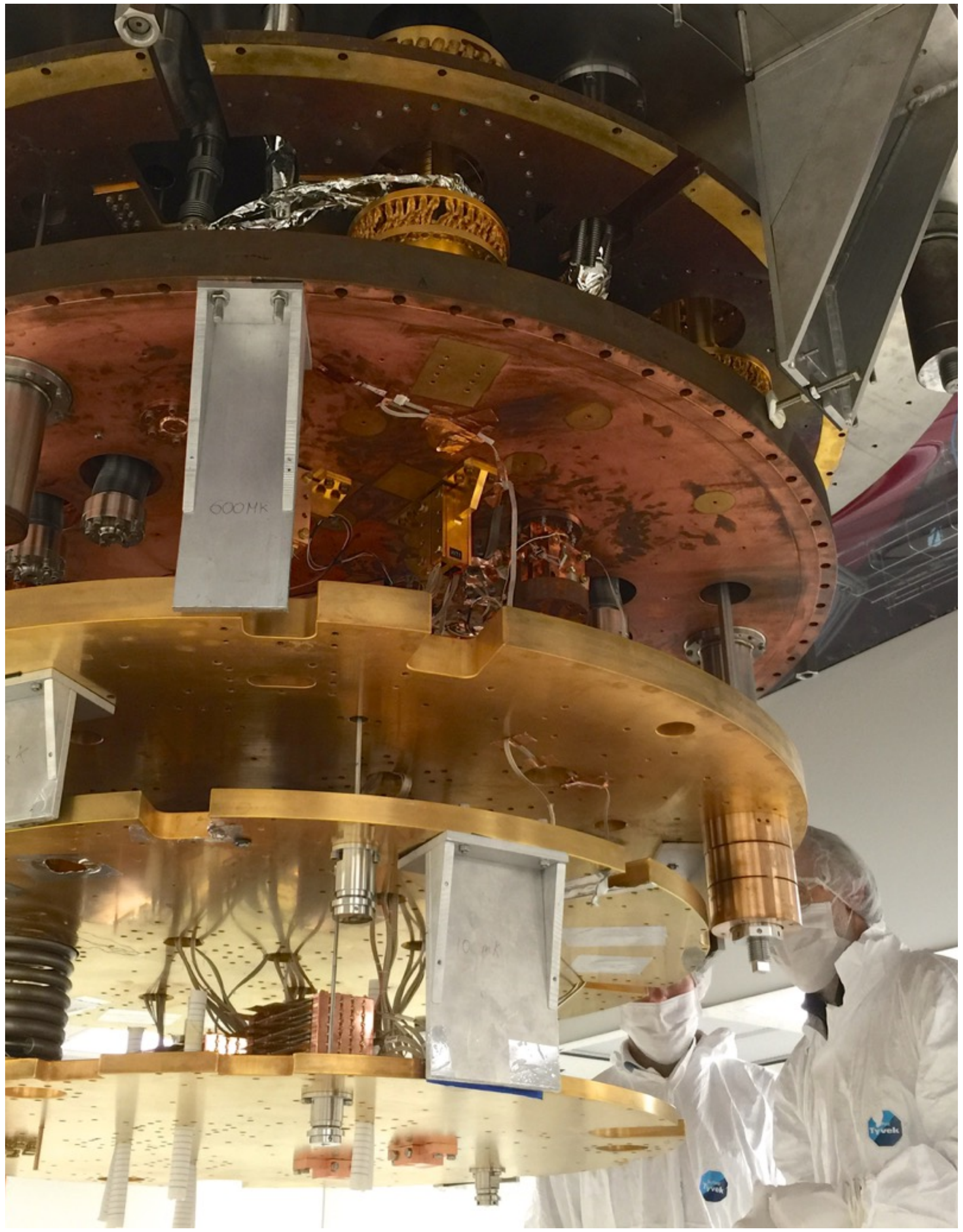
CUORE:
A Search for Neutrinoless Double Beta Decay

Jeremy Cushman

WIDG, 2/24/15

Outline

- History and background
- CUORE detector and cryostat
- Calibration
  - Analysis
  - Detector Calibration System
- Status and prospects



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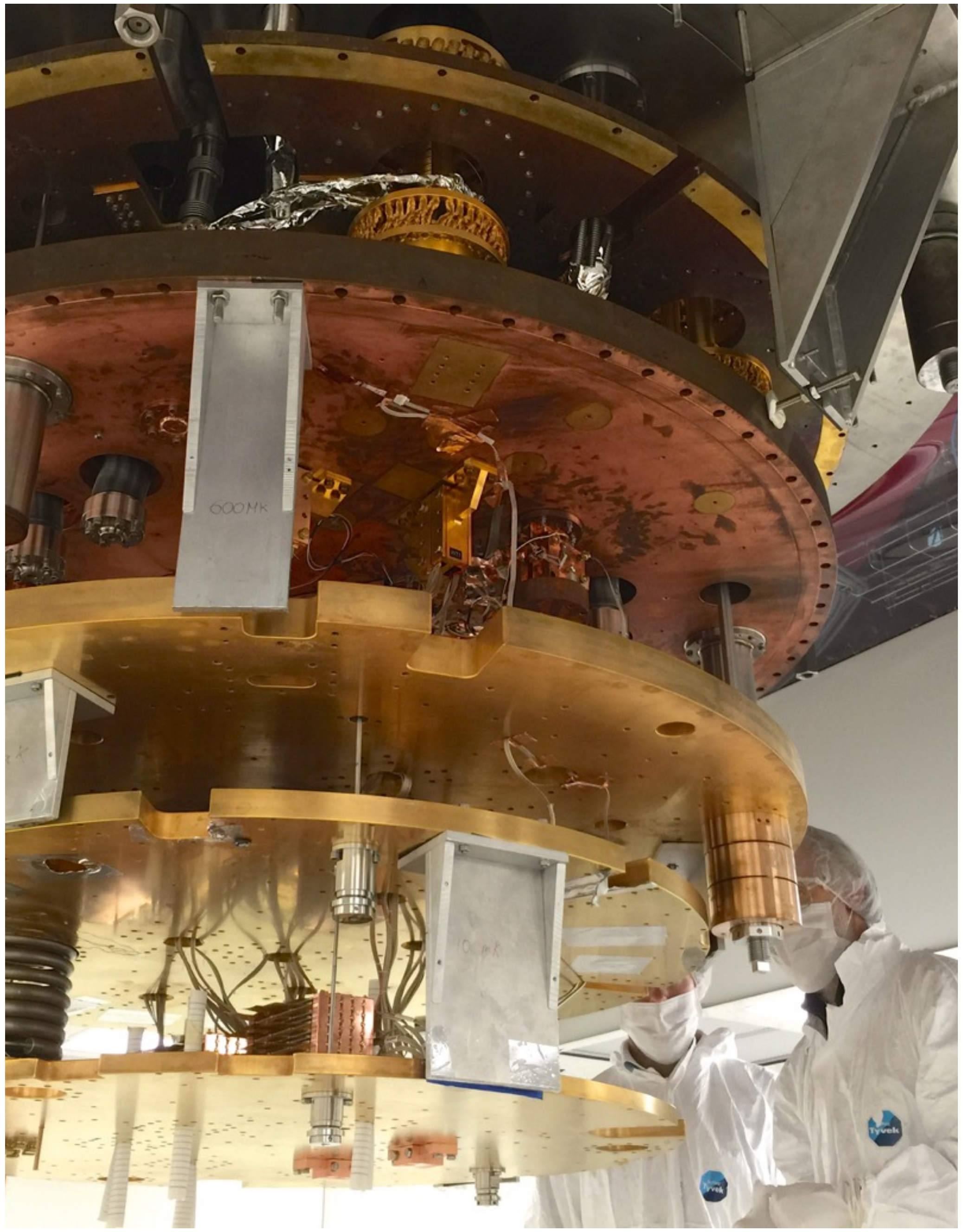
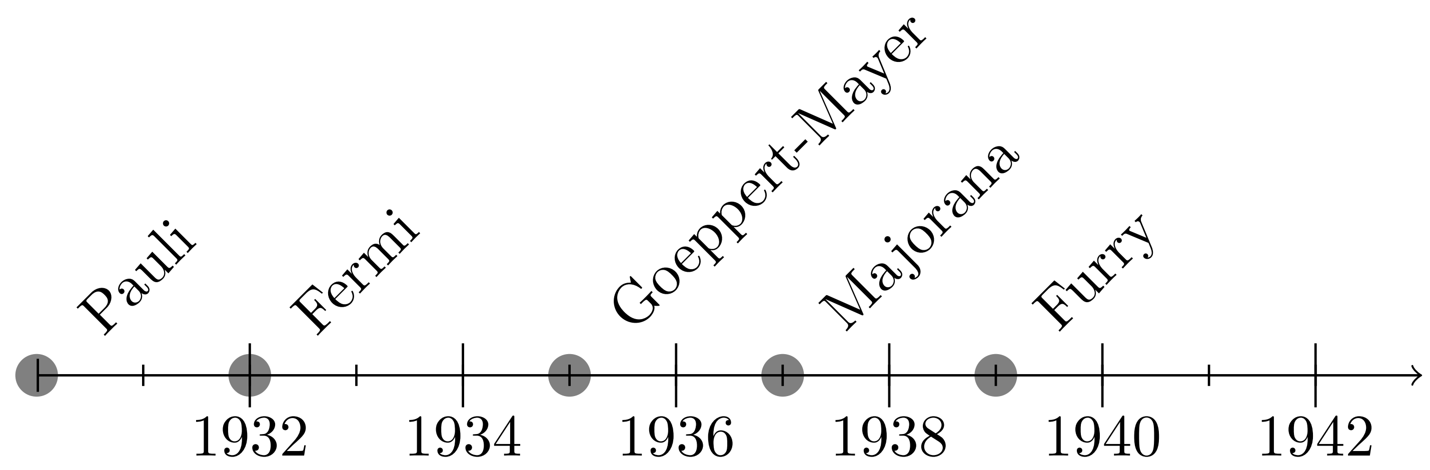


The early days

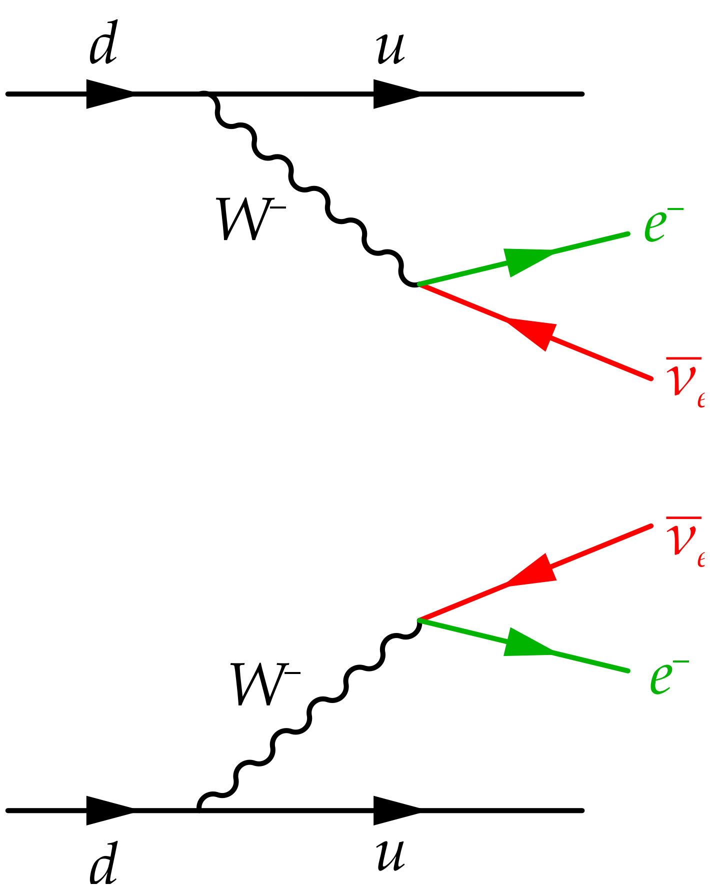


- **Pauli** proposes the idea of the neutrino to conserve energy and momentum in beta decays.
- **Fermi** creates a formal theory of beta decay incorporating the neutrino
- **Goeppert-Mayer** postulates double beta decay: if particles can decay by emitting an electron and a neutrino, they should also 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 two electrons and no neutrinos

Double beta decays

Ordinary (2νββ)

Observed in several isotopes

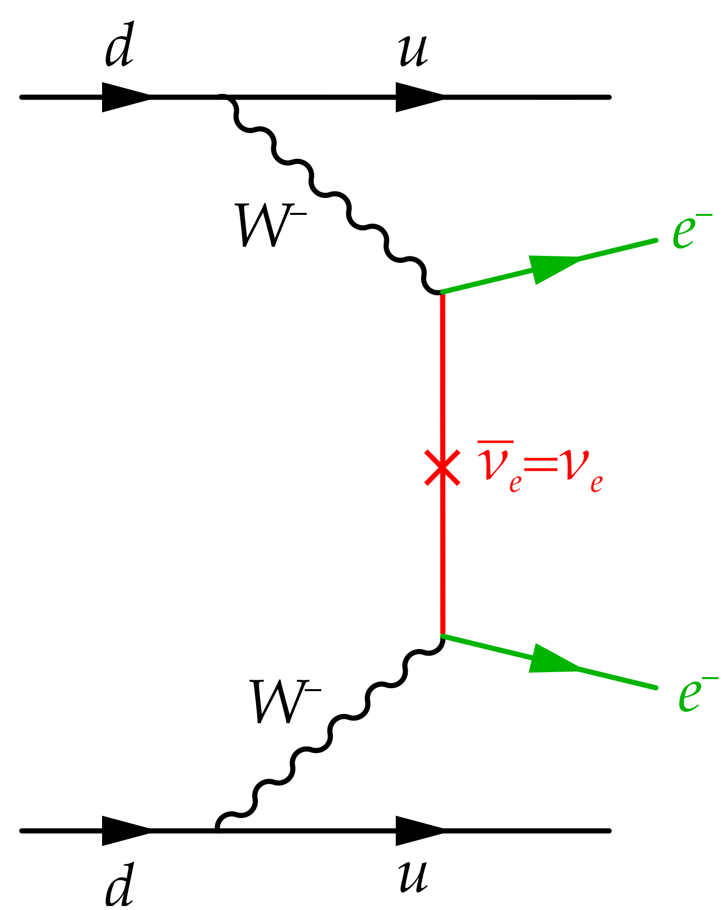


$$2n \rightarrow 2p + 2e^- + 2\overline{\nu}_e$$

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

Neutrinoless (0νββ)

Hypothesized if neutrinos are Majorana fermions

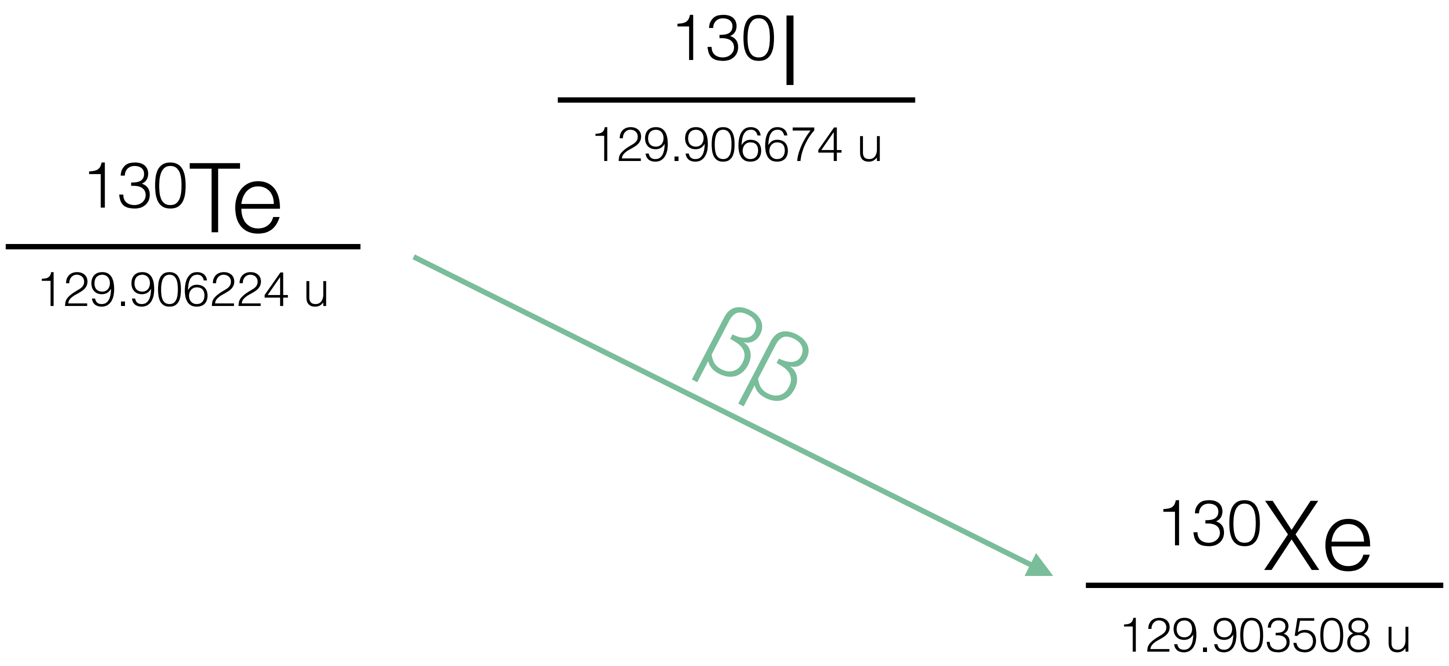


$$2n \rightarrow 2p + 2e^-$$

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

Can we see it?

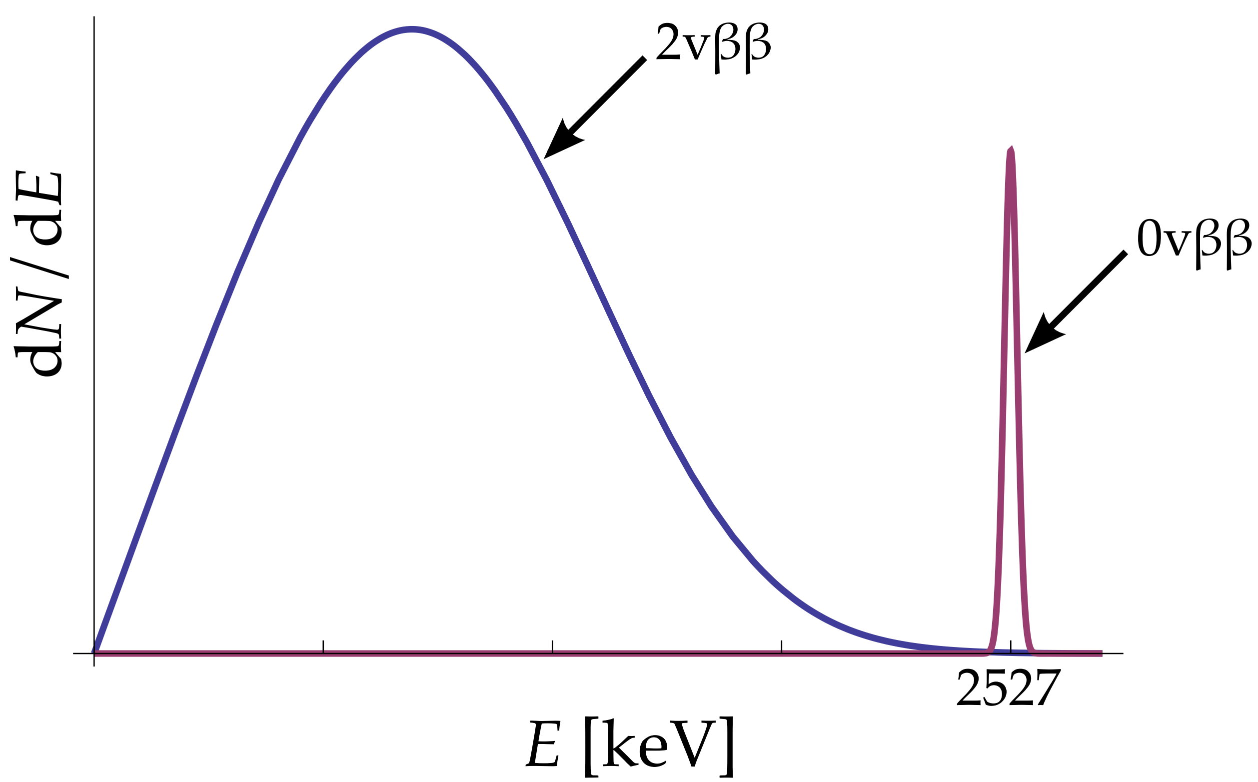
- Double beta decay is a second order process (highly suppressed)
- We have no chance of seeing it in elements for which single beta decay is allowed
- We need to look for elements where double beta decay is allowed and single beta decay is forbidden



Detecting 0νββ

- Measure the summed energy of both electrons released in the decay
- Requires full containment and accurate energy reconstruction of electrons

Double beta decay spectrum



Ordinary (2νββ):
Some energy in electrons, some energy escapes with neutrinos

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

Observation of 0νββ 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 $2\nu\beta\beta$ are $O(10^{21})$ 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 $0\nu\beta\beta$ would be much longer
  - ^{130}Te $0\nu\beta\beta$ limit is $> 10^{24}$ years*
  - A mole of ^{130}Te produces < 1 decay / year
  - A half-life of 10^{26} years requires 32 kg of ^{130}Te to see 1 decay / year

*E. Andreotti *et al.*, Astroparticle Physics 34 (2011) 822–831

Half-lives

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

$T_{1/2}^{0\nu}$ = $0\nu\beta\beta$ 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 element with a high **phase space factor** (high Q-value for 0νββ) and high **nuclear matrix element**
- **Nuclear matrix element** is calculated theoretically, with different models differing by factors of ~2
- **Effective ββ neutrino mass** gives hints about absolute neutrino mass

Detector sensitivity

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

a = source isotopic abundance

ϵ = detection efficiency

M = total mass

t = exposure time

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

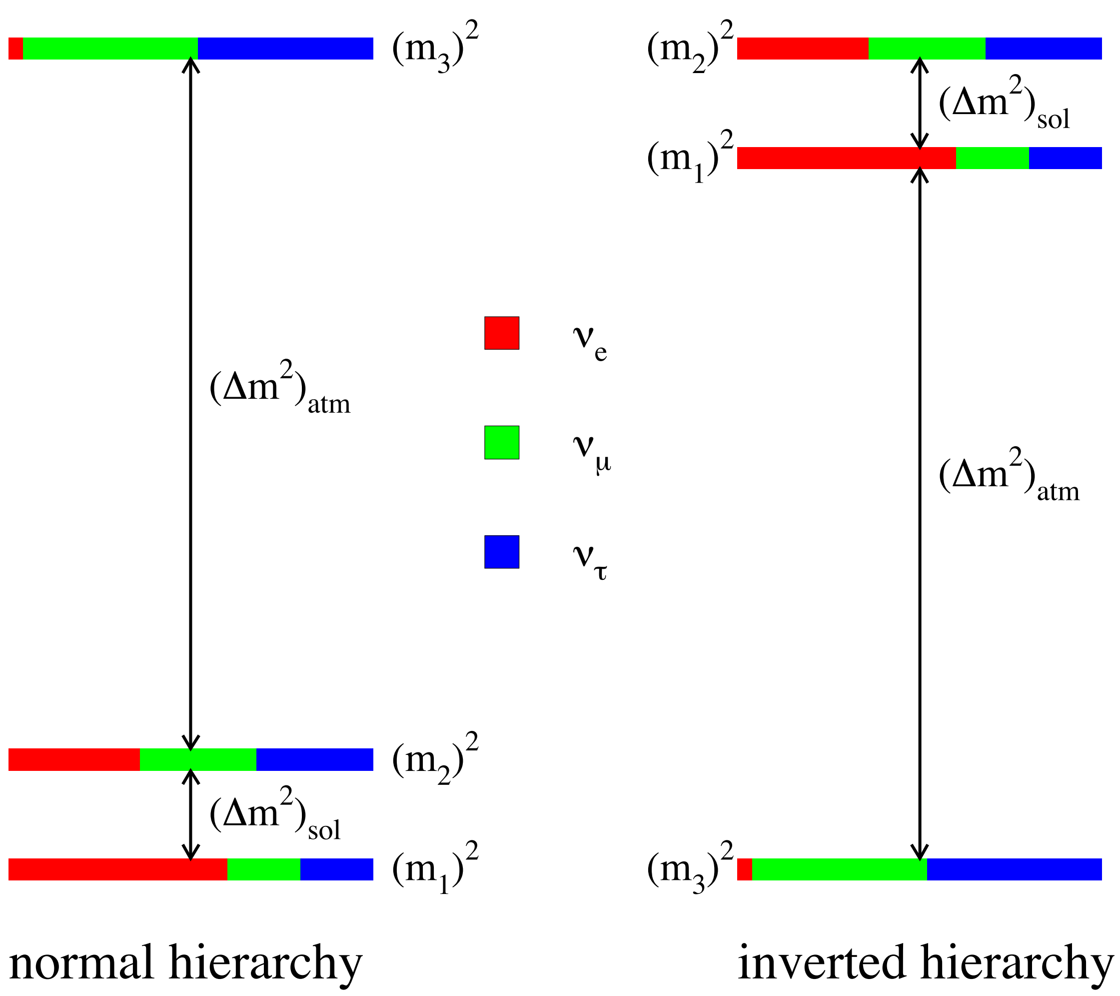
δE = energy resolution

- Choose a source with a high **isotopic abundance** of the $0\nu\beta\beta$ 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

