CUPID: a next-generation cryogenic $0\nu\beta\beta$ decay experiment

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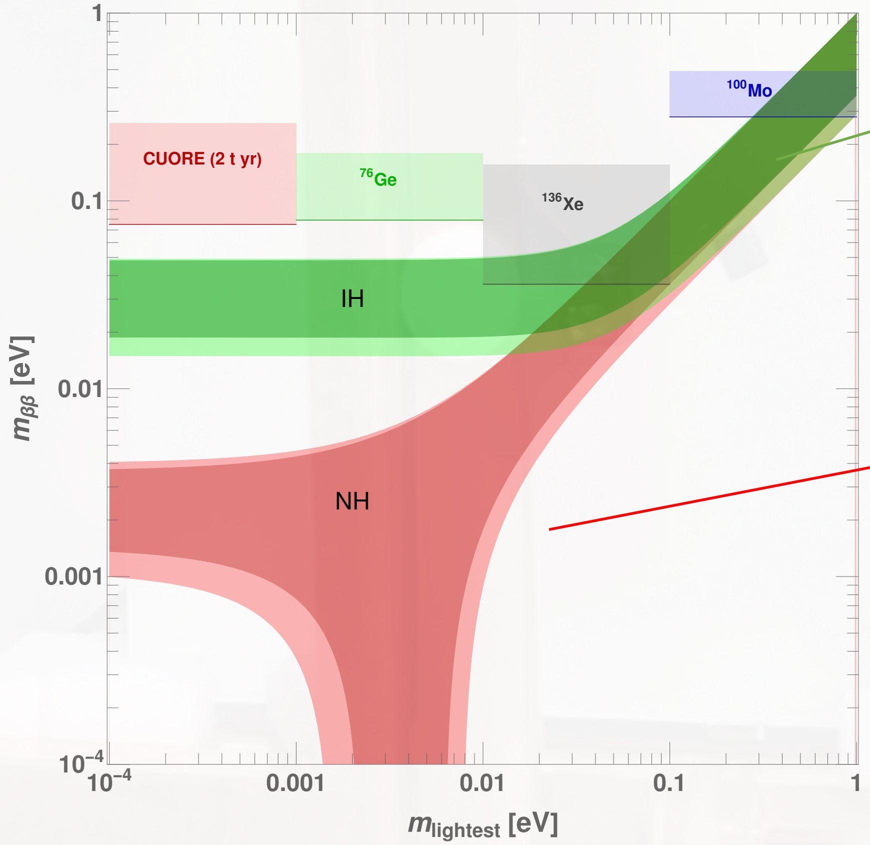
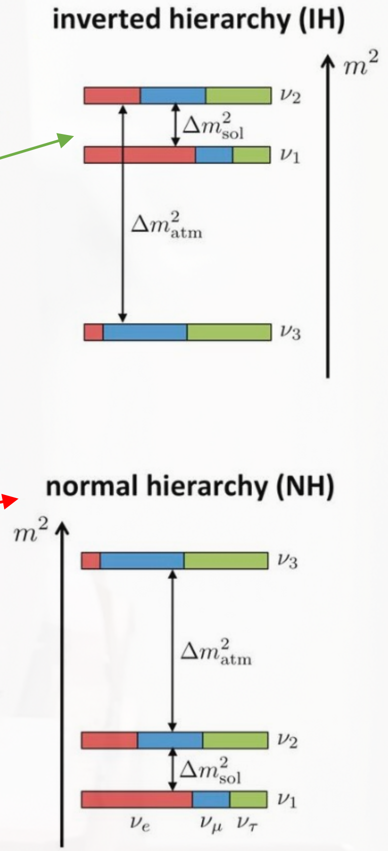
NNN23

Neutrinoless double-beta decay

- $0\nu\beta\beta$
  - $(A,Z) \rightarrow (A,Z\pm 2) + 2e^{\mp}$
  - not allowed in SM
  - not observed (yet): $T_{1/2}^{0\nu} > 10^{24} - 10^{26}$ yr
  - probe for New Physics:
    - would imply $\Delta L = 2 \rightarrow L$ is not a symmetry of nature
    - Majorana nature of ν ($\nu = \bar{\nu}$)
    - constraints ν mass scale and hierarchy
    - effective Majorana mass ($m_{\beta\beta}$)

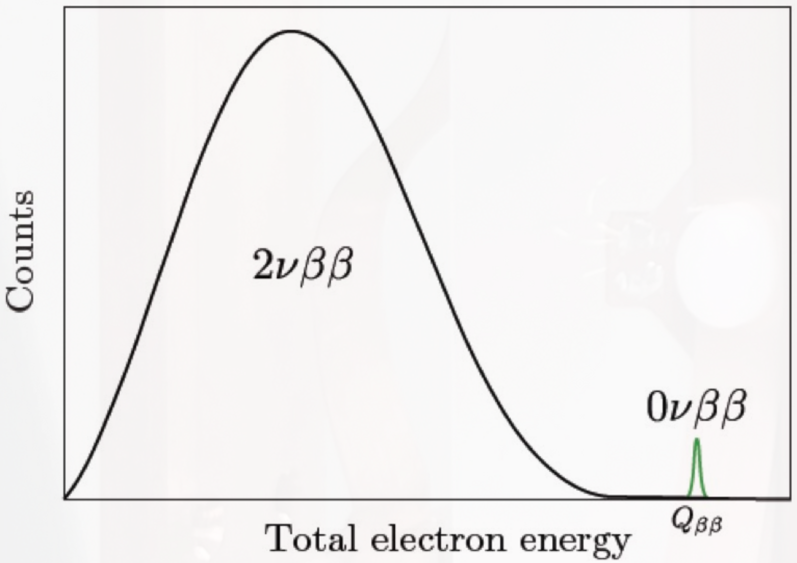
$$m_{\beta\beta} = \left|\sum_{k=1,2,3} U_{ek}^2 m_k\right|$$





Experimental search for $0\nu\beta\beta$

signature of the process



- large-mass detectors
- good energy resolution
- very-low backgrounds in the ROI

In presence of background events in the ROI:

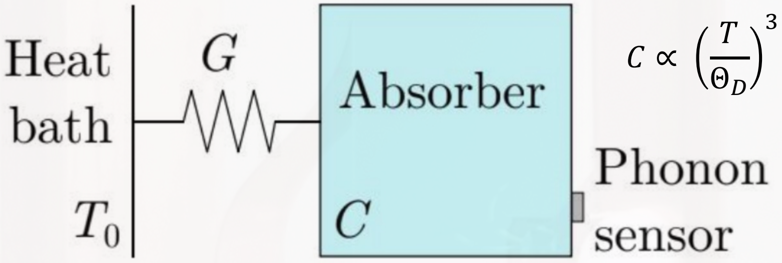
$$S^{0\nu} \propto \epsilon \cdot \eta \cdot \sqrt{\frac{MT}{B\Delta}}$$

- $S^{0\nu}$: experimental sensitivity
- ϵ: detection efficiency
- η: isotopic abundance
- MT: exposure (total mass M × observation time T)
- Δ: energy resolution in the ROI
- B: *background index* in the ROI

In case of no background events (i.e. $MTB\Delta \sim \mathcal{O}(1)$) (zero background condition):

$$S^{0\nu} \propto \epsilon \cdot \eta \cdot MT$$

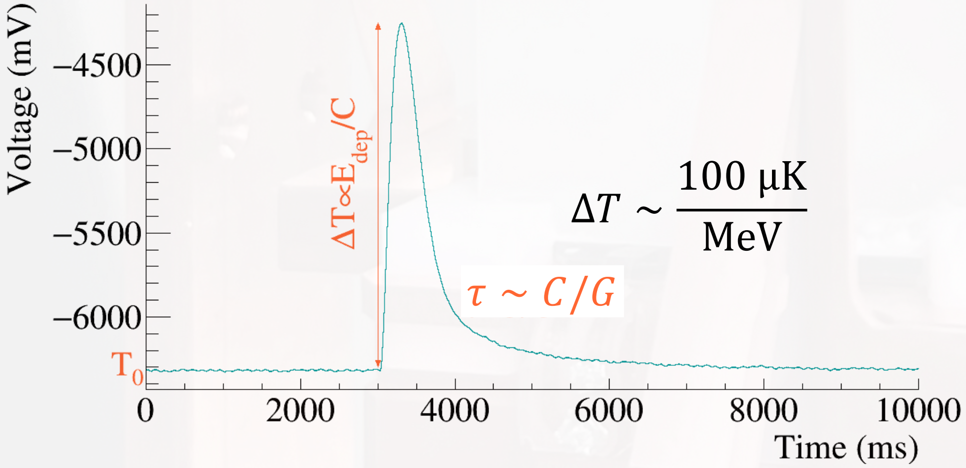
A powerful technique: cryogenic calorimeters



Working principle:

Sensitive to phonon contribution (~ 100% of energy release) $T_0 \sim 10$ mK

Energy deposition read via T variation $\Delta T(t) \sim \frac{E}{C} e^{-t/\tau}$ with $\tau = \frac{C}{G}$



https://rdcu.be/dn1qt

Features:

