Search for $0\nu\beta\beta$ with CUPID

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(for the CUPID collaboration)

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Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

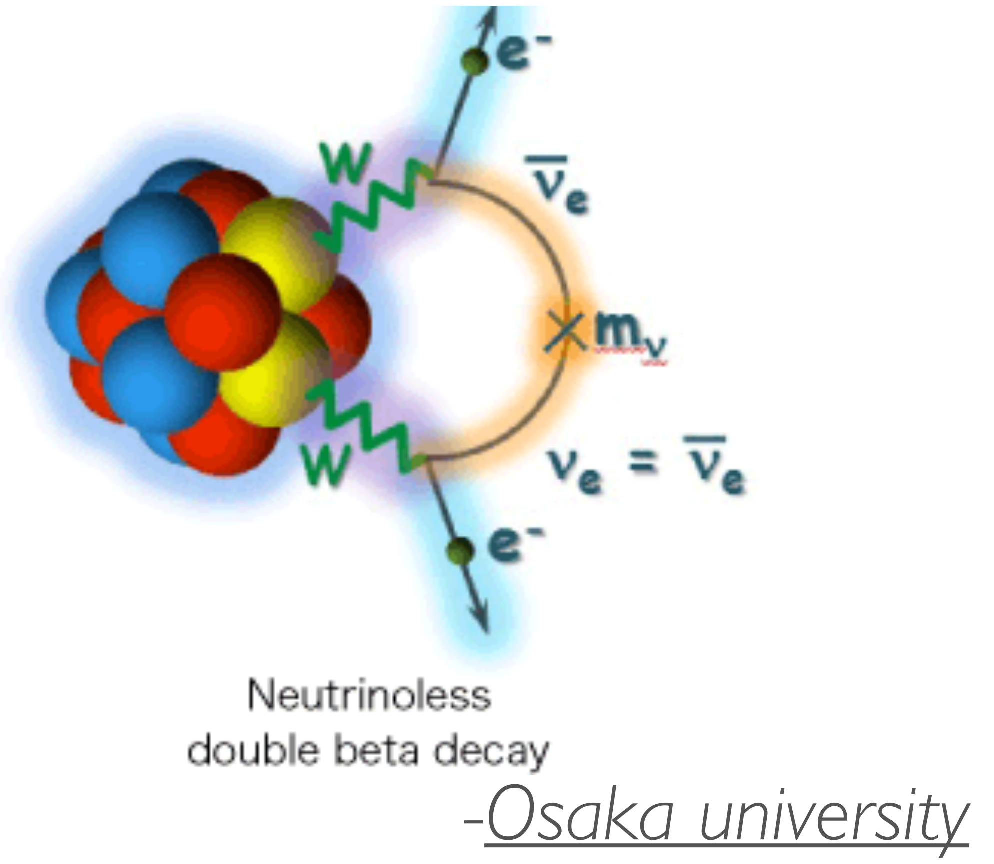
- Hypothesized nuclear process
- If observed, it implies:
  - ν has Majorana mass term
  - Lepton number violation
  - Hints to matter-antimatter asymmetry
- $0\nu\beta\beta$ experiments measure half-life (or decay rate)
- Constrain the ν mass and ordering

$$\langle m_{\beta\beta}\rangle = \left|\sum_j m_j U_{ej}^2\right|$$

Nuclear Matrix elements

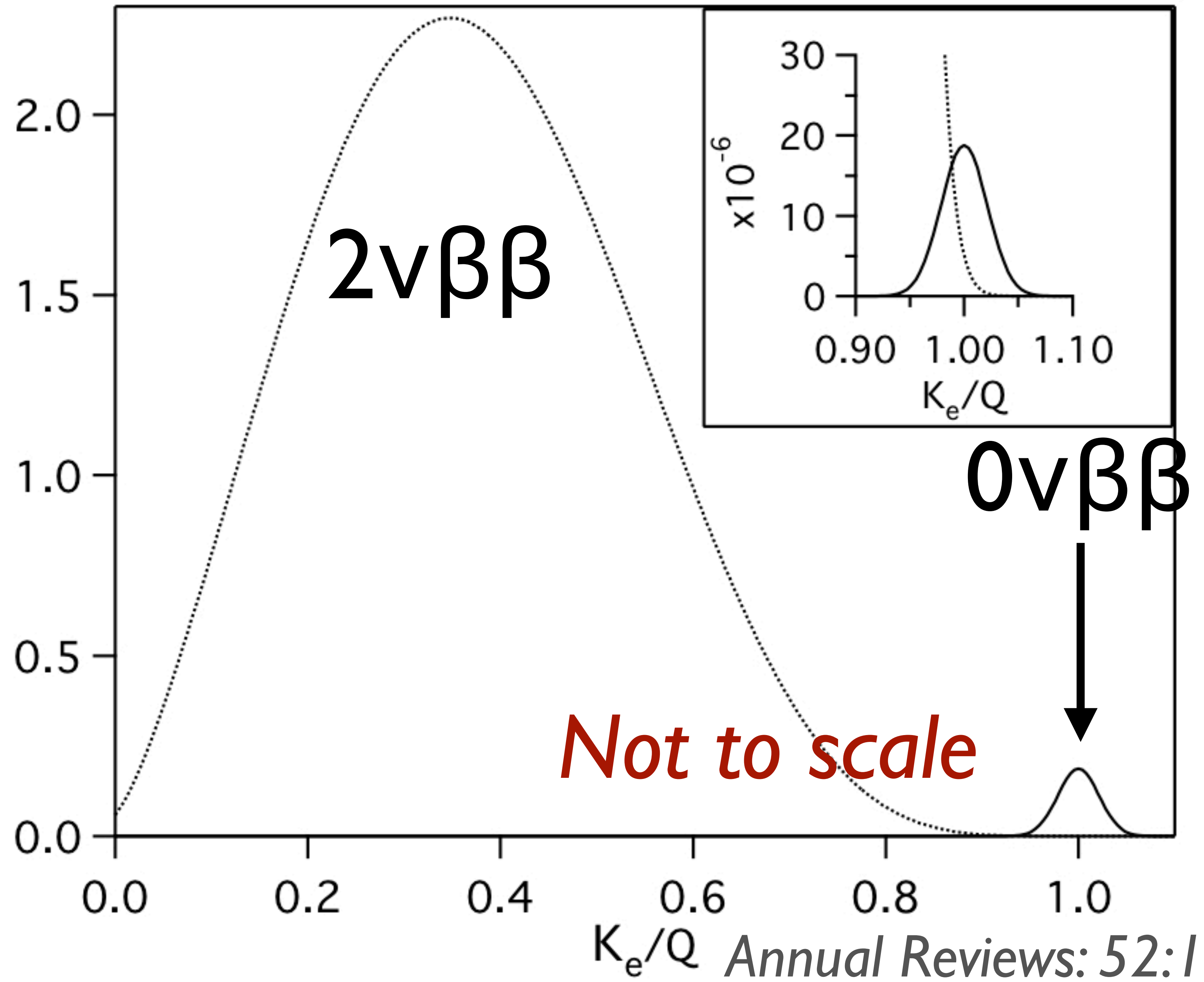
$$T_{1/2}^{0\nu} \propto \left(G|\mathcal{M}|^2 \langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \mathrm{y}$$

Phase space factor — Effective neutrino mass



Neutrinoless double beta decay

-Osaka university



Annual Reviews: 52:115-151

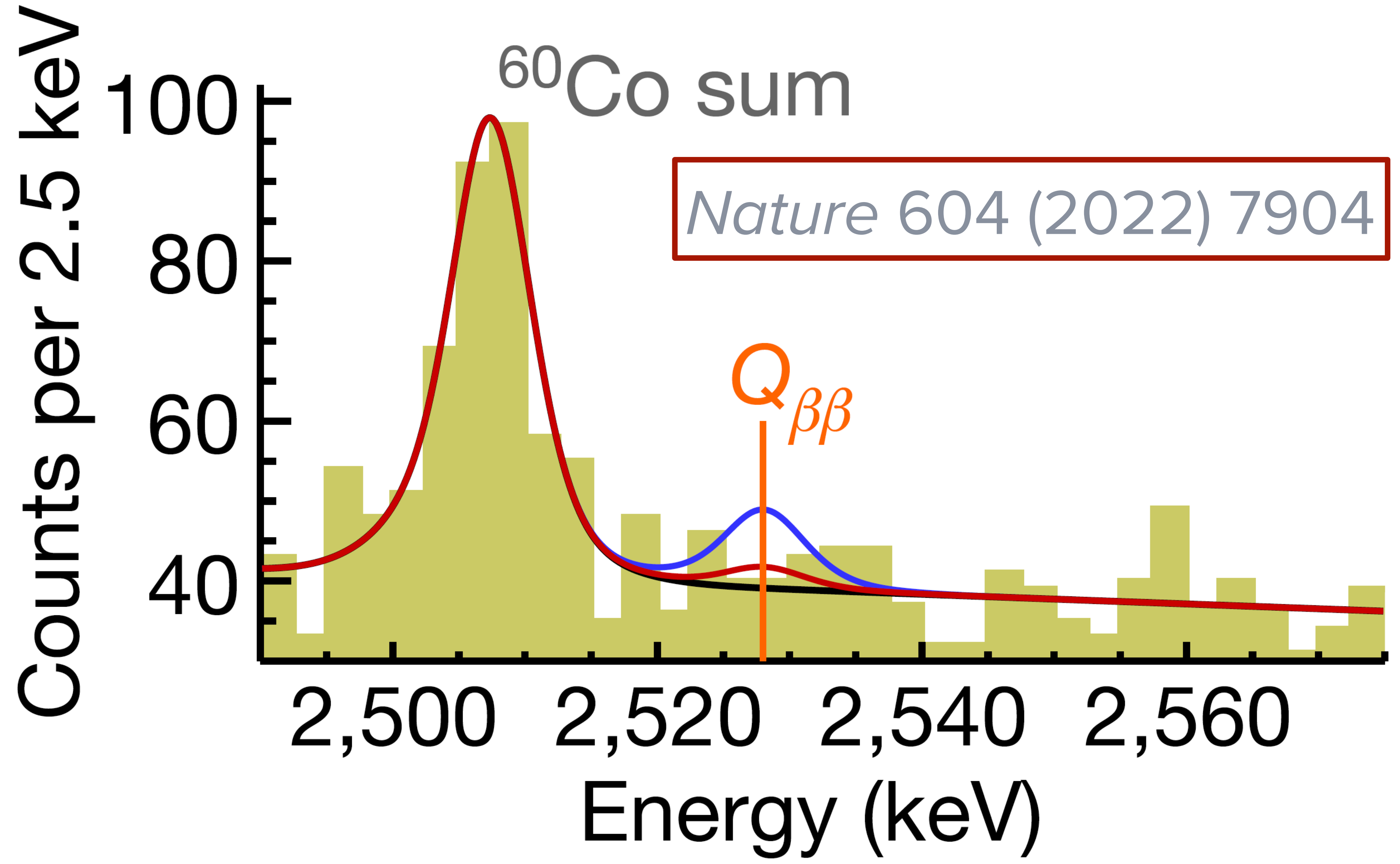
Important to observe $0\nu\beta\beta$ in multiple isotopes

CUORE: Cryogenic Underground Observatory for Rare Events

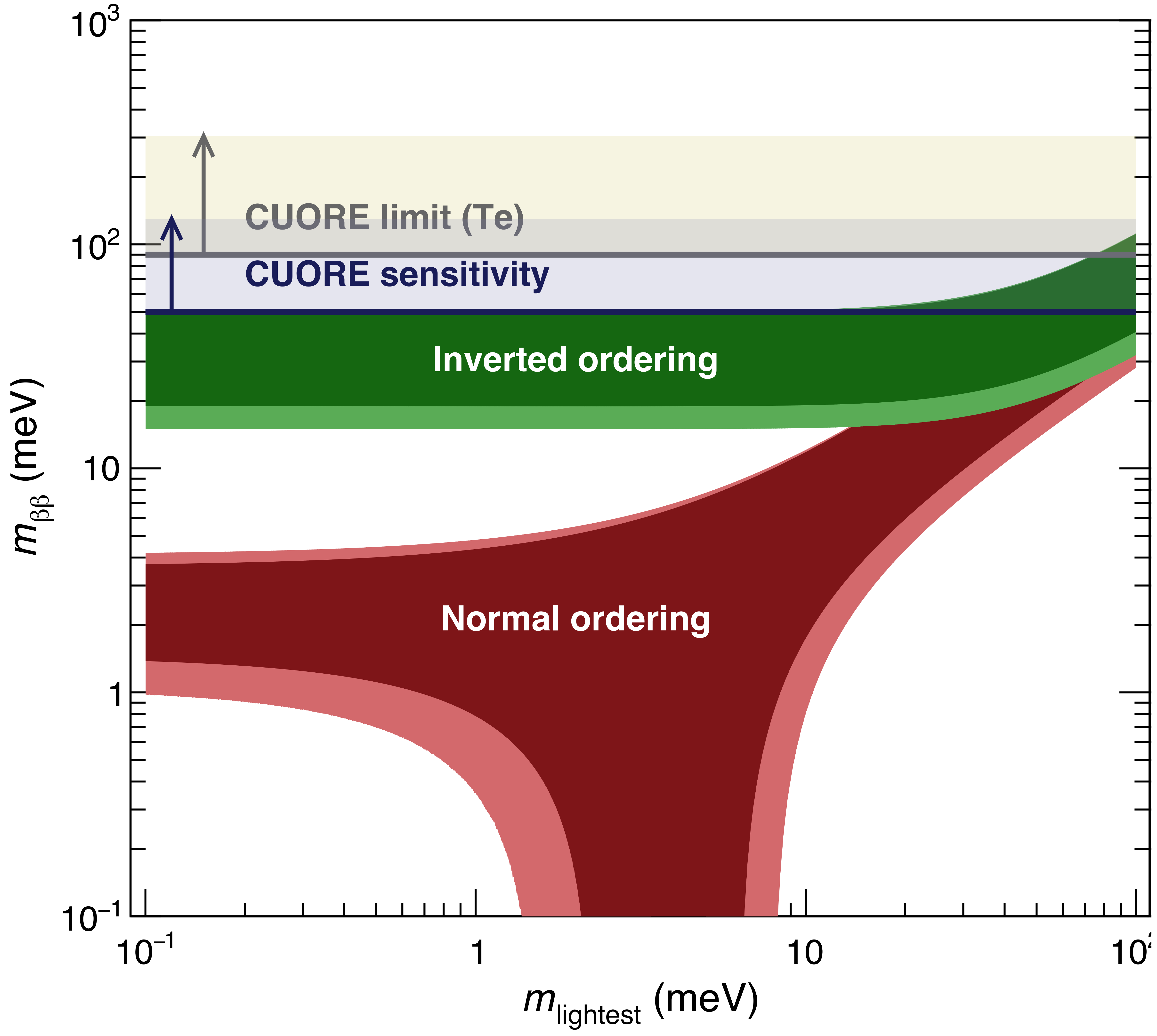
- Located in LNGS under the mountain of Gran Sasso
- **Primary Goal:** Search for $0\nu\beta\beta$ decay in ^{130}Te
- **Design:**
  - 19 towers (total of 988 TeO_2 crystals)
  - *Large mass:* 742 kg of TeO_2 ,206 kg of ^{130}Te
    - $Q_{\beta\beta}$ (2528 keV) - above most γ natural radioactivity
  - *Low backgrounds measured:* 1.49×10^{-2} cts/(keV. kg. yr)
  - *Energy resolution:* Goal of 7.8 keV FWHM at $Q_{\beta\beta}$

CUORE is the first tonne-scale bolometric $0\nu\beta\beta$ decay experiment

CUORE Limits

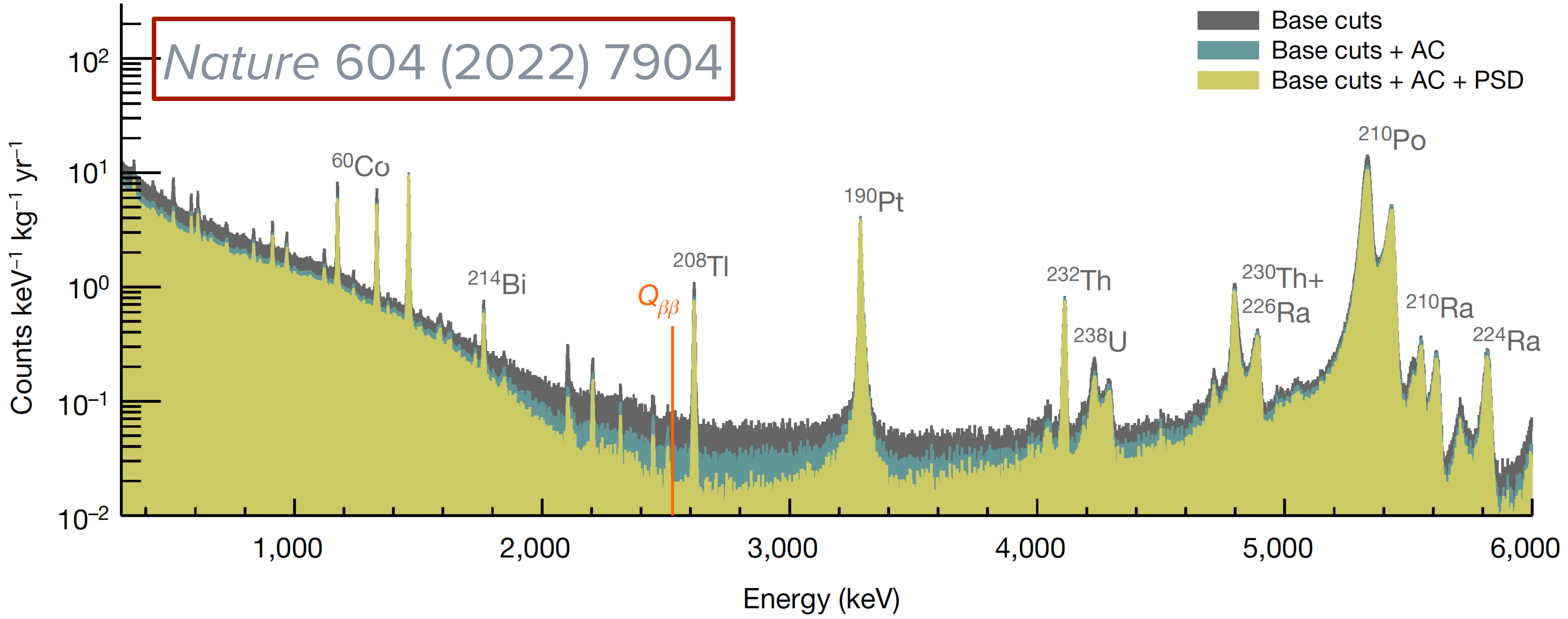


- $T^{0\nu}_{1/2}$ > **2.2 x10^{25}** yr at 90% C.I
- Assuming light neutrino exchange:
  $m_{\beta\beta}$ < **90 - 305 meV**
- Sensitivity (5 yr data taking):
  ^{130}Te $T^{0\nu}_{1/2}$ > **9.0 x10^{25}** yr
  $m_{\beta\beta}$ < **50 - 130 meV**



