A search for neutrinoless double-beta decay in tellurium-130 with CUORE

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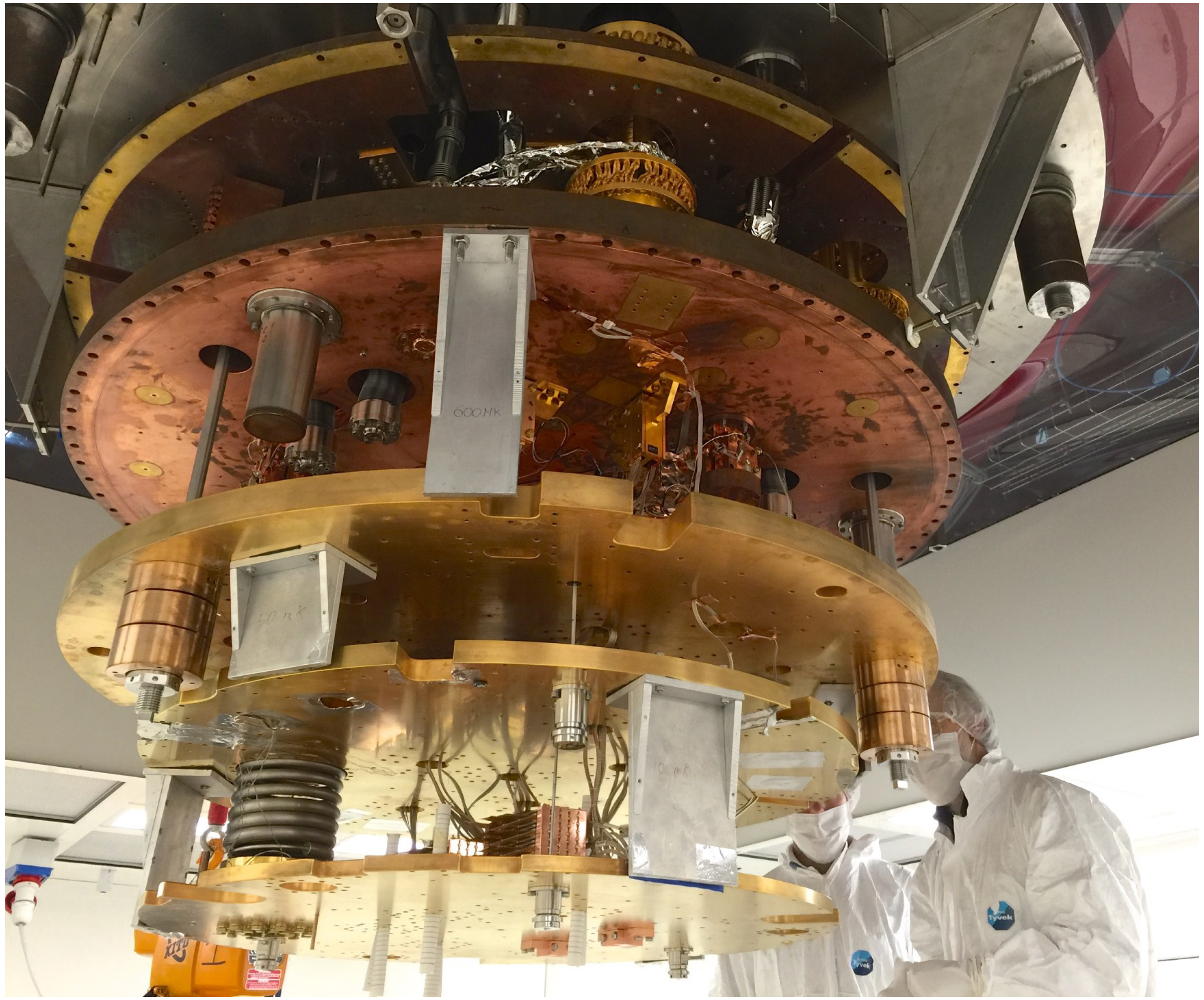
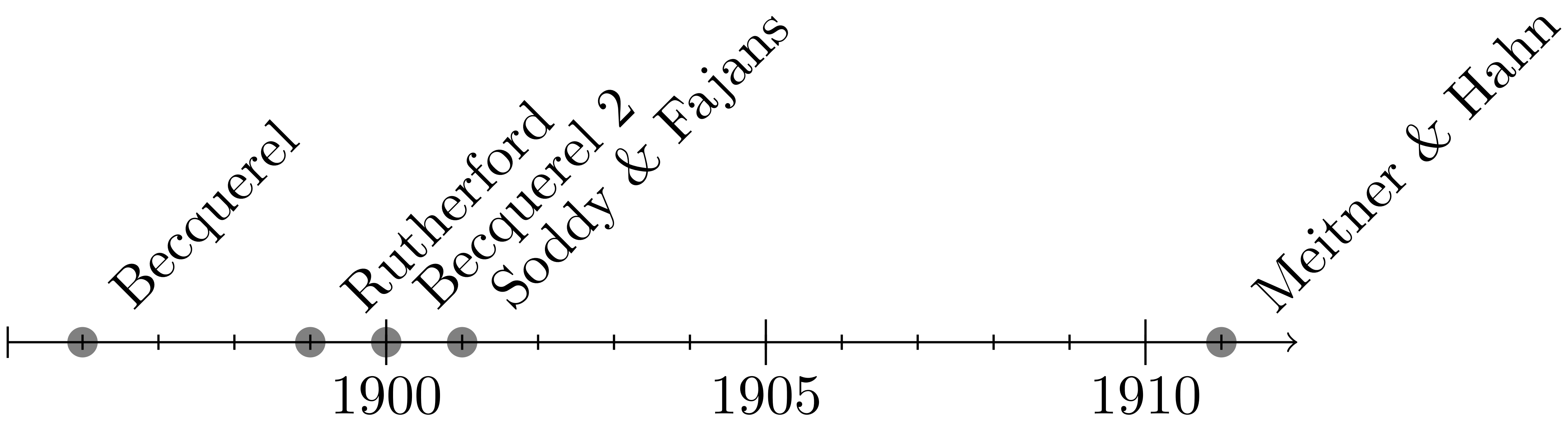
Dissertation Defense
December 15, 2017

Outline

- History and background
- CUORE detector and cryostat
- Detector calibration system
- First physics results

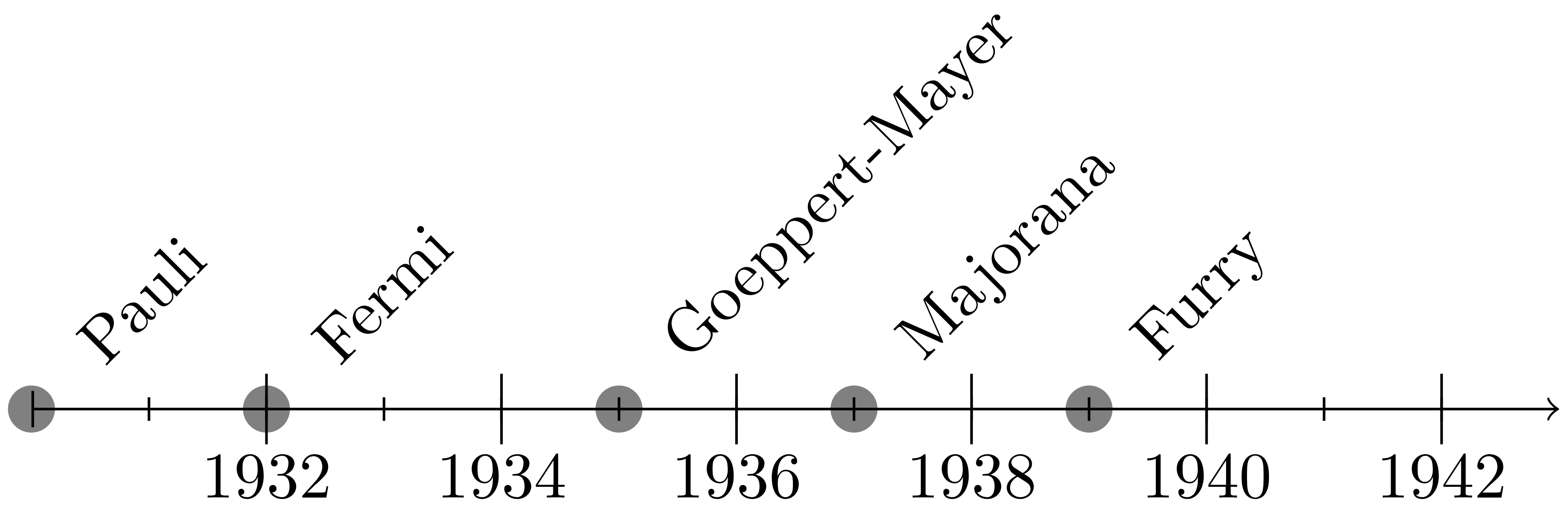


The early days



- **Becquerel** discovers that uranium randomly emits lots of particles. **Curie & Curie** investigate and coin the term "radioactivity."
- **Rutherford** notices that there are two types of emissions, one of which penetrates matter much better than the other; he calls them "alpha" and "beta" particles
- **Becquerel** measures the mass-to-charge ratio of the beta particles, and it exactly matches that of the electron (discovered only 3 years earlier)
- **Soddy & Fajans** establish that beta decay transforms an element into the one to the right of it in the periodic table
- Everyone thinks that beta particles should have specific energies, but **Meitner & Hahn** show that beta particles are actually emitted in an energy continuum
- **Nearly Everyone:** Is the law of conservation of energy in trouble?

The early days

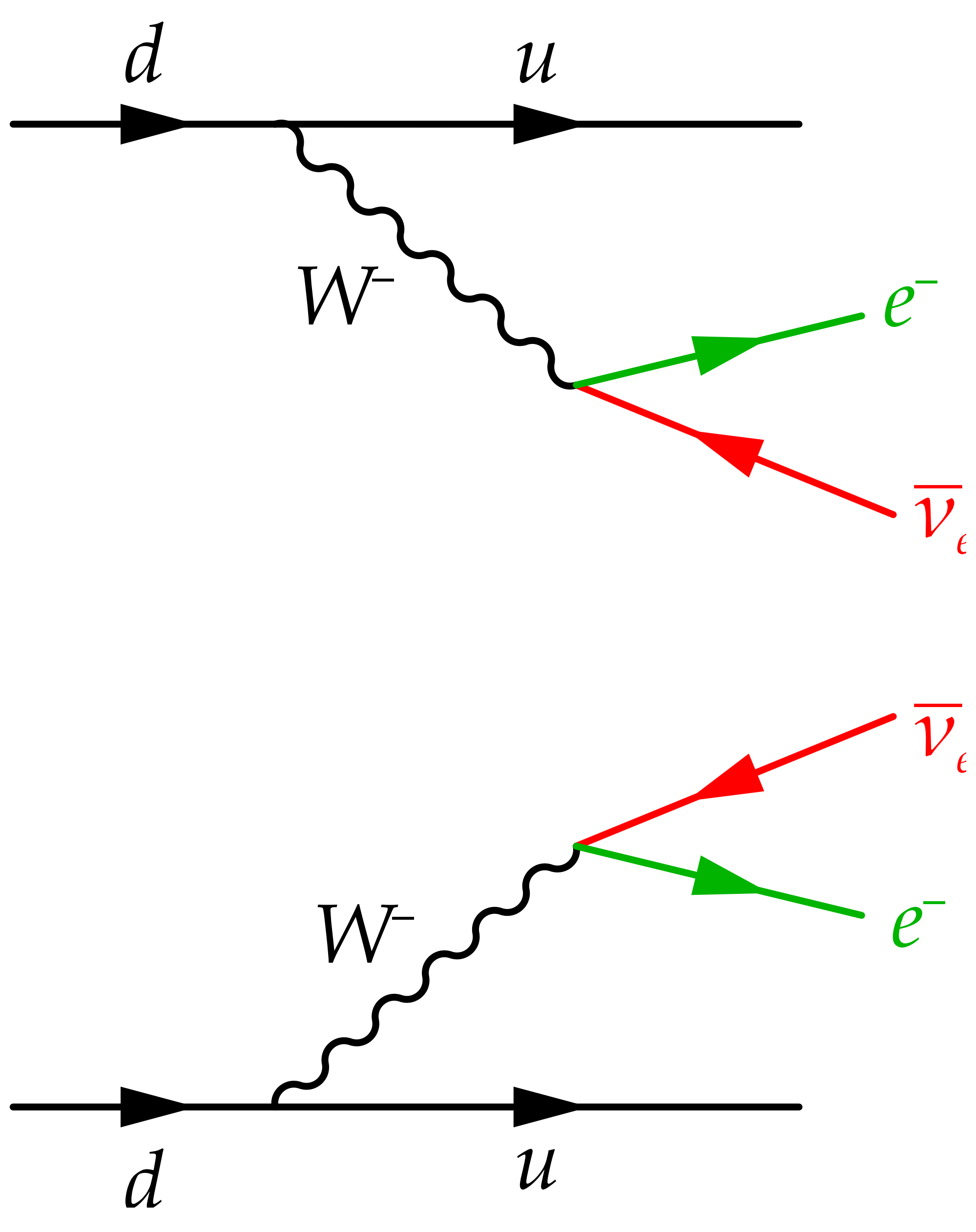


- After 20 years of debate, **Pauli** proposes the idea of the neutrino to conserve energy and momentum in beta decays
- **Fermi** creates a formal theory of beta decay incorporating the neutrino
- **Goeppert-Mayer** postulates double beta decay: if particles can decay by emitting an electron and a neutrino, they should also be able to emit 2 electrons and 2 neutrinos
- **Majorana** proposes that the neutrino and antineutrino may be the same particle; this would not have a noticeable effect on beta decay
- **Furry** postulates that if neutrinos are their own antiparticles, then atoms should be able to decay by emitting just 2 electrons and no neutrinos

Double beta decays

Ordinary (2νββ)

Observed in several isotopes

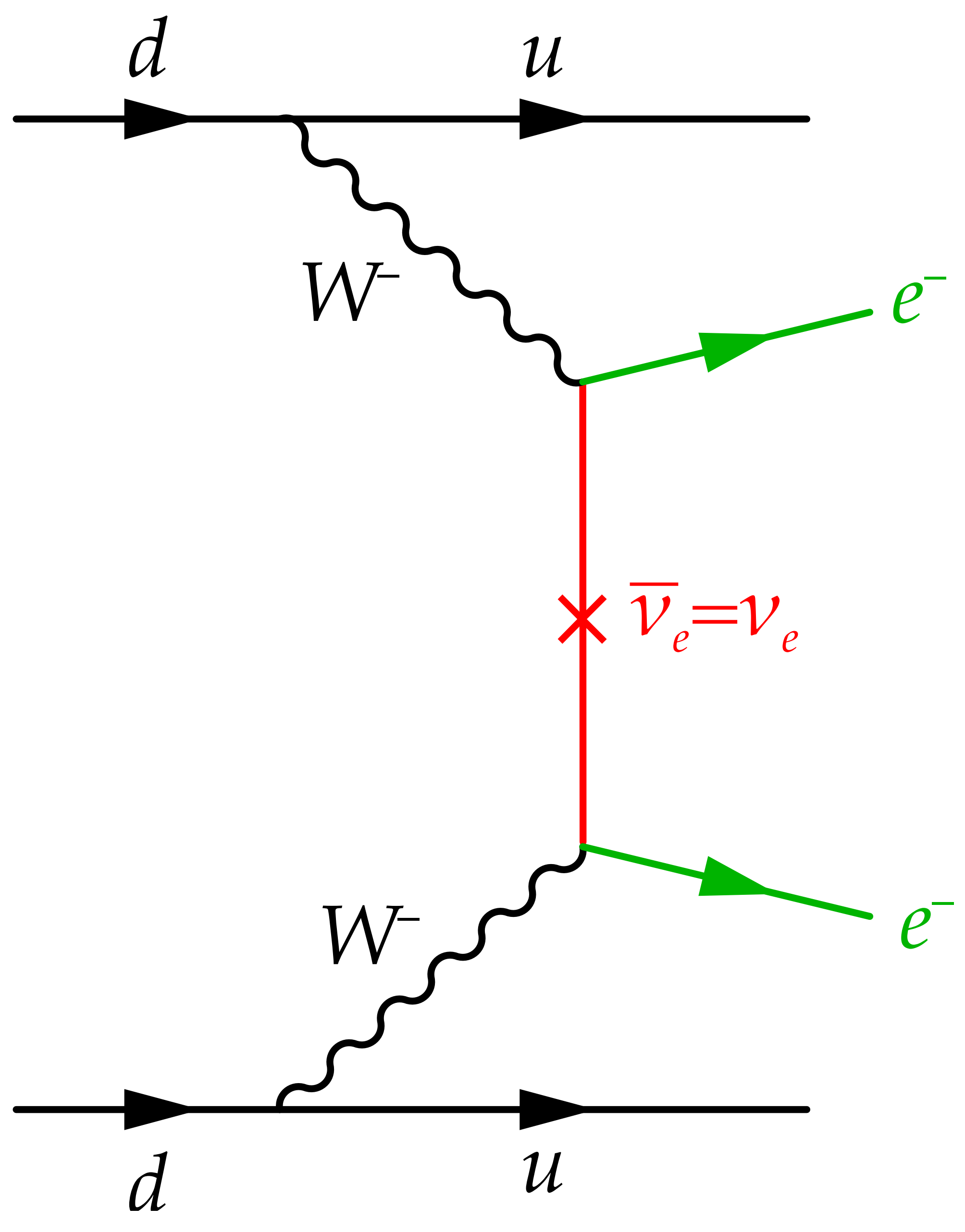


$$2n \rightarrow 2p + 2e^- + 2\overline{\nu}_e$$

$$^A_Z\mathrm{X} \rightarrow {}_{Z+2}^{\ \ A}\mathrm{X}' + 2e^- + 2\overline{\nu}_e$$

Neutrinoless (0νββ)

Hypothesized, if neutrinos are Majorana fermions

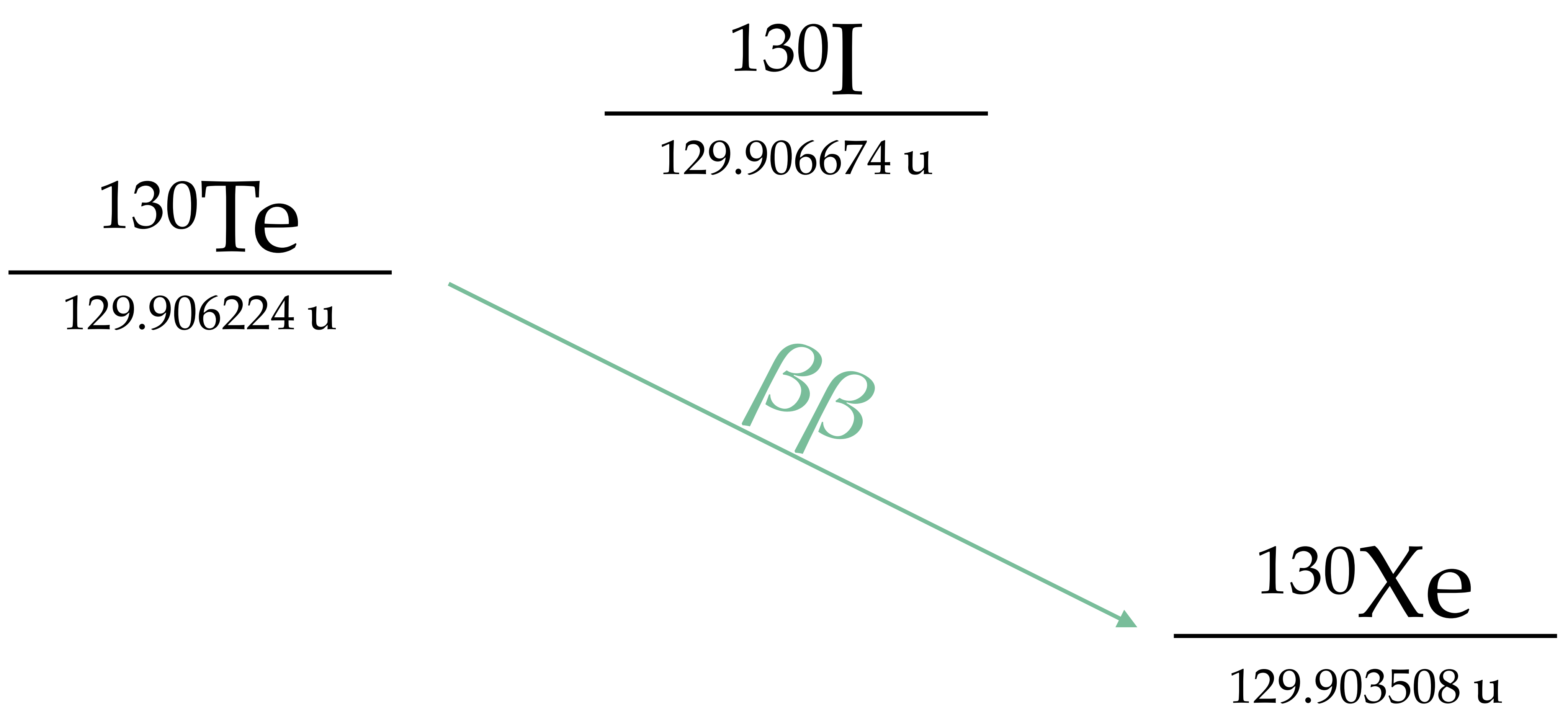


$$2n \rightarrow 2p + 2e^-$$

$$^A_Z\mathrm{X} \rightarrow {}_{Z+2}^{\ \ A}\mathrm{X}' + 2e^-$$

Can we see it?

- Double beta decay is a second-order process (highly suppressed)
- We have no chance of seeing it directly in isotopes for which single beta decay is allowed
- We need to look for cases where double beta decay is allowed and single beta decay is forbidden



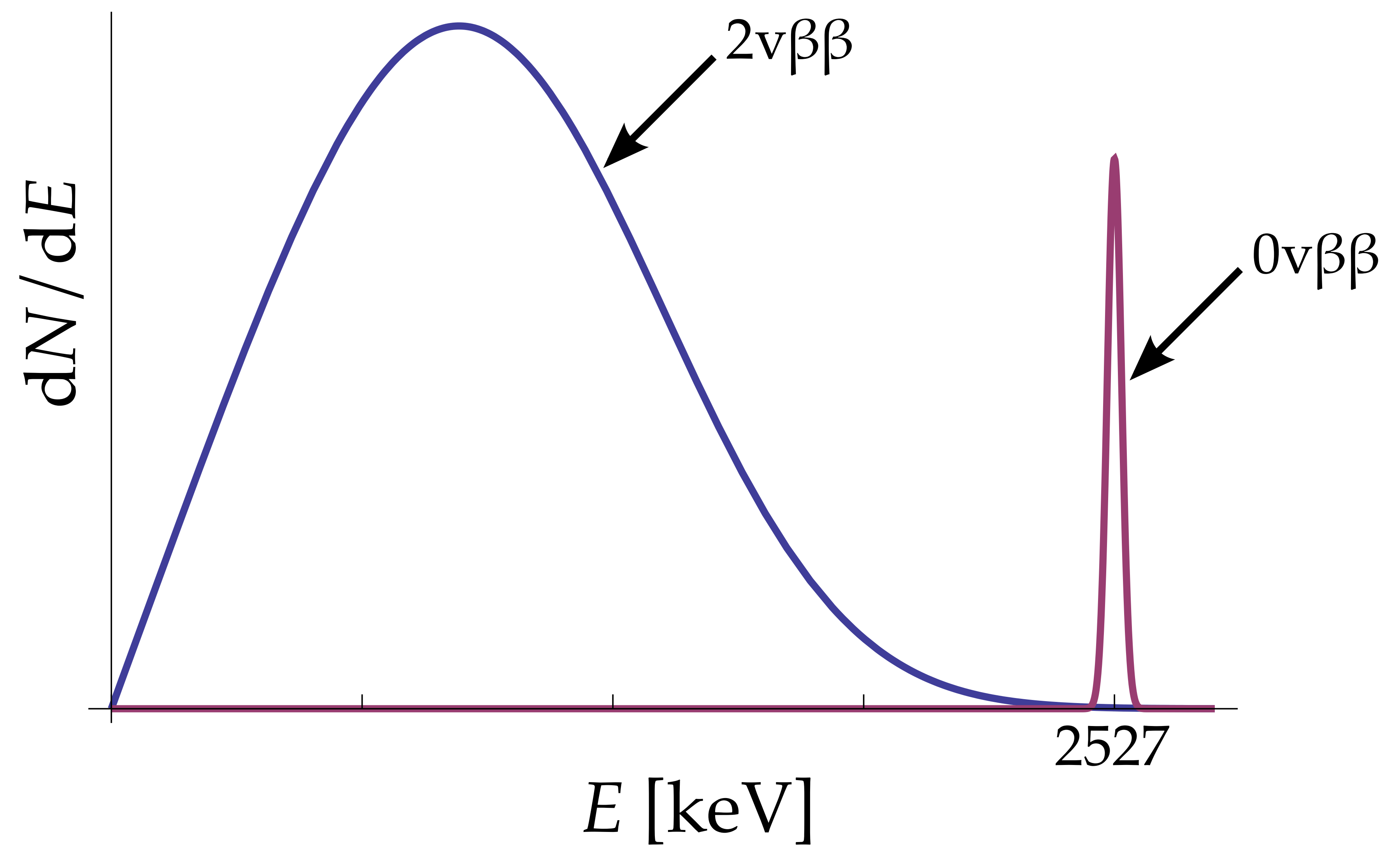
Detecting 0νββ decay

Goal: Measure the summed energy of both electrons released in the decay

Ordinary (2νββ):
Some energy goes into electrons.
Some energy escapes with neutrinos.

Neutrinoless (0νββ):
Summed energy of electrons is always equal to *Q*-value.
No energy escapes.

Double beta decay spectrum



Observation of 0νββ decay would be the first evidence of lepton number violation and unambiguously establish the Majorana nature of the neutrino

How rare?

- Most measured half-lives for 2νββ decay are on the order of 10^{21} years
    - Compare to lifetime of the universe: 10^{10} years
    - Compare to Avogadro's number: 6×10^{23}
    - A mole of the isotope will produce ~1 decay/day
- If it exists, the half-lives of 0νββ decay would be much longer
    - ^{130}Te 0νββ decay limit is $> 10^{24}$ years
    - A mole of ^{130}Te produces < 1 neutrinoless decay/year
    - A half-life of 10^{26} years requires 32 kg of ^{130}Te to see 1 decay/year

Half-lives

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \frac{\left|\langle m_{\beta\beta}\rangle\right|^2}{{m_e}^2}$$

$T^{0\nu}_{1/2}$ = $0\nu\beta\beta$ half-life

$G^{0\nu}(Q,Z)$ = phase space factor ($\propto Q^5$)

$M^{0\nu}$ = nuclear matrix element

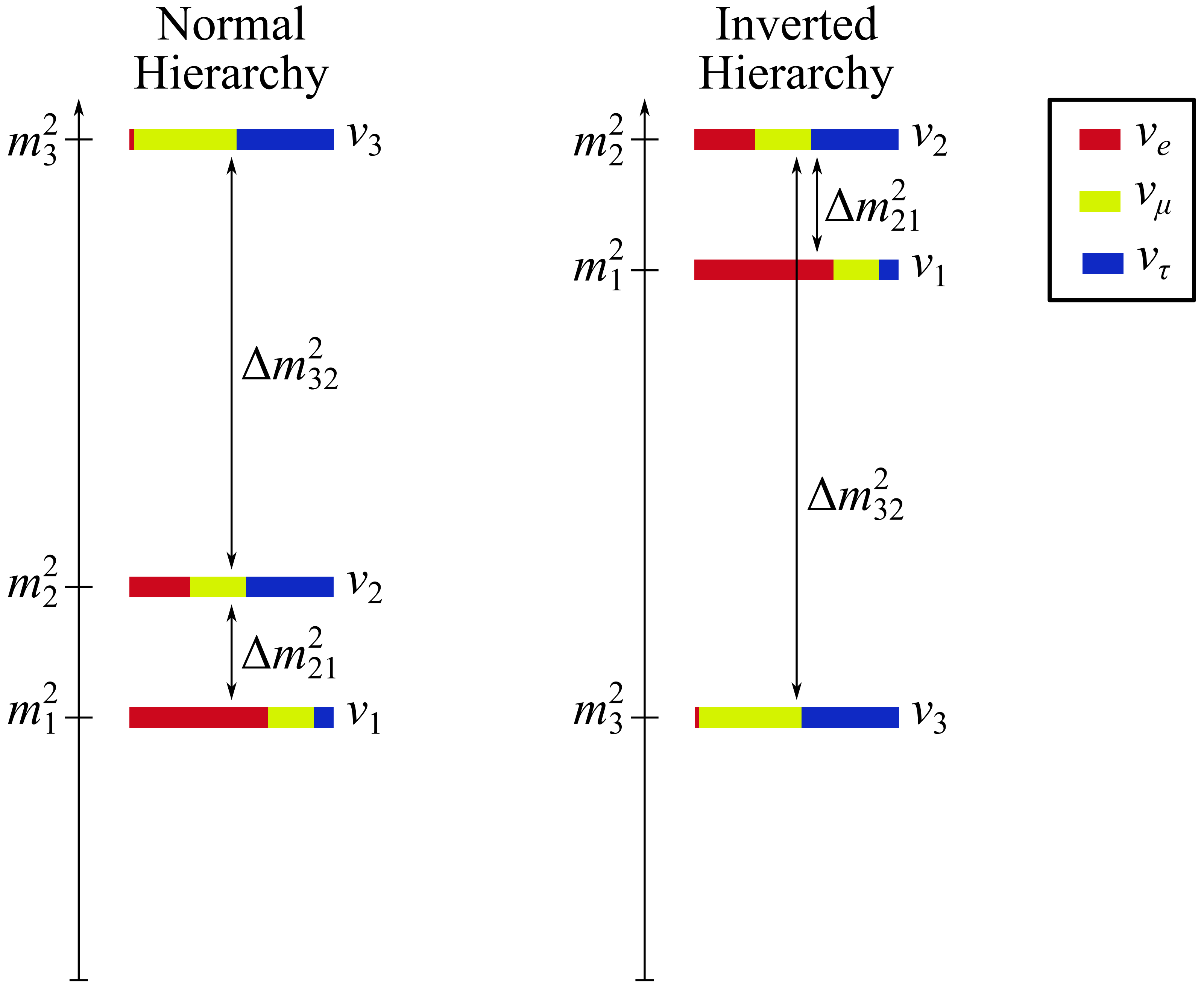
$\langle m_{\beta\beta}\rangle$ = effective $\beta\beta$ neutrino mass

m_e = electron mass

- Shorter **half-lives** are easier to measure, so choose an isotope with a high **phase space factor** (high Q-value) and high **nuclear matrix element**
- **Nuclear matrix element** is calculated theoretically, with different models differing by factors of ~2
- **Effective Majorana neutrino mass** gives hints about absolute neutrino mass

Neutrino masses

Oscillation



Cosmology

$$m_{\text{tot}} = \sum m_i$$

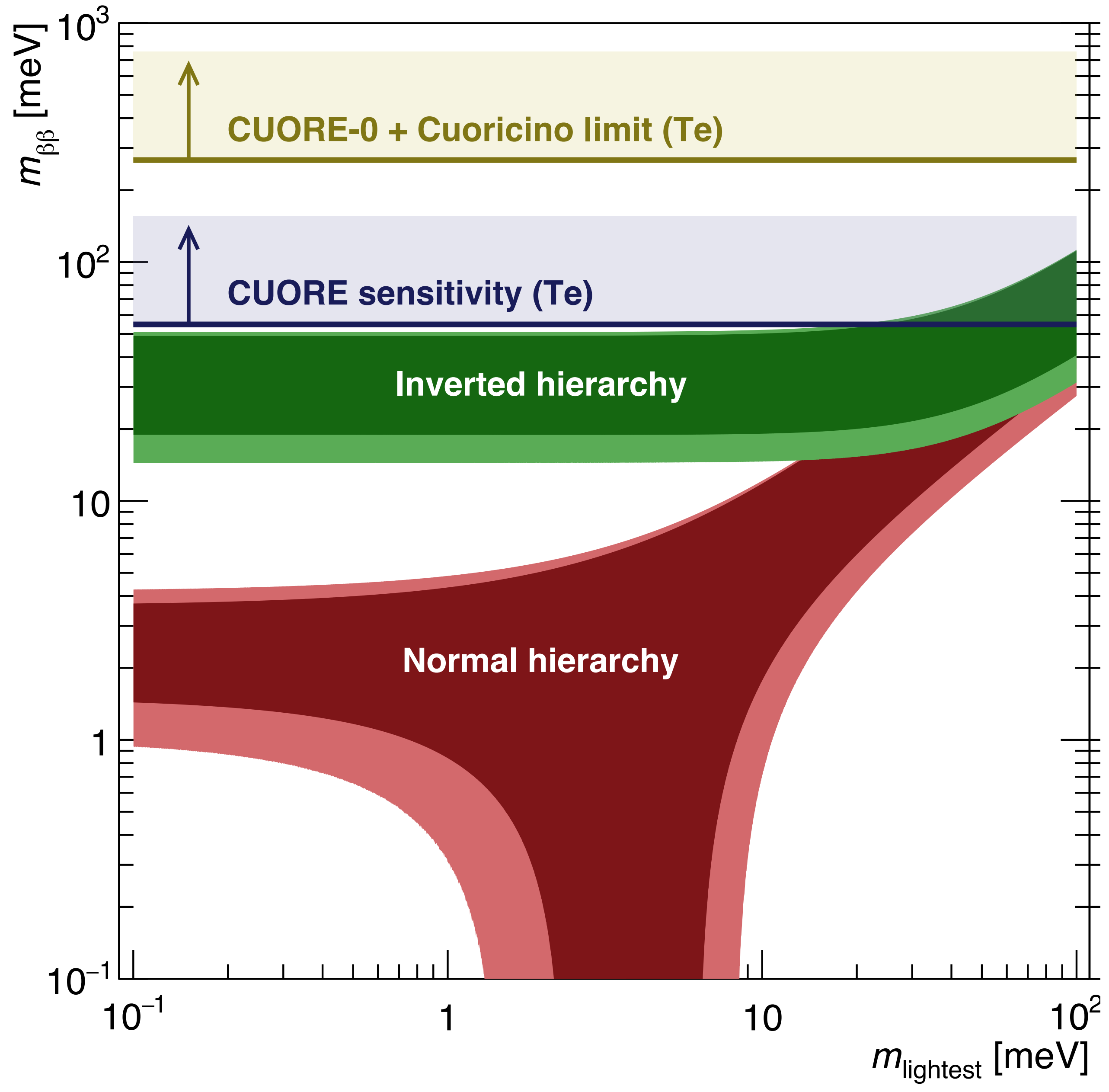
Single beta decay

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Double beta decay

$$m_{\beta\beta} = \left| \sum_i U_{ei} m_i \right|$$

- Calculated assuming model of light Majorana neutrino exchange
- Requires theoretical models of nucleus (nuclear matrix elements) and assumptions on value of axial-vector coupling constant g_A



Detector sensitivity

- Choose a source with a high **isotopic abundance** of the 0νββ decay emitter
- Create a detector with a high **detection efficiency** and good **energy resolution** in a **low-background** environment
- Run experiment for a long **exposure time** with a large **total mass** of the source isotope

$$T_{1/2}^{0\nu} \text{ sensitivity} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

a = source isotopic abundance

ϵ = detection efficiency

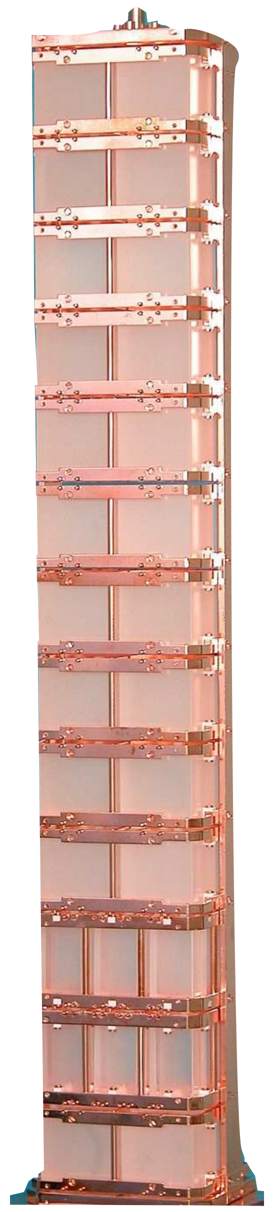
M = total mass

t = exposure time

b = background rate at $0\nu\beta\beta$ energy

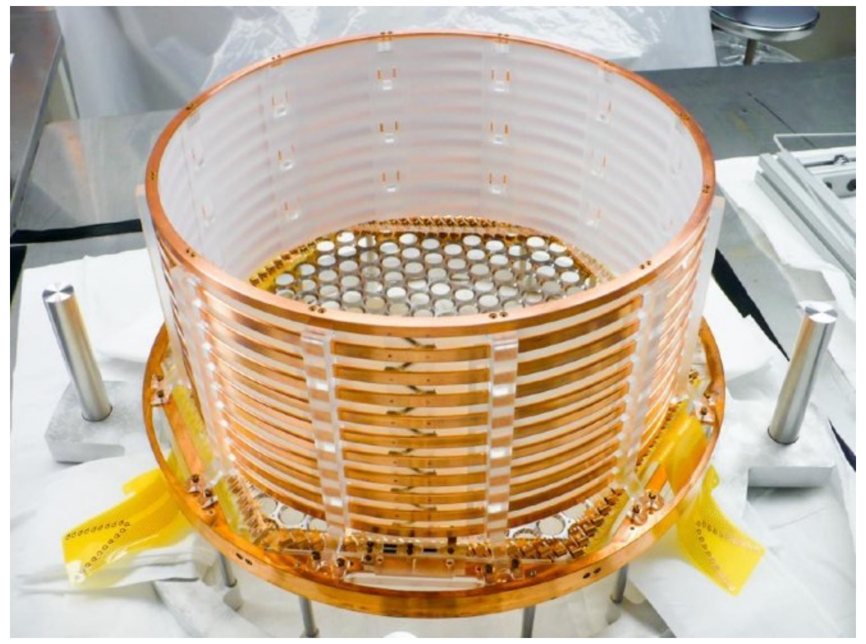
δE = energy resolution

$0\nu\beta\beta$ decay detection techniques



^{130}Te

- Bolometer-based searches: Cuoricino/CUORE-0/CUORE
- Loaded organic scintillator: SNO+
- $T_{1/2} > 4.0 \times 10^{24}$ y with CUORE-0

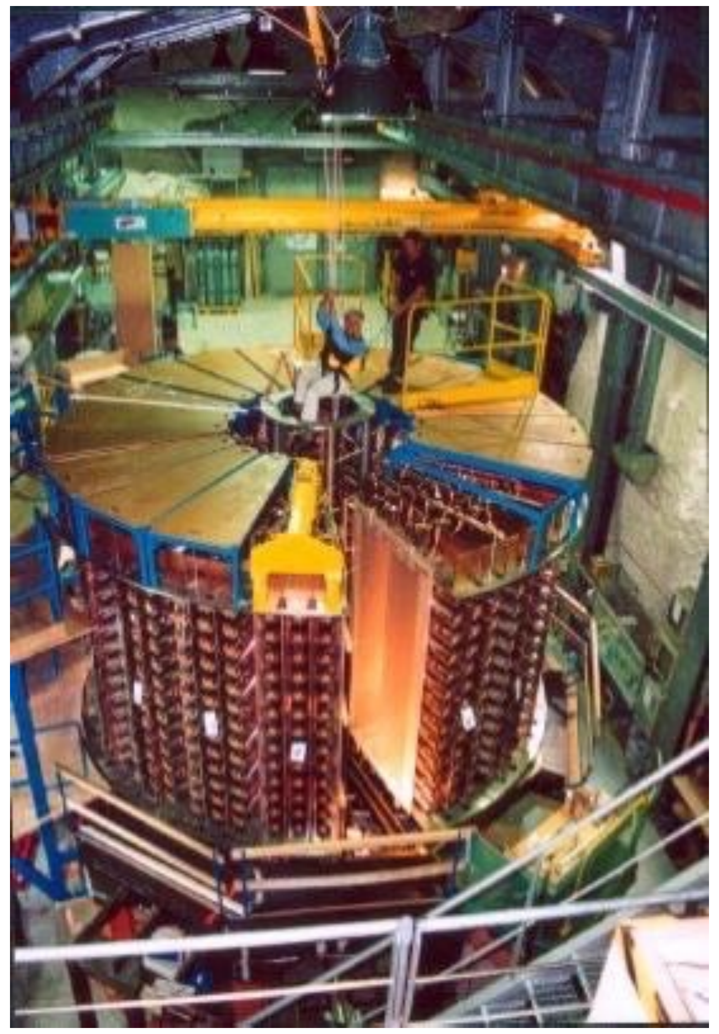


^{136}Xe

- Xe scintillation: KamLAND-Zen
- Liquid TPC & scintillation: EXO-200, nEXO
- Gas TPC: NEXT-100, PandaX-III
- $T_{1/2} > 1.1 \times 10^{26}$ y

^{76}Ge

- High-purity germanium detectors: GERDA/MAJORANA
- $T_{1/2} > 5.3 \times 10^{25}$ y



NEMO-3/SuperNEMO

- Source foils with tracking and calorimetry
- Half-lives for ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, …

A world of experiments

Present and future

Recent results:

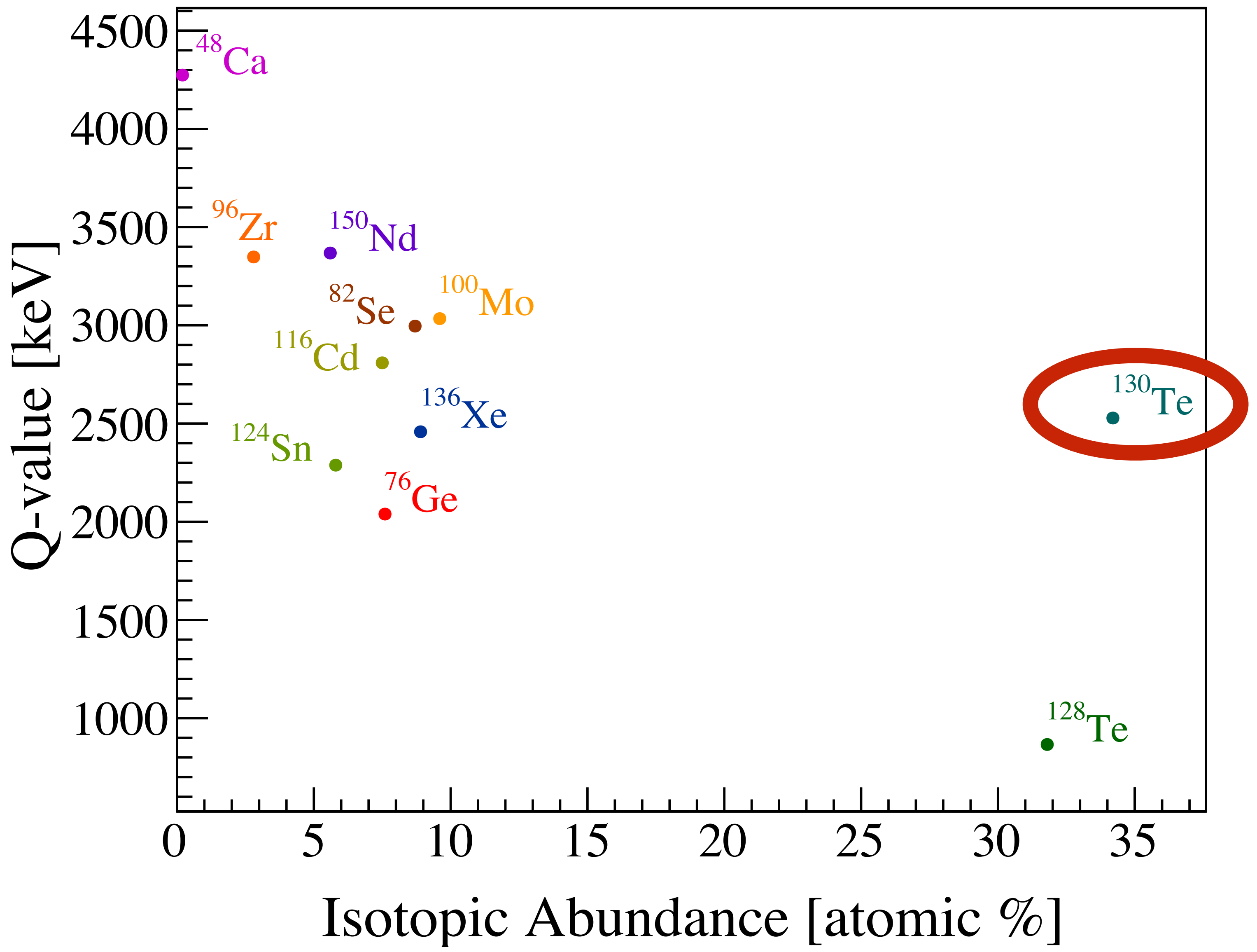
Experiment	Isotope	Detector technology	Half-life limit	Iso. exposure
GERDA	^{76}Ge	Ionization	$> 5.3 \times 10^{25}$ yr	34 kg·yr
NEMO-3	^{100}Mo	Tracker, calorimeter	$> 1.1 \times 10^{24}$ yr	35 kg·yr
CUORE-0	^{130}Te	Bolometers	$> 4.0 \times 10^{24}$ yr	30 kg·yr
EXO-200	^{136}Xe	Liquid TPC	$> 1.1 \times 10^{25}$ yr	100 kg·yr
KamLAND-Zen	^{136}Xe	Scintillation	$> 1.1 \times 10^{26}$ yr	504 kg·yr

