Recent Results from CUORE

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Center for Neutrino Physics
Virginia Tech

CNP Research Day
May 6th 2022

Acknowledgements

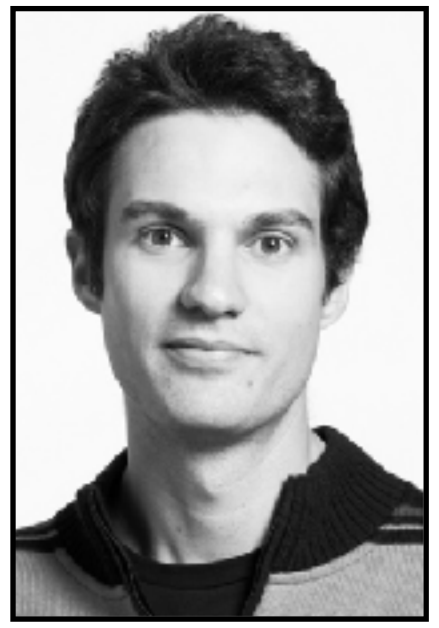
CUORE Collaboration

CUPID Collaboration

VT work supported by DOE

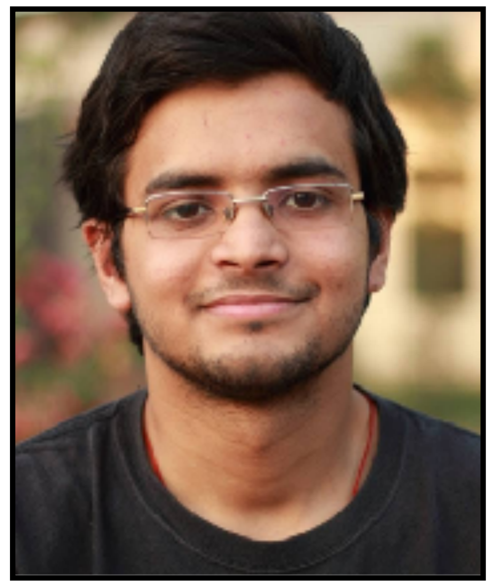
Award#: DE-SC0019316

Award#: DE-SC0020423

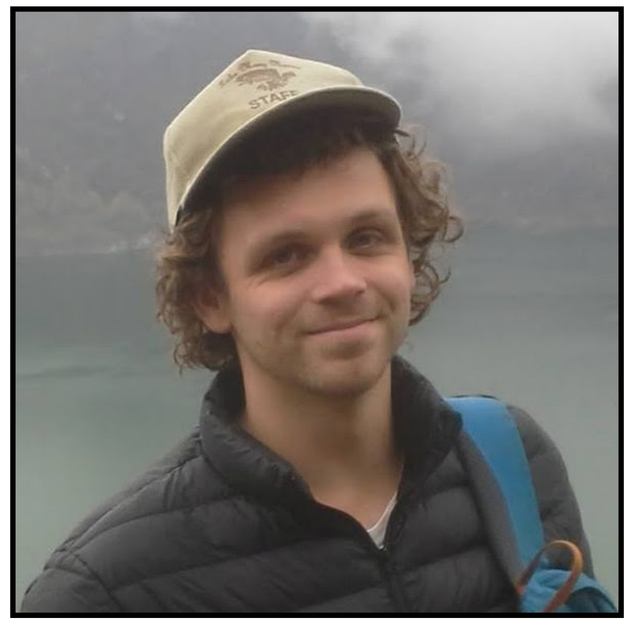


Dr. Stefano Dell'Oro

Dr. Krystal Alfonso



Vivek Sharma

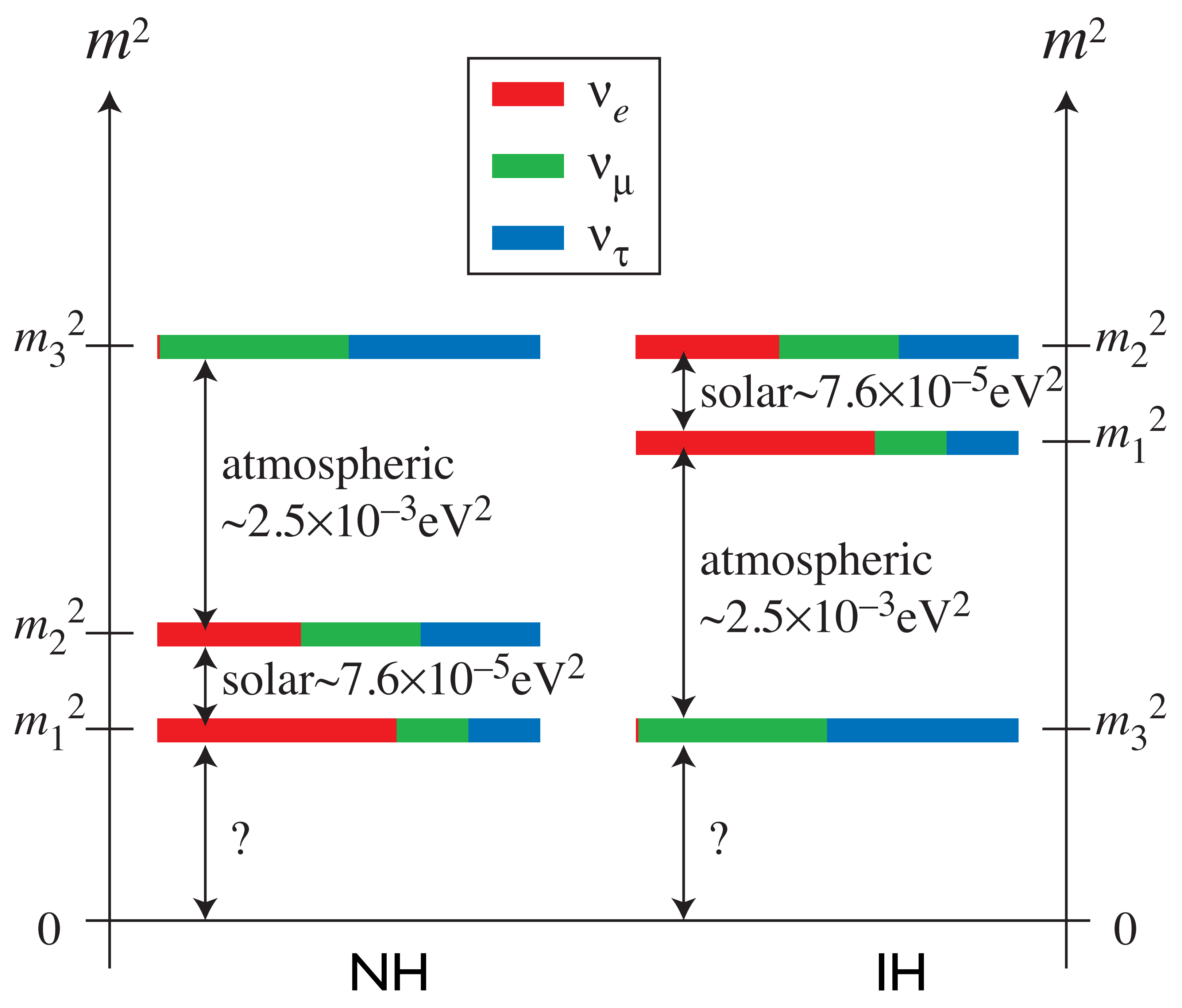


Joe Camilleri

Outline

- Neutrinoless Double beta decay
- The CUORE Experiment
- A new experiment in development: CUPID

Neutrino Mass: Some open questions

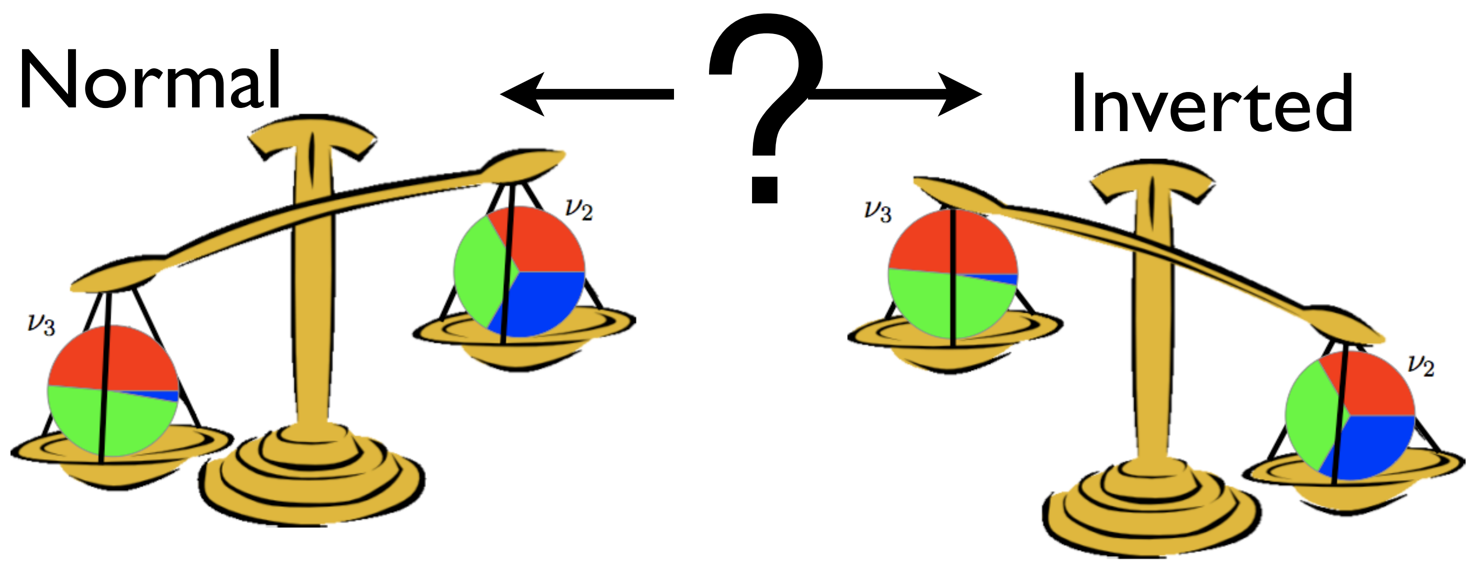


- ☑ ν-oscillations tell us the mass-squared splittings
- ☑ solar matter effects tell us sign of dm^2_{21}

- **What is the absolute offset from zero ?**
- **Sign of dm^2_{23} (Hierarchy)**
- **Are neutrinos Majorana particles?**

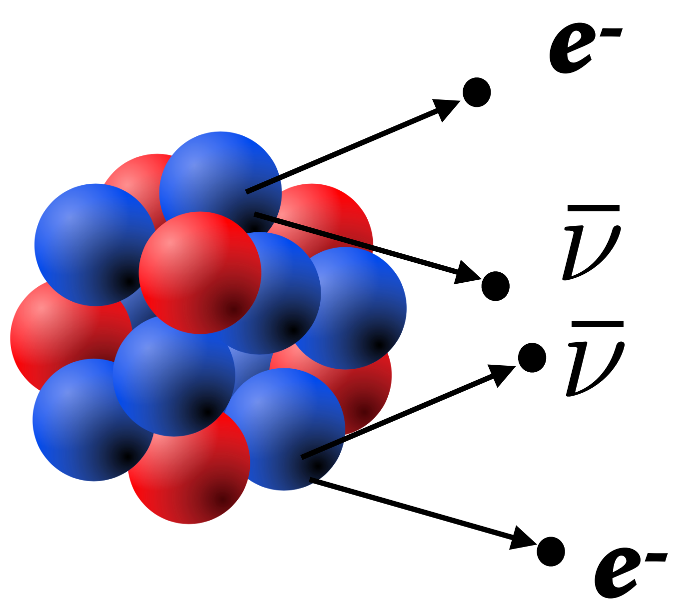
Mass Scale

Hierarchy

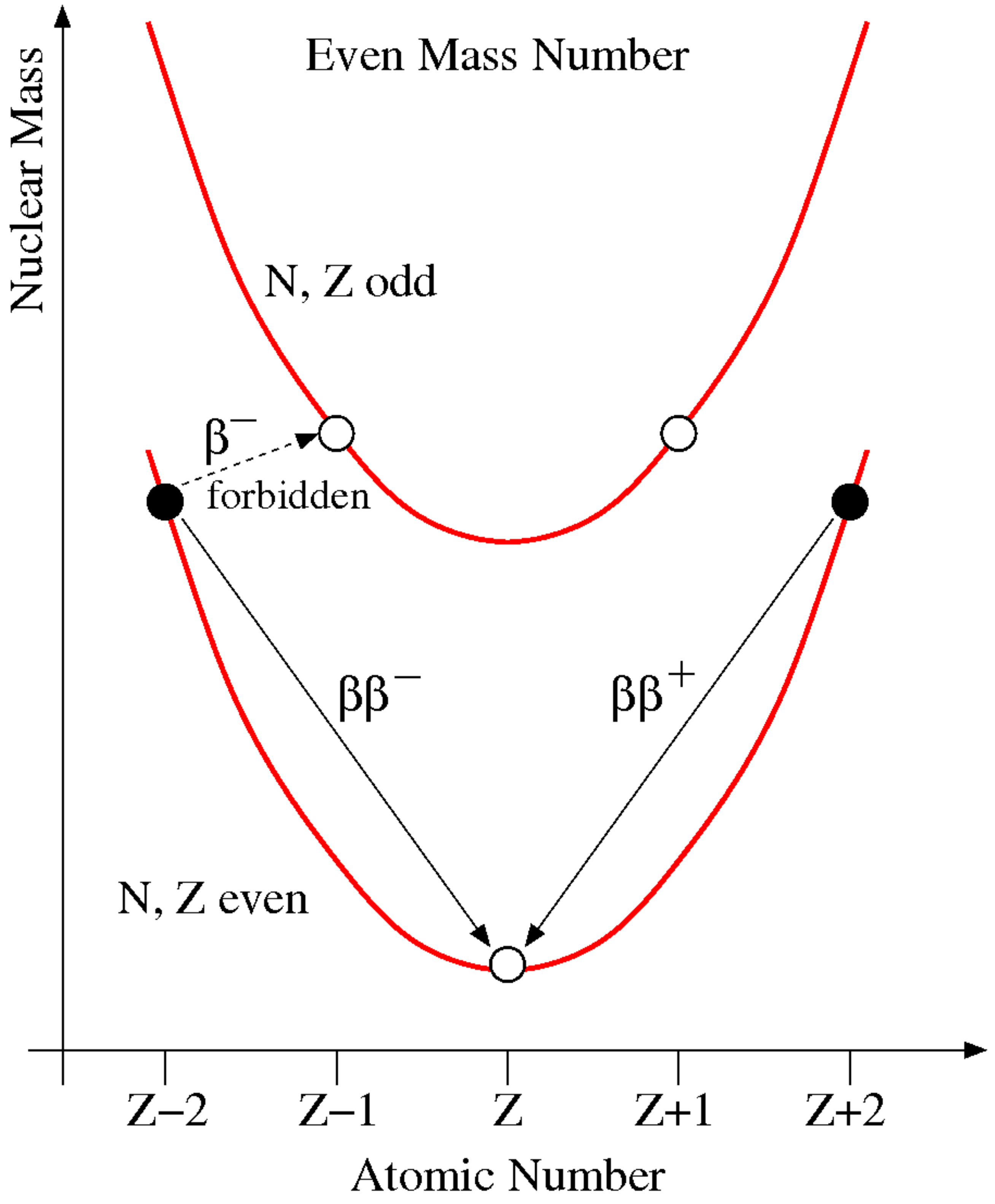


E. Majorana

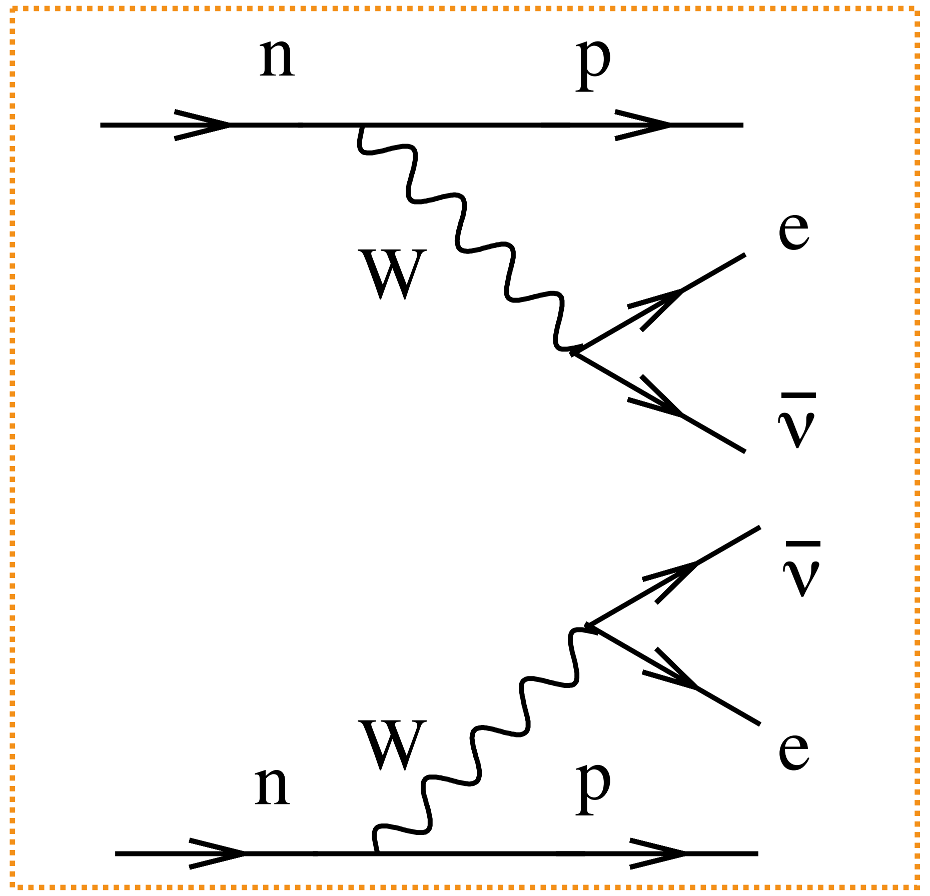
Double-Beta Decay



- First studied by Goeppert-Mayer in 1935
- Simultaneous decay of 2 neutrons in a nucleus
- Second-order weak process, allowed in SM
- Observable only if ‘ordinary’ beta decay is inhibited
- Directly observed in ~12 nuclei



2νββ



half-life

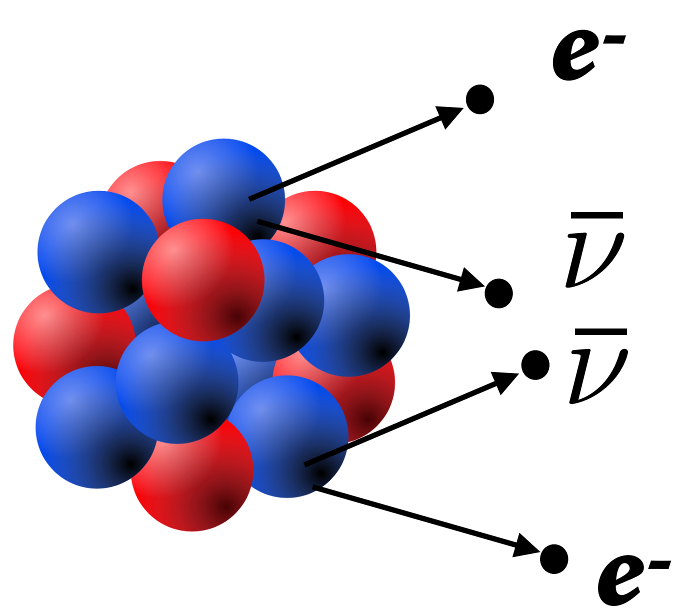
Phase space factor

$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}|M^{2\nu}|^2$$

Nuclear matrix element

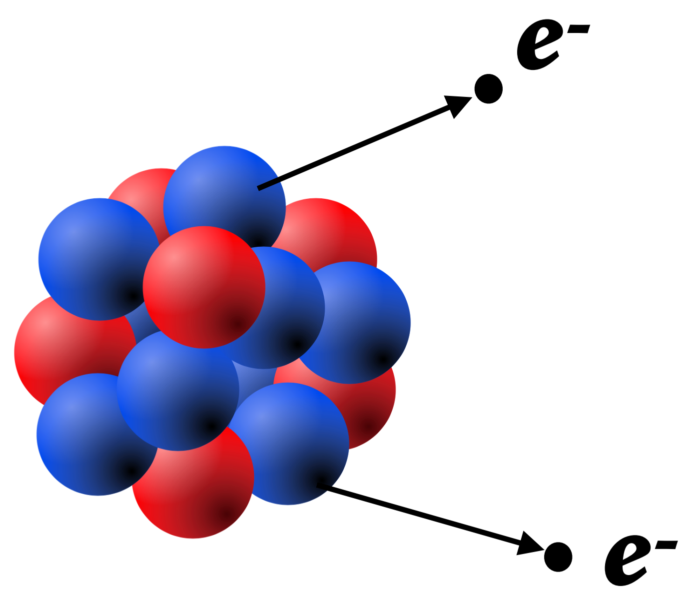
half lives ~10^{19}-10^{21} years !

Neutrinoless Double-Beta Decay



What if a neutrino is exchanged between the two neutrons ?

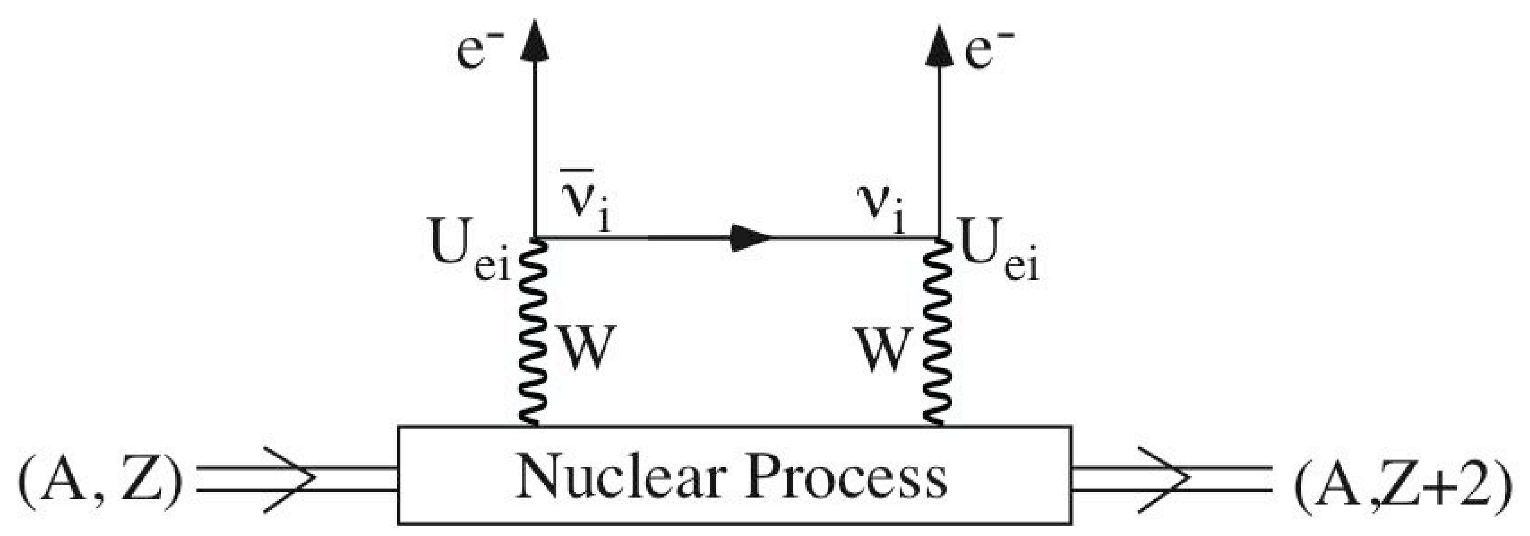
We get no neutrinos in the final state



$$n \longrightarrow p + e^- + \bar{\nu}_e$$

$$\nu_e + n \longrightarrow p + e^-$$

0νββ



- If $m_{\beta\beta}$ = 50 meV estimated half lives ~ 10^{25} - 10^{27} years !

half-life

Phase space factor

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

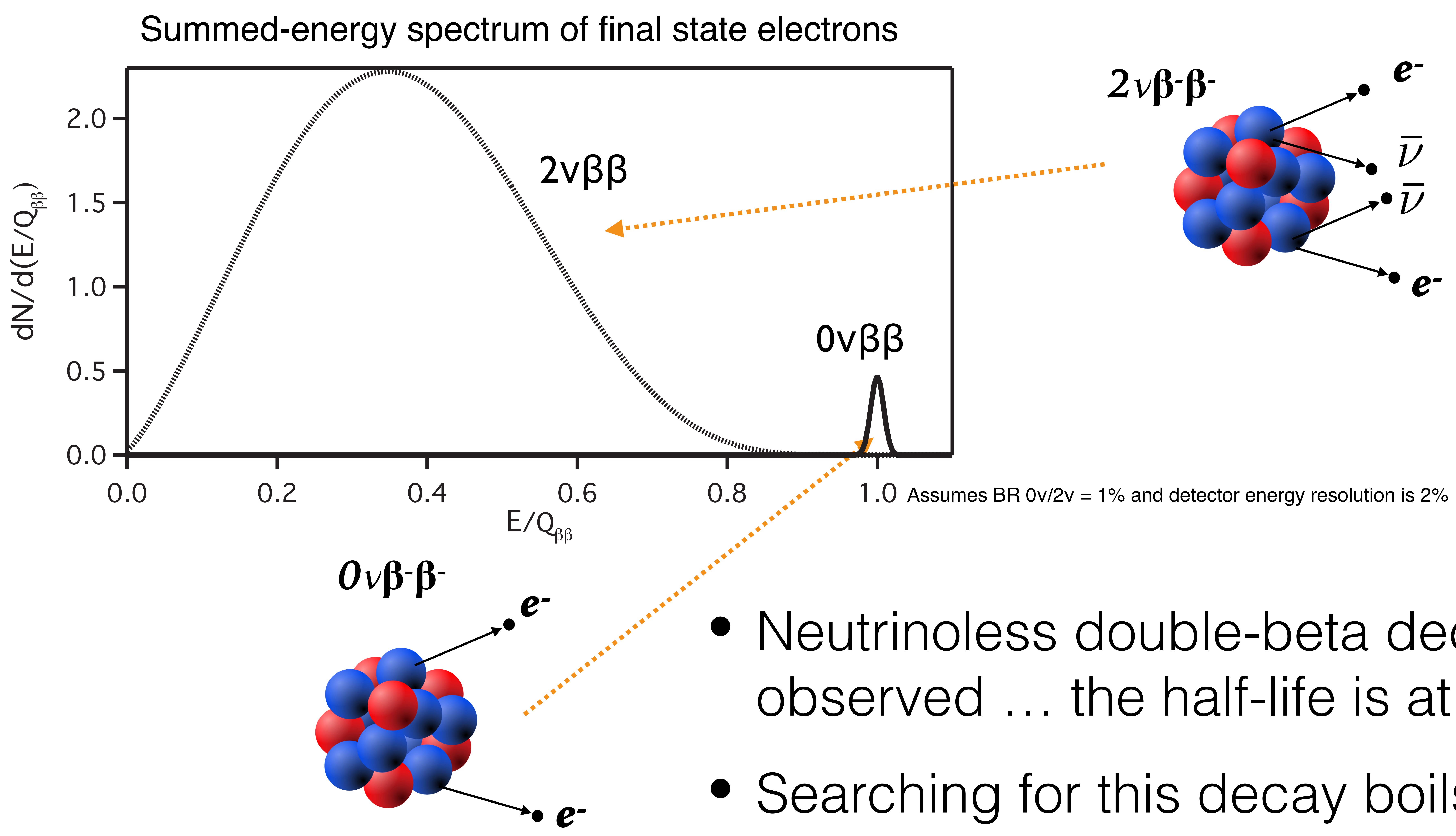
Nuclear matrix element

Effective Majorana neutrino mass: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2\, m_i\right|$

L_{Tot} =0 **L_{Tot} =2**

$$2n \longrightarrow 2p + 2e^-$$

Double-Beta Decay Signature



- Neutrinoless double-beta decay has never been observed … the half-life is at least 10^{25} years
- Searching for this decay boils down to searching for a new peak in the summed electron spectrum

Building a sensitive Experiment

- We want the expected number of signal events to be large compared to statistical fluctuations of the background

Maximize this
Figure of merit

$$\frac{N_{sig}}{\sqrt{N_{bkg}}} \longrightarrow a \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

- Generally we want:
  - Maximize isotopic abundance of decaying nuclei (a)
  - Need to be able to run experiments for a long time (t)
  - Large mass of source material (M)
  - Small background index near the Q-value (b)
  - Excellent energy resolution (small ΔE)

Building a sensitive Experiment

- We want the expected number of signal events to be large compared to statistical fluctuations of the background

