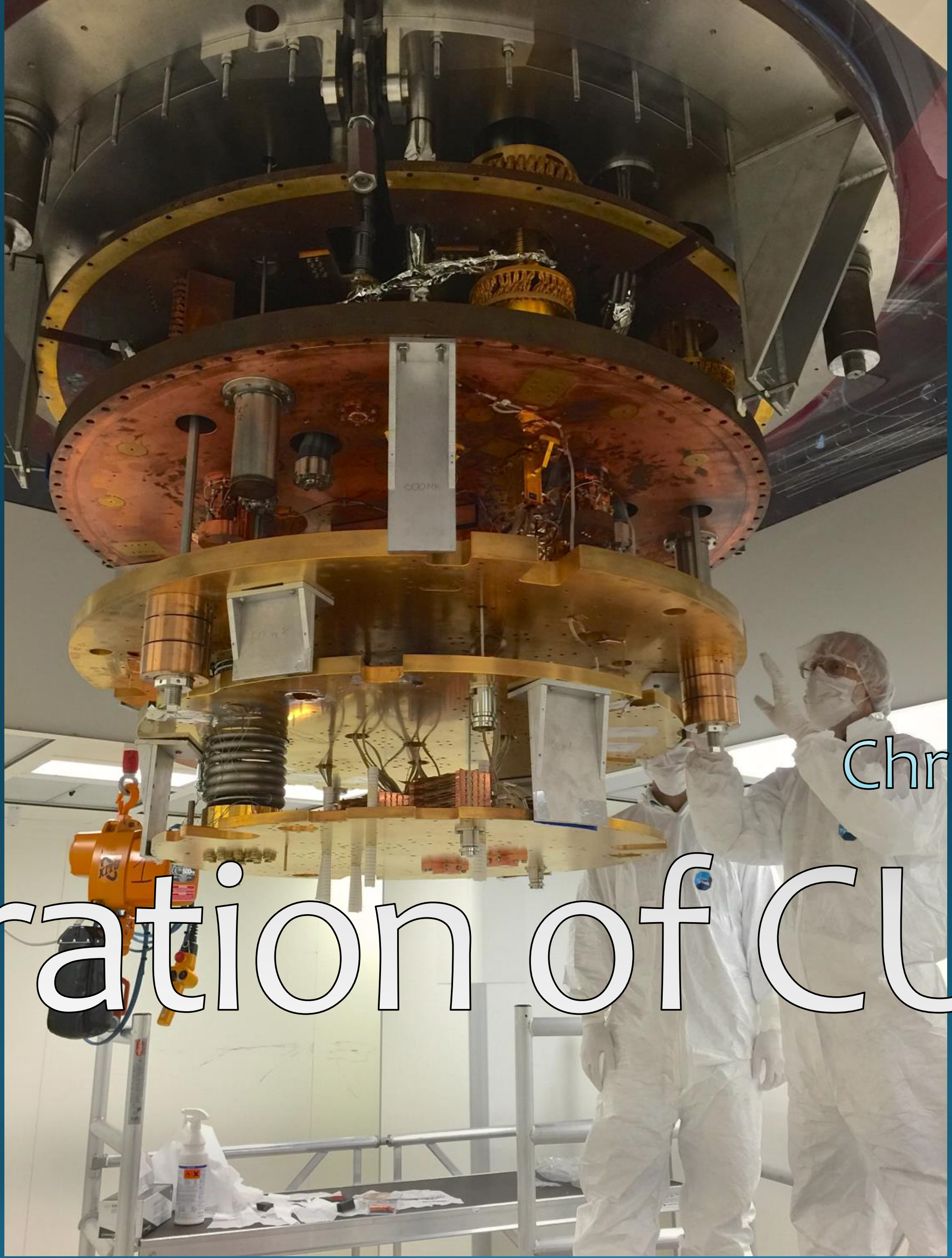
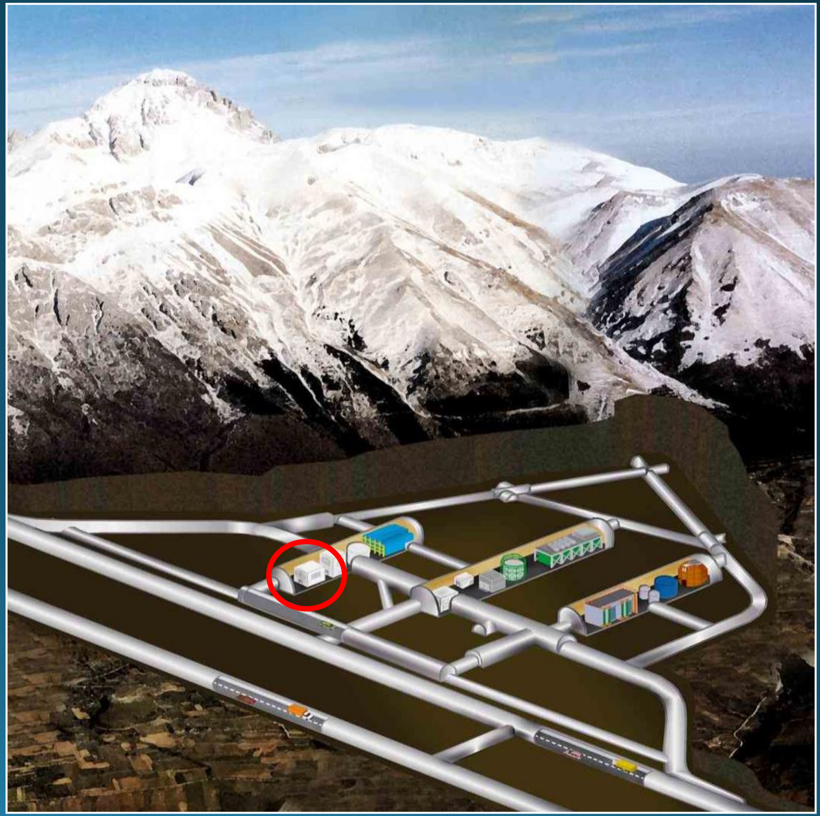


Calibration of CUORE

Christopher Davis

Overview of CUORE

- CUORE- Cryogenic Underground Observatory for Rare Events
- Located in Gran Sasso National Lab in Italy
- Operation and Data taking to begin in Mid 2016
- Searching for neutrinoless double beta decay: $0\nu\beta\beta$

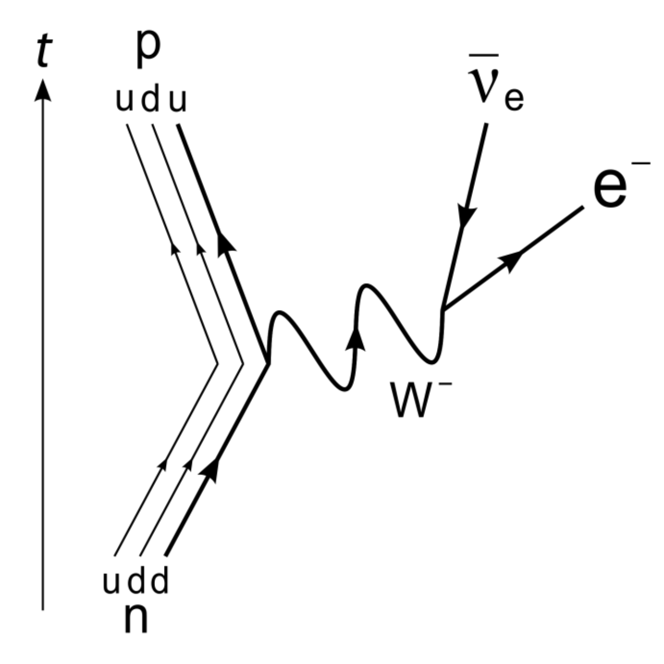


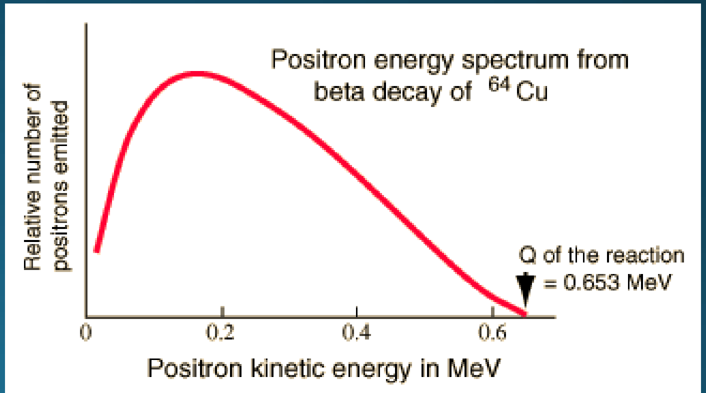
Outline

- Physics of $0\nu\beta\beta$
- How does CUORE detect $0\nu\beta\beta$?
- CUORE-0
- CUORE Detector Calibration System
- CUORE Simulations

History of Beta Decay

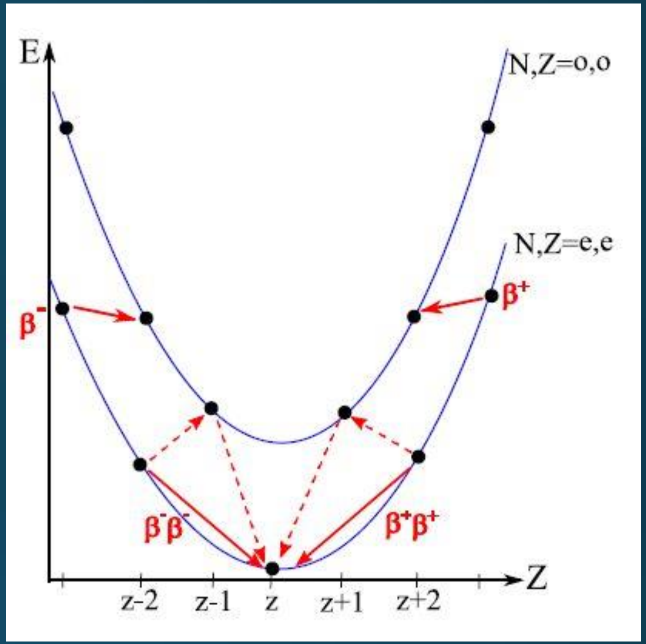
- 1899: Ernest Rutherford categorizes decays into α and β types
- 1900: β particles are determined to be electrons by Henri Becquerel
- 1927: β decay spectrum determined to be continuous with an upper bound
- 1934: Enrico Fermi publishes a model of beta decay that produces neutrinos
- 1956: Antineutrinos discovered in nuclear reactors in Cowan-Reines neutrino experiment

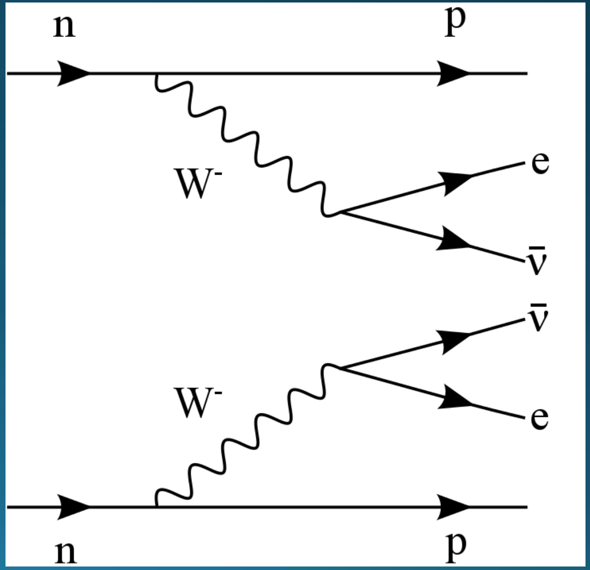




Double Beta Decay

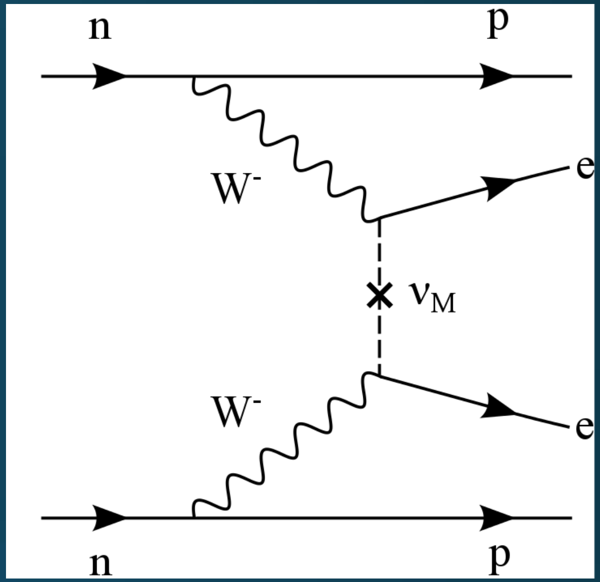
- 1935: Maria Goeppert-Mayer proposed the idea of double beta decay
- Only observable when normal β decay is forbidden
  - Even-even nuclei
- Standard Model process
  - First observed in 1950
- $T_{1/2}$ of Te-130: 7.9×10^{20} years

