CUORE: Bolometers at the Frontier of Neutrinoless Double Beta Decay

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The CUORE Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

SINAP

LUX ET VERITAS

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

Lawrence Livermore National Laboratory

Massachusetts Institute of Technology

UCLA

SAPIENZA UNIVERSITÀ DI ROMA

CSNSM

CUORE

BERKELEY LAB

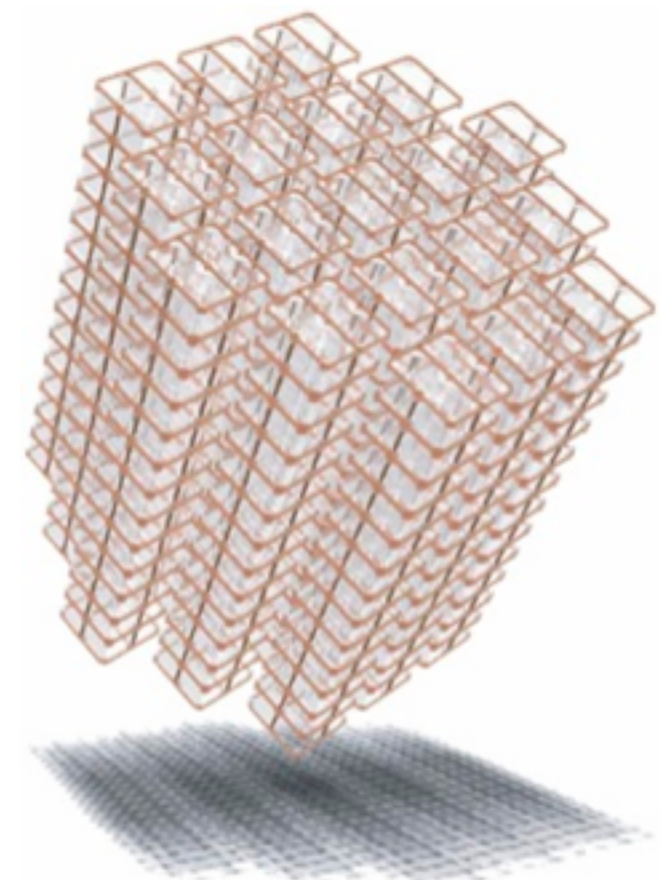
UNIVERSITY OF SOUTH CAROLINA

Outline

CUORE Program:
Search for $0\nu\beta\beta$ decay of ^{130}Te with TeO_2 bolometers

CUORICINO

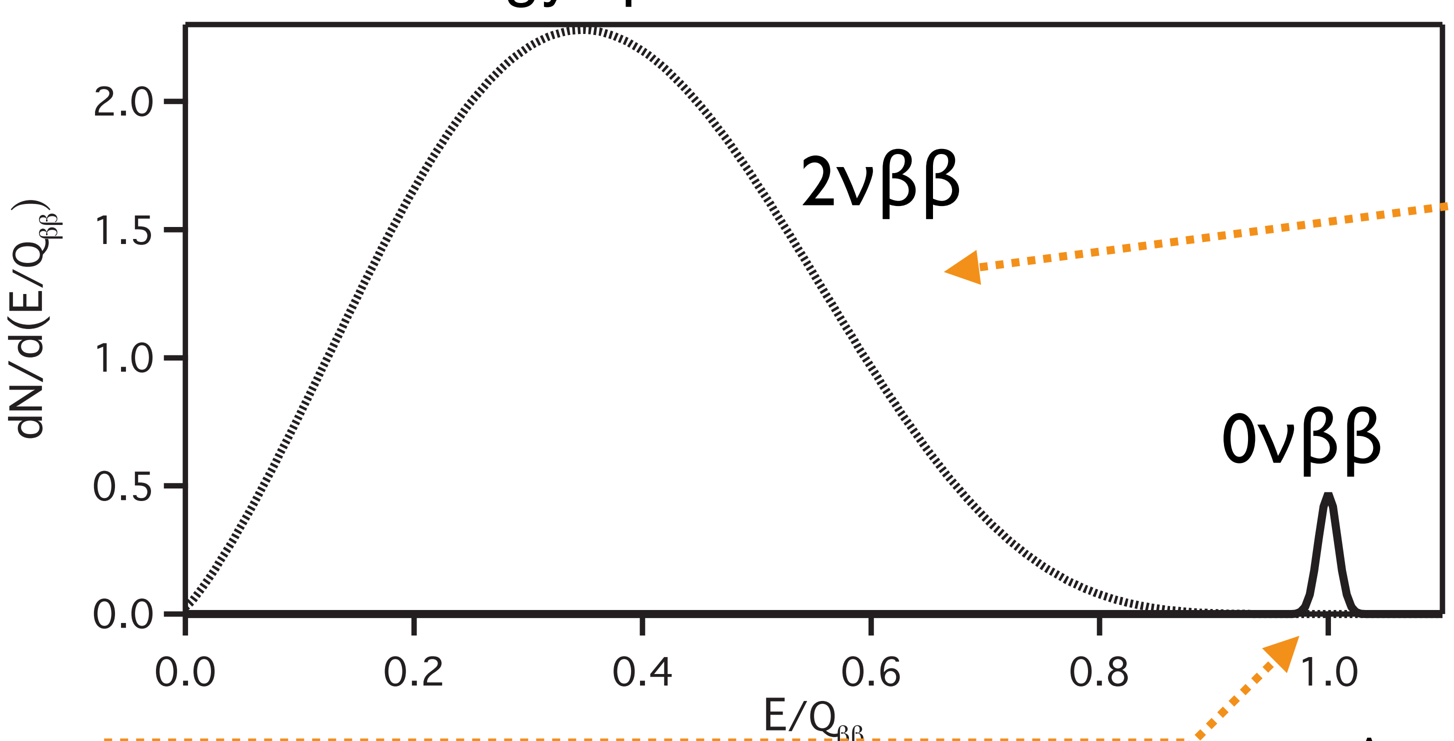
CUORE-0

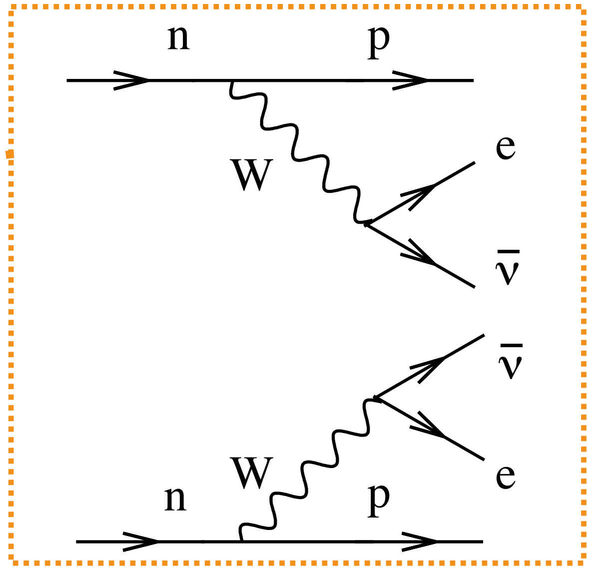


CUORE

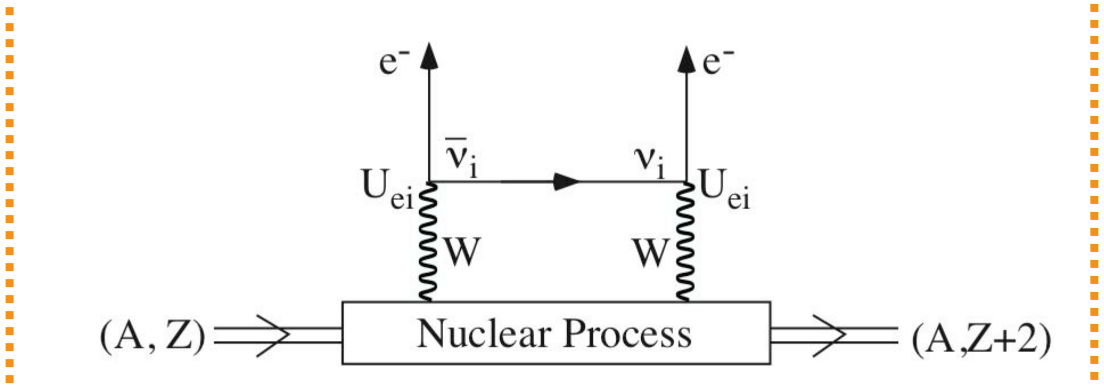
Double-Beta Decay Signature

Summed-energy spectrum of final state electrons





Assumes BR 0v/2v = 1% and detector energy resolution is 2%

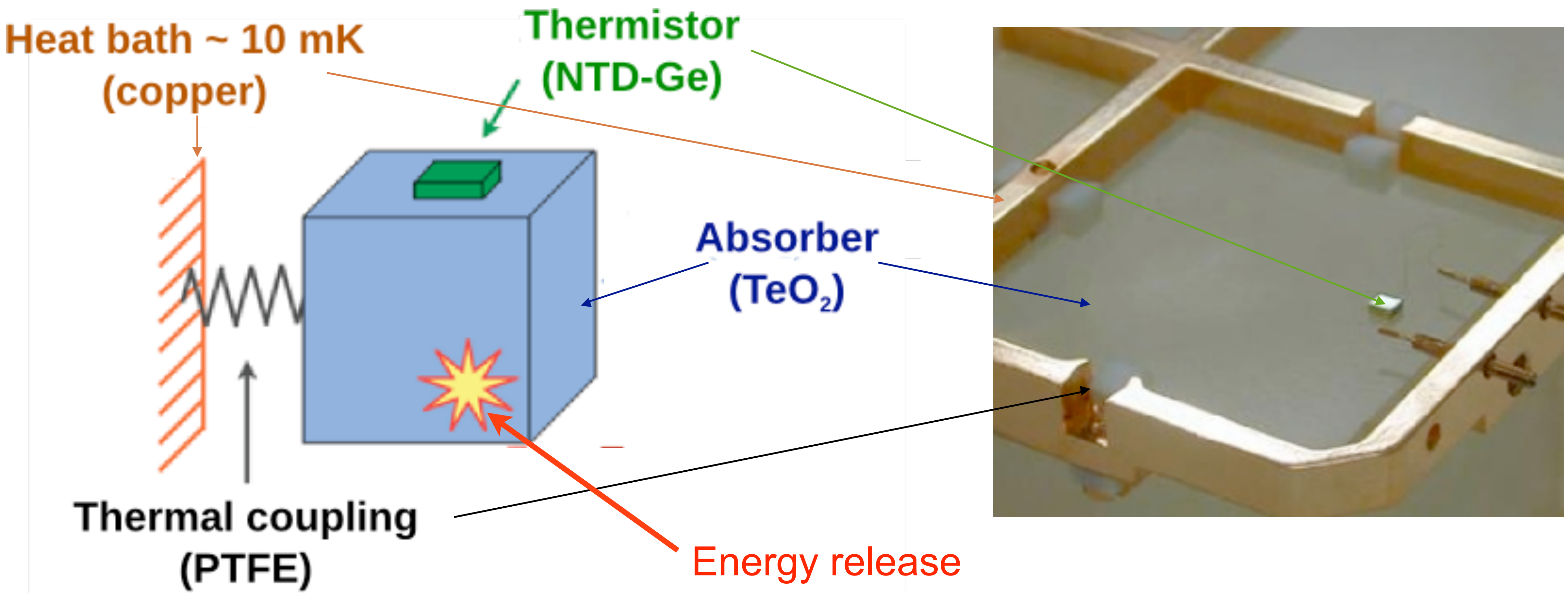


Rule of thumb

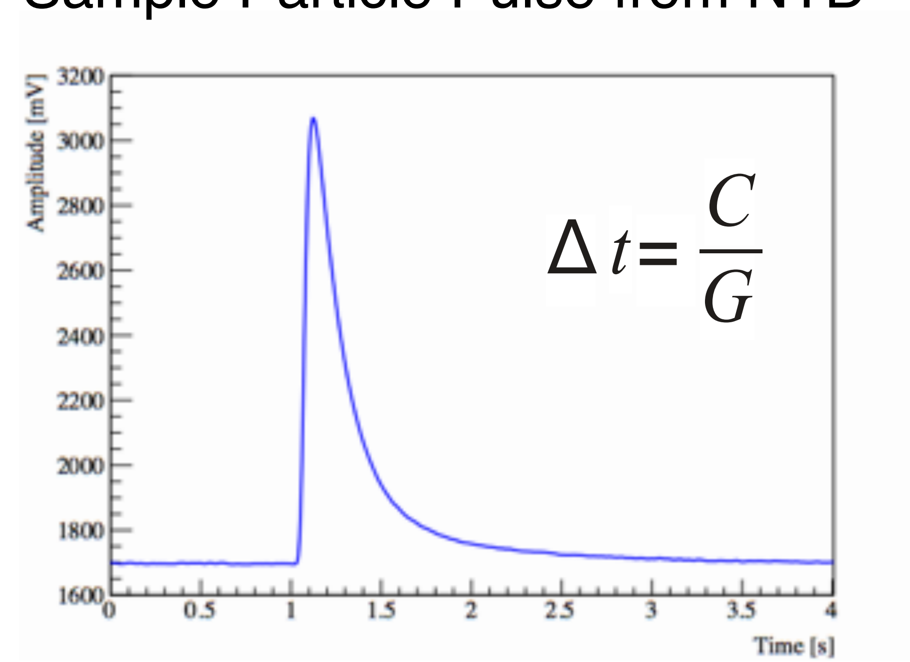
$T^{0\nu}_{1/2}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

a	isotopic abundance of source
ε	detection efficiency
M	Total detector mass
b	bkg rate per unit mass per unit energy
t	exposure time
δE	energy resolution

CUORE Program: Search for $0\nu\beta\beta$ decay of ^{130}Te with TeO2 bolometers



Sample Particle Pulse from NTD

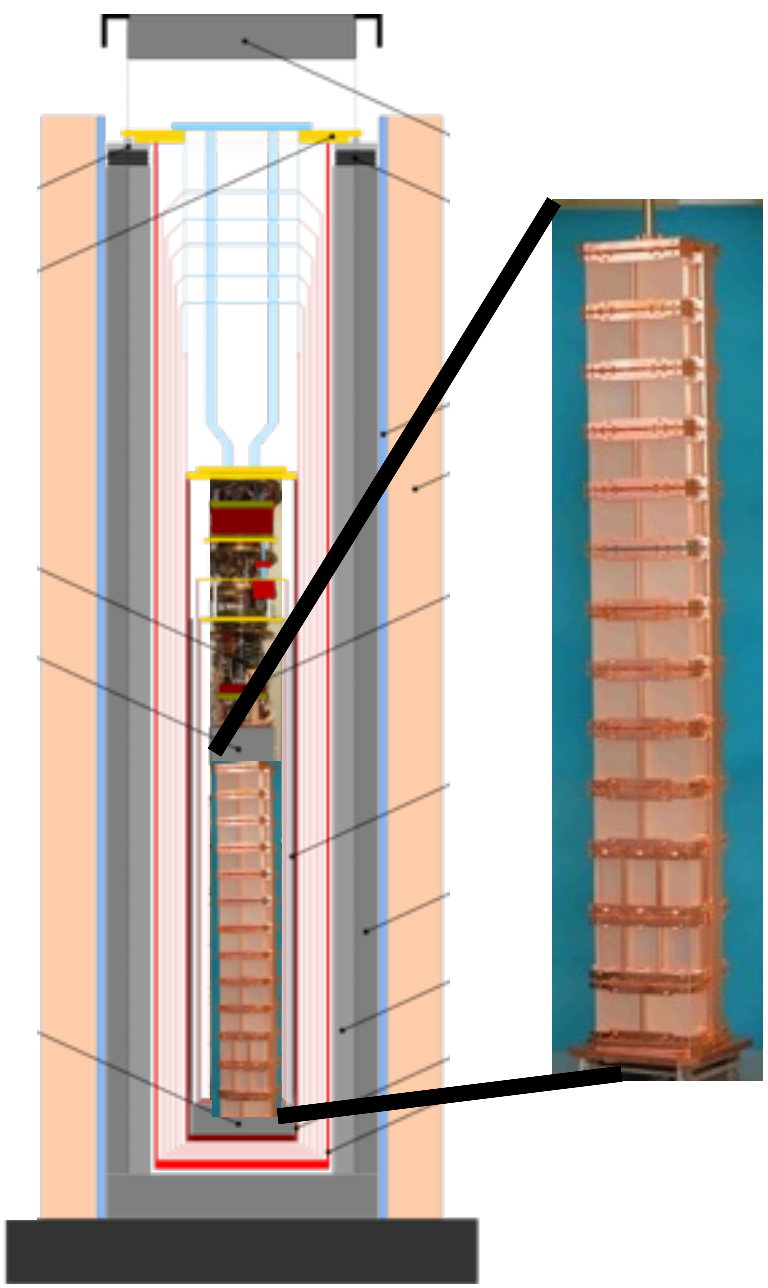


- Energy deposit results in temperature rise
- For TeO_2 crystals configured for CUORE at ~10mK, $\Delta T \sim 0.1$mK per MeV
- Temperature change read out with Ge-NTD

CUORICINO (2003 - 2008)

- 62 crystal TeO_2 bolometer array operated at Gran Sasso Lab, Italy

- ^{130}Te isotopic abundance: ~34%
- ^{130}Te Q-value: ~2528 keV

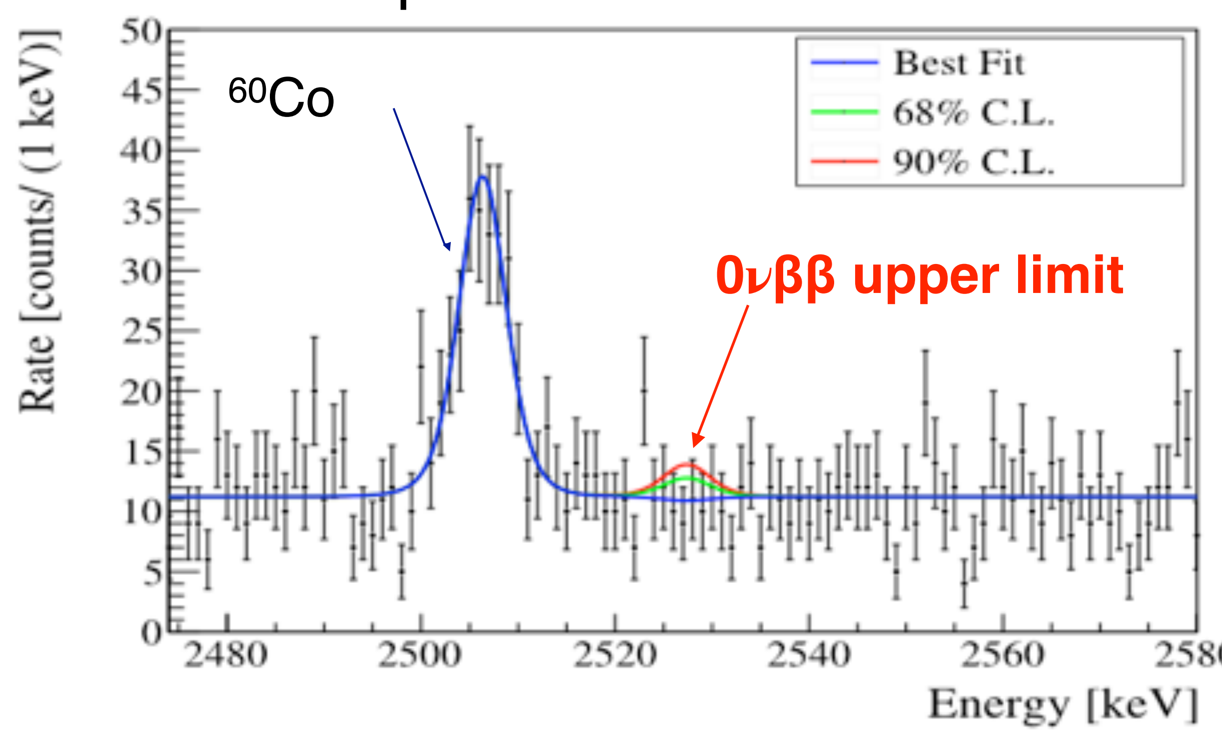


- Final results

$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\,\mathrm{yr} \quad (90\%\ \mathrm{C.L})$$
$$\langle m_{\beta\beta} \rangle < 0.3 - 0.7\,\mathrm{eV}$$

- M.t (^{130}Te): 19.75 kg.yr
- dE: 6.3 +/- 2.5 keV FWHM (mean +/- RMS)
- b: 0.169 +/- 0.006 c/keV/kg/yr

Final Spectrum of CUORICINO



CUORICINO (2003 - 2008)

CUORICINO

Background mainly from:

- ^{232}Th gammas from cryostat materials (a.k.a far sources)
- degraded α's and β's from crystals & Cu surfaces (a.k.a near sources)