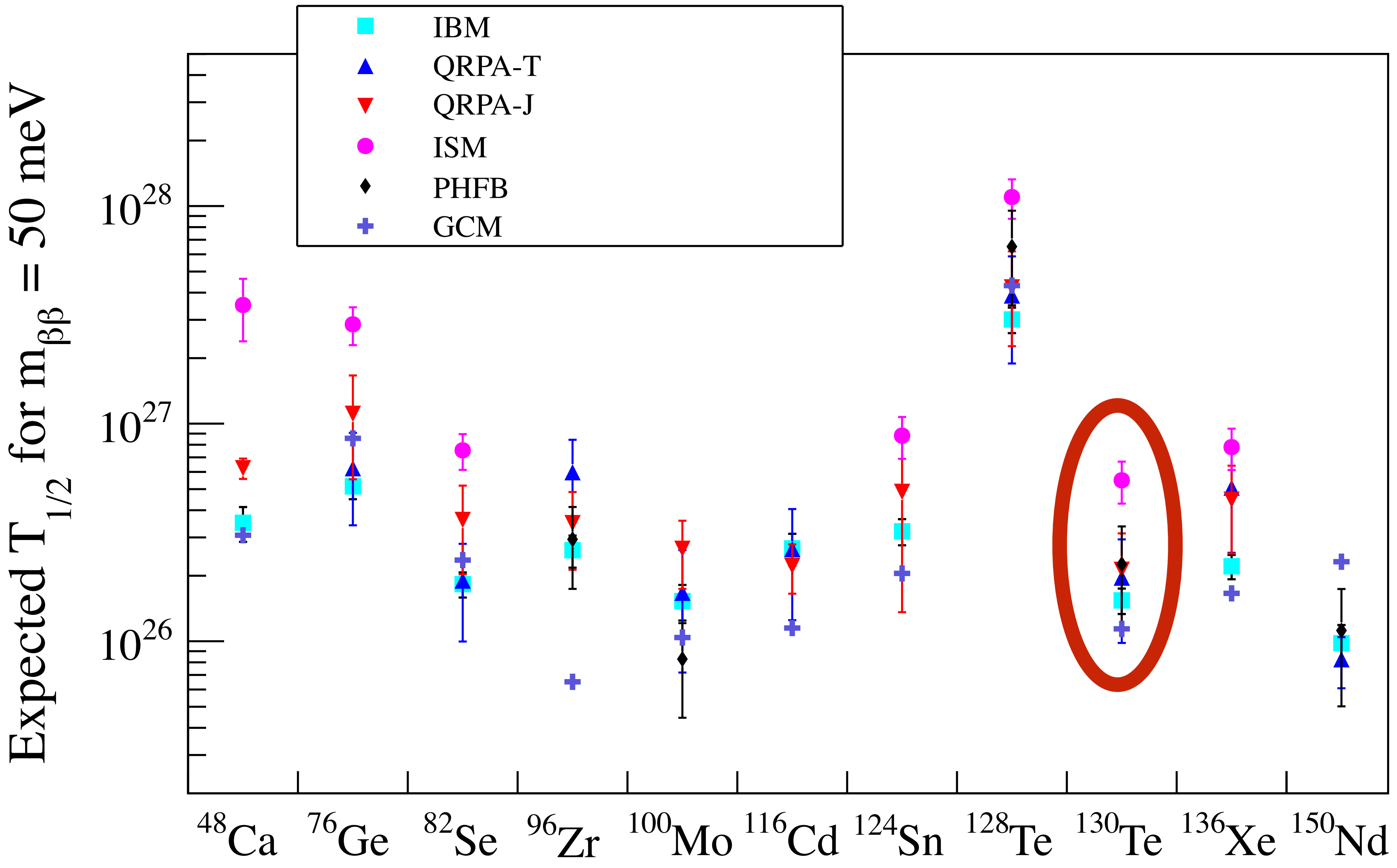
Current and future experiments:

Experiment	Isotope	Detector technology	Sensitivity	Iso. mass	Start
GERDA (Phase II)	^{76}Ge	Ionization	1×10^{26} yr	30 kg	2016
Majorana Demo.	^{76}Ge	Ionization	2×10^{26} yr	26 kg	2016
SuperNEMO	^{82}Se	Tracker, calorimeter	1×10^{26} yr	100 kg	2020?
CUORE	^{130}Te	Bolometers	9×10^{25} yr	206 kg	2017
SNO+	^{130}Te	Scintillation	9×10^{25} yr	800 kg	2018?
EXO-200 (Phase II)	^{136}Xe	Liquid TPC	6×10^{25} yr	76 kg	2016
NEXT-100	^{136}Xe	Gas TPC	6×10^{25} yr	90 kg	2018?
PandaX-III	^{136}Xe	Gas TPC	1×10^{26} yr	180 kg	2019?
KamLAND-Zen	^{136}Xe	Scintillation	2×10^{26} yr	600 kg	2016

Advantages of CUORE

- Excellent energy resolution of TeO_2 bolometers (~0.2% FWHM resolution at 2615 keV)
- ^{130}Te: High natural abundance (no enrichment required), good *Q*-value (above Compton edge of 2615 keV line), relatively accessible 0νββ decay half-life





$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{{m_e}^2}$$

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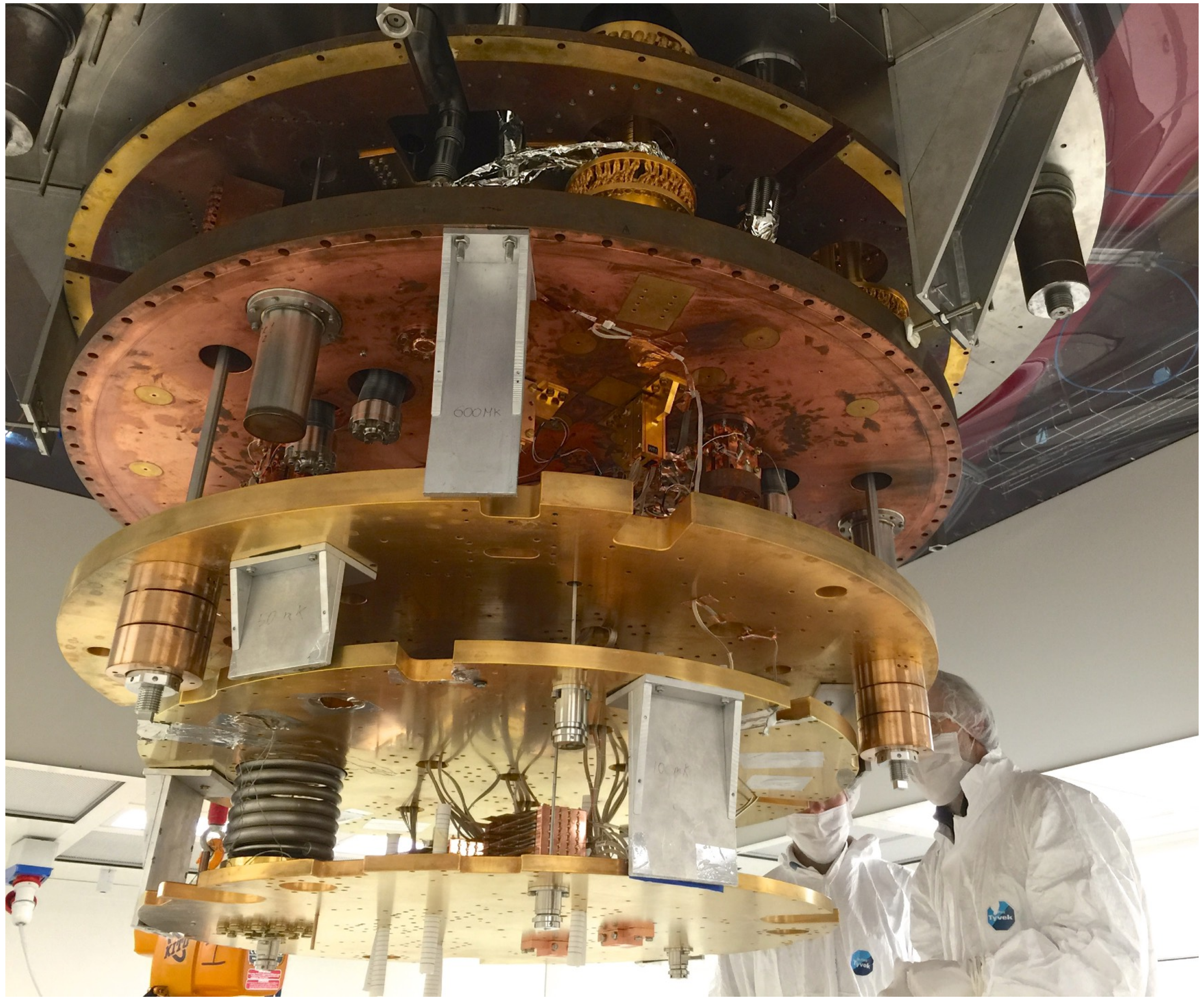
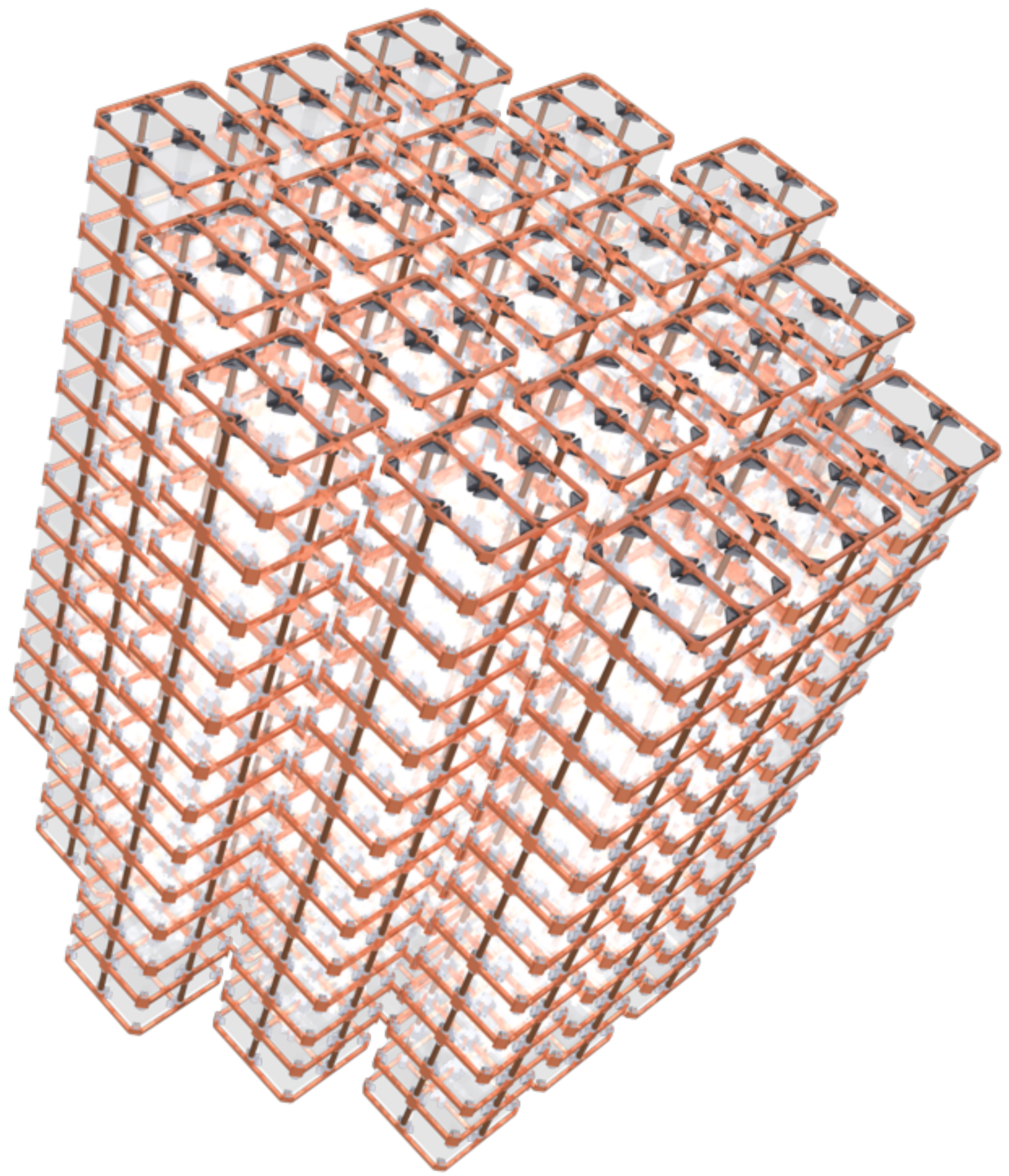


CUORE

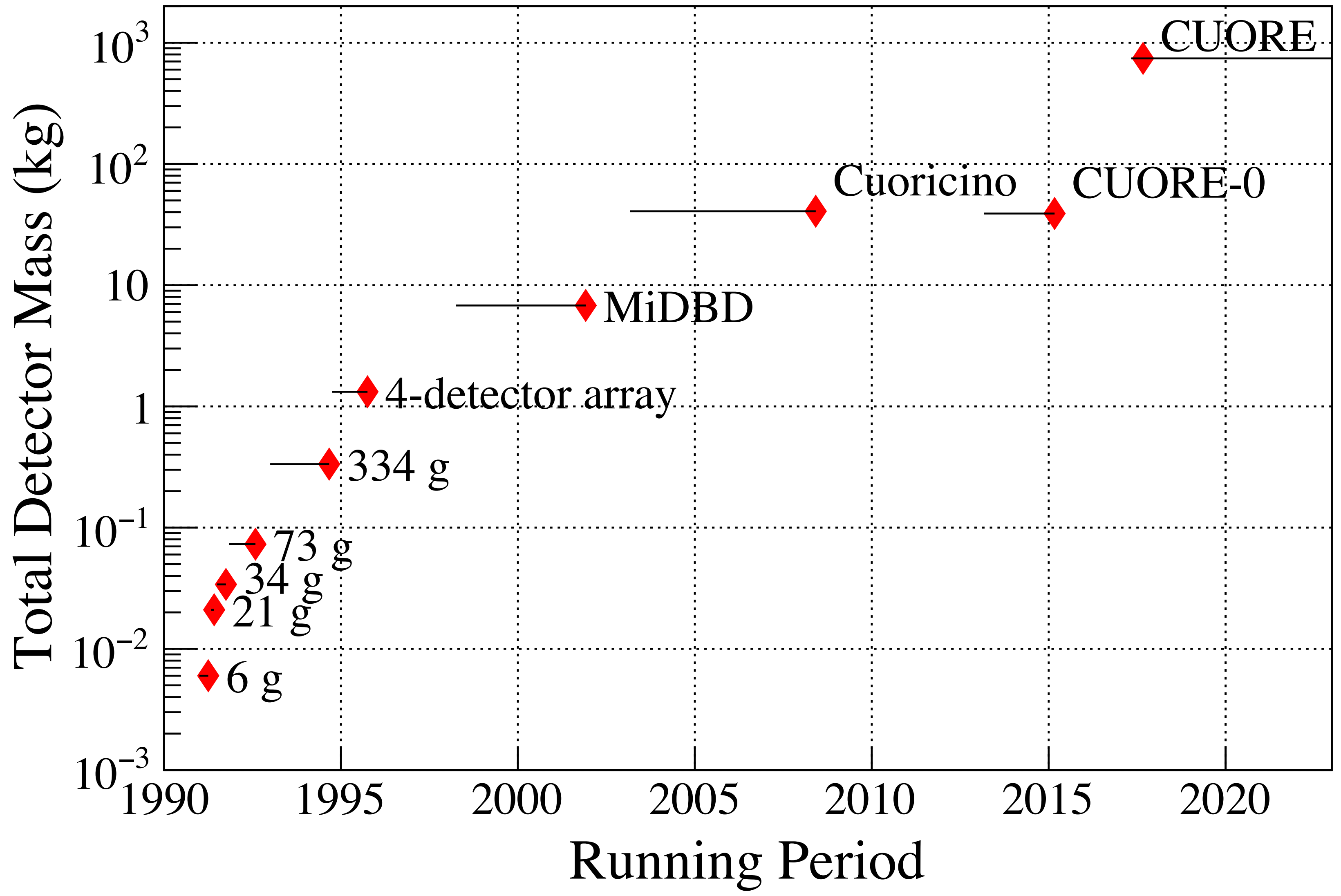
CUORE

- The Cryogenic Underground Observatory for Rare Events (CUORE) searches for $0\nu\beta\beta$ decay in ^{130}Te
- Located deep underground at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy
- Composed of 988 TeO_2 crystals (total mass of 742 kg, with 206 kg of ^{130}Te)
- 19 times the mass of the predecessor experiment CUORE-0
- Runs in a new custom-built cryostat with much lower backgrounds than CUORE-0

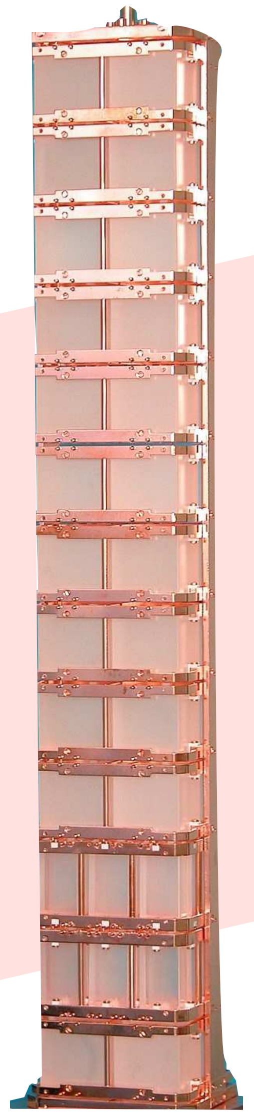


$$T^{0\nu}_{1/2} \text{ sensitivity} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

History



Cuoricino (2003–2008)



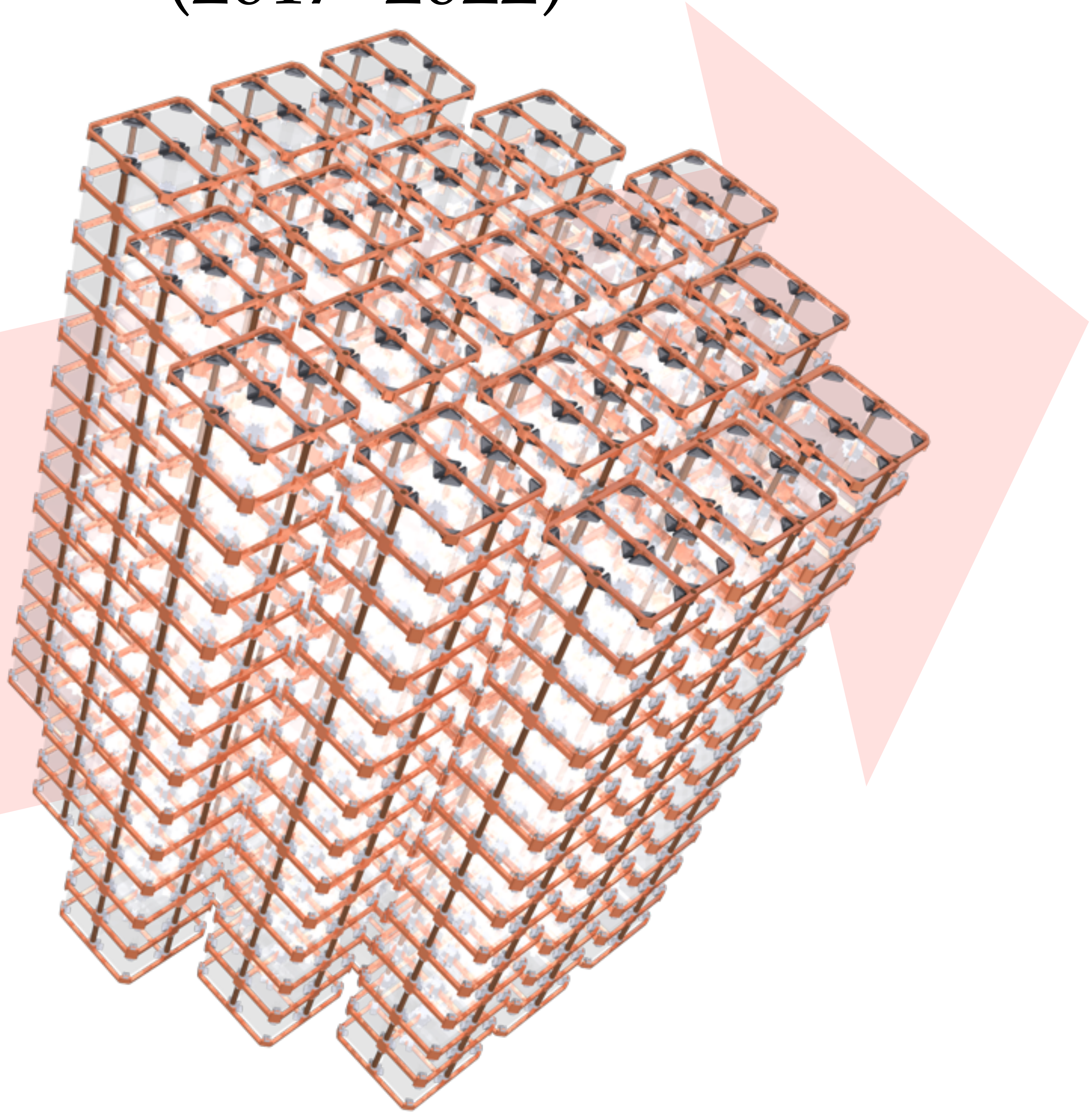
+

CUORE-0 (2013–2015)

$T_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24}$ **y (90% C.L.)**

Phys. Rev. Lett. **115**, 102502 (2015)

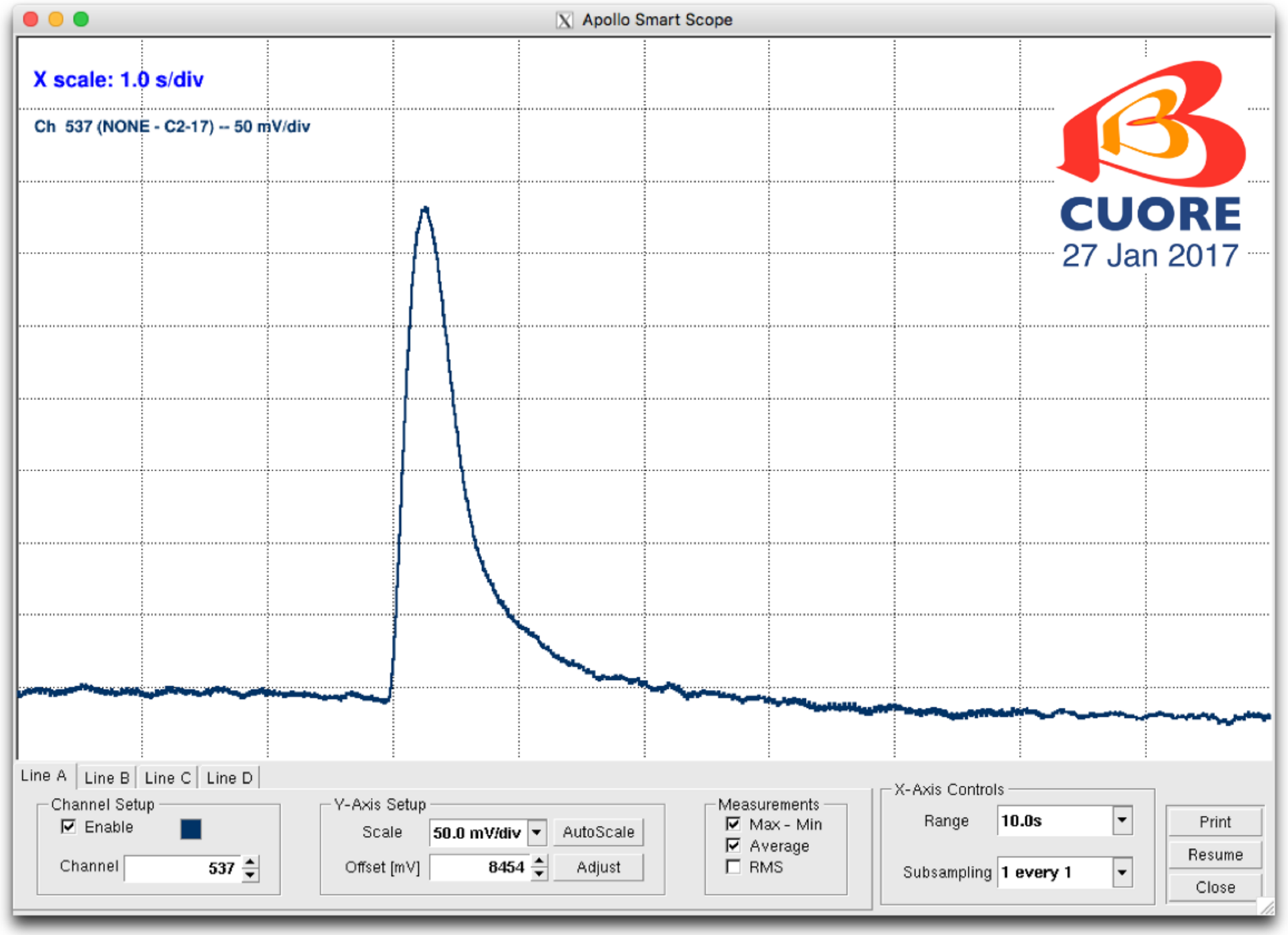
CUORE (2017–2022)

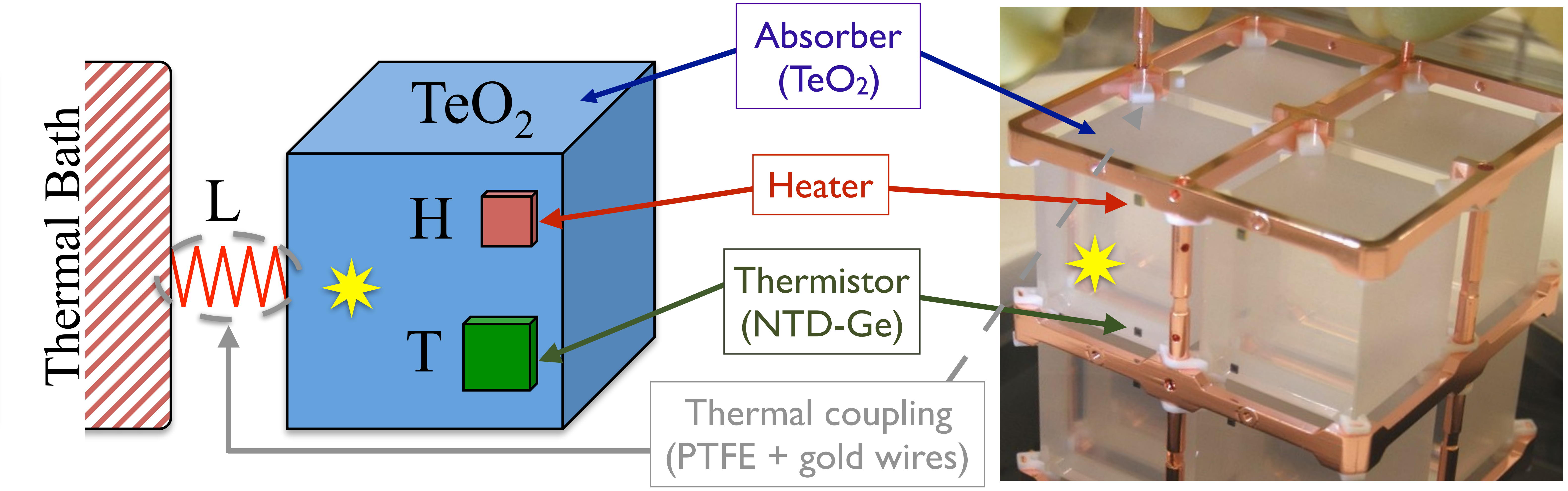


Projected:
$T_{1/2}^{0\nu\beta\beta} > 9 \times 10^{25}$ yr (90% C.L.)
$m_{\beta\beta} < 50 - 130$ meV

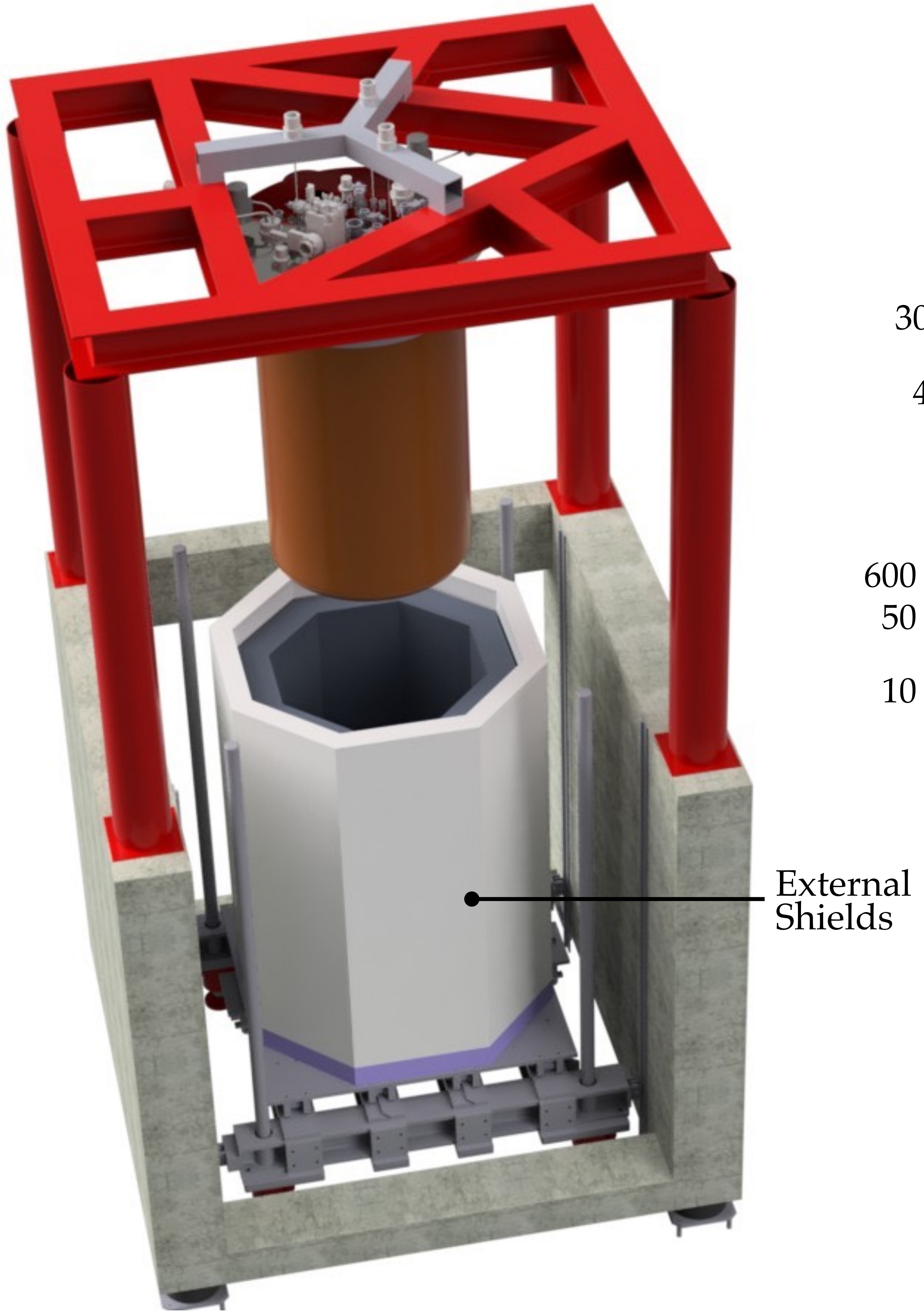
Bolometric detection

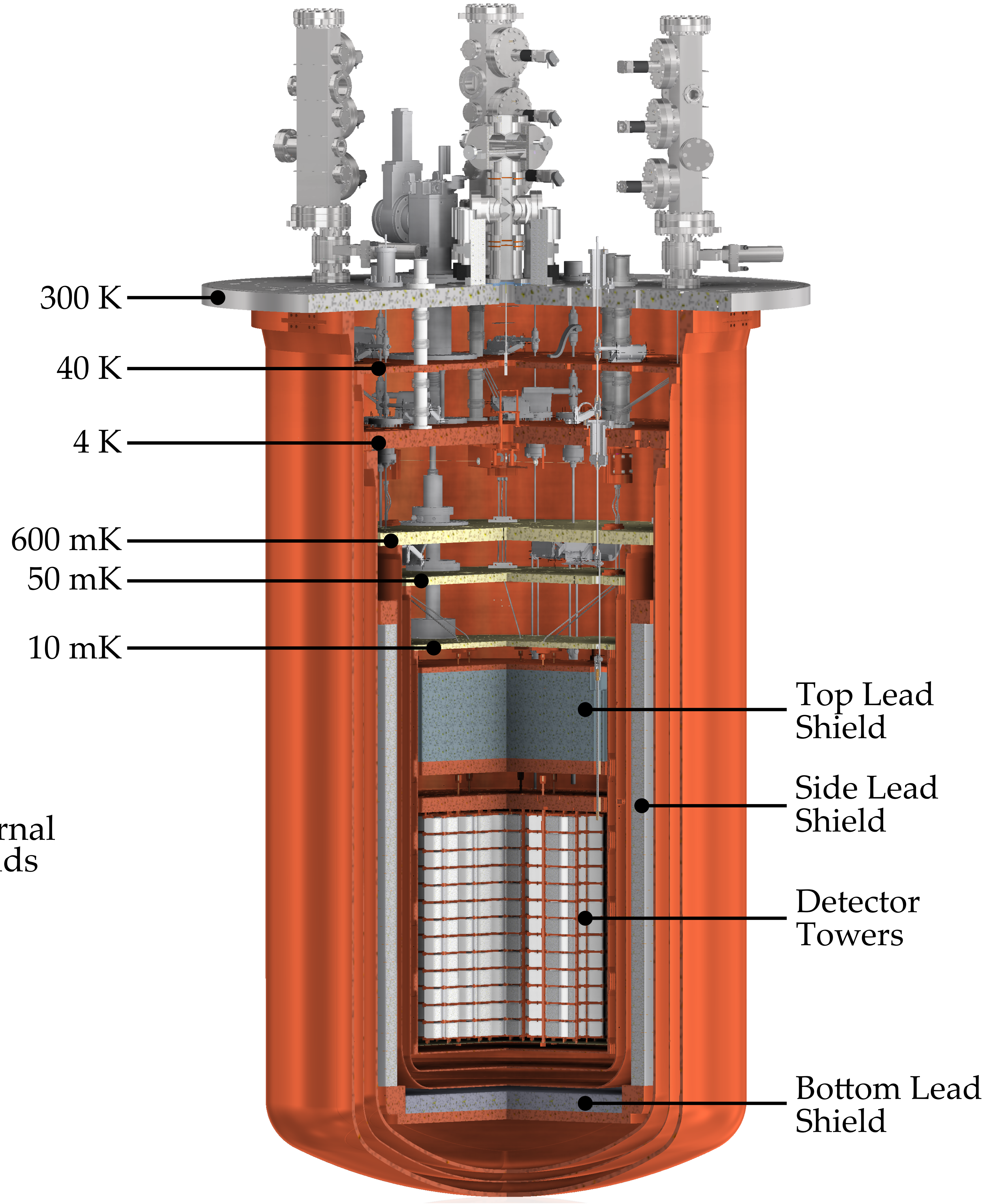
- Bolometers are operated at ~15 mK, so that single particle energy deposits cause a measurable spike in temperature
- Temperature is measured by measuring voltage across temperature-dependent resistors (thermistors)
- Each TeO_2 bolometer crystal is instrumented with a resistive heater and a neutron transmutation doped germanium (NTD-Ge) thermistor





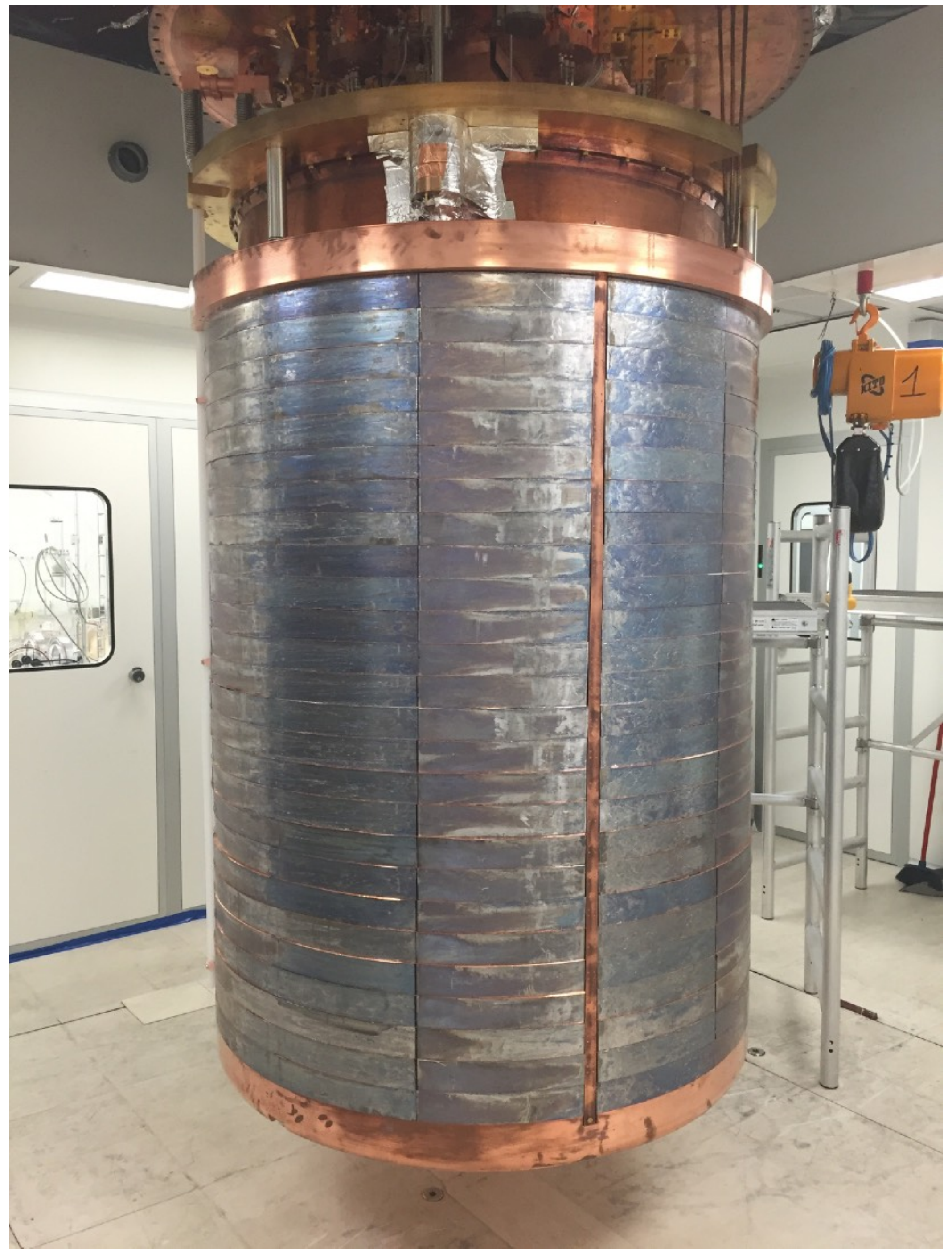
Cryostat and shielding





- Bolometers are assembled into towers and cooled by pulse-tube-assisted dilution refrigerator
- Detector towers are surrounded by copper and lead shields at successively colder temperatures
- Cryostat is surrounded by large lead shield and borated polyethylene neutron shield
- Side lead and bottom lead shields are ancient Roman lead

