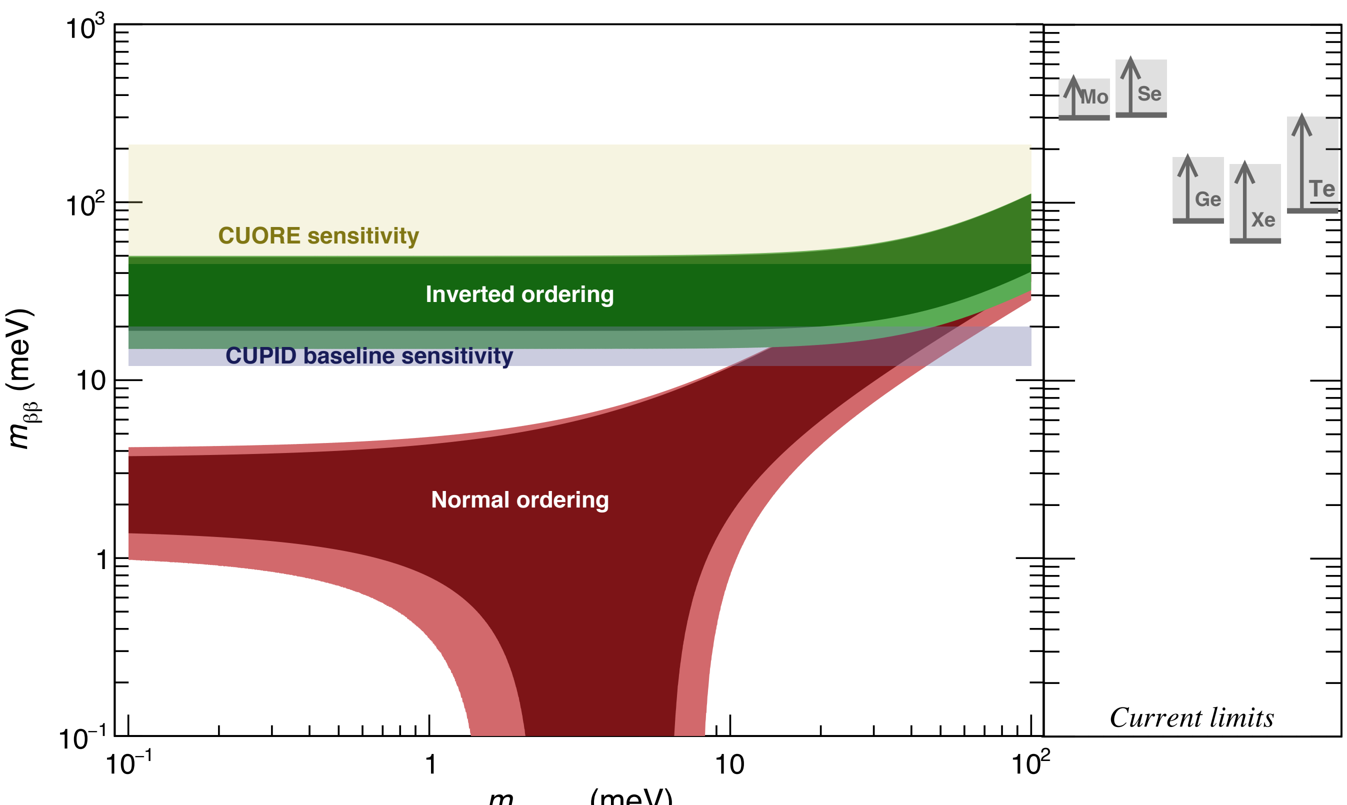
$0\nu\beta\beta \Leftrightarrow \nu$ mass

- The measurable quantity is the half life $T^{0\nu}_{1/2}$:
- Assume exchange of light Majorana ν



$$\Gamma^{0\nu}_{1/2} = (T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z) \cdot g_a^4 \cdot |M^{0\nu}|^2 \cdot m_{\beta\beta}^2$$

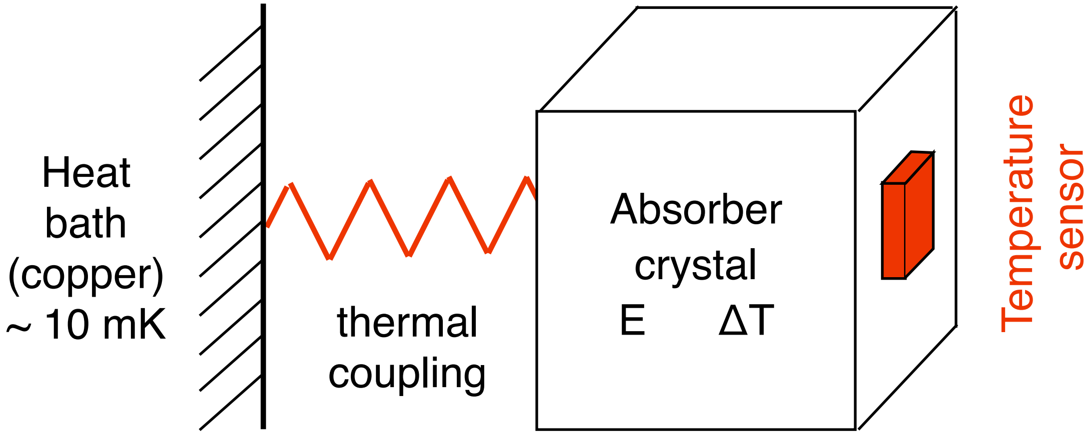
$$m_{\beta\beta} = |\sum m_i \cdot U_{ie}^2| = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

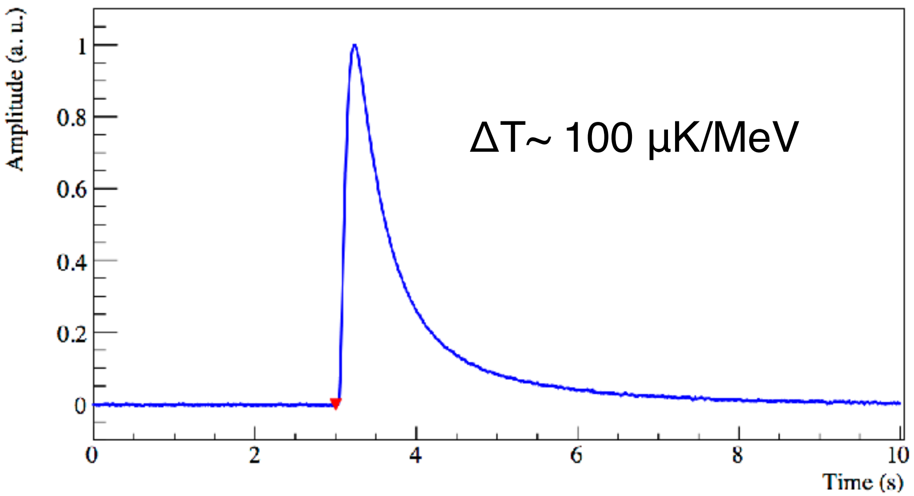


Current limits lie in the range 50-120 meV across the leading isotopes (^{136}Xe, ^{130}Te, ^{76}Ge)

Bolometric detectors

- Solid state detectors operating at low temperatures ~10 mK
- Readout with sensitive low temp. semicon. NTD-Ge thermistor $R(T) \simeq 1\,\Omega \cdot \exp\left(\frac{3\,\mathrm{K}}{T}\right)^{\frac{1}{2}}$
- Isotope of interest embedded in the source
- Flexible choice of Isotopes (Mo,Cd,Se,Te)
- Resolution @0νββ energy: ~0.2% FWHM
- Detector response independent of particle types