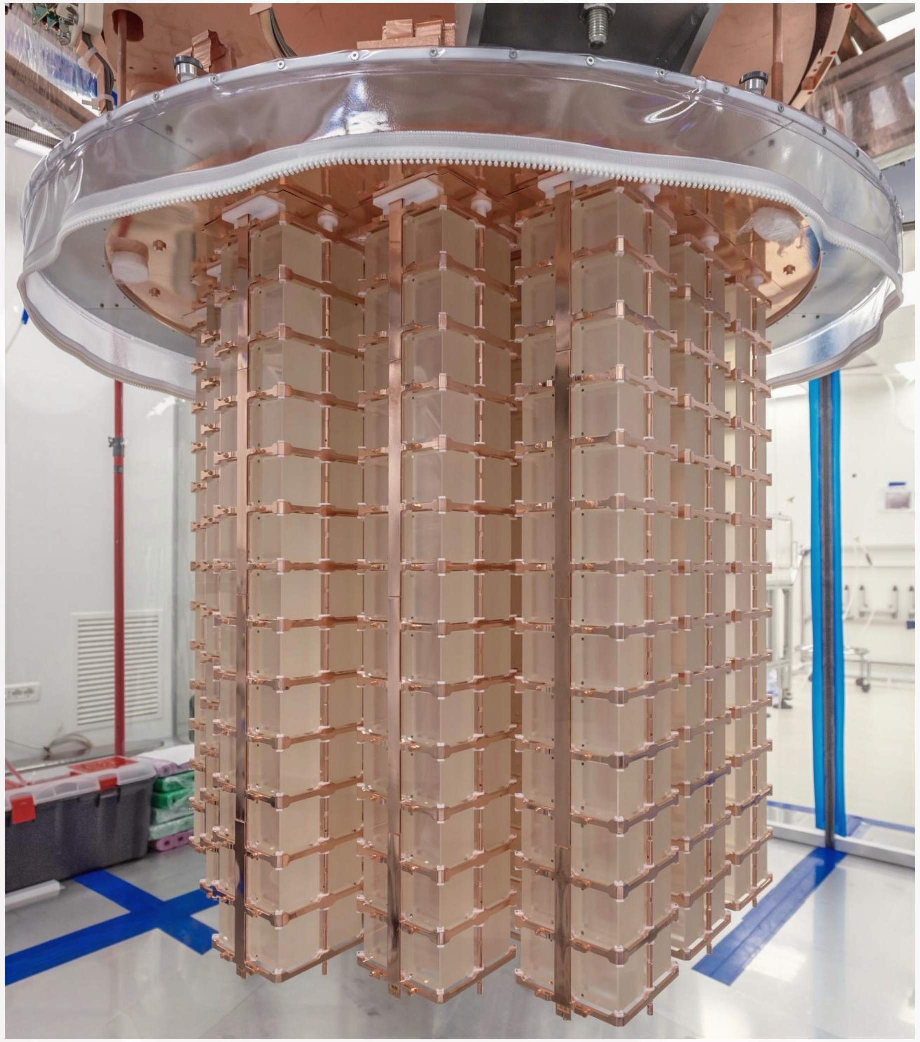
- ✓ Great energy resolution (few keV @ 1 MeV)
- ✓ Scalability: array of detectors
- ✓ Large variety of absorbers
- ✓ Detector = Source approach
- ✓ Slow detectors: ok for rare-events experiments

$$S^{0\nu} \propto \epsilon \cdot \eta \cdot \sqrt{\frac{MT}{B\Delta}}$$

The CUORE experiment

CUORE (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents)

- primary goal: $0\nu\beta\beta$ search in ^{130}Te ($Q_{\beta\beta} = 2527.5$ keV)
- 988 crystals (5×5×5 cm^3) of $^{nat}TeO_2$
- 206 kg of ^{130}Te
- base temperature ~ 15 mK
- operated underground at LNGS (since 2017)



CUORE latest results (preliminary):

- Analyzed exposure 2023 kg·yr
- No evidence of $0\nu\beta\beta$ decay
- Best limit on $T^{0\nu}_{1/2}$ in ^{130}Te:

$$T^{0\nu}_{1/2} > 3.3{\times}10^{25}\ \text{yr}\ \ (90\%\ C.I.)$$

- Upper limit on effective Majorana mass

$$m_{\beta\beta} < 75 - 255\ \text{meV}\ (90\%\ C.I.)$$

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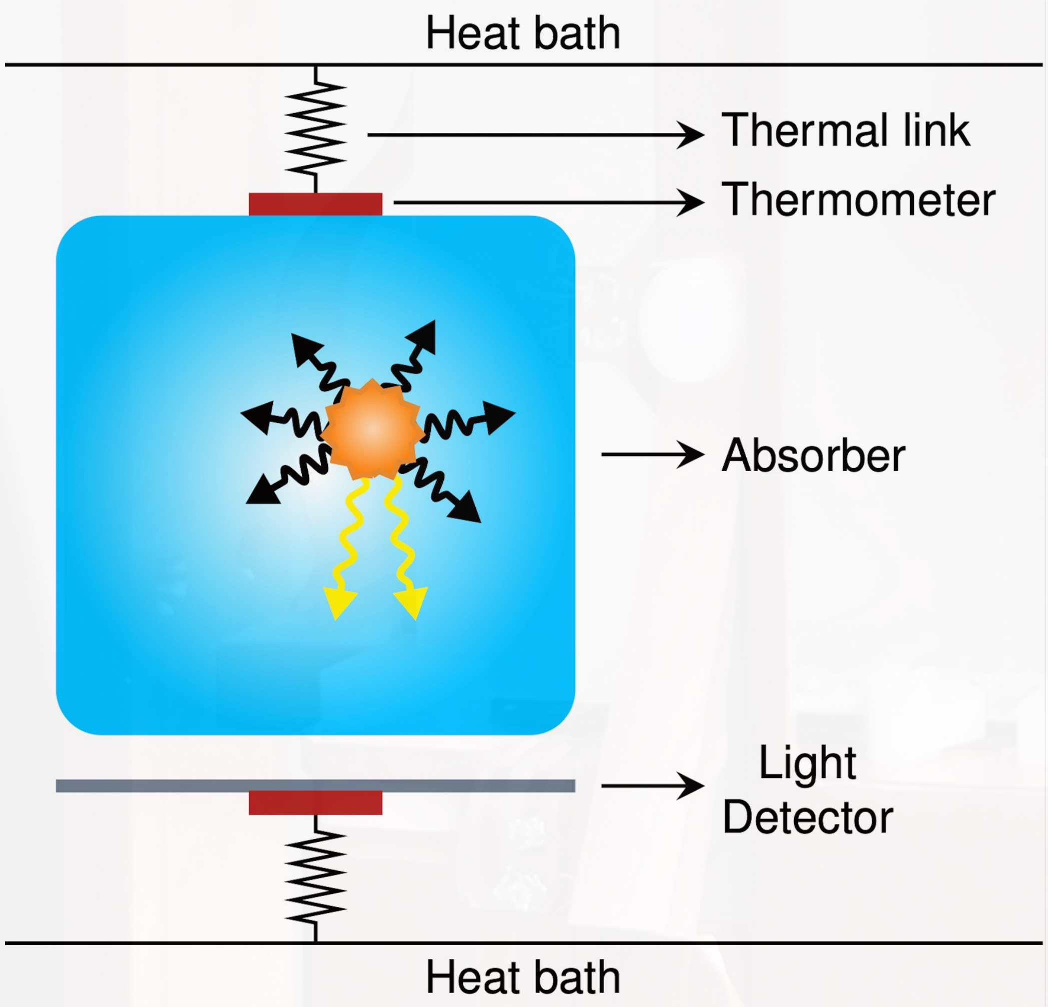
Towards a next-generation experiment

Main limitation to the CUORE sensitivity is background:

- ***Degraded*** **α particles** (which lose energy before interacting with the crystal)
  - **dominant** component (90% contribution to the *background index*)
  - from radioactive decays on the surface of nearby materials
  - from decays in the surface of crystals

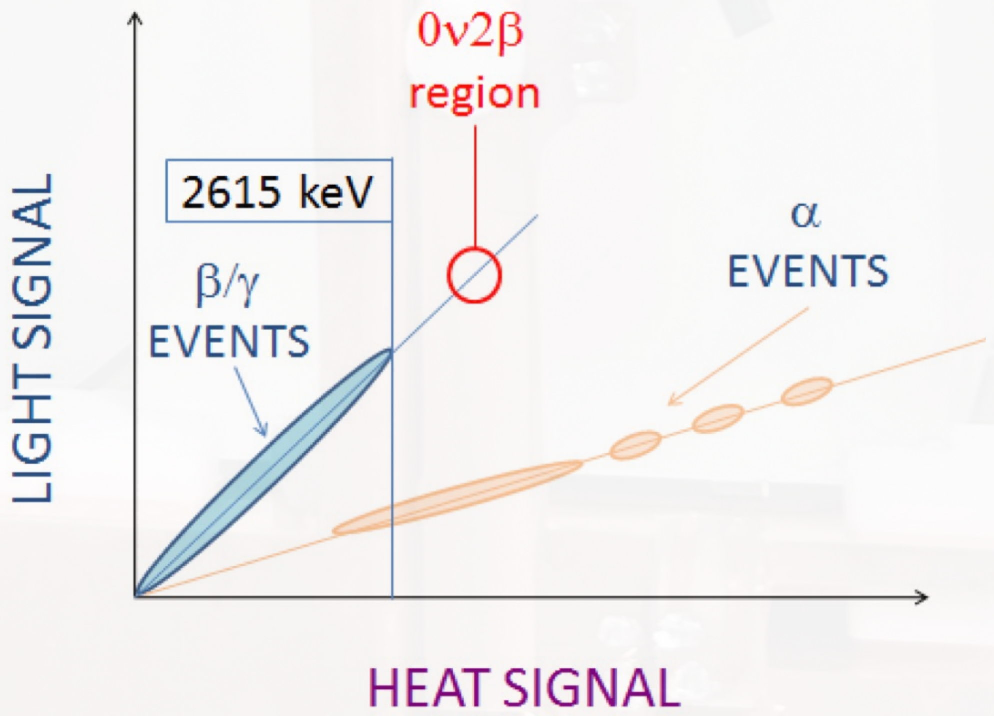
- **γ backgrounds**
  - From radioactive chains $^{232}Th/^{238}U$ contaminants in the crystals and surrounding materials