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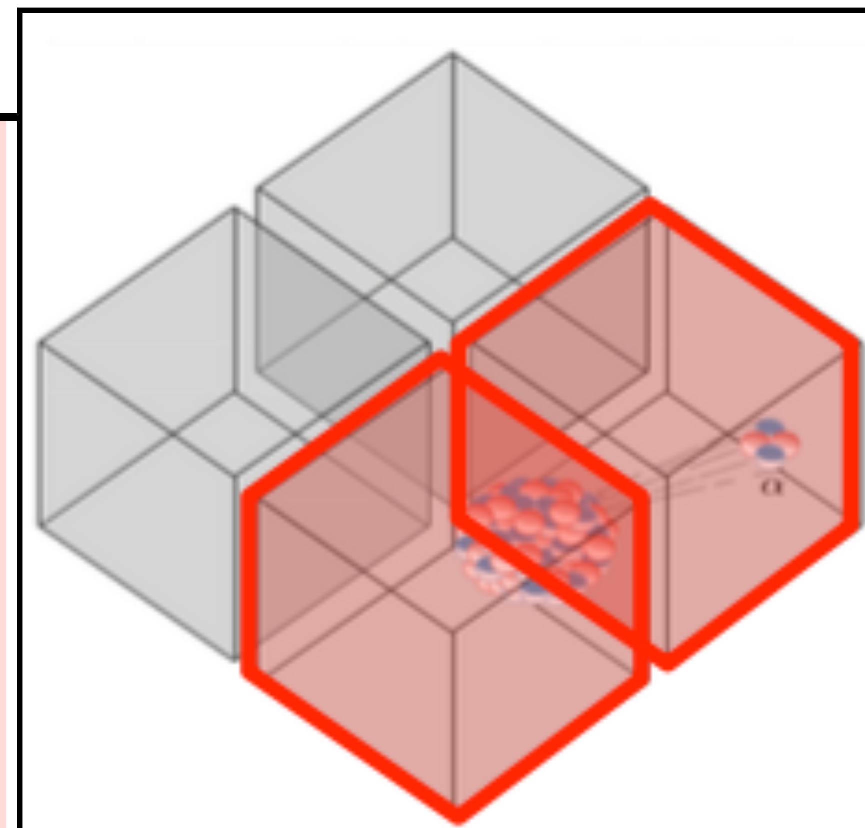


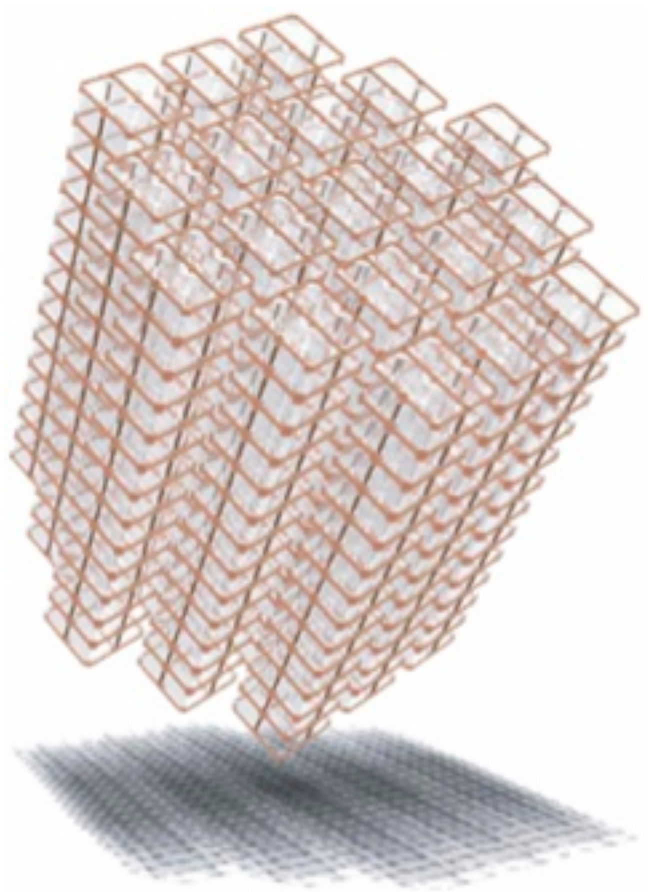
CUORICINO → CUORE

- **M**: **Scale up mass of ^{130}Te (~20x)**
  - 988, 5x5x5 cm^3 $^{nat}TeO_2$ crystals
    - 741 kg of $^{nat}TeO_2$ or 206 kg of ^{130}Te
  - Assembled into 19 towers, 13 floors per tower, 4 crystals per floor

half-life sensitivity

$$\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

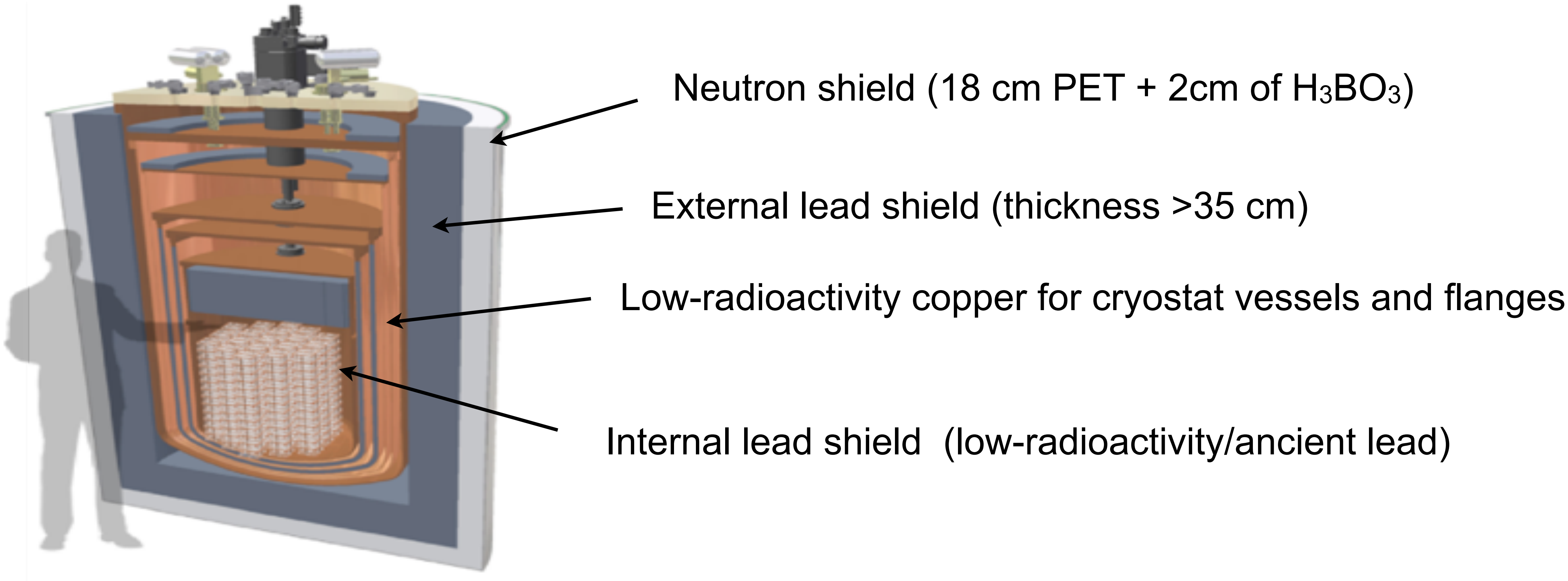
- **t**: **Cryogen-free dilution refrigerator**
  - ➡ Improves detector duty cycle
  - ➡ Improves stability



- **δE**: **Resolution**
  - Resolution of TeO_2 bolometers is excellent, 5keV @2615keV is demonstrated
- **b**: **Background**
  - Goal 0.01 counts/keV/ky/yr (~20x lower than CUORICINO)

Background mitigation efforts for CUORE

- Improve shielding and radio-purity of cryostat materials (Far Sources)

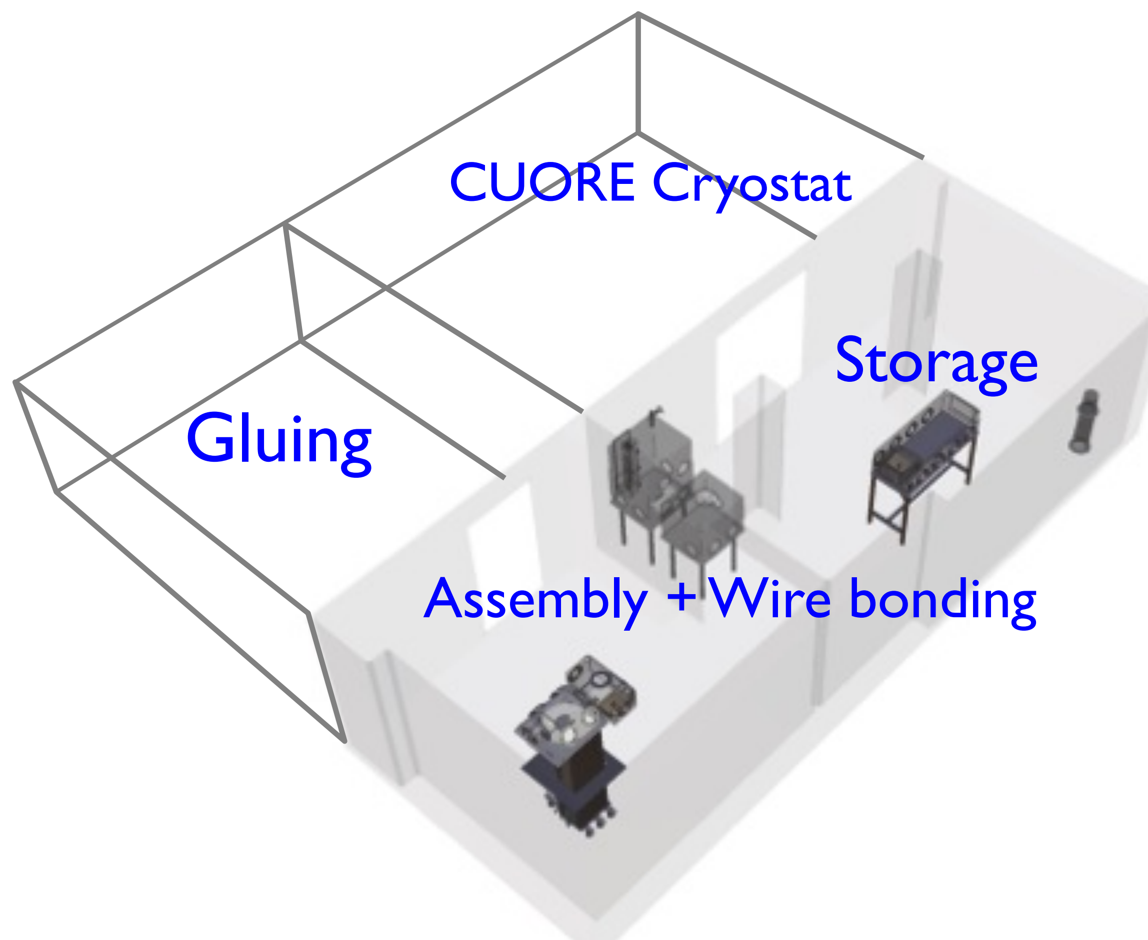


- Improve radio-purity of active and inert surfaces in the detector (Near Sources)
    - Ultra-pure TeO_2 crystals
    - Cu frame optimized to reduce surface area facing the crystals
    - New ultra-cleaning for all Cu components:
        - Tumbling
        - Electropolishing
        - Chemical etching
        - Magnetron plasma etching

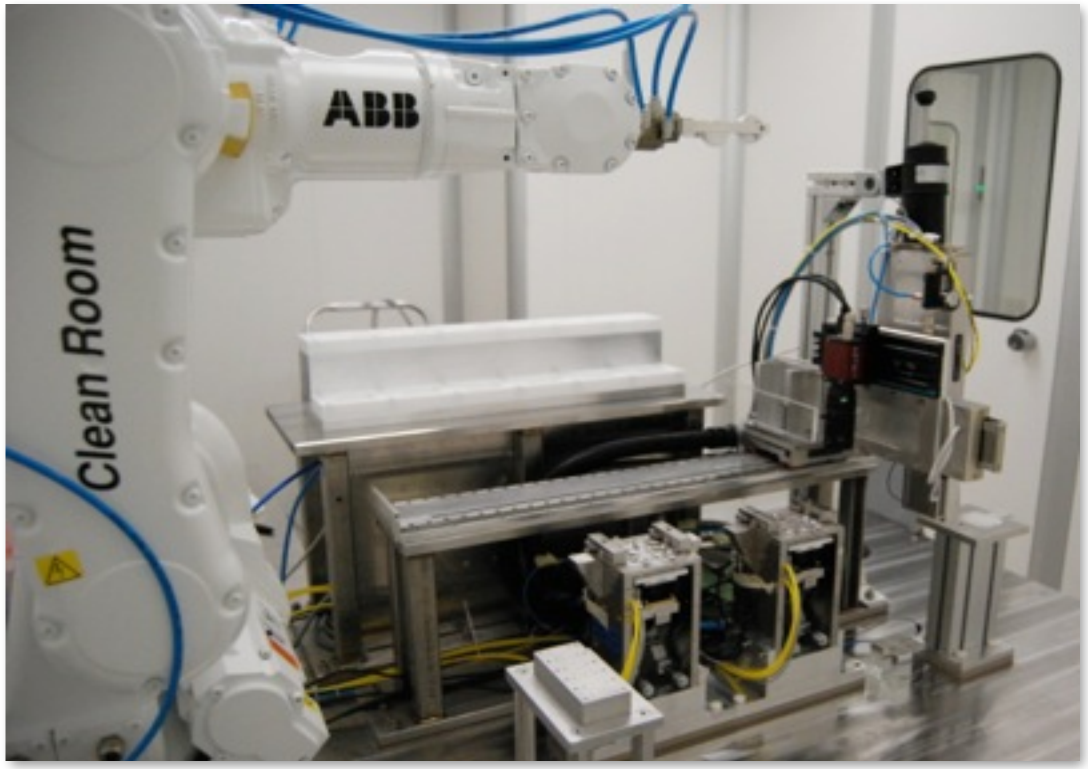
CUORE Assembly Line

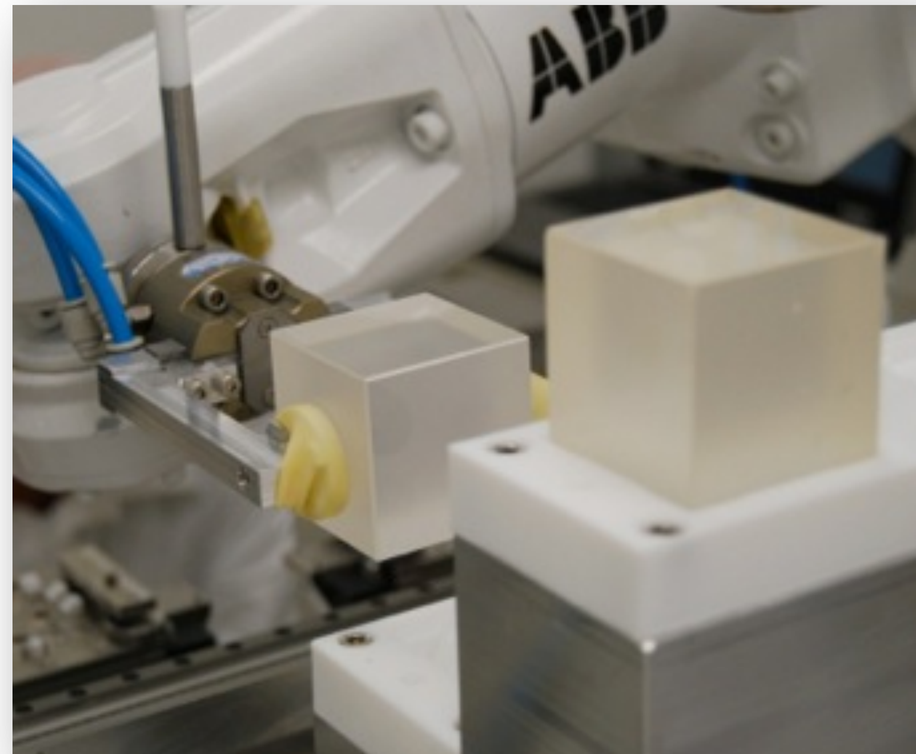
Class 1000 Clean Room for Detector Assembly and Storage

- All parts cleaned/screened according to CUORE protocol
- Stored underground at LNGS
- Assembly in underground clean room in N2 flushed glove boxes



CUORE *Semi-automatic* Gluing Line



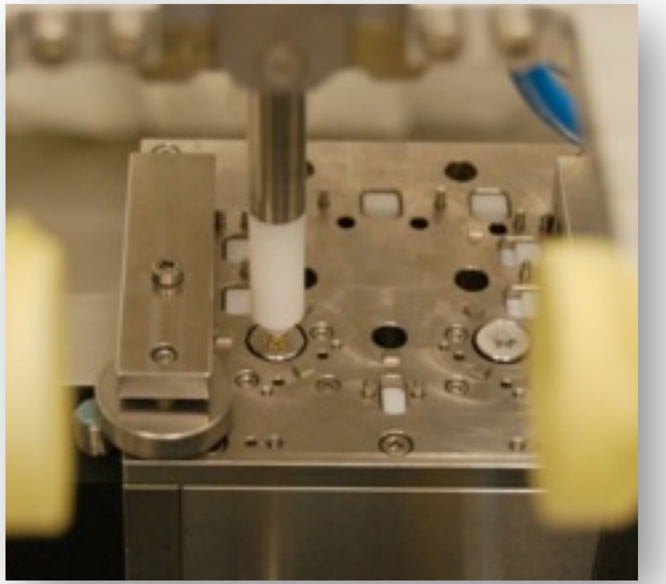


- Attach NTD, heater to each crystal
- Completely enclosed in N2 fluxed glove box
- Minimizes human interaction with parts
- Automatic, highly reproducible glue deposition

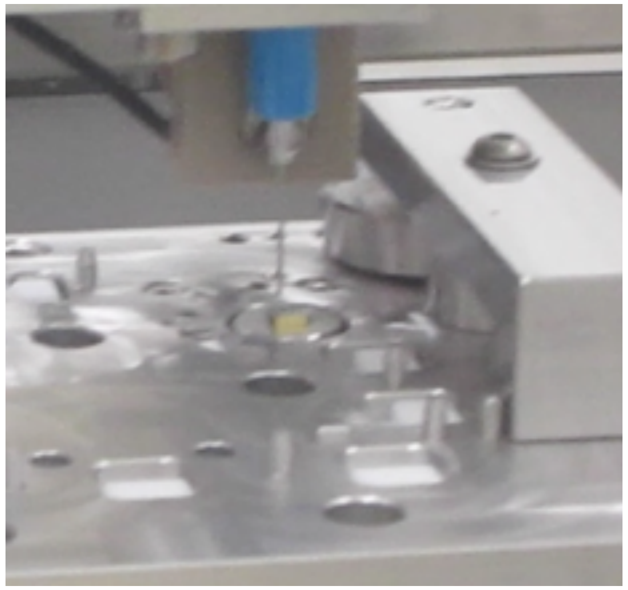
CUORE *Semi-automatic* Gluing Line

for (i =0; i < 1040; i++){ . . .