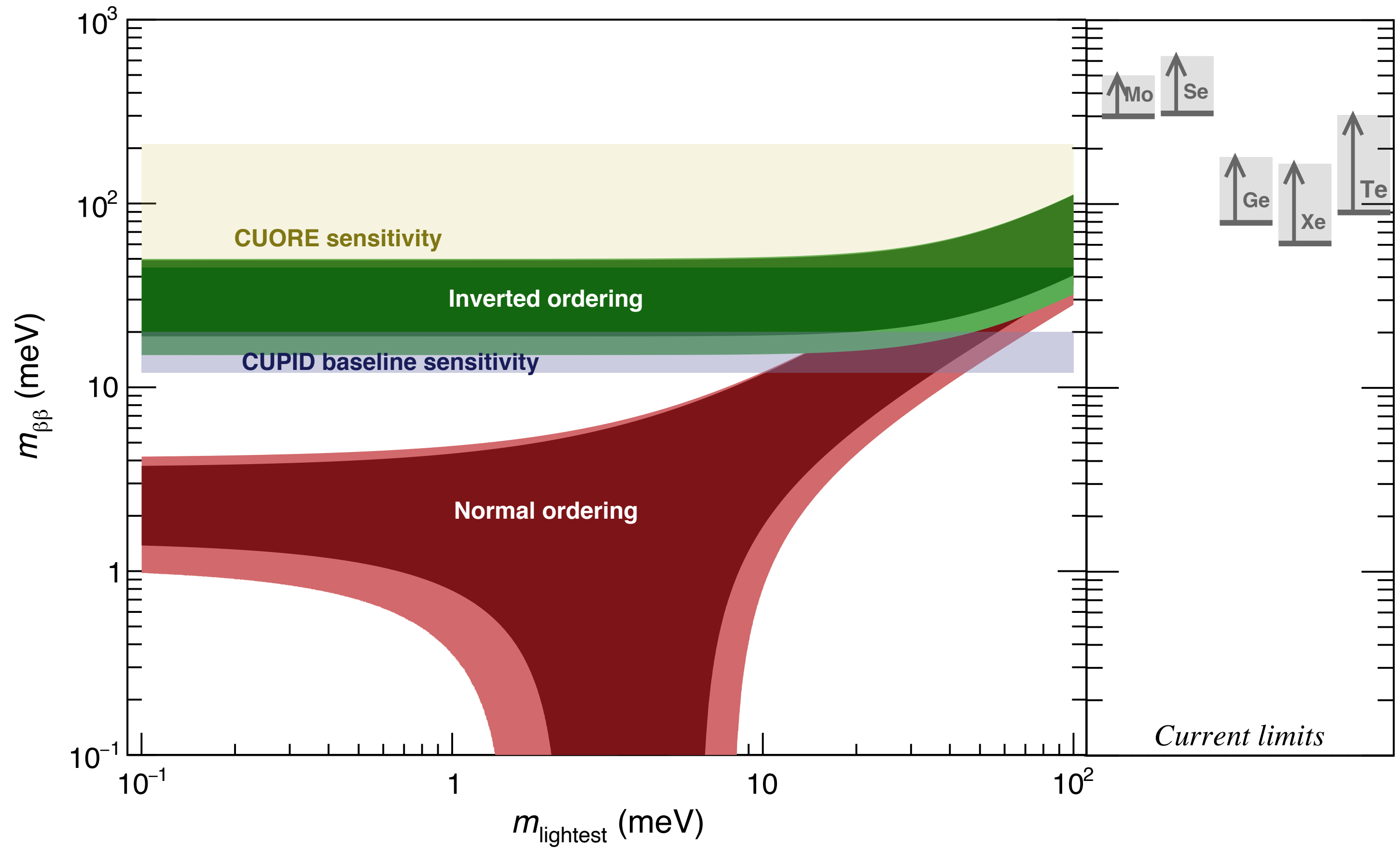
CUORE: a ton scale detector

- **988 $^{nat}TeO_2$ bolometers**
  - **742 kg of TeO2, 206 kg ^{130}Te.**
  - **Larger bolometric detector ever built**
- **Operating in the CUORE cryostat**
  - **Most powerful dilution refrigerator in the world**
- **Stable data taking since 2019**

CUPID builds on years of experience and success with CUORE at LNGS

CUPID

CUPID: CUORE Upgrade with Particle Identification



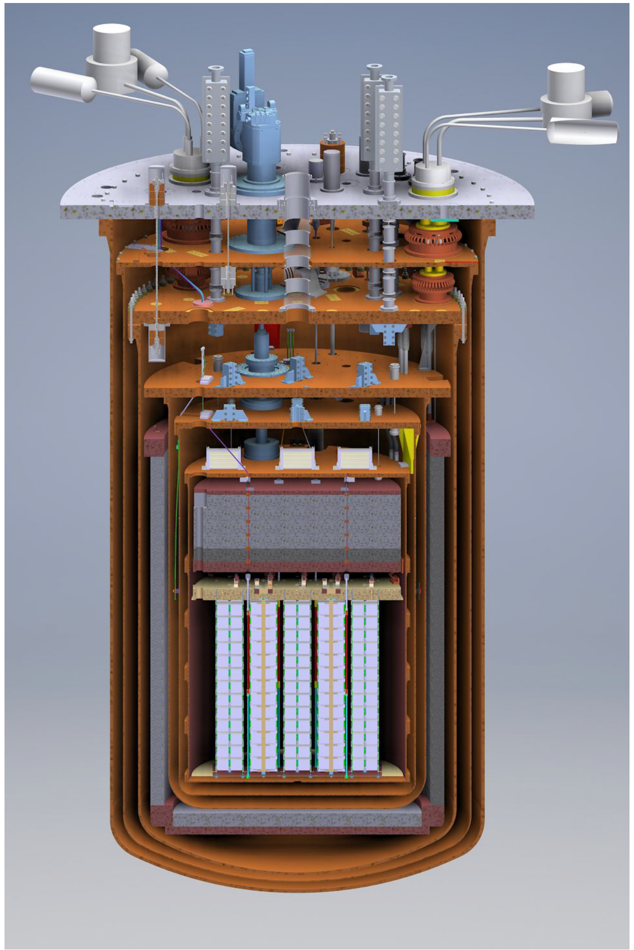
Goal: fully probe the Inverted Hierarchy region

- discovery sensitivity in the 12-20 meV range
- improve the sensitivity to $m_{0\nu\beta\beta}$ by a factor of ~10

CUPID Strategy

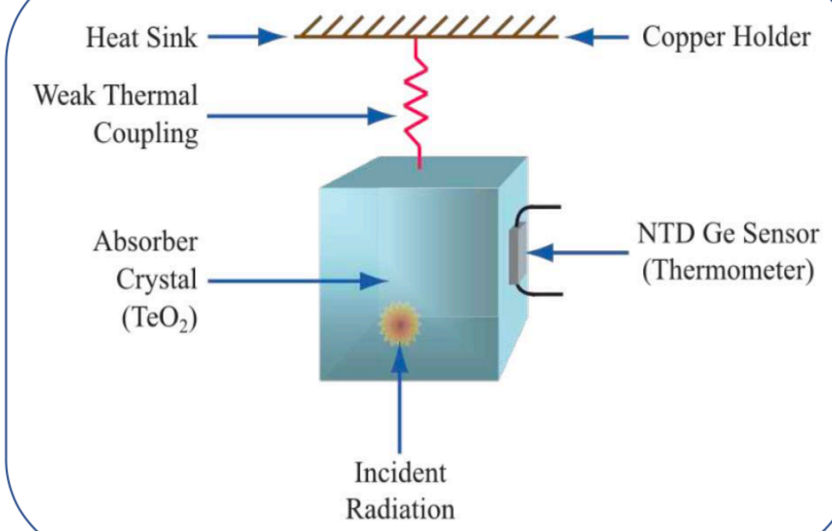
- Re-use CUORE Infrastructure and replace the CUORE TeO_2 detector with a new array, based on 95% enriched $Li_2{}^{100}MoO_4$

