CUORE Upgrade with Particle IDentification

a next generation bolometric $0\nu\beta\beta$ decay experiment

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VIRGINIA TECH

Lake Louise Winter Institute
February 22, 2023

Overview

- Particle IDentification
- $T_{1/2}^{0\nu}$ sensitivity
- Demonstrators
- Detector design
- Relevant backgrounds
- Next-next generation

CUORE Upgrade with Particle IDentification

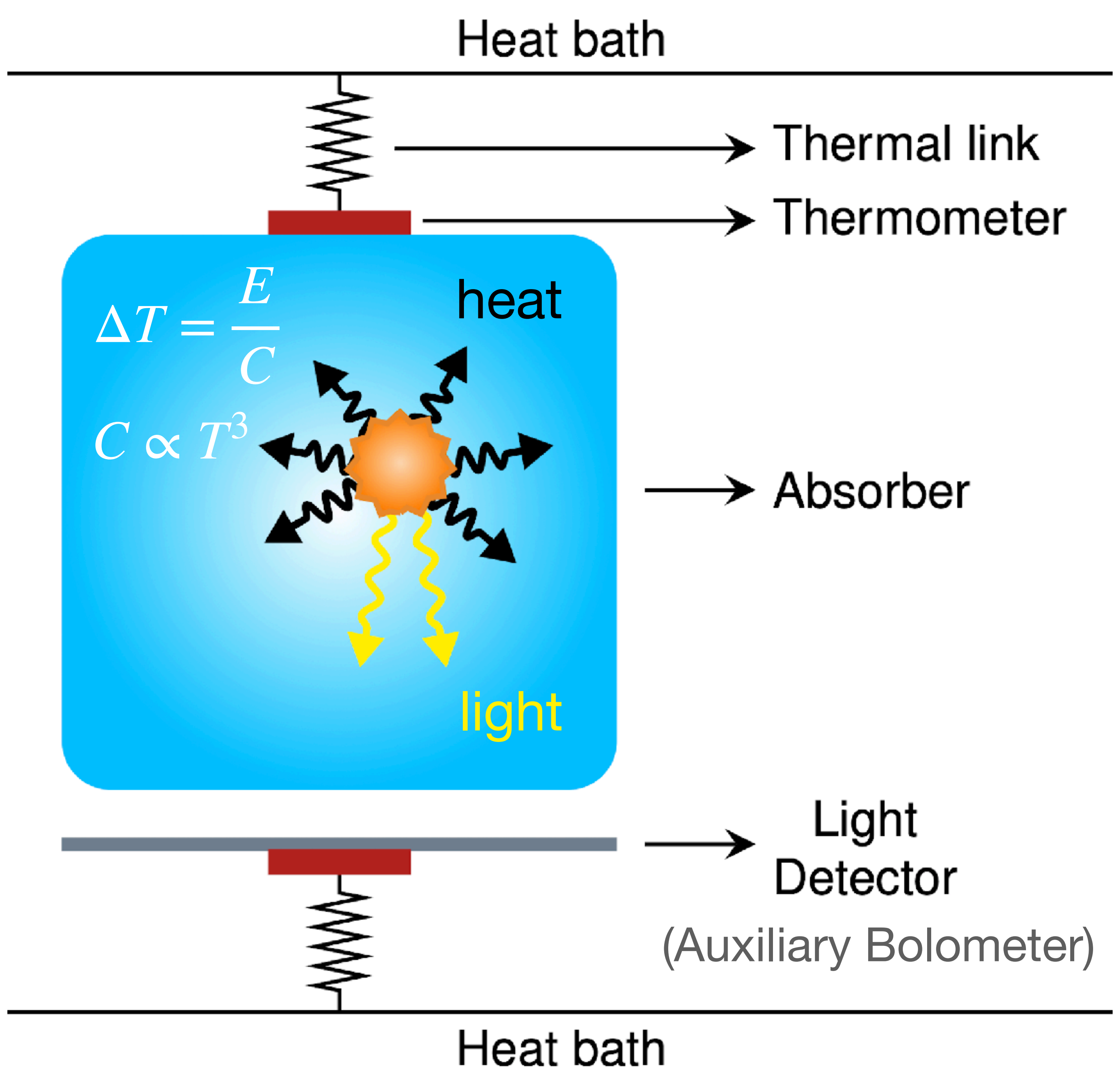
Particle IDentification (PID)

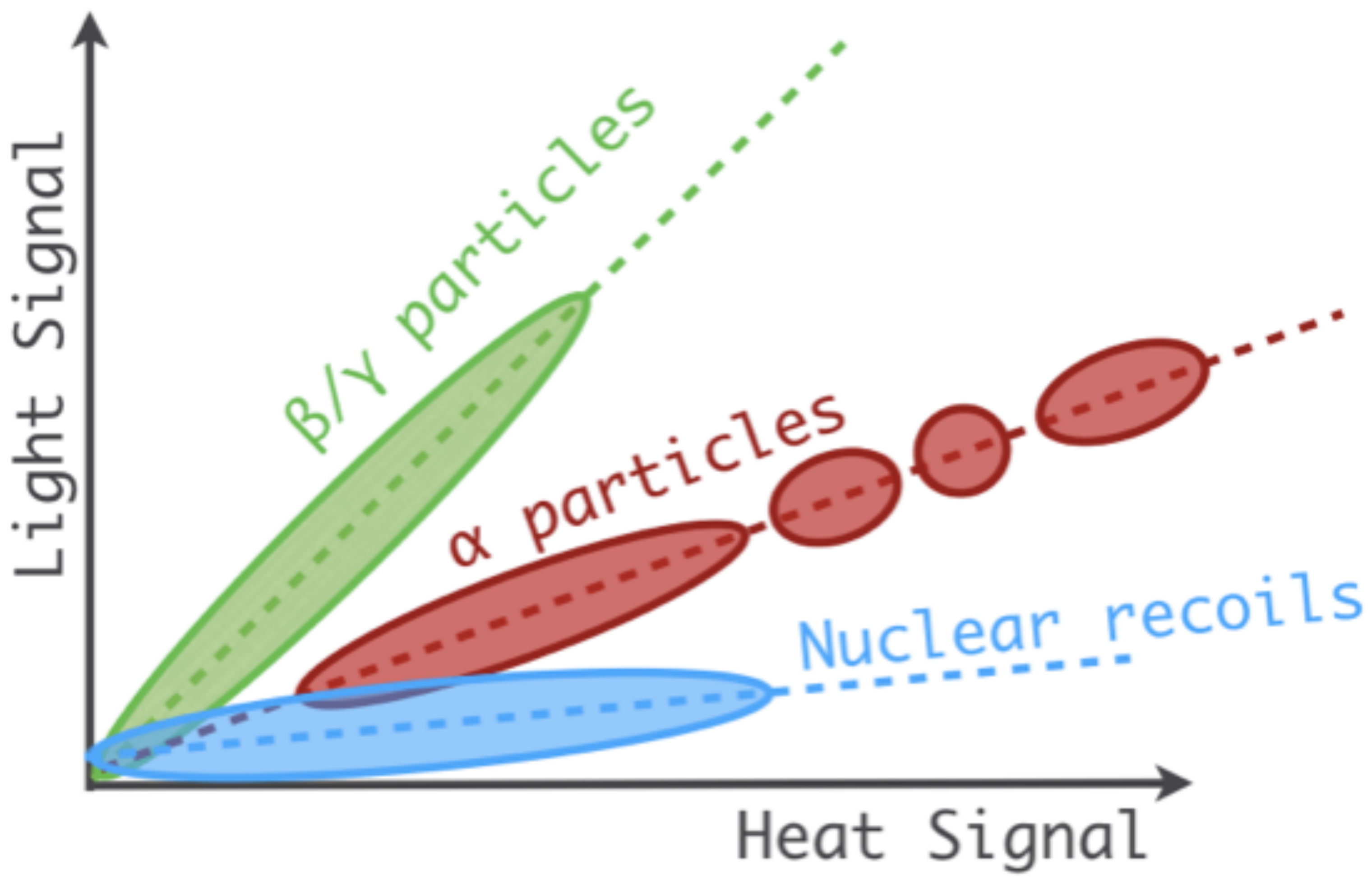
CUORE

- background index: ~10^{-2} counts/(keV·kg·yr)
- ~90% of the background comes from degraded alphas