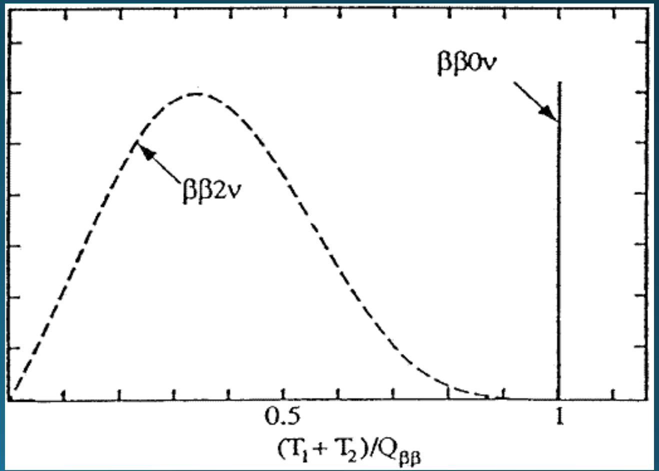




$0\nu\beta\beta$

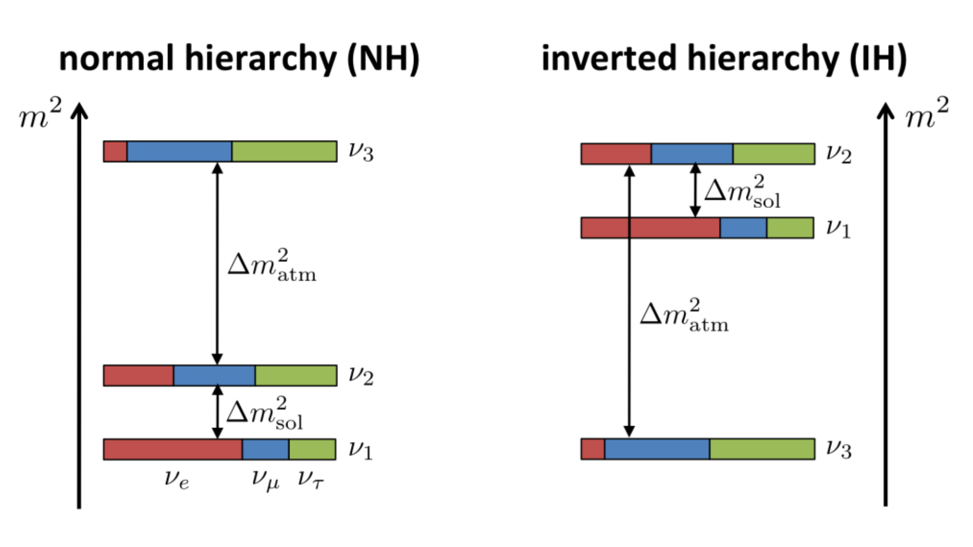
- Neutrinos are neutral particles
- All other SM fermions are charged
  - Antiparticles have opposite charge: $\bar{e} \neq e$
  - Act as Dirac particles
- Do neutrinos have same quantum numbers as antineutrinos: $\overline{\nu_e} = \nu_e$?
  - i.e. Act as Majorana particles
- Would allow for a new process in double beta decay: $0\nu\beta\beta$
- No neutrinos produced in the final state
  - Full energy of the interaction detectable

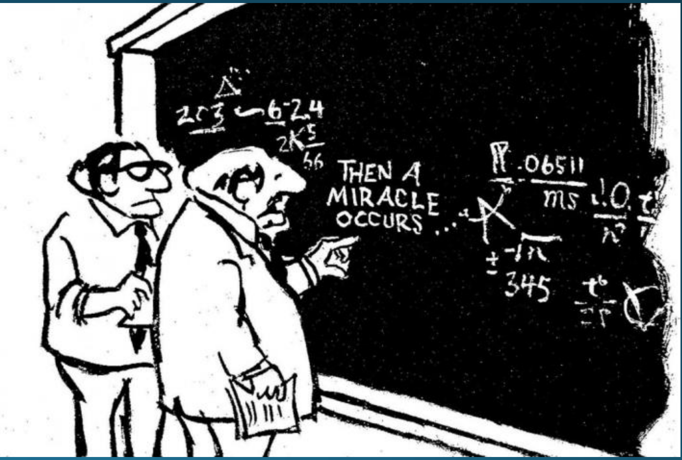




Implications of $0\nu\beta\beta$

- Discovery of $0\nu\beta\beta$ can resolve some long-standing physics questions
- Neutrino mass hierarchy
  - Oscillation experiments have determined Δm^2, not m
  - Allows for two possible scenarios: Normal and Inverted
- Matter-antimatter asymmetry
  - Majorana neutrinos violate lepton number and B-L conservation
- Origin of neutrino mass
  - Seesaw Mechanism



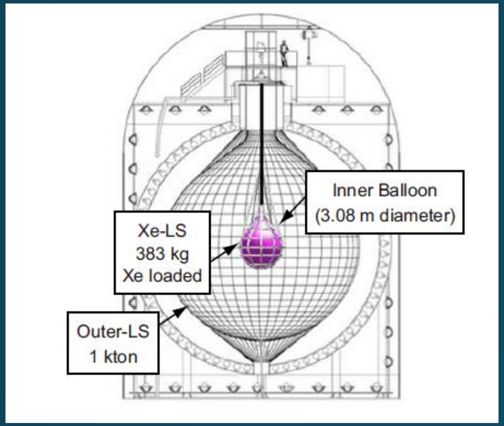


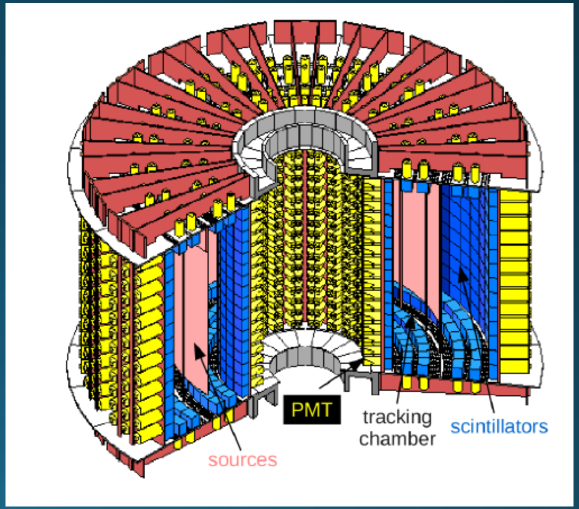
How do we detect $0\nu\beta\beta$?

- Experimental sensitivity to $0\nu\beta\beta$:
  - Sensitivity $\sim a_I \sqrt{\frac{Mt}{b\Delta E}}$
- One of the slowest decays in the universe
  - Need a large source mass, M, and high isotopic abundance a_I
  - Need to wait a long time, t
- Need a clean environment and/or particle ID
  - Experiments take place in deep underground laboratories
  - Parts have to be taken to extreme lengths for radiopurity to reduce background, b
  - $2\nu\beta\beta$ is an irreducible background
- Need good energy resolution, ΔE, to find electron energies at the Q-value

$0\nu\beta\beta$ Experiments

- ^{136}Xe
  - Kamland-Zen
  - EXO-200
- ^{76}Ge
  - Gerda
  - Majorana
- ^{130}Te
  - CUORE
  - SNO+
- Super-NEMO
  - Multiple isotopes (^{82}Se, ^{48}Ca, ^{96}Zr, …)





Outline

- Physics of $0\nu\beta\beta$
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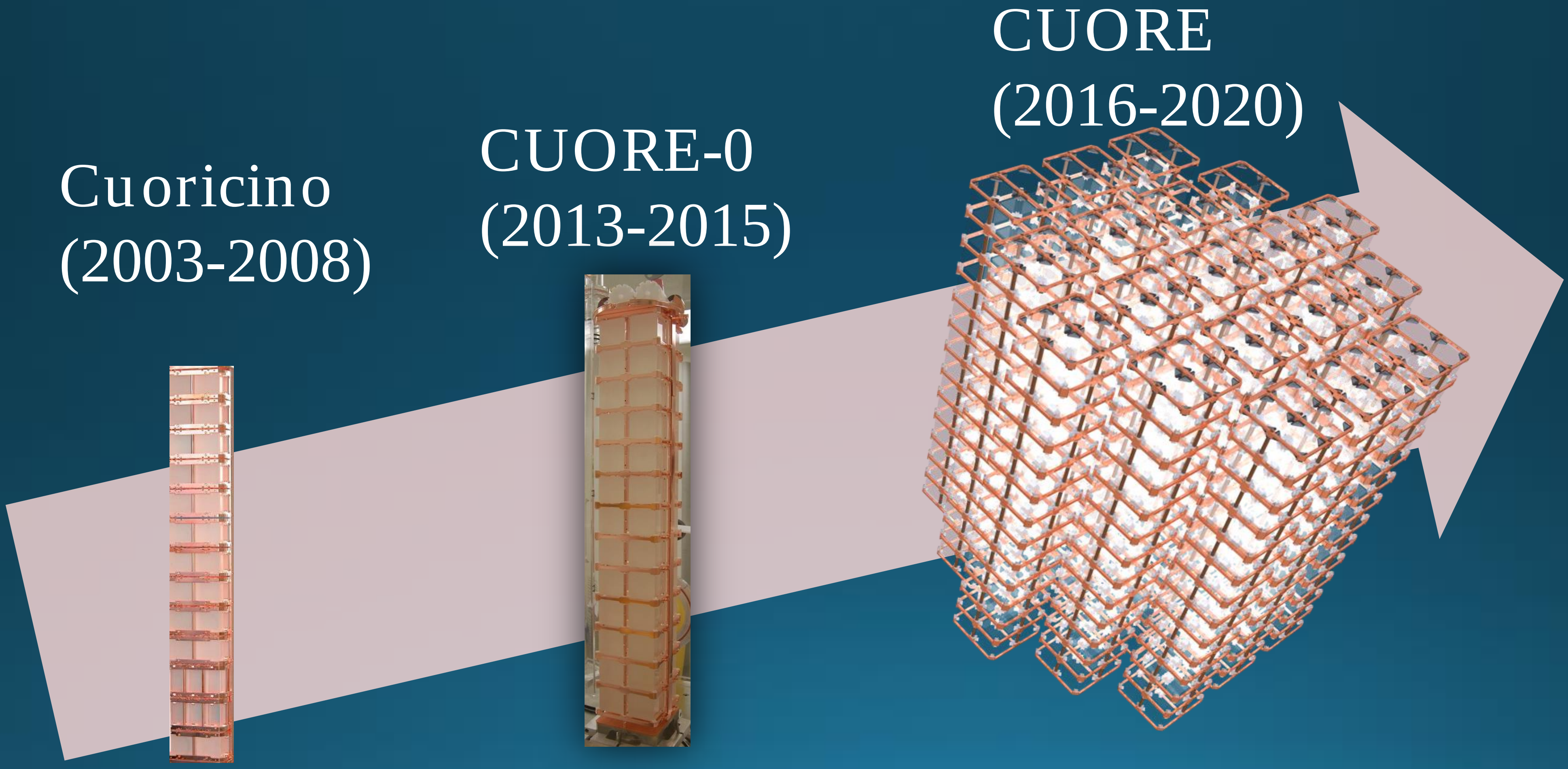
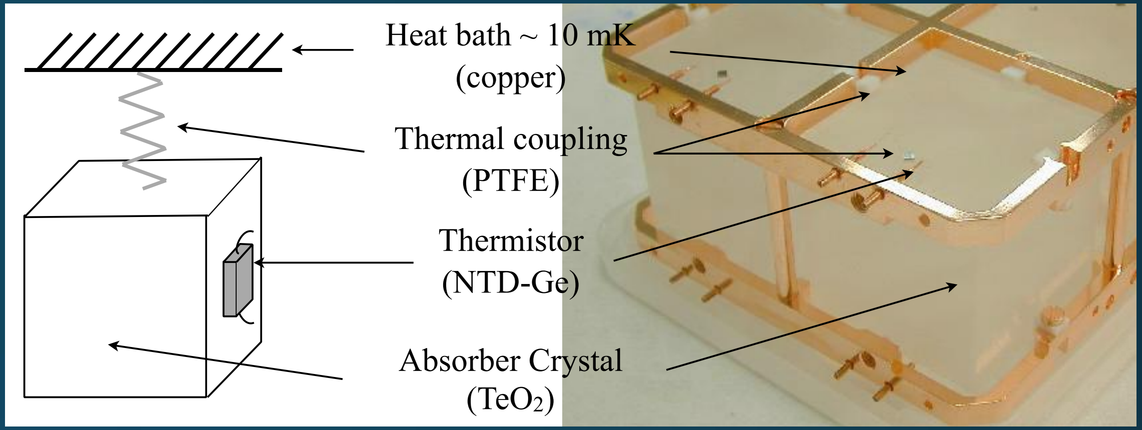
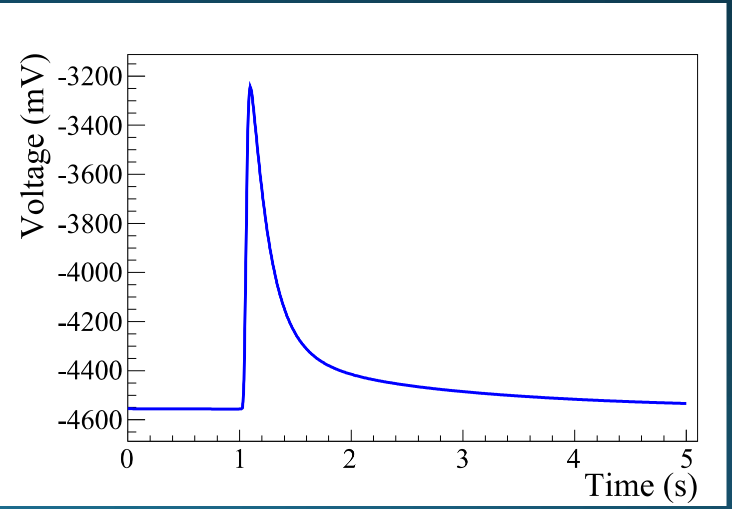
CUORE Timeline