Backgrounds in CUORE

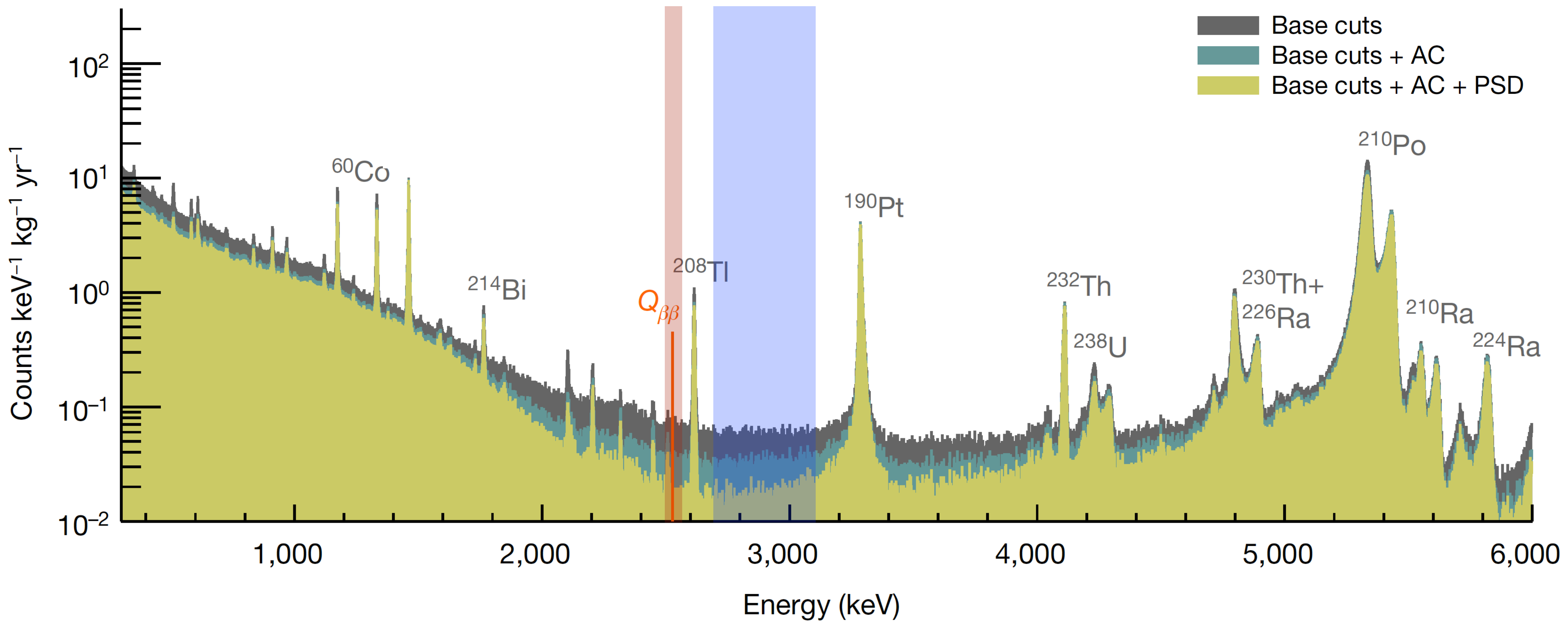
- Below 2615 keV γ/β+α
- Above 2615 keV, primarily from αs (U/Th contamination)

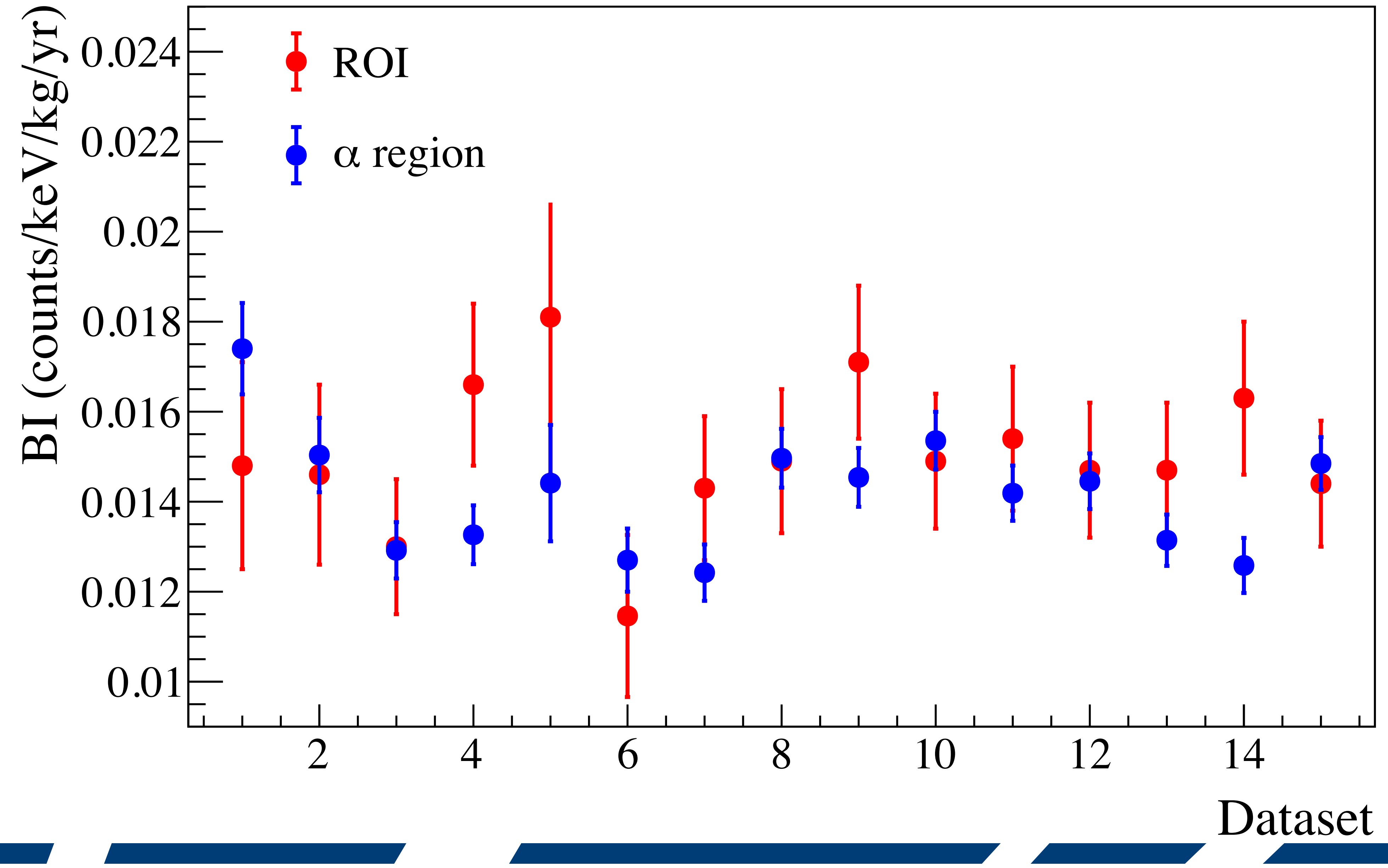


Significant background reduction crucial to improve sensitivity to $0\nu\beta\beta$

Backgrounds in CUORE

- Below 2615 keV γ/β+α
- Above 2615 keV, primarily from αs (U/Th contamination)
- BI in ROI: **1.49(4)x10^{-2}** ckky
- BI in Alpha region: **1.40(2)x10^{-2}** ckky
- **Backgrounds in ROI are dominated by alphas**





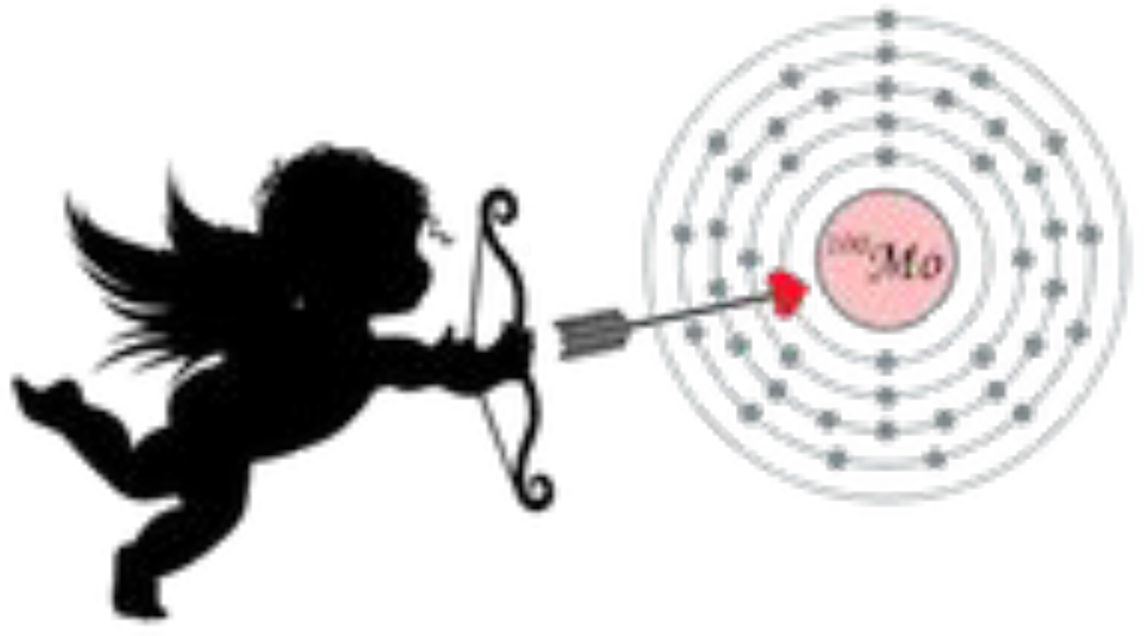
Significant background reduction crucial to improve sensitivity to $0\nu\beta\beta$

CUORE Upgrade with Particle Identification

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

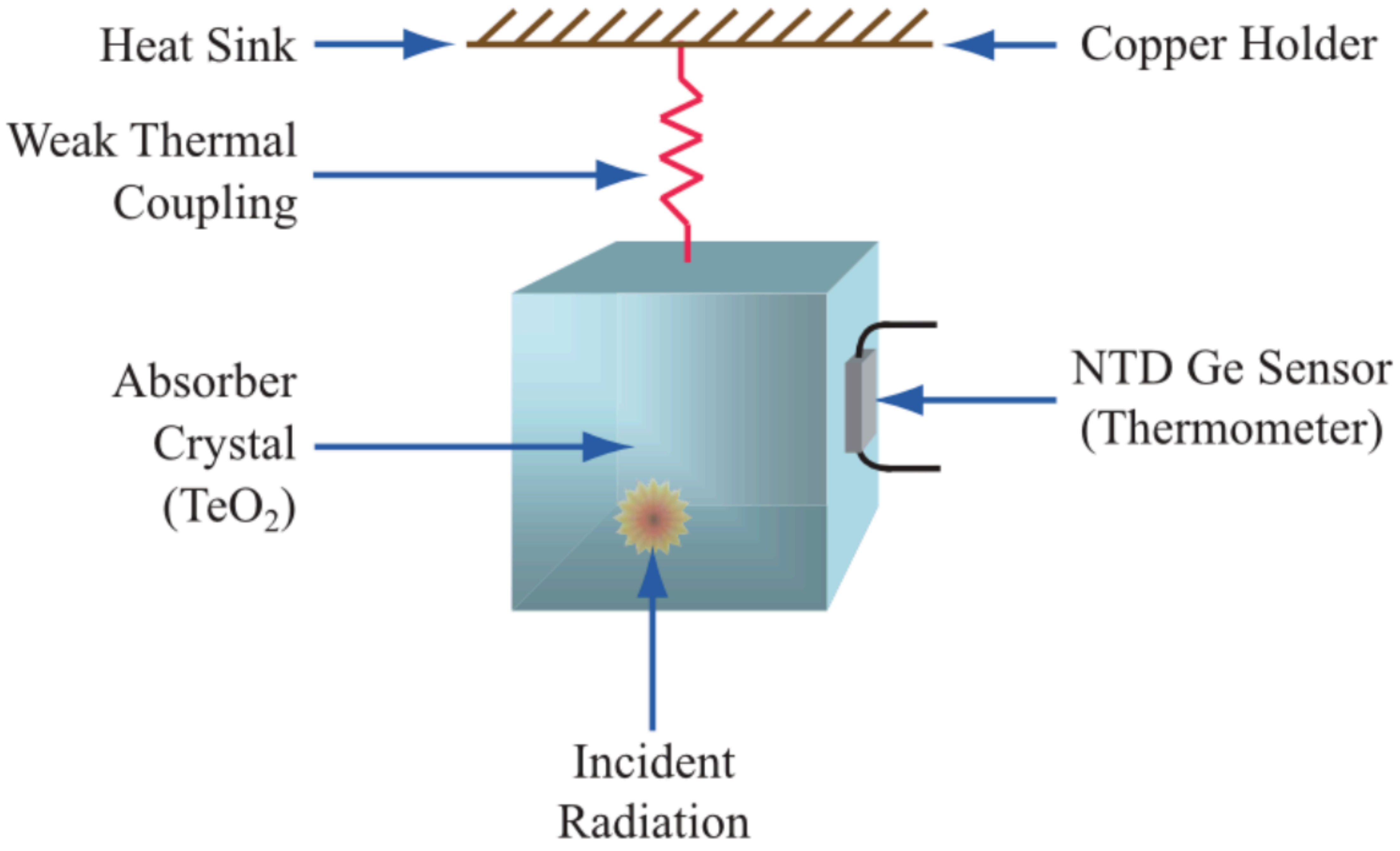
Leverage large-scale cryogenic infrastructure and long-lasting operational experience at LNGS

Build on the expertise in running bolometric experiments with particle identification