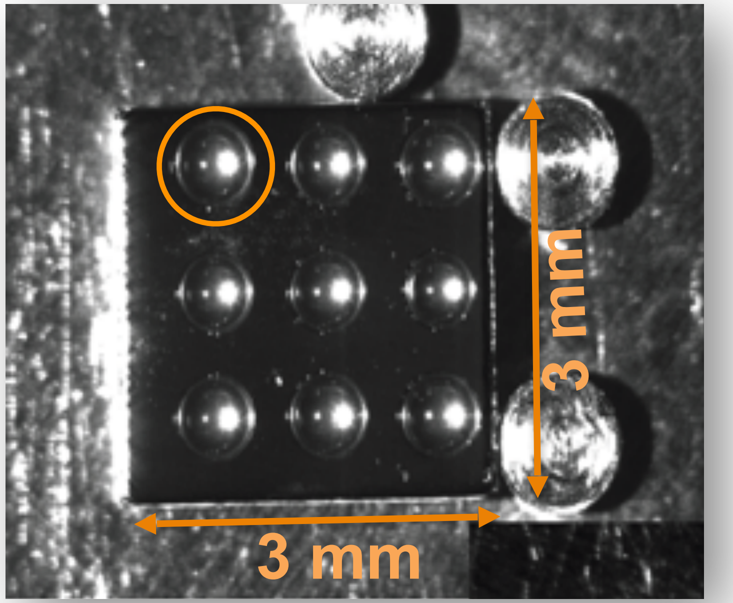
Position Sensors



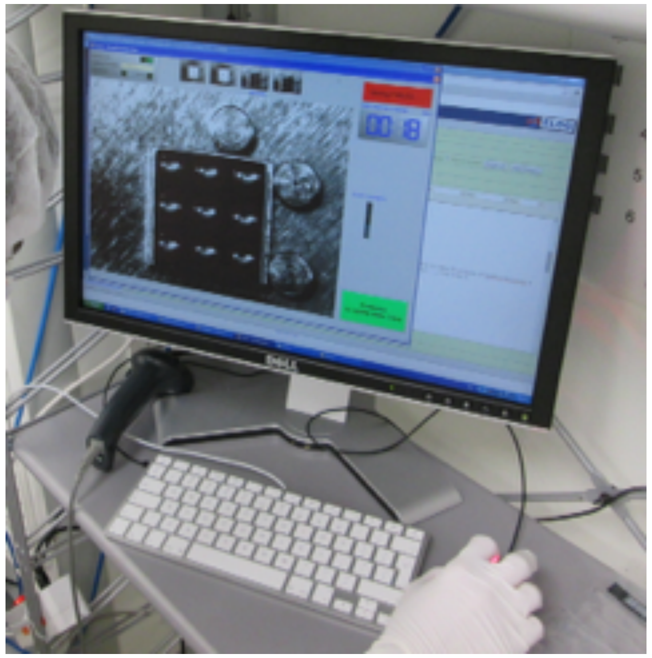
Print Glue Matrix



Inspection



Quality Control

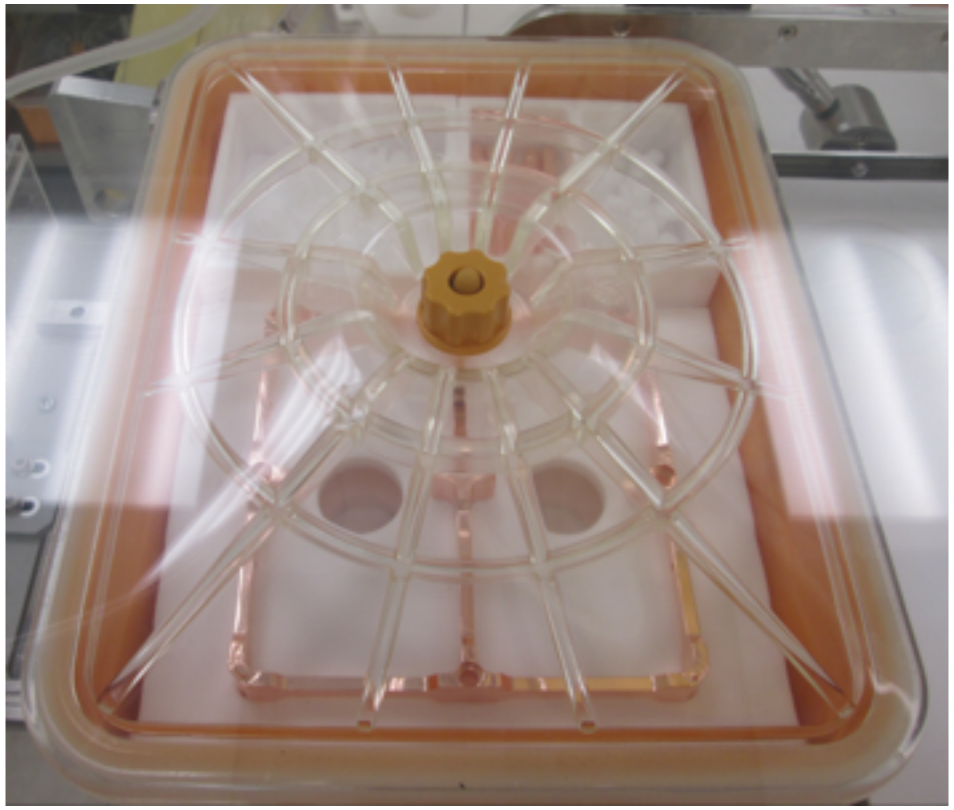


if(bad) {i = i -1; continue;}
if(good) {
deposit crystal;
sleep (25 minutes);} …}

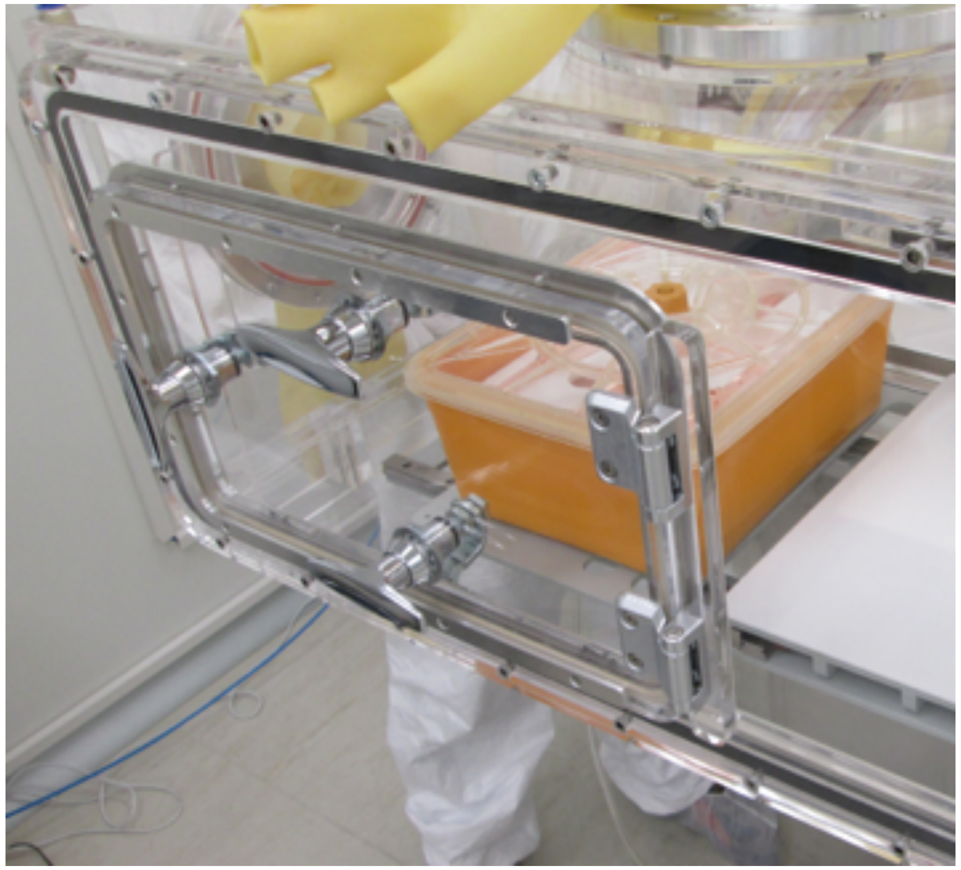
Mechanical Assembly

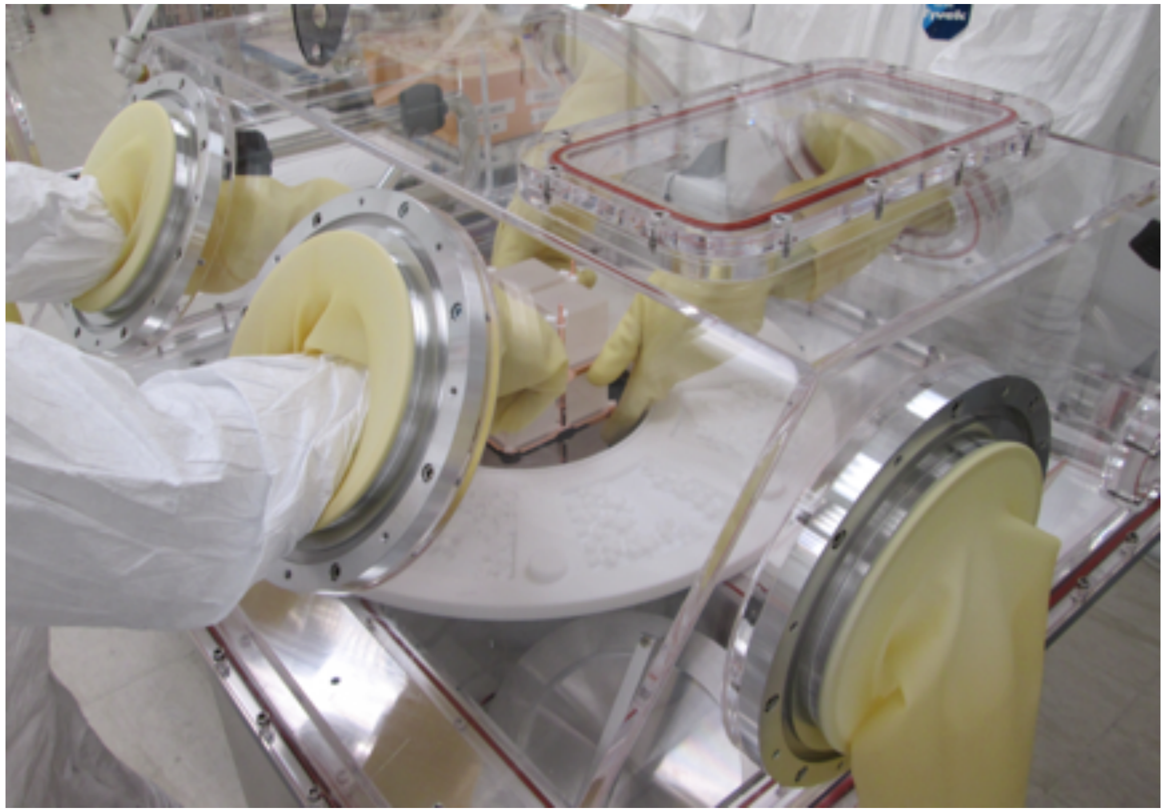
1. Unpack ultra-cleaned copper/PTFE parts and quality-check in N2 atmosphere

Mechanical Assembly



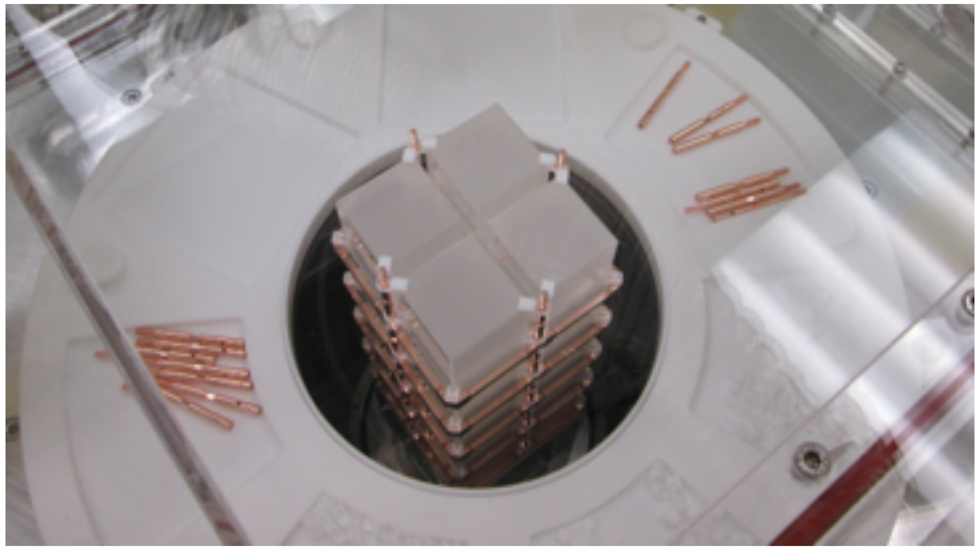
2. Parts and crystals for a floor transferred under vacuum to assembly glove box

