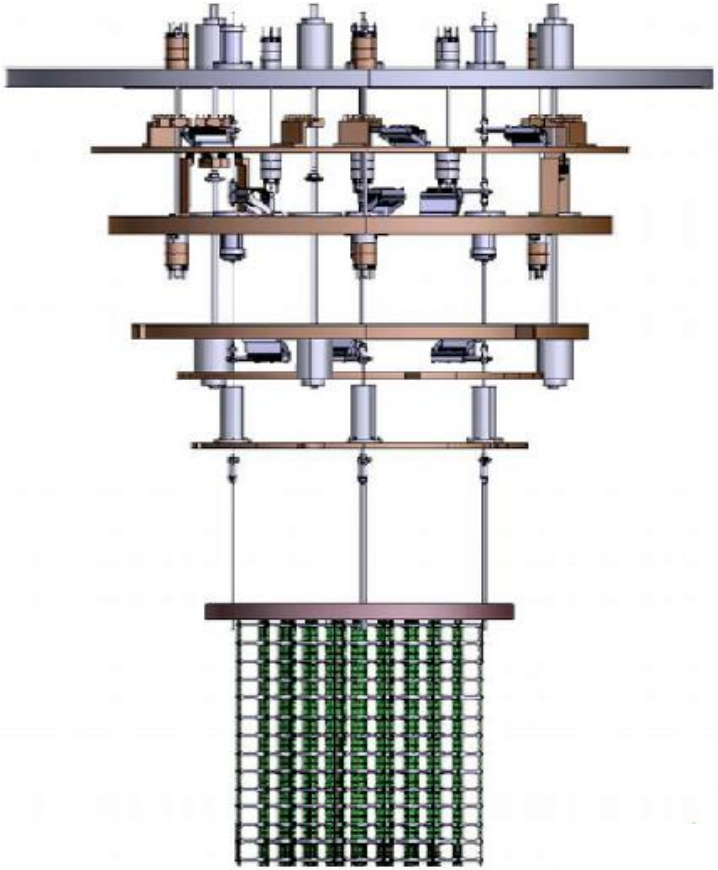
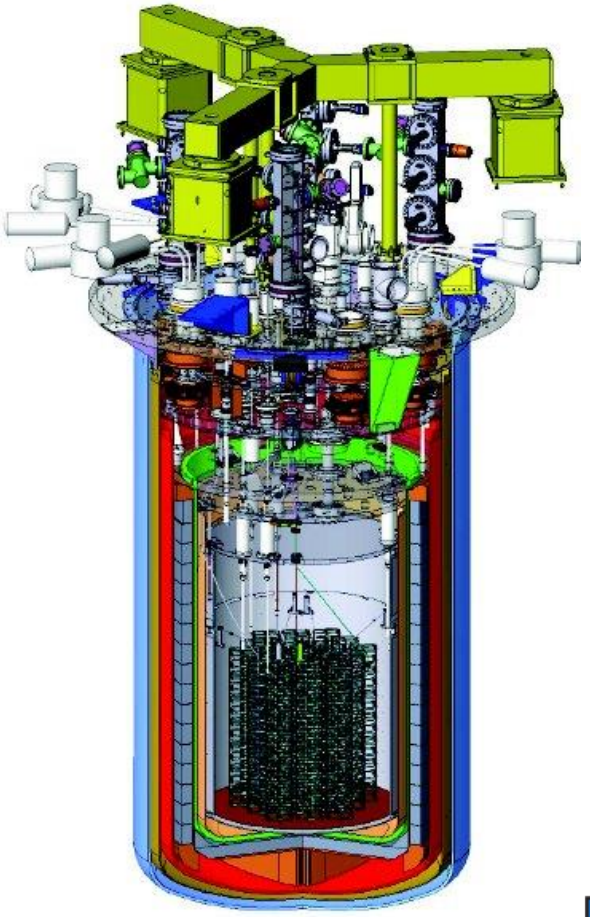
Commissioning of the CUORE Cryostat:

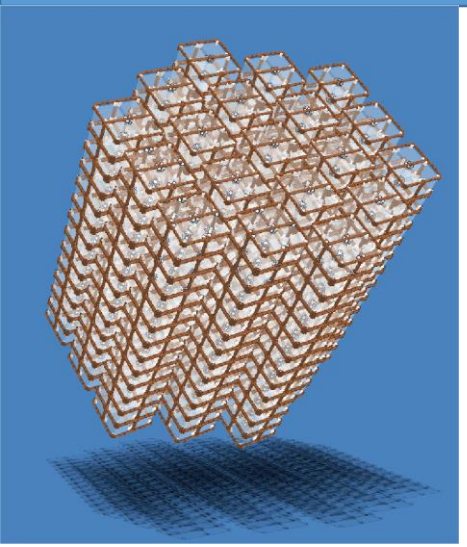
The First Experimental Setup for Bolometric Detectors at the 1 Ton Scale

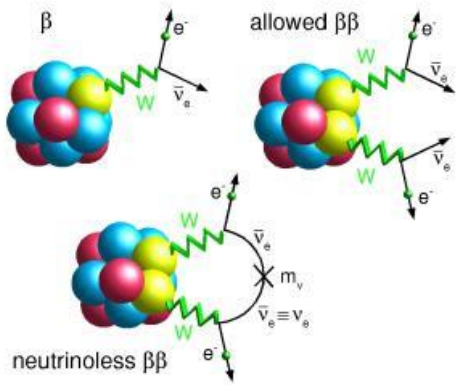


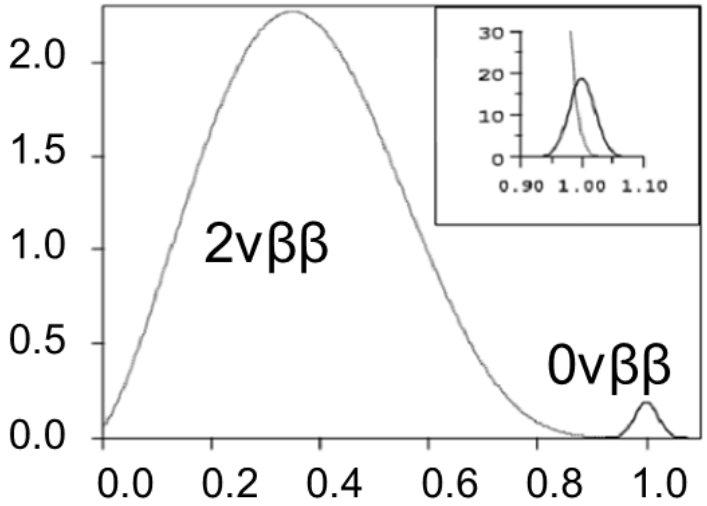


Nicholas I Chott

Cryogenic Underground Observatory for Rare Events

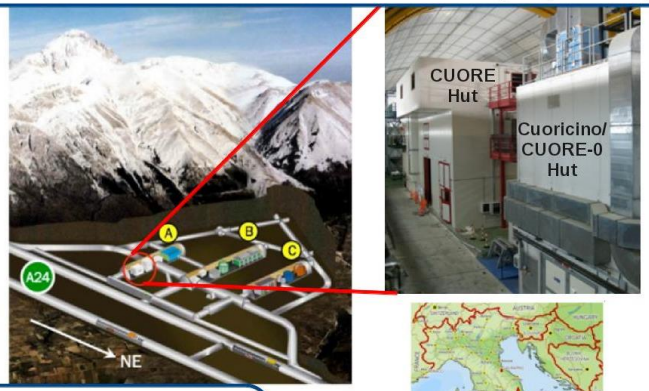






$$Exp.Sensitivity: \quad S^{0\nu} \propto \frac{\epsilon\, a_i}{A}\left(\frac{M\, t}{b\, \Delta E}\right)^{1/2} \qquad b \neq 0$$

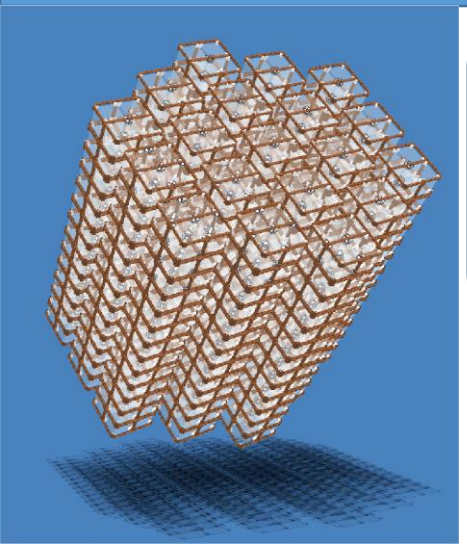
Underground hall A Laboratori Nazionali del Gran Sasso (L'Aquila - Italy)



Average depth ~ 3650 m.w.e.
μ flux $(2.58 \pm 0.3)\cdot 10^{-8}$ m/s/cm^2
n flux <10 MeV: 4×10^{-6} n/s/cm^2
γ flux < 3 MeV: 0.73 g/s/cm^2

M: total active mass in kg
ϵ: detector efficiency
a_i: isotopic abundance
b: background in c/keV/kg/y
ΔE: detector resolution @ROI in keV
t: exposure time in y

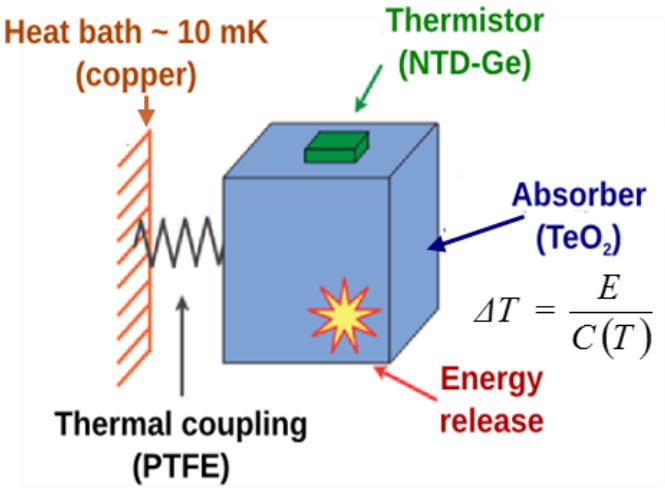
Cryogenic Underground Observatory for Rare Events



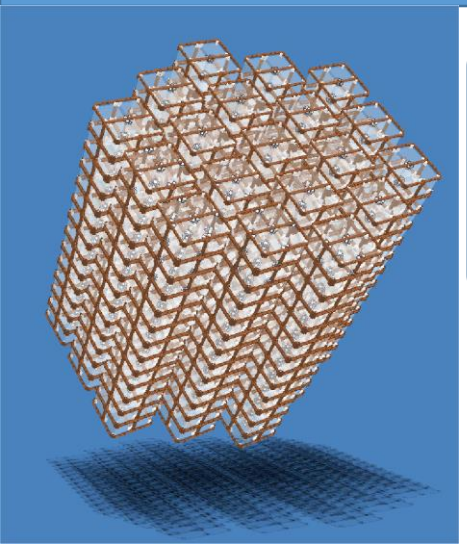
Detector Mass:
741 kg TeO_2 (204 kg ^{130}Te)