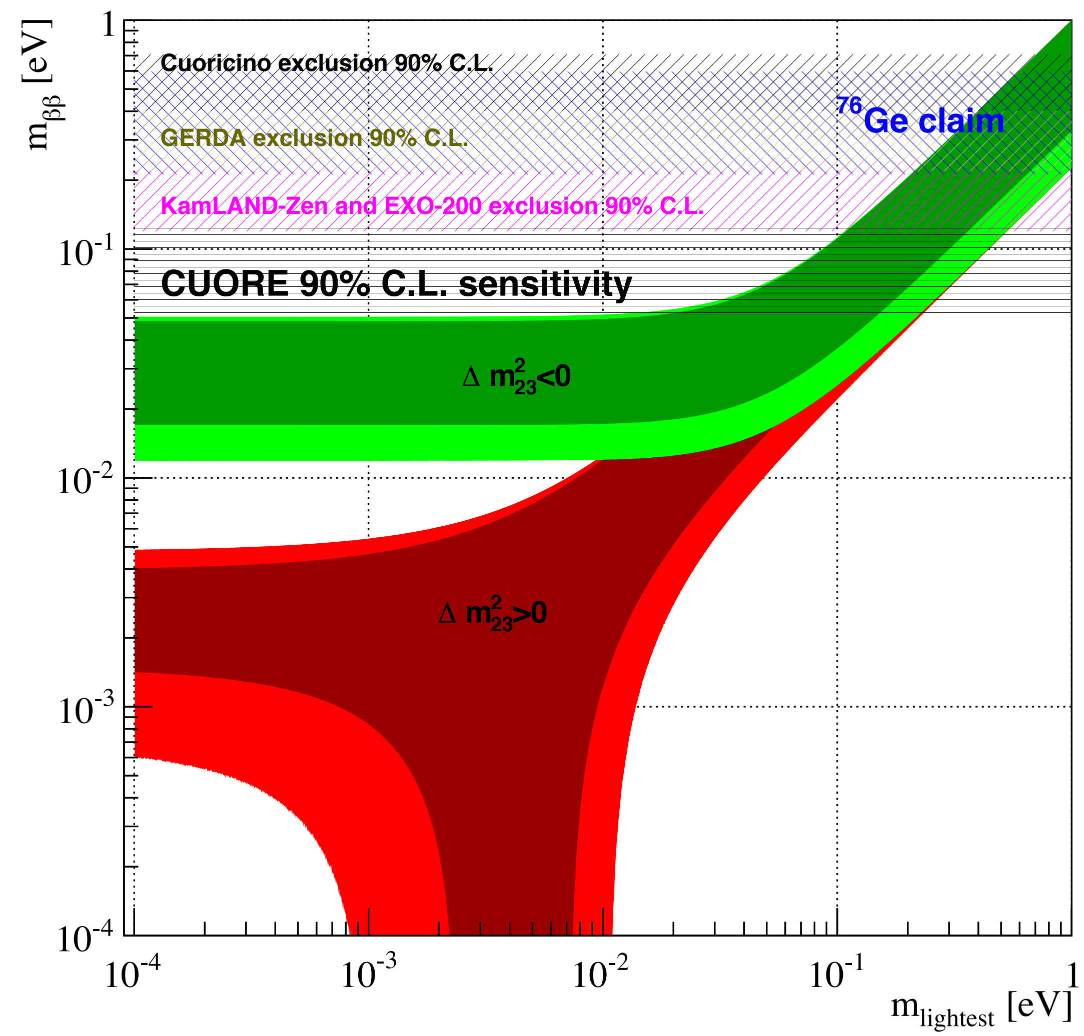
Neutrino mass

Using a measured $0\nu\beta\beta$ half-life, we can deduce an effective Majorana neutrino mass:

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

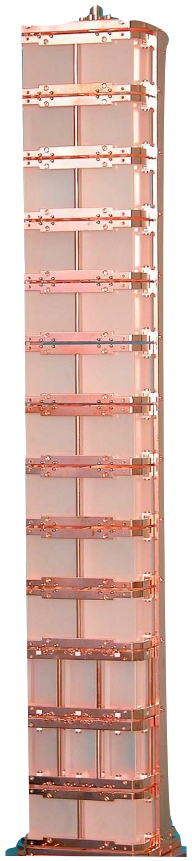


arXiv:1301.1340 (2013)



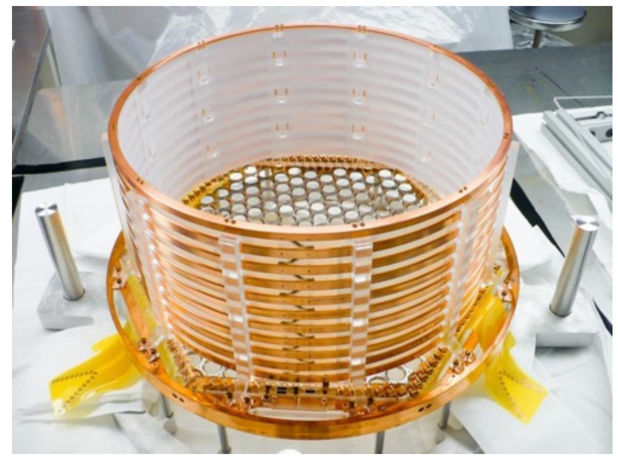
arXiv:1109.0494 (2011)

$0\nu\beta\beta$ efforts



^{130}Te

- Bolometer-based searches: Cuoricino / CUORE-0 / CUORE
- Loaded organic scintillator: SNO+
- $T_{1/2} > 2.8 \times 10^{24}$ y

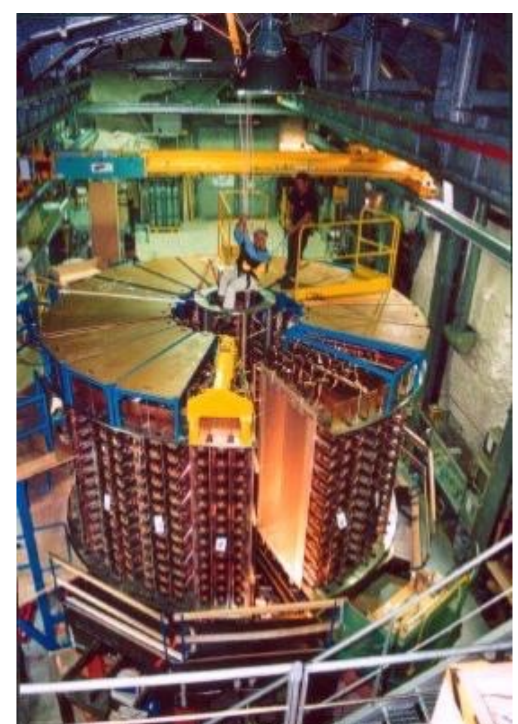


^{136}Xe

- Xe scintillation: Kamland-Zen
- Liquid TPC & scintillation: EXO-200, nEXO
- Gas TPC: NEXT
- $T_{1/2} > 2.6 \times 10^{25}$ y

^{76}Ge

- High-purity germanium detectors: GERDA / MAJORANA
- $T_{1/2} > 2.1 \times 10^{25}$ y

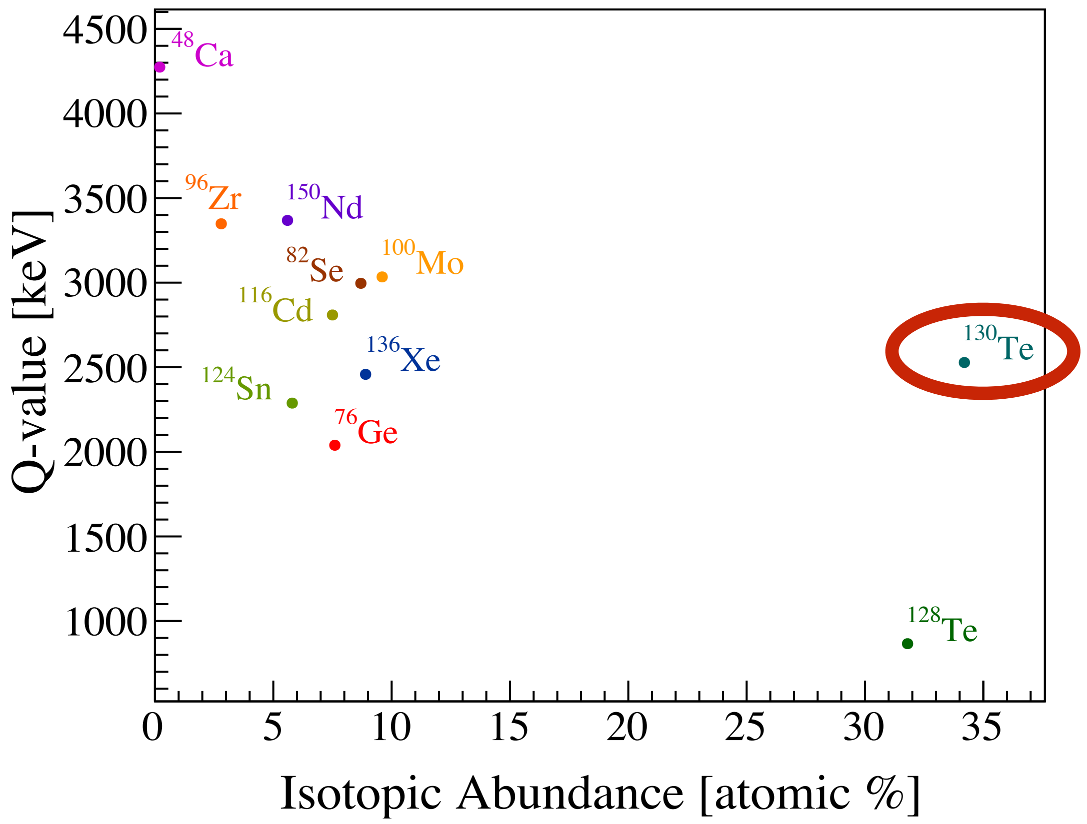


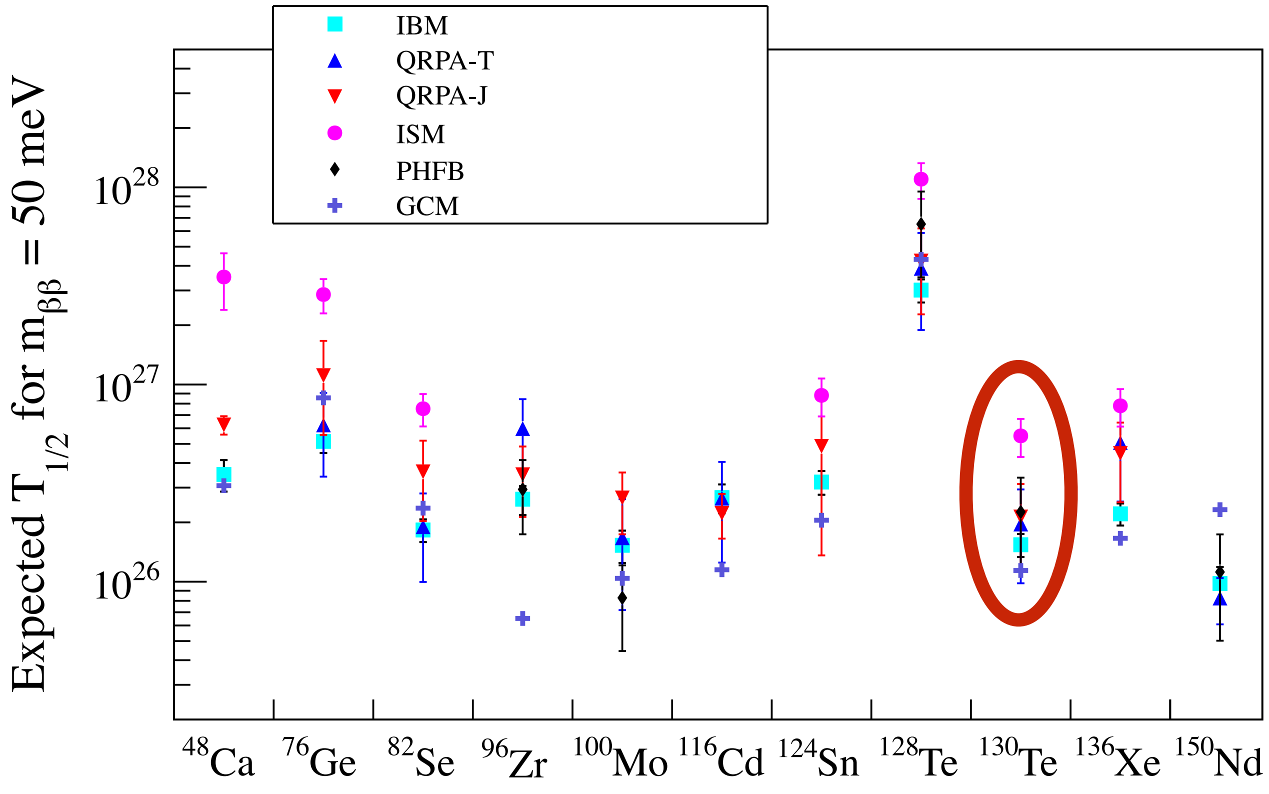
NEMO-3 / SuperNEMO

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

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 half-life





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

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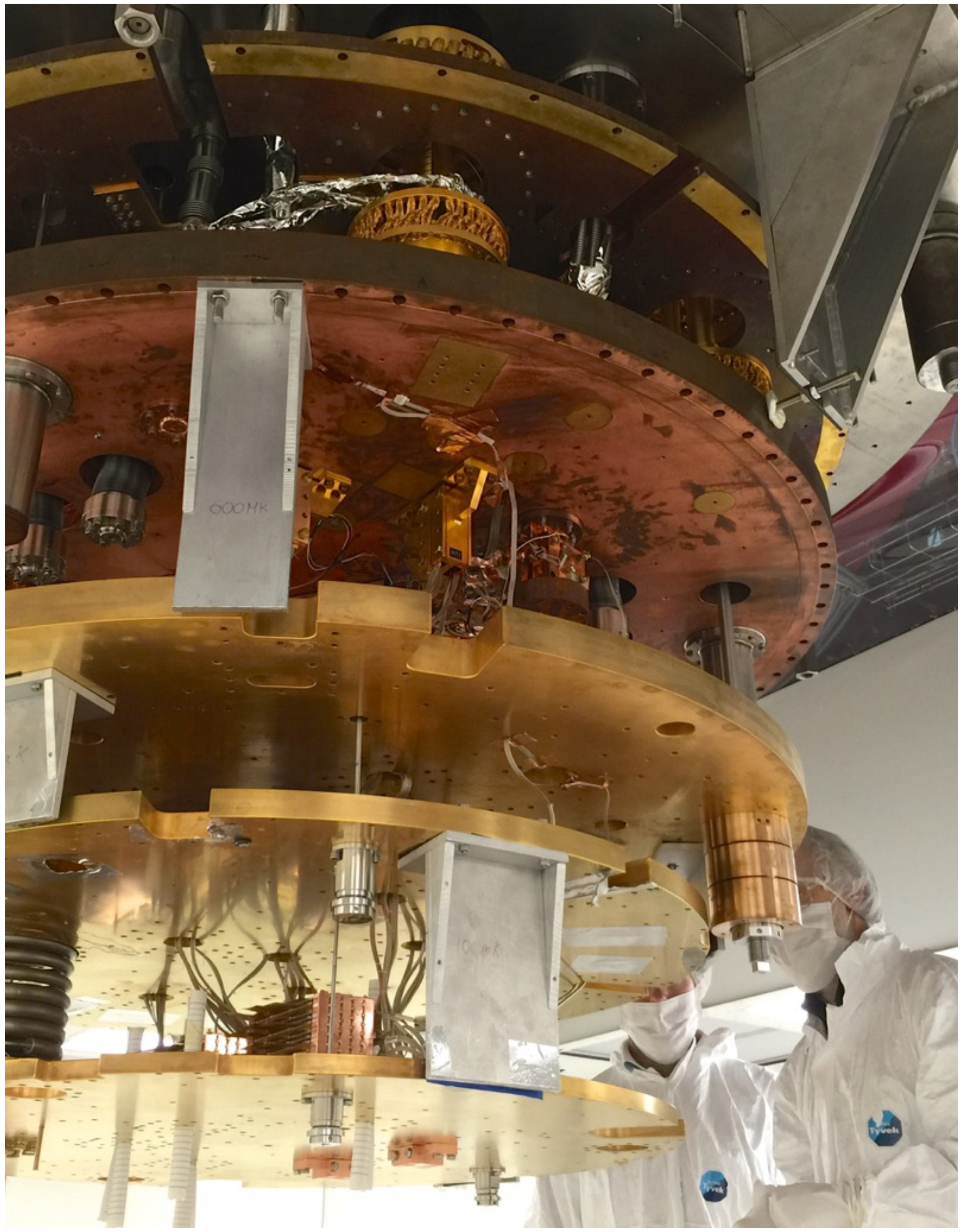
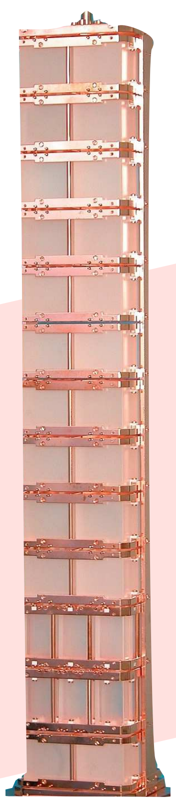


CUORE

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA
UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE – 1979 – SOL PER NOCTEM
INFN Istituto Nazionale di Fisica Nucleare
CAL POLY SAN LUIS OBISPO
SAPIENZA UNIVERSITÀ DI ROMA
Lawrence Livermore National Laboratory
SINAP
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088
UNIVERSITY OF SOUTH CAROLINA
CSNSM
THE UNIVERSITY OF CALIFORNIA 1868 LET THERE BE LIGHT
BERKELEY LAB
UCLA
UNIVERSITAS STUDII PADUANI MCCXXII
LUX ET VERITAS
CUORE

Cuoricino to CUORE

Cuoricino
(2003-2008)

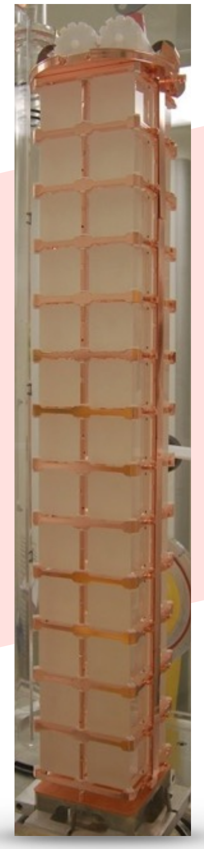


Astropart. Phys. 34 (2011) 822–831

$T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24}$ y (90% C.L.)

$\langle m_{\beta\beta} \rangle_{90\%\ \mathrm{C.L.}} = 300 - 710$ meV

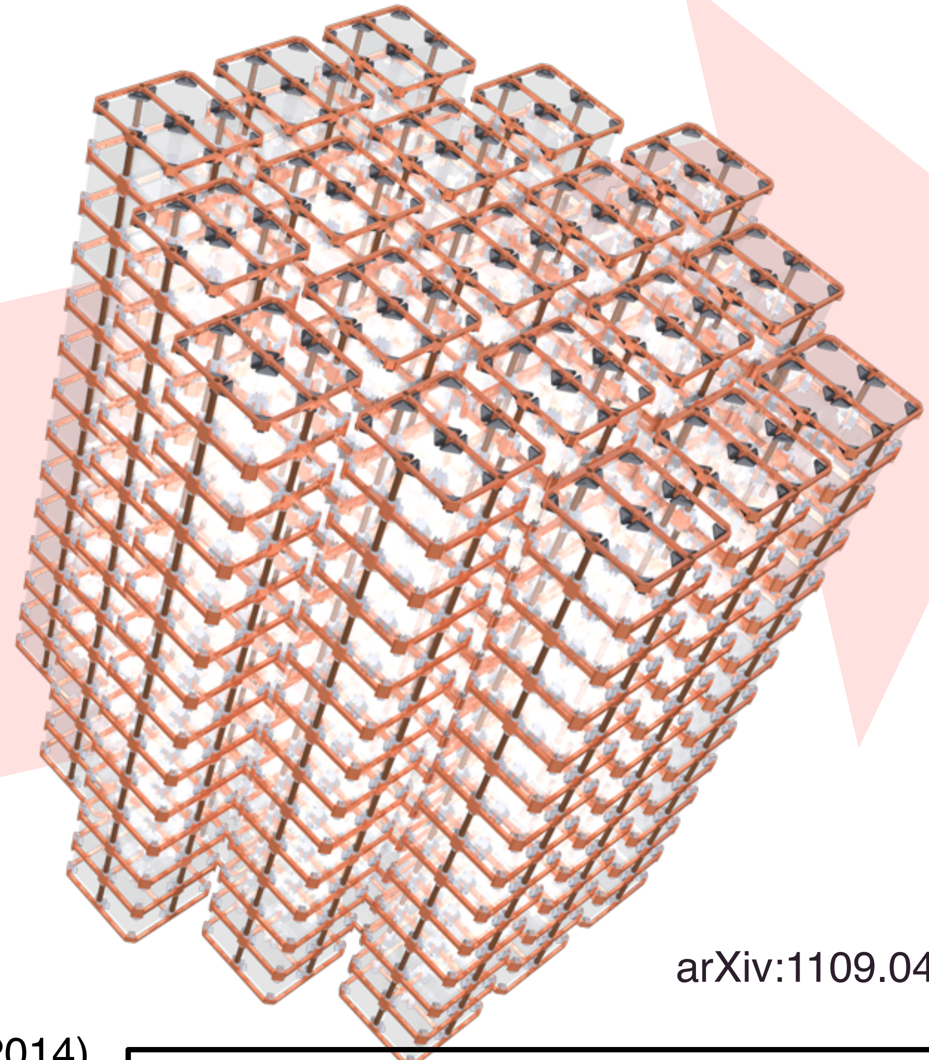
CUORE-0
(2013-2015)



EPJC 74, 2956 (2014)

Surpass Cuoricino w/ ~1-yr data

CUORE
(2015-2020)



arXiv:1109.0494

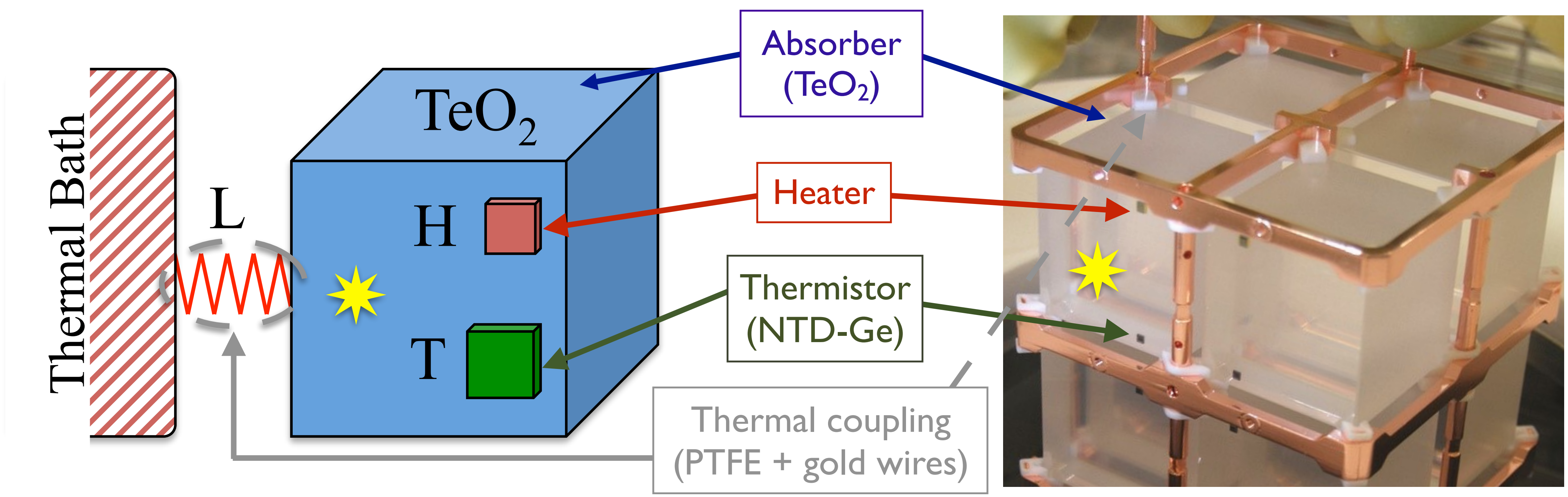
Projected:

$T_{1/2}^{0\nu\beta\beta} > 9.5 \times 10^{25}$ yr (90% C.L.)