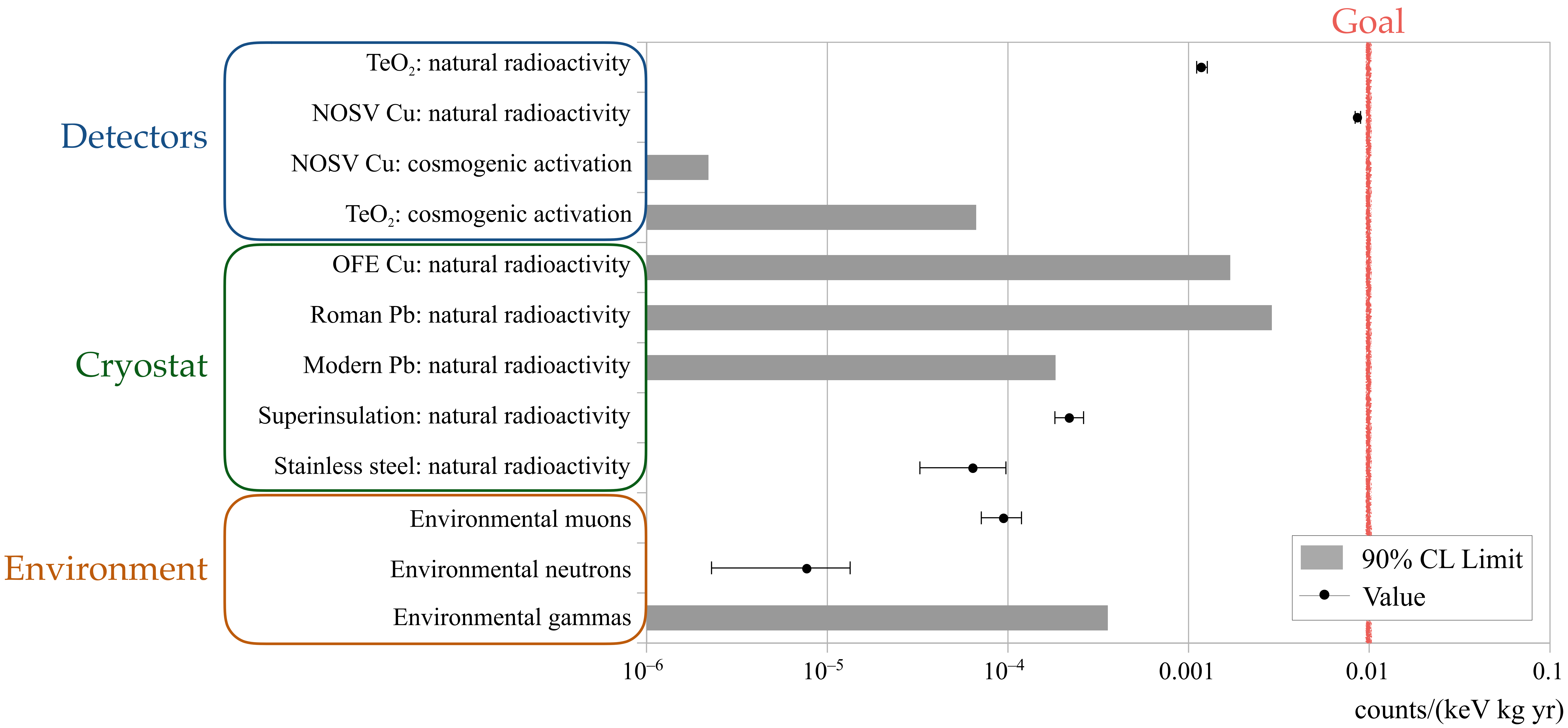
Ancient Roman lead



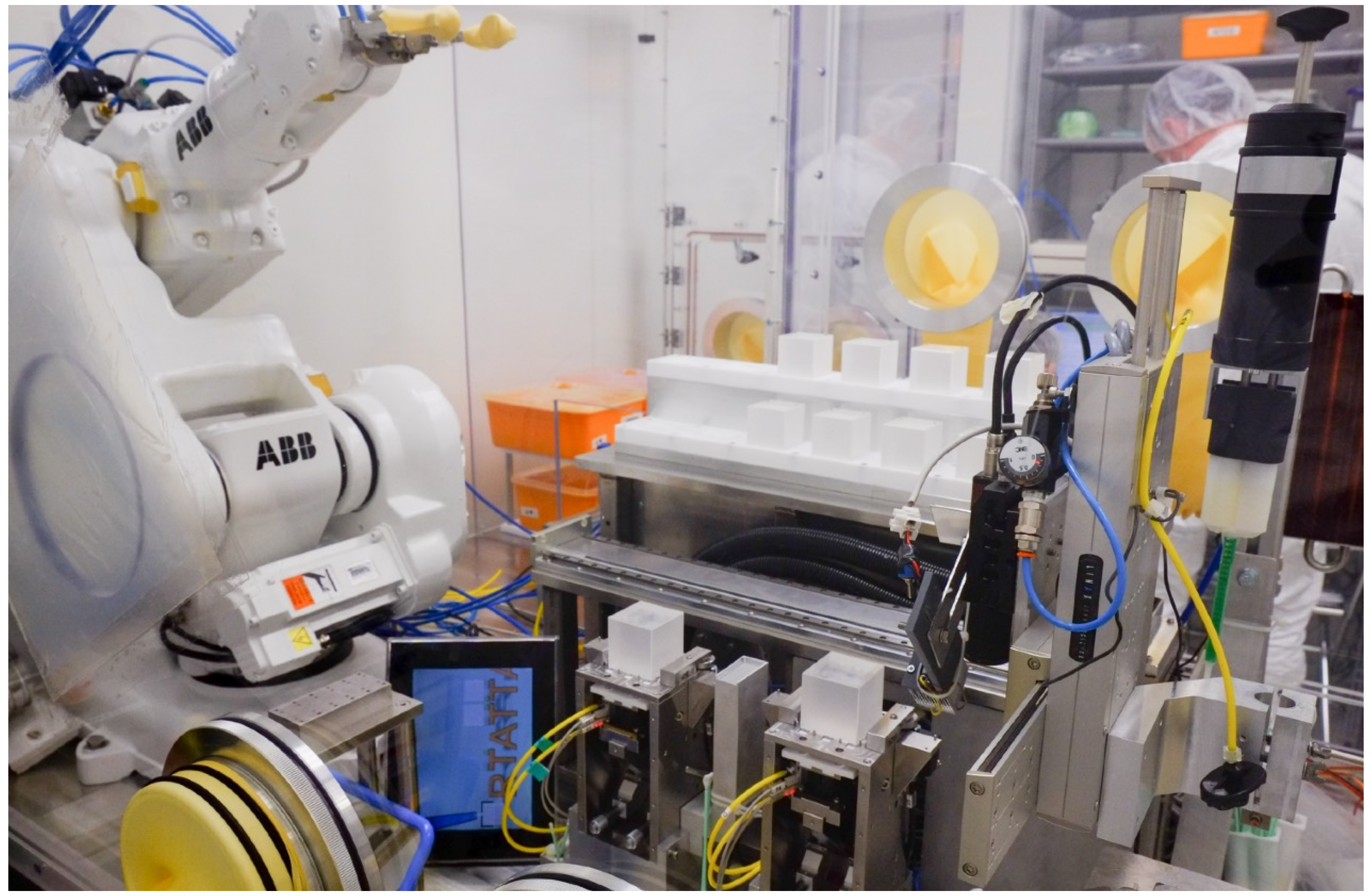
- Radioactive shielding can harm experiment as much as it helps
- All lead contains radioactive ^{210}Pb from the ^{238}U decay chain (^{210}Pb half-life = 22 years) when mined
- Ancient Roman lead recovered from shipwreck is used for CUORE

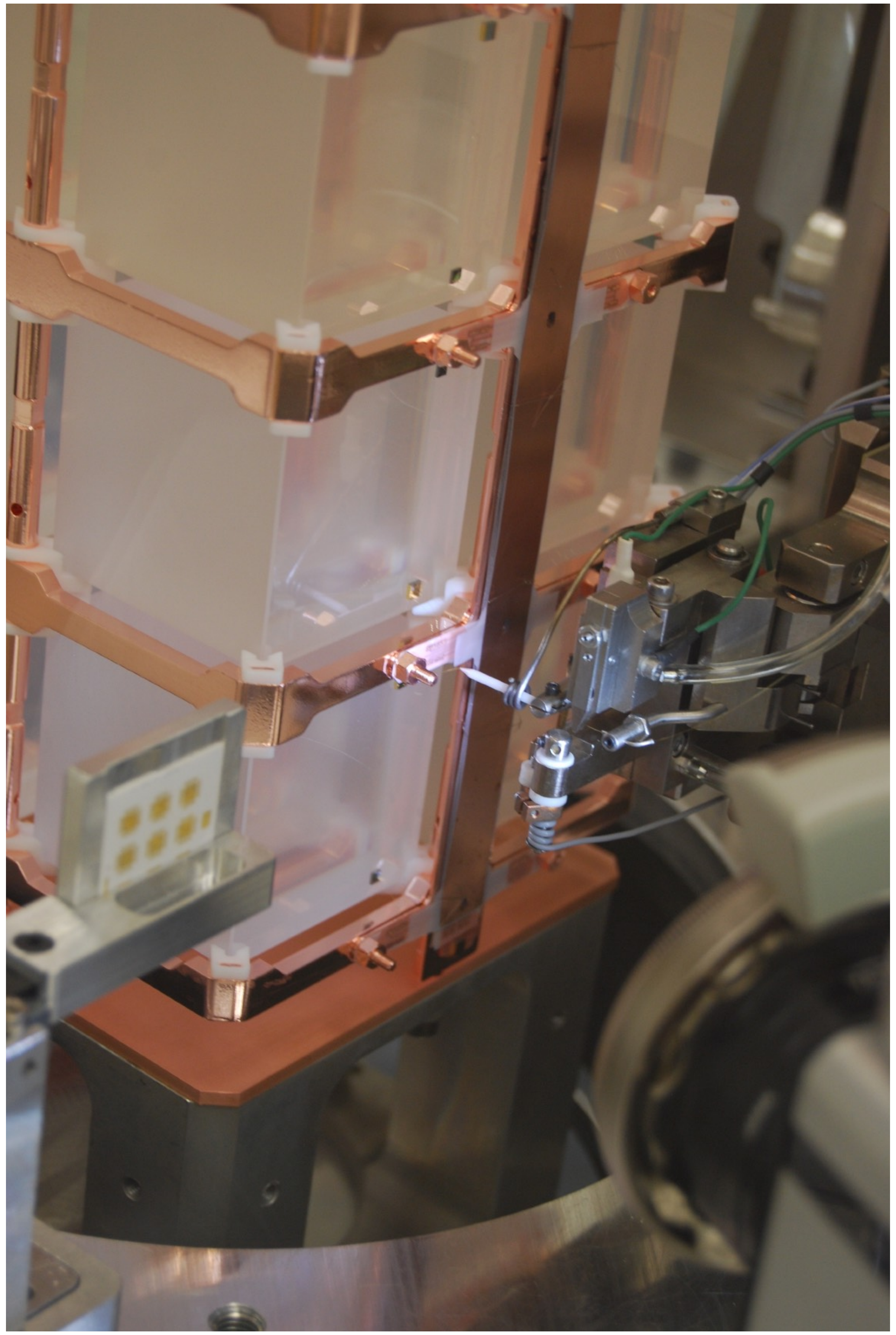
http://www.nature.com/news/2010/100415/full/news.2010.186.html

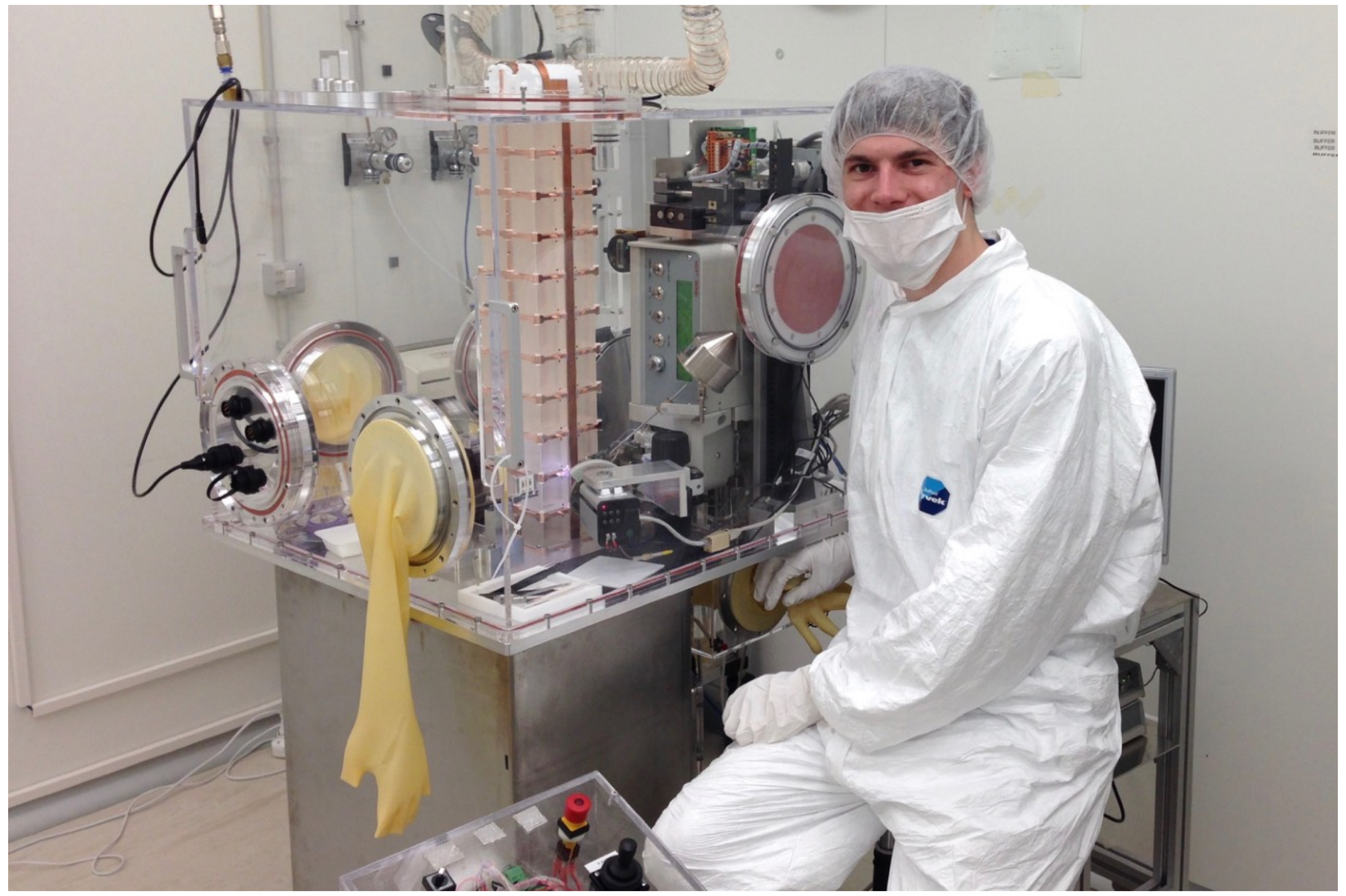
Projected backgrounds

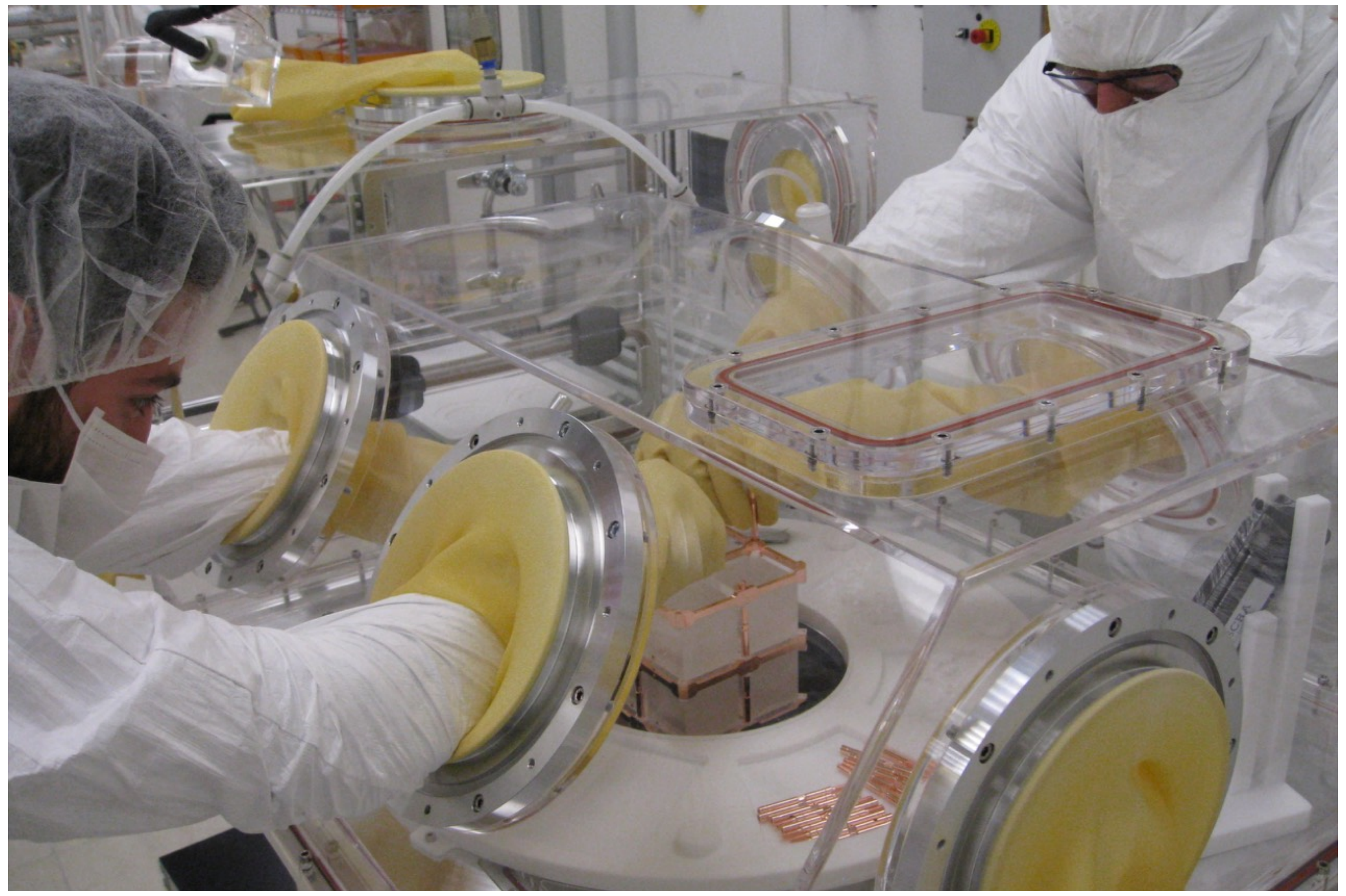


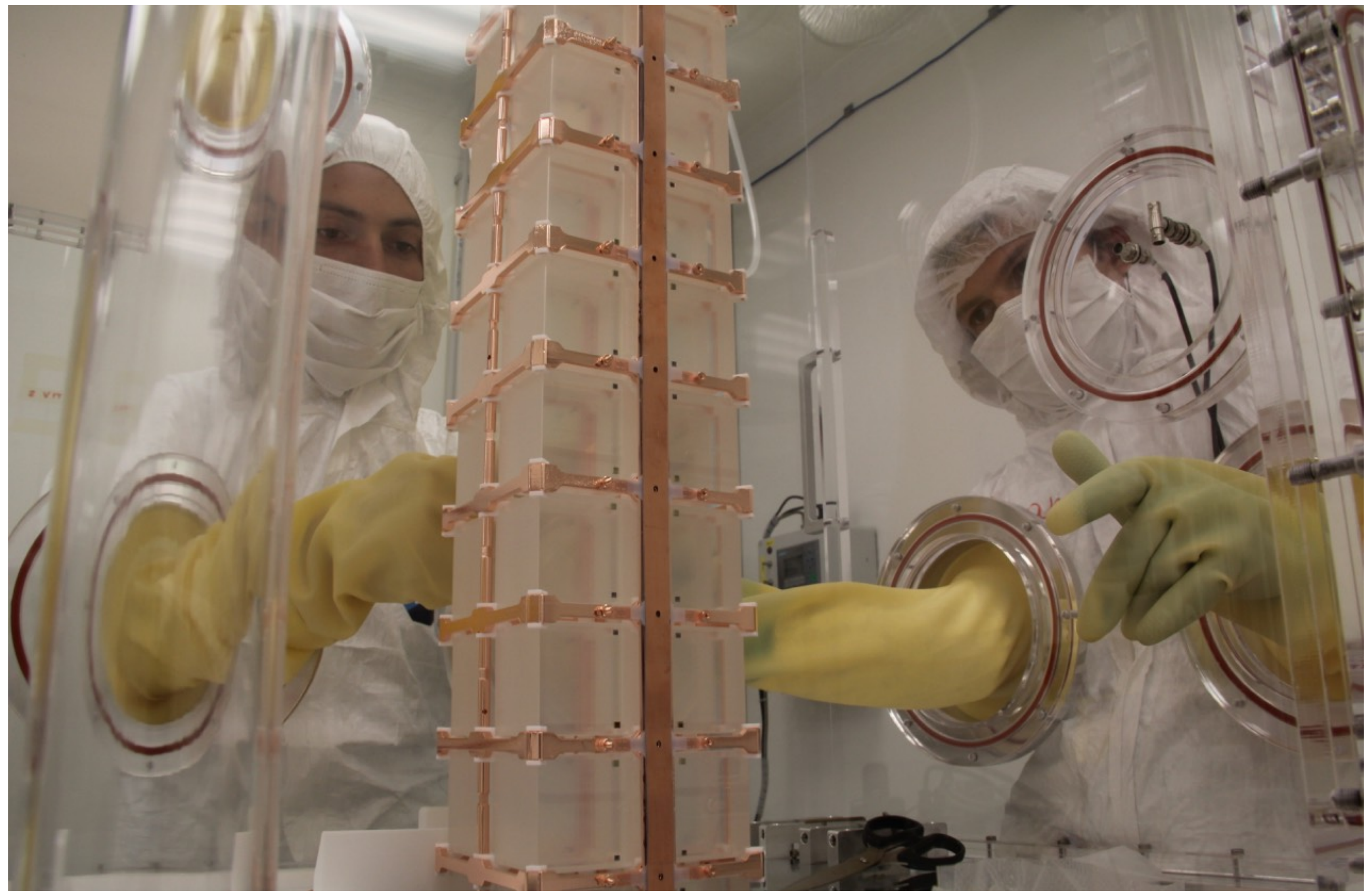
Building the detector towers



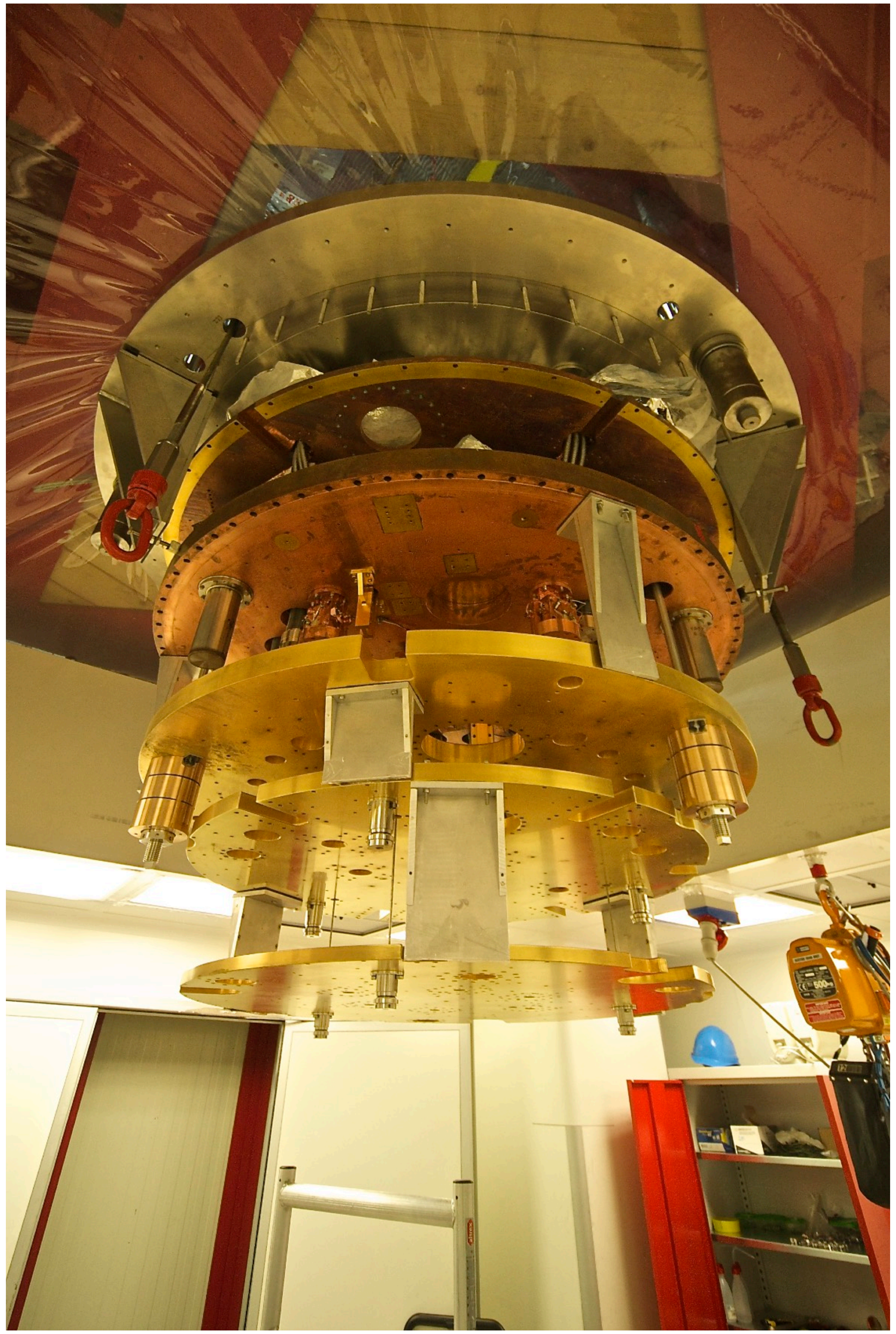




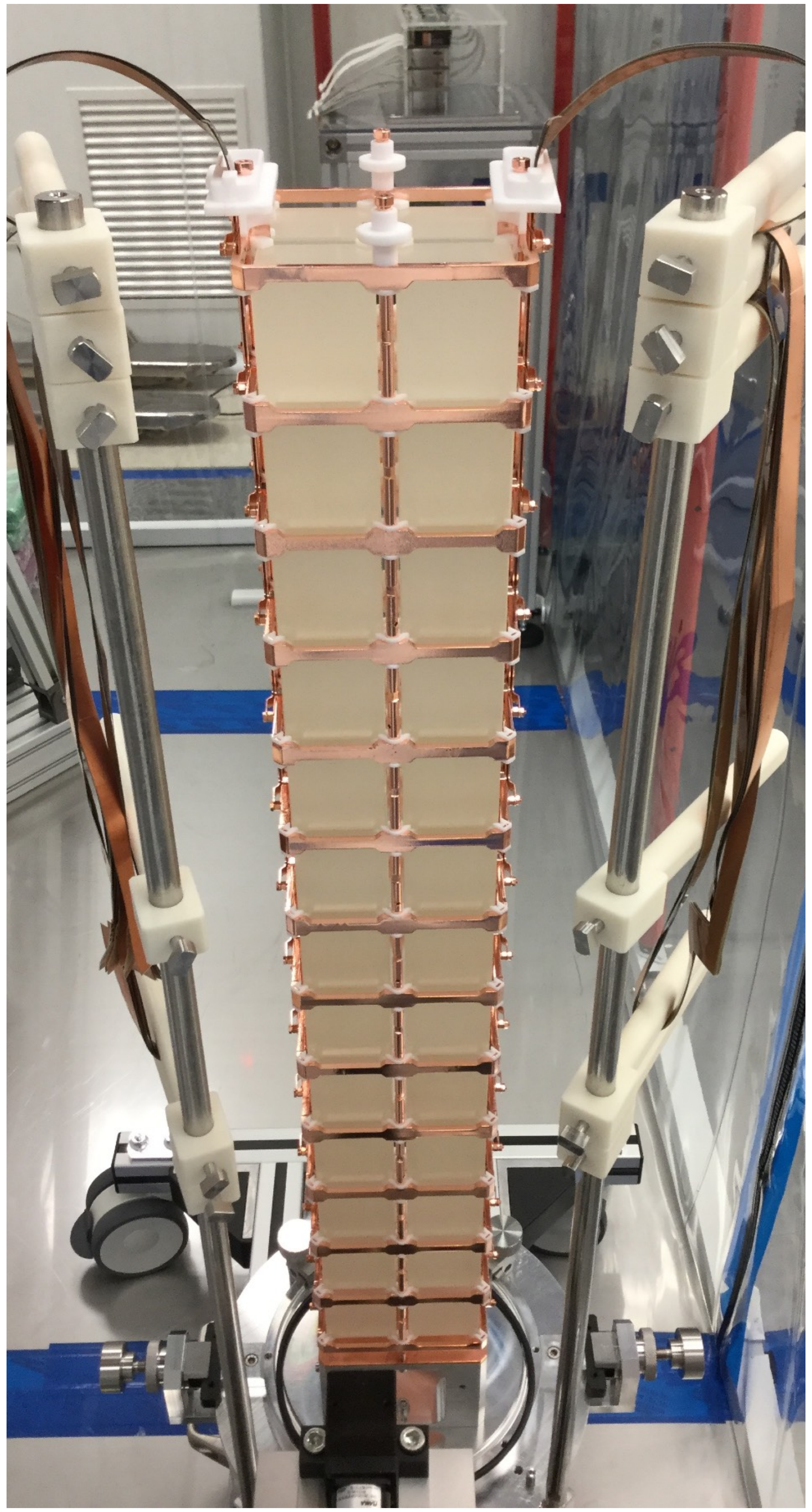


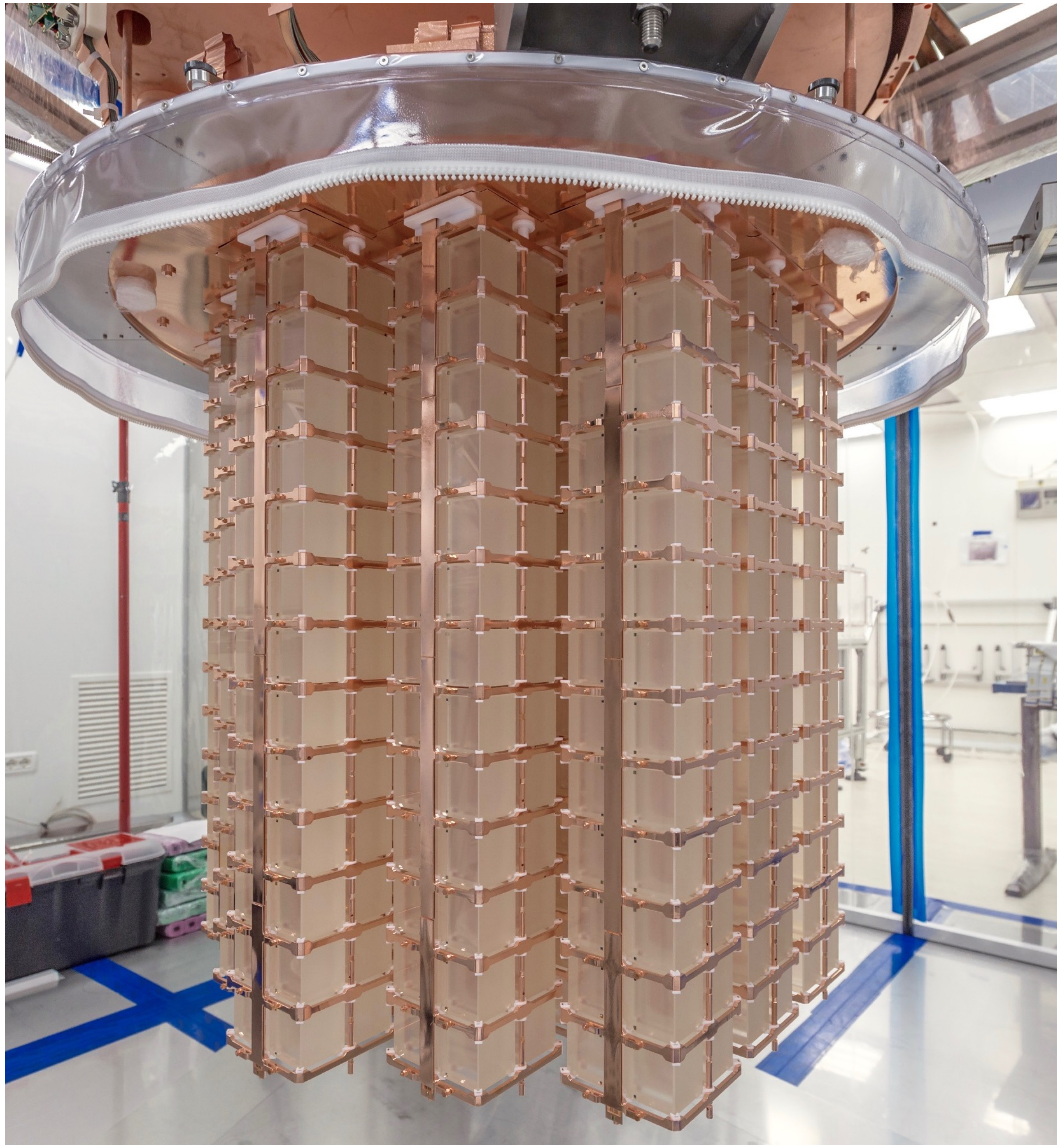


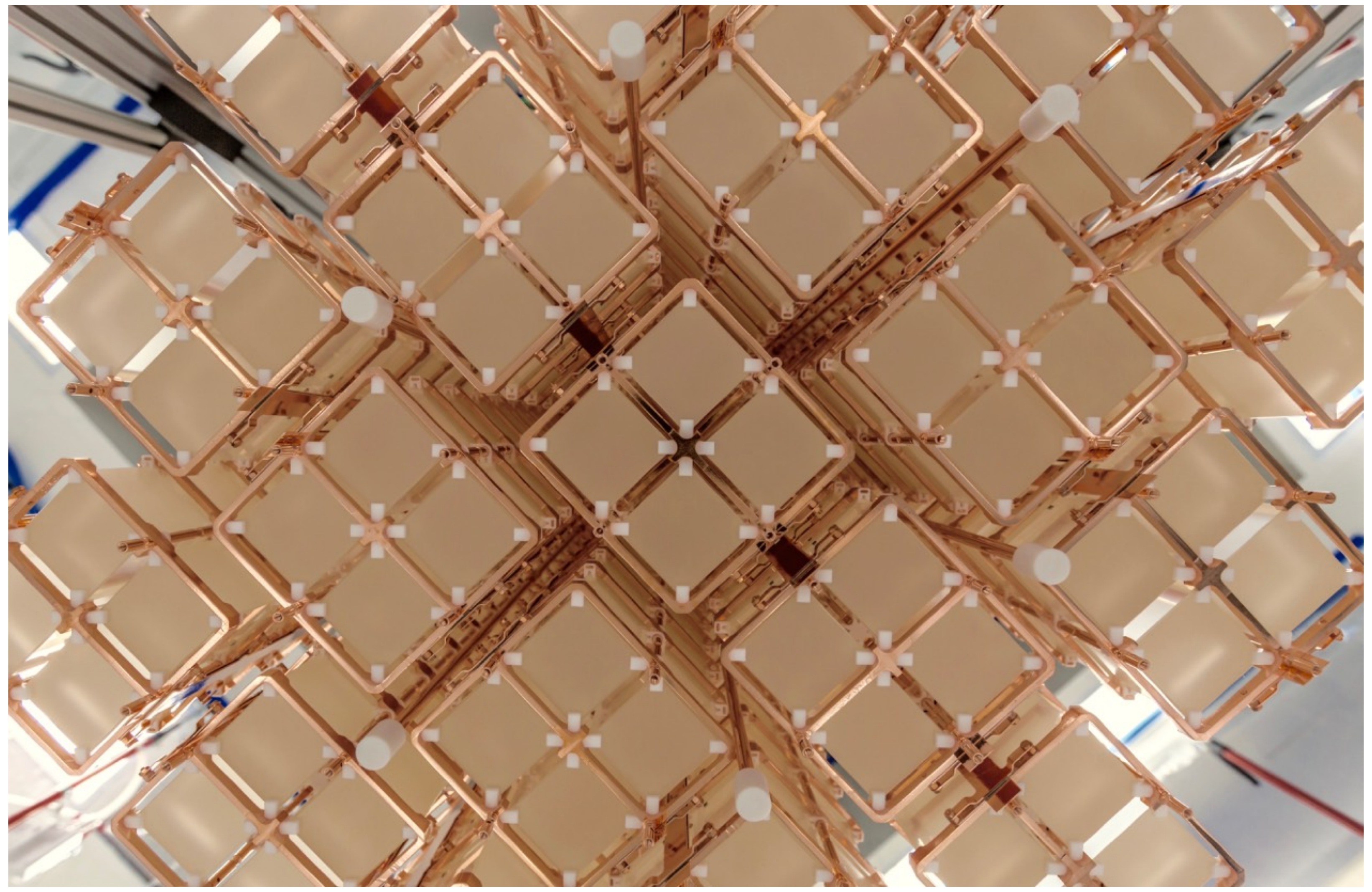
Building and commissioning the cryostat

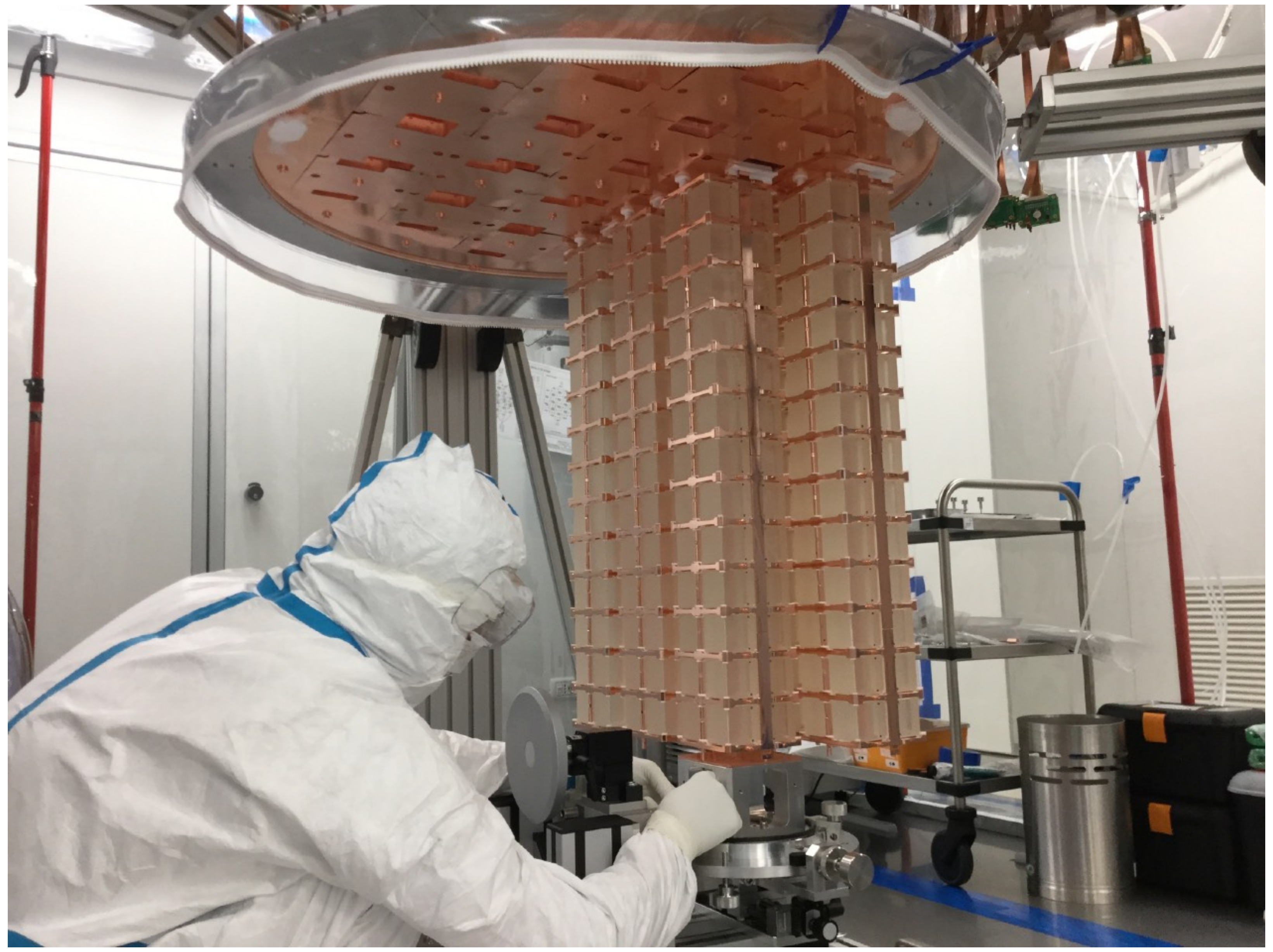


Installing the detectors









Wiring and electronics

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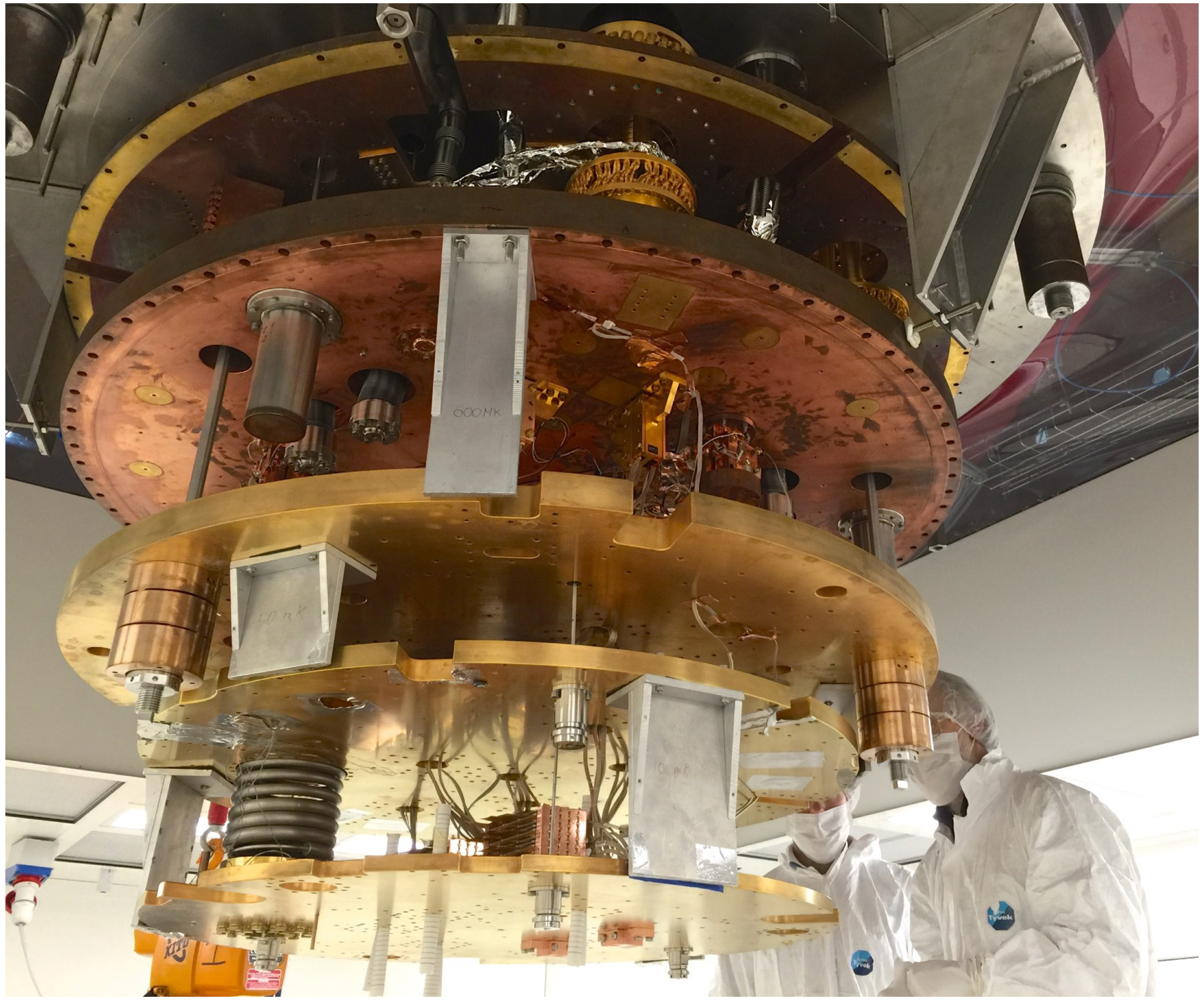
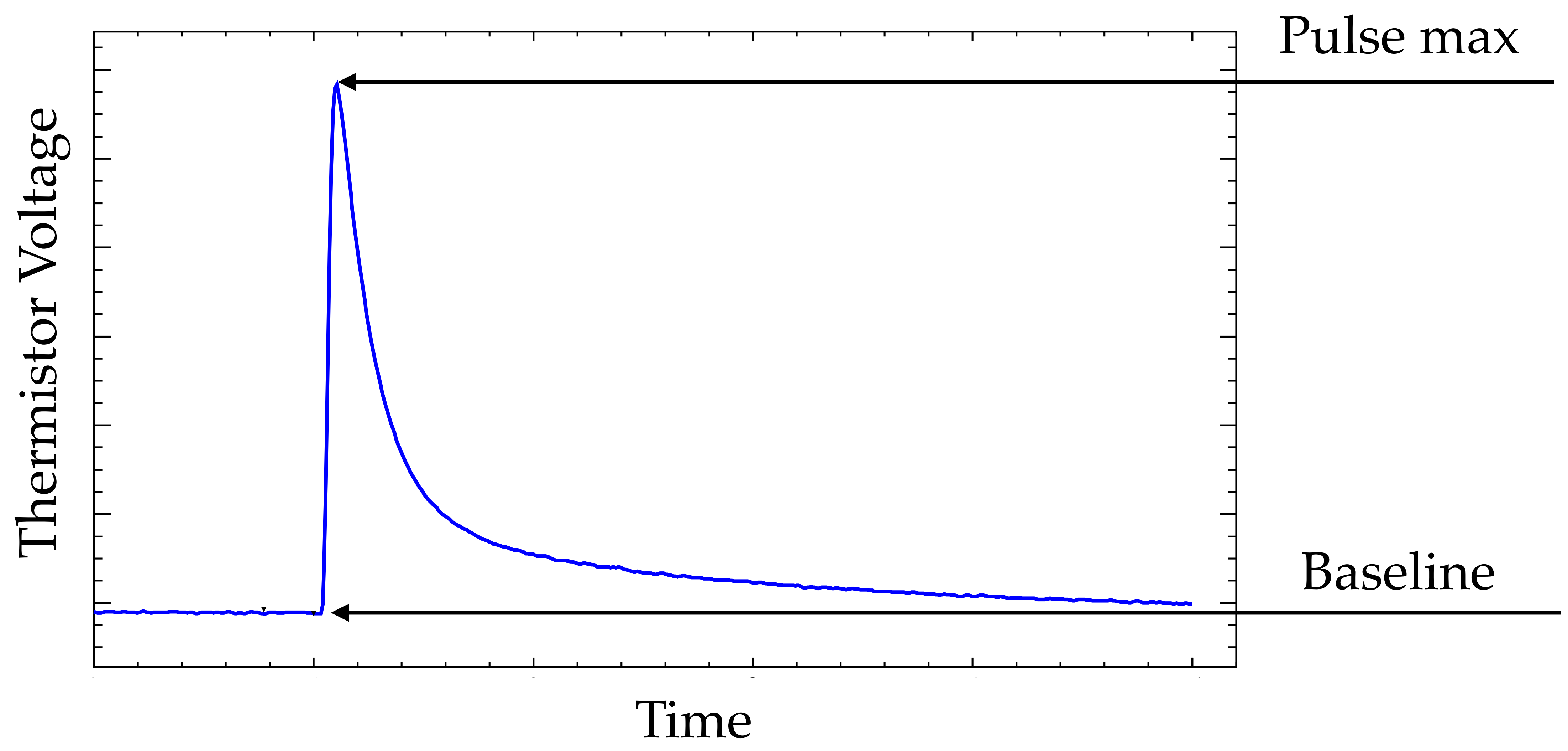