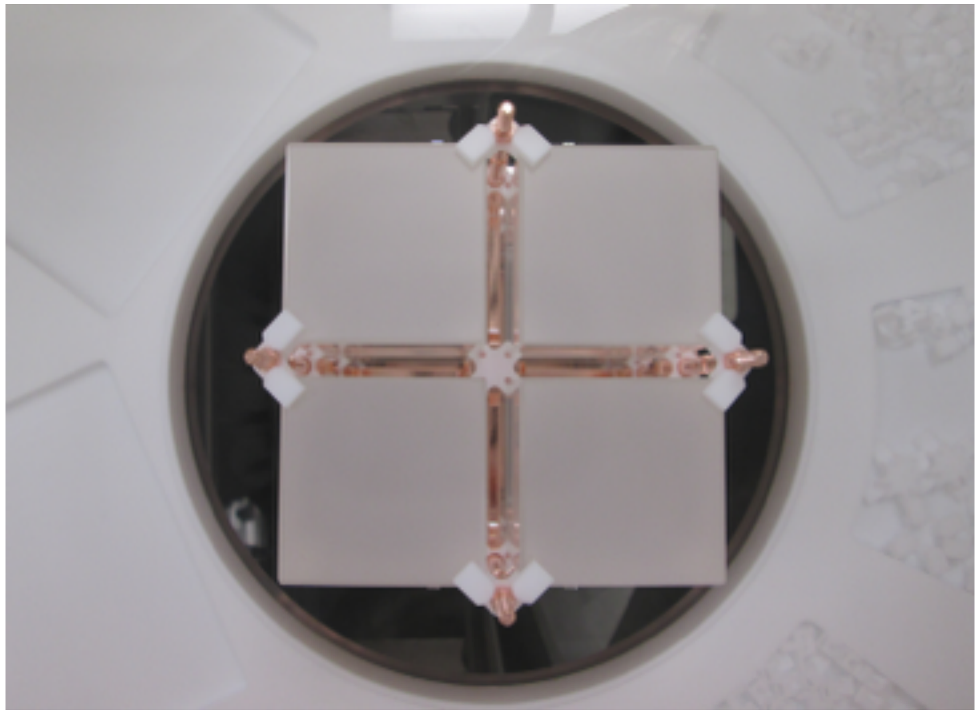


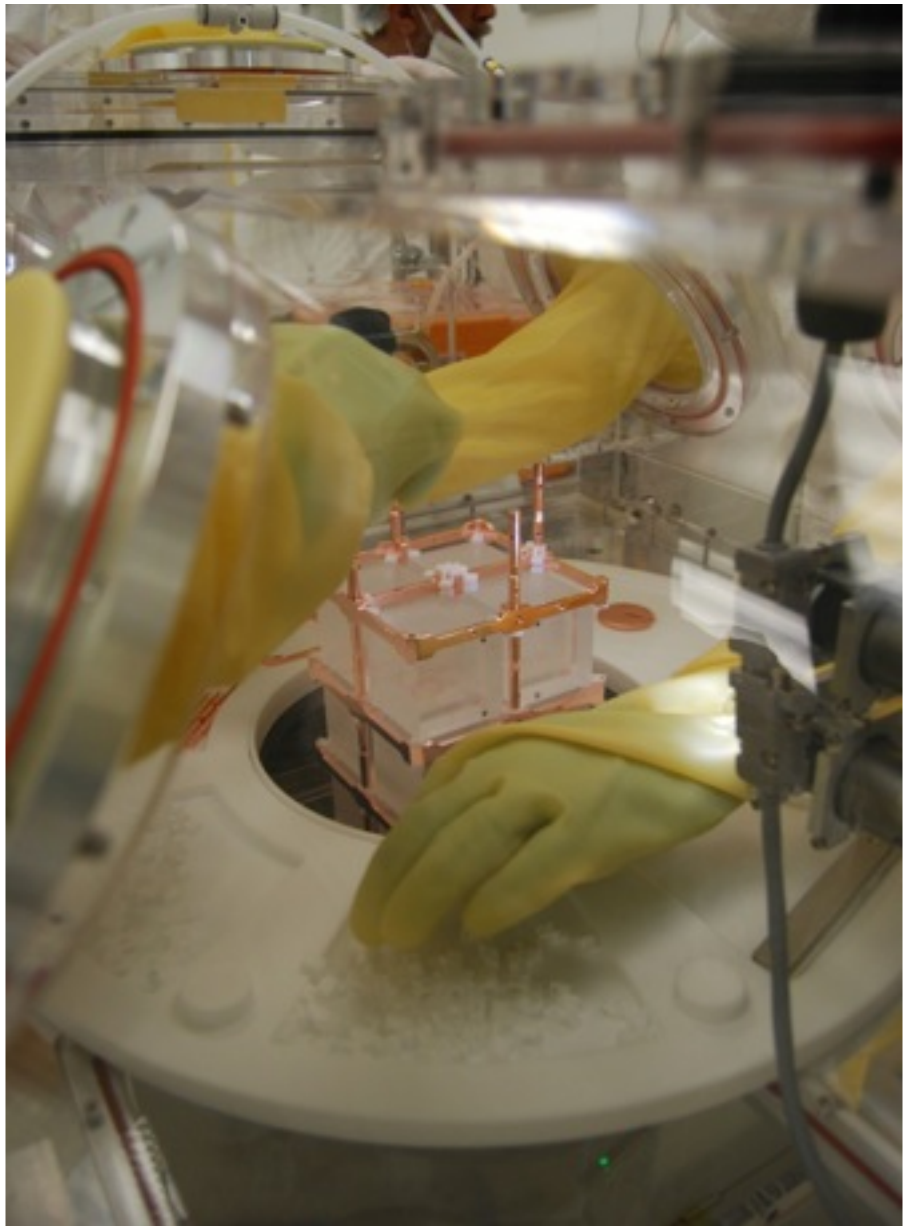


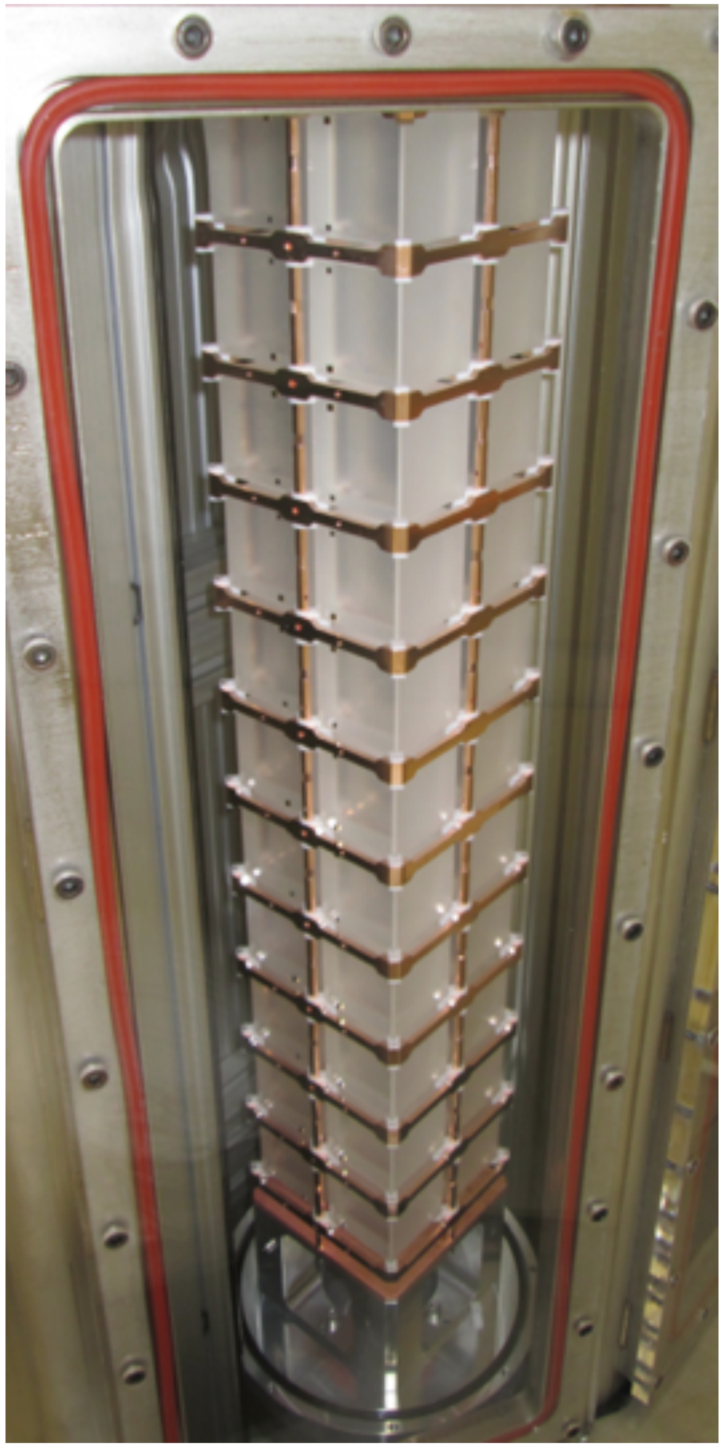
Mechanical Assembly

3. Build up tower floor-by-floor in N2 atmosphere, completed floors lowered into N2-fluxed ‘garage’



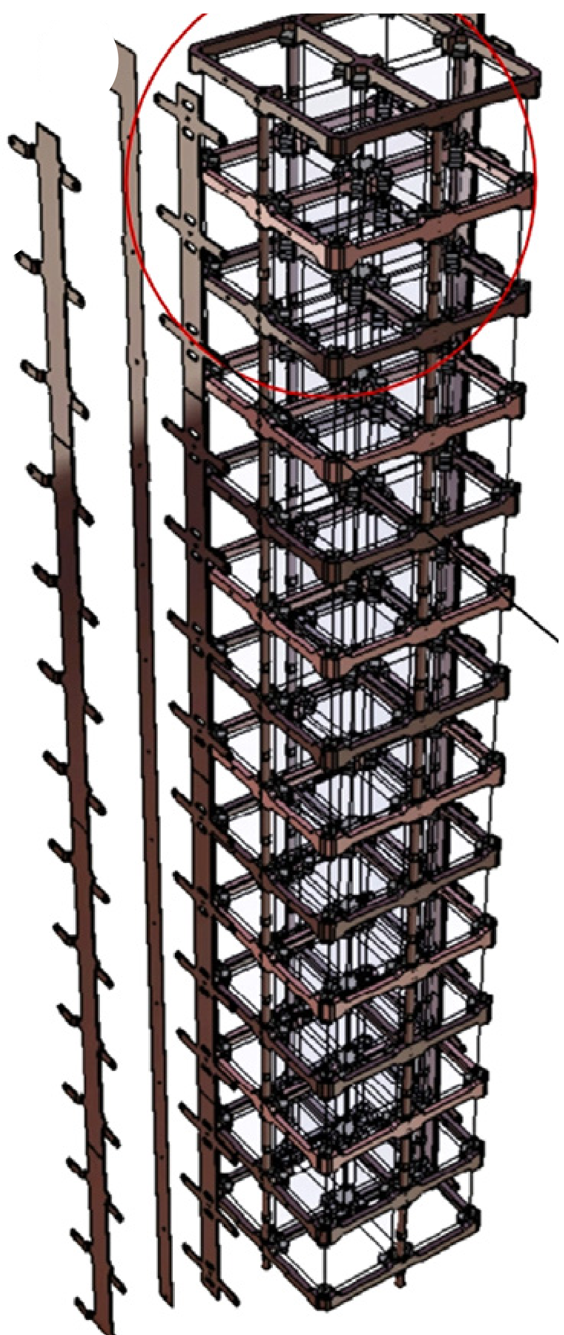


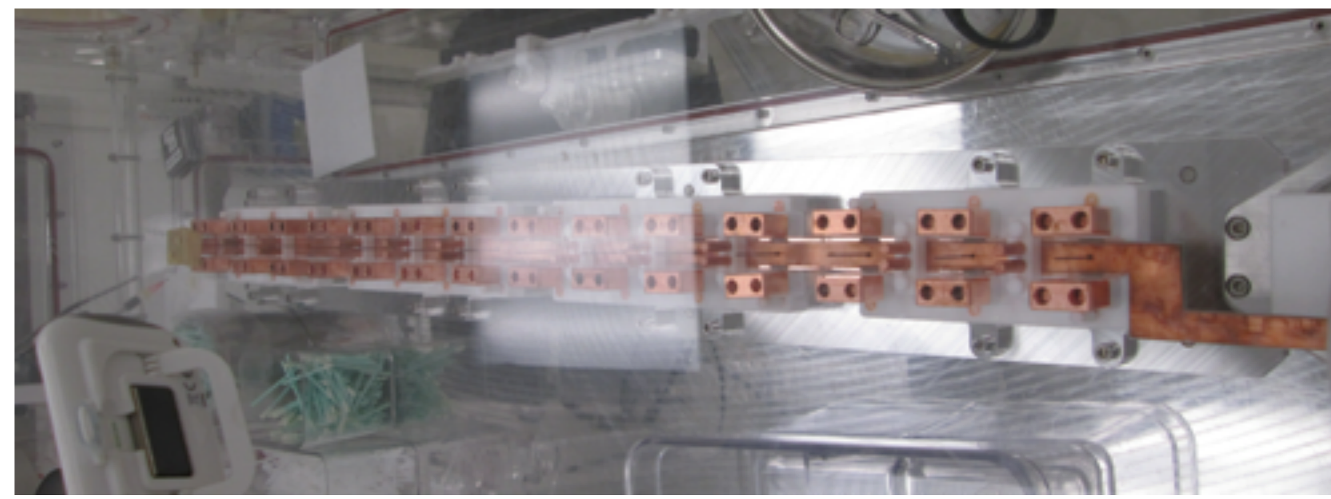




Mechanical Assembly

4. Readout wire-strips (copper traces on flexible PCB) glued to arms and attached to tower in N2 flushed glove box





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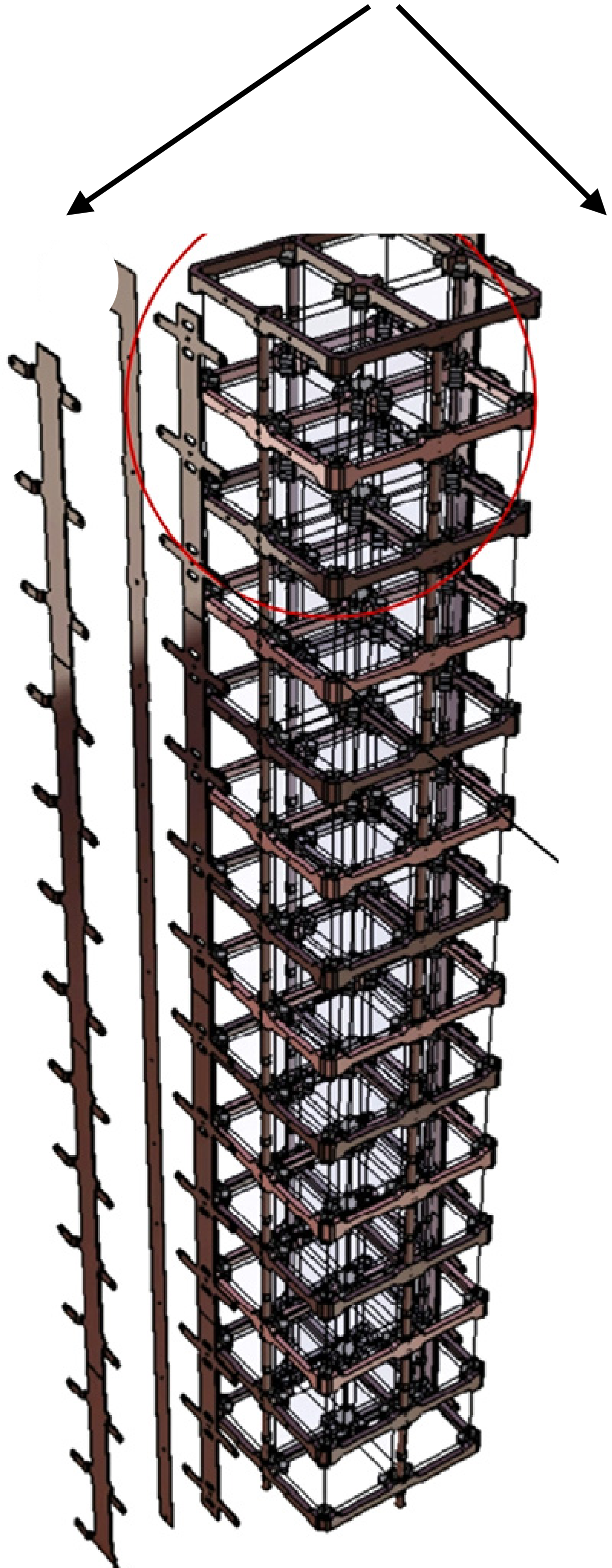
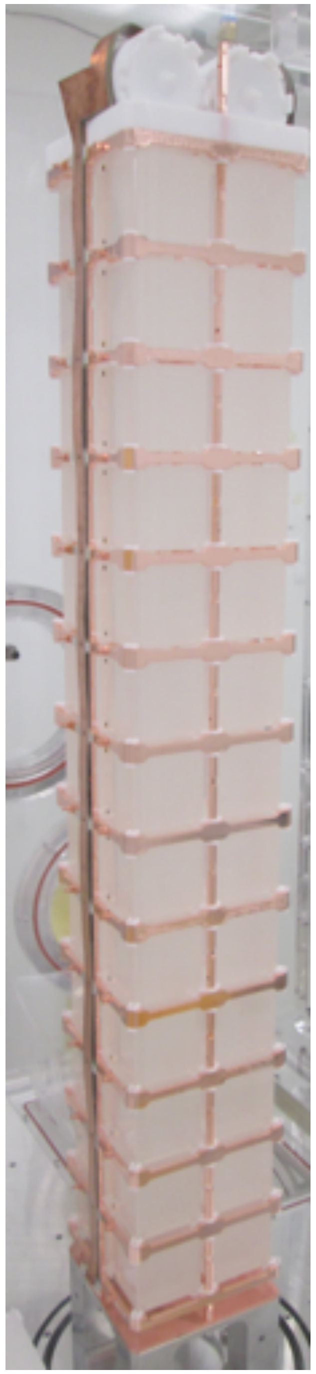
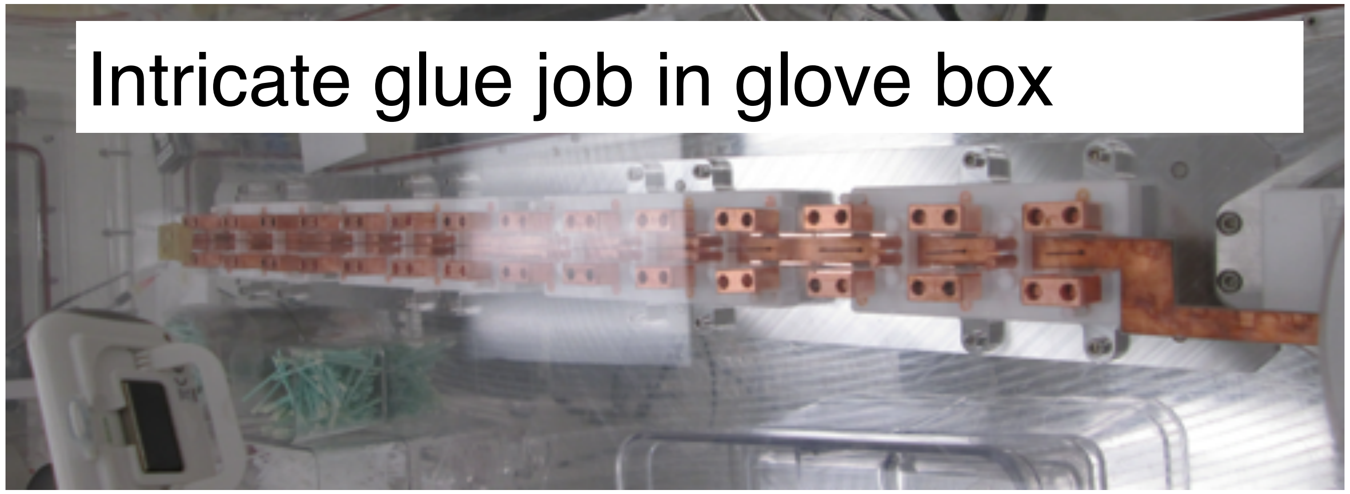
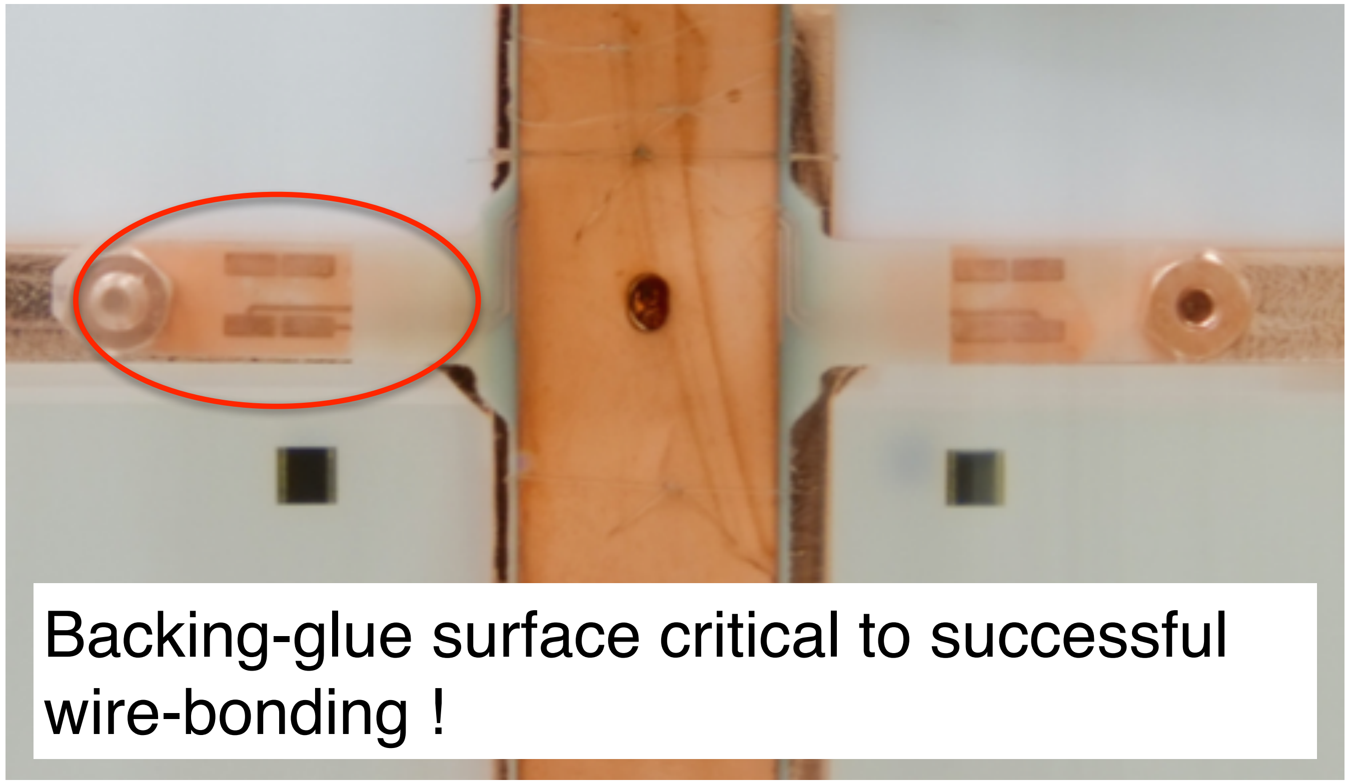
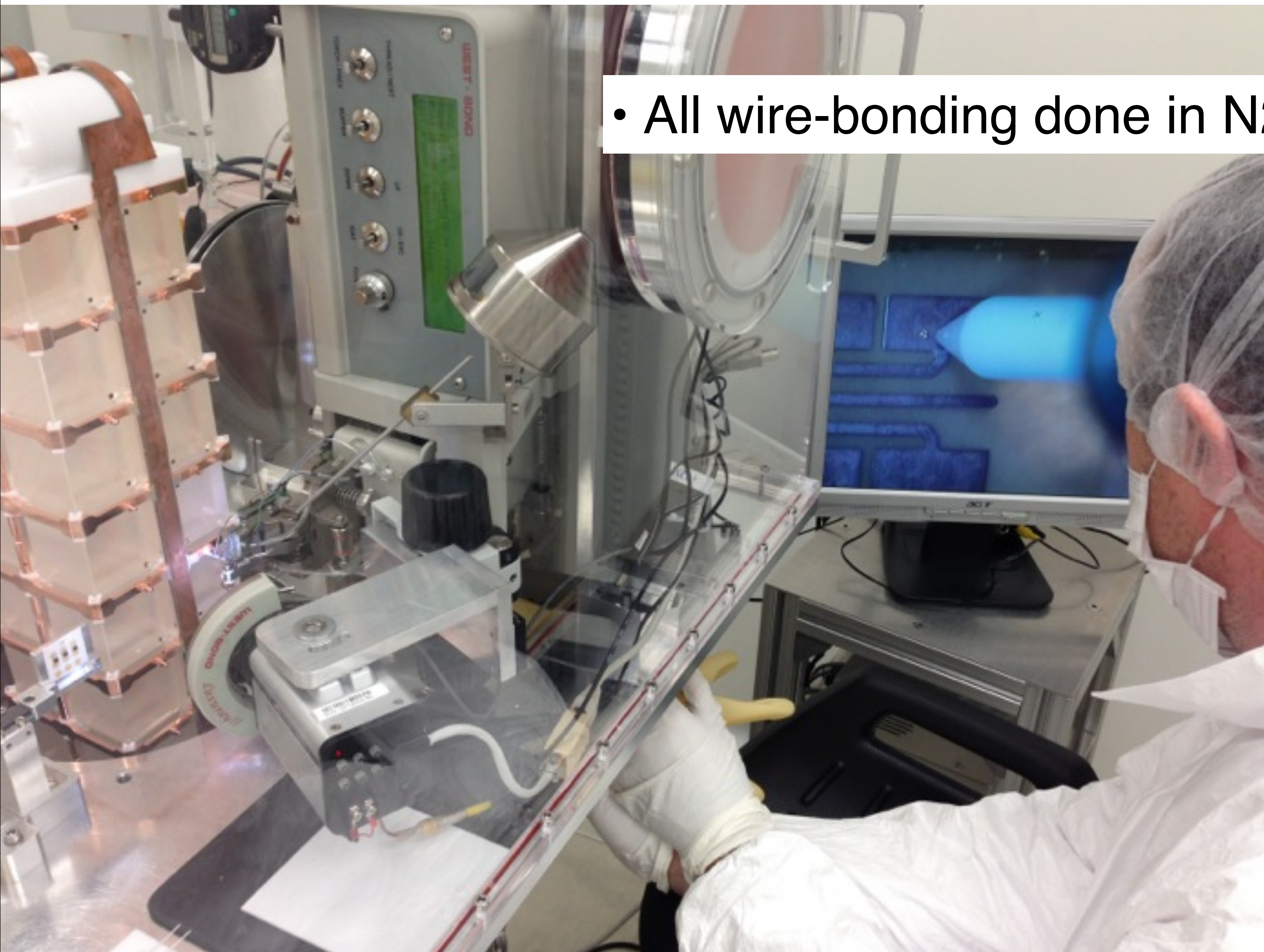