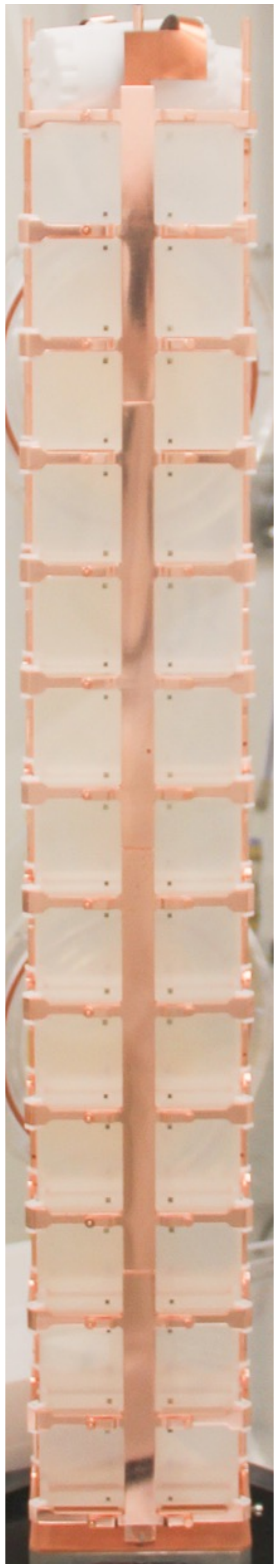
$\langle m_{\beta\beta} \rangle_{90\%\ \mathrm{C.L.}} = 51 - 133$ meV

Bolometric detection

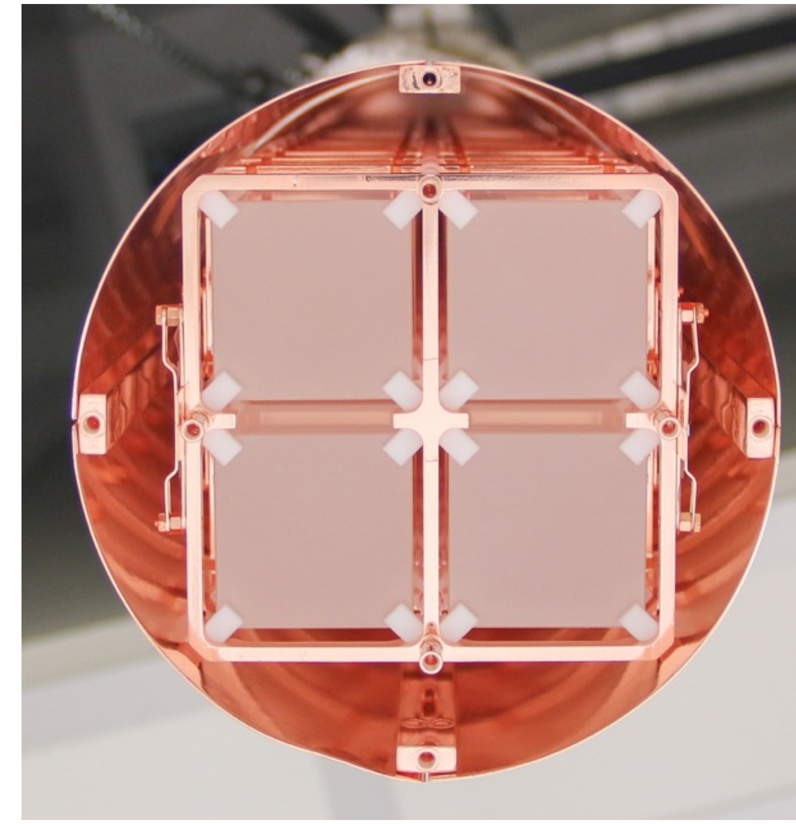
- Bolometers are operated at ~10 mK, so that single particle energy deposits cause a measurable spike in temperature
- Temperature is measured by measuring voltage across temperature-dependent resistors (thermistors)
- Each TeO_2 bolometer crystal is instrumented with a resistive heater and a Neutron Transmutation Doped germanium (NTD-Ge) thermistor.



CUORE-0

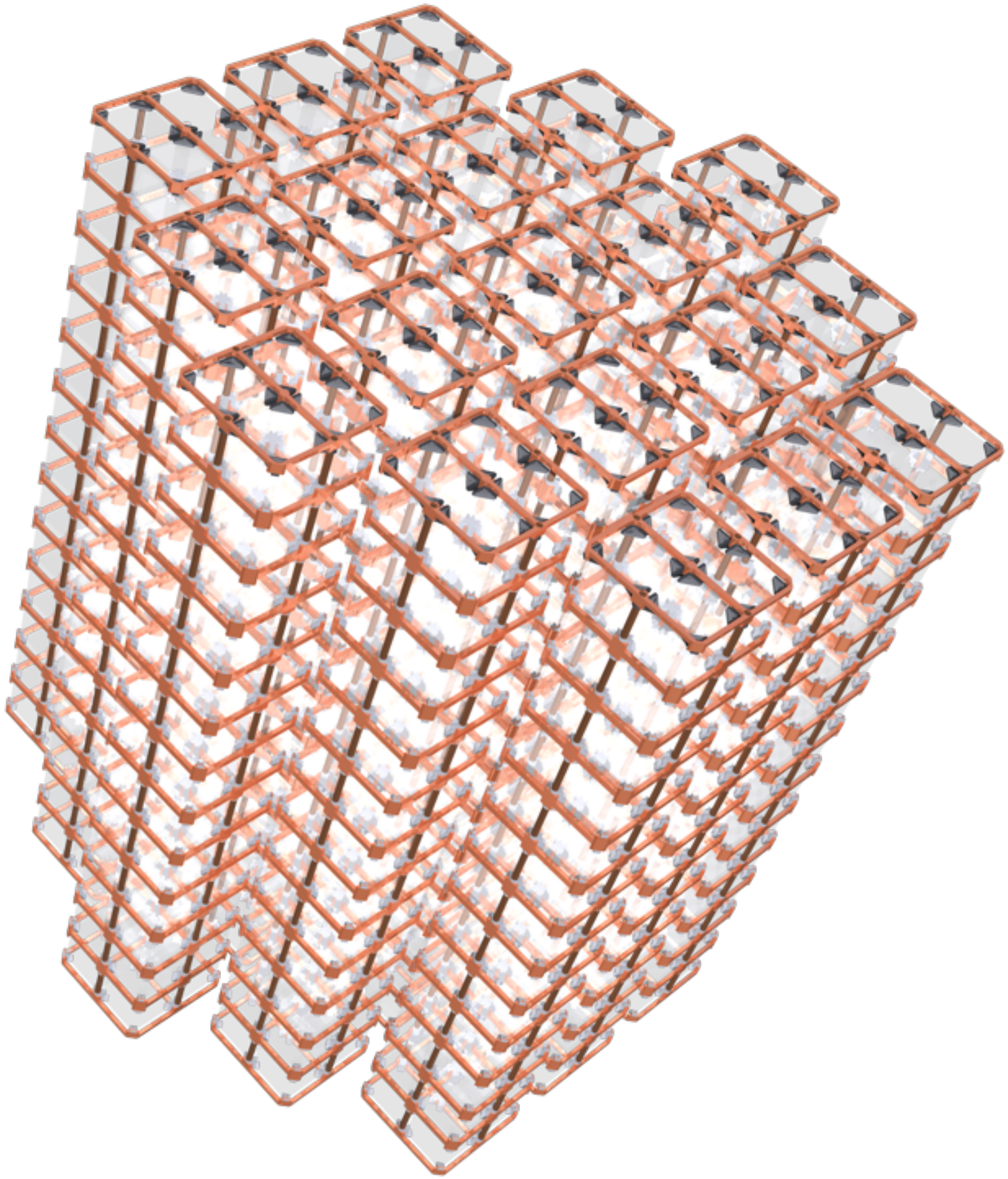


- One 39 kg tower of TeO_2 crystals, which serve as both the 0νββ sources and as bolometric detectors
- Total ^{130}Te mass of 11 kg
- Running in small dilution fridge for the past year
- Serves as a test of the CUORE materials and assembly procedure, and as an experiment of its own
- Unblinding and 0νββ limit to be released soon



CUORE

- The Cryogenic Underground Observatory for Rare Events (CUORE) will search for $0\nu\beta\beta$ in ^{130}Te
- Located deep underground at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy
- CUORE is composed of 988 TeO_2 crystals (total mass of 741 kg with 206 kg of ^{130}Te)
- 19 times the mass of CUORE-0
- Will be run in a new custom-built dilution refrigerator with much lower backgrounds



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

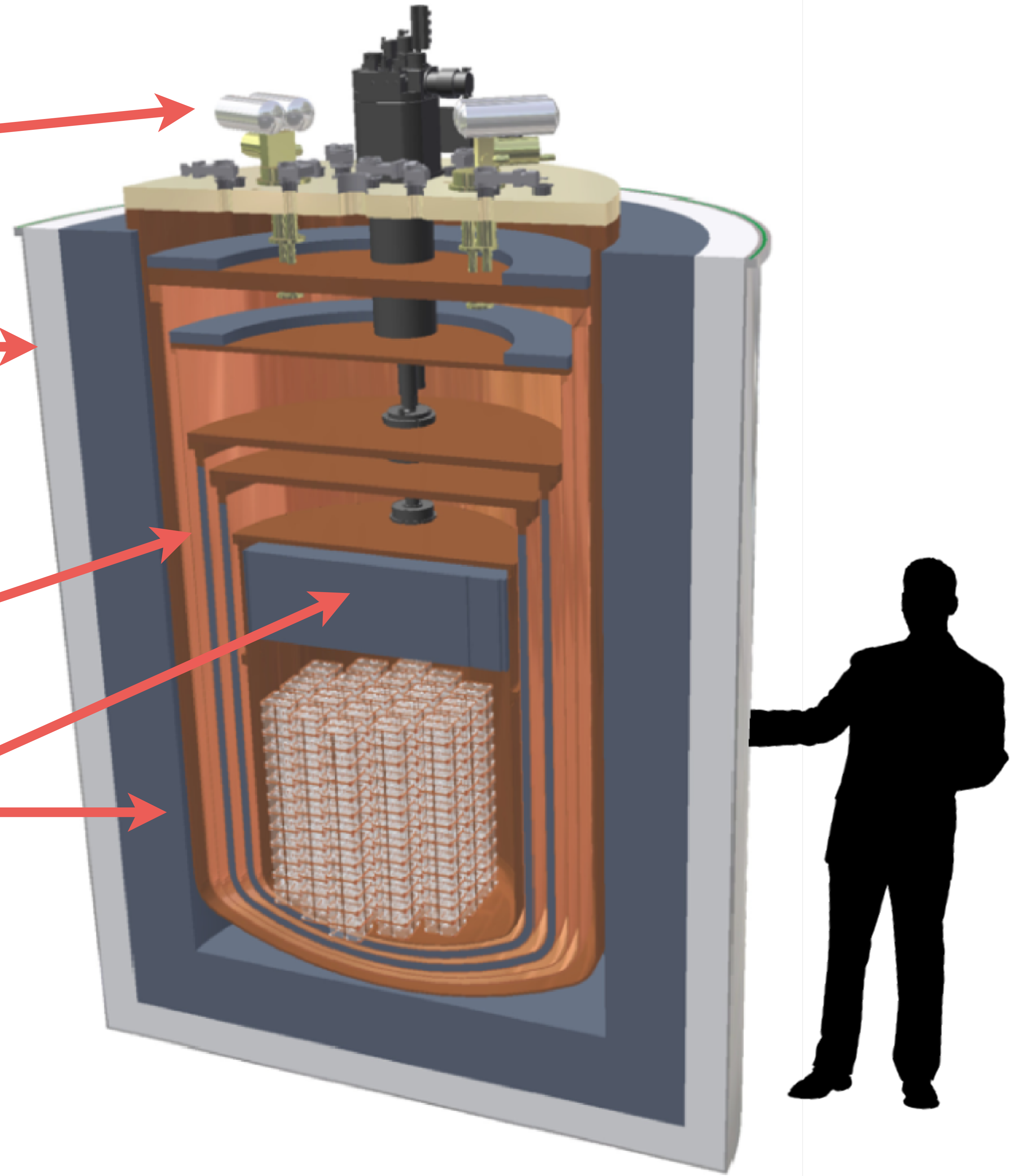
Cryostat

Pulse tubes

Neutron shield
(polyethlene + H_2BO_3)

Copper shields

Lead shields



Ancient Roman lead

- Radioactive shielding can harm experiment as much as it helps
- All lead contains radioactive ^{210}Pb (half-life = 22 years) when mined
- Lead from a Roman shipwreck is used for innermost lead shielding

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

LNGS

CUORE family of experiments are located under the
Gran Sasso (literally, *Great Stone*) mountain in Central Italy

https://commons.wikimedia.org/wiki/Image:Il_Gran_Sasso_d%27Italia,_il_paretone_nord.JPG

LNGS experiment halls

- LNGS is composed of 3 large experimental halls
- Under about 1400 m of mountain rock (roughly factor of 10^6 reduction in cosmic ray muons, or ~3000 m.w.e.)
- Accessed by exit from highway tunnel inside the mountain

http://www.fix.net/wreil/Gran-Sasso-Trip-Technical.htm

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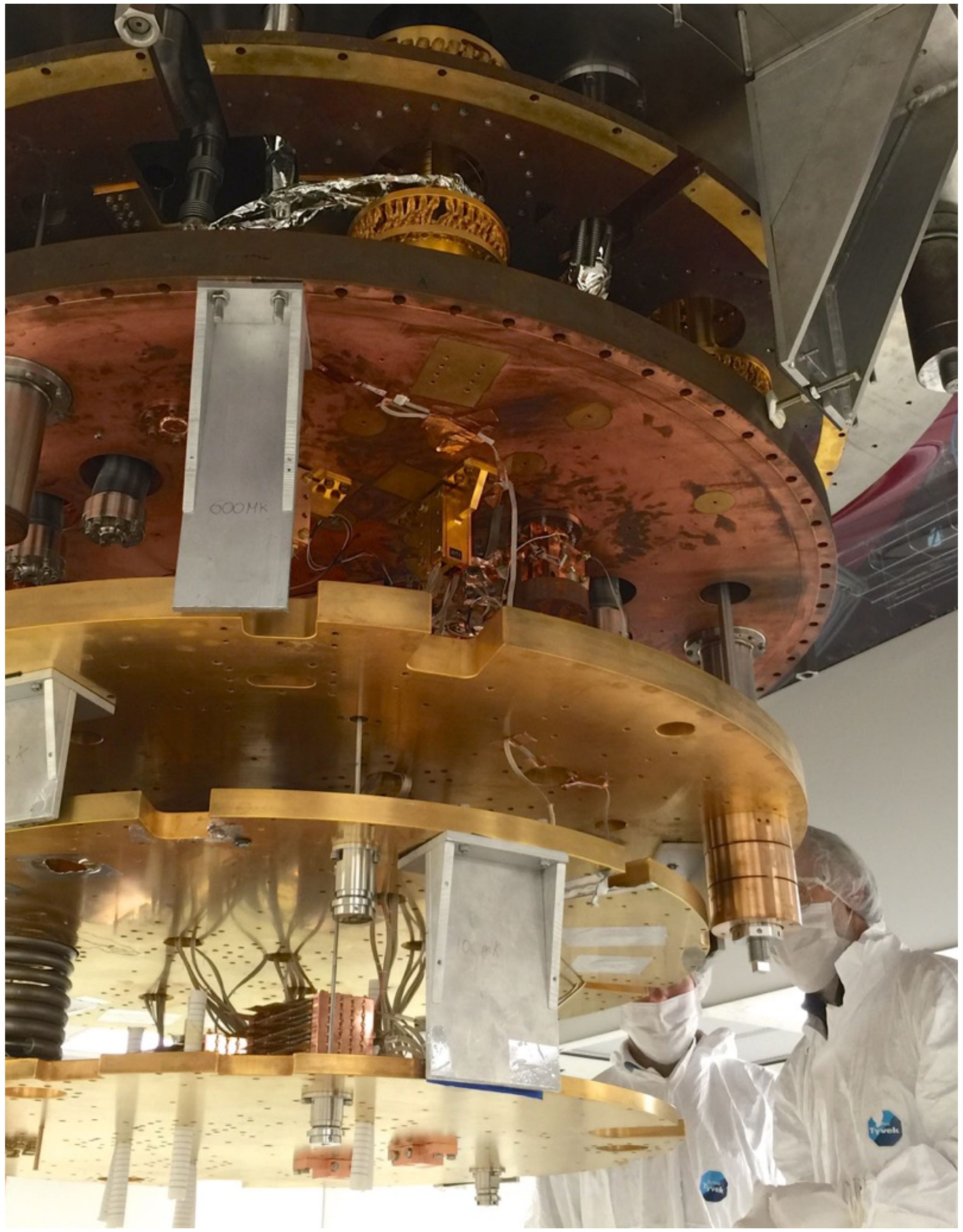
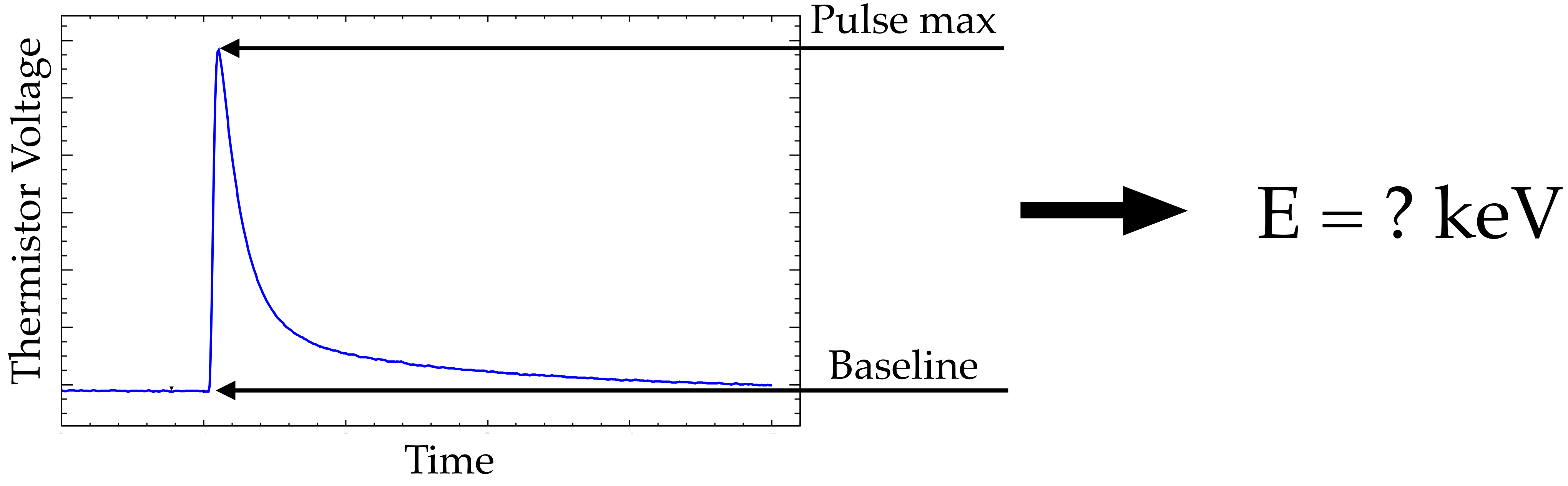


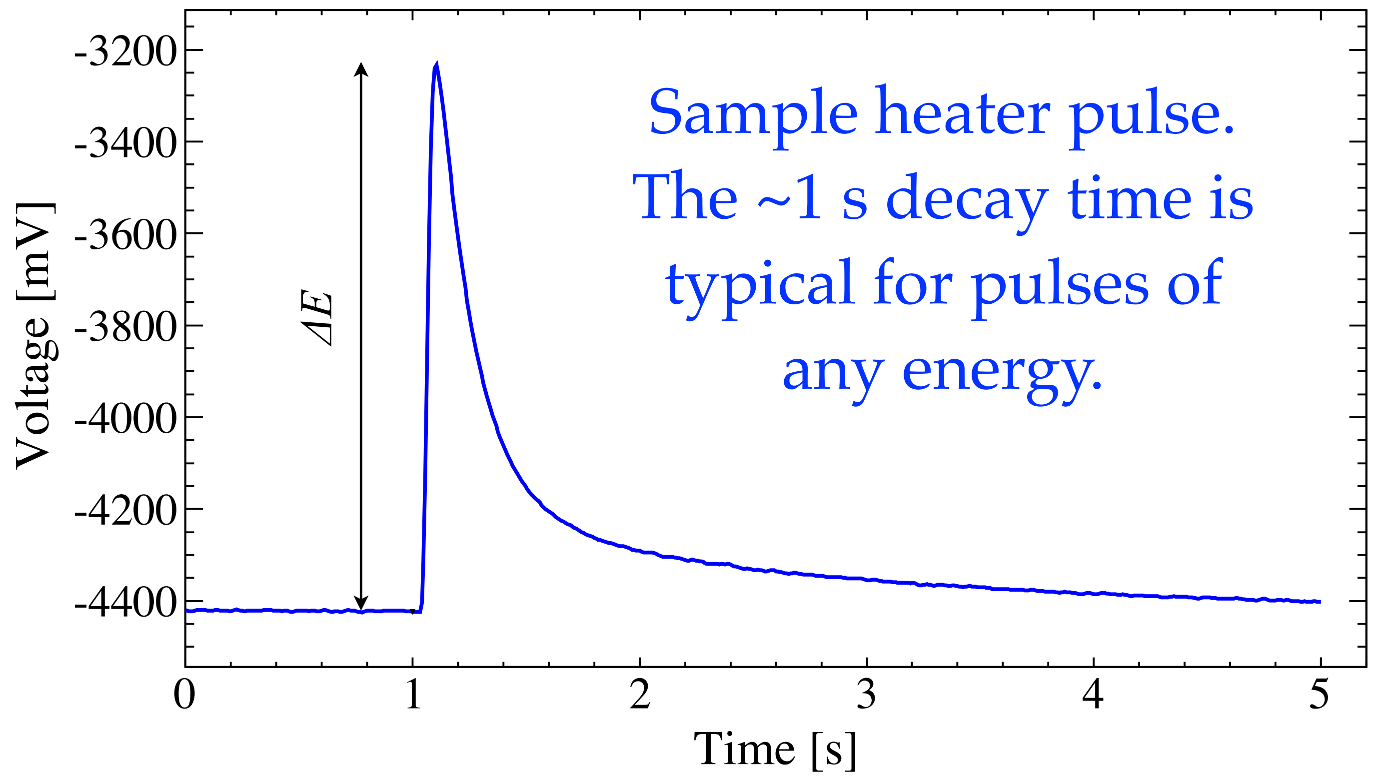
Calibration

- Voltage signals from the thermistors must be calibrated to determine the energy of each event
- Every bolometer must be calibrated independently
- A two-step calibration process will be used:
  1. The thermistor gain is stabilized over time
  2. Thermistor readings are calibrated to absolute energies