Calibration

- Voltage signals from the thermistors must be calibrated to determine the energy of each event
- CUORE only measures energy, so precise energy calibration is crucial

- A two-step calibration process is used:
  1. The thermistor gain is stabilized over time
  2. Thermistor readings are calibrated to absolute energies



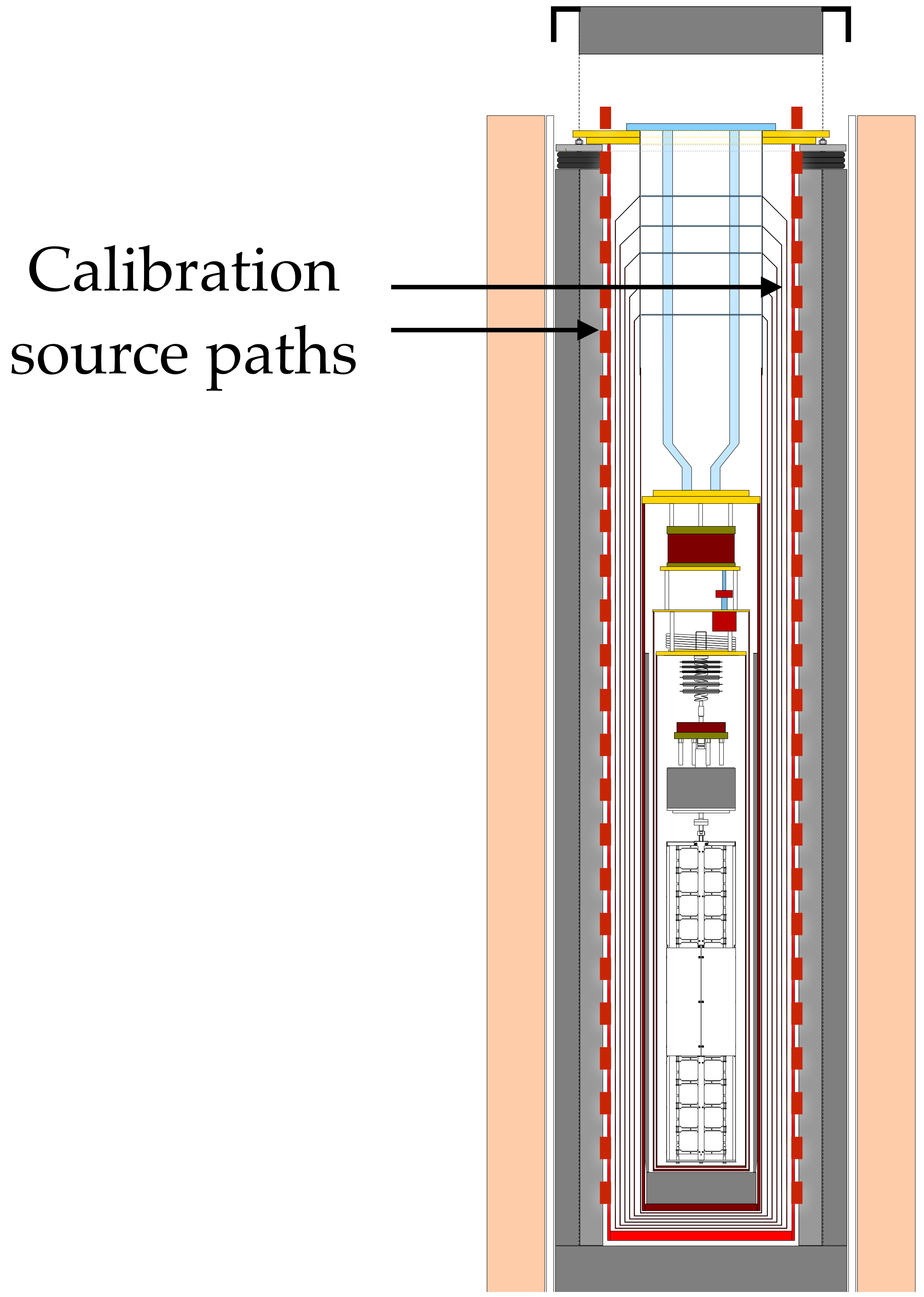
$\rightarrow$ E = ? keV

Calibration hardware

- Bolometers require independent *in situ* energy calibration
  - Bolometers must be calibrated at their operating temperature
  - Moving sources into position must not affect bolometer temperature
- We need to preserve ultraclean conditions for physics data taking
  - Calibration sources must be visible to detectors only during calibration
  - Background contribution of calibration hardware must be low
- Procedure must be stable over expected 5-year lifetime of the experiment

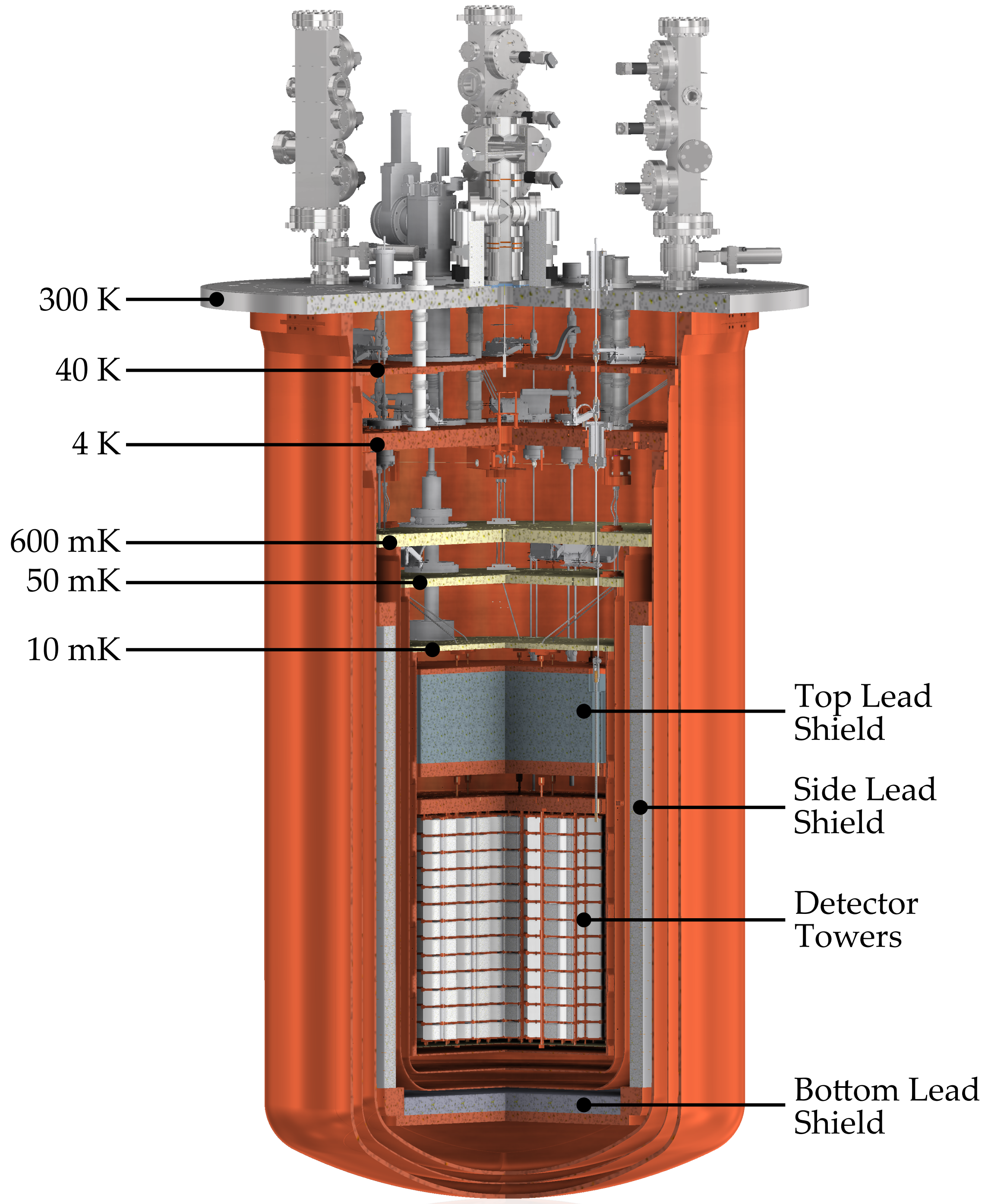
Calibration hardware

CUORE-0



- Only one tower
- Sources can be placed outside cryostat but inside shielding
- Sources can be positioned by hand

CUORE



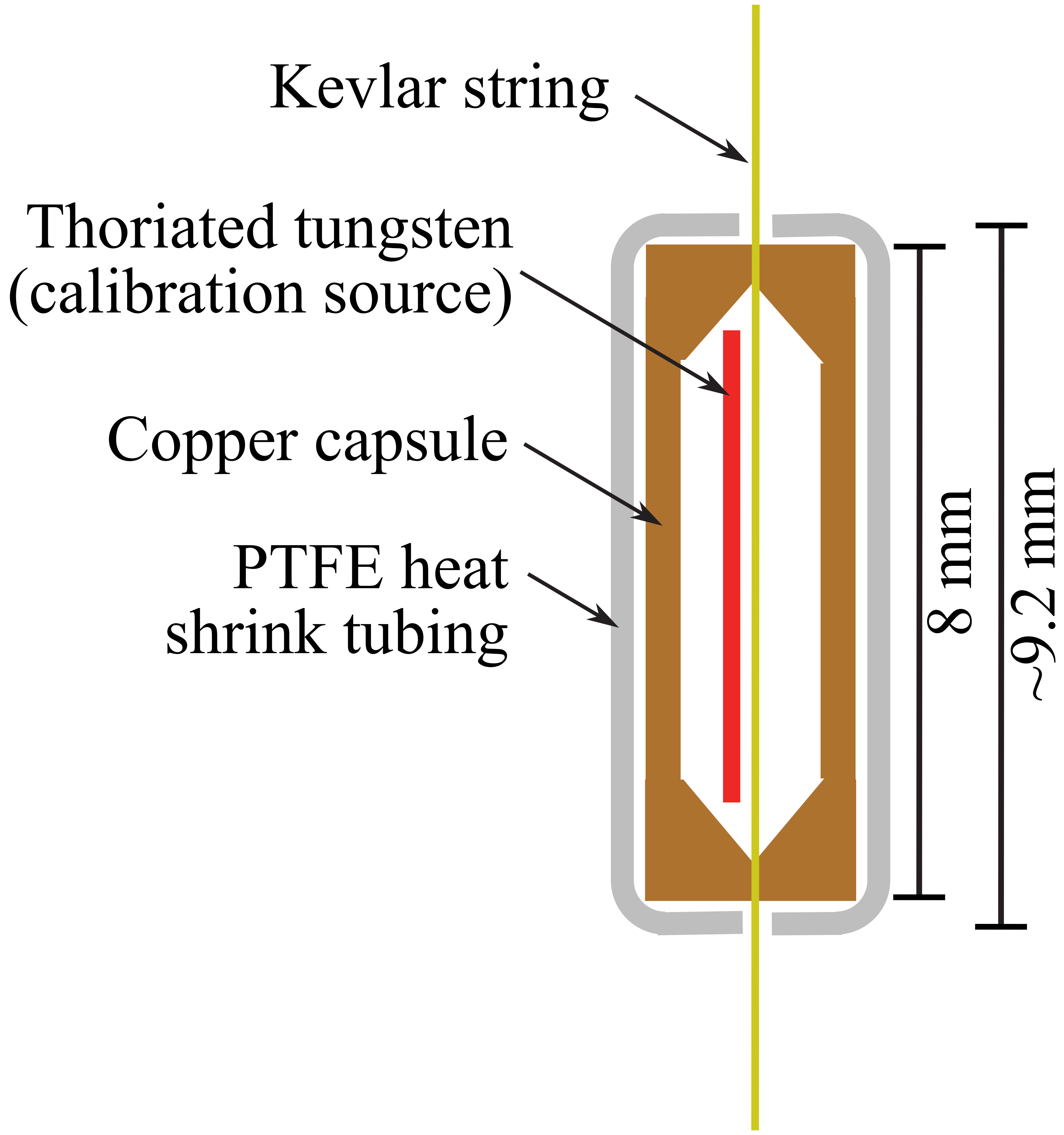
- Outer towers shield inner towers
- Sources must be cold and placed among towers inside cryostat
- Source deployment must be automated
- J. S. Cushman *et al*. NIM A **844**, 32-44 (2017)

Calibration strings

- Twelve source strings are lowered into the cryostat during calibration periods
- Cooled from 300 K to the bolometer operating temperature of ~15 mK

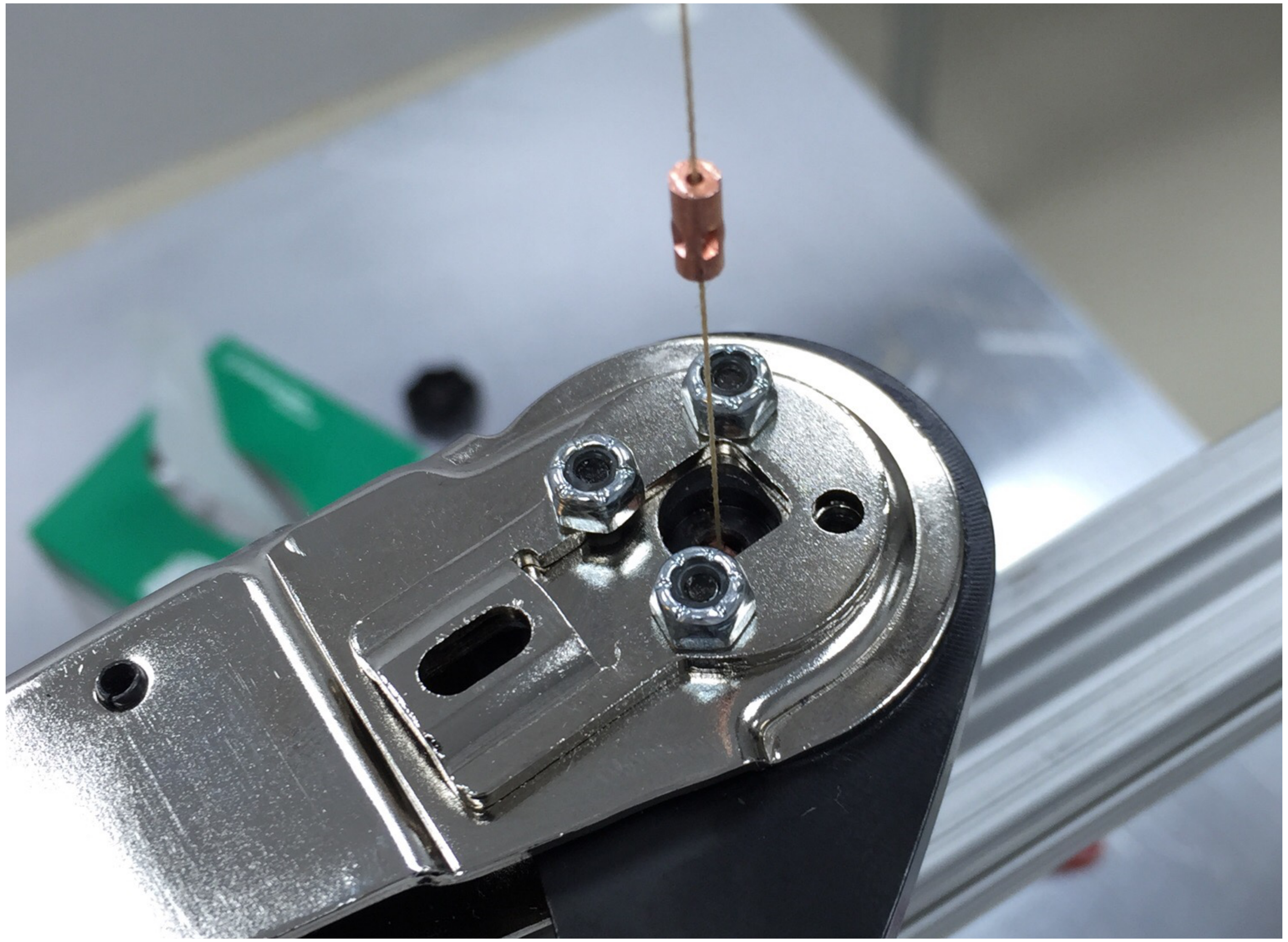
Each source string contains:

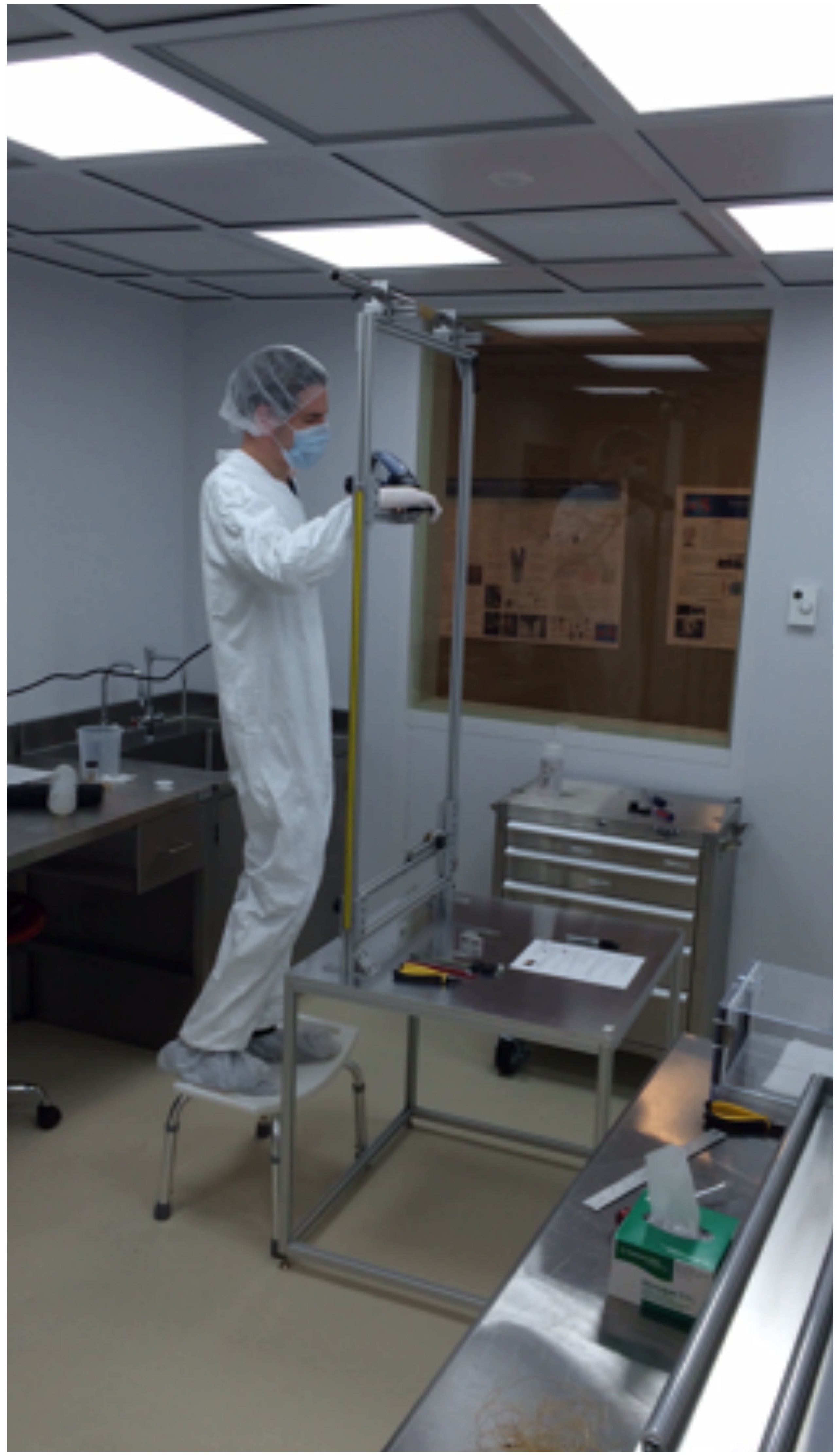
- 25 or 26 source capsules of thoriated tungsten wire (containing ^{232}Th)
- 8 weight capsules
- 1 PTFE guide ball

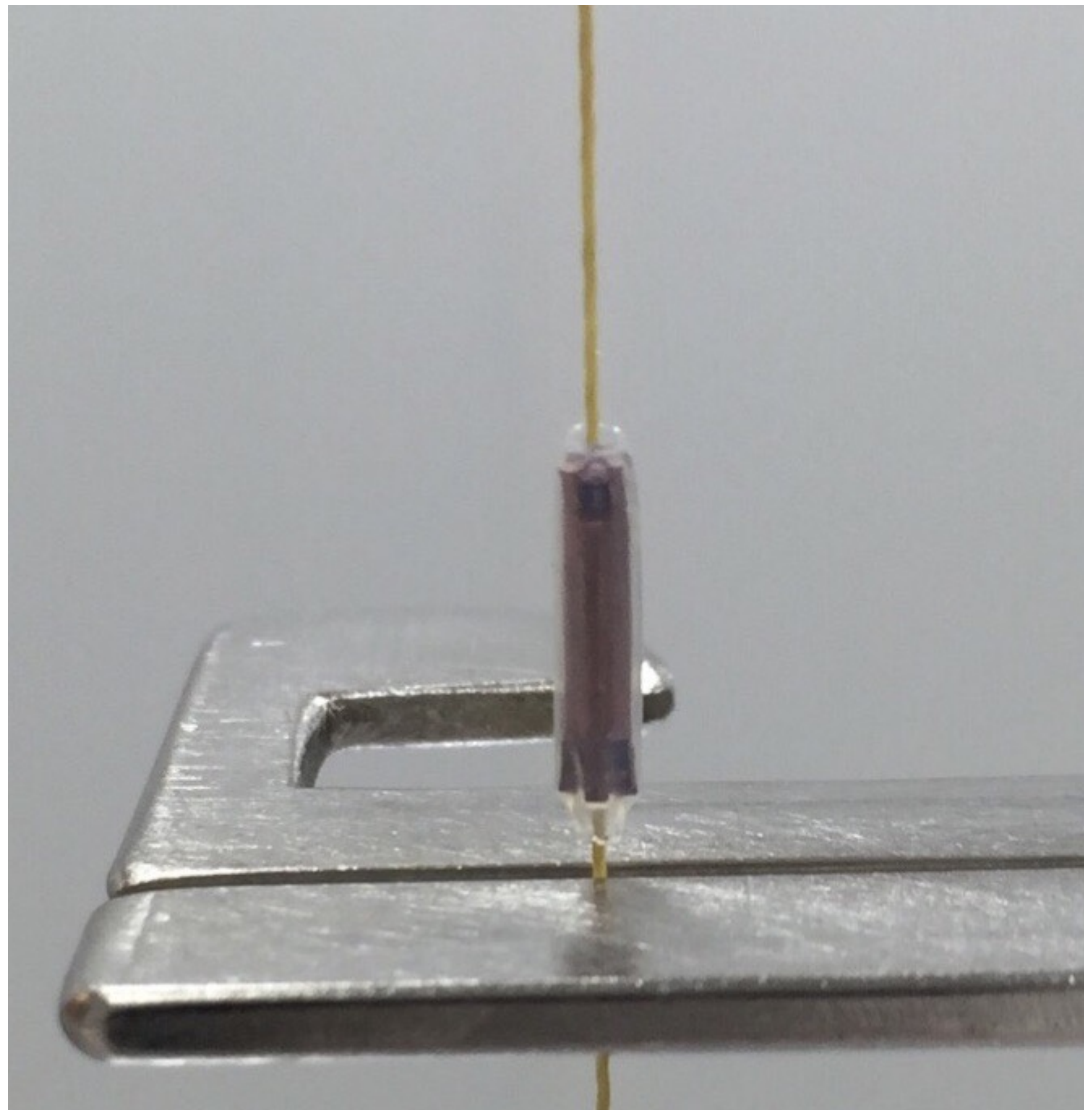


String production

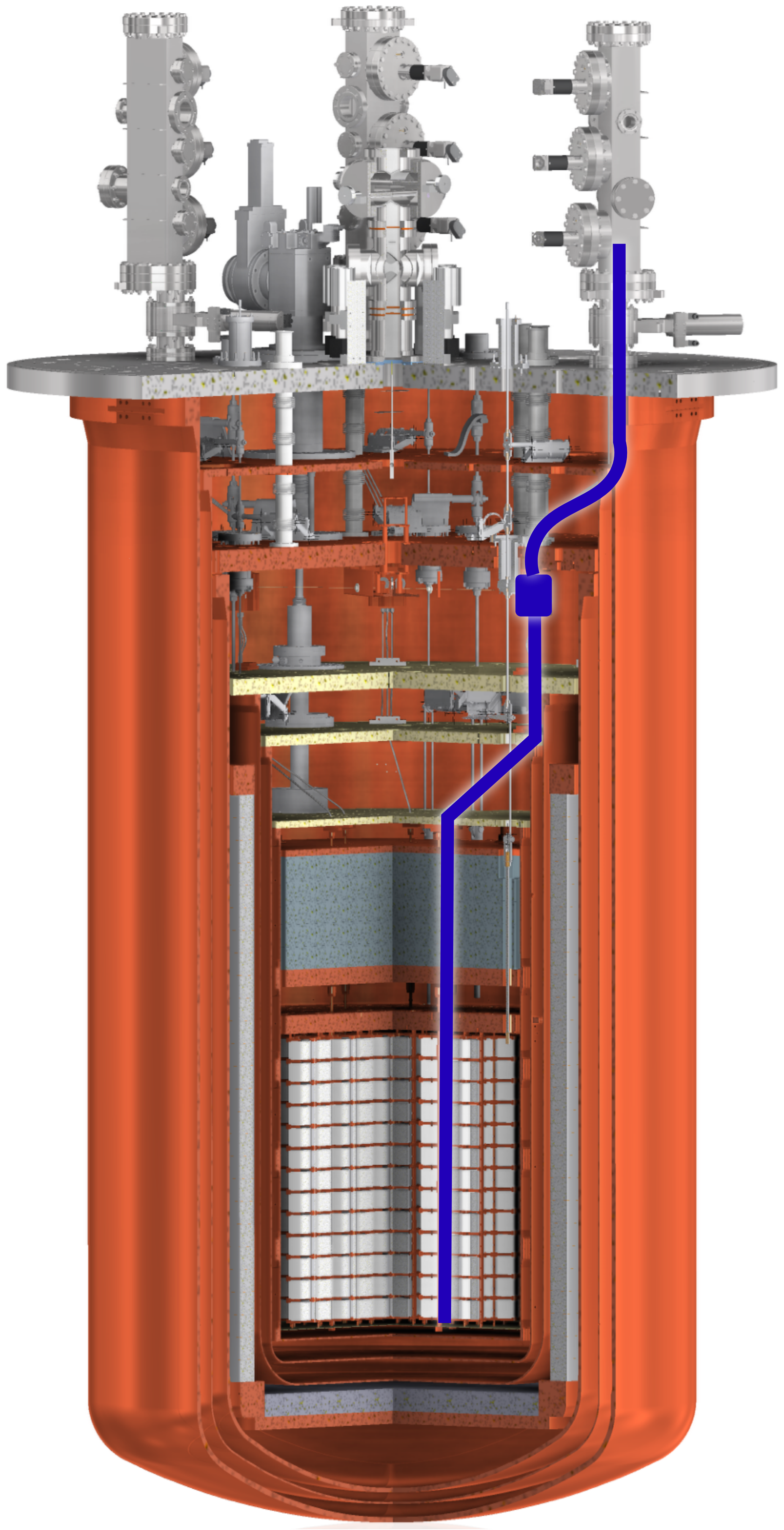
Sources produced at
UW-Madison and Yale







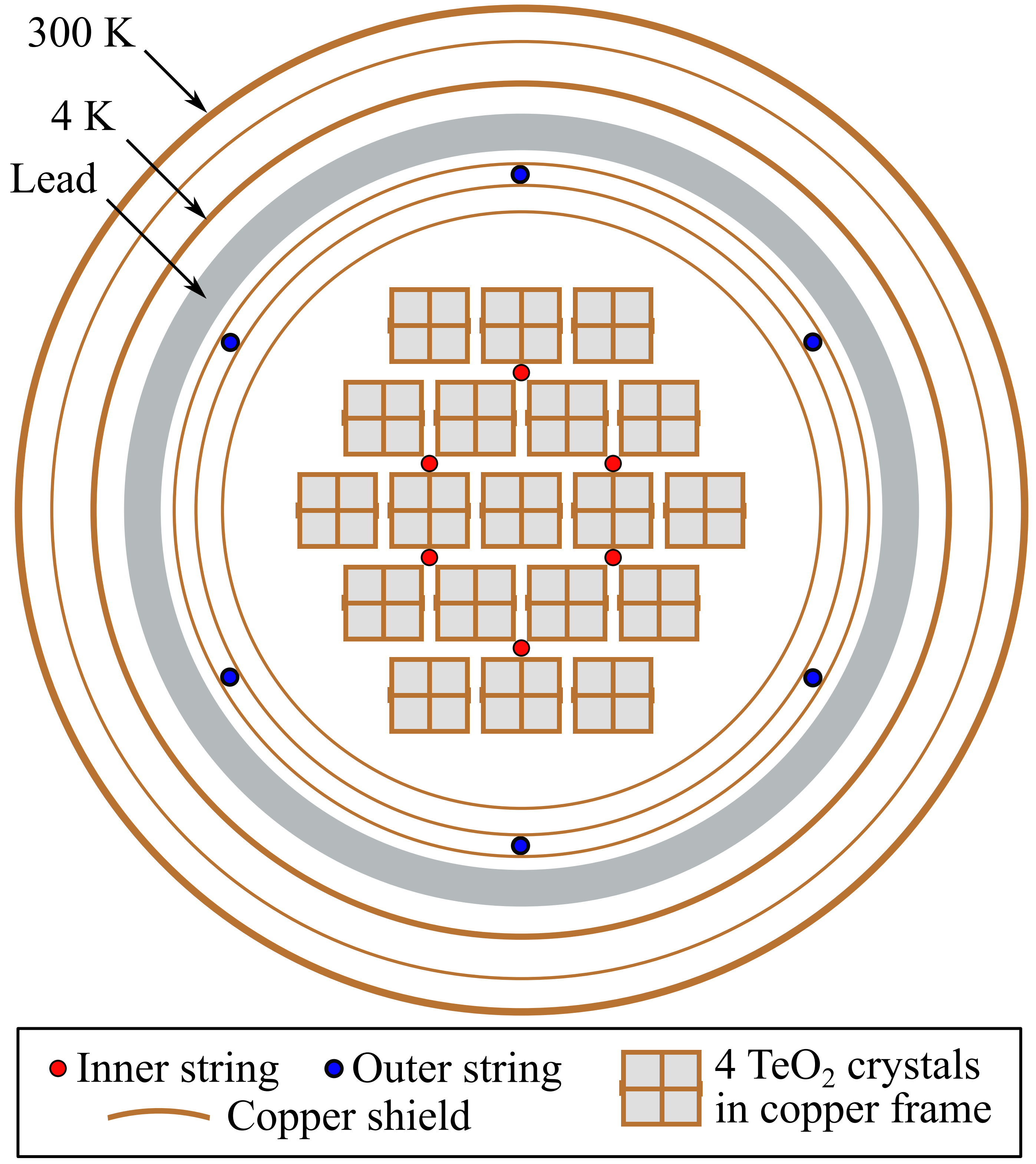
Calibration source deployment



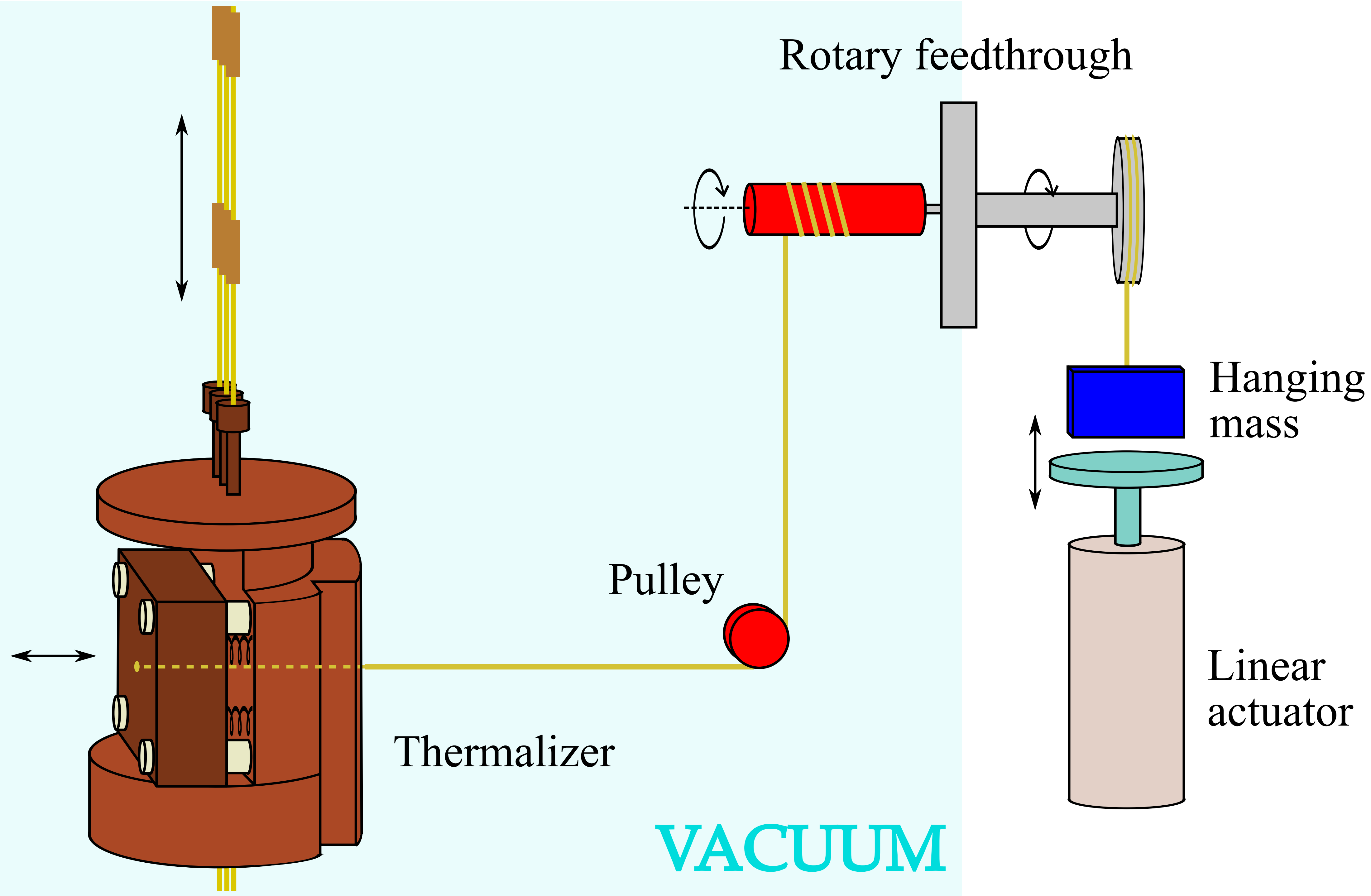
Strings are lowered under their own weight through a series of guide tubes

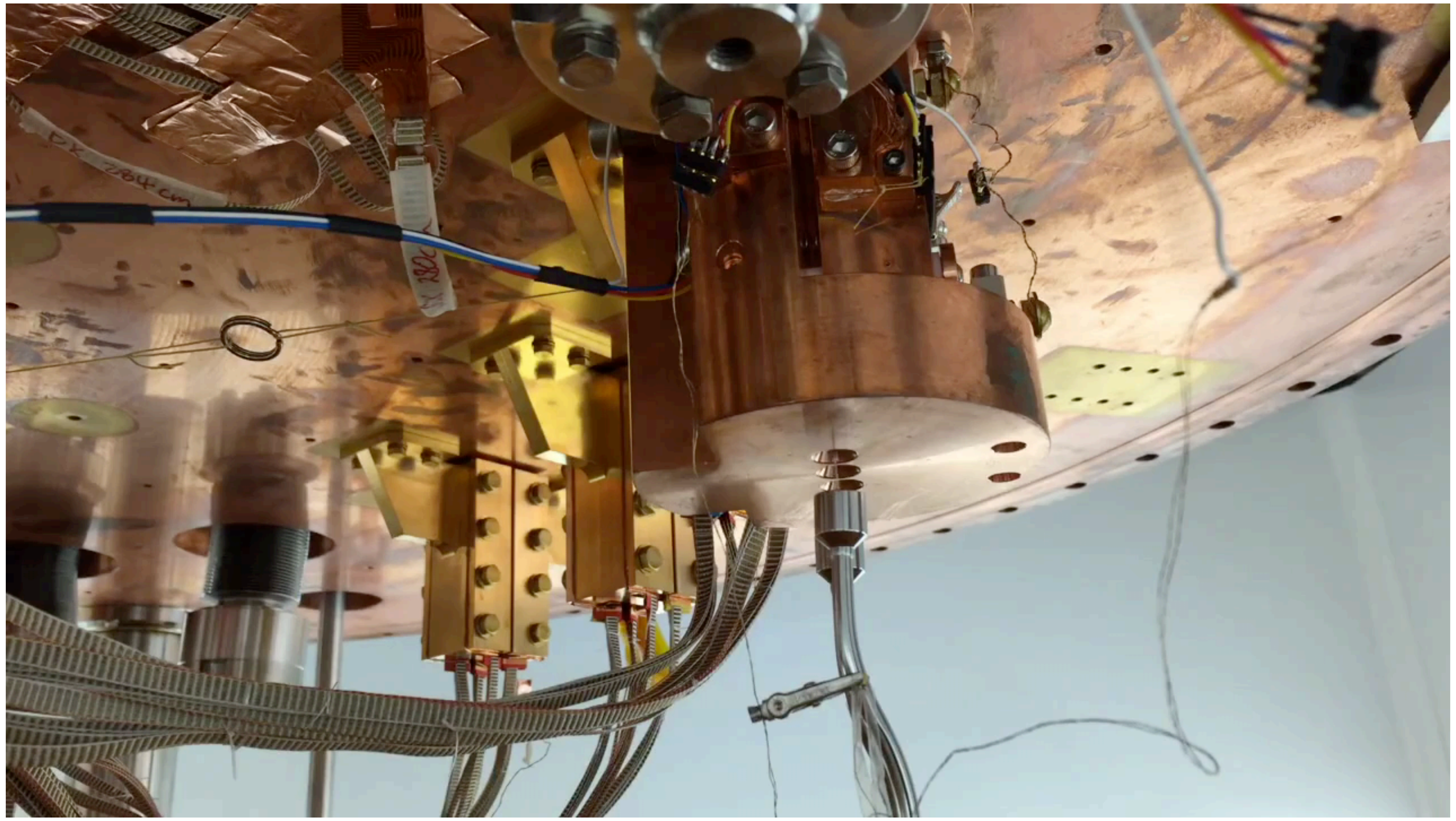
6 inner source strings
- 3.5 Bq each
- Guided between the bolometer towers to illuminate the inner detectors

6 outer source strings
- 19.4 Bq each
- Guided to outside of 50 mK vessel to illuminate outer detectors