Experimental Space:
$\emptyset\ 0.900m, h\ 1.385m$

$$\left(\frac{M\,t}{b\,\Delta E}\right)^{1/2}$$



Cryogenic Underground Observatory for Rare Events



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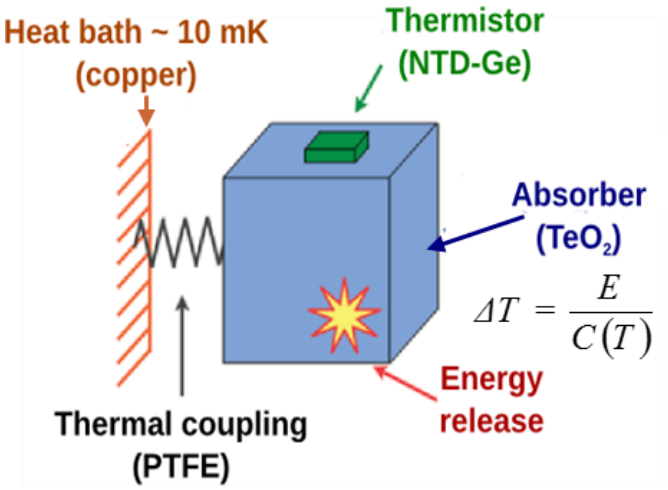
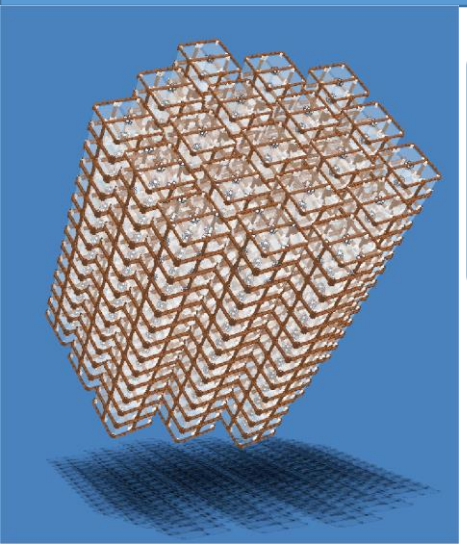
Target background: < 10^{-2} counts/keV/kg/year
Strict selection of low radioactive material

Lead shields: ~10 tons in cryogenic space (T ≤ 4K)

$$\left(\frac{M\,t}{b\,\Delta E}\right)^{1/2}$$



Cryogenic Underground Observatory for Rare Events



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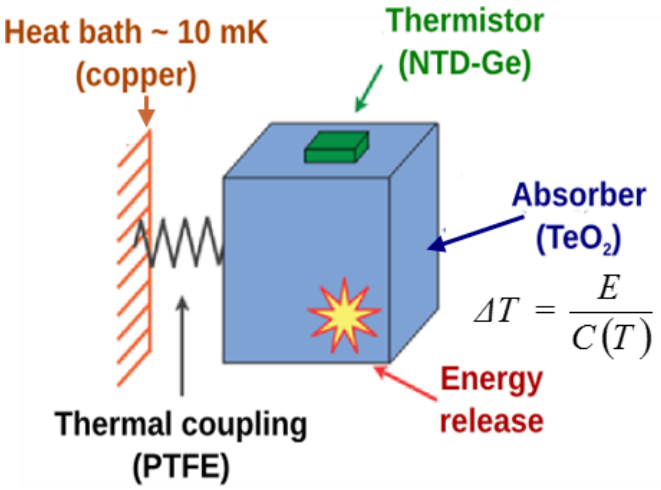
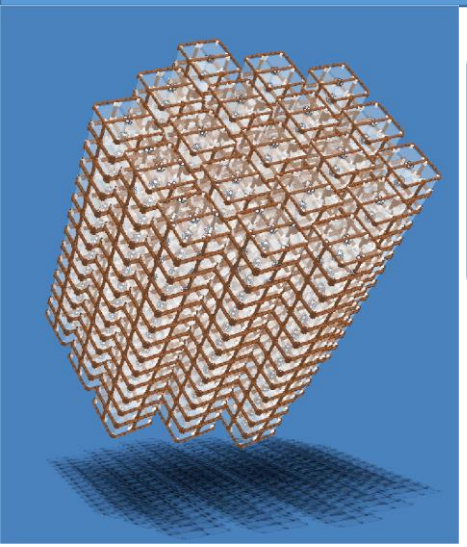
$$\left(\frac{M\,t}{b\,\Delta E}\right)^{1/2}$$

Bolometers = Very good energy resolution
~5keV FWHM at ^{208}Tl peak (2615 keV)
^{130}Te: $Q_{0\nu\beta\beta}$ = 2527keV
Challenges:
Stable operating temperature: ~10mK (or better)
Low vibrational noise of detectors: ~1keV (~10^{-16}J)



Cryogenic Underground Observatory for Rare Events



Detector Mass:
741 kg TeO_2 (204 kg ^{130}Te)

Experimental Space:
$\emptyset\ 0.900m, h\ 1.385m$

Run time: $\geq 5\ years$
Stable
Service-free
High duty cycle
→ Cryogen free

Target background: < 10^{-2} counts/keV/kg/year
Strict selection of low radioactive material

Lead shields: ~10 tons in cryogenic space (T ≤ 4K)

$$\left(\frac{M\,t}{b\,\Delta E}\right)^{1/2}$$

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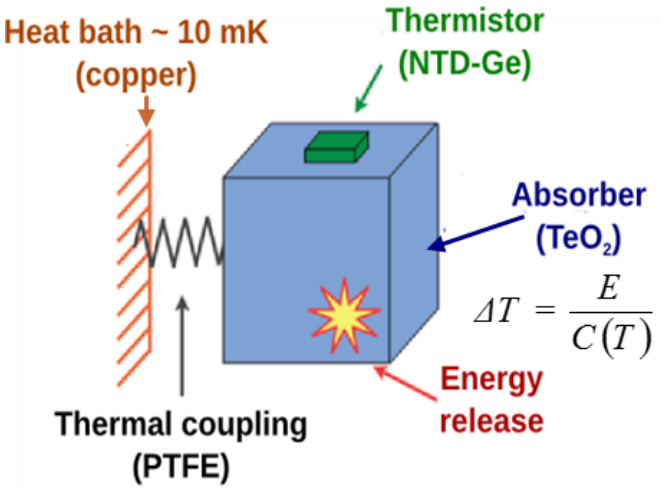
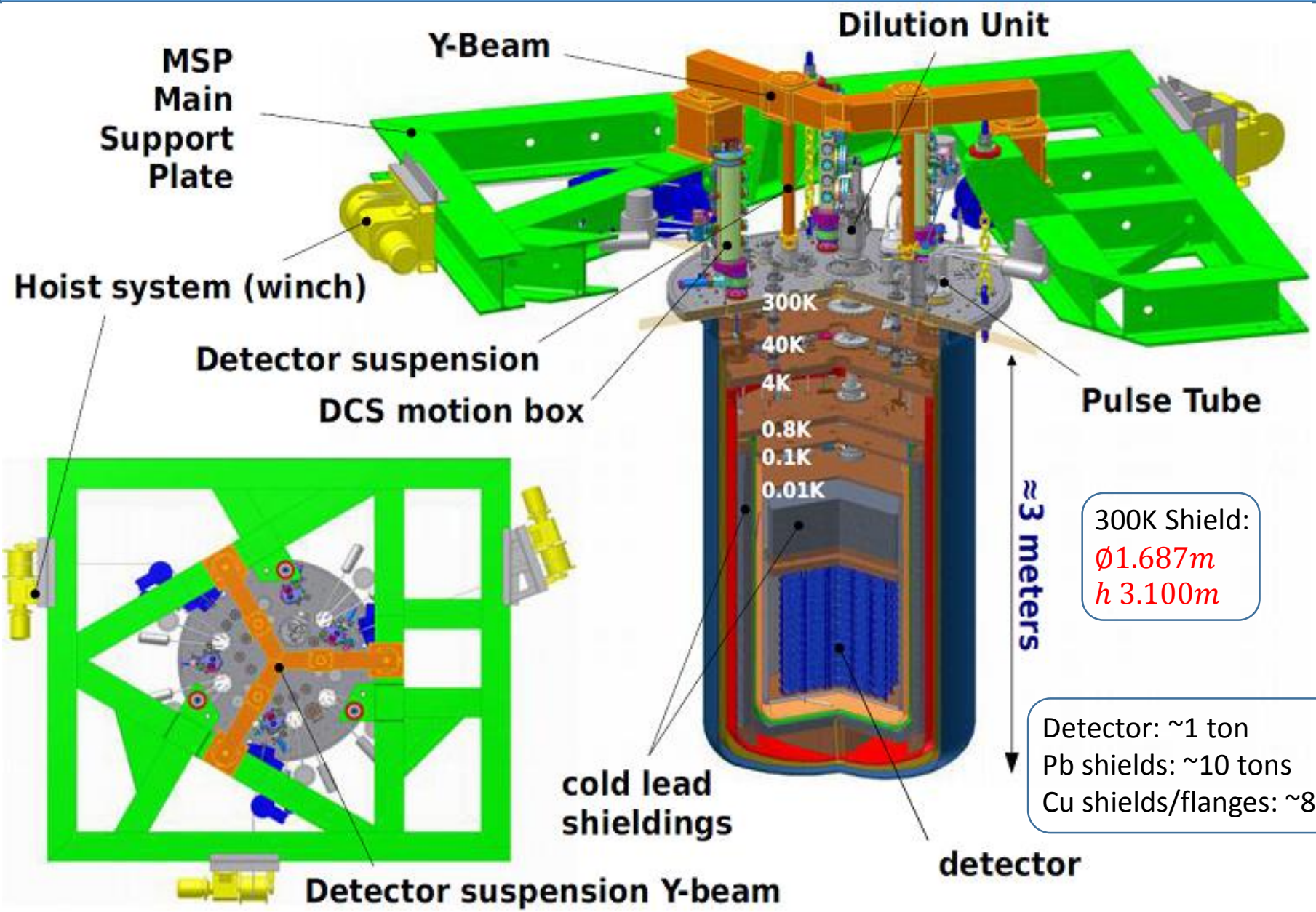
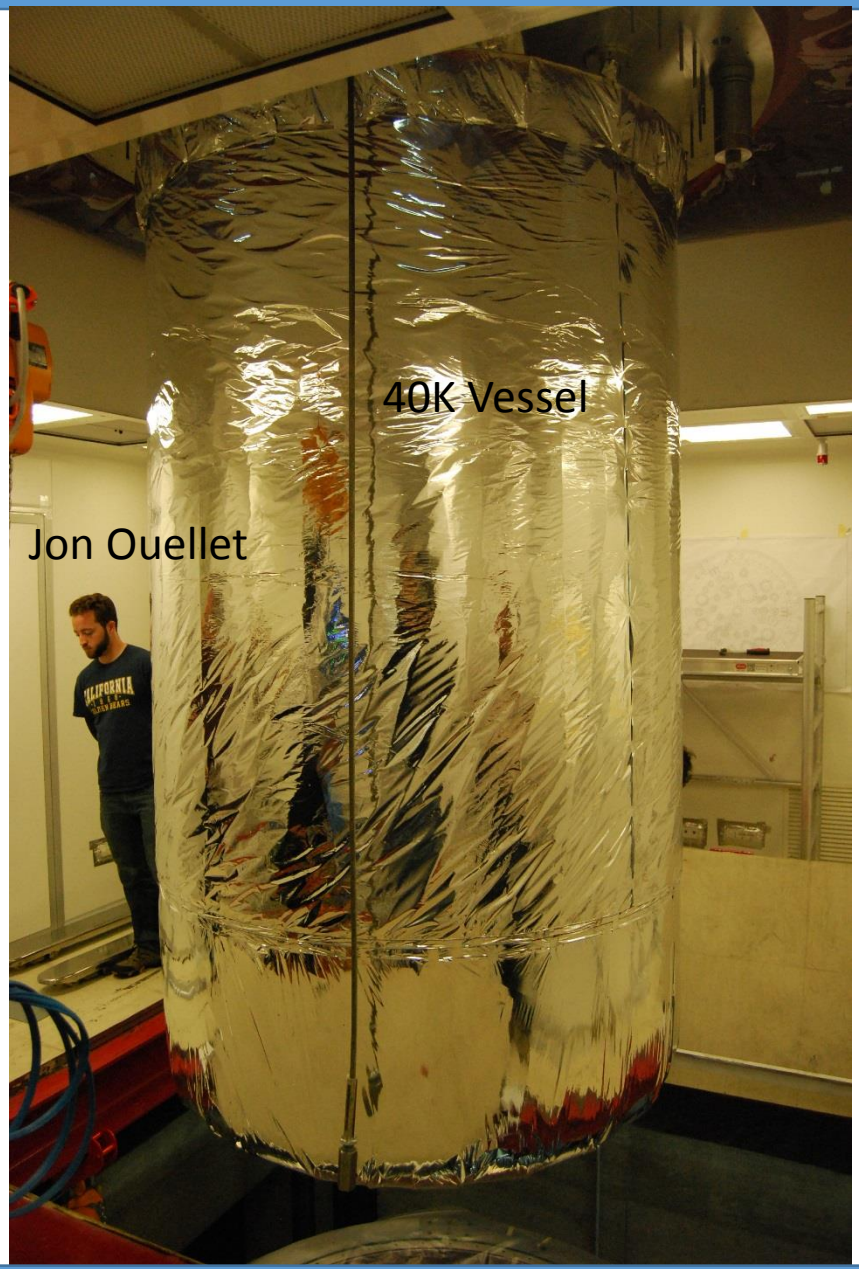


