

The CUORE and CUORE-0 experiments at LNGS

Antonio D'Addabbo - INFN
on behalf of the CUORE Collaboration

The CUORE collaboration



SAPIENZA
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UCLA Yale



Majorana neutrinos

Neutrinos

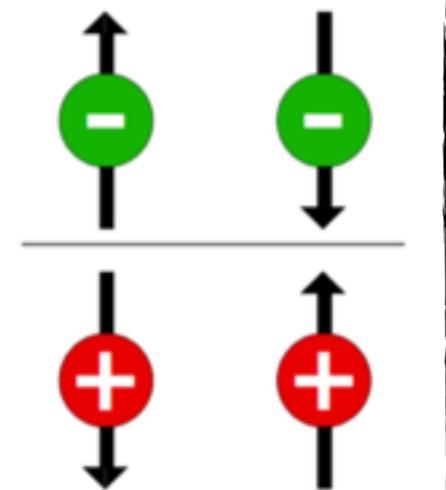
Spin $\frac{1}{2}$ particles: postulated by W. Pauli in 1930 to reconcile data on nuclear beta decay with conservation of energy-momentum and angular momentum



Dirac Basis

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

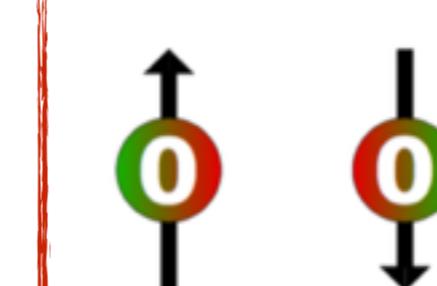
- The γ matrices contain real and imaginary numbers
- The field Ψ is complex
- Particles and antiparticles are different ($\Psi^* \neq \Psi$)



Majorana Basis

$$(i\tilde{\gamma}^\mu \partial_\mu - m)\tilde{\psi} = 0$$

- The γ matrices are purely imaginary. Suggested by Ettore Majorana in 1937
- The field $\tilde{\Psi}$ is real
- Particles and antiparticles are same

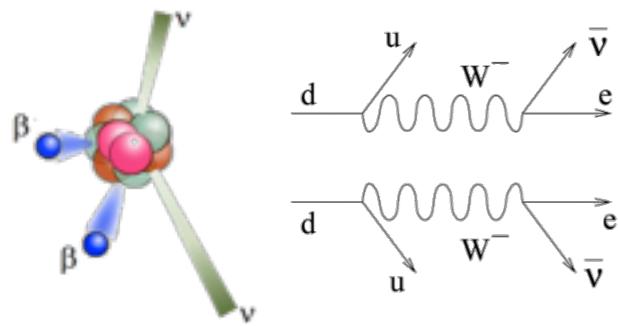


- Neutrinos can be Majorana particles since they are neutral spin $\frac{1}{2}$ particles
- L will be violated by Majorana neutrinos

Double beta decay

with
neutrinos $2\nu\beta\beta$

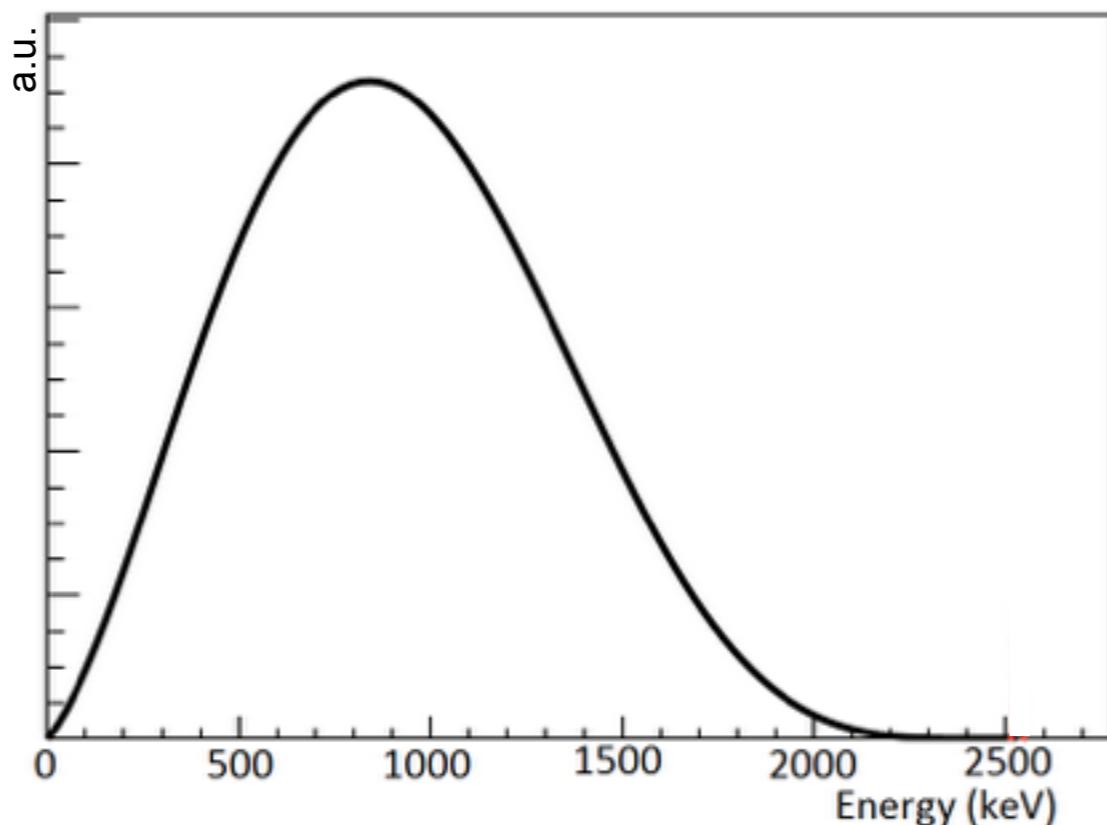
$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}$$



- Allowed by SM ($\Delta L = 0$)
- Observed in several nuclei

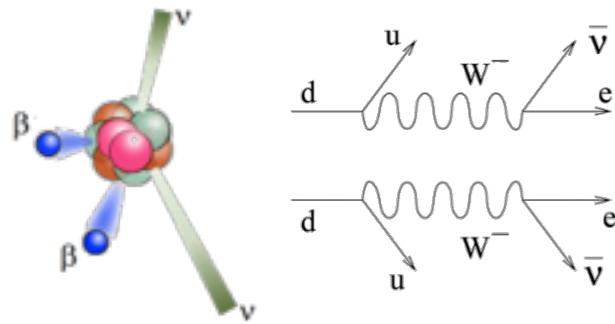
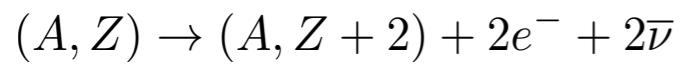
$$\tau_{1/2} \sim 10^{19-21} \text{ years}$$

$\beta\beta$ summed e^- energy spectrum in ^{130}Te



Double beta decay

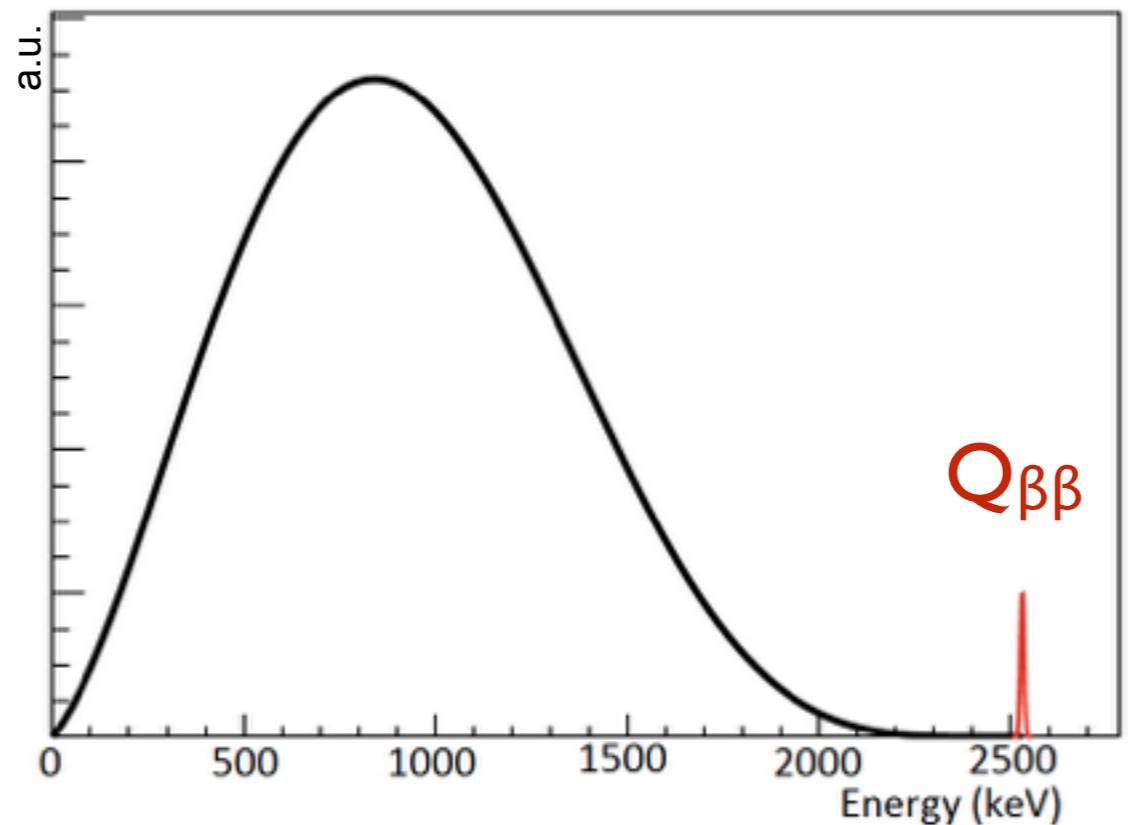
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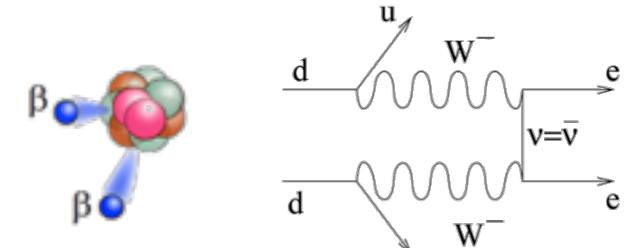
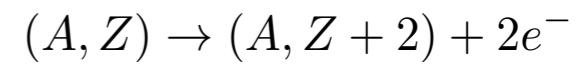
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neutrinoless $0\nu\beta\beta$

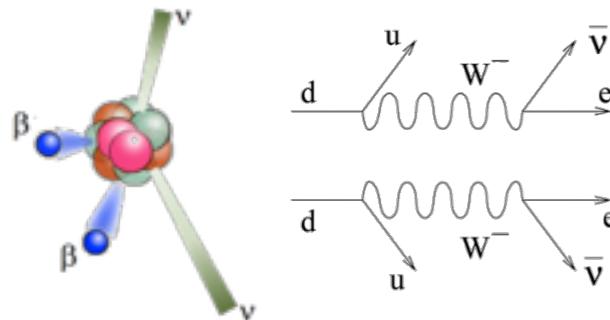
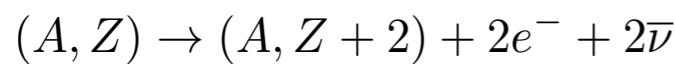


- Beyond by SM ($\Delta L = 2$)
- Never observed

$$\tau_{1/2} > 10^{25-26} \text{ years}$$

Double beta decay

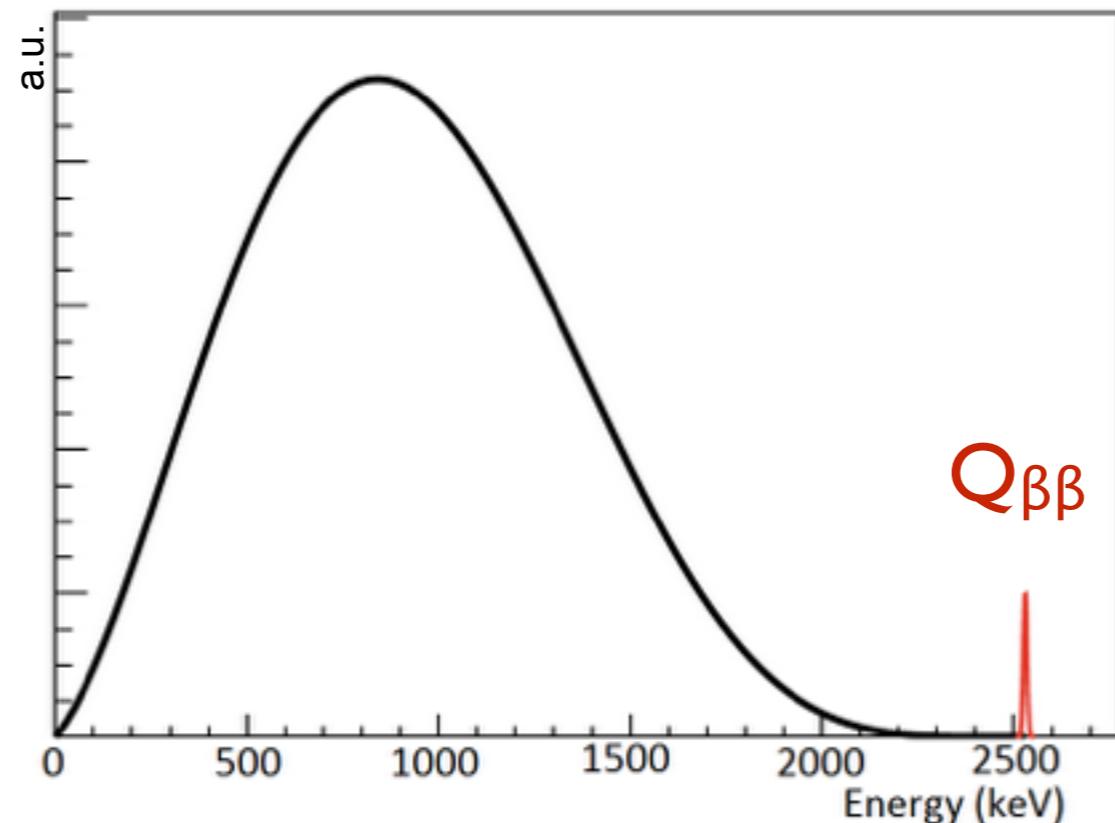
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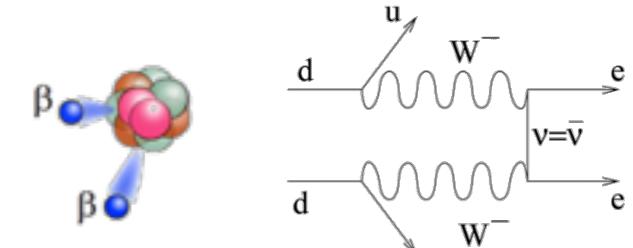
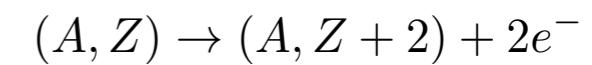
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- Beyond by SM ($\Delta L = 2$)
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Observation of $0\nu\beta\beta$ decay would

1. Demonstrate lepton number violation
2. Establish that neutrinos are Majorana Particles ($\nu = \bar{\nu}$)
3. Constrain ν mass hierarchy and scale

$0\nu\beta\beta$ half-life time

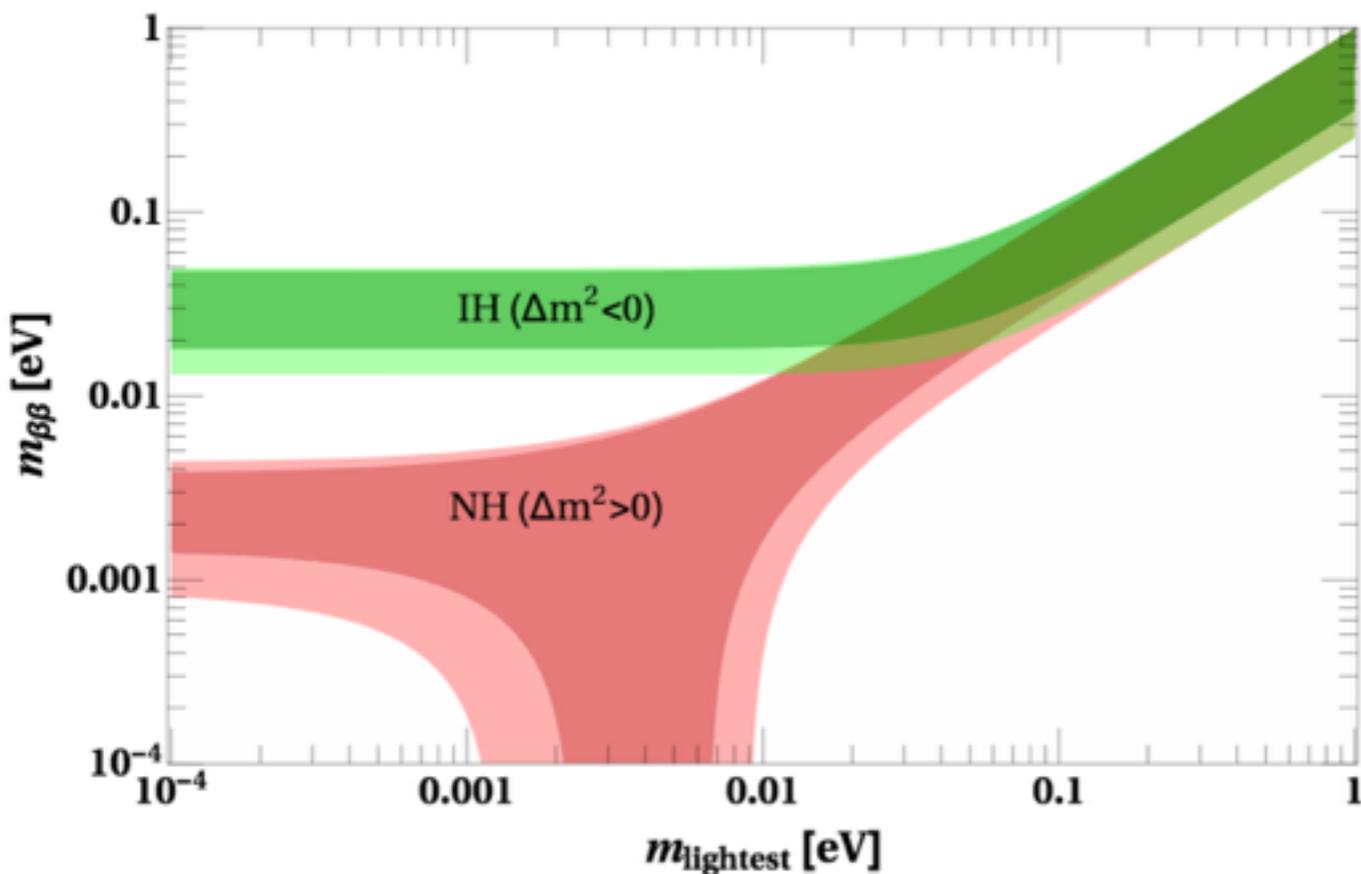
Decay rate:

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

Majorana effective mass $m_{\beta\beta} = |\sum_i m_{\nu_i} U_{ei}^2|$

Nuclear Matrix Element *large uncertainties*

Phase Space Factor ($\propto Q^5$)