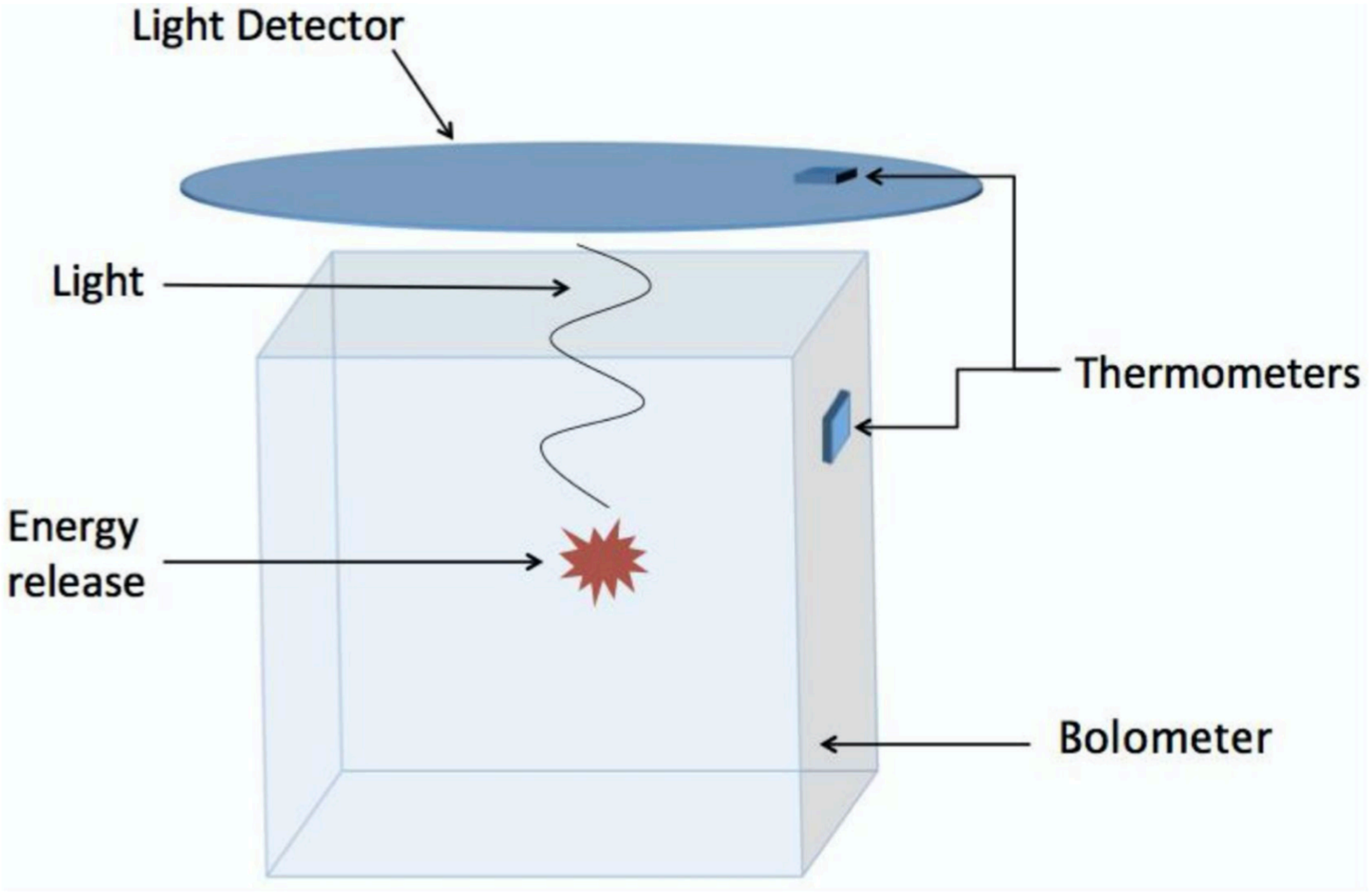
CUPID Technology

CUORE ^{130}Te Bolometer



$Q_{\beta\beta}$ = 2527 keV < 2615 keV peak
Measure only heat
No particle ID

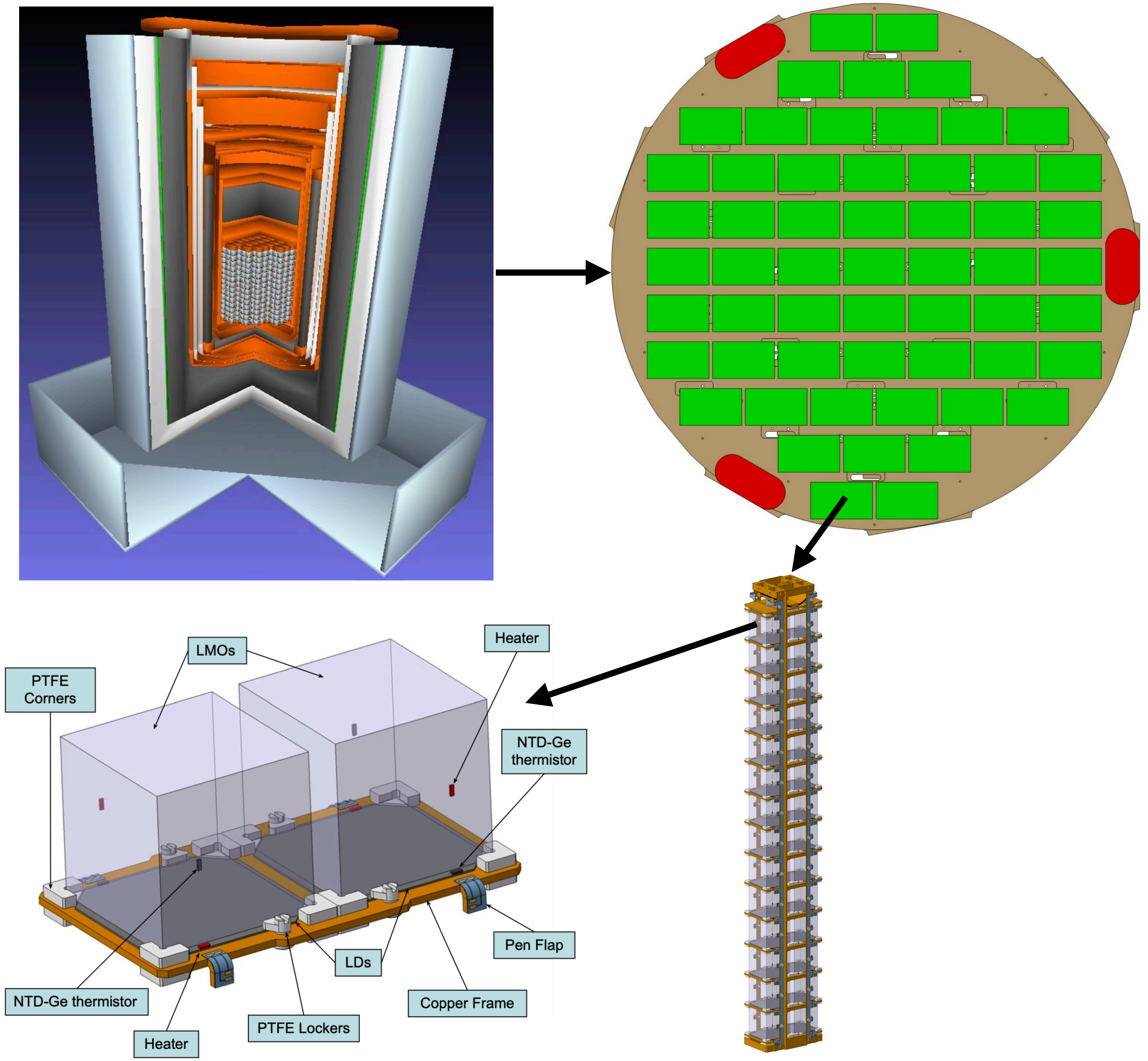
CUPID ^{100}Mo Scintillating Bolometer



$Q_{\beta\beta}$ = 3034 keV: Most β/γ backgrounds reduced
Measure both heat + light
Particle ID to actively discriminate αs

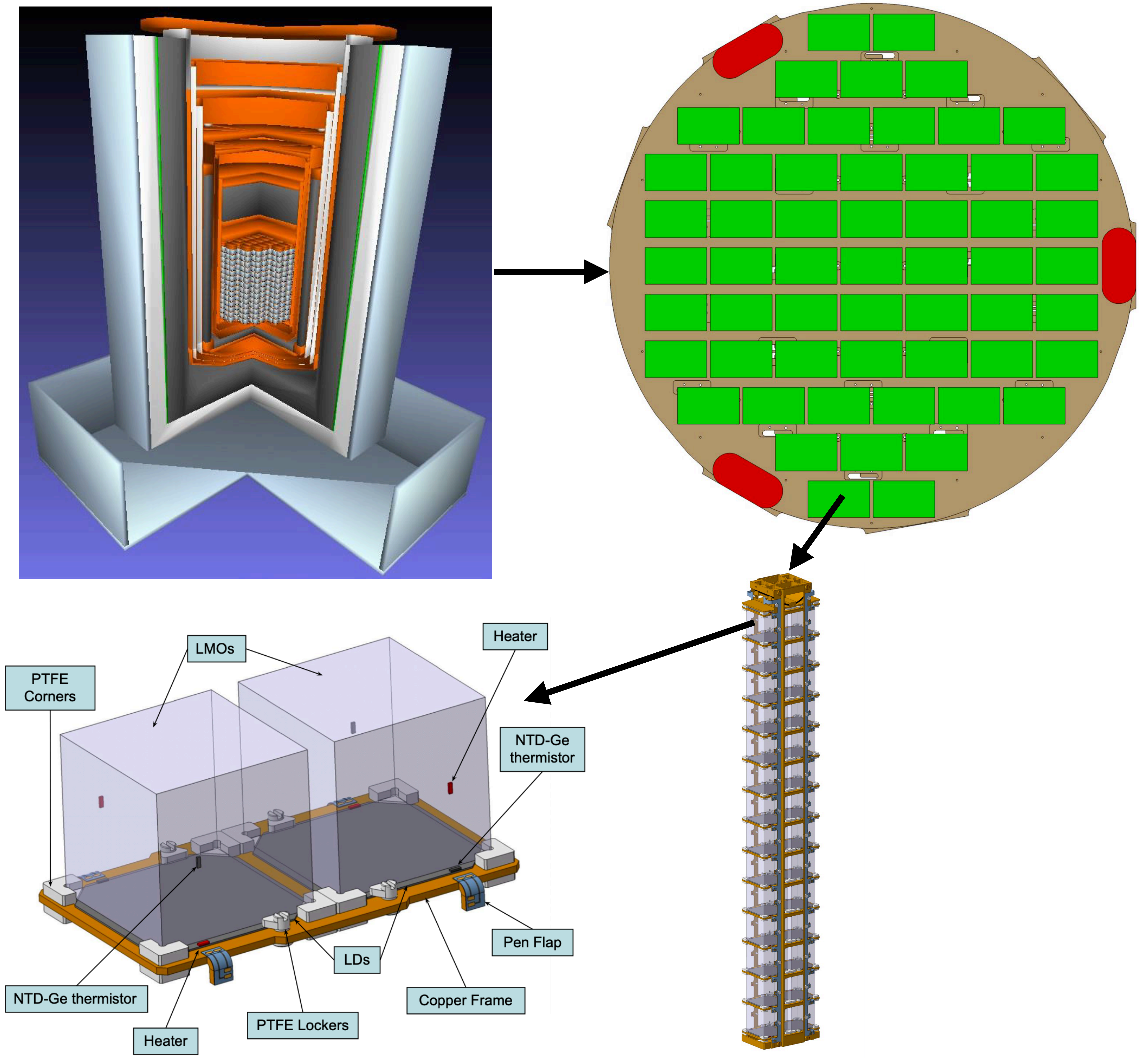
CUPID Concept

- Single detector:
  - $Li_2{}^{100}MoO_4$ with >95% enrichment
  - 45x45x45 mm; 280 g each
  - Ge light detector
- Detector array:
  - 57 towers (total of 1596 crystals)
  - 240 kg of ^{100}Mo



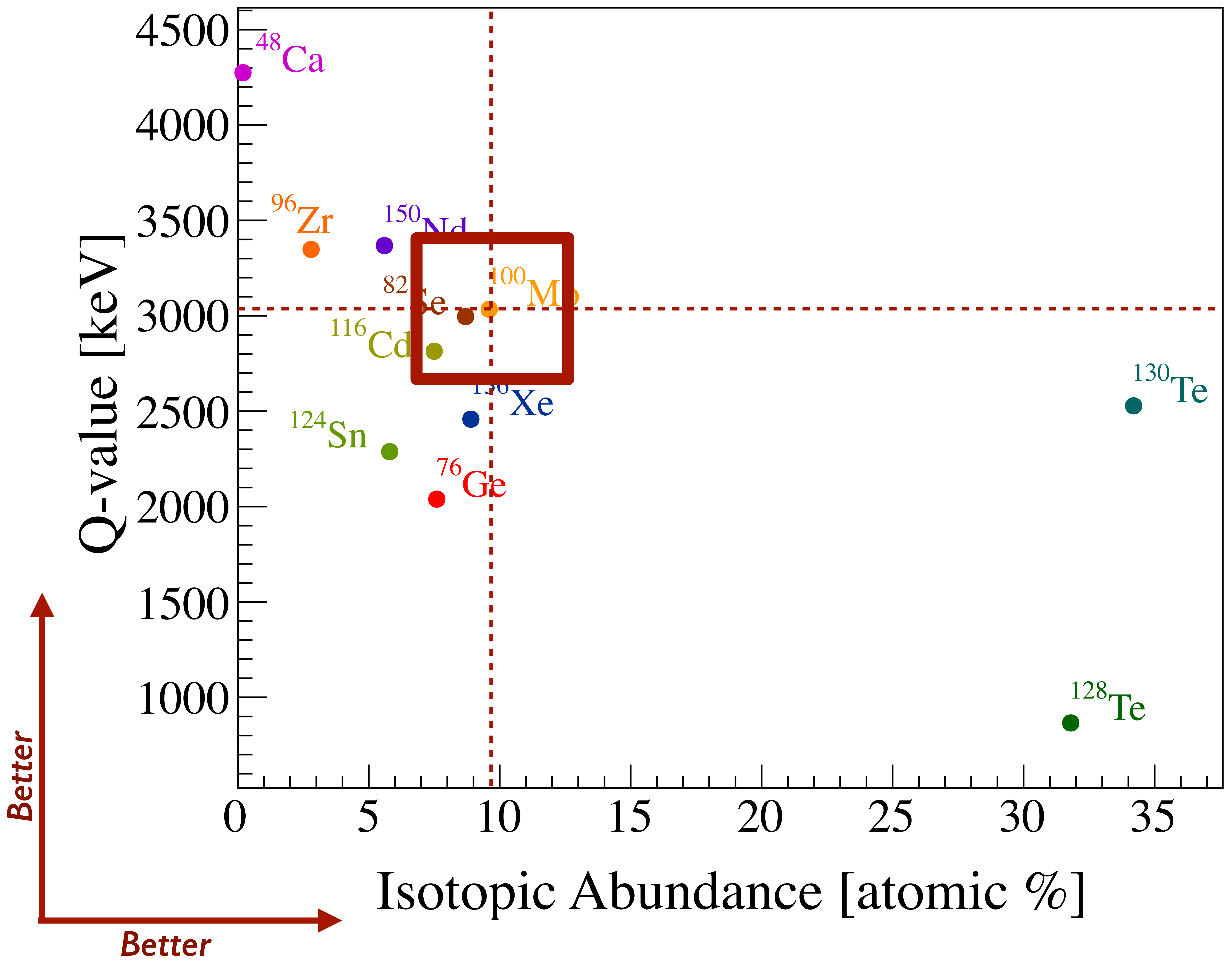
CUPID Concept

- Low background targeted **(10^{-4} cts/keV/kg/yr):**
  - Active α discrimination
  - $Q_{\beta\beta}$ = **3034** keV (> most γ/β backgrounds)
  - Muon veto system
  - Improved background rejection techniques



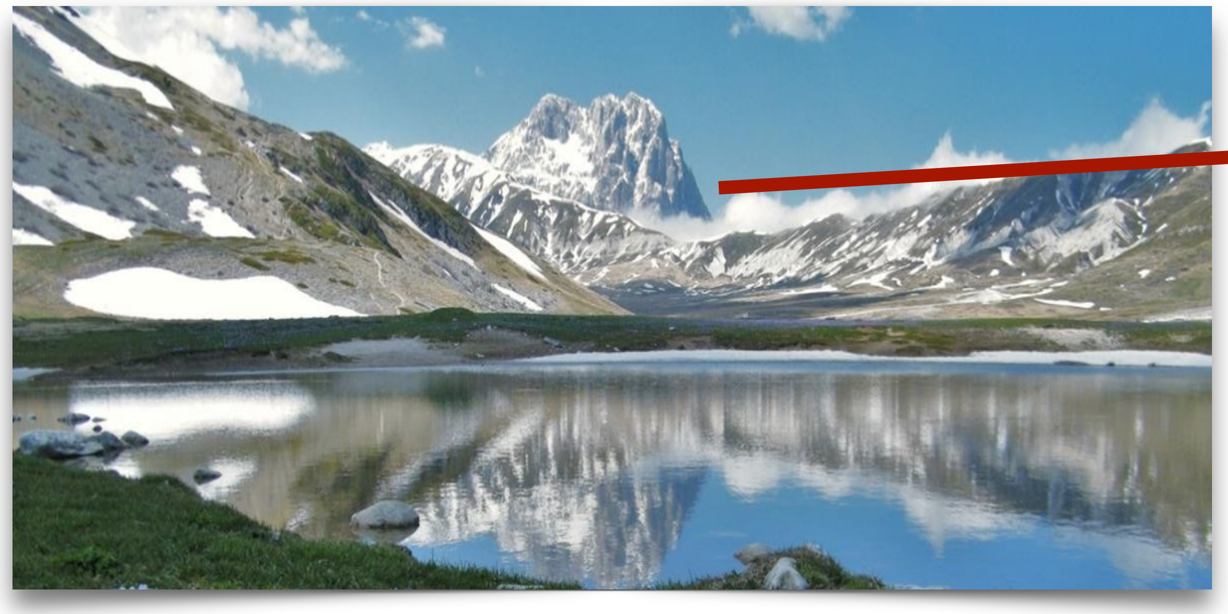
^{100}Mo for CUPID

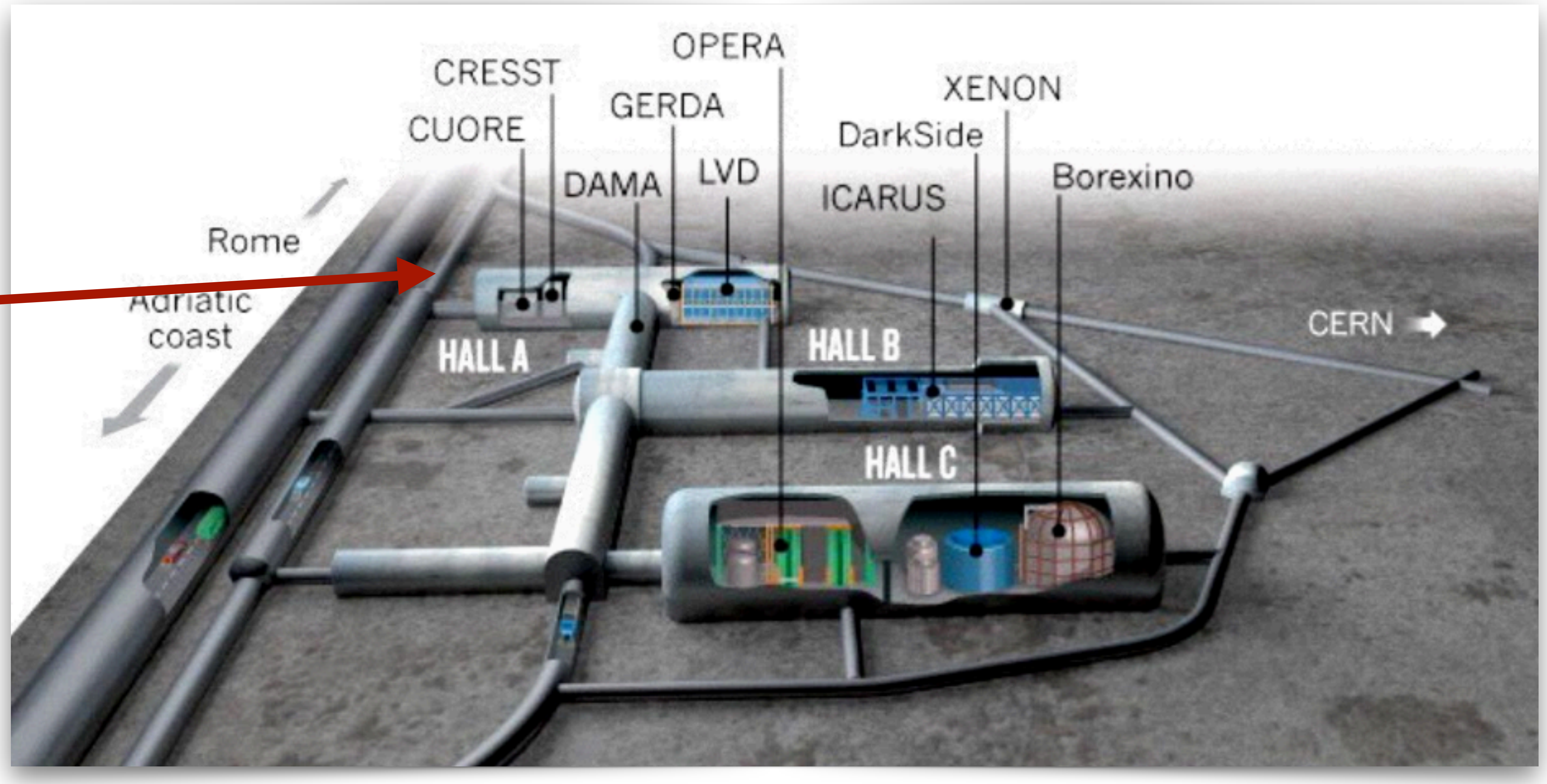
- $Q_{\beta\beta}$ (3034 keV)
  - Above most β/γ natural radioactivity
  - Low backgrounds from $2\nu\beta\beta$
- Isotope within the absorber
- Production of pure $Li_2{}^{100}MoO_4$ crystals demonstrated
- Easily scalable to larger volumes