Gain stabilization

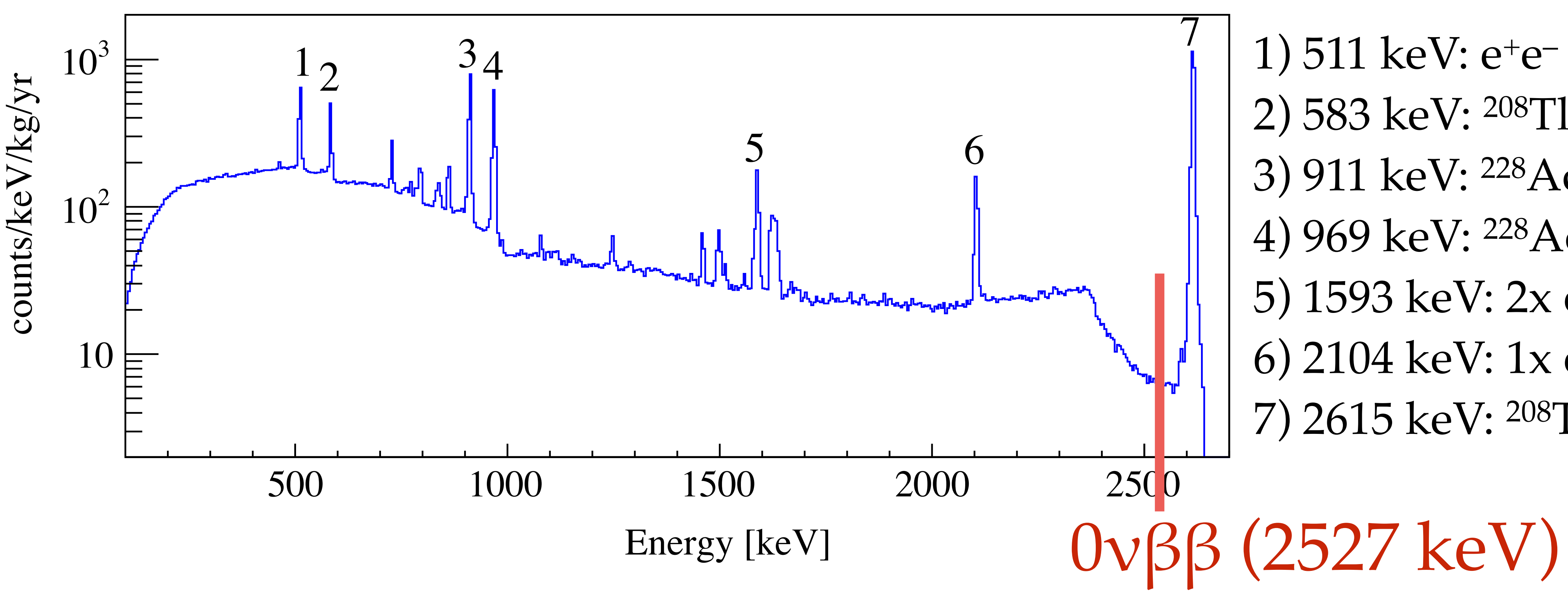
- The gain of each bolometer depends on the baseline, which is temperature-dependent, requiring *in situ* calibration
- Periodic fixed-energy heater pulses are used to establish a gain vs. baseline temperature curve
- All thermistor signal amplitudes can then be converted to arbitrary-unit gain-corrected stabilized amplitudes



Monthly calibration

- Monthly, the crystals are exposed to ^{232}Th γ-ray sources
- This provide several strong peaks in the energy spectrum, including a ^{208}Tl peak at 2615 keV, very close to the $0\nu\beta\beta$ *Q*-value
- An energy vs. stabilized amplitude curve is determined for each channel

CUORE-0 Summed Calibration Spectrum



1) 511 keV: e^+e^-
2) 583 keV: ^{208}Tl
3) 911 keV: ^{228}Ac
4) 969 keV: ^{228}Ac
5) 1593 keV: 2x escape
6) 2104 keV: 1x escape
7) 2615 keV: ^{208}Tl

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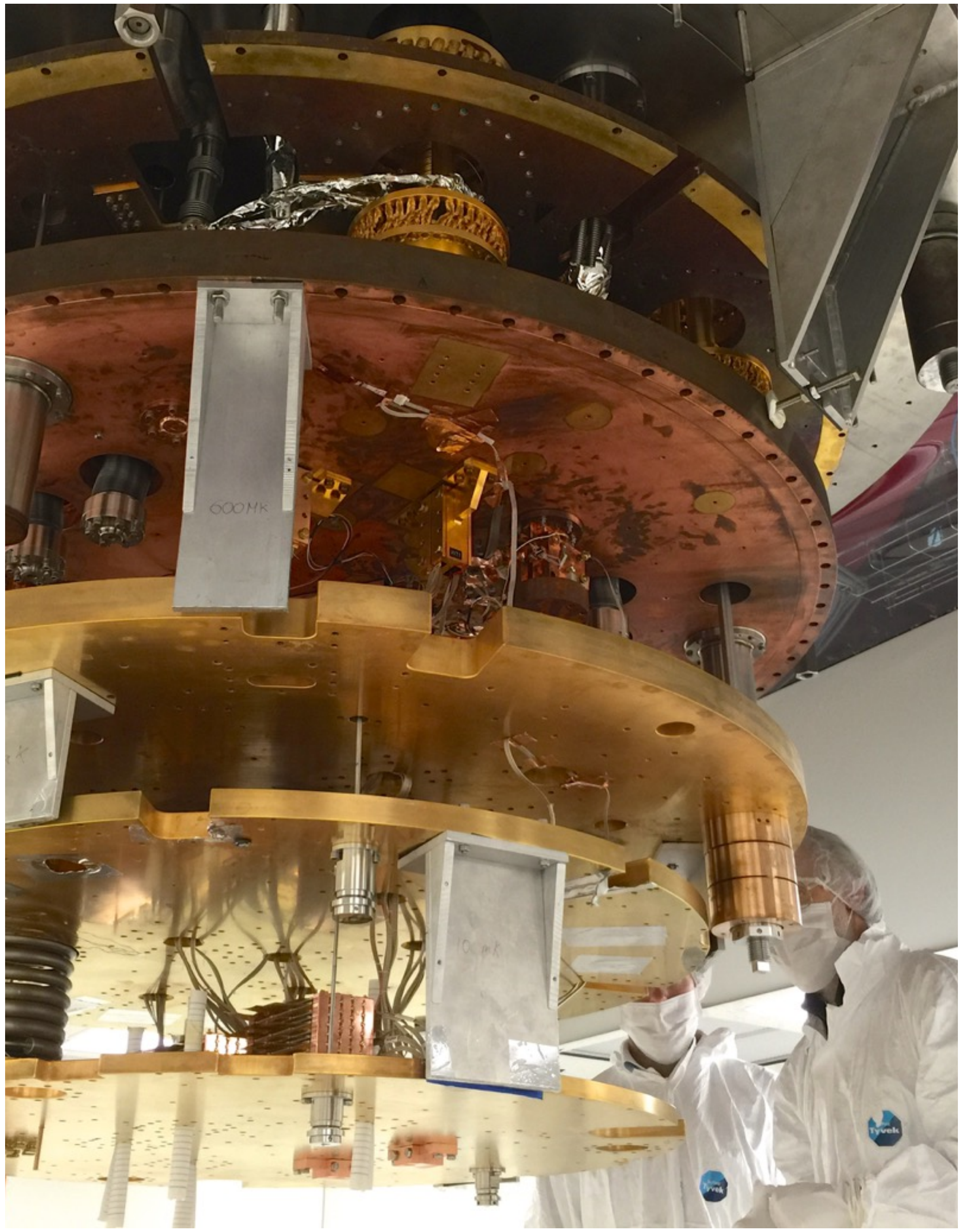
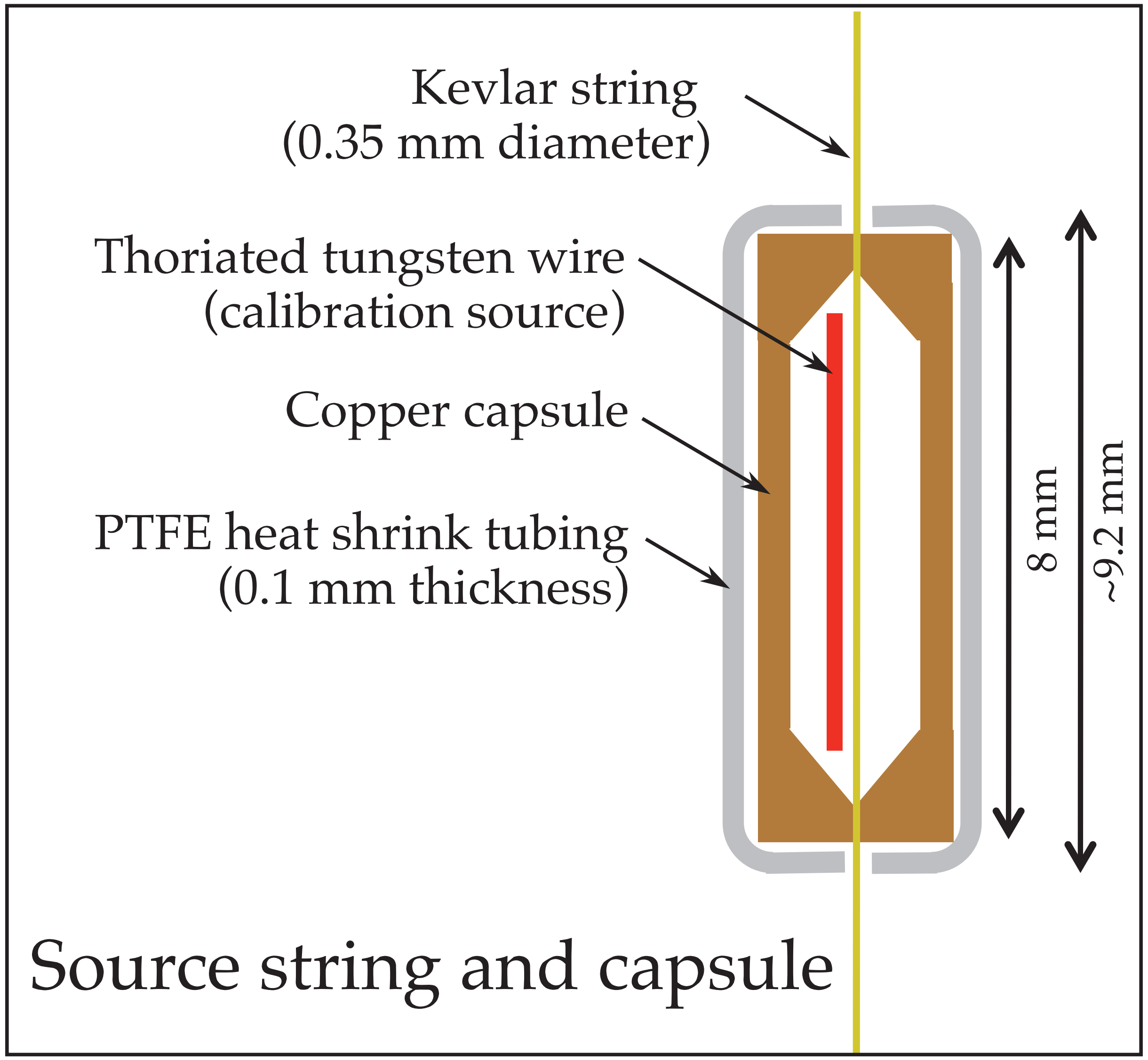


Calibration requirements

- Bolometers require independent *in situ* energy calibration
- Calibration sources must be inside cryostat only during calibration
- Inserting sources must not affect bolometer temperature
- Procedure must be stable over expected 5-year lifetime of the experiment
- Background contribution of calibration hardware must be low (≪0.01 counts/keV/kg/year)

Calibration strings

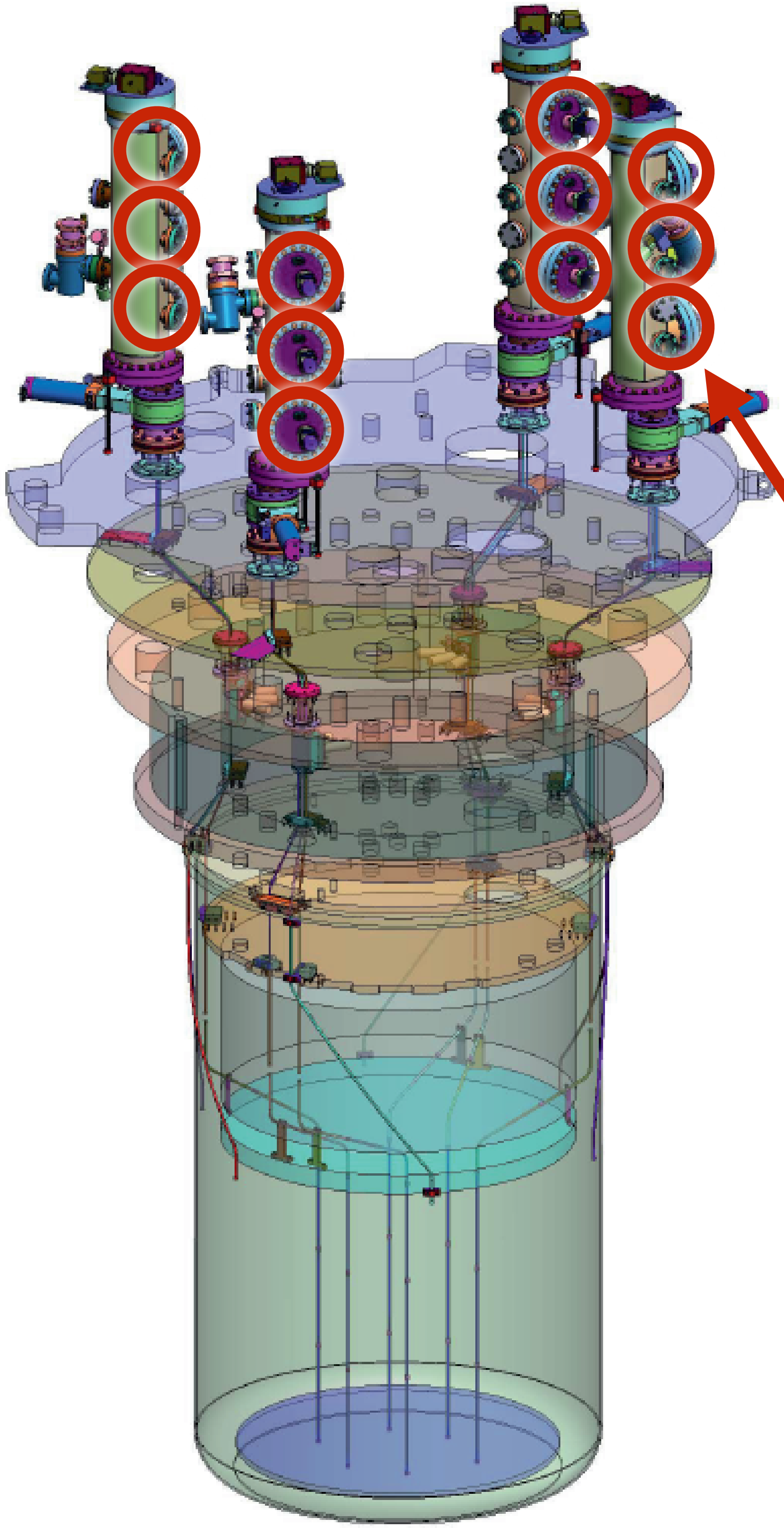


Source string and capsule

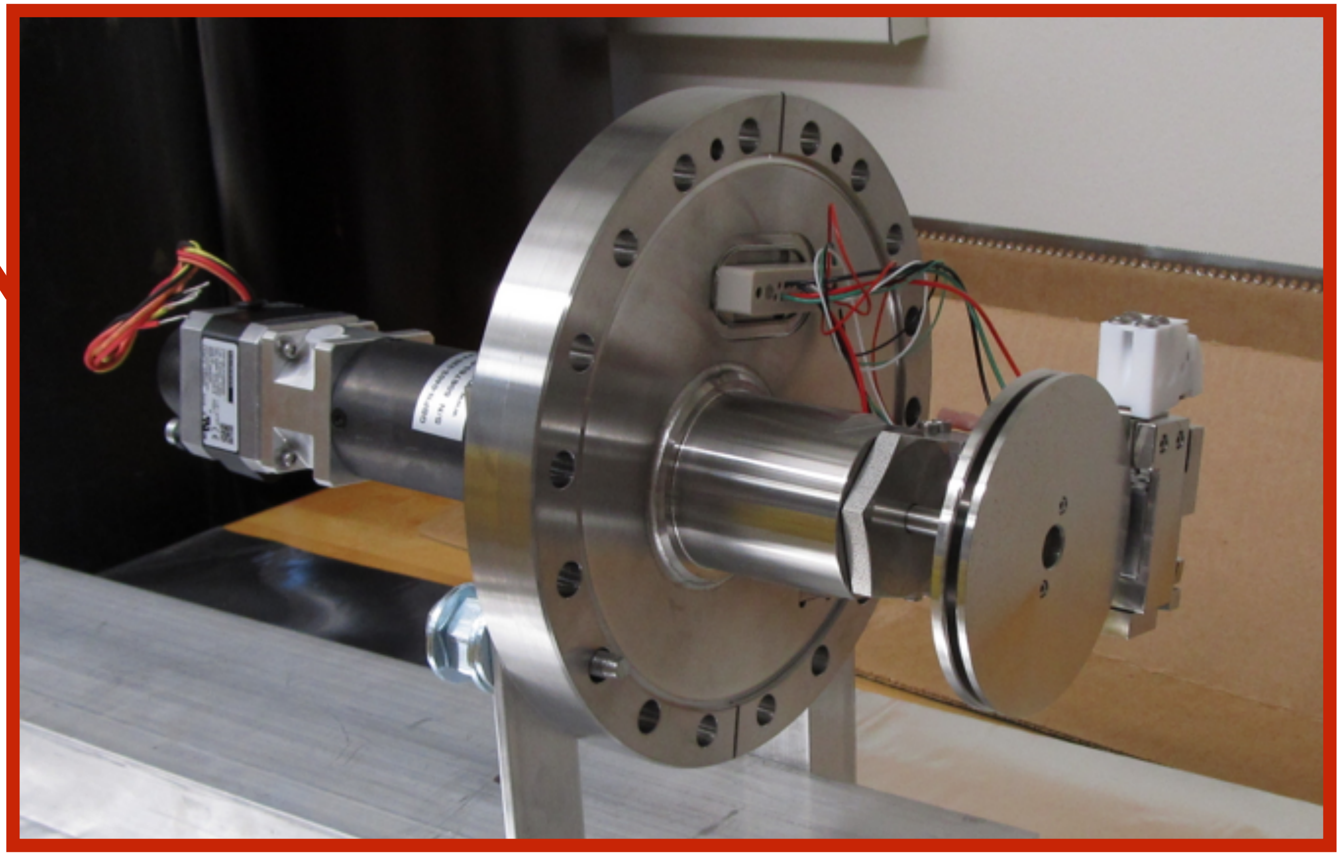
- Twelve source strings will be lowered into the cryostat during calibration periods
- Strings move under their own weight
- Cooled from 300 K to the bolometer region at ~10 mK

Each source string contains 25 source capsules of thoriated tungsten wire (containing ^{232}Th), 8 weight capsules, and a PTFE guide ball

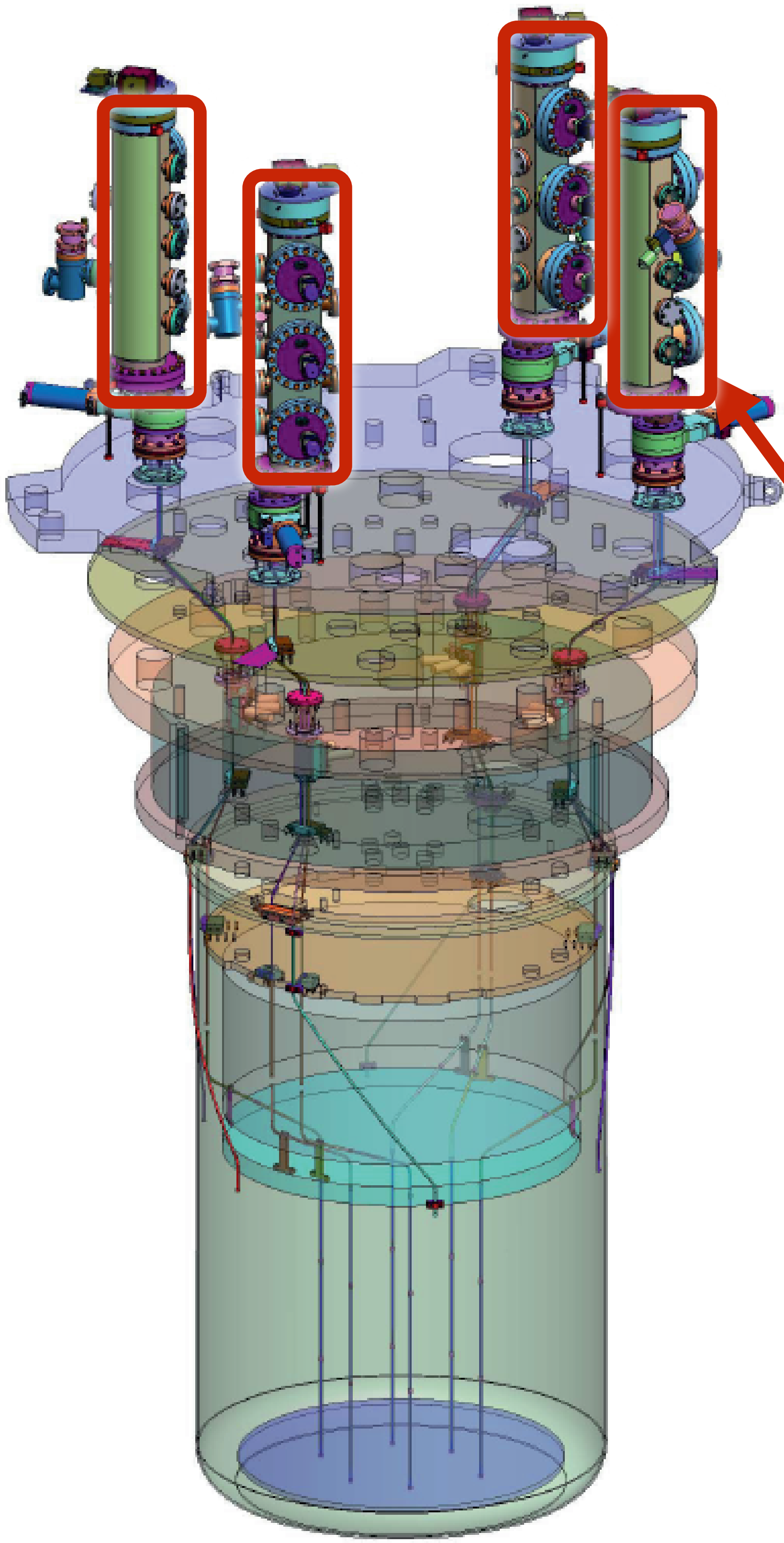
Motors and spools



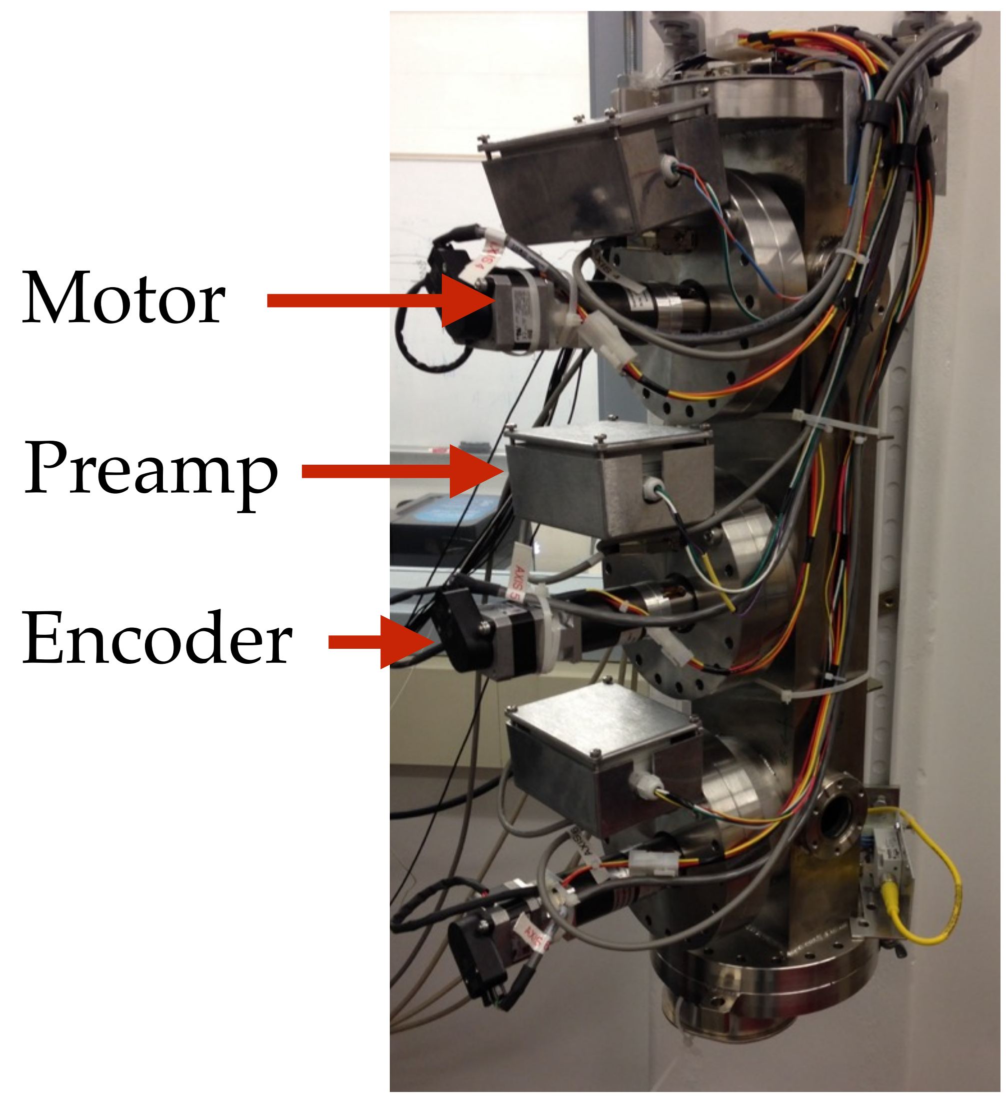
Each source string is wound around a spool and connected to a motor, which turns the spool to raise and lower the calibration sources