CUORE Cryostat

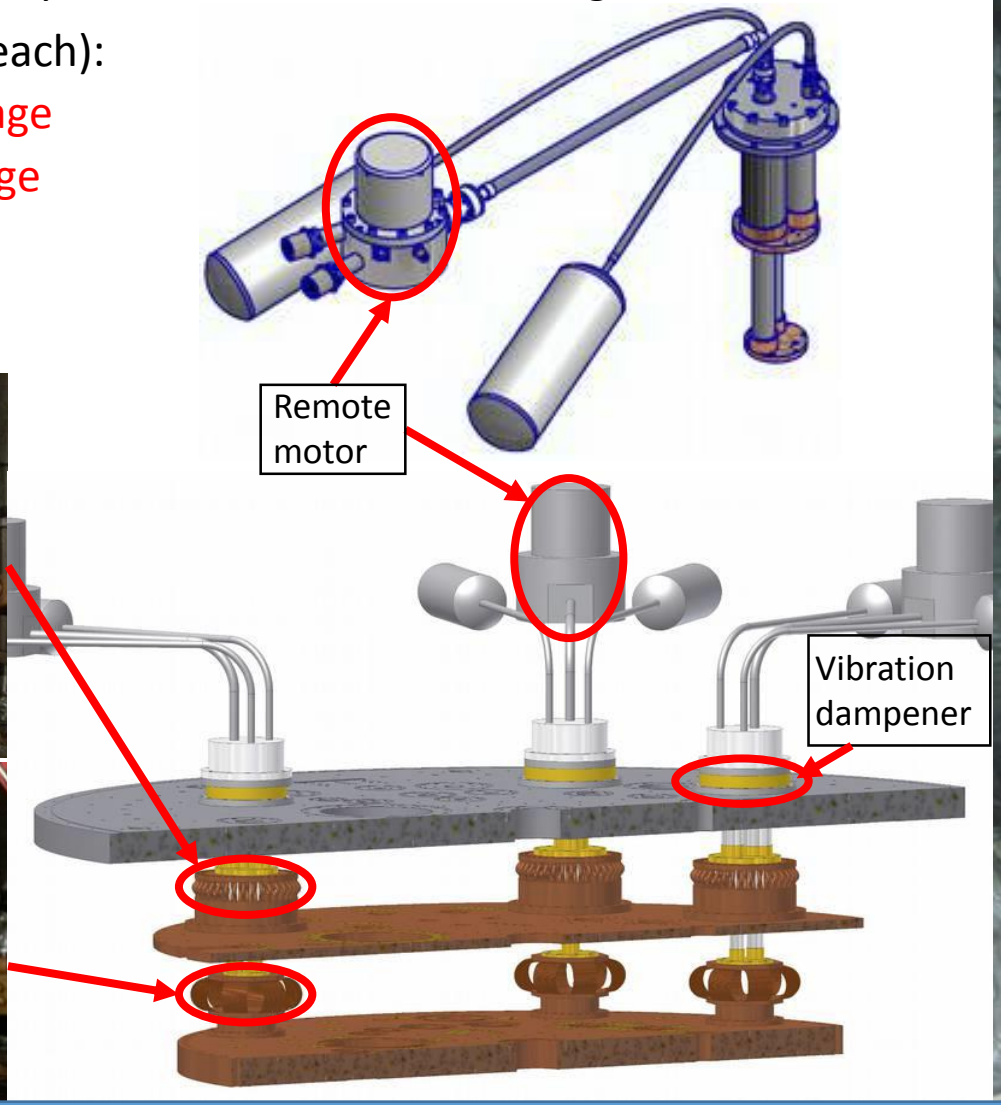


CUORE Cryostat



Pulse Tube Refrigerators

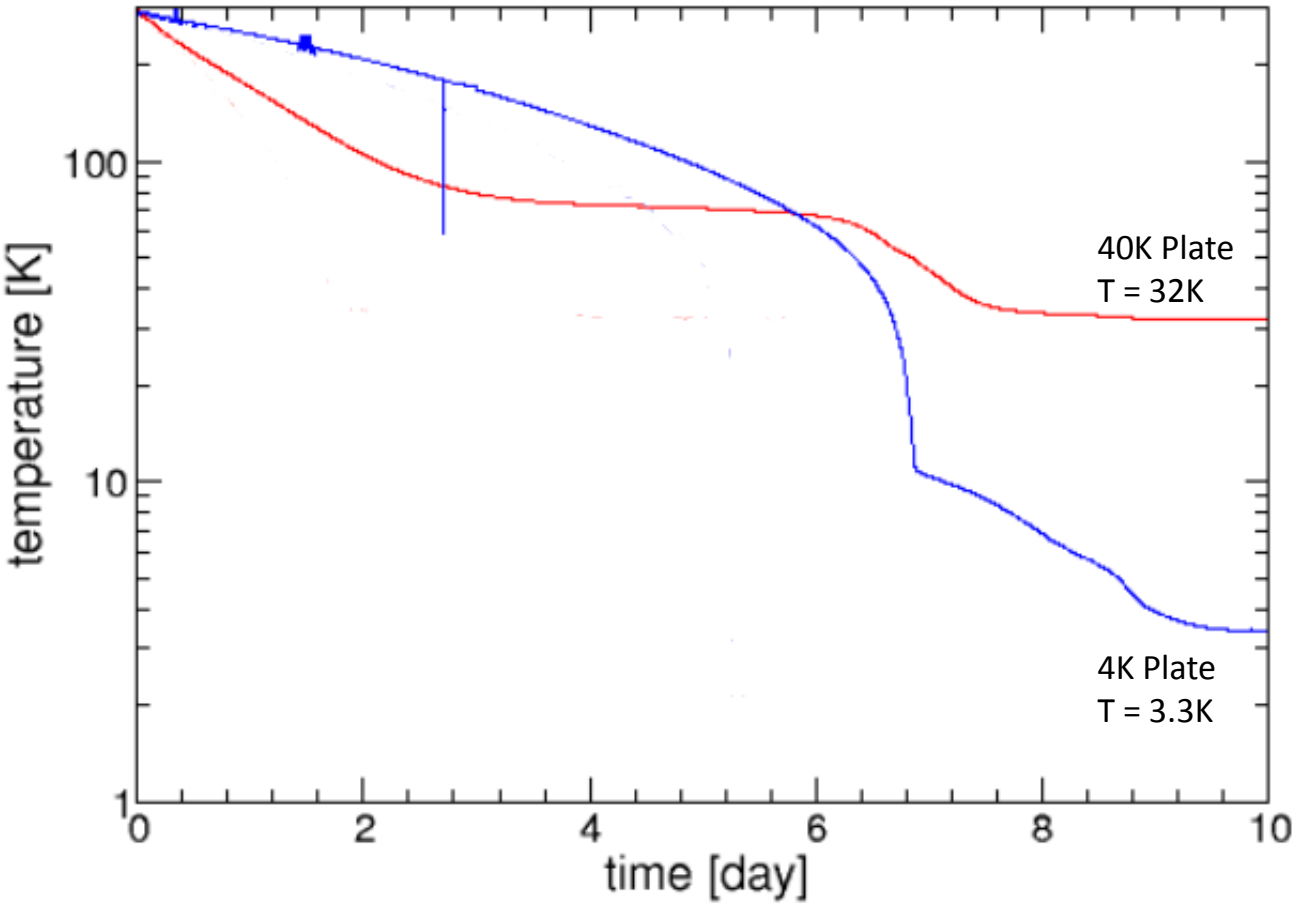
- 5 Pulse Tubes (Cryomech PT415 w/ remote motor)
- Initial cooling of cryostat at 40K and 4K/IVC stages
- Cooling power (each):
  - 40W at 40K stage
  - 1.5W at 4K stage



CUORE Cryostat: 4K Commissioning

- Commissioned with 3/5 PTs
- 3 Shields: 300K/OVC, 40K and 4K/IVC
- 2 cold runs to 4K:
  1. No Load
  2. w/Detector Calibration System (DCS) mockup beam

- Final Temperatures:
  32K at 40K stage
  3.3K at 4K stage
- Cooling time:
  ~1 week with 3PTs



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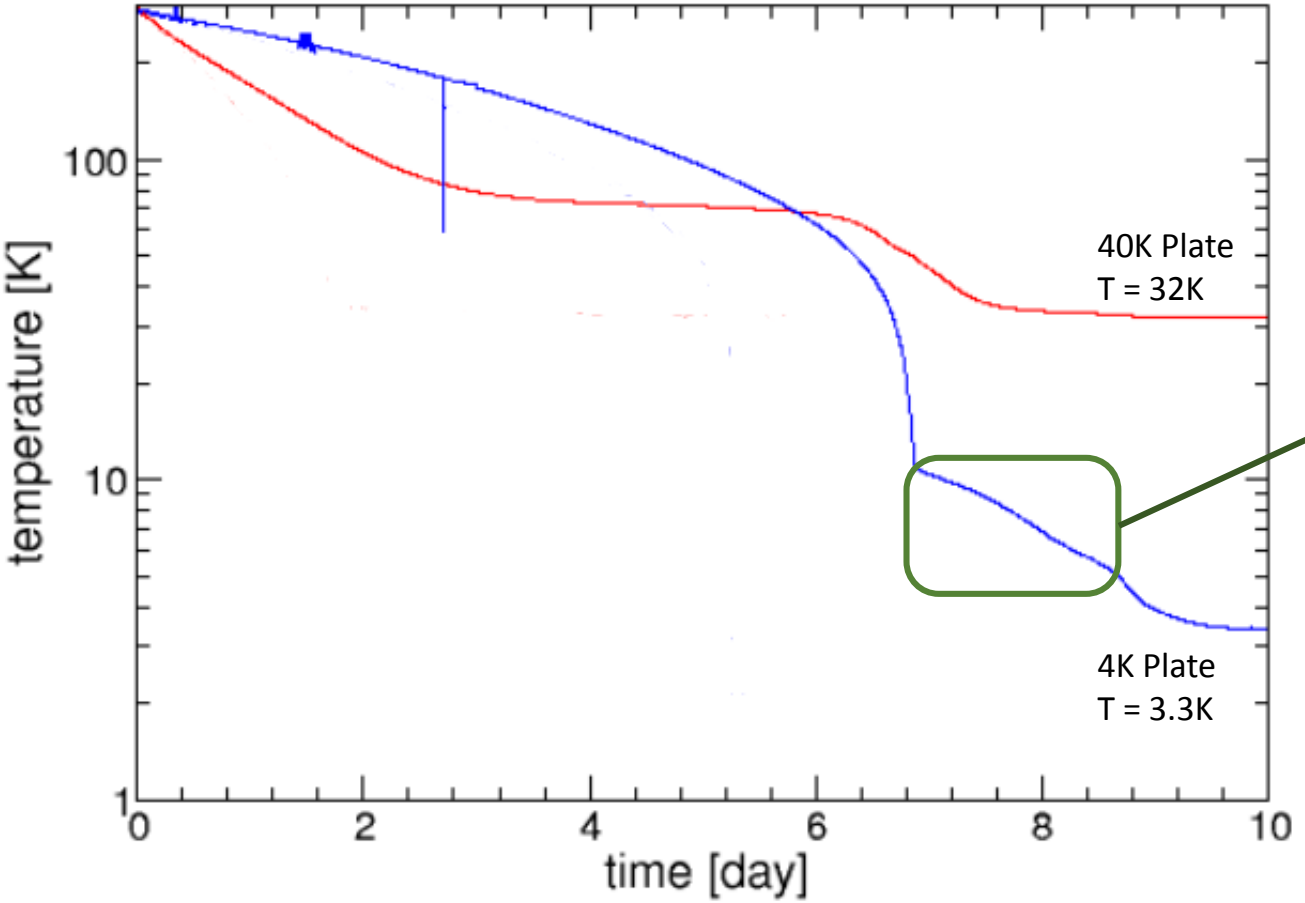