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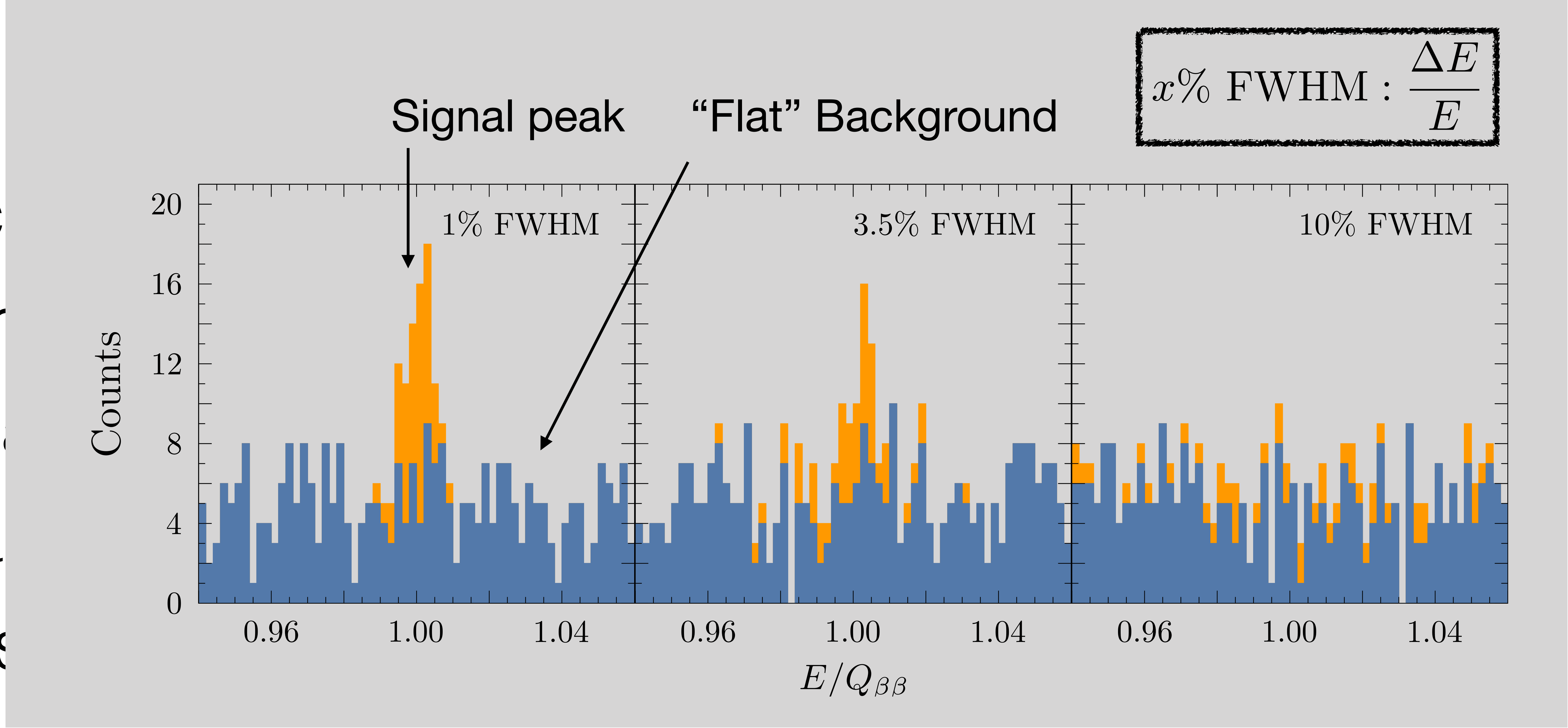
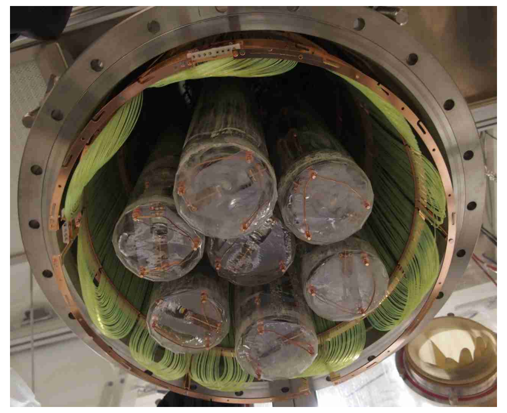


Experimental Techniques (incomplete list)

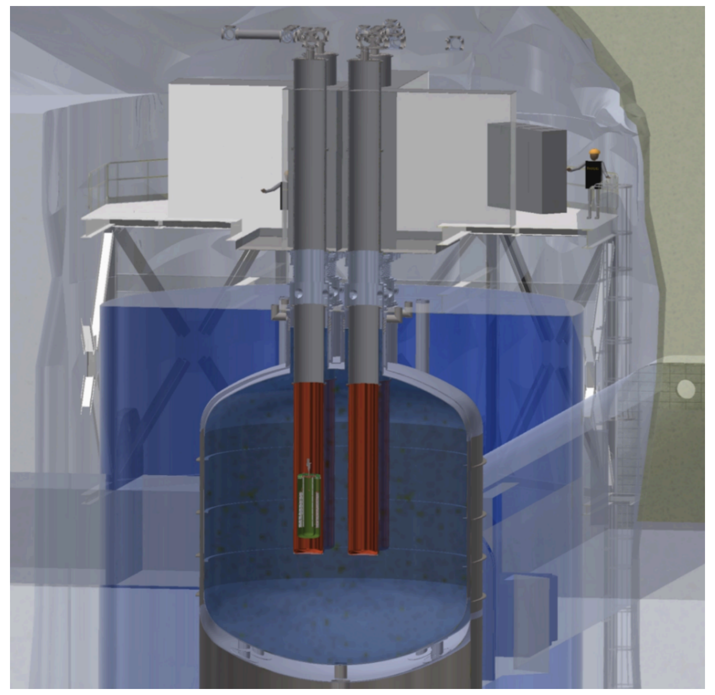
- **Ge Diodes**
  - ➡ Excellent energy resolution (~0.1% FWHM in the region of interest)
  - ➡ Mature purification techniques (HPGe)
  - ➡ Bkg rejection through pulse shape analysis
  - ➡ Large masses possible
  - ➡ Limited to ^{76}Ge



GERDA

Majorana

LEGEND (planned)



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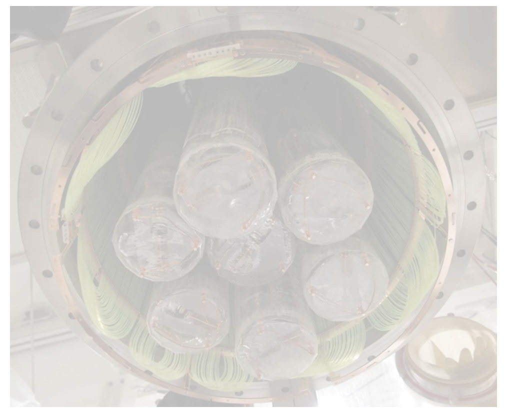

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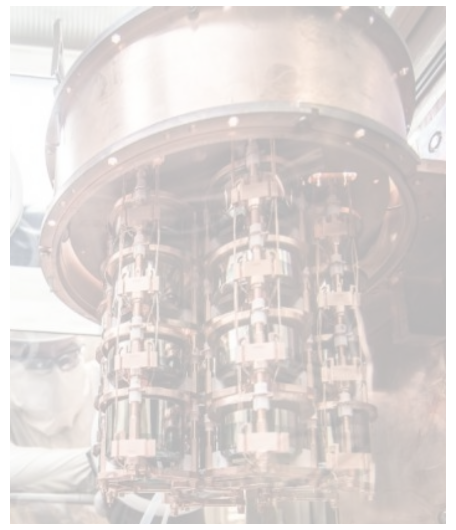

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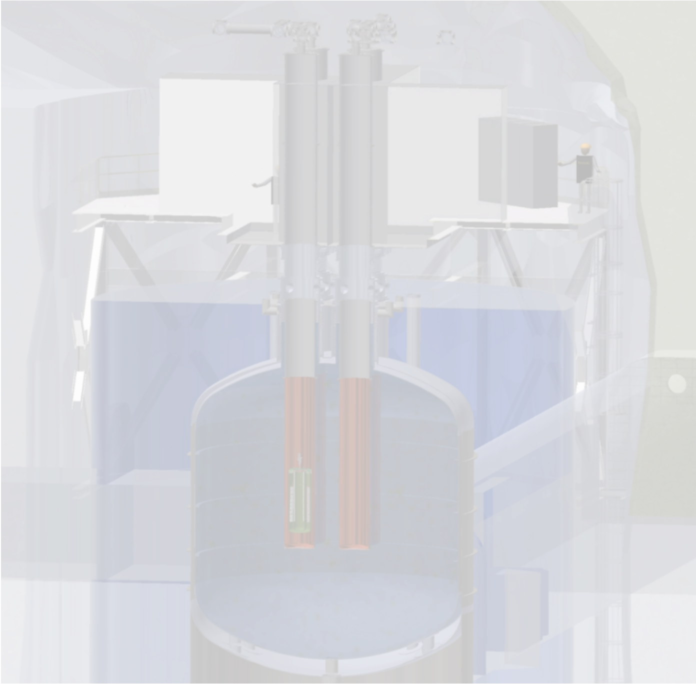
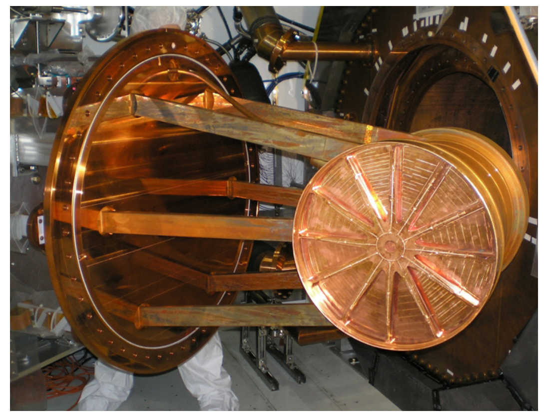
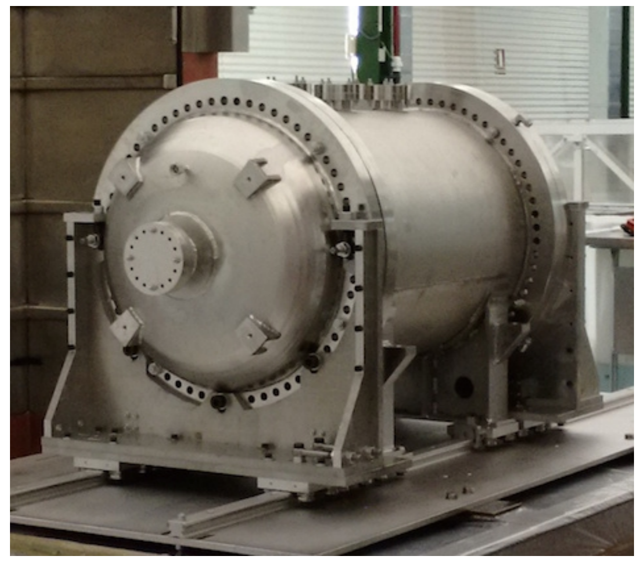


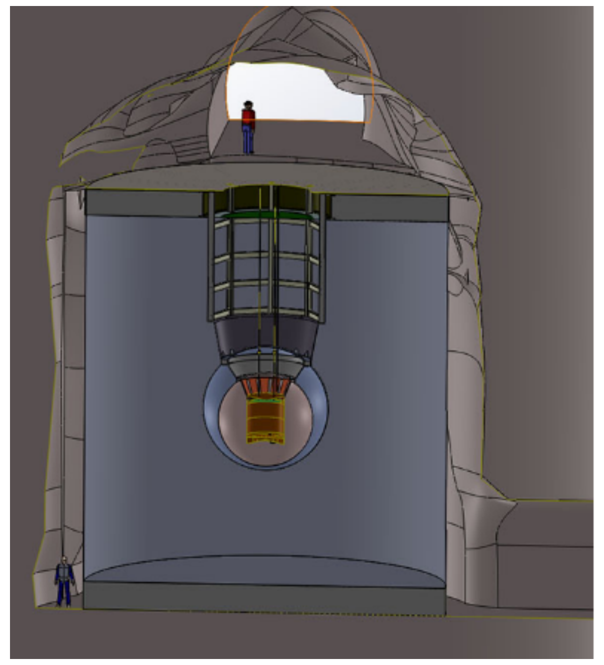
- **TPCs liquid and high pressure gas (^{136}Xe)**
  - Enrichment and purification is relatively easy
  - Event topology reconstruction
  - Low background due to fiducialization and self-shielding
  - Poorer energy resolution (~2% FWHM for liquid Xe)
  - Large detector masses possible



EXO



NEXT (planned)



nEXO (Planned)

Experimental Techniques (incomplete list)

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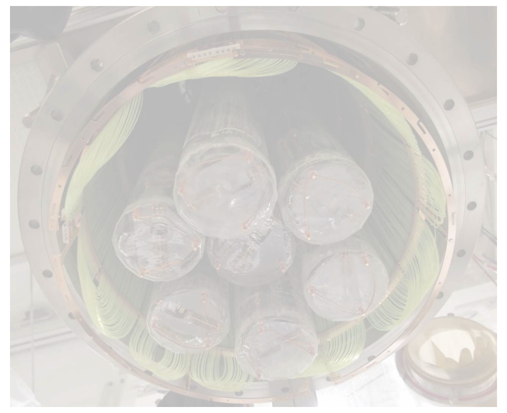

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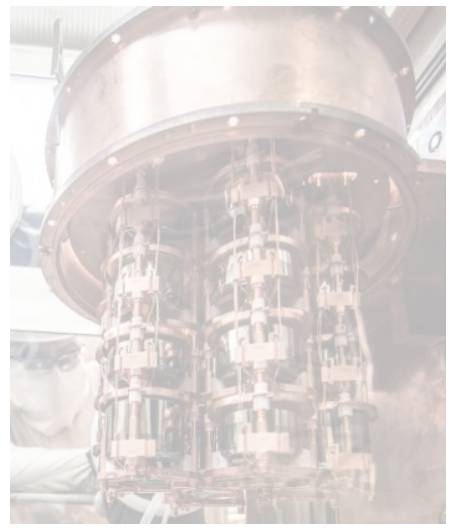
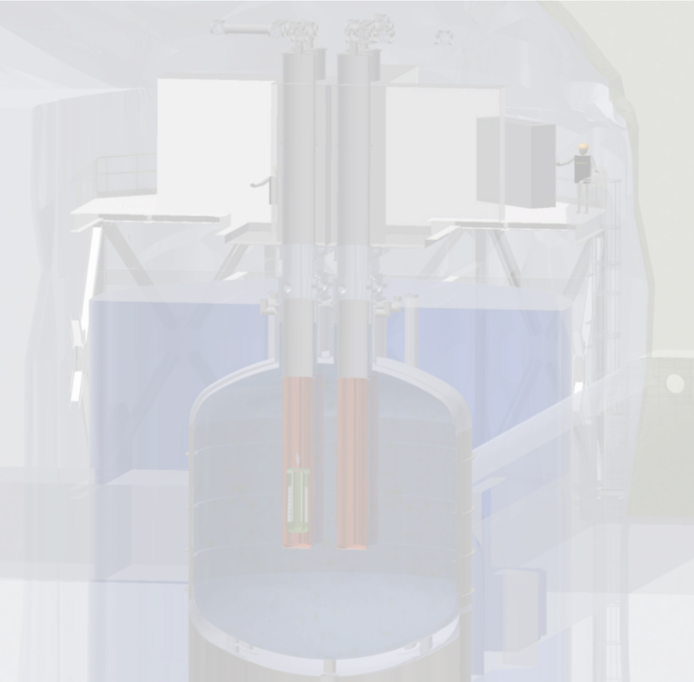


Majorana

LEGEND (planned)



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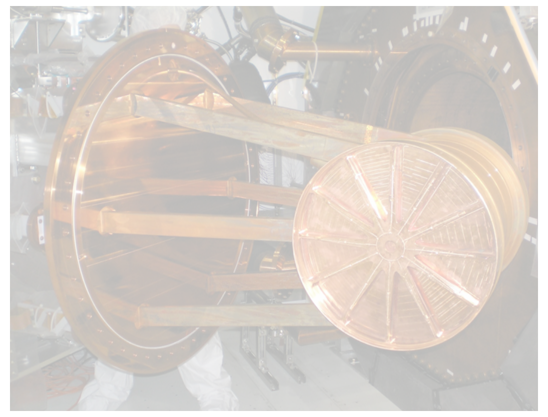
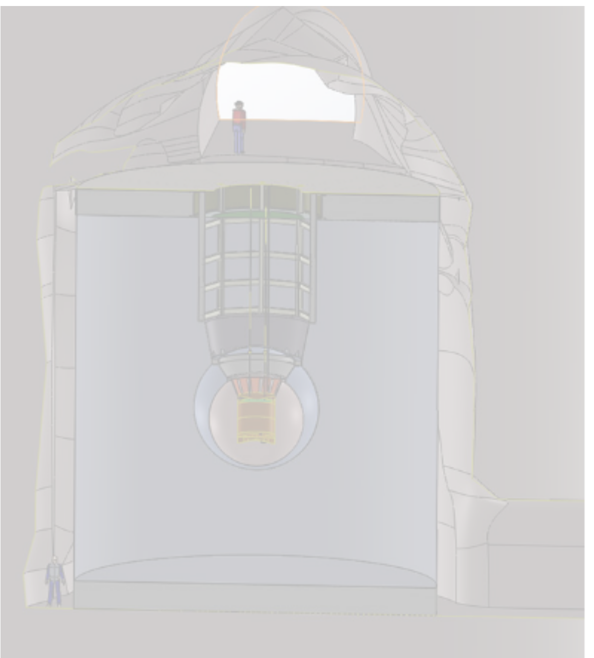


EXO

NEXT (planned)

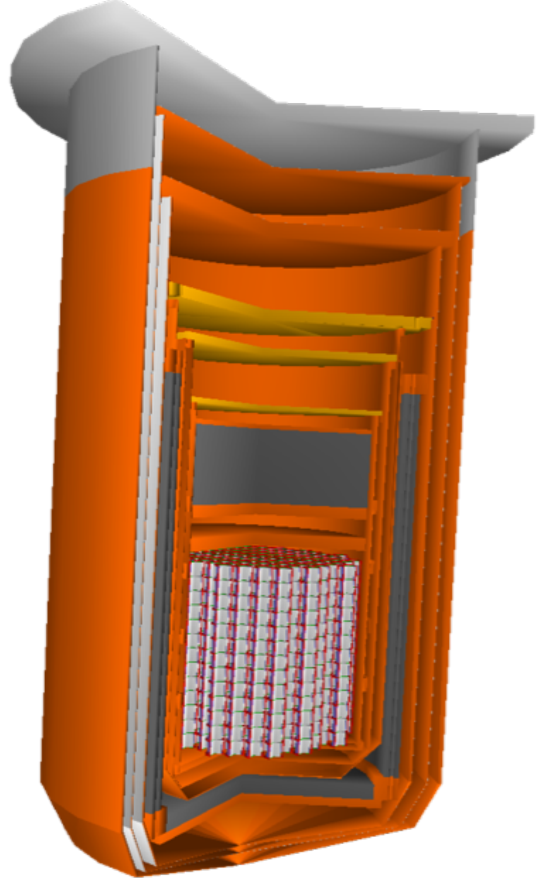


nEXO (Planned)

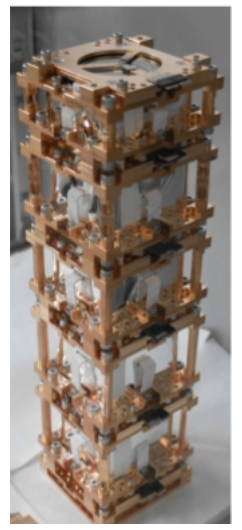
- **Cryogenic (scintillating) bolometers**
  - ➡ Excellent energy resolution (~0.2-0.3% FWHM in the region of interest)
  - ➡ Several target isotopes possible (130Te, 100Mo,48Ca, 82Se)
  - ➡ Bkg rejection through heat/light analysis
  - ➡ Large masses possible
  - ➡ Low-temperature cryogenics

CUORE

CUPID(planned)

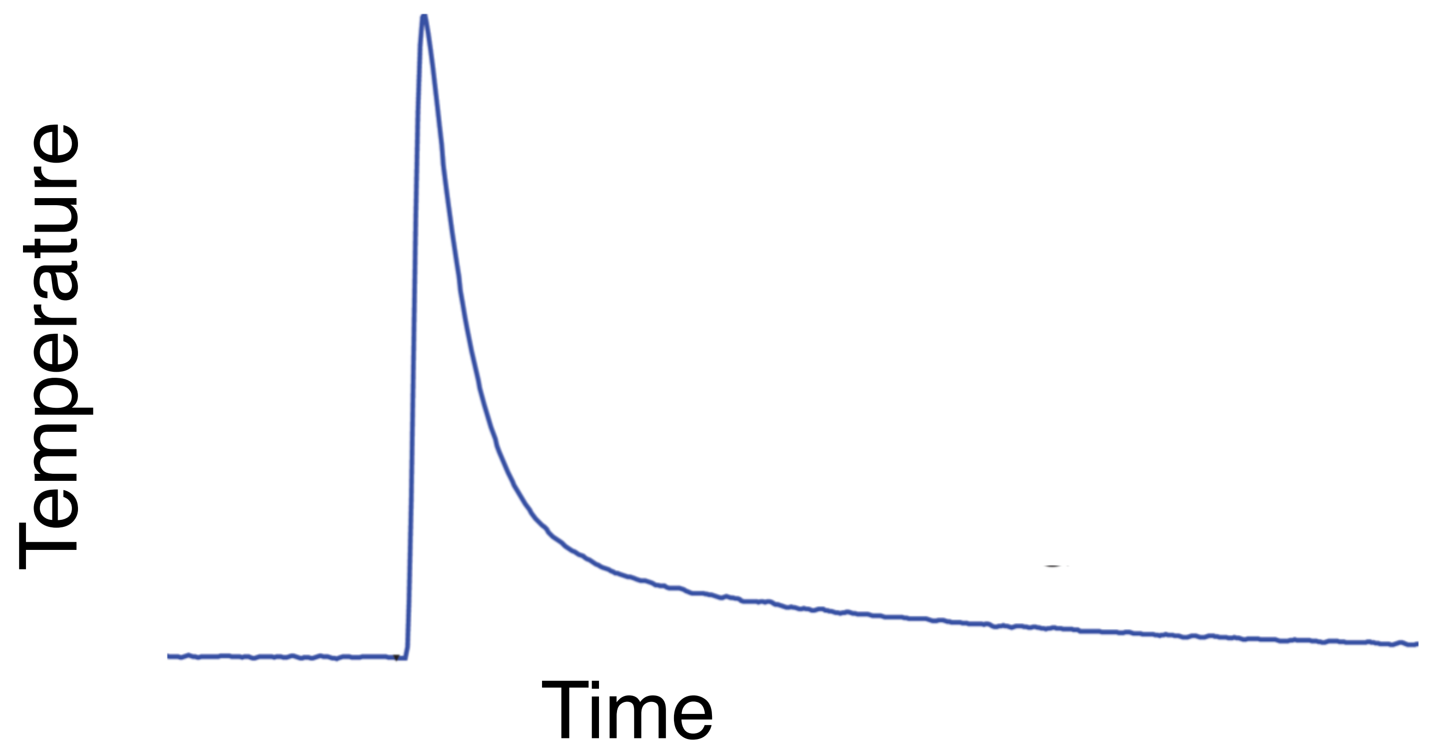


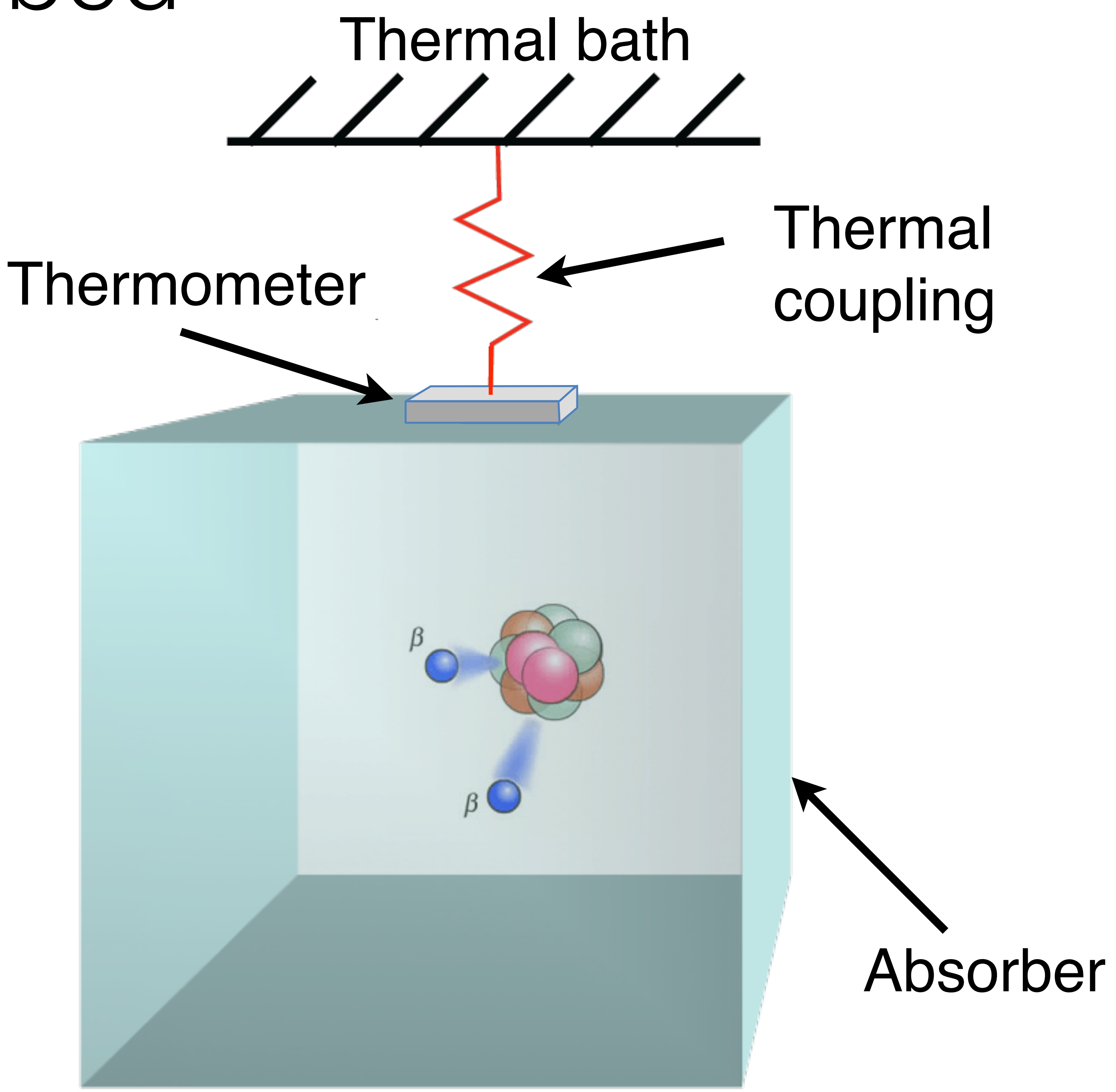
AMoRE



Cryogenic Bolometer Technique

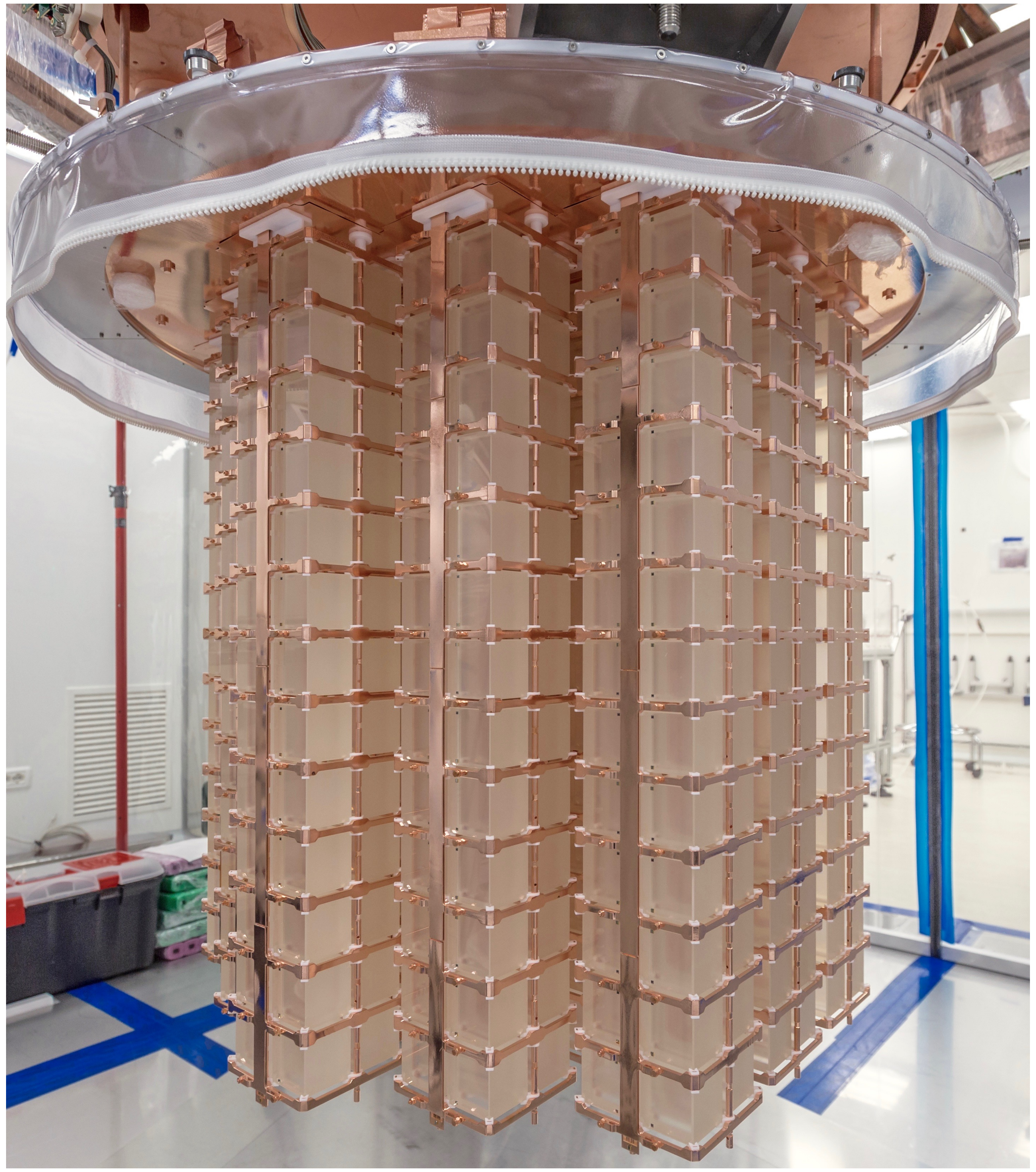
- The absorbed energy causes an increase in absorber temperature
- Use temperature change to measure energy absorbed