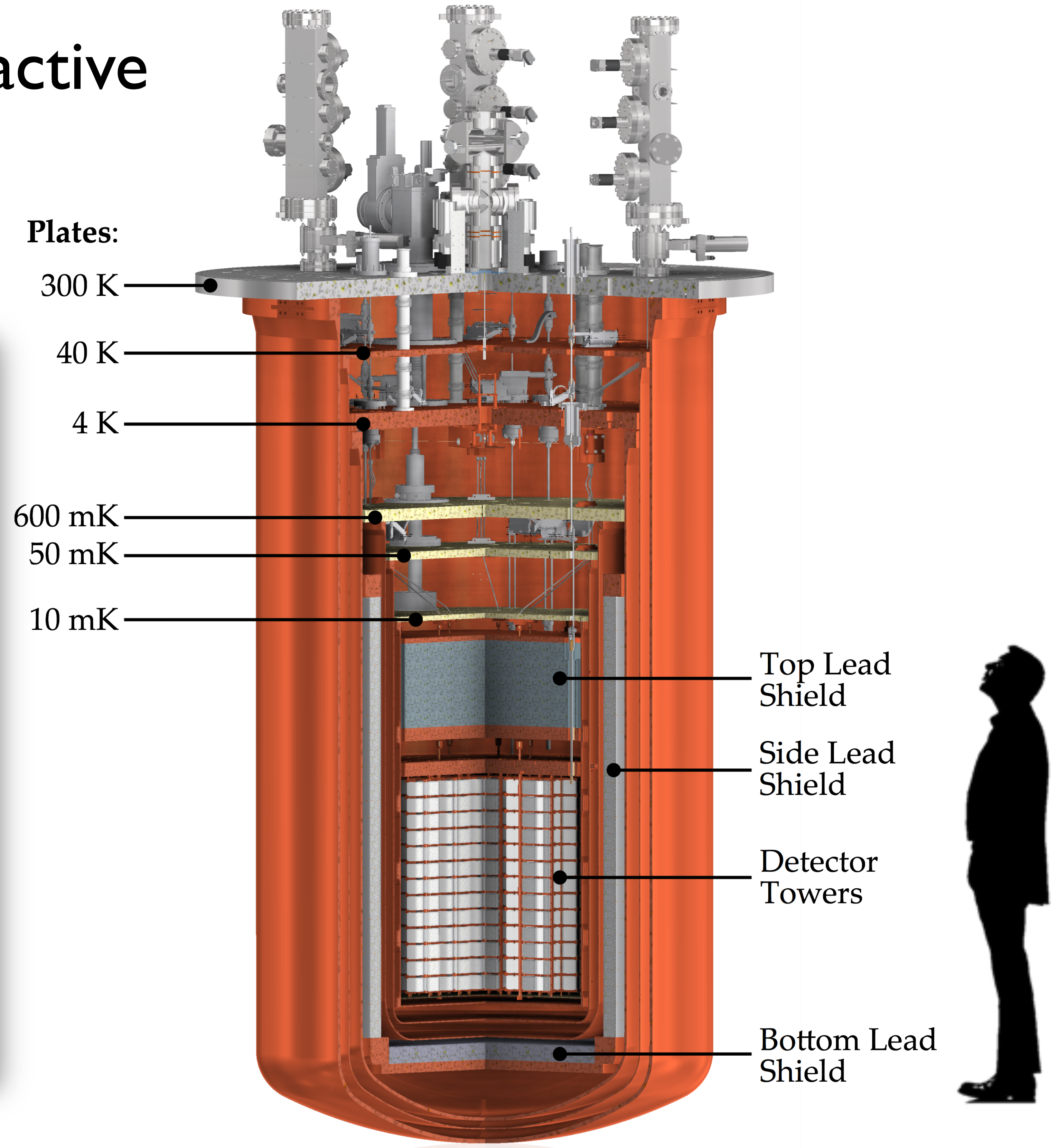


Building on CUORE

- CUORE cryostat: multiple stage cryogen-free cryostat to cool 1 ton to 10 mk
- LNGS Location: Natural shielding (3600 m.w.e) from by the mountain of Gran Sasso
- Passive shielding from rock, lead, polyethylene, and boric acid
- Careful material selection: Ancient Lead and low radioactive

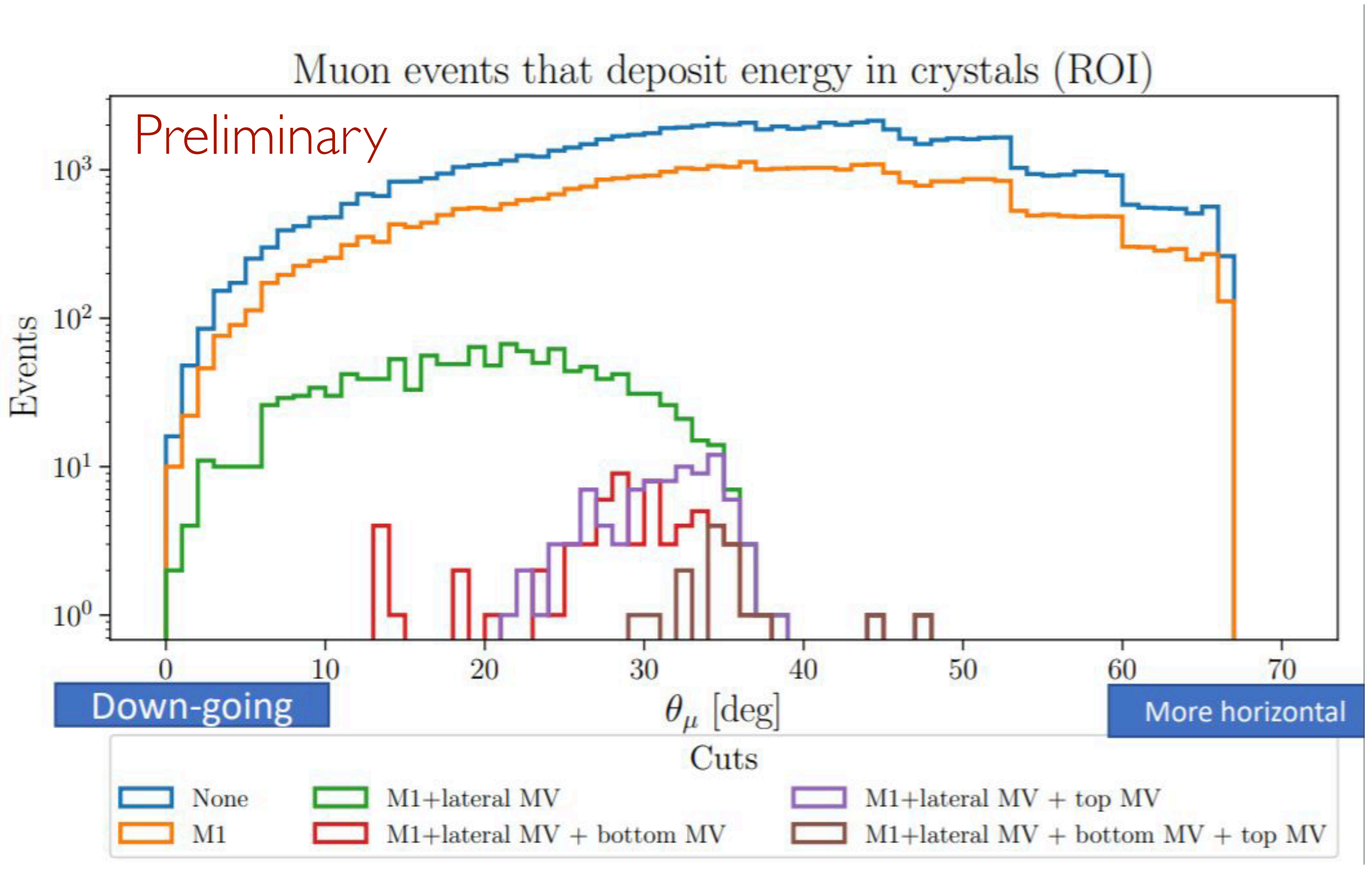




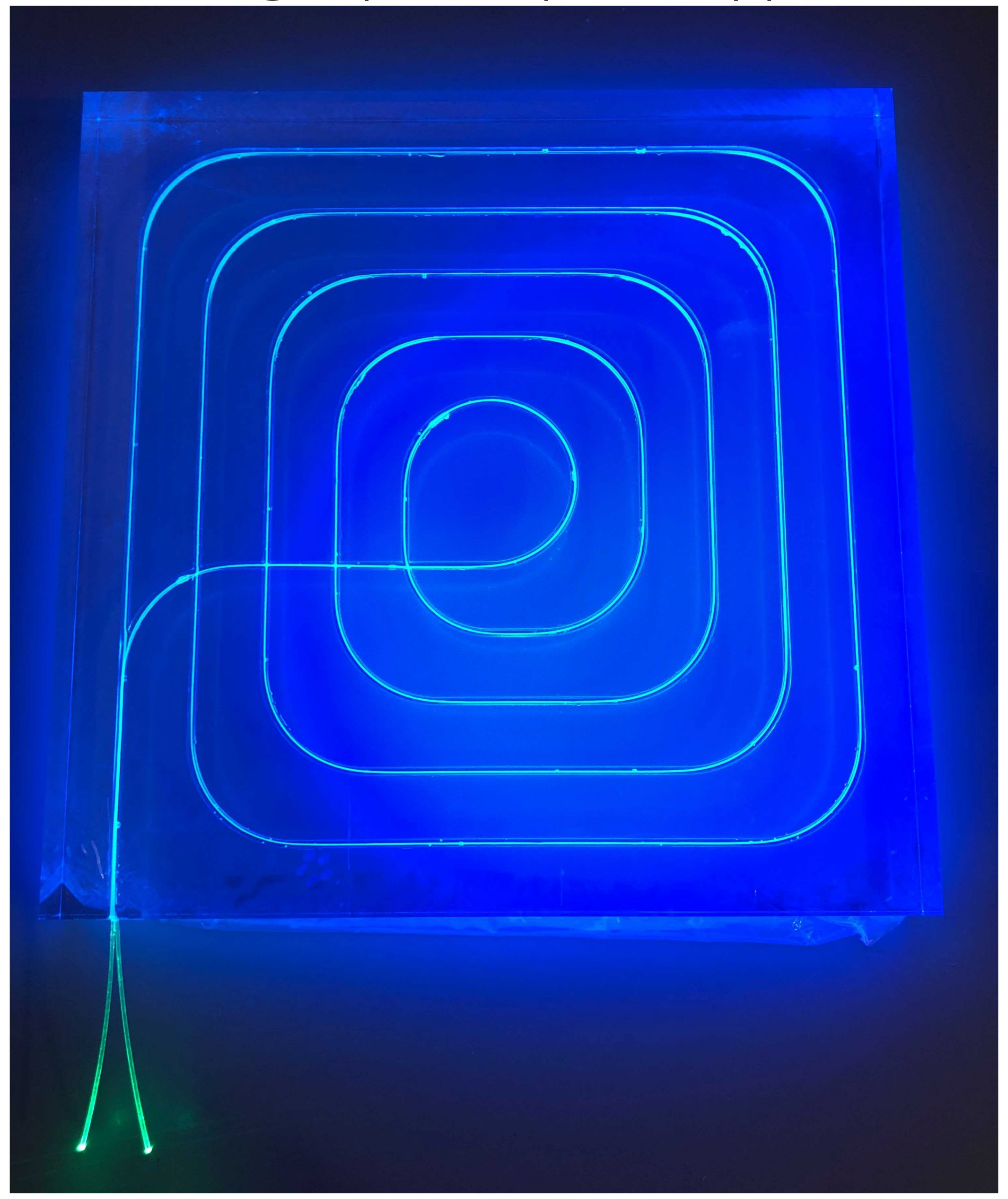


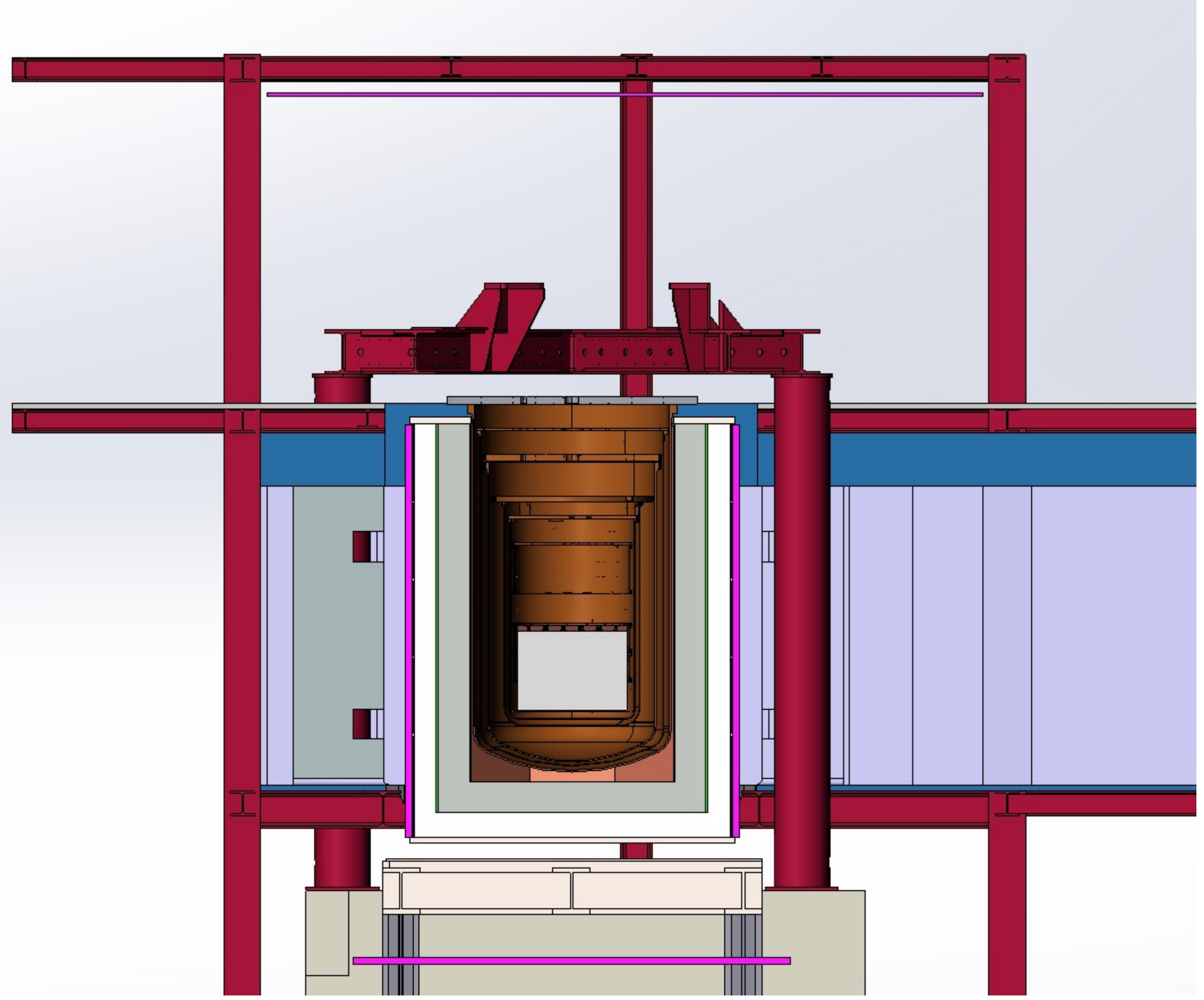
Active Background Rejection: Muon Veto

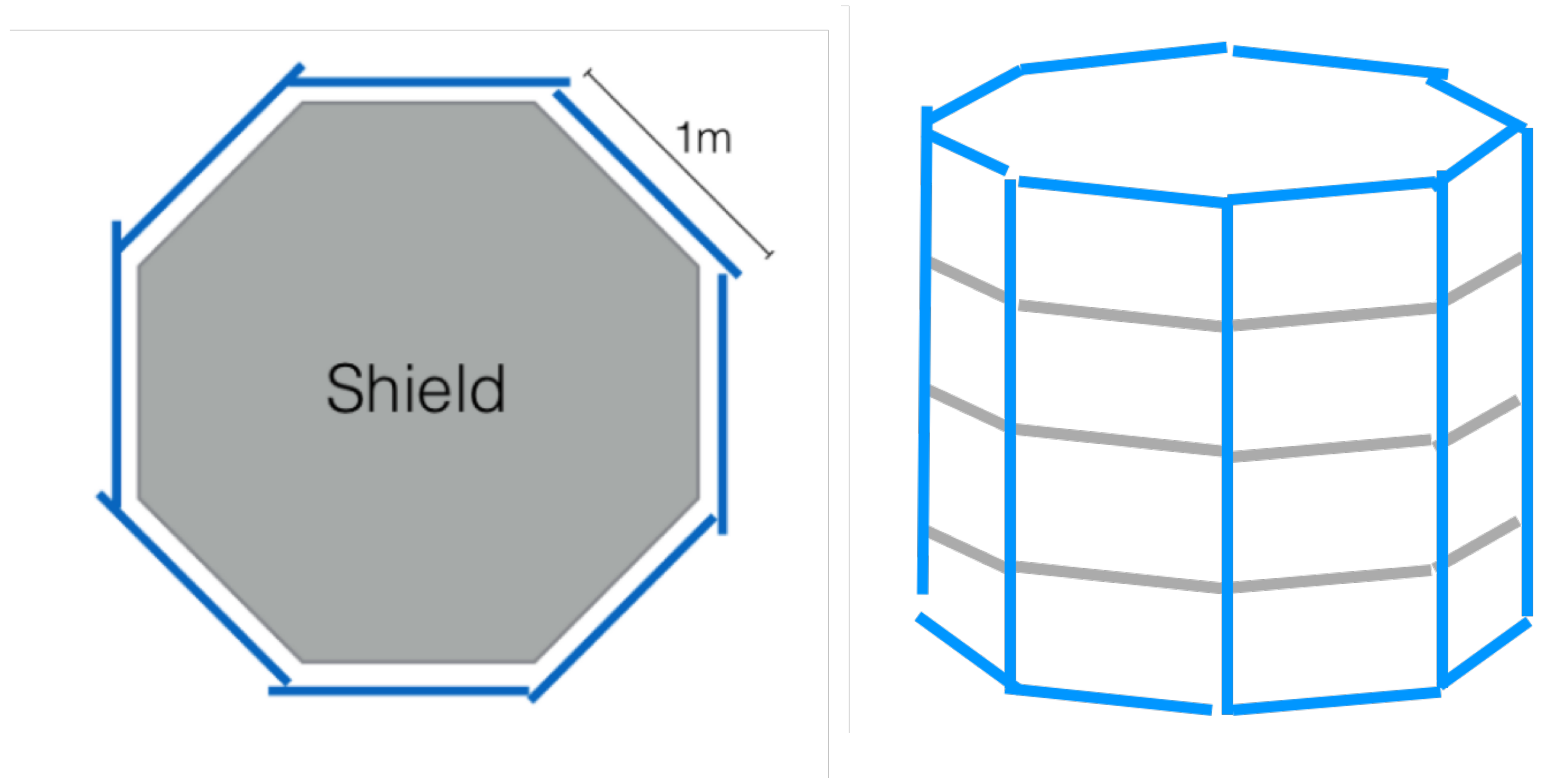
- Projected muon related background ~ 1x10^{-4} cts/keV/kg/yr
- Modular system with plastics scintillator + WLS fibers readout by SiPMs
- Panels surrounding detector + bottom/top panels
- Configuration (efficiency + structural constraints) currently being optimized