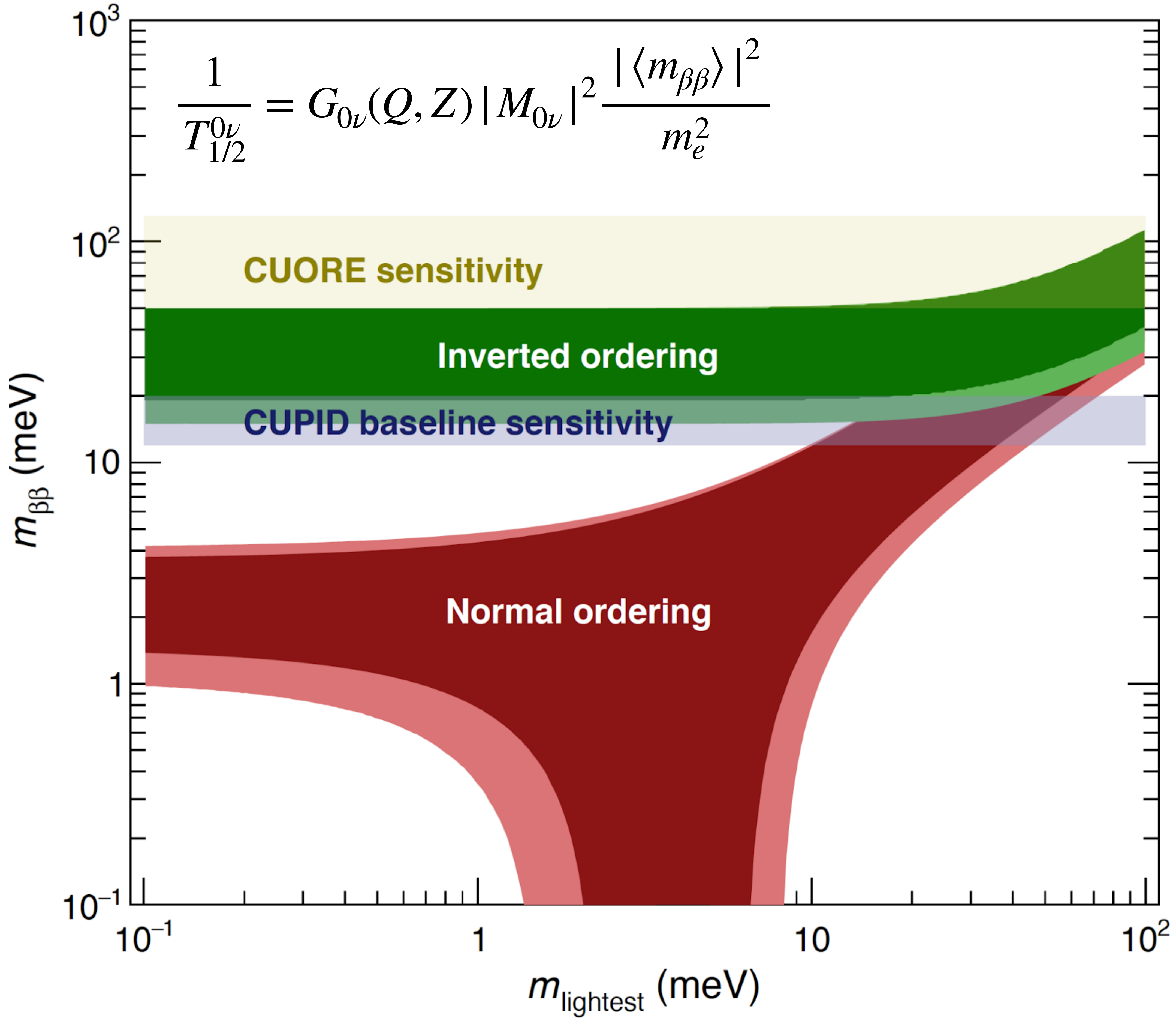
CUPID

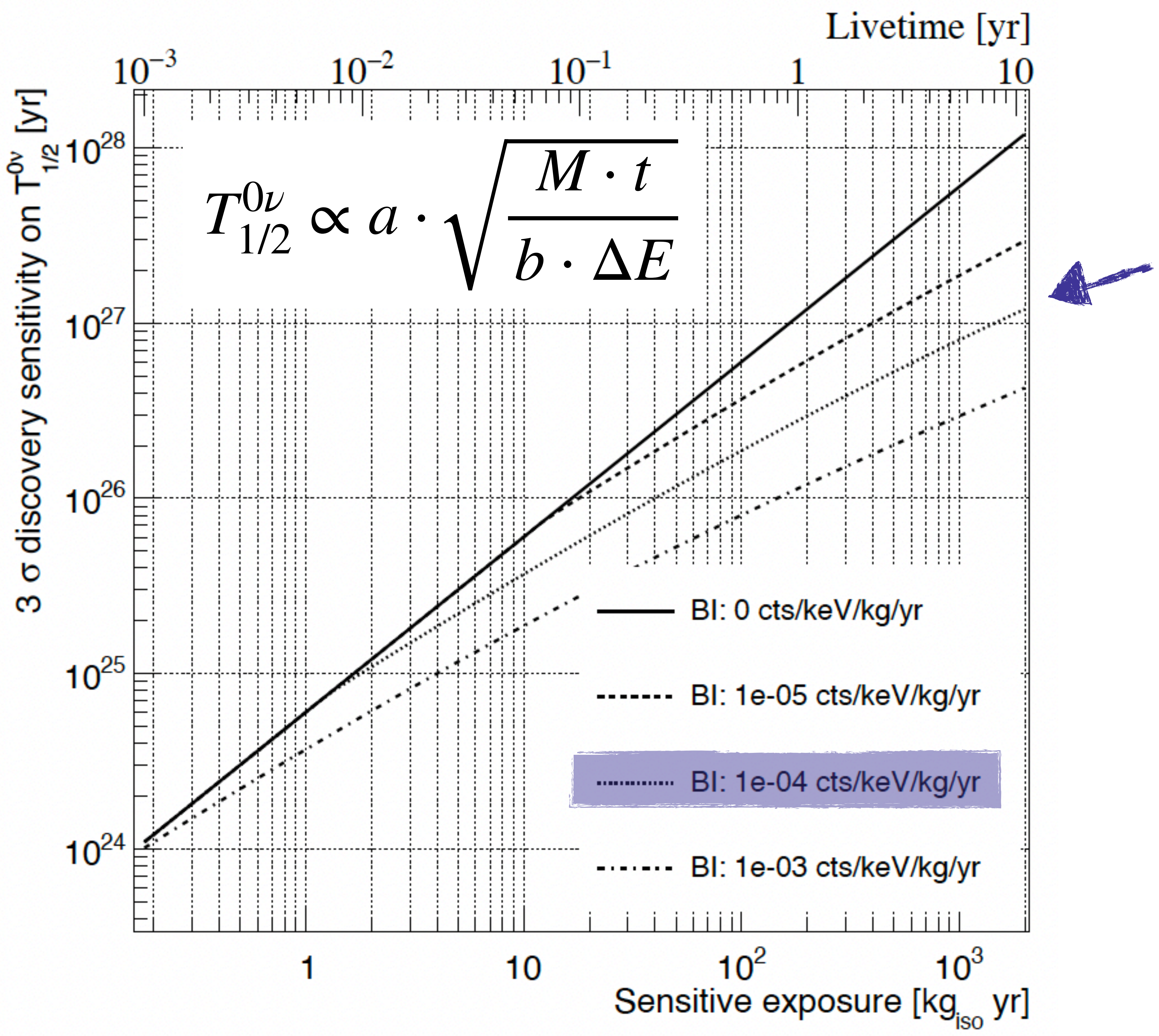
- scintillating crystal absorbers with particle-dependent light response
- auxiliary light detectors to measure light signal
- dual readout to compare heat/light signals — enable particle identification (alpha rejection)





Sensitivity

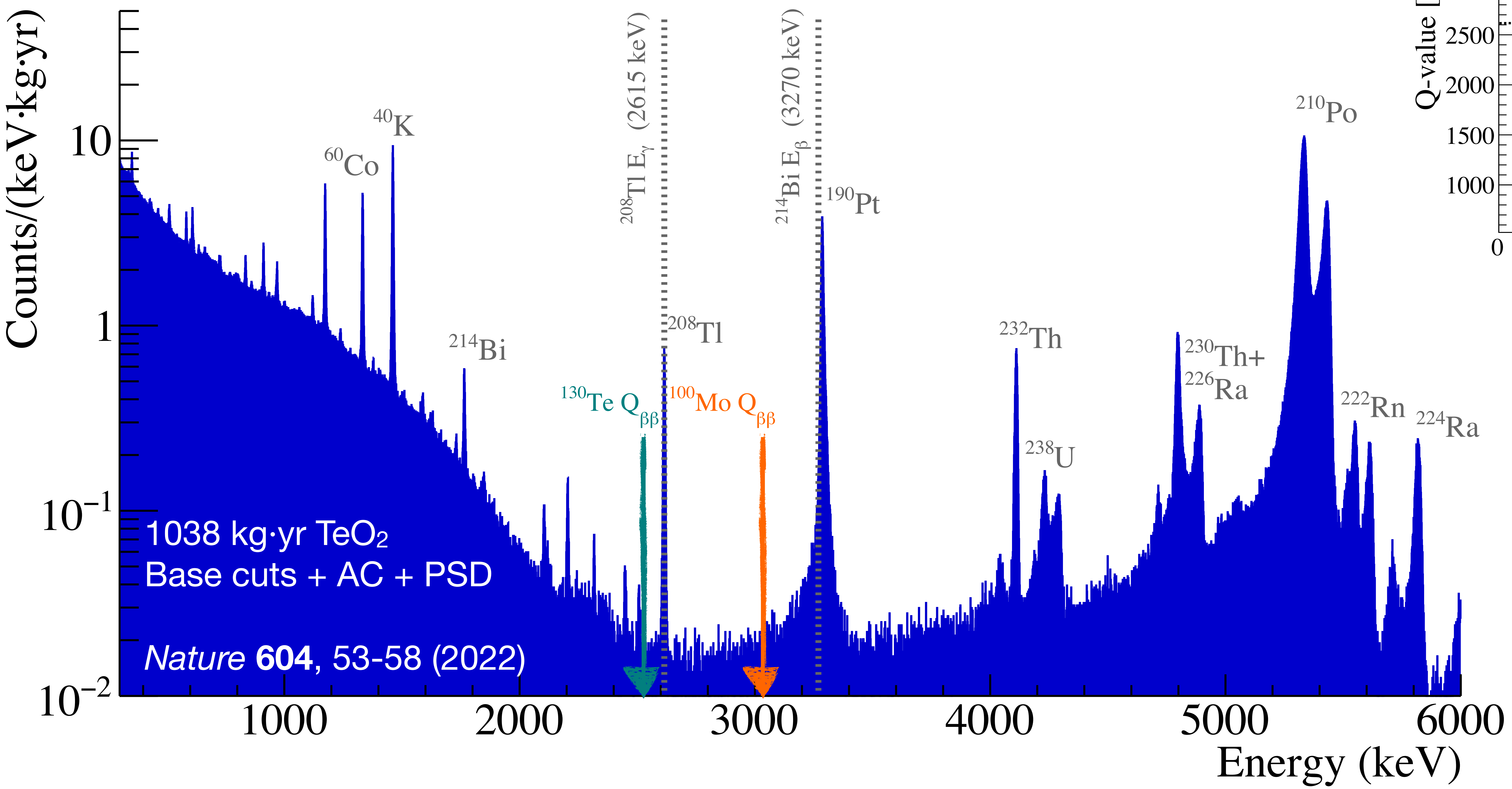


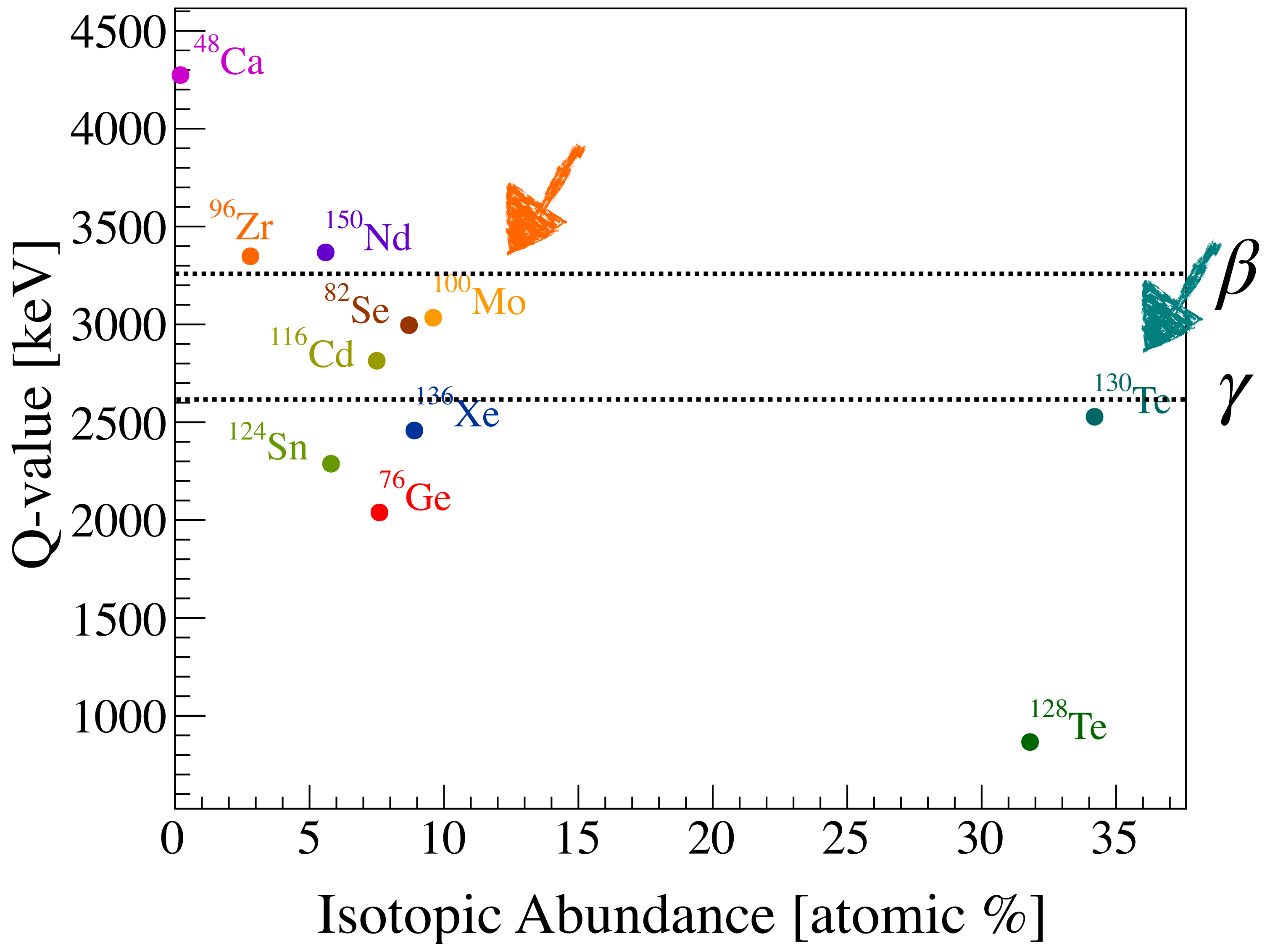


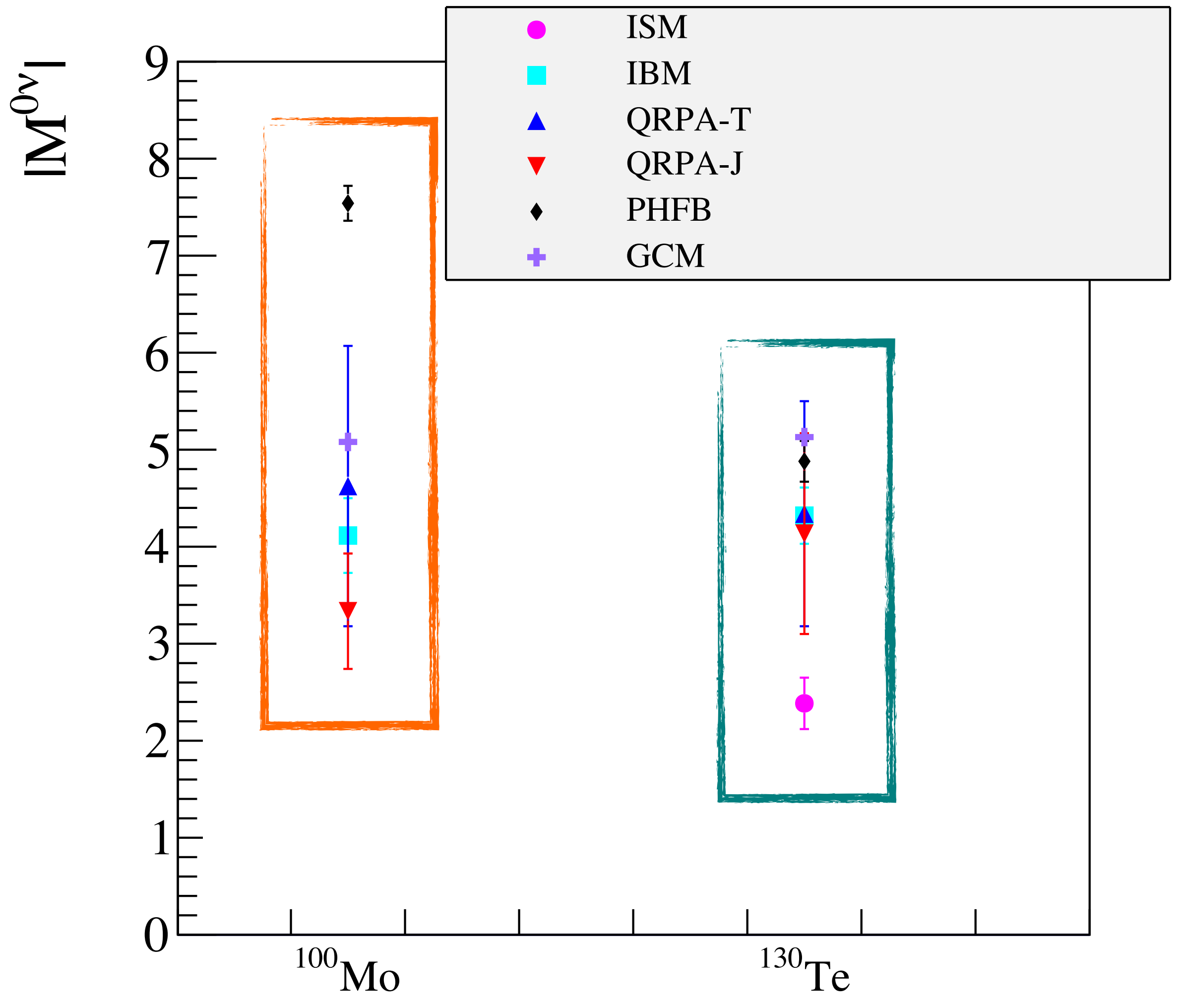
Goal: Fully probe the "Inverted Hierarchy" region