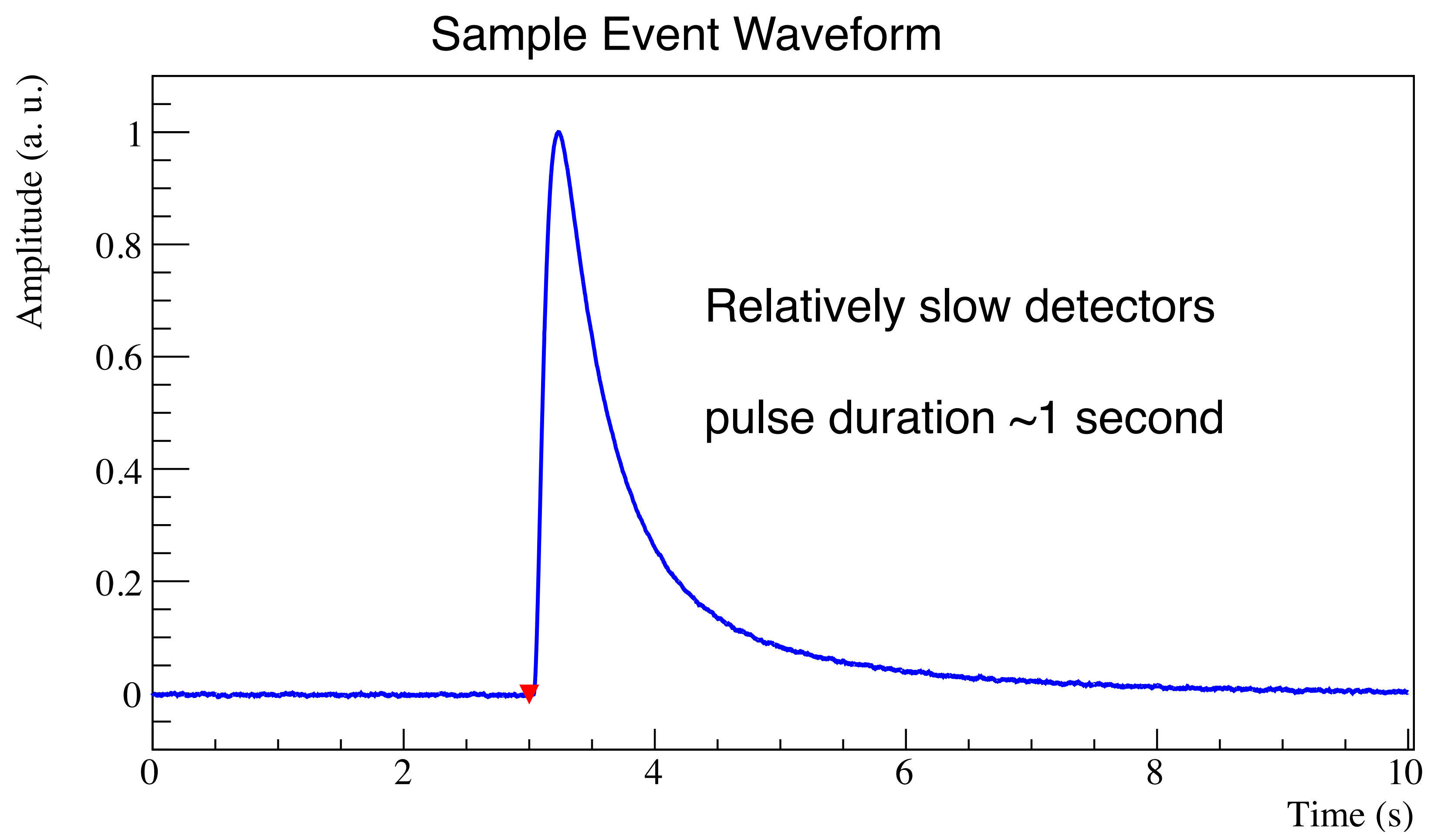


- For dielectric crystal absorbers heat capacity follows the Debye law $$C \propto \frac{T^3}{T_D^3}$$
- Typically operated at ~10mK !
- Excellent energy resolution $$\frac{\Delta E}{E} \simeq 0.2\%$$

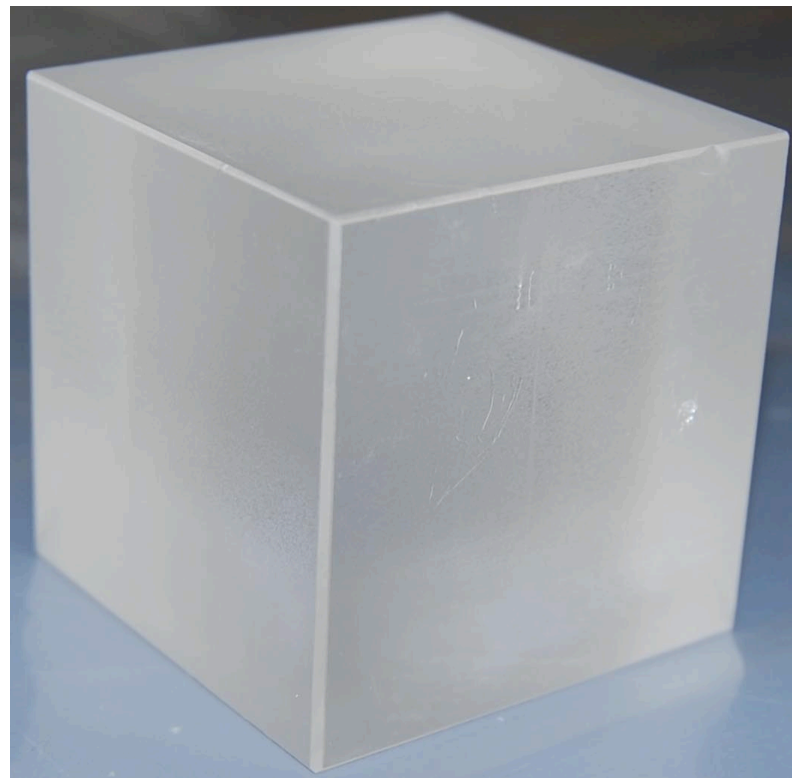
CUORE: **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents

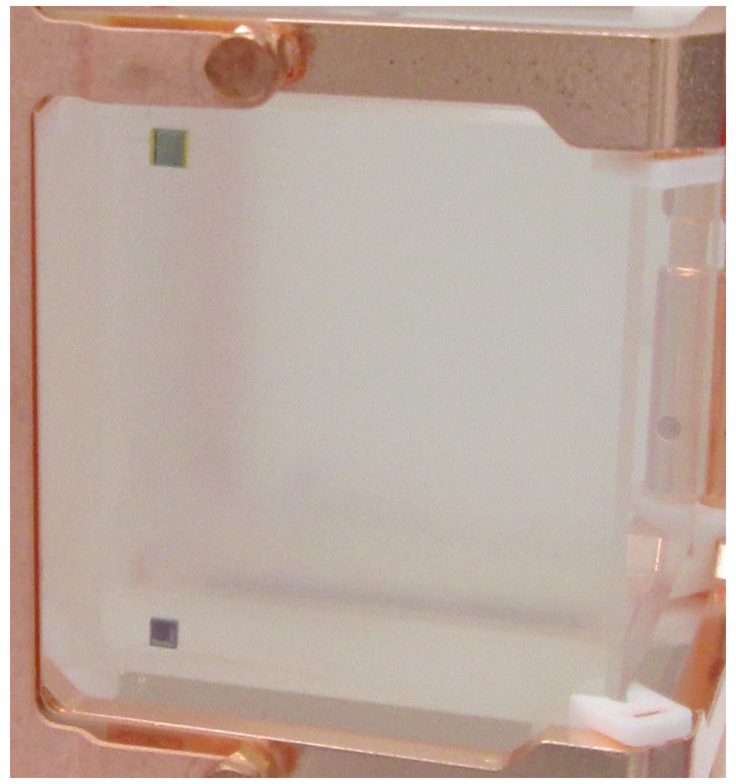


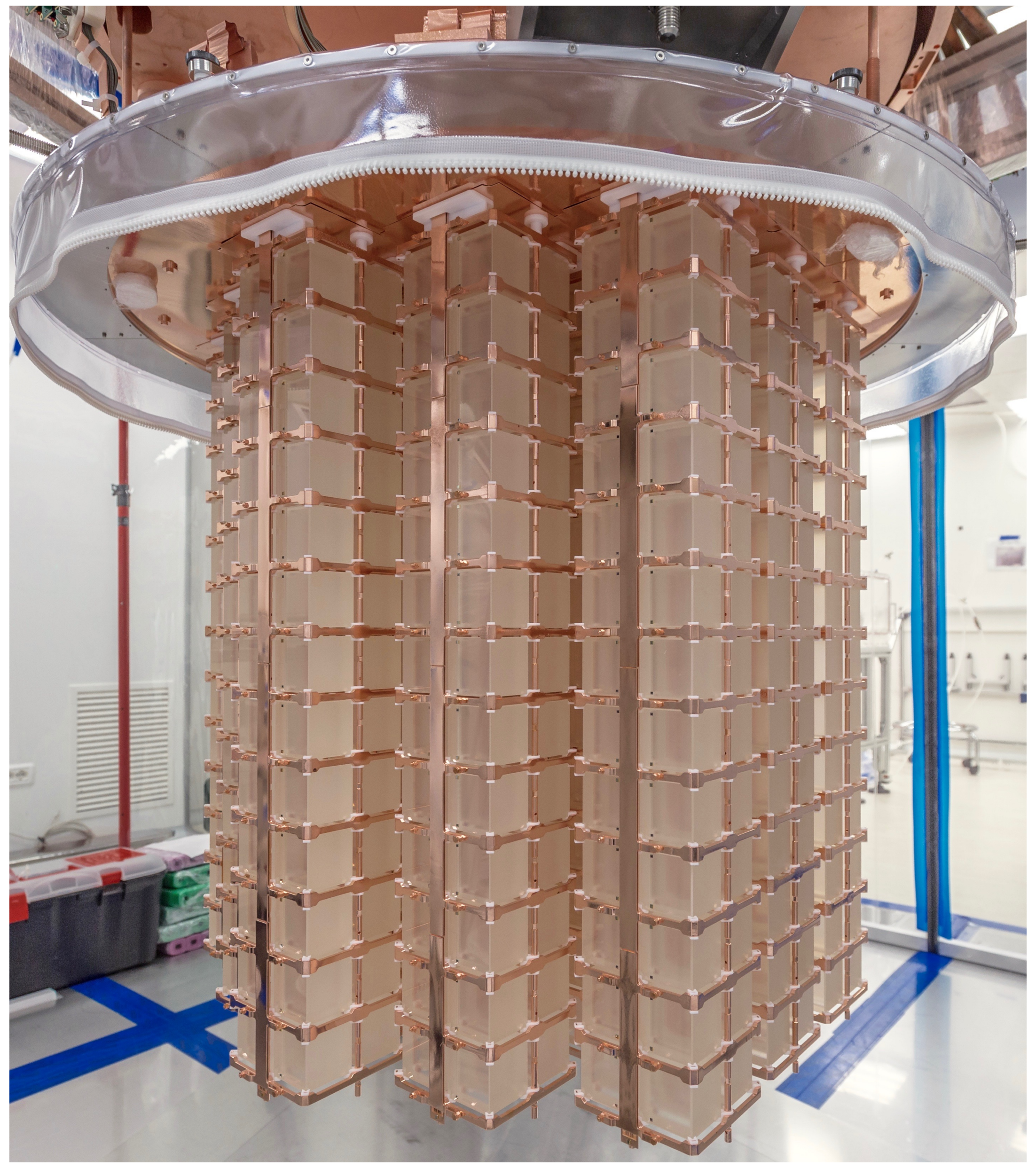
- Close-packed array of 988 $^{nat}TeO_2$ bolometers (Total mass: 742 kg)
- Operated at T~11.8 mK
- Primary physics goal: 0νββ decay of ^{130}Te
  - Isotopic abundance 34% => 206 kg
  - Q-value: 2527.5 keV



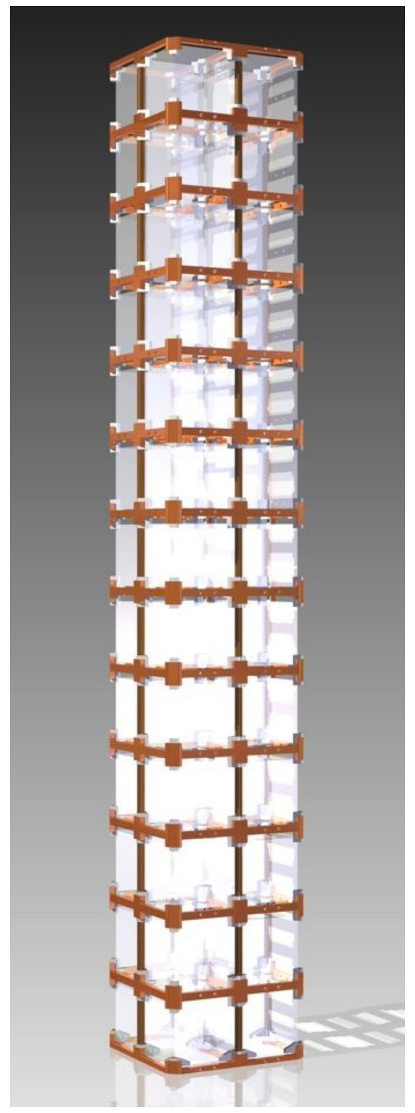
CUORE Tower Structure

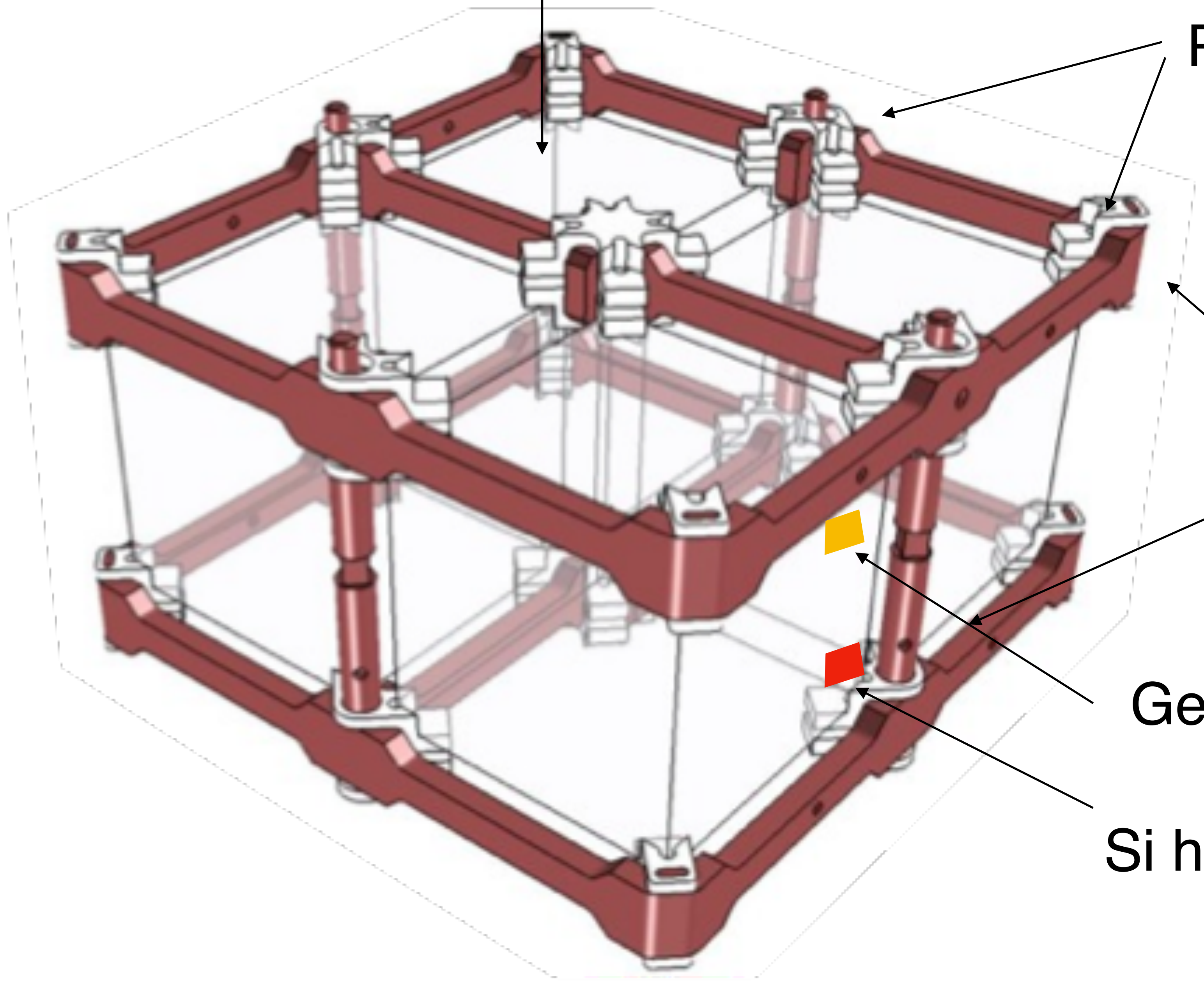






13 floors per tower





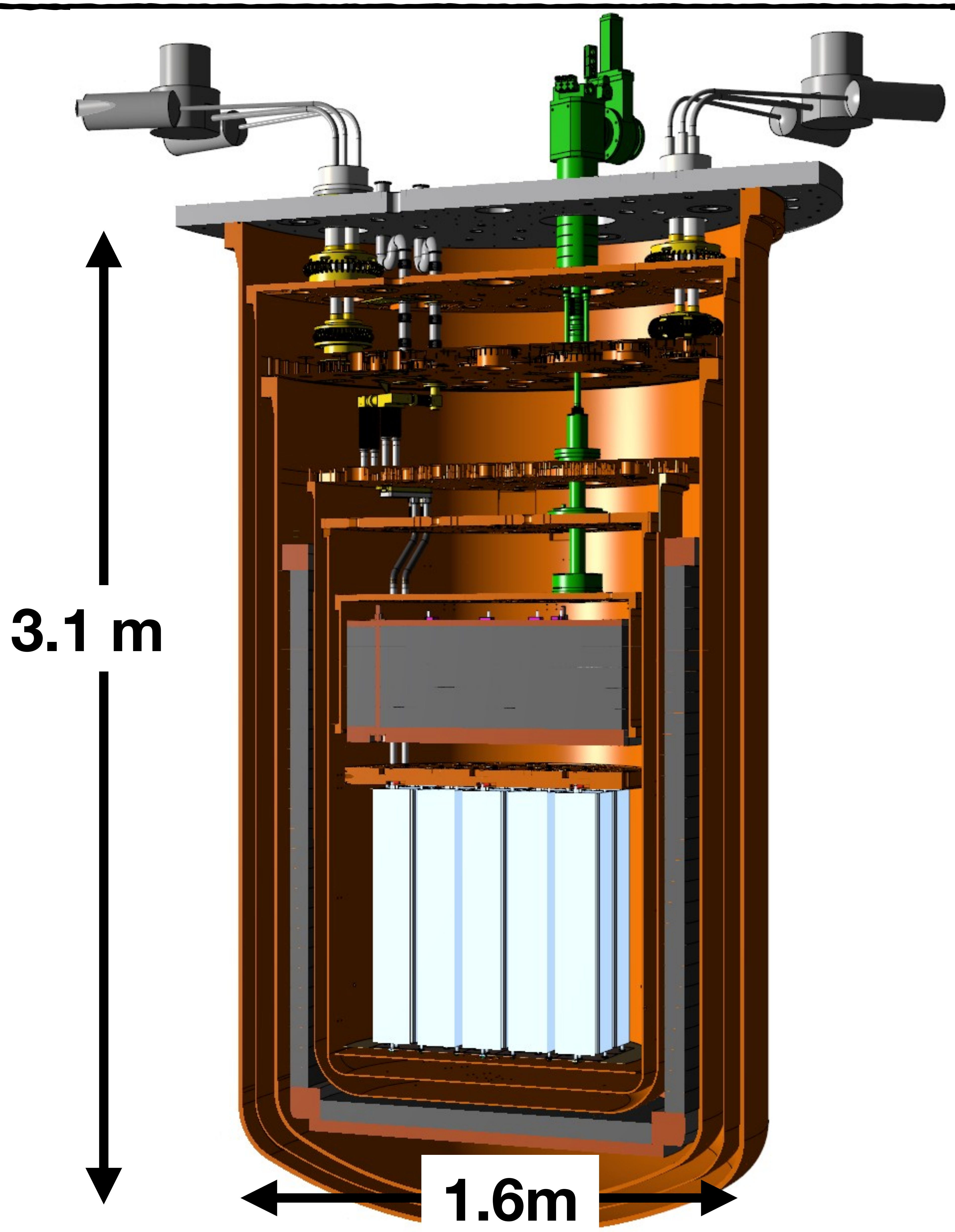
Gran Sasso Underground Lab

Photo: courtesy Gran Sasso Lab

1400 m of rock (~3600 m.w.e.) deep

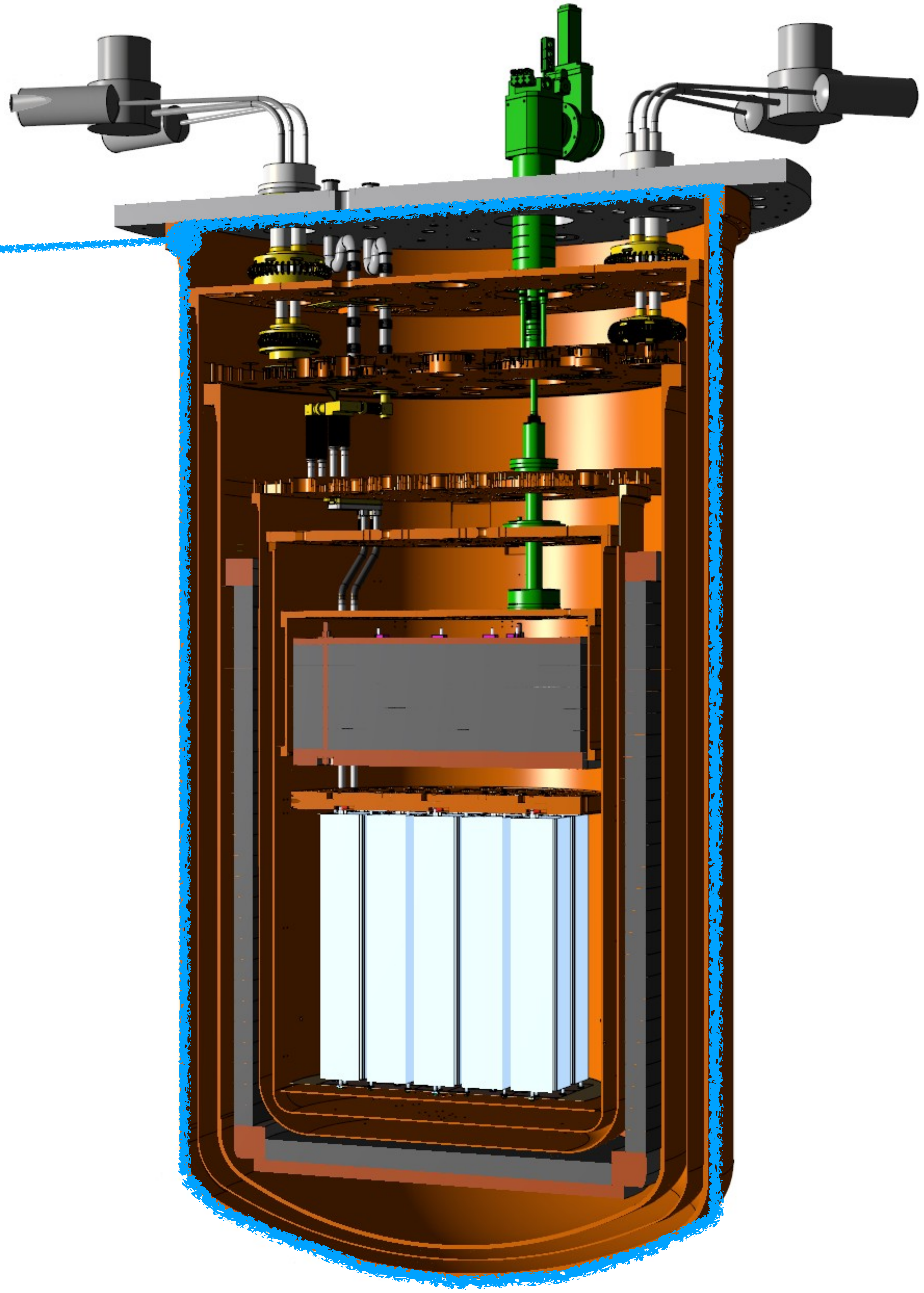
- μ's: ~3×10^{-8} / (s·cm^2)
- γ's: ~0.73 / (s·cm^2)
- neutrons: 4×10^{-6} n/(s·cm^2) below 10 MeV