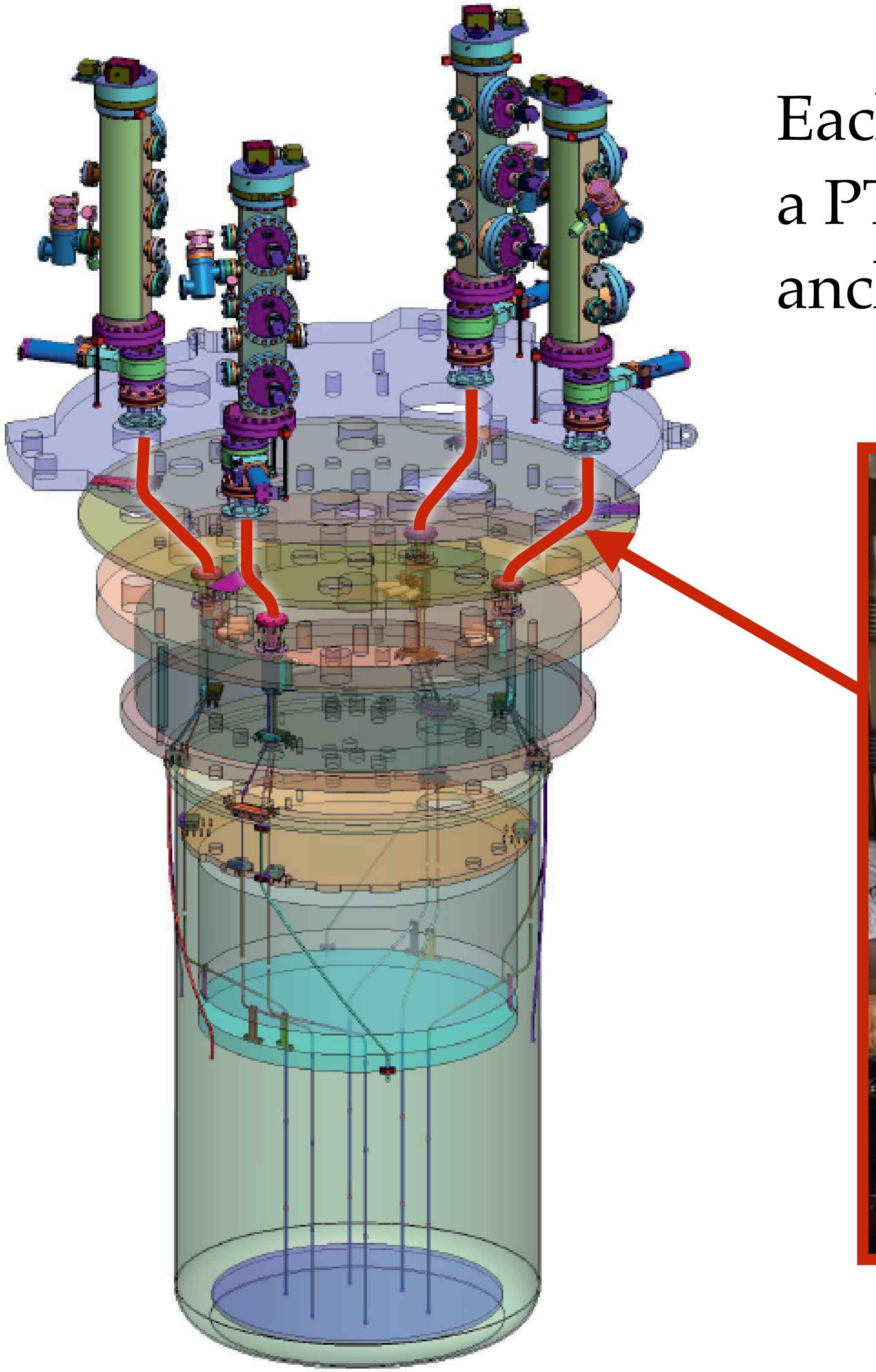
Motion Boxes



The motors are contained within four motion boxes, each of which controls three source strings



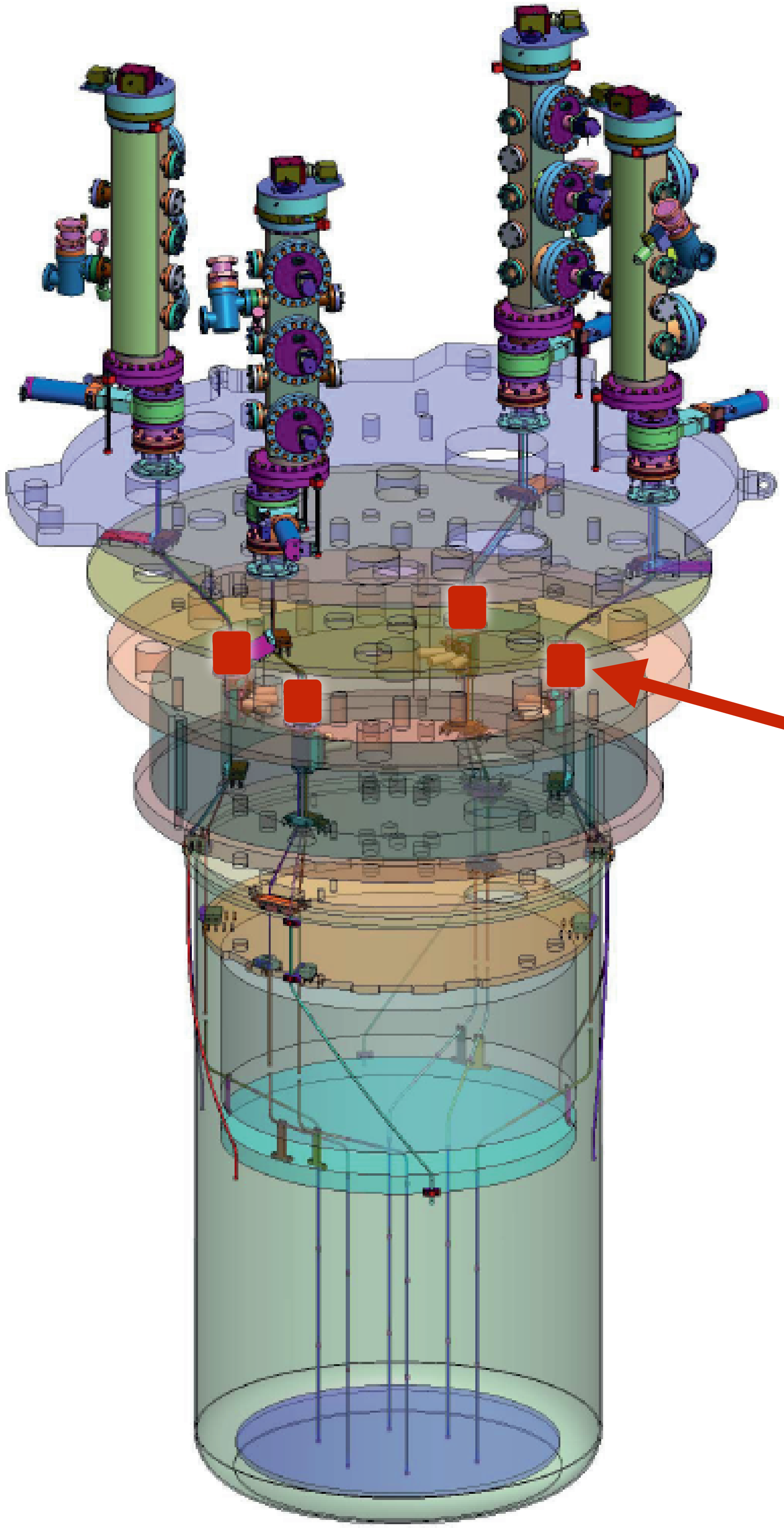
S-tubes



Each source string is guided from 300 K to 4 K in a PTFE-coated stainless steel bellows ("S-tube") anchored to the 40 K plate

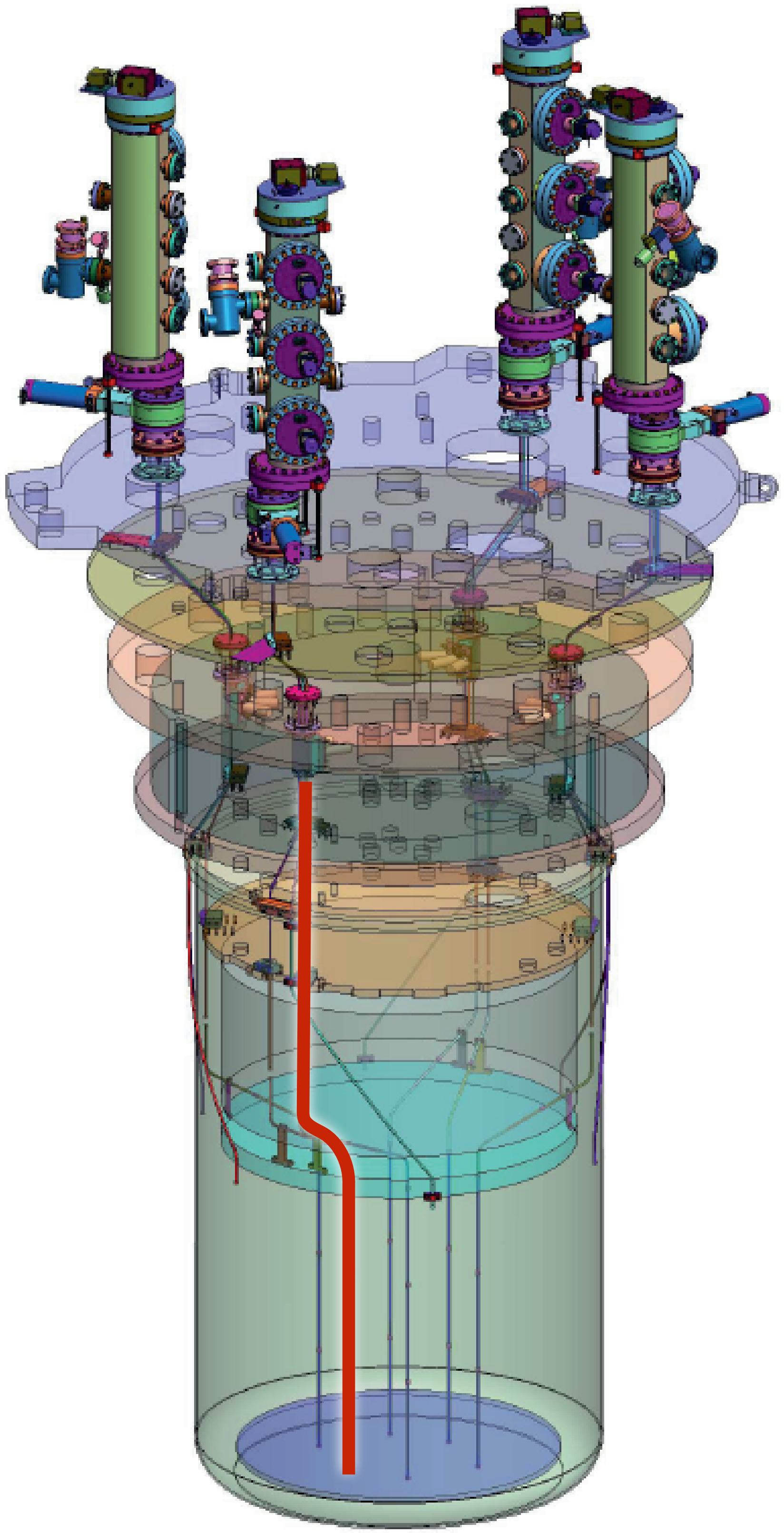
Bends in the tube allow the sources to thermalize with the tube

Thermalizers

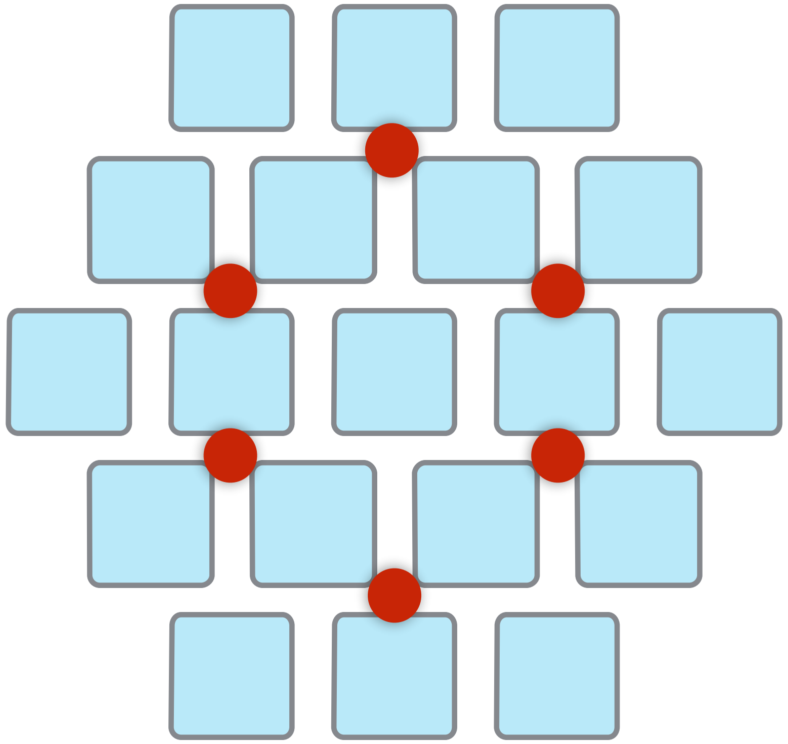


Source strings are cooled to 4 K by mechanical squeezing before being lowered further into the cryostat

Inner guide tubes

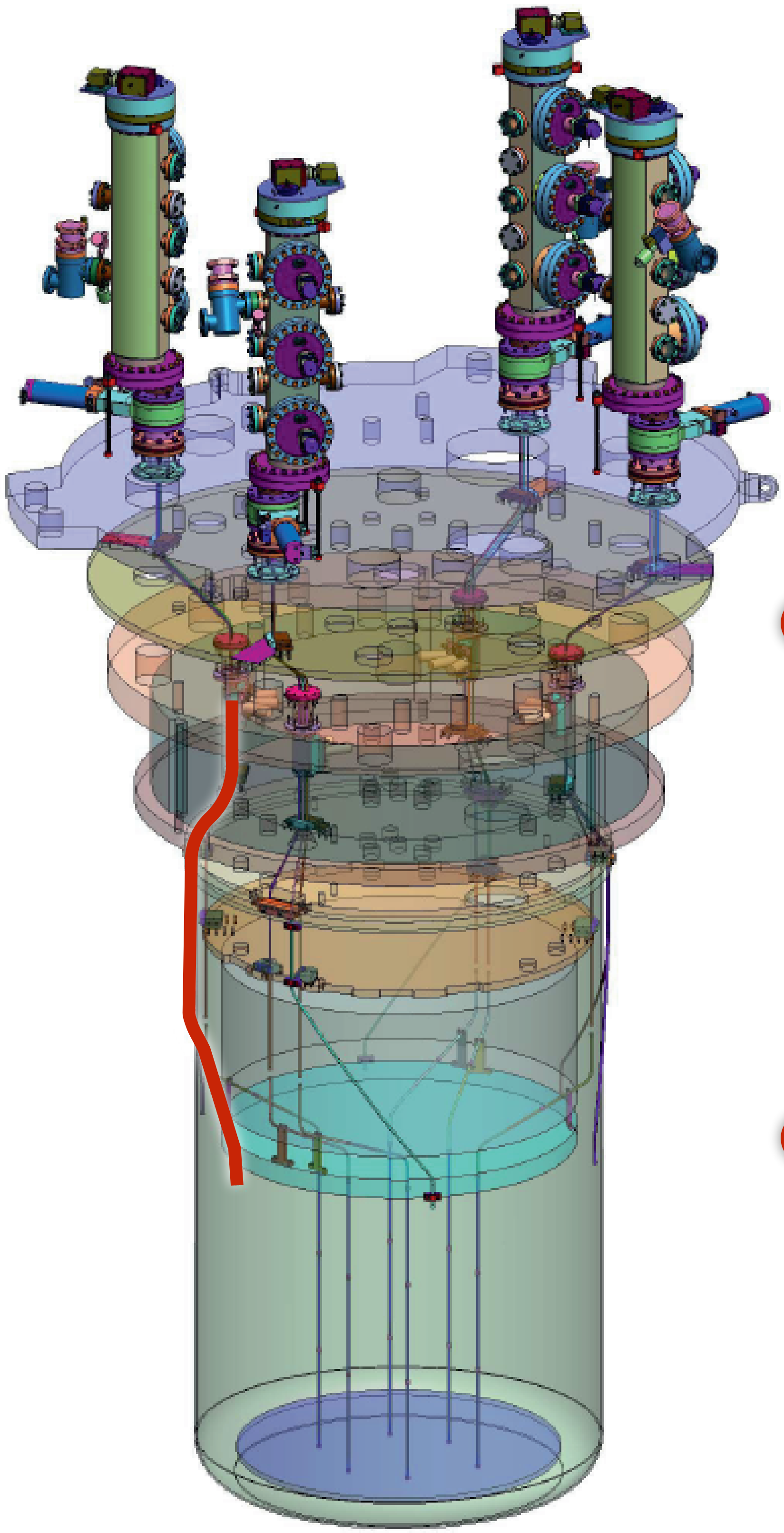


6 source strings (3.5 Bq each) are guided between the bolometer towers in copper tubes to illuminate the inner detectors