4-K Thermalization

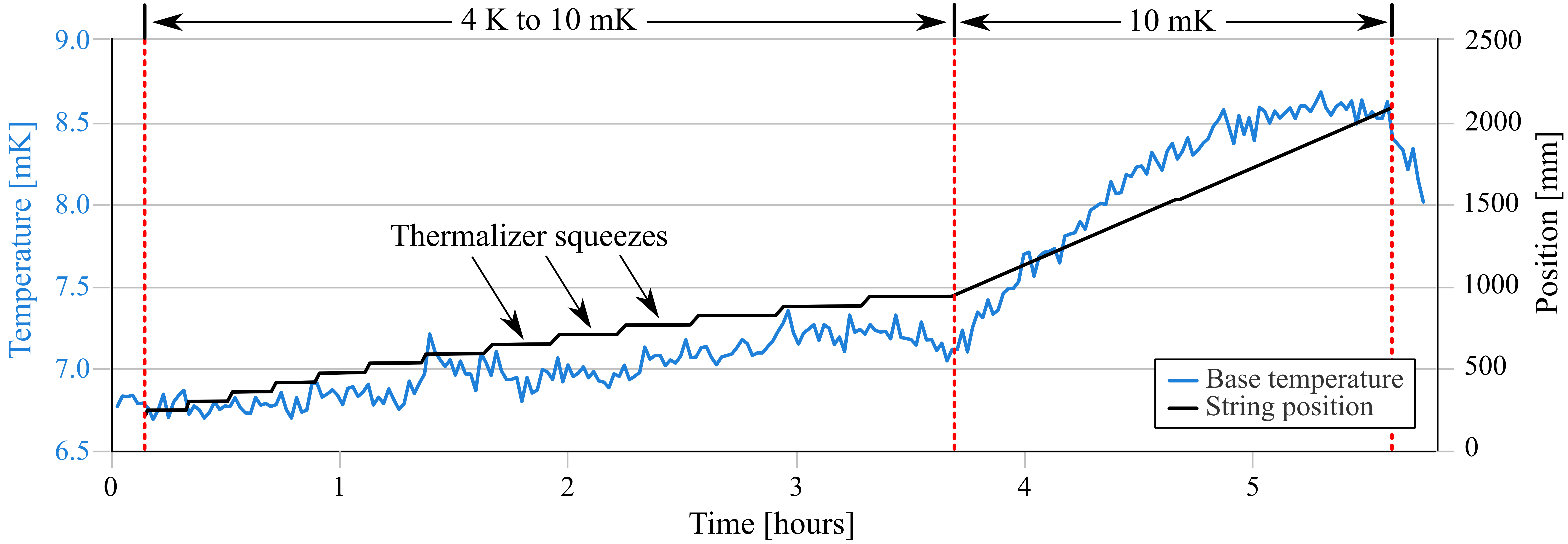




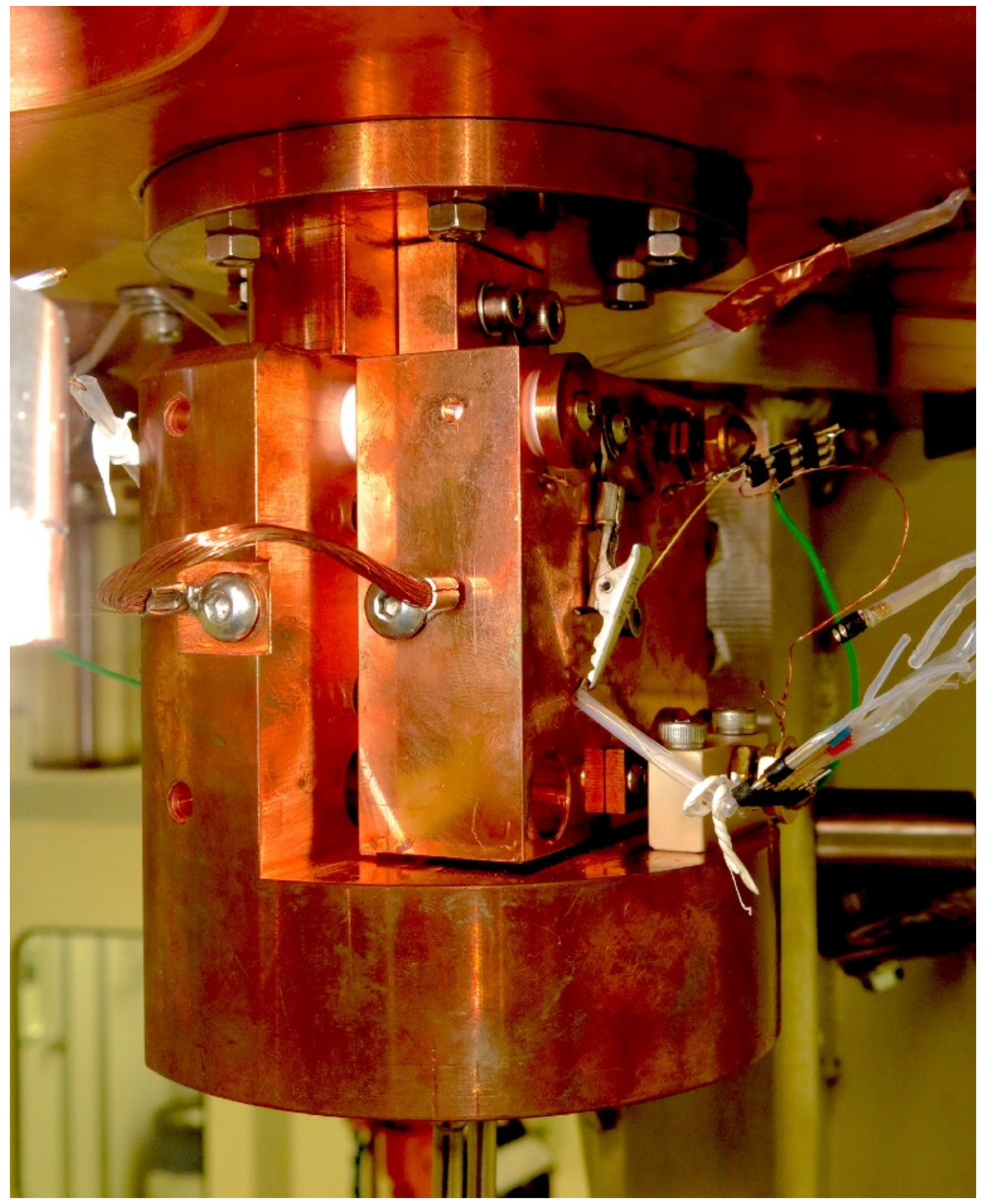
- Source capsules are fully thermalized at 4 K before being lowered further into the cryostat
- 4 K stage is cooled by pulse tube cryocoolers and thus has significant cooling power

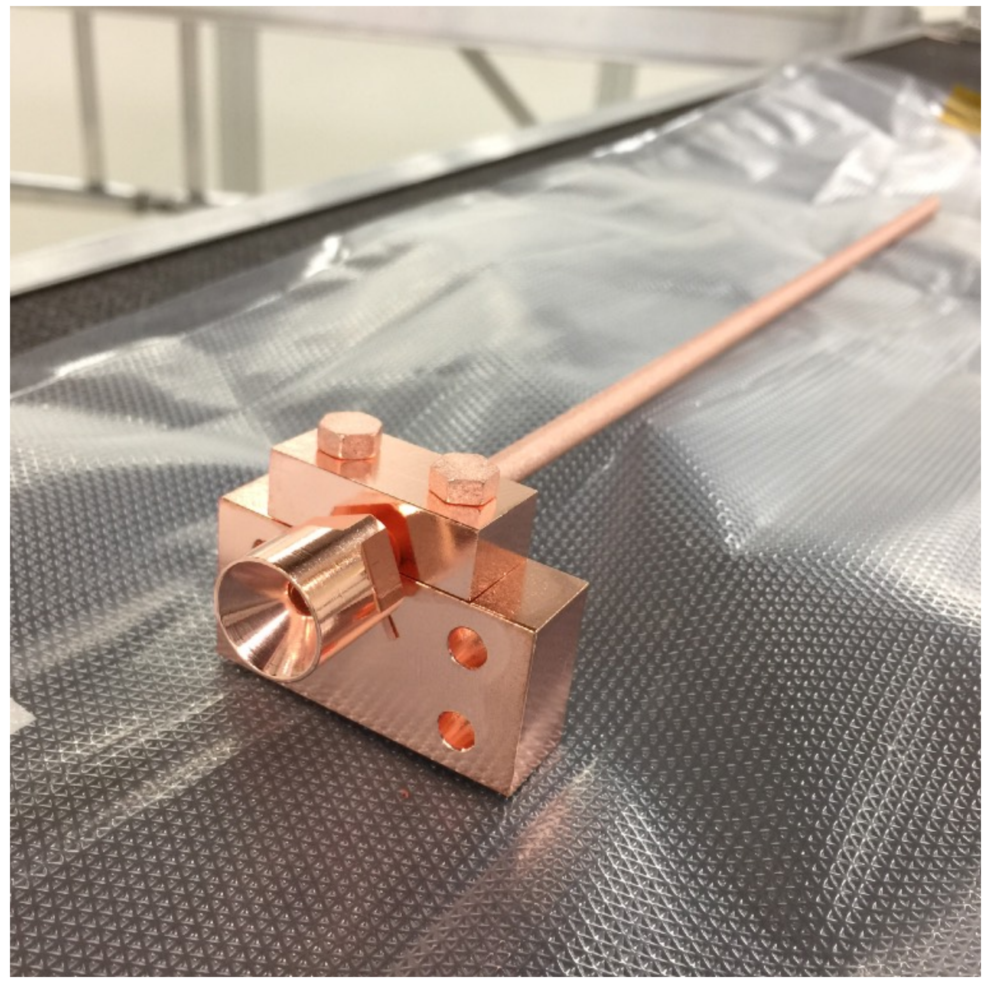
Cryostat temperature

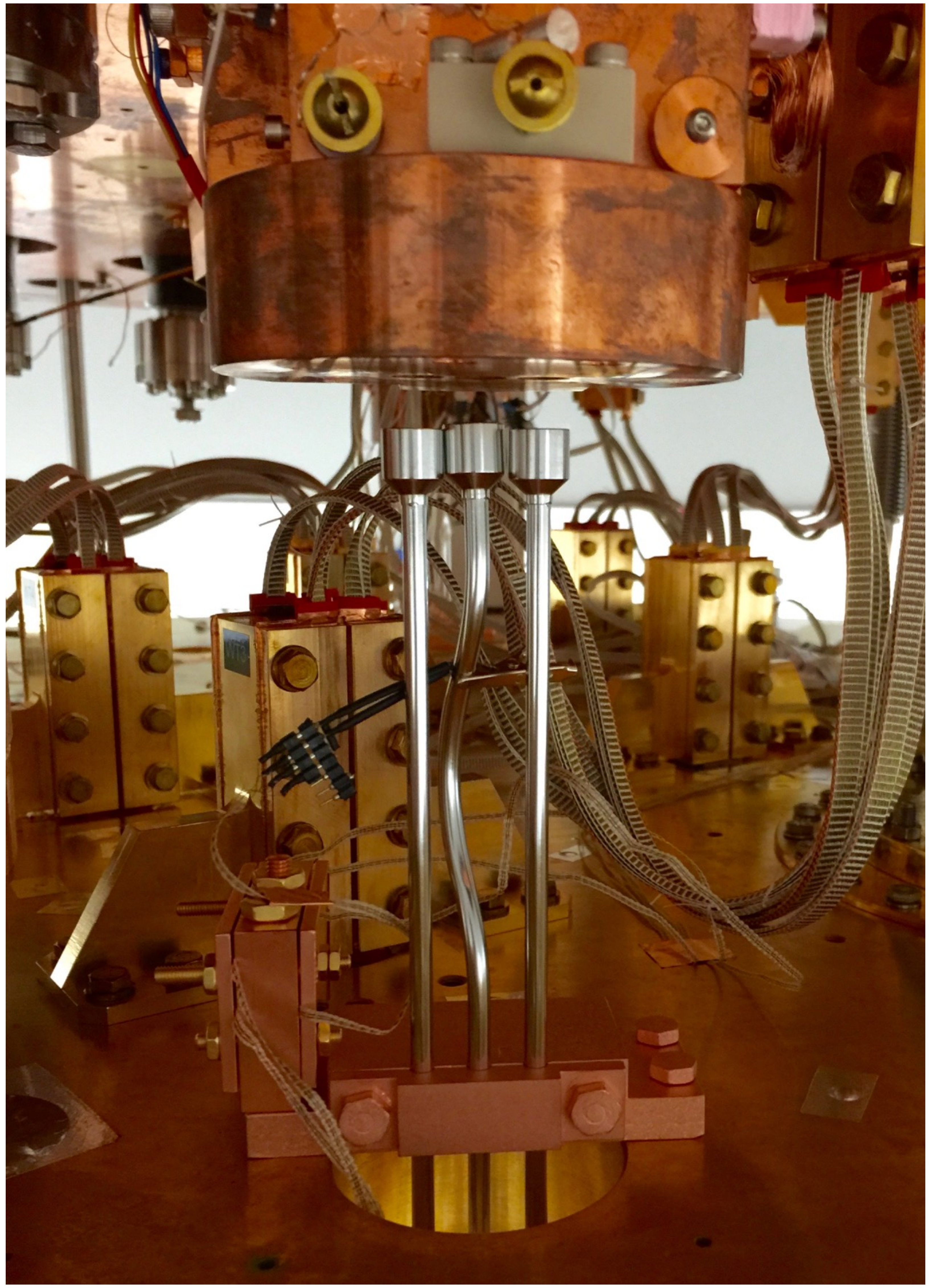
- Deployment of a single inner string takes about 6 hours
- Staggered deployment of all 12 strings takes about 24 hours

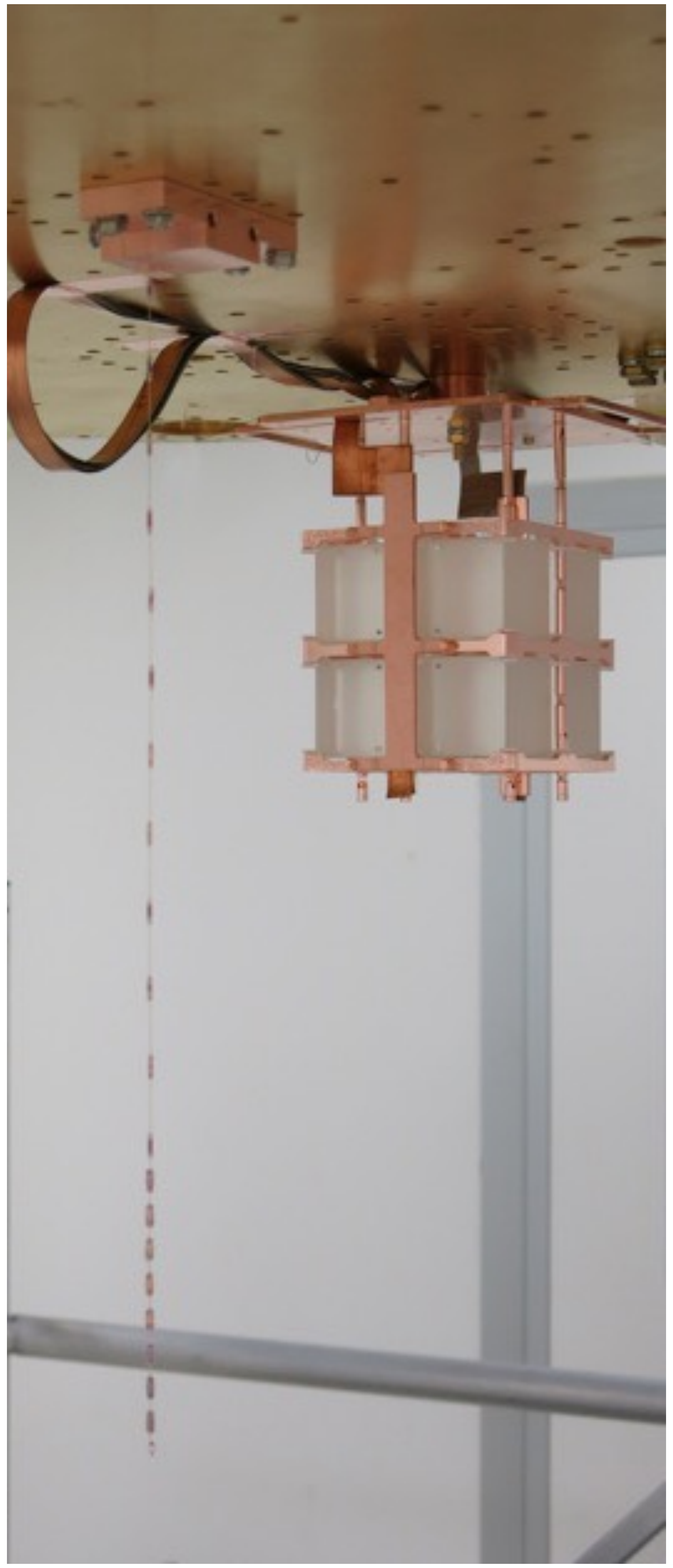


Integration



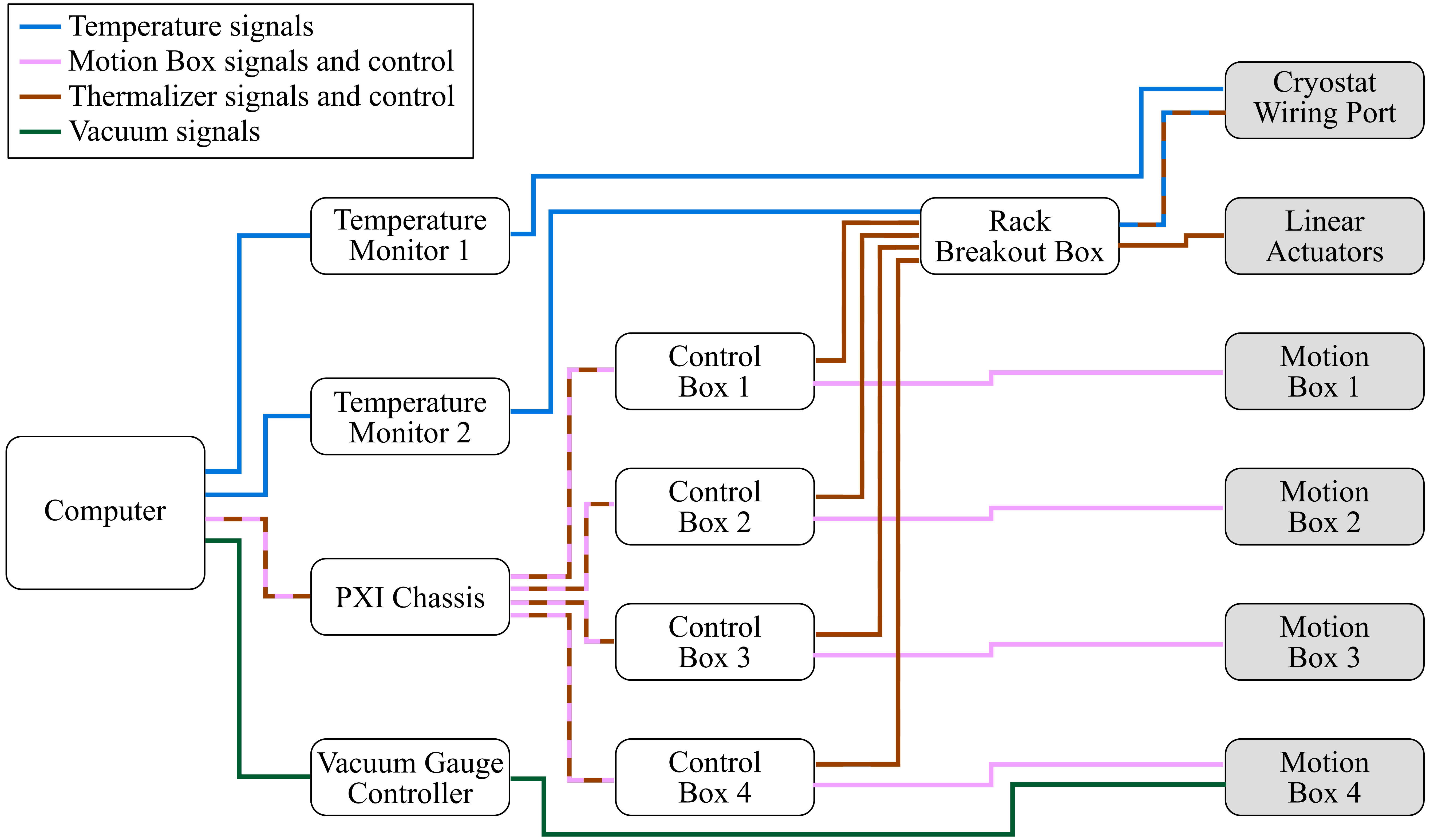




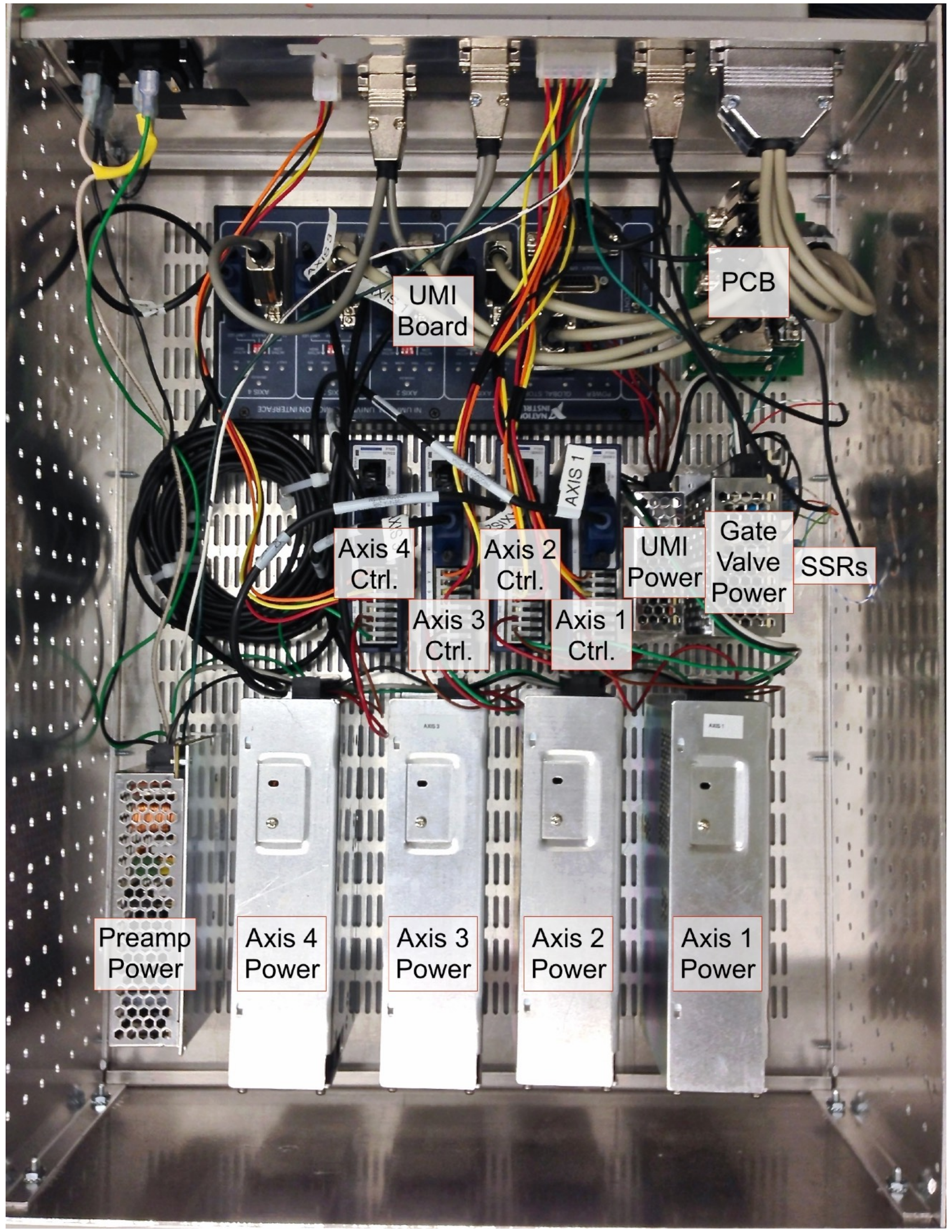


Control electronics

- All system control and readout is done through a rack near the cryostat
- Signal and power cables connect the rack to the motion hardware on the cryostat



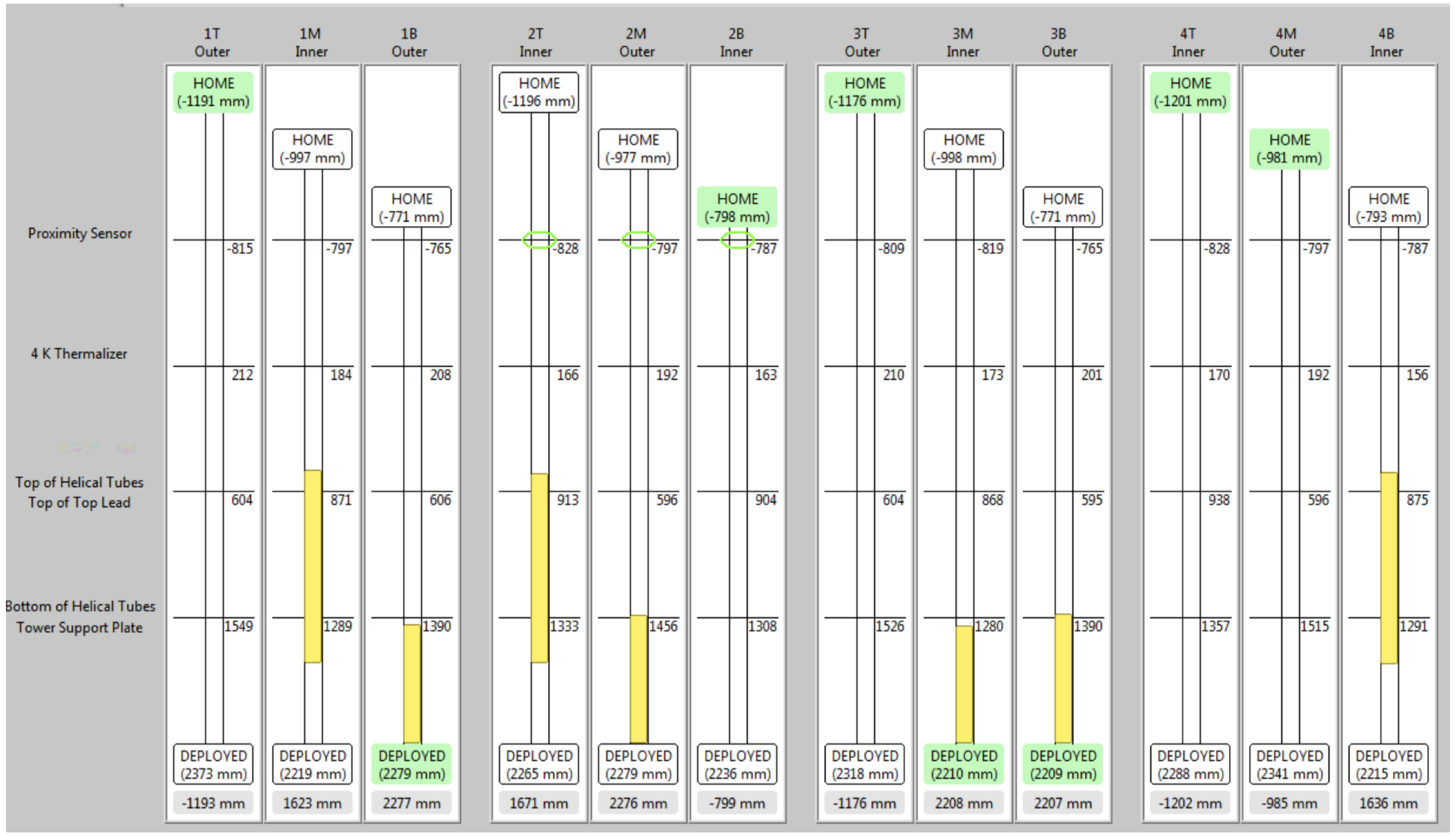
Motion control boxes



- Majority of the motion control electronics are contained inside 4 boxes
- 3 strings + 4-K thermalizer controlled by each box
- Contain power supplies, motor controllers, custom PCBs, relays, and more
- All designed, built, and tested at Yale and installed at LNGS

Software control

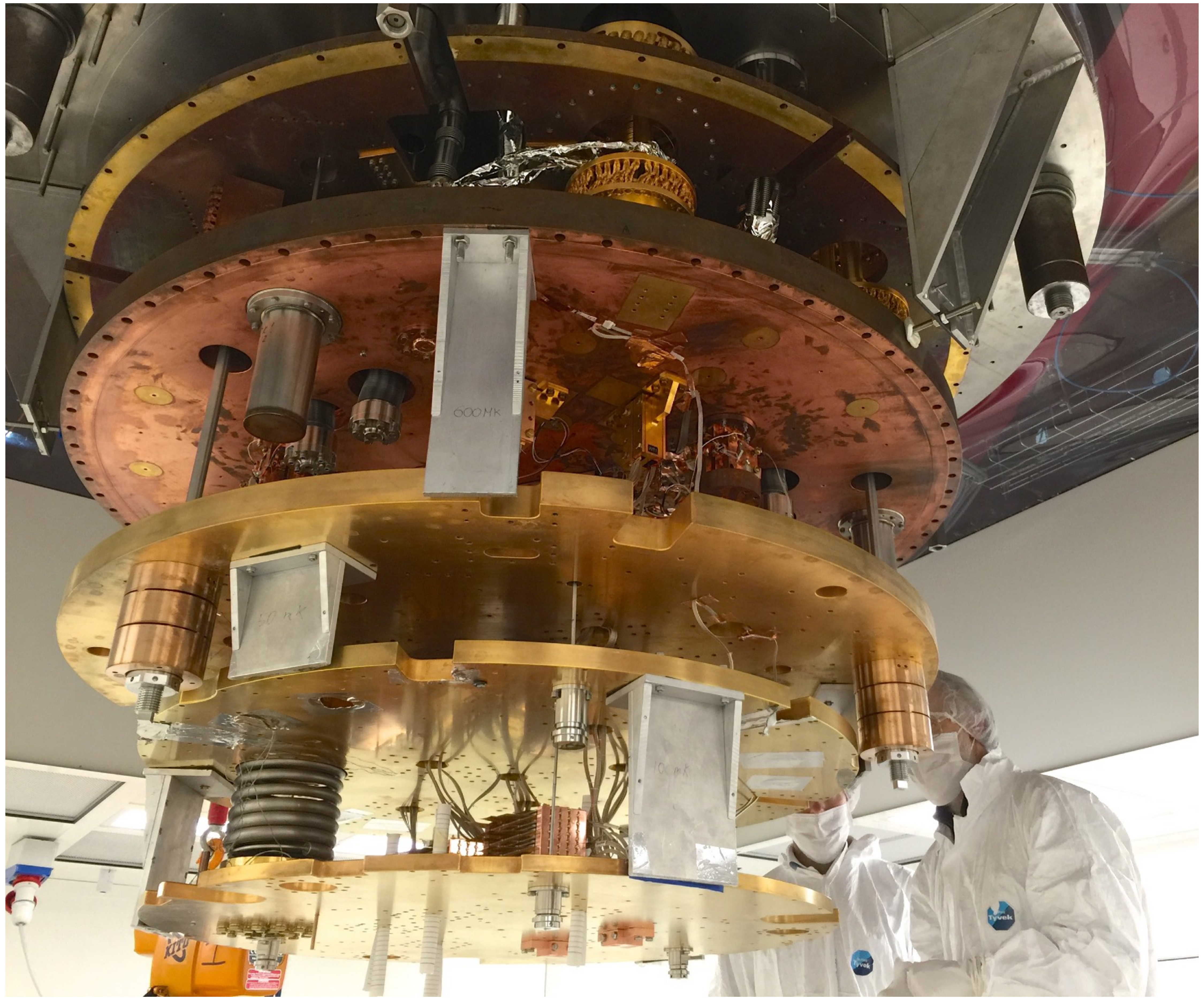
- Wrote software that controls and monitors every aspect of the calibration system during operation
- Allows for full, automated, and remote operation of the calibration system



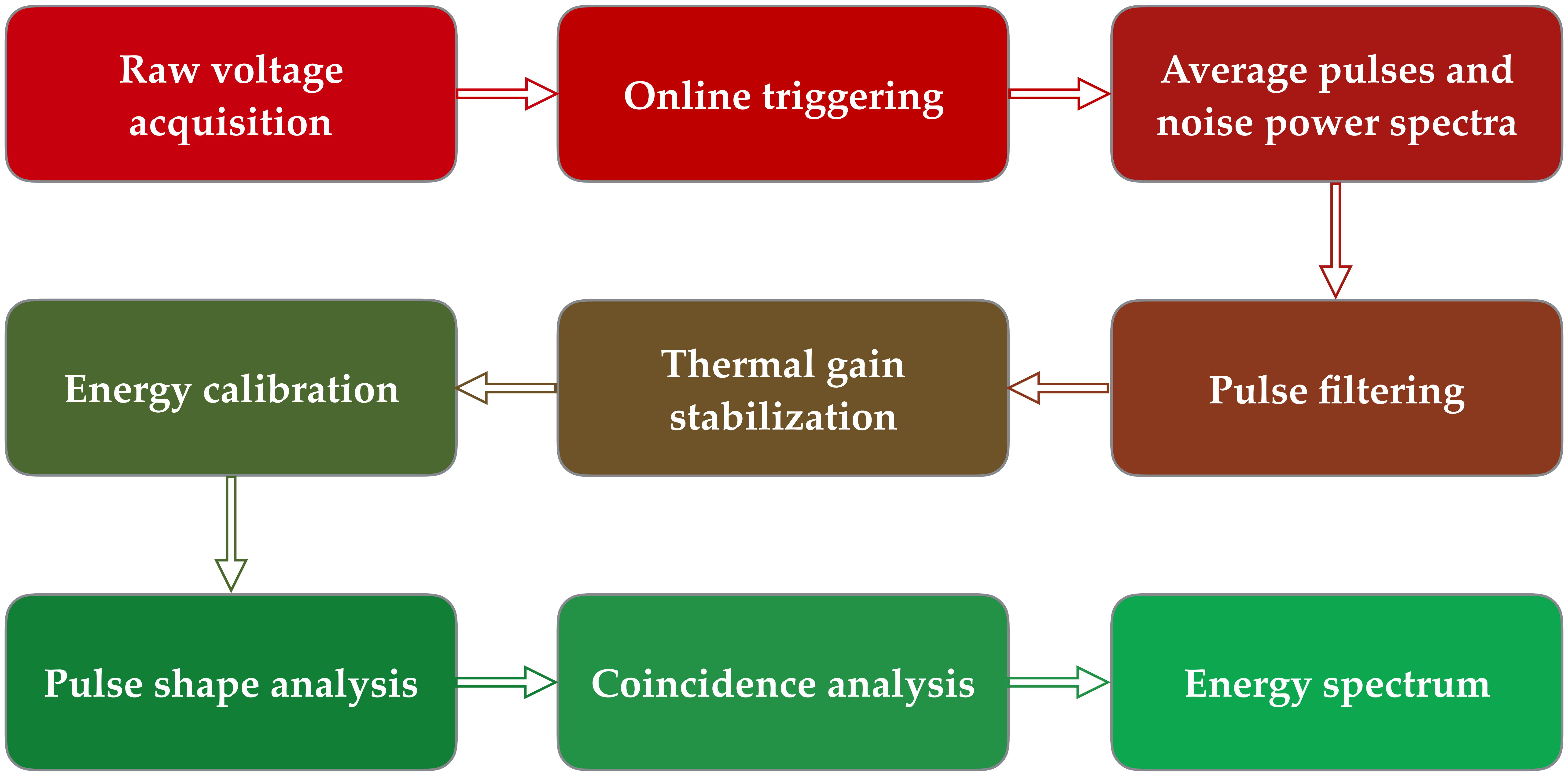
- Clear visual overview allows operator to see current status and next steps
- Monitors string position, string tension, guide tube temperatures, vacuum pressure, and other parameters during deployments to ensure safe operation
- Saves and records all parameters for future review and analysis
- Successfully used in first deployments of calibration sources for CUORE

Outline

- History and background
- CUORE detector and cryostat
- Detector calibration system
- First physics results

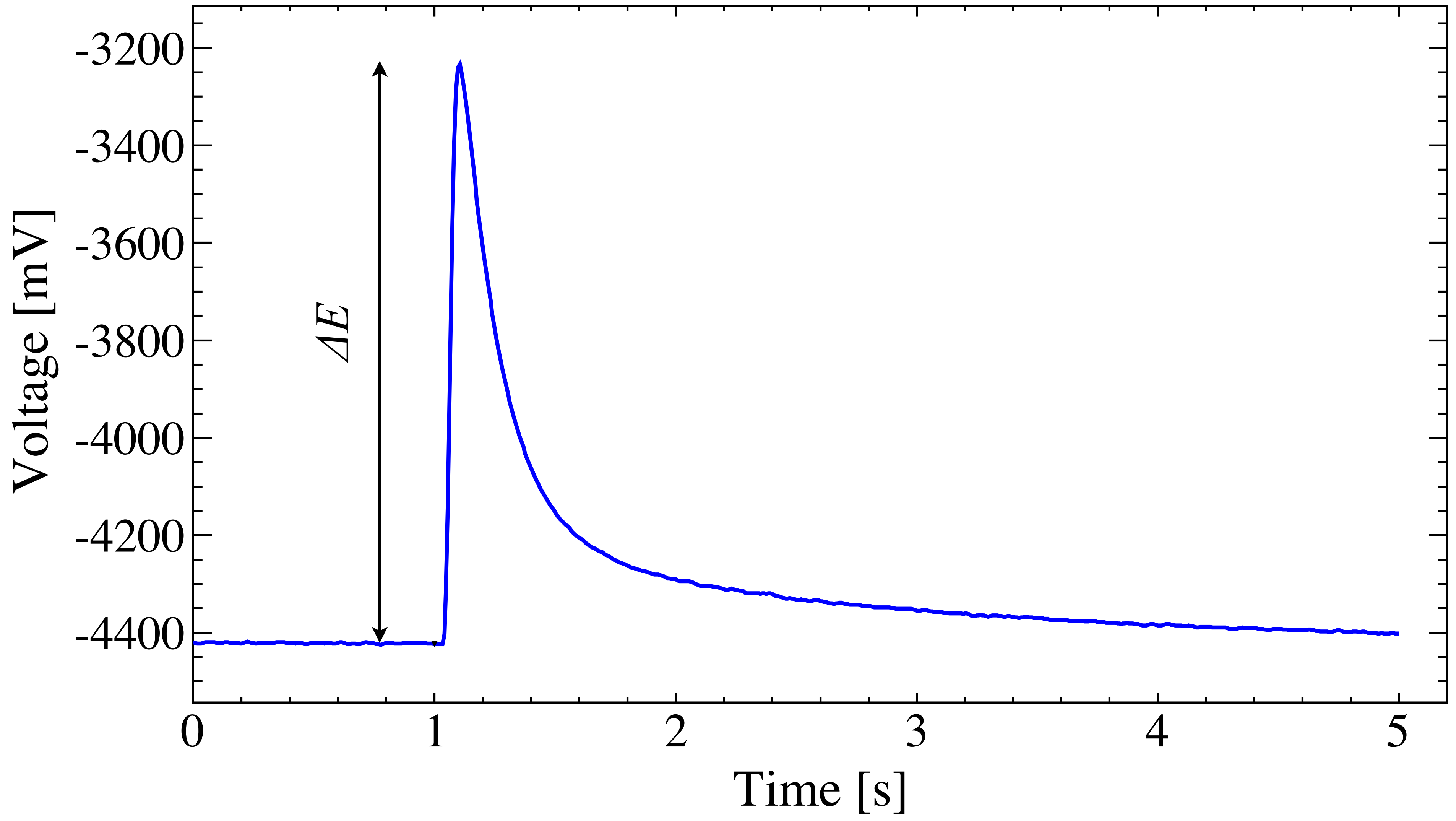


Data processing overview



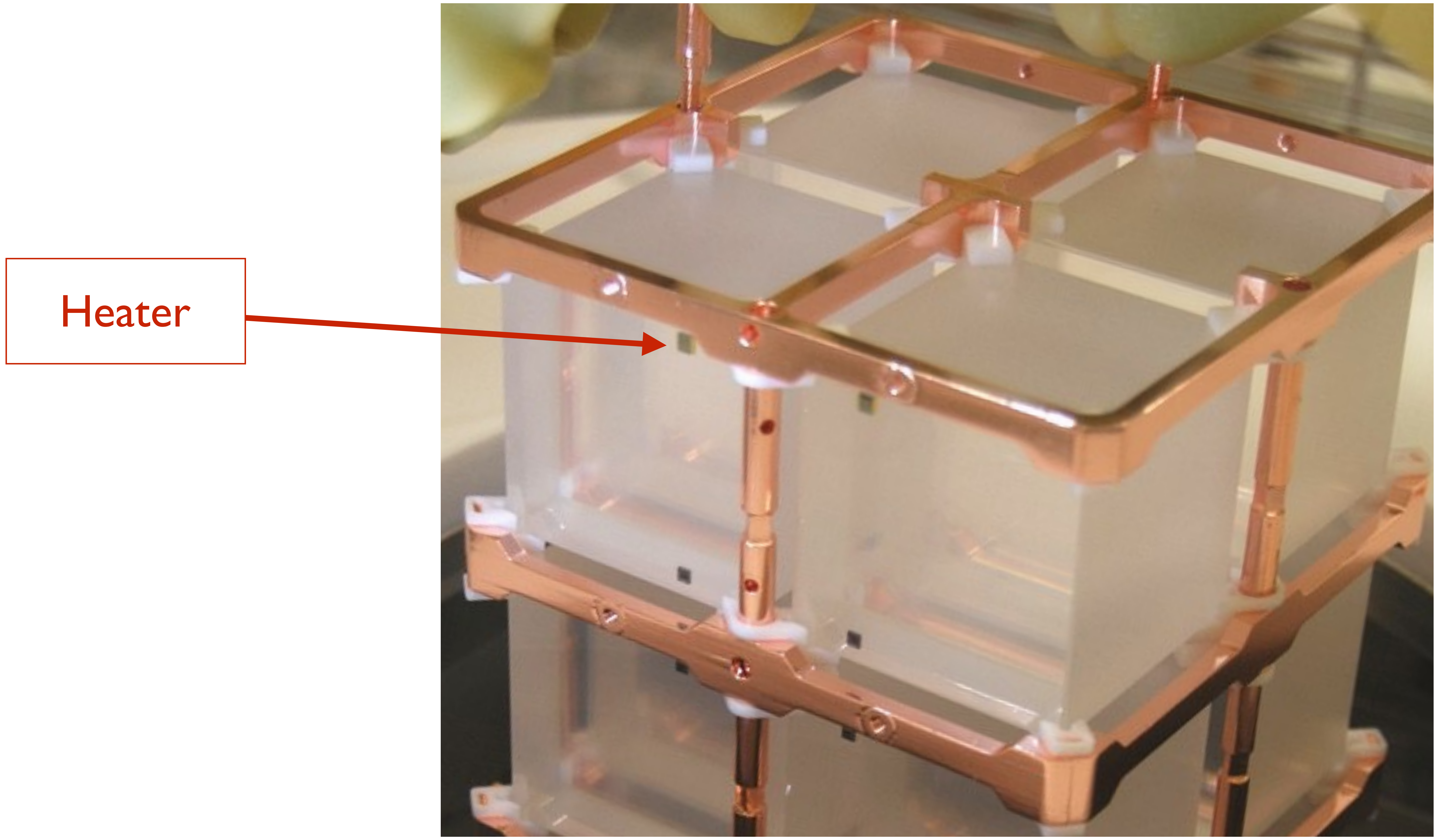
Acquiring data

- 984/988 (99.6%) of detectors are operational; 90% are used in this analysis
- We acquire data continuously from operating detectors at a rate of 1 kHz
- We trigger on a channel and save a 10-second waveform when the slope of the signal is above a channel-dependent threshold
- Acquired in runs (~1 day) and grouped into datasets (~1 month), which begin and end with a calibration
- We compute an average pulse shape and average noise power spectrum for each channel and use this to filter the waveforms