arxiv:1907.09376

Isotope selection



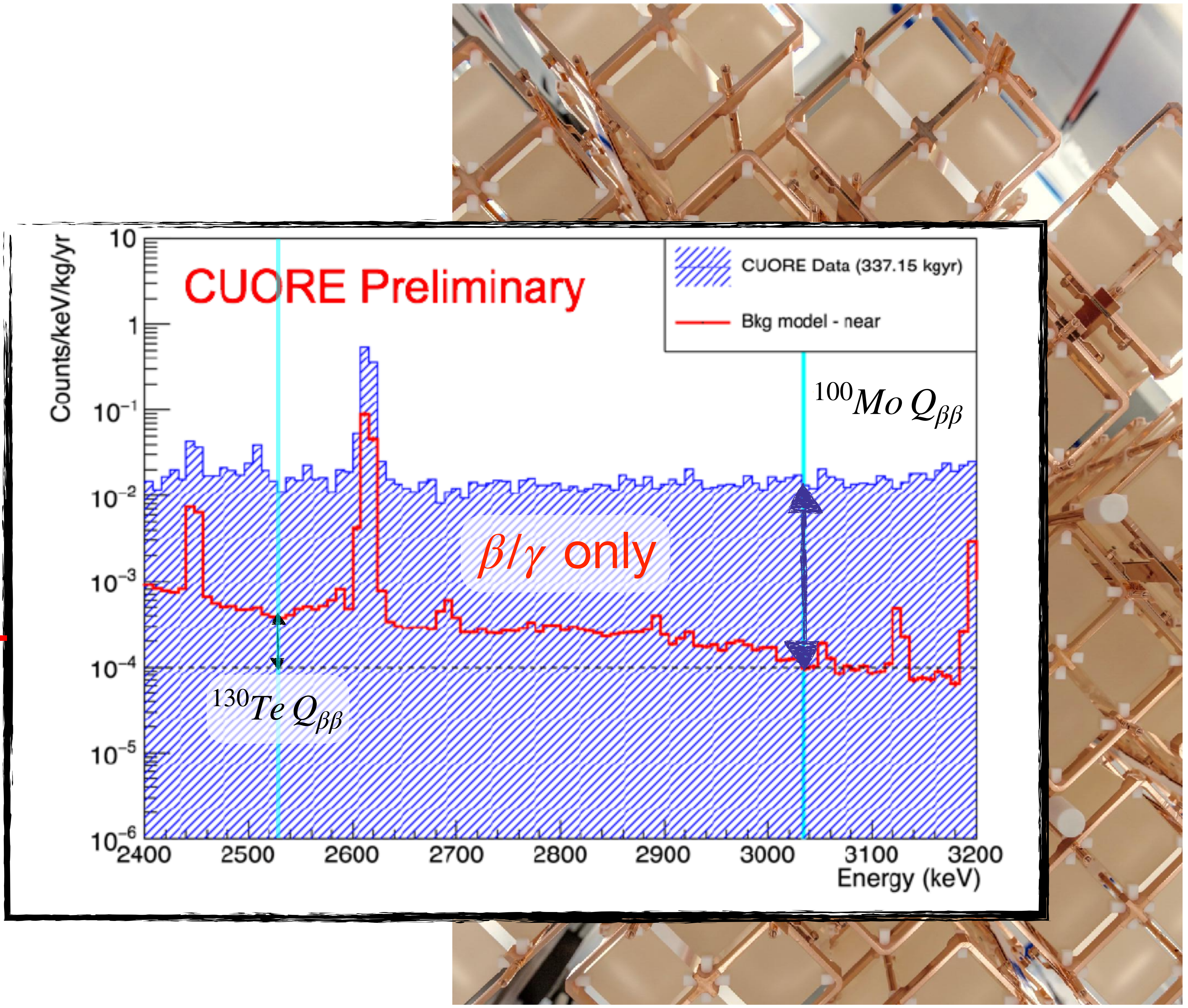




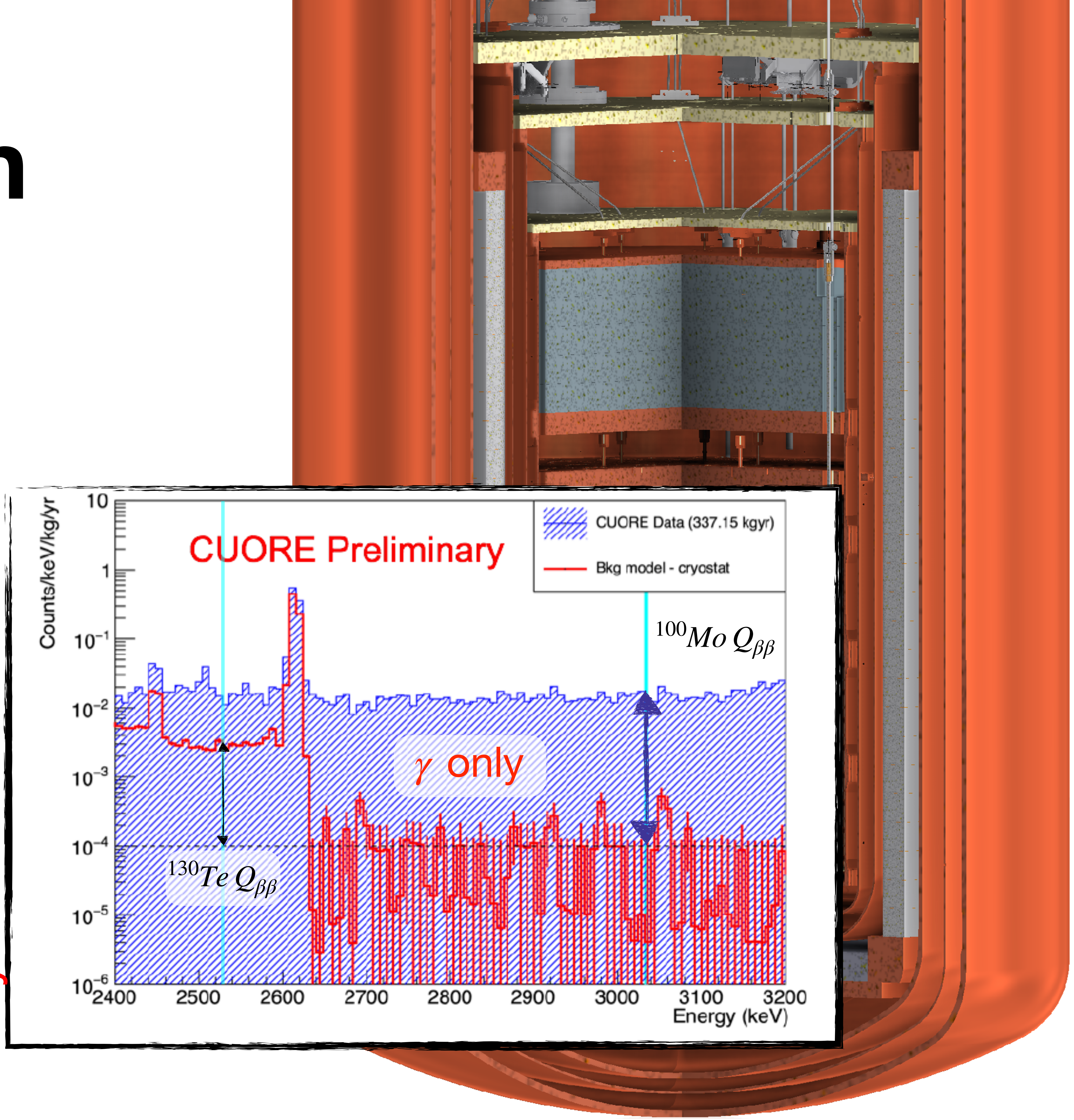
- ^{130}Te Q-value: 2527 keV — below 2615 keV γ; below 3270 keV β; isotopic abundance ~34%
- ^{100}Mo Q-value: 3034 keV — above 2615 keV γ; below 3270 keV β; isotopic abundance ~10%

PID + isotope selection

Detector parts



Cryostat and shields



Background reduced by a factor of 100 — in conformance with CUPID goal

arxiv:1907.09376

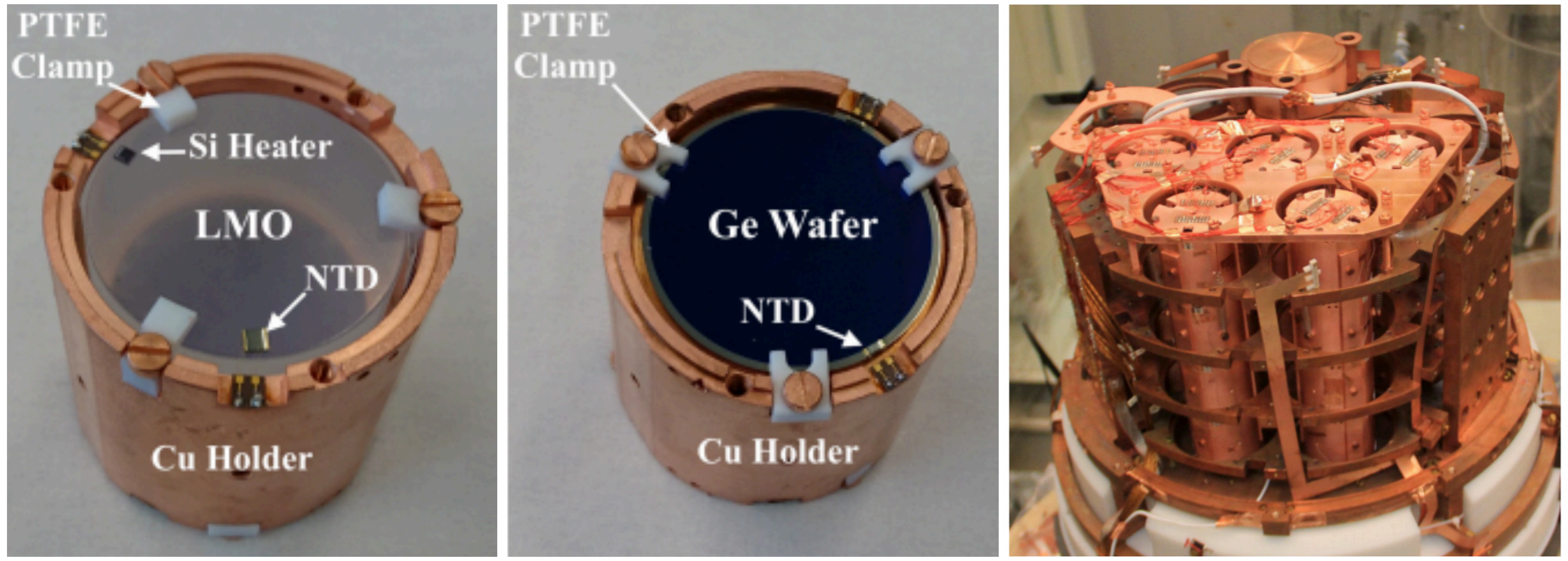
CUPID-Mo (2019 – 2020)

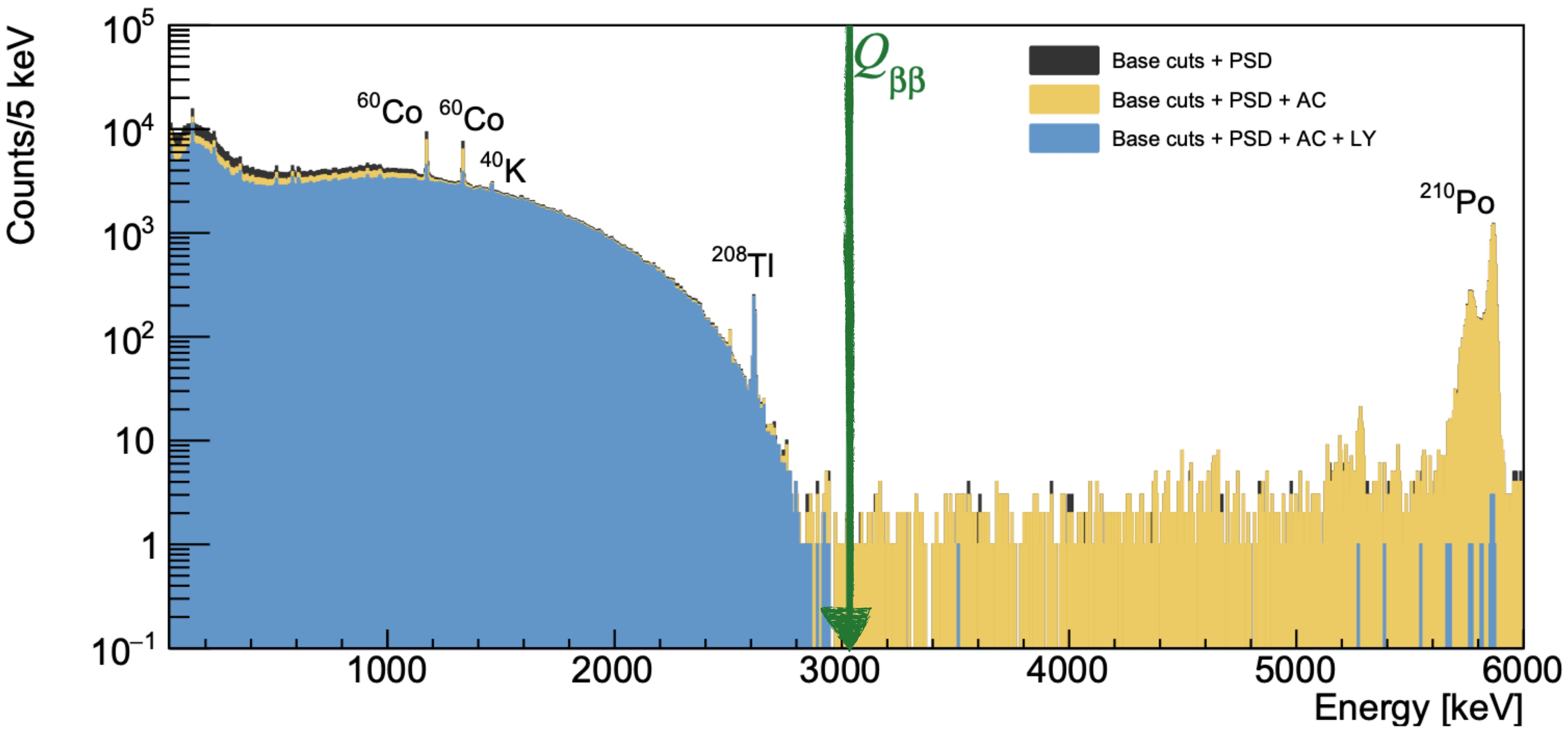
Configuration

- 20 Li_2MoO_4 crystal bolometers with reflective foil
  - enriched in ^{100}Mo to ~97%
  - cylindrical (~⌀44x45 mm)
  - ~210 g
- 20 Ge light detectors with SiO antireflective coating
  - round (⌀44.5 mm)
- cryogen-free cryostat (EDELWEISS)
  - Modane Underground Laboratory (LSM) in France (4800 mwe)
  - ~20 mK
- muon veto system
  - 46 plastic scintillator modules

