Search for 0νββ decay and prospects for dark matter detection with CUORE

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Interplay between Particle and Astroparticle physics

22-August-2014

… on behalf of the CUORE Collaboration

Outline

$0\nu\beta\beta$: why do we care ?

CUORE Program ($0\nu\beta\beta$ of ^{130}Te ?)

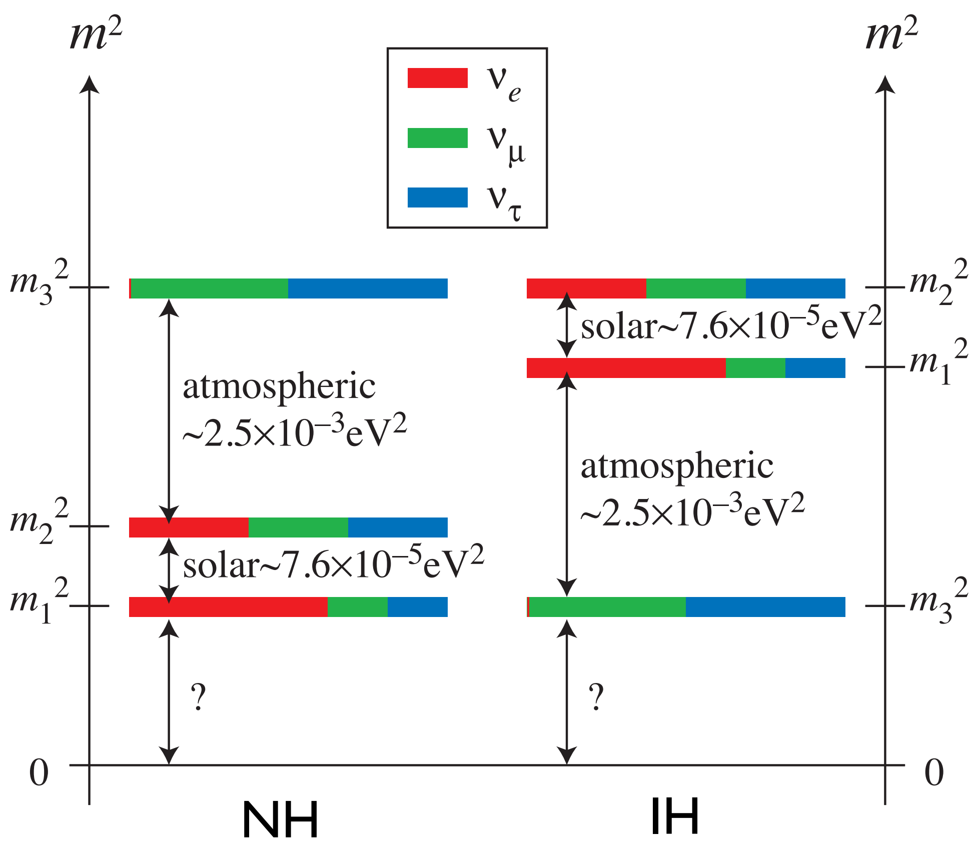
Legacy of CUORICINO

CUORE

CUORE-0

Other opportunities with CUORE: WIMP DM

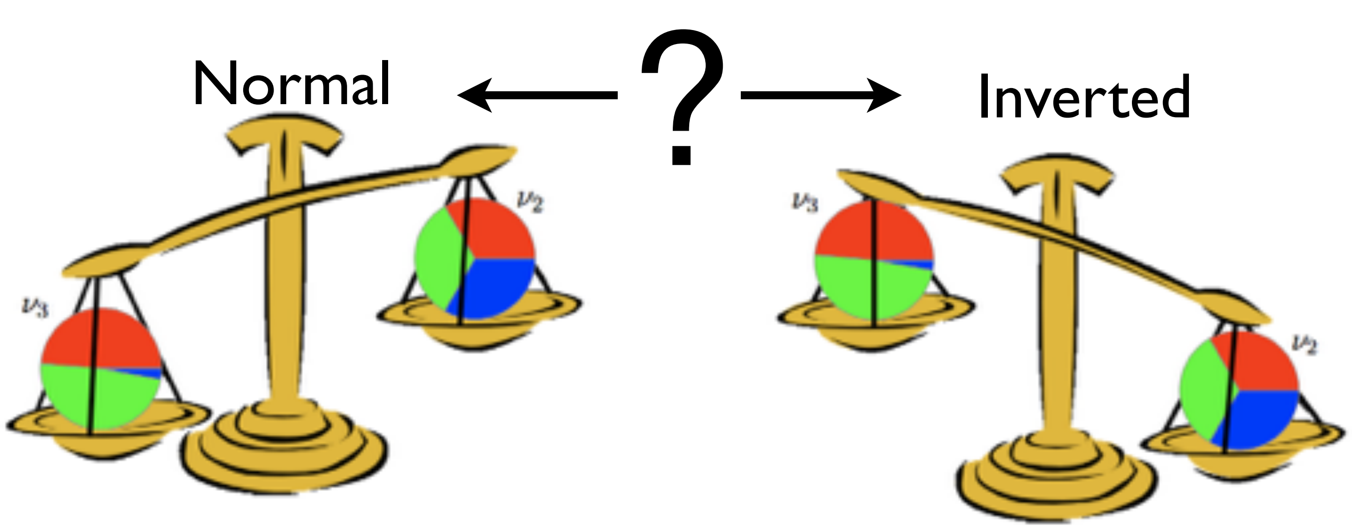
Neutrino Mass: Some open questions