Bolometer Method

- In CUORE, we use bolometers to detect $0\nu\beta\beta$
- Each bolometer is weakly coupled to a thermal bath
- The energy deposited into a bolometer causes its temperature, T, to rise
  - Energy resolution improves at low temperature
  - CUORE will operate at ~10mK
- Thermistor measures the temperature rise and determines the incident energy





CUORE Detectors

- CUORE uses TeO_2 crystals as our detectors
- Act as both source and detector
  - ^{130}Te has 34.2% isotopic abundance
  - Scalable
  - Q-value at 2528 keV
  - Tl-208 calibration peak is at 2615 keV
- CUORE will have 988 5x5x5 cm bolometers in 19 towers
  - Total active mass: 741 kg
  - Mass of ^{130}Te: 206 kg

Outline

- Physics of $0\nu\beta\beta$
- How does CUORE detect $0\nu\beta\beta$?
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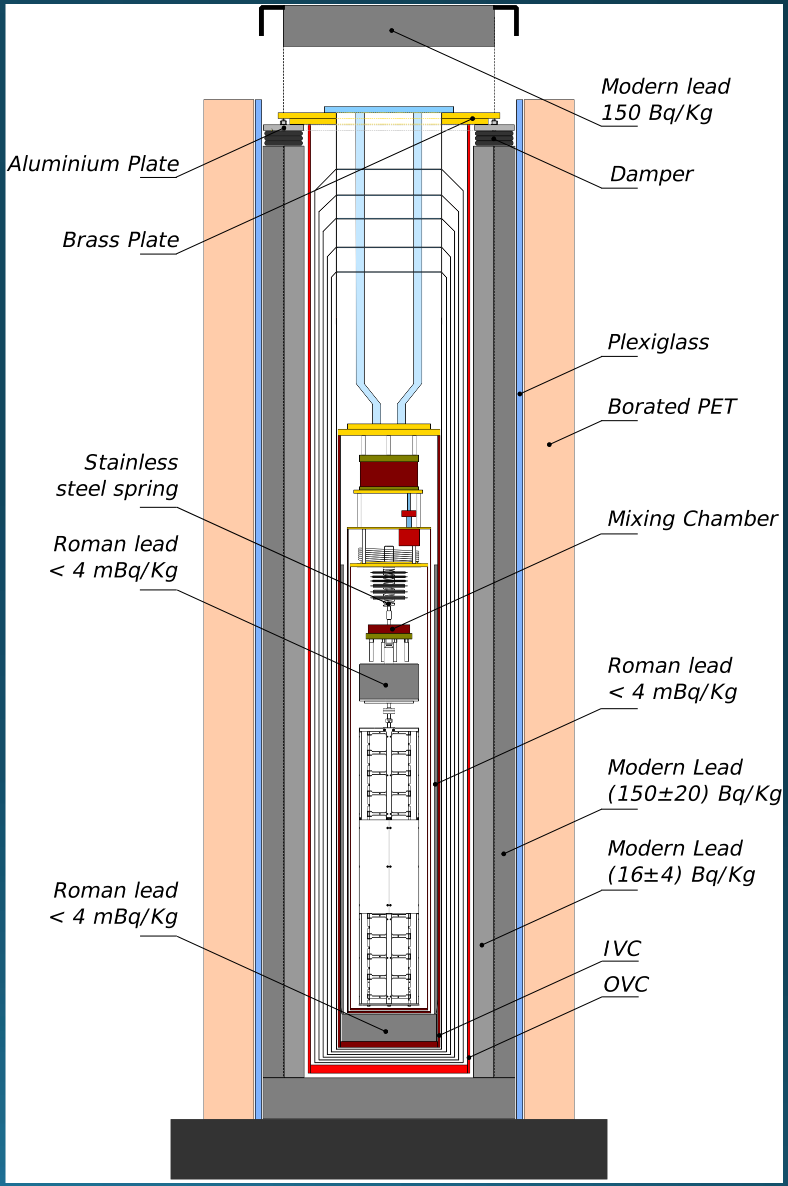
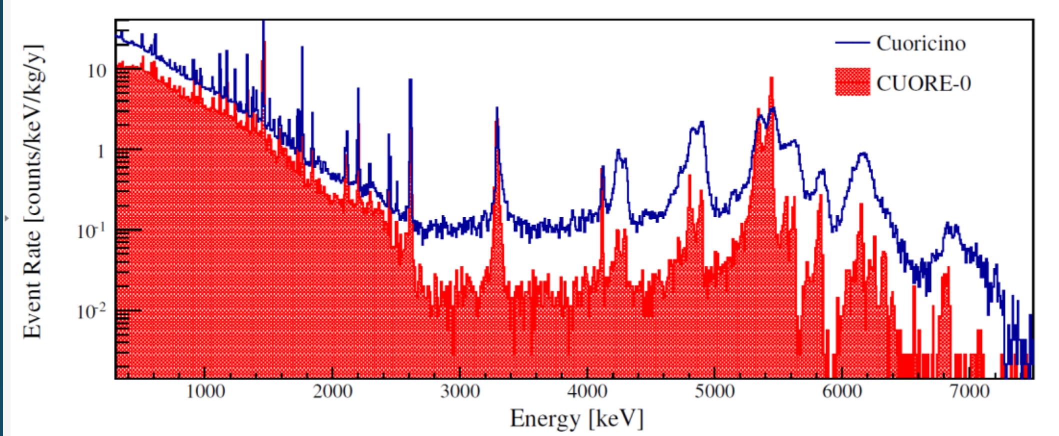
CUORE-0

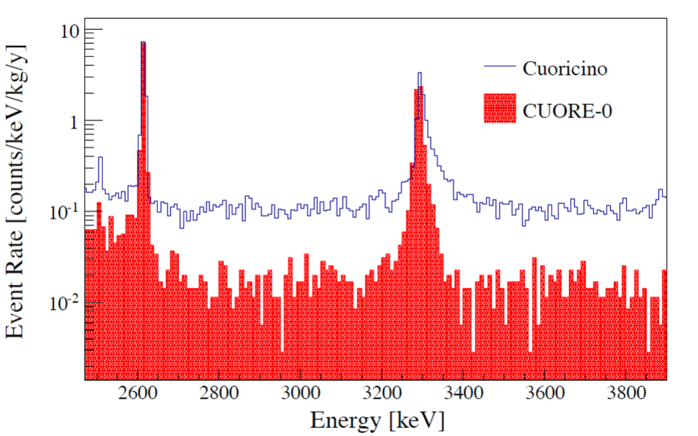
- CUORE-0 was an experiment done on the first CUORE tower prepared
- Placed into the Cuoricino cryostat
- Data collection started in Mar 2013
- Finished data collection in Feb 2015
  - Successful verification of tower instrumentation and radiopurity in crystal growth



CUORE-0 and Cuoricino Backgrounds

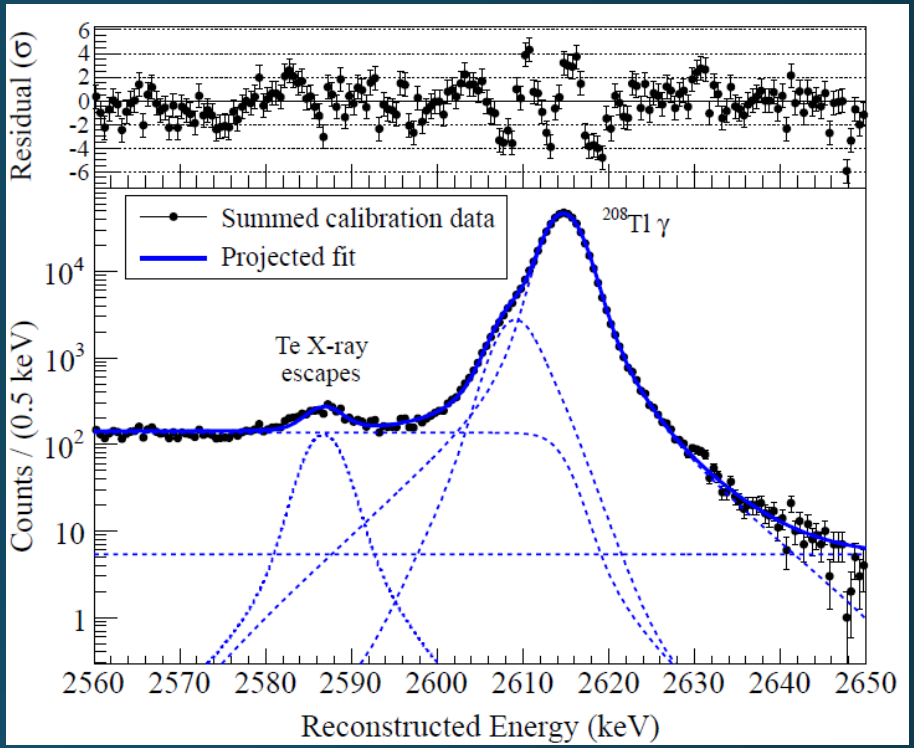
- ^{238}U and ^{232}Th α lines reduced due to detector surface treatment
- Improved Radon control reduced ^{238}U γ lines
- ^{232}Th γ lines are from cryostat
  - Same cryostat so no expected reduction
- Verifies improvements made for CUORE

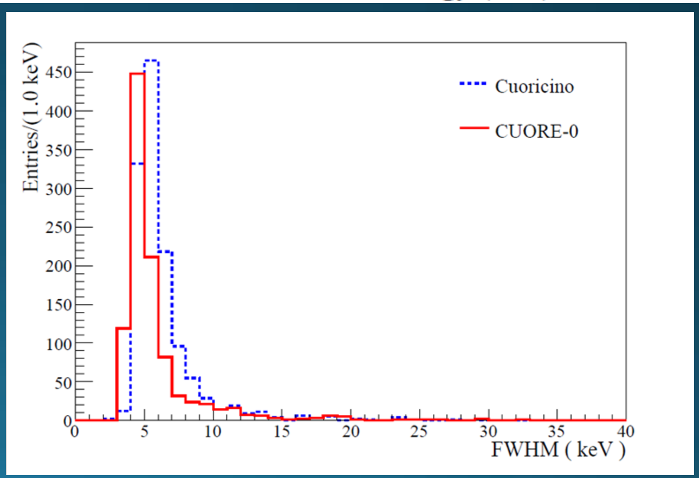




CUORE-0 Calibration

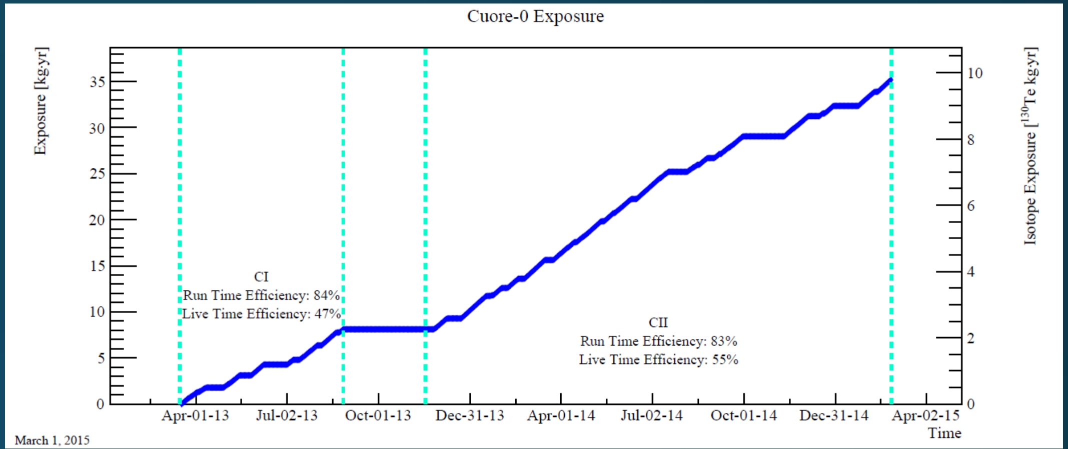
- Used ^{232}Th sources to calibrate the detector
  - Inserted between the outer and inner lead shields
- Inserted sources ~monthly for 60 hours of calibration
- FWHM from ^{208}Tl peak
  - Used to establish detector response near 2528 keV Q-value