PID Performance

- > 99.9% α rejection
- > 99.9% β/γ acceptance
- background index: O(10^{-3}) counts/(keV·kg·yr)





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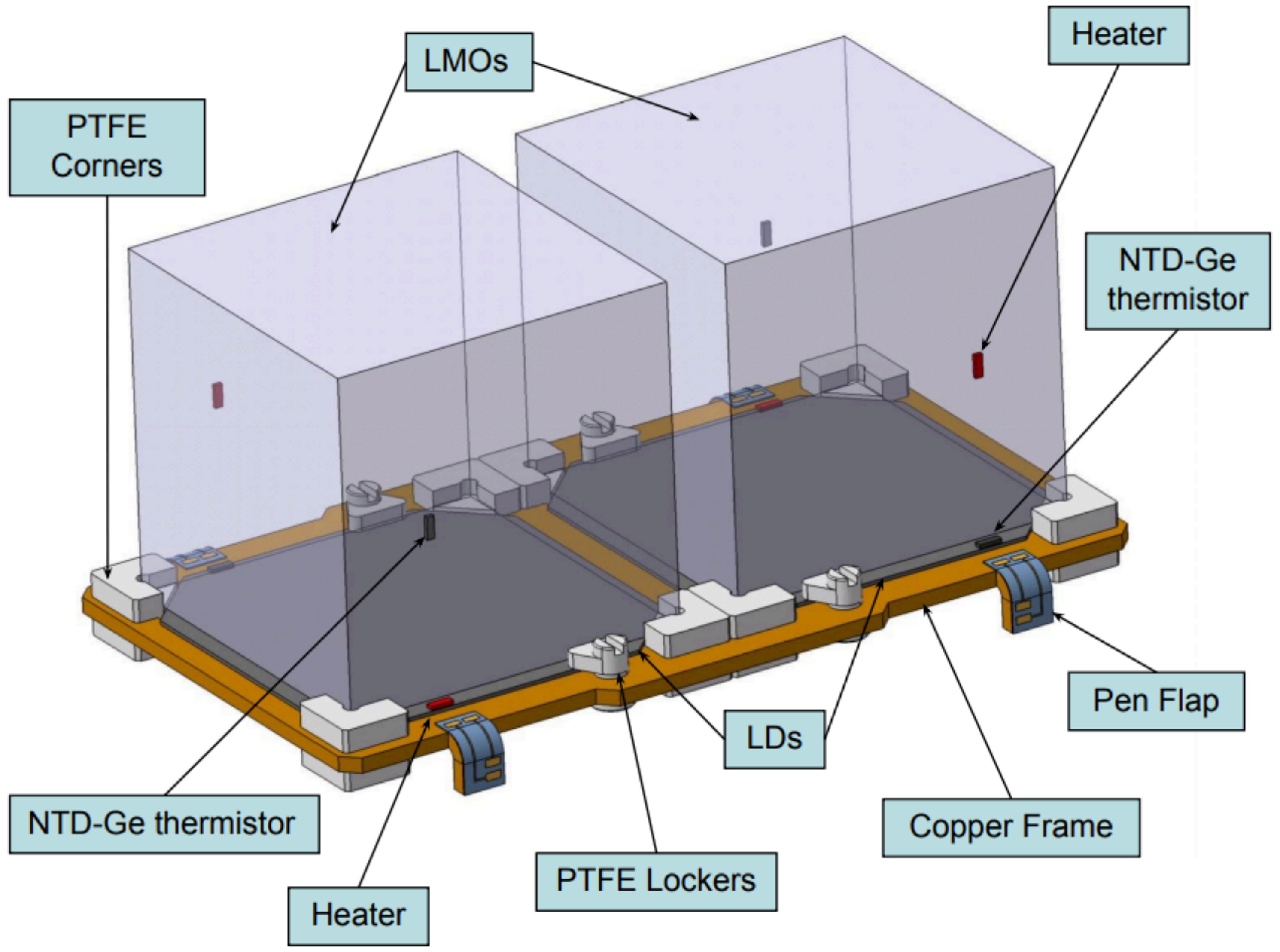
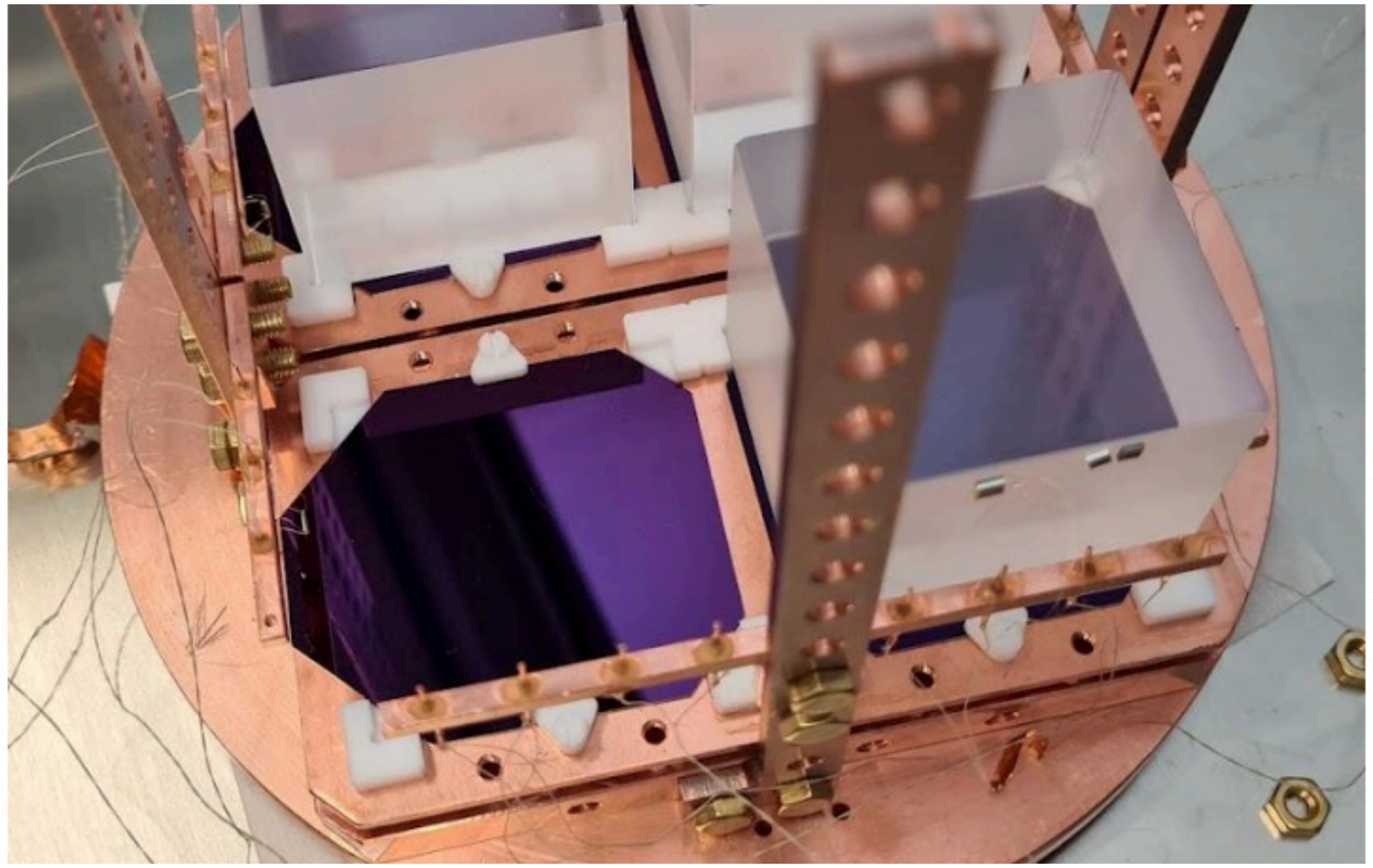
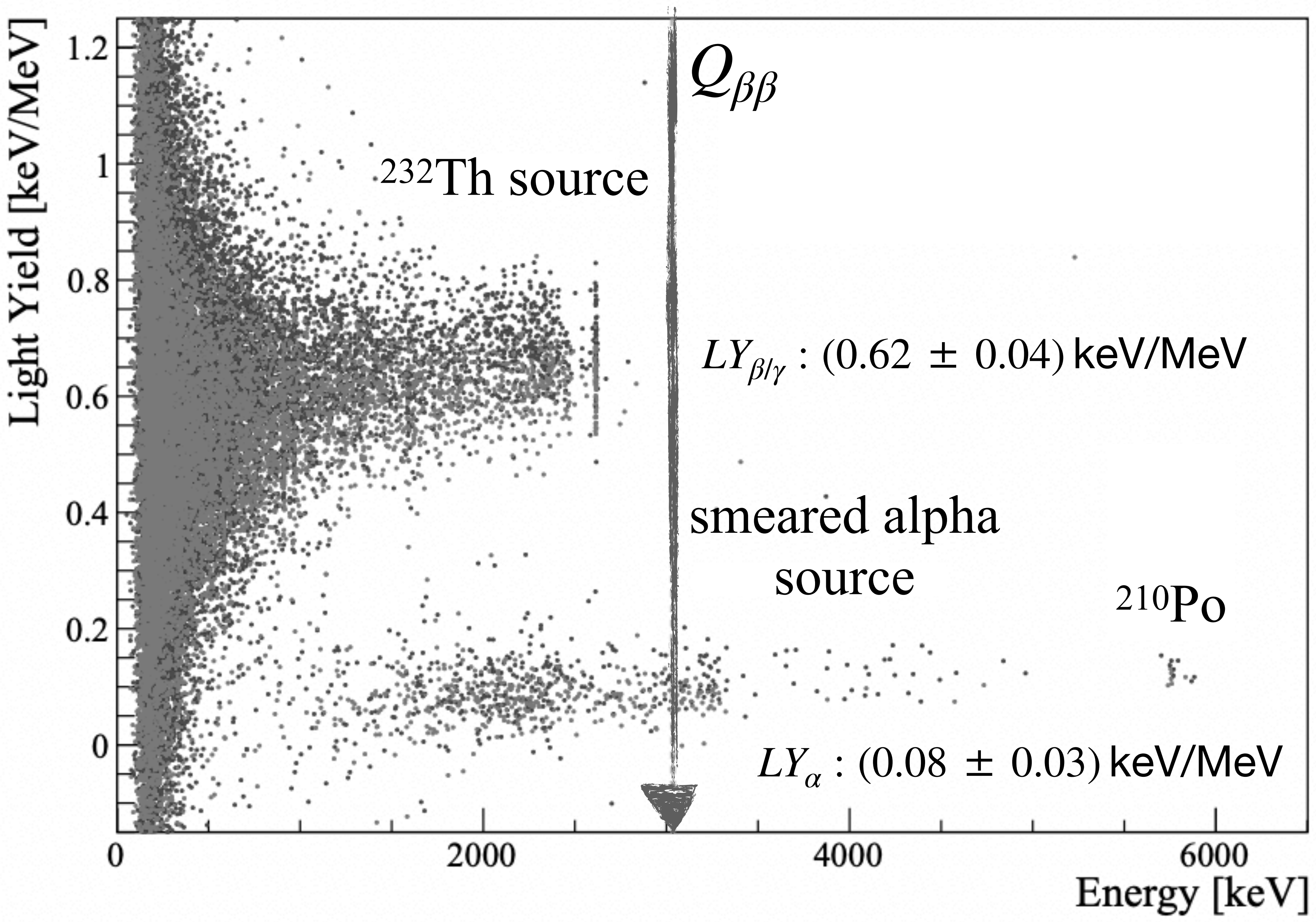
CUPID mini-towers (2021)

Configuration
- 2 mini-towers
  - 2 floors with 2 crystals on each floor
- 8 Li_2MoO_4 crystal bolometers
  - natural Mo
  - cubic (45x45x45 mm^3)
  - 280 g
- 12 Ge light detectors
  - SiO antireflective coating
  - quasi-square
- cryostat (Hall C)
  - LNGS in Italy
  - ~15 mK