0νββ half-life time

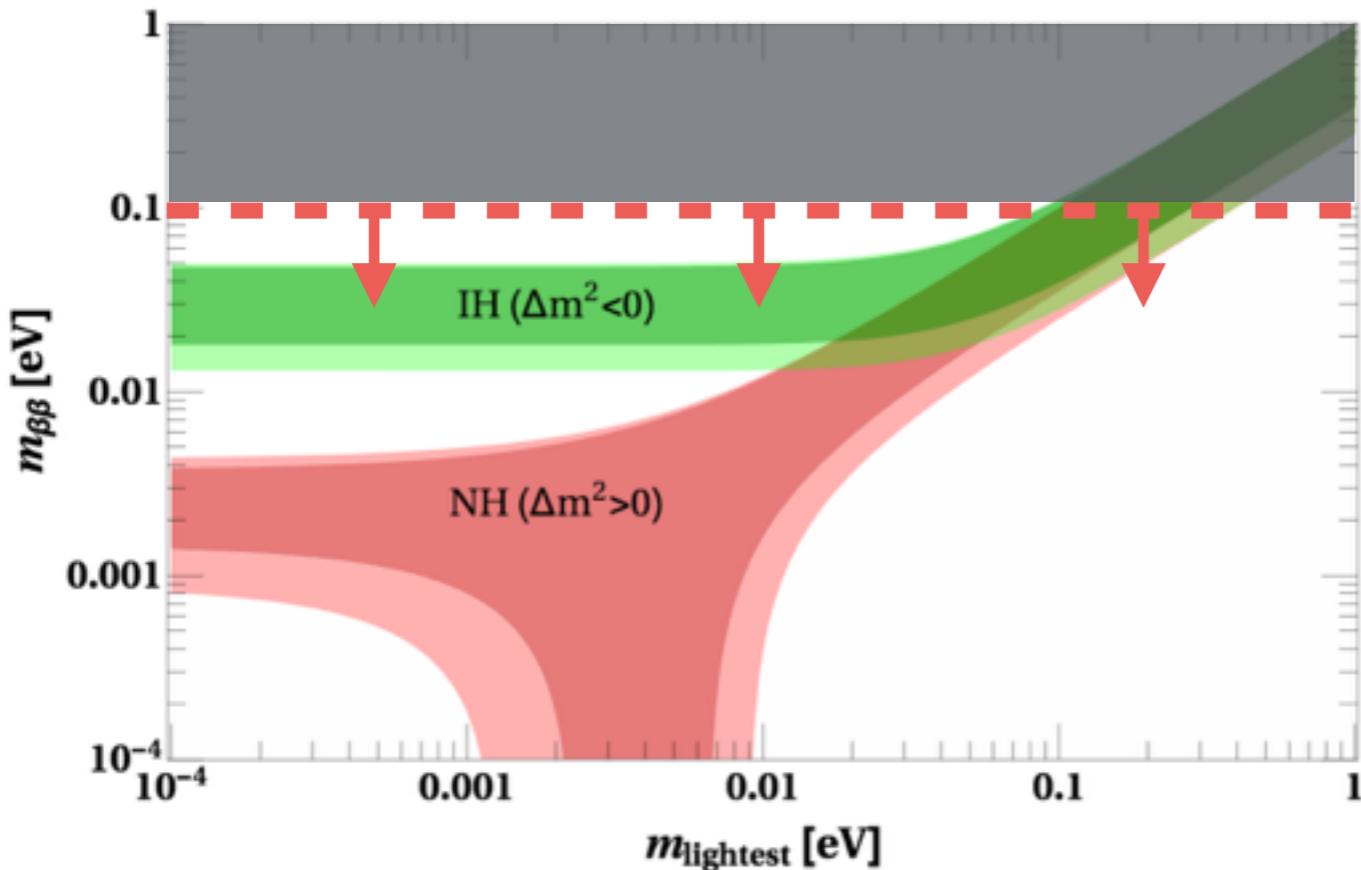
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from decay rate measurements one can infer
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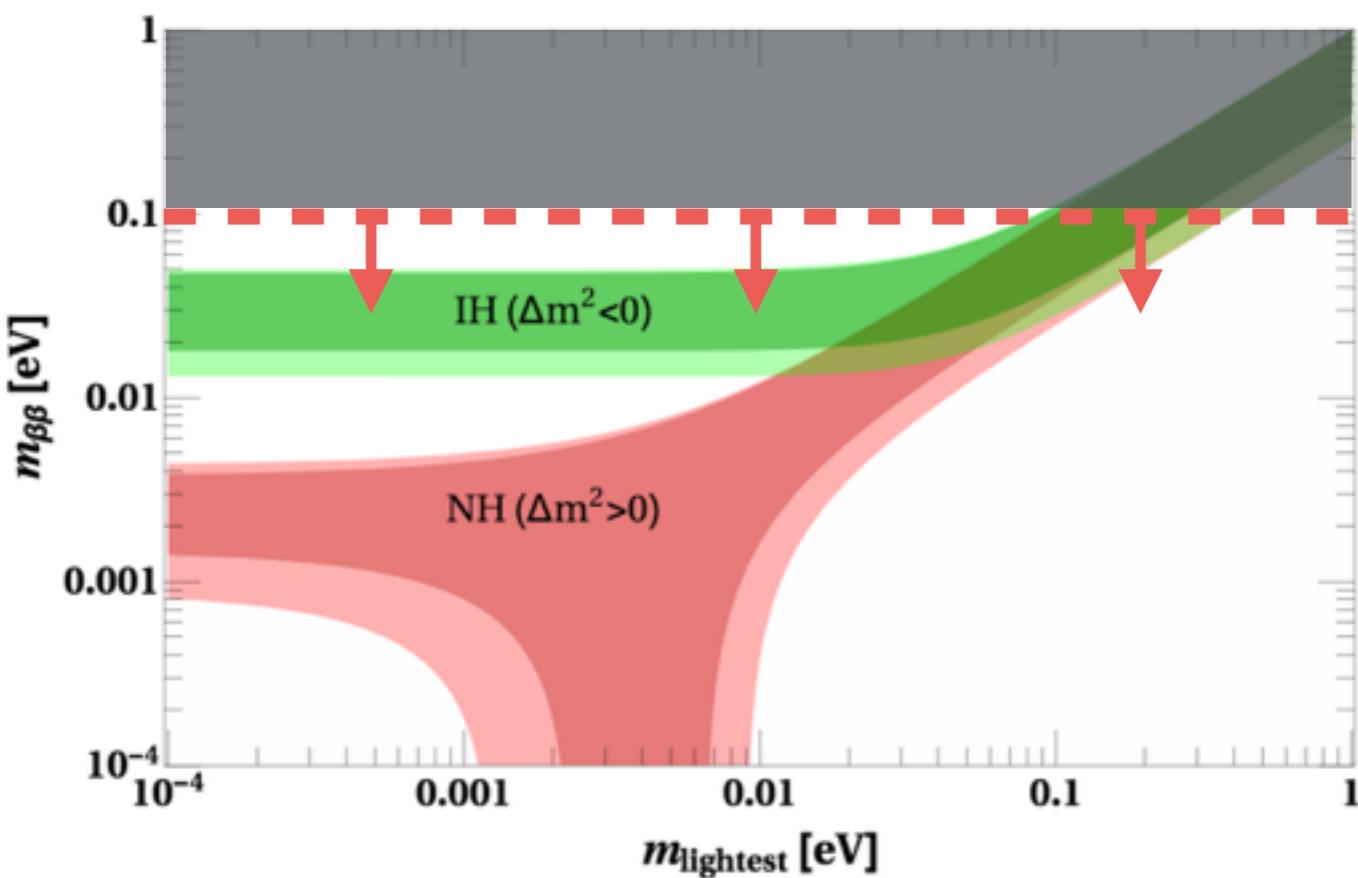
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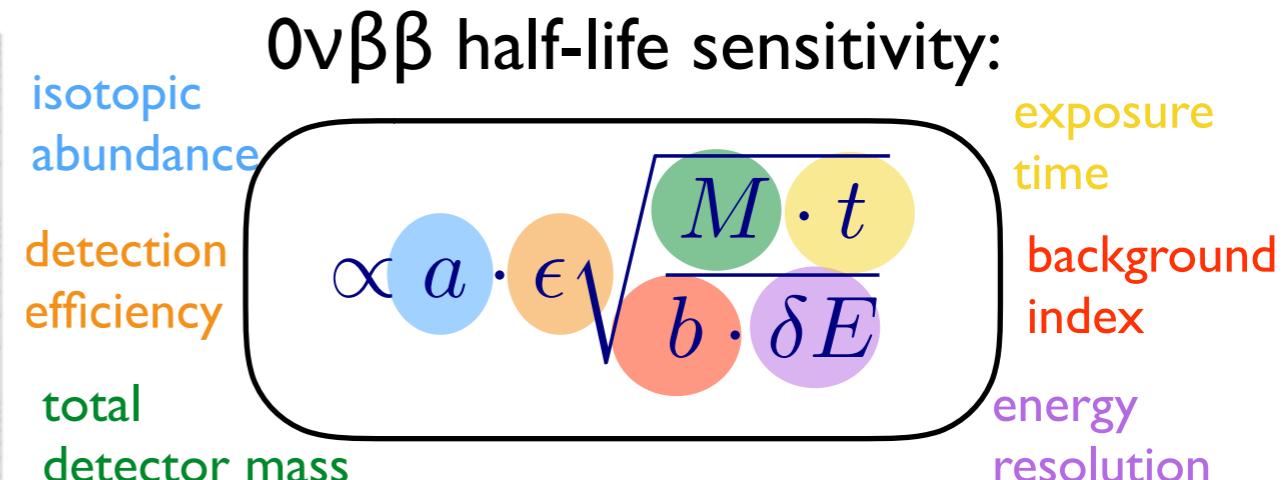
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- Competitive 0νββ experiment:**
- High Q-value reaction
 - High isotopic abundance
 - Large total mass
 - Extremely low background
 - Excellent energy resolution

The CUORE experiment @ LNGS



CUORE: Cryogenic Underground Observatory for Rare Events

primary goal:

search for neutrino less double beta ($0\nu\beta\beta$) decay in ^{130}Te

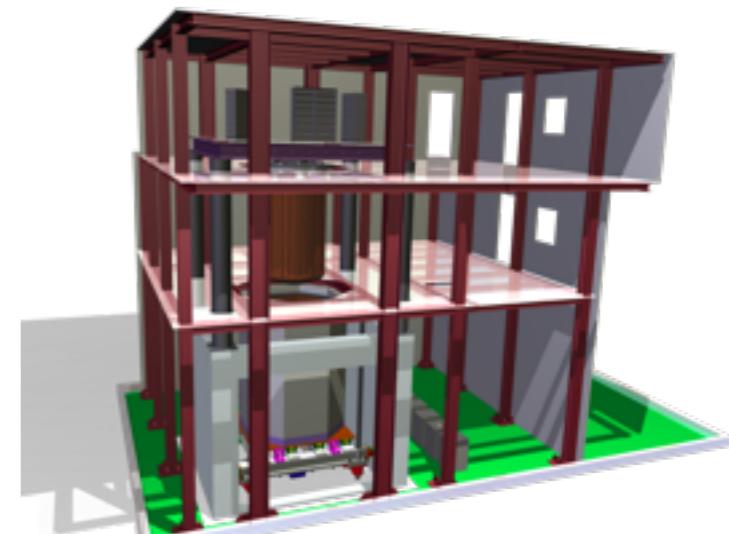


CUORE installation hall A @ LNGS



- ~3600 m.w.e. deep
- $\mu\text{s}: \sim 3 \times 10^{-8} / (\text{s cm}^2)$
- $\gamma\text{s}: \sim 0.73 / (\text{s cm}^2)$
- neutrons: $4 \times 10^{-6} \text{ n}/(\text{s cm}^2)$

CUORE HUT



The CUORE experiment

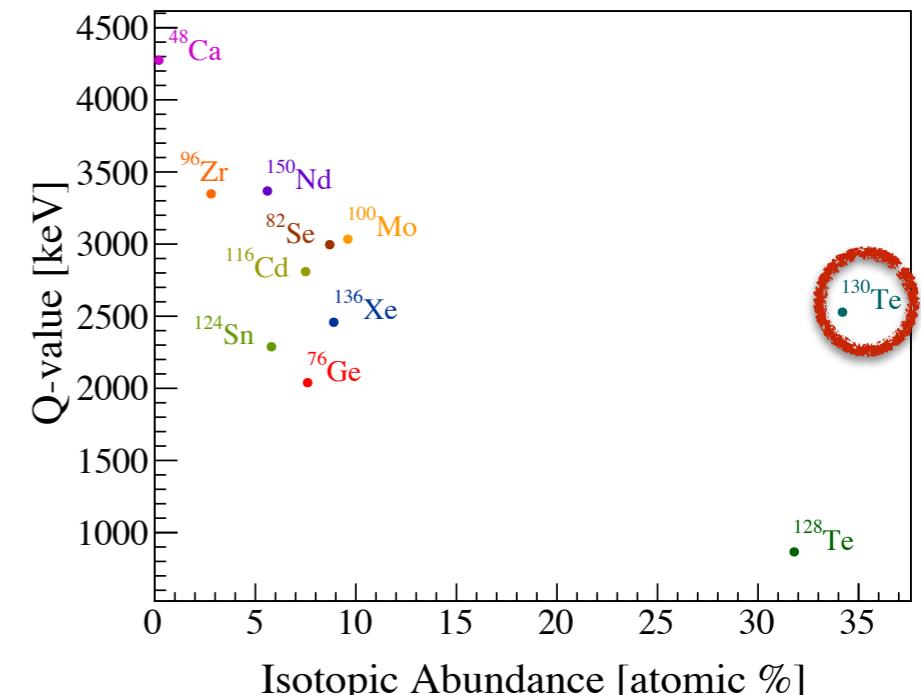
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primary goal:

search for $0\nu\beta\beta$ decay in ^{130}Te

main features &
requirements:

- $Q_{\beta\beta} ({}^{130}\text{Te}) \sim 2528 \text{ keV}$
- Highest isotopic abundance



Competitive $0\nu\beta\beta$ experiment requirements

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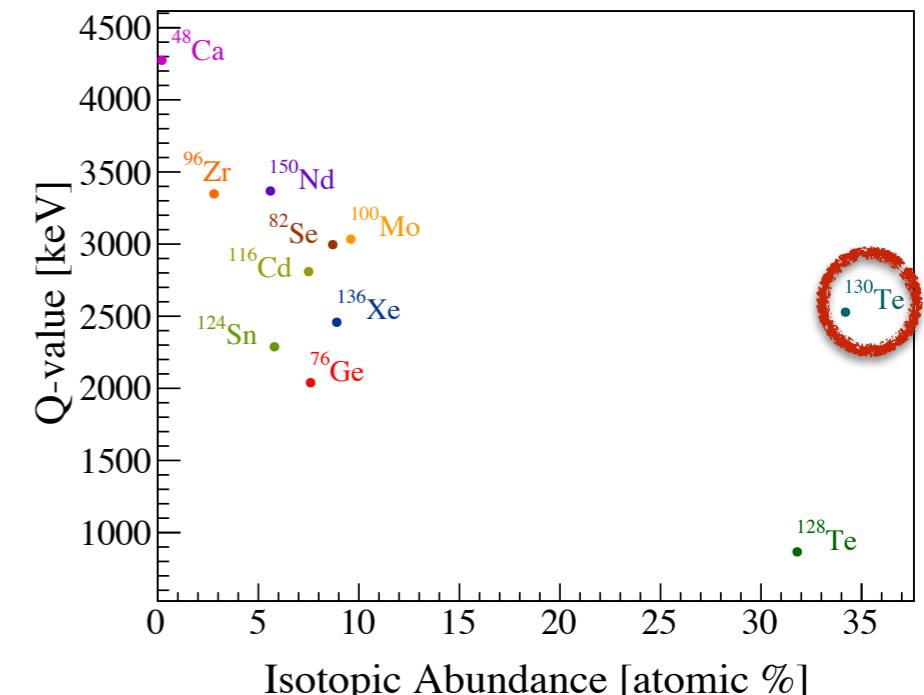
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- Mass of TeO_2 : 741 kg ($\sim 206 \text{ kg of } {}^{130}\text{Te}$)



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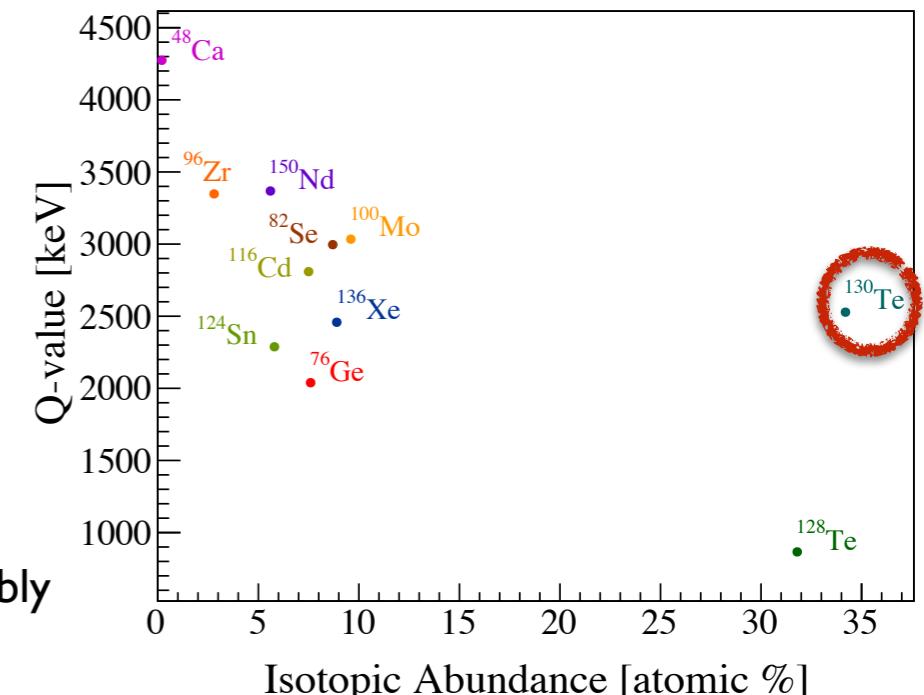
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 - deep underground location
 - stringent radiopurity controls on materials and assembly



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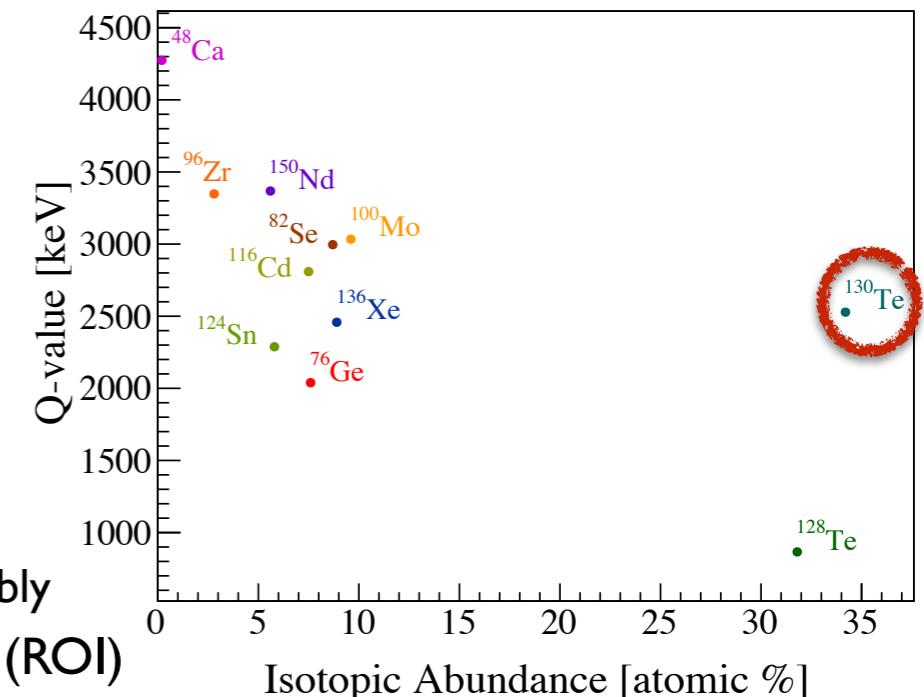
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- Background aim: $10^{-2} \text{ c/keV/kg/year}$
 - deep underground location
 - stringent radiopurity controls on materials and assembly
- Energy resolution: 5 keV in the Region Of Interest (ROI)



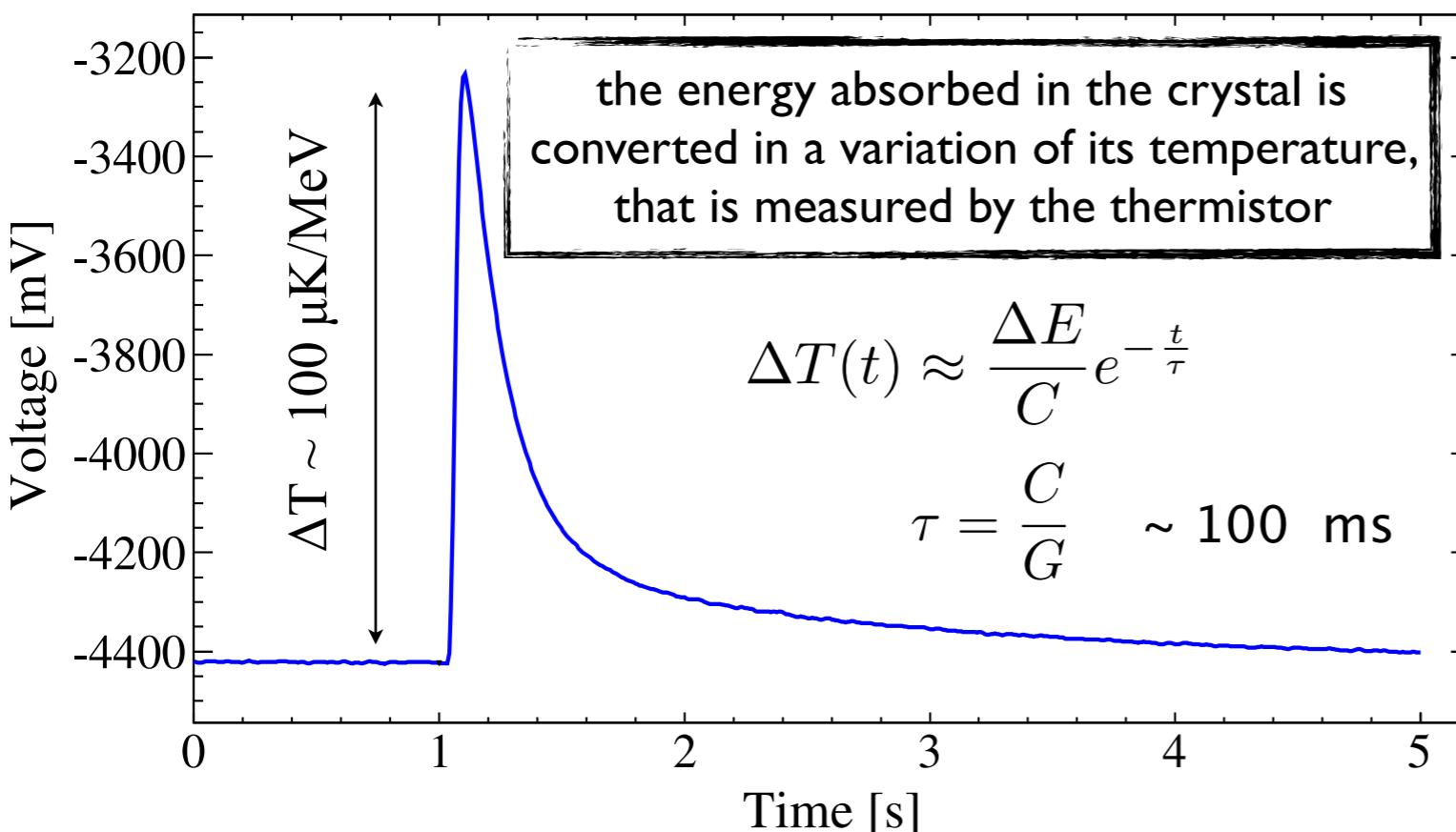
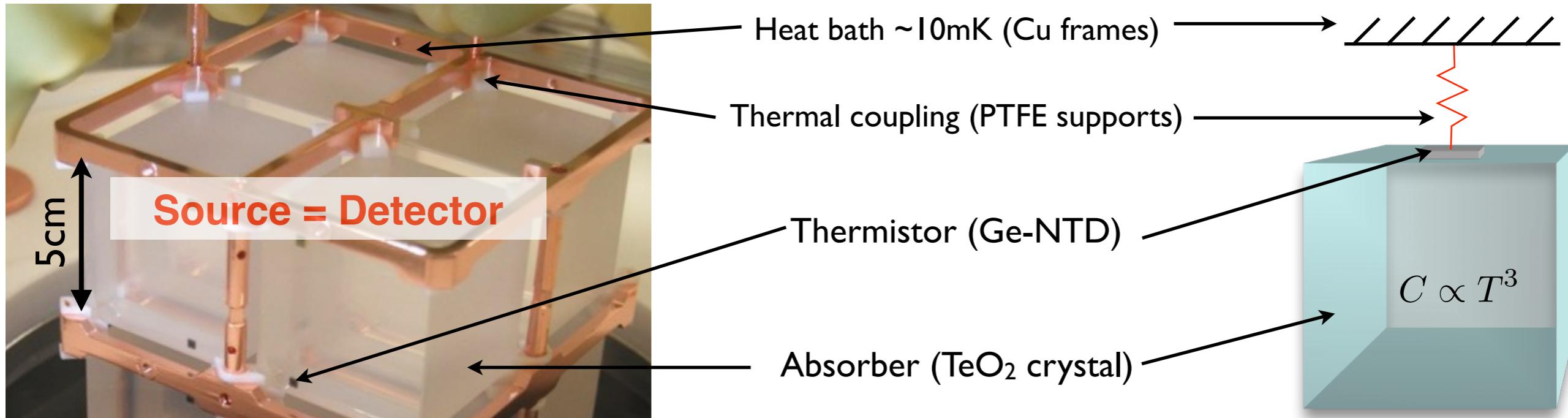
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**CUORE projected
sensitivity (5 years, 90% C.L.):**

$$T_{1/2} > 9.5 \times 10^{25} \text{ yr}$$

Large mass thermal detectors



Thermal detectors

- low heat capacity @ T_{work}
- excellent energy resolution (~0.2% FWHM)
- equal detector response for different particles
- slowness (suitable only for rare event searches)

The CUORE challenge

Cool down to 10mK a ~1ton detector in stable temperature conditions and extremely low background environment