Single panel prototype



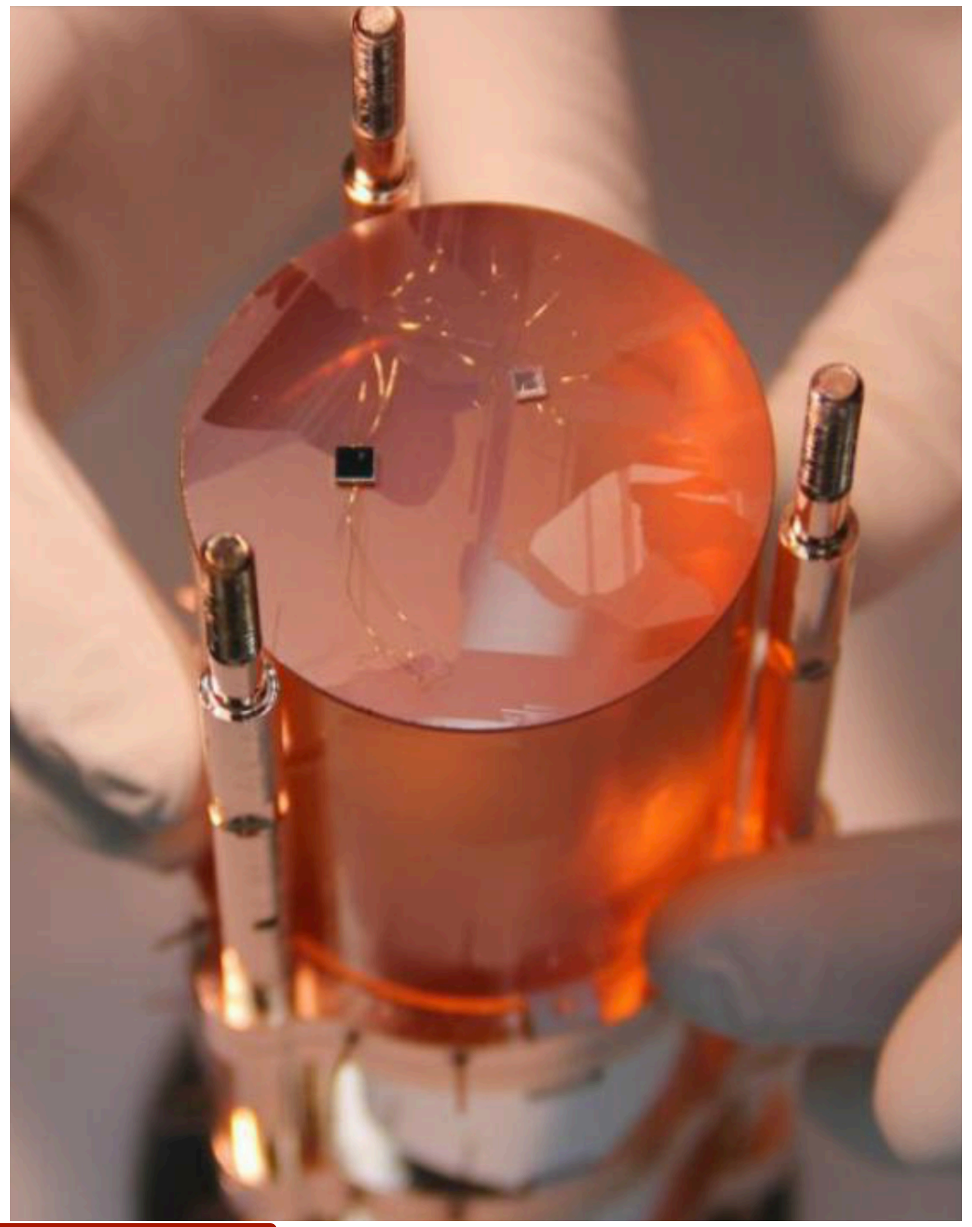


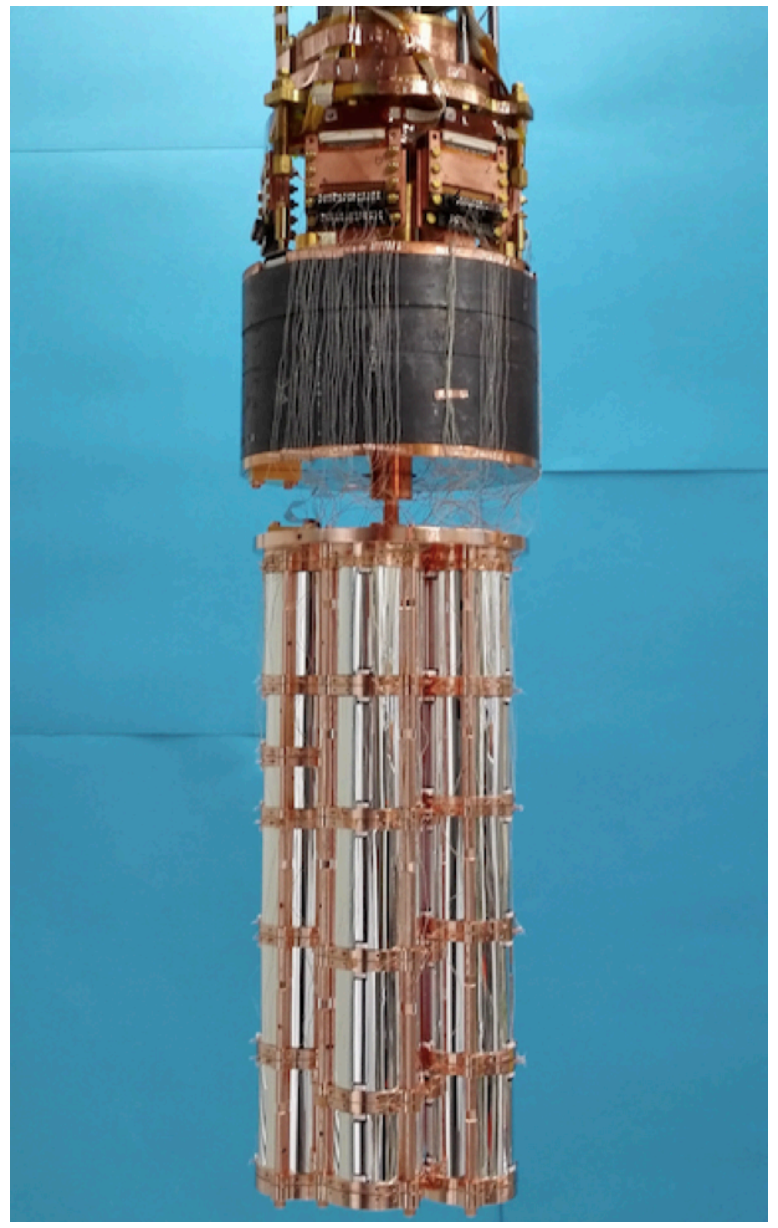


Prototype Demonstrators: Precursors to CUPID

CUPID-0:

- Located in the CUORE-0 cryostat at LNGS, Italy
- 24 $Zn^{82}Se$ (95% enrichment) +2 $Zn^{nat}Se$ crystals
  - 5.17 kg of ^{82}Se
- Ge light detectors and NTD thermistors

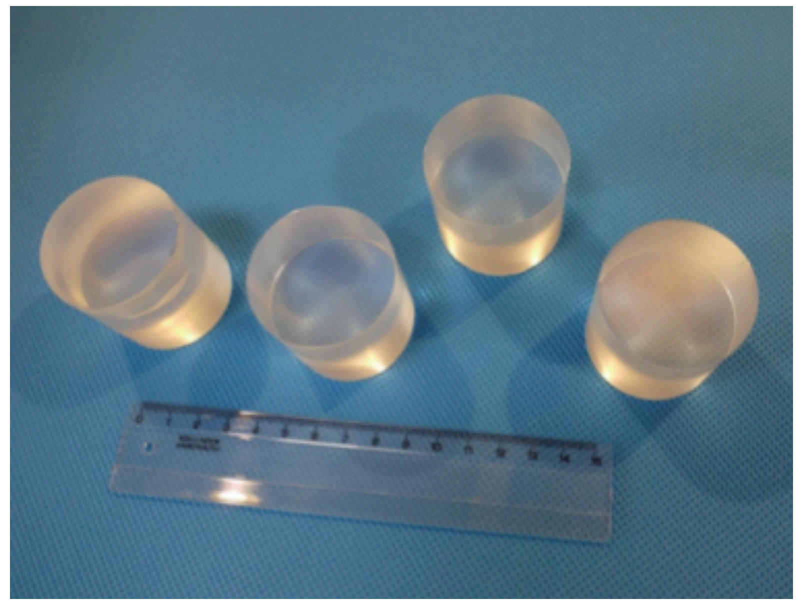


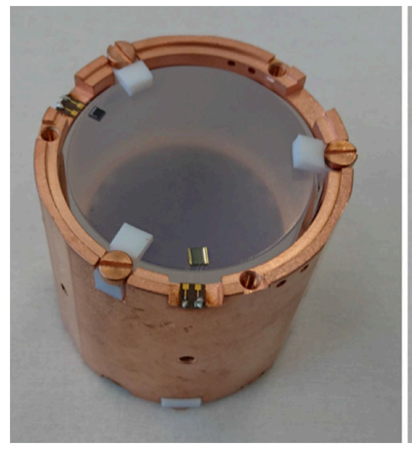


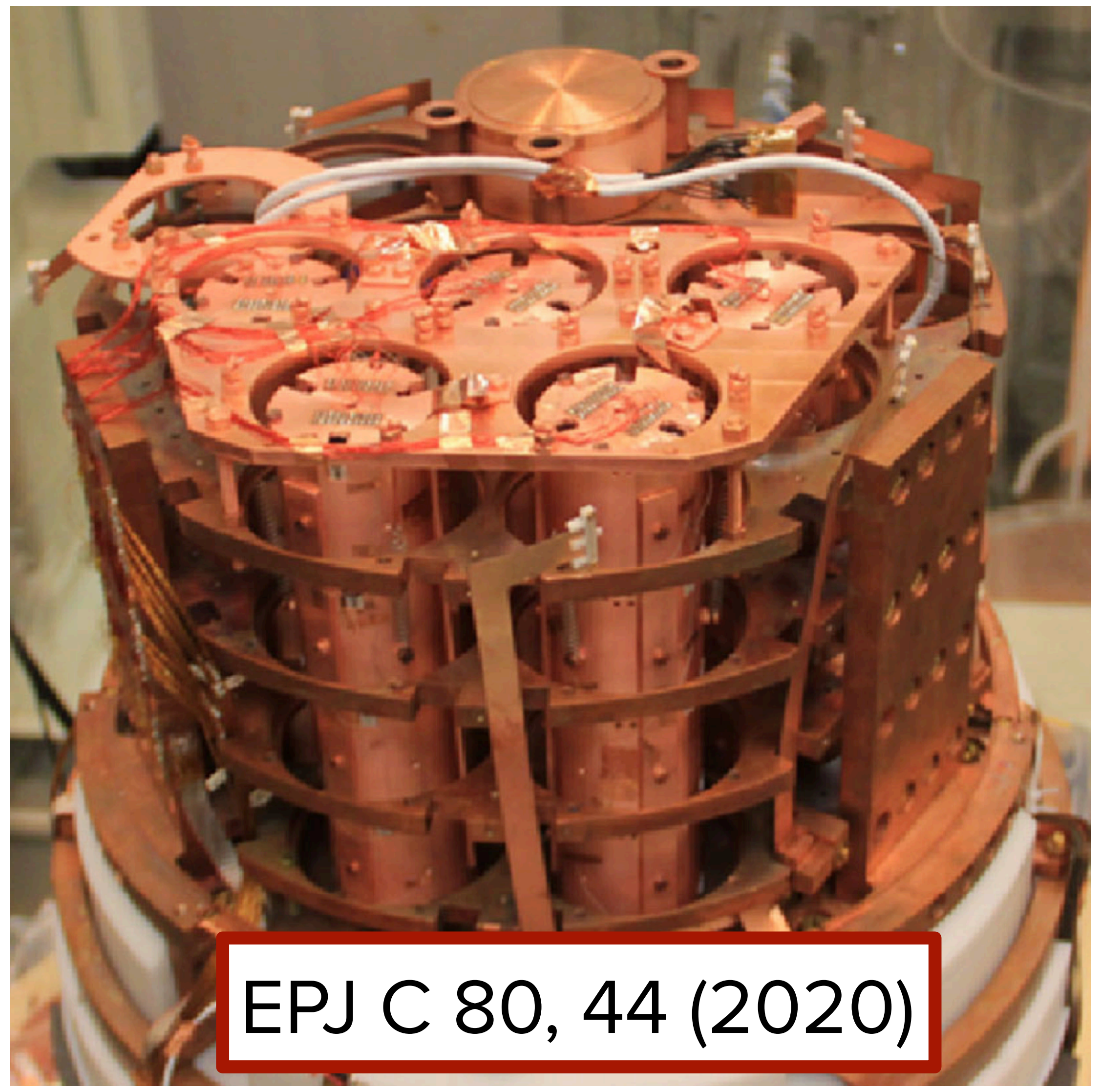
Phys. Rev. Lett. **123**, 032501

CUPID Mo:

- Located in the LSM, France
- 20 enriched $Li_2{}^{100}MoO_4$ (97% enrichement) crystals
  - 2.26 kg of ^{100}Mo
- Ge light detectors and NTD thermistors