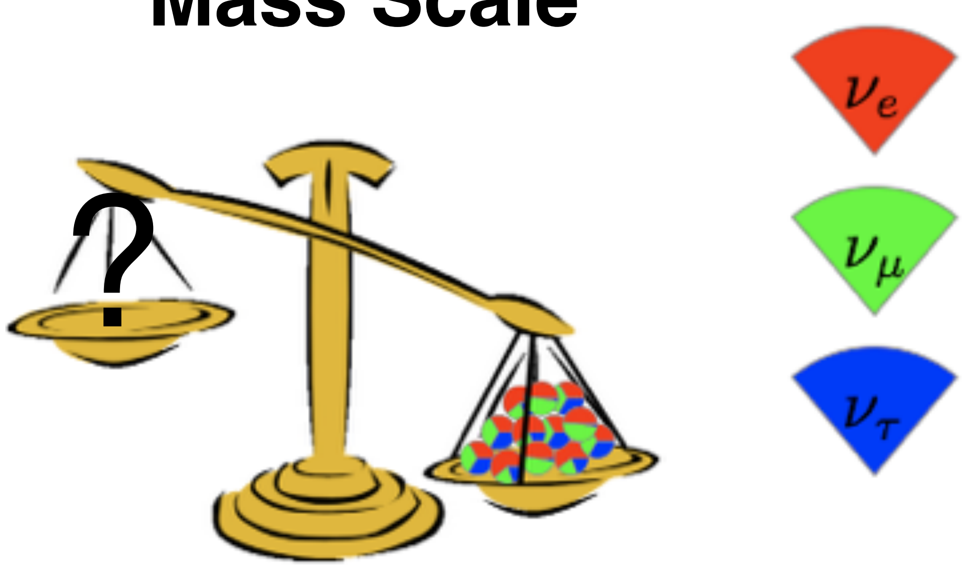
- ☑ ν-oscillations tell us the mass splittings
- ☑ solar matter effects tell us sign of dm^2_{21}

- **Absolute offset from Zero**
- **Sign of dm^2_{23} (Hierarchy)**

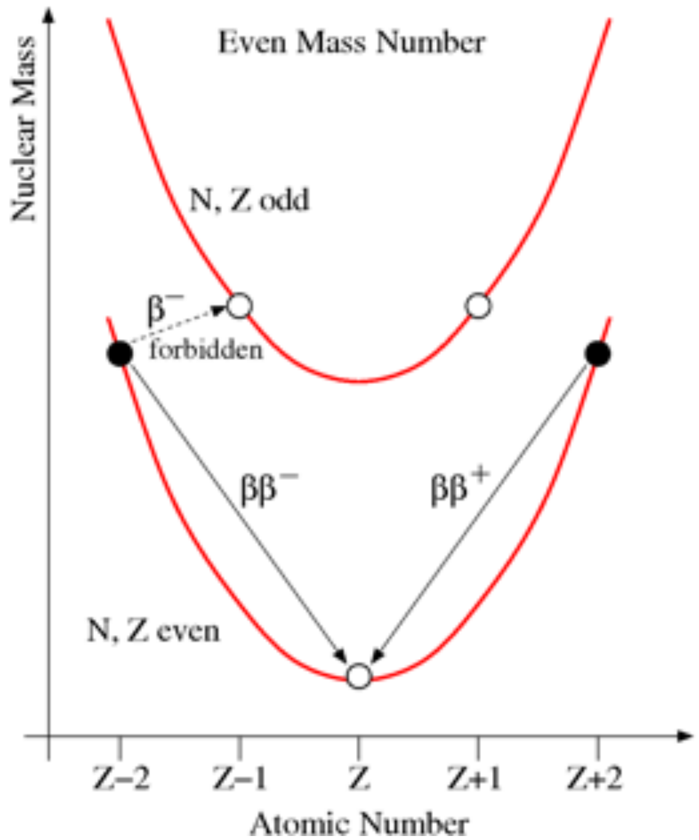
Hierarchy



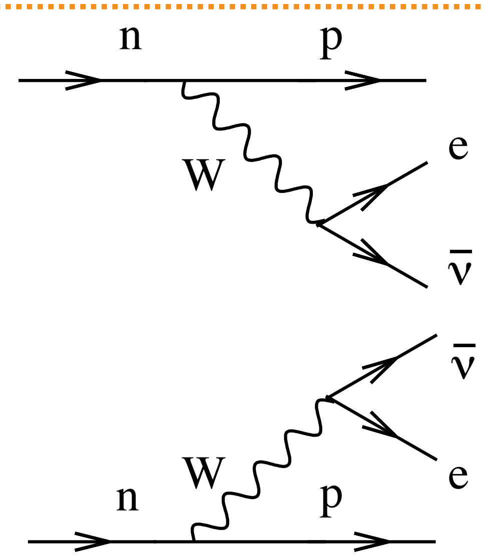
Mass Scale



Double Beta Decay



2νββ



half-life

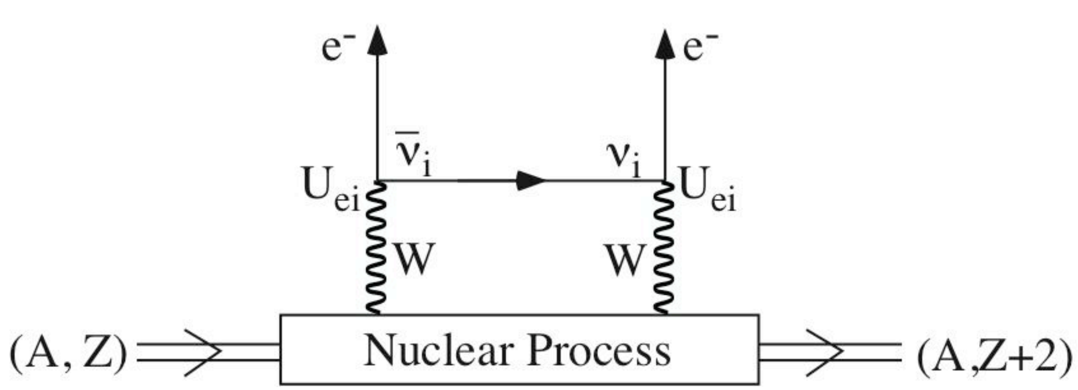
Phase space factor

$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}|M^{2\nu}|^2$$

Nuclear matrix element

half lives ~10^{19}-10^{21} years !