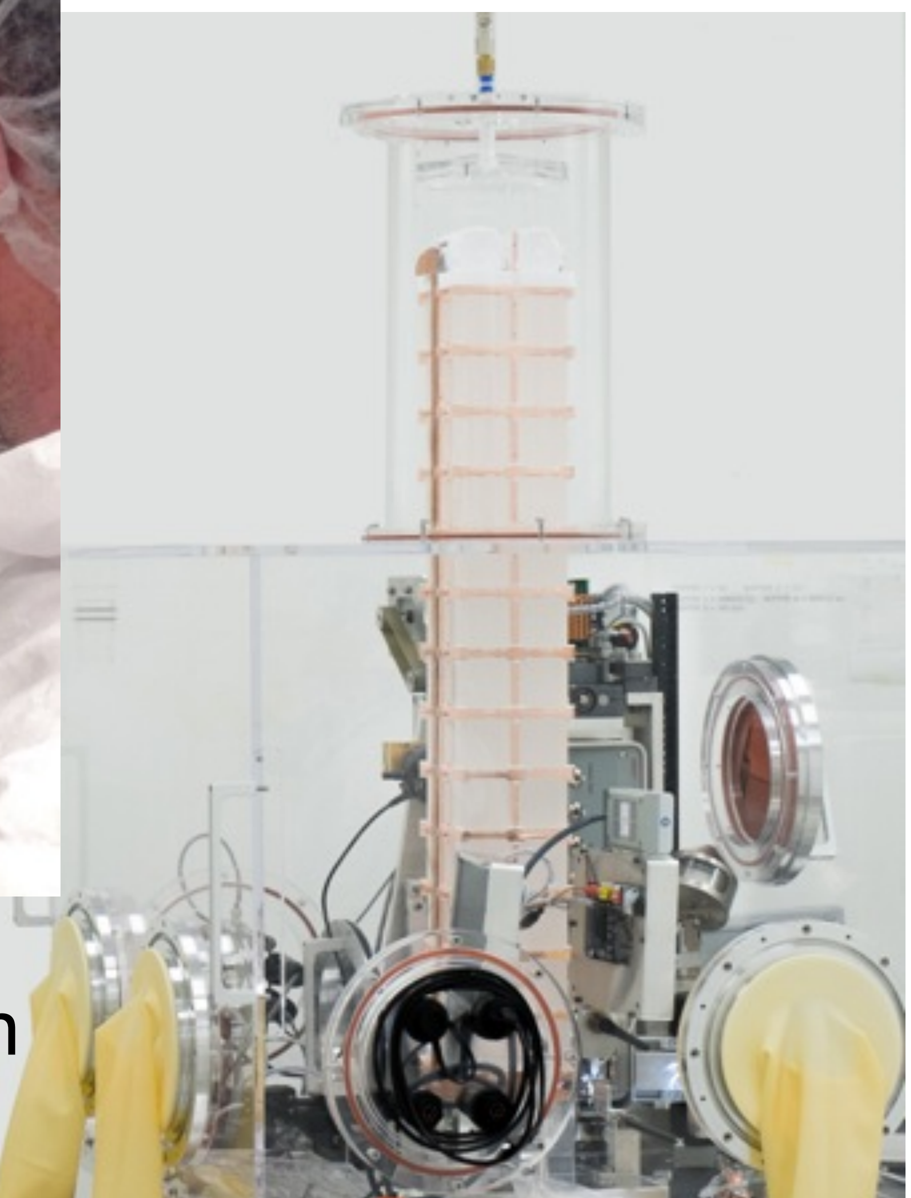




Connection to readout: Wire bonding

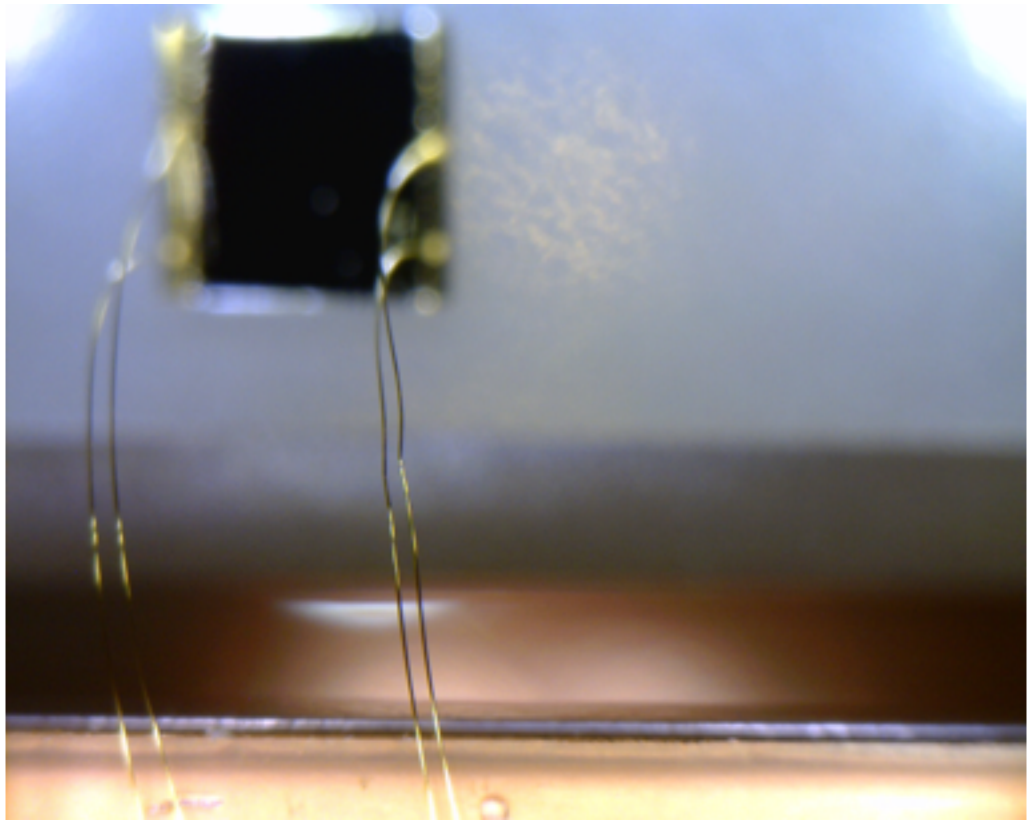


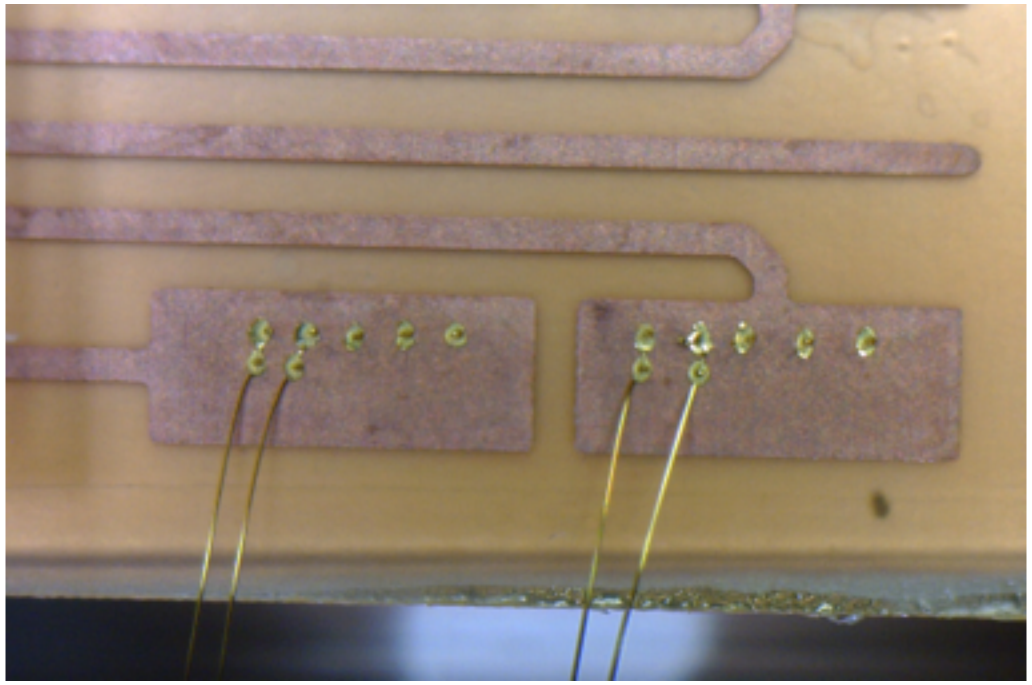
- All wire-bonding done in N2 flushed glove box

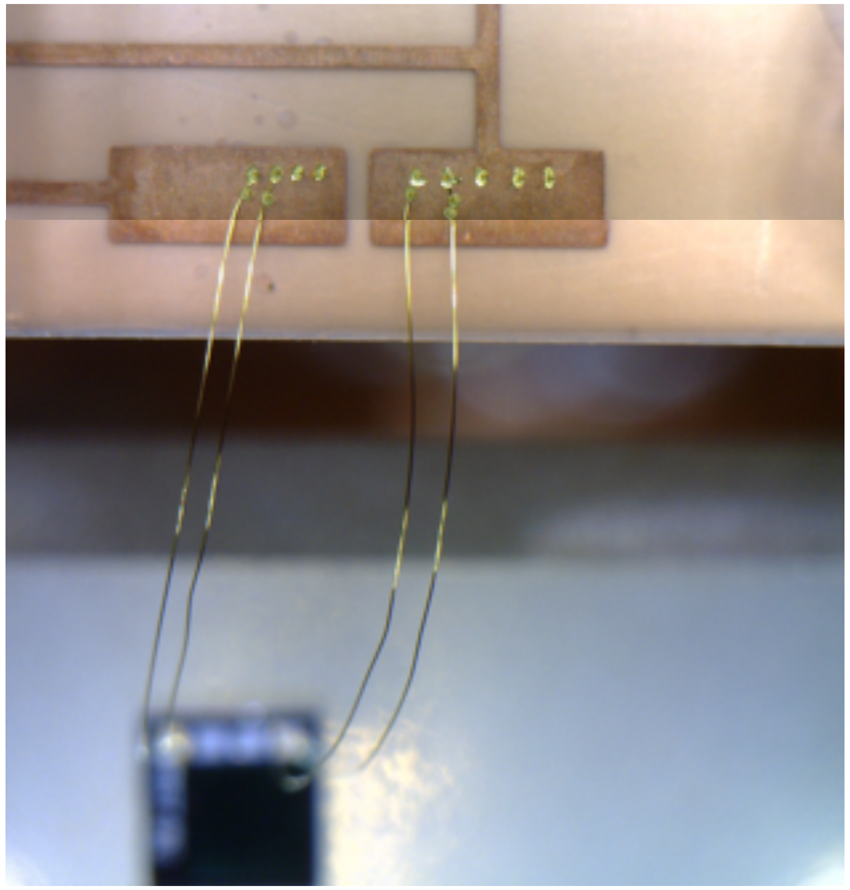


- Vertical bonding machine with auxiliary X-Y motion

Connection to readout: Wire bonding



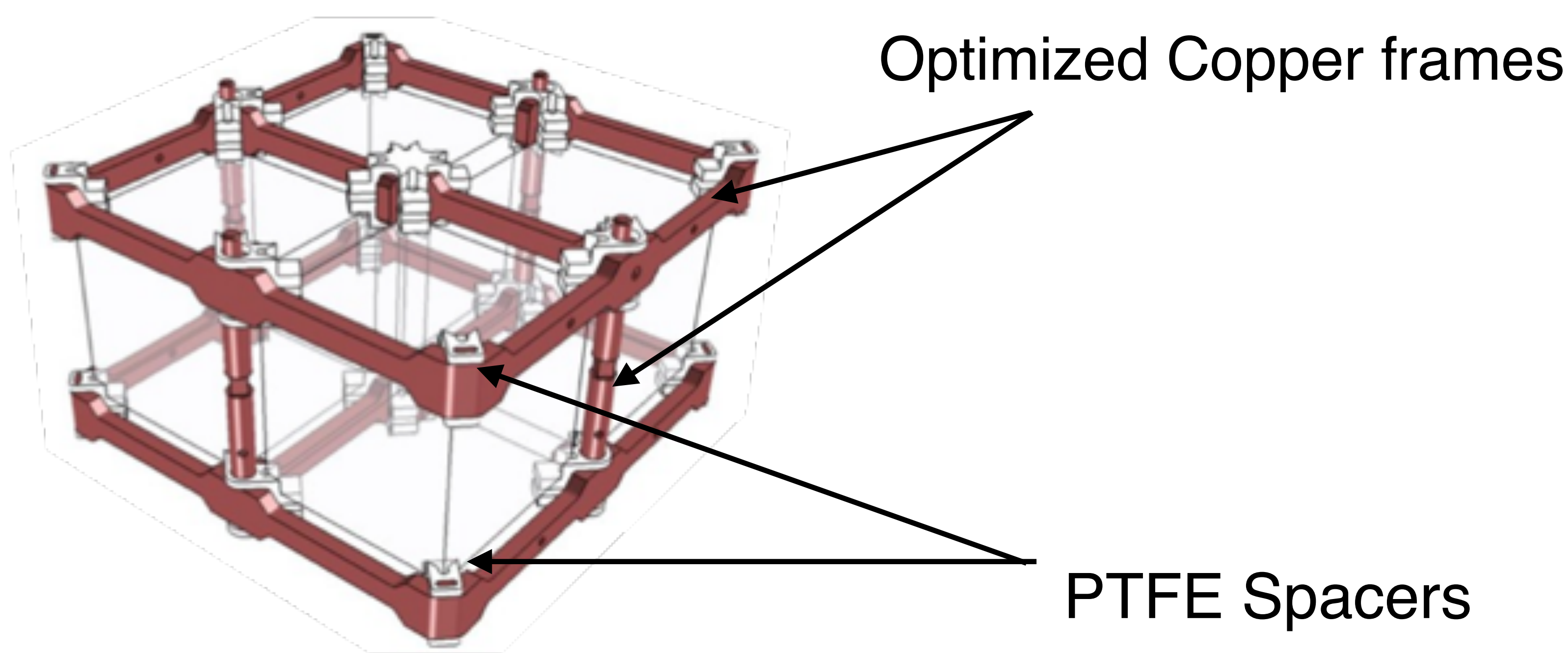




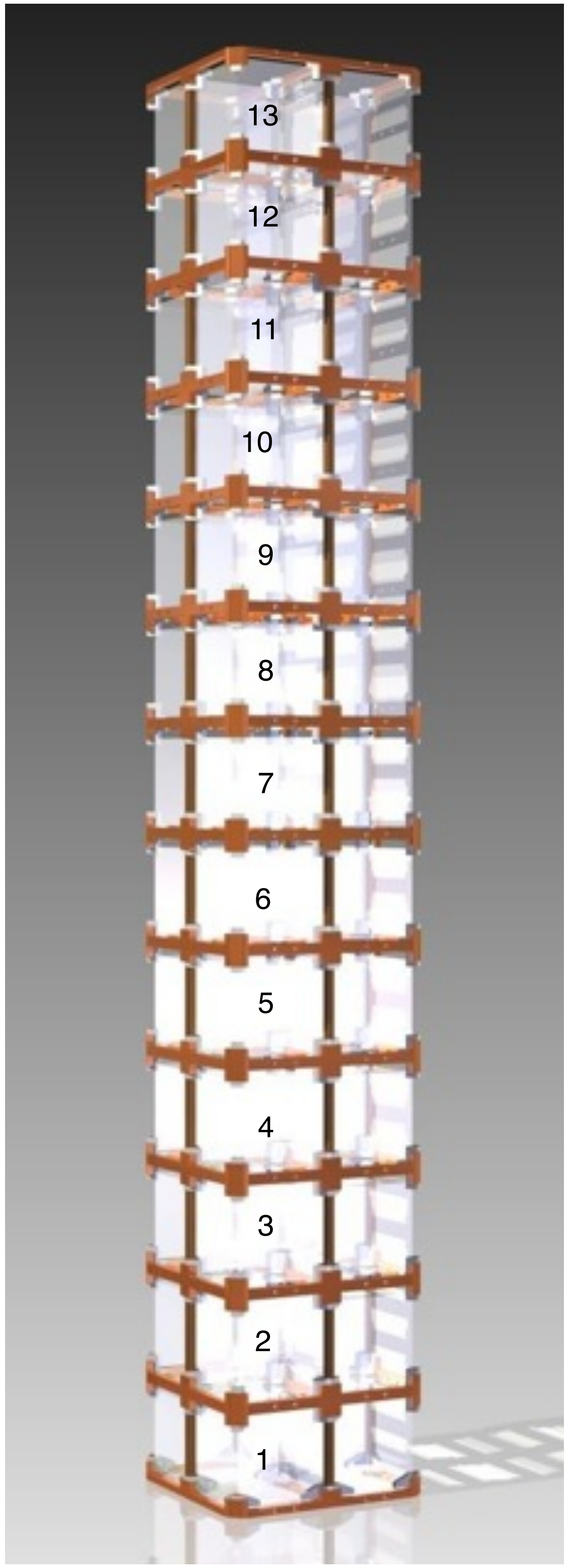
- ~8000 wire-bonds in total for CUORE
- Payout about 1.5 cm of wire per bond

CUORE-0

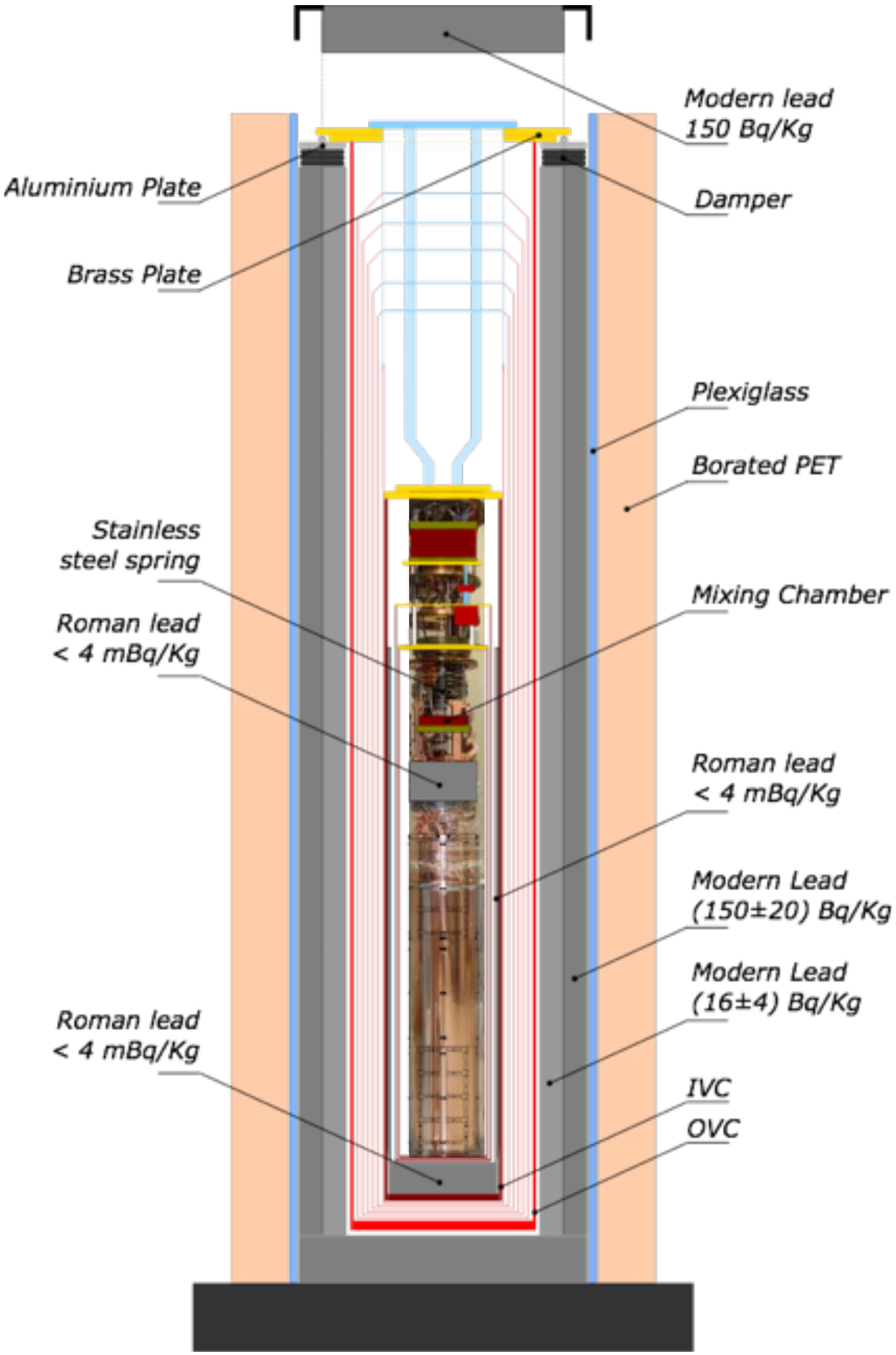
- A CUORE-style tower assembled between Fall 2011 - Spring 2012
  - 4 crystals per floor, 13 floors



  - 39 kg TeO_2 => 10.9 kg ^{130}Te



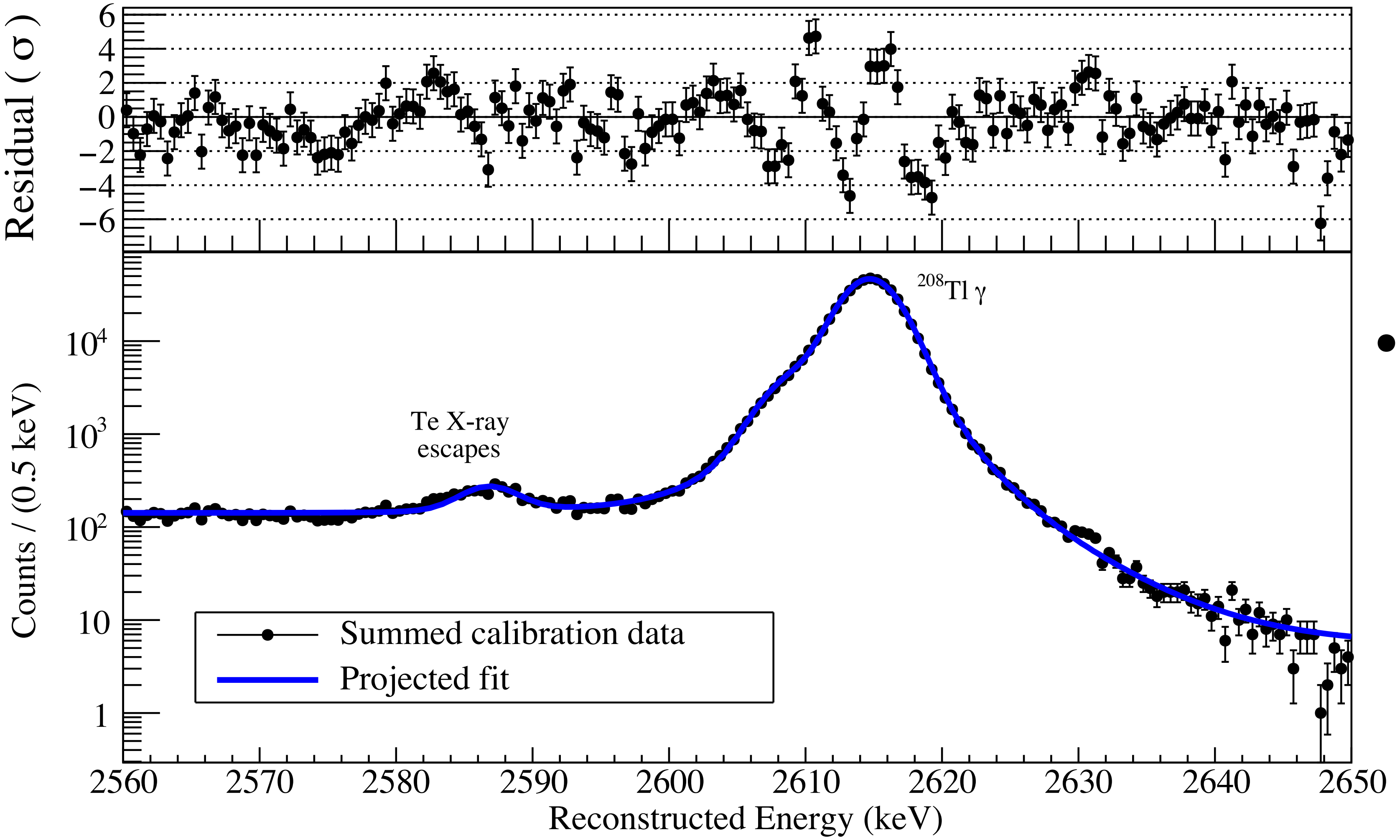
CUORE-0



- Uses the old CUORICINO cryostat
- Electronics from CUORICINO
- Shielding from CUORICINO
- Cooled to base T (~10 mK) Mar 2013
- Collected about 20 datasets so far
- 51 readable bolometers