Stainless steel mockup for calibration system test
NOT present in CUORE

CUORE Dilution Unit [DRS-CF3000]

- Modified DRS-CF2000 model:
  - Joule-Thompson condensing stage designed for high circulation rates
  - 50% longer heat exchanger (HEX) between Still and MC
  - Variable impedance system:

<u>High cooling power</u>

Initial DU operation

Mixture flow > 8 mmol/s

Quickly get to base T from 4K

<u>Low base temperature</u>

Standard operation

Mixture flow < 1 mmol/s

Avoid heating from incoming mixture

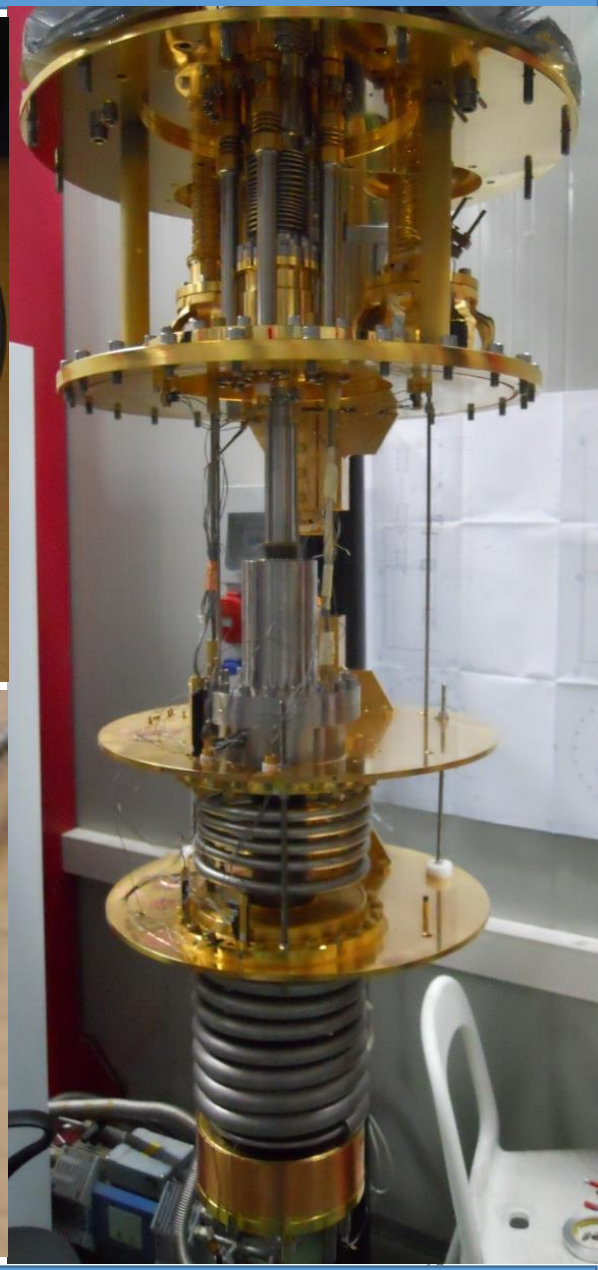
- Commissioned at Leiden Cryogenics:

Test cryostat with 2PTs

<u>Mixing Chamber Power</u>:

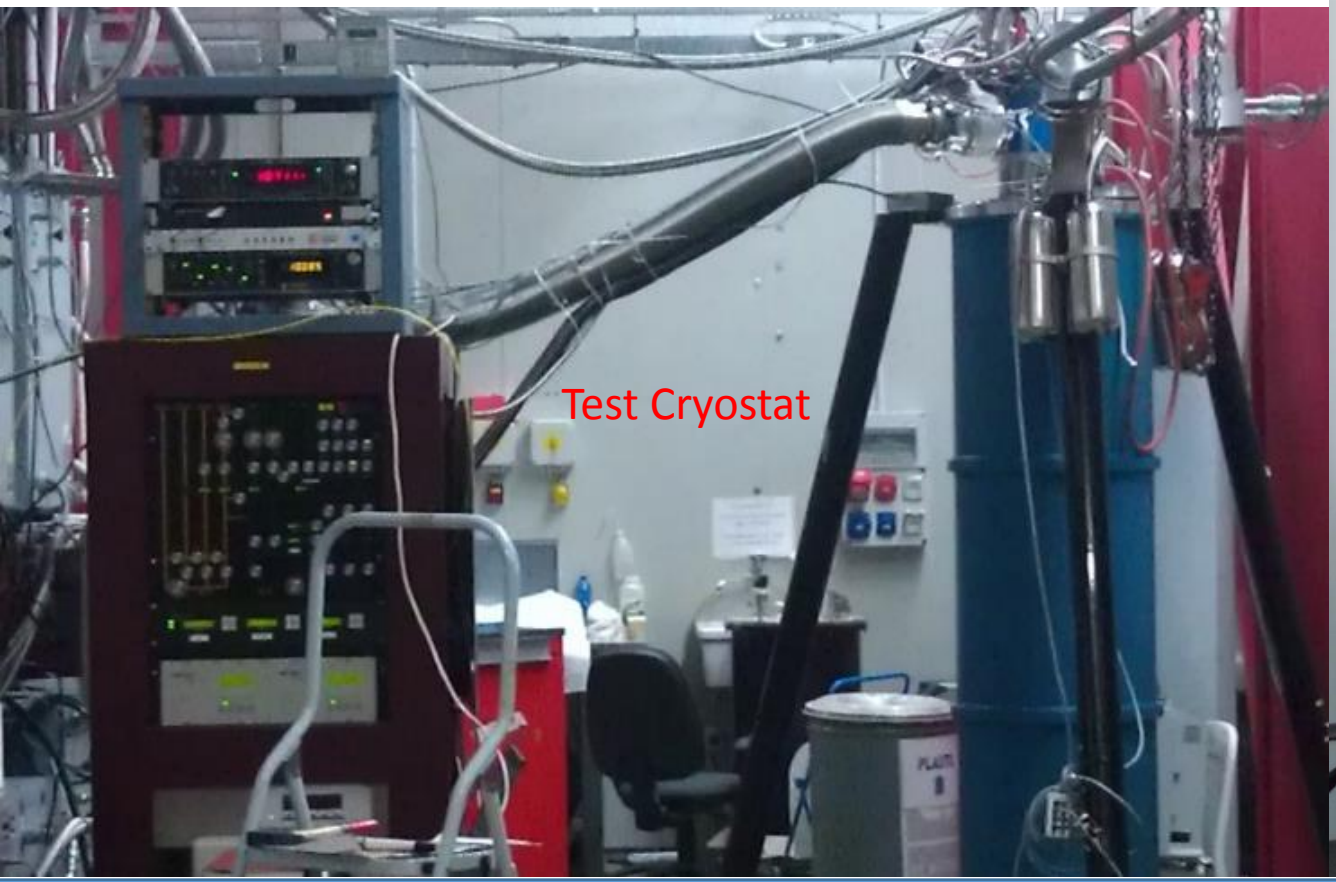
2mW @ 100mK (3mW @ 123mK)