0νββ



half-life

Phase space factor

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

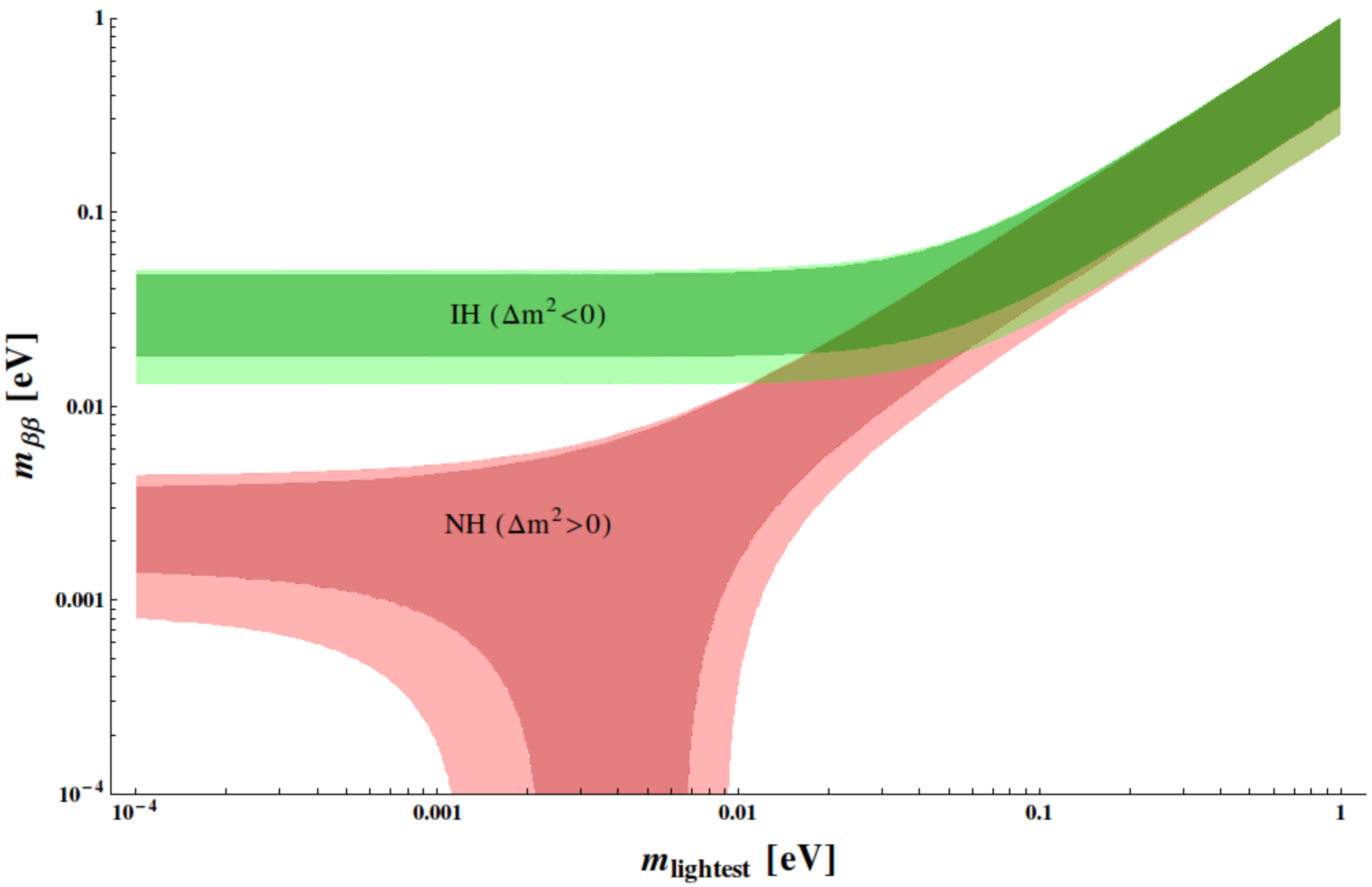
Nuclear matrix element

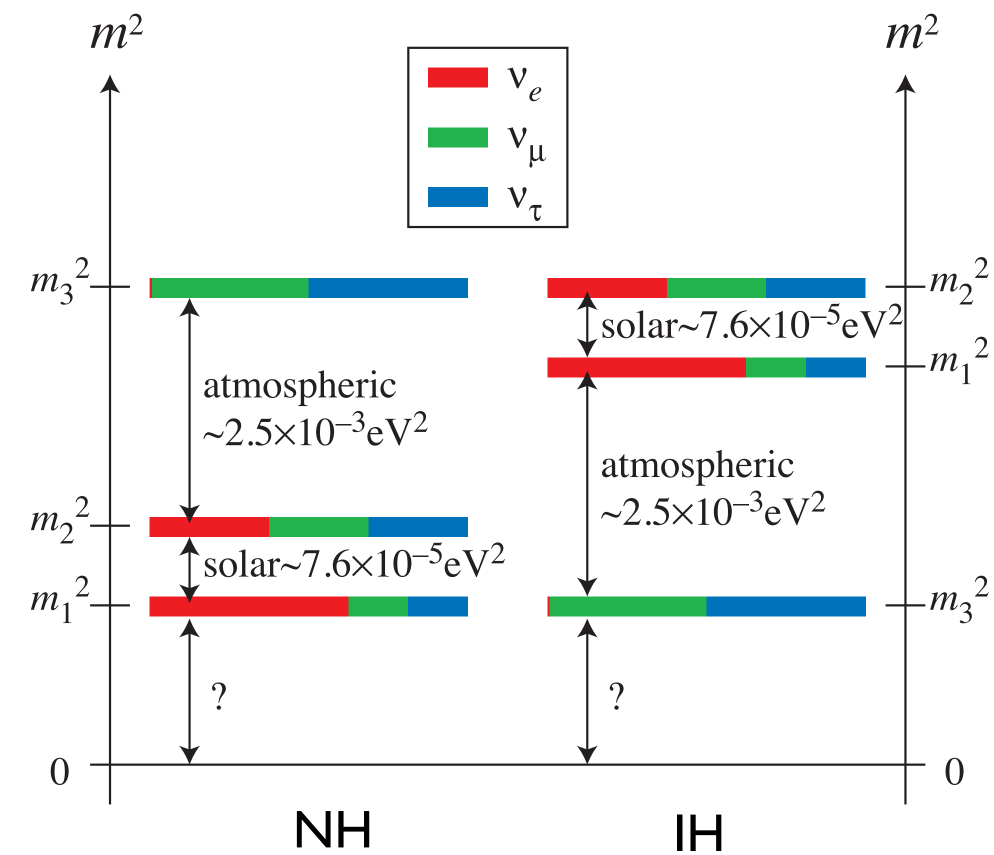
- If $m_{\beta\beta}$ = 50 meV estimated half lives ~ 10^{25} - 10^{27} years !