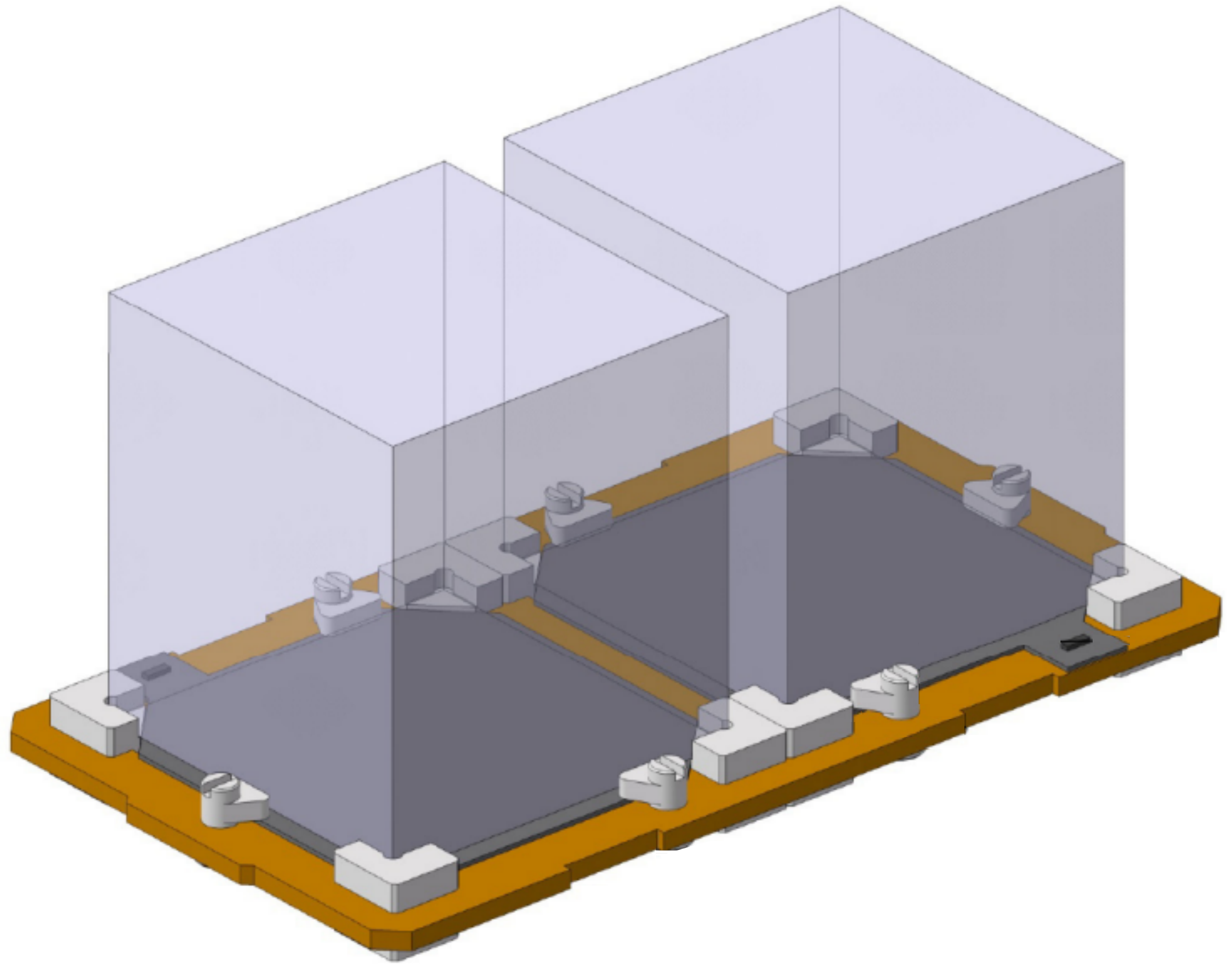
PID Performance
- Discrimination Power (DP)
  - DP (2 LD): 7.3 - 8.2
  - DP (1 LD): 3.9 - 6.2
- > 99.9% α rejection (DP > 3.1)

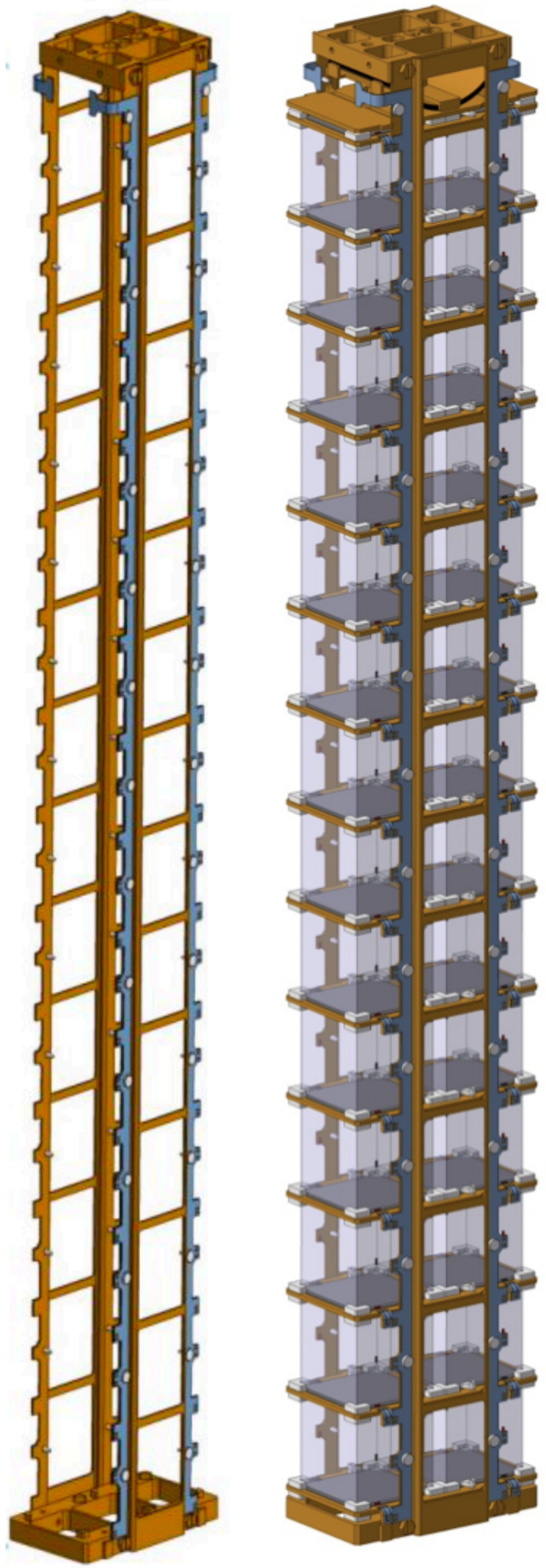
$$DP \equiv \frac{|LY_{\beta/\gamma} - LY_{\alpha}|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}}$$

Eur. Phys. J. C 82, 810 (2022)

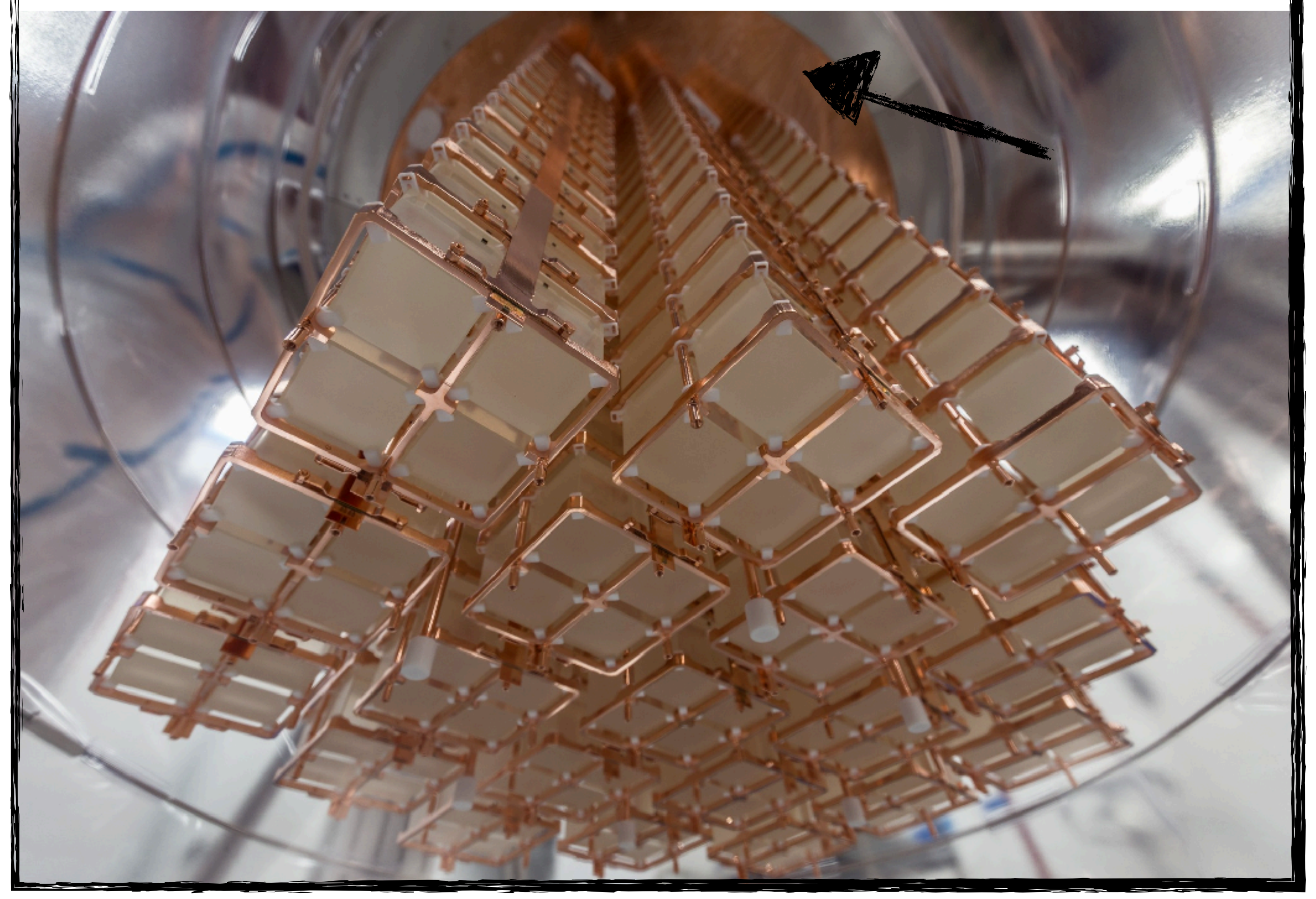
CUPID detector

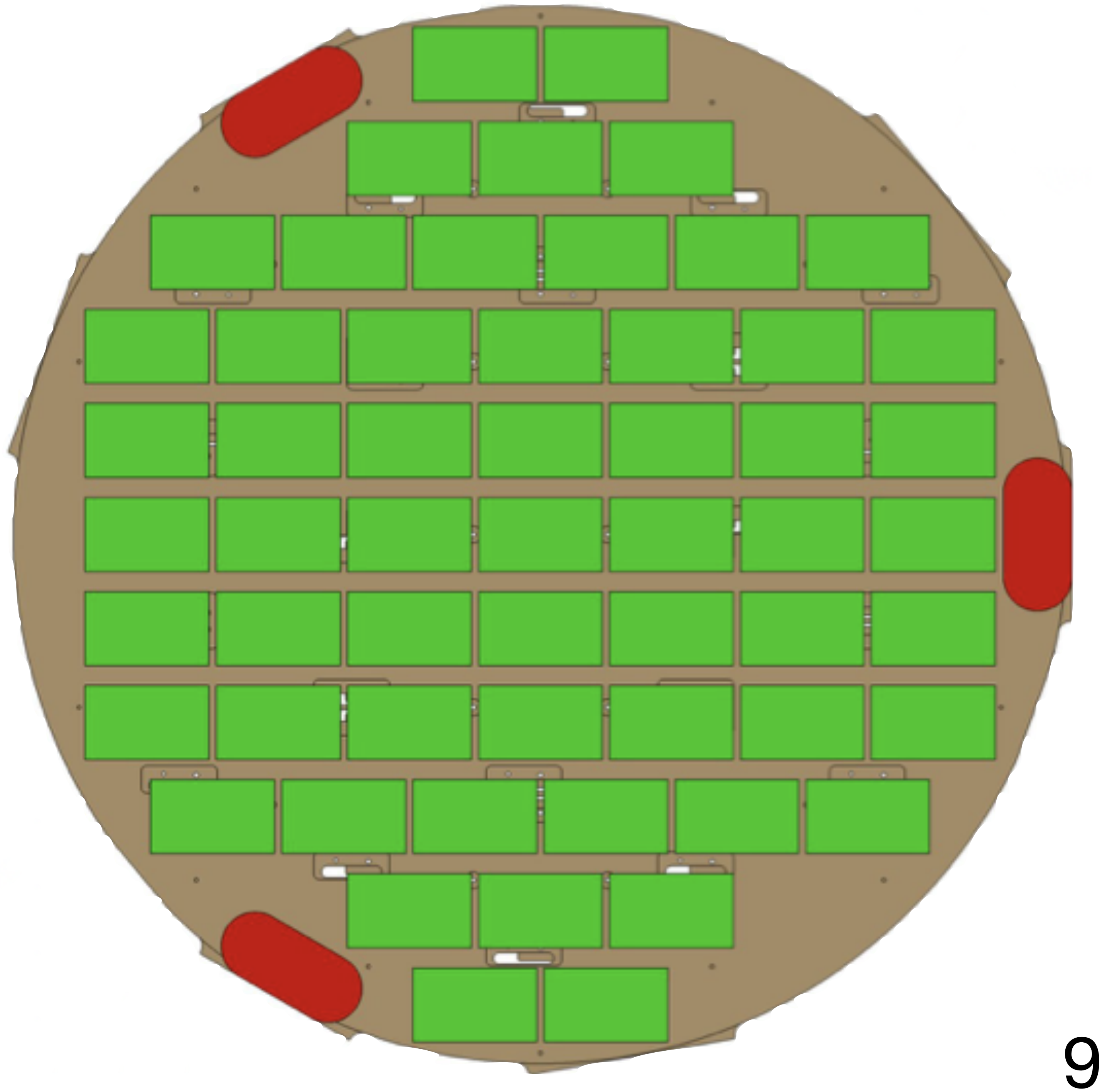
- 57 towers
  - 14 floors with 2 crystals on each floor
- 1596 Li_2MoO_4 crystal bolometers
  - enriched in ^{100}Mo to ~95%
  - cubic (45x45x45 mm^3)
  - 280 g (450 kg Li_2MoO_4, **240 kg ^{100}Mo**)
- 1710 Ge light detectors with SiO
  - quasi-square
- 3306 sensors
  - Ge-NTD
- cryostat (CUORE)
  - ~10 mK