The **CUPID** experiment (**CU**ORE **U**pgrade with **P**article **ID**entification)



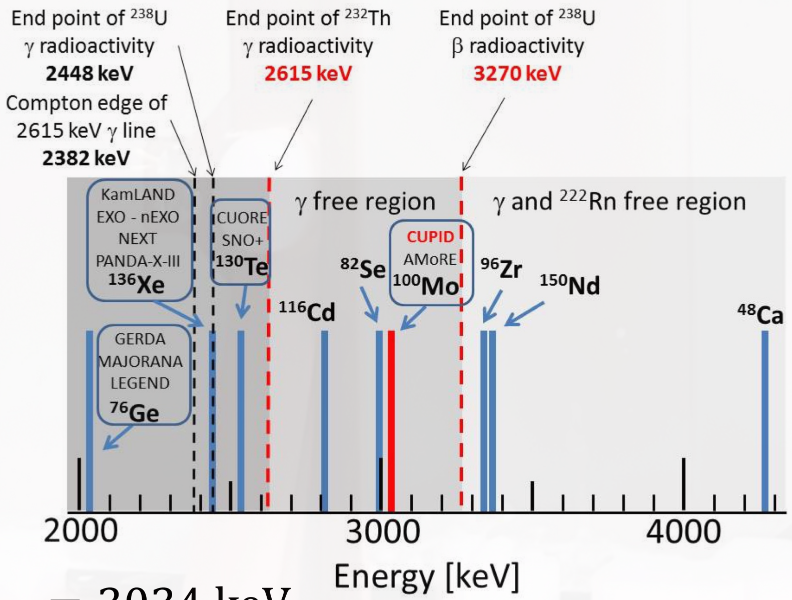
Scintillating cryogenic calorimeters:

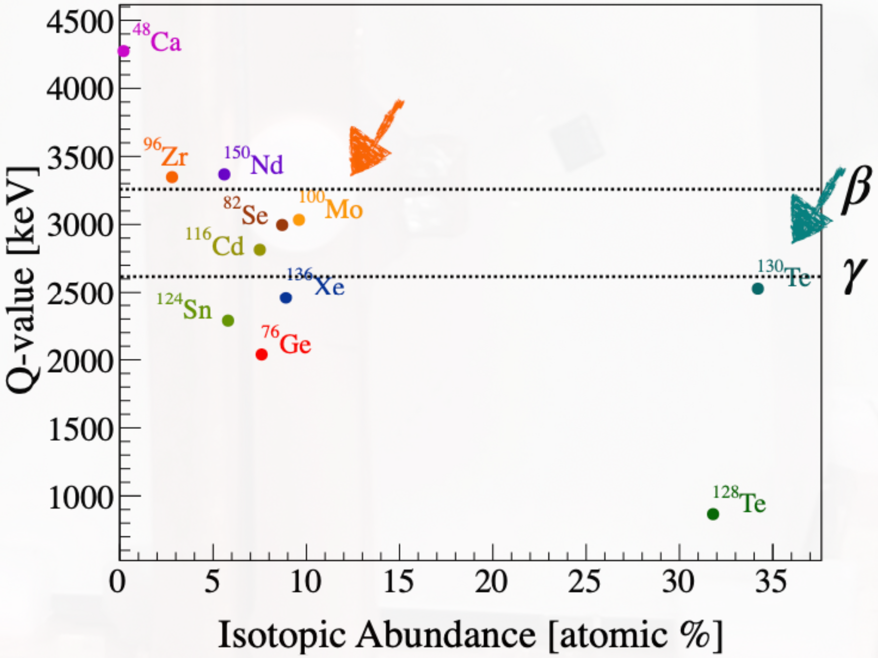
- active event-by-event particle identification strategy
- α - β/γ discrimination



CUPID: crystal and isotope selection

Choice criterion: **Balance** between **performance** (background, energy resolution, detector performance) and **feasibility** (cost, isotope enrichment, crystal growth).



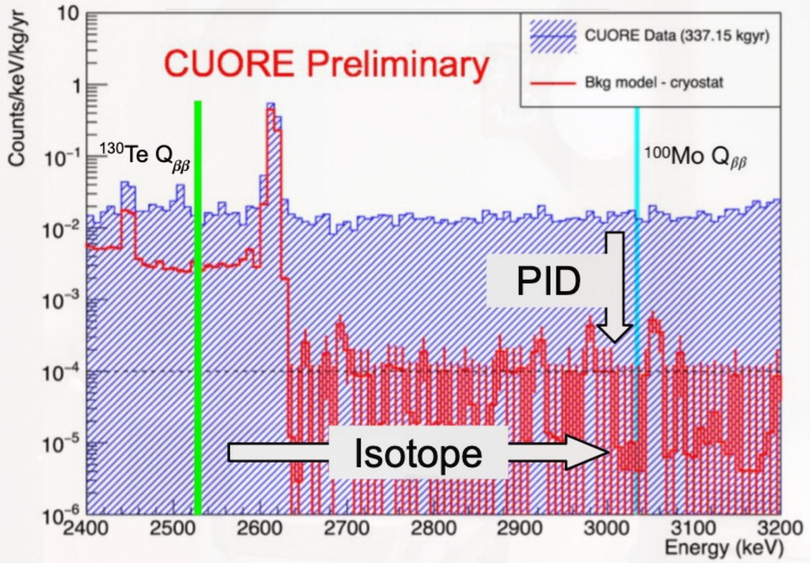


$0\nu\beta\beta$ of ^{100}Mo $Q_{\beta\beta} = 3034$ keV

- Q-value above most of natural radioactivity
- good quality scintillating crystal for good $\alpha - \beta/\gamma$ discrimination
- existing enrichment technology

→ $Li_2{}^{100}MoO_4$

CUPID background reduction



from CUORE to CUPID:

×100 background reduction in the ROI

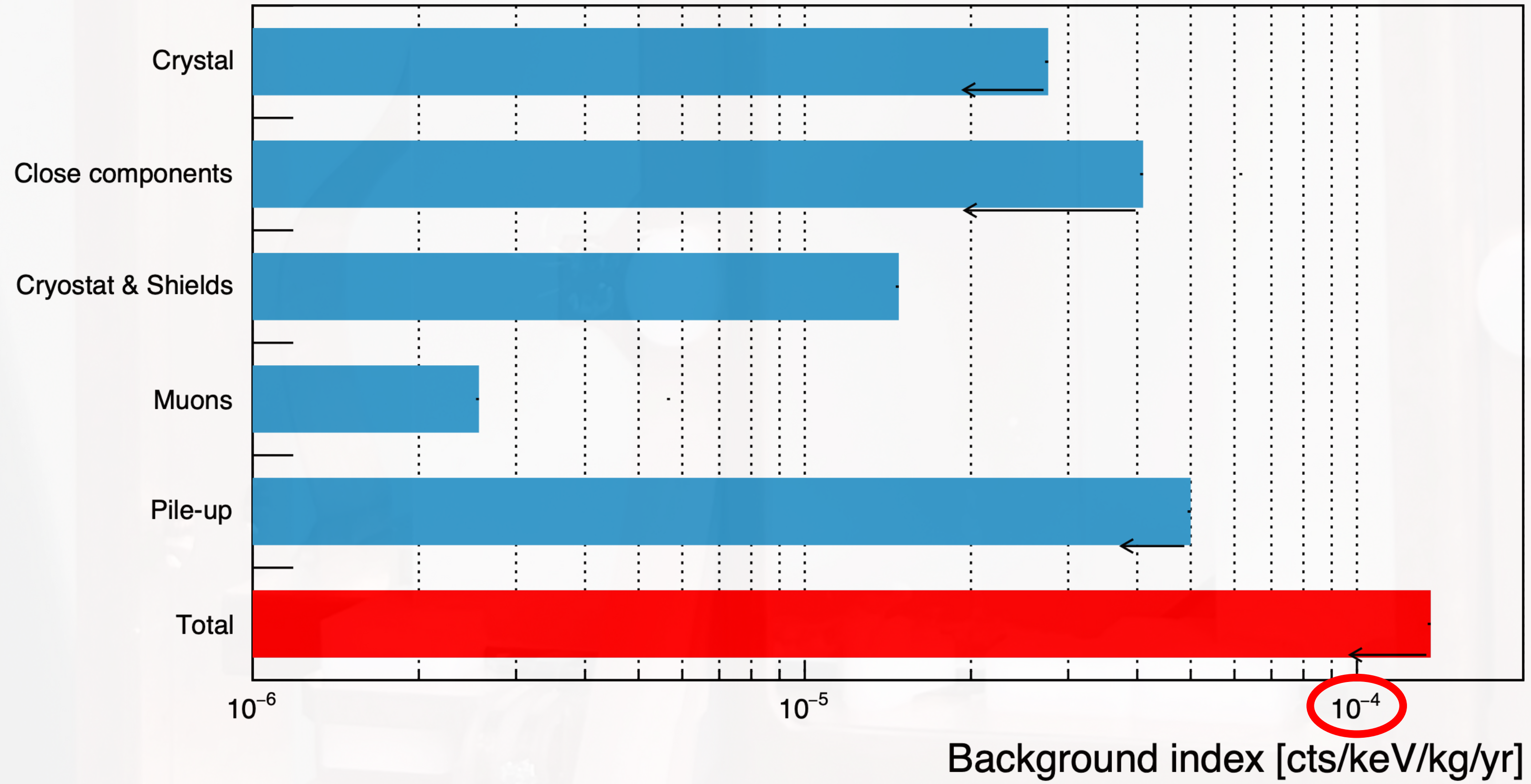
achieved with **PID + isotope selection**

average CUORE background index in the ROI (preliminary)