CUORE Cryogenic System



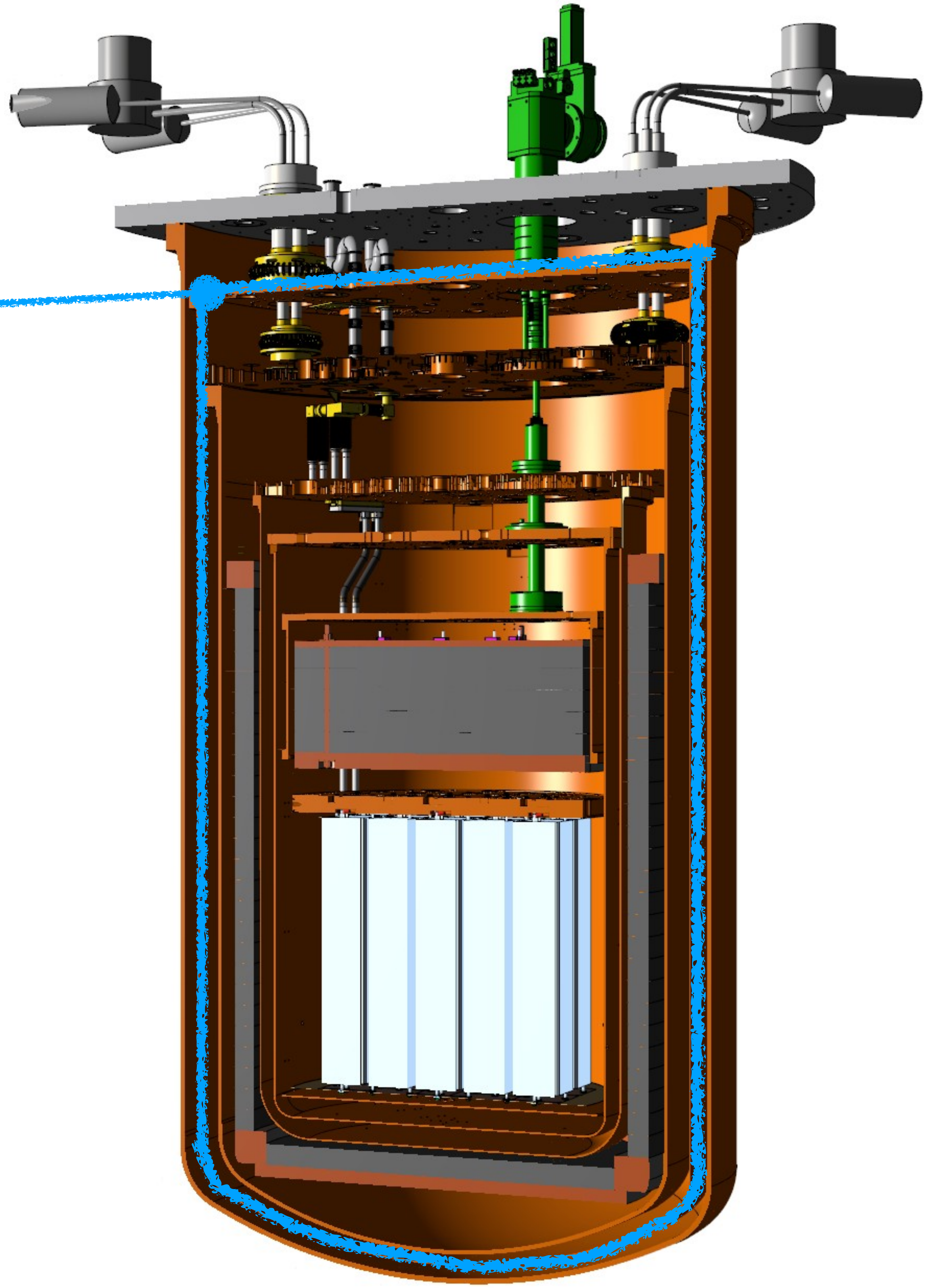
CUORE Cryogenic System

300K vessel (3500 kg)
Outer vacuum chamber



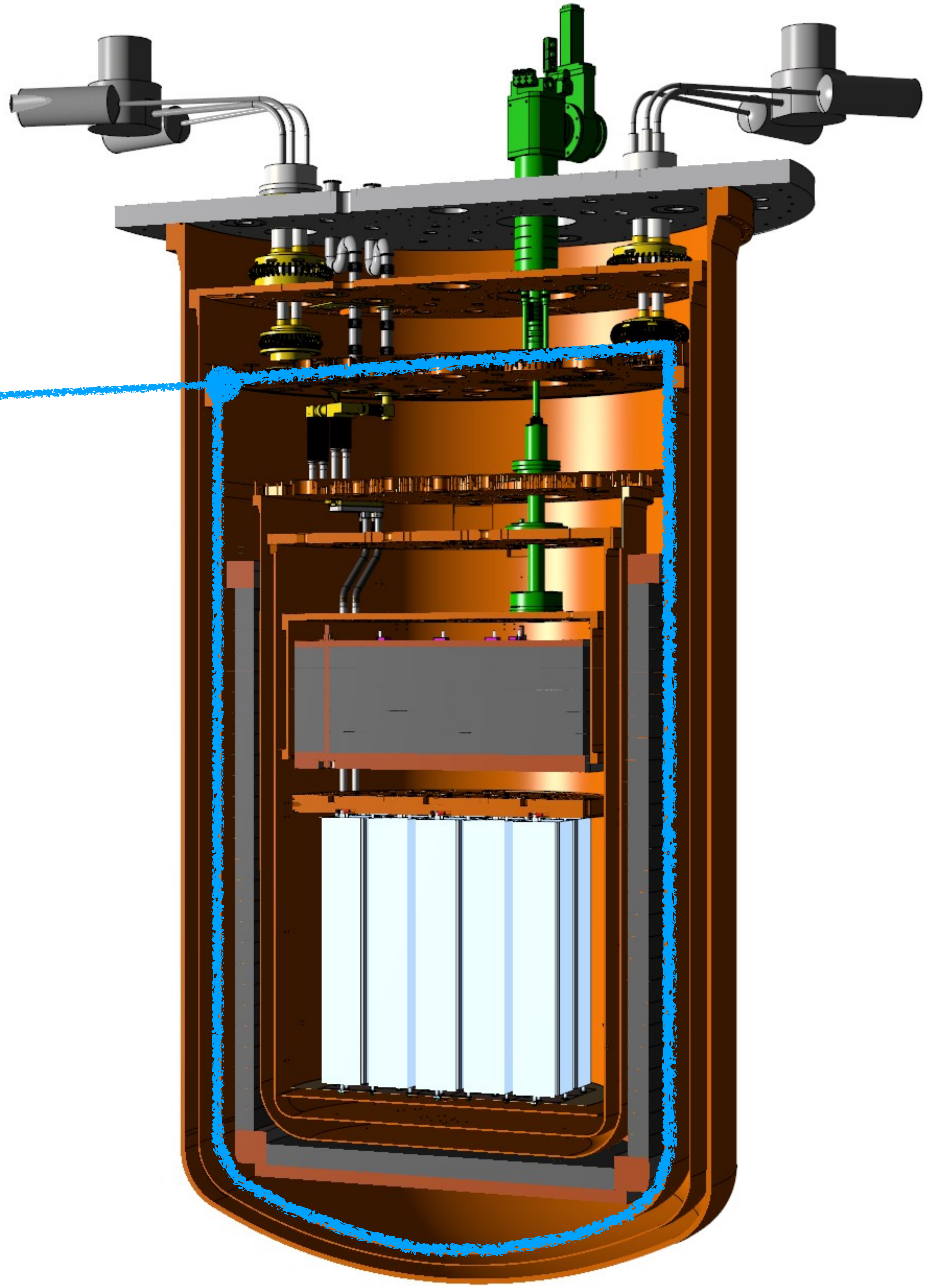
CUORE Cryogenic System

40K vessel (980kg)



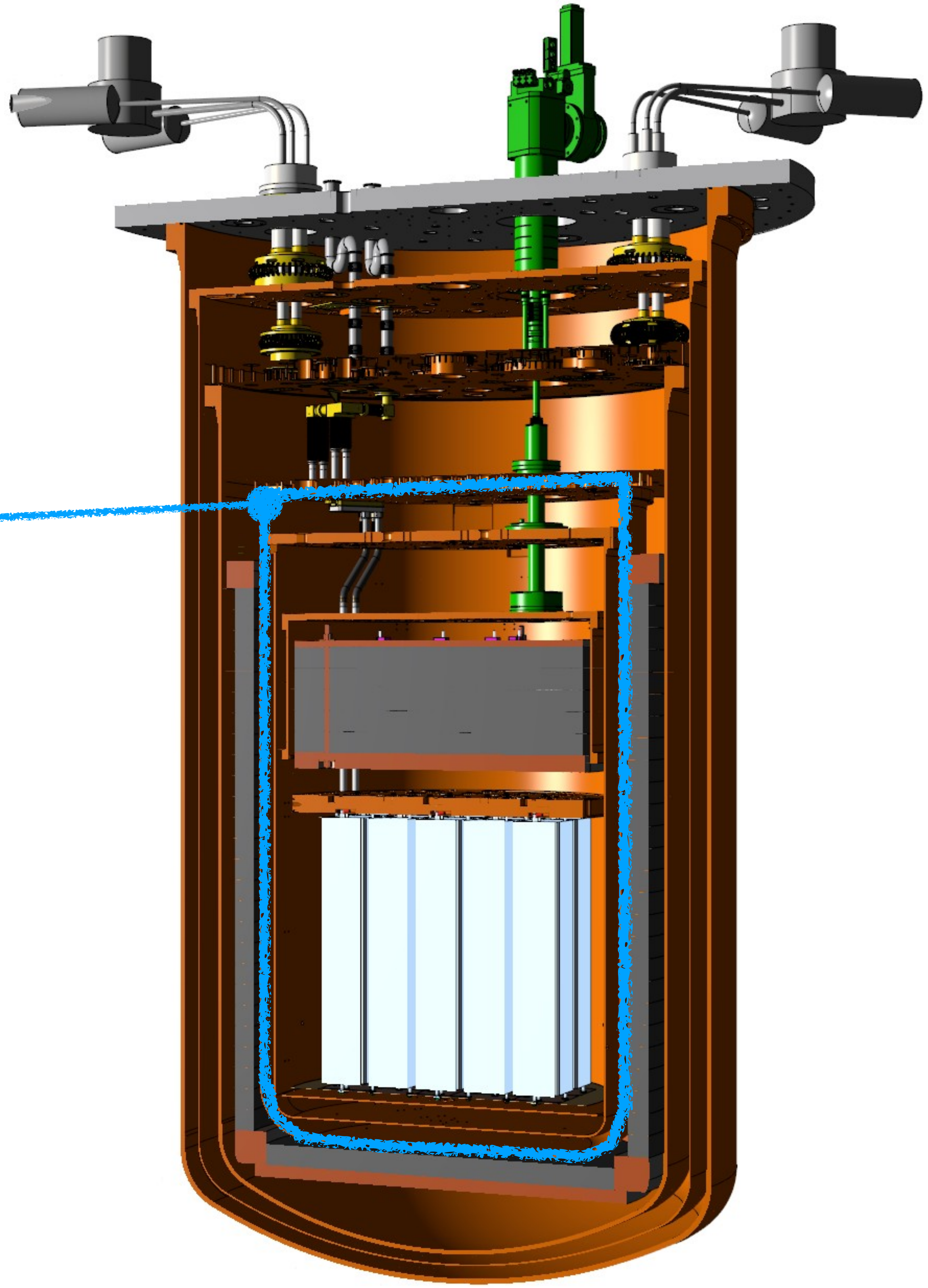
CUORE Cryogenic System

4K vessel (1990kg)
Inner vacuum chamber

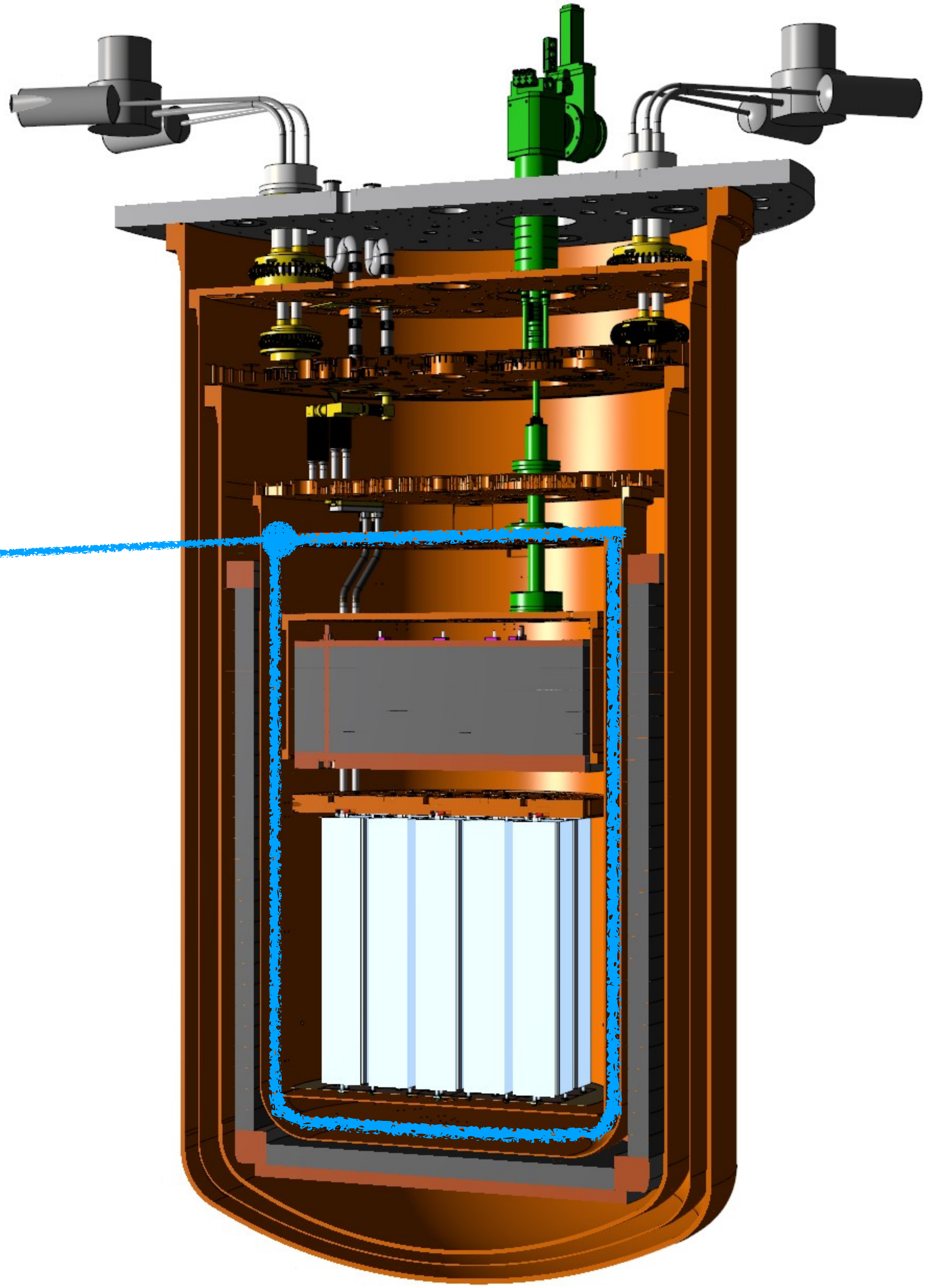


CUORE Cryogenic System

Still vessel (840kg)
(~800mK)

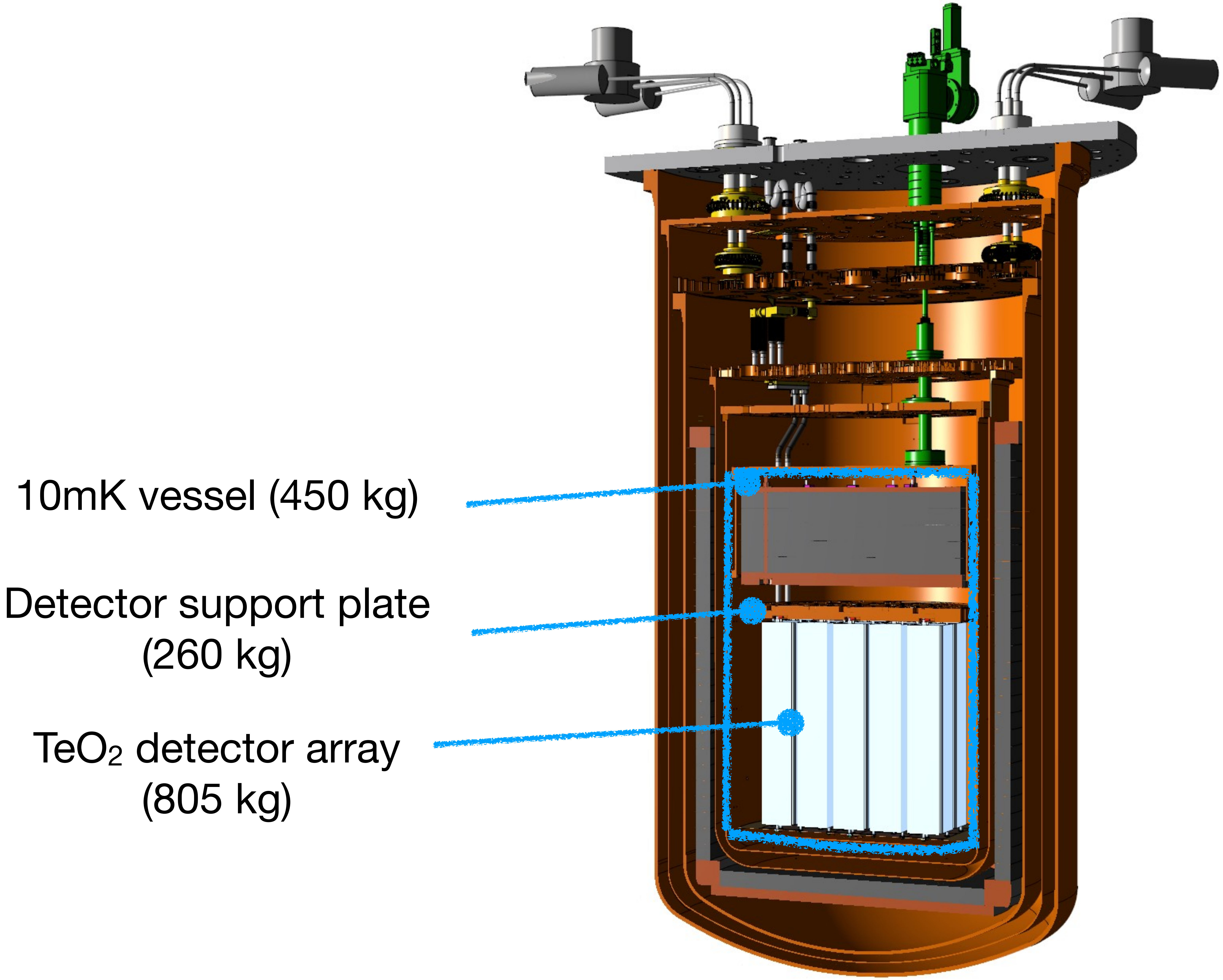


CUORE Cryogenic System



Heat-Exchanger vessel (510 kg)
(~50mK)

CUORE Cryogenic System



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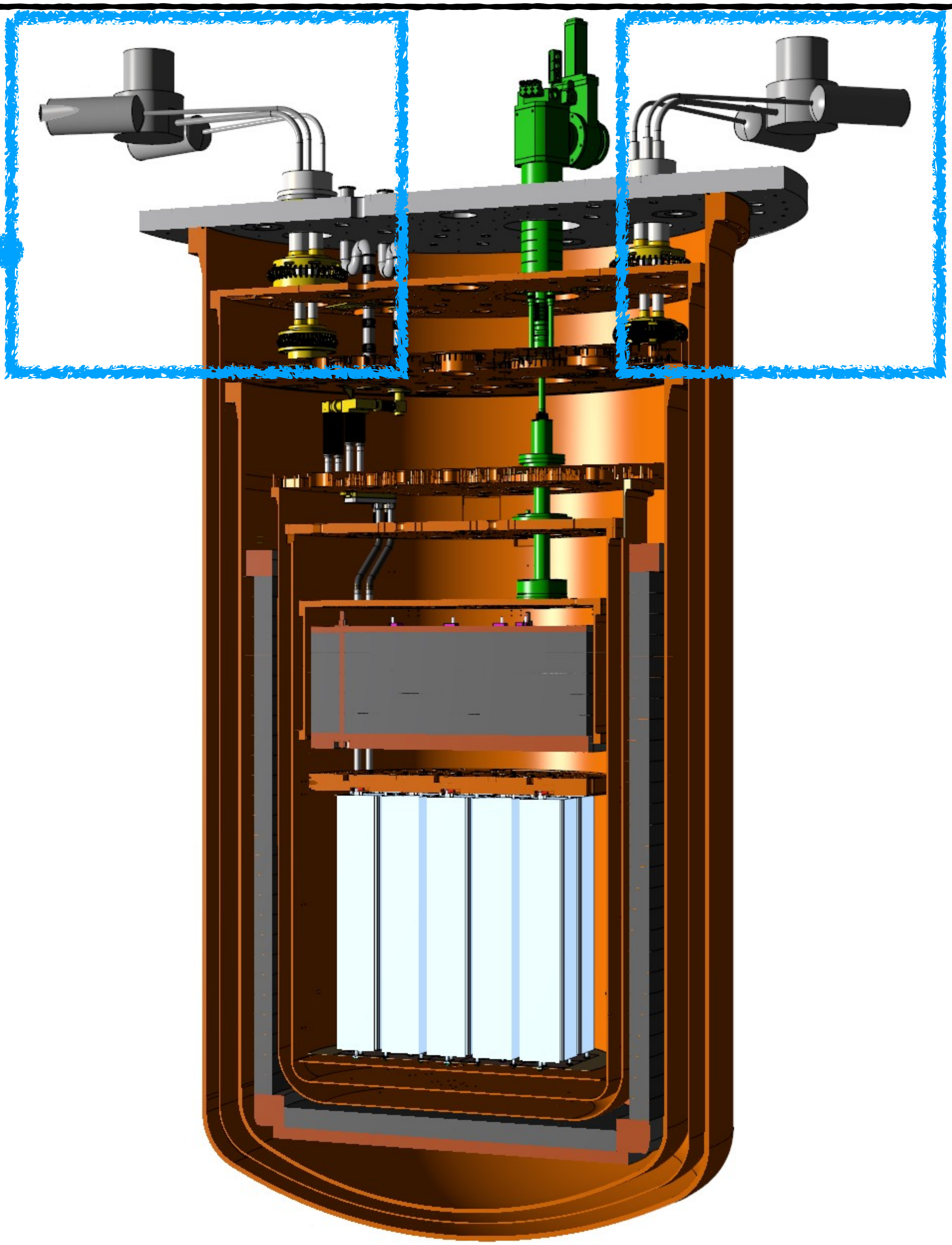
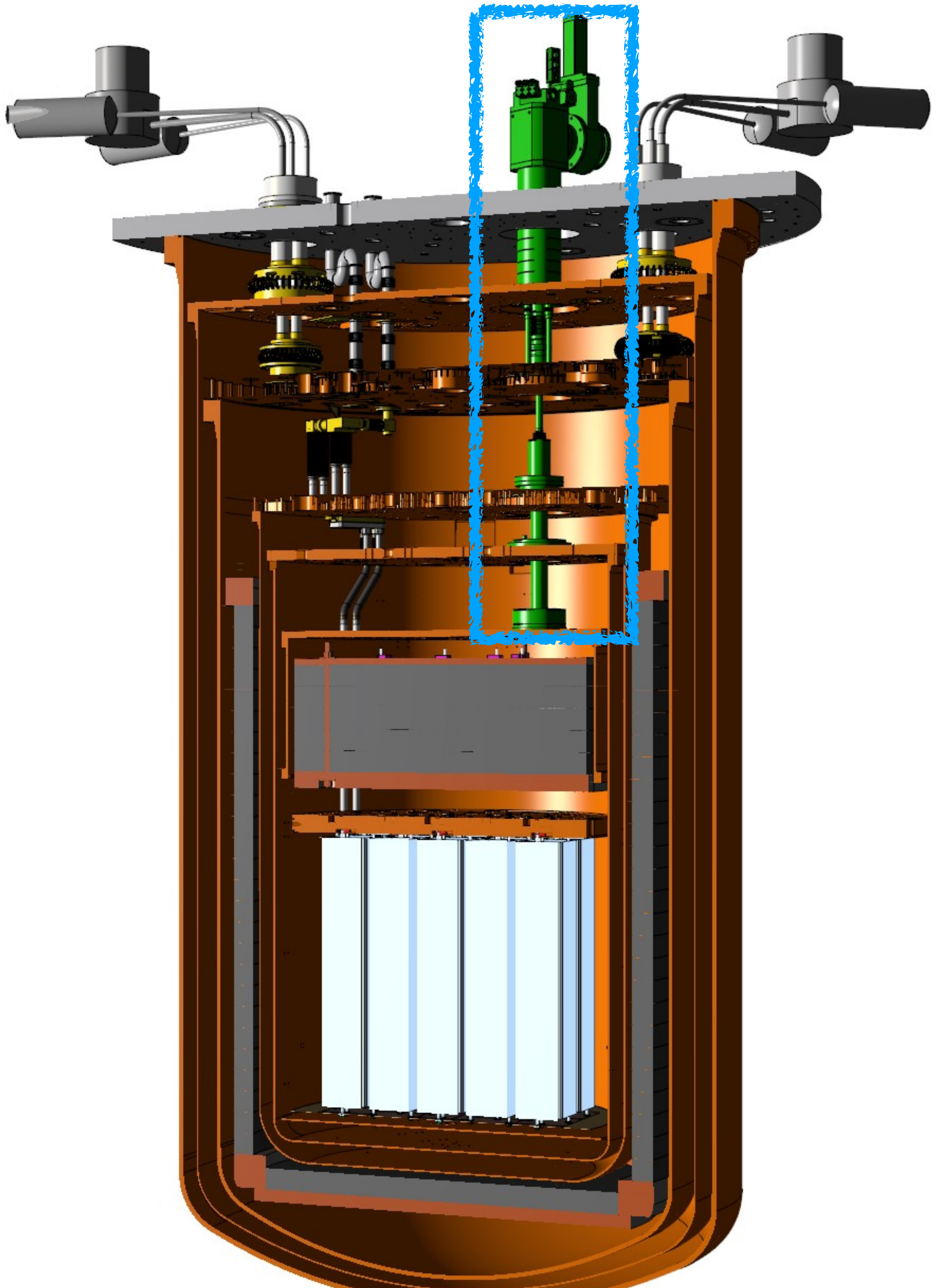


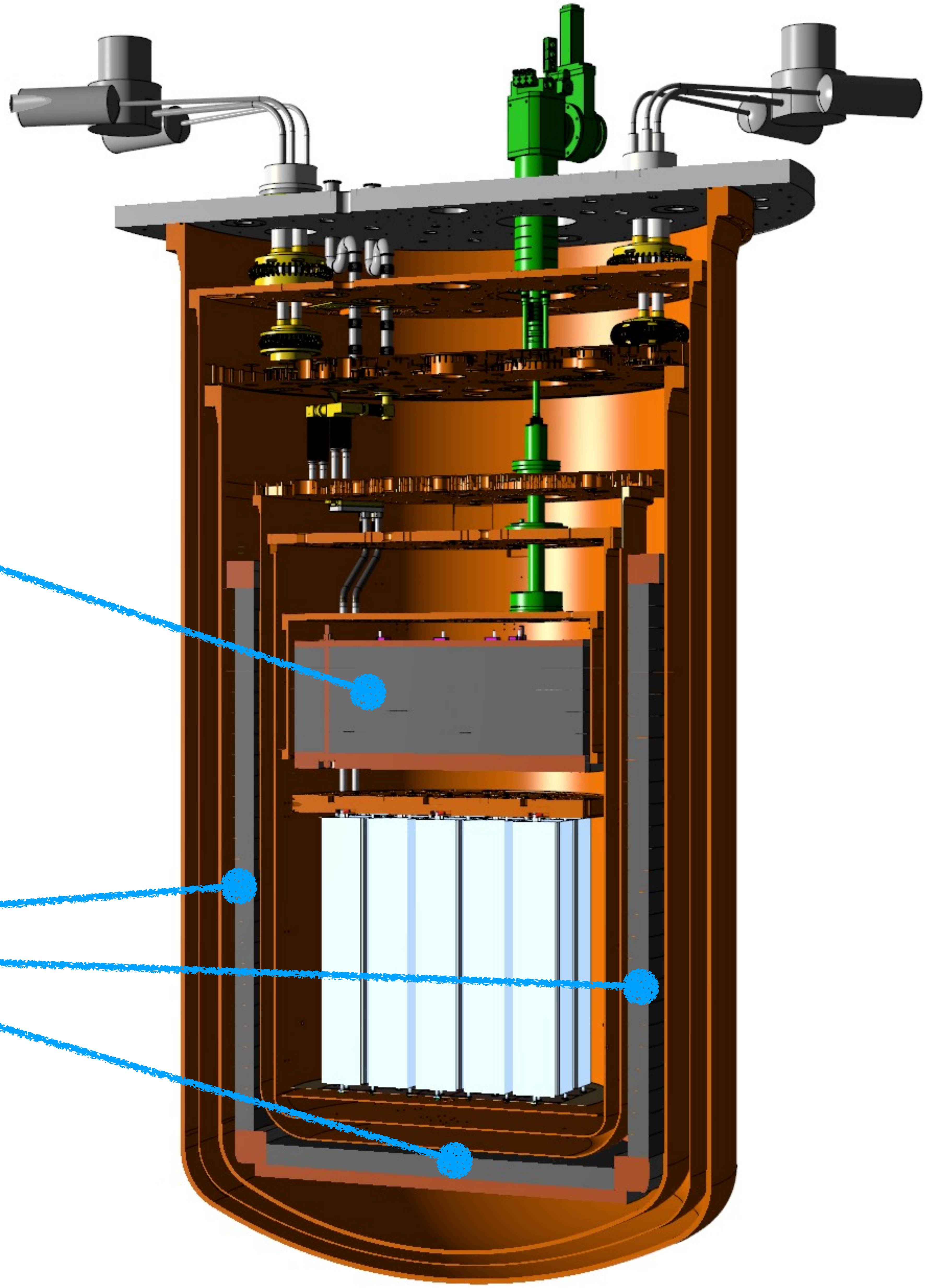
5x pulse tube cryocoolers
Pre-cool to 4K