- Enough to take a leap forward in sensitivity because we reduce dramatically ~(150) the background in the $0\nu\beta\beta$
  - the new ββ candidate **^{100}Mo** has a higher transition energy than the ^{130}Te CUORE candidate: **less γ-induced background in ROI, more favourable phase space and matrix elements**
  - the new detector has a very efficient **α particle rejection** capability: **remove the dominant background source seen in CUORE**

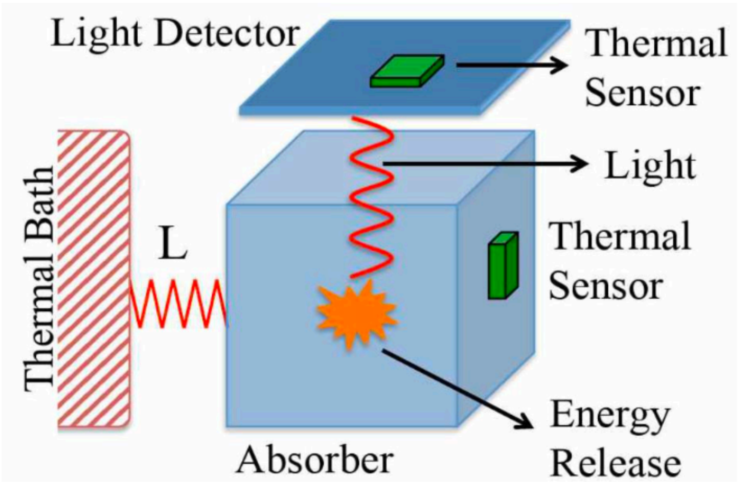


CUPID Concept

CUORE ^{130}Te
pure thermal detector
(**bolometer**)



CUPID ^{100}Mo
heat + light
(**scintillating bolometer**)



No PID
Q = 2527 keV **< 2615 keV**

α background
γ background

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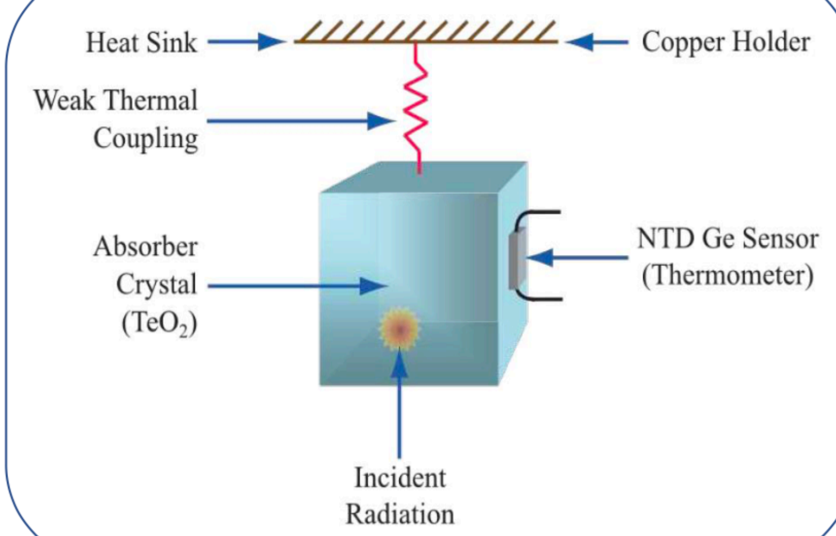
pure thermal detector
(**bolometer**)



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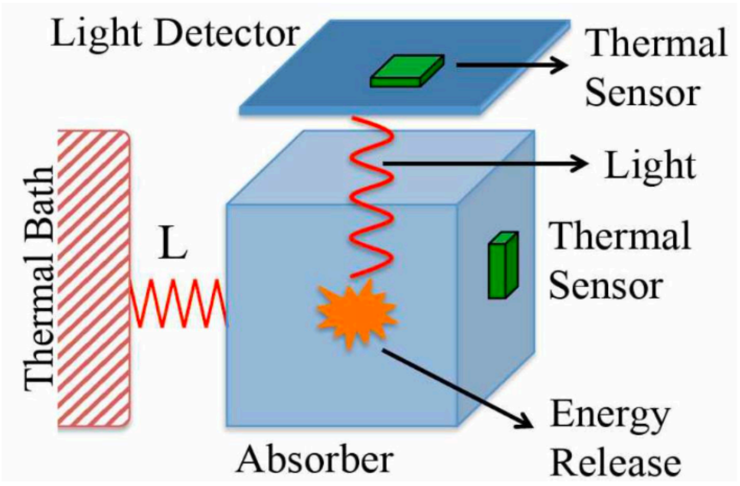


No PID
Q = 2527 keV **< 2615 keV**

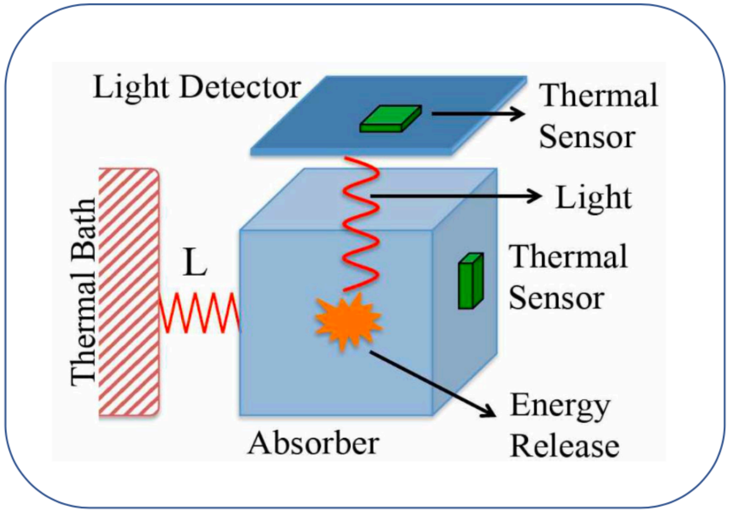
~~α background~~
γ background

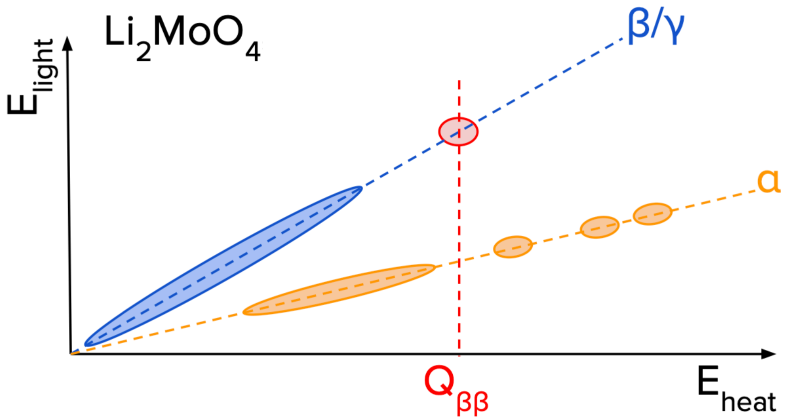
PID with light detection

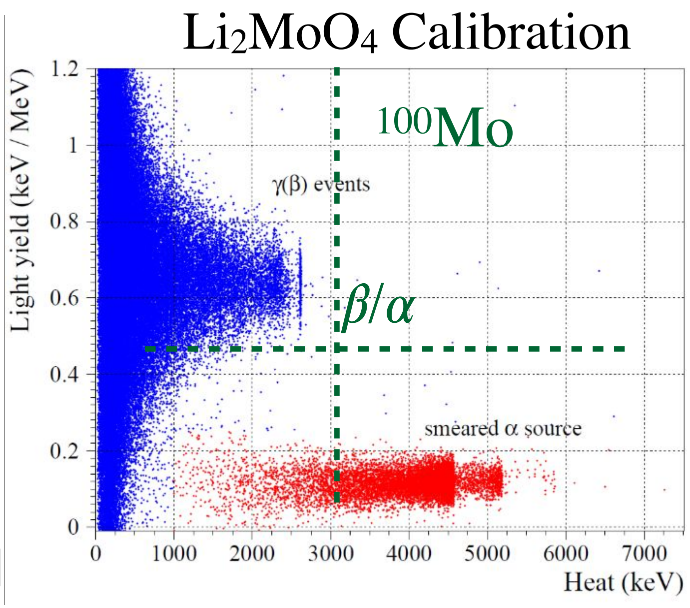
CUPID Concept

- Technology demonstrated on CUPID-0 and CUPIDMo prototypes

CUPID ^{100}Mo
heat + light
(scintillating bolometer)