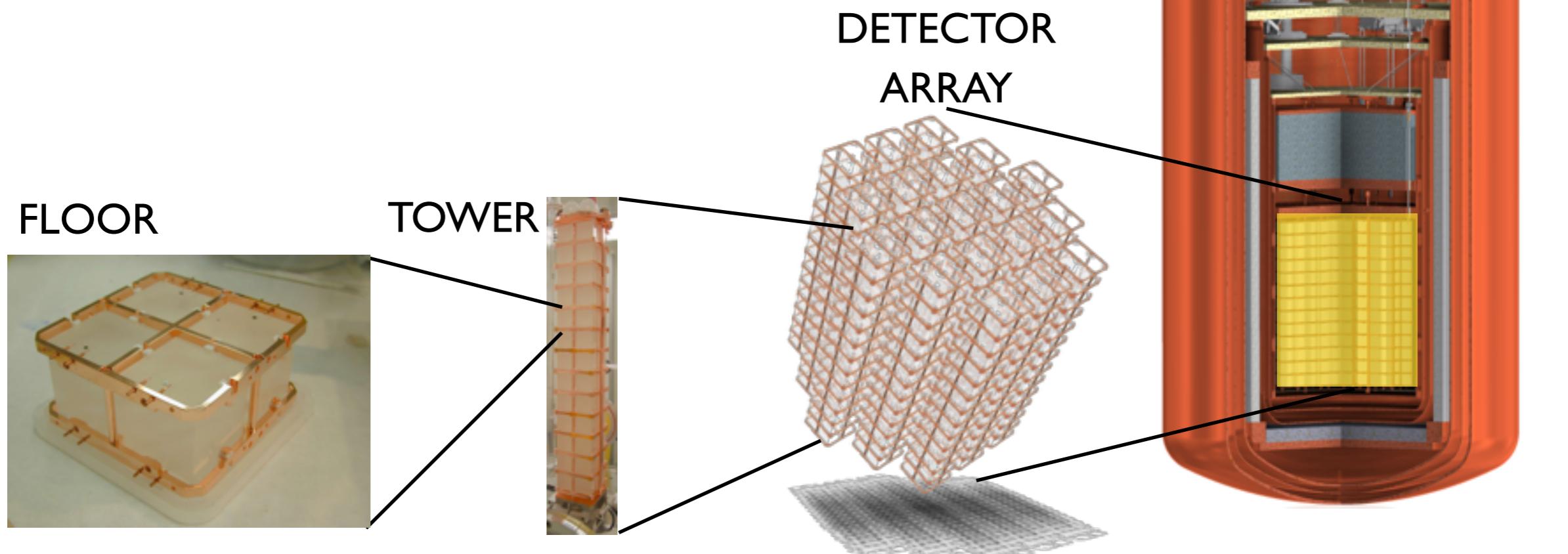


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Cool down to 10mK a ~1ton detector in stable temperature conditions and extremely low background environment

detector:

- Closely packed array of 988 TeO₂ crystals
- 19 towers of 52 crystals 5×5×5 cm³, 0.75 kg each



The CUORE challenge

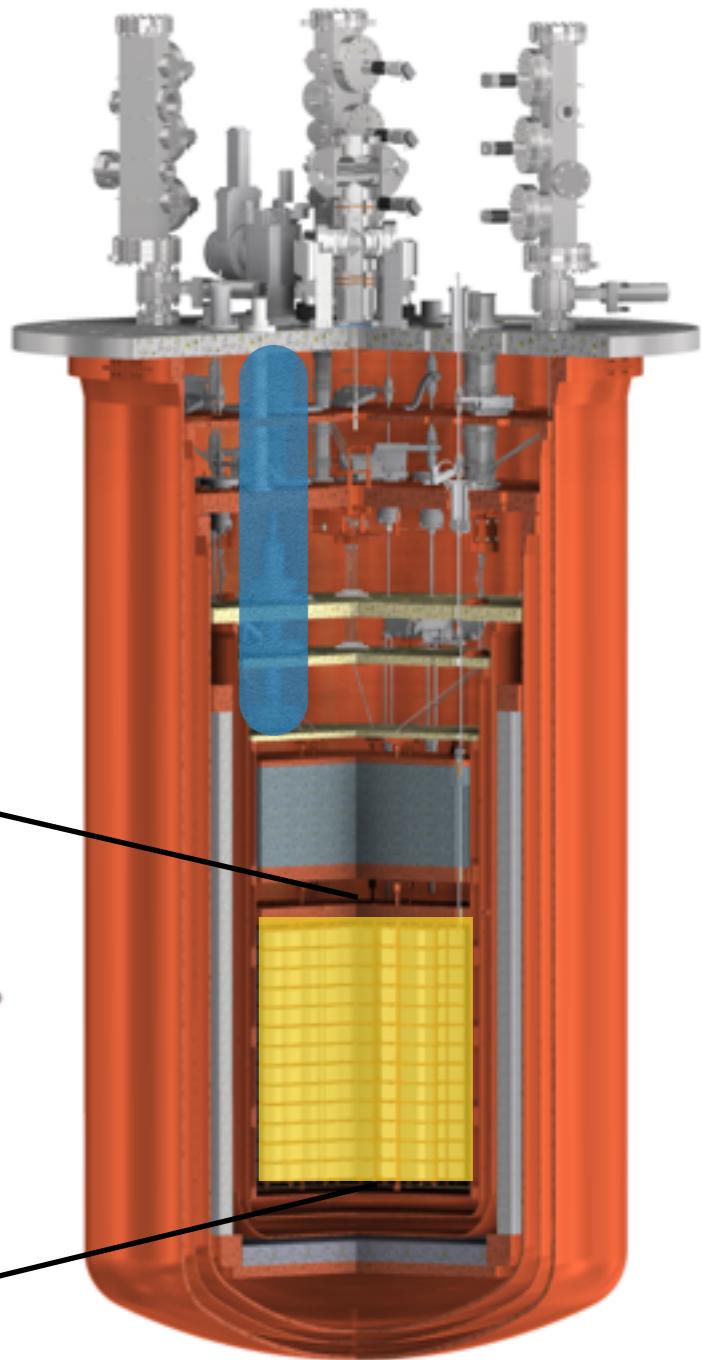
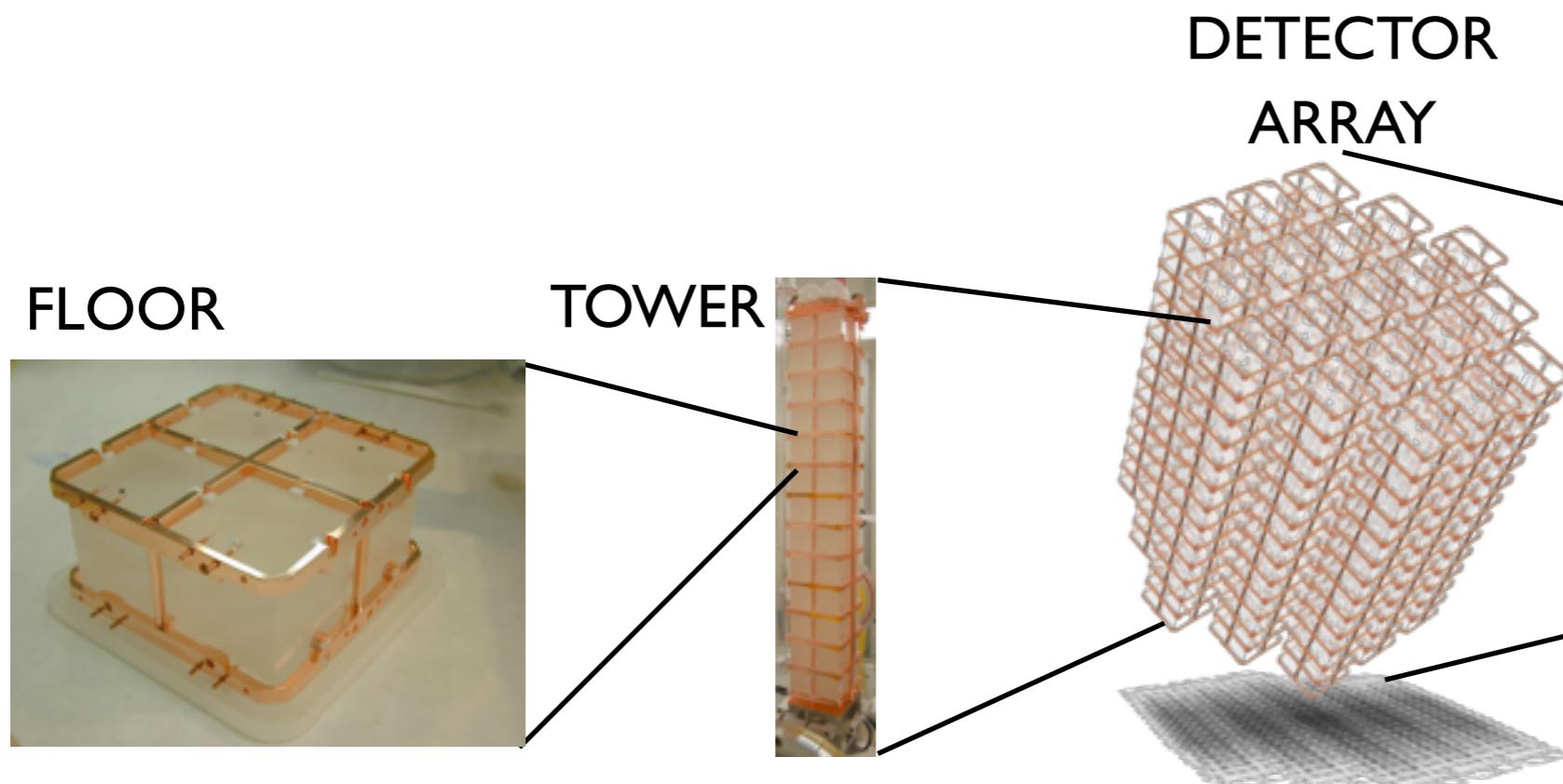
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cryogenics:

- Operating temperature $\sim 10\text{mK}$
- Cryostat total mass ~ 30 tons
- Mass to be cooled < 4 K: ~ 15 tons



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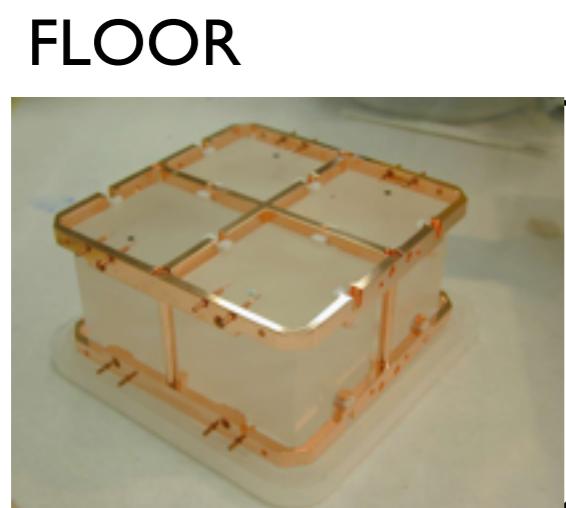
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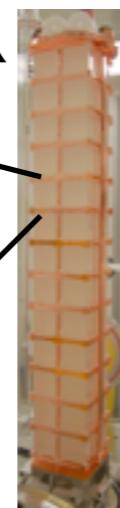
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lead shields:

- top modern lead (~ 2 tons)

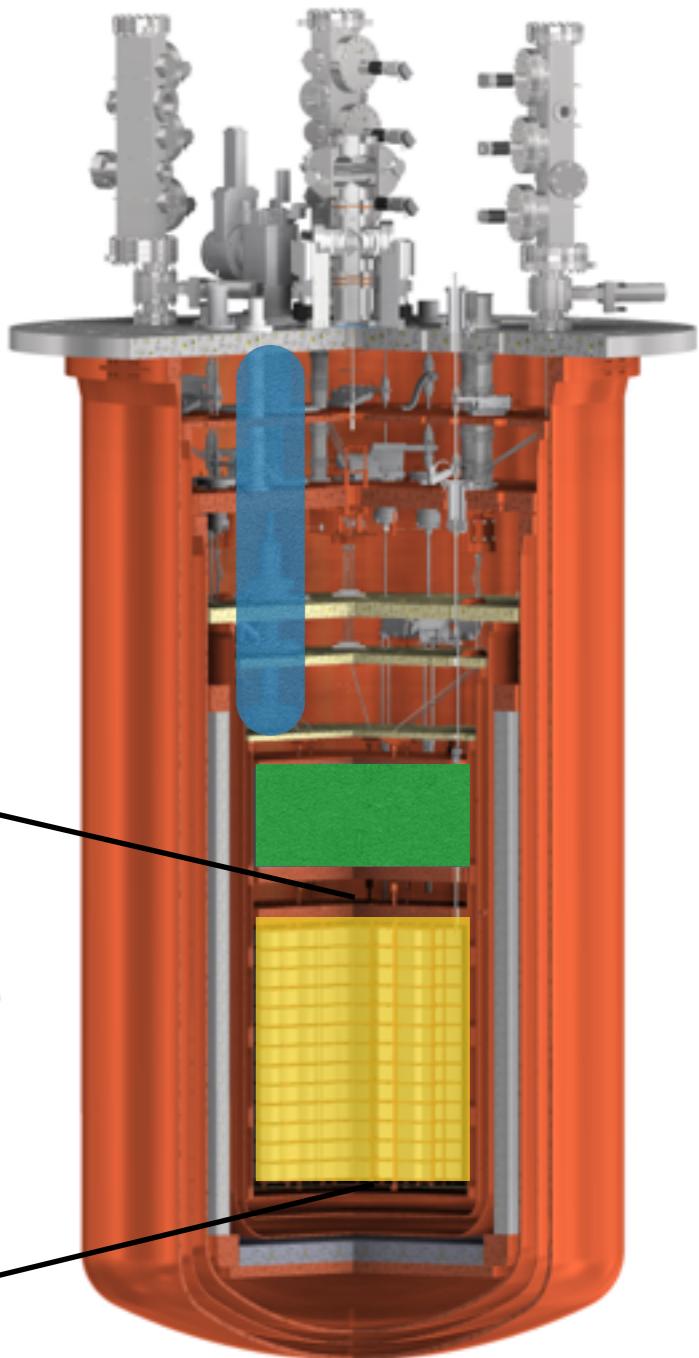
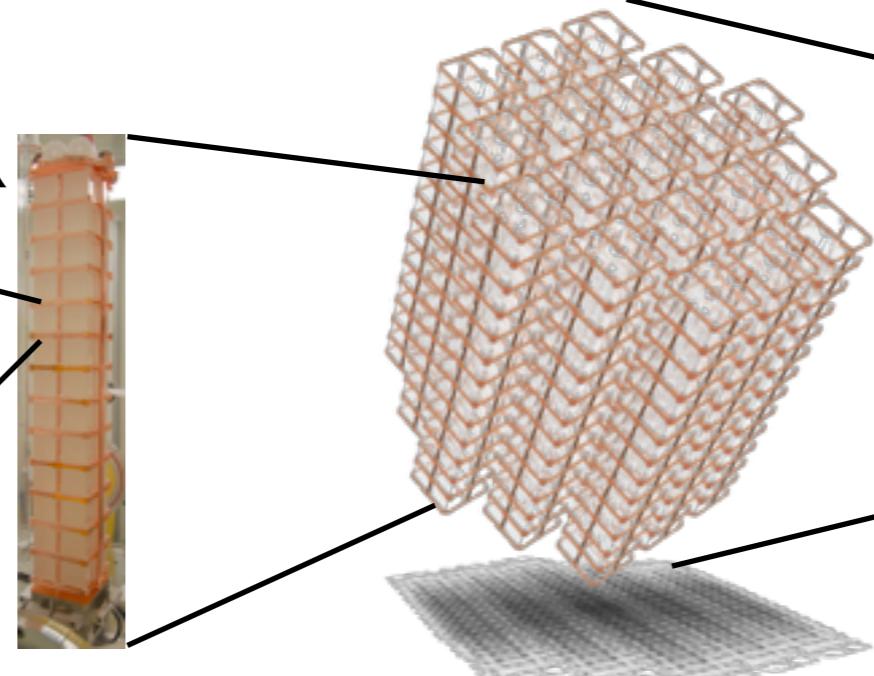


TOWER



FLOOR

DETECTOR
ARRAY



The CUORE challenge

Cool down to 10mK a ~1ton detector in stable temperature conditions and extremely low background environment

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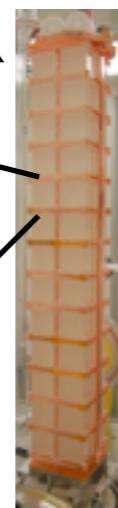
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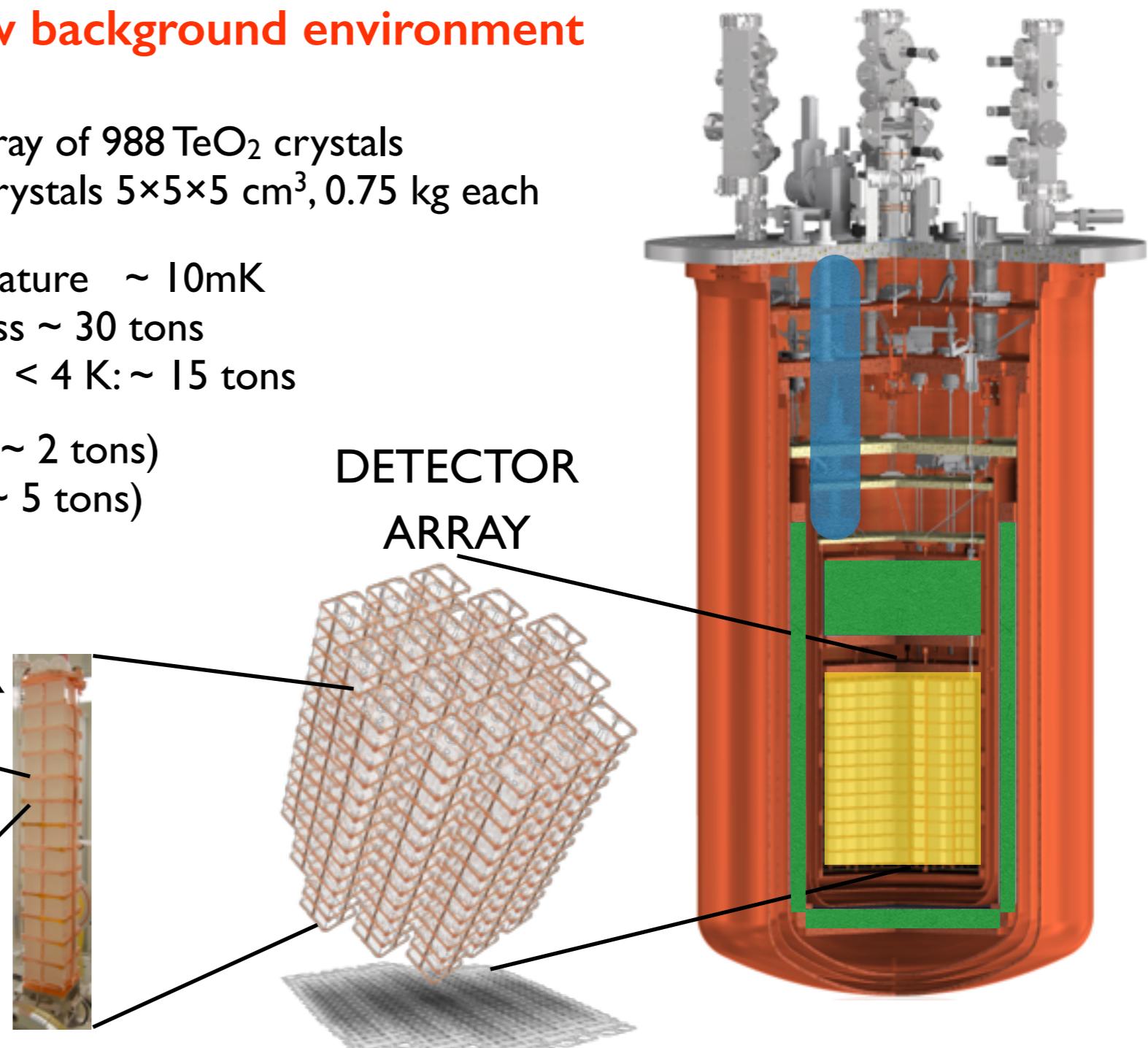


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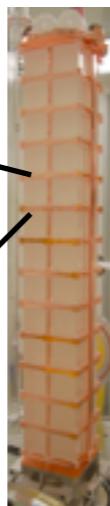
- Operating temperature ~ 10mK
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- side roman lead (~ 5 tons)
- room temperature lead (~ 70 tons)

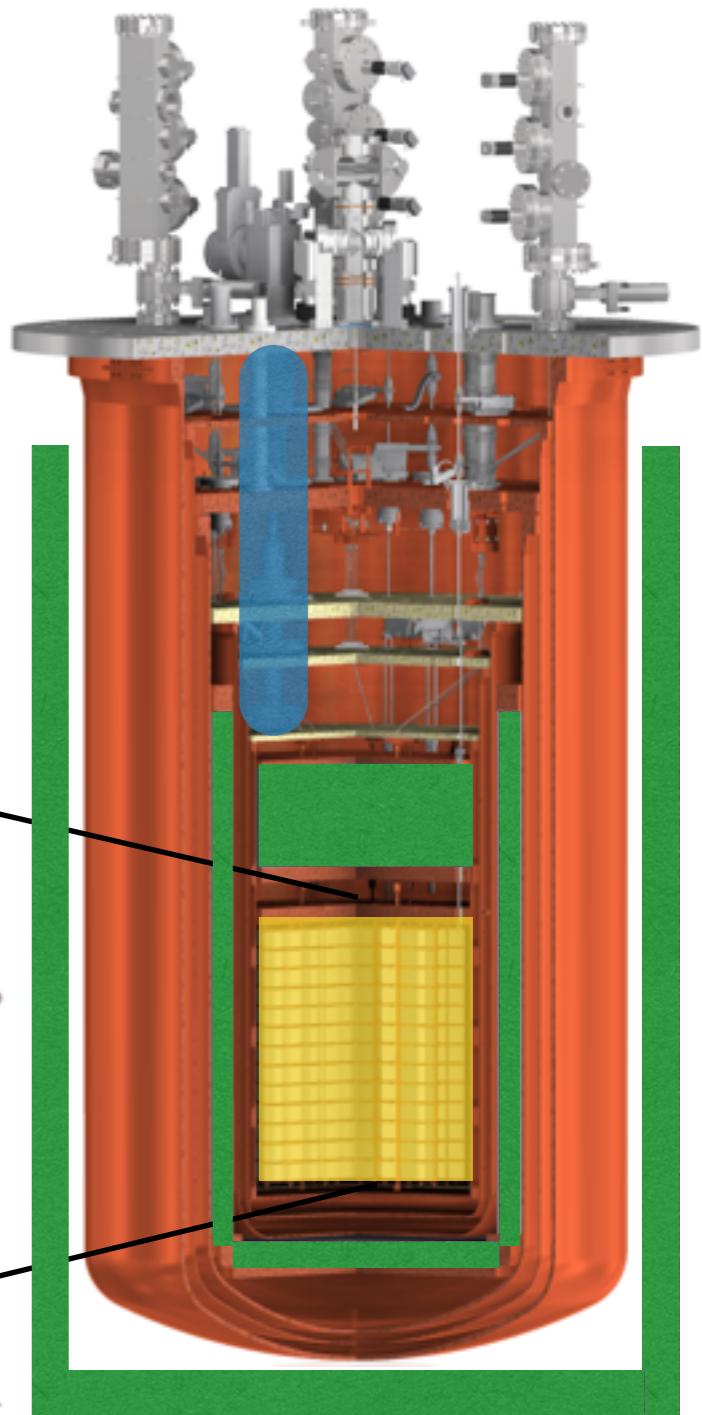
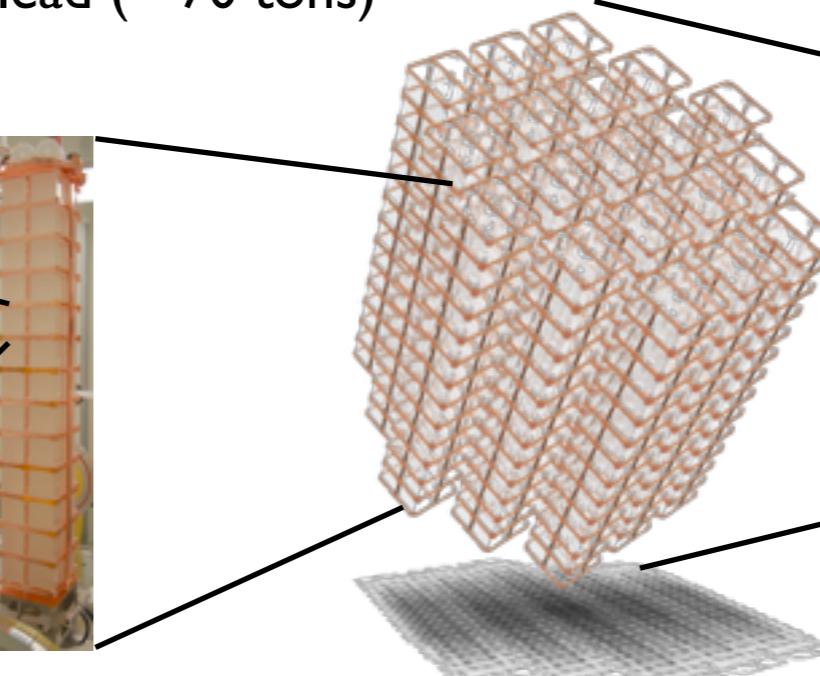