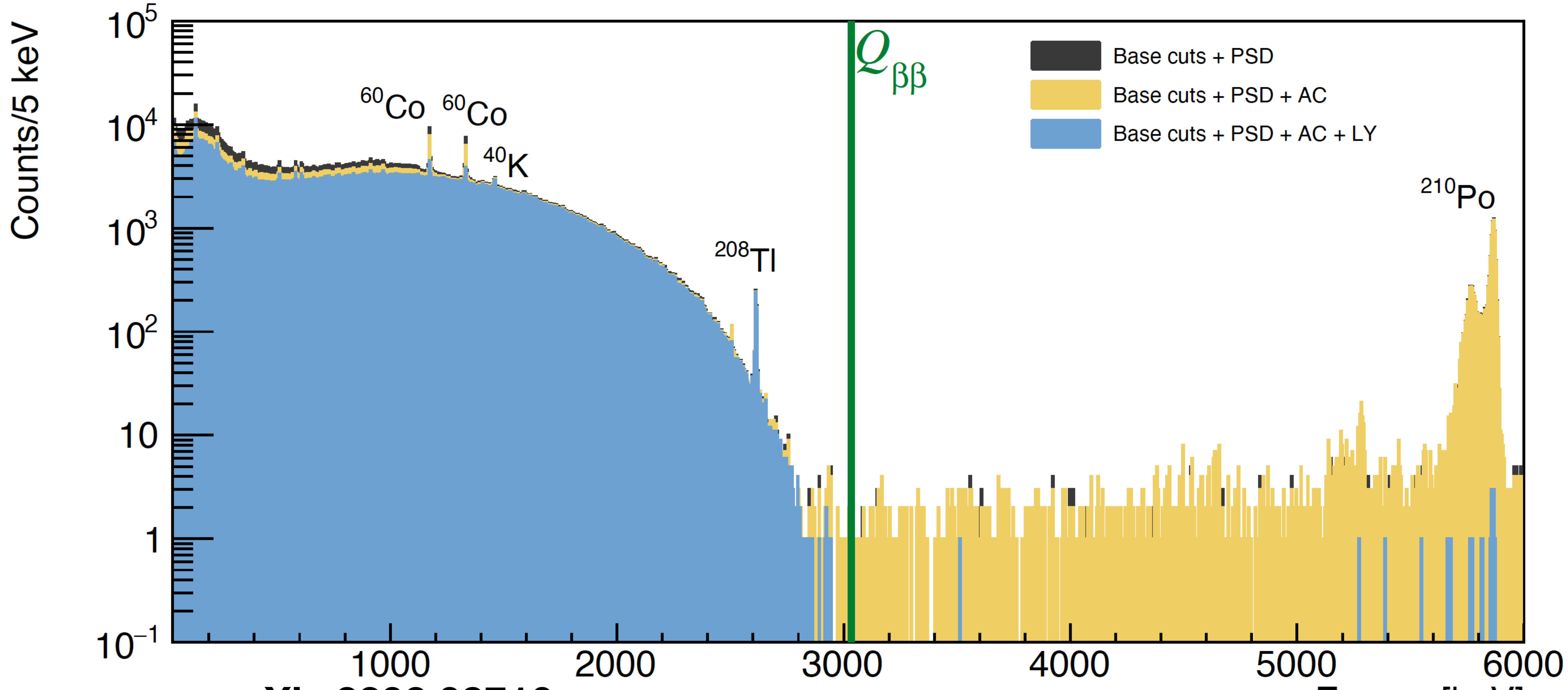




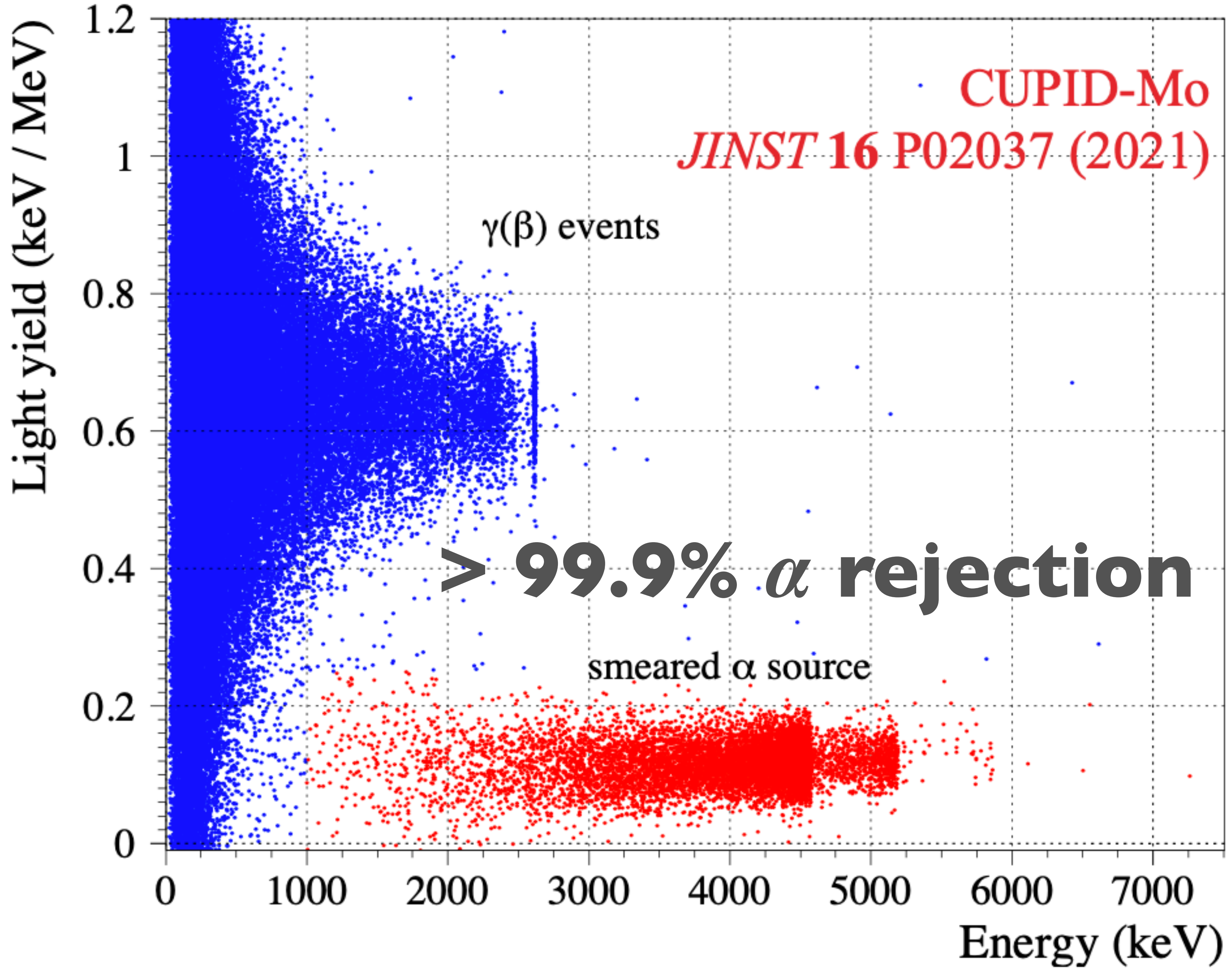
EPJ C 80, 44 (2020)

Results from CUPID-Mo

- Exposure: 1.47 kg.yr of ^{100}Mo
- Resolution of $Q_{\beta\beta}$ (3034 keV): 7.4 ± 0.4 keV
- Alphas efficiently discriminated
- **No background events in ROI**



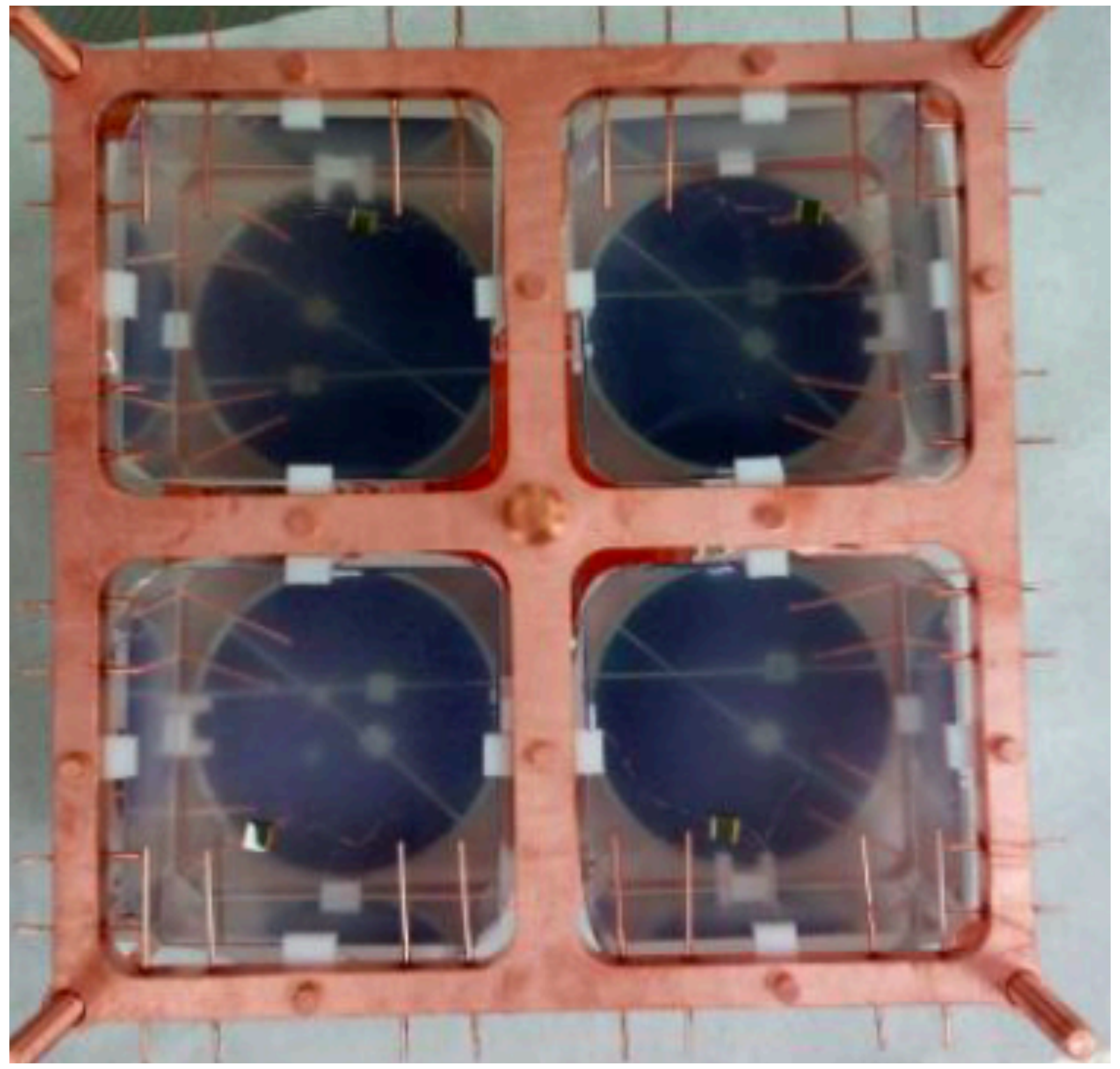
arXiv:2202.08716

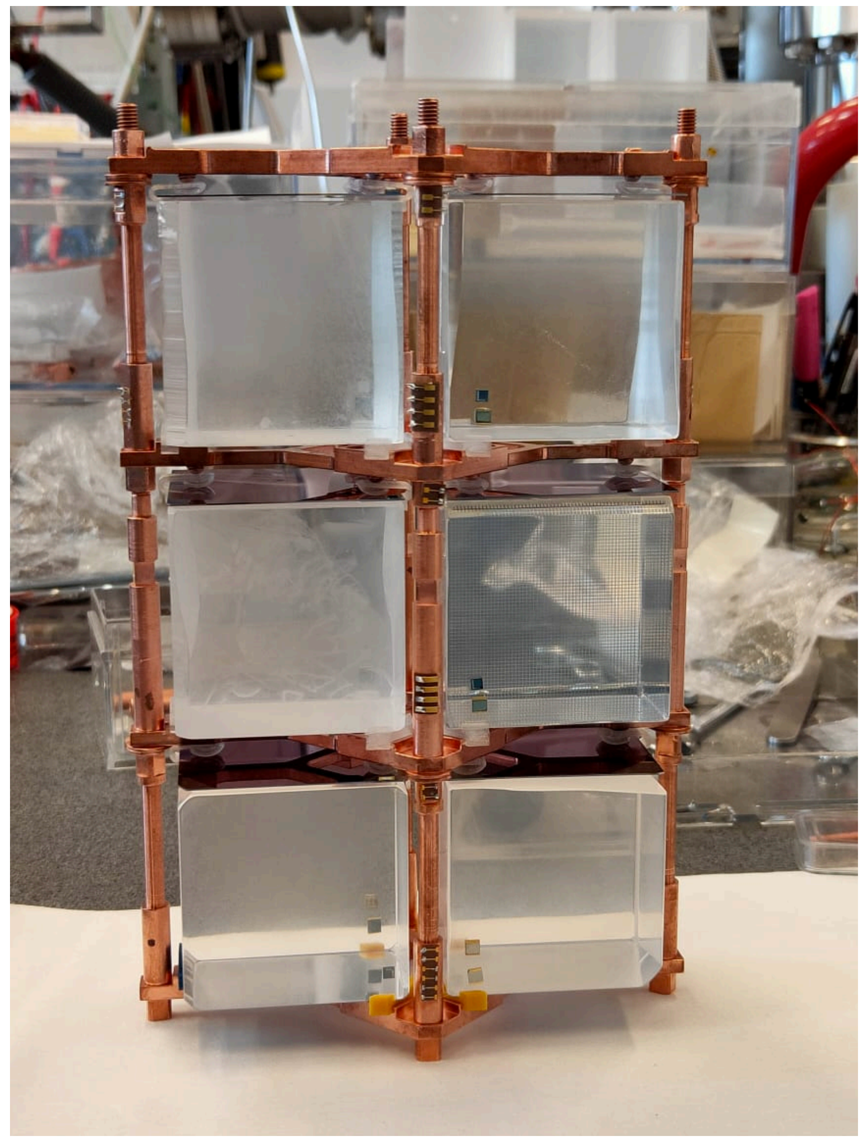
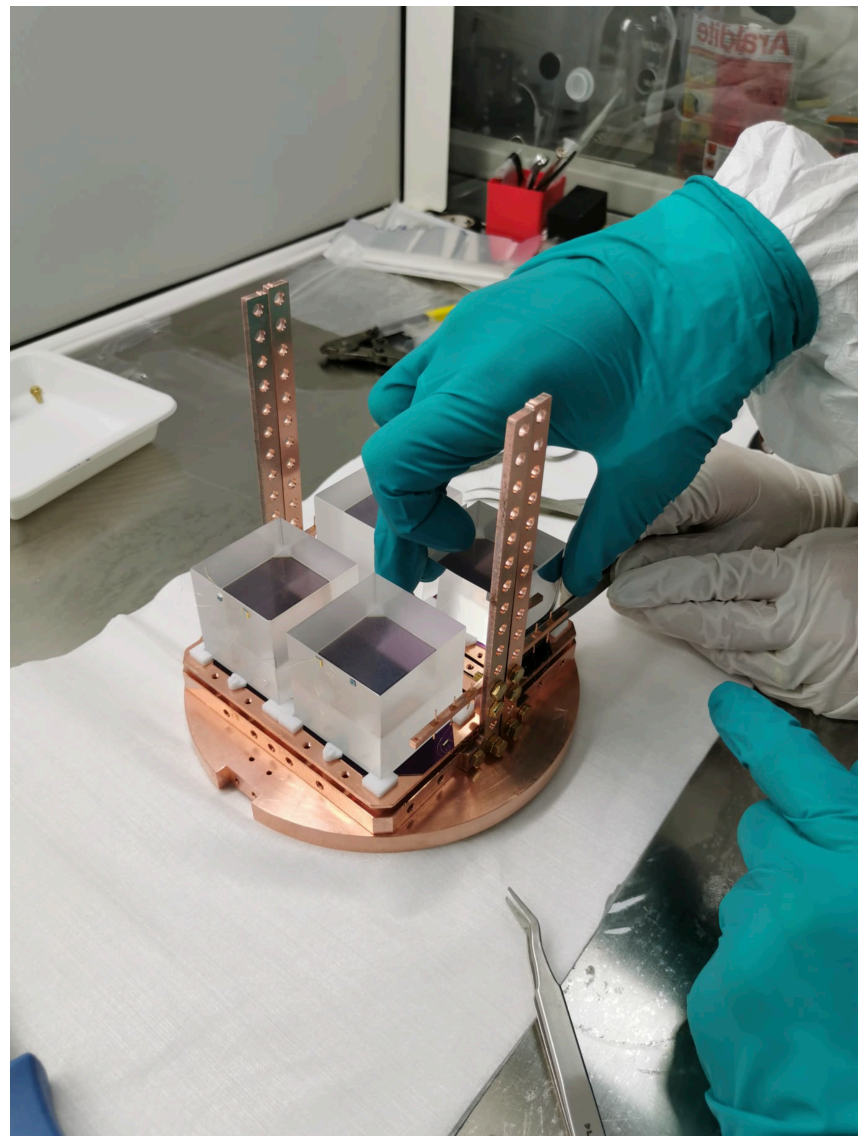
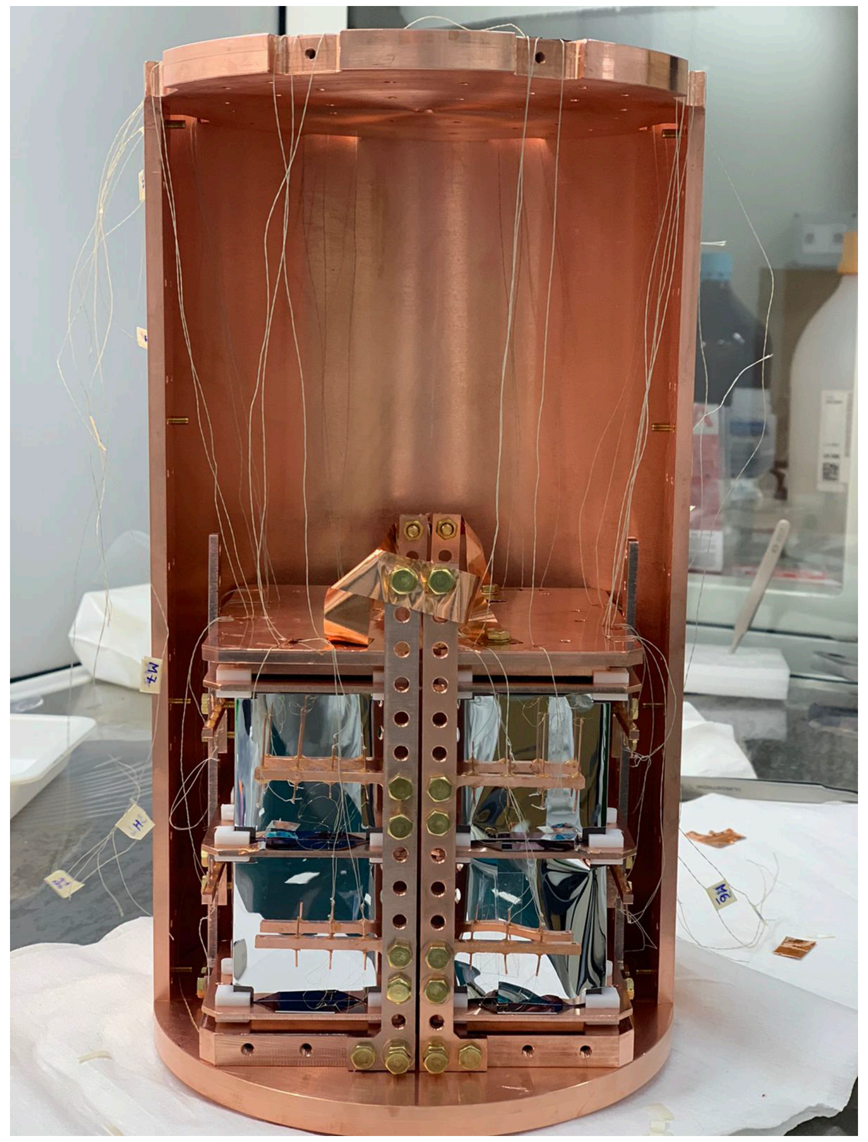