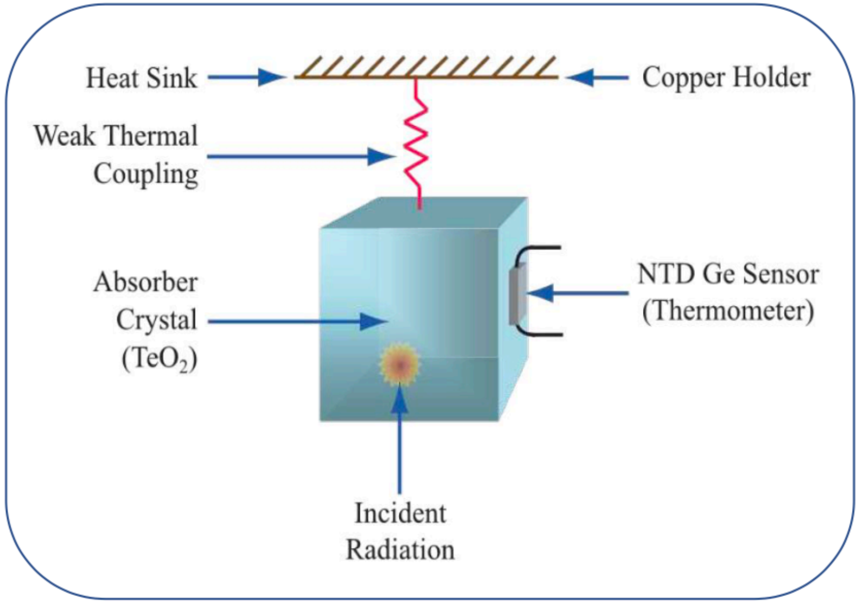
Measure heat and light from energy deposition

Heat is particle independent, but light yield depends on particle type

Actively discriminate α using measured light yield

CUPID Concept

CUORE ^{130}Te
pure thermal detector
(**bolometer**)



CUPID ^{100}Mo
heat + light
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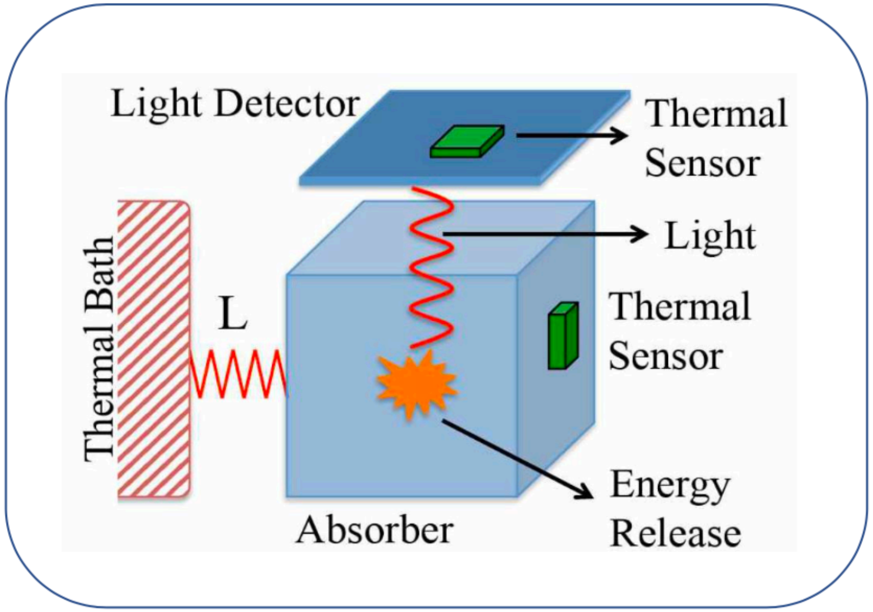


No PID
Q = 2527 keV **< 2615 keV**

~~α background~~
~~γ background~~

PID
Q = 3034 keV **> 2615 keV**

CUPID Infrastructure

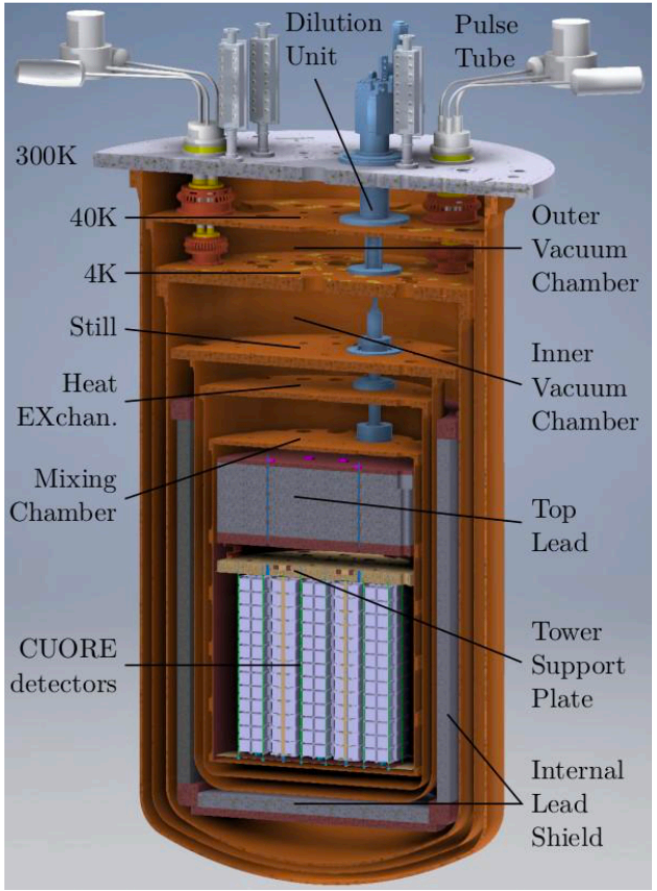
CUPID will utilize existing infrastructure (CUORE cryostat, experimental site)