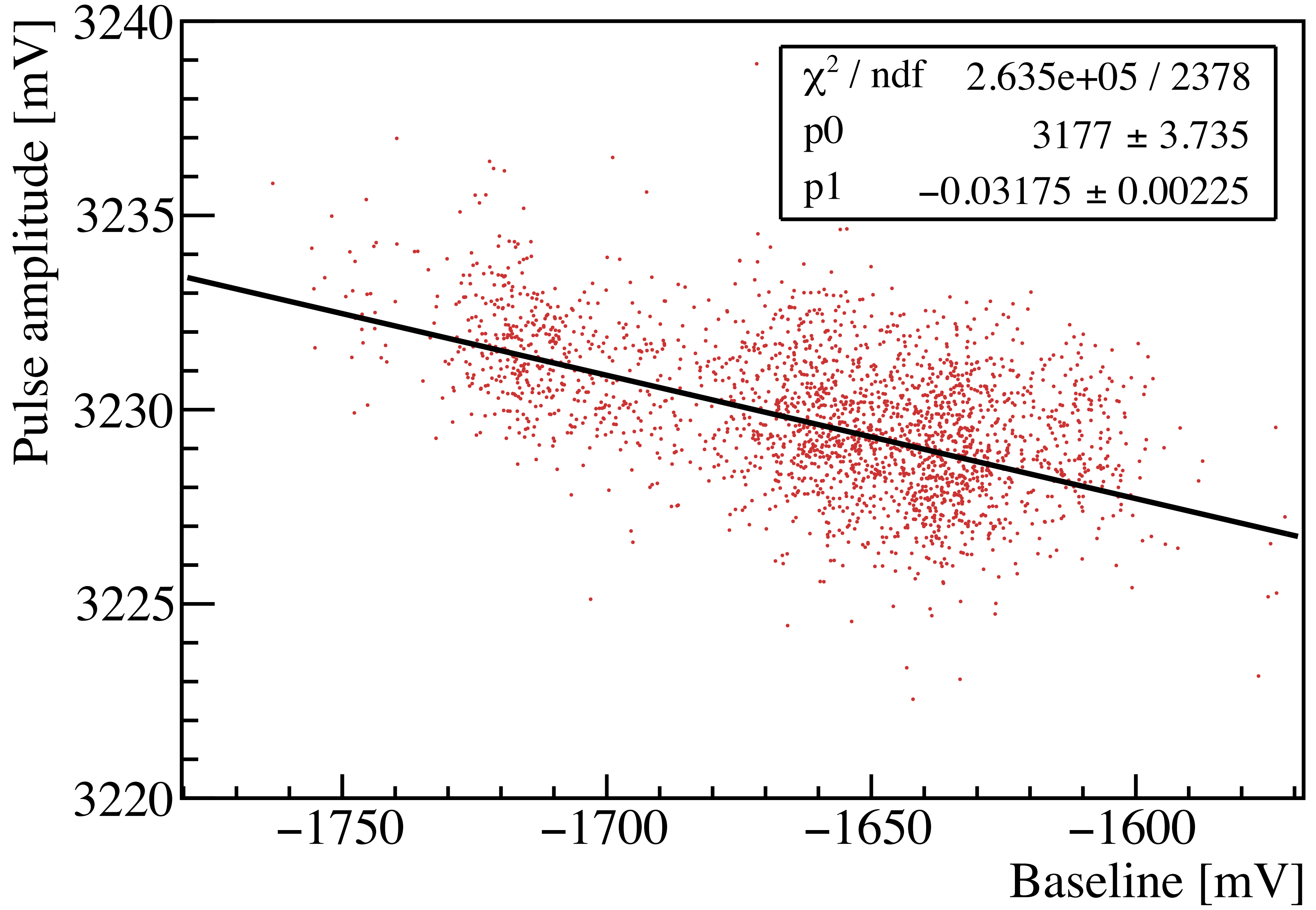
Thermal gain stabilization

- Heat capacity of the TeO_2 crystals ($C \propto T^3$) and resistance of the NTD Ge thermistors are strongly temperature dependent
- Therefore, our pulse amplitude for a given energy deposition is strongly dependent on temperature (which fluctuates slightly while taking data)
- To correct for this, we periodically (every ~300 s) inject fixed amounts of energy with Si heaters attached to the crystals



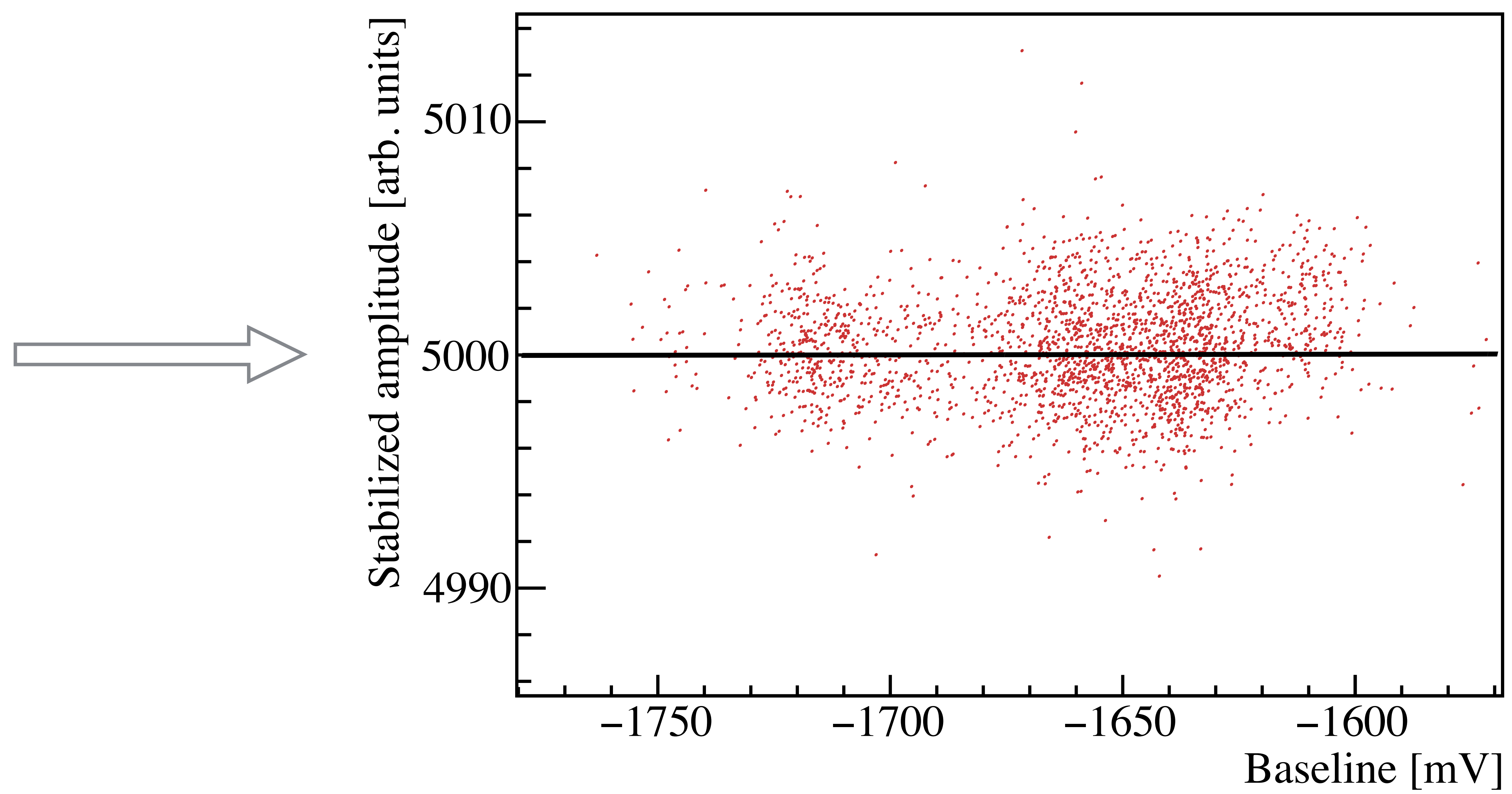
Thermal gain stabilization

- Baseline voltage of the pulse is an (uncalibrated) measure of bolometer temperature
- Fit a curve to determine the estimated heater pulse amplitude at any baseline



- Each event is assigned an arbitrary-unit stabilized amplitude:

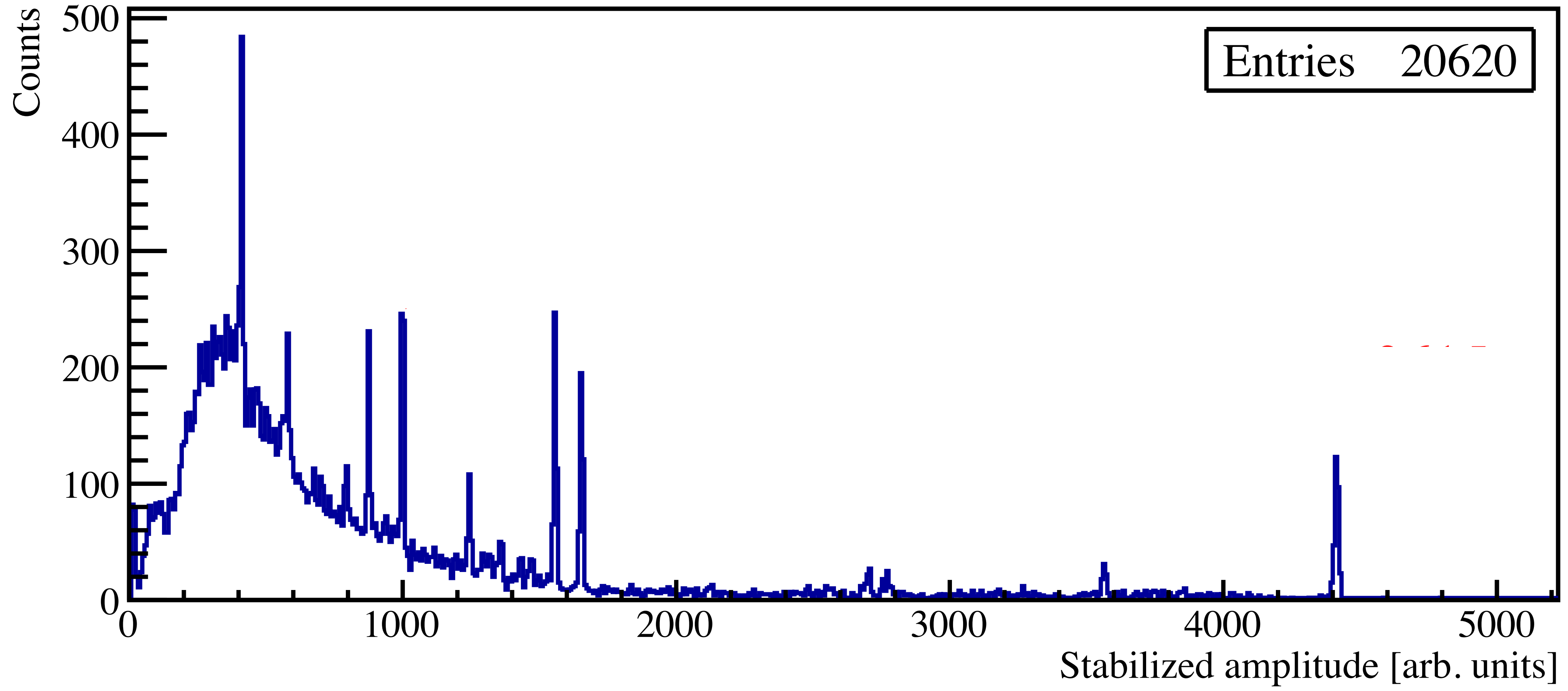
$$\frac{\text{Pulse stabilized amplitude}}{5000} = \frac{\text{Pulse raw amplitude}}{\text{Heater amplitude at pulse baseline}}$$



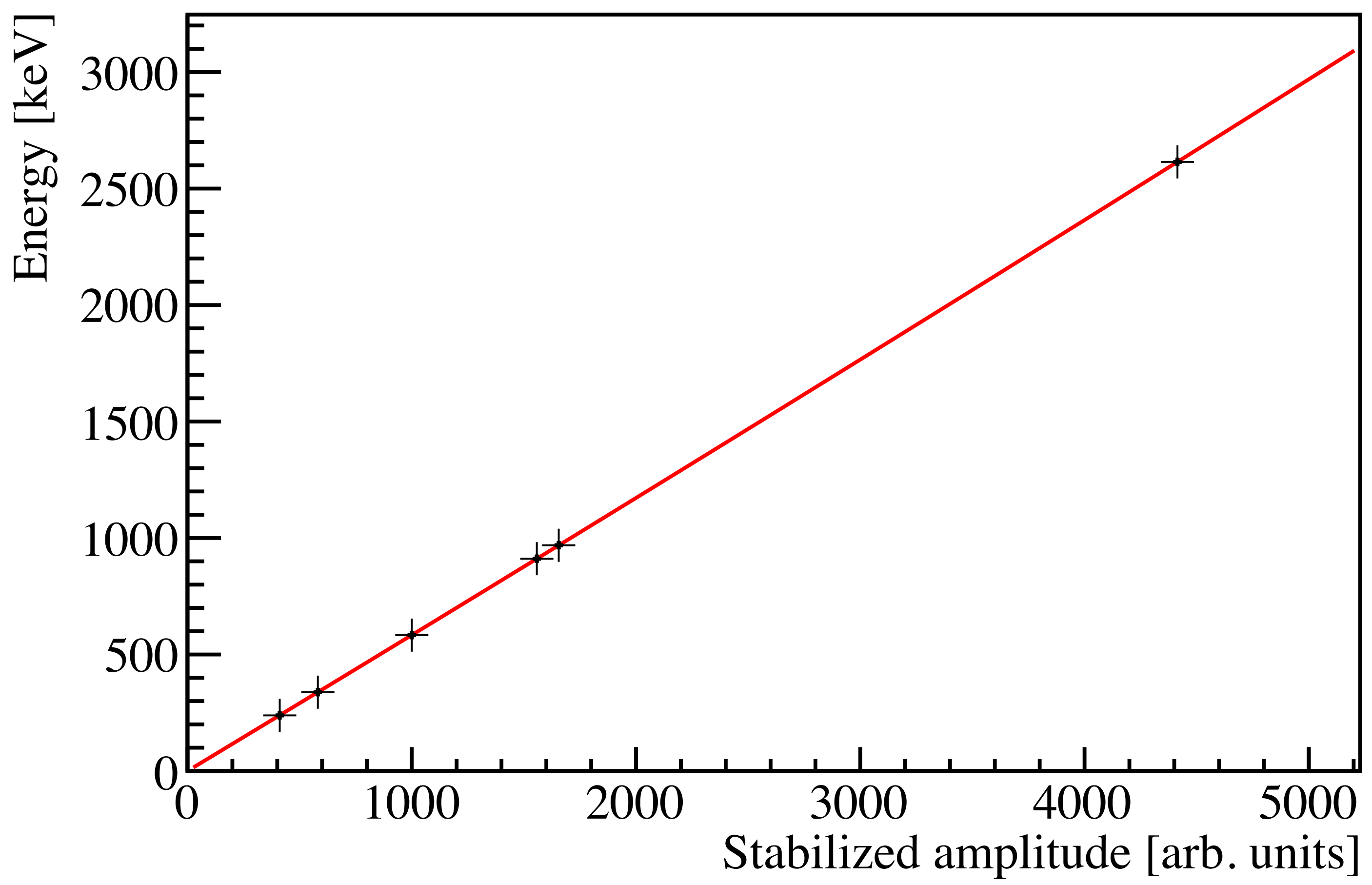
Monthly calibration

- We still need to convert stabilized amplitudes to real-world energies
- After deploying the ^{232}Th sources, we acquire several days of calibration data
- Provides several strong peaks in the energy spectrum

Calibration spectrum in 1 channel



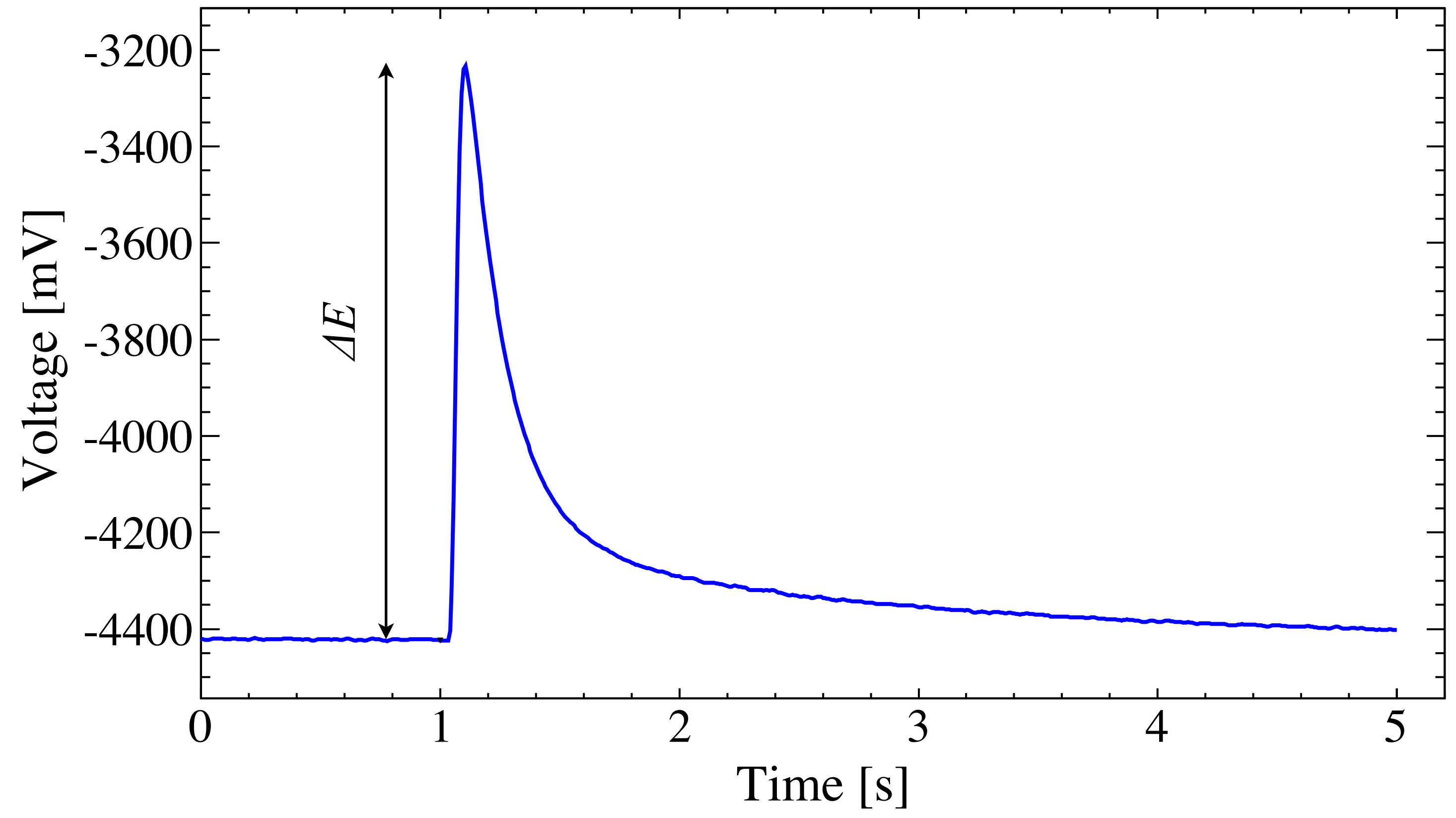
Example calibration function



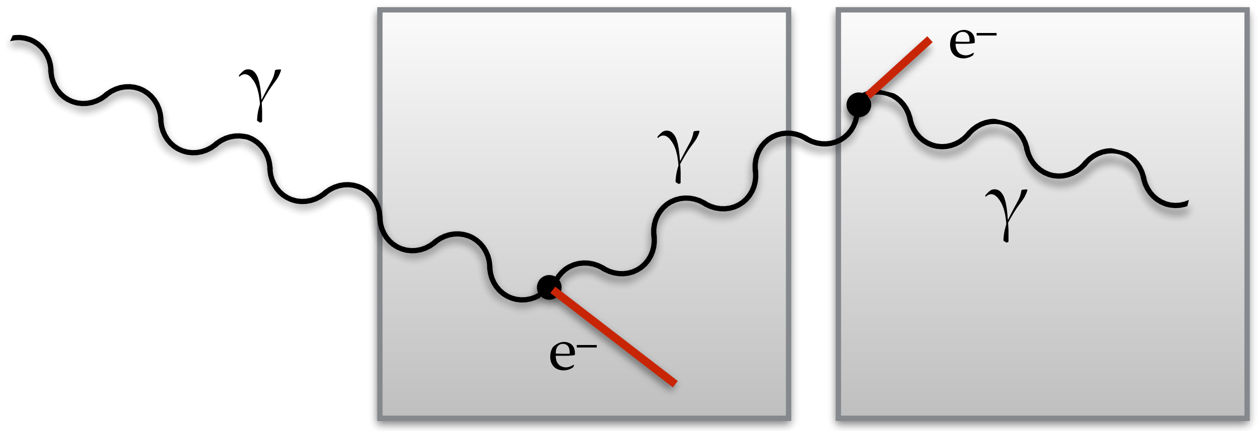
- We use these lines to create a channel-by-channel map from stabilized amplitude to true energy

Event selection

- In order to select candidate $0\nu\beta\beta$ decay events, we apply a variety of cuts to the data
- Several pulse shape parameters are measured, and limits are set on:
  - Baseline slope
  - Rise time and shape
  - Decay time and shape

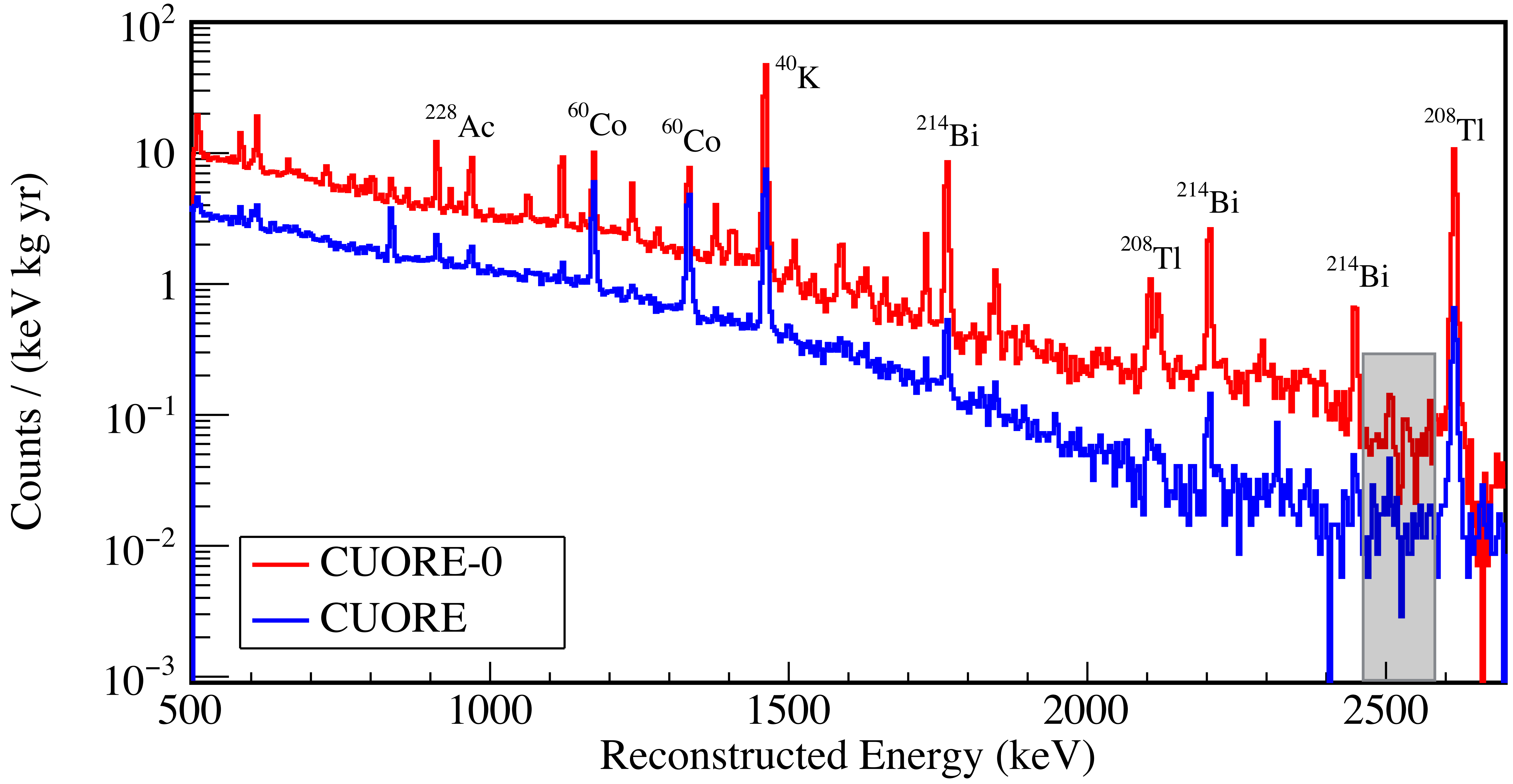


- We also only accept events that are not simultaneous with events in other crystals
  - Gammas often Compton scatter in multiple crystals
  - Muons almost always deposit energy in multiple crystals



Physics spectrum

- Calibrated physics spectrum from our first two datasets, after event selection
- 83.6 kg yr of TeO_2 exposure, from Dataset 1 (May – June) and Dataset 2 (August – September)
- Factor of 4 reduction in background rate in $0\nu\beta\beta$ decay region of interest compared to CUORE-0, thanks to new cryostat



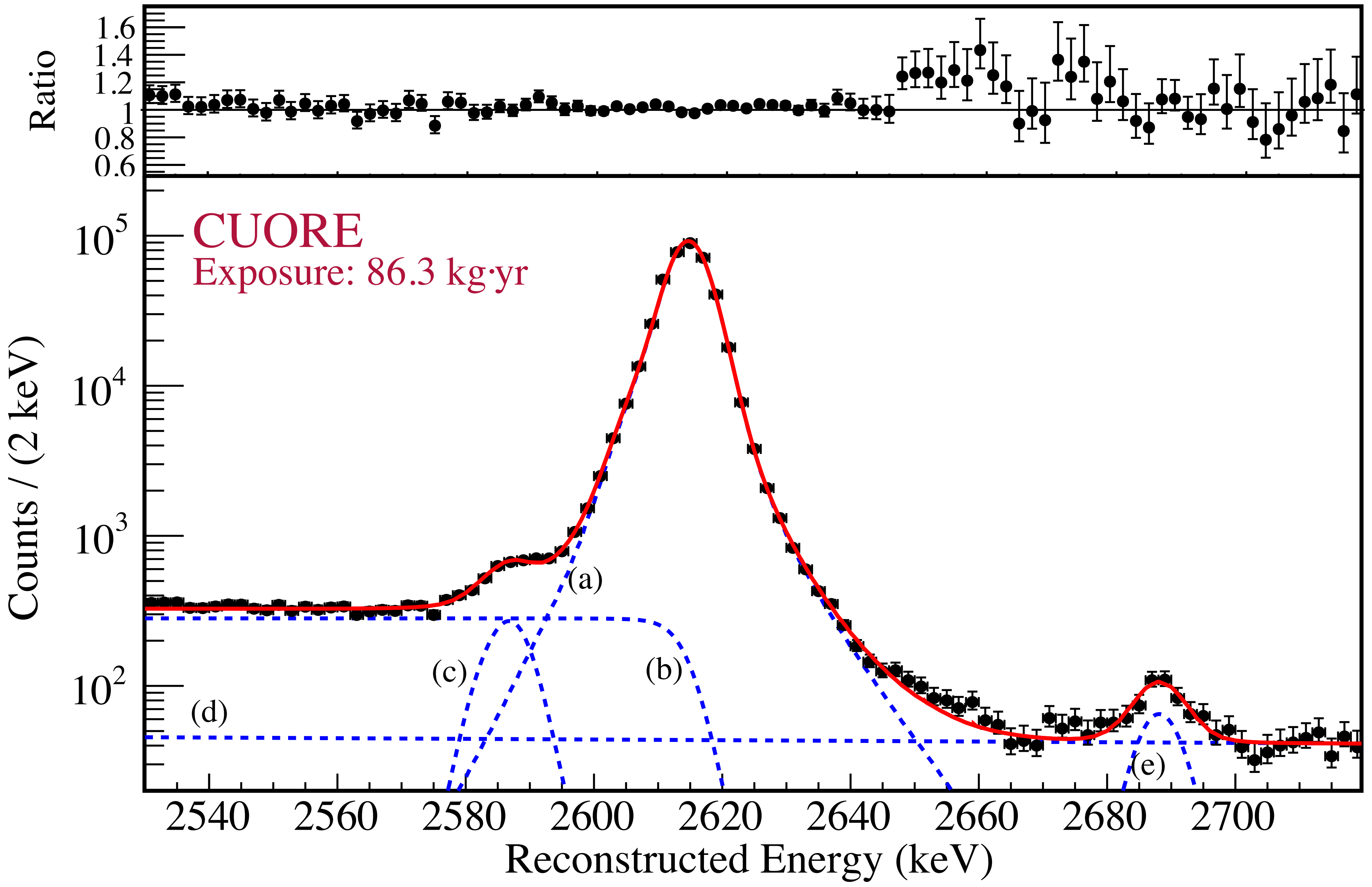
Selection efficiency

- We need to evaluate the overall selection efficiency: probability of us observing a $0\nu\beta\beta$ decay event given that one has occurred
  - Evaluate efficiency on gamma lines in the physics spectrum (from ^{40}K and ^{208}Tl)
  - Overall, our efficiency on gamma lines is $(90.5 \pm 1.9)\%$ in Dataset 1 and $(92.7 \pm 1.4)\%$ in Dataset 2
- $0\nu\beta\beta$ decay events are entirely contained in 1 crystal 88.3% of the time (estimated from simulation)
- Together, we estimate that we would see $(79.9 \pm 1.9)\%$ of $0\nu\beta\beta$ decays in Dataset 1 and $(81.9 \pm 1.4)\%$ in Dataset 2

Source	Selection efficiency (%)	
	Dataset 1	Dataset 2
Pile-up cut	97.6 ± 1.1	96.7 ± 1.0
Pulse shape cut	93.9 ± 1.6	96.8 ± 1.0
Anti-coincidence	99.8 ± 0.1	$100. \pm 0.1$
Trigger and reconstruction	99.0 ± 0.1	99.0 ± 0.1
Total excluding containment	90.5 ± 1.9	92.7 ± 1.4
Containment	88.3 ± 0.1	88.3 ± 0.1

Line shape

- We need to know what a $0\nu\beta\beta$ decay signal might look like
- For this, we use the 2615 keV calibration line
  - Close in energy to $Q_{\beta\beta} = 2528$ keV
  - Sufficient channel-by-channel statistics to estimate line shape

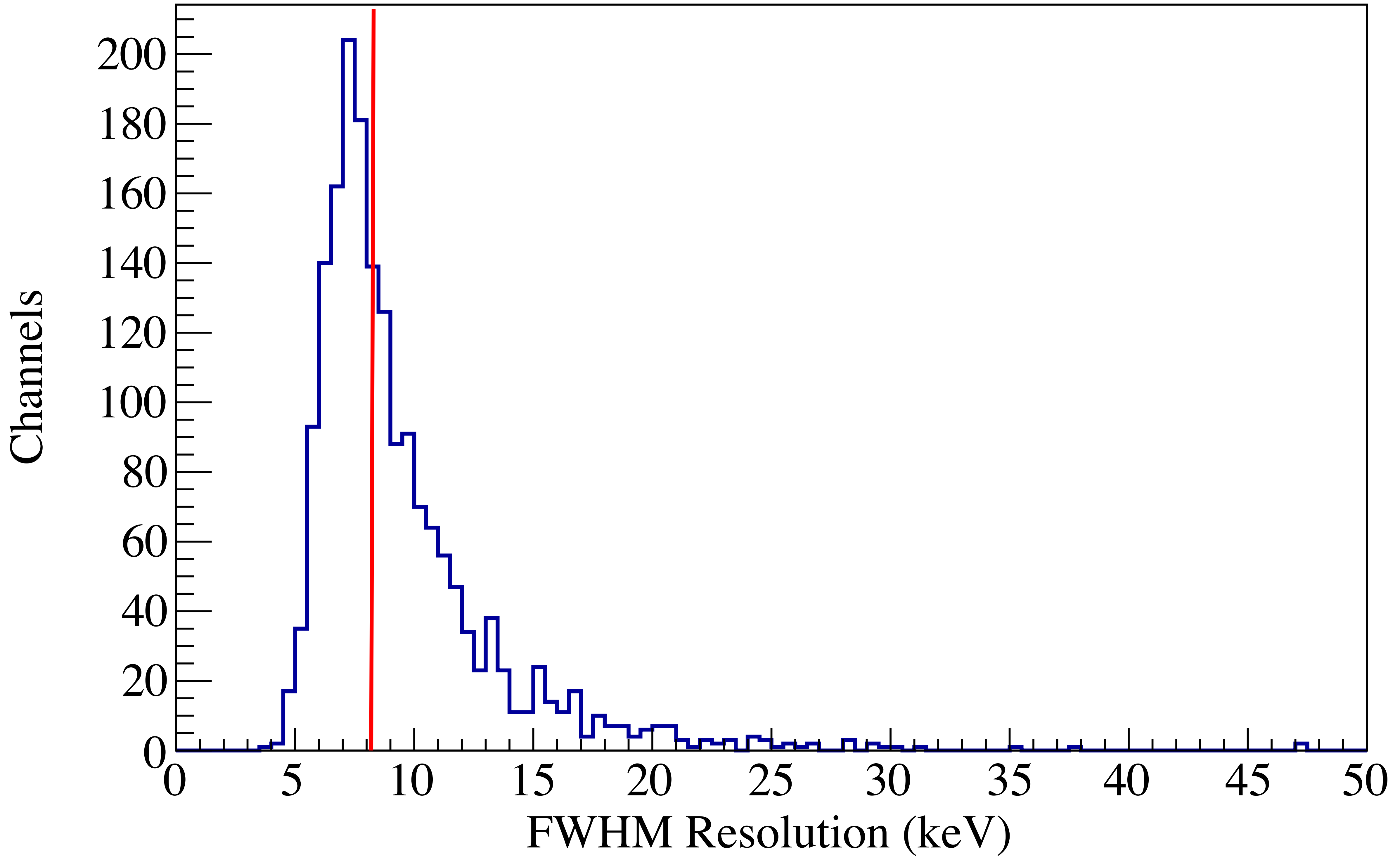


arXiv:1710.07988

(a) Main photopeak (modeled as sum of 3 Gaussians)
(b) Compton multi-scatter continuum
(c) X-ray escape after 2615 keV deposition
(d) Flat background
(e) Coincident 2615 keV and 583 keV deposition followed by pair production and single escape

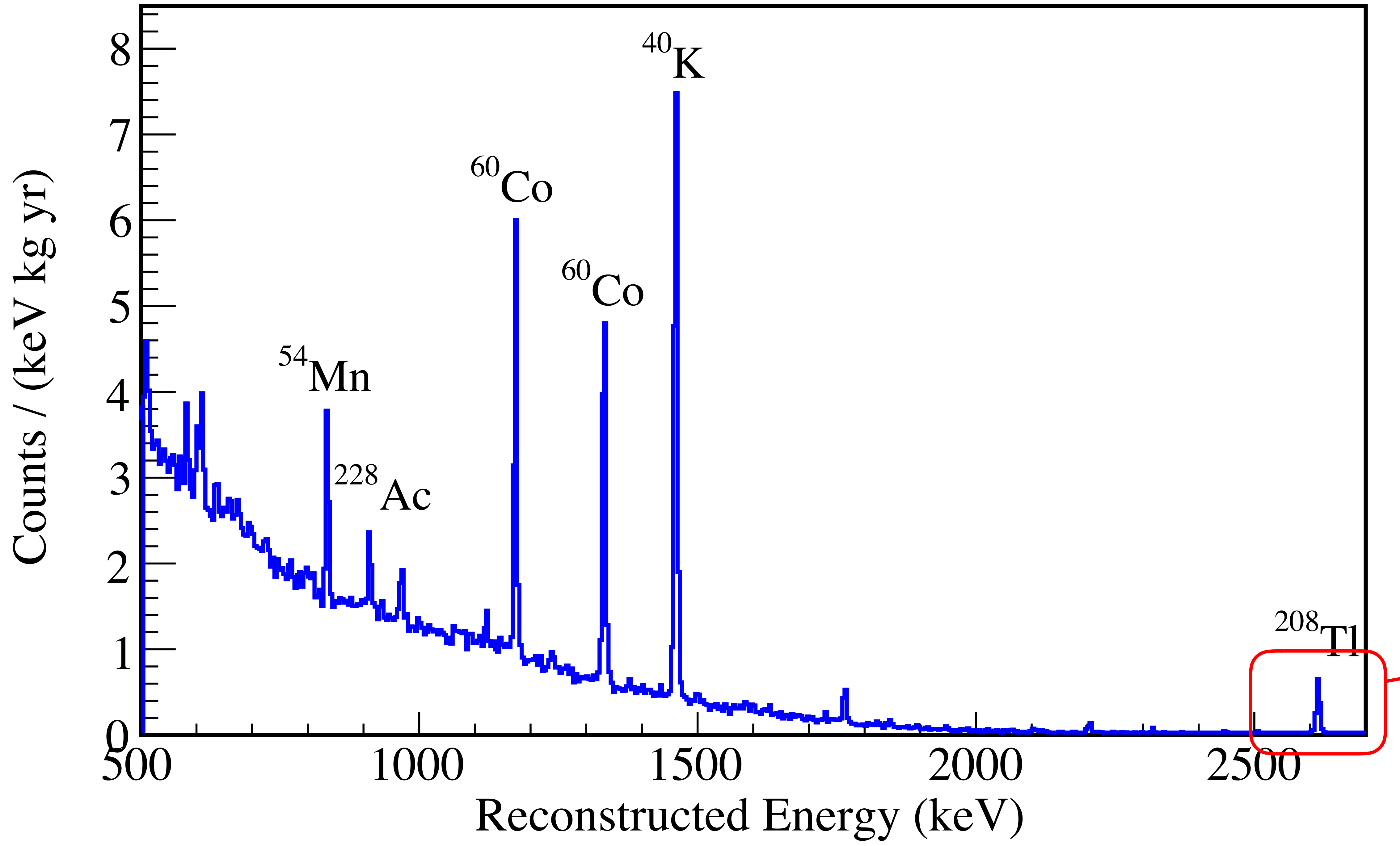
Calibration resolution

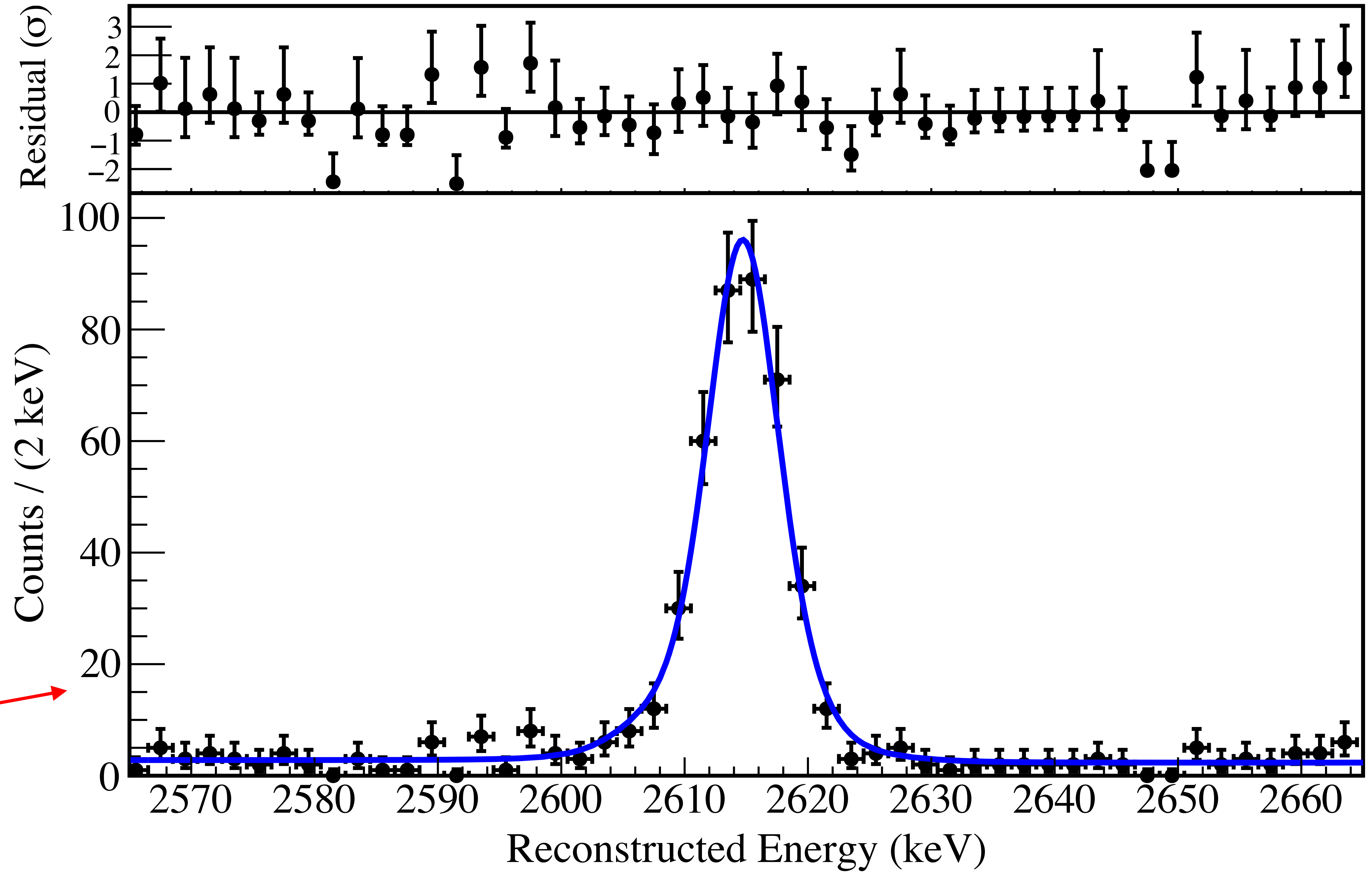
- We use the 2615 keV line to estimate our calibration resolution
- Physics-exposure-weighted harmonic mean resolution = 8.3 keV (in calibration data at 2615 keV)