CUPID-Mo demonstrates high α rejection power

Past R&D: Finalize Detector Design

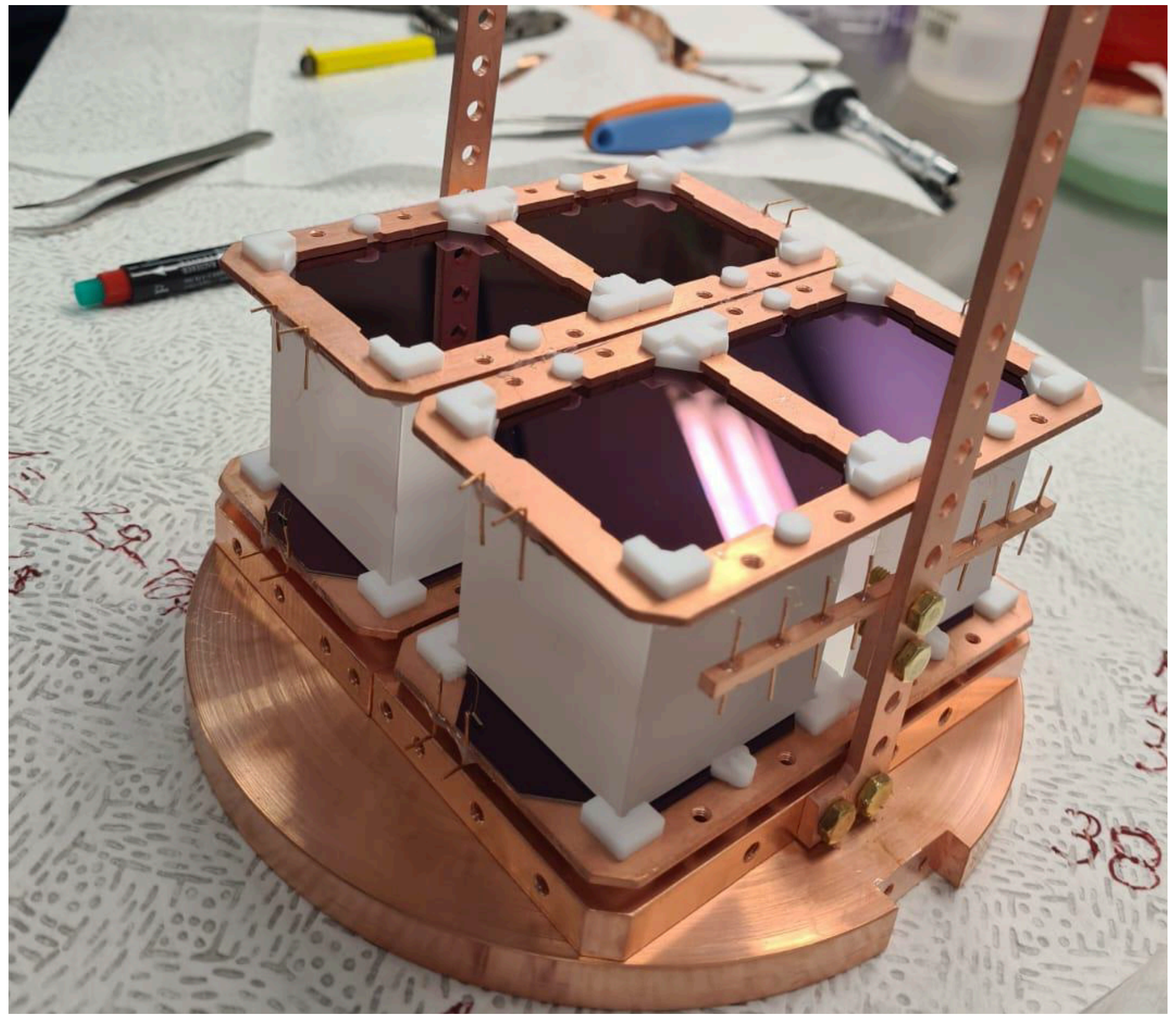
- Final CUPID design based on several R&D tests performed that helped:
  - Define crystal shape
  - Define Tower structure
  - Optimize light detector position
  - Test the use of reflecting foil
  - Optimize pile-up rejection techniques

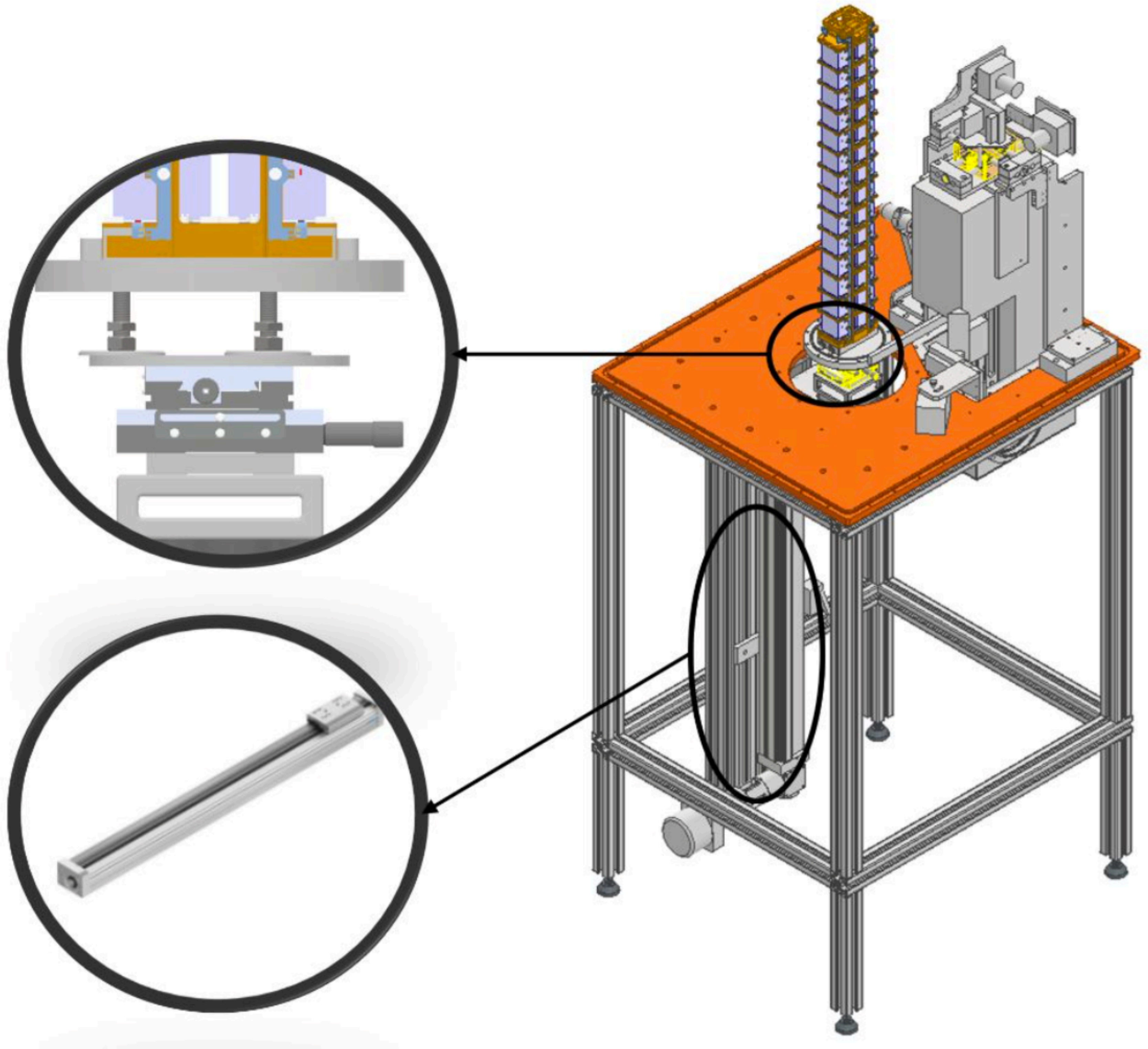


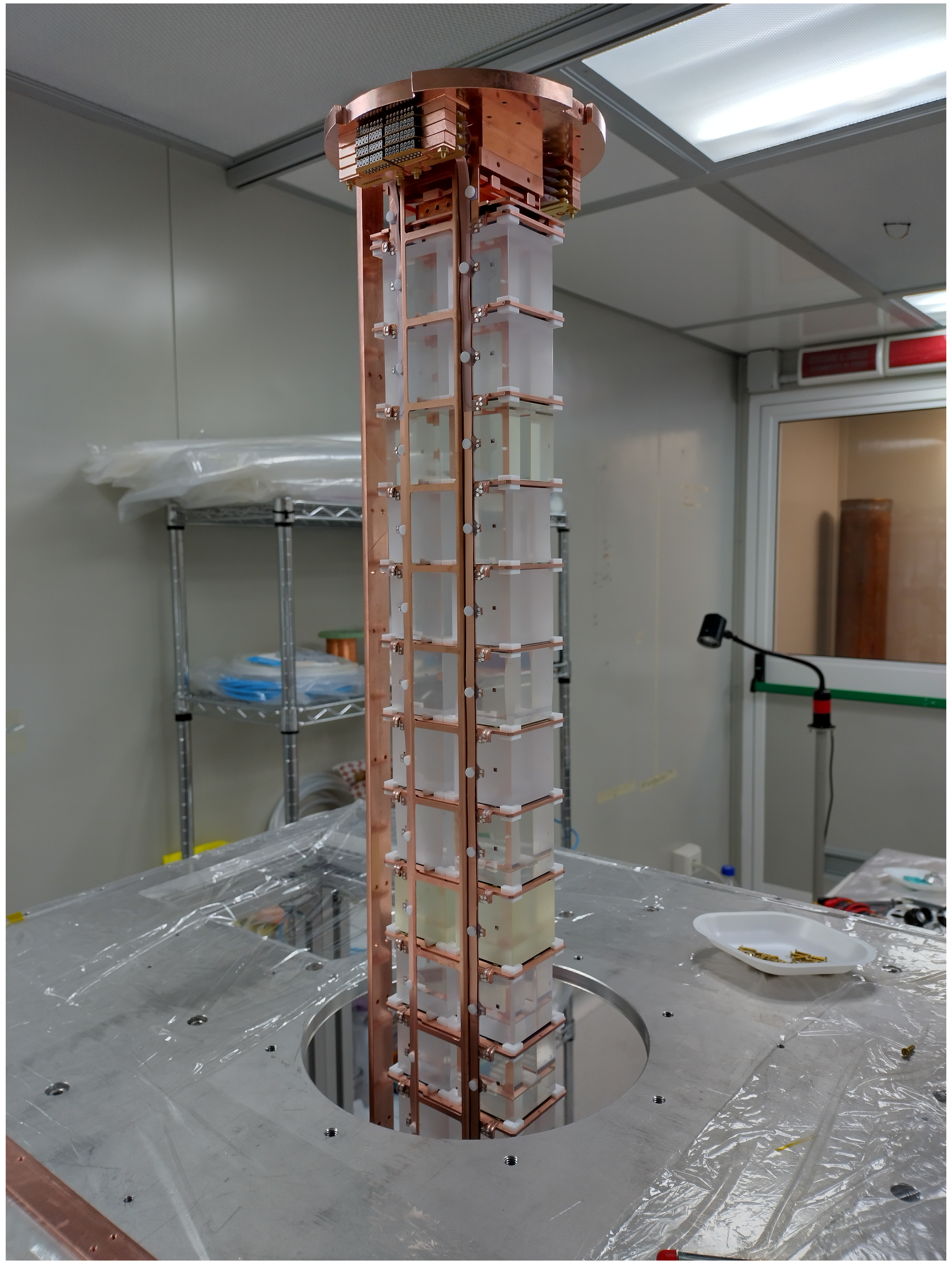




Ongoing R&D: Design Validation

- Ongoing R&D:
  - Full CUPID baseline tower:
    - To test mechanical, thermal and vibrational characteristics
    - Testing assembly procedures
  - Test quality of the crystals

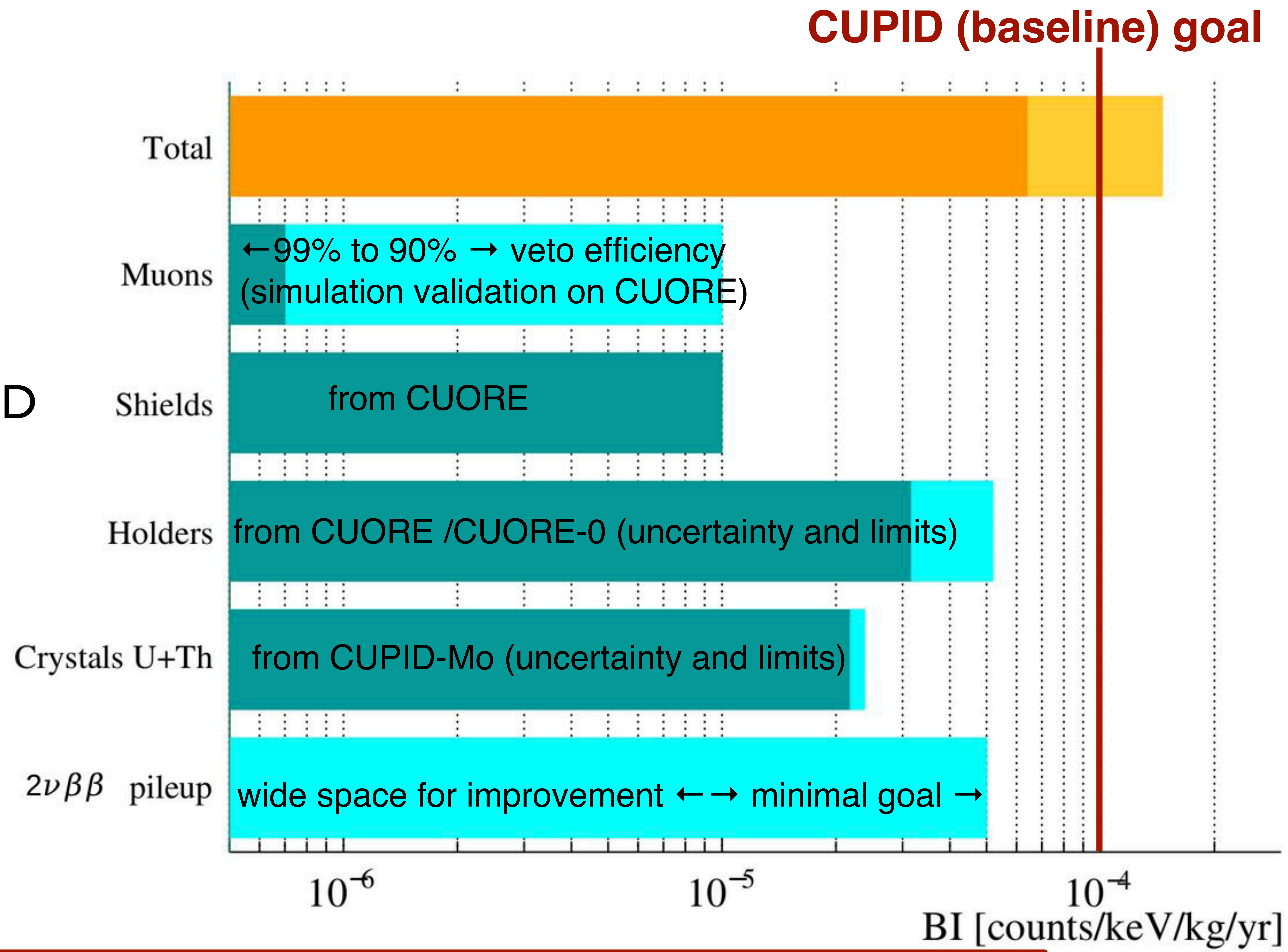






CUPID Background Budget

- Data-driven background model:
  - Based on CUORE, CUPID-0 and CUPID-Mo
  - Backgrounds from material to be used in CUPID well-understood
  - Wide space in pileup rejection possible



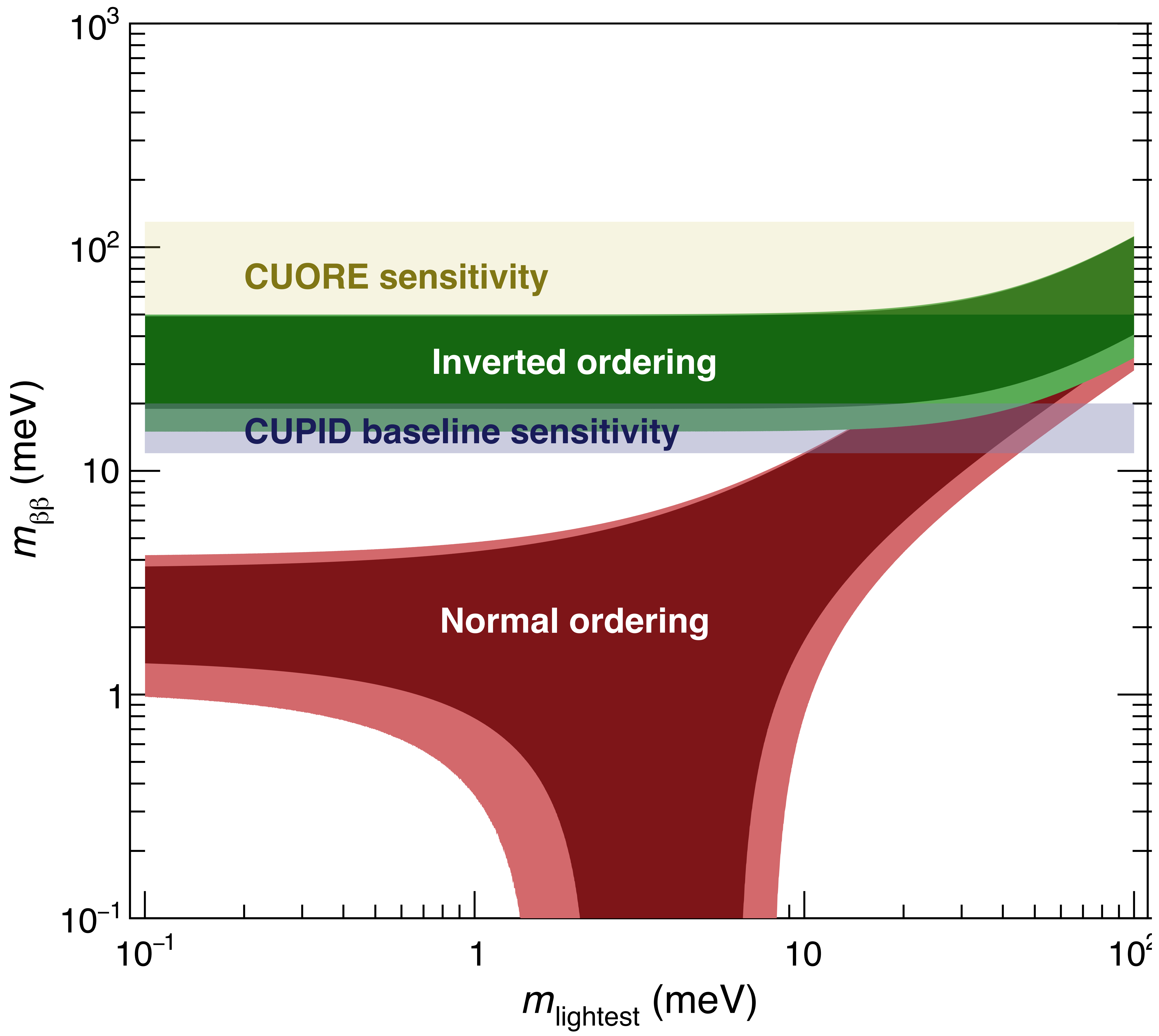
The path to achieve CUPID background goal is well understood and conservative