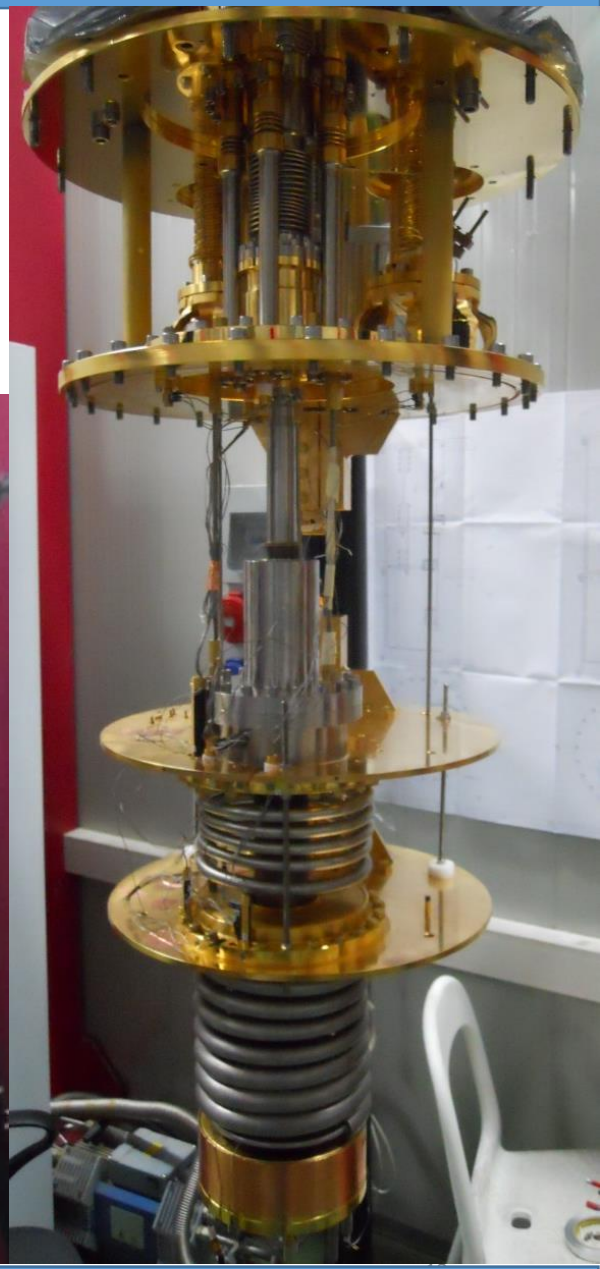
T_{min} = 5.26mK



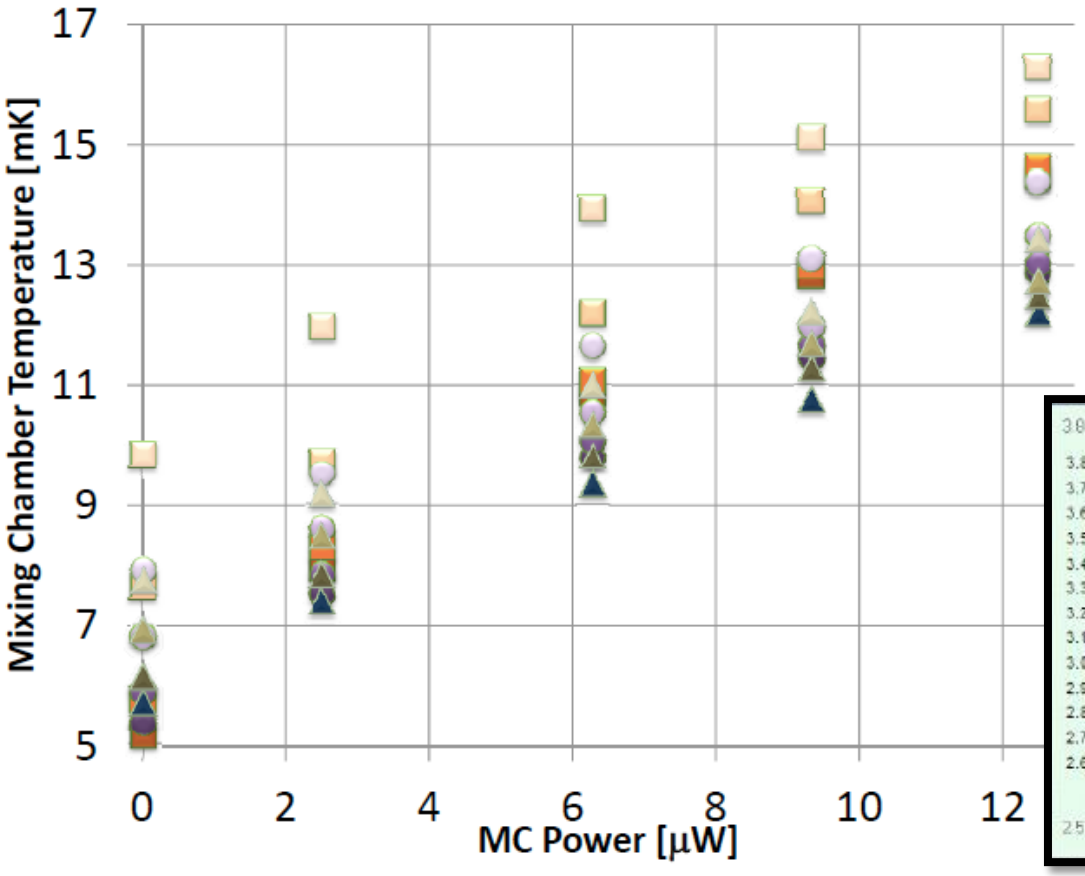
CUORE Dilution Unit [DRS-CF3000]

- LNGS onsite testing (test cryostat with 2 PTs):
  Lowest temperature: 4.95 mK
- DU characterized by injecting power on cold stages:
  Still, Heat Exchange (HEX), and Mixing Chamber (MC)

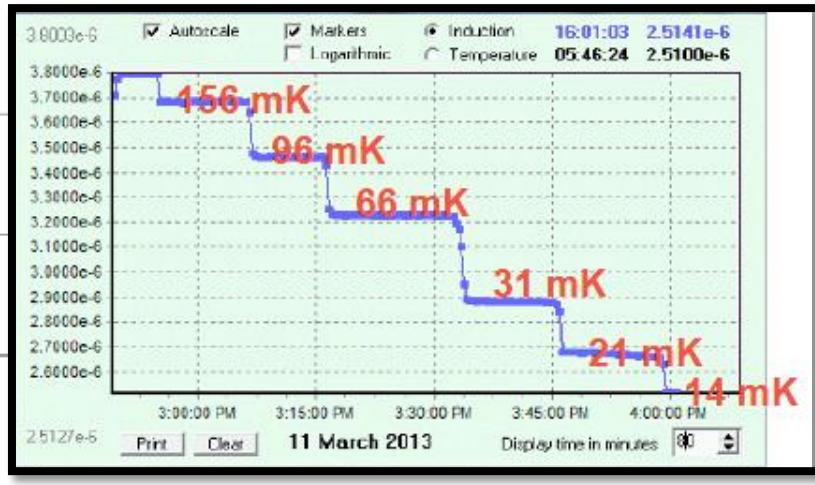




CUORE DU Characterization



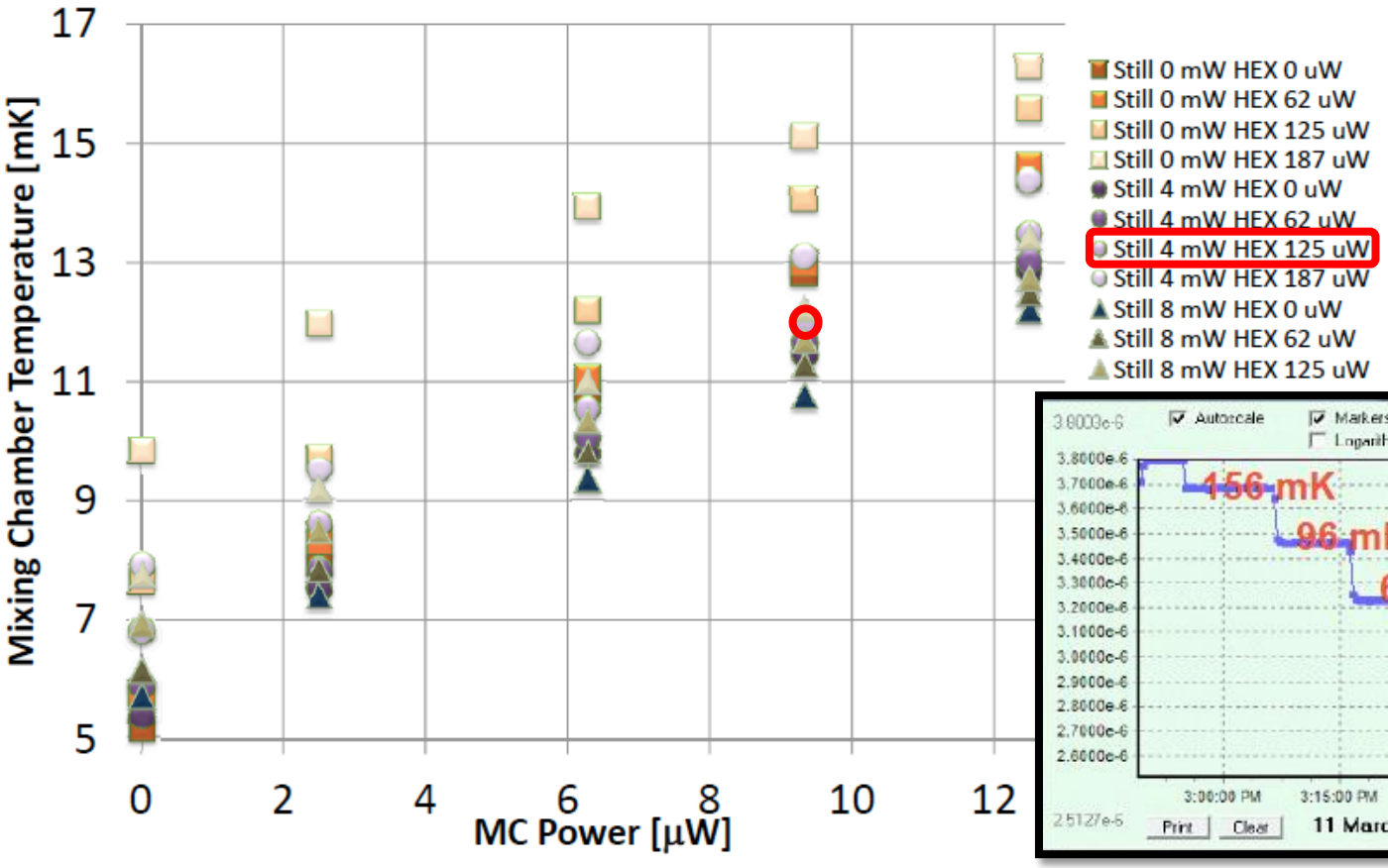
Fixed Point and Cerium Magnesium Nitrate (CMN) thermometers on Mixing Chamber stage



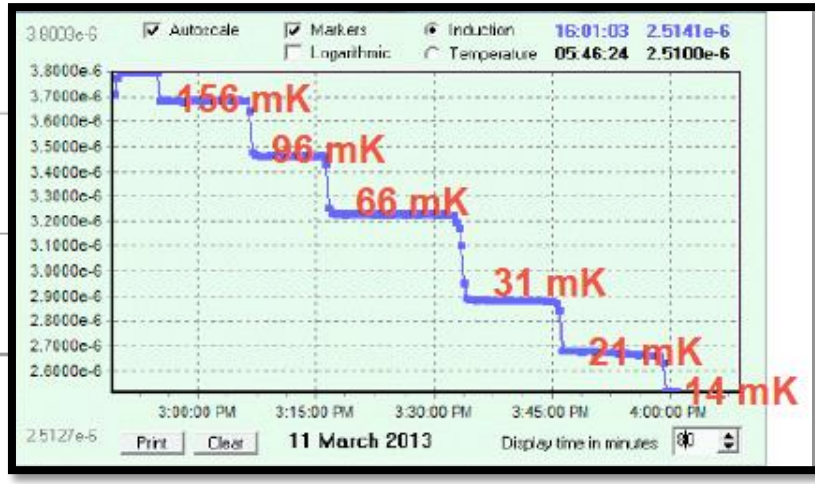
Power Budget/Requirements:

Still/600mK:	3 mW
HEX/50mK:	125 µW
MC/10mK:	5 µW @ 12mK

CUORE DU Characterization



Fixed Point and Cerium Magnesium Nitrate (CMN) thermometers on Mixing Chamber stage



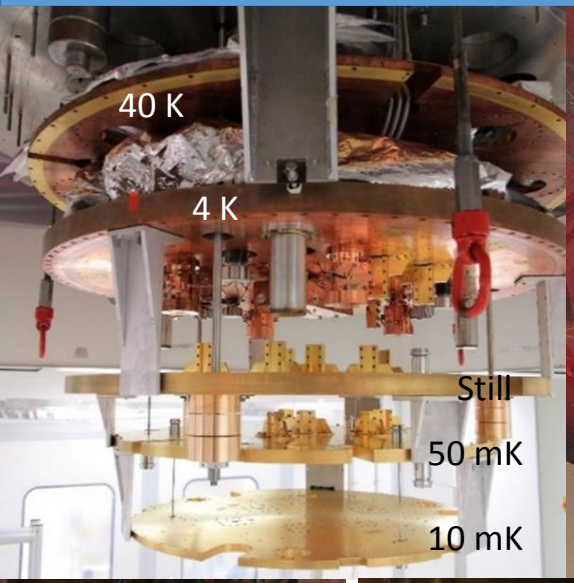
Power Budget/Requirements:

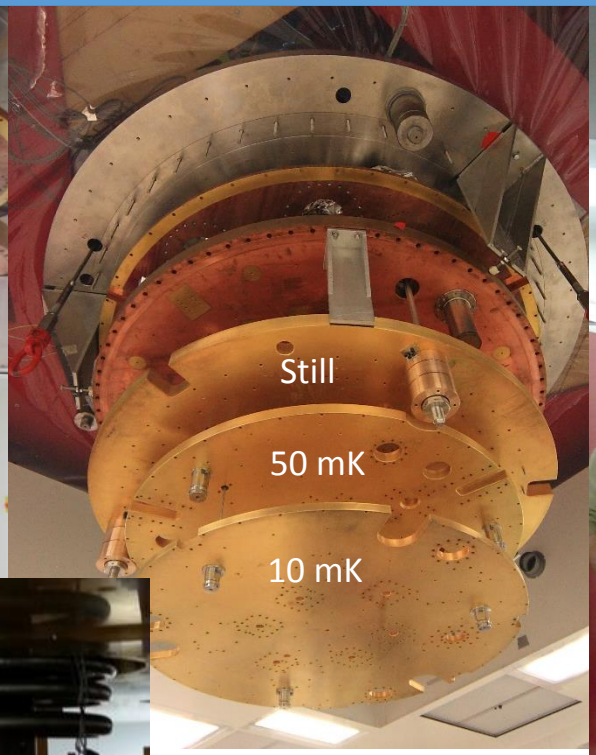
Still/600mK:	3 mW
HEX/50mK:	125 µW
MC/10mK:	5 µW @ 12mK

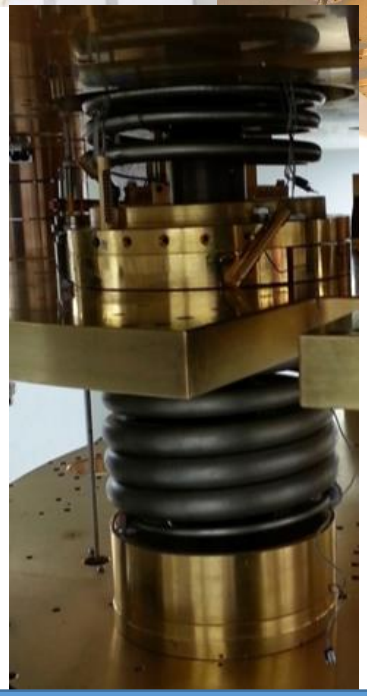
Power Budget/ Results:

Still/600mK:	4 mW
HEX/50mK:	125 µW
MC/10mK:	~10 µW @ 12mK

Merge Cryostat + DU



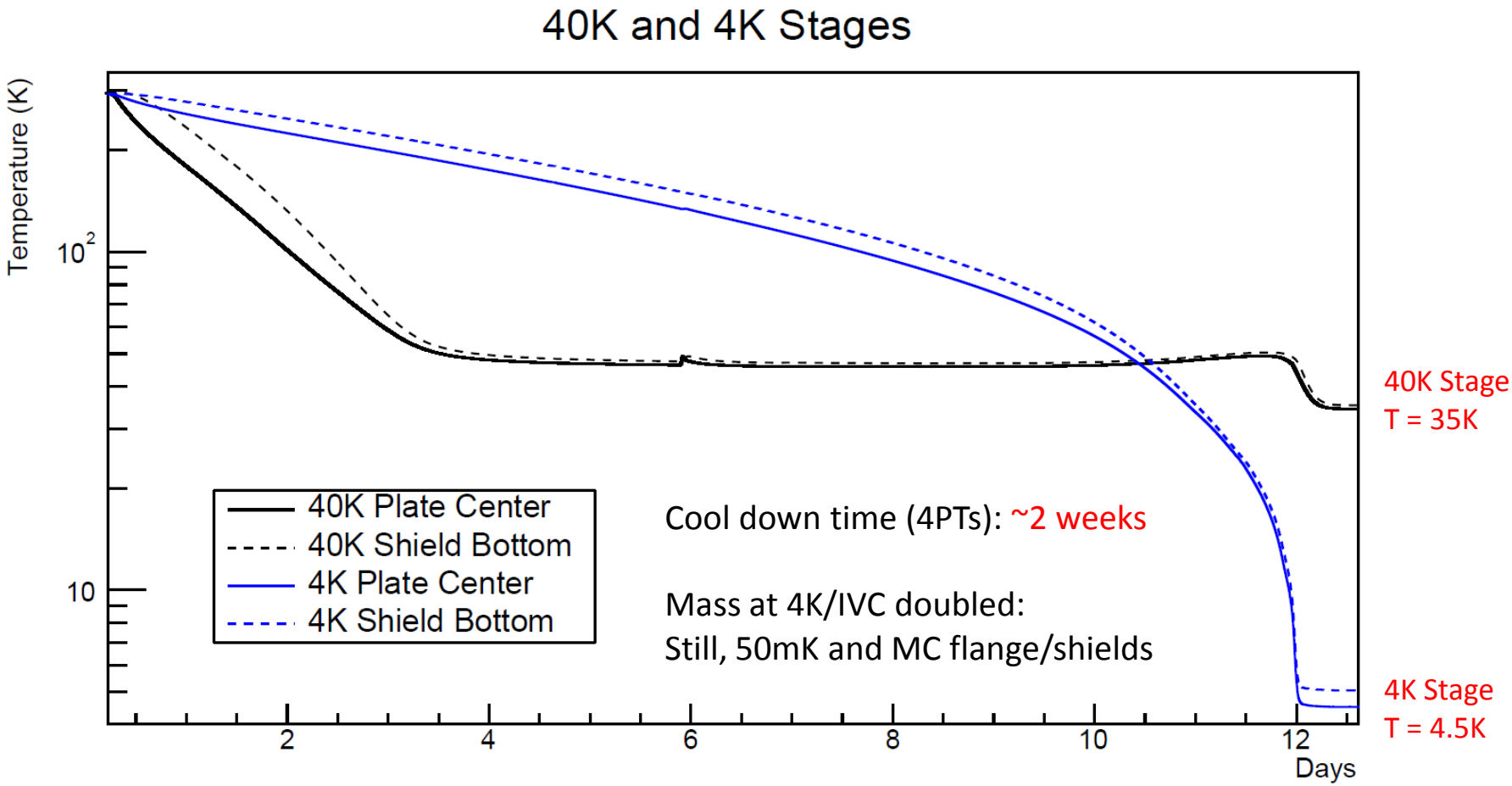




Inner flanges installed
Cryostat and DU merged
Completed January 2014

Base Temperature Cooldown

- First "complete" cryogenic cold run began 7th March 2014
  - All 6 flanges/shields
  - Pulse Tubes (4/5)
  - Thermalization
  - Dilution Unit
  - Suspensions
  - Thermometry
- Crucial stage of commissioning: Guarantees the full operation of the cryostat at base temperature
- Goal: Reach a stable temperature of 10mK with "no load" on the first try



Base Temperature Cooldown

- Very successful:
  - Stable temperature of 14mK (10.2mK in single-shot)
  - DU preformed very well: 4K to base T in ~12 hours

- Why not 10mK?
  Thermalization/radiation problems
  ~25mW of power on the Still

- First Cooldown Results:
  40K stage: 35K
  4K stage: 4.5K
  Still: 1.1K
  MC: 14mK

- Cryostat warmed up and problems addressed
- Second base temperature cooldown underway

Cold Lead Shielding

Top Lead:

- Located between MC and detector support plate
- Shields detectors from upper part of cryostat
- 2745kg Pb @ T = 50mK
  30cm modern lead disc (5 sections of 6cm each)
  (+ 570kg Cu OFE supports)
- 10cm thick ultra pure Cu

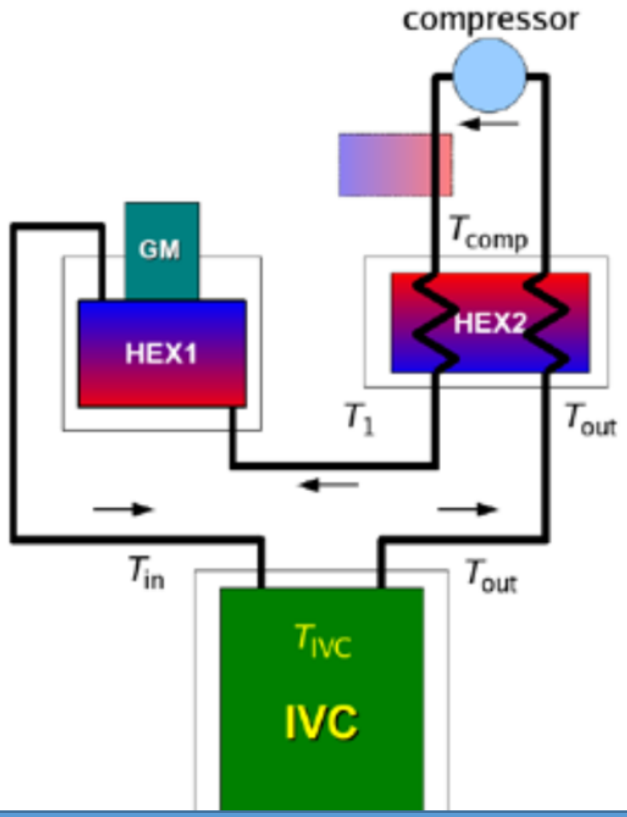
Lateral Lead:

- Located between 4K and Still shields
- 5562kg @ T = 4K
  6cm thick ring of Roman lead
  (+ 775kg Cu OFE supports)

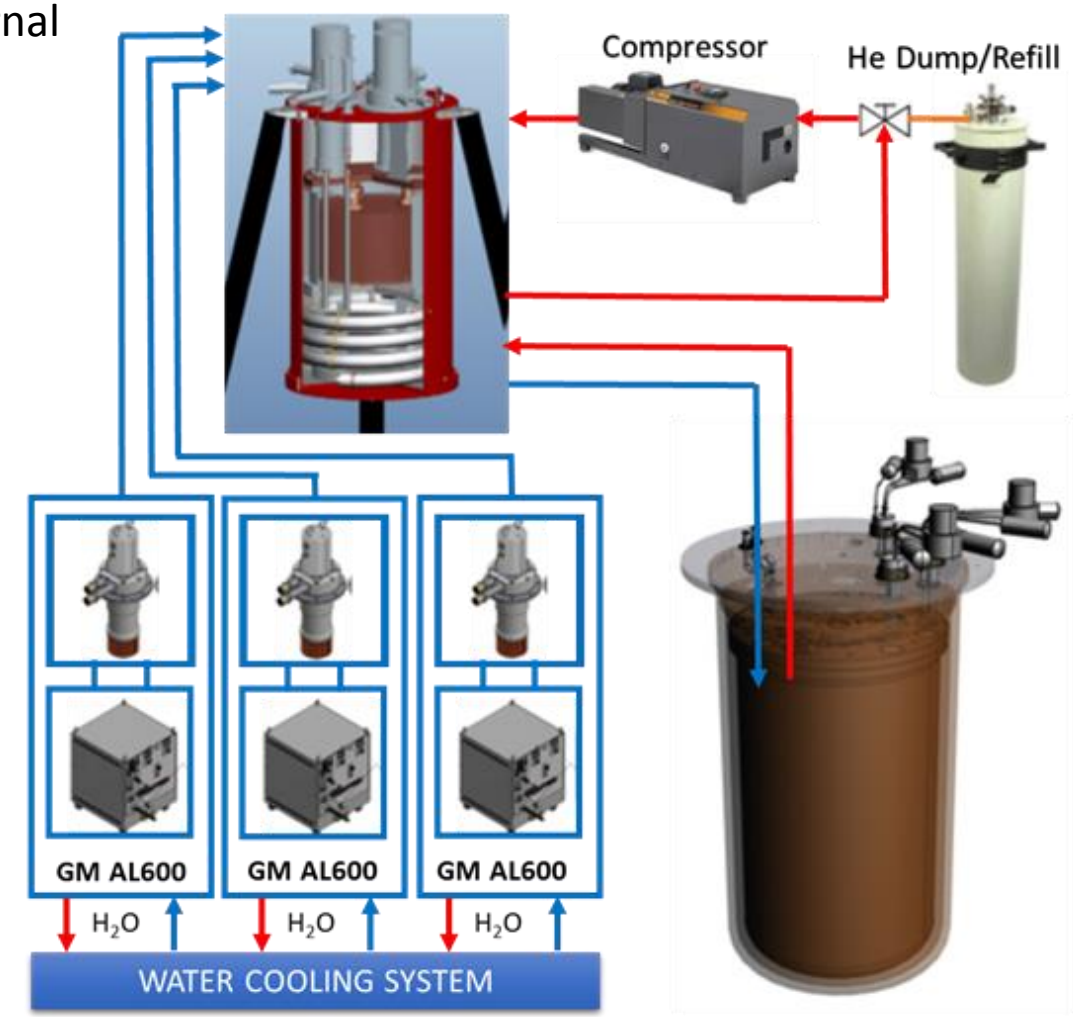
Cold Lead shields + External lead shield:
30cm of lead surrounding detectors in all directions