$1.30(3)\times10^{-2}$ cts/(keV · kg · yr) TAUP23 talk

CUPID projected background index: $< 10^{-4}$ cts/(keV · kg · yr)

CUPID background budget



Target: $B < 10^{-4}$ cts/ keV / kg/ yr

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Relevant backgrounds

- External (cosmic rays):
  - muons

muon veto

- Infrastructure (γ from $^{232}Th/^{238}U$)
  - ^{214}Bi: $E_\gamma > 3034$ keV
  - ^{208}Tl: 2615/583 keV cascade

delayed coincidence cuts

- Crystals
  - surface ^{214}Bi and ^{208}Tl (from $^{232}Th/^{238}U$)
  - $2\nu\beta\beta$ pile−up from ^{100}Mo

improve SNR of LDs with Neganov-Luke amplification

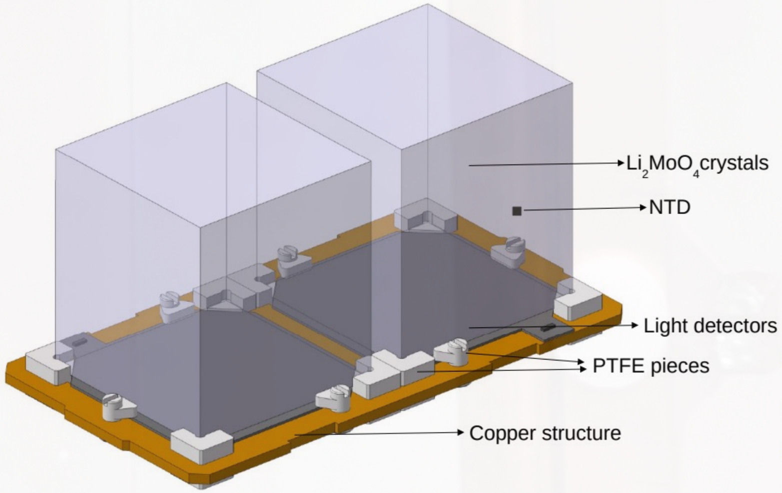
improve timing resolution on LD

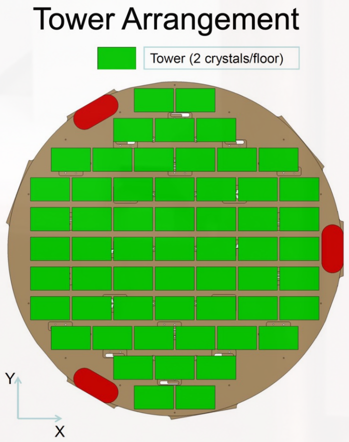
CUPID baseline detector

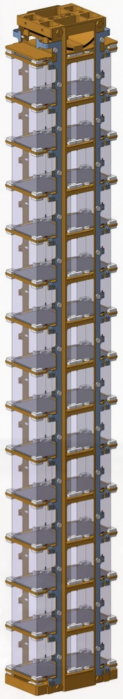
✓ CUORE cryostat + infrastructure

Very large array:

- 57 towers
  - 14 floors, 2 crystals per floor
- 1596 Li_2MoO_4 cryogenic calorimeters
  - enriched in ^{100}Mo to ~ 95%
  - cubic 45×45×45 mm^3
  - 280 g (450 kg Li_2MoO_4, 240 kg ^{100}Mo)
- 1710 Ge light detectors
  - Neganov-Luke amplification
- 3306 Ge-NTD sensors







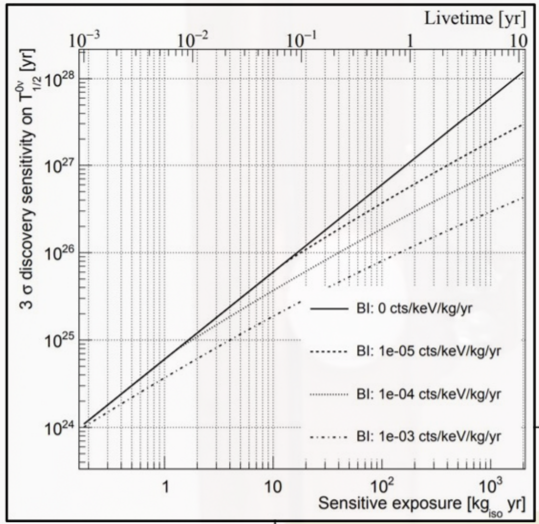
Physics goal

G O A L :

fully probe the *inverted hierarchy* region

$$S^{0\nu} \propto \epsilon \cdot \eta \cdot MT$$

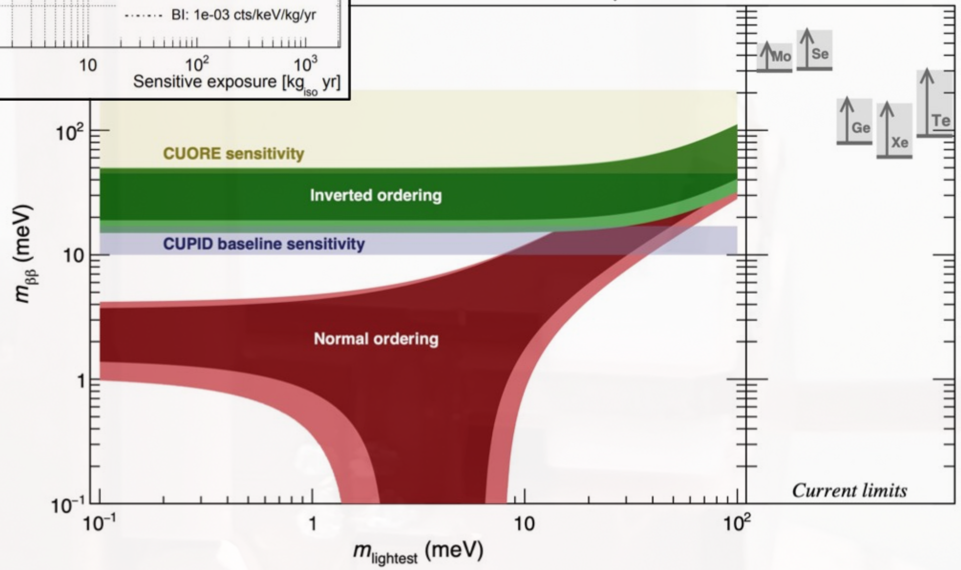
$$S^{0\nu} \propto \epsilon \cdot \eta \cdot \sqrt{\frac{MT}{B\Delta}}$$



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

Baseline discovery sensitivity

- $T^{0\nu}_{1/2} > 1.1{\times}10^{27}$ (3σ)
- $m_{\beta\beta} \sim 12 - 20$ meV



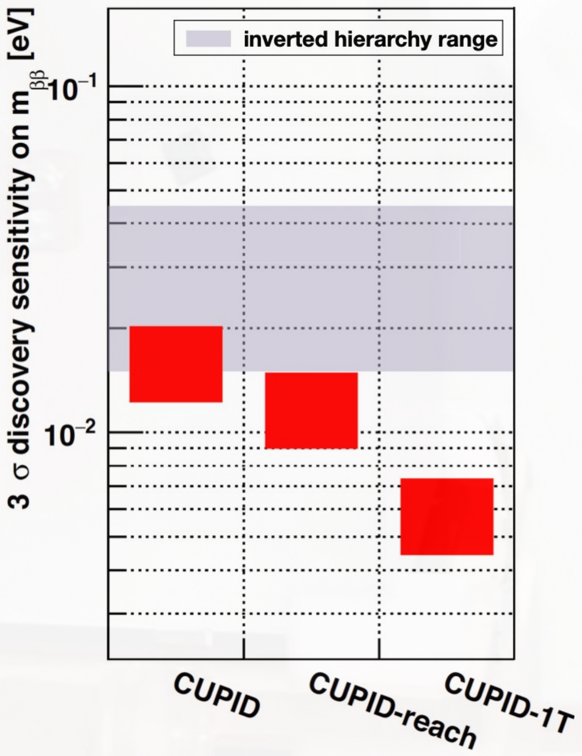
arXiv.1907.09376

Next-next generation experiment: CUPID-1T

CUPID-1T:

- 4× scale up – larger or multiple cryostat
- 1000 kg of ^{100}Mo

Parameter	CUPID baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	450	450	1871
^{100}Mo mass (kg)	240	240	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	78%	78%	78%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.4×10^{27} y	2.2×10^{27} y	9.1×10^{27} y
Half-life discovery sensitivity (3σ)	1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.4–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	9–15 meV	4.4–7.3 meV



Conclusions

- $0\nu\beta\beta$ search with CUORE proves the feasibility and effectiveness of ton-scale cryogenic experiments
- already existing infrastructure
- CUPID will explore inverted hierarchy: $T_{1/2}^{0\nu} > 10^{27}$ (3σ), $m_{\beta\beta} \sim 12 - 20$ meV
- Data-driven background model reaches a baseline goal of $\mathrm{B} < 10^{-4}$ cts/ keV / kg/ yr

Thanks for your attention!