Effective Majorana neutrino mass:

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

What might we learn ?



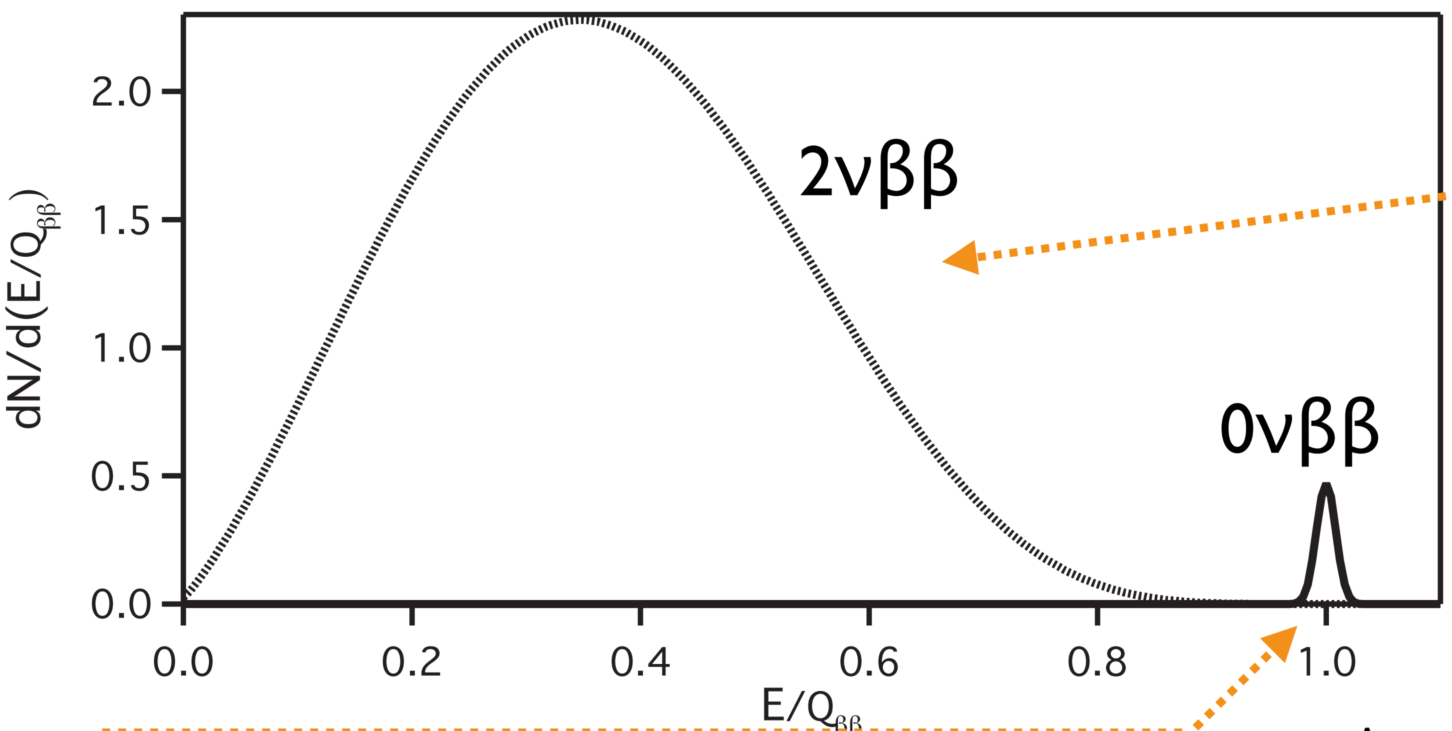


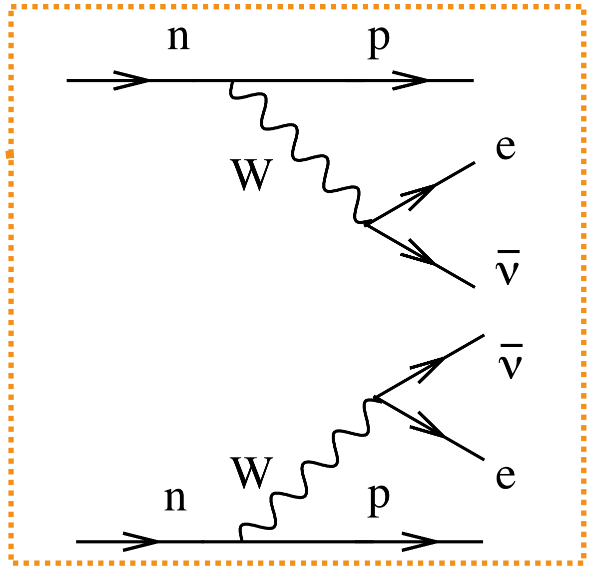
- If observed: learn neutrinos are Majorana fermions, lepton number violation; maybe the hierarchy, constraints on absolute mass scale