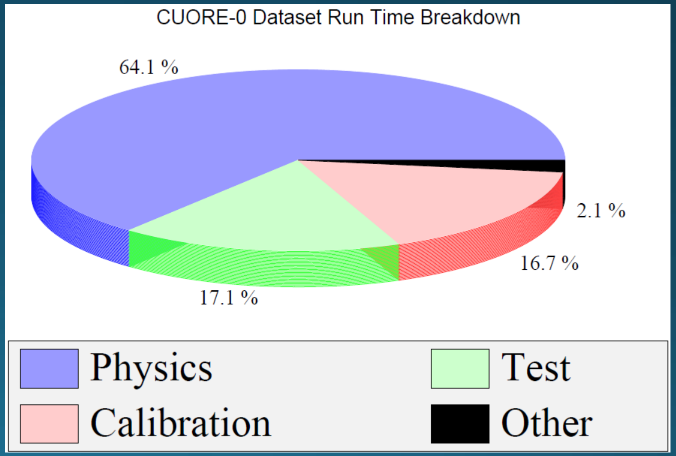




CUORE-0 Data Collection

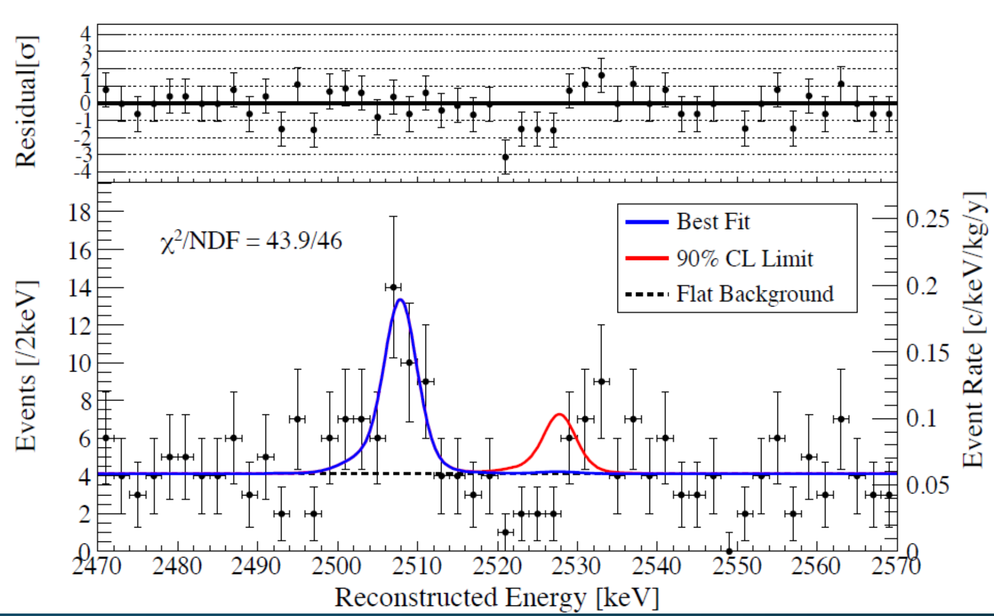
- Data collection took place in two "campaigns"
- Improvements made in between significantly improved noise performance
  - Added temperature stabilization to mixing chamber in addition to the tower
- Tested out analysis software and data collection techniques

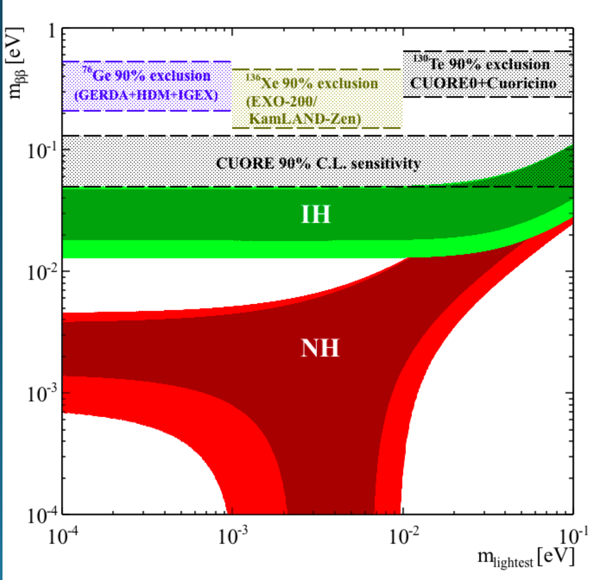




CUORE-0 Results

- Fit a flat background plus a ^{60}Co peak near the Q-value
- Observed no $0\nu\beta\beta$ events
- Set combined CUORE-0 and Cuoricino limit on $0\nu\beta\beta$ in ^{130}Te
  - $T_{1/2} \geq 4.0 \times 10^{24}$ yr at 90% CL
    - Most stringent limit ^{130}Te limit to date
- Results released April 2015
  - Phys Rev Lett **115**, 102502





Moving from CUORE-0 to CUORE

- CUORE-0 was a successful proof of concept of the CUORE detector and analysis systems
- Learned more about detector response and how to reduce and mitigate noise sources
- Learned more about how to use calibration to understand energy resolution and detector response

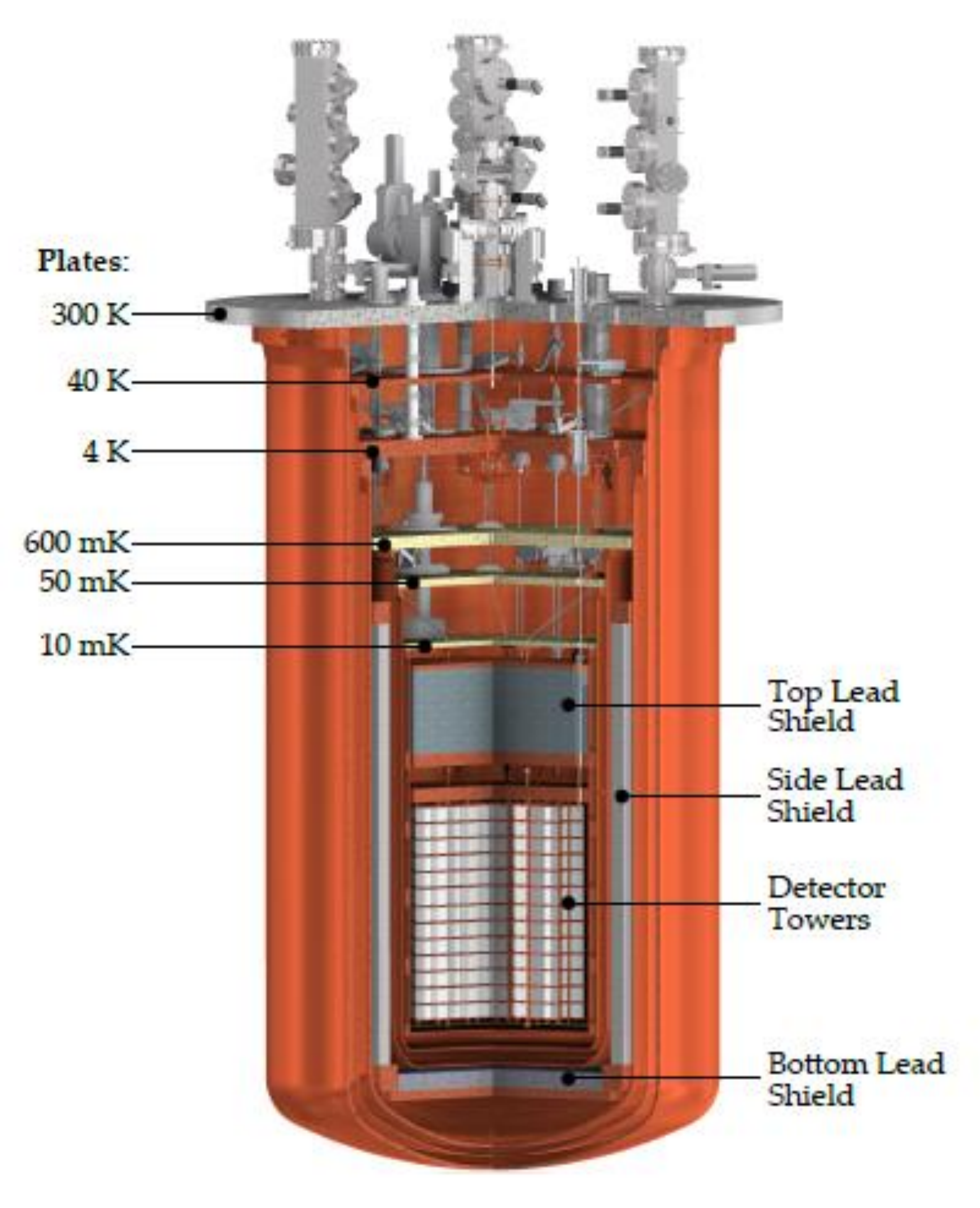
- CUORE will have a new custom cryostat
- Will have 19x the towers and 19x the data

Outline

- Physics of $0\nu\beta\beta$
- How does CUORE detect $0\nu\beta\beta$?
- CUORE-0
- CUORE Detector Calibration System
- CUORE Simulations

CUORE Cryostat

- The CUORE detectors will be placed in a larger cryostat to hold all 19 towers
- Improved temperature stabilization
- Thicker and more layers of shielding
- Higher radiopurity of materials

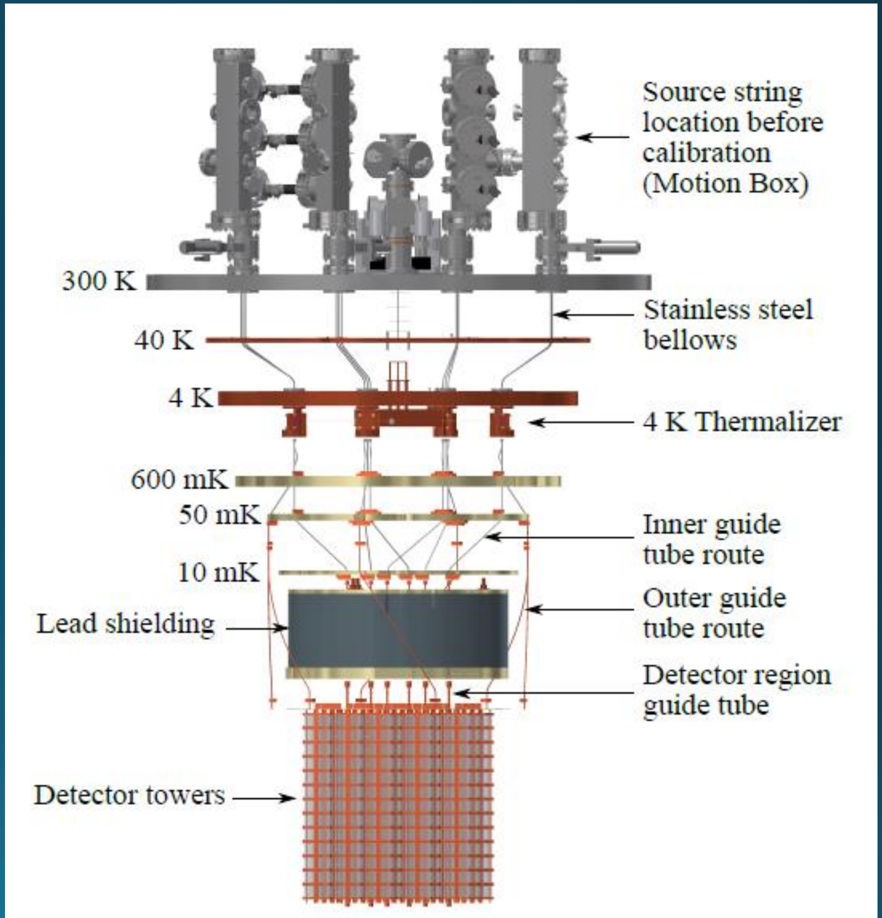


CUORE Calibration Requirements

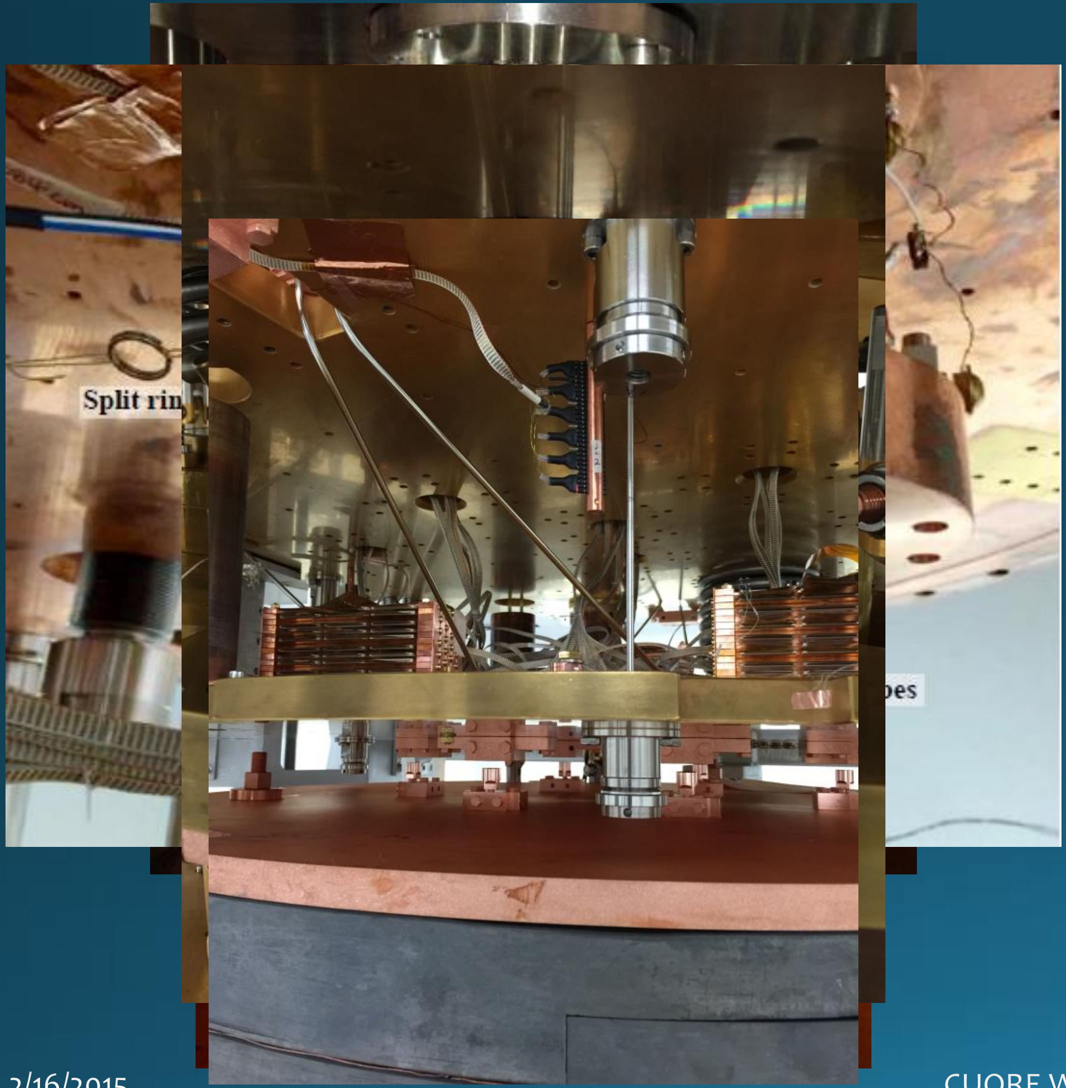
- In CUORE-0, calibration sources inserted away from crystals
  - Can be done by hand
- The towers are dense enough that we need to have sources in between detectors
  - Need to have a mechanical system deploy sources
  - Crystals need to have a minimal temperature effect from deployment and extraction
- Deployment time needs to be minimized to reduce dead time