CUORE Cryogenic System

Dilution refrigerator insert
gets us to very low T

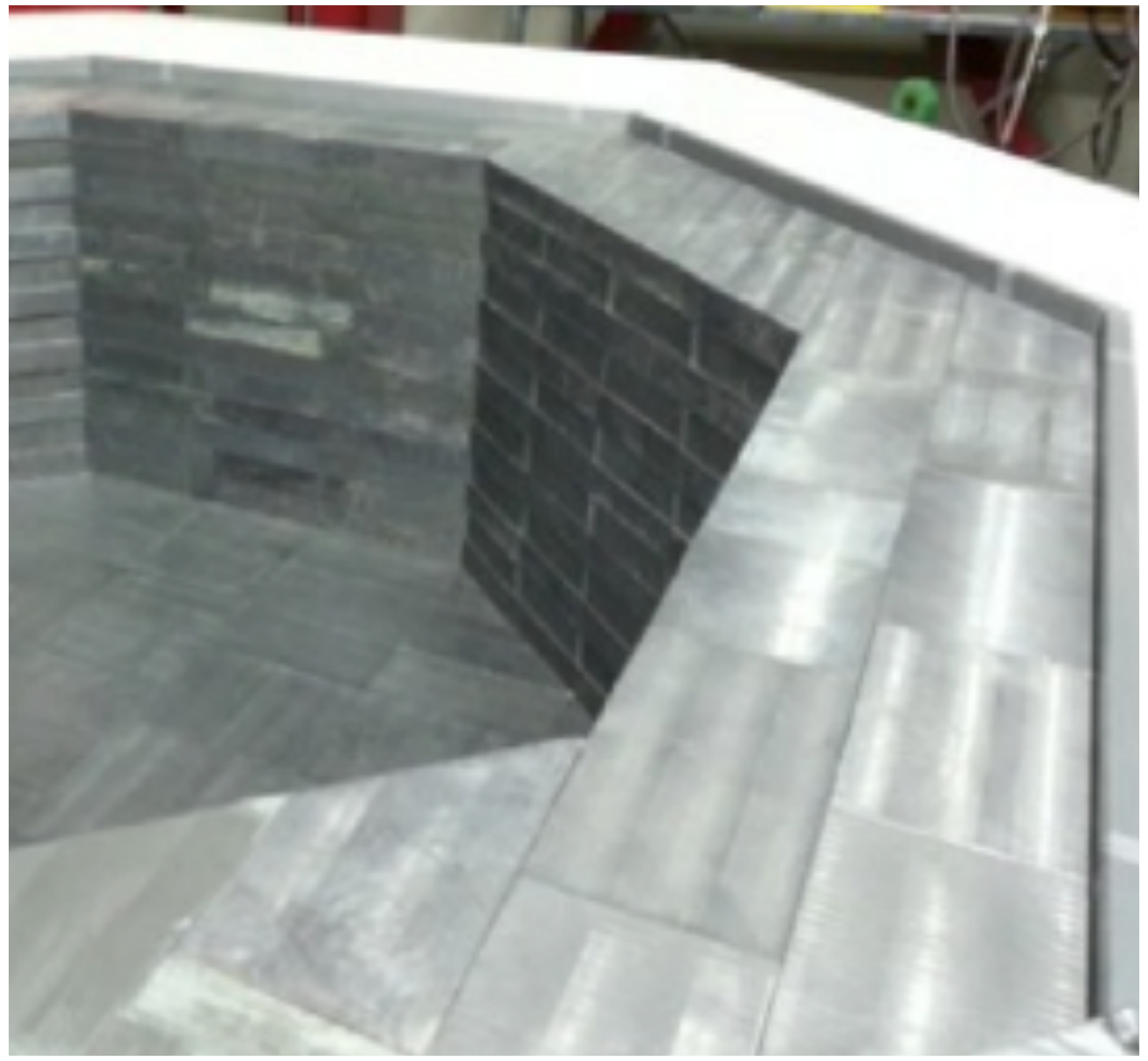


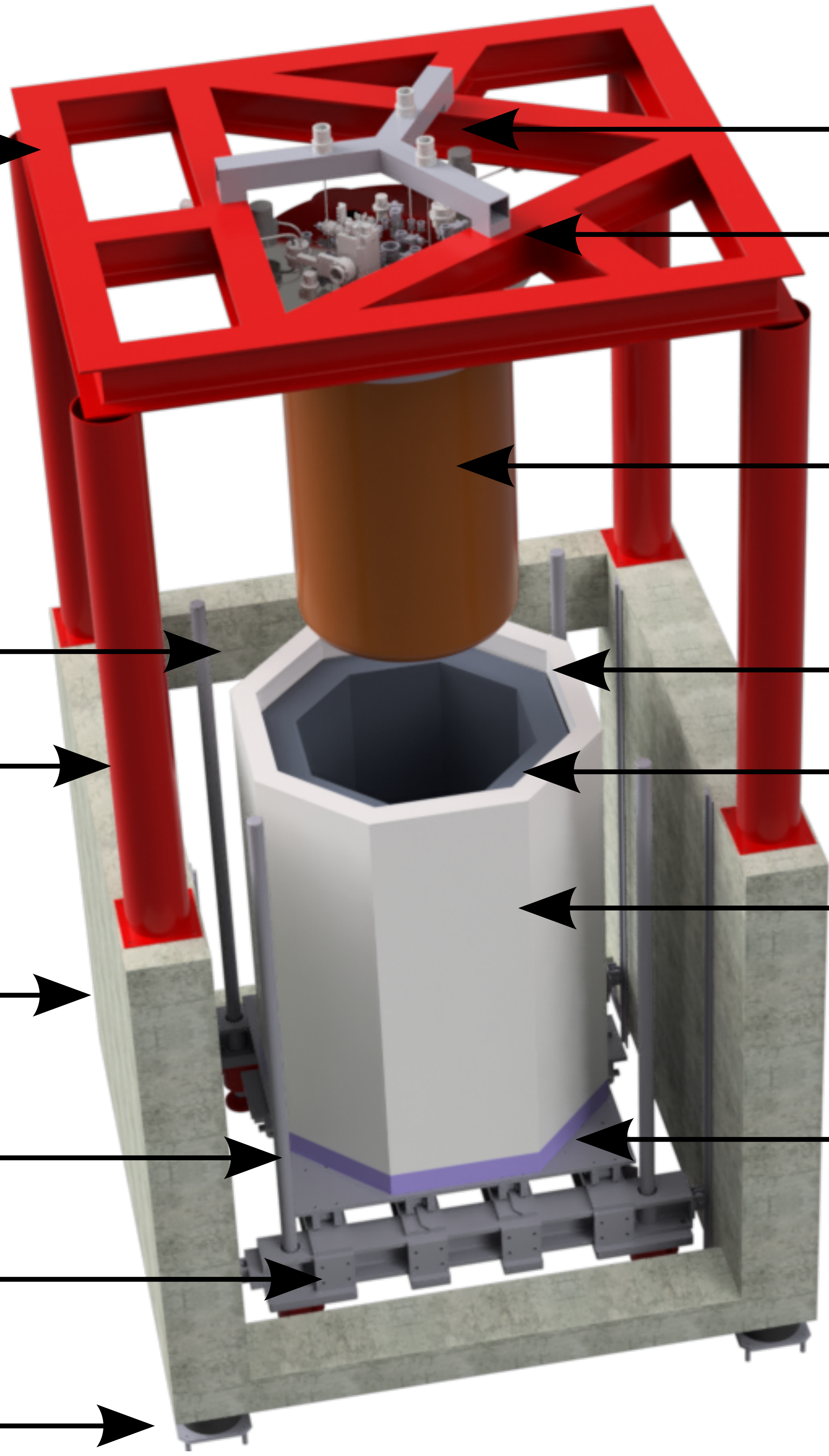
CUORE Cryogenic System



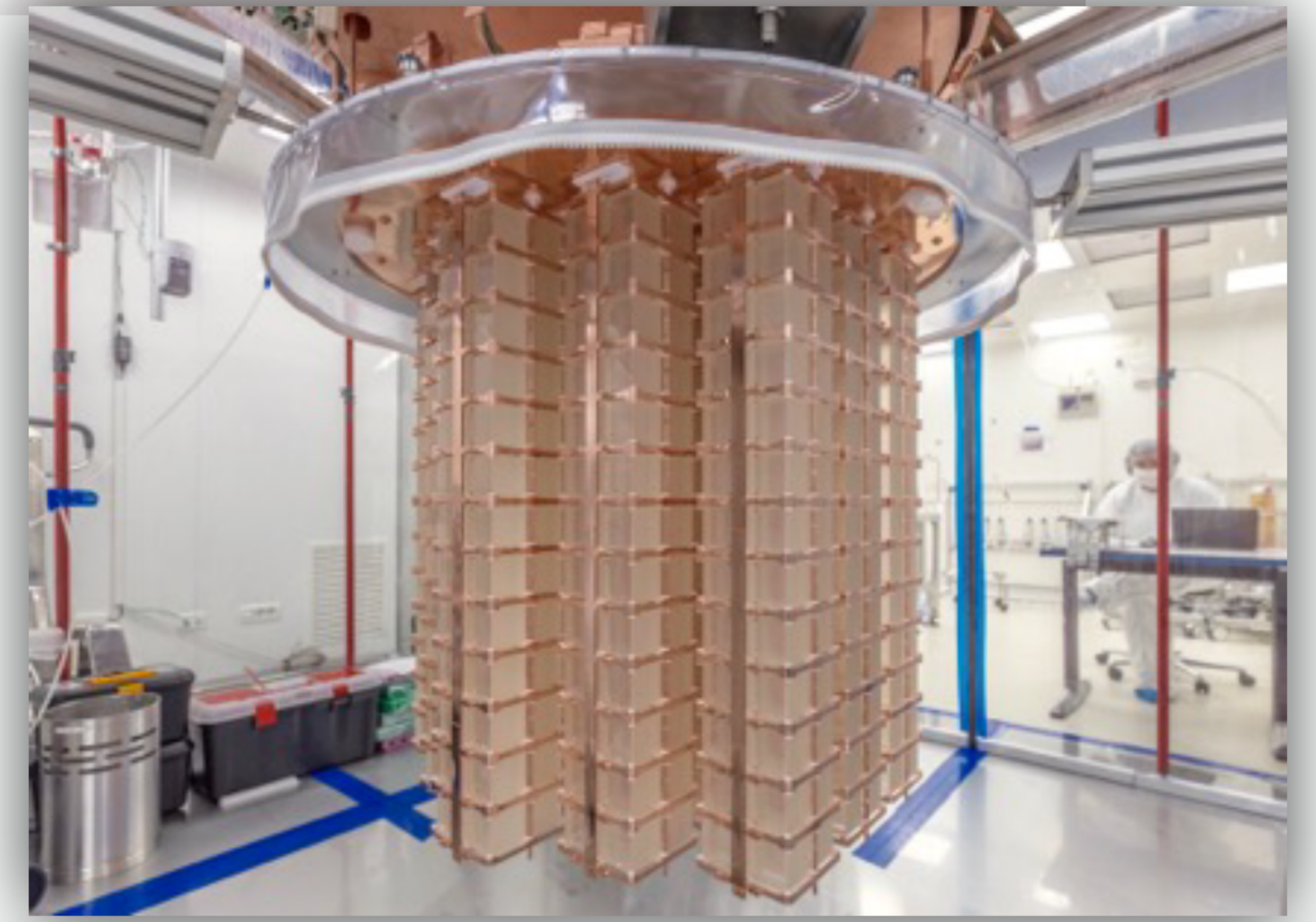
External Shielding

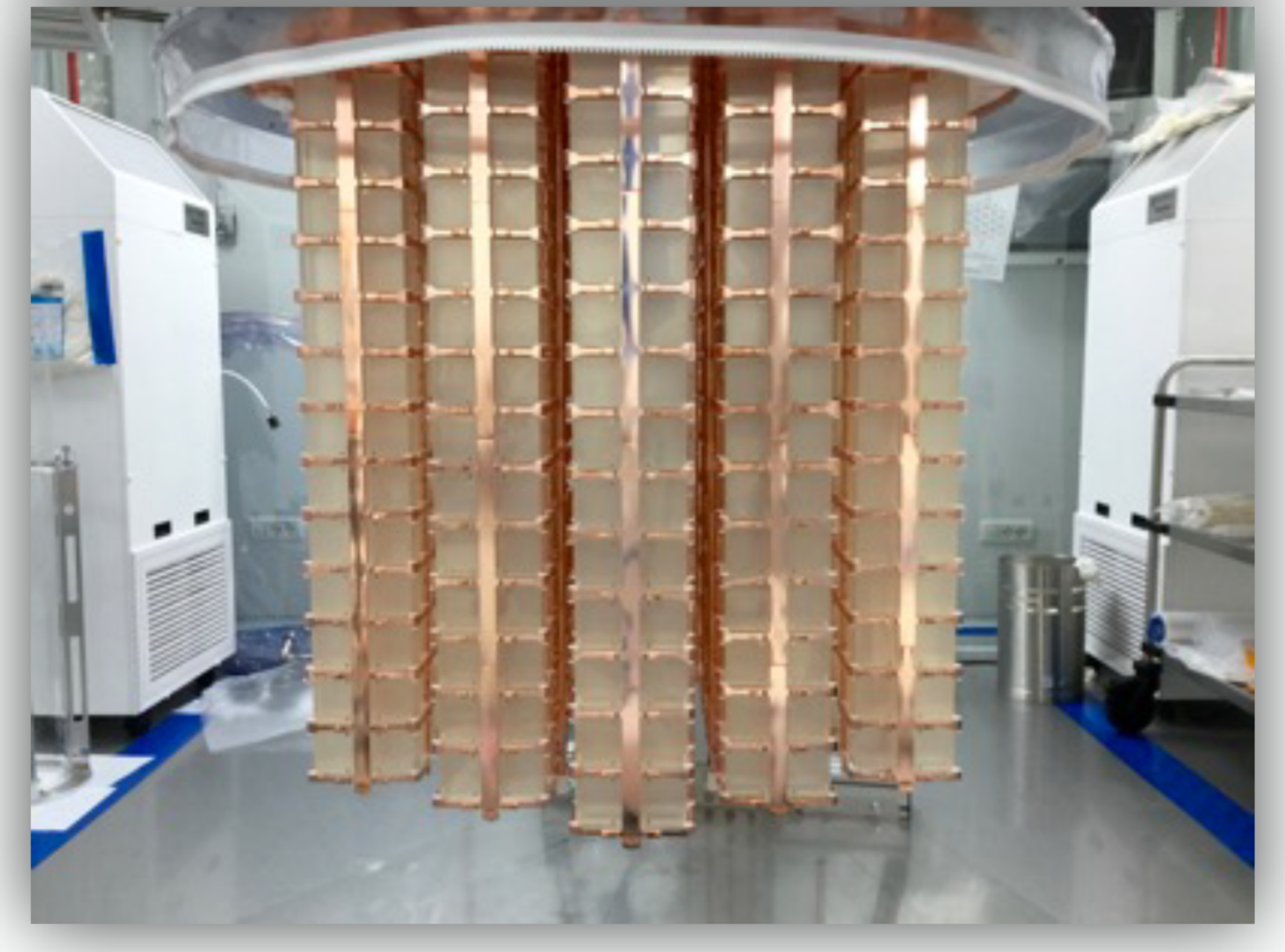
- Polyethylene to slow down neutrons
- Boron to absorb slow neutrons
- Lead to absorb gamma rays

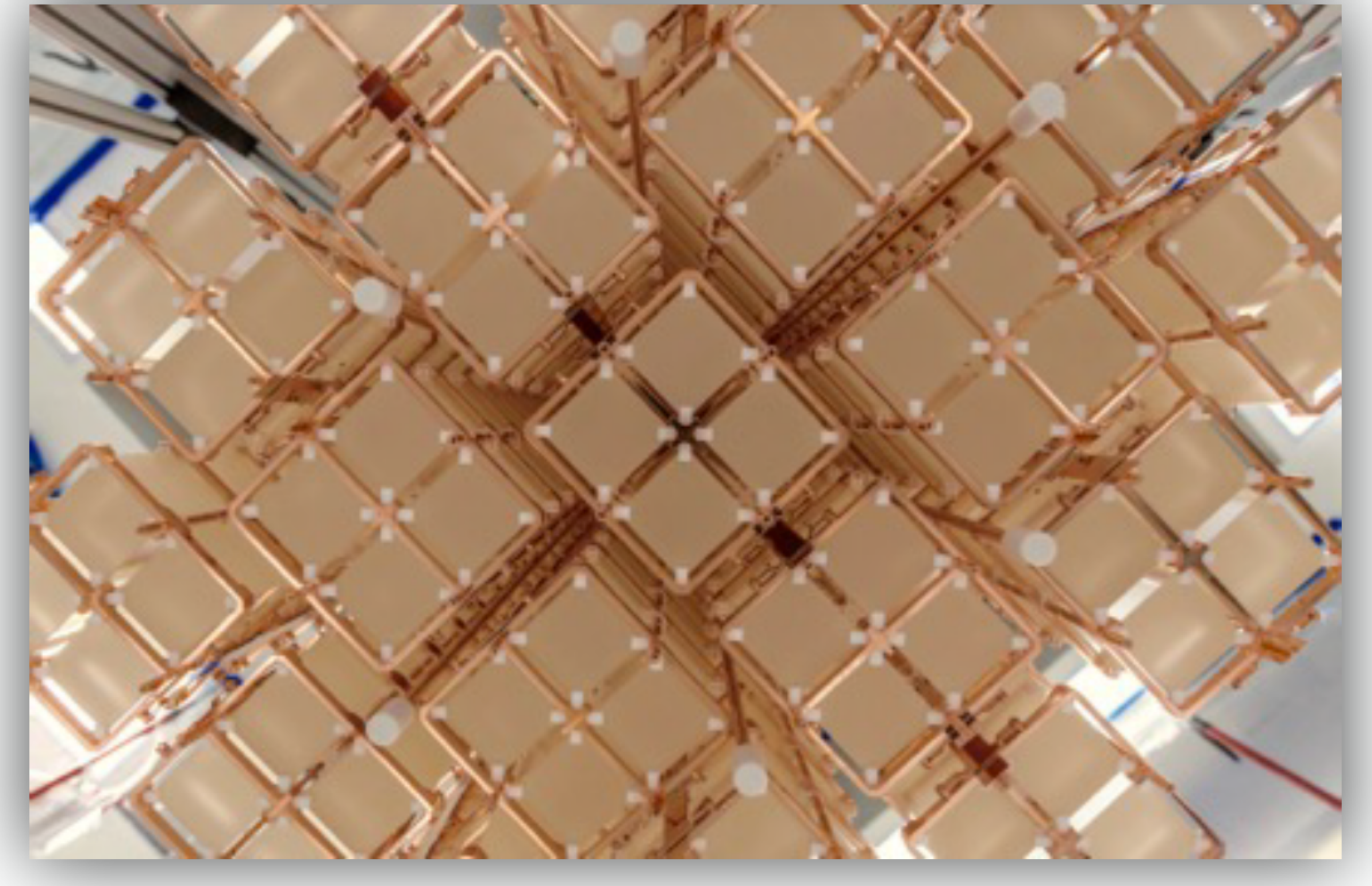




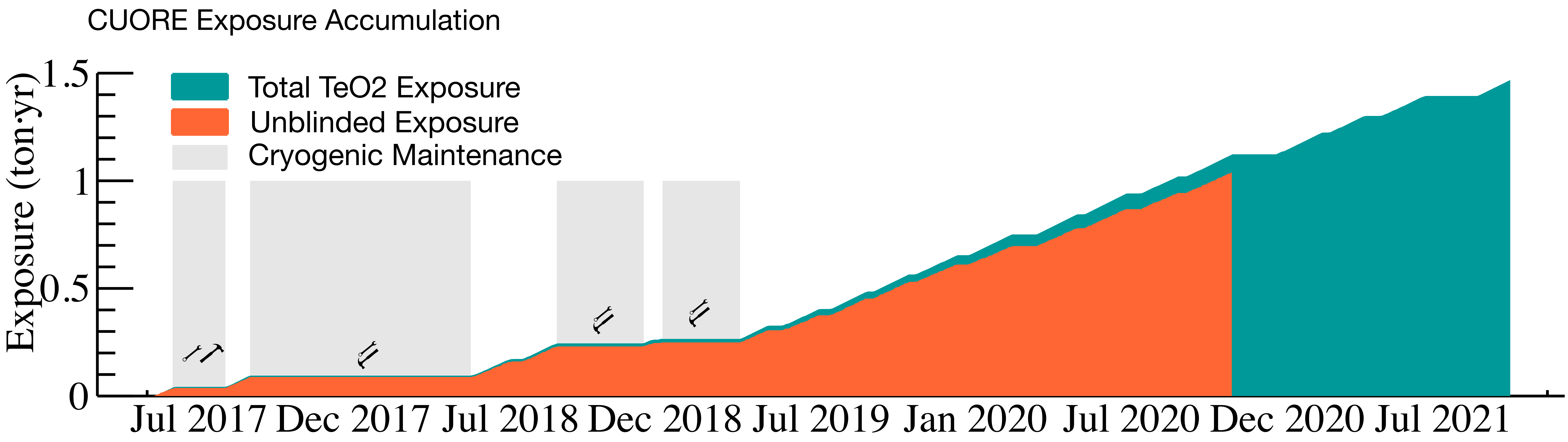
Tower Installation on 10mK stage





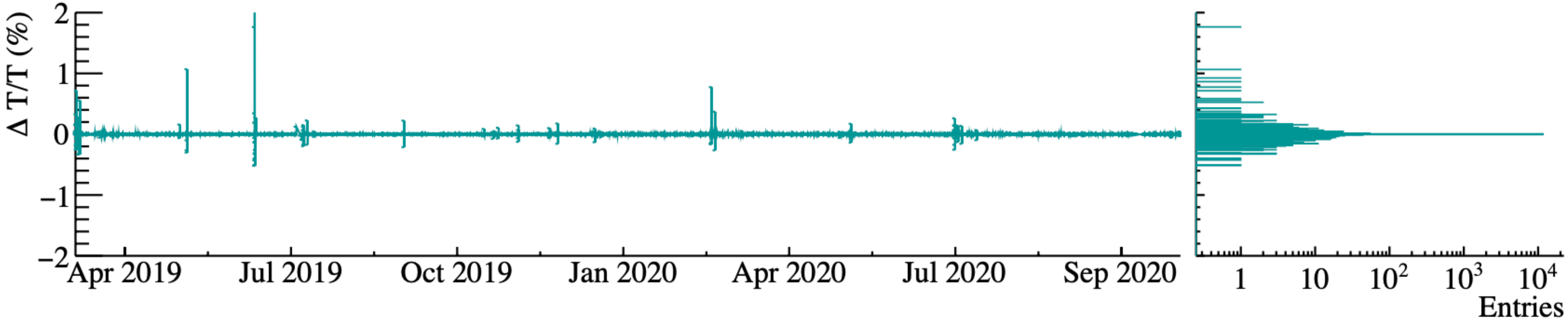


CUORE Status: Stable data taking (t)



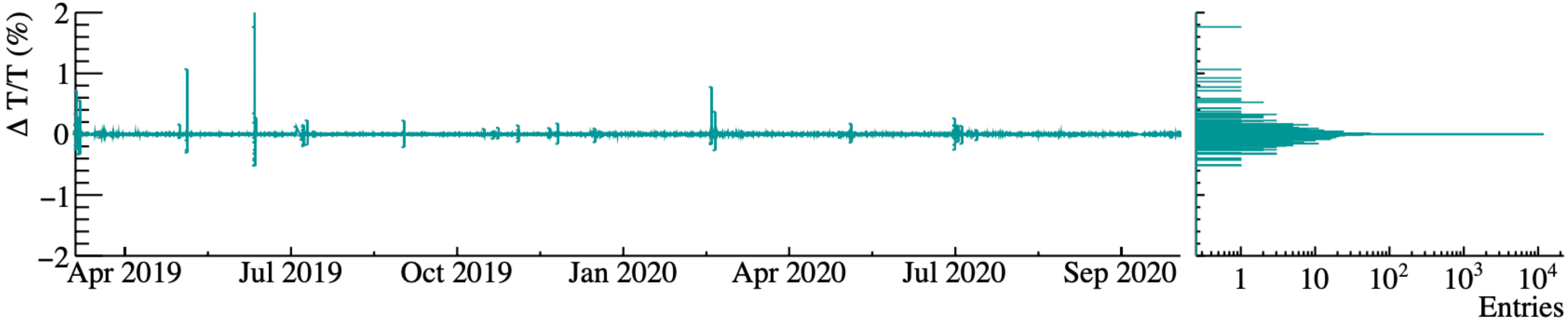
- After initial data taking phase, significant effort devoted to understanding the system and optimizing data taking conditions
- Since March 2019 data taking is continuing smoothly (now > 3 years at ~10 mK!)

CUORE Status: Stable data taking (t)

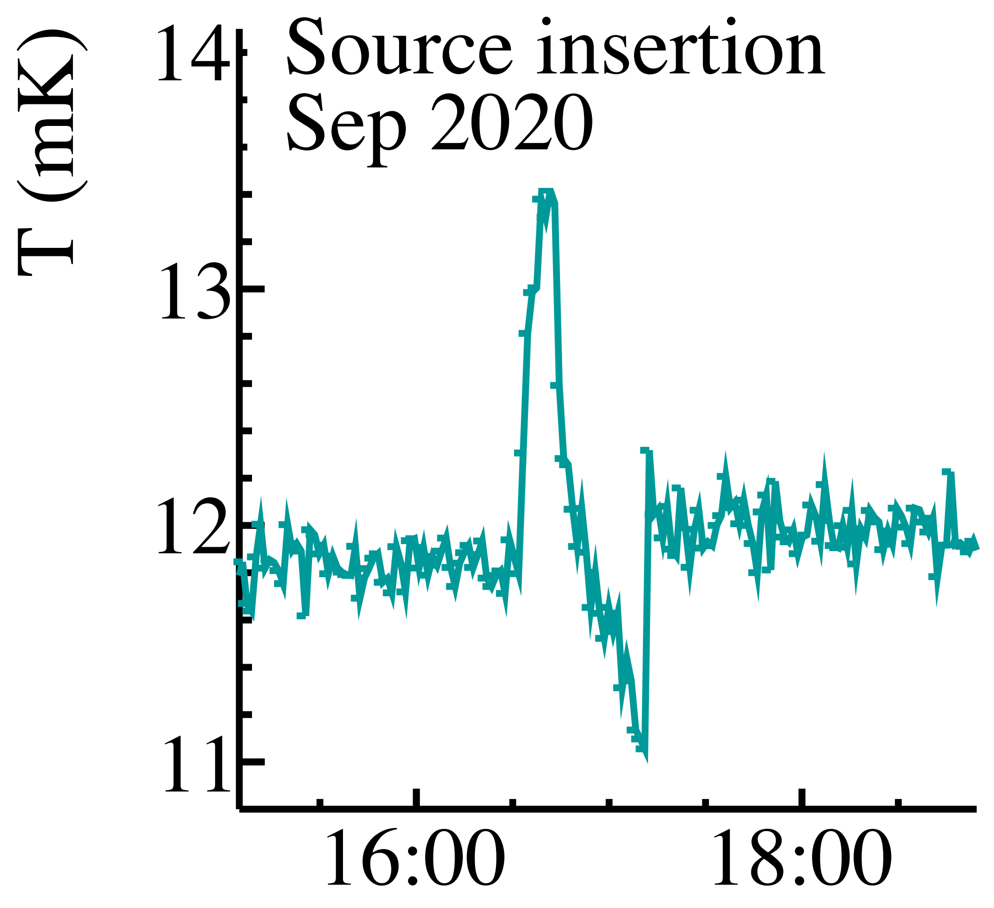


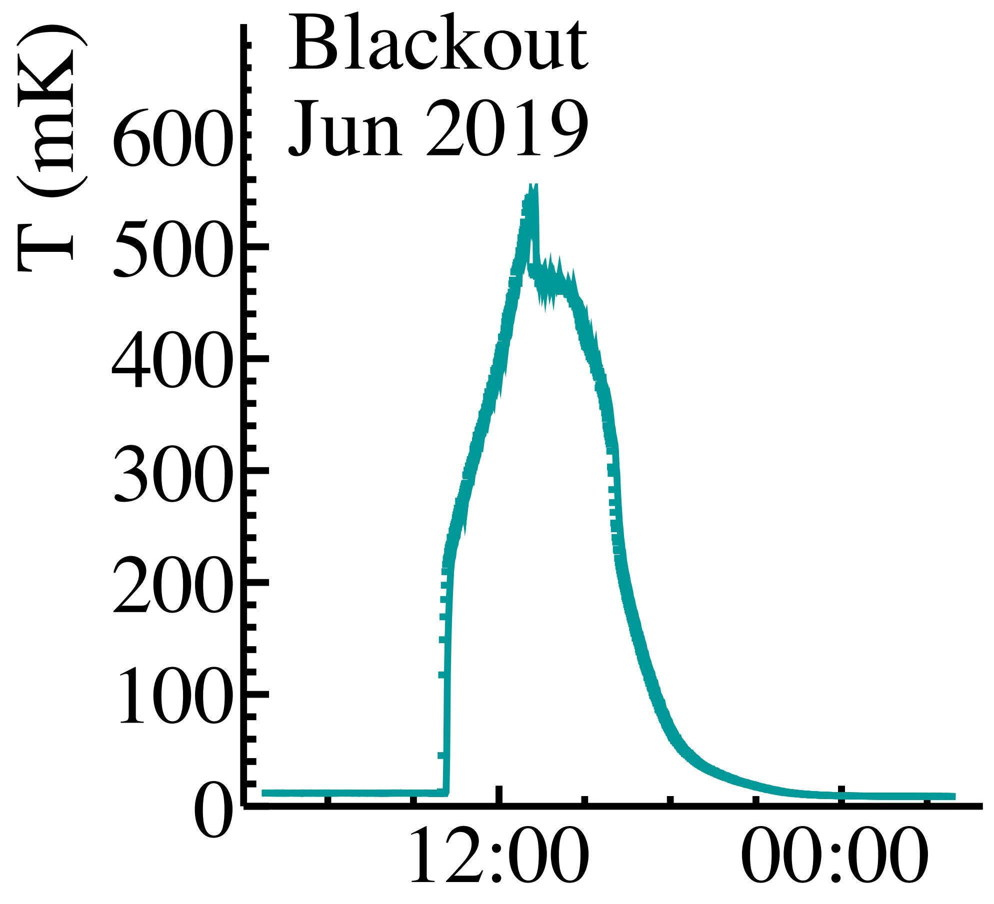
- Temperature stable to < 0.2% over the course of more than 1 year