- If not observed: stringent limits help make the most of future neutrino data, maybe show neutrinos are not Majorana

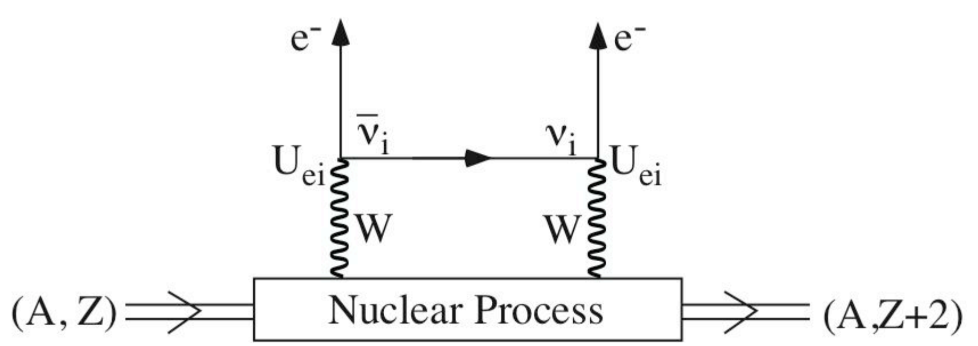
Double Beta Decay - Signature

Summed-energy spectrum of final state electrons





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



Rule of thumb

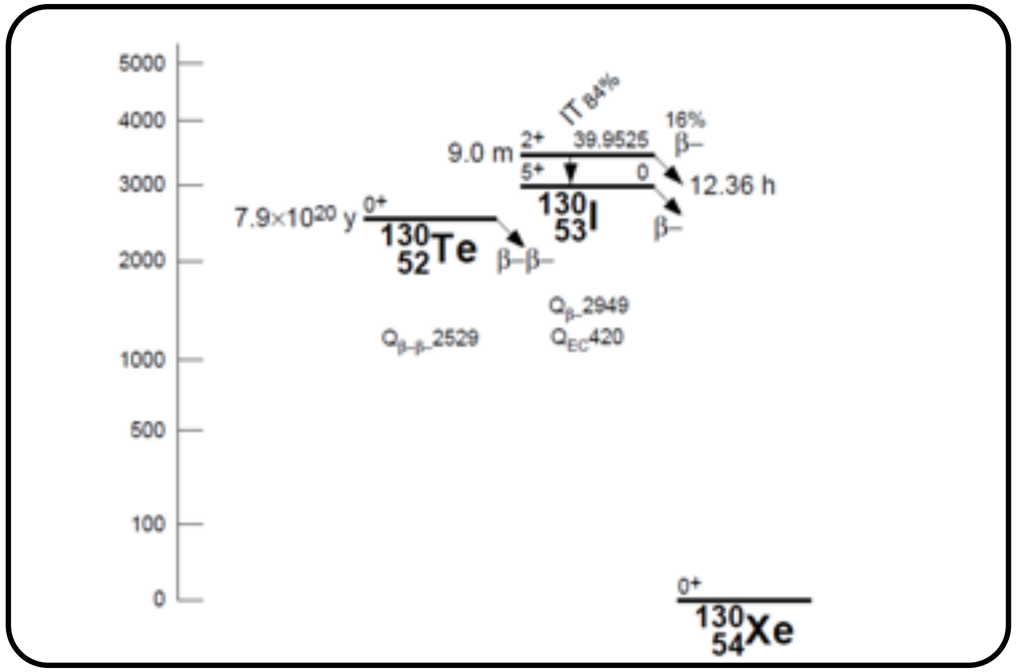
$T^{0\nu}_{1/2}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

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

ββ Decay of ^{130}Te

- Fairly high Q value: ~2528 keV
- High natural abundance: 34.2%
- State of the art from CUORICINO using TeO_2 bolometers:
  - Exposure (^{130}Te): 19.75 kg.yr
  - Energy resolution: 6.3 +/- 2.5 keV FWHM
  - Background index: 0.169 +/- 0.006 c/keV/kg/yr