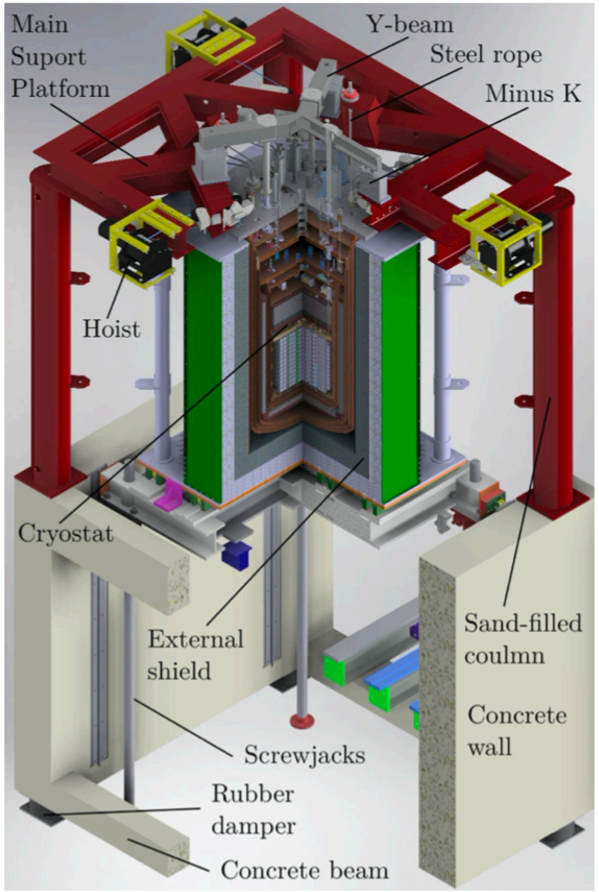
CUORE cryostat

- Multistage cryogen-free cryostat
- Cooling systems: fast cooling system, Pulse Tubes (PTs), and
- Dilution Unit (DU)
  $\sim$15 tons @ < 4 K
  $\sim$ 3 tons @ < 50 mK
- anti-vibration system
- Active noise cancelling

CUORE (passive) shielding

- Ancient Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene



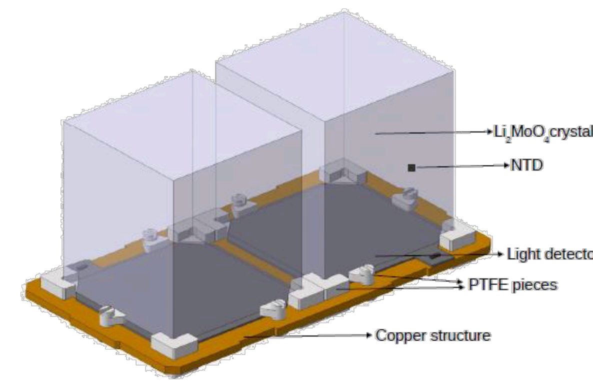


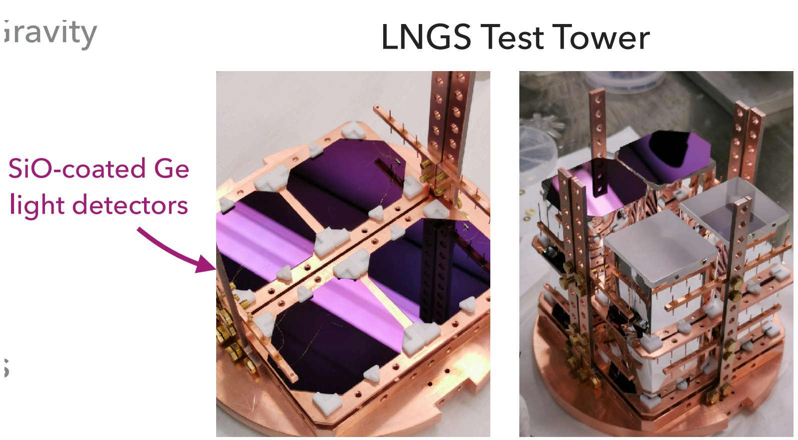
- CUORE hut and faraday cage
- AntiRadon and clean room
- Storage area

CUPID Detector

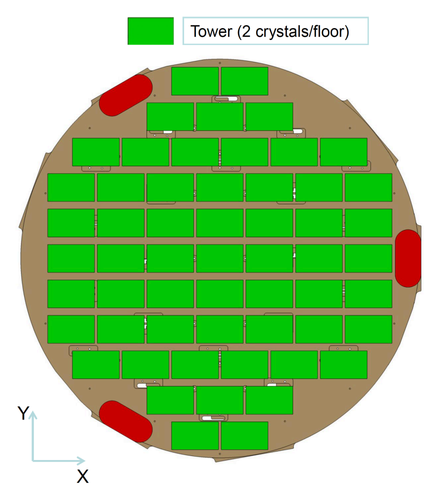
- Single module: $Li_2{}^{100}MoO_4$, 45x45x45 mm, 280 g
- Detector: 57 towers of 14 floors with 2 crystals each, 1596 crystals
- ~240 kg of ^{100}Mo with >95% enrichment
  ~$1.6 \cdot 10^{27}$ ^{100}Mo atoms
- Ge light detector with SiO antireflective coating as in CUPID-Mo, CUPID-0
  - Each crystal has top and bottom LD
- NTD readout for both LD and $Li_2{}^{100}MoO_4$

Detector Module

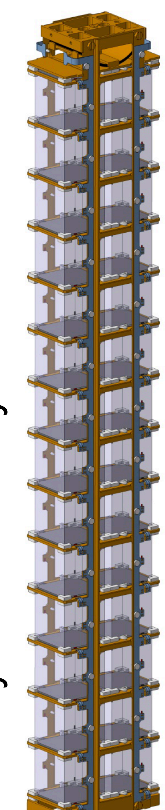




Tower Arrangement



Gravity stacked structure
Crystals thermally interconnected



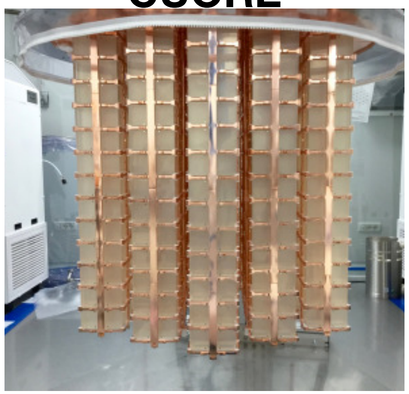
Tower

CUPID Background model

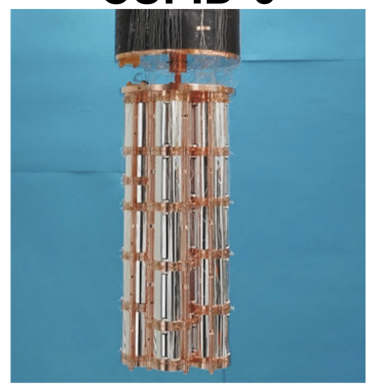
Our background model reconstruction approach is well validated in multiple experiments.

All the materials for CUPID have been directly measured in bolometric setups.