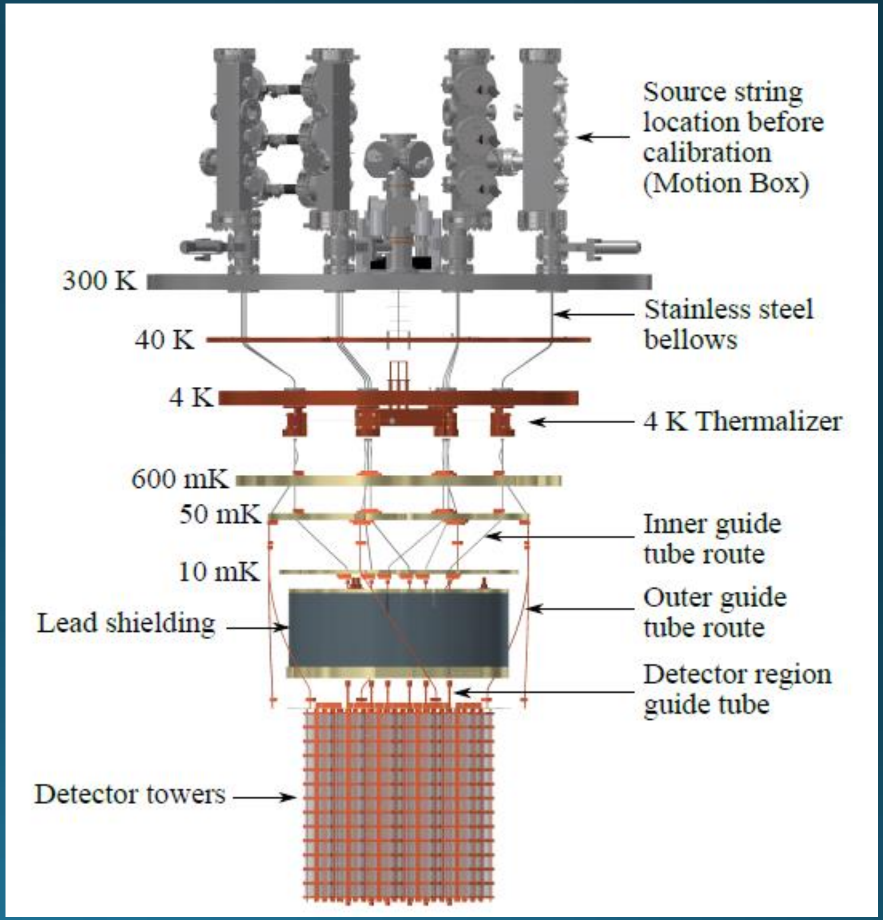
CUORE Calibration System

- Solving these technical challenges required a novel system
  - Designed and implemented the Detector Calibration System (DCS)
  - 12 strings containing calibration sources to deploy in the cryostat
  - Deployed through tubes from 300K to 50mK (outer) and 10mK (inner) by a
  - Lower under their own gravity and are raised by motors
- Recently completed successful test of DCS



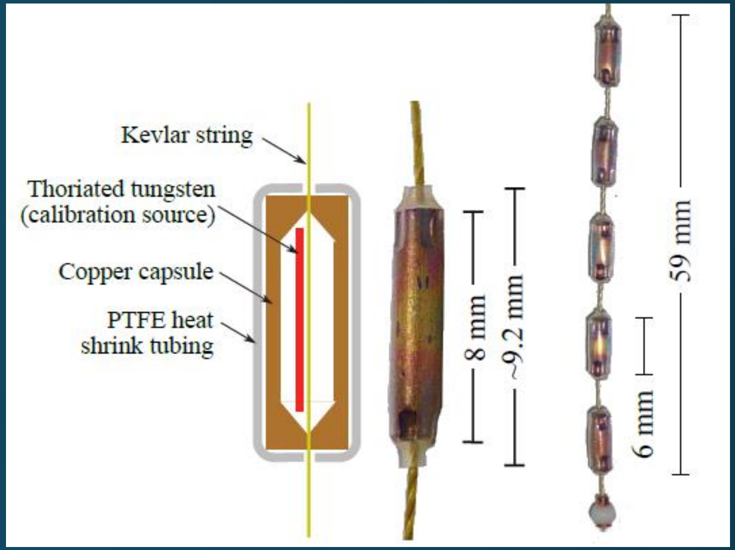
CUORE Calibration System Tubes

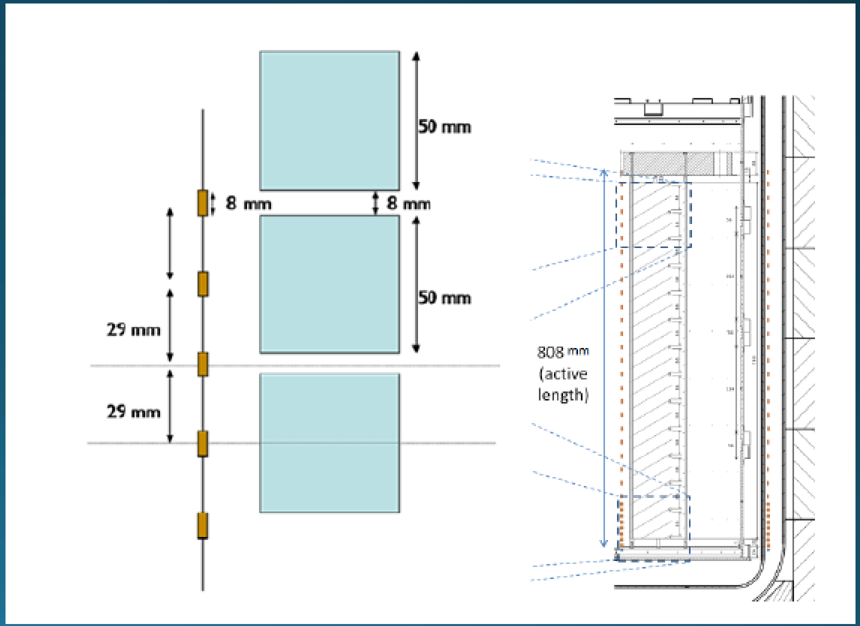




Source Strings

- Sources are made out of 2% thoriated tungsten wire
  - ^{232}Th half-life $\sim 10^{10}$ years
- Sources are placed into a copper capsule which is covered in PTFE heat shrink
  - PTFE reduces friction, a major heat load during deployment
- The string is made of Kevlar coated in PTFE
- The bottom 8 capsules are heavier to aid in deployment
- 33 (outer) & 34 (inner) capsules in total

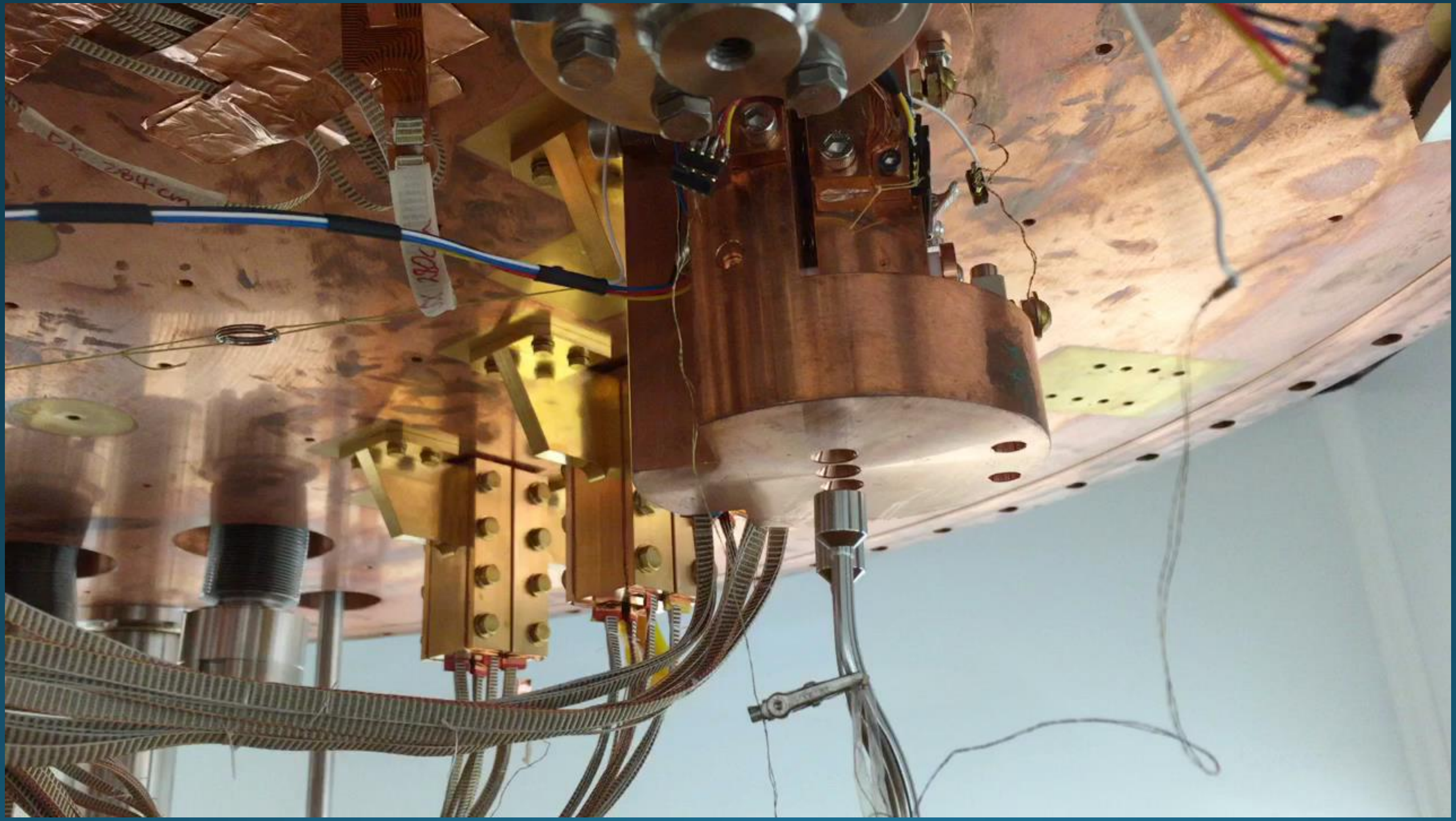




String Cooling

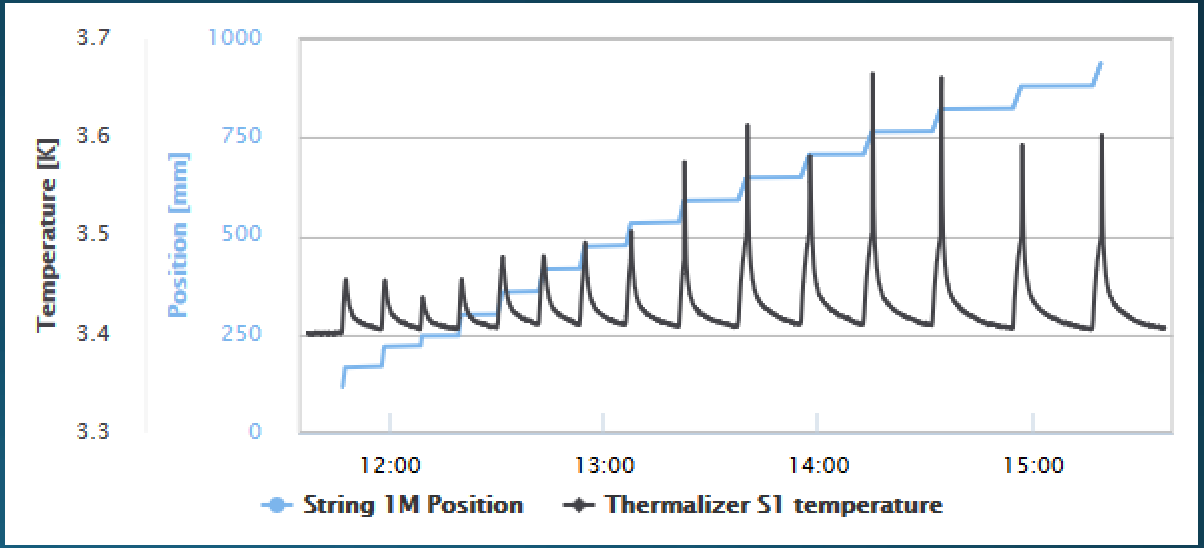
- Strings start in Motion Boxes above the Cryostat
- Before a calibration run, we lower the strings to a few cm above the 4K thermalizers
- Let strings cool overnight ~12 hr
- Leaves background at manageable levels
  - Allows for improved cooling later
  - Can still take data while precooling
- Then begin to lower strings through 4K thermalizer
  - Squeezes on the capsules
- Then deployed to final calibration positions