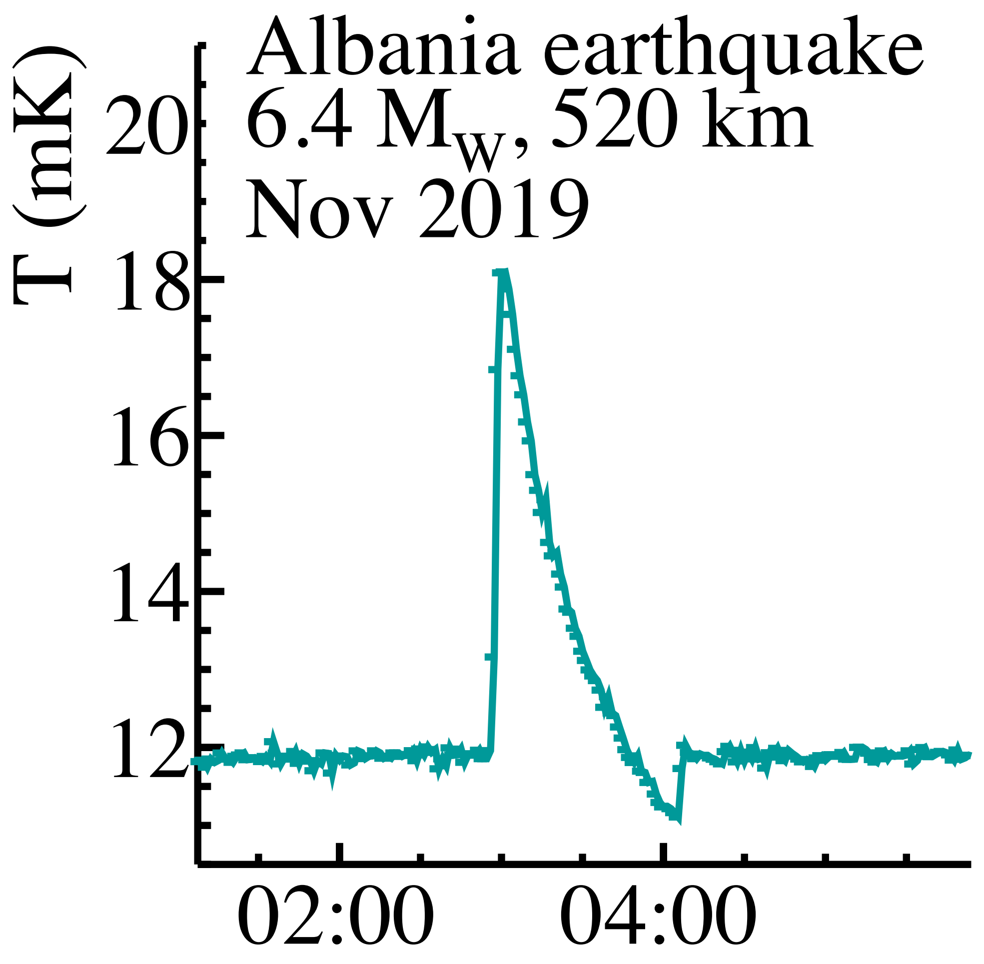
CUORE Status: Stable data taking (t)



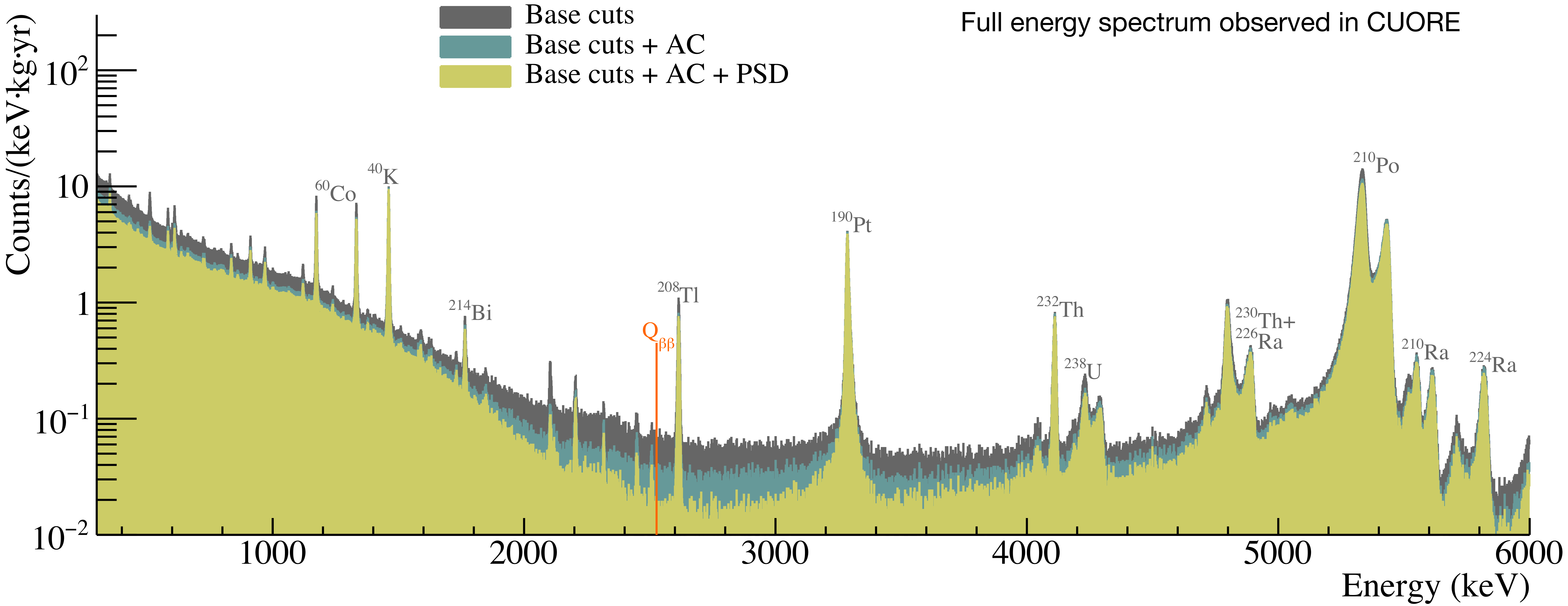
- Temperature stable to < 0.2% over the course of more than 1 year







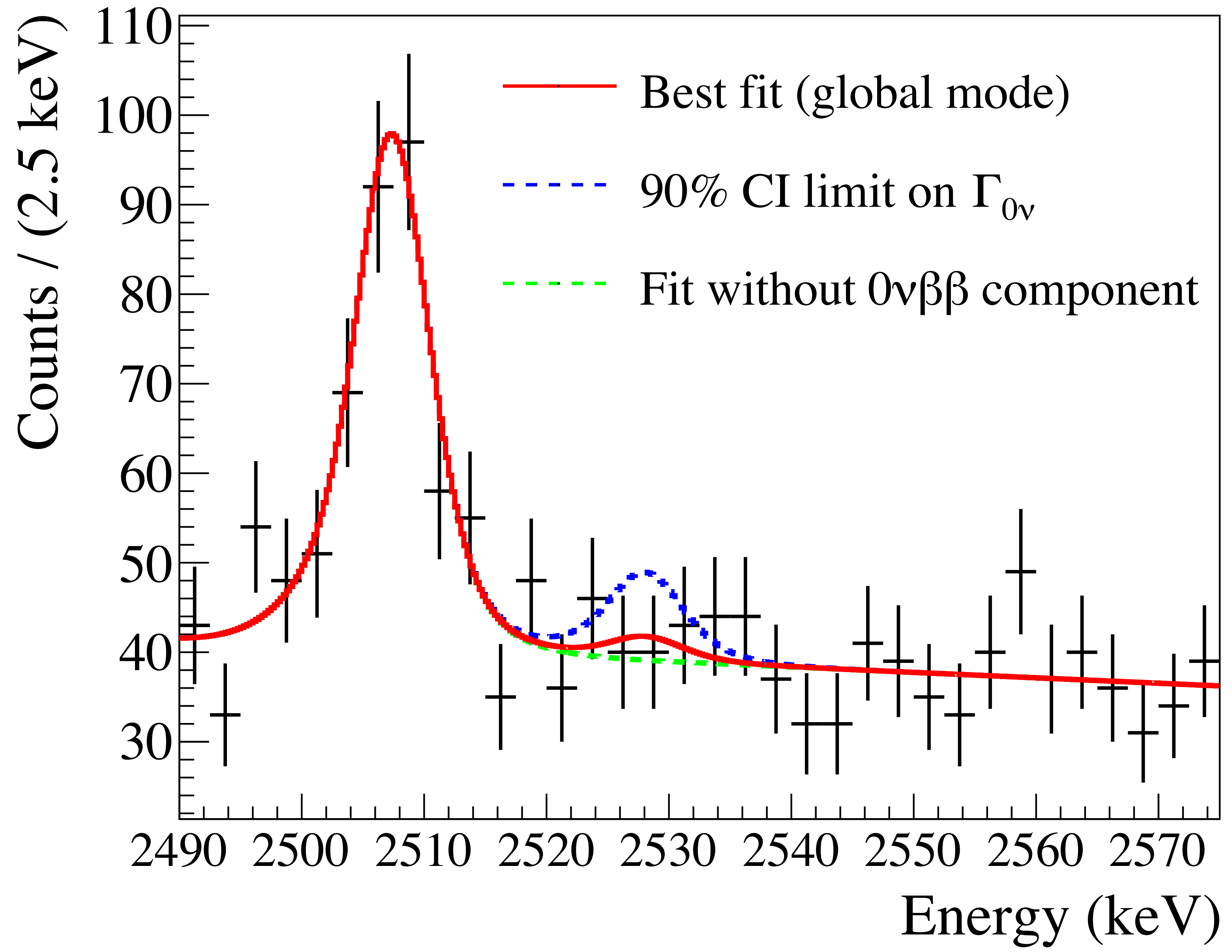
CUORE: 0νββ Decay Search



CUORE: 0vββ Decay Search

Nature **604,** 53–58 (2022)

CUORE ROI Spectrum



- No evidence for 0vββ decay (yet !)

$$T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ \mathrm{yr}$$ (90% C.I)

- Interpretation in context of light Majorana neutrino exchange

$$m_{\beta\beta} < 90 - 310\ \mathrm{meV}$$

- Total exposure TeO_2: $1038.4\ \mathrm{kg \cdot yr}$
- Likelihood model: flat continuum (BI), posited peak for 0vββ (rate), peak for ^{60}Co (rate + position)
- Unbinned fit on physical range (rates non-negative), uniform prior on $\Gamma_{0\nu}$
- Systematic uncertainties: <0.8% impact on limit

Detector Performance Parameters

Background Index

$$(1.49 \pm 0.04) \times 10^{-2}\ \ \mathrm{counts/(keV \cdot kg \cdot yr)}$$

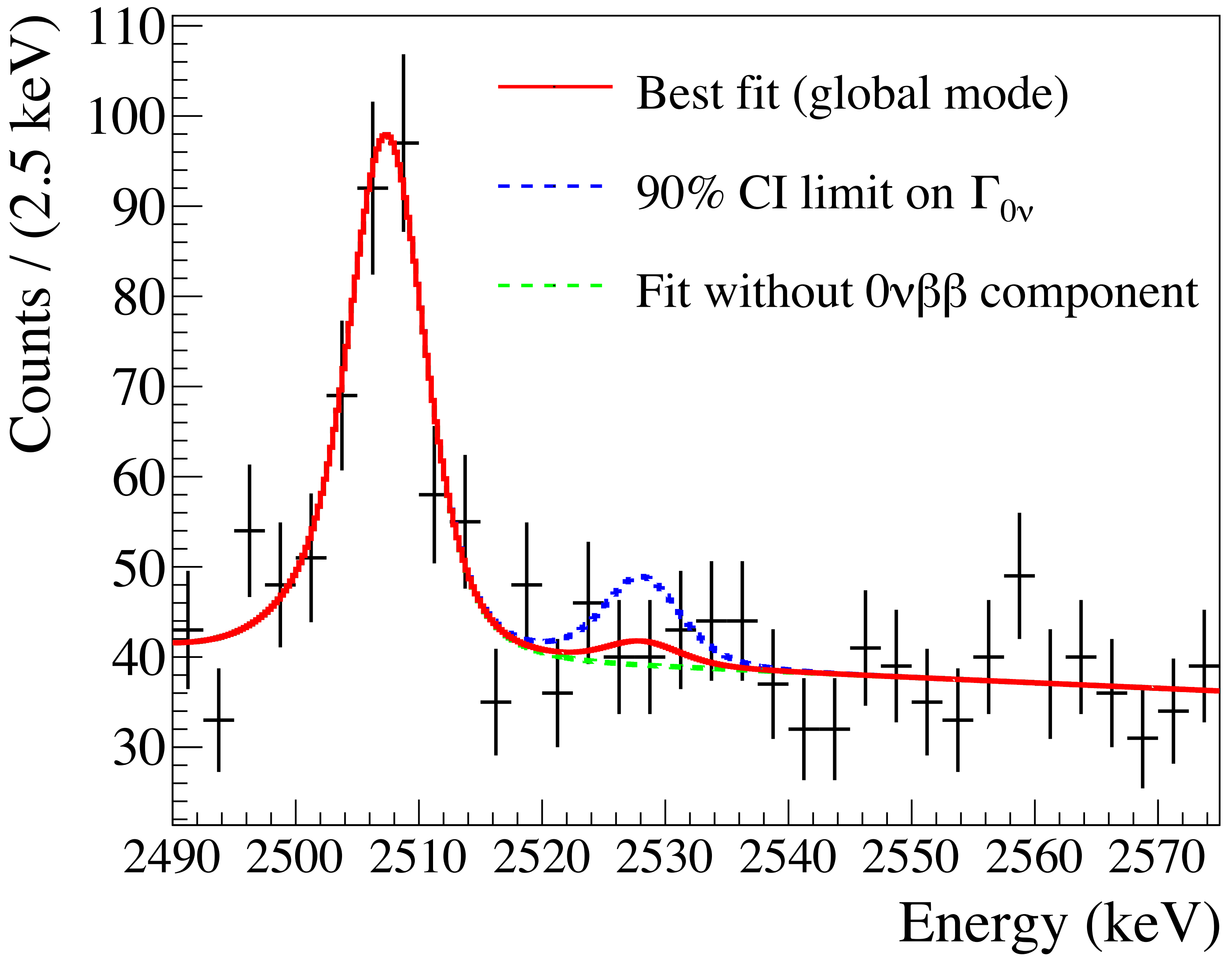
Characteristic FWHM ΔE at $Q_{\beta\beta}$

$$7.5 \pm 0.5\ \mathrm{keV}$$

CUORE: 0νββ Decay Search

Nature **604,** 53–58 (2022)

CUORE ROI Spectrum



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- Systematic uncertainties: <0.8% impact on limit

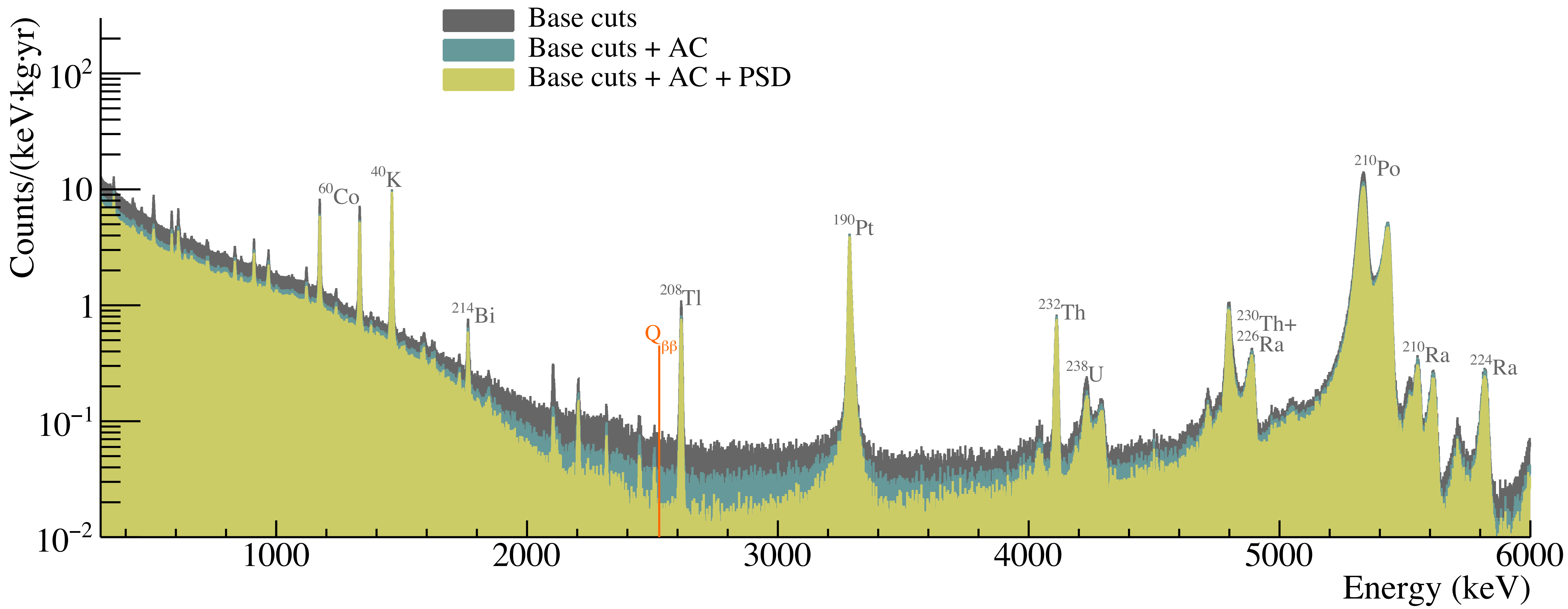
Detector Performance Parameters

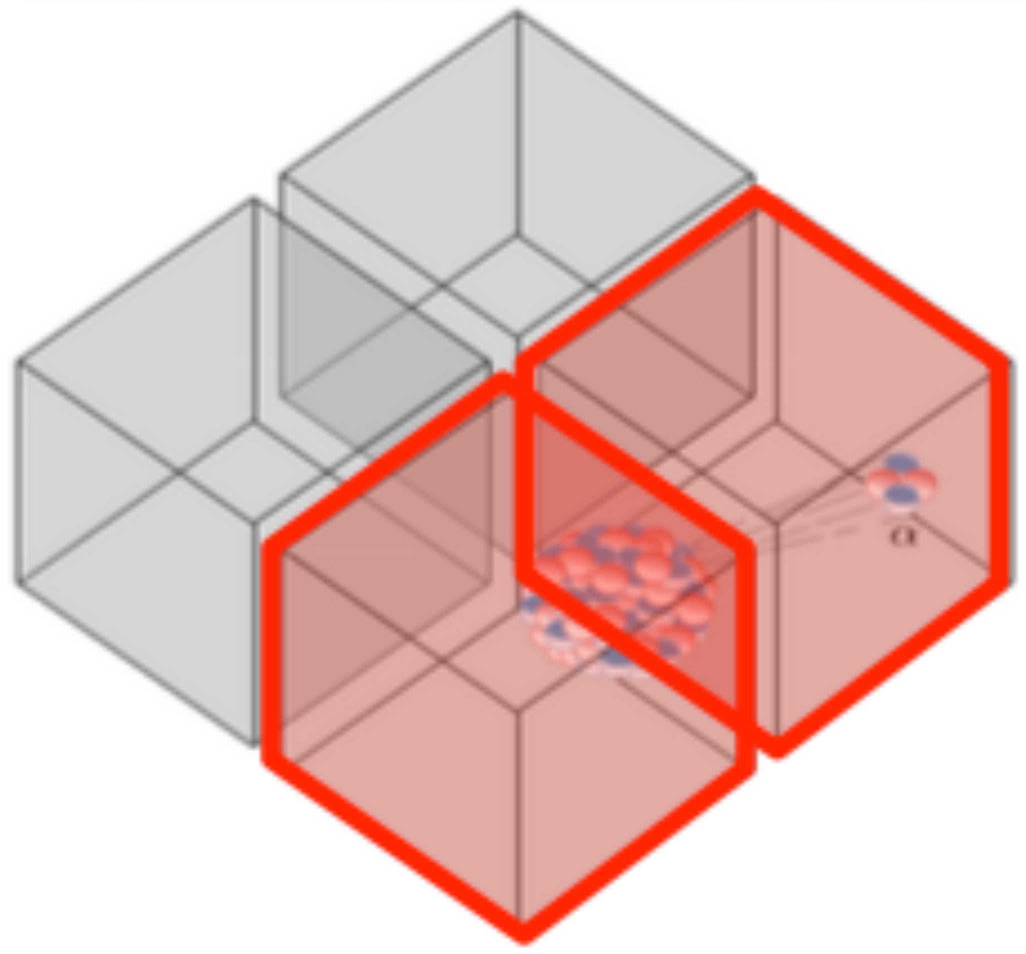
Data taking continues smoothly
~1800 kg.yr as of May 6 2022

$7.5 \pm 0.5\ \mathrm{keV}$

What Next ?

What Next ?

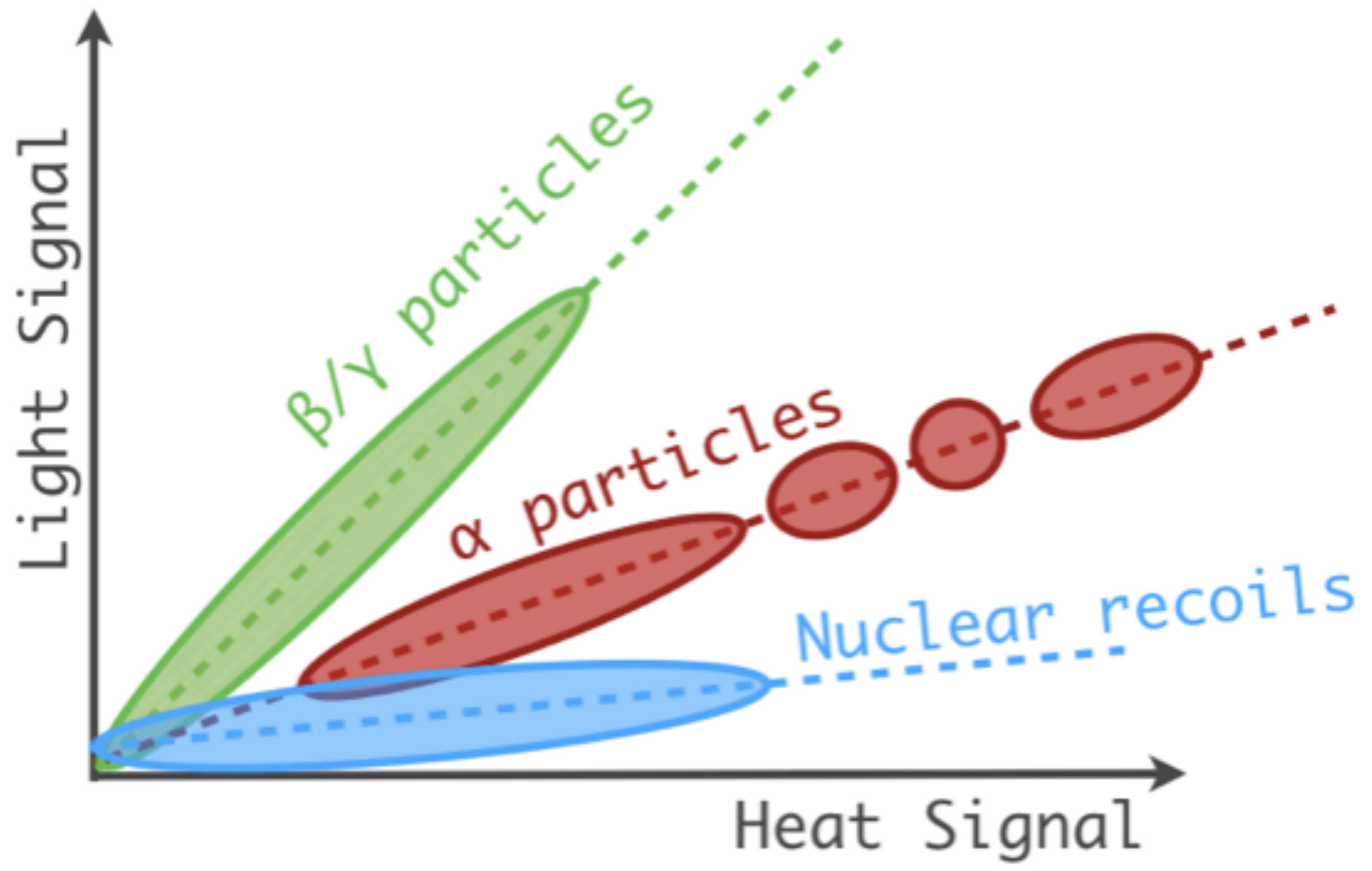


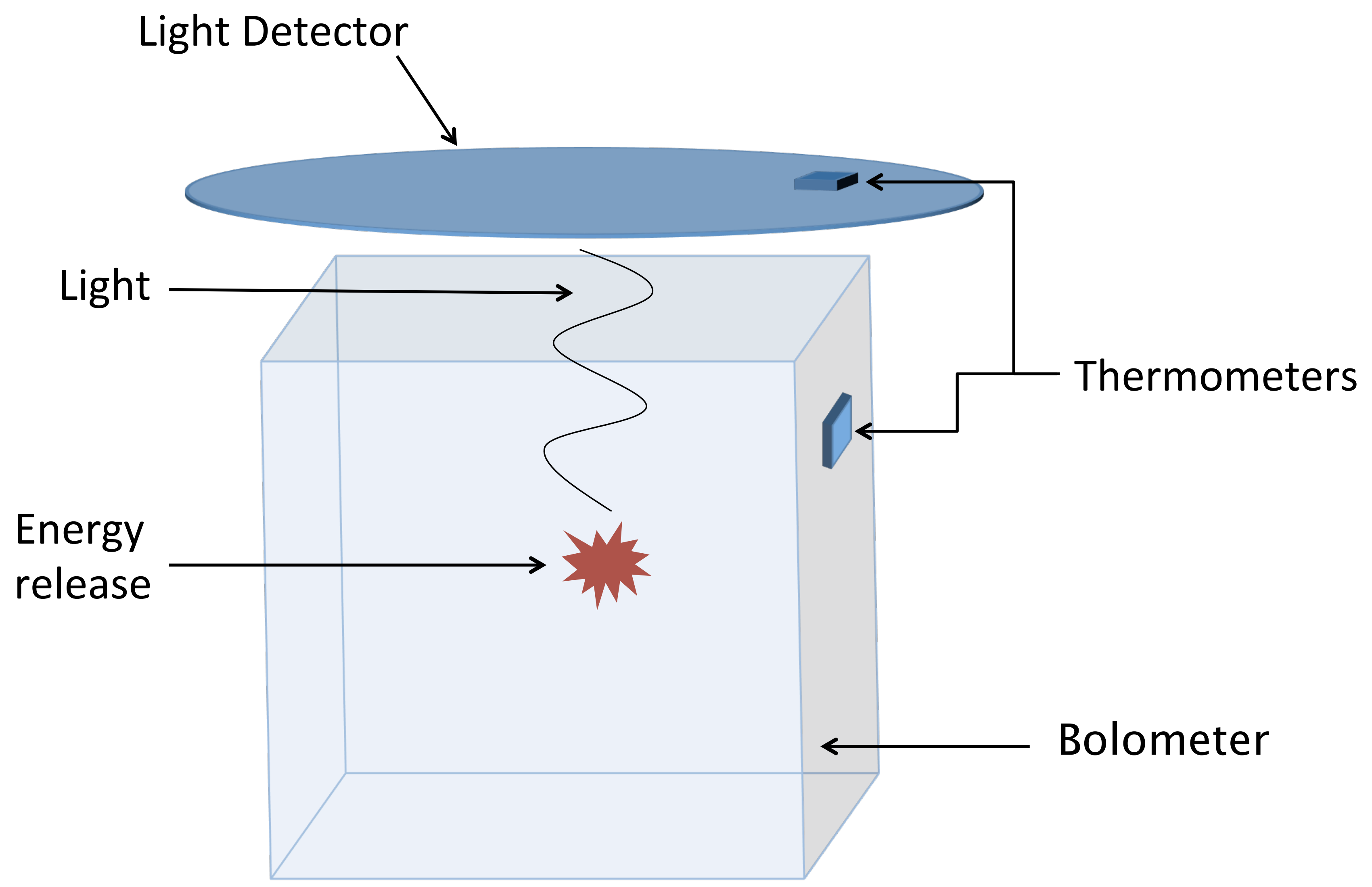


- ~90% of the background comes from degraded alpha particles coming from shallow surface contamination
- ~10% from beta/gamma decays
- CUORE just sees thermal signal, no way to distinguish alpha particles

CUPID: CUORE Upgrade with Particle ID

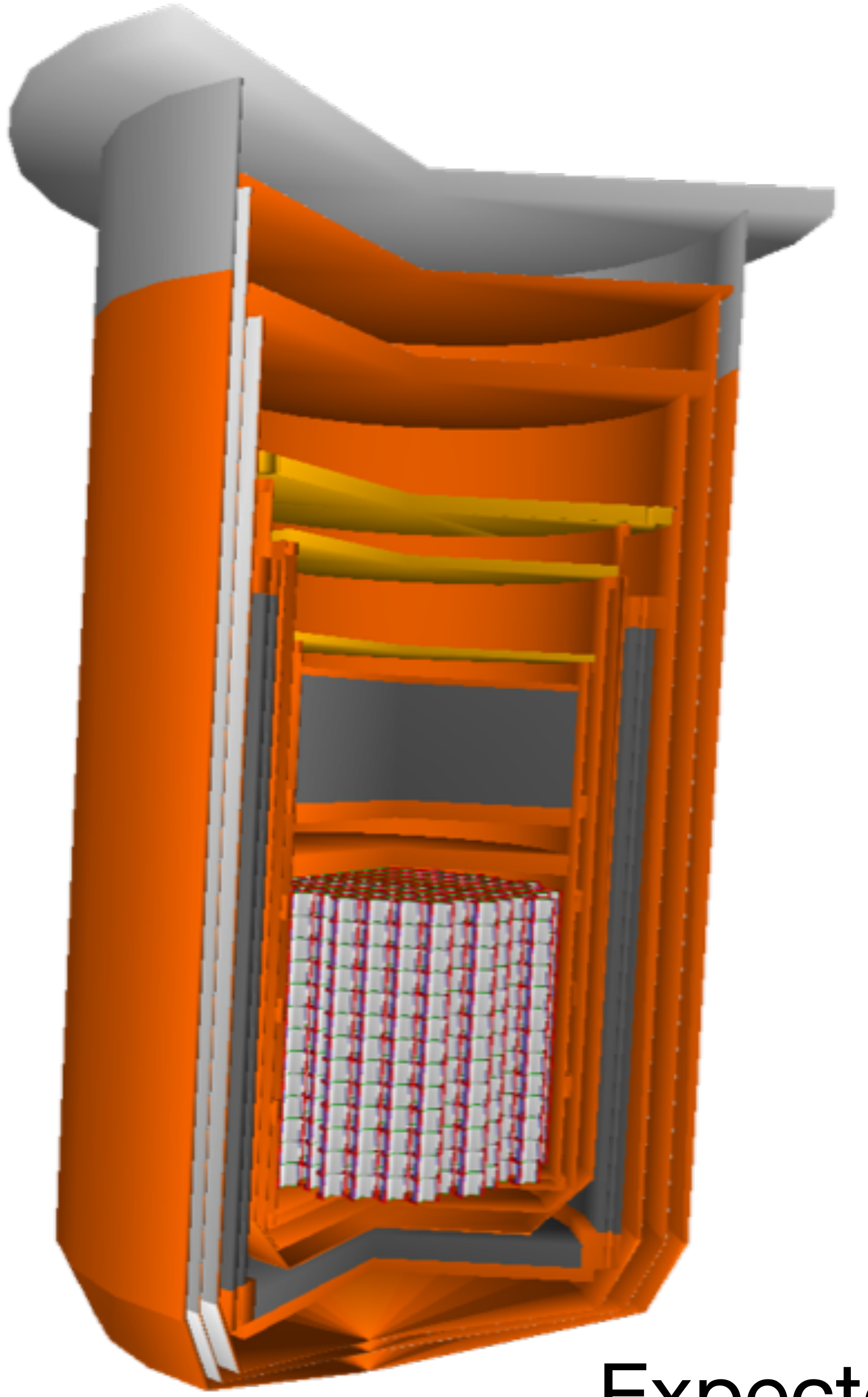
- If the absorber also scintillates measuring both the thermal and light signal enables particle discrimination