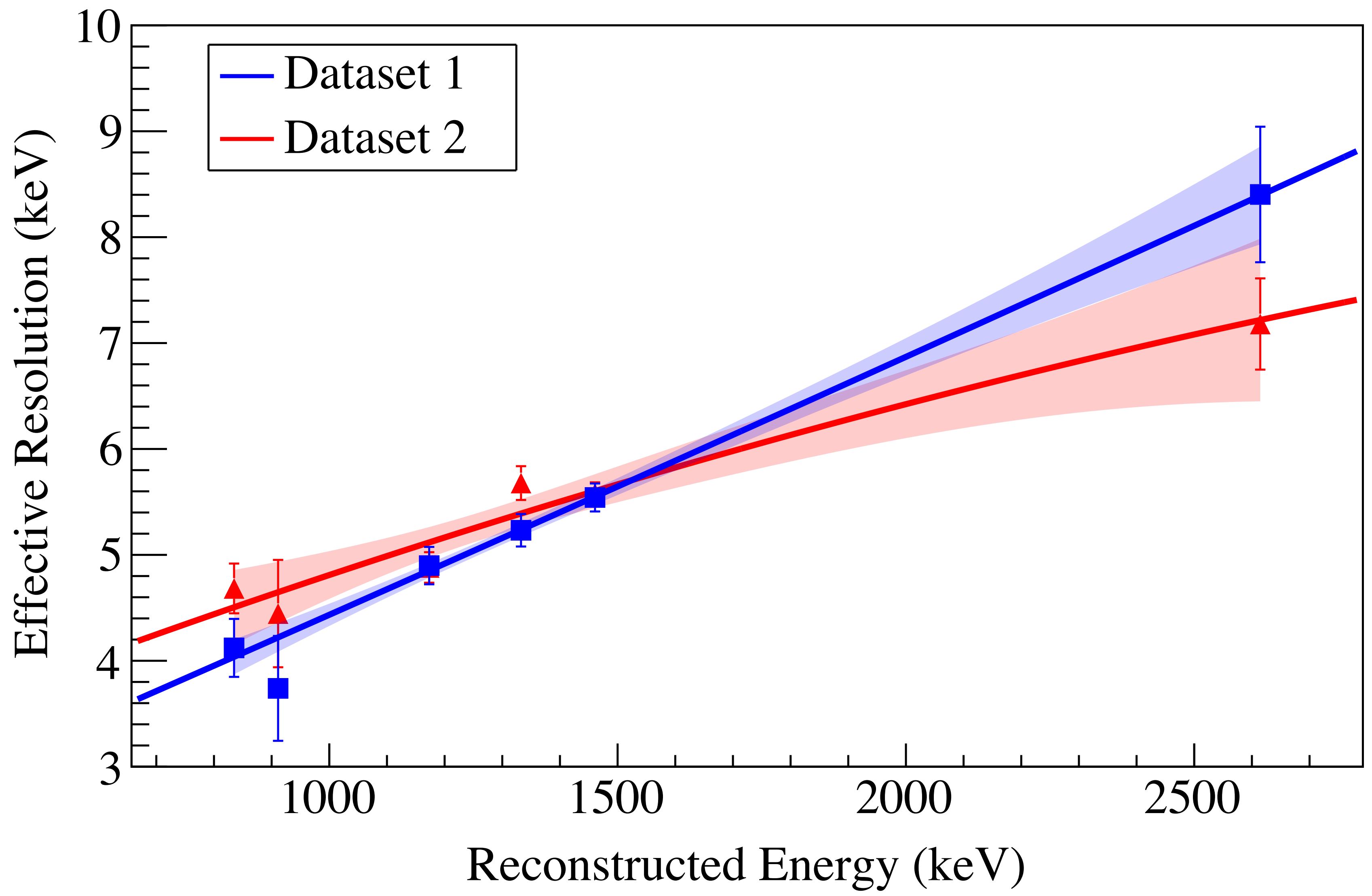
Full spectrum analysis

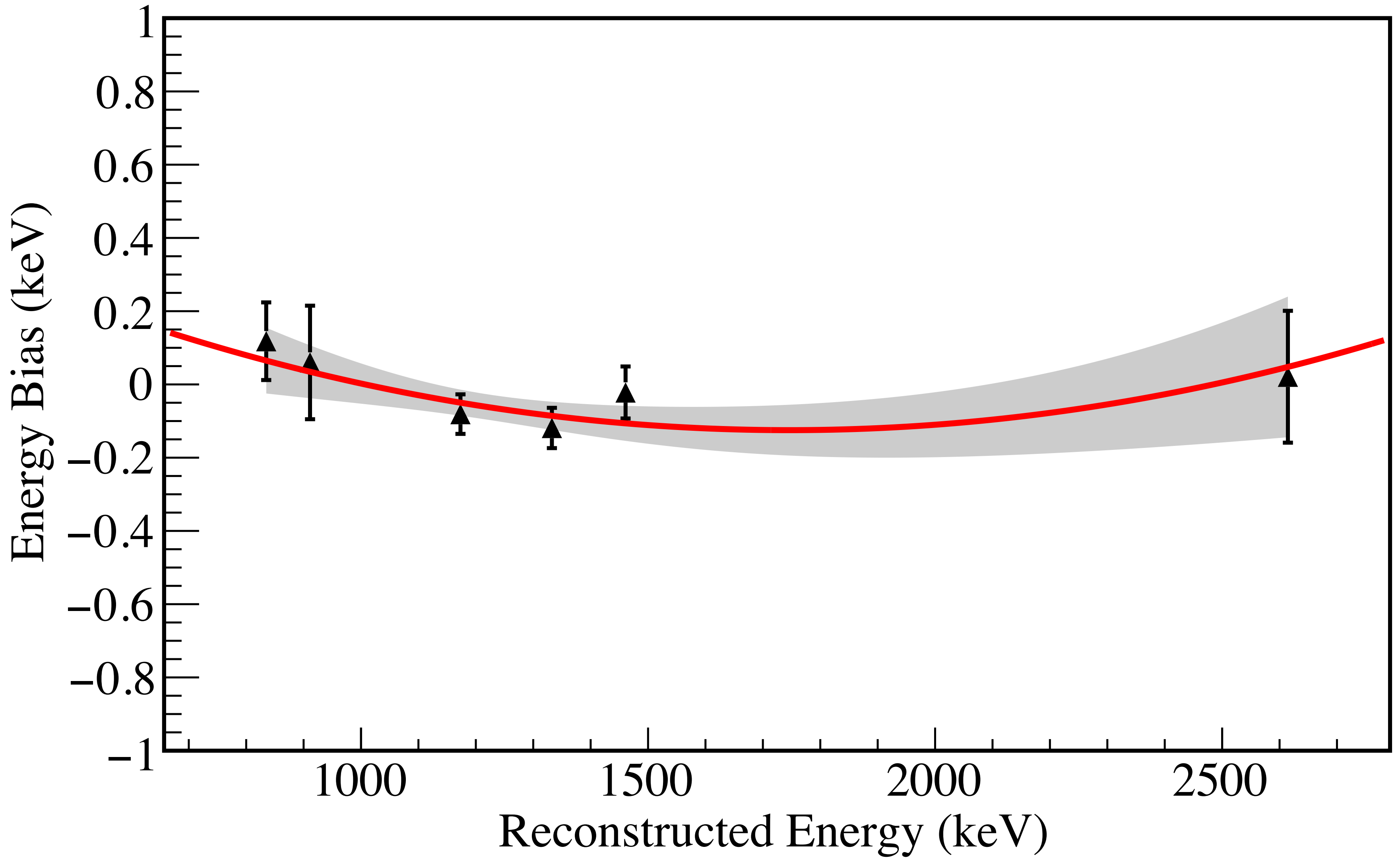
- Using the 2615 keV calibration line shape, we perform fits to other visible lines in the physics spectrum
- Allows us to estimate our resolution and energy bias in the physics data





Resolution and energy bias



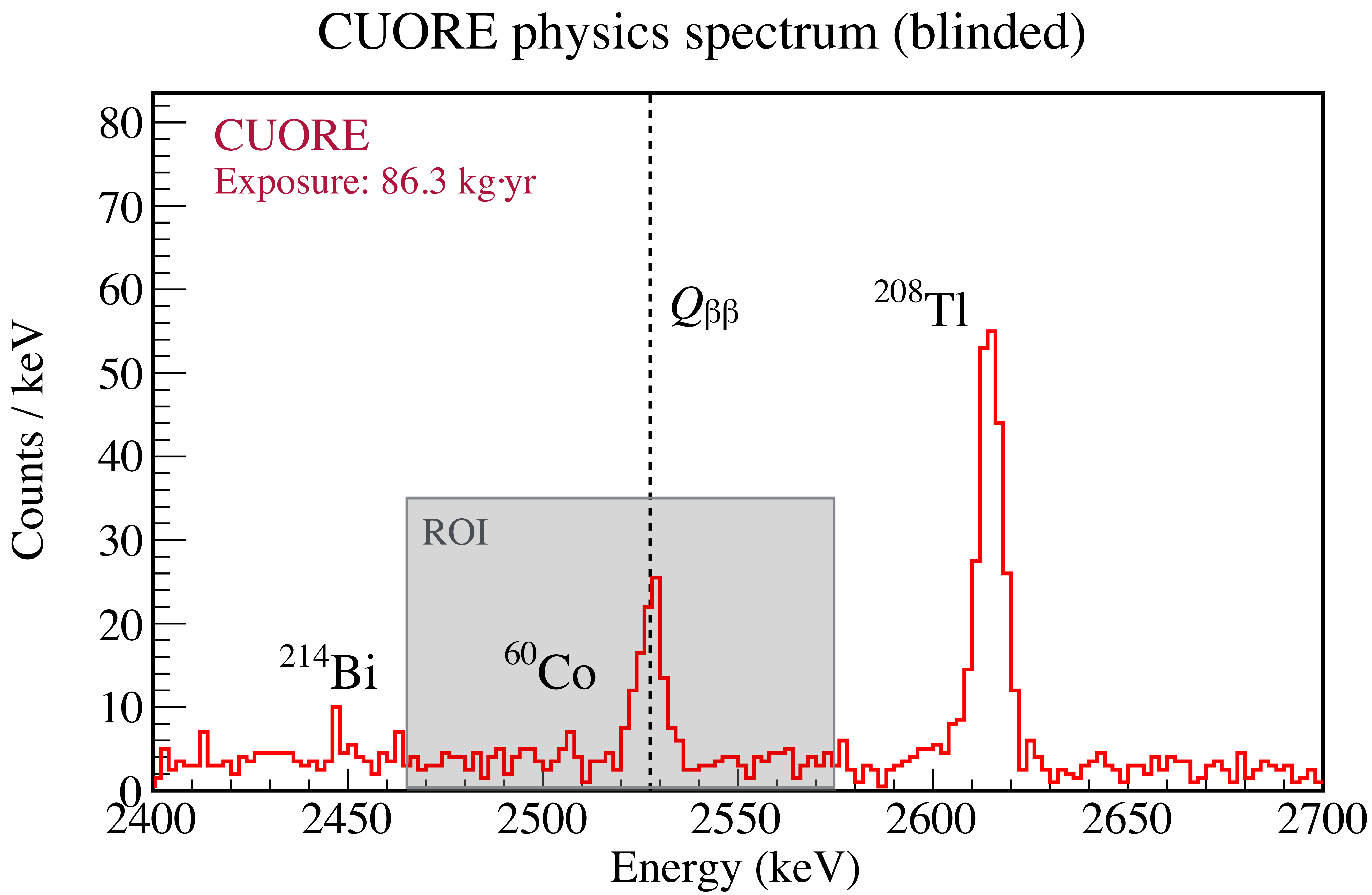


- Extrapolating to $Q_{\beta\beta}$ = 2528 keV, we find a physics resolution of:
  - (8.2 ± 0.4) keV in Dataset 1
  - (7.1 ± 0.7) keV in Dataset 2
- Working hard to achieve resolution goal of 5.0 keV

- We see no evidence of an energy bias, and conservatively set a systematic uncertainty of ±0.5 keV on $Q_{\beta\beta}$

Blinded spectrum

- The spectrum is blinded during data analysis by inserting a fake peak at $Q_{\beta\beta}$
- Events are swapped between the region around $Q_{\beta\beta}$ and 2615 keV



Blinded spectrum

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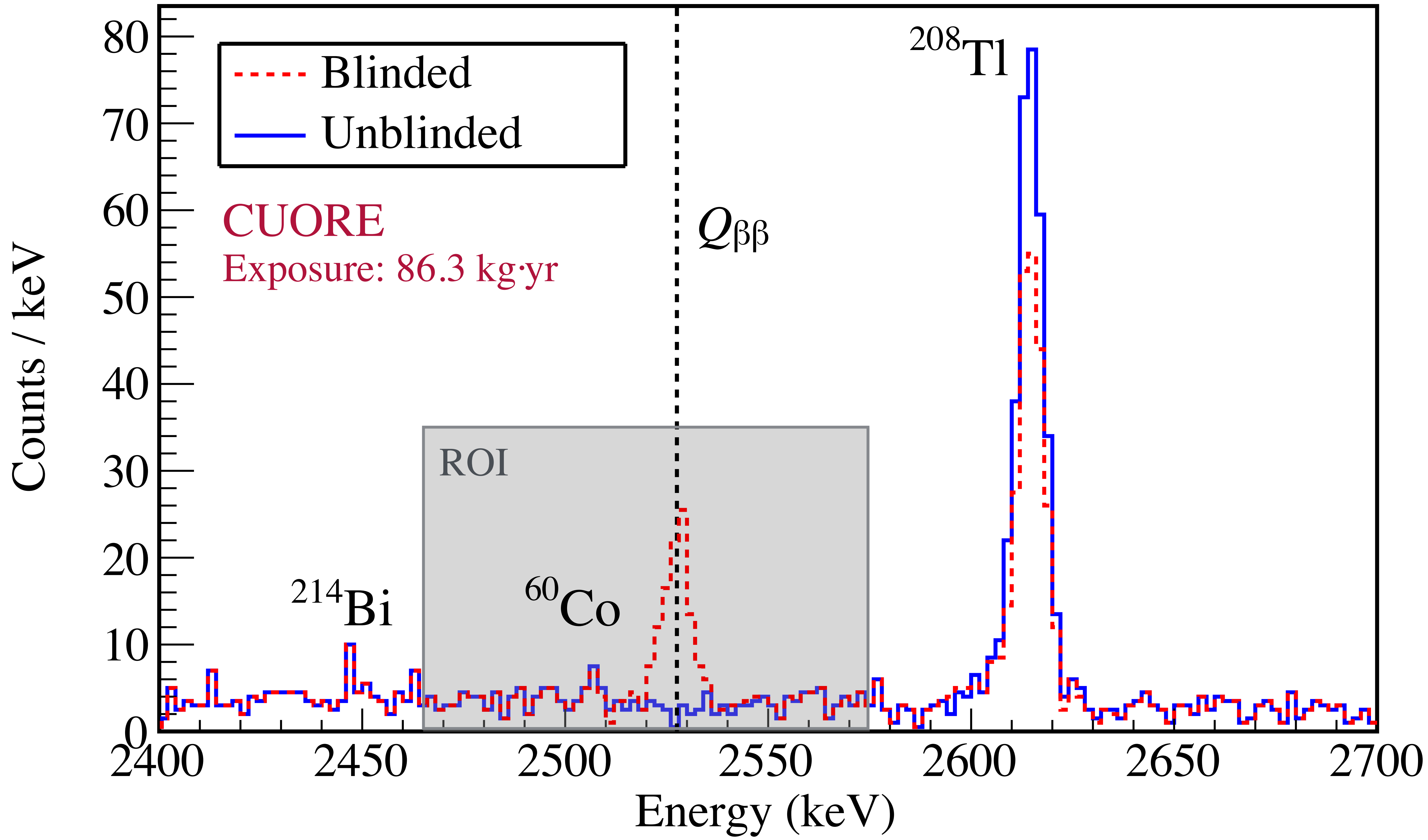
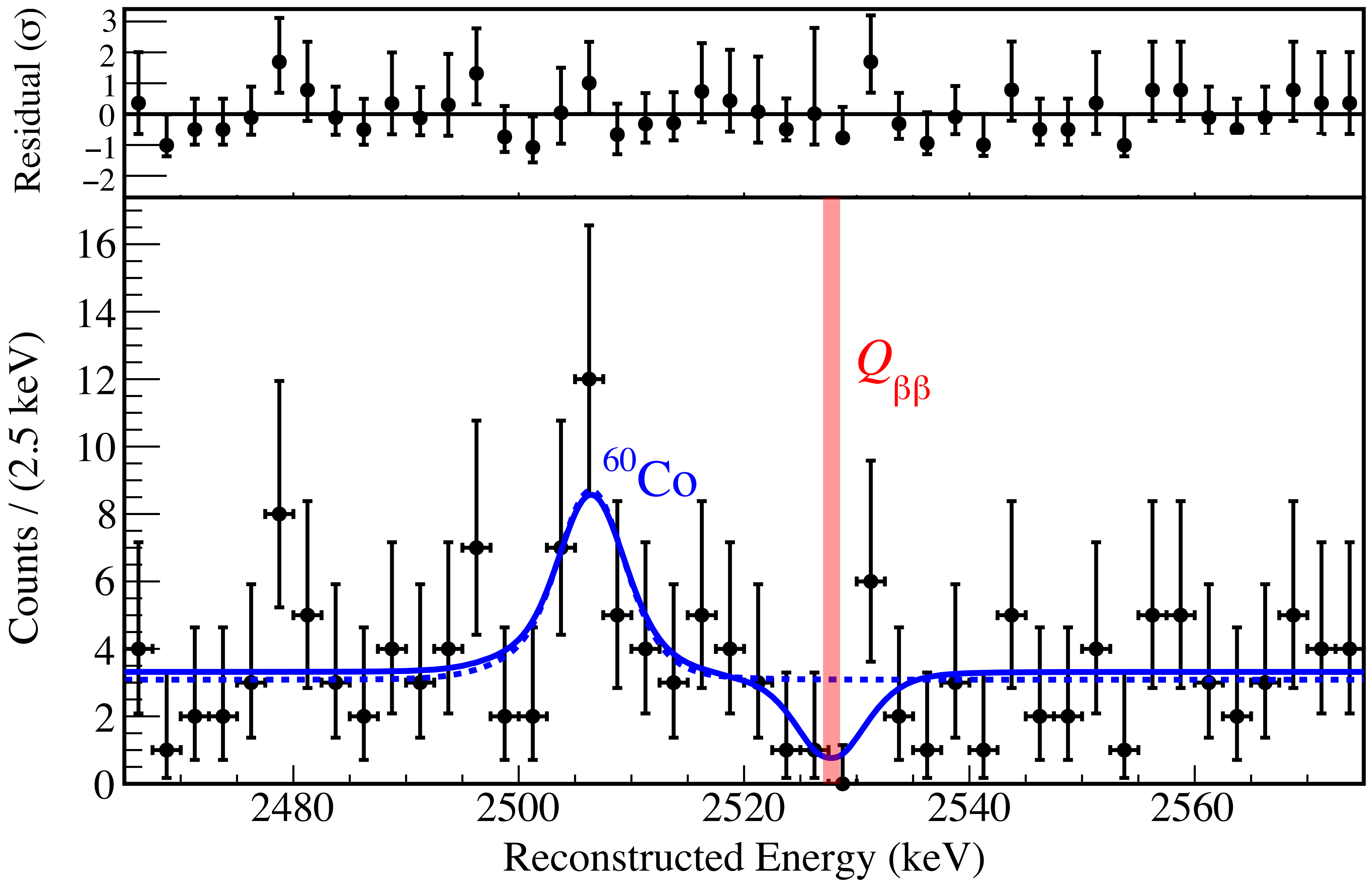


Region of interest

- Unbinned extended maximum likelihood fit in the region of interest
- Using the line shapes in each channel obtained from calibration data
- Floating parameters: 0νββ decay rate, background rate, ^{60}Co location, and ^{60}Co rate



Best-fit decay rate:

$$(-1.0\ ^{+0.4}_{-0.3}\ (\text{stat.})) \times 10^{-25}\ \text{yr}^{-1}$$

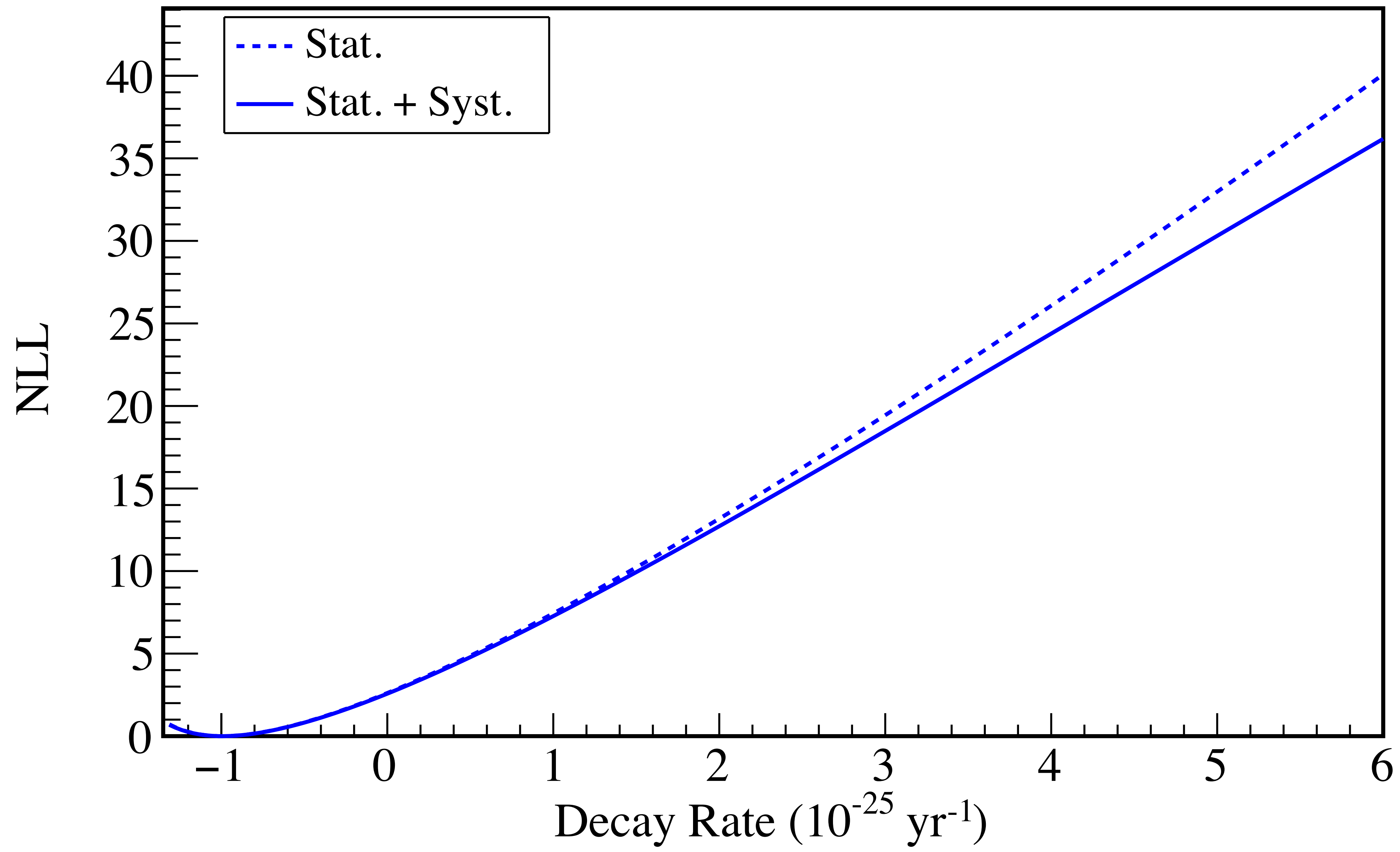
Background index (no-signal model):

$$(0.014 \pm 0.002)\ \text{counts}/(\text{keV kg yr})$$

Systematic uncertainties

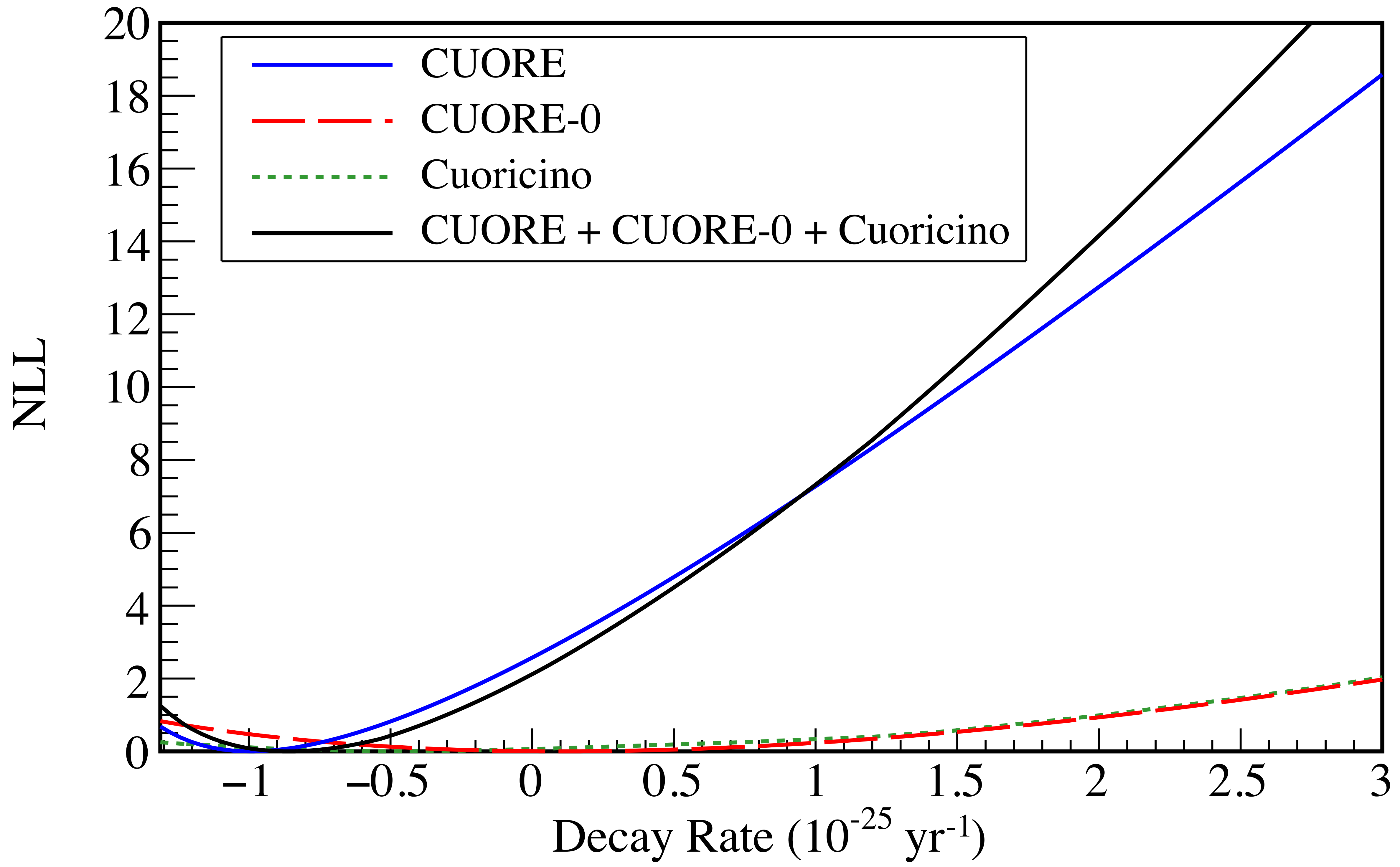
- We account for several systematic uncertainties:
  - Line shape (perhaps the $0\nu\beta\beta$ decay peak does not have the 3-Gaussian structure)
  - Resolution (there is uncertainty in the resolution evaluation due to low background statistics)
  - Efficiency (there is uncertainty in our efficiency for the same reason)
  - Background shape (it could be slightly not flat)
- For each, we evaluate an absolute and relative bias using Monte Carlo simulations and adjust the negative log-likelihood curve appropriately

	Absolute uncertainty [yr^{-25}]	Relative uncertainty [%]
Resolution	—	1.5
Energy reconstruction	—	0.2
Line shape	0.02	2.4
Background shape	0.05	0.8
Efficiency	—	1.8



Half-life limit

- Integrate the negative log-likelihood in the physical region (decay rate > 0) to obtain a 90%-C.L. limit on 0νββ decay



CUORE half-life limit (90% CL):

$$T^{0\nu}_{1/2} > 1.4 \times 10^{25}\ \text{yr}$$

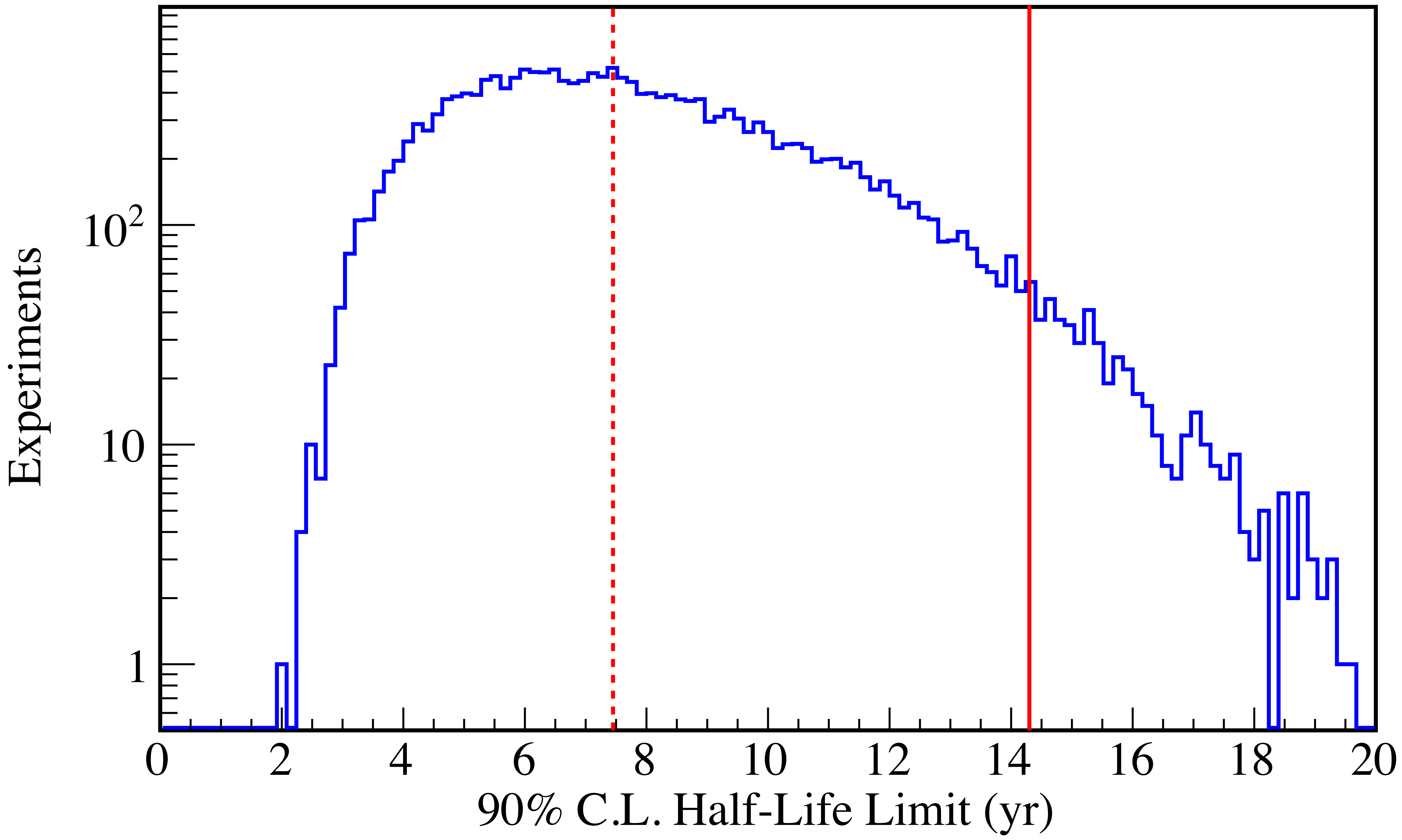
CUORE + CUORE-0 + Cuoricino:

$$T^{0\nu}_{1/2} > 1.5 \times 10^{25}\ \text{yr}$$

Strongest limit on 0νββ decay in ^{130}Te to date

Sensitivity

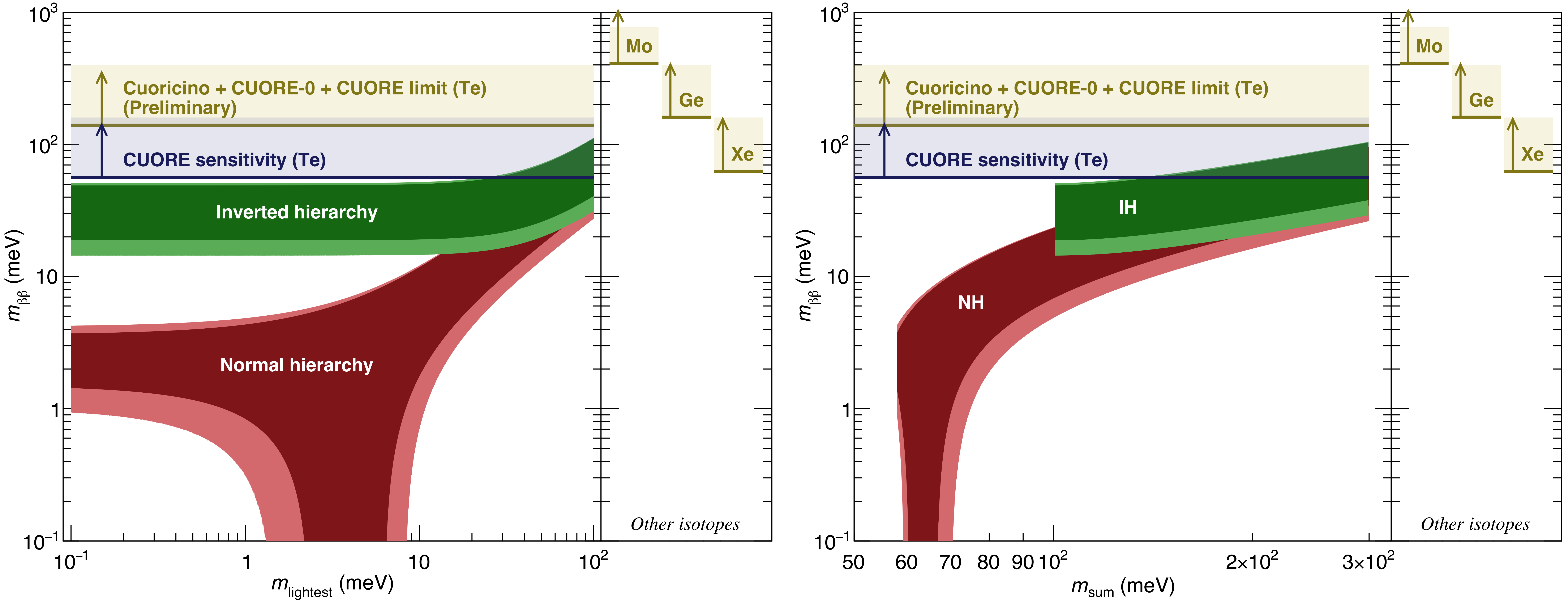
- We perform 20,000 toy Monte Carlo experiments to evaluate median half-life limit given the background rate we observe



- Sensitivity of our search (dashed red line): 7.5×10^{24} y
- Probability of observing a more stringent limit than the one we observe (solid red line): 2.6%

Effective Majorana mass

- We can interpret these results as an effective Majorana neutrino mass assuming:
  - $0\nu\beta\beta$ decay is mediated by light neutrino exchange
  - $g_A = 1.27$ (free space value)
- We obtain $m_{\beta\beta} < 140 - 390$ meV (depending on nuclear matrix elements)

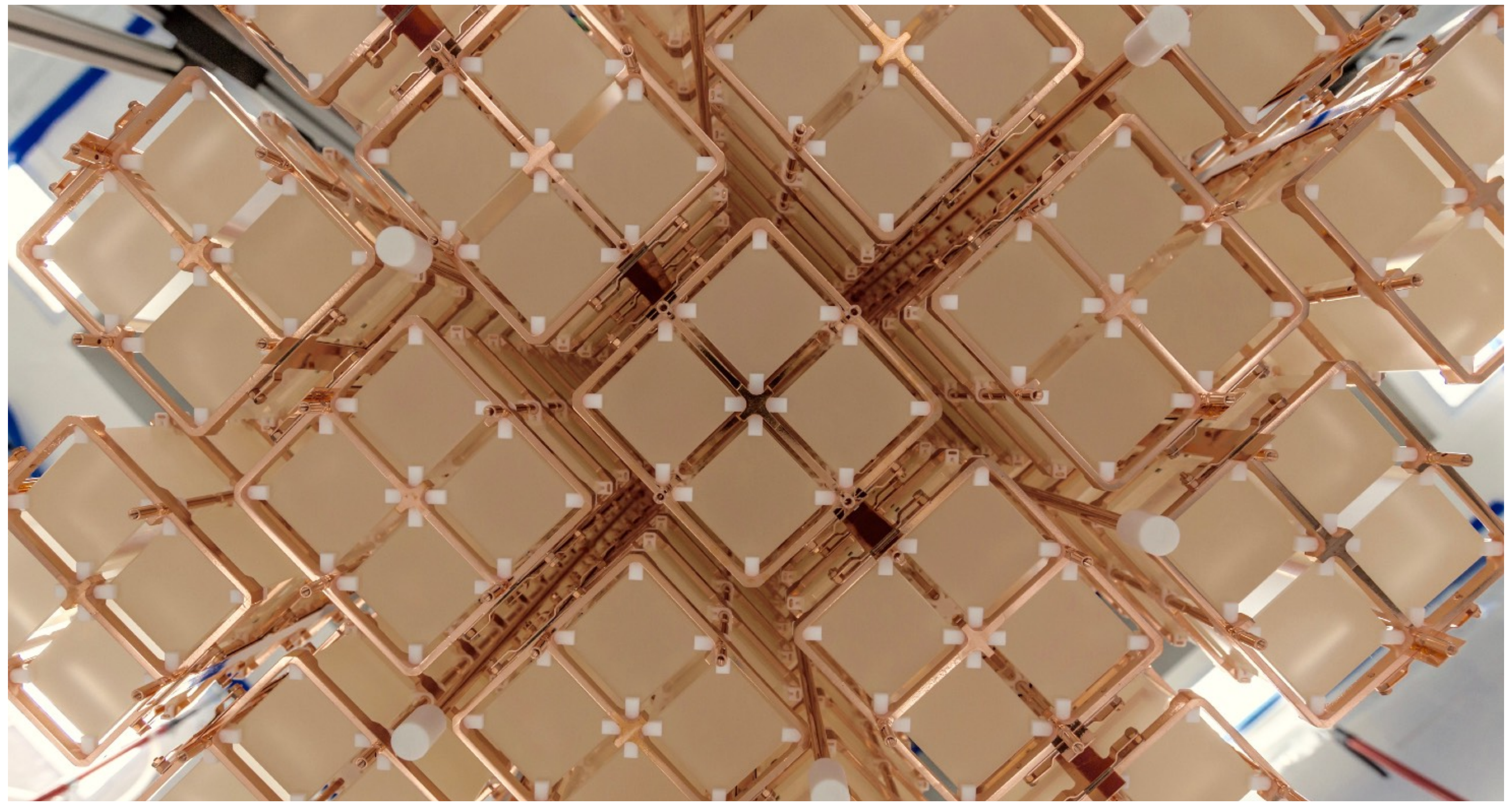


Nuclear matrix elements:
- Phys. Rev. C 91, 034304 (2015)
- Phys. Rev. C 87, 045501 (2013)
- Phys. Rev. C 91, 024613 (2015)
- Nucl. Phys. A 818, 139 (2009)
- Phys. Rev. Lett. 105, 252503 (2010)

Half-life limits:
- ^{130}Te: 1.5×10^{25} yr from this analysis
- ^{76}Ge: 5.3×10^{25} yr from Nature 544, 47–52 (2017)
- ^{136}Xe: 1.1×10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
- ^{100}Mo: 1.1×10^{24} yr from Phys. Rev. D 89, 111101 (2014)
- CUORE sensitivity: 9.0×10^{25} yr

Summary

- We have collected almost 100 kg yr of exposure with CUORE
- CUORE has set a world-leading limit on ^{130}Te 0νββ decay, greater than 10^{25} years: arXiv:1710.07988
- The CUORE cryostat, a huge engineering feat, has been operating smoothly and reliably in these first datasets
- With 5 years of live time, the sensitivity of CUORE will improve by over an order of magnitude from its current value
- Thanks to the DOE Office of Science, Nuclear Physics, and Yale University for funding this research
- More physics results are on the way!