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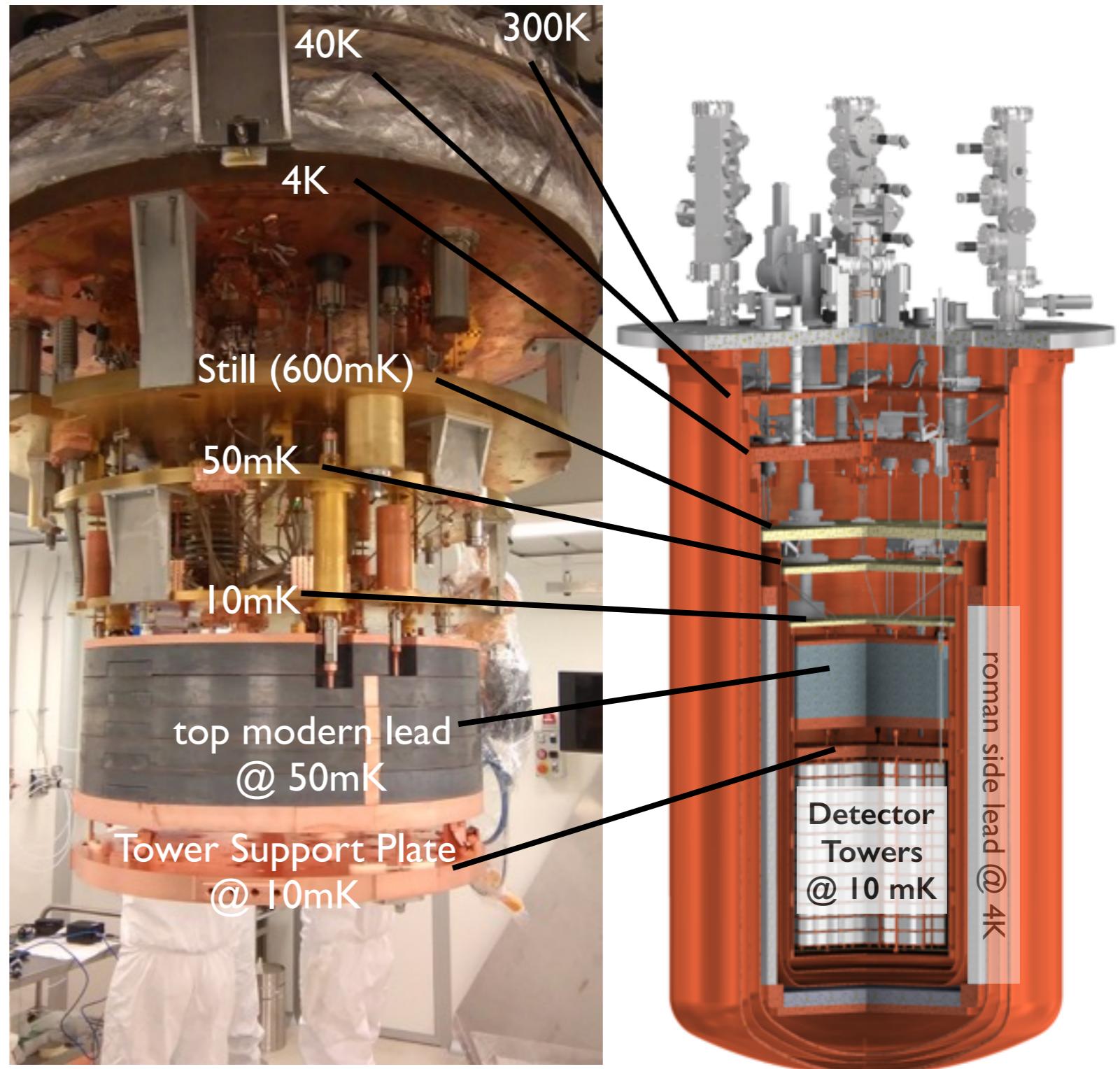
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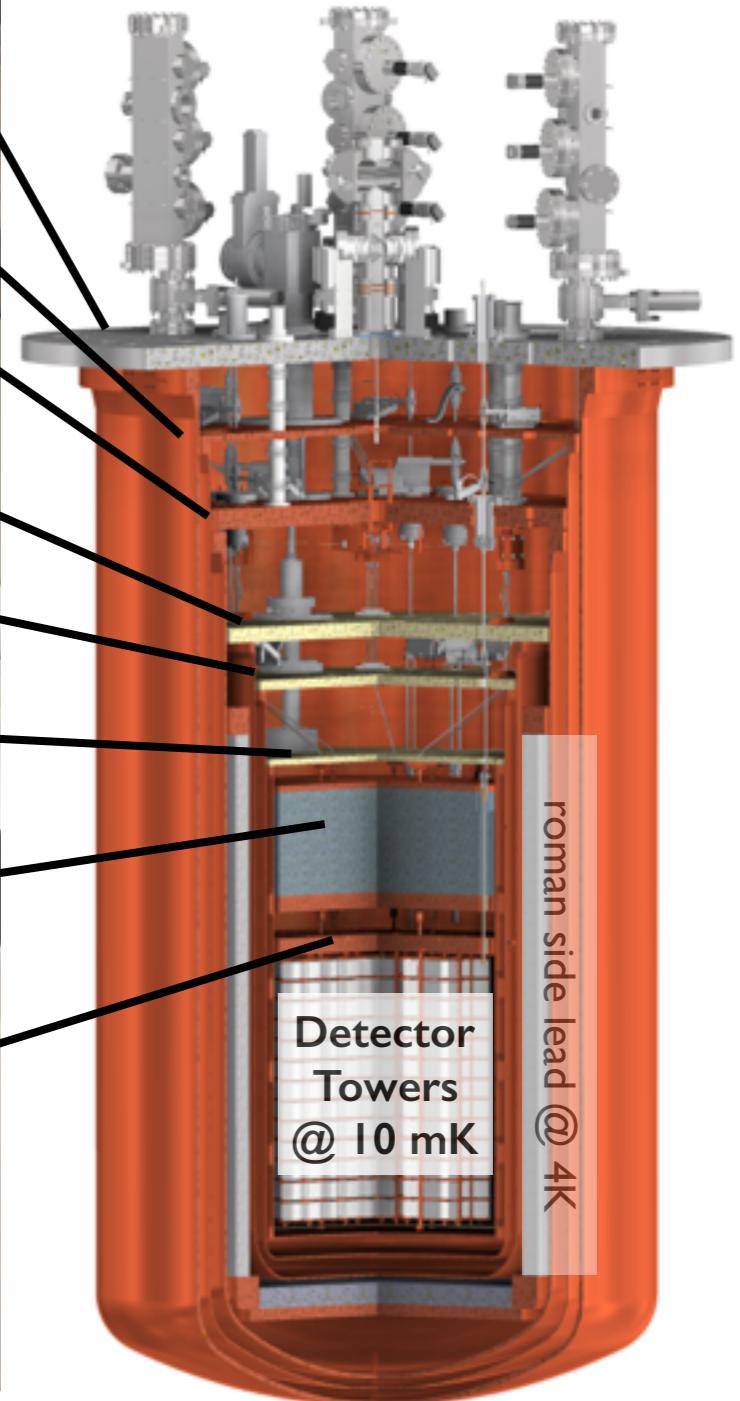
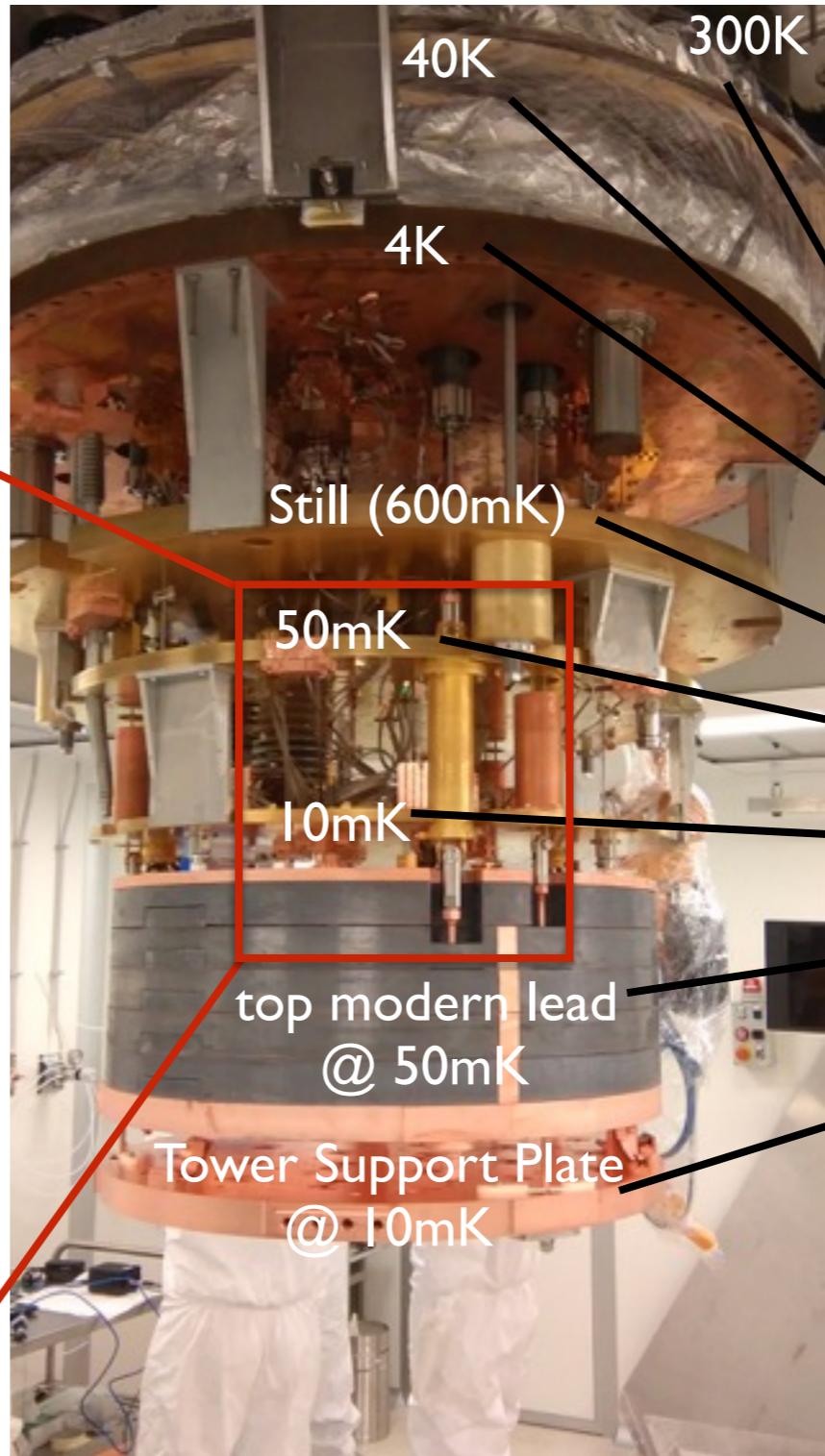
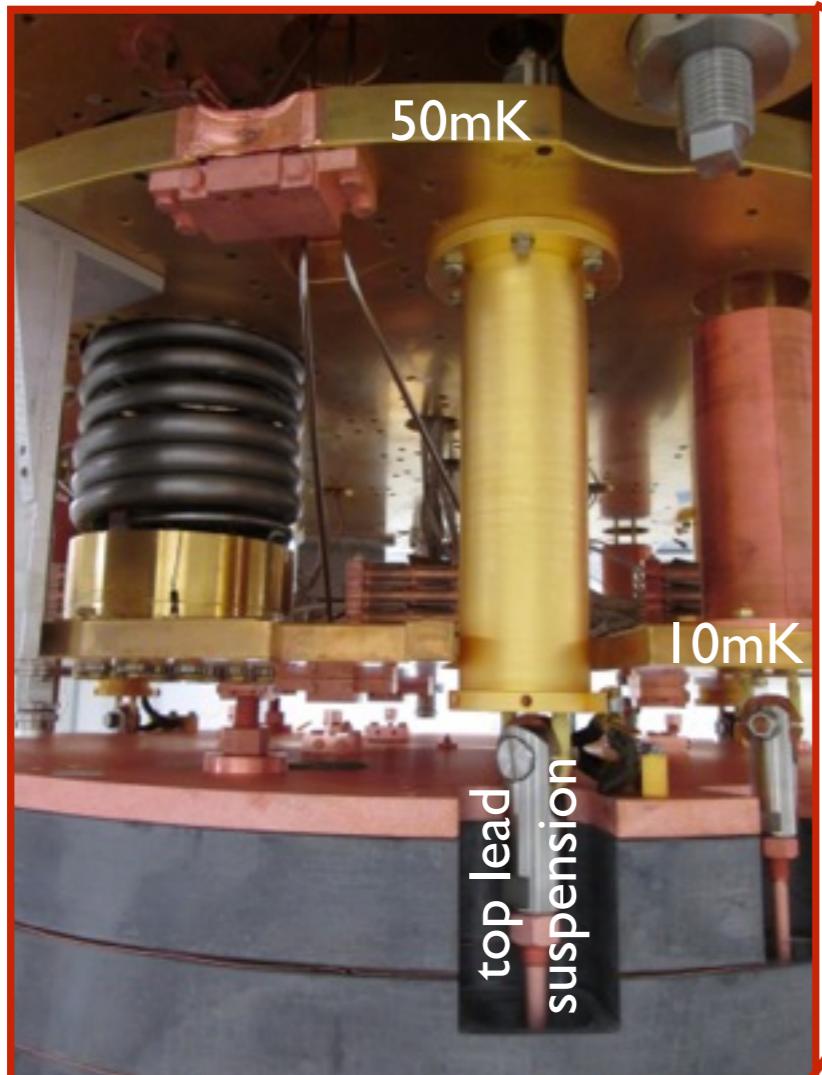
The CUORE cryostat

- Fast Cooling System (^4He vapour) down to $\sim 50\text{K}$
- 5 Pulse Tubes cryocooler down to $\sim 4\text{K}$
- Dilution refrigerator down to operating temperature $\sim 10\text{mK}$
- Nominal cooling power: $3 \mu\text{W}@10\text{mK}$