➡ ~1000 bolometer-datasets

CUORE-0 Performance

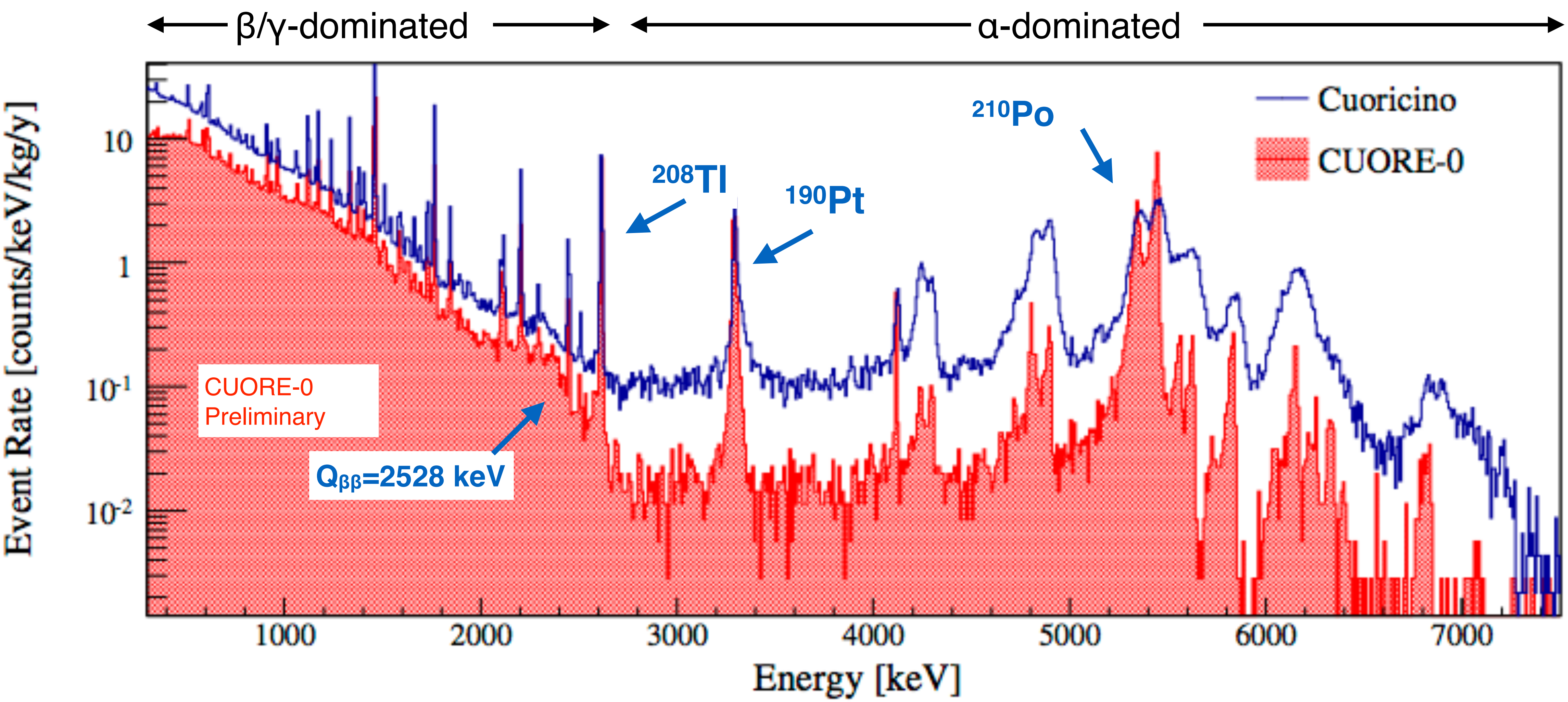


Calibration Data

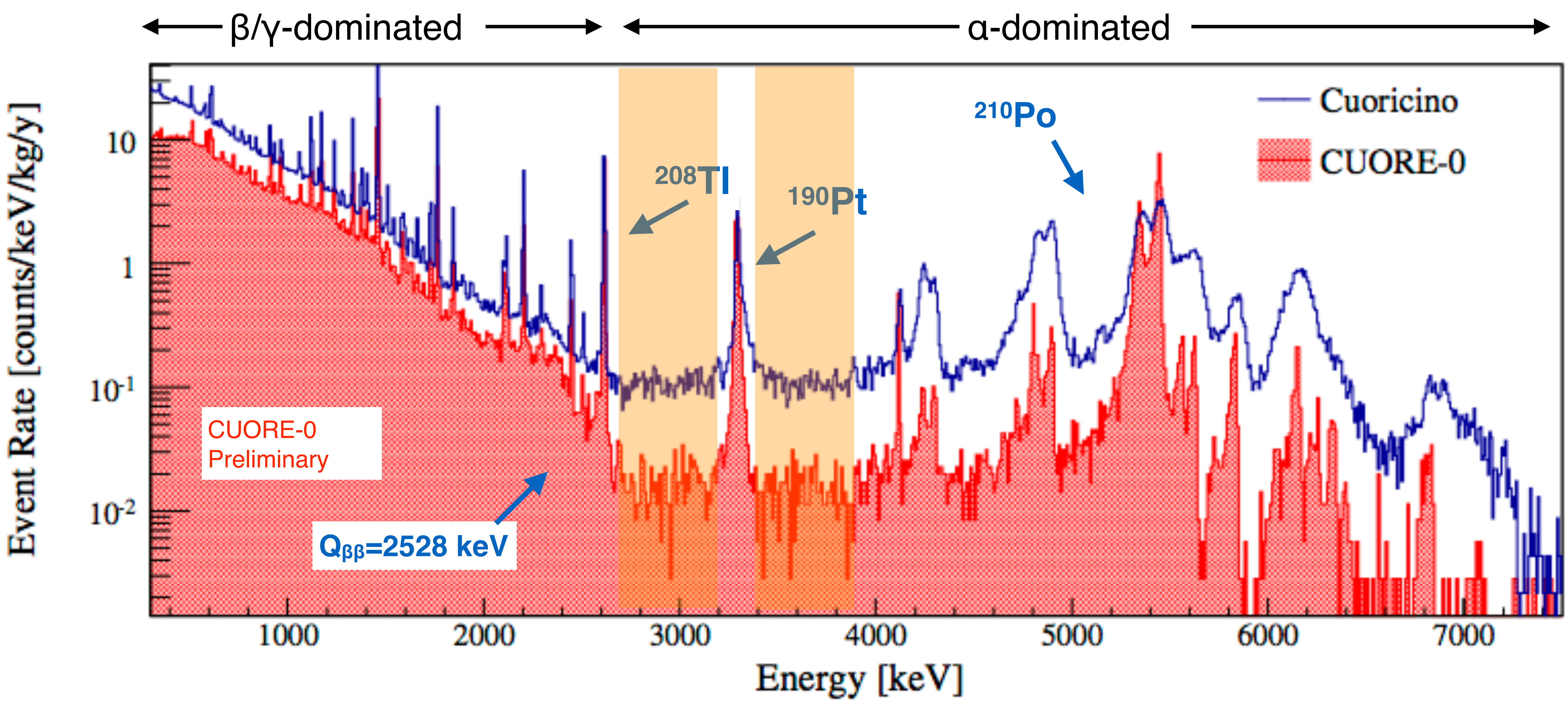
- Exposure weighted sum of the line-shapes of each bolometer-dataset overlaid 2615 keV calibration data

✓ FWHM of bolometers inline with CUORE goal of 5 keV near ROI

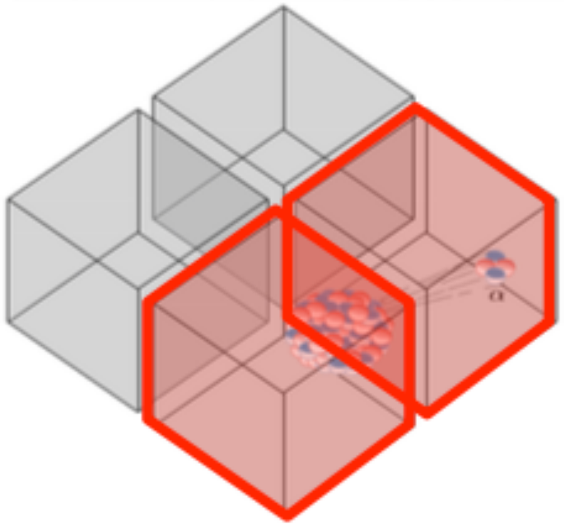
CUORE-0: Background measurement



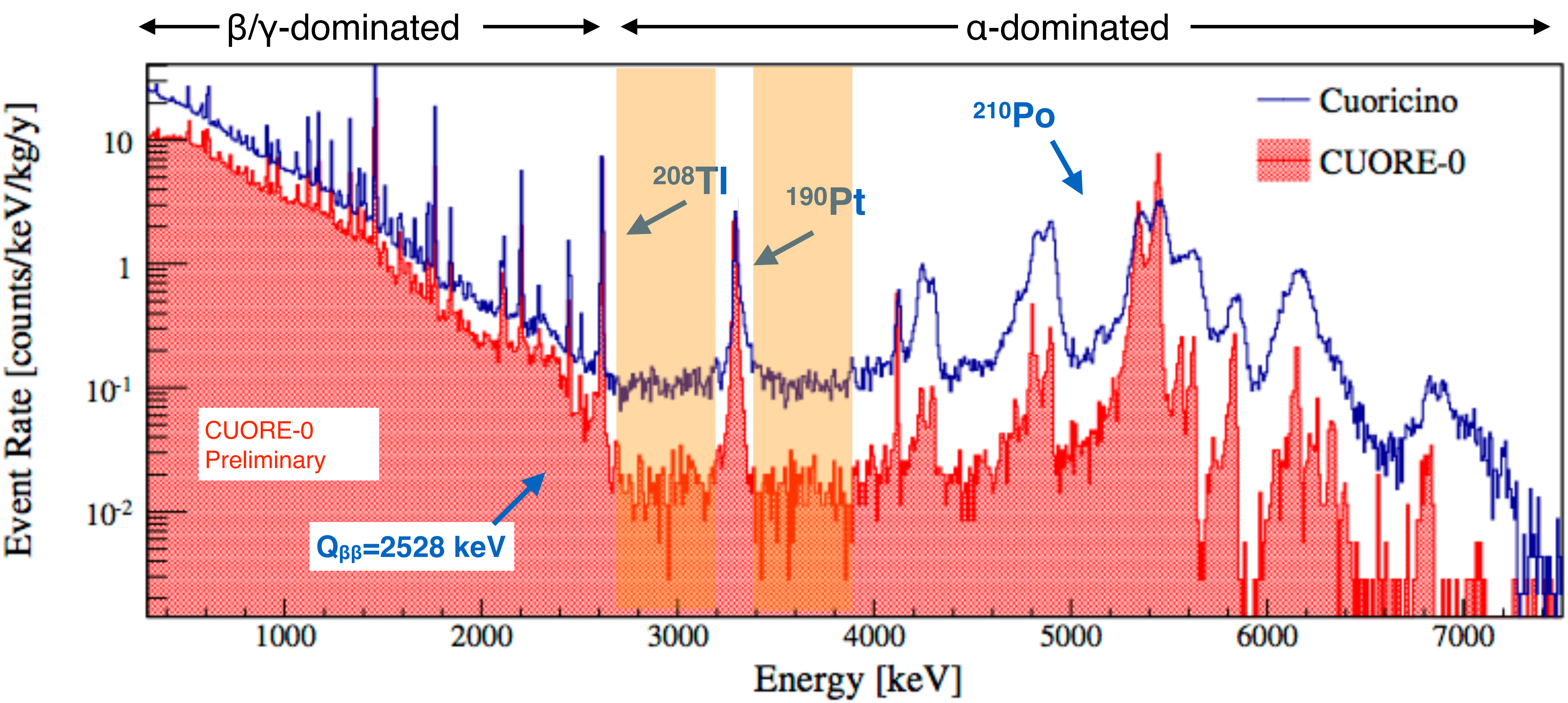
CUORE-0: Background measurement



- Use continuum in region 2700-3900 keV excluding (190Pt) to benchmark background from degraded alphas



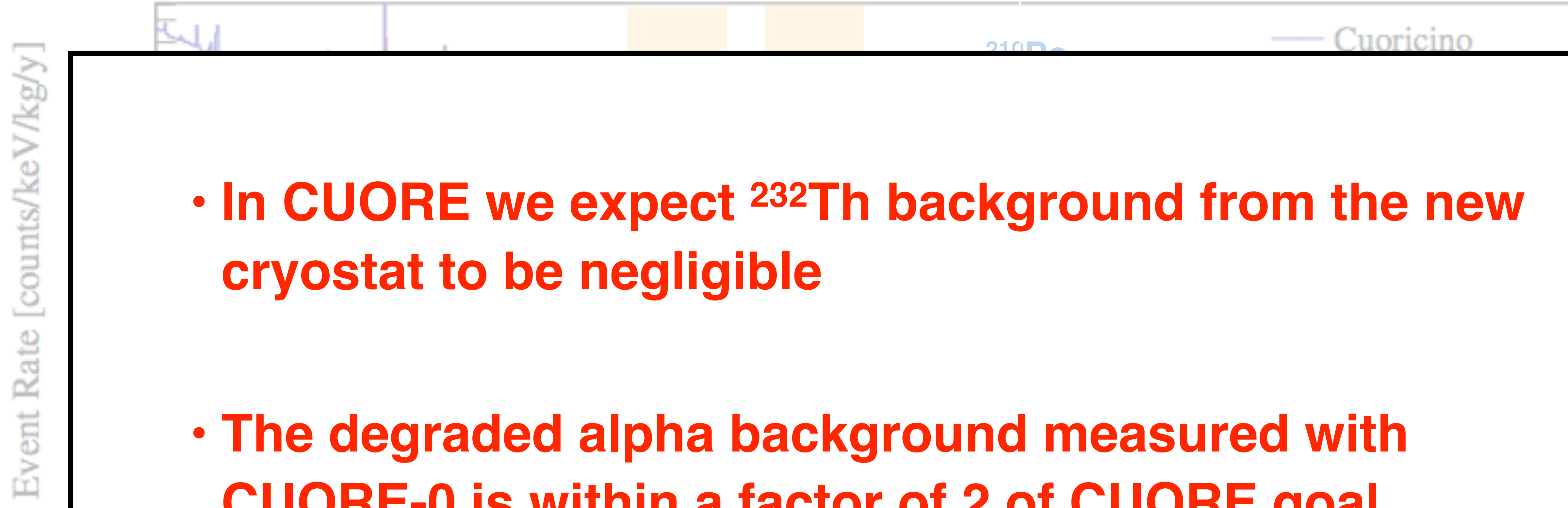
CUORE-0: Background measurement



	0νββ region (c/keV/kg/yr)	2700-3900 keV * (c/keV/kg/yr)
CUORICINO ε = 83%	0.169 +/- 0.006	0.110 +/- 0.001
CUORE-0 ε = 81%	0.058 +/- 0.004	0.016 +/- 0.001

CUORE-0: Background measurement

← β/γ-dominated → ← α-dominated →



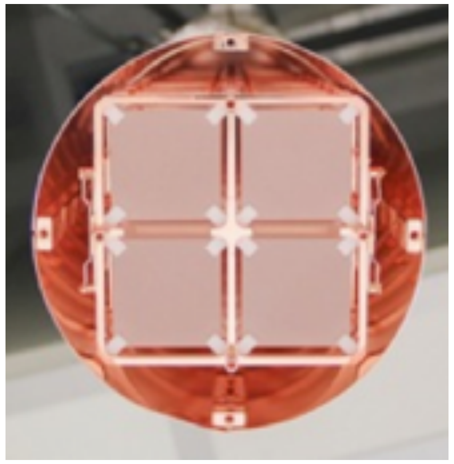
- **In CUORE we expect ^{232}Th background from the new cryostat to be negligible**

- **The degraded alpha background measured with CUORE-0 is within a factor of 2 of CUORE goal (0.01 counts/keV/kg/yr)**

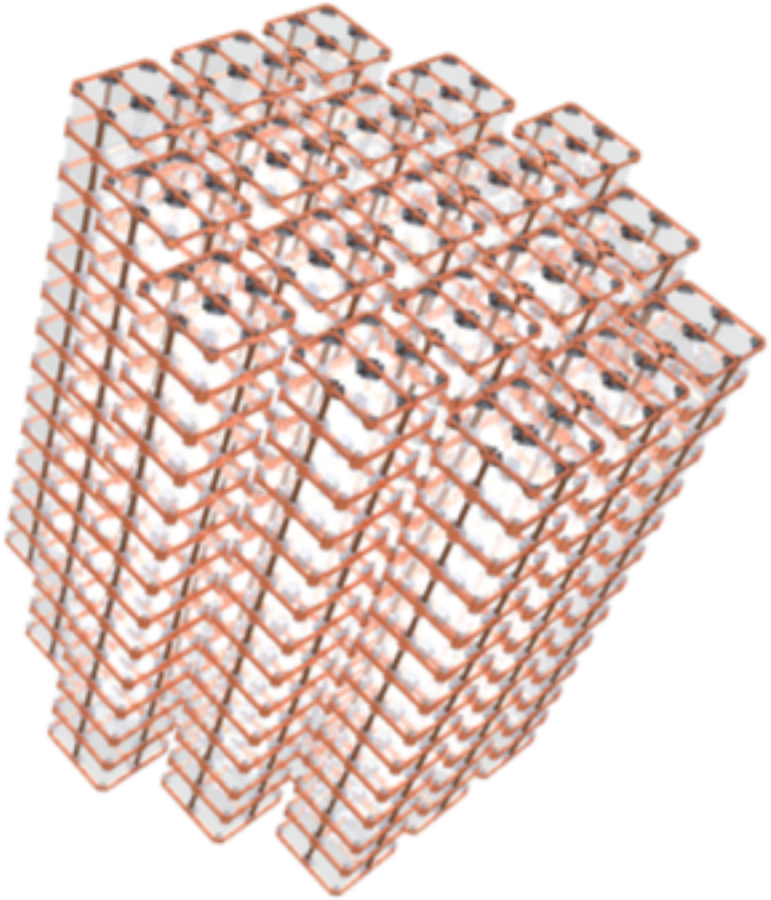
	0νββ region (c/keV/kg/yr)	2700-3900 keV * (c/keV/kg/yr)
CUORICINO ε = 83%	0.169 +/- 0.006	0.110 +/- 0.001
CUORE-0 ε = 81%	0.058 +/- 0.004	0.016 +/- 0.001