4K Thermalization Squeezes



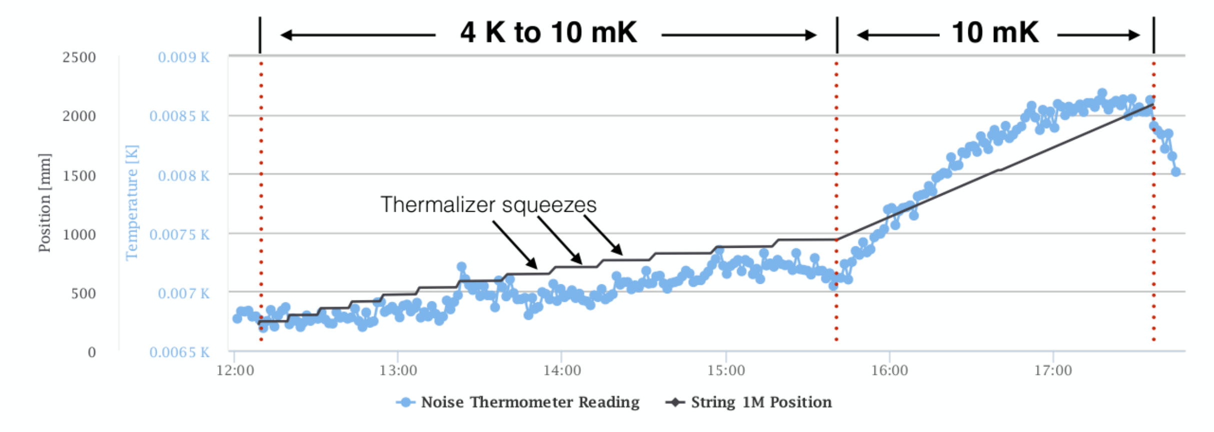
4K Thermalization

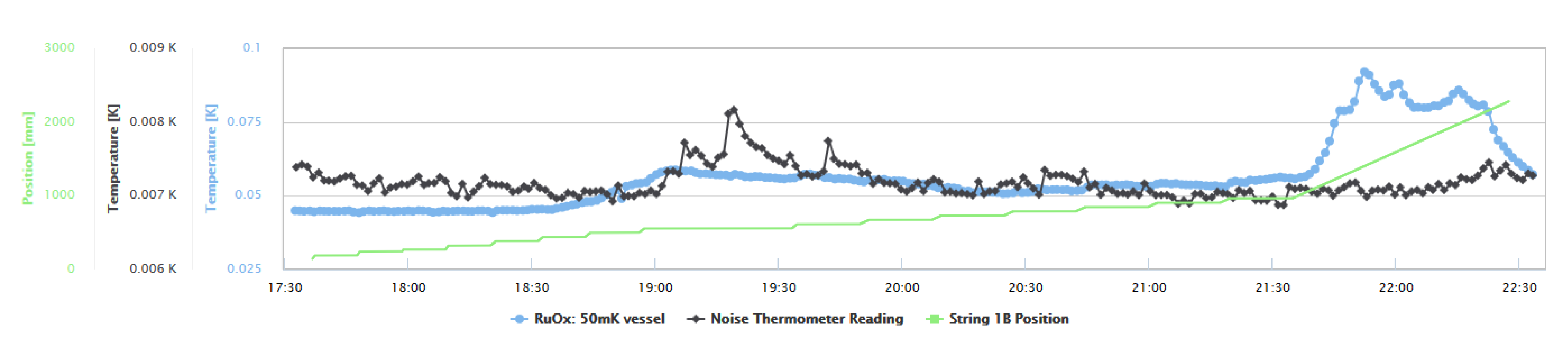
- Main thermalization occurs at 4K
- Push on each capsule with a copper sliding block on the 4K plate
- Drops the temperature of the capsules down to 4K
- 20 minute squeezes
- Later capsules come in hotter
  - Precooled higher in the cryostat



Deploying a Single String

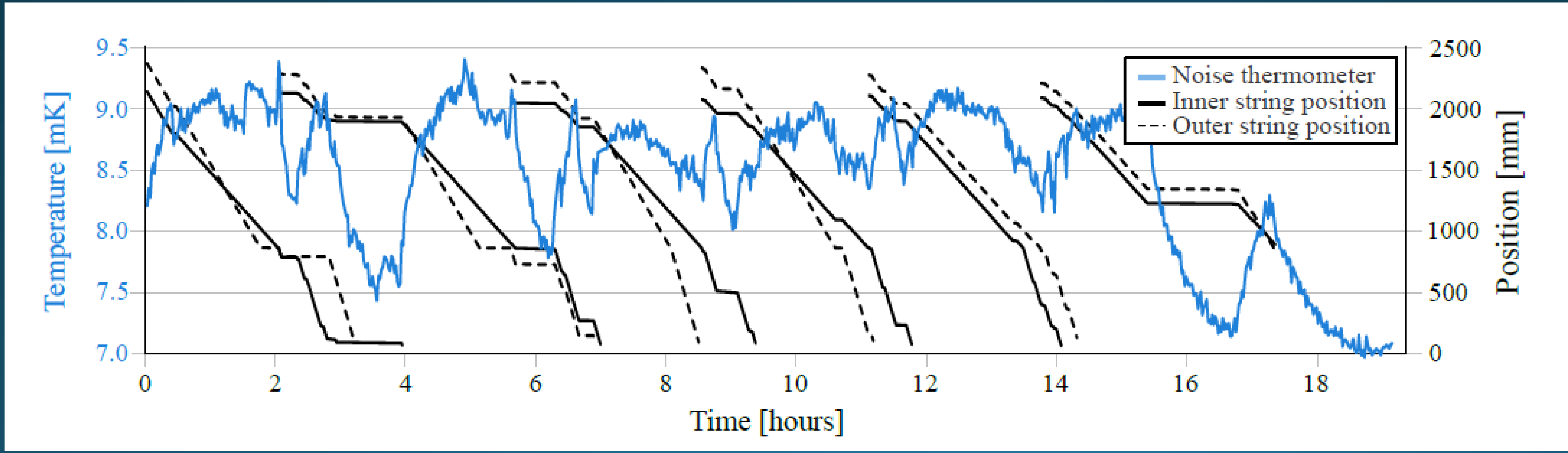
- Base temperature is kept below 9mK during deployment
  - Outer strings add heat only at the end into 50mK vessel
  - Allows for stabilization at 9mK or above





DCS String Extraction

- Extract an inner and outer string as a pair
- Start next pair when heat load begins to drop
- Can be done in ~16 hours
- Base temperature kept below 9.5 mK



Deployment and Extraction Summary

- First deployment and extraction of all 12 strings from 300K down to base temperature
- Takes ~20 hours to deploy and ~16 hours to extract
  - With ~12 hours precooling beforehand
- This is the beginning and end of time needed for calibration

- How long do we need to keep the strings in the cryostat?
  - Said differently, how long to calibrate each tower?
- Need to determine via calibration

Outline

- Physics of $0\nu\beta\beta$
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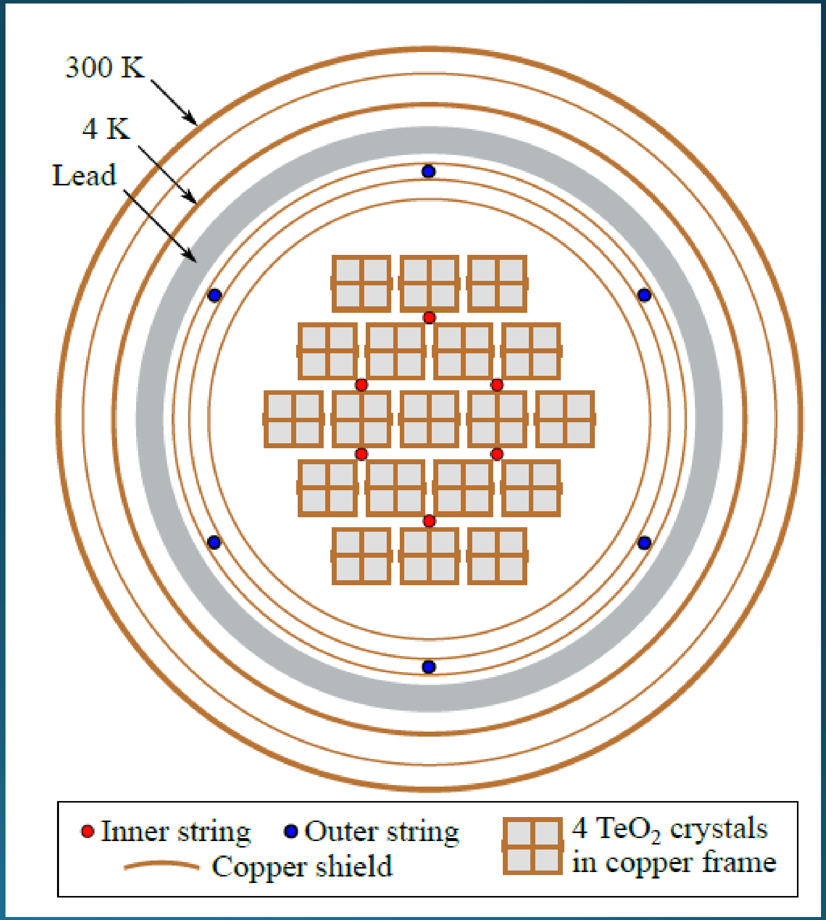
CUORE Simulations

- CUORE simulations are done via Geant4
  - Cryostat modeled with high levels of precision near the detectors
- Strings are modeled as they are in the cryostat
  - Tungsten sources in a hollow copper capsule surrounded by Teflon
- Simulate decay chains of ^{232}Th
- Source strings have non-uniform activity
  - Top and Bottom capsules have more activity
  - Total activities per string: 3.6 Bq (Inner), 19.4 Bq (Outer)