- Light detection at mK temperatures is achieved with secondary bolometer (such as Ge wafer)

CUPID



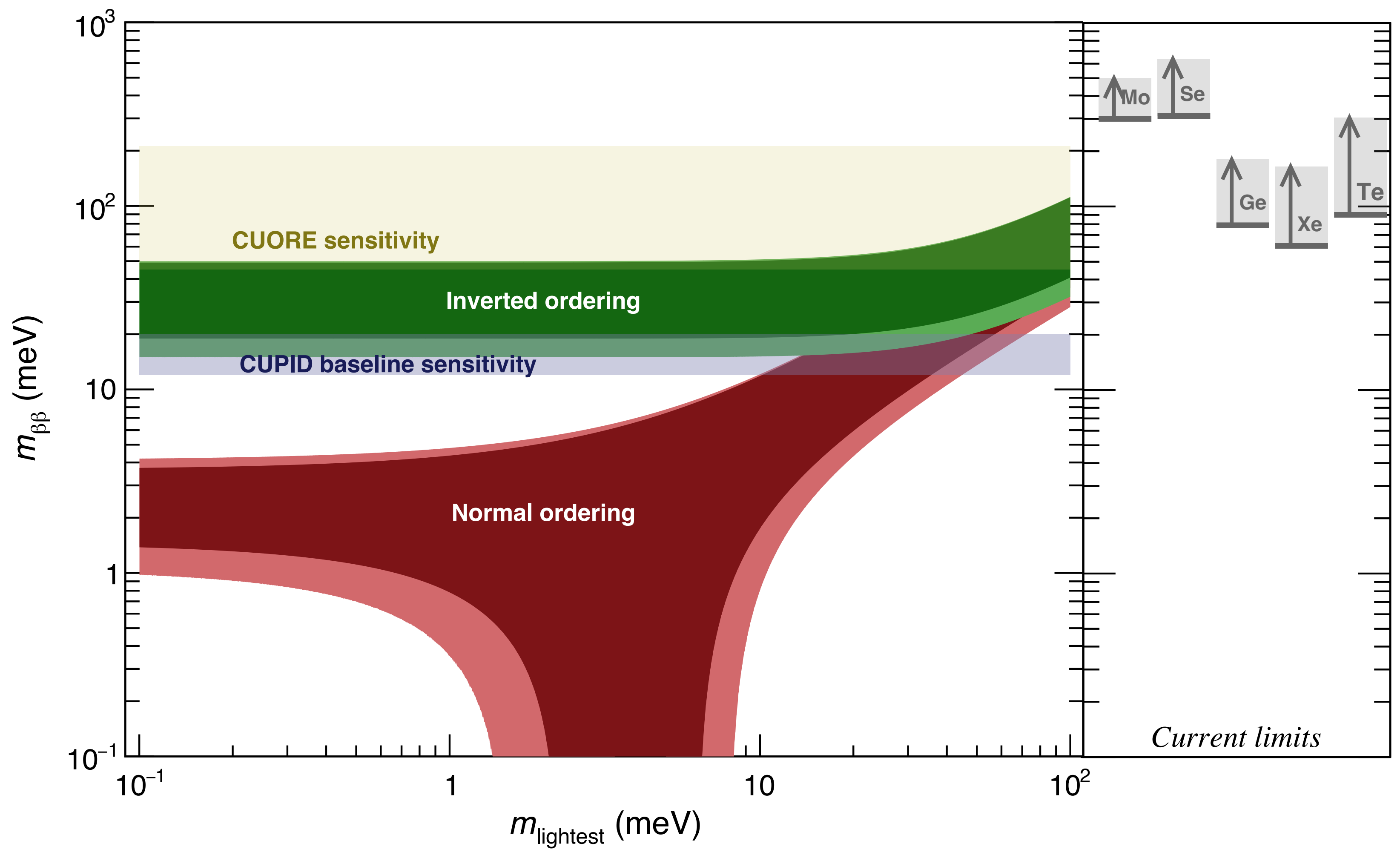
- Array of 1596 $Li_2{}^{100}MoO_4$ **scintillating** bolometers
- Enriched to >95% in ^{100}Mo (240kg of ^{100}Mo)
- ^{100}Mo Q-value: 3034 keV β/γ background significantly reduced
- Exploit Particle ID using scintillation bolometer technique to remove surface-alpha background
- Reuse CUORE cryogenic infrastructure at LNGS

Expected exclusion sensitivity

$$T^{0\nu}_{1/2} : 10^{27} yr$$

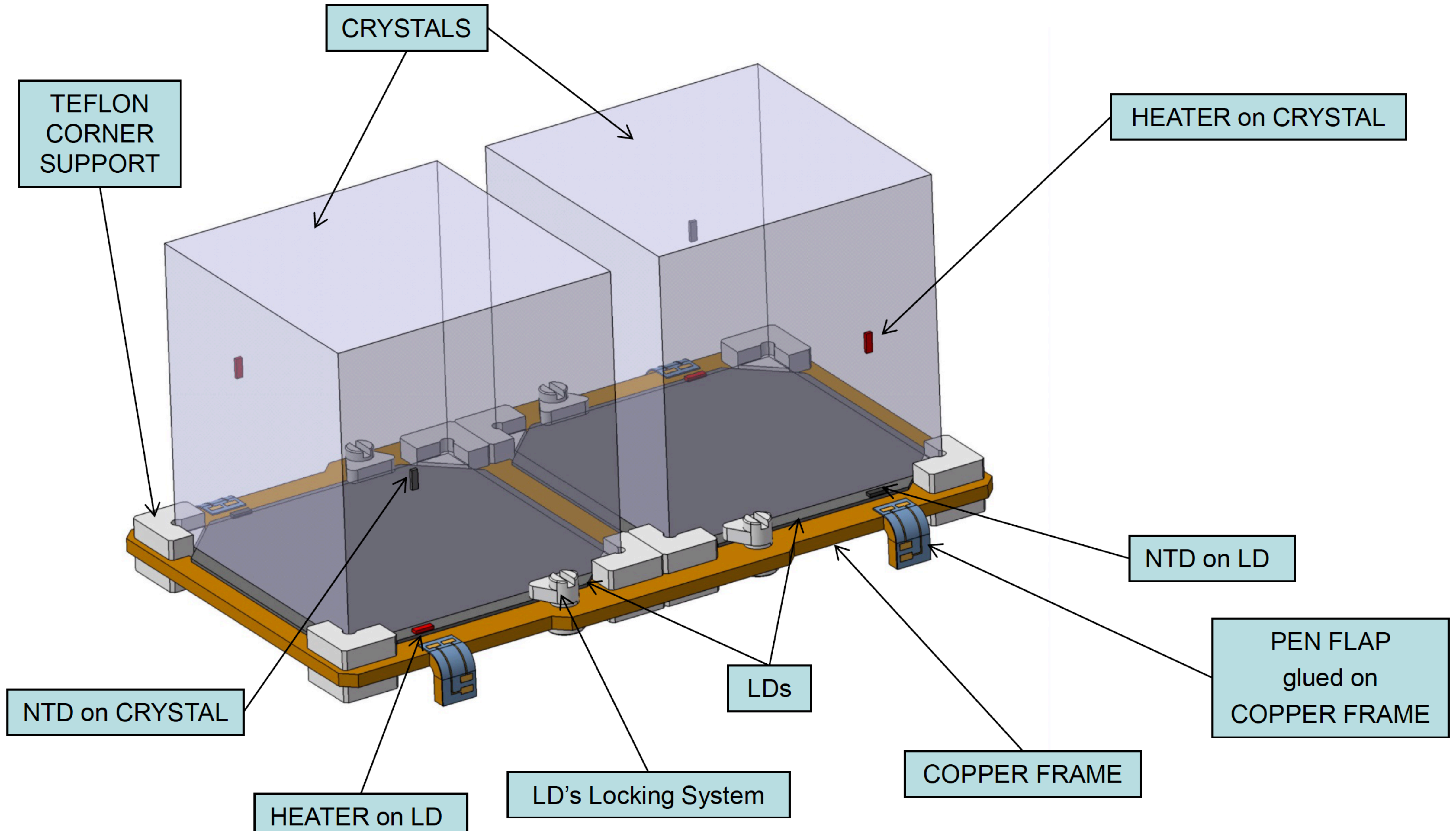
$$m_{\beta\beta} : 10 - 20\ meV$$

projected sensitivity   current limits

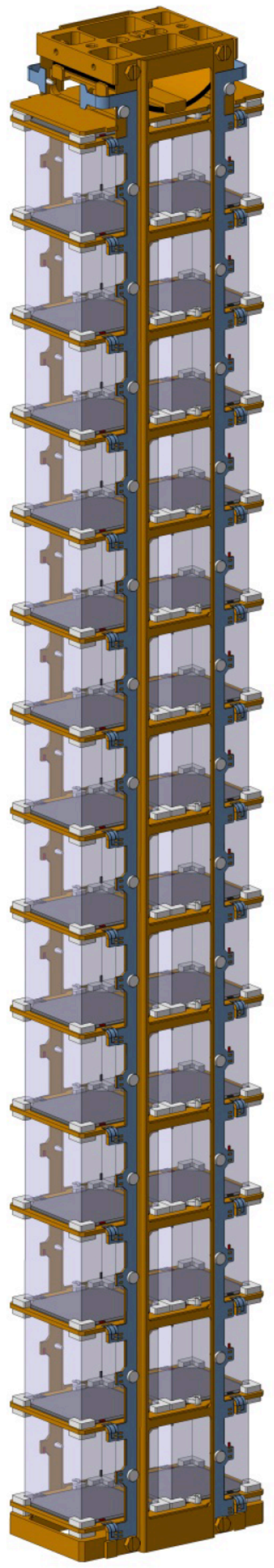


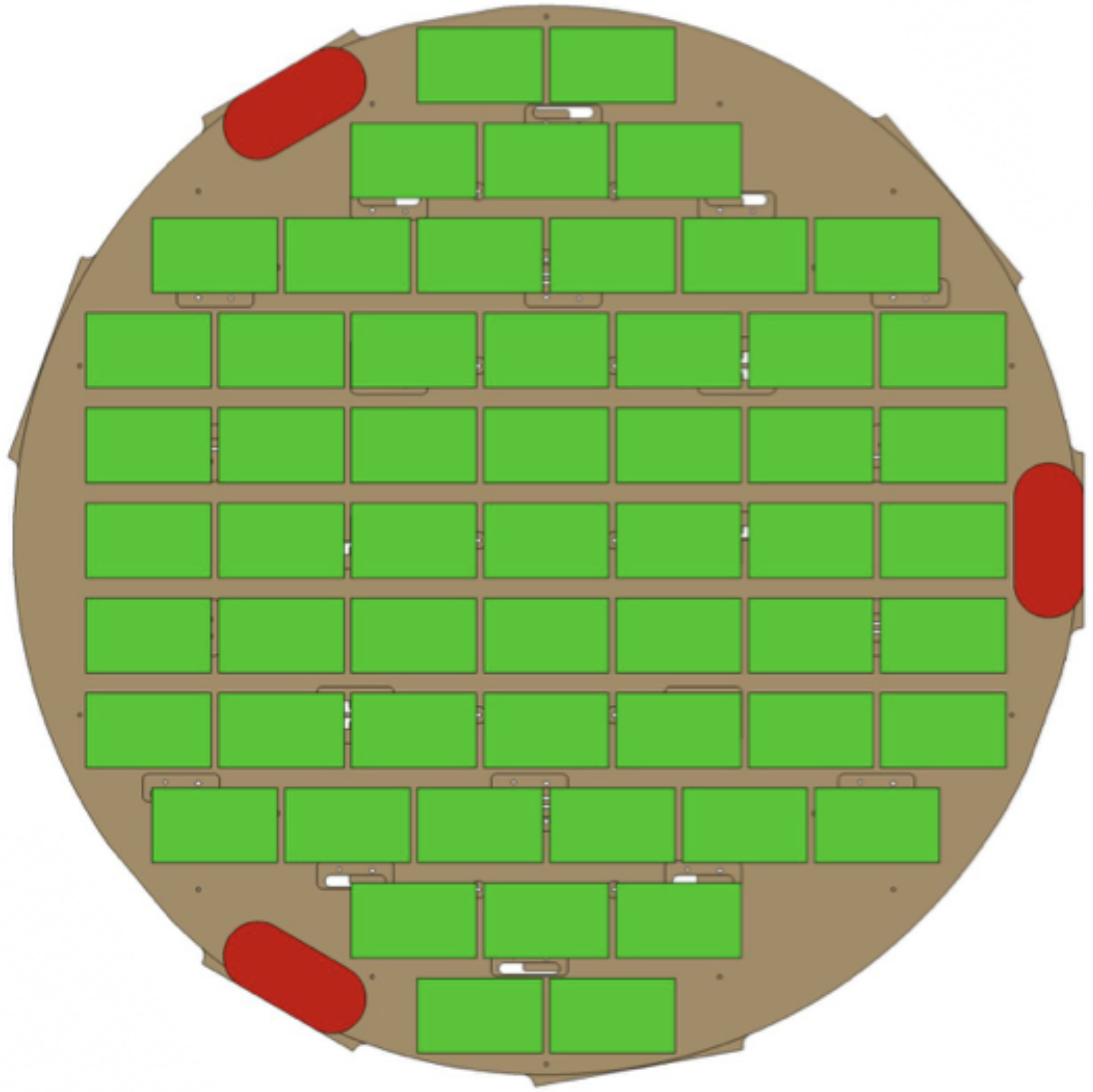
CUPID

Detector Module



Tower

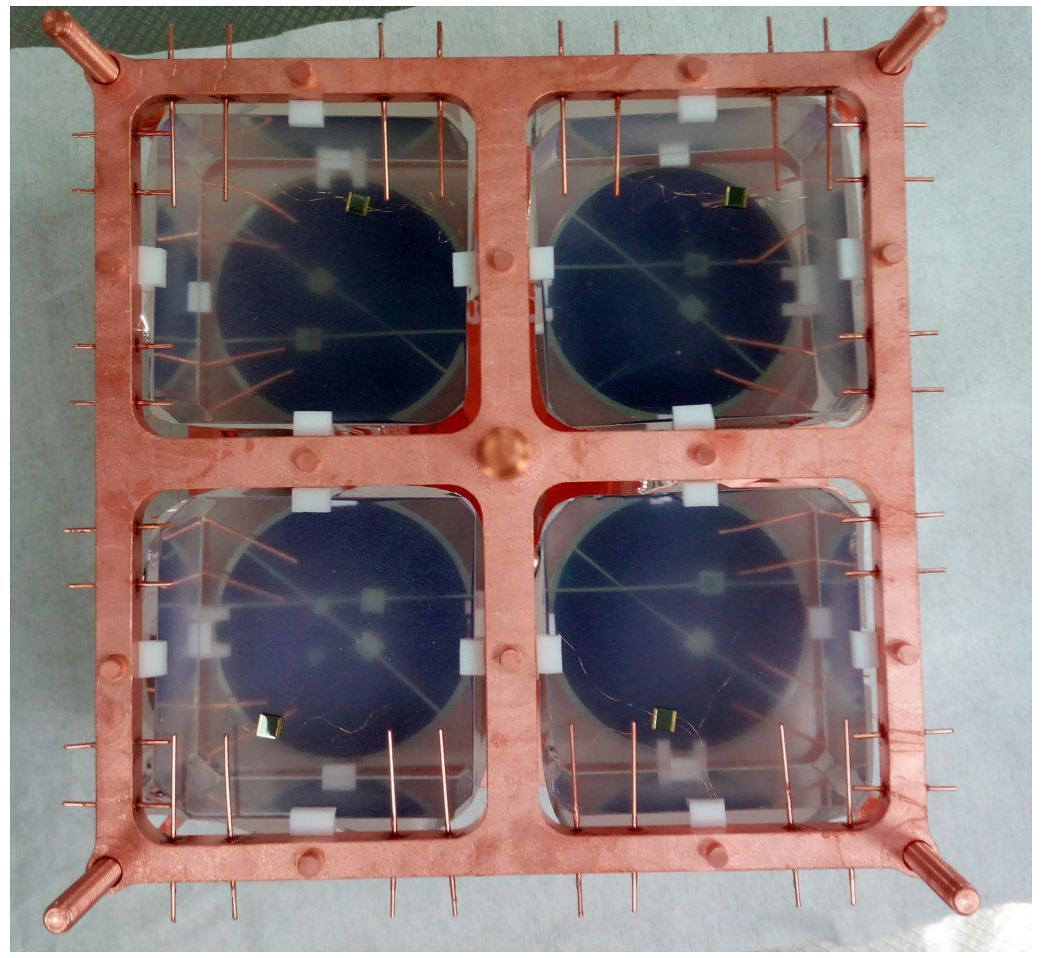




CUPID R&D@VT

- Background modeling and simulations
- Low-background prototyping at LNGS, material activation measurments, analysis at VT

Optimizing light-collection efficiency



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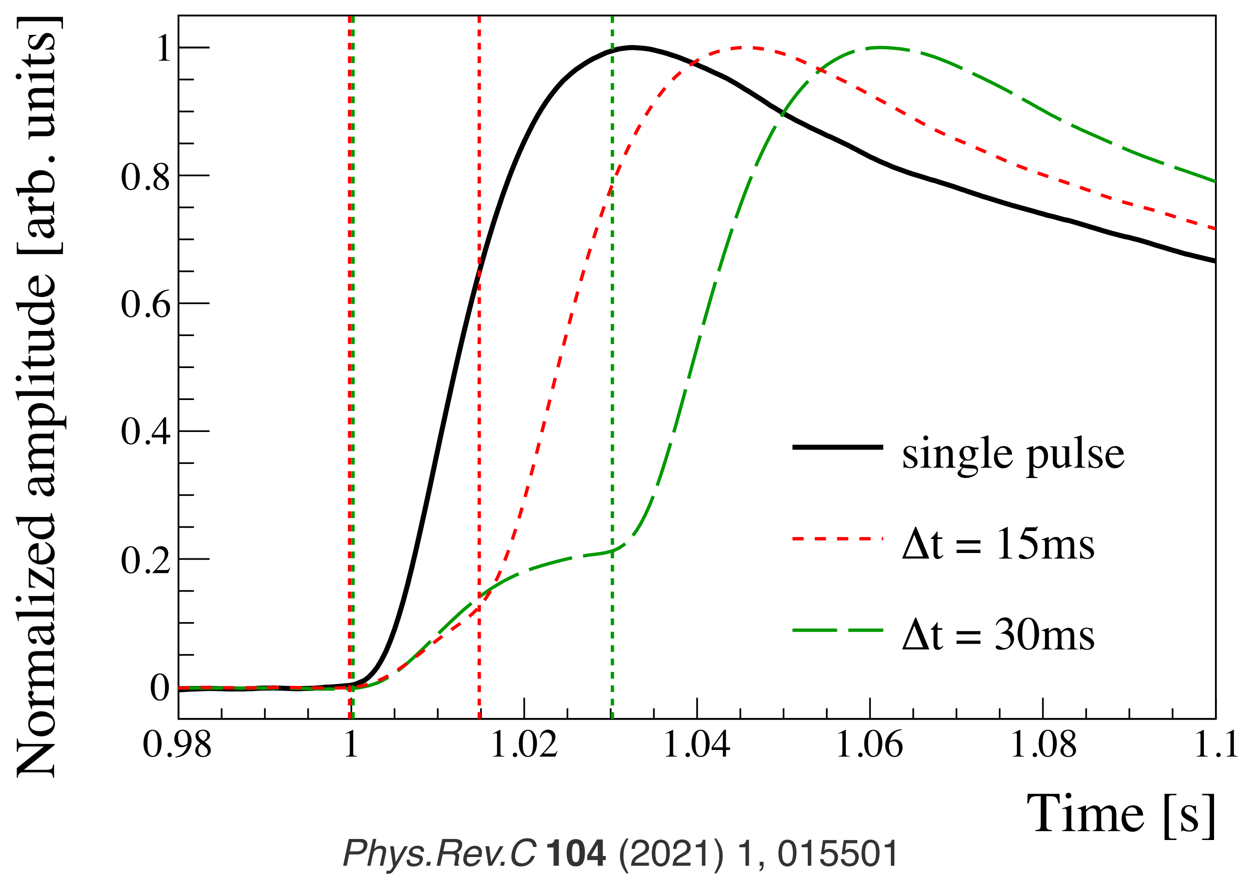
Investigating pile-up rejection



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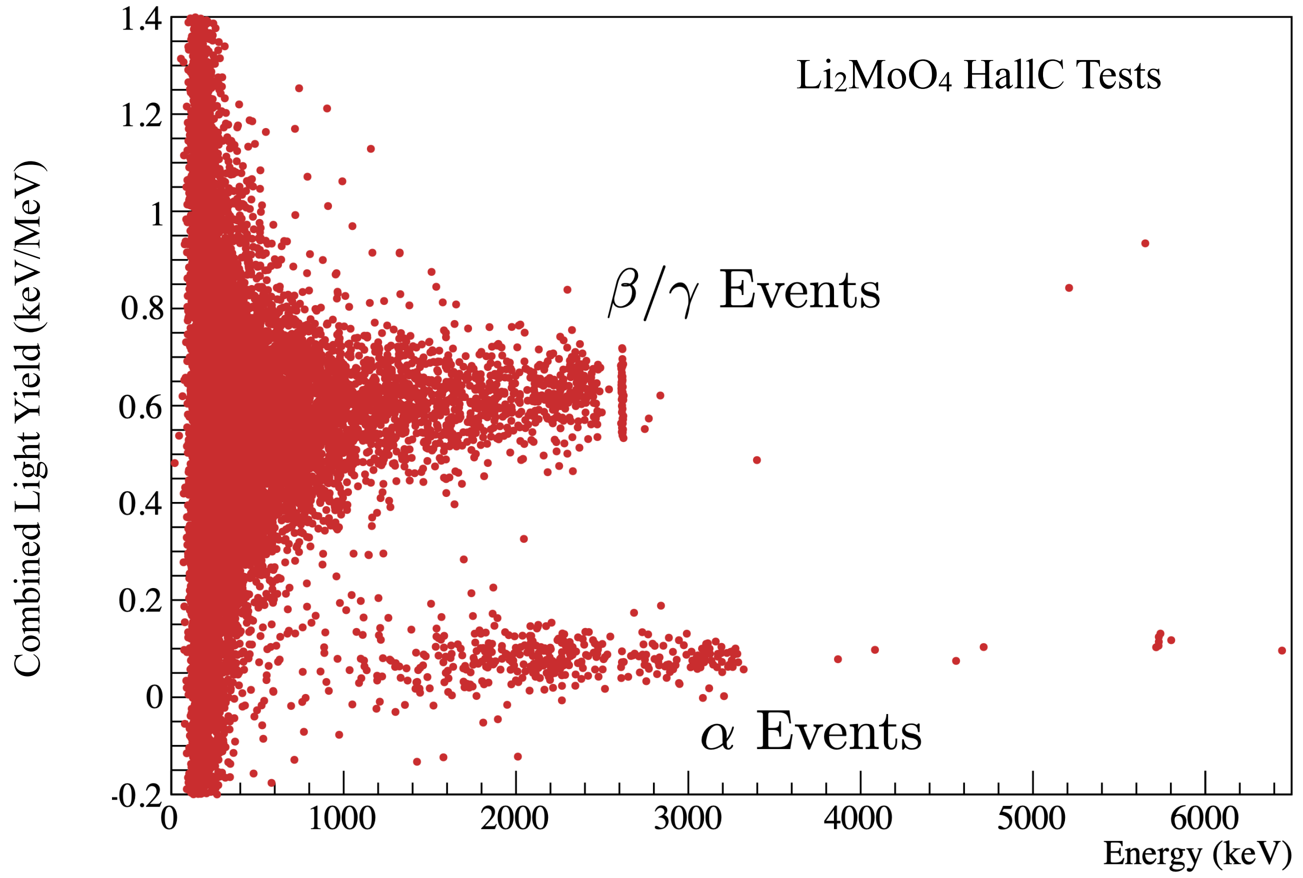
Optimizing Particle ID



In preparation

- Sensor testing and light detector prototyping at VT cryogenic facility

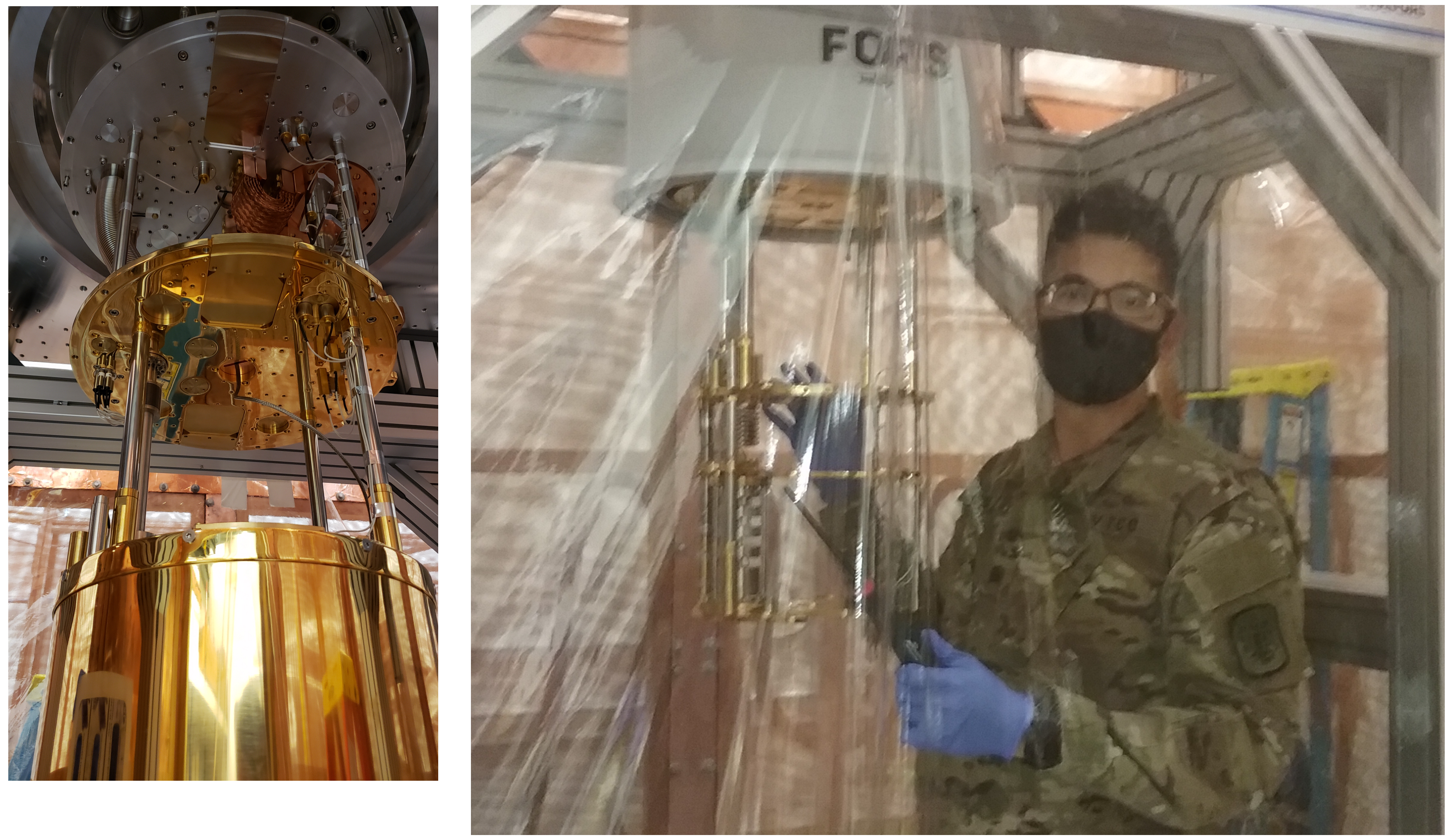
Cryogenic Test Facility at VT

- Bluefors LD-400 cryogen-free dilution refrigerator
- Arrived at VT in March 2020 (just before lockdown began)
- Now operational in Rm 10 Robeson
  - Base temperature: 8 mK
  - Cooling power @ 20mK: 17uW
  - Cooling power @ 100 mK: 580uW