CUORE: Self Shielding

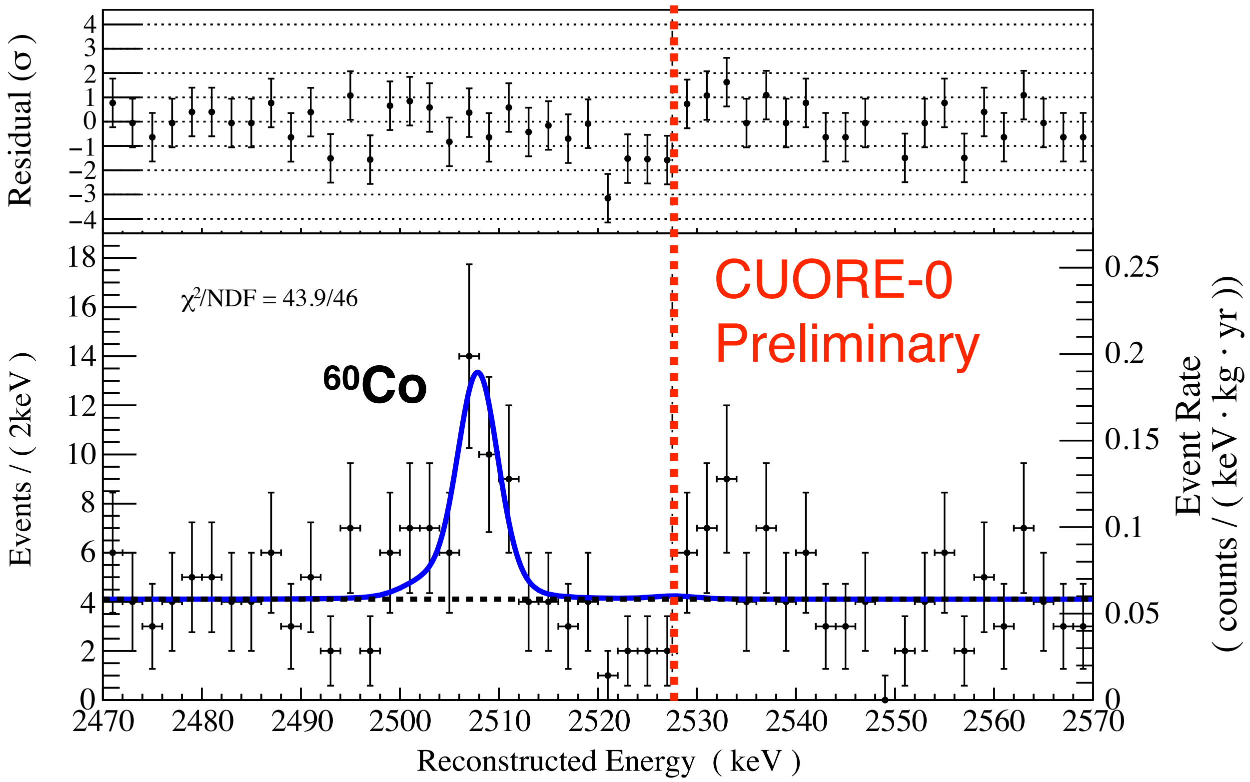
- CUORE-0: All bolometers face 10 mk shield

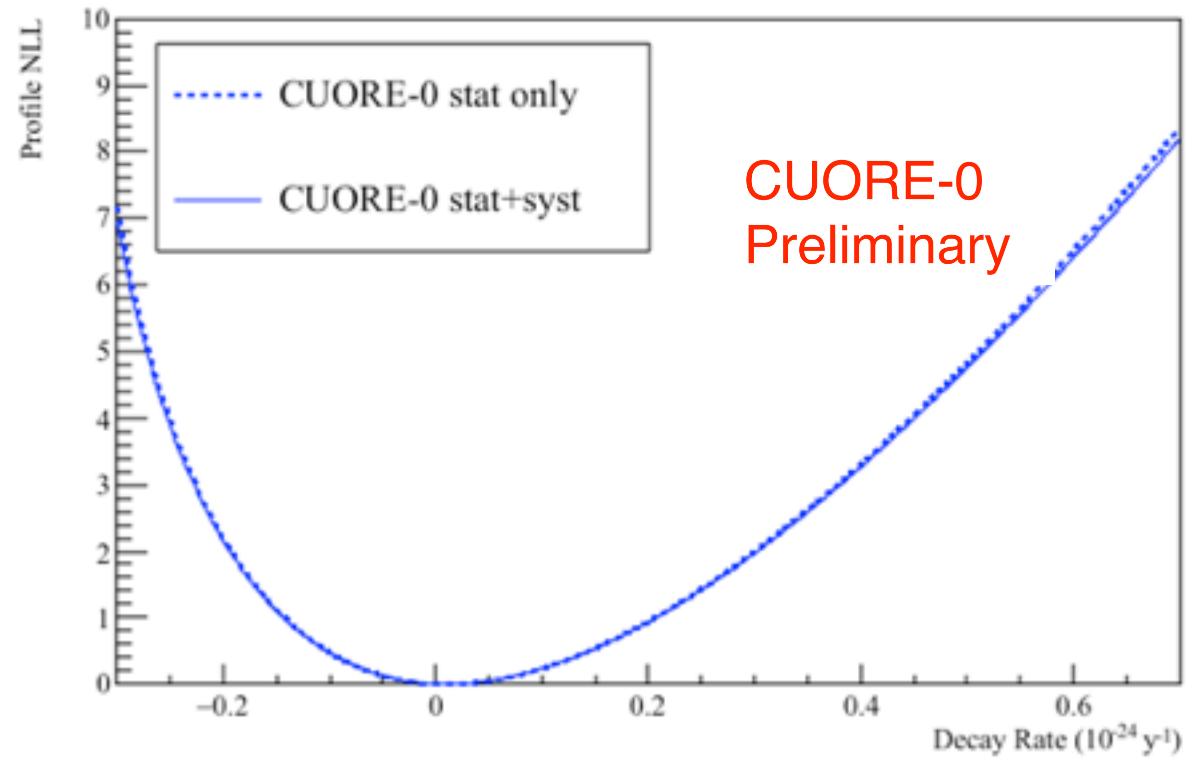


- CUORE: Only outermost crystals face 10mk shield



CUORE-0: $0\nu\beta\beta$ Search





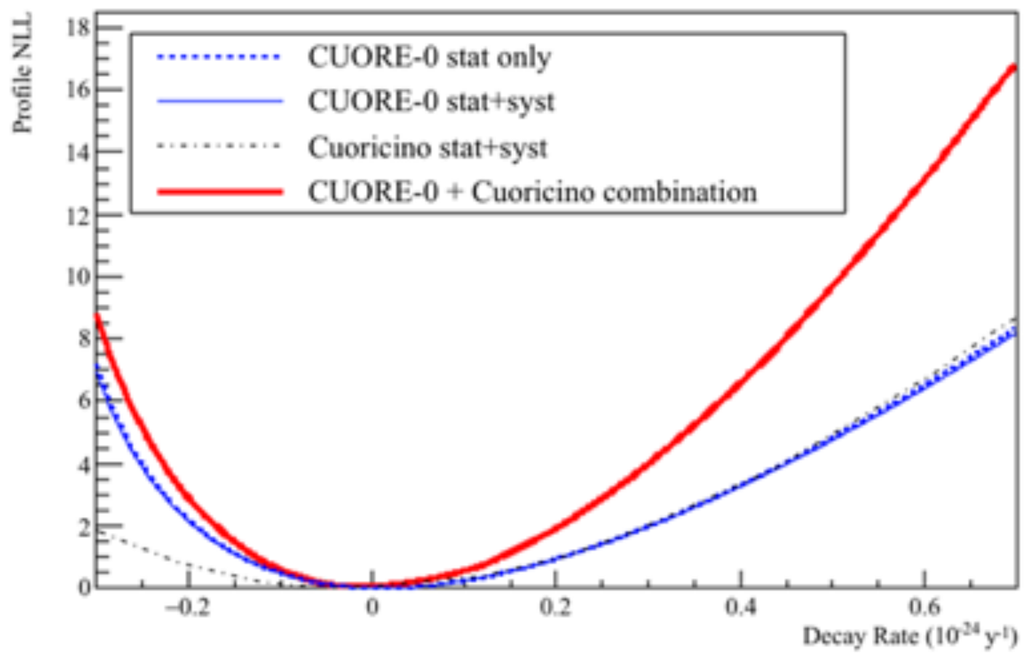
$Q_{\beta\beta}$ @ 2527.5 keV

- After all cuts: 233 events in 9.8 kg × yr exposure of ^{130}Te in ROI [2470-2570 keV]

$\Gamma_{0\nu}$	$0\nu\beta\beta$ decay rate	$0.01 \pm 0.12\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \times 10^{-24}\ \text{yr}^{-1}$
Γ_B	Background rate	$0.058 \pm 0.004\,(\text{stat.}) \pm 0.002\,(\text{syst.})\ \text{counts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$

➡ Bayesian lower limit $T^{0\nu}_{1/2} > 2.7 \times 10^{24}\ \text{yr}$ 90% C.L.

CUORE-0: Combination with CUORICINO

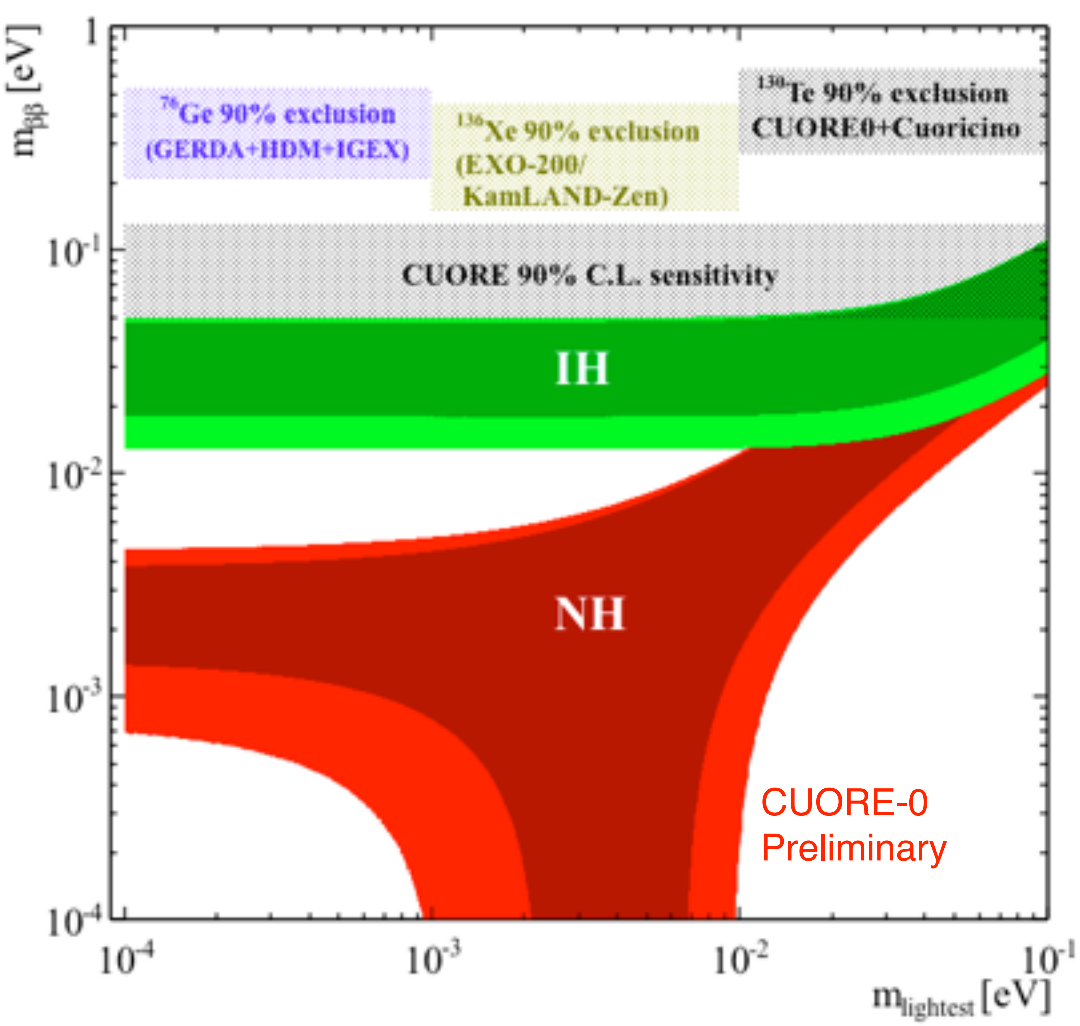


- The 90% C.L. (Bayesian) lower limit based on the combined profile function

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

- This is the most stringent limit on this half-life !

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



$\langle m_{\beta\beta} \rangle < 270 - 650$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

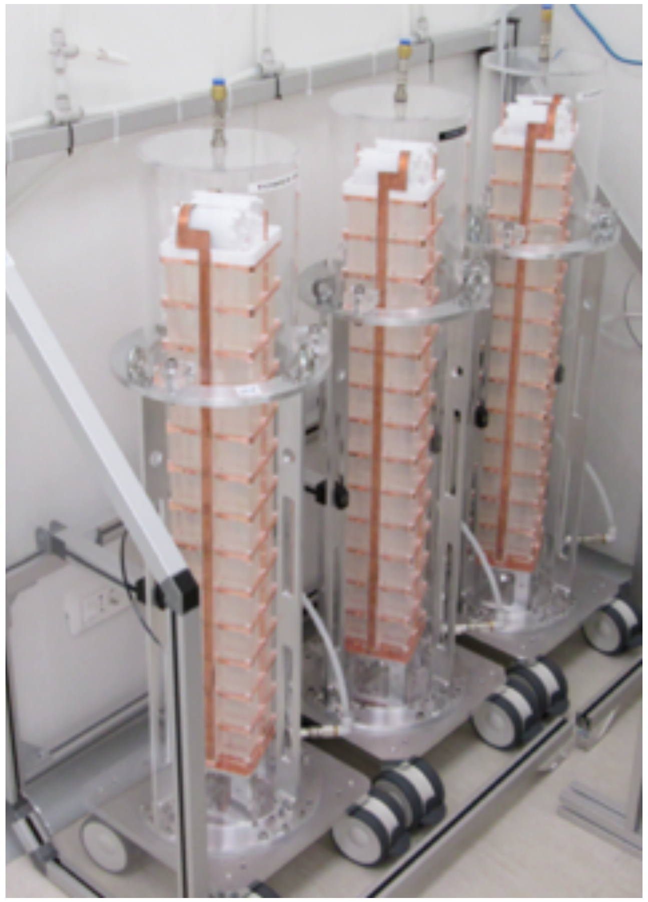
$\langle m_{\beta\beta} \rangle < 270 - 760$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME

Status of CUORE

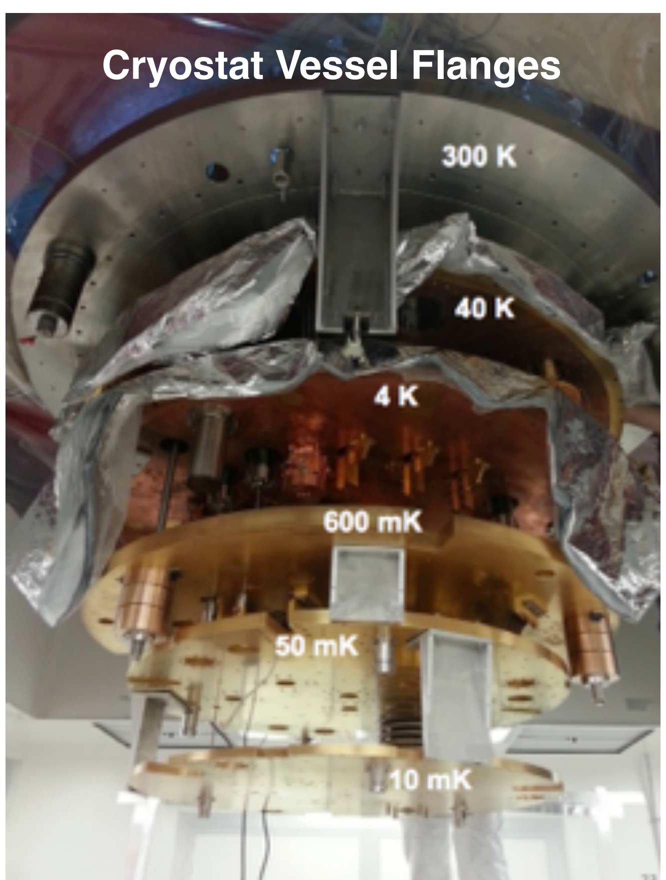
☑ Assembly of all 19 towers completed

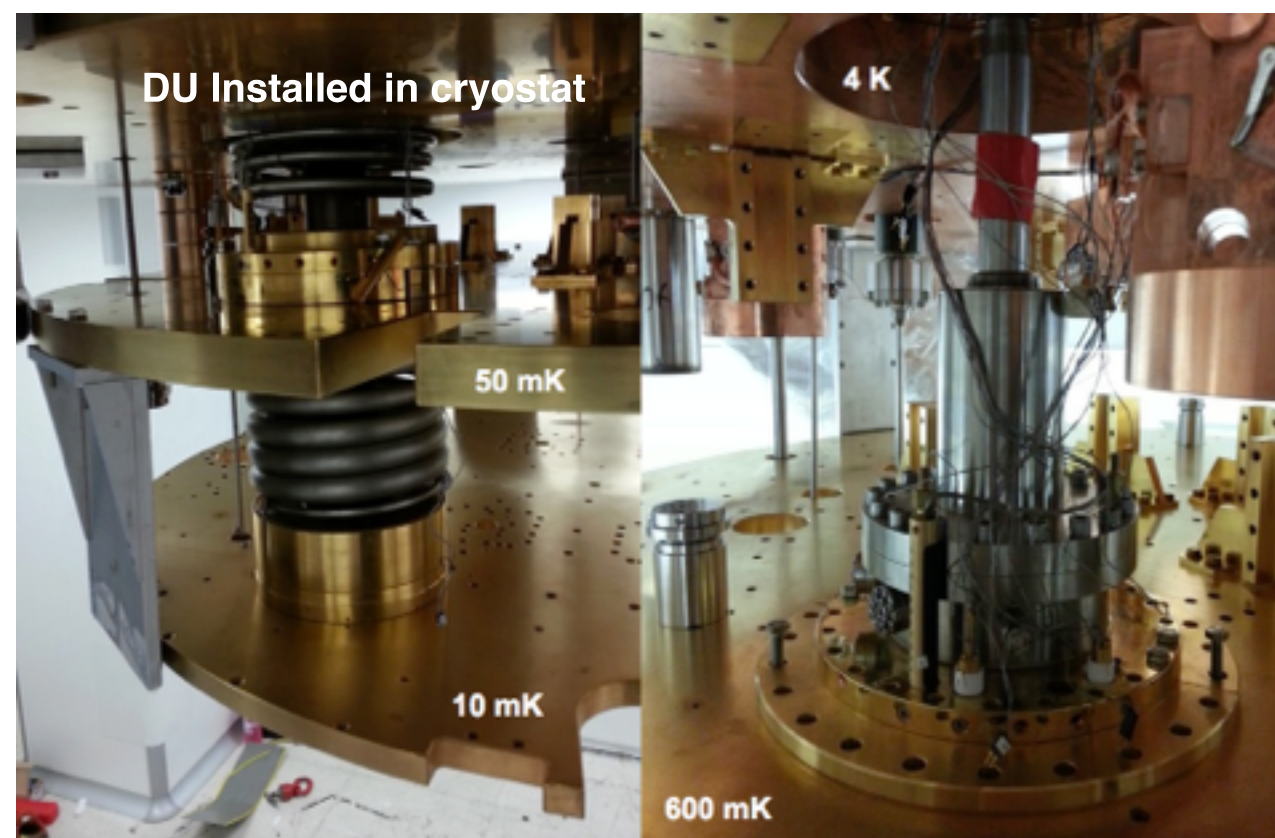


☑ Expect to deploy the array in the cryostat later this year

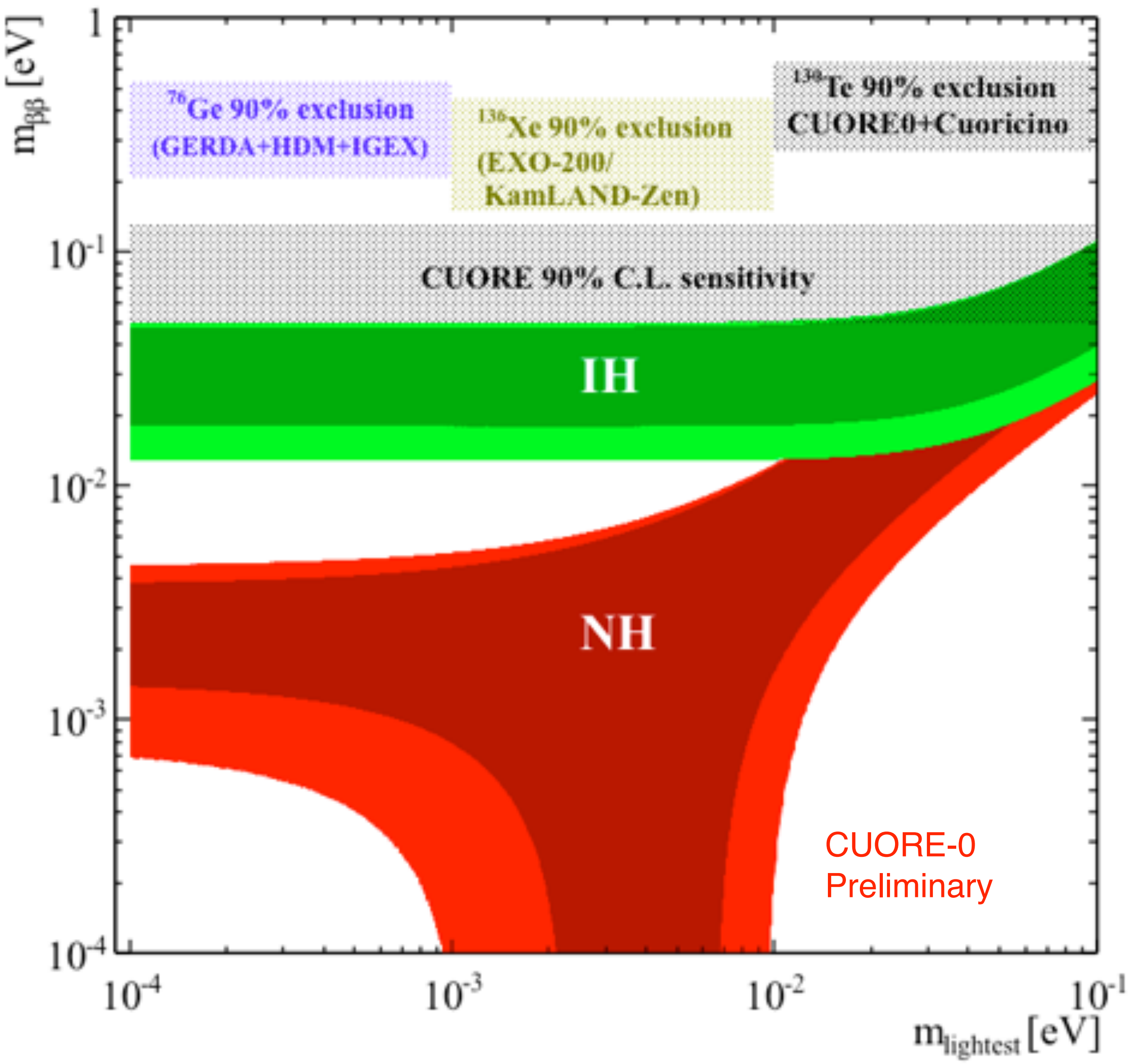
Status of CUORE: Cryogenic System

- ☑ Cryostat assembled, passed 4K commissioning test
- ☑ Dilution unit delivered to LNGS, able to maintain ~5mK in standalone commissioning tests
- ☑ 2 out of 3 planned integration runs already reached ~6mK base T
- ☑ Final integration run (everything except detectors) is ongoing