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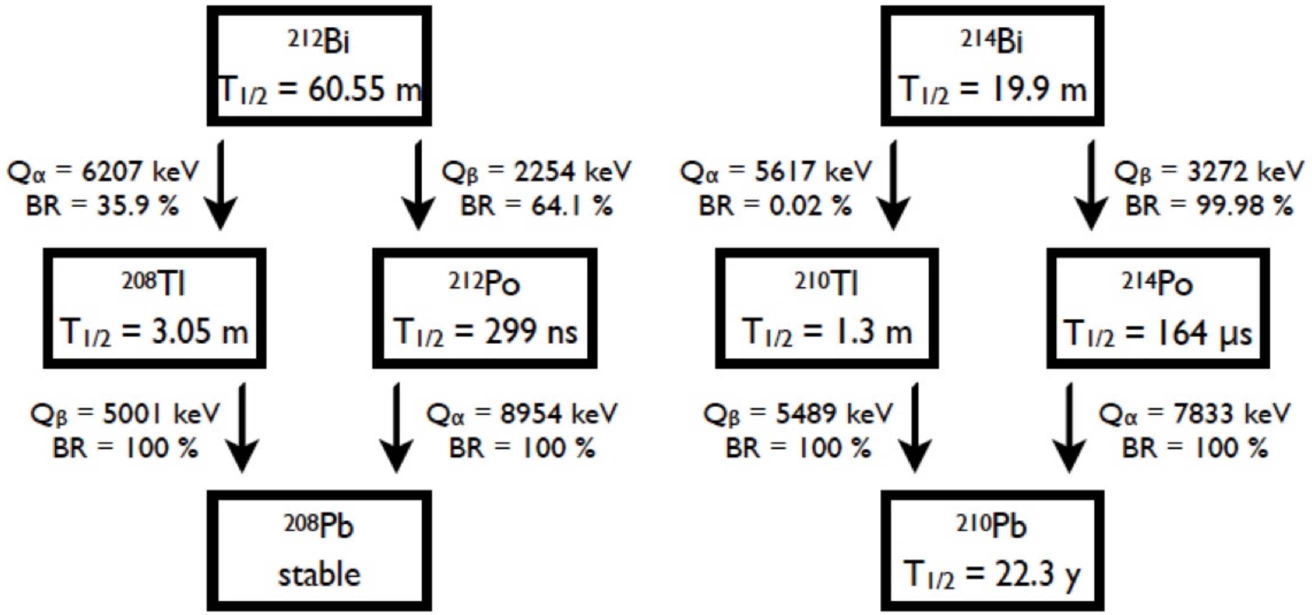
Other materials

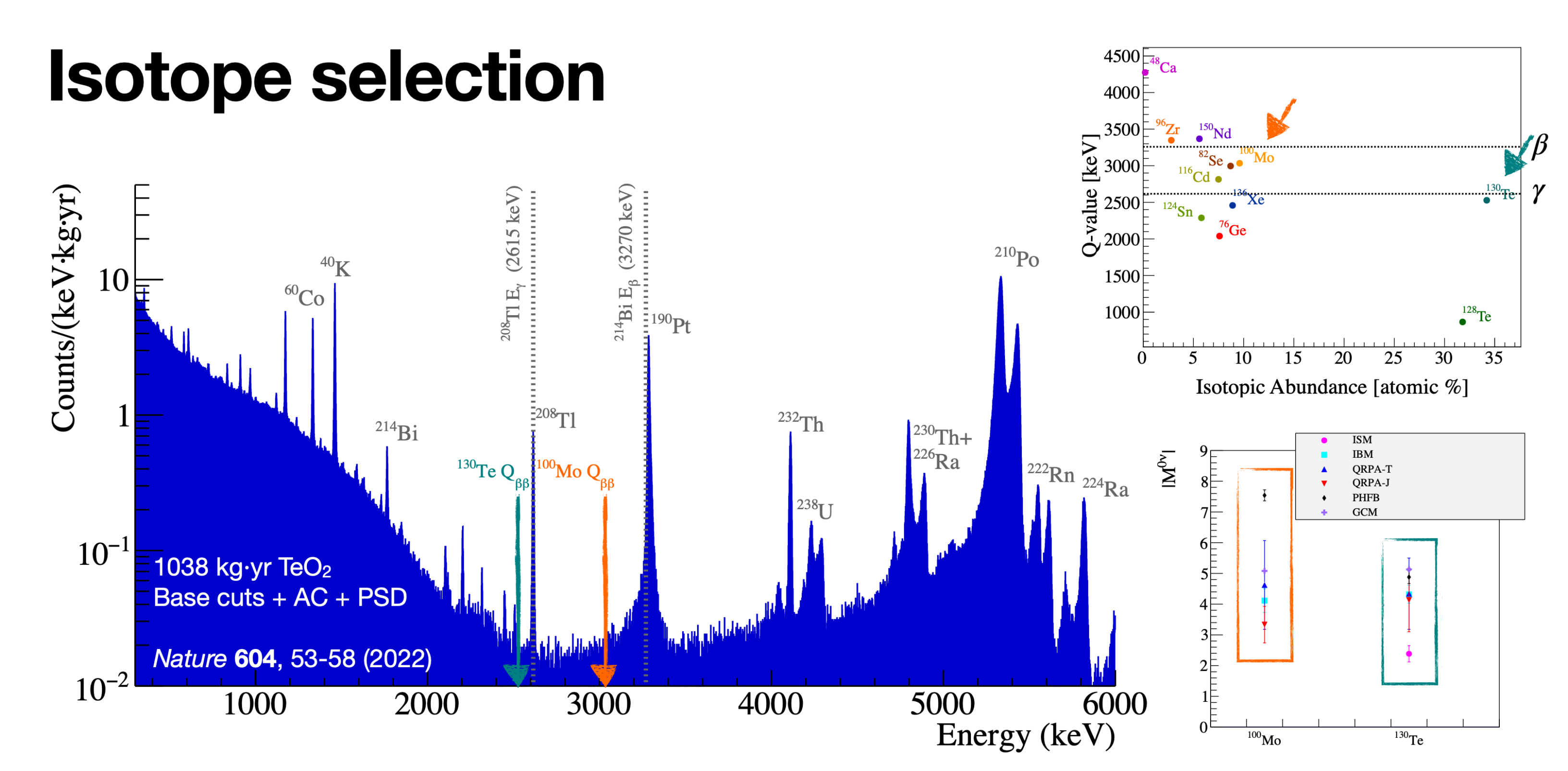
Other materials

^{100}Mo 2νββ decay pile-up ($T_{1/2}$ = 7.1 x 10^{18} years)