CUORE: 988 crystals arranged in 19 towers with 13 floors of 2x2 crystal array





arxiv:1907.09376

Relevant backgrounds

External (cosmic rays)

- muons

Infrastructure (gammas from $^{238}U/^{232}Th$)

- ^{214}Bi: $E_\gamma > 3034$ keV
- ^{208}Tl: 2615 keV/583 keV cascade decay

Holders (alphas/gammas/betas from $^{238}U/^{232}Th$)

- surface: ^{214}Bi and ^{208}Tl β decays

Crystals

- surface: ^{214}Bi and ^{208}Tl β decays from $^{238}U/^{232}Th$
- ^{100}Mo 2νββ decay pile-up ($T_{1/2} = 7.1 \times 10^{18}$ years)

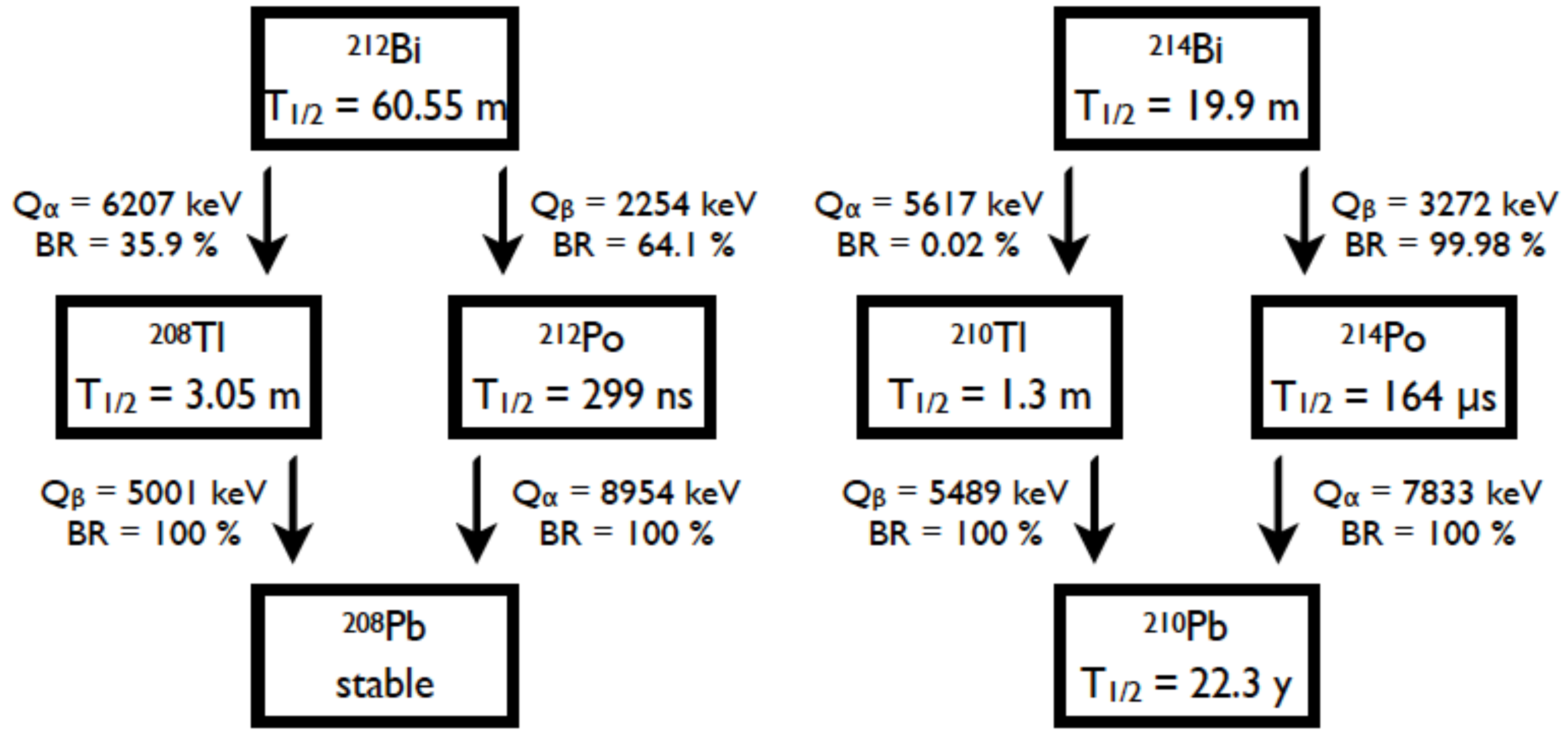
Mitigation strategies

Muons

- muon veto: plastic scintillator panels with SiPMs around and below external shielding (≳ 99% tagging efficiency)

^{214}Bi and ^{208}Tl β decays from $^{238}U/^{232}Th$

- delayed coincidence cut:

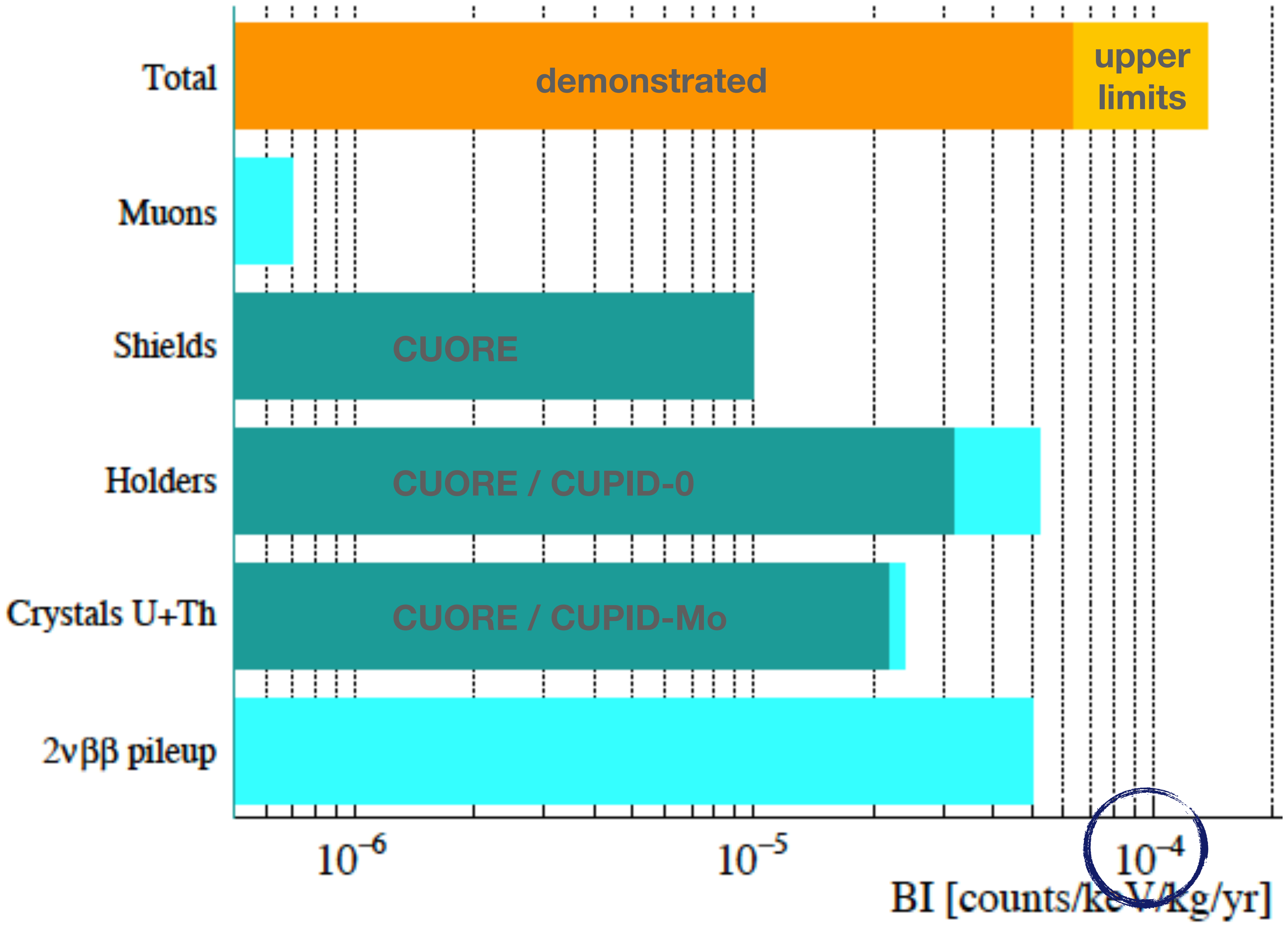


2νββ decay pile-up

- improve timing resolution: decrease rise time and/or increase SNR
- smaller LD NTDs (lower heat capacity)

arxiv:1907.09376

Projected background index



Informed by data-driven background models of CUPID demonstrators and CUORE:

Shields

- CUORE cryostat

Holders

- CUORE/CUPID-0 Cu and PTFE material and surface treatment

Crystals

- surface: CUORE (surface treatment)
- bulk: CUPID-Mo (crystal production)

Conservative: Does not account for planned improvements that are expected to reduce the BI

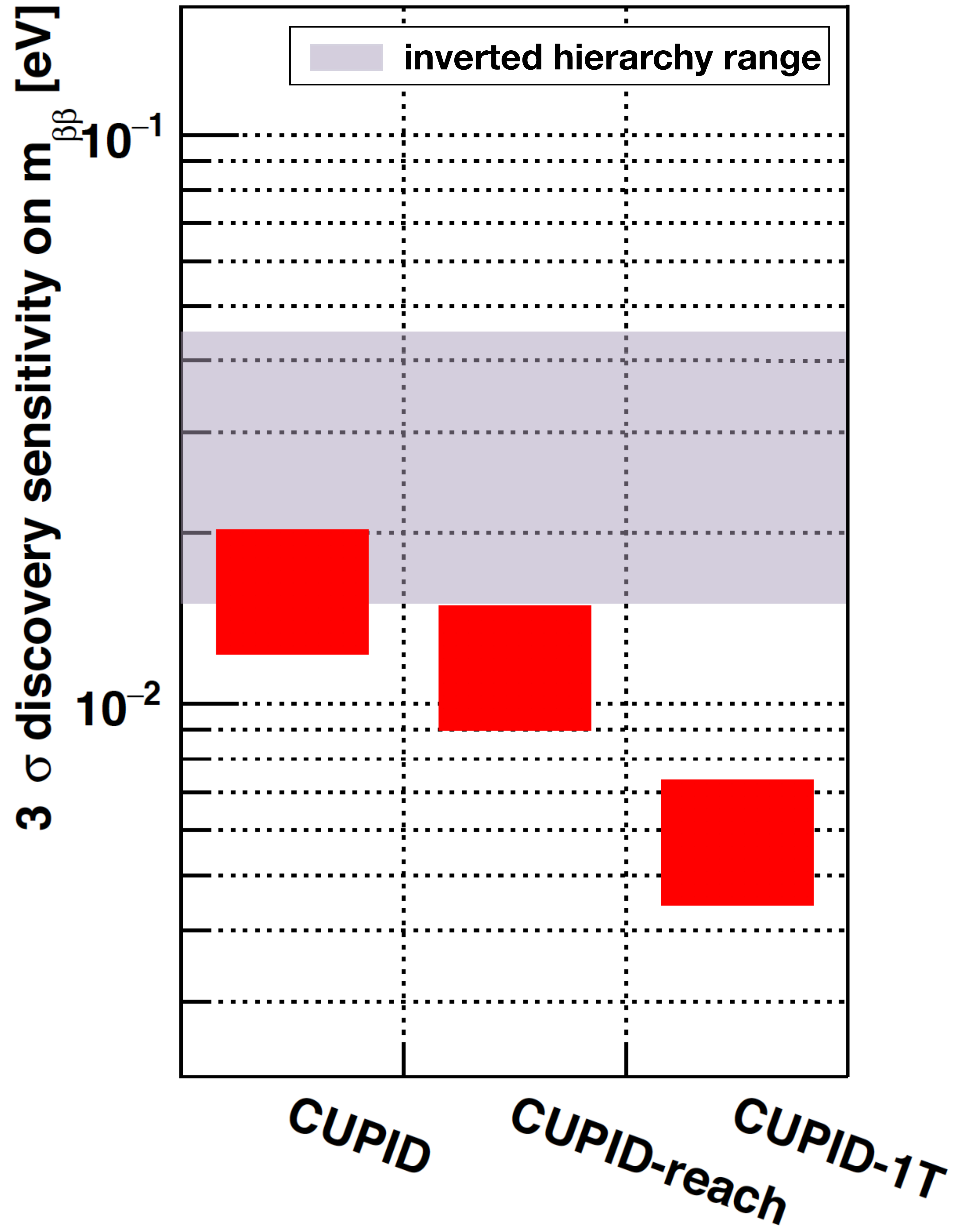
arxiv:1907.09376

CUPID-1T

discussed

feasible with developed technologies

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



<u>CUPID-1T</u>

- 4x scale up — larger or multiple cryostat(s)
- ambitious, but feasible within the next decade with emerging technologies
- could also be used to explore other multiple isotopes in parallel