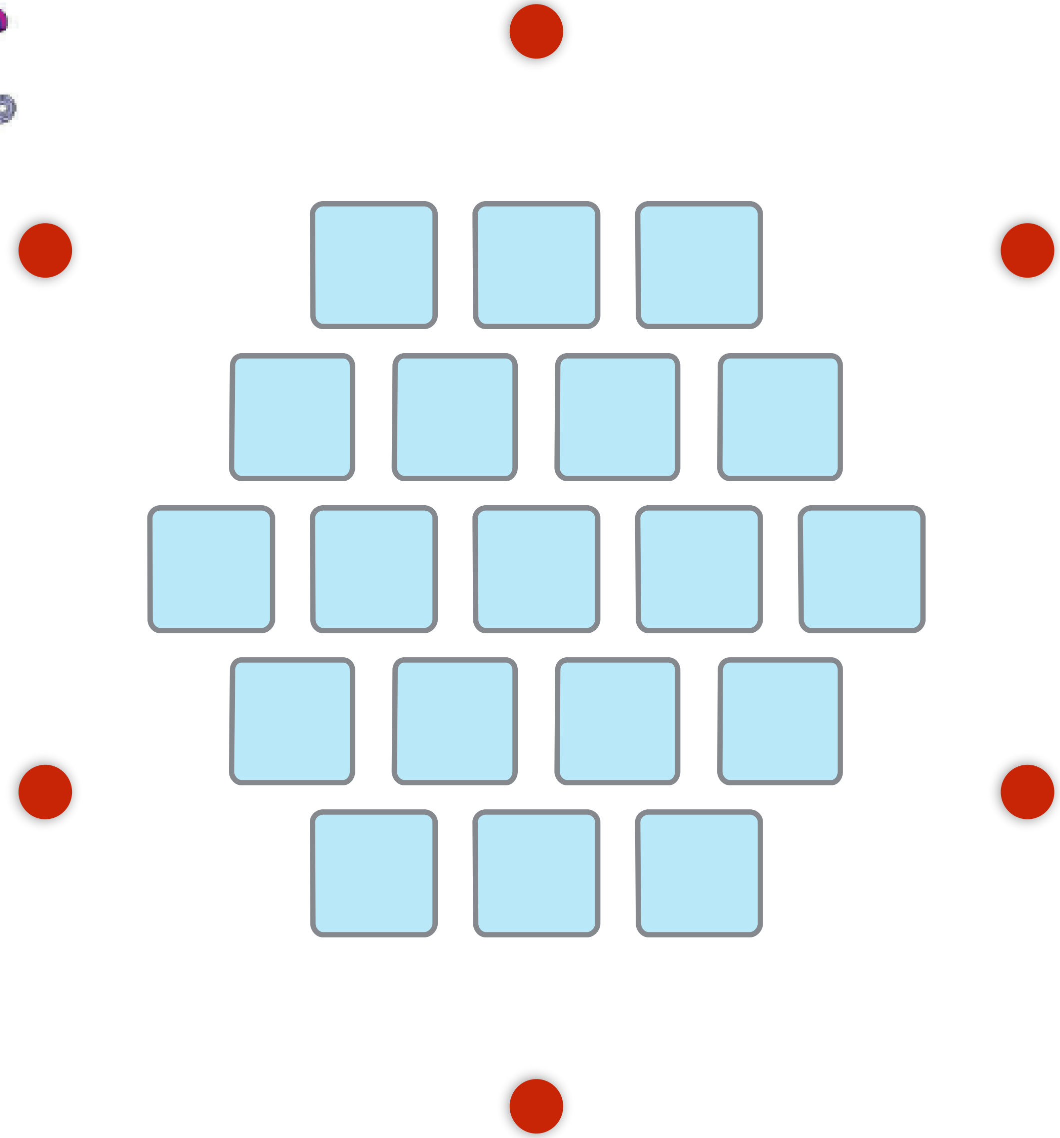


Top-down view of detector towers with inner guide tube placement

Outer guide tubes

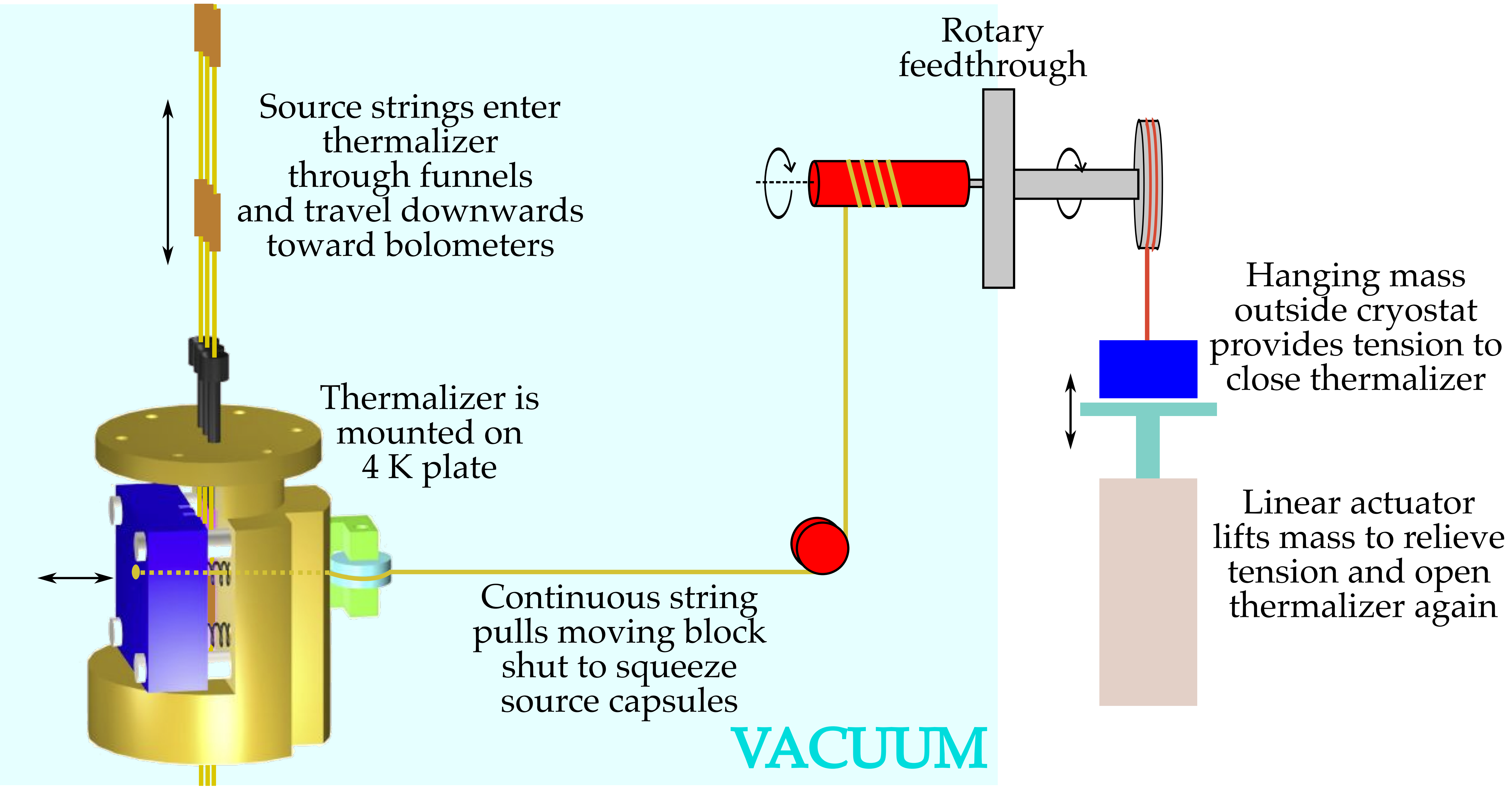


6 source strings (19.4 Bq each) are guided in copper tubes to the region outside of the detector towers and then are allowed to hang freely



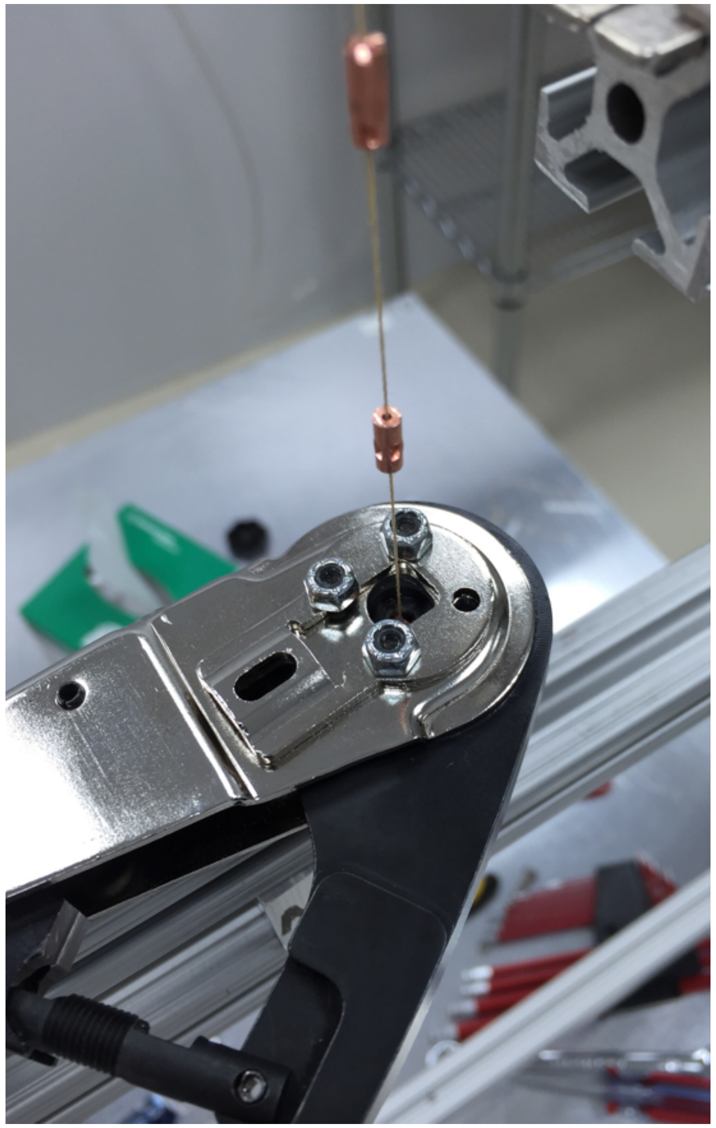
Top-down view of detector towers with outer guide tube placement

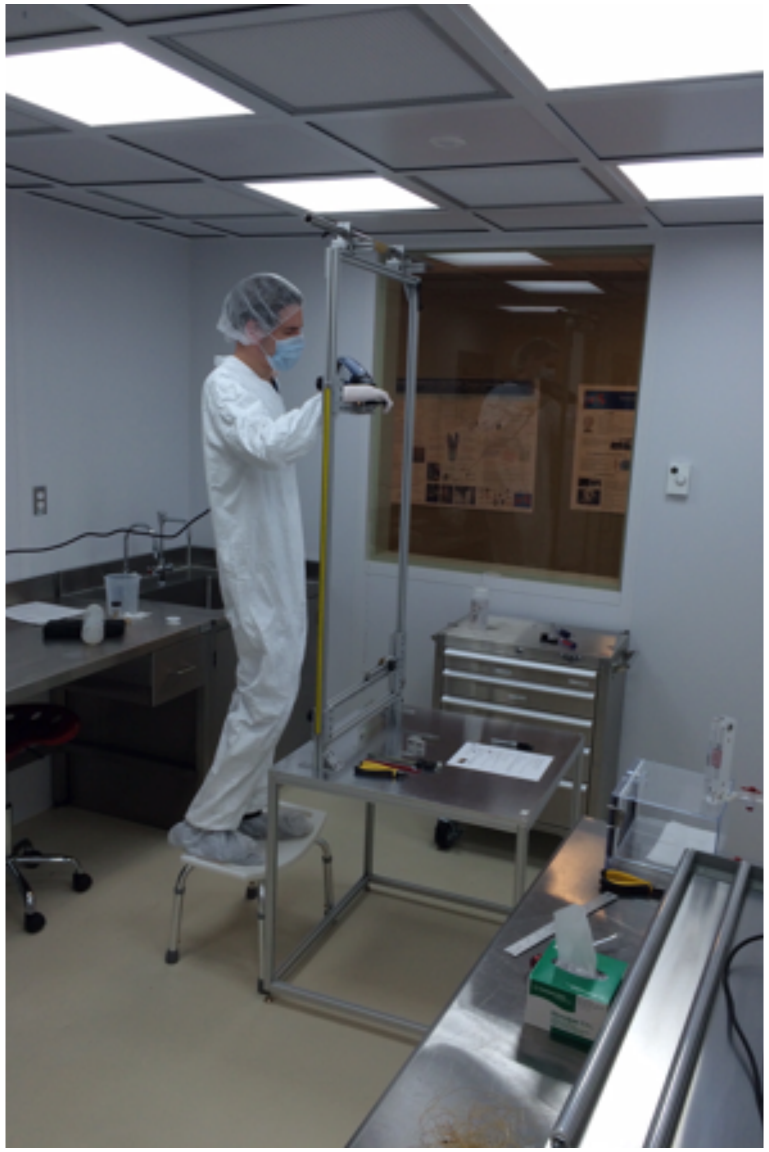
Thermalization

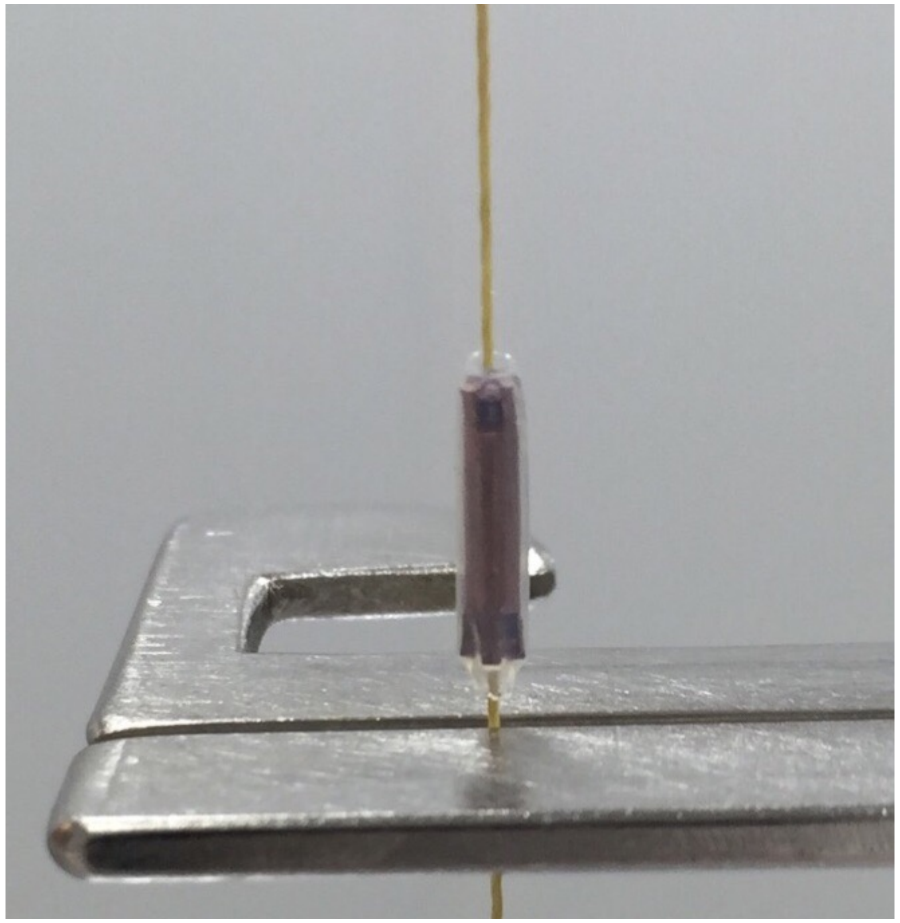


String production

- Inner source strings produced at UW-Madison
- Outer source strings produced at Yale

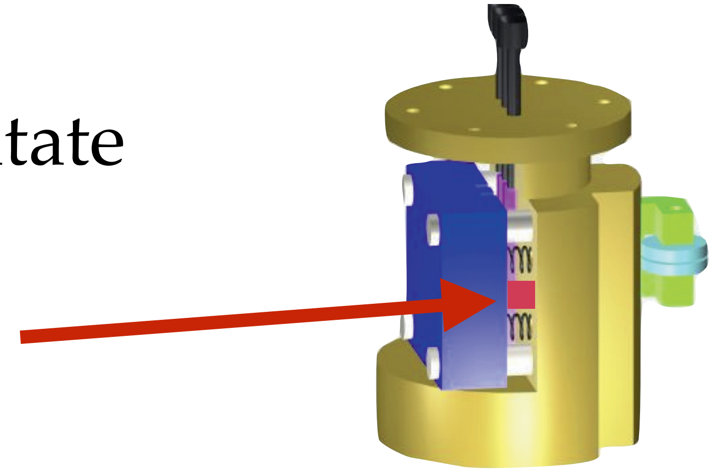


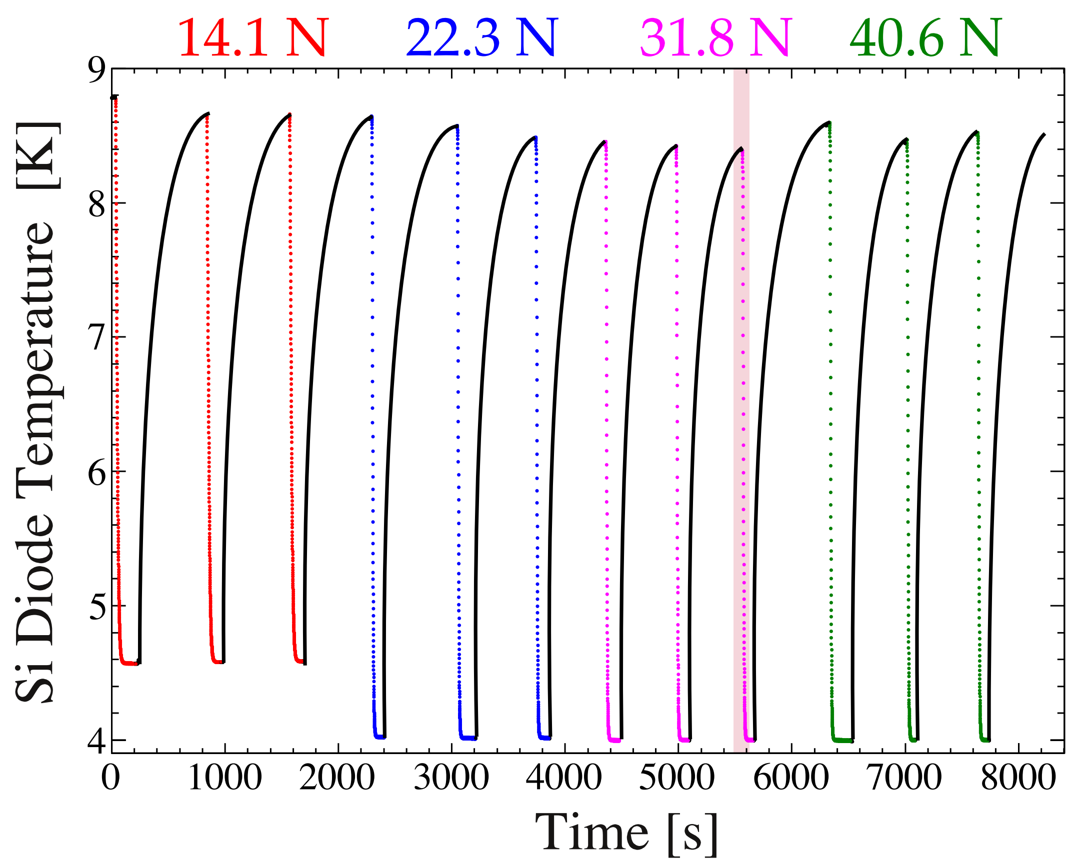


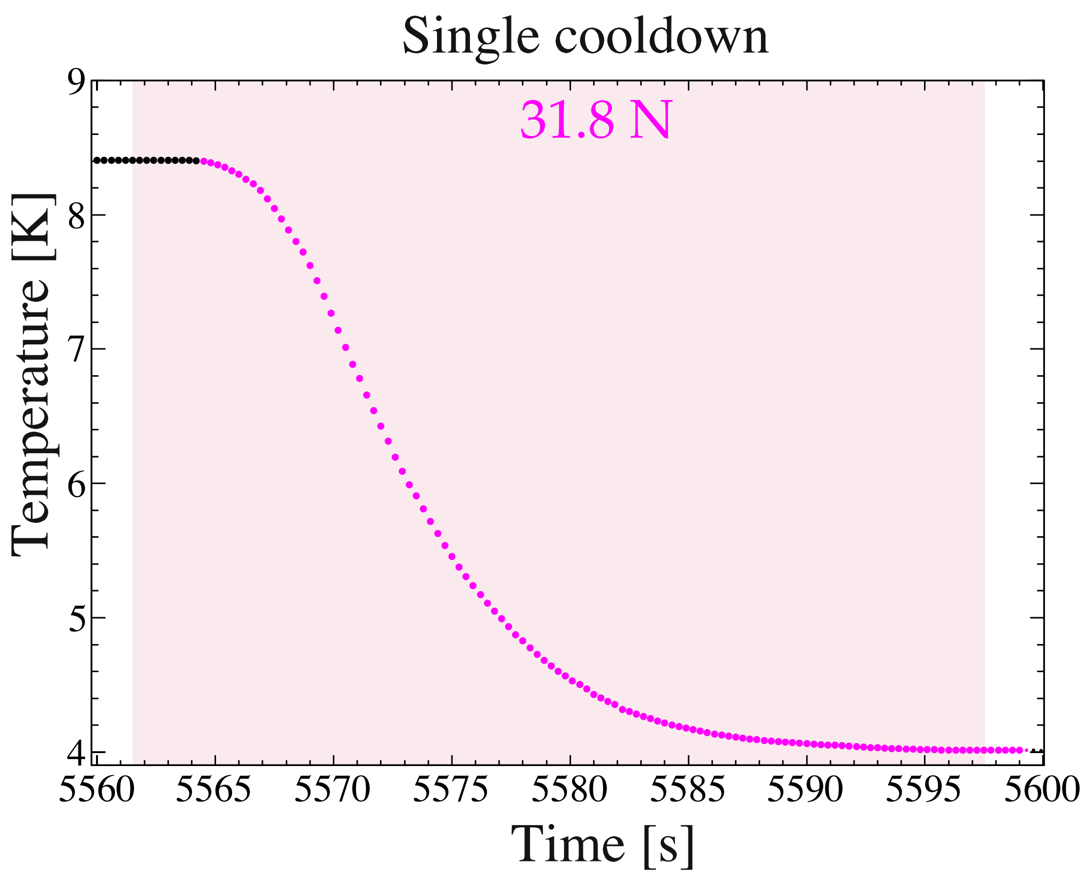


Thermalizer force

- For testing, a Si diode thermometer made to imitate a copper source capsule was attached to the moving block and squeezed by the thermalizer.



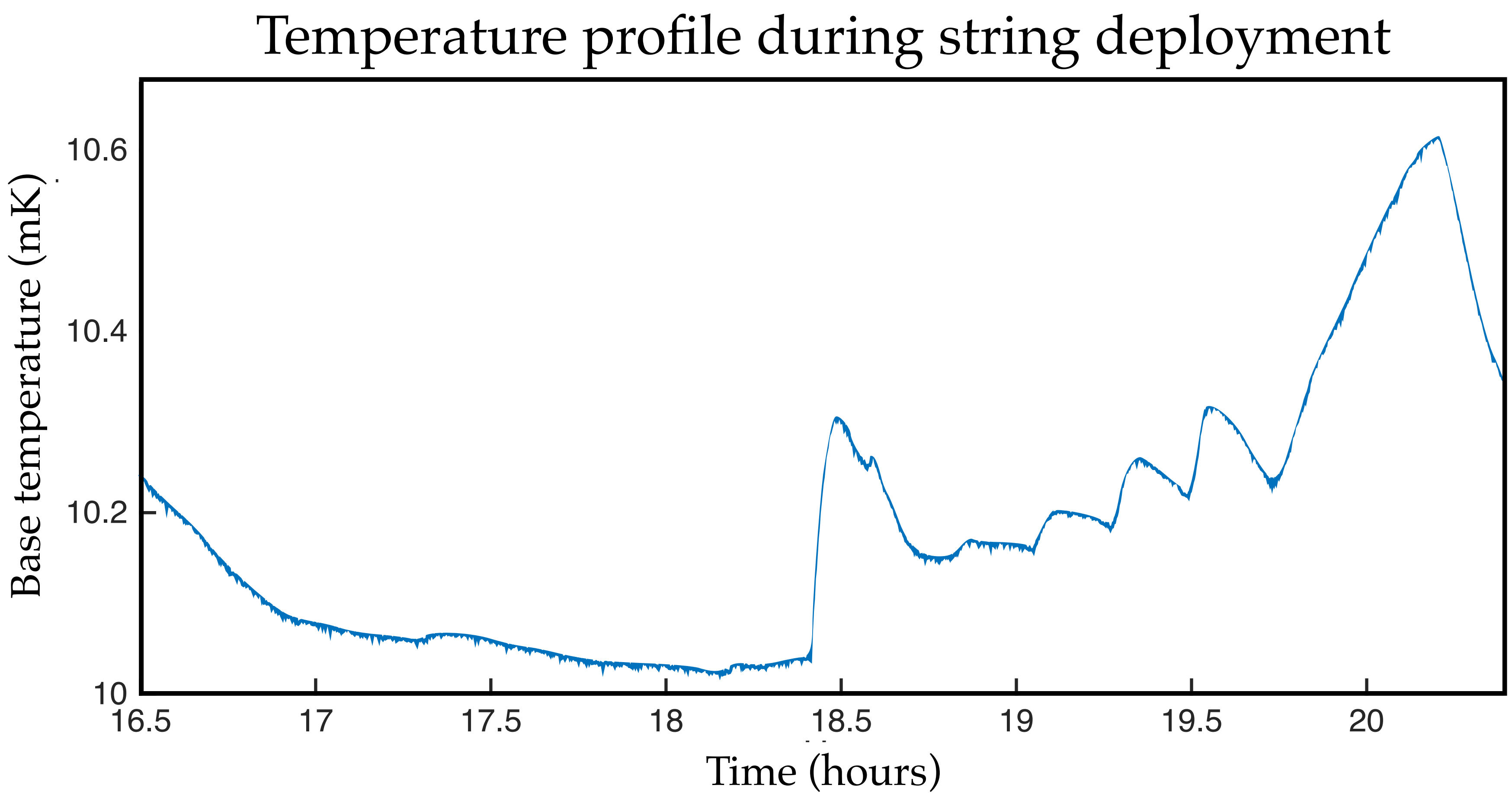




- A force of 31.8 N cools the capsule to base temperature in approximately 30 seconds.