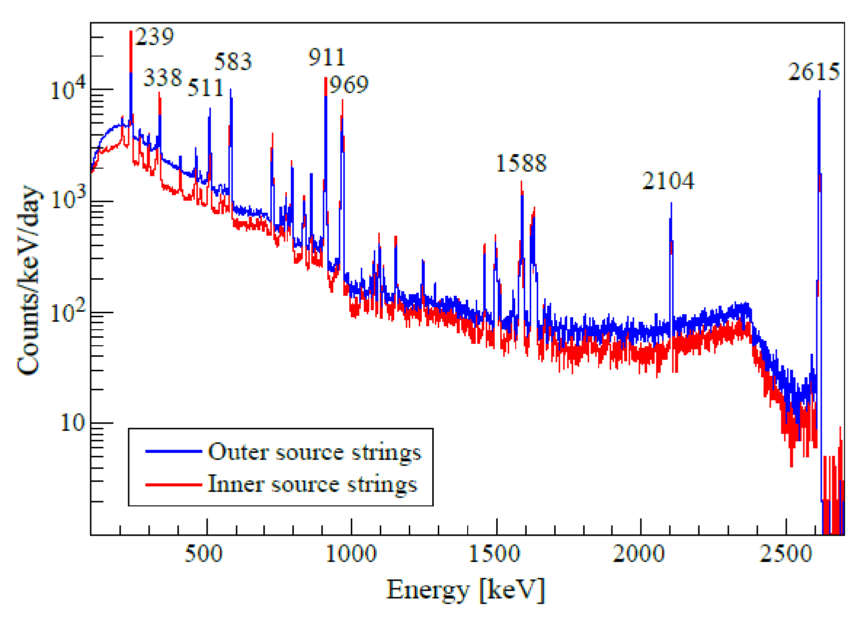
Deployment Locations

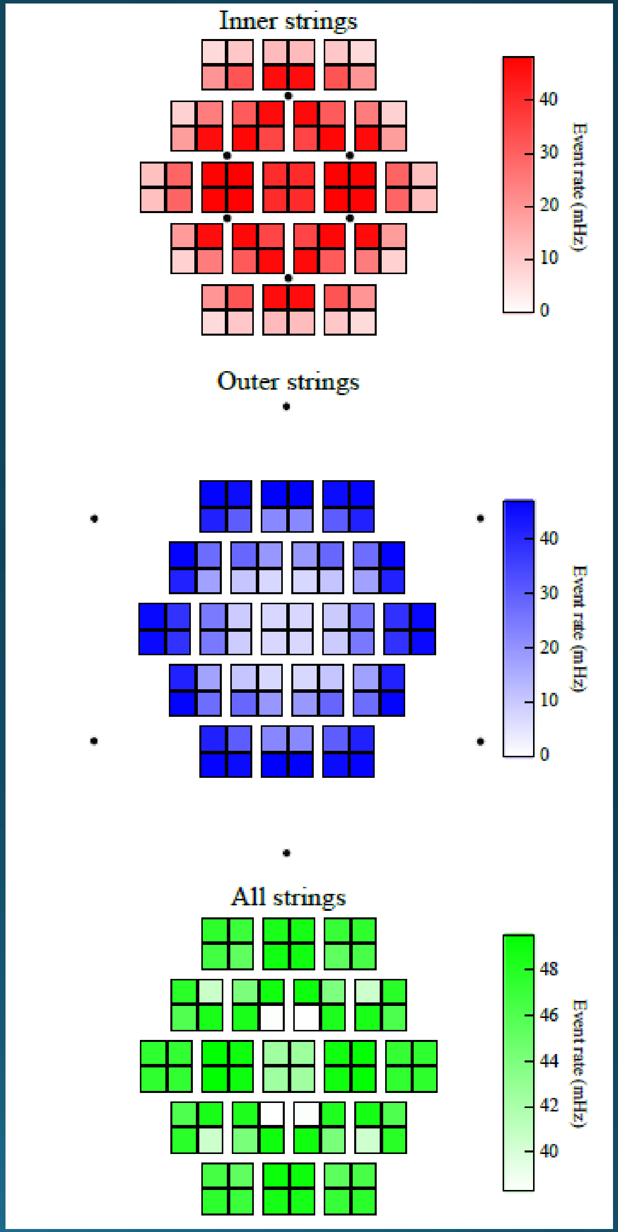
- Distribution designed to irradiate the towers equally
- 6 “inner” strings in the detector volume at 10mK
- 6 “outer” strings outside 50mK shielding



Inner and Outer Sources

- Outer strings are more shielded than inner
  - Have to travel through 50mk and 10mK vessels
  - Reduces peak height, increases background



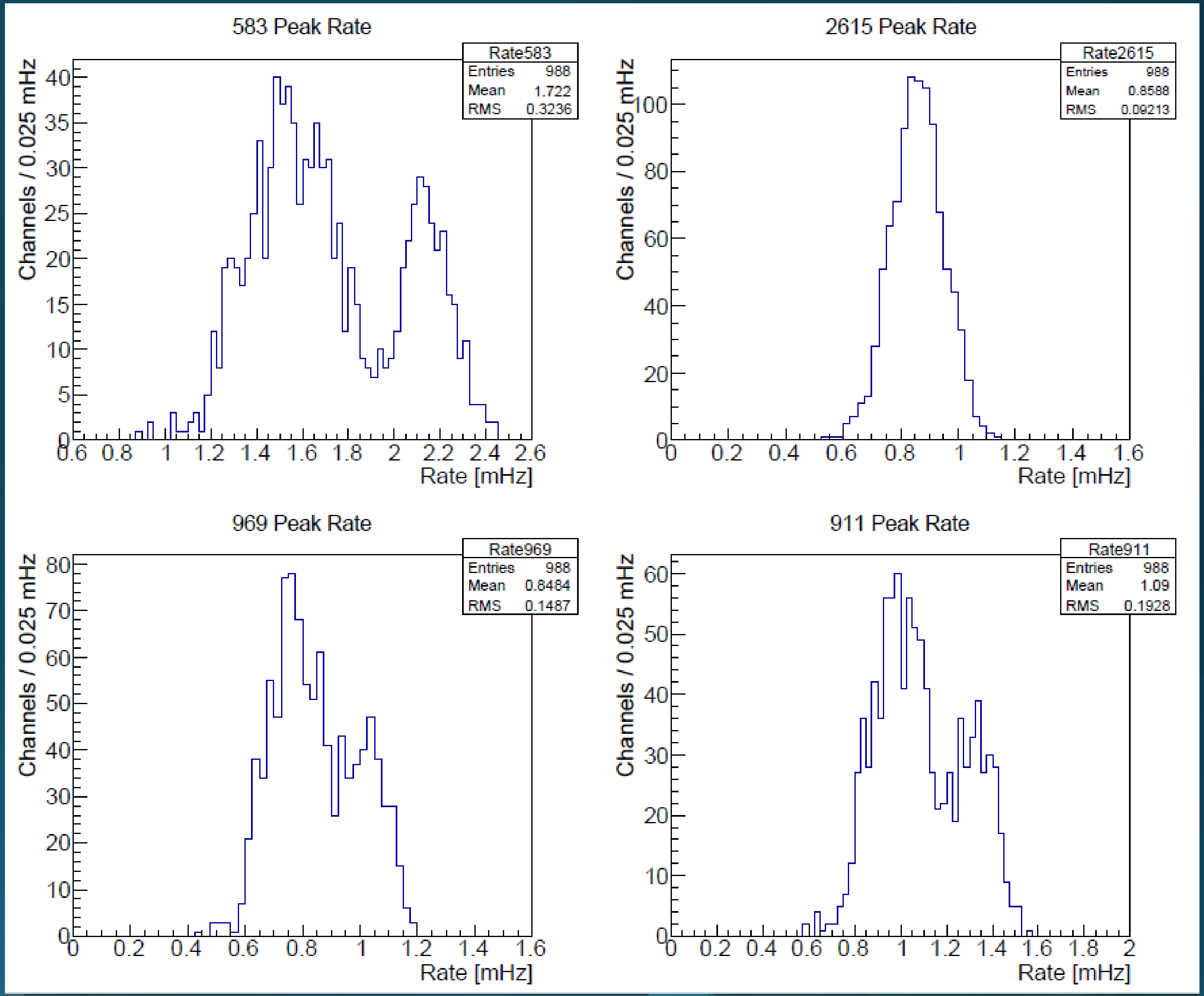


Calibrating the Detector

- We calibrate the detectors with the known ^{232}Th peaks
  - 511, 583, 911, 969, 1588, 2103, and 2615 keV
- To check calibration, take 4 of these peaks
    - 583, 911, 969, 2615
- Call a channel "calibrated" when roughly 100 counts in a peak have been counted
  - Count events in $\pm$5keV window
  - ~10 counts in a peak is enough to fit a peak

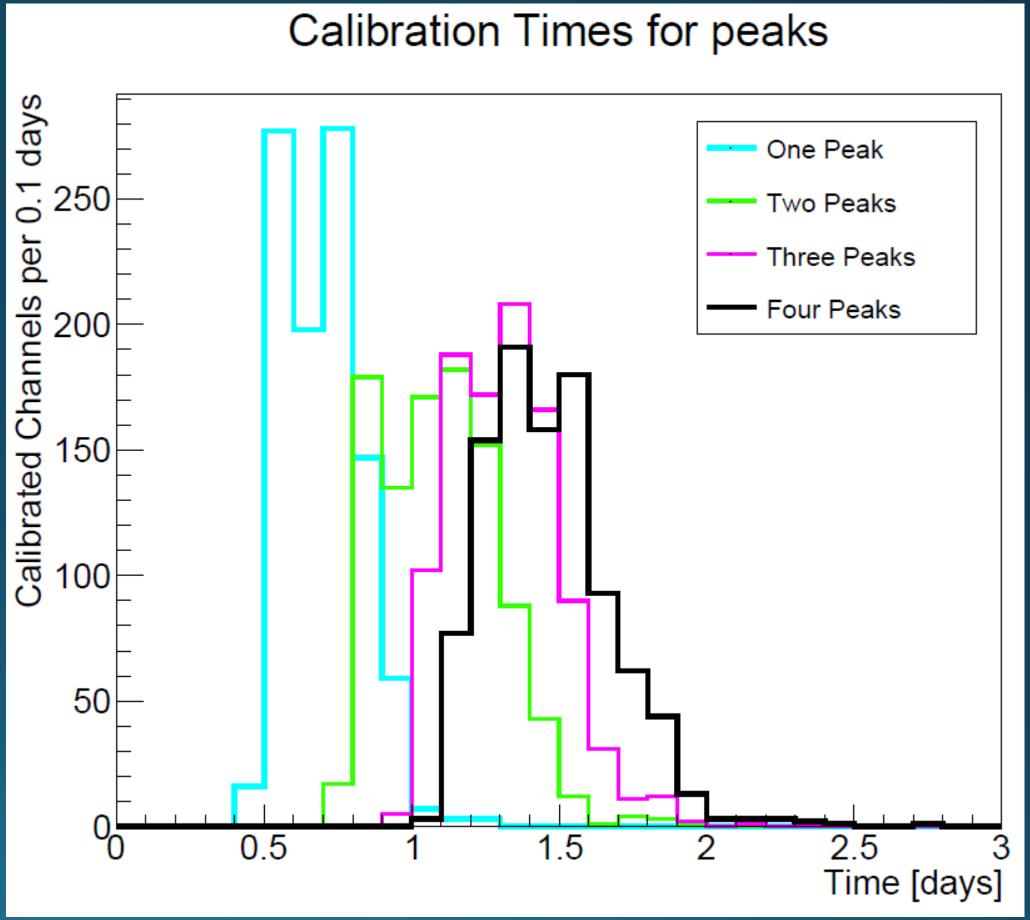
Peak Rates

- Low energy peak rates differ for inner and outer strings
  - Shielding blocks lower energy photons easier



Calibration Time per Peak

- Most channels get a single peak quickly
- Other channels take longer to get the final peaks
- Most channels “calibrated” in 2 days



DCS Calibration Summary

- Successfully tested deployment and extraction procedures
- ~4 day deployment
  - 14 hour precooling
  - 20 hour deployment
  - 48 hour calibration
  - 16 hour extraction
- Still room for optimization and refinement in deployment
  - Speeds can be optimized
    - Can change from constant speeds with abrupt changes to a velocity profile

Conclusions and CUORE Next Steps

- $0\nu\beta\beta$ has discovery potential in CUORE
- CUORE-0 was a successful test run of CUORE concept
  - Able to set world's best limit on $0\nu\beta\beta$ in ^{130}Te
  - Demonstrated improvements made for CUORE detectors
  - Gained insight into how to process CUORE data and perform analysis
- Recently demonstrated the DCS for calibration of CUORE
  - Performed deployment and extraction of 12 strings without exceeding temperature stability requirements
- Simulations show feasibility of DCS calibration

Thanks!