arxiv:1907.09376

Summary

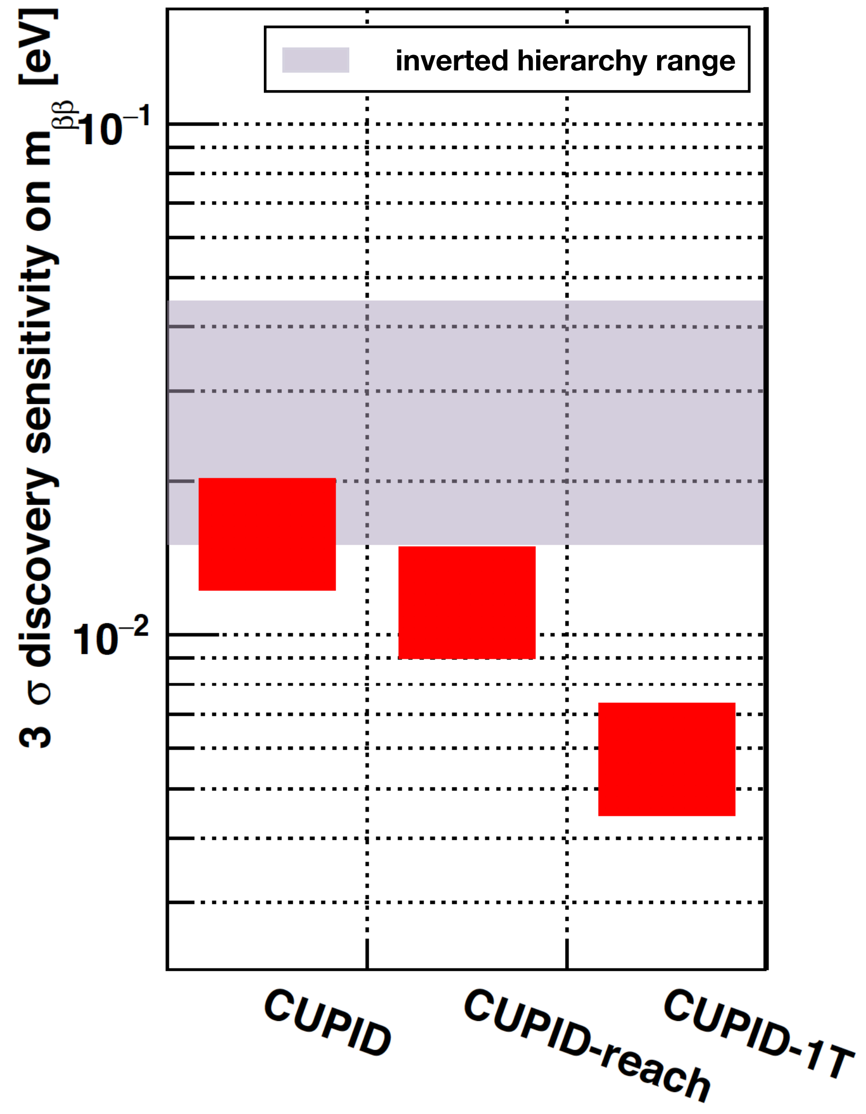
- CUPID baseline sensitivity (3σ):

$$T^{0\nu}_{1/2} : 10^{27}\, yr\,, \qquad m_{\beta\beta} : 12 - 20\, meV$$

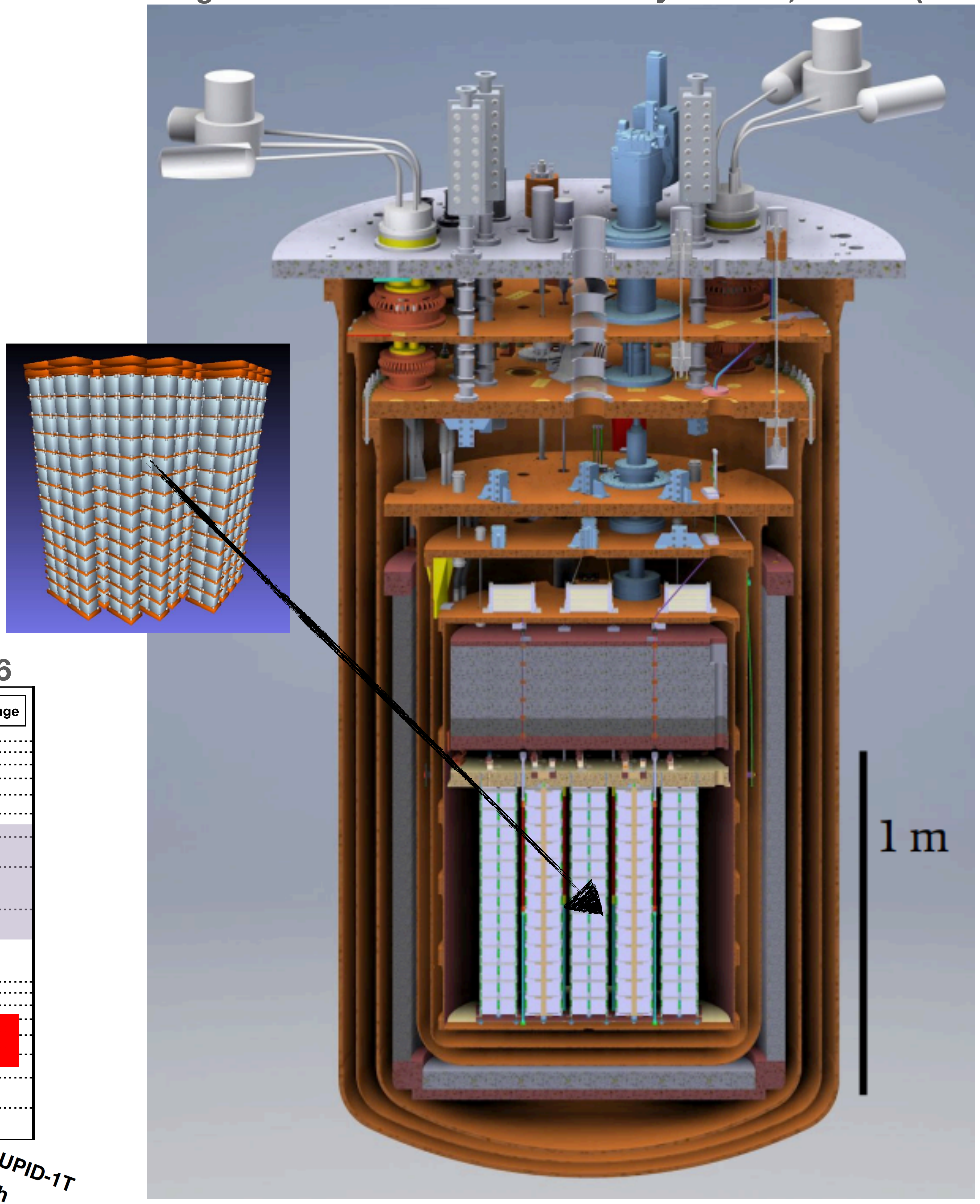
- CUPID can achieve this with existing detector technology and infrastructure

- CUPID-1T concept:
  - inverted hierarchy precision measurement device across multiple isotopes (discovery)
  - probe into the normal hierarchy range (exclusion)

arxiv:1907.09376



Progress in Particle and Nuclear Physics 122, 103902 (2022)



CUPID Collaboration

cnrs IN2P3
NRC KI-ITEP
Università degli Studi di Milano Bicocca
iP2i
Beijing Normal University 1902
Shanghai Jiao Tong University
University of California 1868
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UCLA
IJCLab Irène Joliot-Curie
Johns Hopkins University
Argonne National Laboratory
Cal Poly
Université de Lyon
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Berkeley Lab
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CUPID
Massachusetts Institute of Technology
Northwestern
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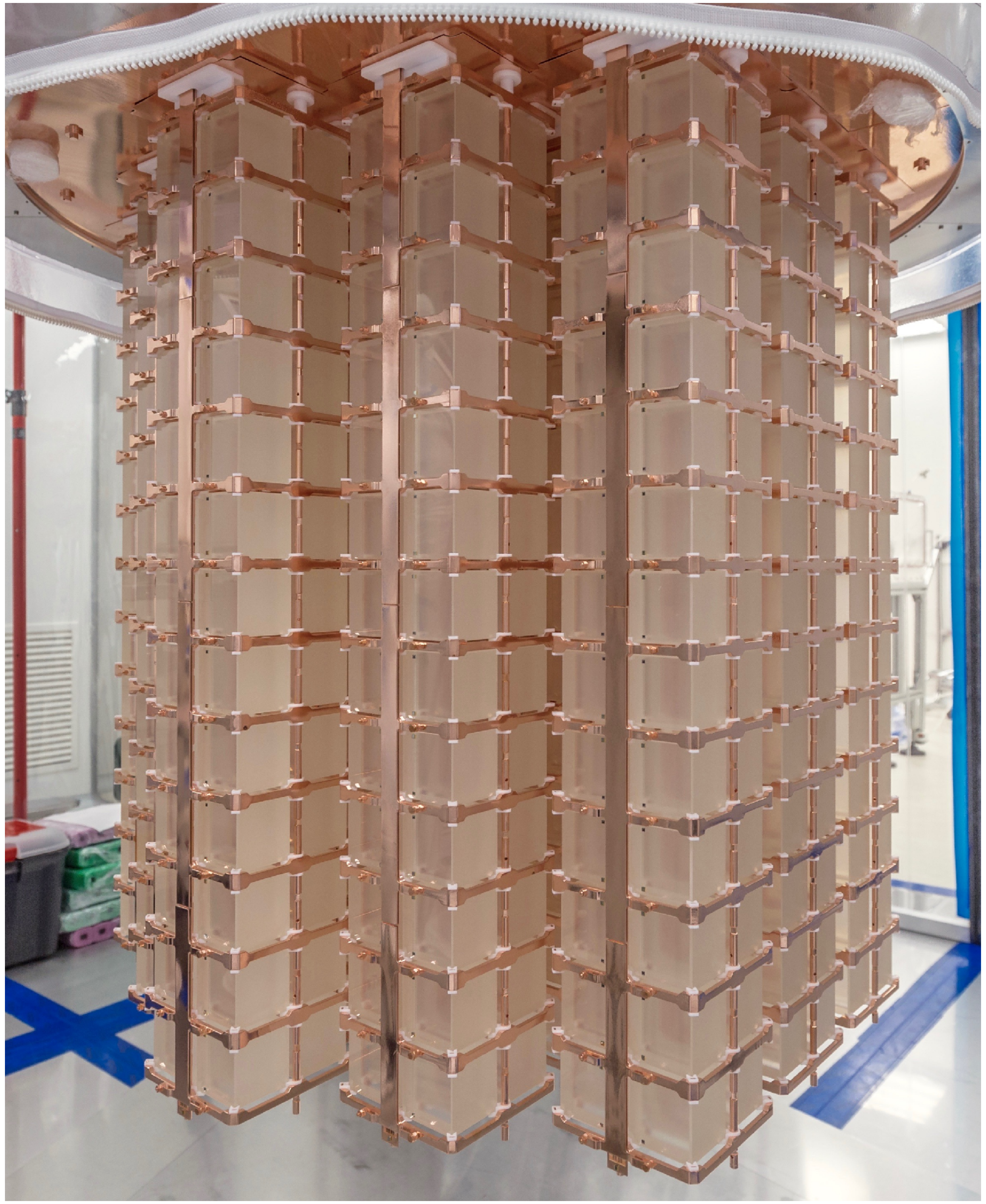
Yale
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
Boston University
Drexel University
GSSI

CUORE

- 19 towers
    - 13 floors with 4 crystals on each floor
- 988 TeO_2 crystal bolometers
    - ^{130}Te isotopic abundance ~34%
    - 280 g (742 kg TeO_2, 206 kg ^{130}Te)
    - cubic (5x5x5 cm^3)
- cryostat (CUORE)
    - ~10 mK



exposure: 1038.4 kg·yr TeO_2 (288.8 kg·yr ^{130}Te)

BI: 1.49×10^{-2} counts/(keV·kg·yr)

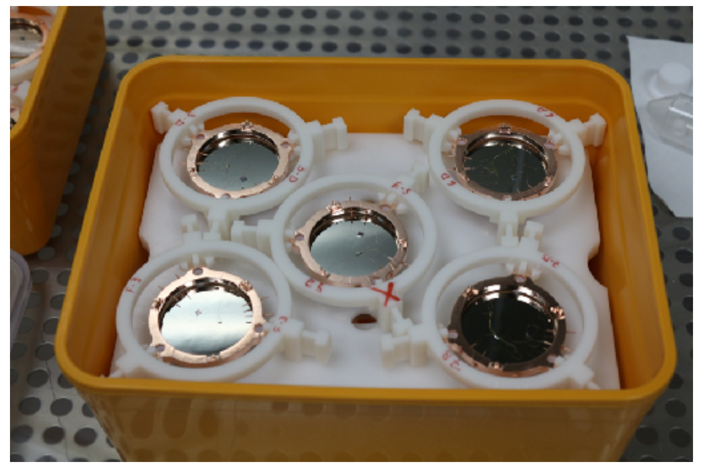
resolution: 7.8 keV (FWHM)