Fast Cooling System

- Fast Cooling System:
  - External vessel with 2 heat exchangers
  - 3 GM (Gifford-McMahon) cryo-coolers
    Cooling Power: 600W @ 77K (each)
- Helium is progressively cooled in external vessel and injected into cryostat IVC
  - 4K, Still and 50mK vessel (NOT 10mK)
  - $\Delta T < 40K$ (incoming/outgoing helium)



- Allows quick pre-cooling of IVC to 4K
  - IVC, Still, HEX and MC flanges/vessels: ~4 tons
  - Cold lead shielding: ~10 tons
  - Detector mass: ~1 ton



Fast Cooling System

Fast Cooling Unit

HEX 1

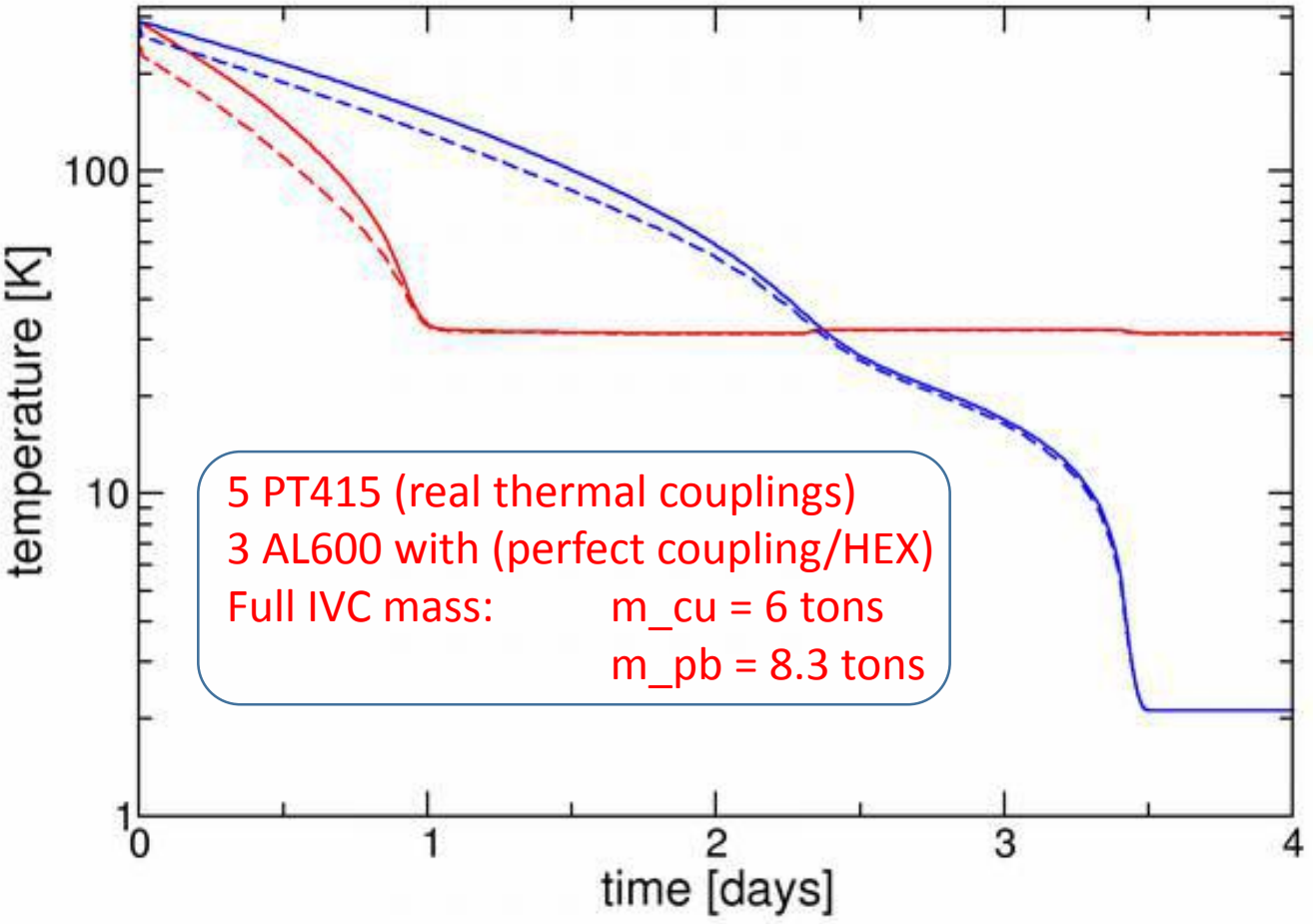
COPPER HEX

HEX 2

Counter Flow HEX

Fast Cooling System [Simulation]

- Estimated time to cool down < 1 week (complete cryostat)
- Want to keep actual cool down time between 1-2 weeks
- Final commissioning at Leiden Cryogenics: June 2014
- Expected delivery at LNGS: July 2014



Conclusion

- CUORE will be the largest bolometric array ever operated which requires a large cryostat
- CUORE cryostat will be the largest cryostat to be operated at ~10mK
- Constructing and commissioning such a large cryostat to 10mK is a challenge, but constructing one using low radioactive materials is even more of a challenge
- CUORE Cryostat is designed to overcome three main challenges:
  - Cool down large mass to base temperature of 10mK
  - Reduce vibrational noise of detectors for good energy resolution
  - Low background through strict selection of cryostat materials
- Both the Cryostat and DU have met the required design specifications
- Commissioning of the full CUORE cryostat is in its final phase and has been underway since January 2014
- Some problems with first base temperature run but nothing too serious

CUORE Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

SAPIENZA UNIVERSITÀ DI ROMA

Lawrence Livermore National Laboratory

Universidad Zaragoza

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FLORENTINA STUDIORUM UNIVERSITAS

CSNSM

BERKELEY LAB

UCLA

THE UNIVERSITY OF CALIFORNIA 1868

LUX ET VERITAS

UNIVERSITAS STUDII PADUANI MCCXXII

CUORE

Back Up Slides

Thermometry

40K and 4K Stages

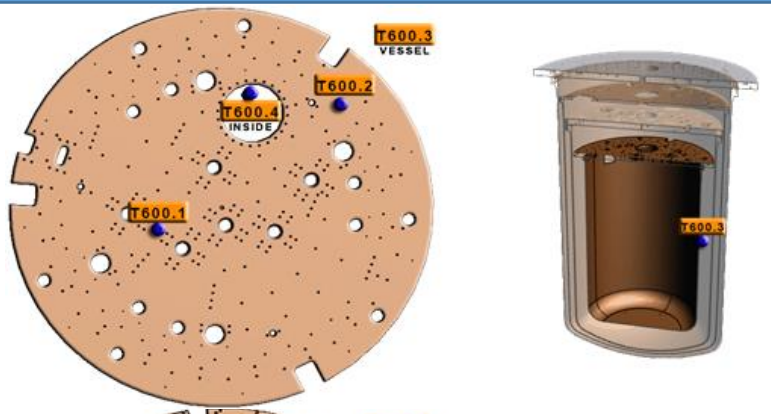
- Platinum (PT102) mounted on 40K flange/vessel
  - Temperature range: 300K – 30K
- Diode (DT470) mounted on 4K flange/vessel
  - Temperature range: 300K – 1K
- Read out with 3 LakeShore (model 218) temperature monitor

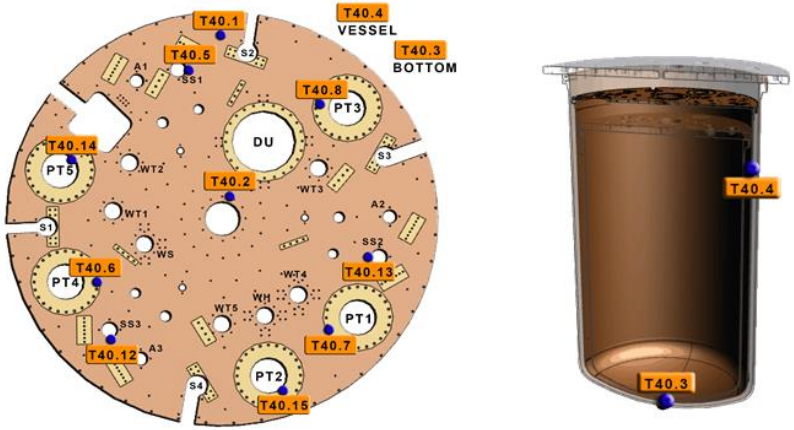
Still, 50 mK, and MC Stages

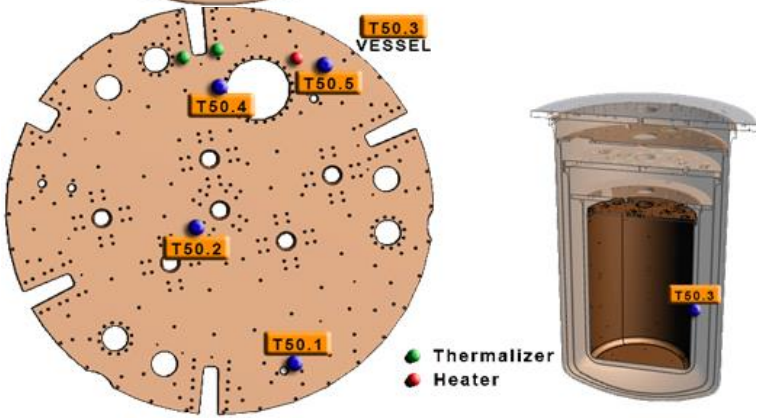
- 3 Platinum (PT102); (one on each stage)
- RuO_2 mounted on Still, 50mK and MC flange/vessels
  - Temperature range: 30K – 40mK
- Fixed Point (FP) mounted on 10mK stage
- Cerium Magnesium Nitrate (CMN) mounted on 10mK stage
- PT and RuO_2 read out with AVS-47B AC Resistance bridge
- CMN and FP read out with Digital Mutual Inductance bridge
- Use embedded DU wiring