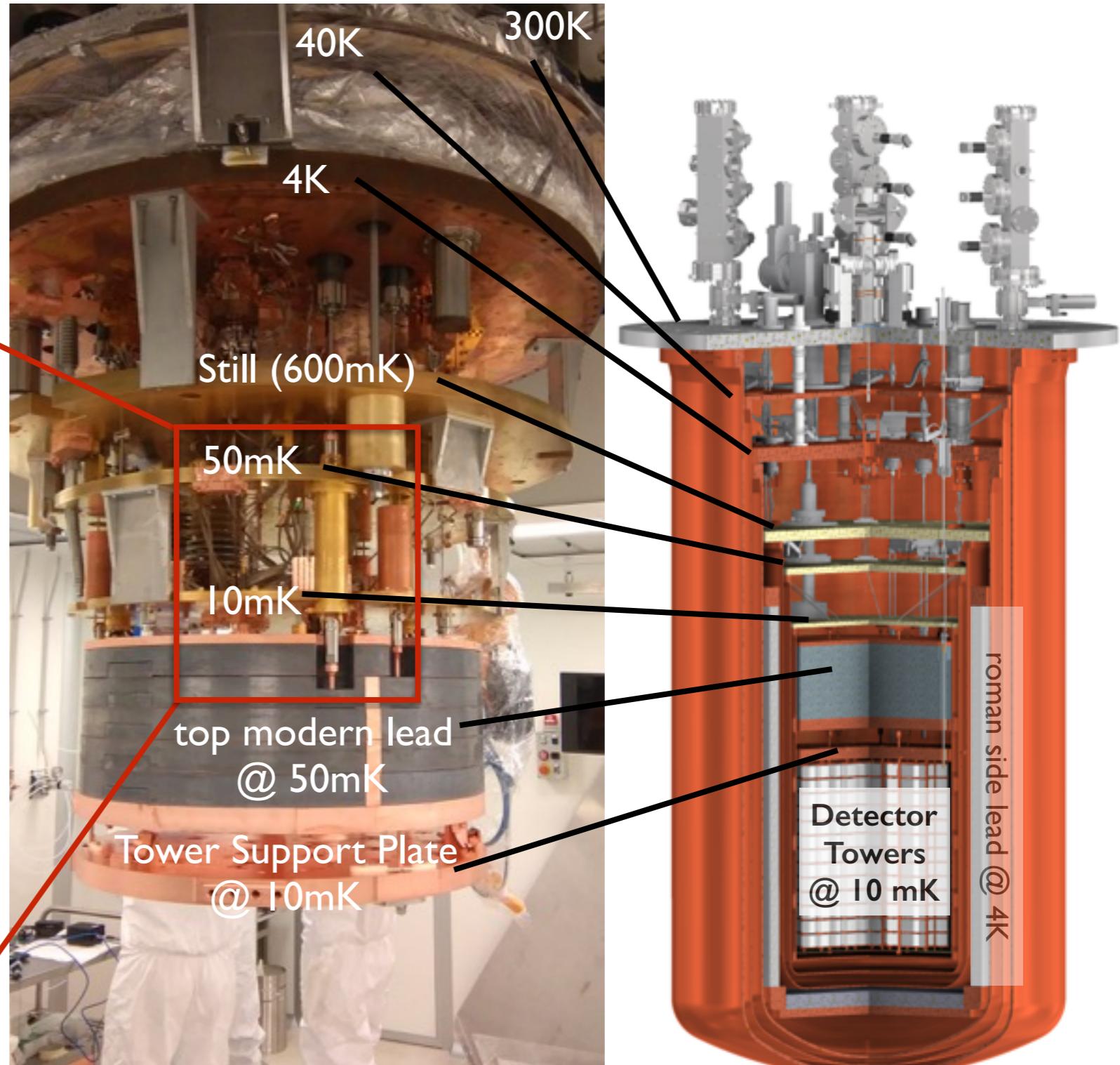
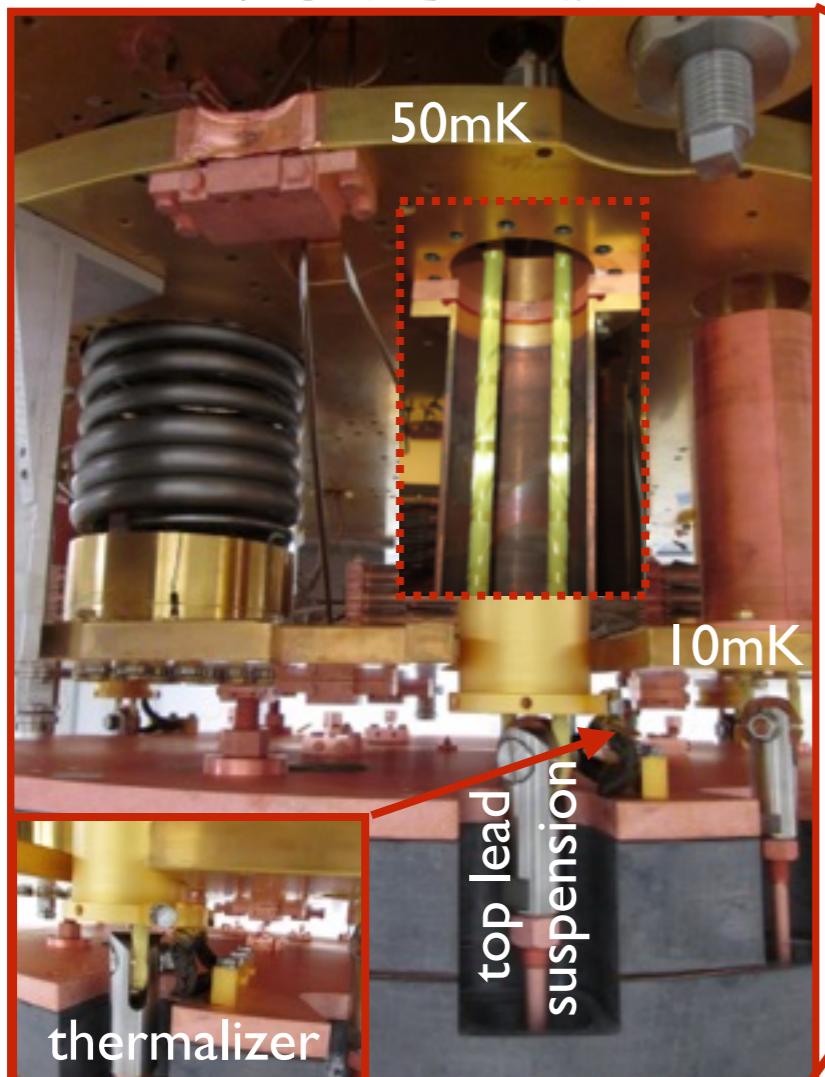
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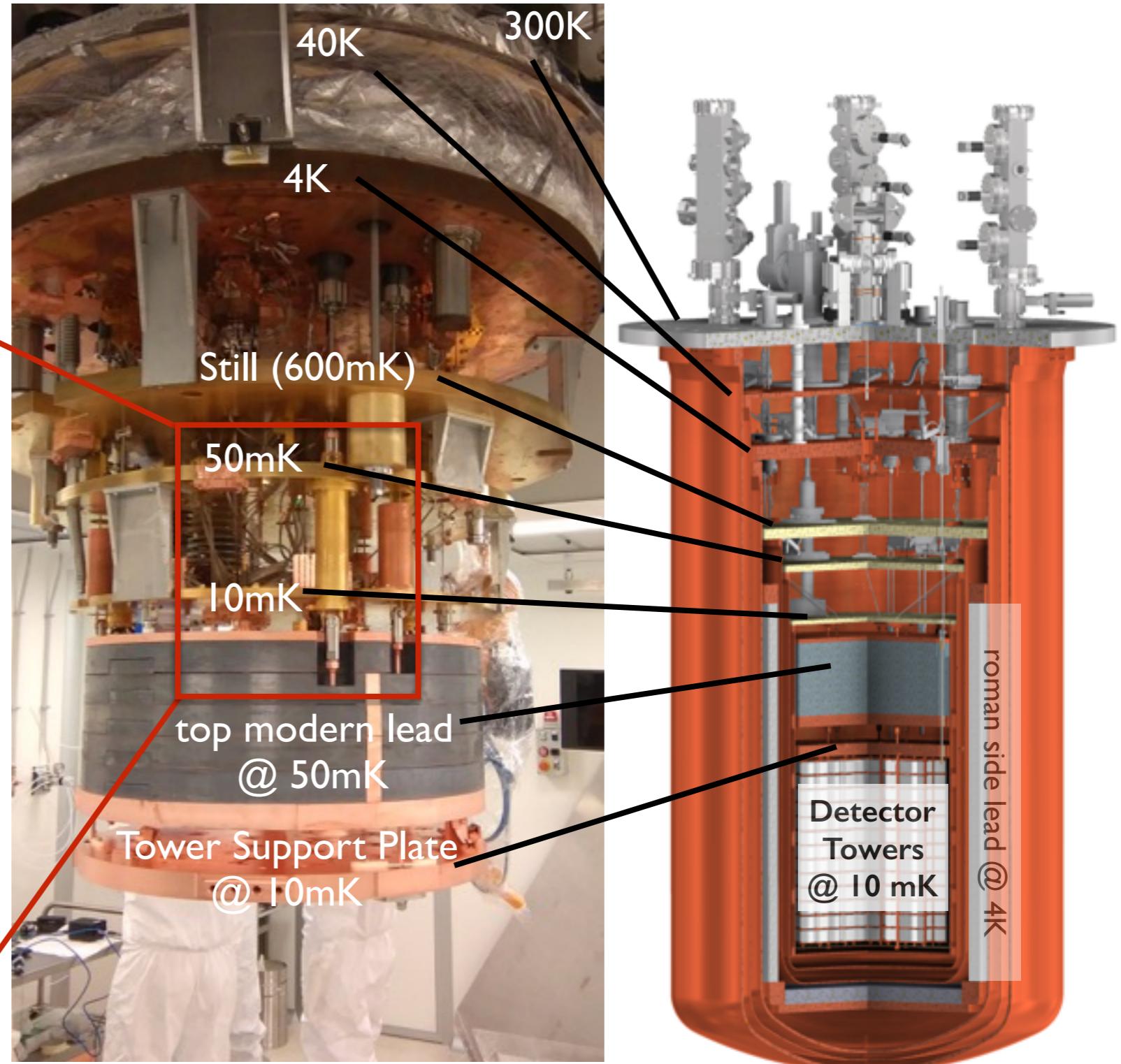
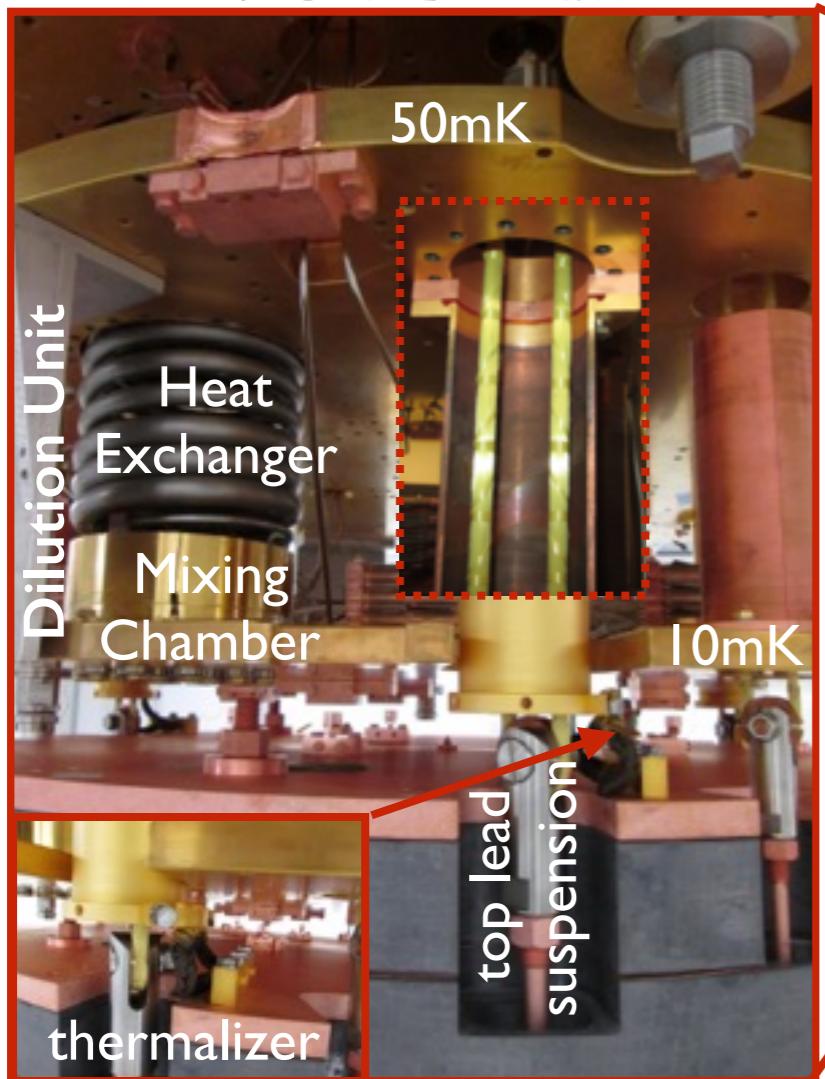
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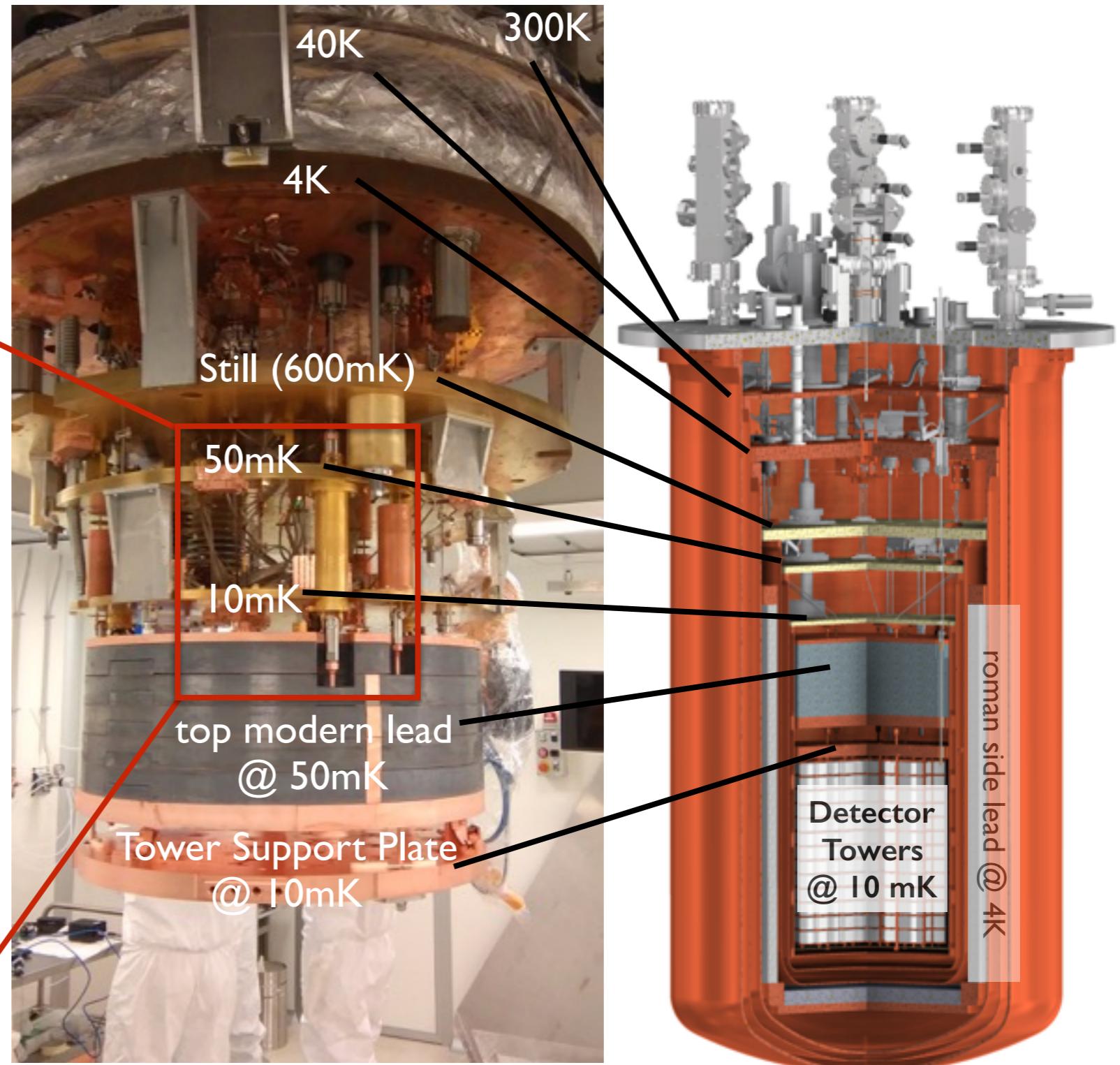
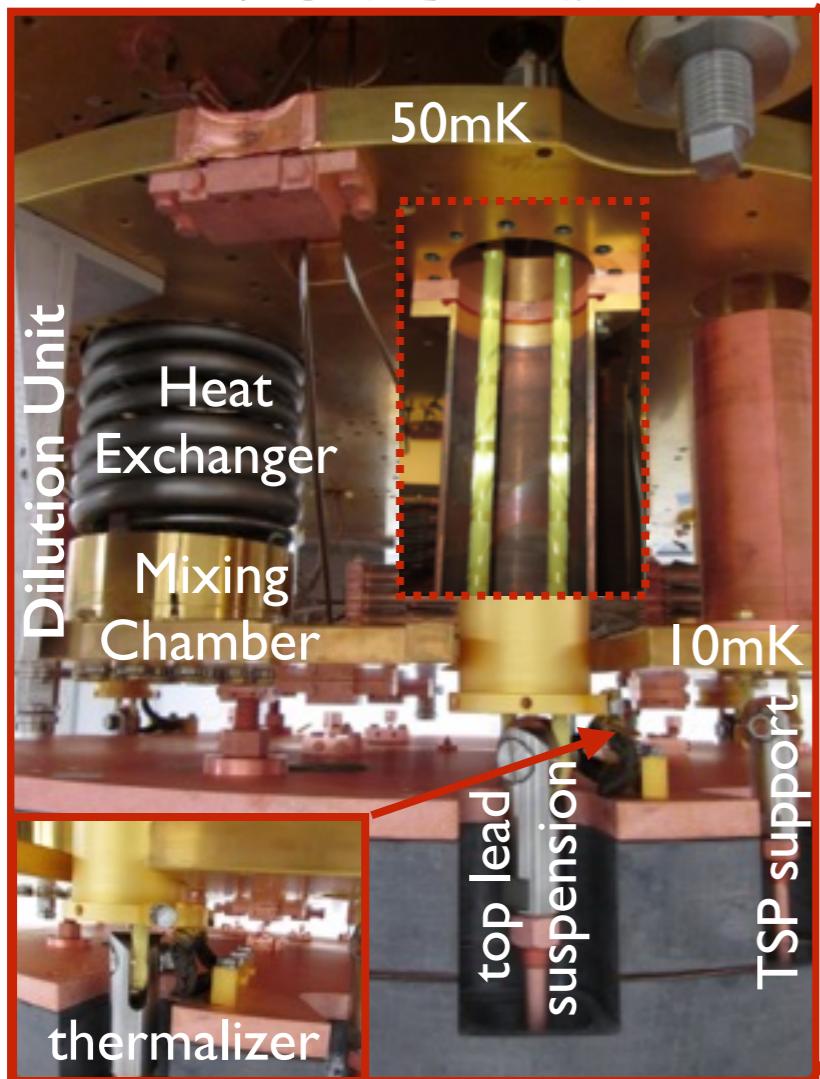
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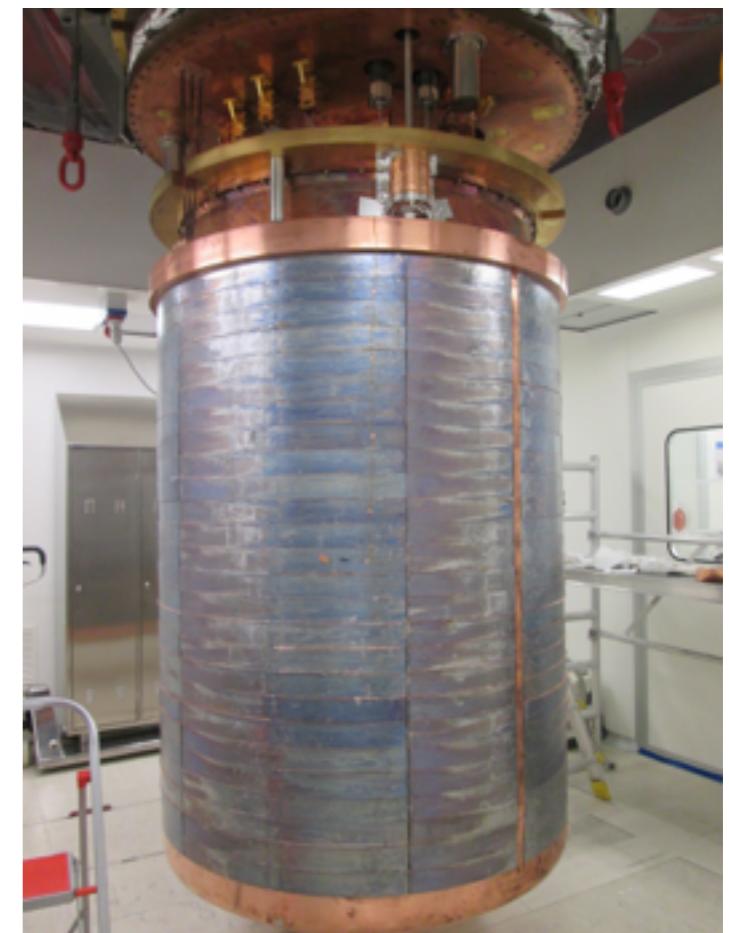


The CUORE cold lead shields



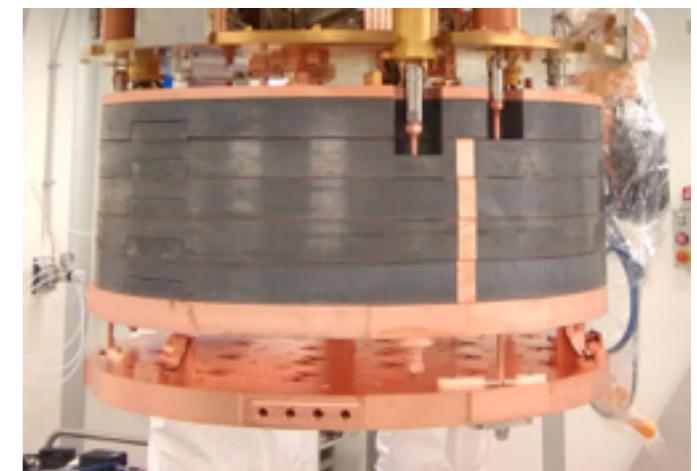
**Ancient (I sec B.C.) roman lead:
~5 tons @ 4K**

- Ingots found in sunk roman ship
- Custom ingots cast in summer 2015
- Shield assembled in Oct/Nov 2015
 - Side shield (6cm thick)
- First cooldown in early 2016



**Modern lead:
~2 tons @ 50mK**

- Top shield suspended by 3 kevlar ropes
- 5 disks 6 cm thickness each



The CUORE-0 detector



CUORE-0: first CUORE-like tower produced

- Proof of concept of CUORE detector
- Validation of the CUORE tower **assembly line**
- Validation of the CUORE **cleaning** procedure
- Test of the CUORE **DAQ** and analysis framework

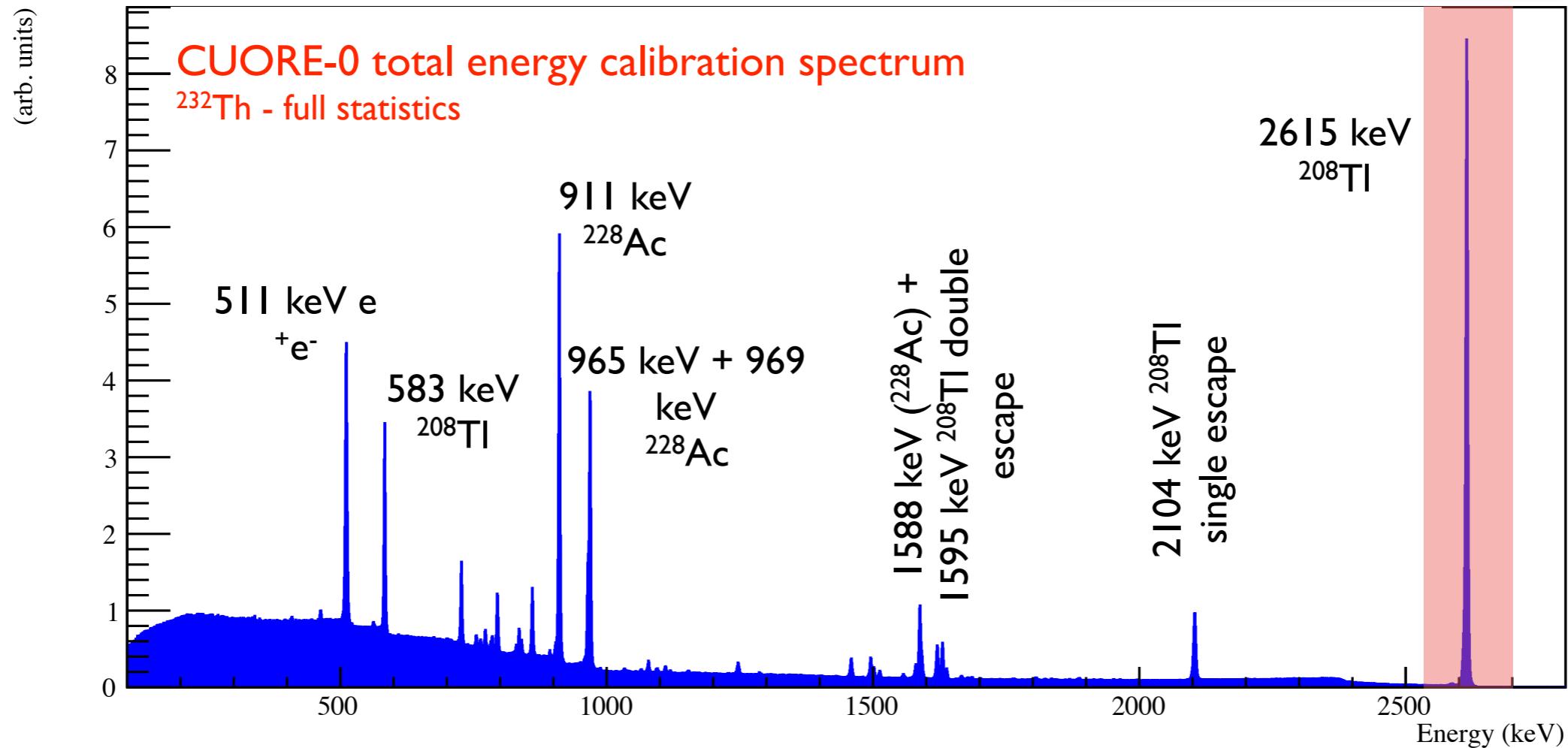
Data taking from March 2013 to March 2015:

- Total collected exposure: $9.8 \text{ kg} \cdot \text{yr}$ of ^{130}Te
- Validation of CUORE detector performance
- Sensitive $0\nu\beta\beta$ experiment

CUORE-0 resolution

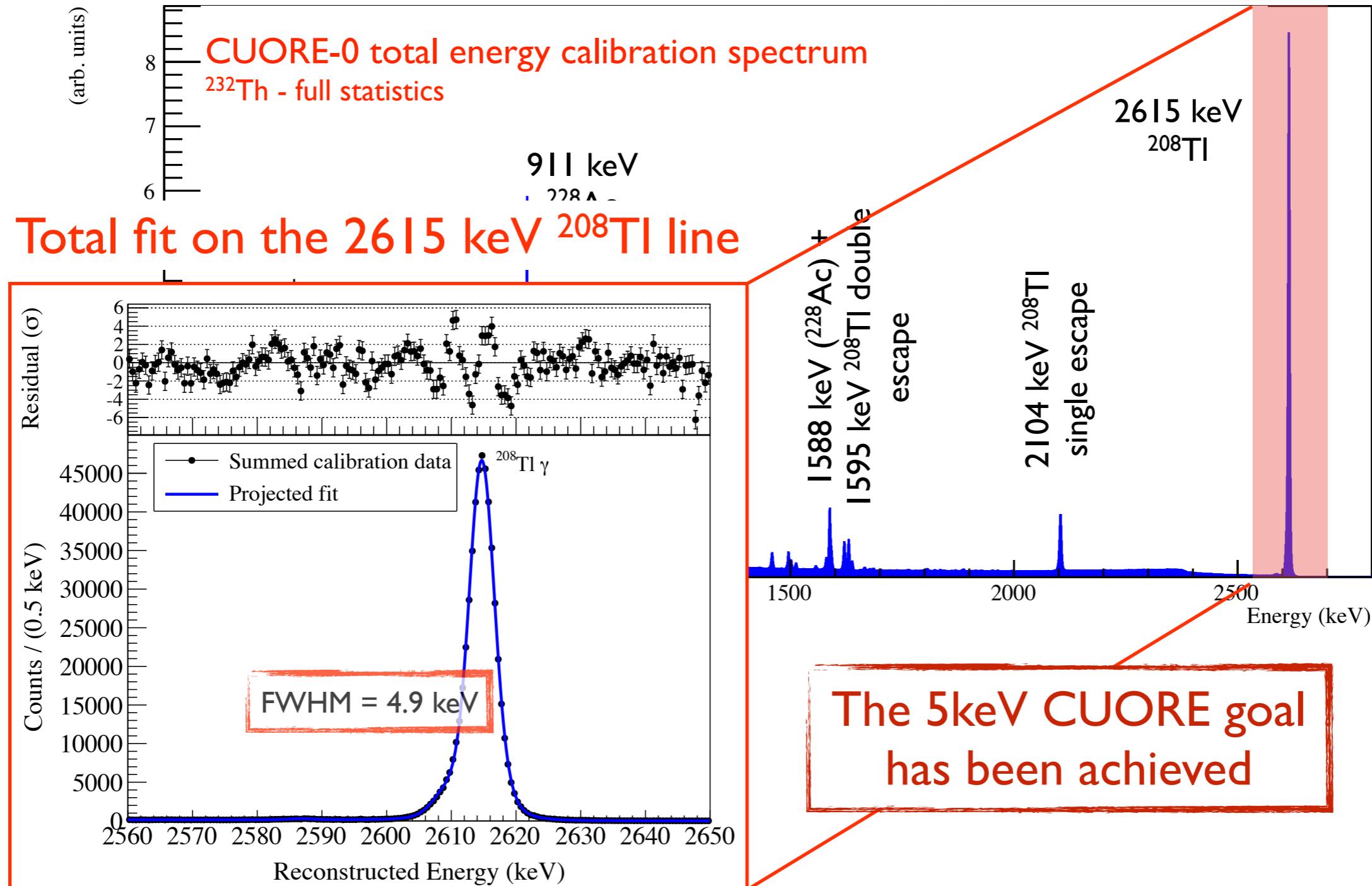


Phys.Rev.Lett. 115, 102502 (2015)