Decay Scheme of ^{130} Te

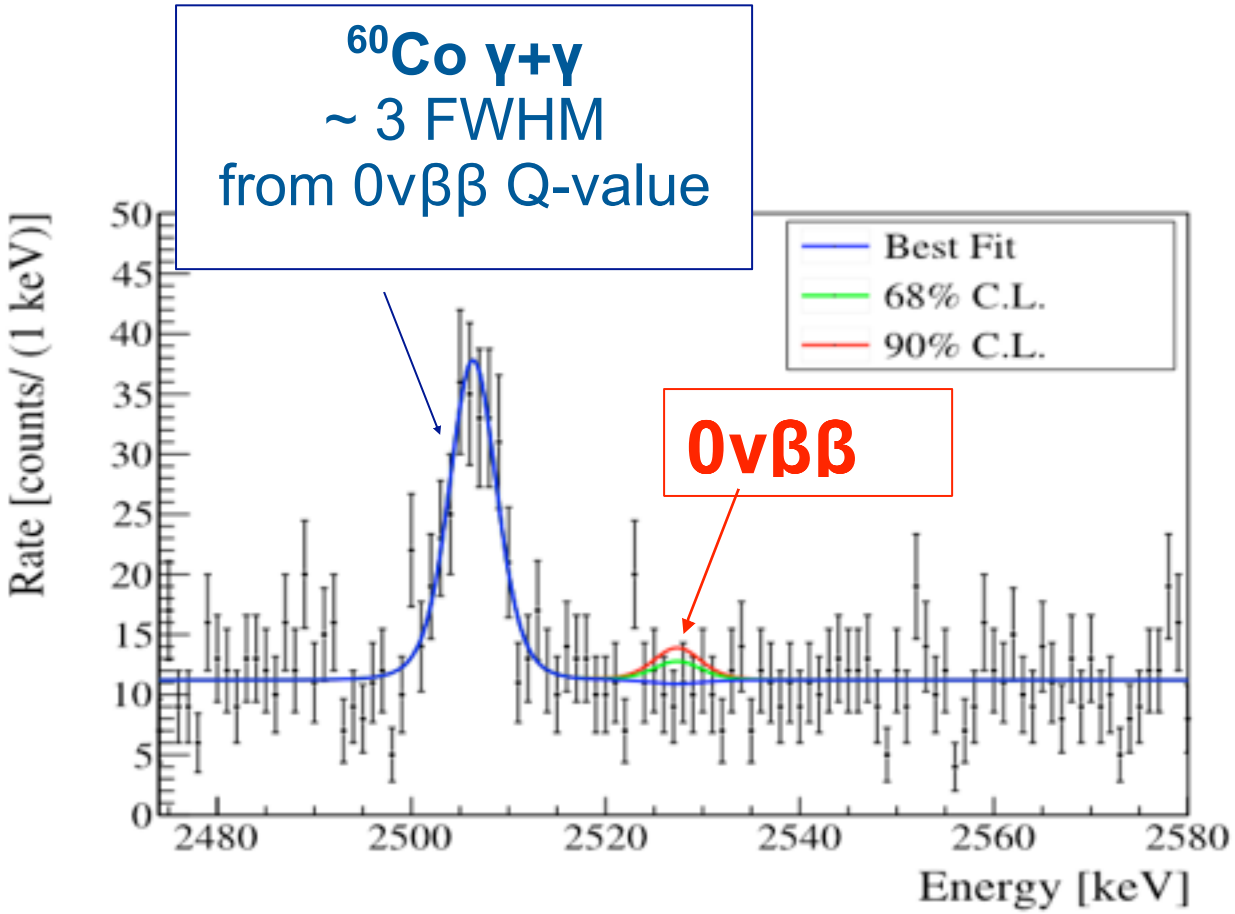


- Final limit from CUORICINO:

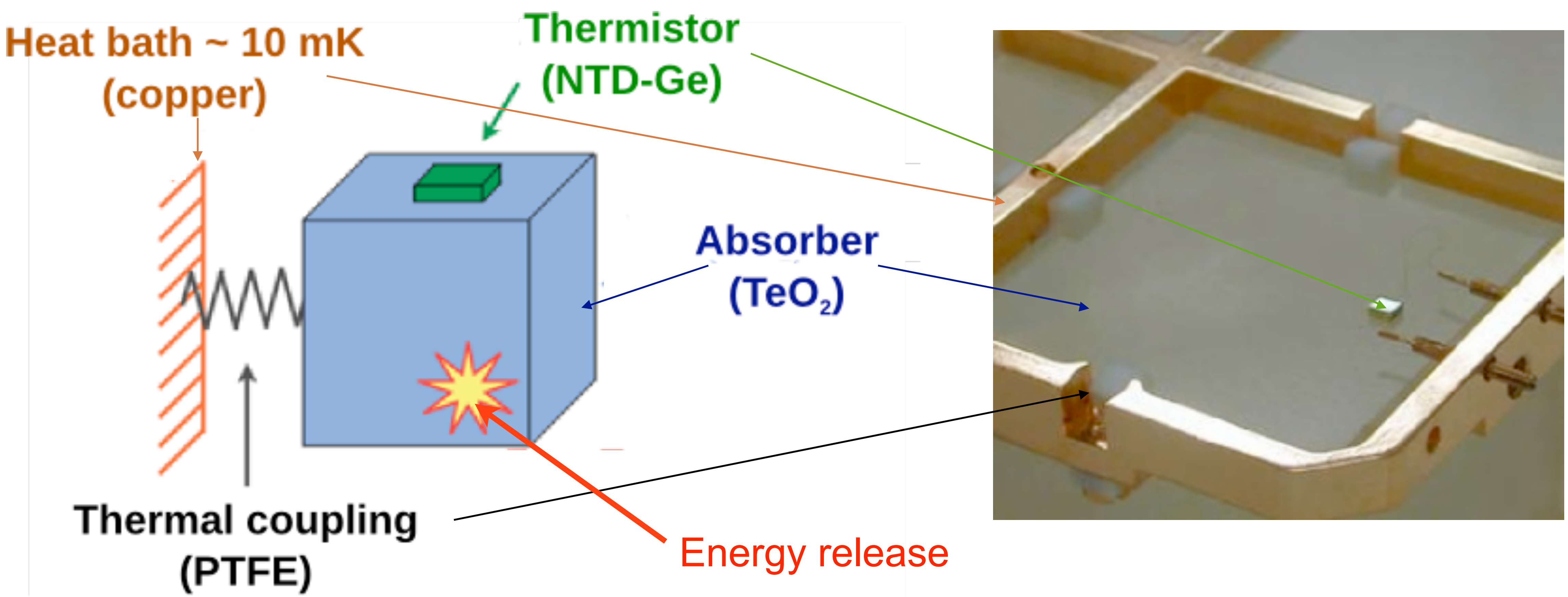
$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\,\text{yr} \quad (90\%\ \text{C.L})$$

$$\langle m_{\beta\beta} \rangle < 0.3 - 0.7\,\text{eV}$$

- Background mainly from:
  - ^{232}Th γ from cryostat
  - degraded α's and β's from crystal and Cu surfaces
- The next step is CUORE