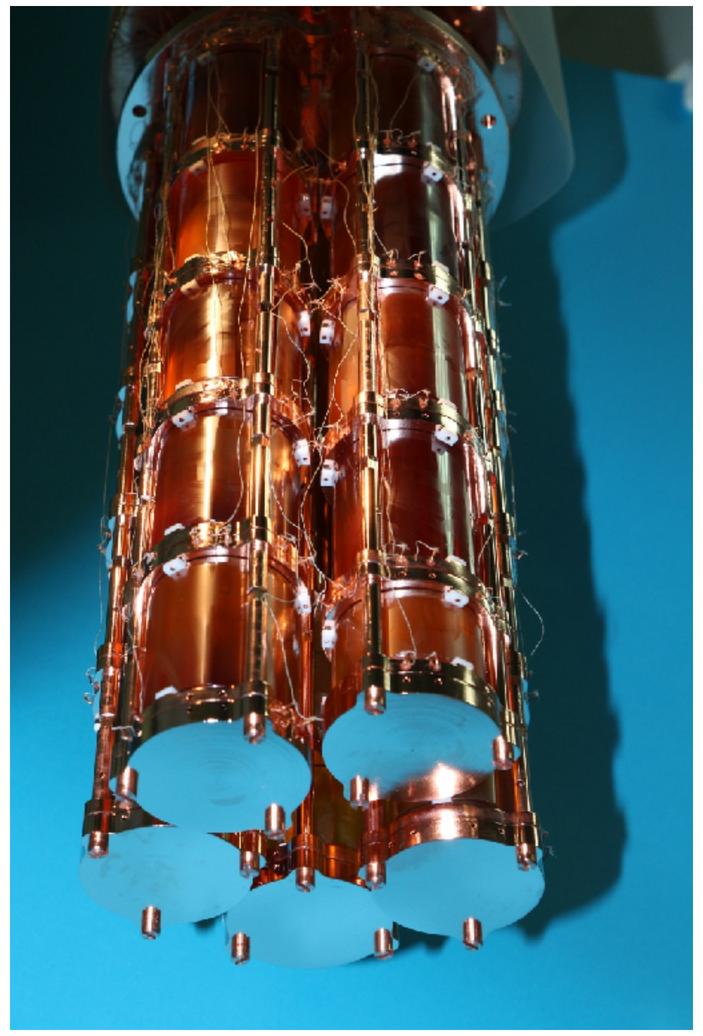
$$T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ years\ (90\%\ C.I.)$$
$$\langle m_{\beta\beta} \rangle < 90 - 305\ meV$$

Nature 604, 53-58 (2022)

Scintillating bolometers R&D

Phys. Rev. Lett. 129, 111801 (2022)



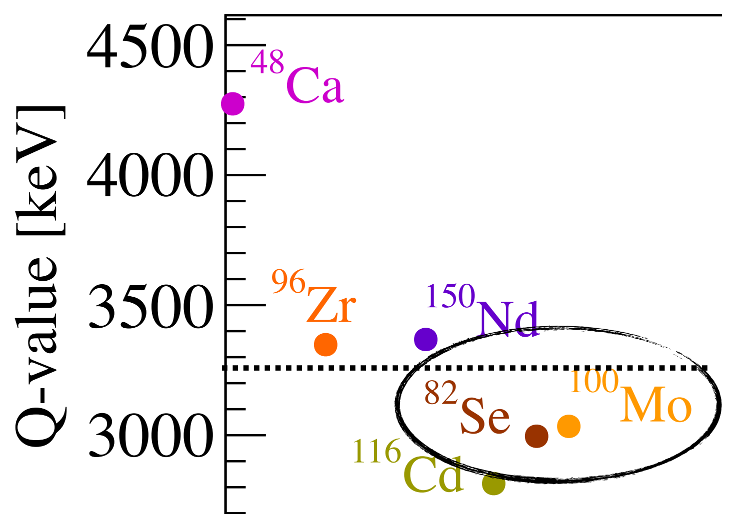


The first array of enriched scintillating bolometers for 0νββ decay investigations

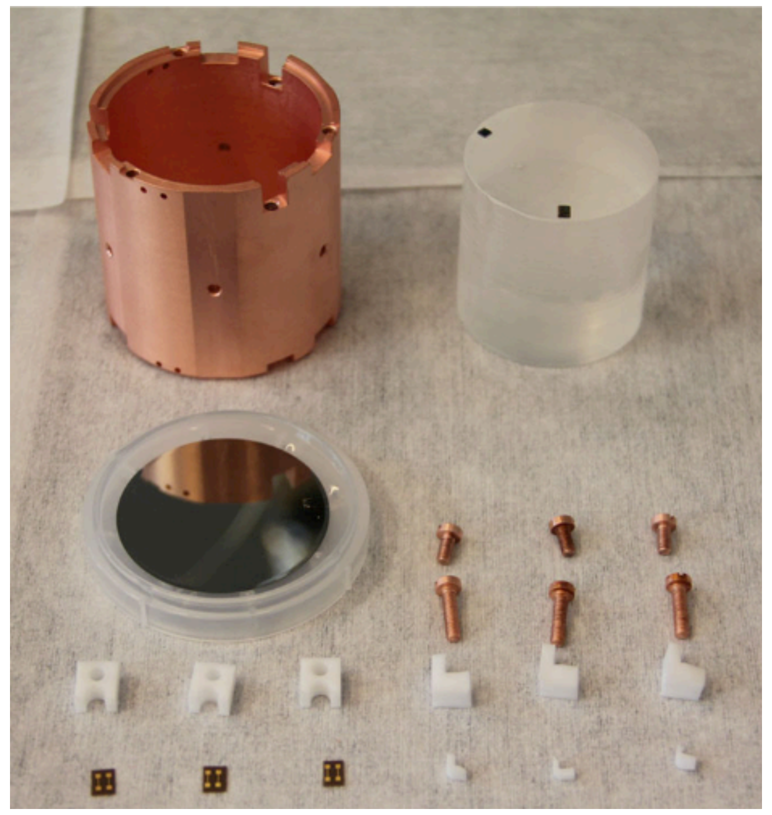
CUPID-0 (2017-18, 2019-20): $Zn^{82}Se$

- LUCIFER: ZnSe / $ZnMoO_4$
- Mass: 10.5 kg (5.17 kg ^{82}Se)
- Exposure: 16.59 kg·yr (8.82 kg·yr ^{82}Se)
- BI: O(10^{-3}) counts/(keV·kg·yr)
- Resolution: 21.8 keV (FWHM)

$$T^{0\nu}_{1/2} > 4.6 \times 10^{24}\, yr\ (90\%\ C.I.)$$
$$\langle m_{\beta\beta} \rangle < 263 - 545\ meV$$



- **$Li_2{}^{100}MoO_4$ (enriched in ^{100}Mo to ~95%)**
  - **high reproducibility**
  - **high optical quality**
  - **good energy resolution**
  - **negligible bulk contamination**
- **cubic crystal geometry**
  - **close-packed array**
  - **higher anti-coincidence efficiency**
- **no reflective foil**
- **quasi-square light detector**
  - **more light yield compared to round**
- **holders (copper frame + PTFE)**
  - **less complicated with less passive material**



CUPID-Mo (2019 — 2020): $Li_2{}^{100}MoO_4$

- LUMINEU: Li_2MoO_4 / $ZnMoO_4$
- Mass: 4.16 kg (2.26 kg ^{100}Mo)
- Exposure: 2.71 kg·yr (1.47 kg·yr ^{100}Mo)
- BI: O(10^{-3}) counts/(keV·kg·yr)
- Resolution: 7.4 keV (FWHM)

$$T^{0\nu}_{1/2} > 1.8 \times 10^{24}\, yr\ (90\%\ C.I.)$$
$$\langle m_{\beta\beta} \rangle < 0.28 - 0.49\ eV$$

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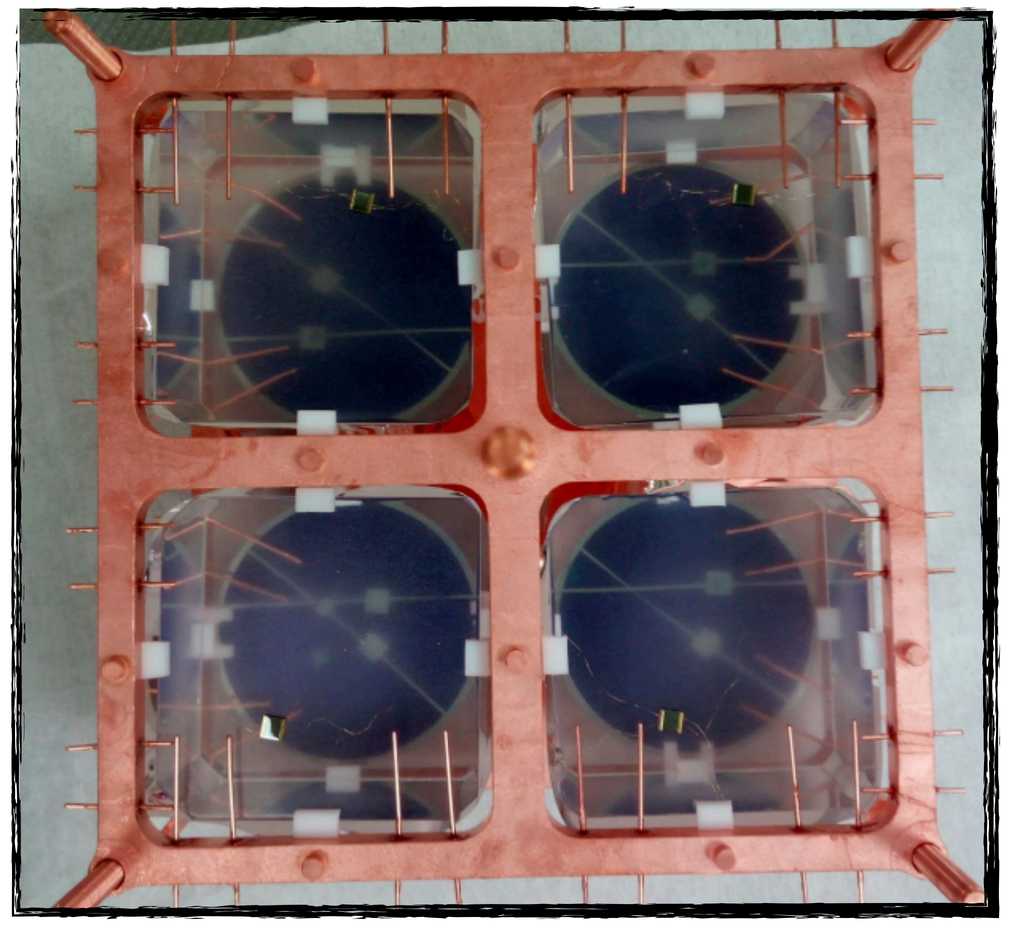
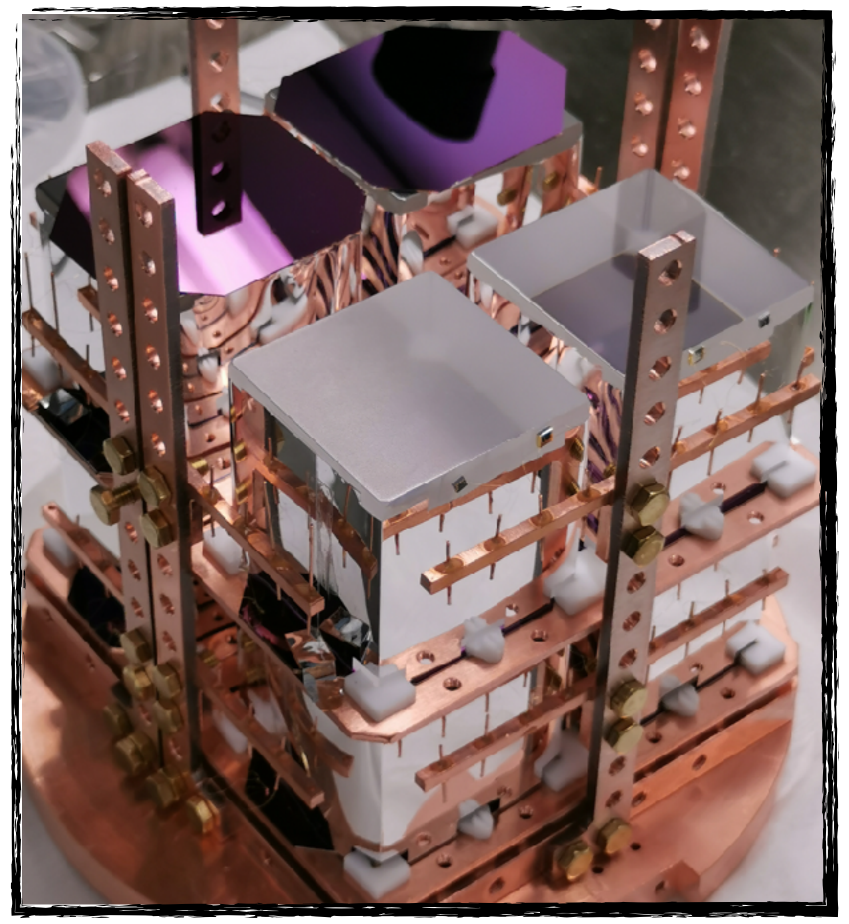


Eur. Phys. J. C 81, 104 (2021)



Eur. Phys. J. C 82, 810 (2022)

Isotope Procurement / Crystal Production

- We are working with several potential vendors to explore isotope production for CUPID. Some of the discussions are covered by non-disclosure agreements (NDA).
- This includes established vendors and new production facilities.
- We are considering all options that are viable for Italy and the US.
- The collaboration has experience with crystal production from CUORE, CUPID-0, and CUPID-Mo.
- We are testing crystals from multiple vendors and expect to have baseline and alternative vendors defined by DOE CD-1 review in late 2023.