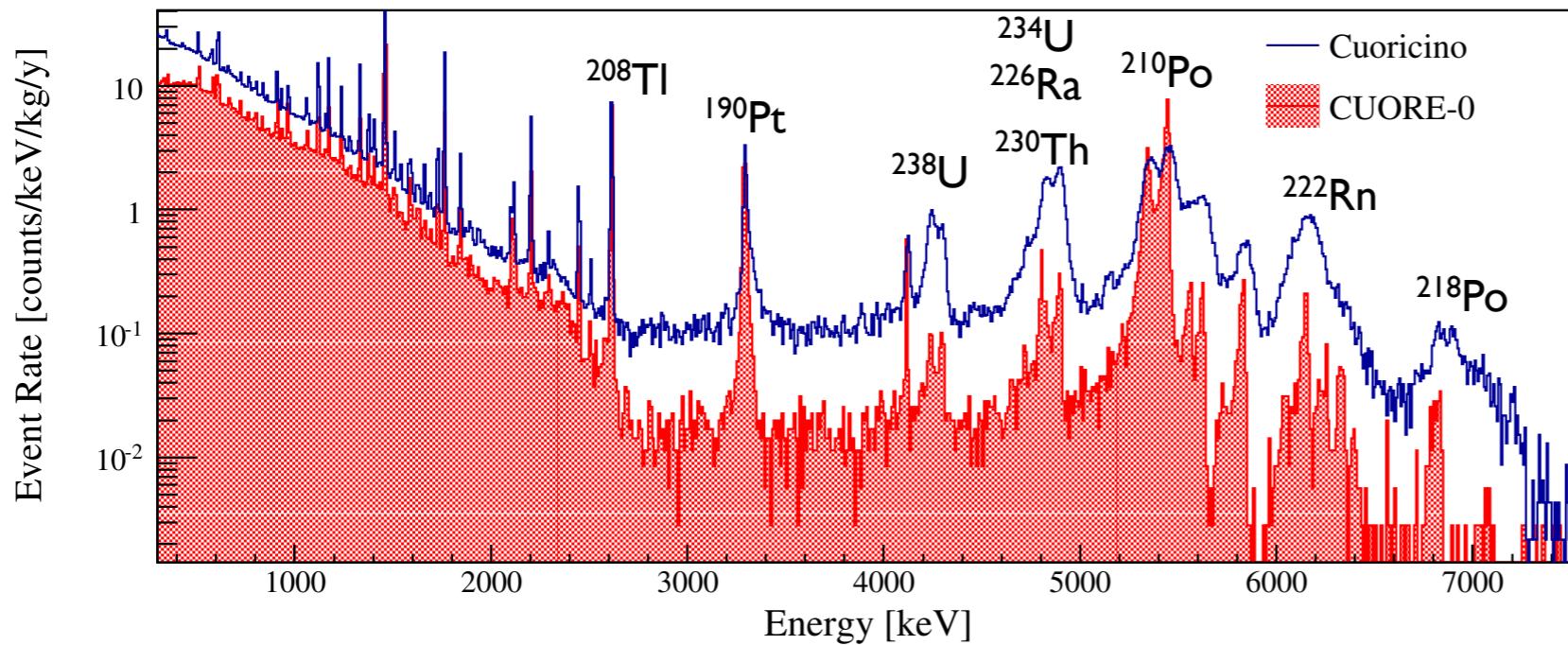
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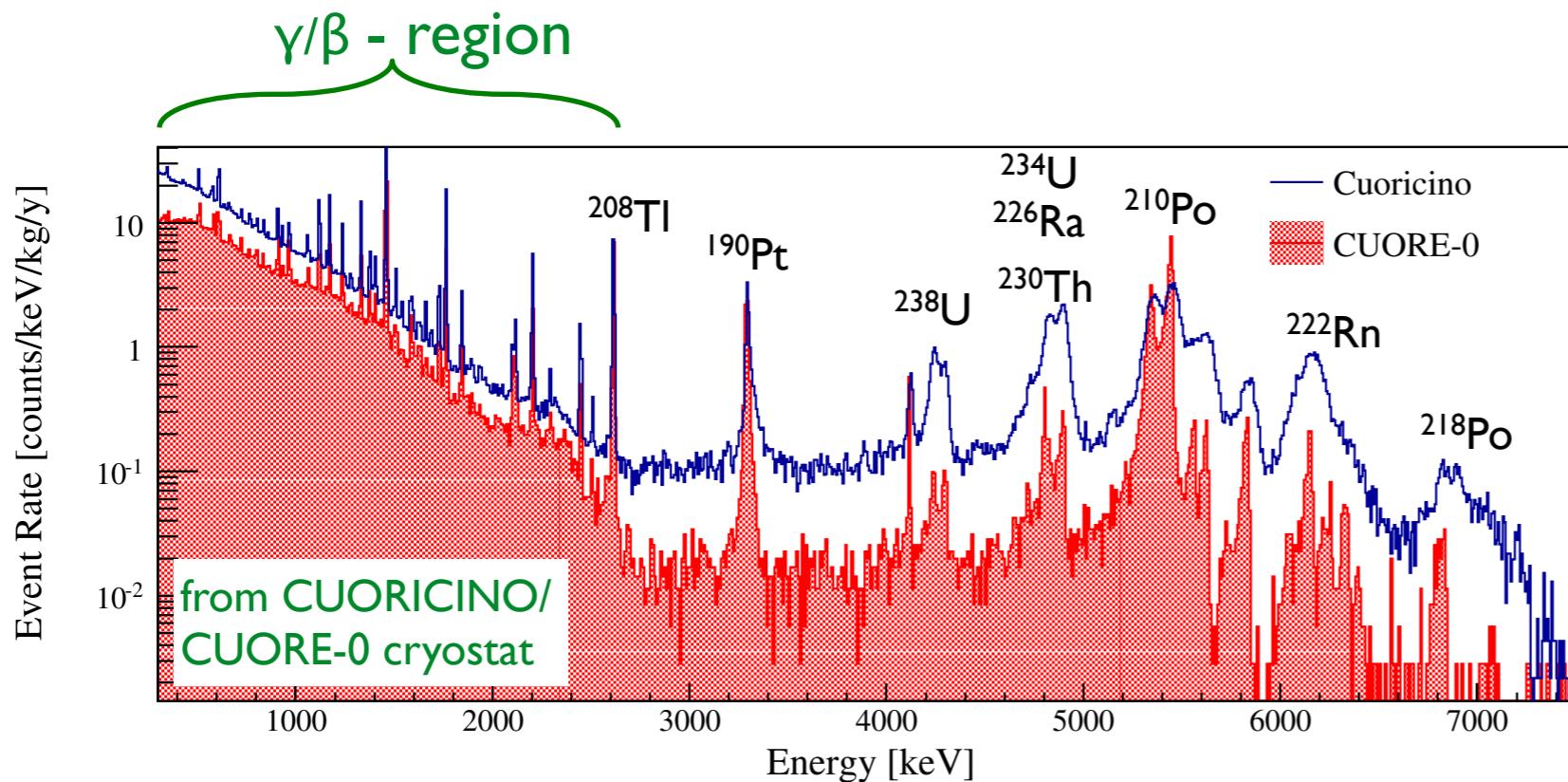
CUORE-0 background

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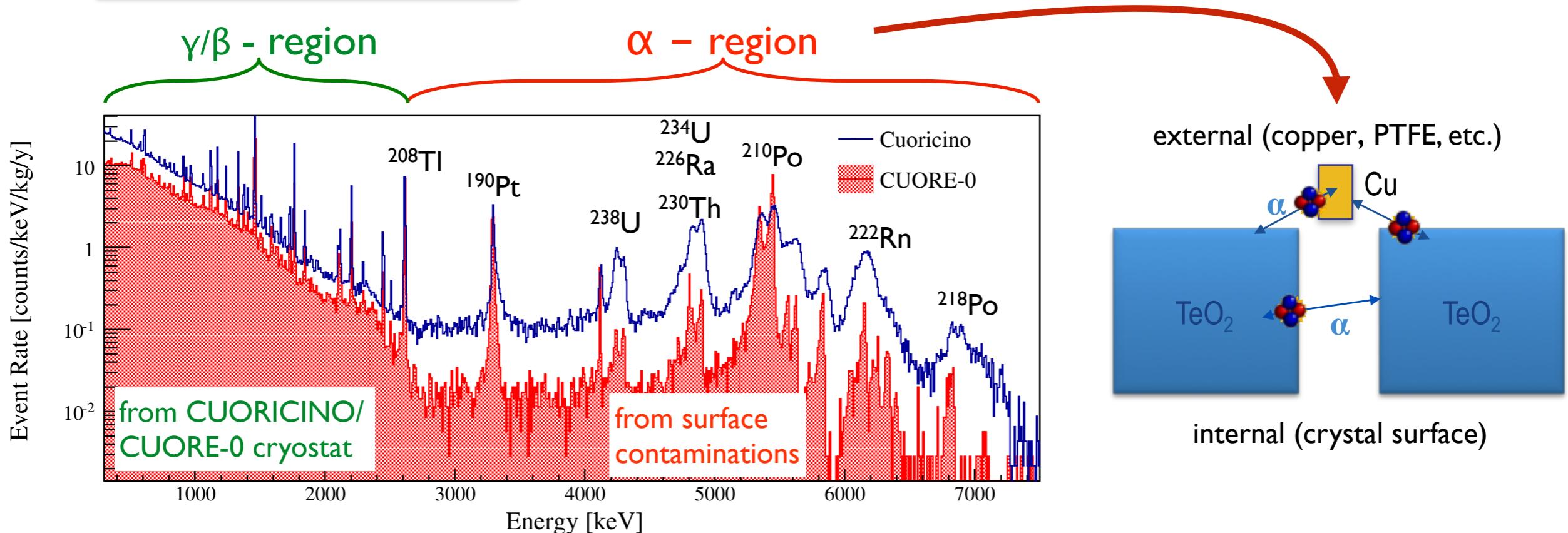
CUORE-0 background

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



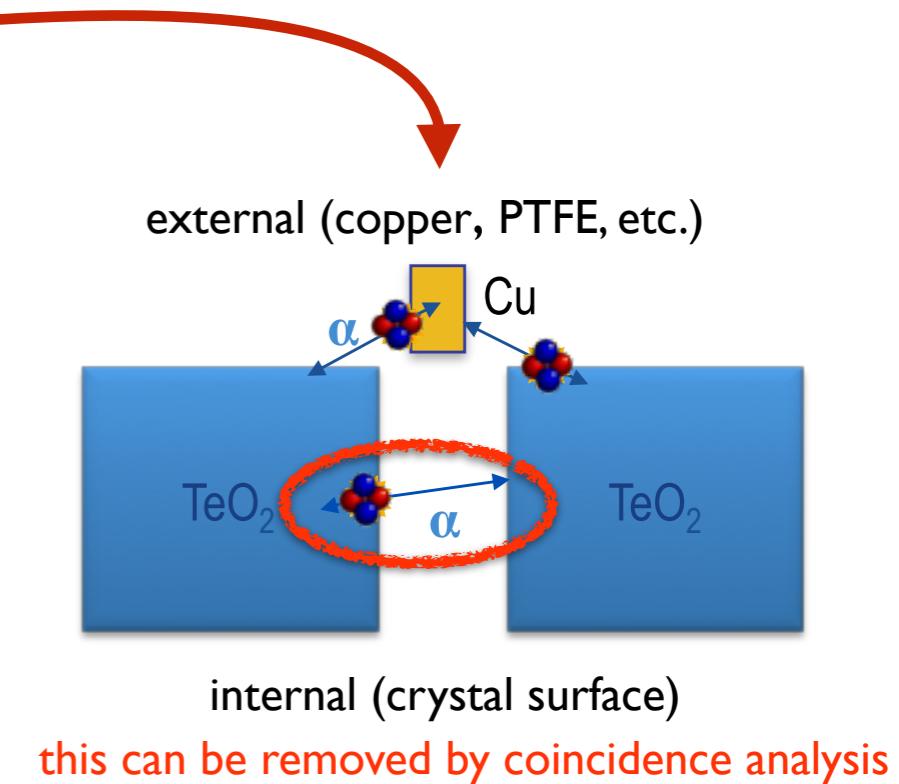
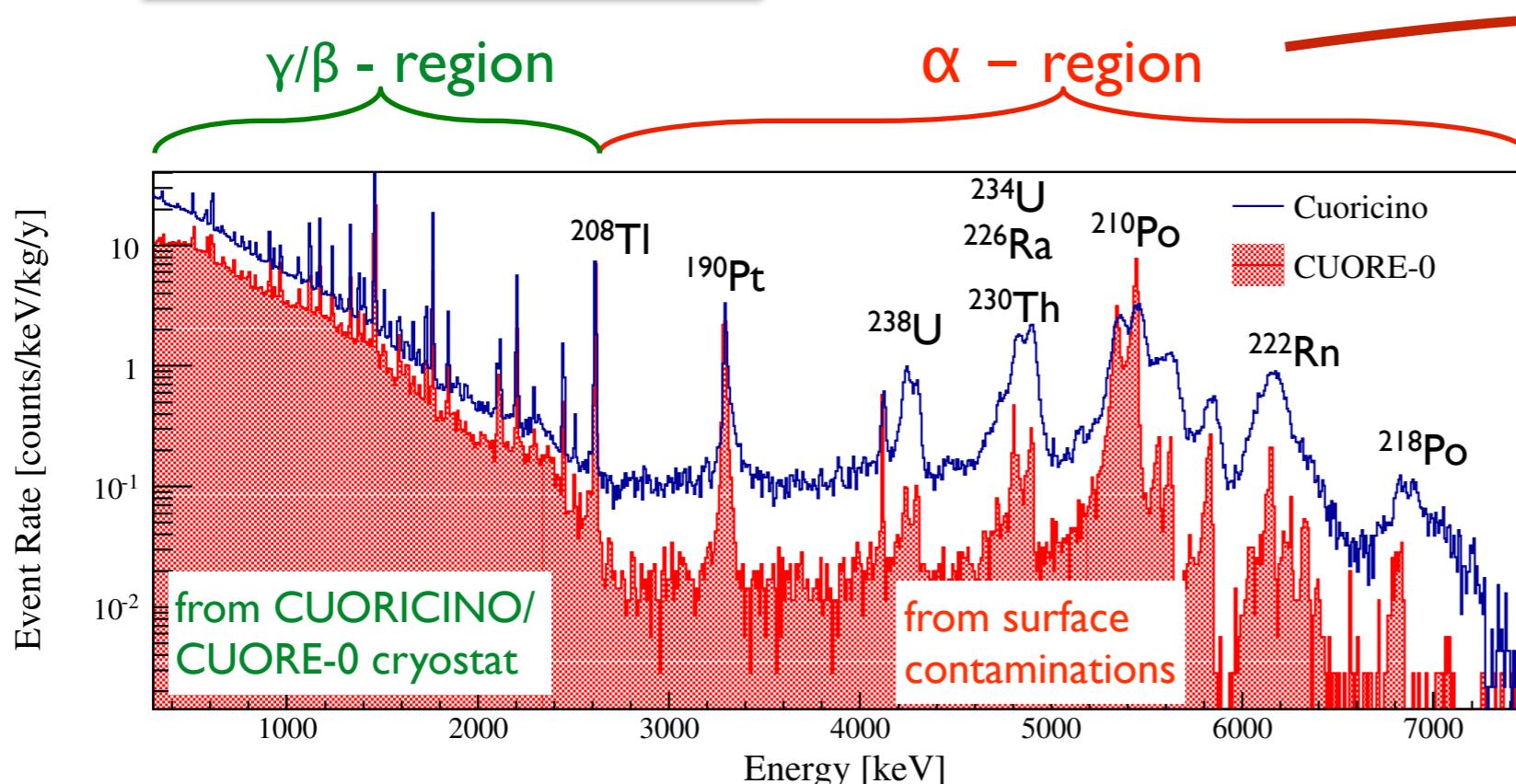
CUORE-0 background

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



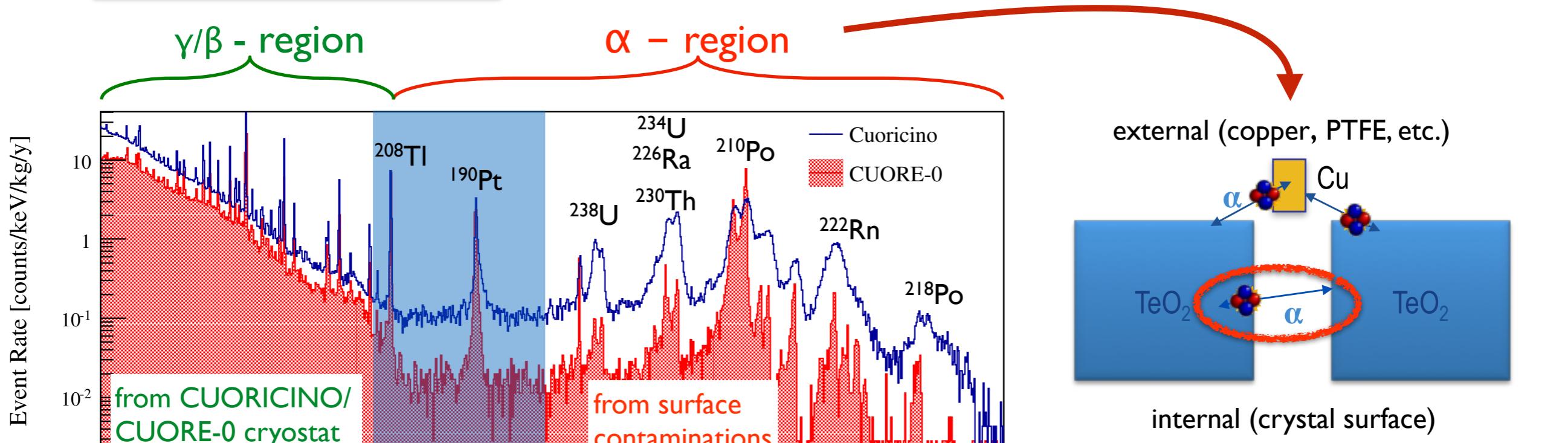
CUORE-0 background

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



CUORE-0 background

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



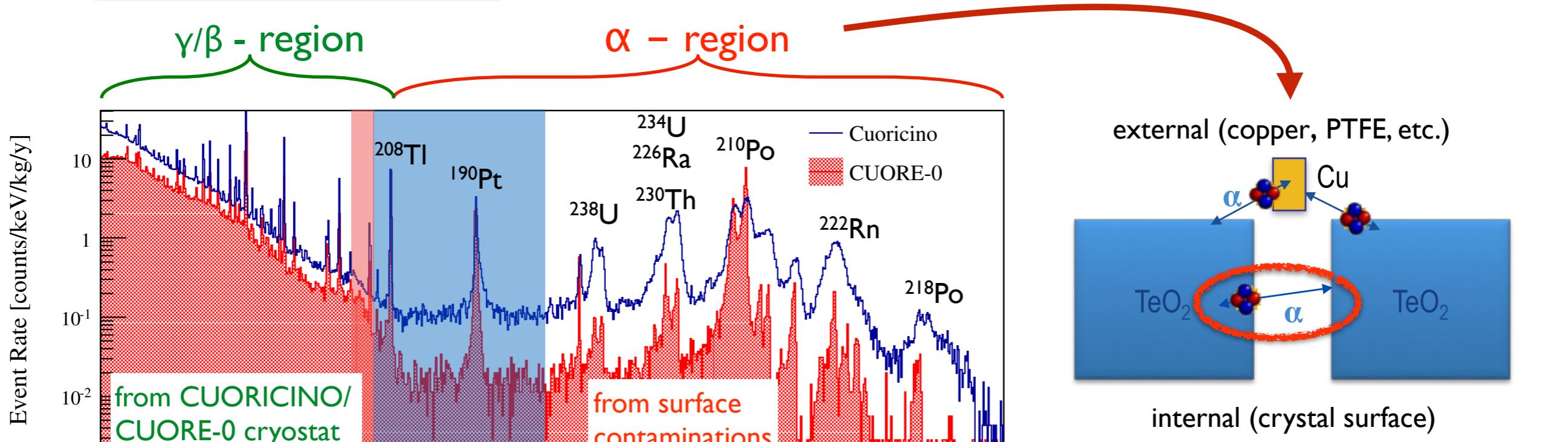
| | 2.7-3.9 MeV [c/keV/kg/y] | ROI [c/keV/kg/y] |
|-----------|-----------------------------|---------------------|
| Cuoricino | 0.110 ± 0.001 | 0.169 ± 0.006 |
| CUORE-0 | 0.016 ± 0.001 | 0.058 ± 0.004 |

Background reduction thanks to CUORE-0 cleaning procedure:

- factor ~ 7 in the α -continuum region

CUORE-0 background

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



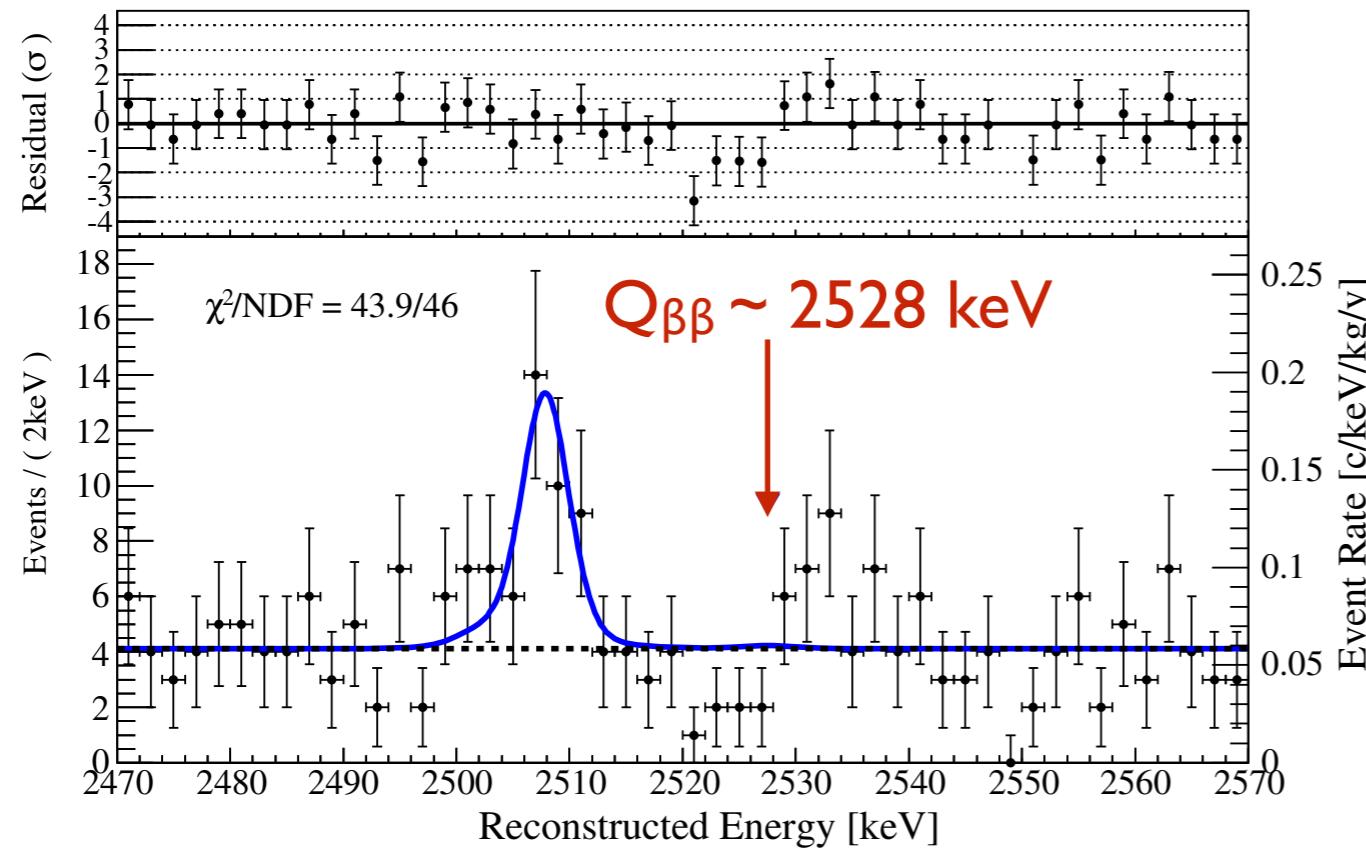
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Background reduction thanks to CUORE-0 cleaning procedure:

- factor ~ 7 in the α -continuum region
- factor ~ 2.5 in the ROI

CUORE-0 0νββ results

Region Of Interest (2470-2570 keV)



CUORE-0 0νββ limit

(Bayesian 90% C.L.):

$$T_{1/2} (0\nu) > 2.7 \times 10^{24} \text{ yr}$$

CUORINO + CUORE-0

0νββ limit (Bayesian 90% C.L.):

$$T_{1/2} (0\nu) > 4.0 \times 10^{24} \text{ yr}$$

Best Fit Background index:

$$0.058 \pm 0.004 \text{ (stat.)} \pm 0.002 \text{ (syst.) c keV}^{-1} \text{ kg}^{-1} \text{ yr}^{-1}$$

Best Fit Decay Rate:

$$\Gamma^{0\nu} (^{130}\text{Te}) = 0.01 \pm 0.12 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \times 10^{-24} \text{ yr}^{-1}$$

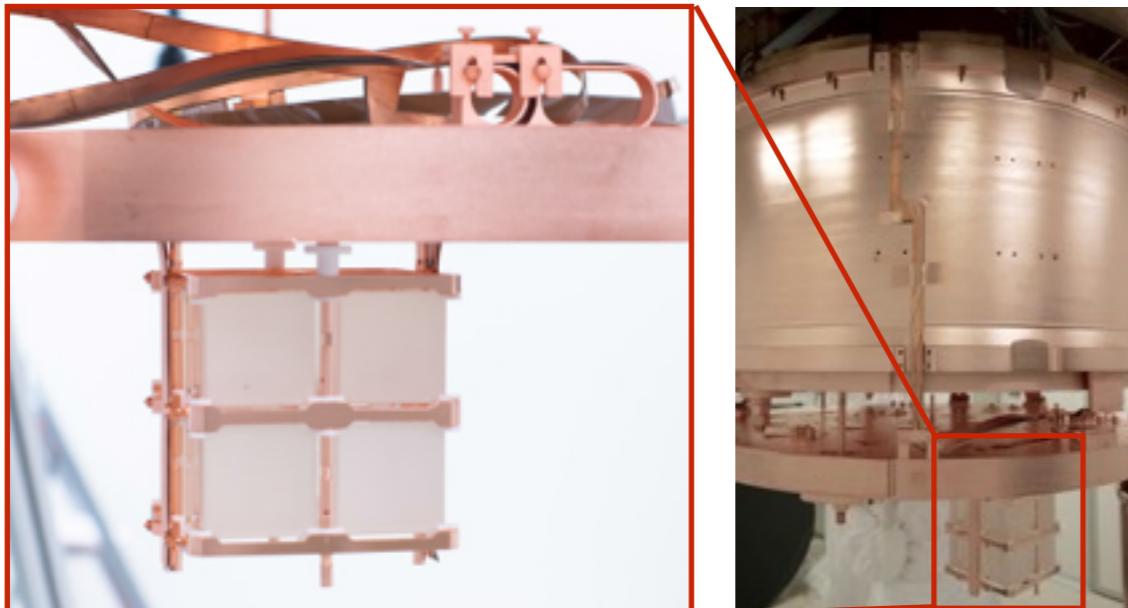
$$m_{\beta\beta} < 270 - 650 \text{ meV}$$

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

CUORE commissioning

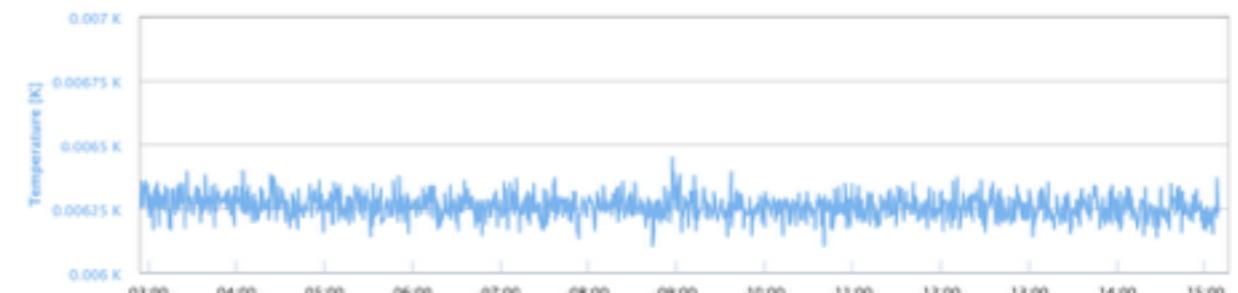
Mini-Tower test detector

- Encouraging detector performance (energy resolution) on 8 detectors array (Mini-Tower)
- Commissioned electronics, DAQ, temperature stabilization, and detector calibration systems



Cryostat

- All the cryostat components well thermalized at different stages
- No evident heat leaks
- **Base temperature: 6.3 mK**
- Base T stable for more than 70 days
- Proved nominal cooling power: $3\mu\text{W}@10\text{mK}$
- Working temperature stabilised around 10mK for a stable detector response



Detector prototype performances validated and cryostat commissioning completed in Spring 2016

CUORE detector installation will start by the end of July 2016

Conclusions

CUORE-0:

- 1 tower: 52 TeO₂ 5x5x5 cm³ crystals (~750 g each)
- total detector mass: 39 kg TeO₂ (10.9 kg of ¹³⁰Te)

- Achieved its energy resolution and background level goals
 - Background: 5.8×10^{-2} c/keV/kg/year
 - Energy resolution: 4.9 keV @ 2615 keV [FWHM]
- Improved 0νββ limit for ¹³⁰Te (in combination with CUORICINO)
 - $T_{1/2}(0\nu) > 4.0 \times 10^{24}$ yr
 - no 0νββ decay evidence
- Indicated CUORE sensitivity goal is within reach



CUORE:

- 19 CUORE-0 like towers: 988 TeO₂ crystals
- Mass of TeO₂: 741 kg (~206 kg of ¹³⁰Te)

- Assembly of CUORE towers completed
- Cryostat commissioning completed
 - Stable base temperature of ~ 6.3 mK over 70 days
 - Encouraging on noise and performances
- Detector installation is up to come (end July 2016)
- CUORE cool down is planned in October 2016
- Data taking from 2017



Conclusions

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CUORE:

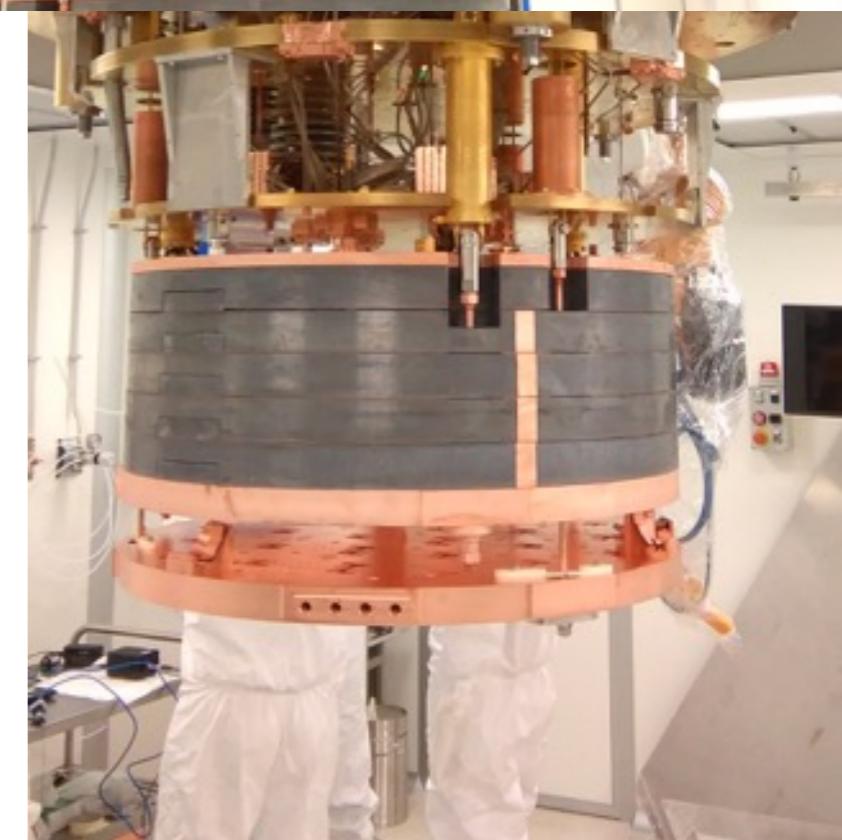
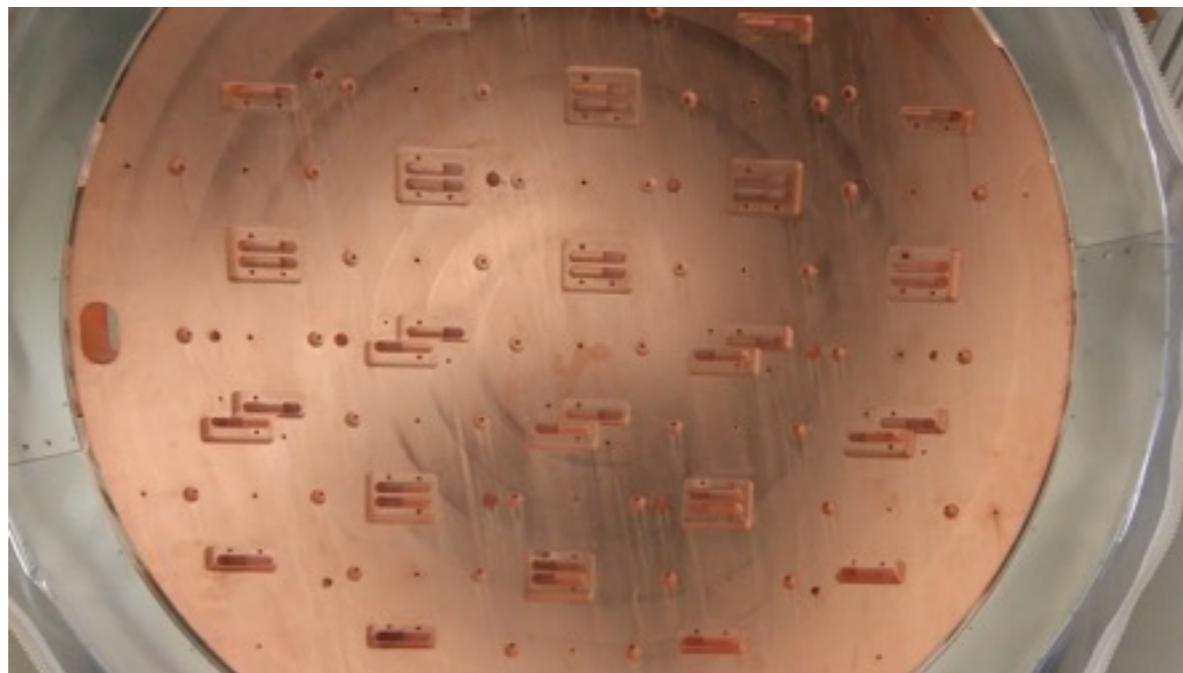
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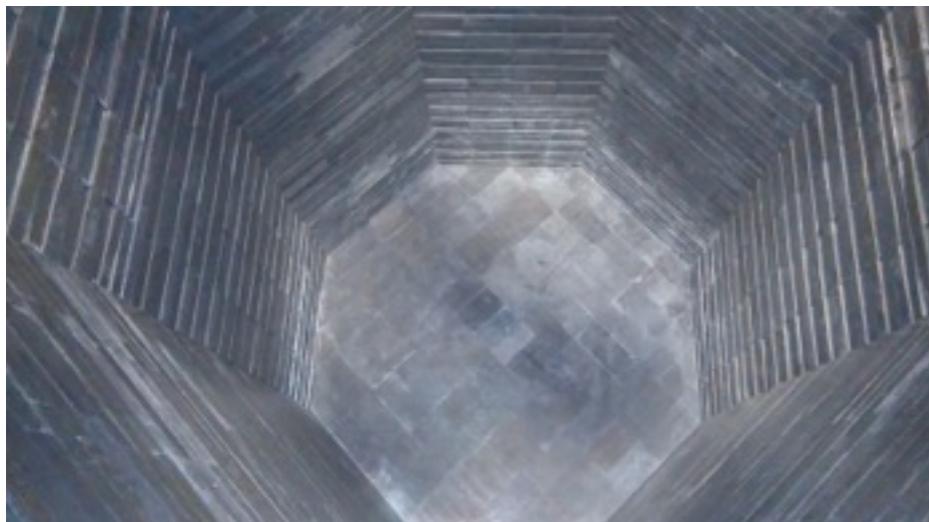
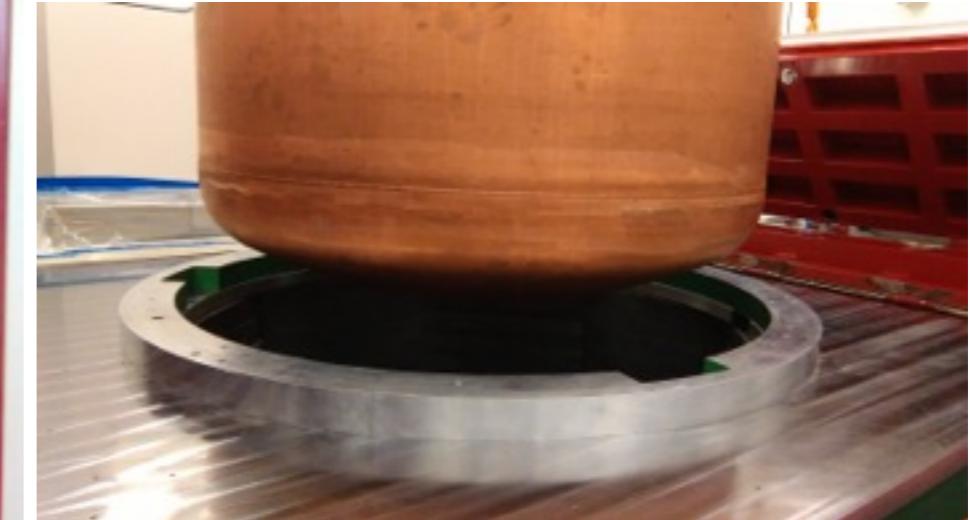
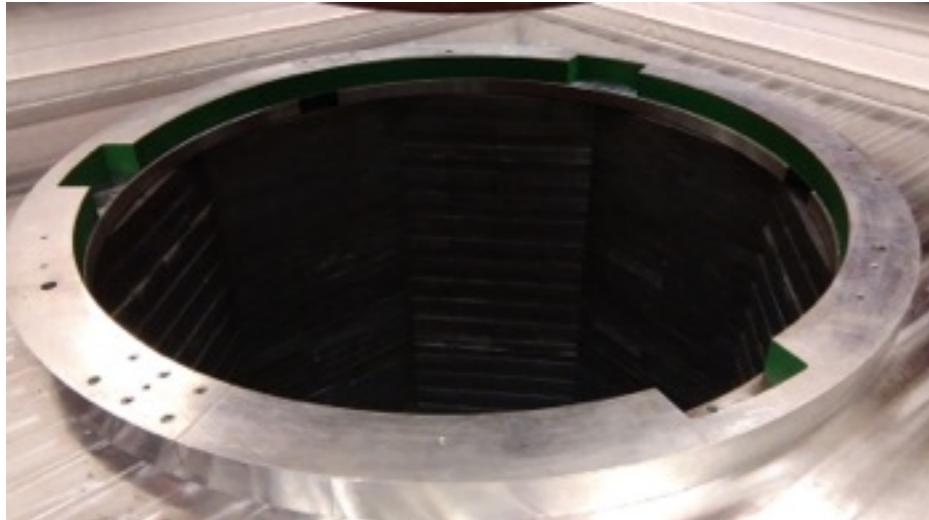


Backup slides

The CUORE cryostat



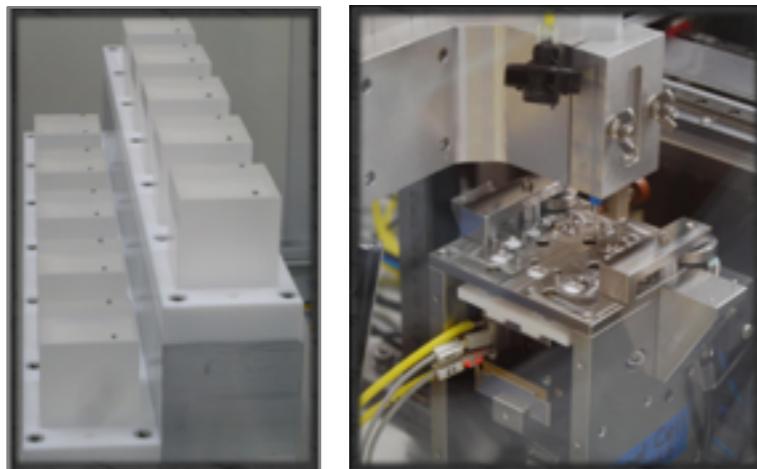
The CUORE external lead shield



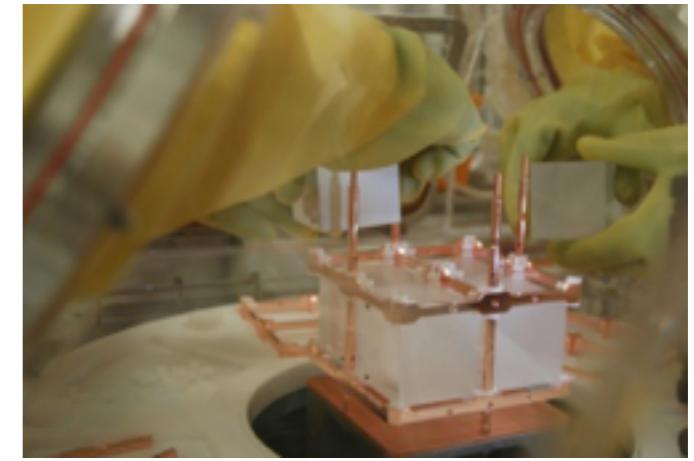
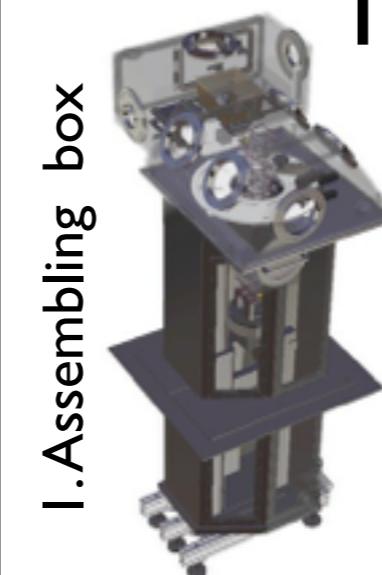
CUORE-0: test the CUORE assembly line



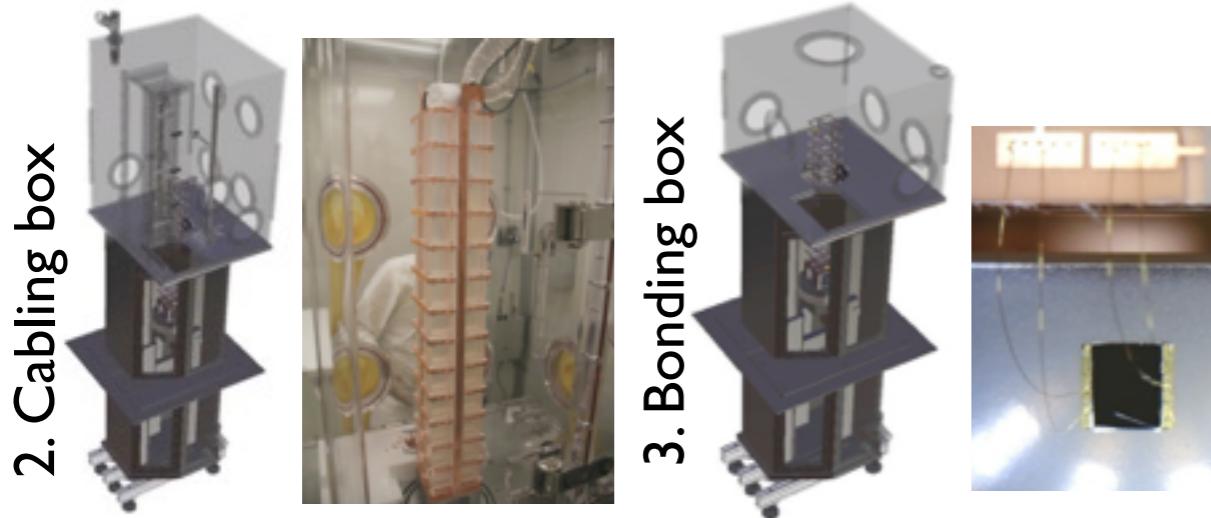
Thermistor gluing



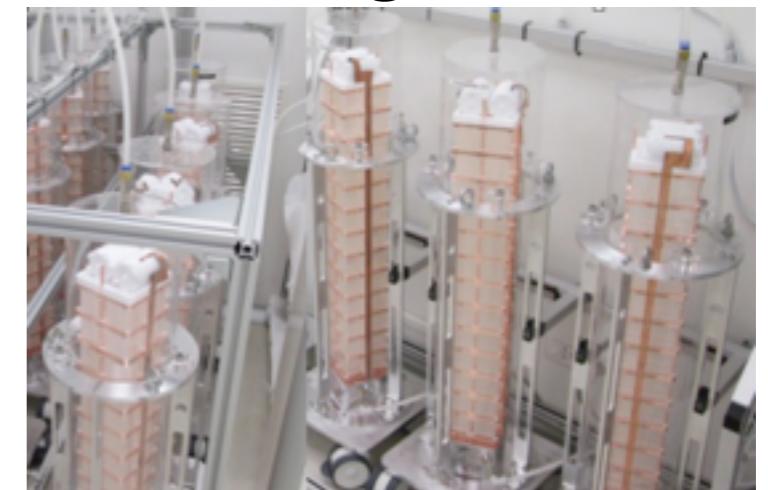
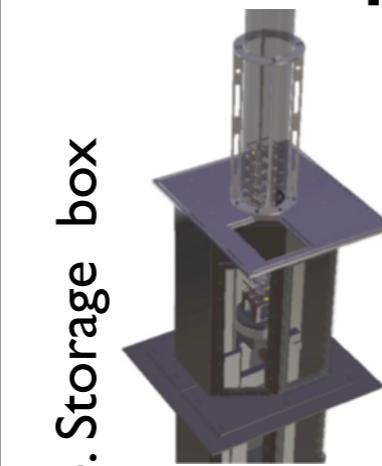
Tower assembly