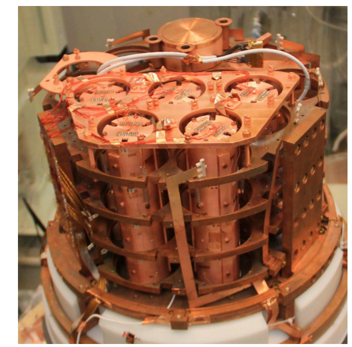
CUORE

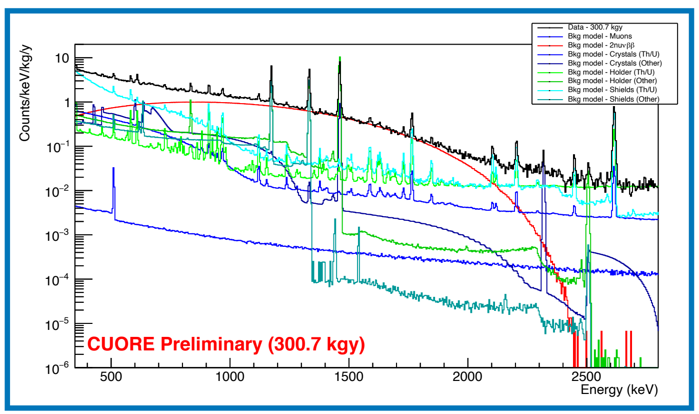


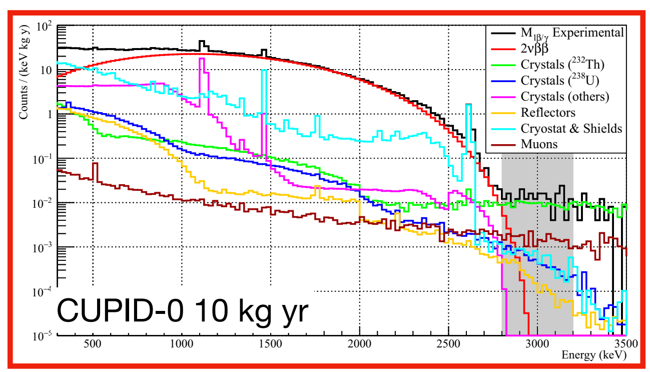
CUPID-0

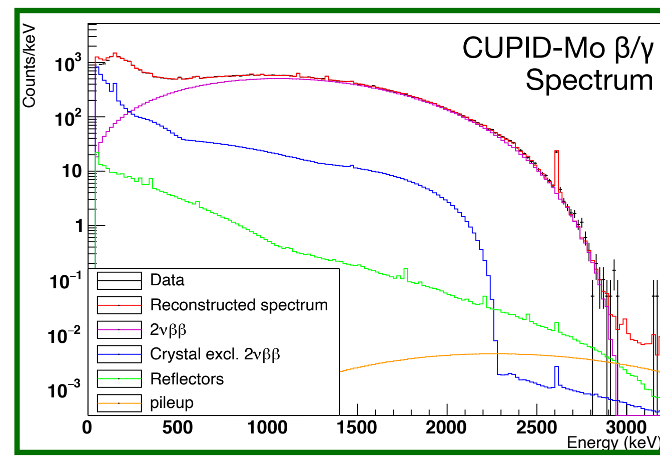


CUPID-Mo









Characterize β/γ background from cryogenic system and detector holders in the ^{100}Mo ROI ($Q_{\beta\beta}$= 3034 keV)

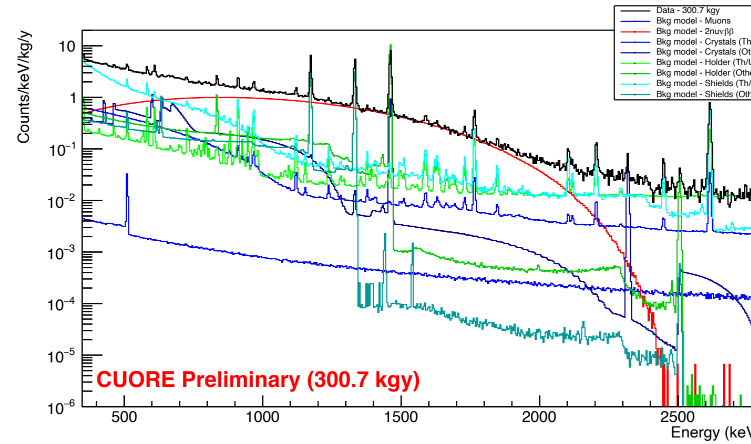
Alpha-rejection Confirms the β/γ background from detector holders in 3 MeV ROI

Data confirms:

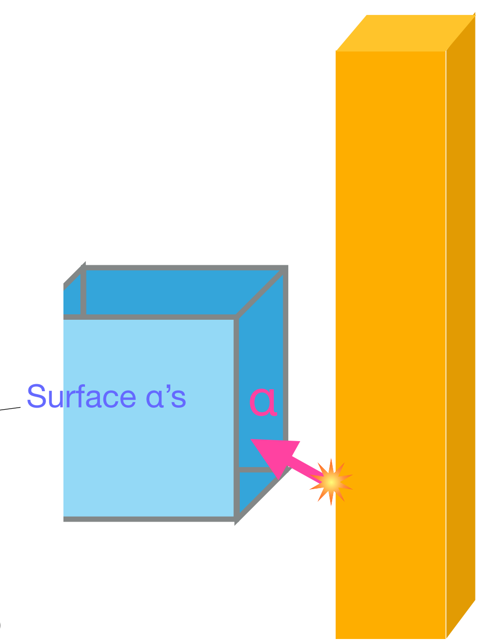
- α tagging performance
- Radiopurity of crystals
- Energy resolution

Primary background in CUORE

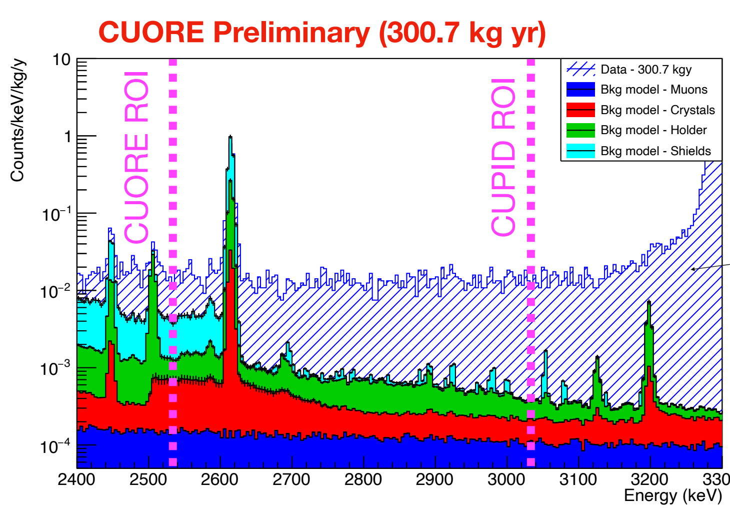
- Same cryogenic infrastructure as CUPID (direct measurement)
- Fit to the observed spectra to extract origin and level of contaminants (based on 300 kg · yr exposure)



- Degraded α background
  - Decays with Q-value in 4-8 MeV range that lose part of the energy in nearby passive materials
  - Background in CUORE ROI: 1.5 10^{-2} ckky



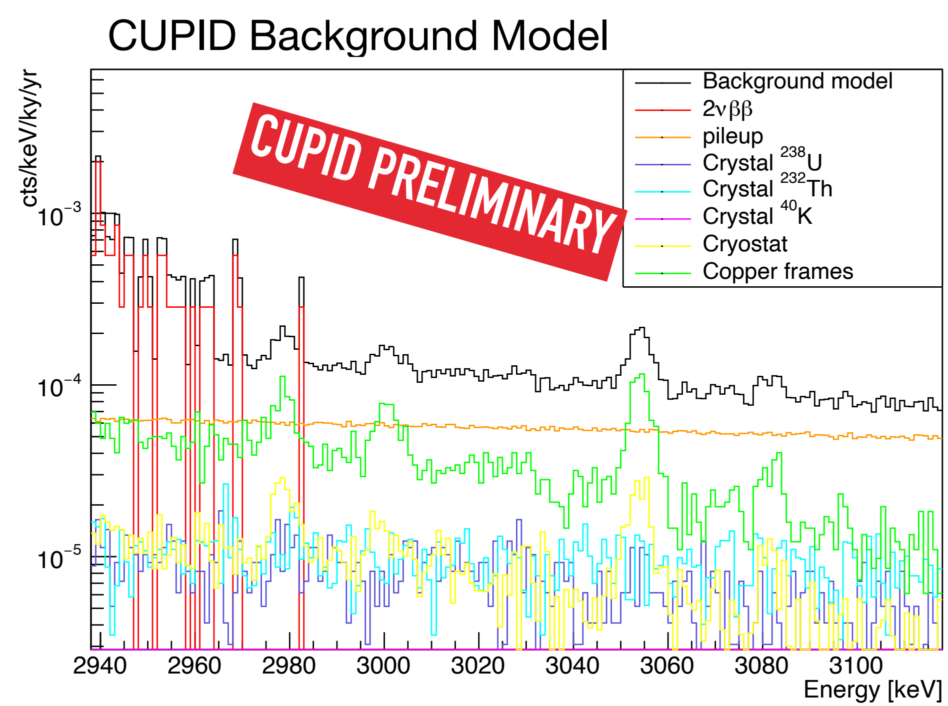
- Gamma background
  - CUORE $Q_{\beta\beta}$(2528 keV): 10^{-3} ckky
  - CUPID moves $Q_{\beta\beta}$ at 3034 keV <10^{-4} ckky