Base temperature effect

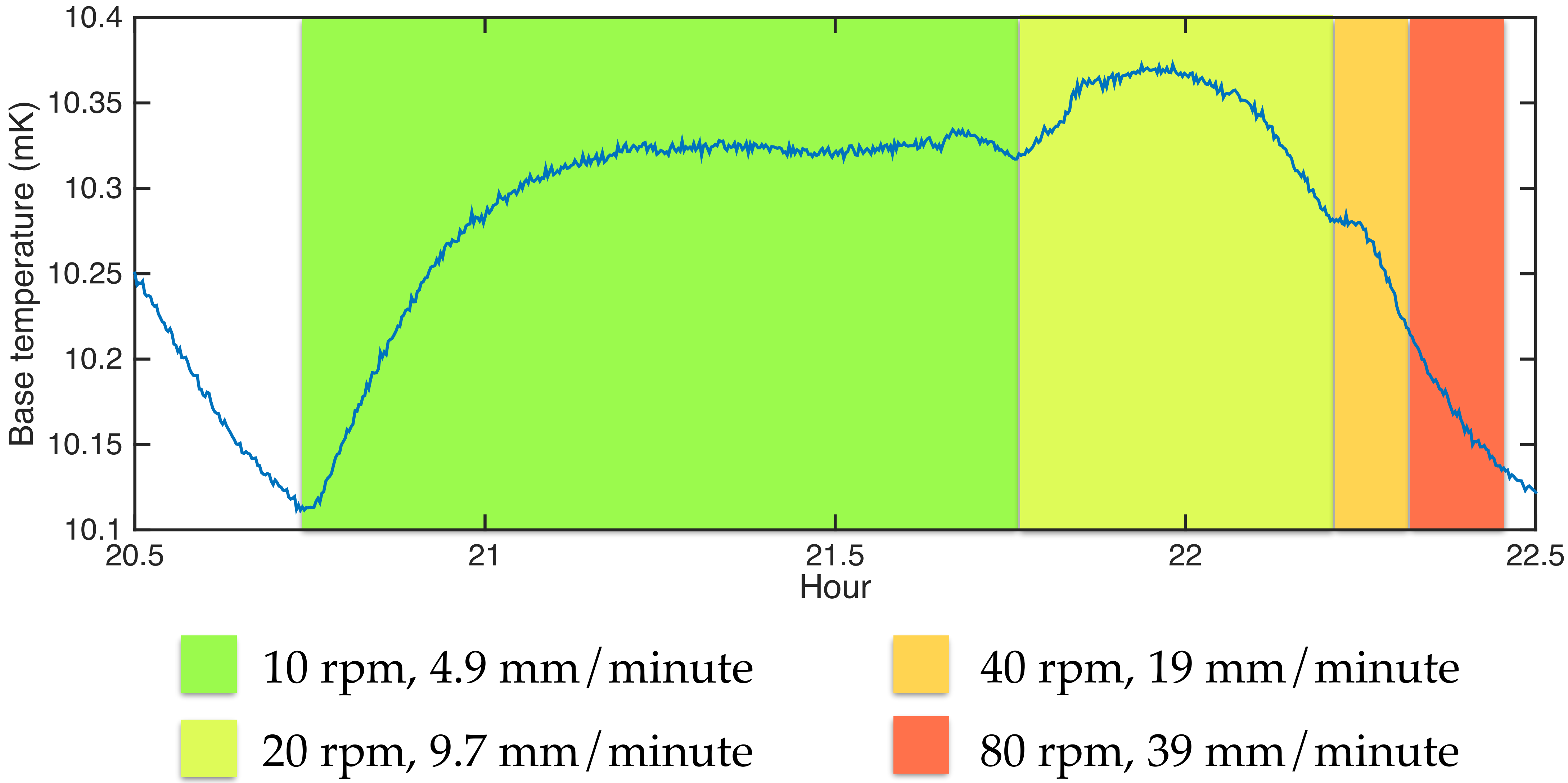
- Cryostat base temperature was measured during deployment down to 10 mK region



- Very little effect was seen on the base temperature during string cooling and lowering

String extraction

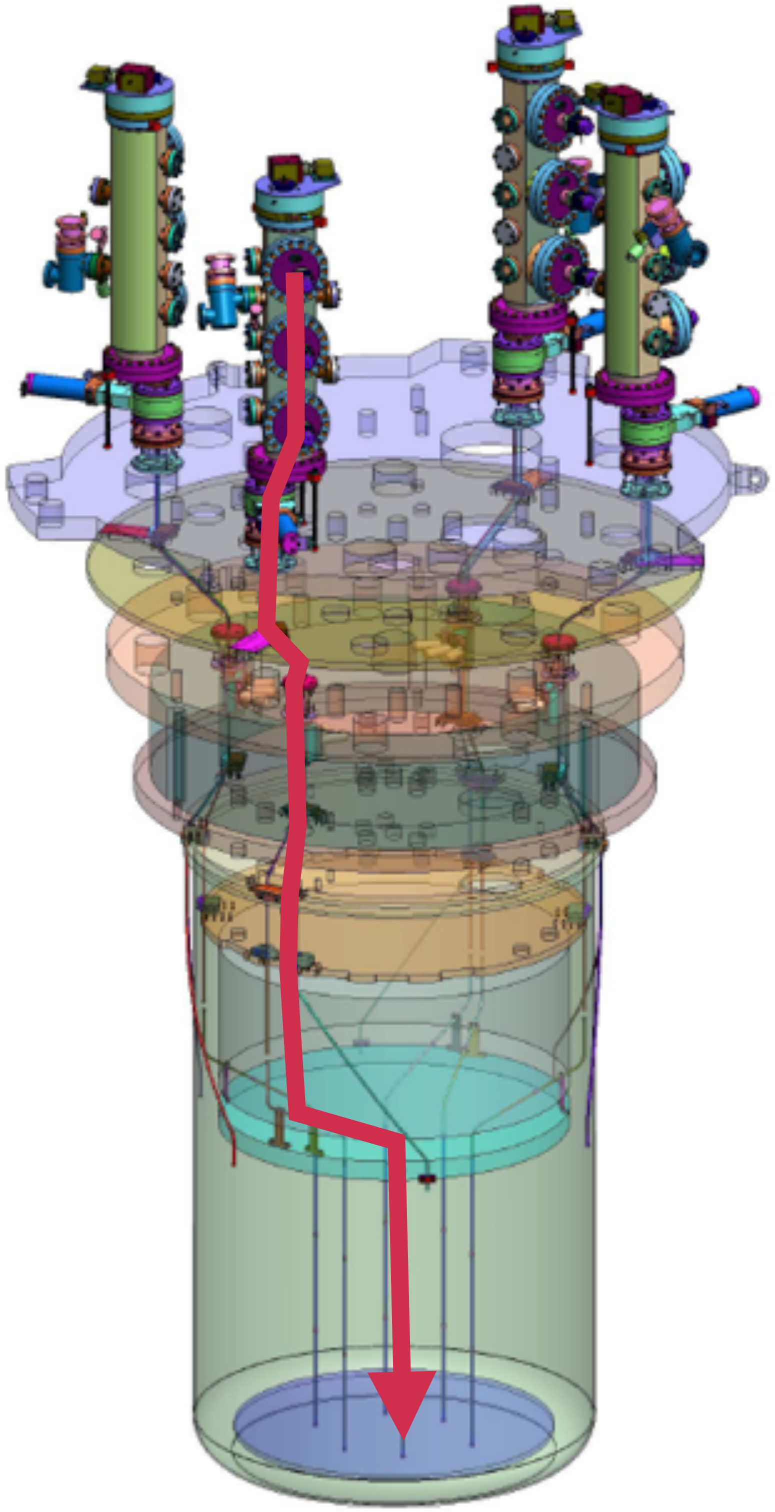
- Cryostat base temperature was also measured during string extraction



- Very slow raising speed is required when sources are in 10 mK region due to frictional heating

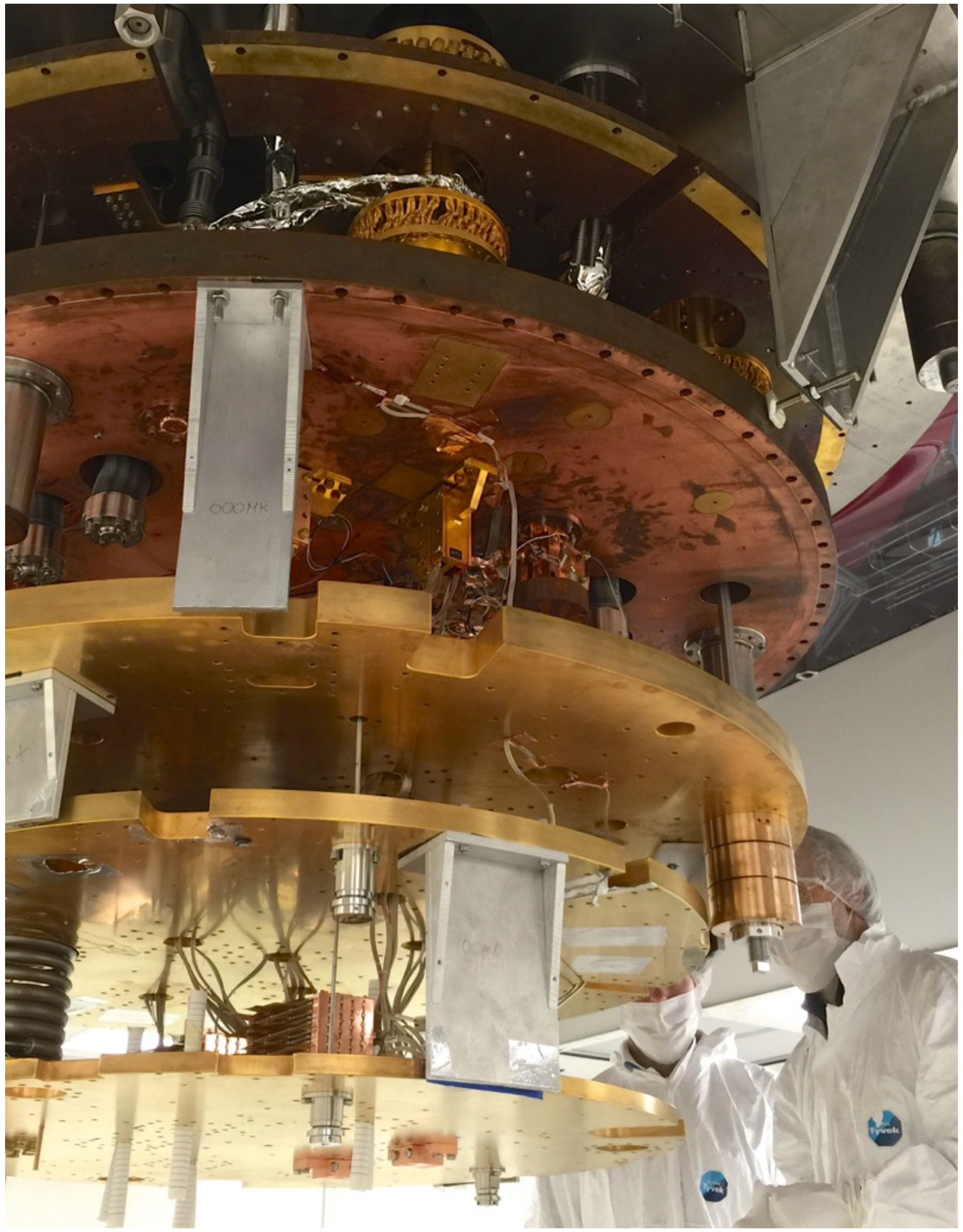
Cold test results

- We can lower strings from 300 K down to base temperature without large disruption to the cryostat
- Capsules can be cooled to 4 K with mechanical squeezes in very short time scales (under 1 minute)
- With a ~3 hour deployment (0.4 mm/s string speed) after string thermalization at 4 K, the maximum effect on base temperature was a 5% deviation from baseline
- With a very slow string extraction in the detector region, base temperature effects can be kept very small (3% deviation from baseline)



Outline

- History and background
- CUORE detector and cryostat
- Calibration
  - Analysis
  - Detector Calibration System
- Status and prospects



CUORE-0 first results

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Initial performance of the CUORE-0 experiment

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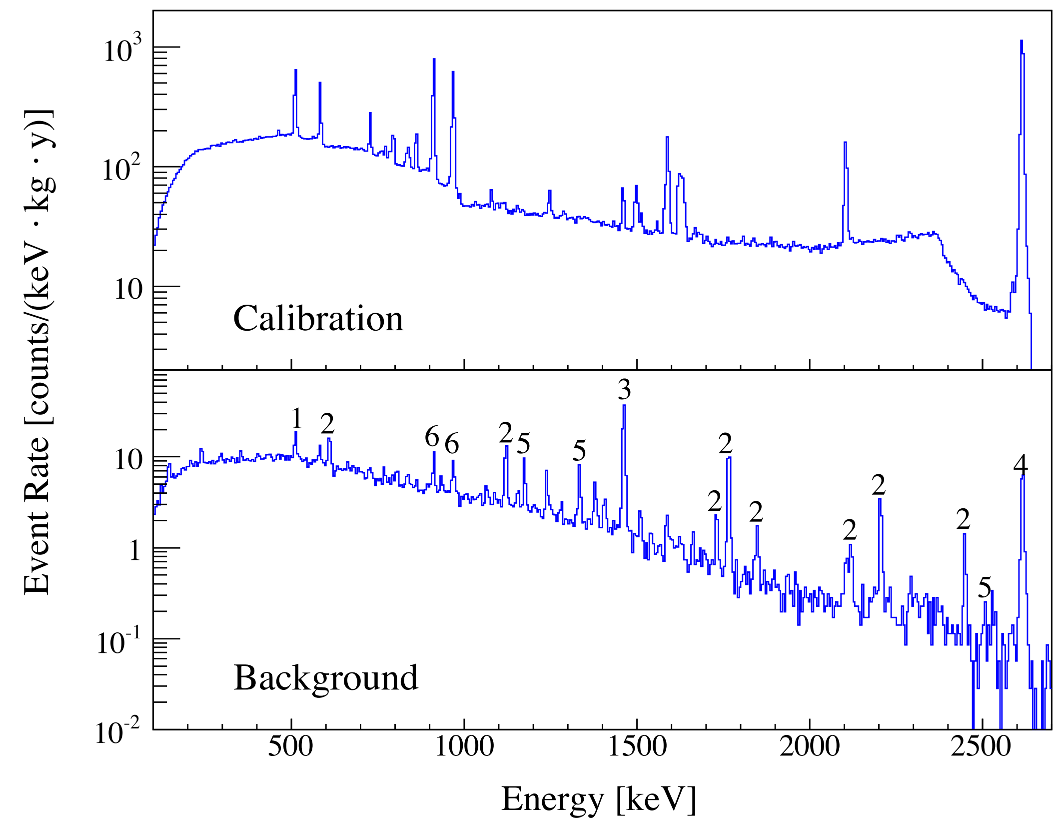
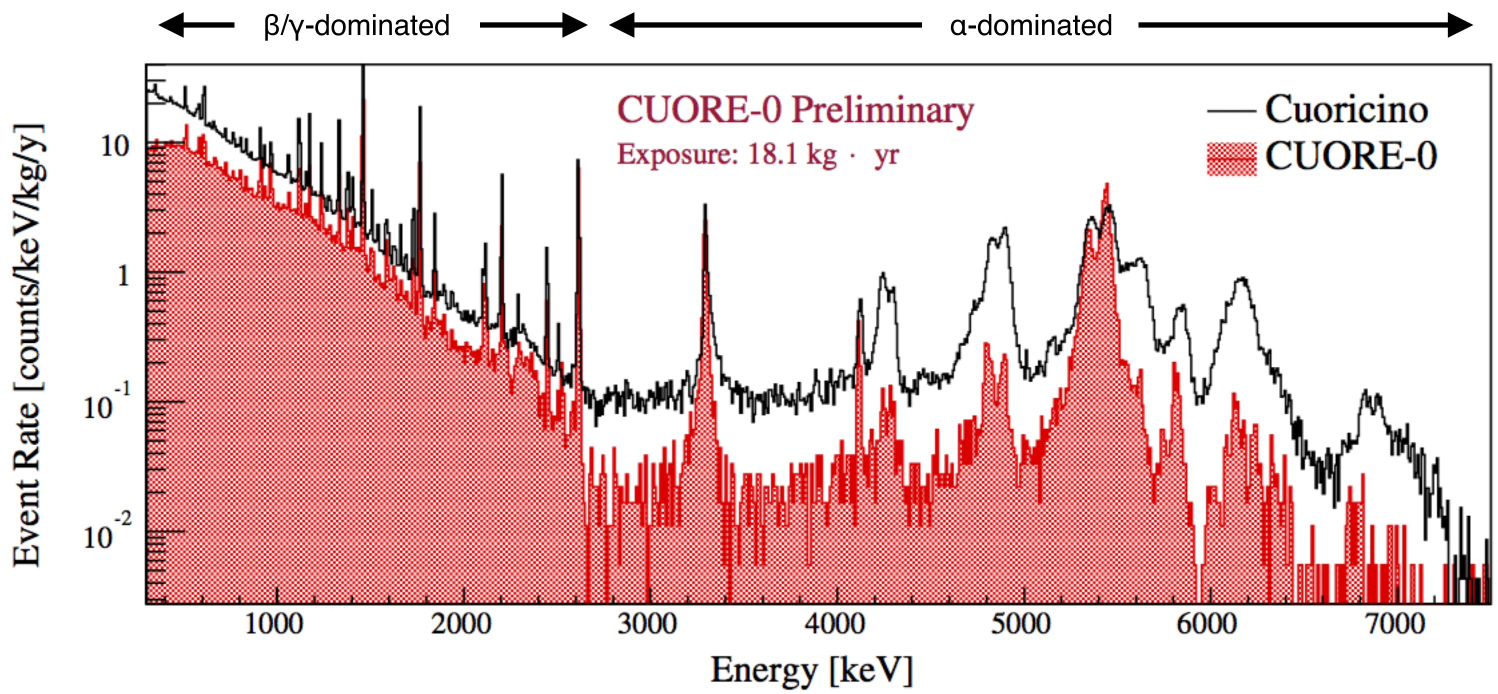
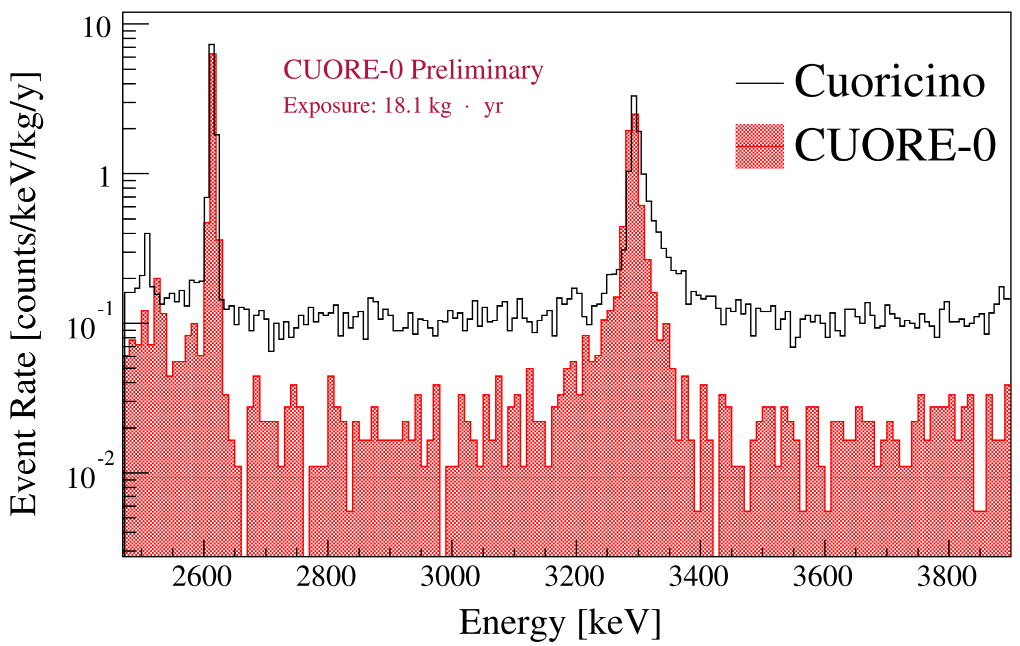


Fig. 2: CUORE-0 calibration (top panel) and background spectrum (bottom panel) over the data taking period presented in this work. γ-ray peaks from known radioactive sources in the background spectrum are labeled as follows: (1) e^+e^- annihilation; (2) ^{214}Bi; (3) ^{40}K; (4) ^{208}Tl; (5) ^{60}Co; and (6) ^{228}Ac.

Look for CUORE-0 unblinded results and 0νββ limit this spring!

Backgrounds





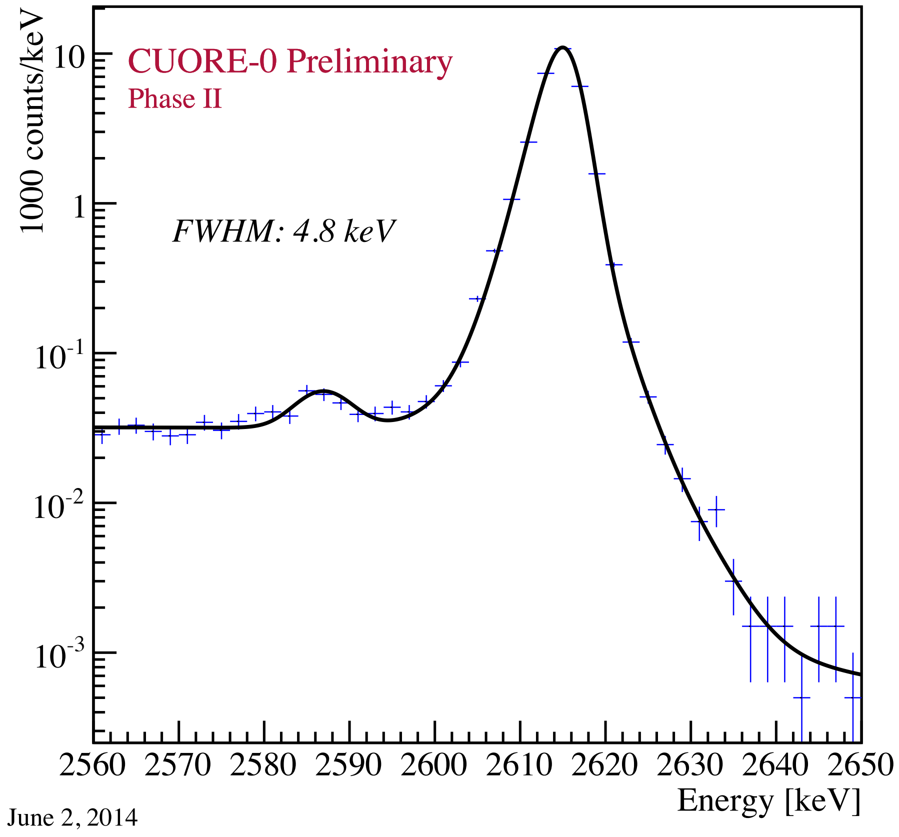
- 6-fold reduction in α-dominated background moving from Cuoricino to CUORE-0 from improved cleaning and assembly procedures
- 2.5-fold reduction of background in 0νββ region from stringent radon control in COURE-0

	0νββ region [c/keV/kg/yr]	2700 – 3900 keV [c/keV/kg/yr]
Cuoricino	0.153 ± 0.006	0.110 ± 0.001
CUORE-0	0.063 ± 0.006	0.020 ± 0.001
CUORE	0.01 (projected)	