Sensitivity to $0\nu\beta\beta$

CUPID Baseline:

- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$ (**Mo**)
- Run time: **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- $m_{\beta\beta}$ discovery sensitivity: **12 - 20 meV (3σ)**

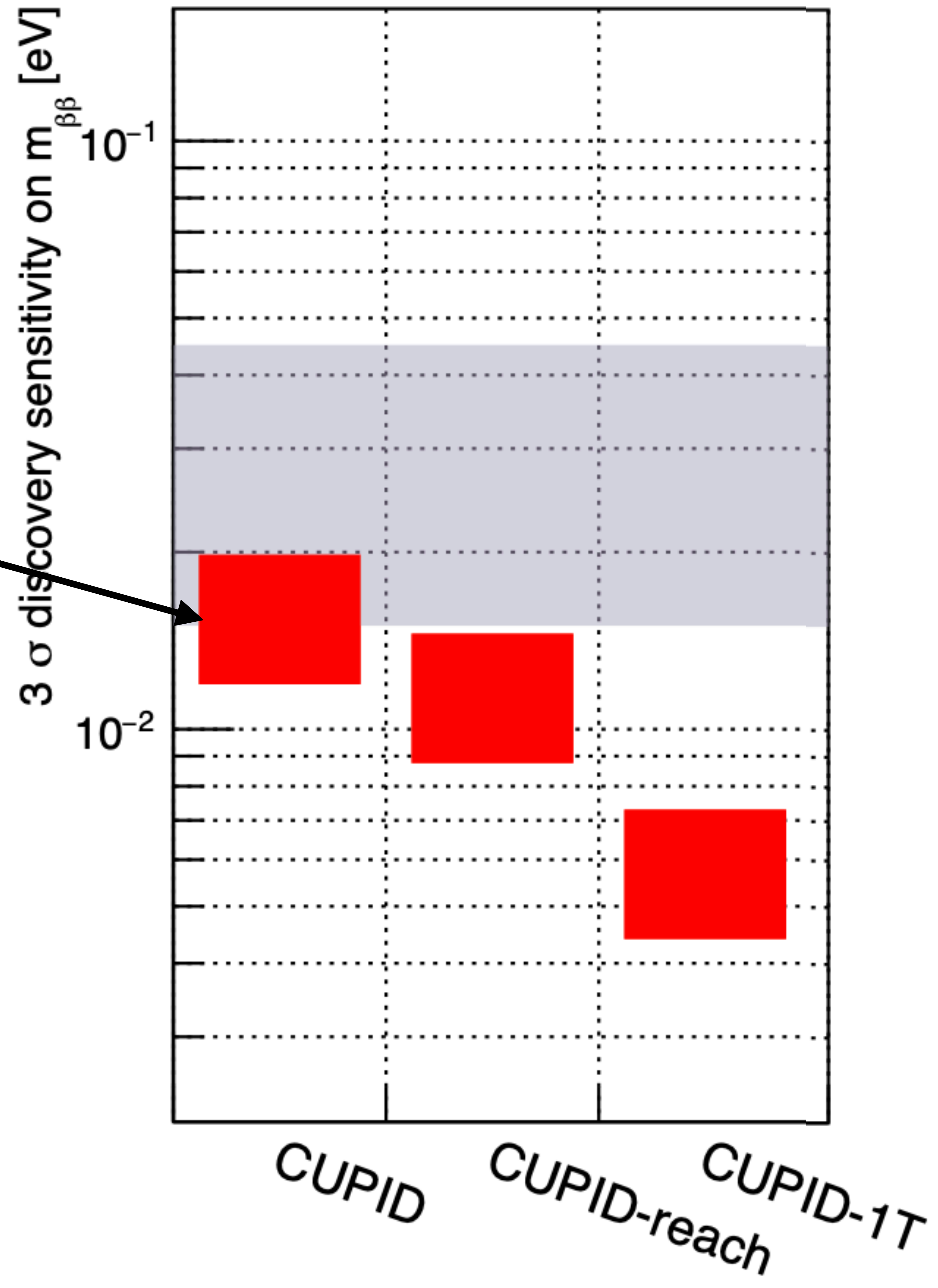
CUPID aims to cover the inverted ordering and a fraction of normal ordering



Extending CUPID

Conservative (Can build now)

Discovery sensitivity $T_{1/2} > 1\times10^{27}$ yr (3σ)



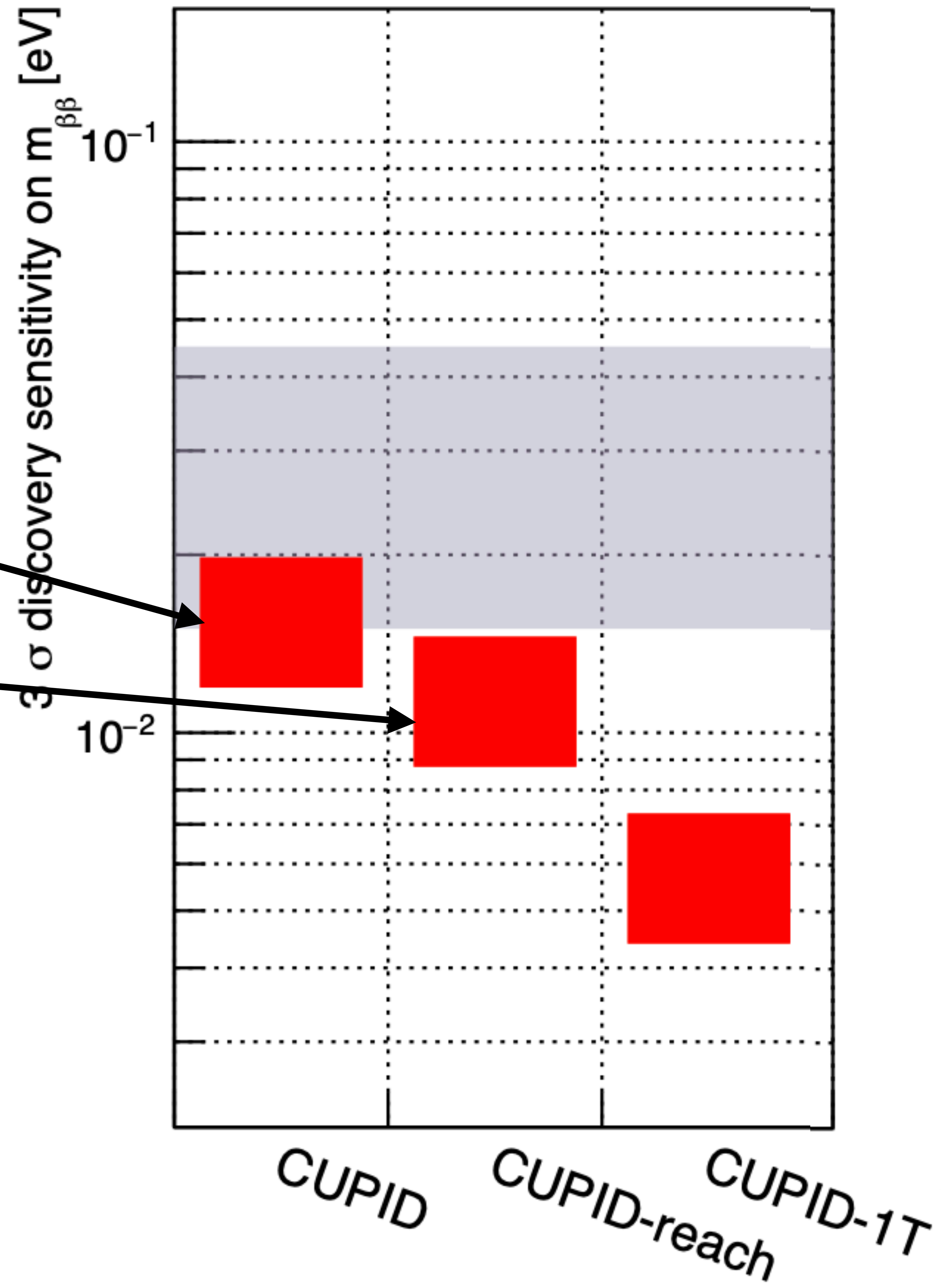
Extending CUPID

Conservative (Can build now)

Discovery sensitivity $T_{1/2} > 1\times10^{27}$ yr (3σ)

More R&D for further background reduction by radio purity and reduce pileup background

Discovery sensitivity $T_{1/2} > 2\times10^{27}$ yr (3σ)



Extending CUPID

Conservative (Can build now)

Discovery sensitivity $T_{1/2} > 1\times10^{27}$ yr (3σ)

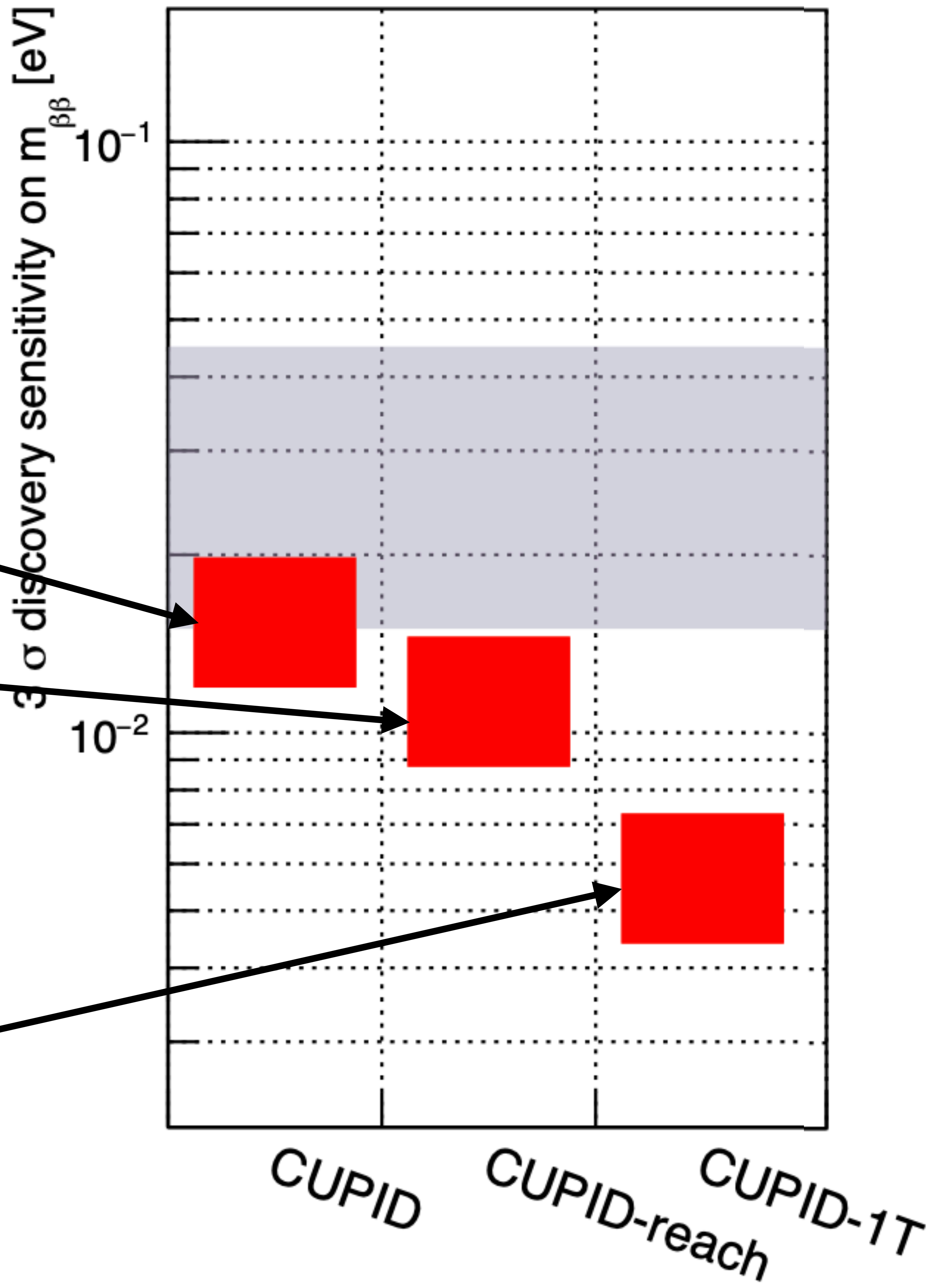
More R&D for further background reduction by radio purity and reduce pileup background

Discovery sensitivity $T_{1/2} > 2\times10^{27}$ yr (3σ)

Ultimate bolometer sensitivity:

1000 kg of ^{100}Mo

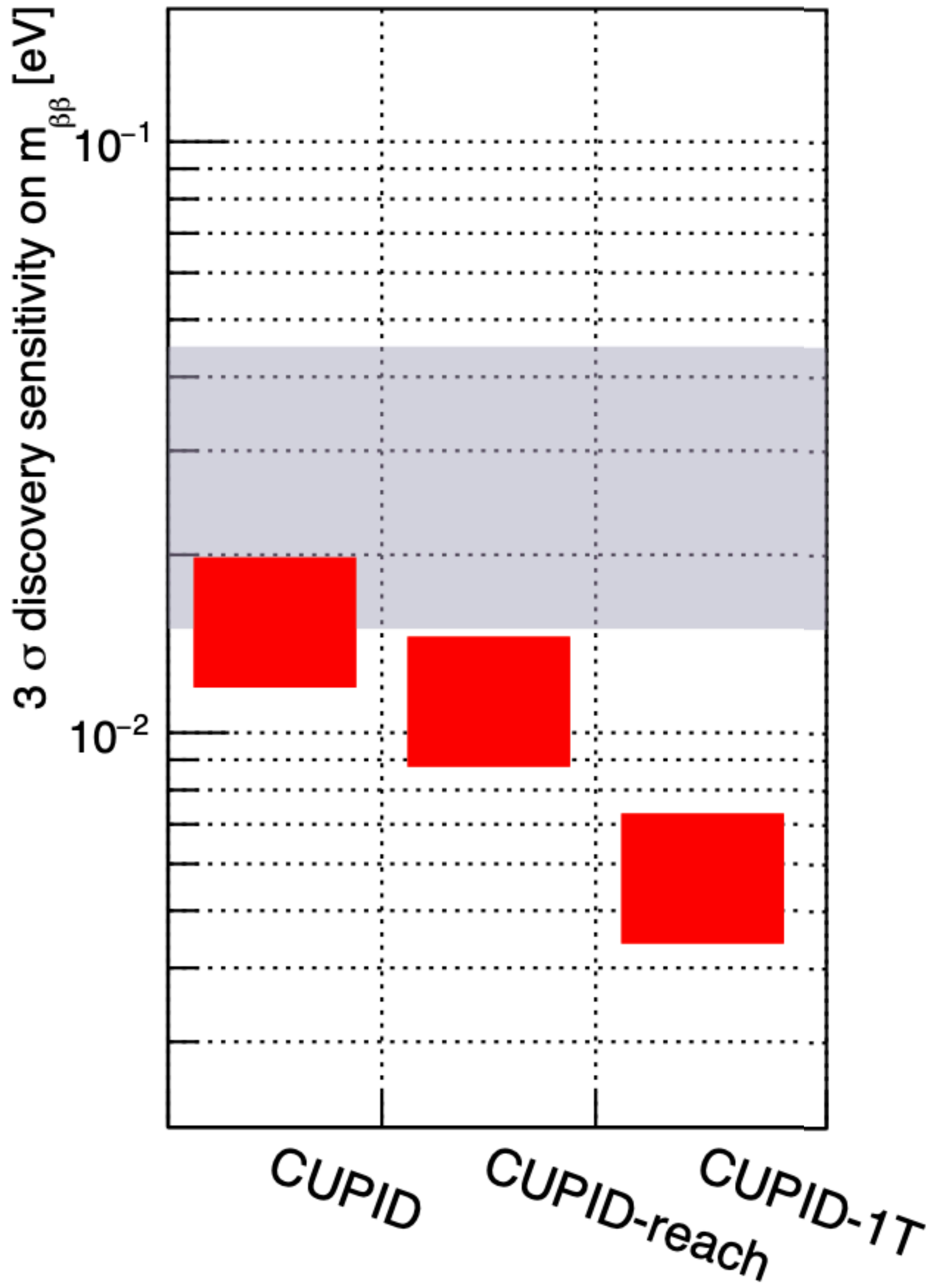
Discovery sensitivity $T_{1/2} > 8\times10^{27}$ yr (3σ)



Extending CUPID

In case of discovery, CUPID infrastructure, assembly procedures and analysis techniques could be used to search for $0\nu\beta\beta$ in other candidates:

- ^{82}Se
- ^{116}Cd
- ^{130}Te



Conclusions

- CUPID is an upcoming bolometric $0\nu\beta\beta$ experiment to explore inverted ordering
- Experiment is designed based on extensive expertise, infrastructure, and experience of past and ongoing experiments
- The collaboration has extensive experience operating tonne-scale bolometric experiment at LNGS
- Data driven background model projects that CUPID baseline goal is achievable
- Projected sensitivity $T^{0\nu}_{1/2}$ > **10^{27}** yr and $m_{\beta\beta}$ < **12 - 20 meV**