Background in CUPID

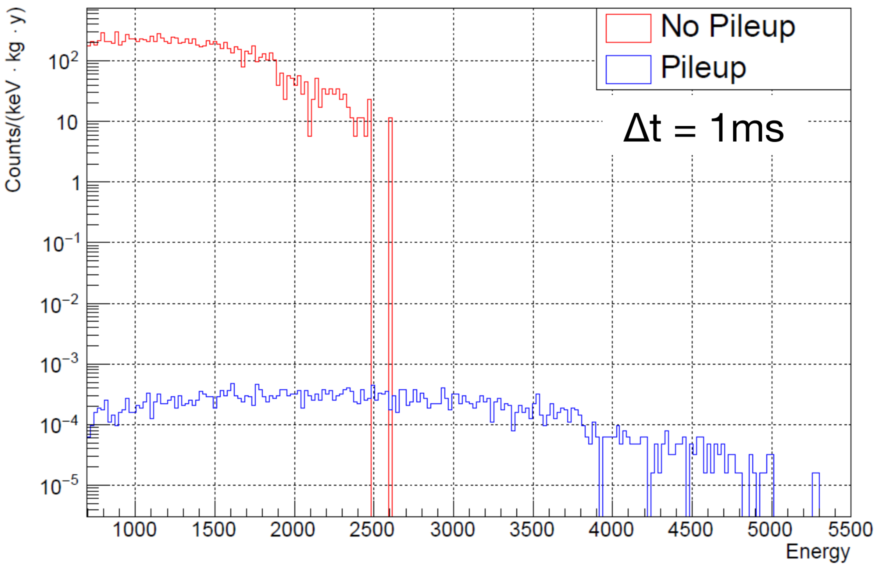
- Background goal: 10^{-4} ckky
- CUPID will reduce backgrounds primarily by
  - Eliminating surface α's with PID
  - Reducing β/γ continuum backgrounds by moving the ROI from 2.5 MeV to 3 MeV (~10x), lower cross section and delayed coincidence (bkgd from ^{214}Bi/^{208}Tl β continuum from contaminations in crystal bulk and on nearby surfaces)
  - Eliminating muons with a muon tagger

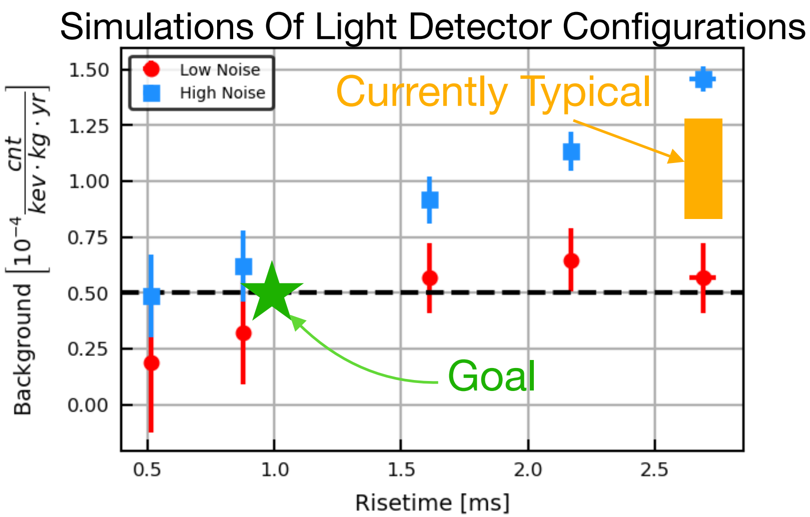
	CUORE BI (at 2527 keV) ckky	CUORE BI (at 3034 keV) ckky	Mitigation	CUPID BI Goal (at 3034 keV) ckky
Surface α's	1.4×10^{-2}	1.4×10^{-2}	Particle Identificatio n	Negligible
Compto n γ's	10^{-3}	10^{-4}	Moving the ROI Delayed Coincidence	5×10^{-5}
Muons	10^{-4}	10^{-4}	Muon Veto Panels	$<10^{-6}$
Pileup	Negligible	Negligible	LD Timing Resolution	5×10^{-5}



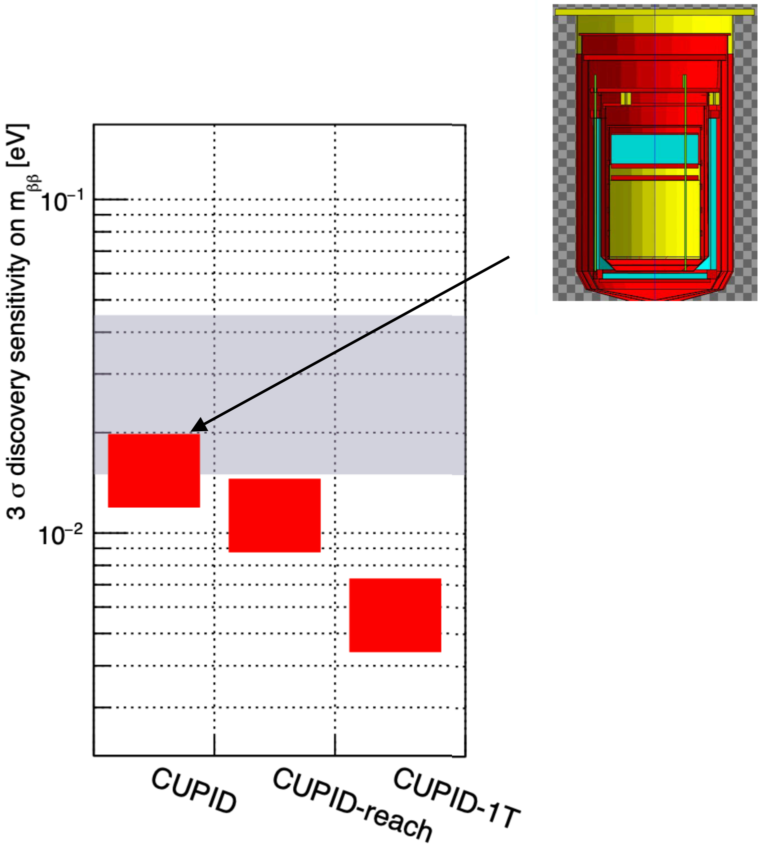
Pile up

- The relatively fast decay rate of ^{100}Mo ($T_{1/2\,2\nu}$ = 7.1x10^{18} yr) leads to the possibility of two 2vββ decays events piling up and reconstructing in the ROI
- Need ~170 µs effective timing resolution
  - Li_2MoO_4 are intrinsically slow Δt demonstrated down to ~1ms
  - Light detectors have much faster intrinsic time constants-> higher sampling rate, wider bandwidth electronics, lower noise, smaller NTD, ML techniques
  - Developed simulations that allow us to test various rise time, noise, and system bandwidth configurations
  - a factor of 2-3 improvement over current (typical) performance required