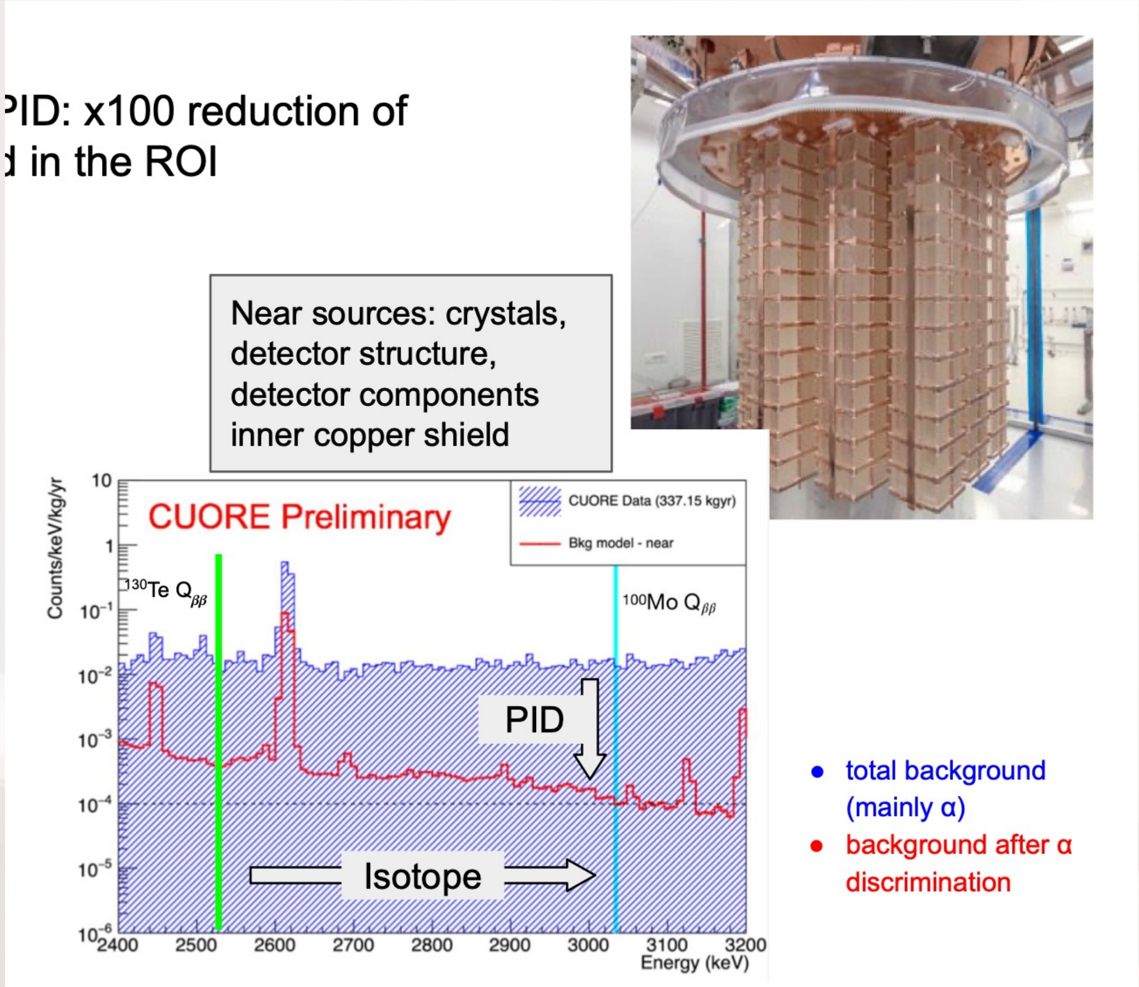
- delayed coincidence cut:



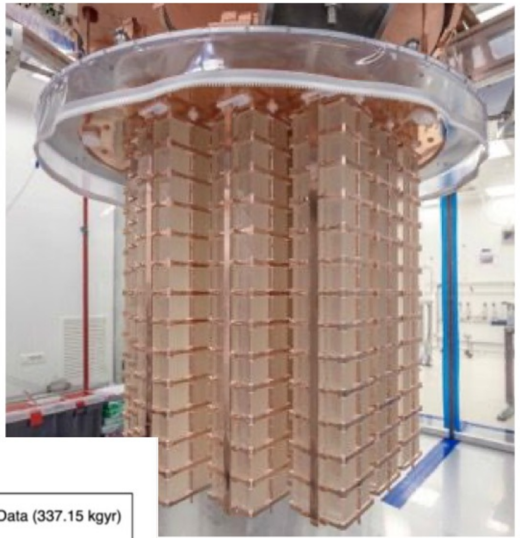
Other materials



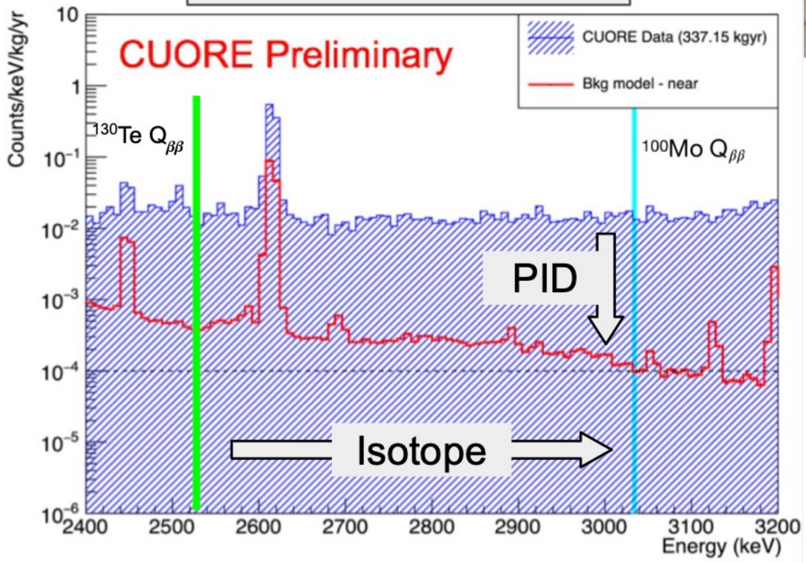
Other materials



ID: x100 reduction of
in the ROI

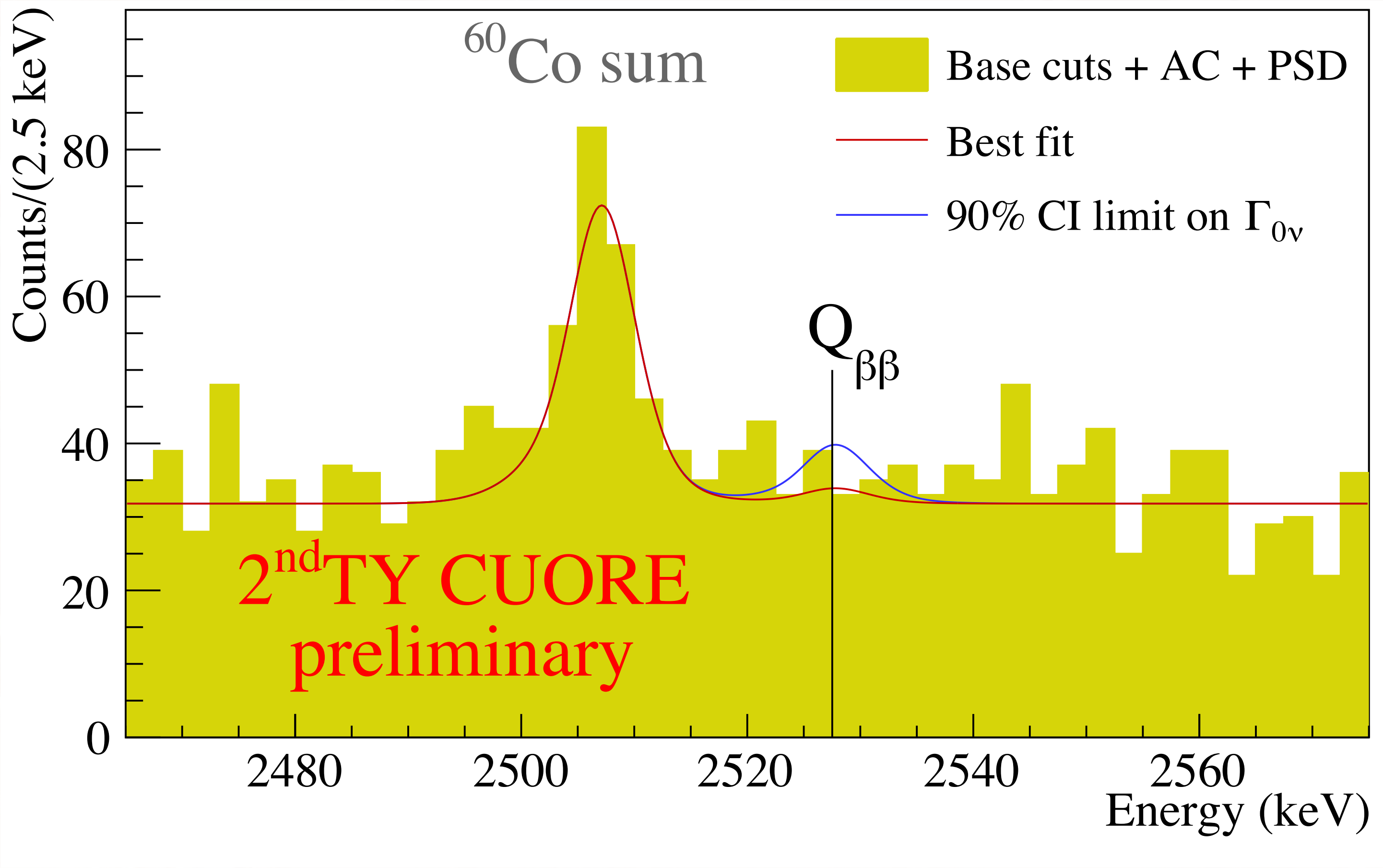


Near sources: crystals, detector structure, detector components inner copper shield



- total background (mainly α)
- background after α discrimination

The CUORE $0\nu\beta\beta$ limit



CUORE (preliminary):

- Exposure 2023 kg·yr
- No evidence of $0\nu\beta\beta$
- Best limt on $T^{0\nu}_{1/2}$ in ^{130}Te:

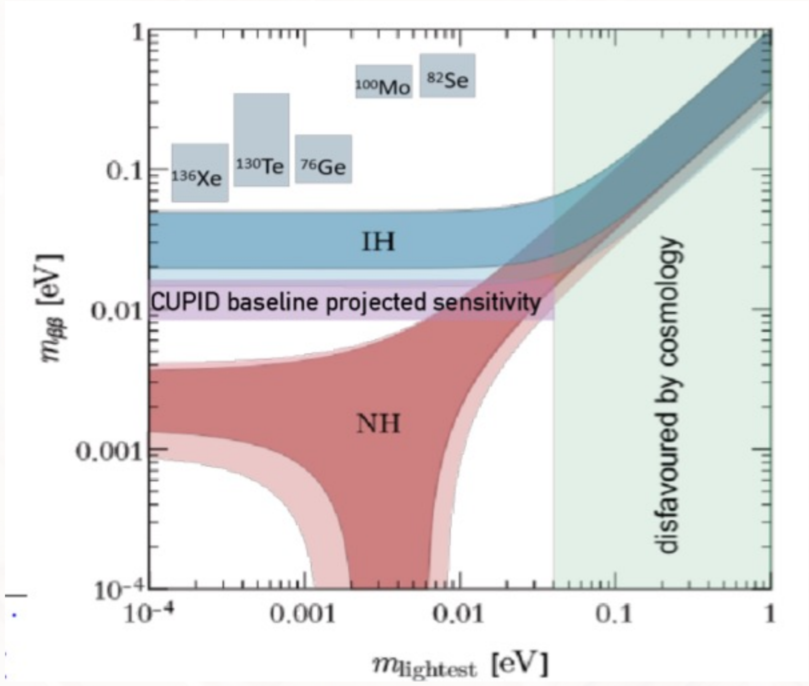
$$T^{0\nu}_{1/2} > 3.3\times10^{25}\ \text{yr}\ \ (90\%\ C.I.)$$

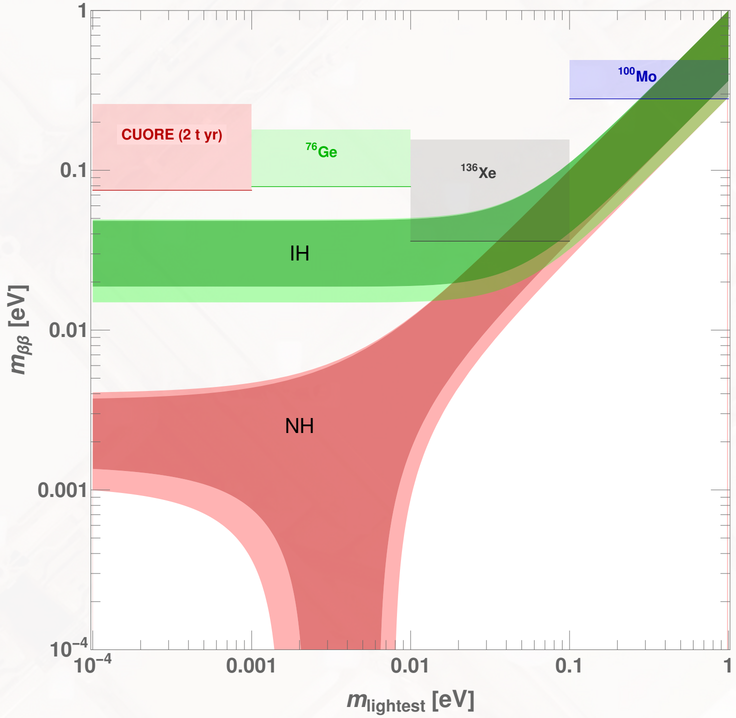
- Upper limit on effective Majorana mass

$$m_{\beta\beta} < 75 - 255\ \text{meV}\ (90\%\ C.I.)$$

Ref.: TAUP23 talk

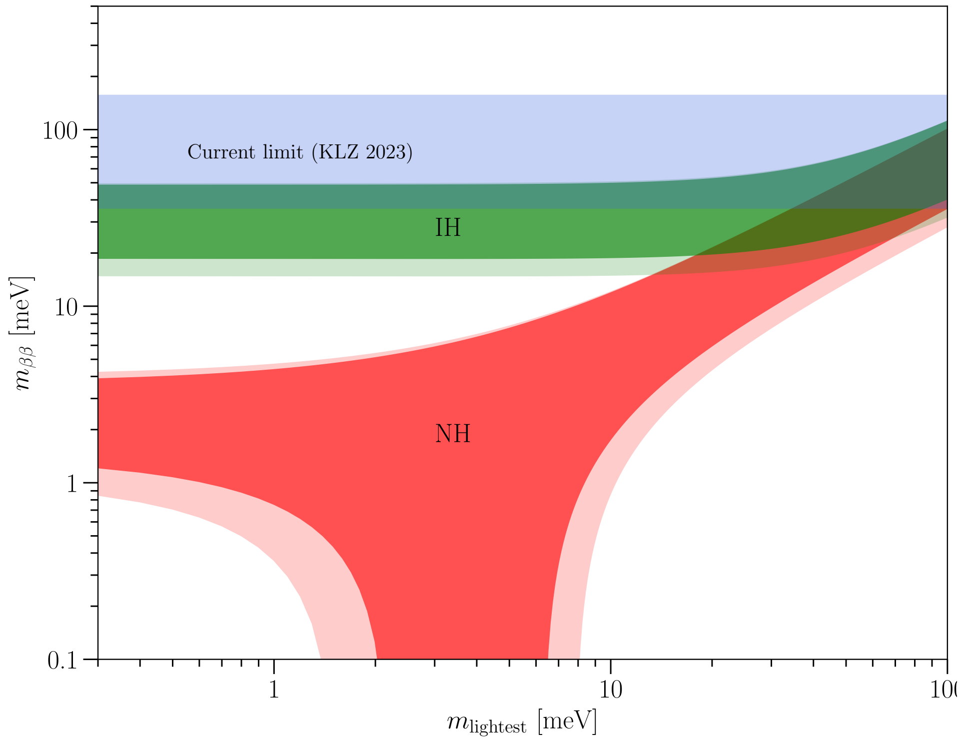
Lobster Plot





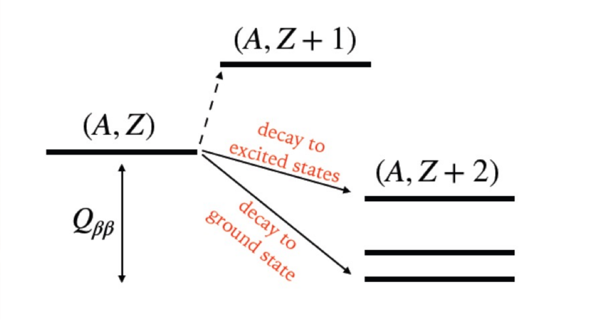
$$T_{1/2}^{0\nu} = \left[G_{0\nu} g_A^4 |M_{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2} \right]^{-1}$$

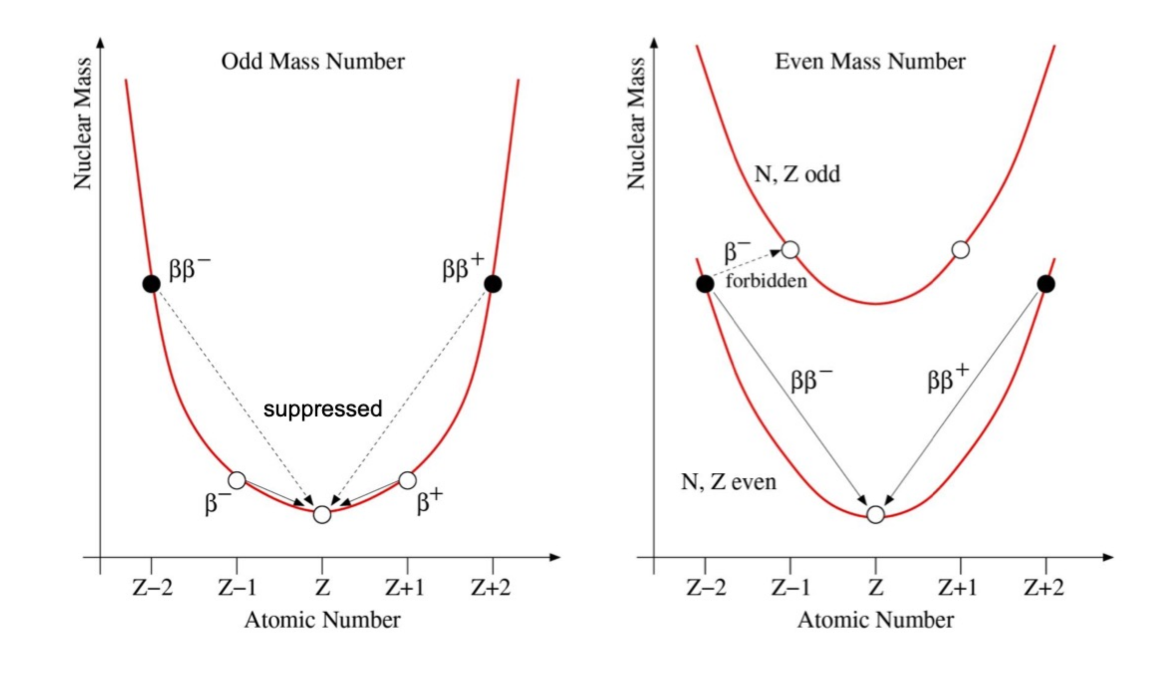
Incertezze nella conoscenza dell'elemento di matrice nucleare → grande intervallo di valori per limiti su $m_{\beta\beta}$