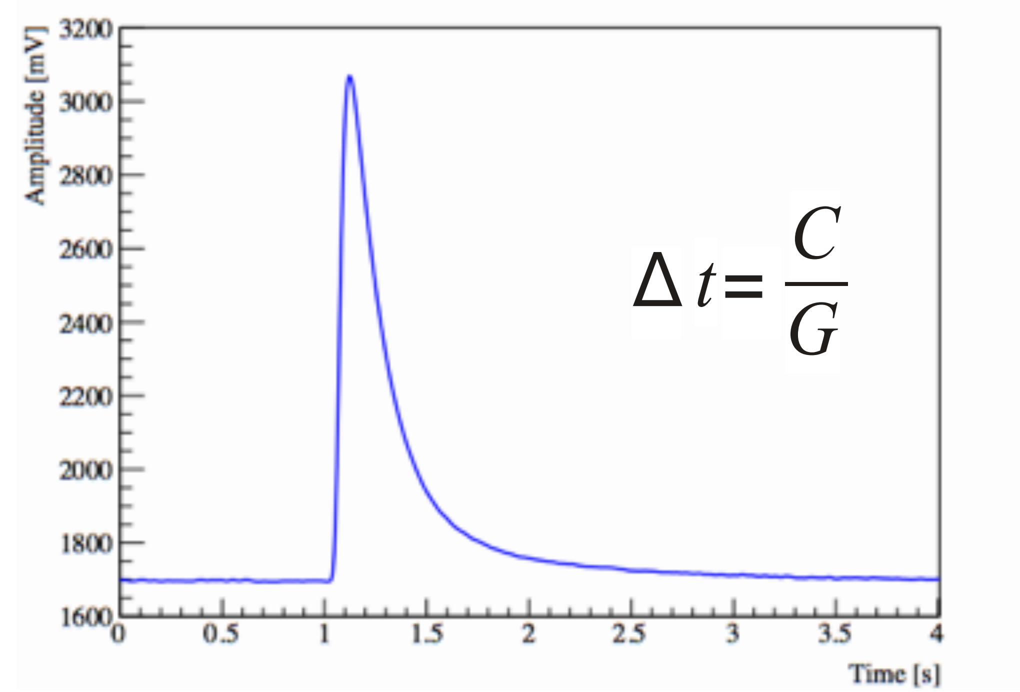


A word about bolometer technique



- Energy deposit in absorber results in temperature rise
- For TeO_2 crystals configured for CUORE at ~10mK, ΔT ~ 0.1mK per MeV
- Temperature change read out with Ge-NTD
- Energy response can be calibrated with sources