CUORE Sensitivity



half-life sensitivity

$$\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Assumptions:

- 988 bolometers
- 5 years of lifetime
- δE = 5 keV FWHM at 2615 keV
- b = 0.01 counts/(keV · kg · yr)

$$T^{0\nu}_{1/2} > 9.25 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

- Interpretation of ^{130}Te 0νββ half-life limit in terms of $m_{\beta\beta}$

$$m_{\beta\beta} < (50 - 130\,\mathrm{meV})$$

- CUORE may start to explore the inverted-hierarchy (depending on the NME)

Conclusion

- Lessons learned from CUORICINO have guided the CUORE-0/CUORE design

- Data from CUORE-0 verifies the new assembly line, materials selection, and ultra-cleaning protocols reduce pernicious surface backgrounds

- CUORE-0 combined with CUORICINO provides the most stringent limit to date on $0\nu\beta\beta$ decay of ^{130}Te

http://arxiv.org/abs/1504.02454
Submitted to PRL

$$T^{0\nu}_{1/2} > 4.0 \times 10^{24}\ \mathrm{yr}$$ (90% C.L.) $$\langle m_{\beta\beta} \rangle < 270 - 760\ \mathrm{meV}$$

- CUORE array is ready and cryogenic commissioning is advancing

- Expect array to be deployed in cryostat in 2015

Other slides

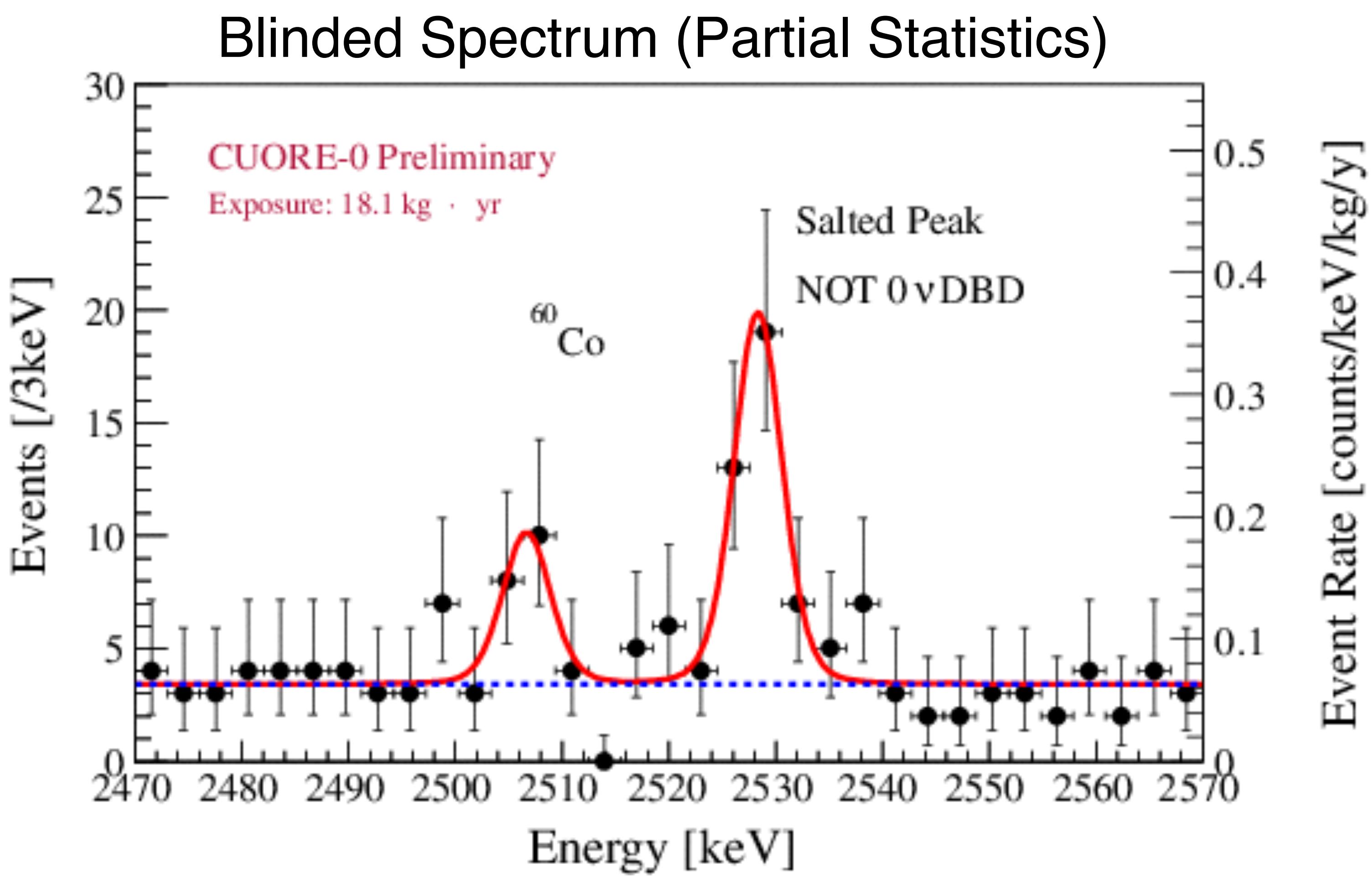
CUORE

CUORE-0: Selection Efficiency

- The data quality cuts reduce the total exposure by 7%
- Effective exposure: 35.2 kg × yr TeO_2 or 9.8 kg × yr ^{130}Te
- Selection efficiencies

Selection	Efficiency (%)
Trigger & reconstruction	98.529 ± 0.004
Pileup & Pulse shape	93.7 ± 0.7
Anticoincidence ($0\nu\beta\beta$ containment)	88.4 ± 0.09
Anticoincidence (survive accidental)	99.6 ± 0.1
Total	81.3 ± 0.6

CUORE-0: Fit procedure for ROI



- Model ROI [2470 - 2570 keV] with:
  - Peak for possible $0\nu\beta\beta$ events
  - Peak for ^{60}Co events
  - Continuum underlying background (use 0th-order polynomial)

Free parameters of the fit model

$\Gamma_{0\nu}$	$0\nu\beta\beta$ decay rate
$N_{^{60}\mathrm{Co}}$	Number of ^{60}Co events
$\Delta\mu(^{60}\mathrm{Co})$	^{60}Co energy offset
Γ_B	Background rate

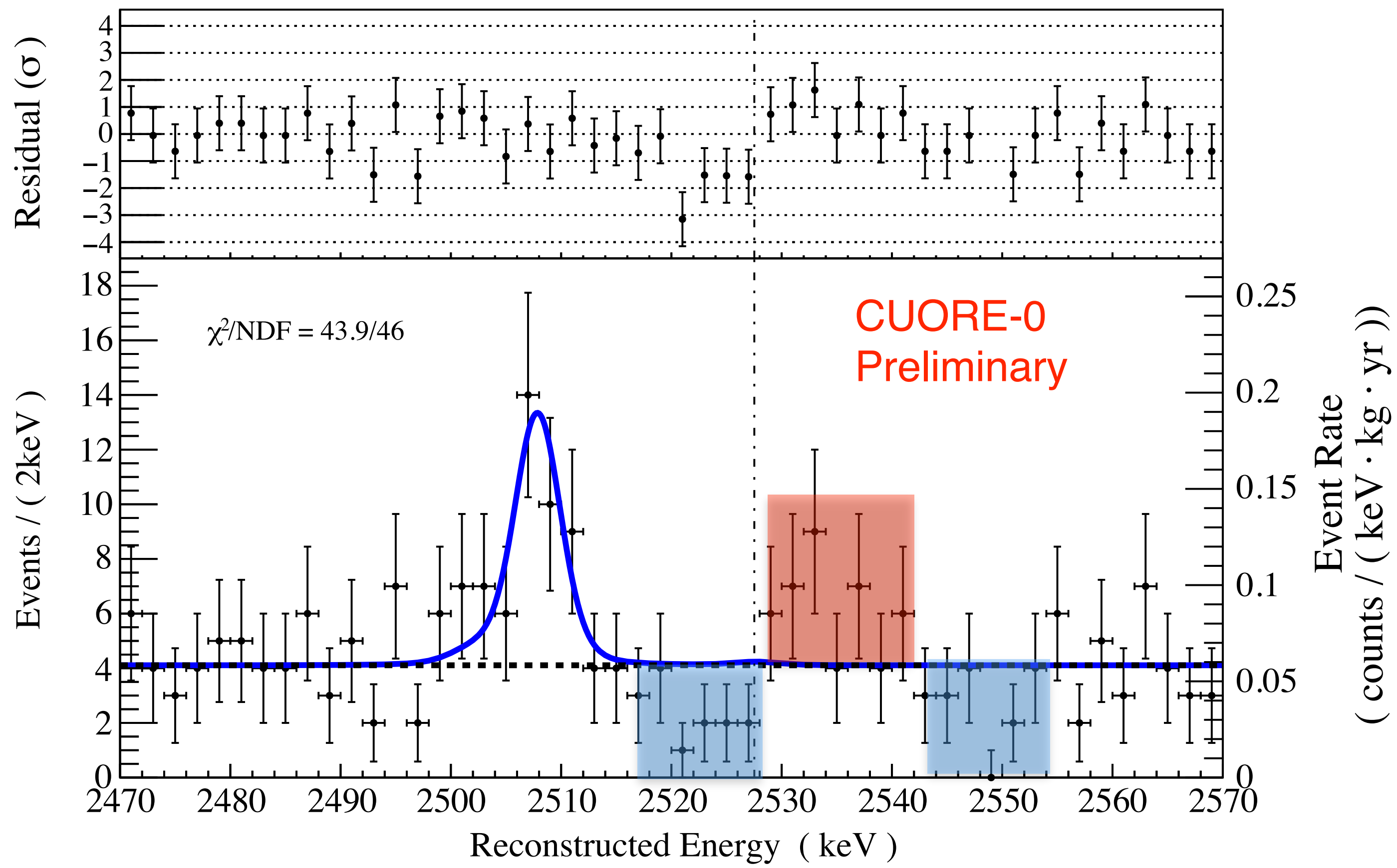
CUORE-0: Systematic Uncertainty

- We estimate systematic uncertainties and how they scale with $0\nu\beta\beta$ decay rate using toy Monte Carlo
  - ➡ Fit Bias: Find fit procedure is not biased
  - ➡ Line-shape: studied single and triple gaussian alternatives
  - ➡ Continuum Background: studied 1st and 2nd order polynomial alternatives
  - ➡ Energy resolution: varied the resolution scaling parameter $\alpha(Q_{\beta\beta})$ within its uncertainty (0.05 %)
  - ➡ Energy scale: Varied the energy offset parameter $\Delta\mu(Q_{\beta\beta})$ within its uncertainty (0.12 keV)

Systematic uncertainties on $\Gamma_{0\nu}$ in the limit of zero signal (Additive) and how they scale with nonzero signal (Scaling)

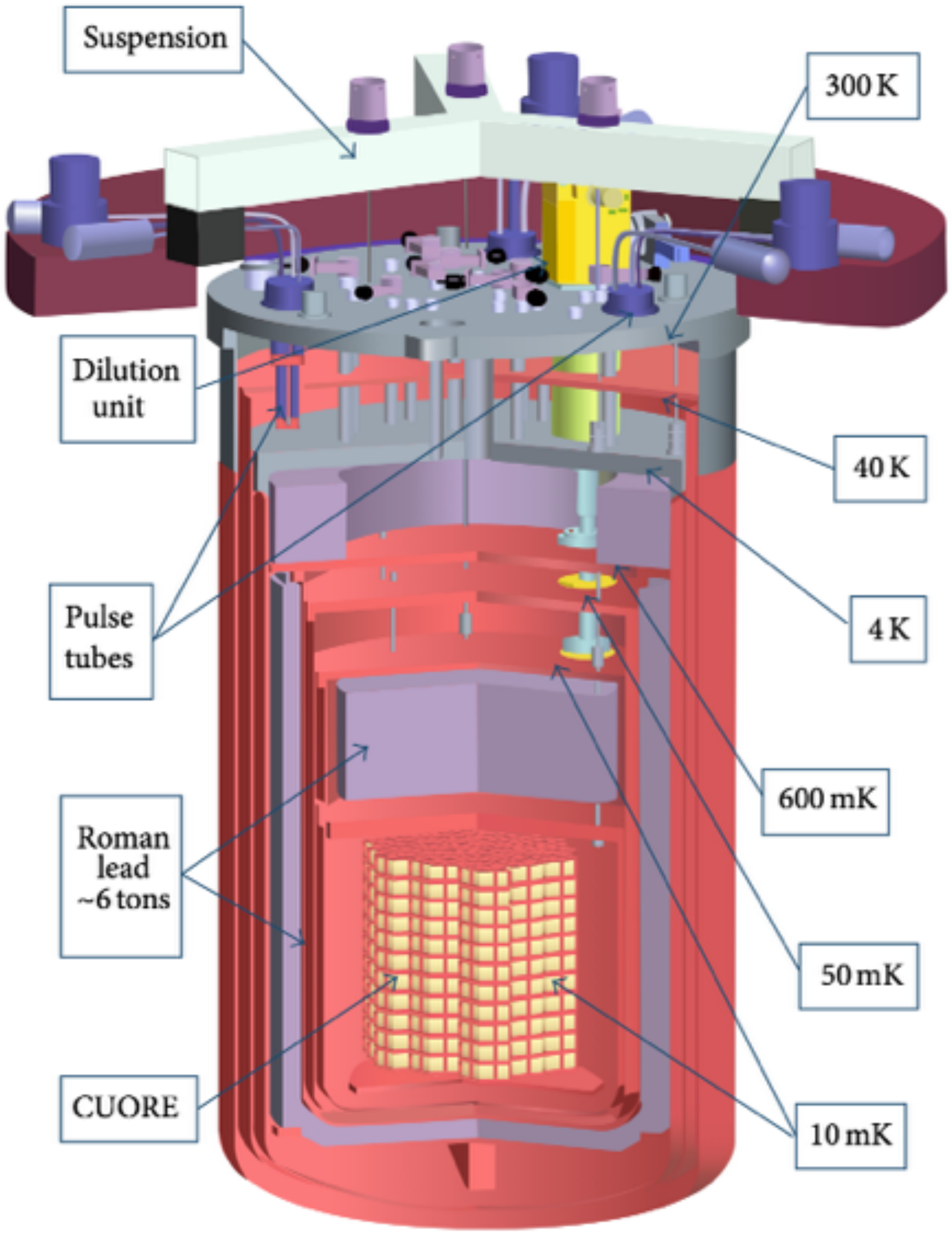
	Additive (10^{-24} y^{-1})	Scaling (%)
Lineshape	0.007	1.3
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Signal normalization	0.7%	

Significance of fluctuations



- Estimate the significance of the fluctuations from a likelihood ratio test
- Compare hypotheses modeling the fluctuations with a peak to our best-fit model
- All fluctuations have significance < 3 sigma C.L
- Probability to observe the largest fluctuation somewhere in the 100 keV ROI is ~10%

Status of CUORE: Cryogenic System



- OVC(300K):
  - h = 3.1 m
  - d = 1.7 m
- Mass:
  - Detectors ~ 1 ton
  - Pb shielding ~ 8 tons
  - Cu vessels/thermal shields ~ 8 tons
- Cryogen free
  - 5 pulse tubes for pre-cooling
- High cooling-power dilution unit
  - 2 mW @ 100 mK

Beyond CUORE ?

- Next generation aims to use active rejection techniques to dramatically reduce background: CUORE Upgrade with Particle ID (CUPID)

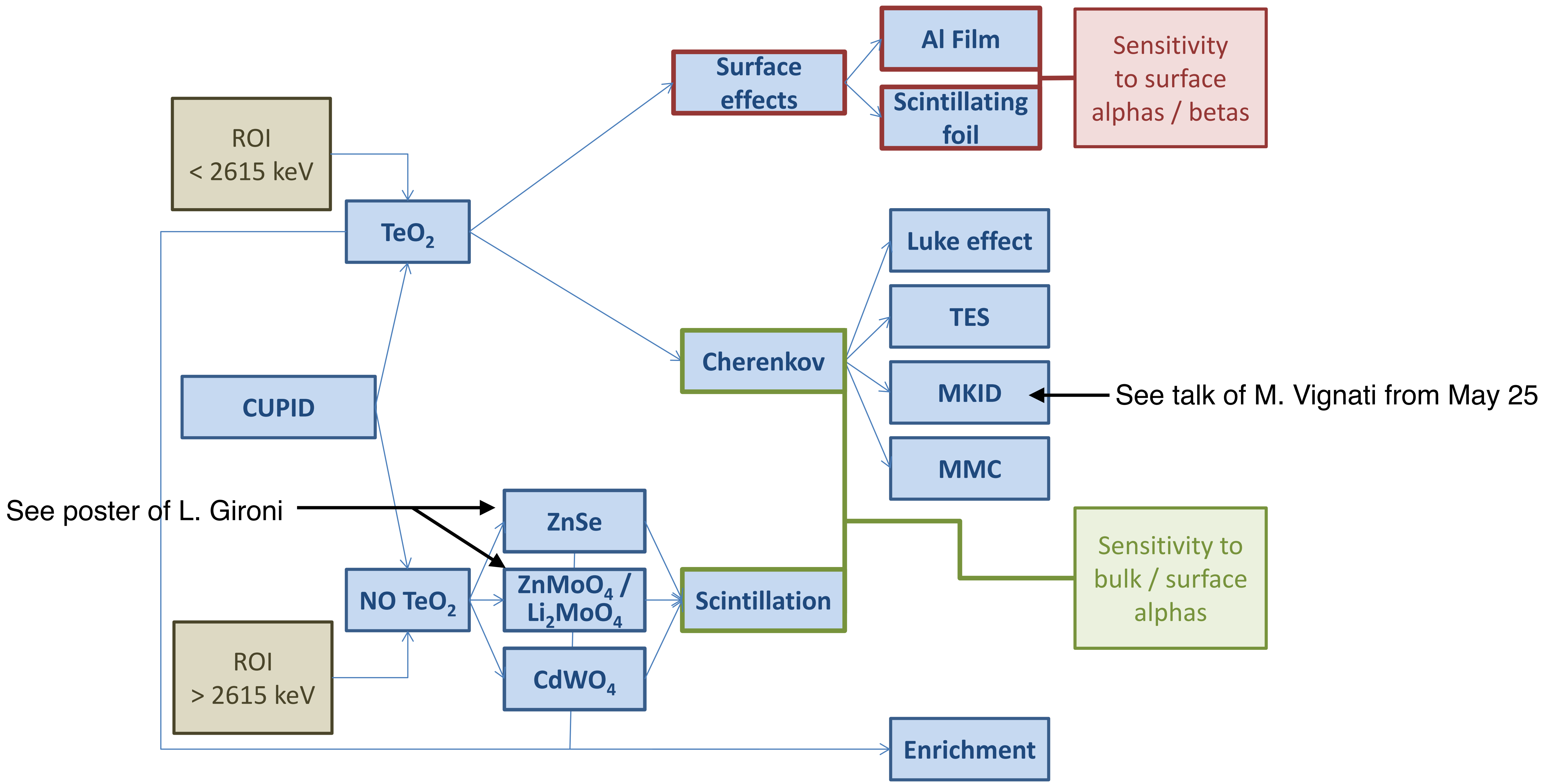


FIG. 1: Scheme of the R&D detector activities for CUPID