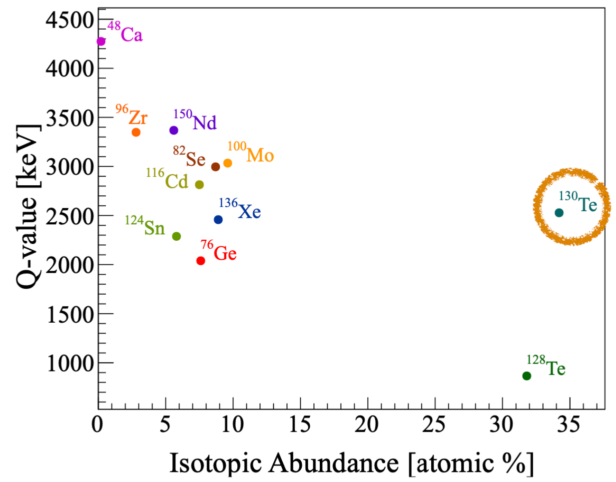
Current limit (KLZ 2023)
IH
NH
100
10
1
0.1
1
10
100
$m_{\beta\beta}$ [meV]
m_{lightest} [meV]

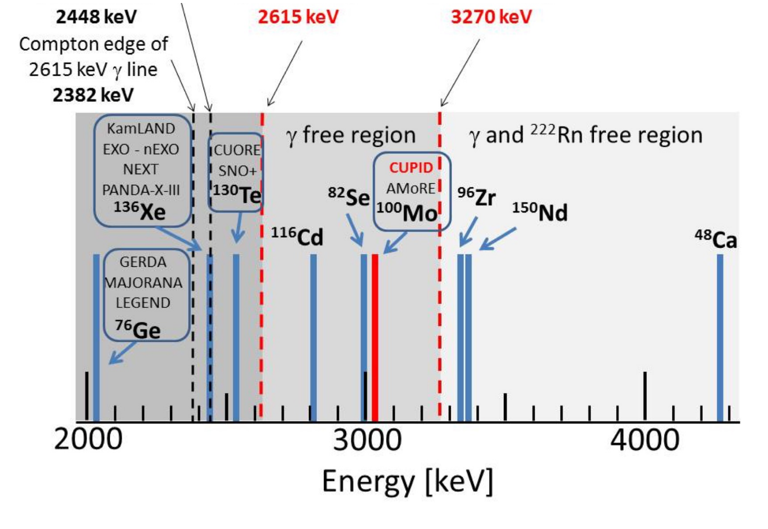
Decadimento doppio beta





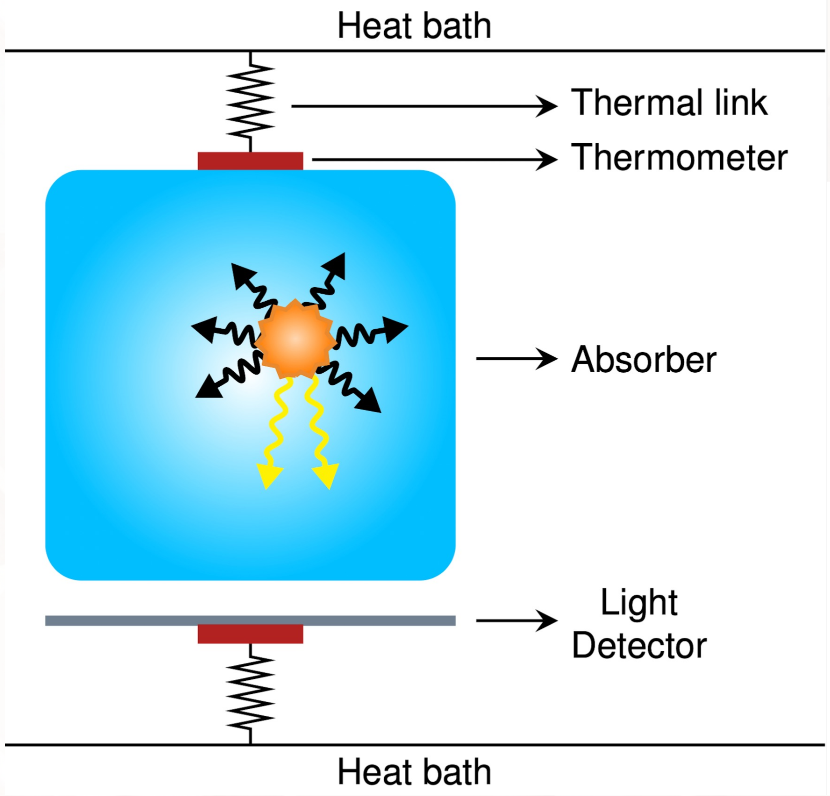
$\beta\beta$ Decay Reaction	Isotopic Abundance [atomic %]	Q-value [keV]
$^{48}Ca \to {}^{48}Ti$	0.2	4274
$^{76}Ge \to {}^{76}Se$	7.6	2039
$^{82}Se \to {}^{82}Kr$	8.7	2996
$^{96}Zr \to {}^{96}Mo$	2.8	3348
$^{100}Mo \to {}^{100}Ru$	9.6	3034
$^{116}Cd \to {}^{116}Sn$	7.5	2814
$^{124}Sn \to {}^{124}Te$	5.8	2288
$^{128}Te \to {}^{128}Xe$	31.8	866
$^{130}Te \to {}^{130}Xe$	34.2	2528
$^{136}Xe \to {}^{136}Ba$	8.9	2458
$^{150}Nd \to {}^{150}Sm$	5.6	3368



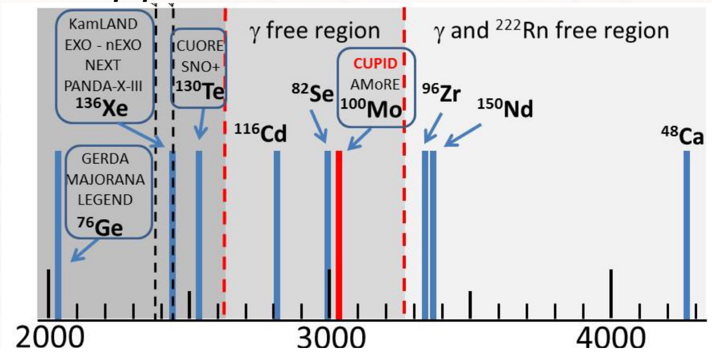


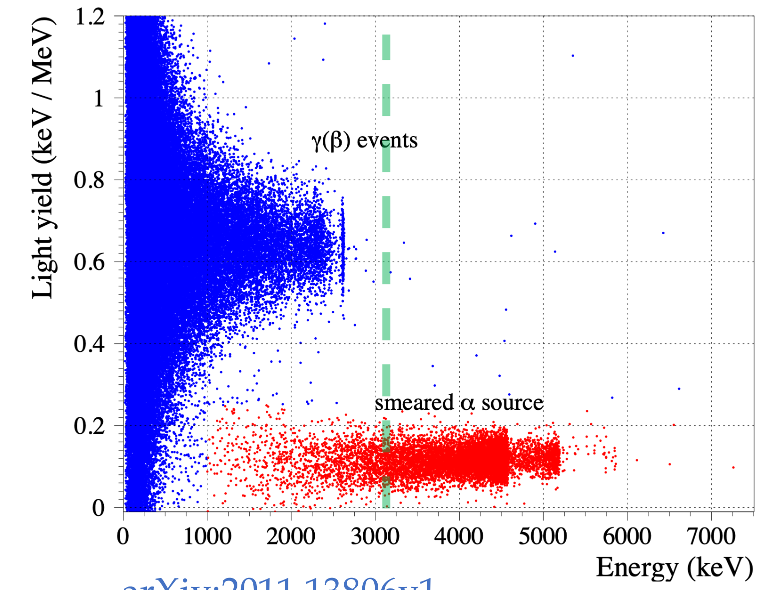
L'esperimento CUPID (**C**UORE **U**pgrade with **P**article **Id**entification)

Calorimetri criogenici scintillanti:
- ➢ sfruttano cristalli scintillanti di Li_2MoO_4
- ➢ sistema a doppia lettura (luce + calore)
- ➢ lettura calorimetrica della luce di scintillazione

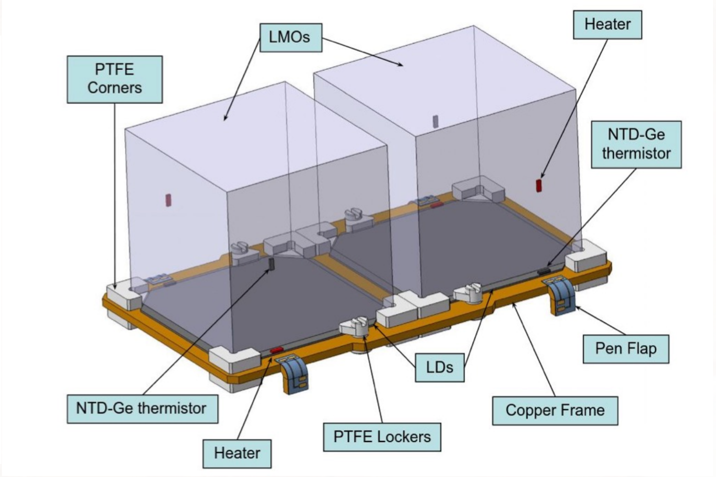


$0\nu\beta\beta$ del ^{100}Mo





arXiv:2011.13806v1



- ✓ Diverse tipologie di particelle interagenti hanno diverse rese in luce (*light yield*)
- ✓ Strategia attiva di identificazione delle particelle interagenti basata sulla luce misurata dal LD