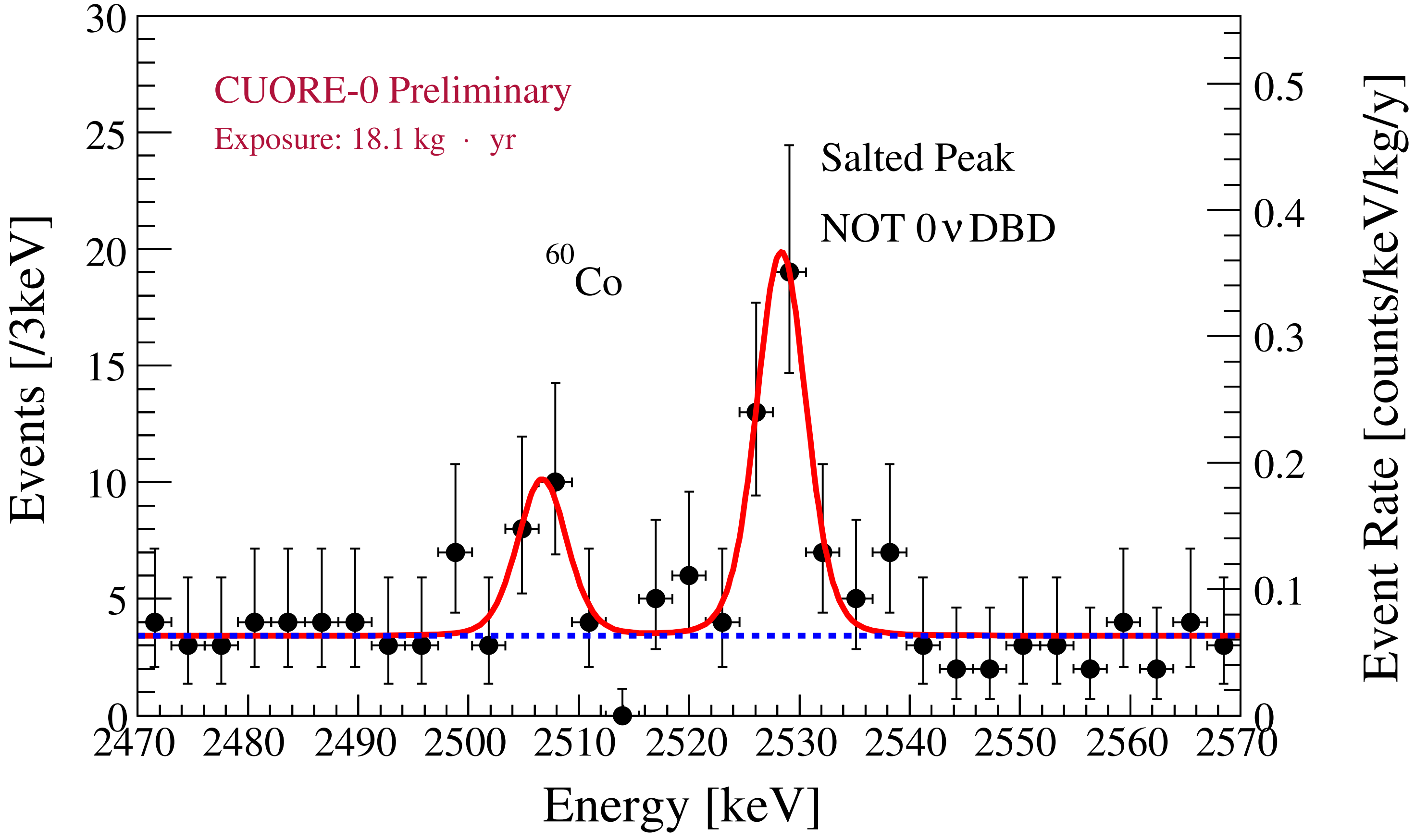
Resolution

- ^{208}Tl line (2615 keV) is used to estimate energy resolution at 0νββ *Q*-value (2527 keV)
- Design goal of 5 keV FWHM for CUORE-0 and CUORE exceeded

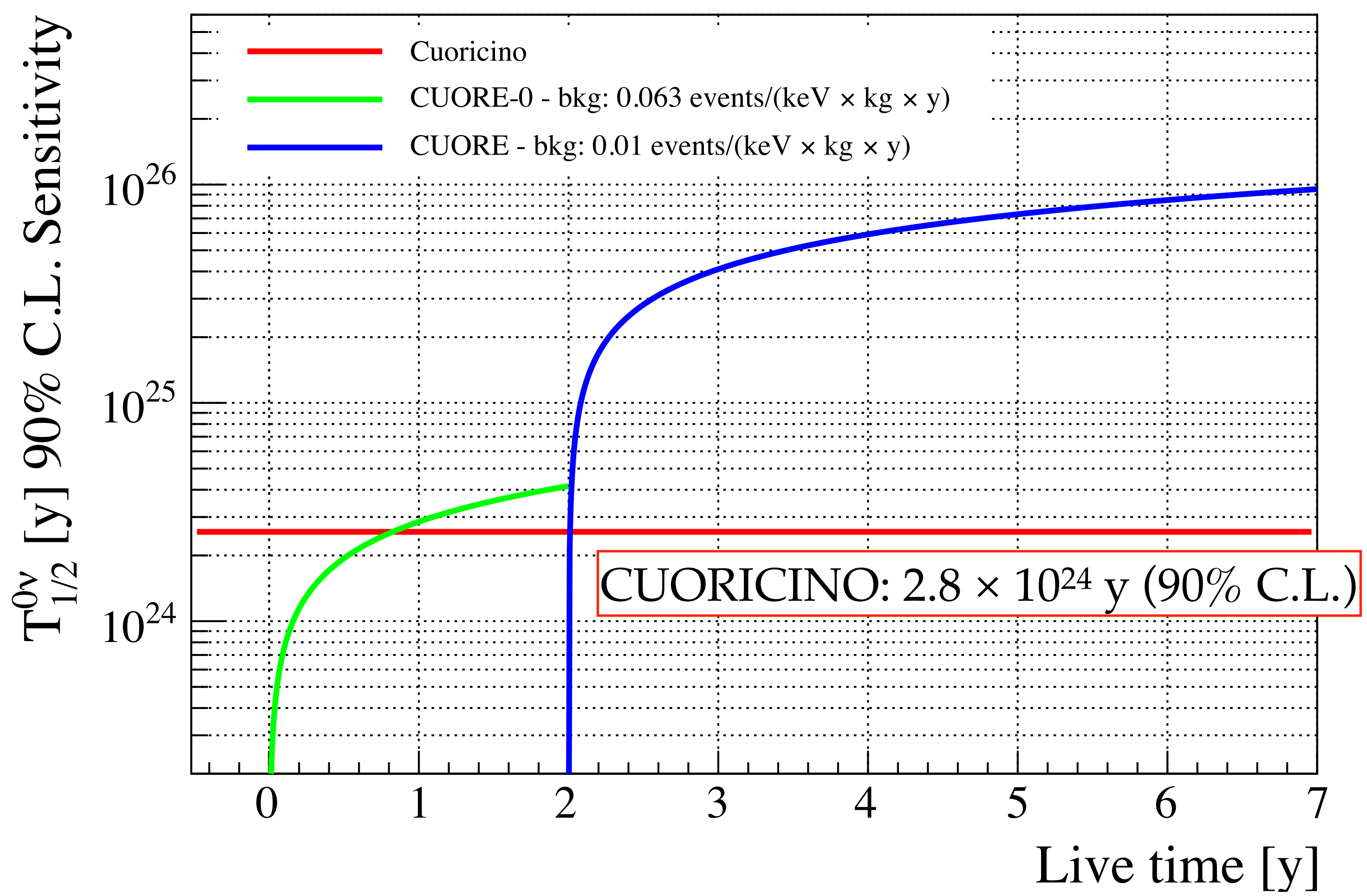
CUORE-0 ^{208}Tl Calibration Spectrum

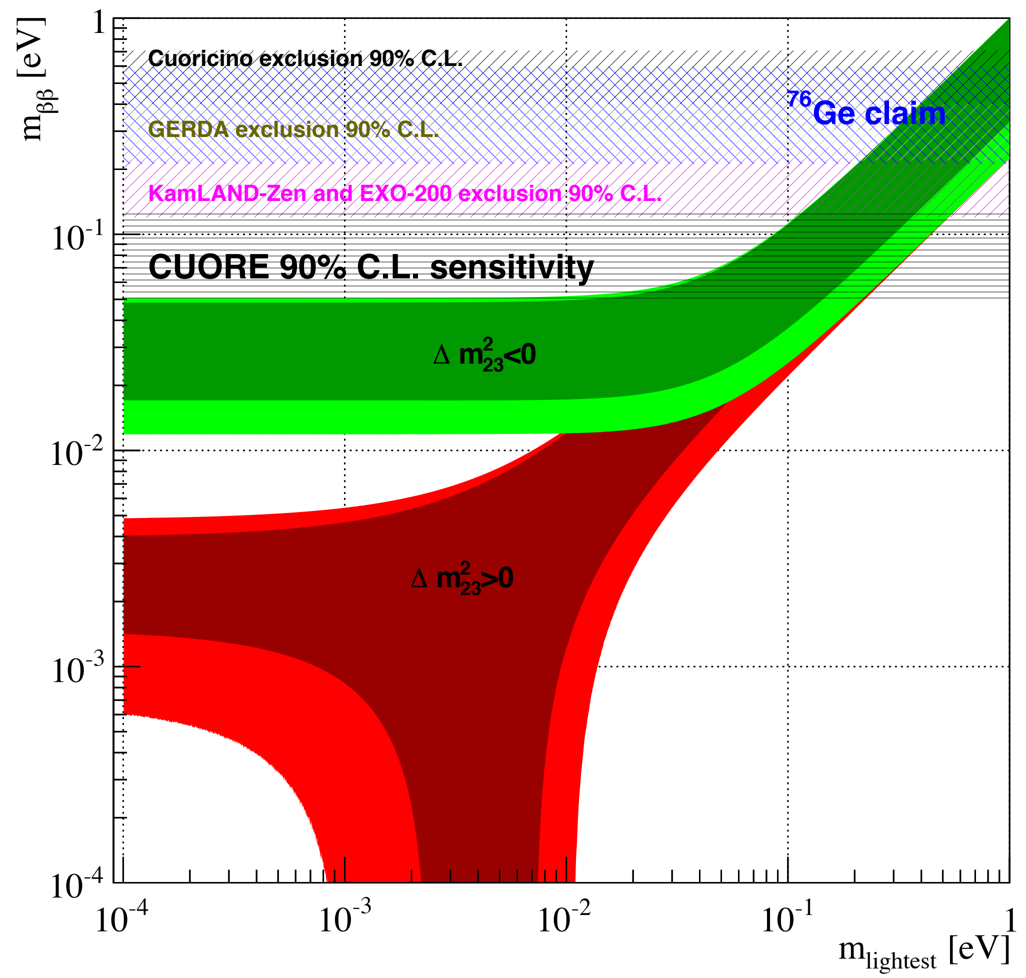


CUORE-0 Background in 0νββ region



Sensitivity

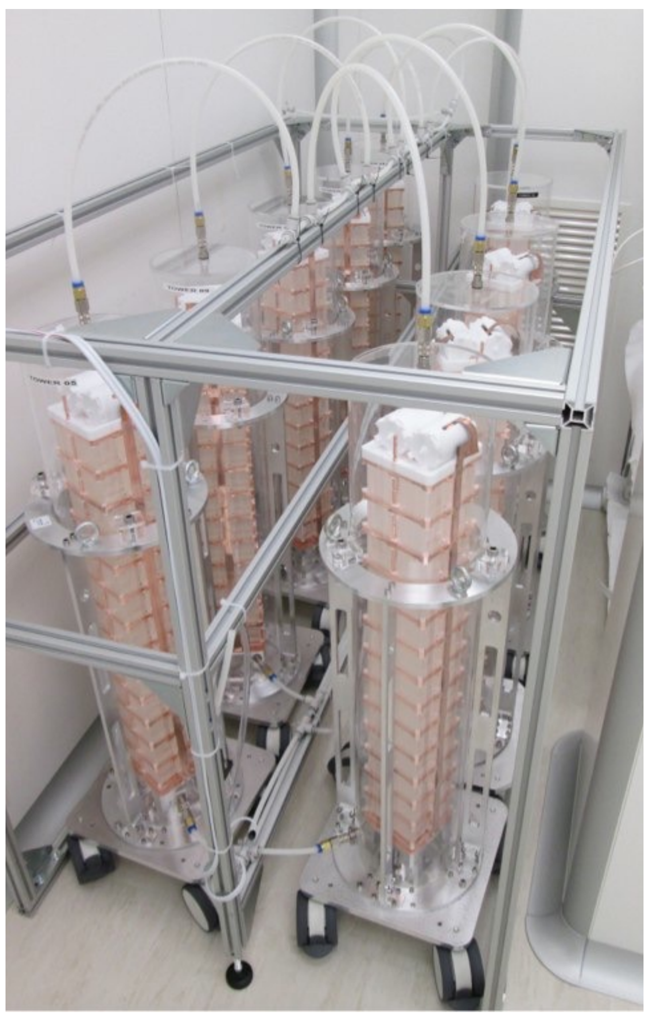


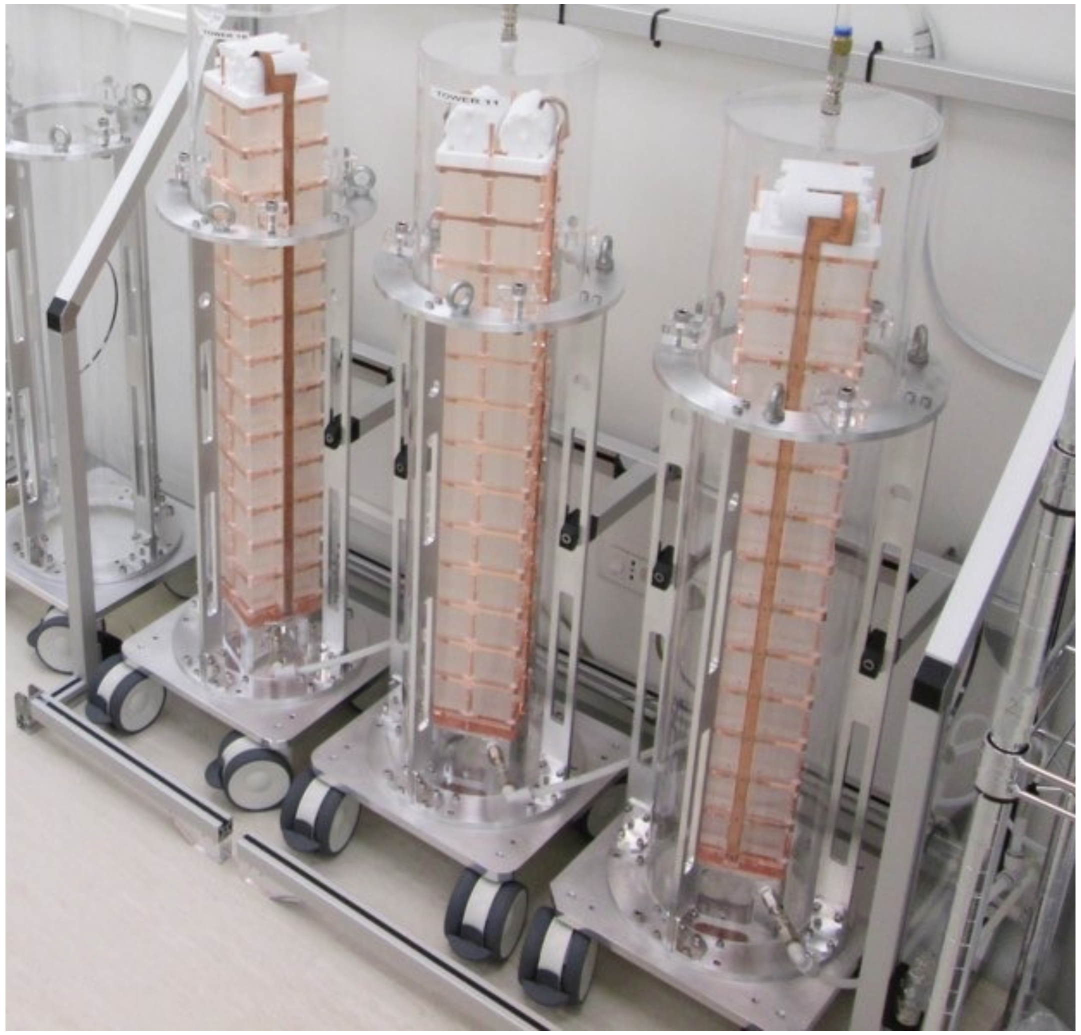


- CUORE $T_{1/2}^{0\nu\beta\beta}$ sensitivity goal: **9.5 × 10^{25} y** @ 90% C.L.
- Effective Majorana mass: **51 - 133 meV** @ 90% C.L.
- Assumptions: 5 keV FWHM resolution in 0νββ region, background rate of 0.01 cts/keV/kg/yr, 5 years of live time

Tower construction

- Construction of all 19 CUORE towers is complete
- Towers are stored under nitrogen to avoid radon contamination

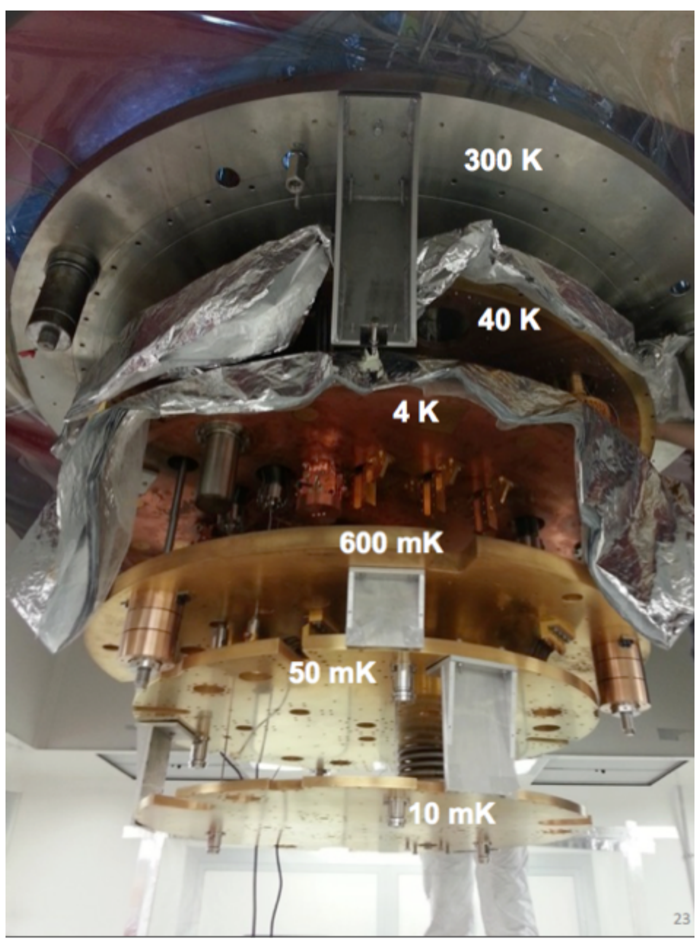




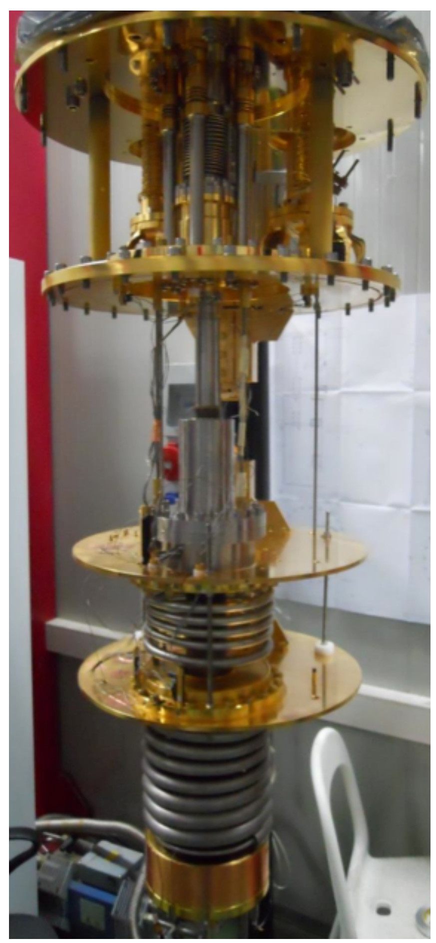
Cryostat commissioning

- CUORE Cryostat has reached stable base temperature of 5.9 mK in test runs
- Mini-tower successfully operated in cryostat to test wiring and electronics
- Final preparations are underway for full detector installation this summer

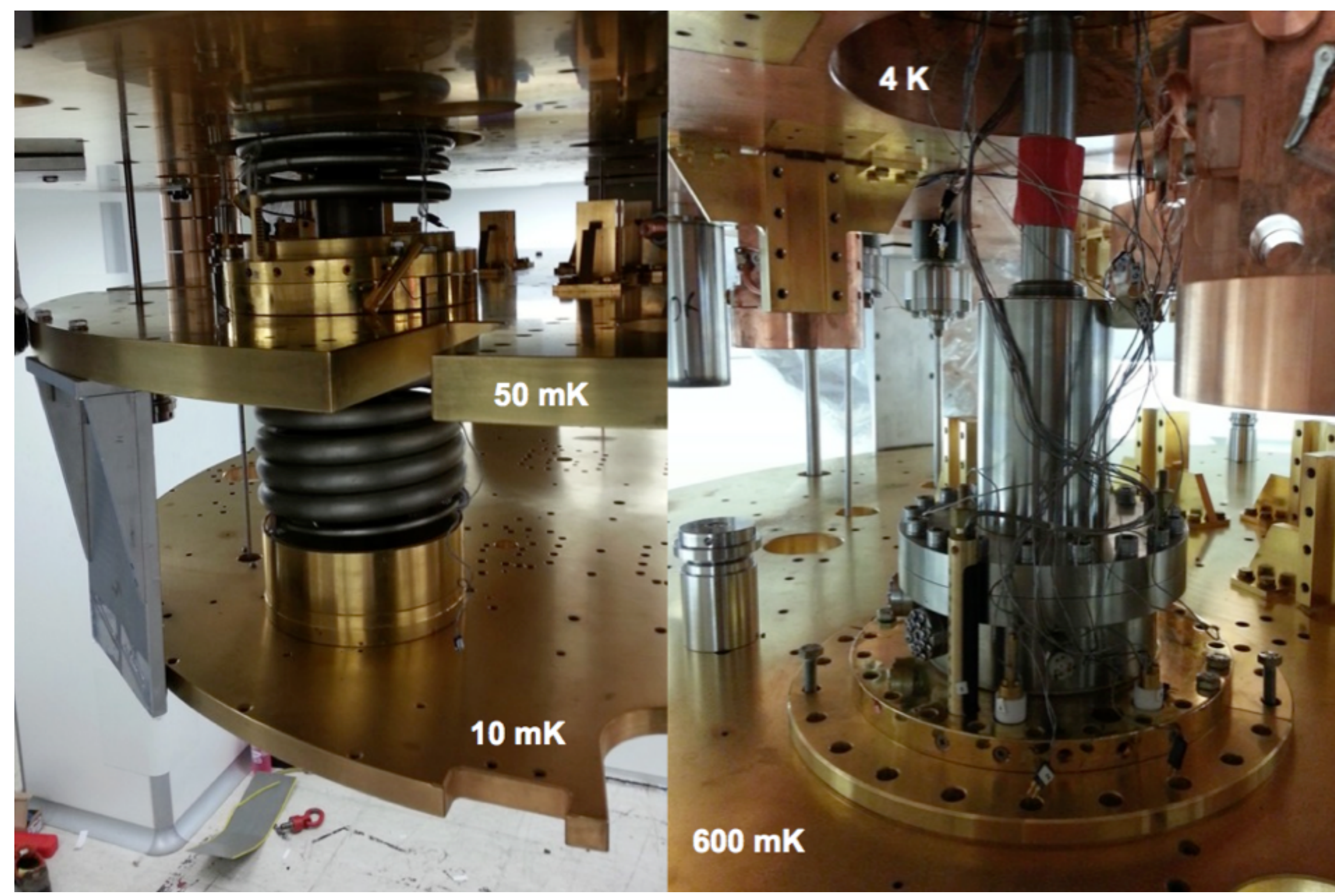
Cryostat vessel flanges



Dilution unit test stand



Dilution unit installed in cryostat



Upcoming steps

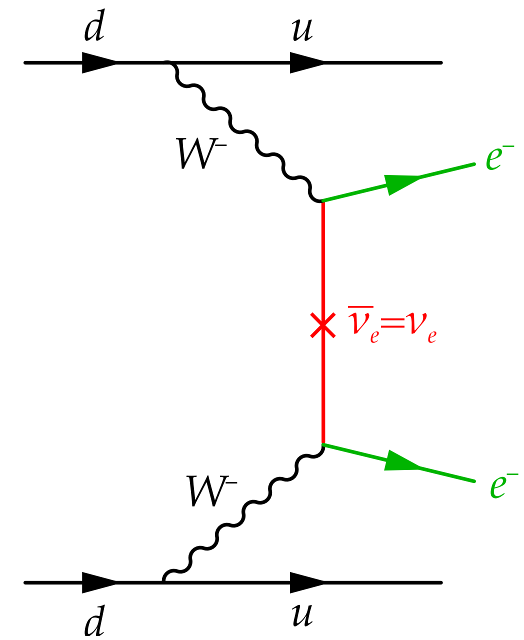
Spring 2015: Full installation and commissioning of all cryostat components without detectors

Summer 2015: Detector installation in radon-suppressed clean room

Fall 2015: Cryostat and detector characterization and commissioning

Early 2016: First physics data from CUORE

Prospects



- Observation of 0νββ would unambiguously establish the Majorana nature of the neutrino and the existence of lepton number violation,
- The 0νββ half-life is also a window into the absolute neutrino mass scale
- CUORE will have a 90% C.L. sensitivity to a 0νββ half-life of 9.5×10^{25} y, almost two orders of magnitude better than the current limit
- This corresponds to an effective Majorana neutrino mass sensitivity of 51 – 133 meV