Wire bonding



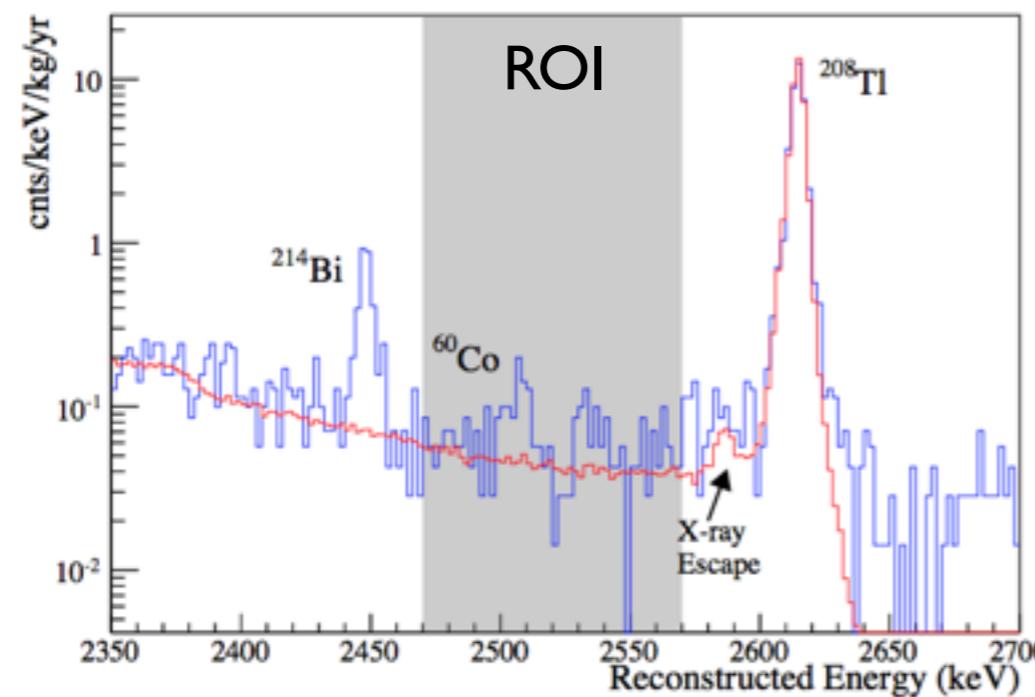
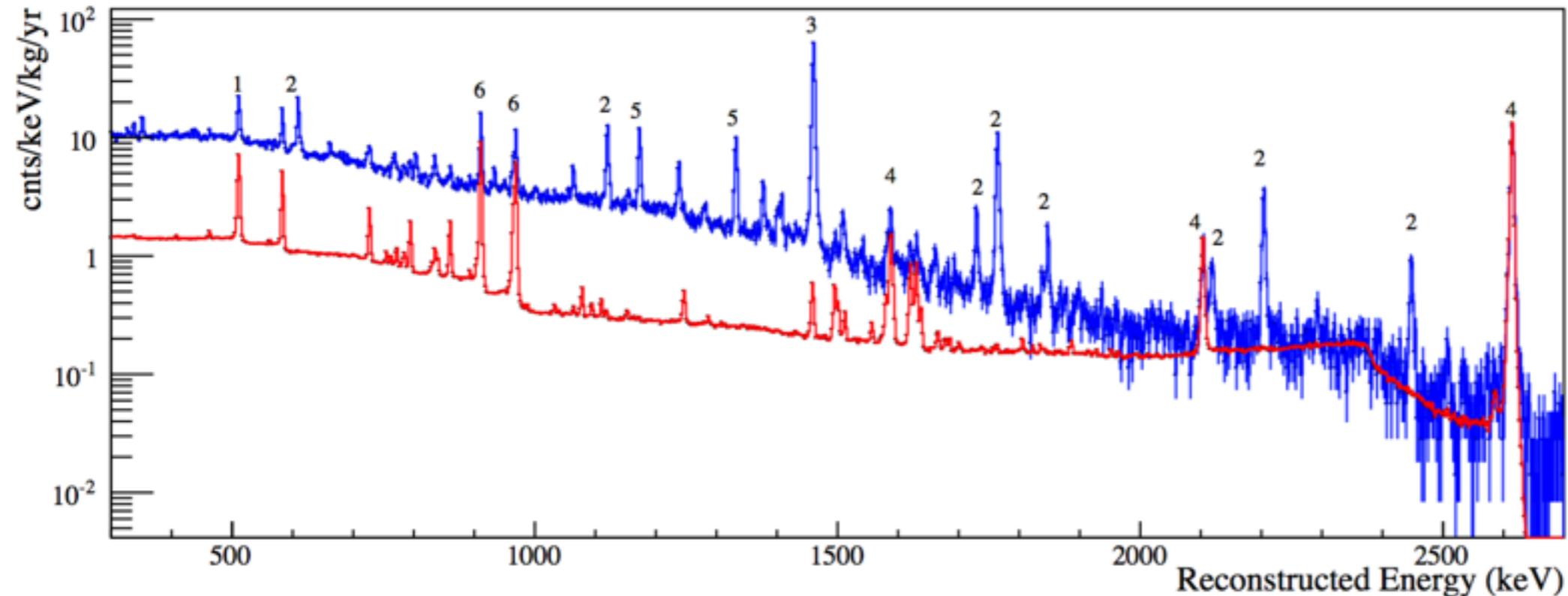
Towers storage



All procedures performed in N₂ atmosphere and in a contactless approach to minimise radioactive recontaminations

The successful operation of CUORE-0 demonstrated the validity of the CUORE tower assembly line and of the CUORE cleaning procedures

CUORE-0 calibration and physics spectra



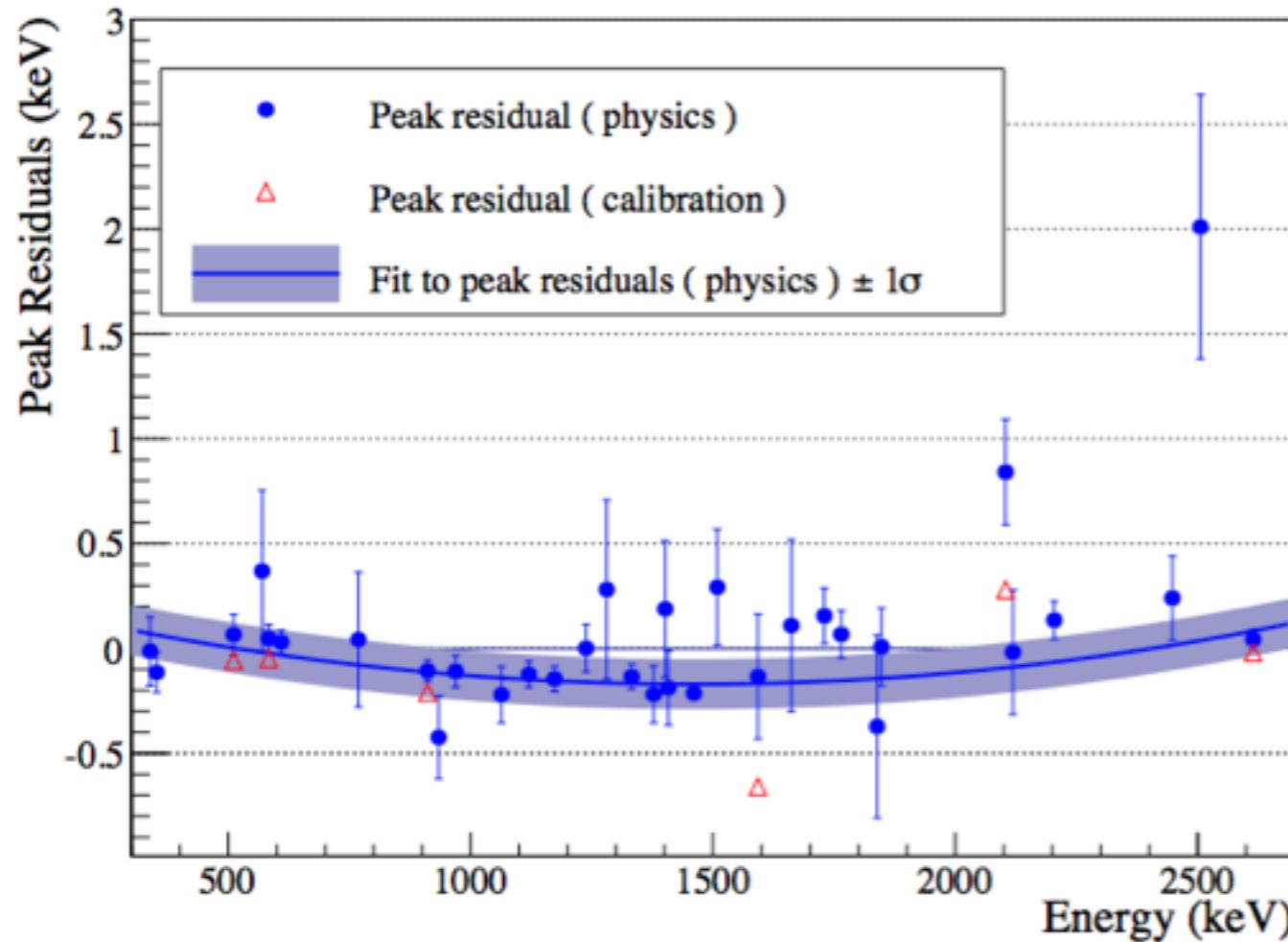
The final CUORE-0 physics spectrum (blue) and the calibration spectrum (red). The latter has been normalised to match the rate of the physics spectrum around the 2615 keV ^{208}TI peak.

The most prominent peaks in the physics spectrum are from the decay of known radioactive backgrounds:
 (1) e^+e^- annihilation, (2) ^{214}Bi , (3) ^{40}K , (4) ^{208}TI , (5) ^{60}Co ,
 (6) ^{228}Ac

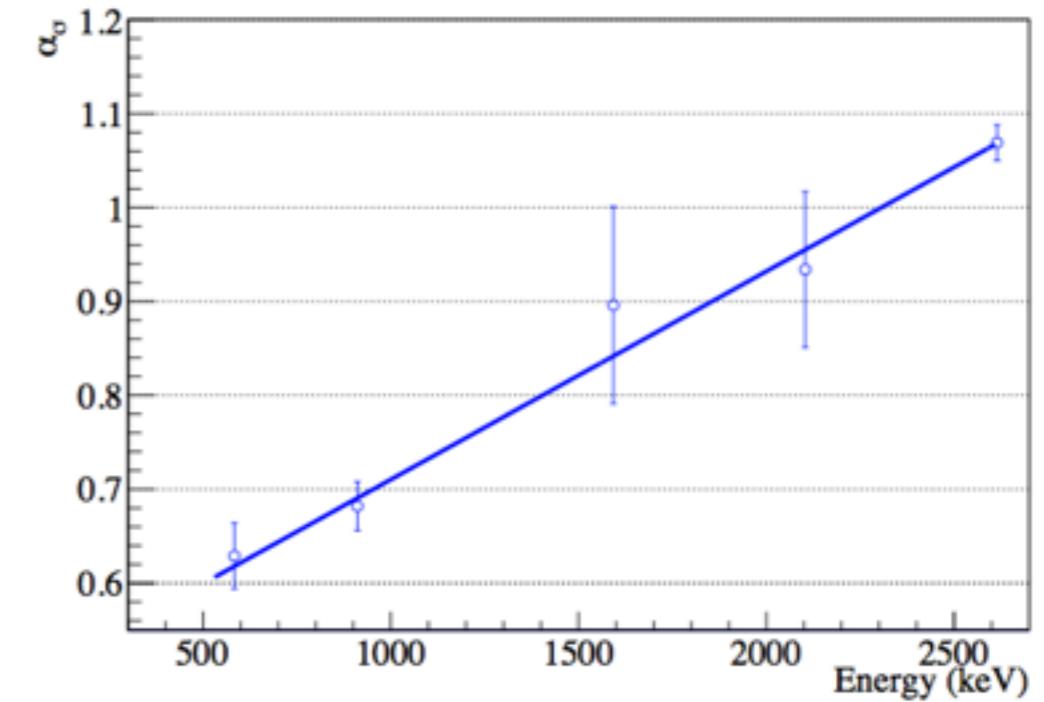
CUORE-0 calibration and physics spectra

Residuals of the best-fit reconstructed peak energy and expected peak energy (fit - expected) for the physics data (blue circles) and calibration data (red triangles).

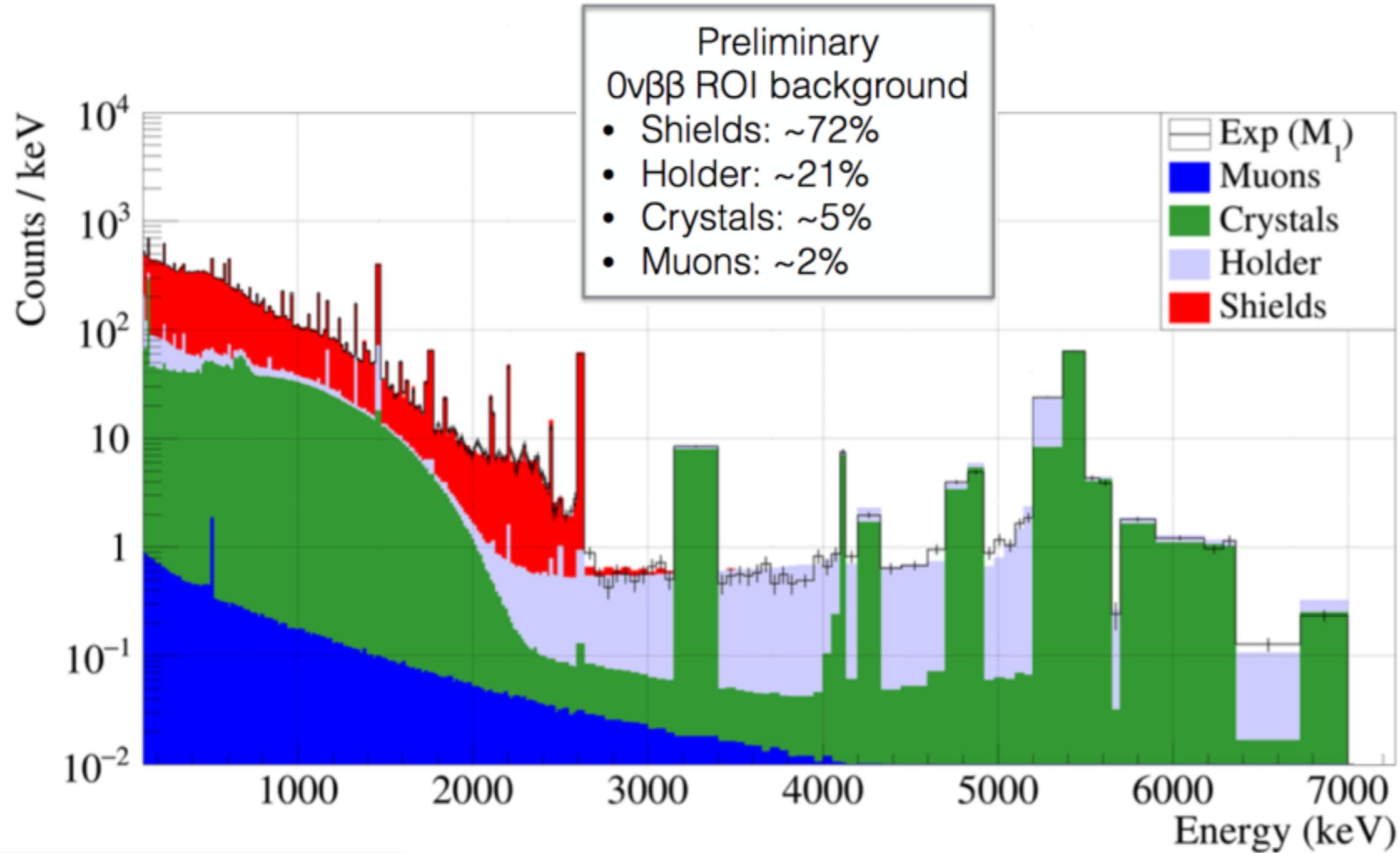
The blue curve and shaded band are the fit to the peak residuals and the 1-sigma uncertainty band



Best-fit resolution scaling parameter for a few of the peaks in the physics spectrum, as well as the best-fit interpolation

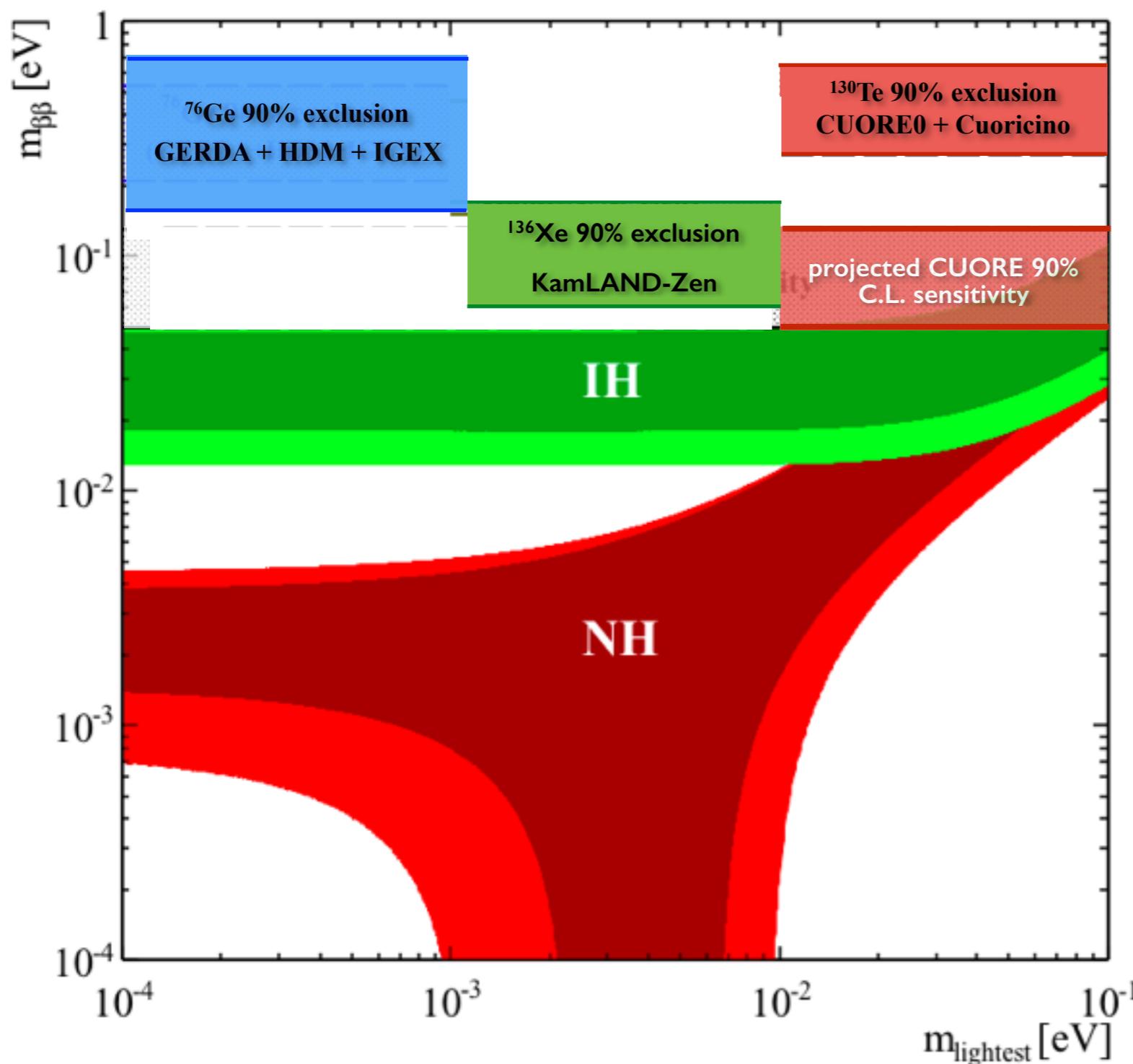


CUORE-0 background



C. Arduino et al. in preparation

CUORE-0 limit on effective Majorana mass



Combination of the CUORE-0 result with the existing $19.75 \text{ kg} \cdot \text{yr}$ of ${}^{130}\text{Te}$ exposure from Cuoricino (90% C.L.):

$$T_{1/2} > 4.0 \times 10^{24} \text{ yr}$$

The combined result gives a limit on the effective Majorana neutrino mass:

$$m_{\beta\beta} < 270 - 650 \text{ meV}$$

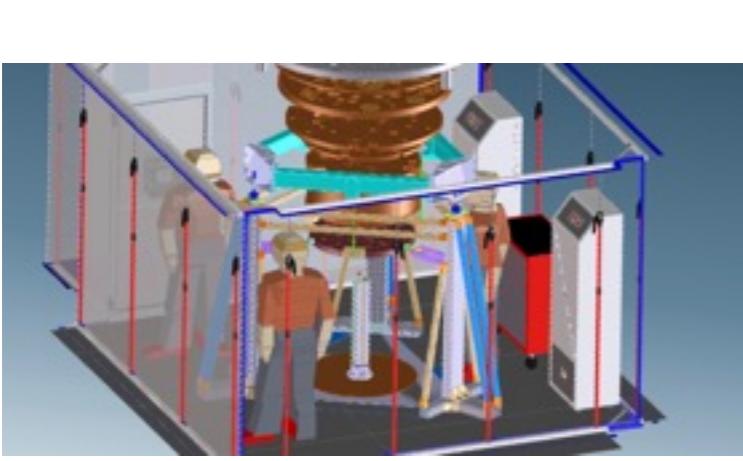
IBM-2 Phys. Rev. C 91, 034304 (2015)
 QRPA-TU Phys. Rev. C 87, 045501 (2013)
 pnQRPA Phys. Rev. C 91, 024613 (2015)
 ISM Nucl. Phys. A 818, 139 (2009)
 EDF Phys. Rev. Lett. 105, 252503 (2010)

CUORE projected sensitivity (5 years, 90% C.L.):

$$T_{1/2} > 9.5 \times 10^{25} \text{ yr}$$

$$m_{\beta\beta} < 50 - 130 \text{ meV}$$

Preparing the CUORE detector installation



CUORE detector
installation will
start by the end of
July 2016