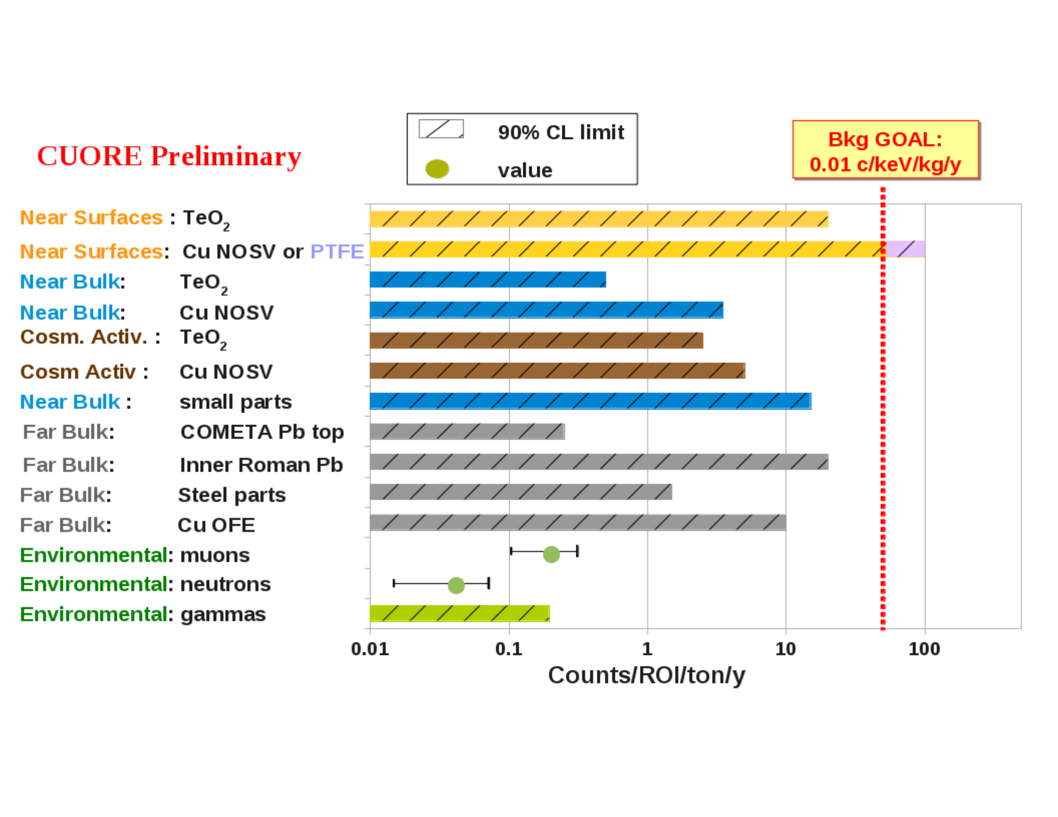
Backup Slides

String Parking Positions

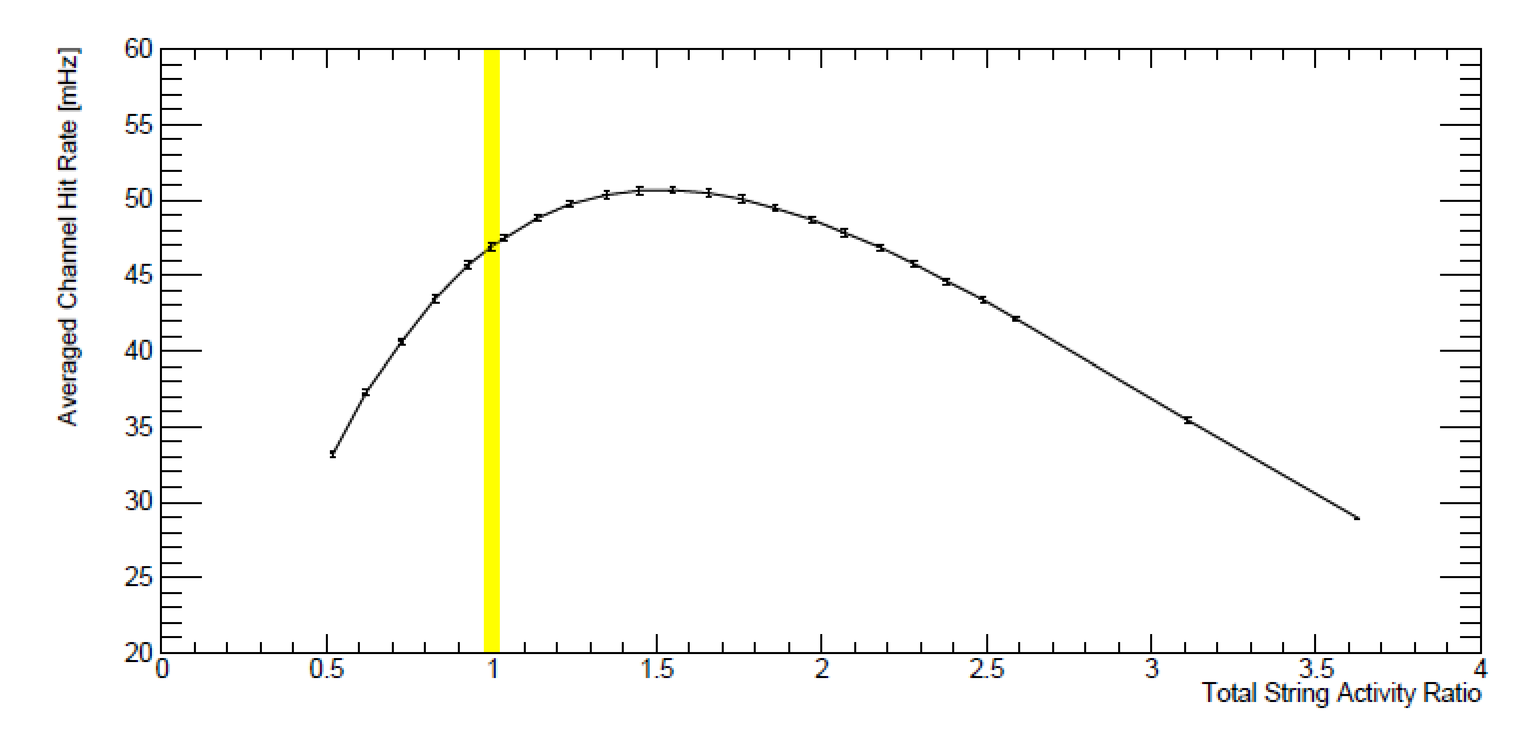
- Also simulated possible locations of parking positions:
  - Need to have negligible effect on the background budget

String Locations	c/ROI/ton/y	c/keV/kg/yr
10 mK plate	712±74	0.1424±0.0148
50 mK plate	53.6±20.3	0.0107±0.0041
600 mK plate	1.53±1.08	0.000306±0.000217

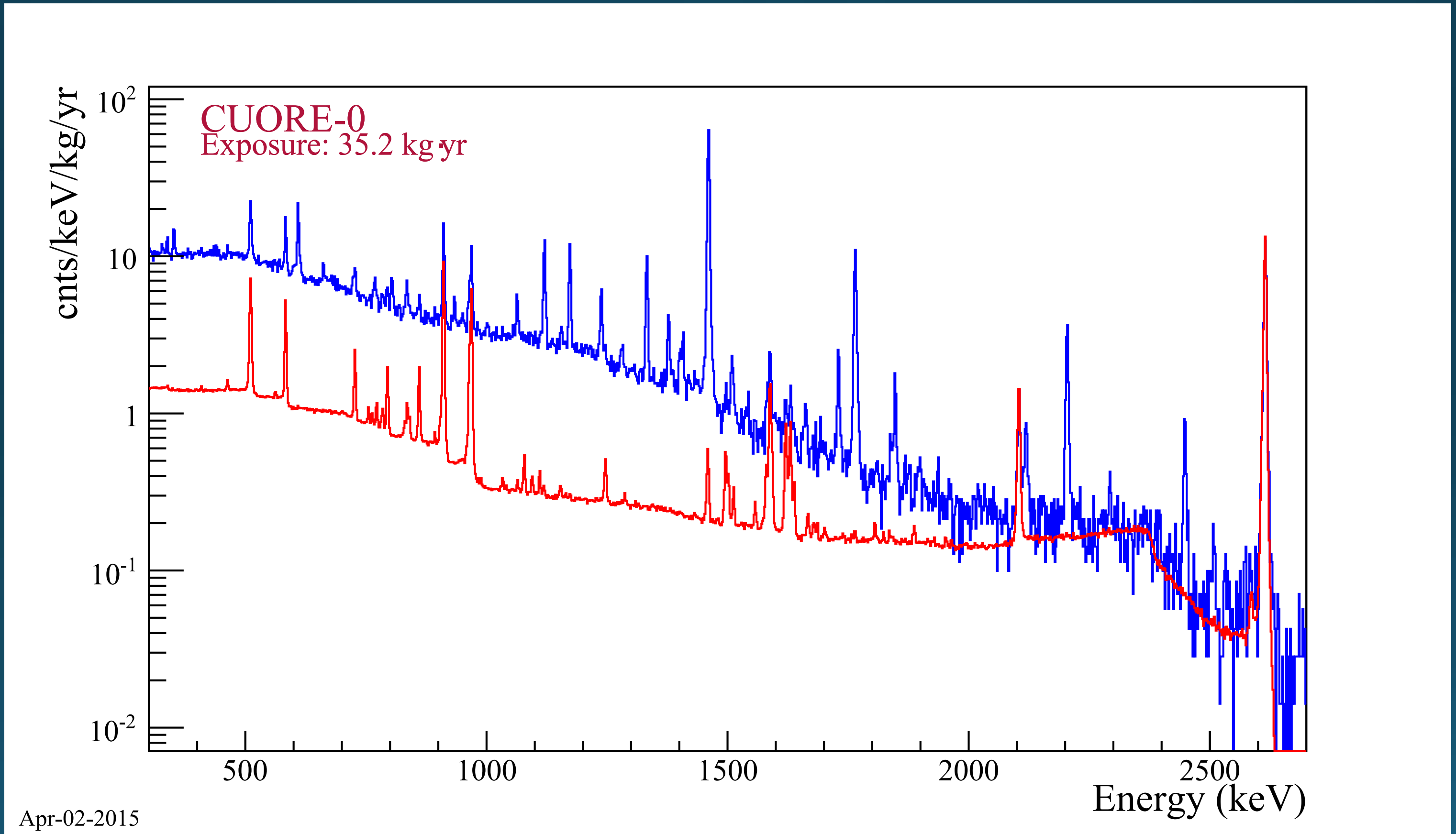
- ~10% decrease per stage
  - Decide to precool at 4K



Activity Testing

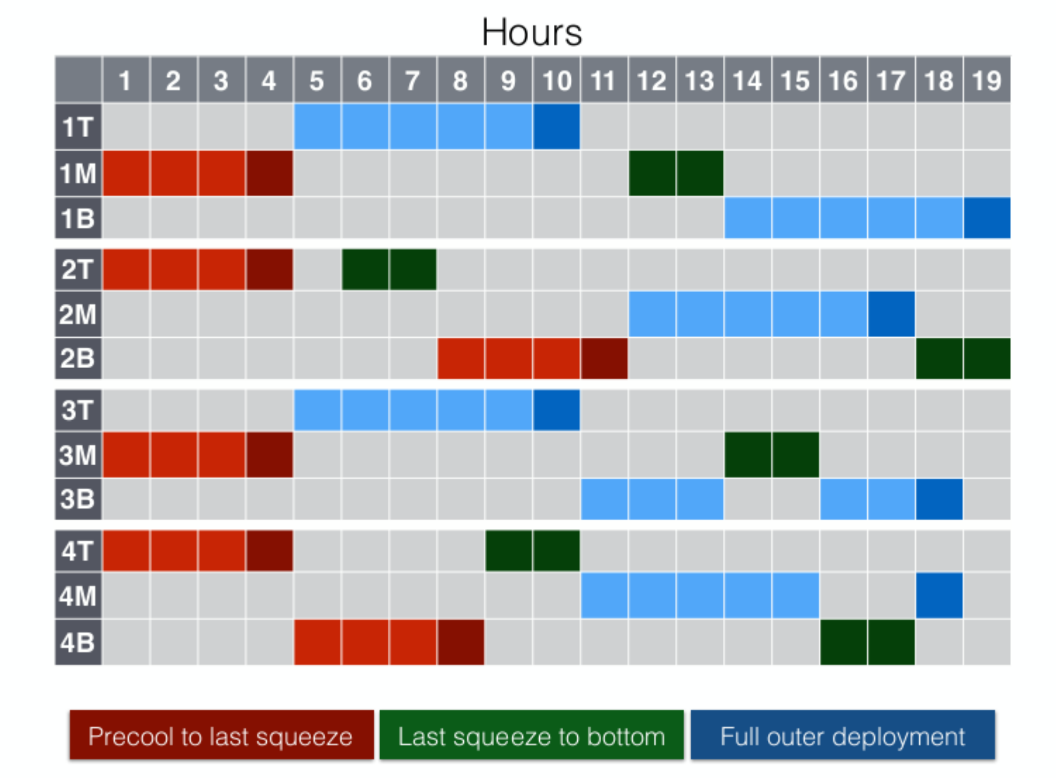


CUORE-0 Background and Calibration



DCS Deployment Strategy

- Can move up to 4 strings at a time
  - 1 per motion box
  - Thermalization at 4K can be fully parallelized
- Can only fully deploy one inner string at a time
  - Limiting factor in deployment
  - Move 3 other strings while fully deploying 1
- Heat load mostly due to “hot” strings moving to lower stages



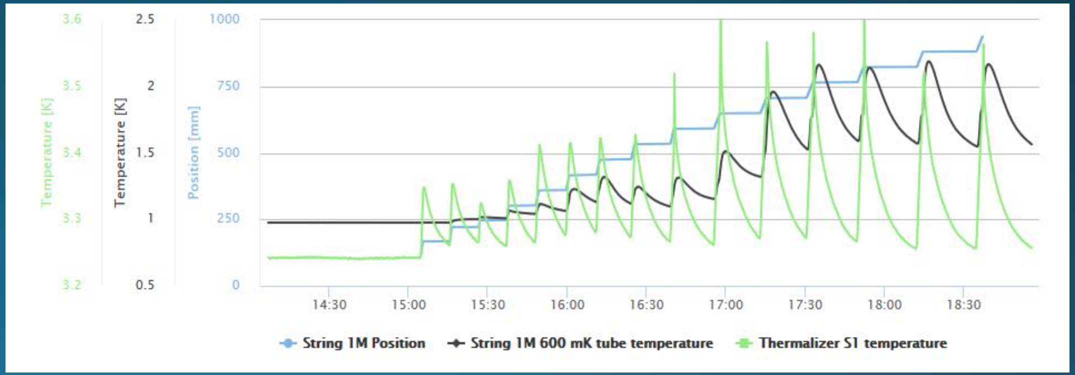
Thermalization Strategy

- One of the main challenges is cooling down the strings as they descend in the cryostat
- The cooling power of the cryostat decreases at colder stages
- Thermalize at the higher stages
  - Strongest thermalization at 4K
  - Then thermalize to each stage slowly

Thermal Stage	Cooling Power
40K	1 W
4K	300mW
600mK	550μW
50mK	1.1μW
10 mK	1.2μW

Thermalization at 600mK and Beyond

- Also have thermalization below 4K
  - 600mK
  - 50mK or 10mK
- Thermalization due to contact with tubes
  - 4K was due to applied force



Extracting a Single String

- Extraction is similar to deployment
  - Heat load purely due to friction
  - Bends in tubes are the points where heat is applied
- Heat load depends on velocity
- Minimal heat load from outer strings
  - Move at 15 mm/minute
- Heating from inner strings in detector region
  - Move at 15 mm/minute
  - Once out of the region, can increase speeds to 75 mm/minute