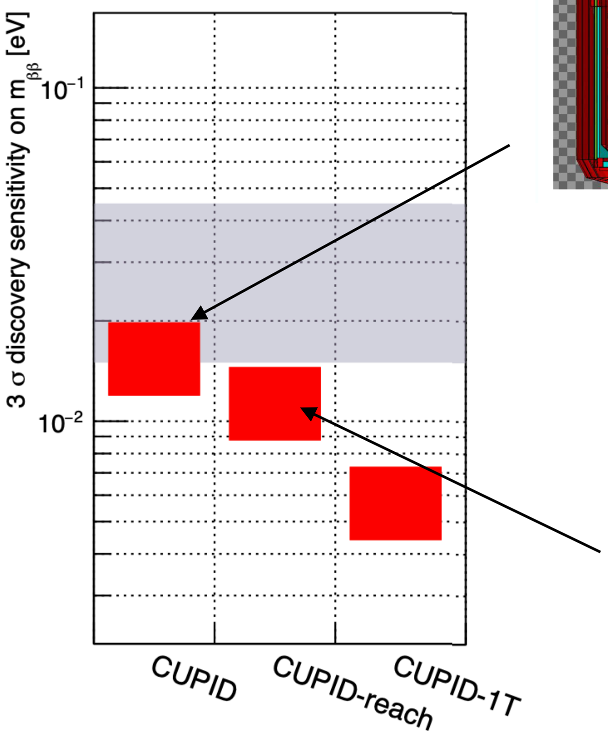
CUPID scenarios

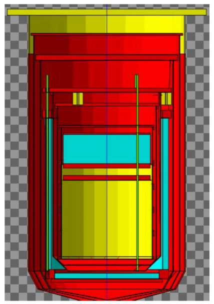


CUPID Baseline

- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/(keV kg yr)
- Discovery sensitivity **$T_{1/2}$ > 1.1×10^{27} yr (3σ)**
- Discovery sensitivity **$M_{\beta\beta}$ > [12-20] meV (3σ)**
- Conservative, limited technology verification remaining

CUPID scenarios





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CUPID-reach can be realized within existing cryogenic setup

- Same payload as CUPID baseline
- Background: 2 **10^{-5}** cts/(keV kg yr)
- Discovery sensitivity **$T_{1/2}$ > 2×10^{27} yr (3σ)**
- Discovery sensitivity **$M_{\beta\beta}$ > [9-15] meV (3σ)**

Pileup background below ~1×10^{-5} cnts/(keV kg yr).

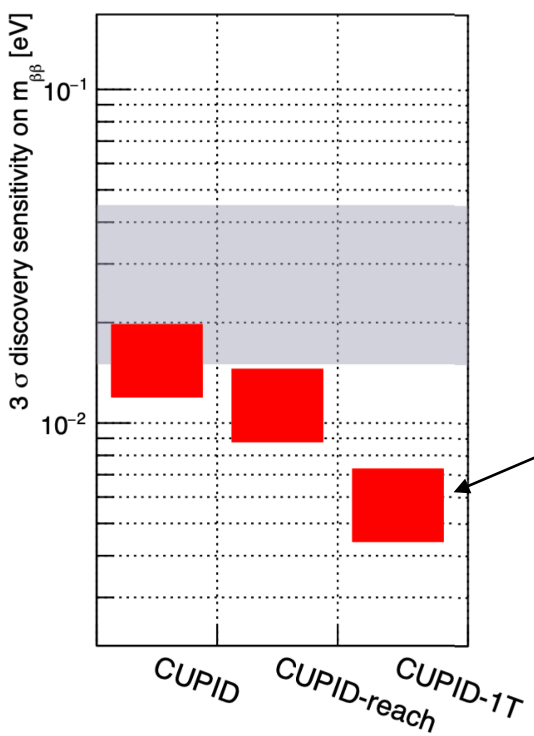
- achieved e.g. with the use of TES-based light detectors.

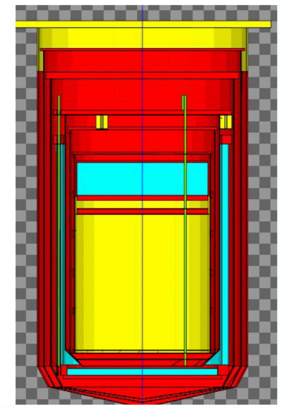
Surface backgrounds from the holders reduced by a factor of ~3.

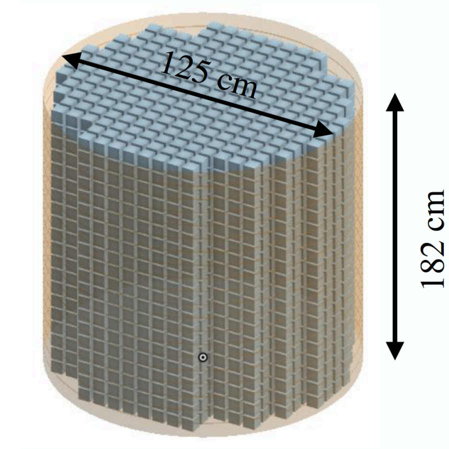
- Baseline background budget from crystals and holders amounts to 3.6×10^{-5} cnts/(keV kg yr).
- Could be reduced e.g. through the use of the laser machining

CUPID 1 Ton

An Inverted Hierarchy Precision measurement device across multiple isotopes or a Normal Hierarchy Explorer







- Mass: 1000 kg of ^{100}Mo
- Energy resolution: **5 keV** FWHM
- Background: **5x10^{-6}** cts/(keV kg yr)
- Discovery sensitivity **$T_{1/2}$ > 8×10^{27} yr (3σ)**
- Discovery sensitivity **$M_{\beta\beta}$ > [4-7] meV (3σ)**

– Multi-cryostat setup or large-scale dilution refrigerator(cooling power comparable to CUORE) , technologically achievable (increasingly common in Quantum Computing)
– Background goal of 5×10^{-6} cts/(keV kg yr) requires more effort
– Likely require full implementation of next-generation (TES or mKID) low-noise, high-bandwidth quantum sensors
– Need to consider/verify subdominant backgrounds

Conclusions

- CUPID **builds on an existing and well-functioning international collaboration**
- Collaboration has **operational experience at LNGS for ton-scale, bolometric experiment** and utilizes **existing infrastructure**
- **Cost effective, timely,** and **leverages international investments.**
- **Limited technology verification remaining** for CUPID baseline.
- **Data-driven background mode**l reaches baseline goal of b~10^{-4} ckky.
- Particle identification demonstrated in medium scale prototypes
- Enrichment and crystal growth demonstrated at required scale

CUPID prepared to fully explore the inverted ordering region using only 240 kg of ^{100}Mo

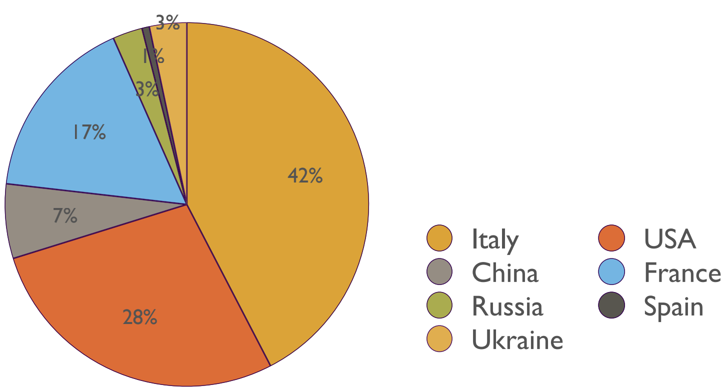
Plans for CUPID-1T experiment are feasible and within technical reach of bolometer technology. CUPID baseline/reach will help understand backgrounds for CUPID-1T.

CUPID Collaboration

- A strong international collaboration: ~140 collaborators across 7 countries

Countries	Authors
Italy	64
USA	42
France	25
China	10
Ukraine	5
Russia	4
Spain	1

https://cupid.lngs.infn.it/



LNGS Laboratory

120 km from Rome

~ 3600 m.w.e. deep

μ flux: ~ 3×10^{-8}/(s cm^2)

γ flux: ~ 0.73/(s cm^2)

neutrons: 4×10^{-6} n/(s cm^2) below 10 MeV