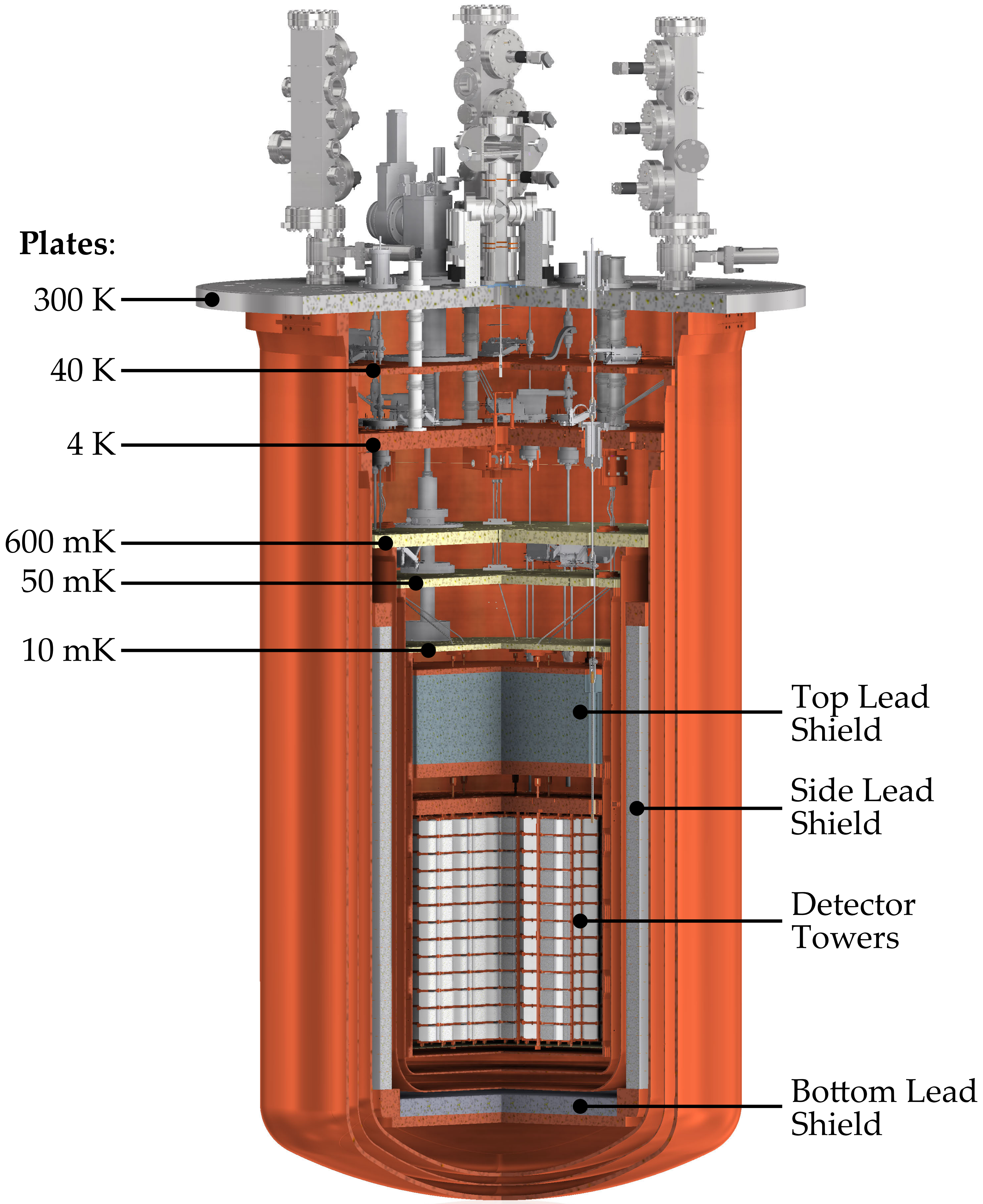


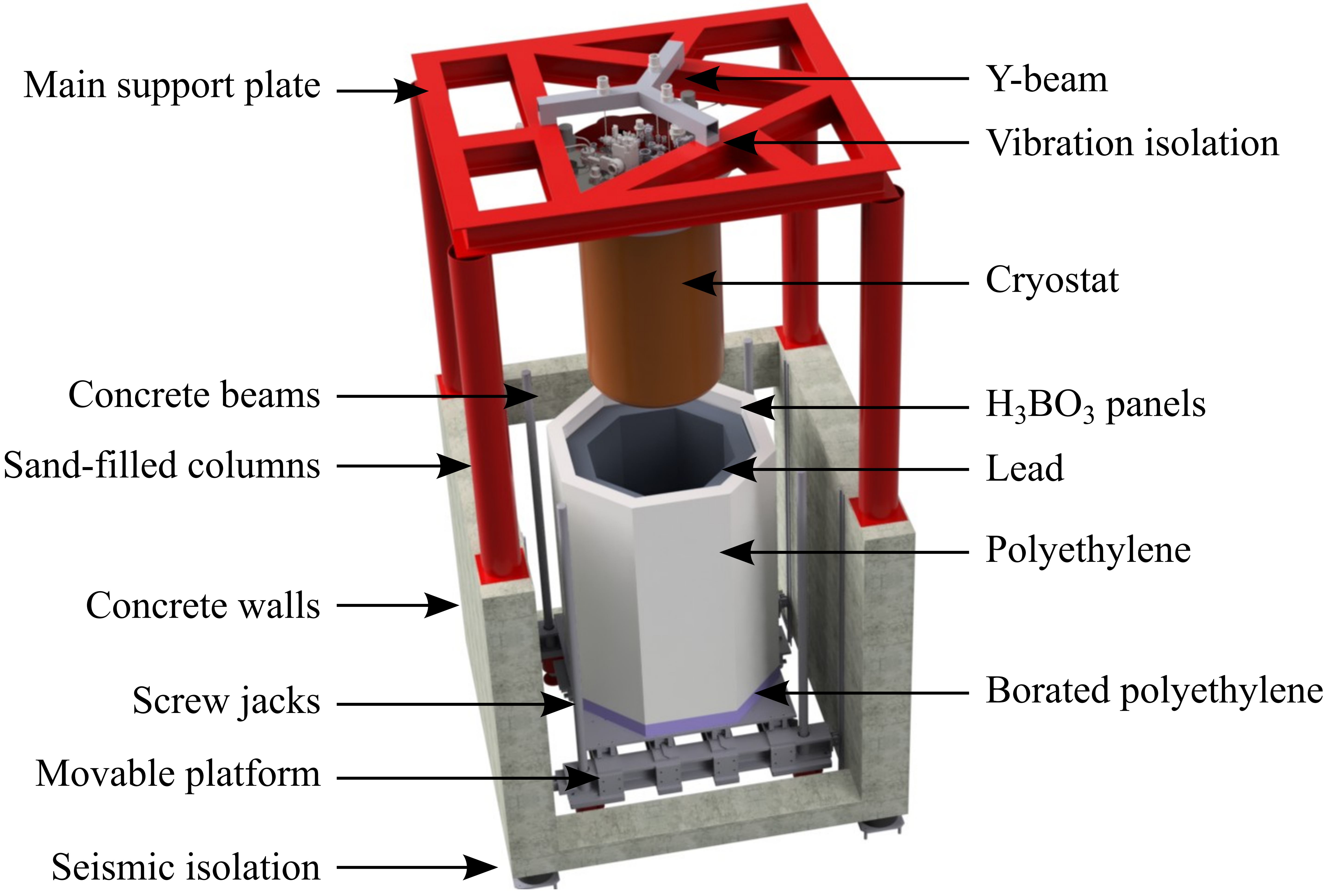
Thanks

Thank you to all current and former members of the Yale CUORE group!
Karsten Heeger, Reina Maruyama, Tom Wise, Ke Han, Kyungeun Lim, Danielle Speller, Christopher Davis, Surya Dutta, Byron Daniel, Katie Melbourne, Ivy Wanta, Nikita Dutta, Basil Smitham

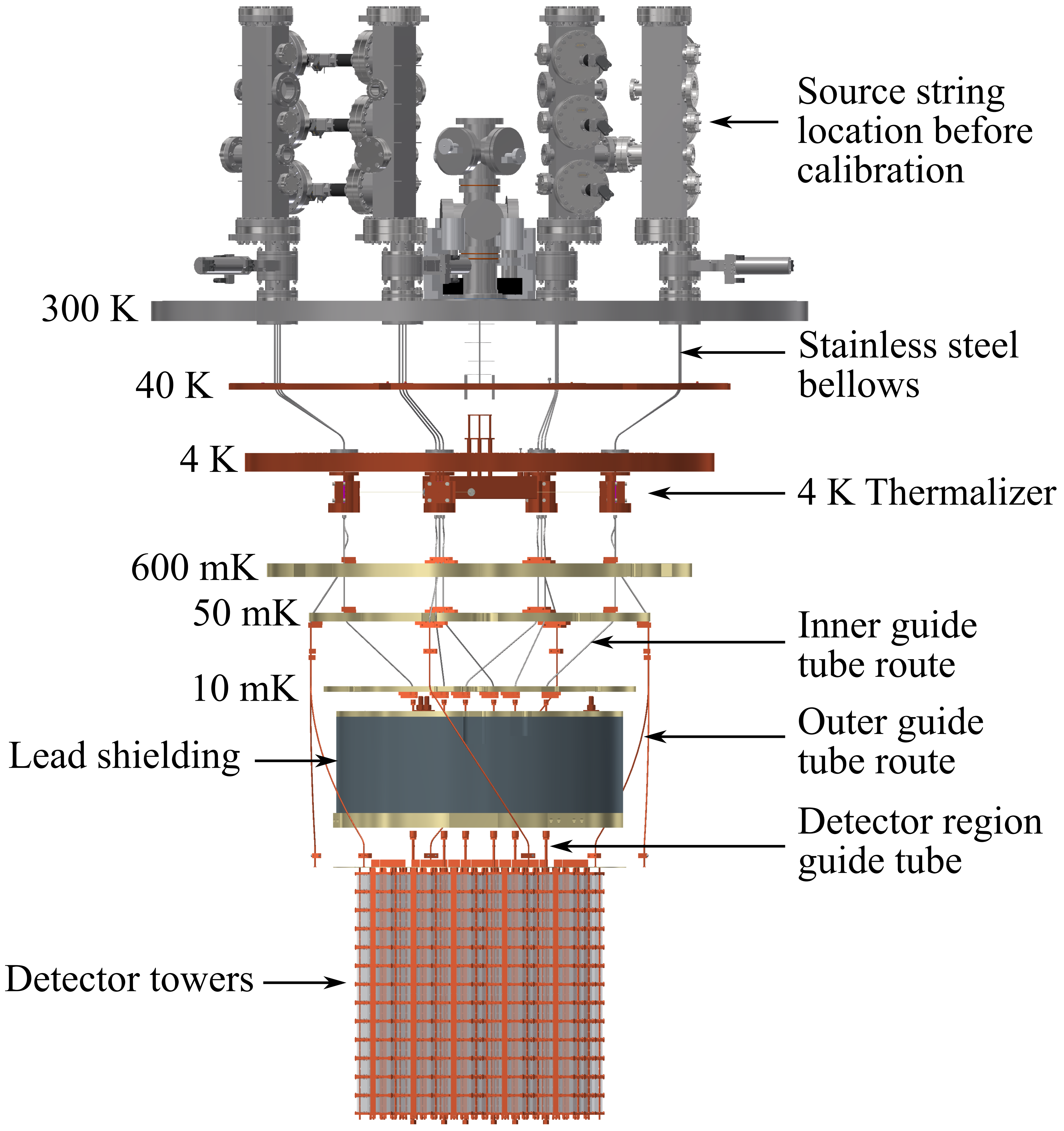
Backup

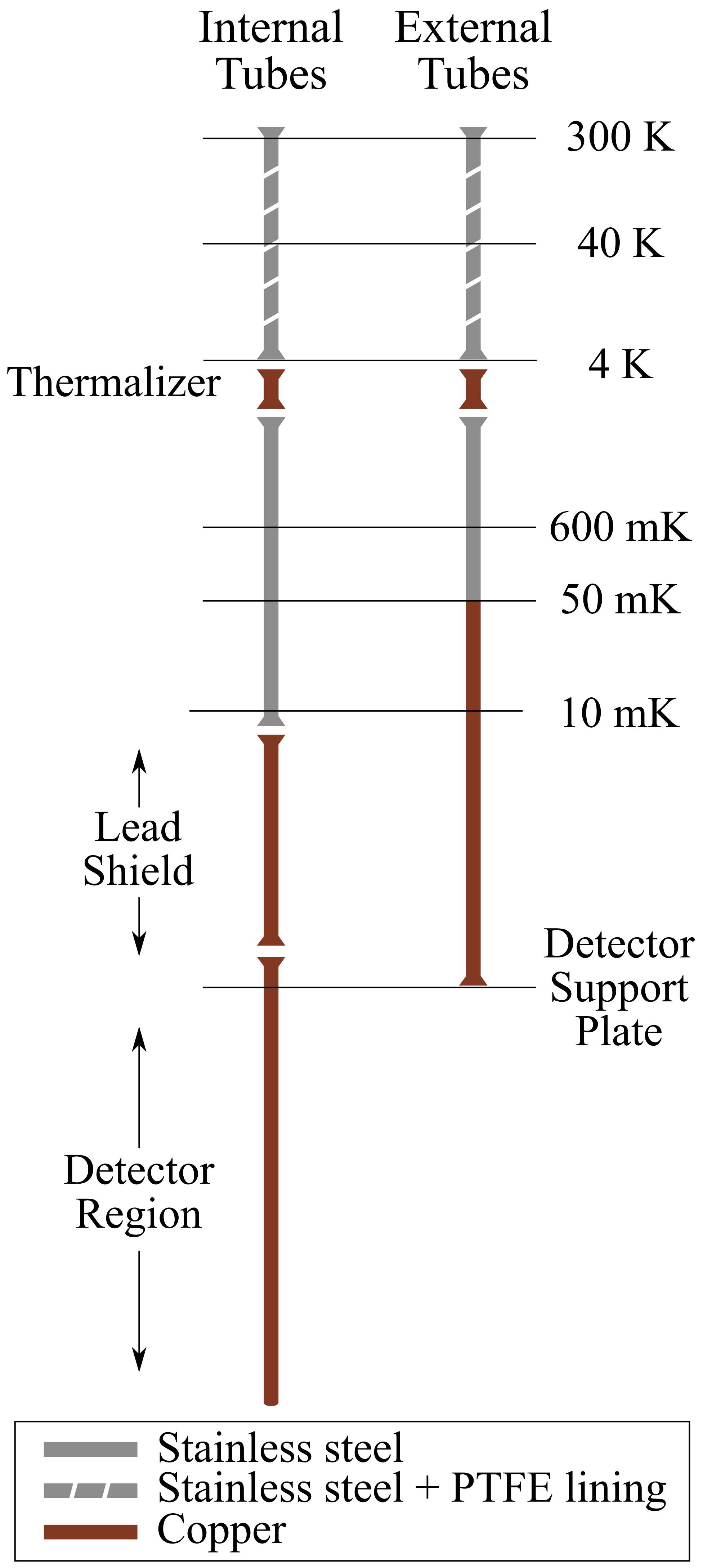
Cryostat support structure





Calibration integration





Line fitting strategy

- Perform a simultaneous unbinned extended maximum likelihood fit over all channels, with a separate fit for each line in the background spectrum
- Fit parameters:
  - Fixed, and split by channel:
    - Exposure (some channels were not live in some datasets)
    - Reference width (each channel has a different resolution)
  - Floating, and split into two layers (inner and outer detectors):
    - Peak rate (counts/kg yr)
    - Background rate (counts/keV kg yr)
  - Floating, and common to all channels:
    - Peak mean (floating in order to evaluate our energy reconstruction)
    - Overall scaling of resolution (the resolution is energy-dependent)

Line fit results

Energy [keV]	Signal rate [counts/(kg·yr)]	Background rate [counts/(keV·kg·yr)]	FWHM resolution [keV]	Bias [keV]
2614.511	2.04 ± 0.33 (inner) 6.07 ± 0.34 (outer)	0.011 ± 0.002 (inner) 0.015 ± 0.002 (outer)	8.40 ± 0.64 (DS 1) 7.18 ± 0.43 (DS 2)	0.02 ± 0.18
1460.822	44.0 ± 1.5 (inner) 64.1 ± 1.2 (outer)	0.418 ± 0.073 (inner) 0.453 ± 0.099 (outer)	5.54 ± 0.13 (DS 1) 5.58 ± 0.11 (DS 2)	-0.02 ± 0.07
1332.492	14.0 ± 1.0 (inner) 47.2 ± 1.0 (outer)	0.561 ± 0.018 (inner) 0.581 ± 0.022 (outer)	5.23 ± 0.15 (DS 1) 5.68 ± 0.16 (DS 2)	-0.12 ± 0.05
1173.228	13.6 ± 1.0 (inner) 44.4 ± 1.0 (outer)	0.790 ± 0.022 (inner) 0.981 ± 0.037 (outer)	4.90 ± 0.18 (DS 1) 4.88 ± 0.14 (DS 2)	-0.08 ± 0.05
911.204	3.64 ± 0.78 (inner) 7.88 ± 0.67 (outer)	1.18 ± 0.03 (inner) 1.56 ± 0.03 (outer)	3.74 ± 0.50 (DS 1) 4.45 ± 0.51 (DS 2)	0.06 ± 0.16
834.848	4.87 ± 0.87 (inner) 18.3 ± 0.8 (outer)	1.29 ± 0.03 (inner) 1.77 ± 0.05 (outer)	4.12 ± 0.27 (DS 1) 4.68 ± 0.23 (DS 2)	0.12 ± 0.11

ROI fit

$$f(E) = \xi_C \xi_\gamma \varepsilon R_{\beta\beta} \left[\mathcal{N}(\chi_{\beta\beta}\mu, \eta\sigma; E) + \kappa_L \mathcal{N}(\epsilon_L \chi_{\beta\beta}\mu, \eta\sigma; E) + \kappa_R \mathcal{N}(\epsilon_R \chi_{\beta\beta}\mu, \eta\sigma; E)\right]$$

$$+ \xi_\gamma \varepsilon R_{\mathrm{Co}} e^{-t/\tau_{\mathrm{Co}}} \left[\mathcal{N}(\chi_{\mathrm{Co}}\mu, \eta\sigma; E) + \kappa_L \mathcal{N}(\epsilon_L \chi_{\mathrm{Co}}\mu, \eta\sigma; E) + \kappa_R \mathcal{N}(\epsilon_R \chi_{\mathrm{Co}}\mu, \eta\sigma; E)\right]$$

$$+ \varepsilon b \Delta E.$$

$$\hat{R}_{\beta\beta} = (-0.13 \pm 0.04)\ \text{counts}/(\text{kg}\cdot\text{yr})$$

$$\hat{R}_{\mathrm{Co}} = (0.23 \pm 0.08)\ \text{counts}/(\text{kg}\cdot\text{yr})$$

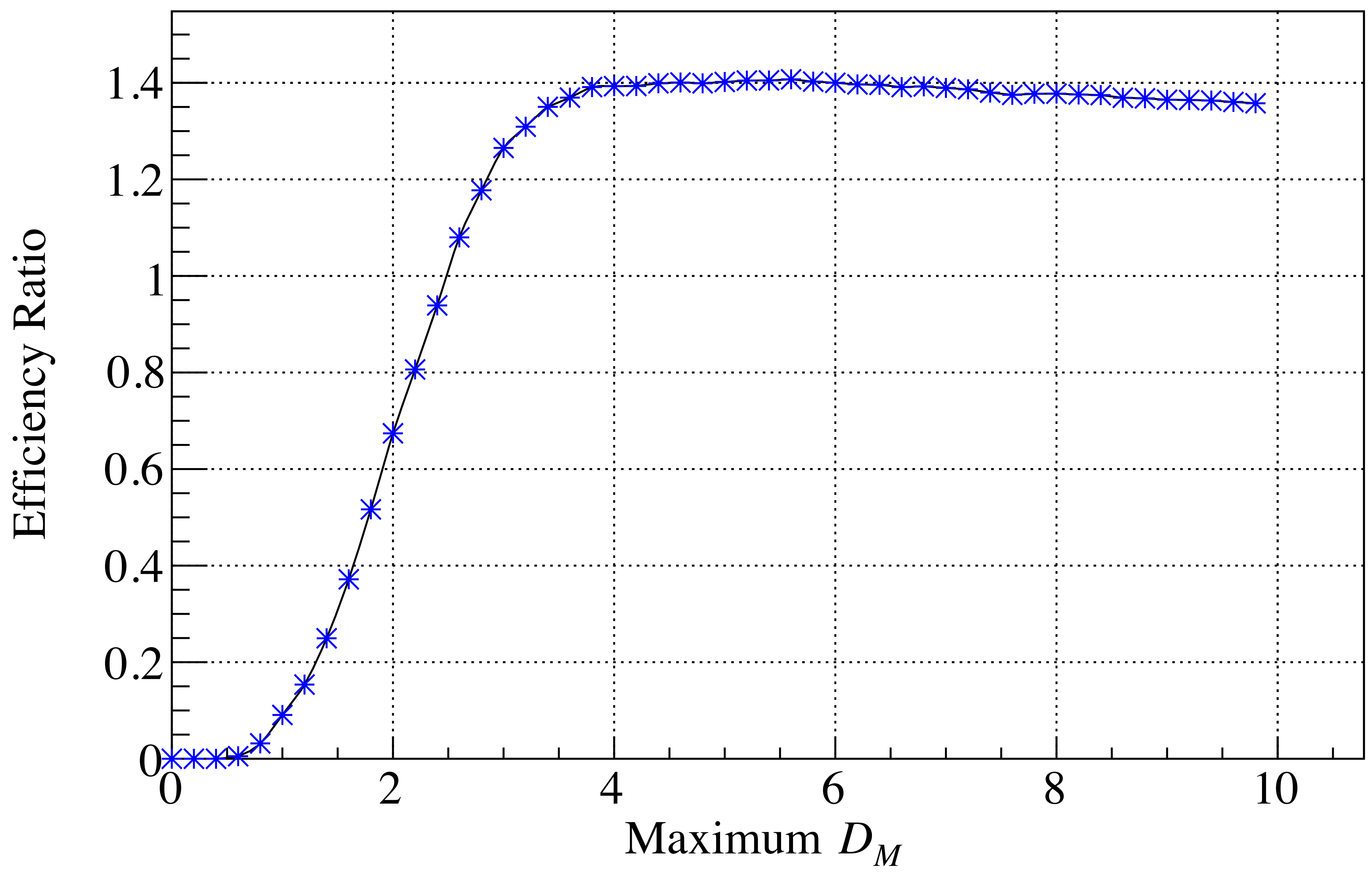
$$\hat{b}_1 = (0.016 \pm 0.002)\ \text{counts}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$$

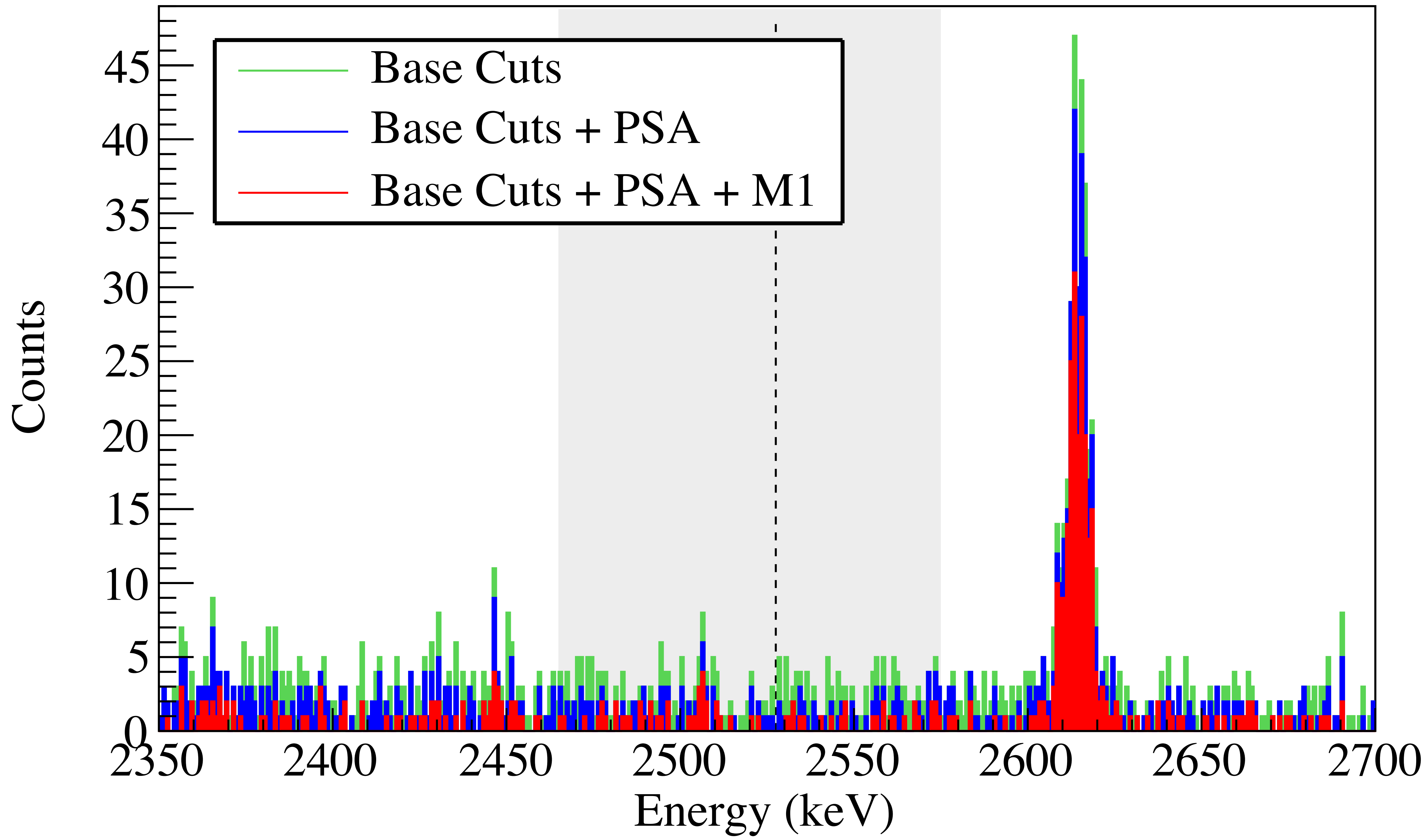
$$\hat{b}_2 = (0.015 \pm 0.002)\ \text{counts}/(\text{keV}\cdot\text{kg}\cdot\text{yr}).$$

$$\Gamma^{0\nu} = R_{\beta\beta} \times \frac{\mathcal{M}_{\mathrm{TeO_2}}}{a N_A} = R_{\beta\beta} \times \frac{159.6\ \mathrm{g\,mol^{-1}}}{(0.3417)(6.022 \times 10^{23}\ \mathrm{mol^{-1}})}$$

$$\hat{\Gamma}^{0\nu} = (-0.99^{+0.37}_{-0.27}) \times 10^{-25}\ \mathrm{yr}^{-1}$$

Pulse shape cuts

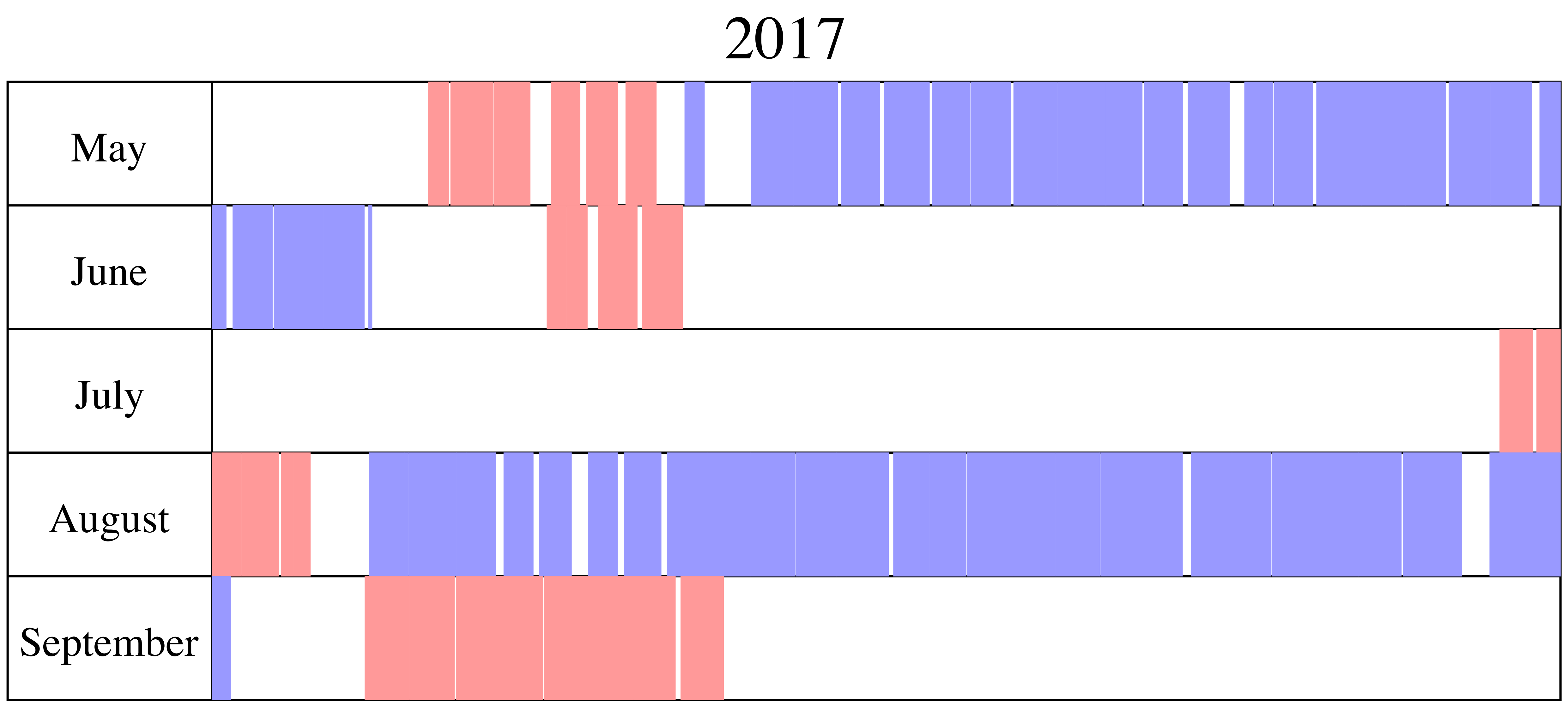


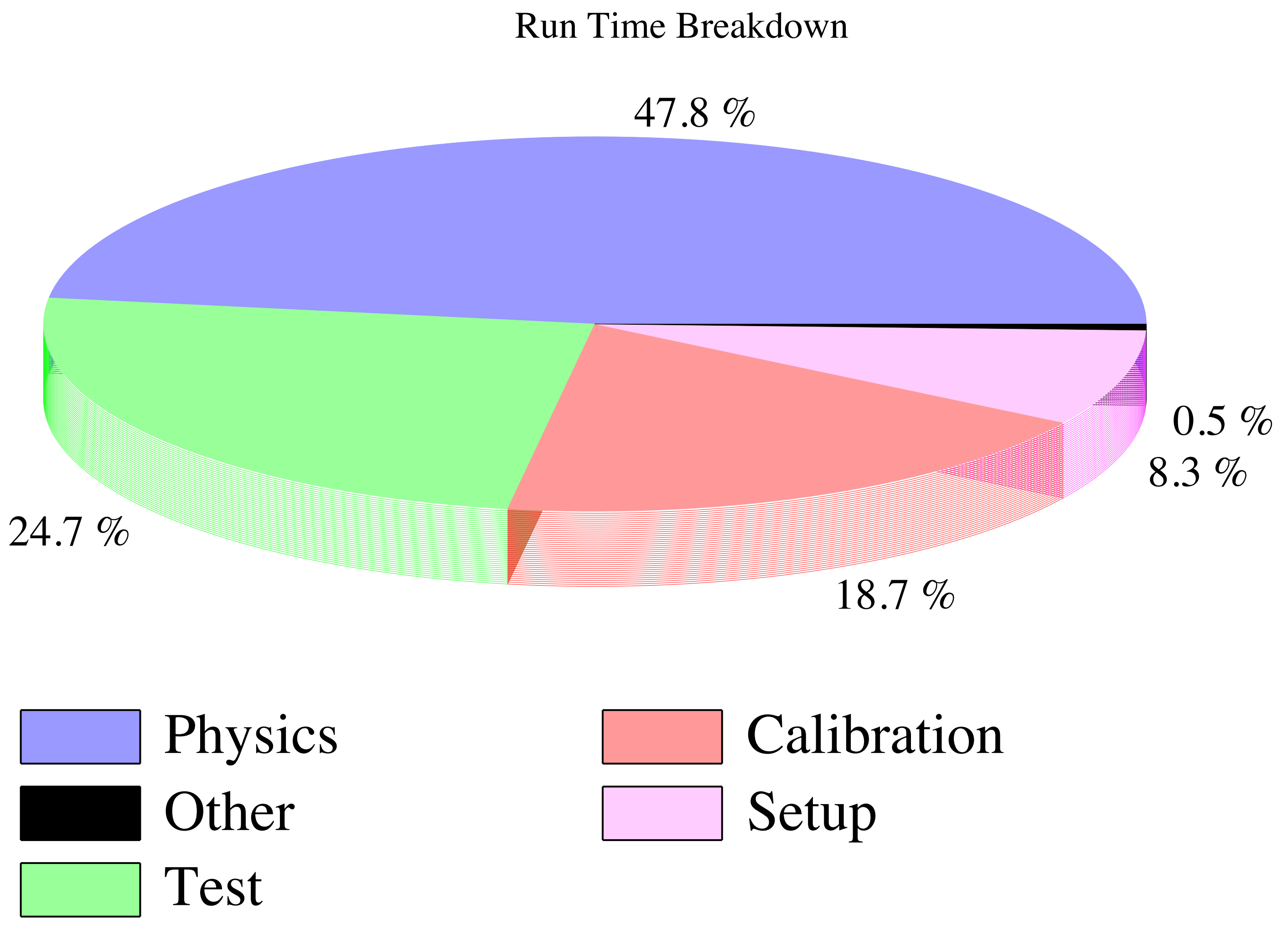


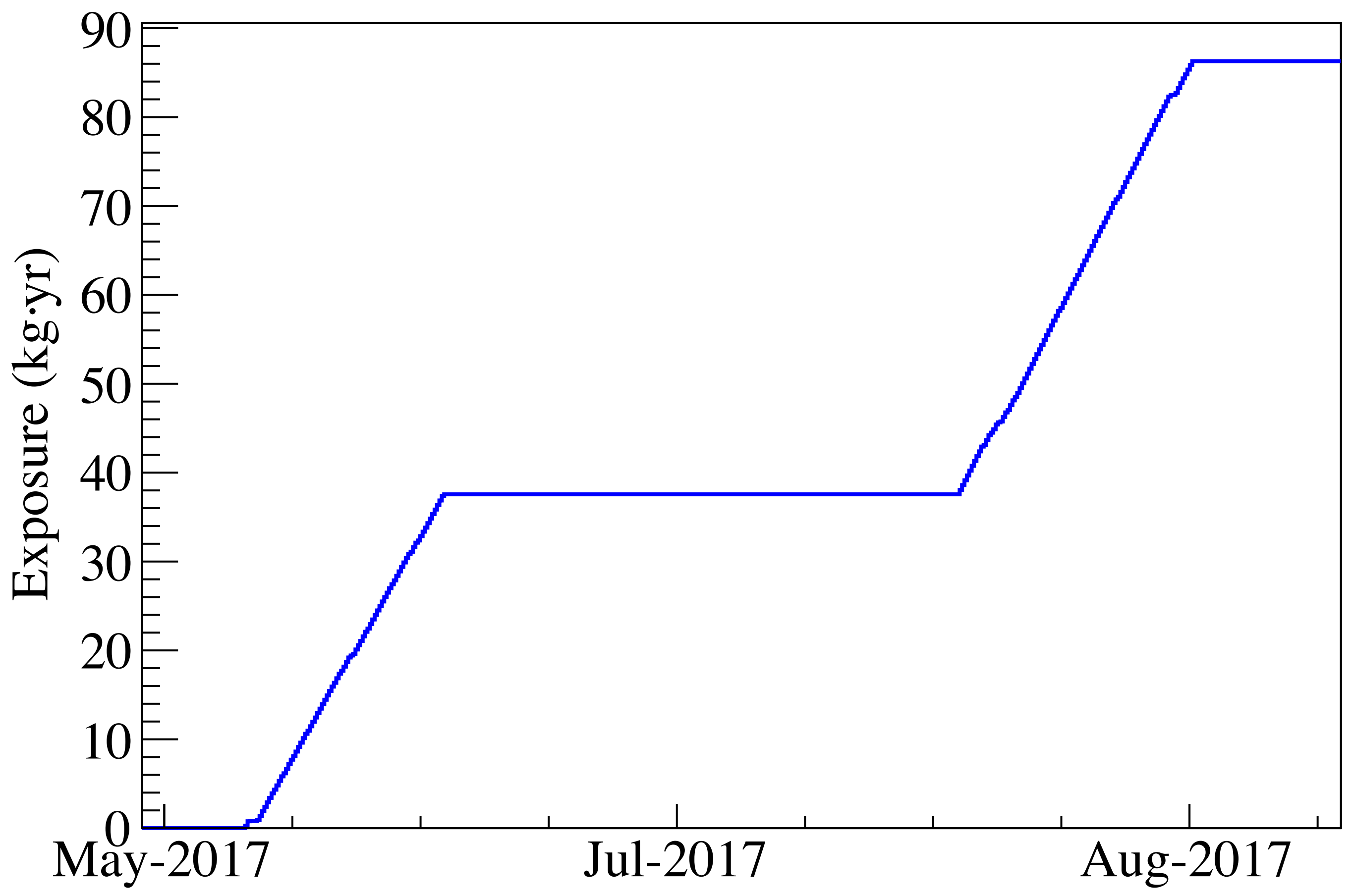
$$D_M(\vec{x}) = \sqrt{(\vec{x}-\vec{\mu})^T S^{-1}(\vec{x}-\vec{\mu})},$$

where $\vec{\mu}$ is the vector of parameter means and S is the covariance matrix.

Run time breakdown

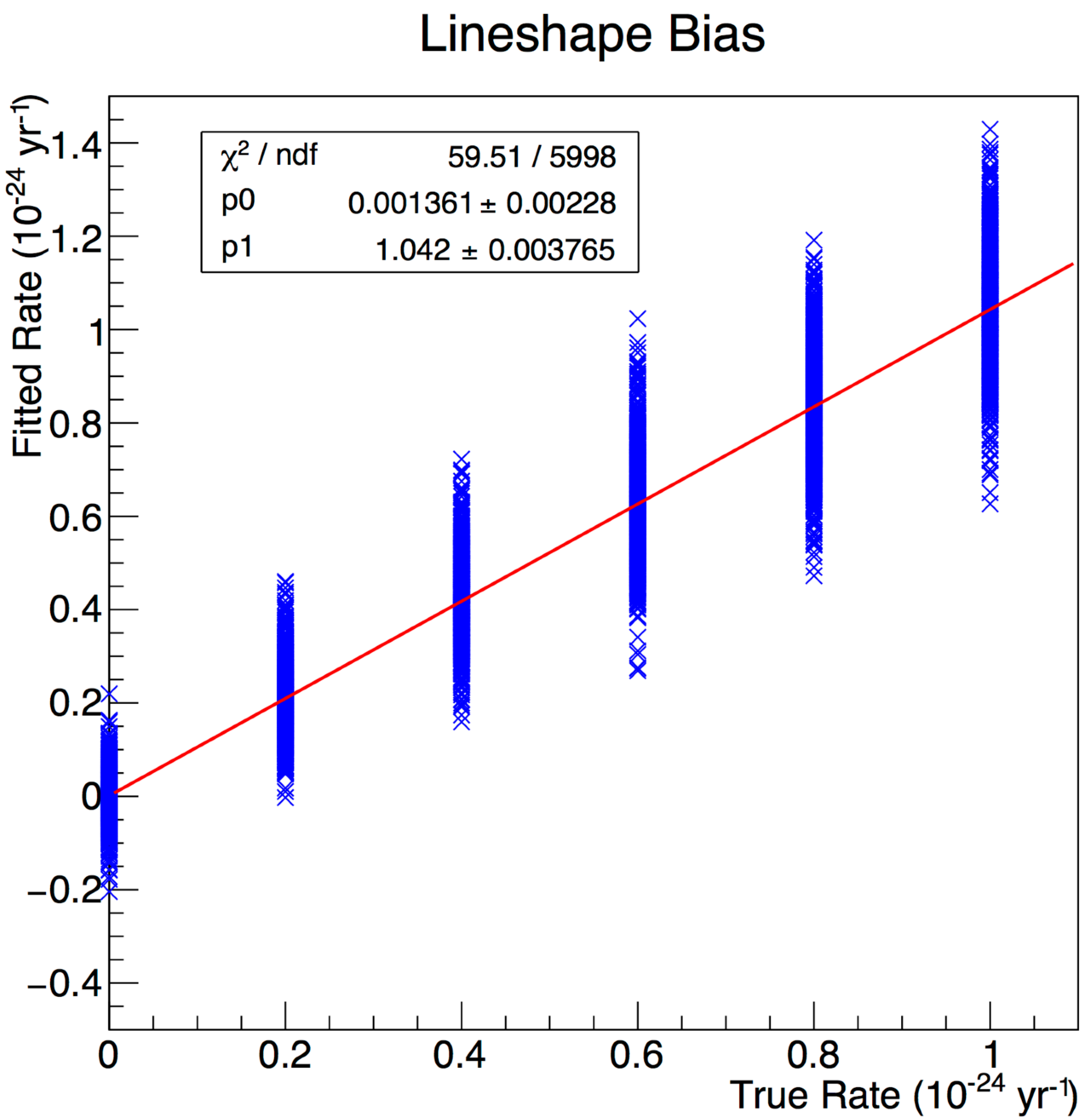






155 ROI pulses

Systematics

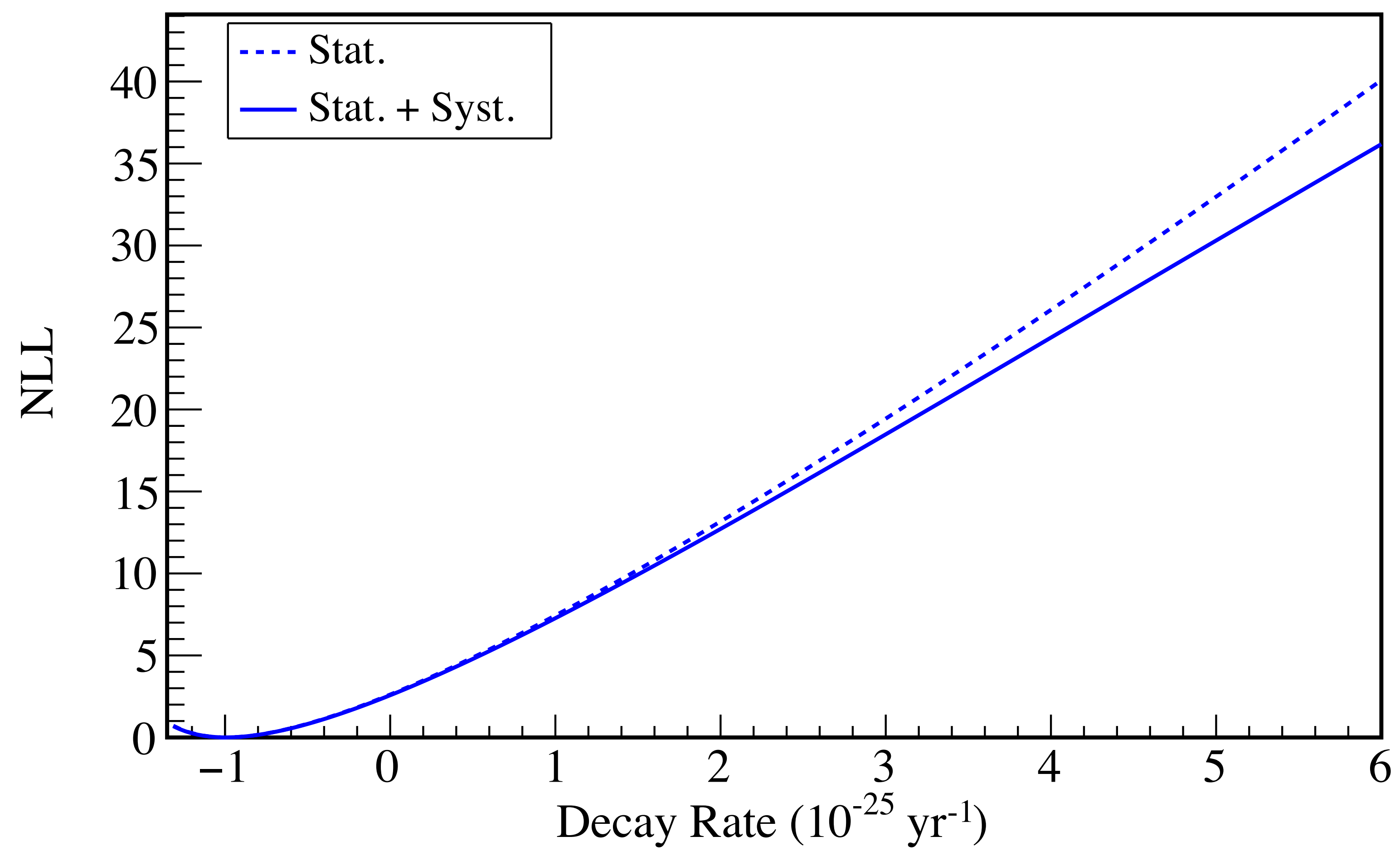


$$\chi^2_{\text{stat}} = -2\left(\text{NLL} - \text{NLL}_0\right)$$

$$\chi^2_{\text{syst}} = \frac{\Gamma^{0\nu} - \hat{\Gamma}^{0\nu}}{\sigma_{\text{syst}}\left(\Gamma^{0\nu}\right)}, \qquad \sigma_{\text{syst}}\left(\Gamma^{0\nu}\right) = \sum_i \left(\sigma_{i,\text{abs}} + \Gamma^{0\nu}\sigma_{i,\text{rel}}\right)^2$$

$$\frac{1}{\chi^2_{\text{tot}}} = \frac{1}{\chi^2_{\text{stat}}} + \frac{1}{\chi^2_{\text{syst}}}$$

$$\text{NLL} = -\tfrac{1}{2}\chi^2_{\text{tot}}$$



Models for nuclear matrix elements

- Interacting Shell Model (ISM)
  - Nucleus is a collection of fermions that obey the Pauli Exclusion Principle
  - Basis states are harmonic oscillator states with perturbations
  - Includes all possible shell configurations, sums over a small number of state energies (computational limitations)
- Quasi-Random Phase Approximation (QRPA)
  - Uses particle–hole pair and quasiparticle dynamics to include a larger number of energy states, but in fewer shell configurations
- Interacting Boson Model (IBM)
  - Considers pairs of protons or neutrons as bosons
  - Useful for even-even nuclei

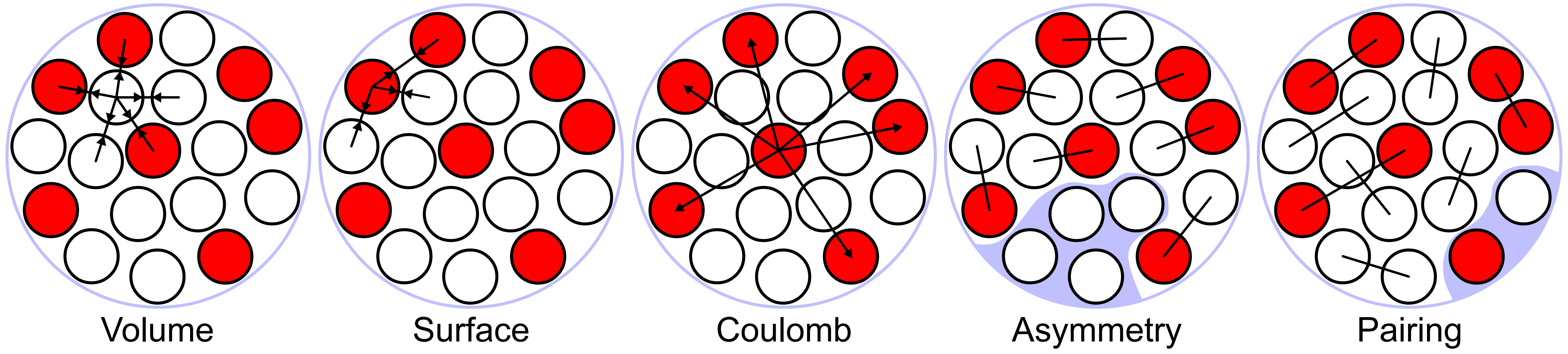
$$M_{0\nu} = \langle {}^{A}\mathrm{X}; 0_1^+ | H | {}^{A}\mathrm{Y}; J_F \rangle$$

$$M_{0\nu} = g_A^2 \left[M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A} \right)^2 M_F^{(0\nu)} + M_T^{(0\nu)} \right]$$

Semi-empirical mass formula

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{ even } (A \text{ even}) \\ 0 & A \text{ odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$



https://en.wikipedia.org/wiki/File:Liquid_drop_model.svg

Neutrino mass

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} = \begin{bmatrix}0.82\pm0.01 & 0.54\pm0.02 & -0.15\pm0.03\\ -0.35\pm0.06 & 0.70\pm0.06 & 0.62\pm0.06\\ 0.44\pm0.06 & -0.45\pm0.06 & 0.77\pm0.06\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$= \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1} & 0 & 0\\ 0 & e^{i\alpha_2} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

Double beta decay

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

Single beta decay

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$