Cryogenic Test Facility at VT

Cryogenic Test Facility at VT



Undergraduate A. Brown installing noise thermometer
(4316 Research project Fall 2020)

Undergraduates J. Stevic and G. Bimstefer installing optical fibers to pulse cryogenic light detectors
(4316 Research project Spring 2021)

Summary

- Neutrinoless double beta decay is a probe of Majorana neutrinos
- CUORE is progressing smoothly, largest ultra-cryogenic detector in the world
- No evidence for neutrinoless double beta decay (yet)

$$\boxed{T^{0\nu}_{1/2} > 2.2 \times 10^{25}\ \mathrm{yr} \quad \text{(90\% C.I)}}$$

$$\boxed{m_{\beta\beta} < 90 - 310\ \mathrm{meV}}$$

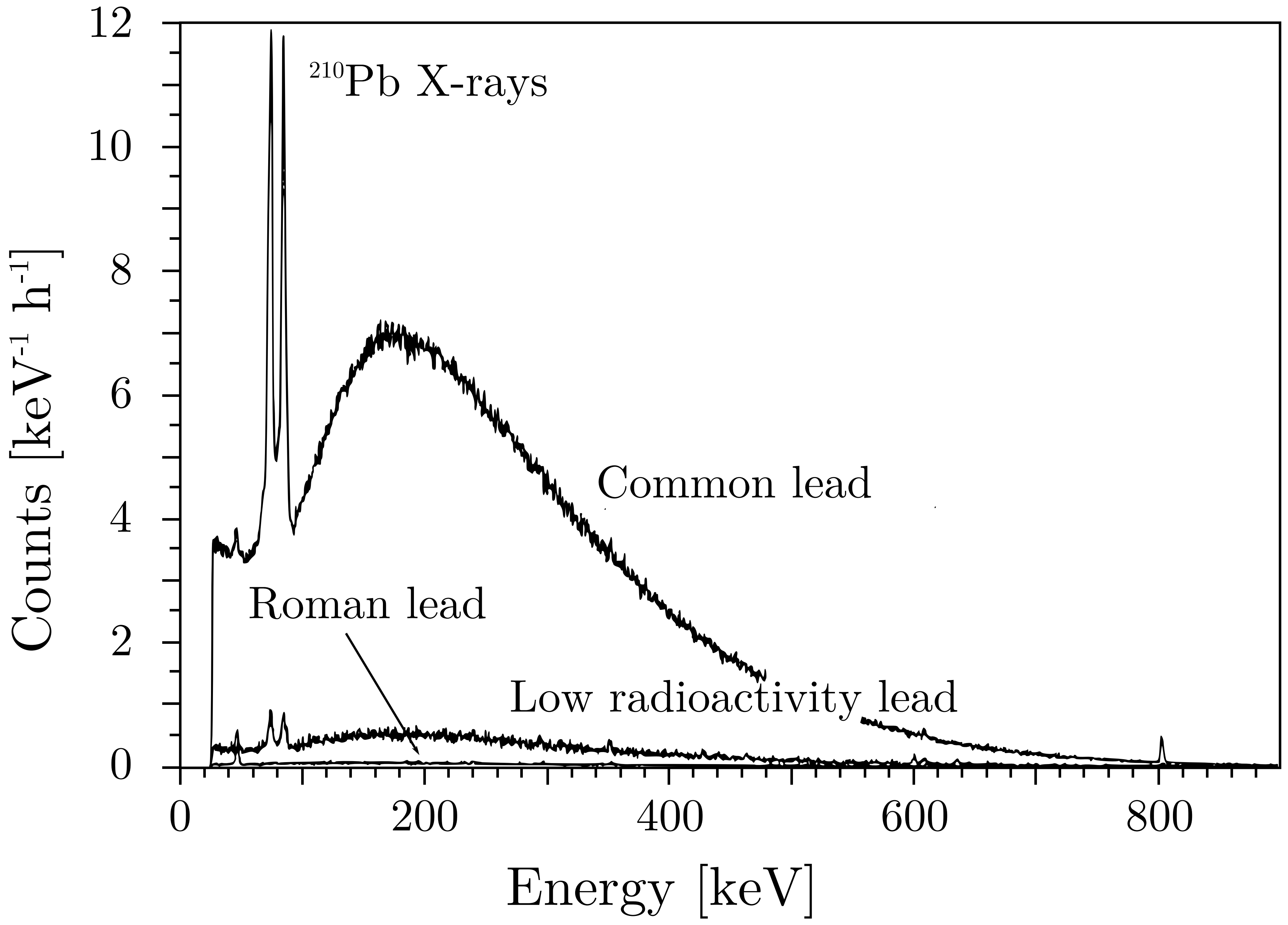
- CUORE cryogenic infrastructure will be the host facility for a next-generation neutrinoless double beta decay search: CUPID

Acknowledgements

The CUORE Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare (INFN); the National Science Foundation under Grant Nos. NSF-PHY-0605119, NSF-PHY-0500337, NSF-PHY-0855314, NSF-PHY-0902171, NSF-PHY-0969852, NSF-PHY-1307204, NSF-PHY-1314881, NSF-PHY-1401832, and NSF-PHY-1913374; the Alfred P. Sloan Foundation; the University of Wisconsin Foundation; and Yale University. This material is also based upon work supported by the US Department of Energy (DOE) Office of Science under Contract Nos.DE-AC02-05CH11231, DE-AC52-07NA27344, DE-SC0012654, and DE-SC0020423 ; by the DOE Office of Science, Office of Nuclear Physics under Contract Nos. DE-FG02-08ER41551 and DE-FG03-00ER41138; and by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 754496. This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of the DIANA data analysis and APOLLO data acquisition software which has been developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 collaborations.

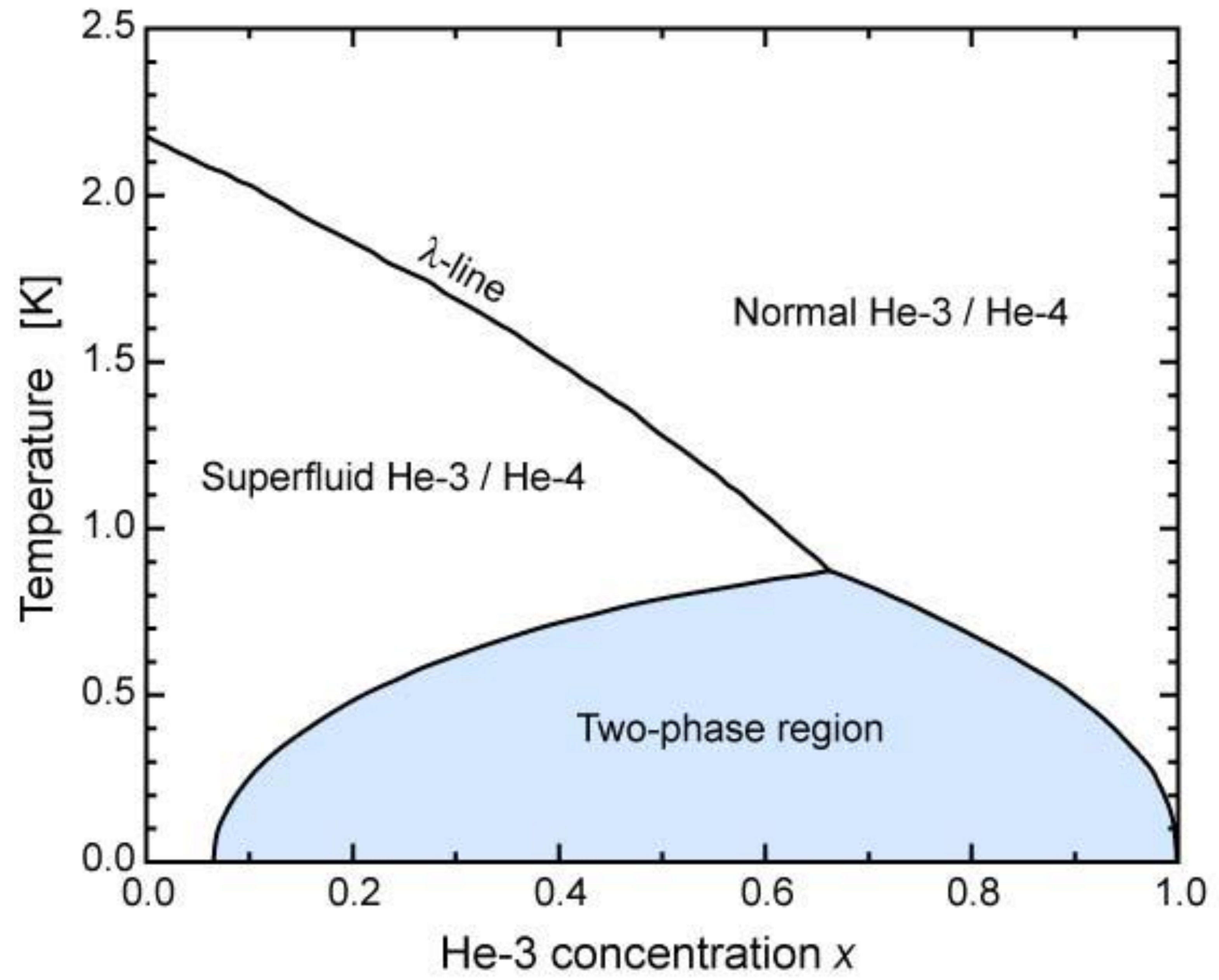
VT group's work is supported by DOE Office of Science, Office of Nuclear Physics

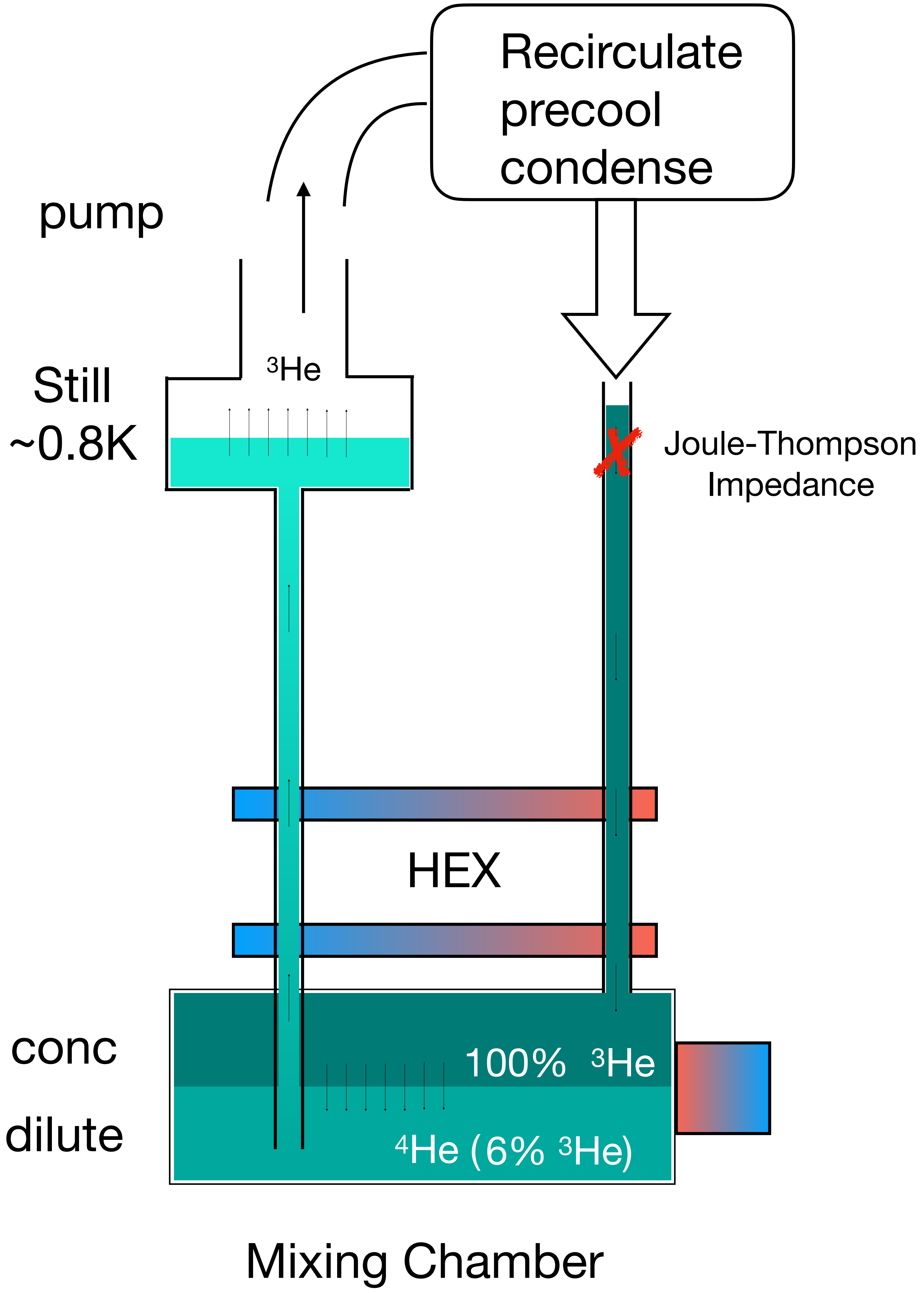
Cryogenic Lead Shielding (Ancient Lead)

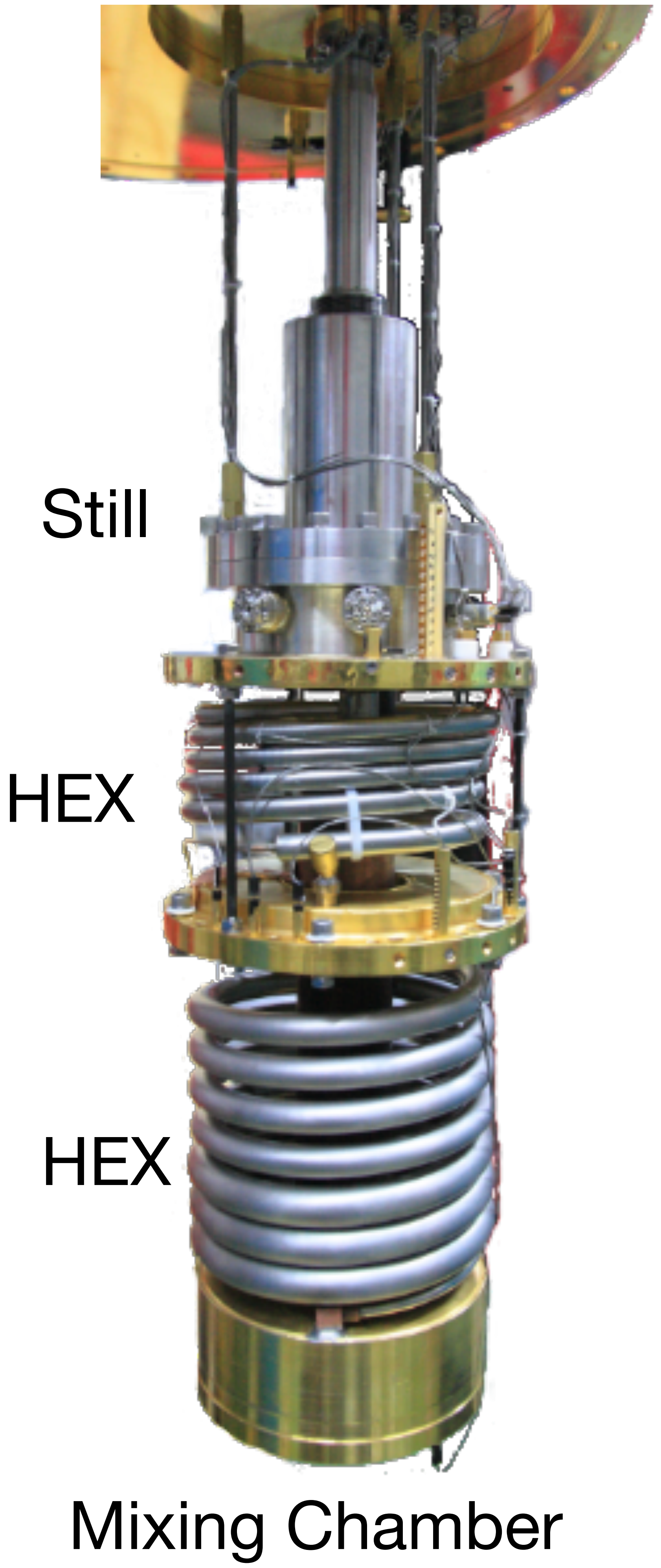


Ancient lead is extremely radiopure !

Dilution Refrigerator Principle

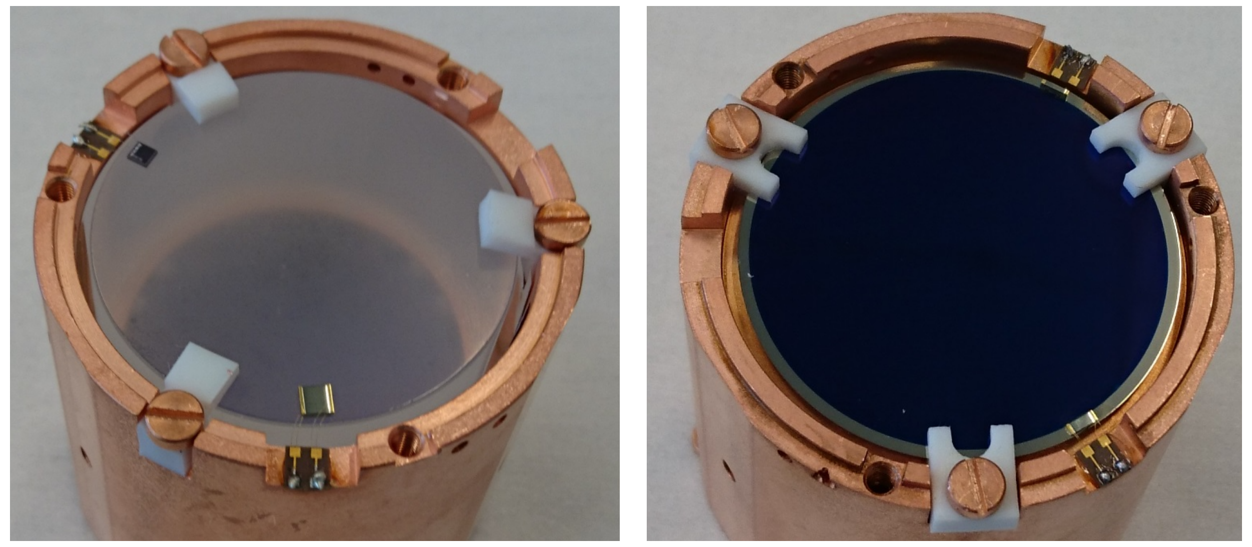




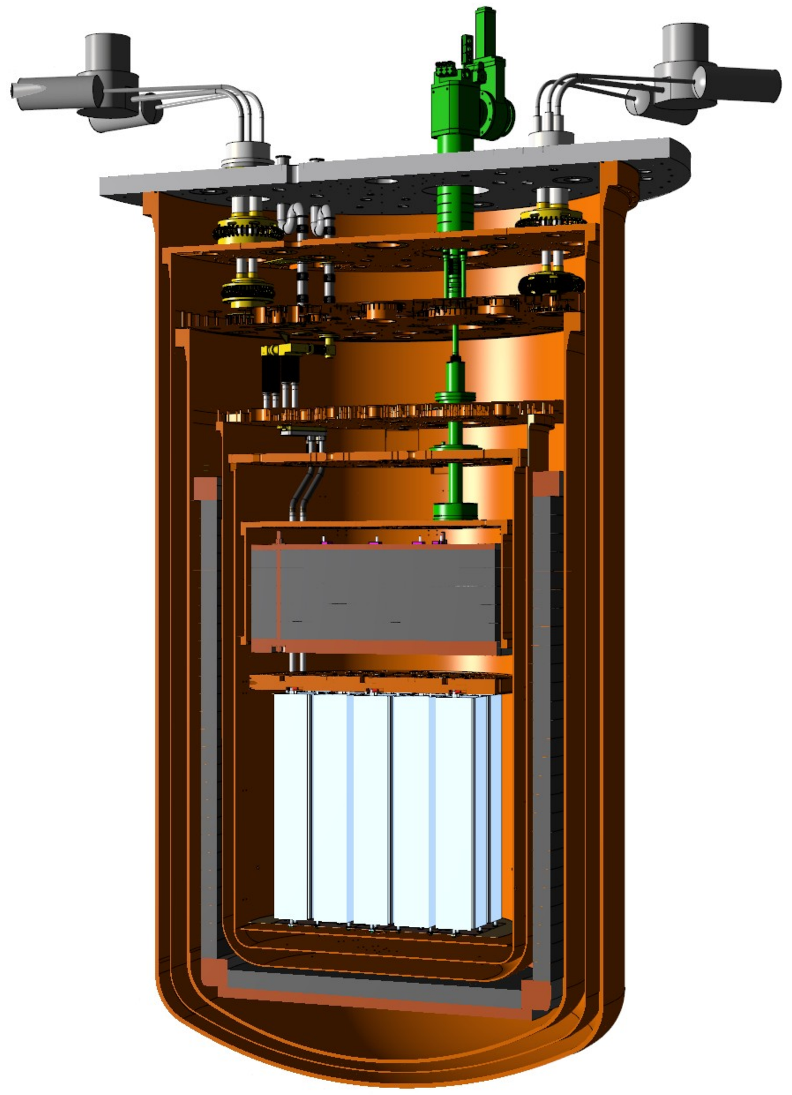


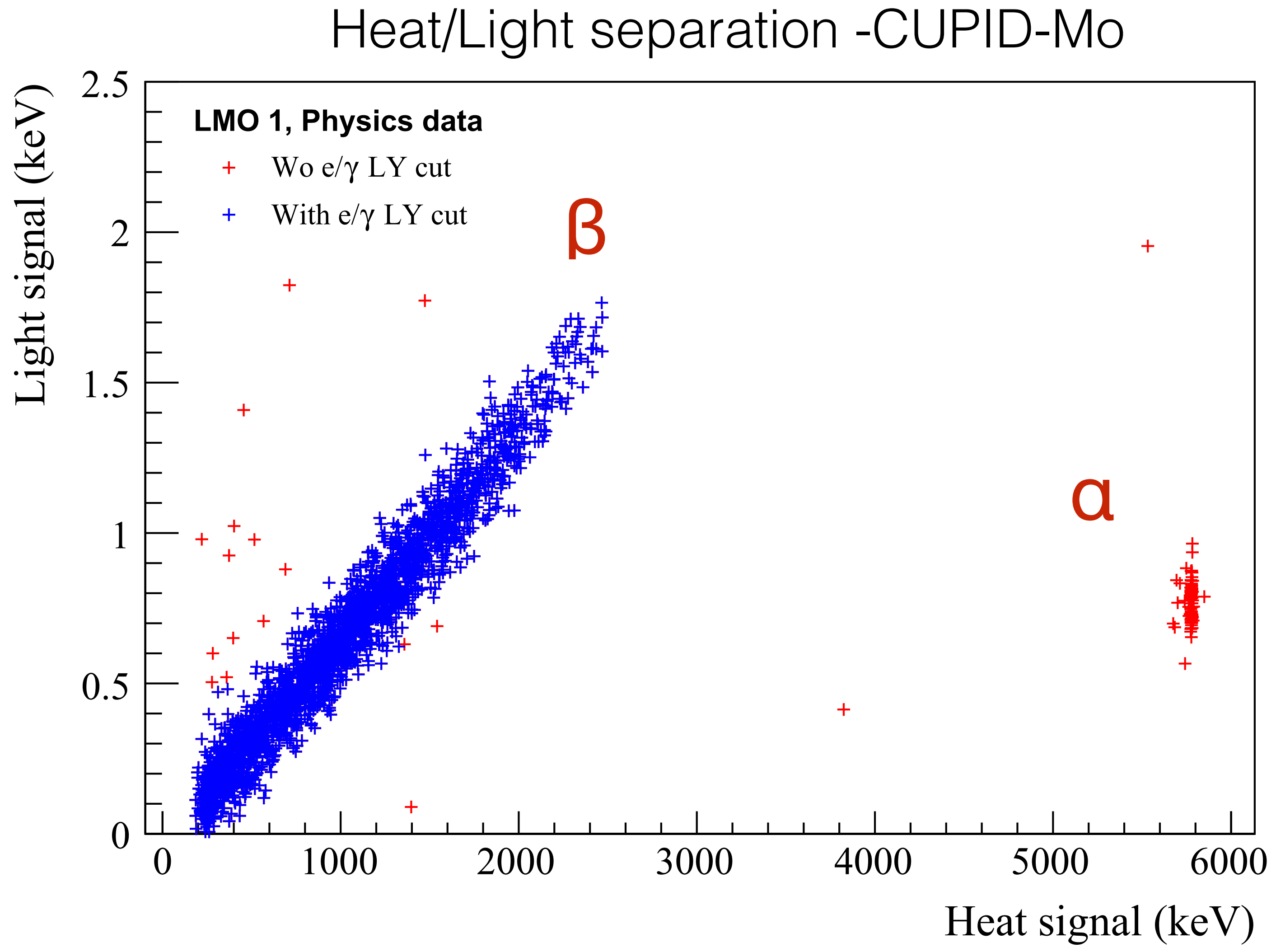
From CUORE to CUPID

Alpha-tagging



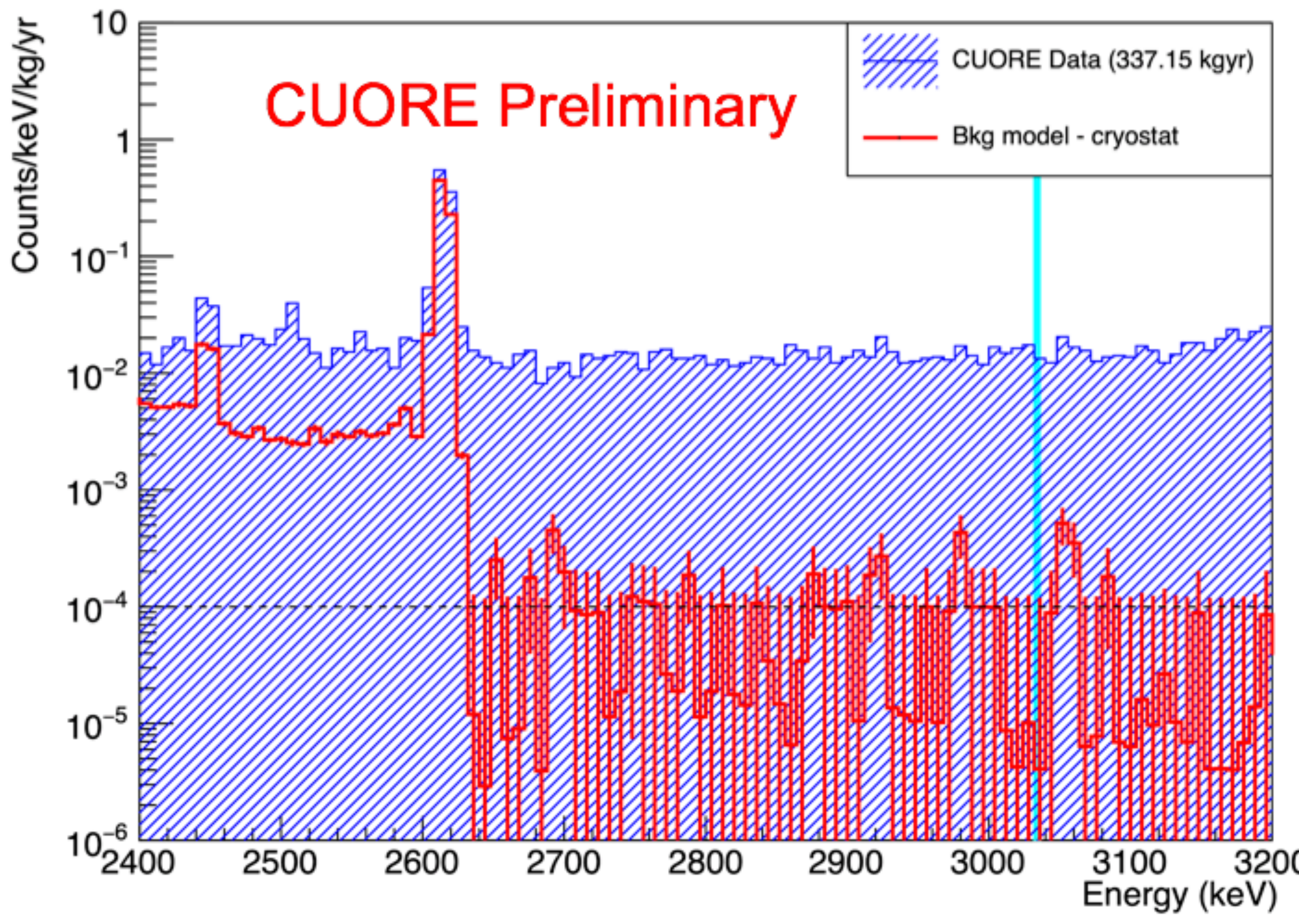
Higher Q-value —> lower background





Alpha Rejection

- Light yield for β/γ events is 5x greater than for α particles
  - > 99.9% α separation
  - > 99.9 % β/γ acceptance



- Background at 100Mo Q-value measured in CUORE
- Simulations to decompose into different sources

β/γ component

$$< 1 \times 10^{-4} \frac{\mathrm{cnts}}{(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})}$$