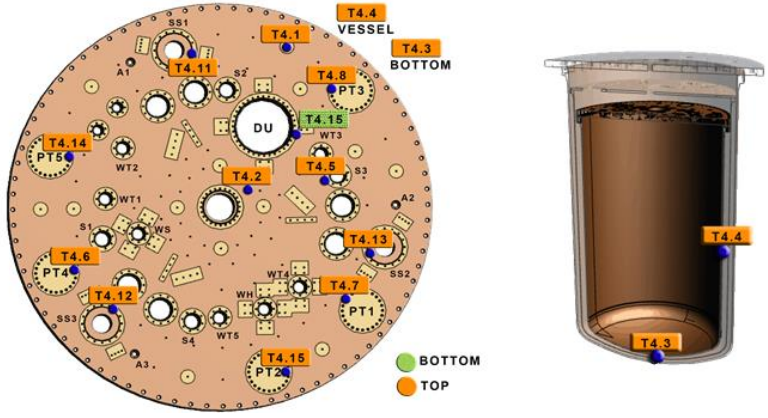
Thermometry

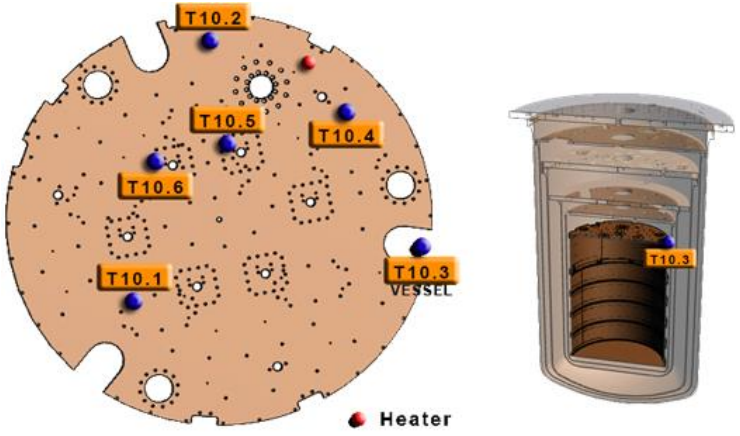
12 Platinum (PT102) on 40K stage
12 Diode (DT470) on 4K stage
3 Platinum (PT102) on Still, HEX and MC stages (1 each)
10 RuO_2 on Still, HEX and MC stages
Fixed Point (FP) on MC stage
2 Cerium Magnesium Nitrate (CMN) on MC stage





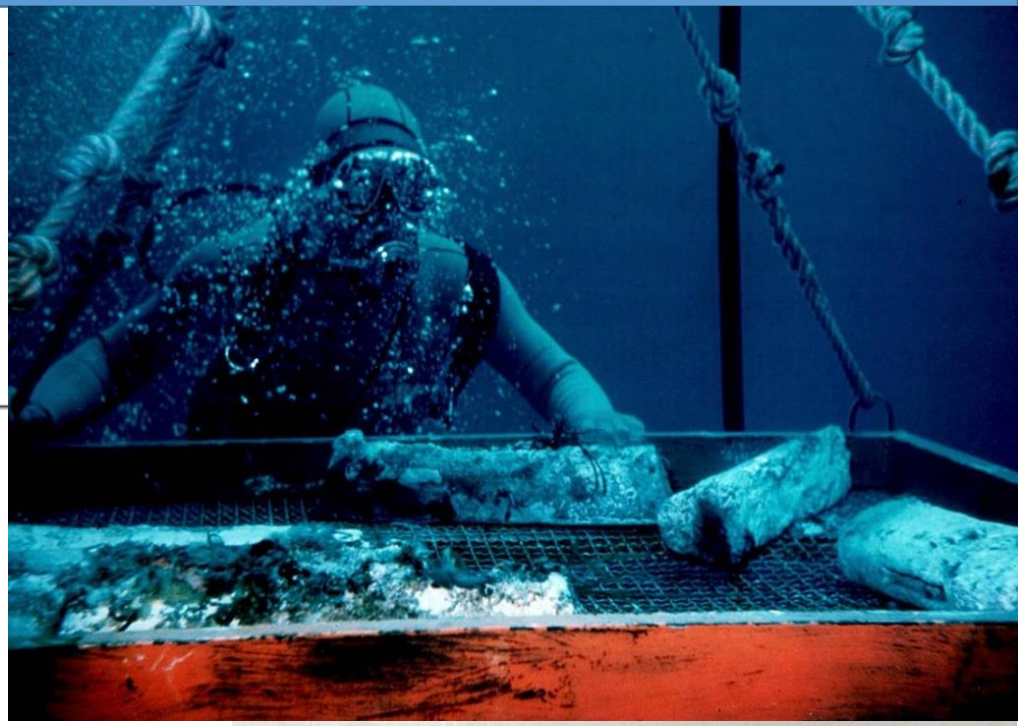


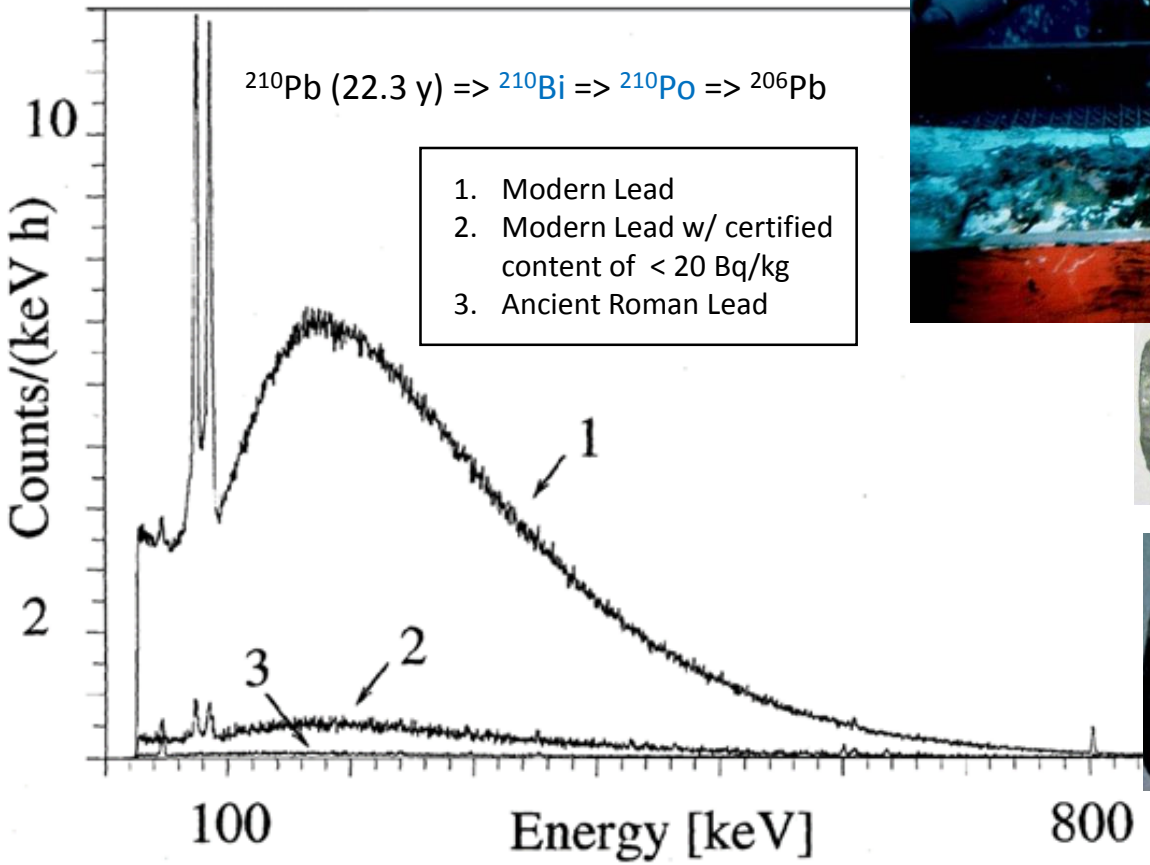




Ancient Roman Lead

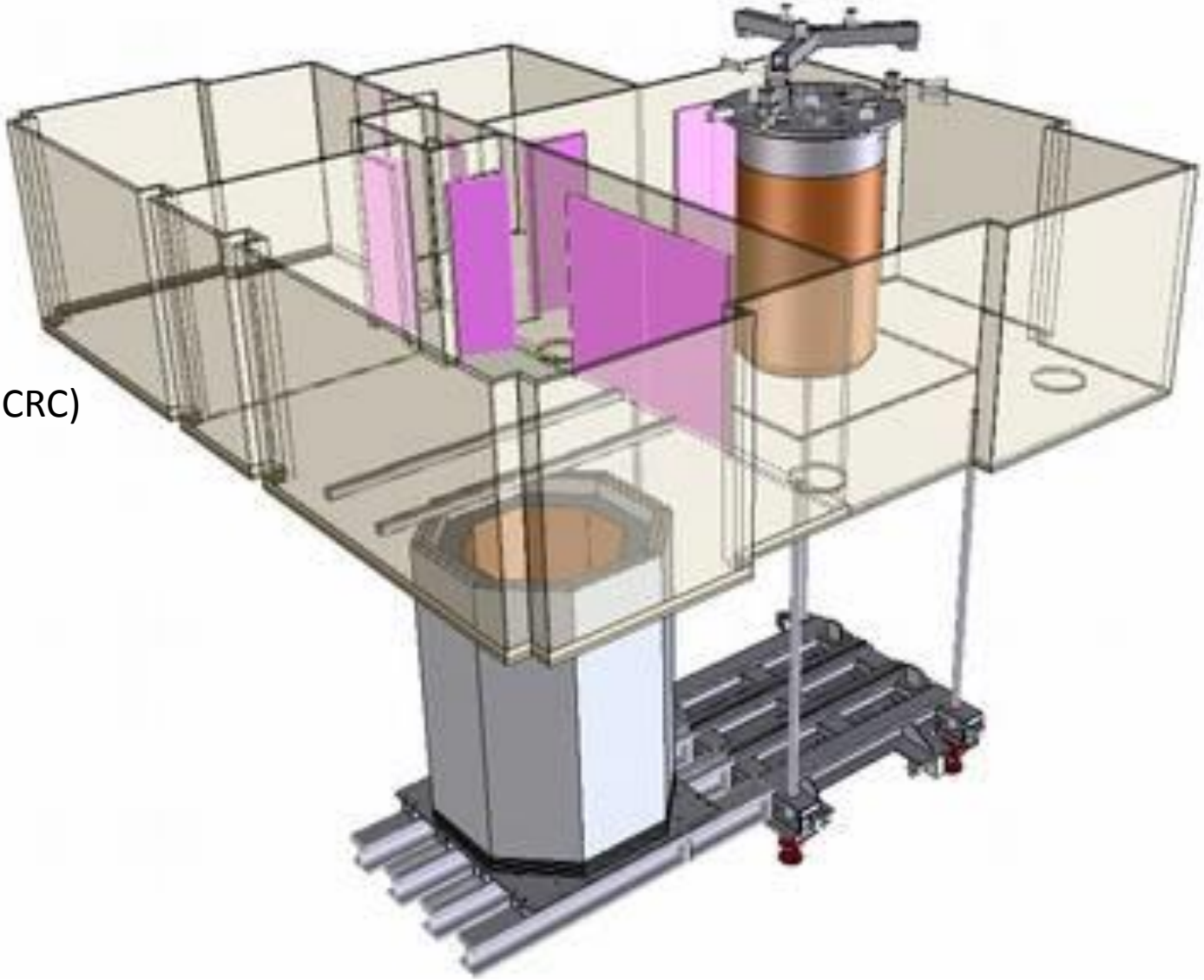
- Modern lead:
  - ^{210}Pb 10-1000 Bq/kg
  - ^{210}Pb: half life of 22.3 years
- Ancient Roman Lead:
  - ^{210}Pb with < 4 mBq/kg
  - Romans extracted Ag from the Pb (and ^{238}U)





Mass Inventory

- 2nd Floor
  - Top Flange Access
  - Suspension Access
  - Electronics and DAQ
- 1st Floor
  - Cryostat Access
  - CUORE Clean Room (CRC)
- Ground Floor
  - Pumps
  - Compressors
  - DU gas handling
  - Shield storage



Suspensions and Thermalization