Sample Particle Pulse from NTD

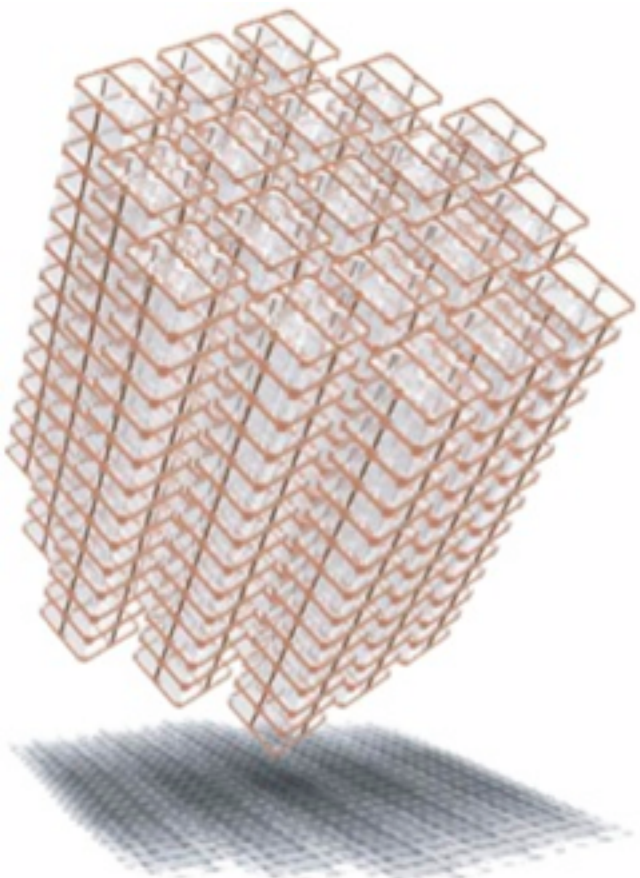


CUORICINO → CUORE

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

half-life sensitivity

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

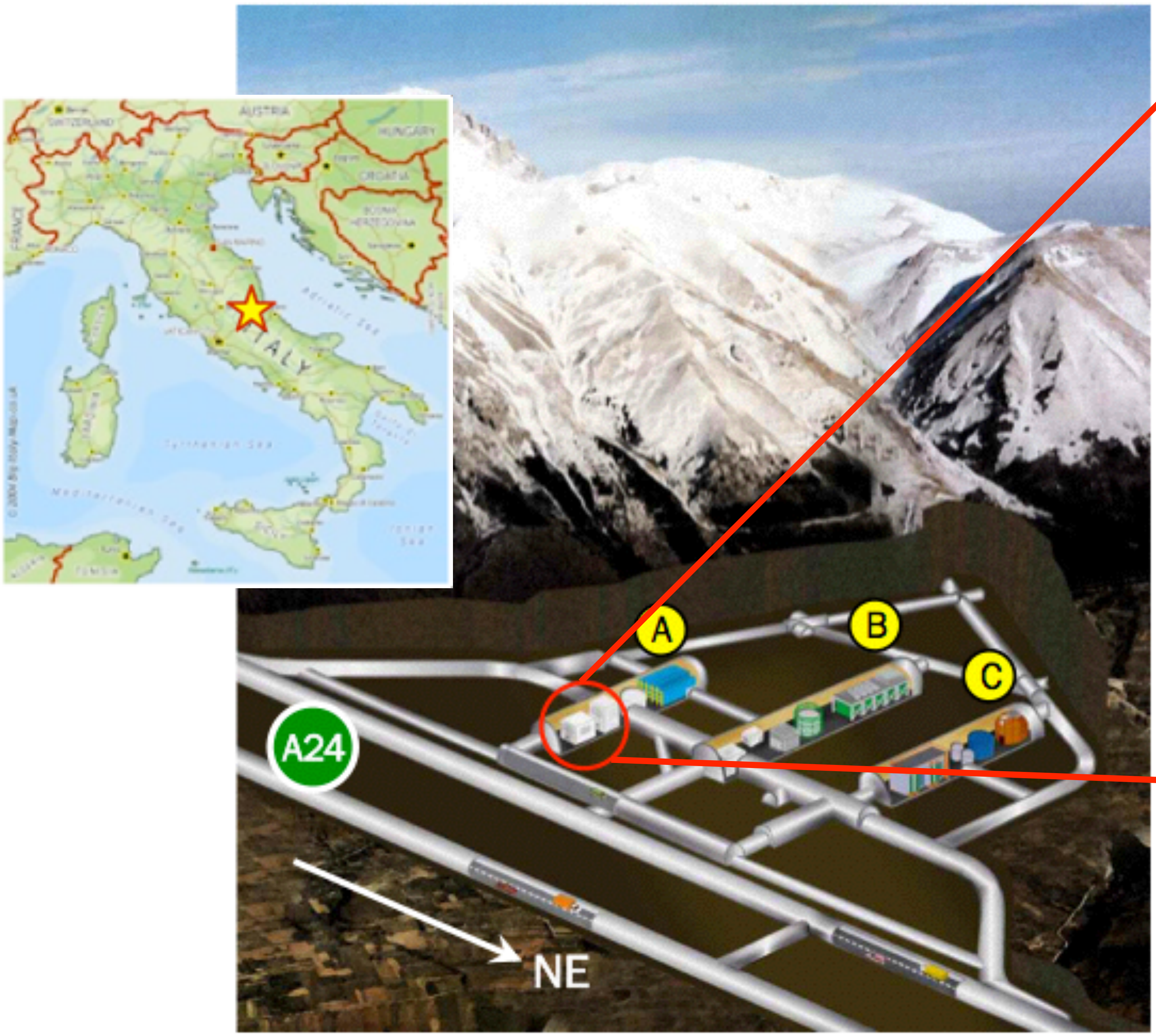


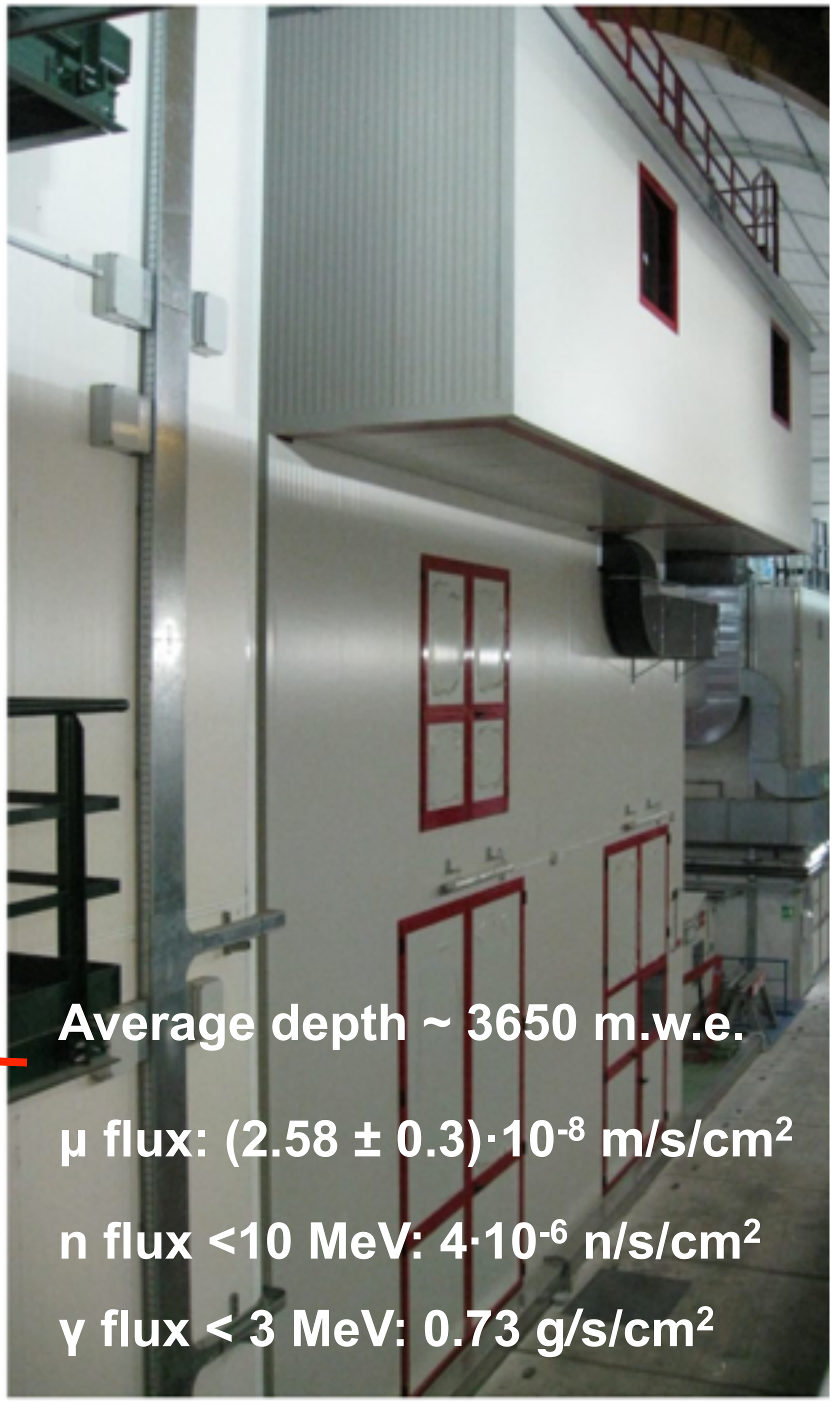
- **t**: Cryogen free dilution refrigerator
  - Improves detector duty cycle
  - Improves stability

- δ**E**: Resolution of TeO_2 bolometers is excellent, 5keV @2616keV is demonstrated

- **b**: Reduce background (~20x)

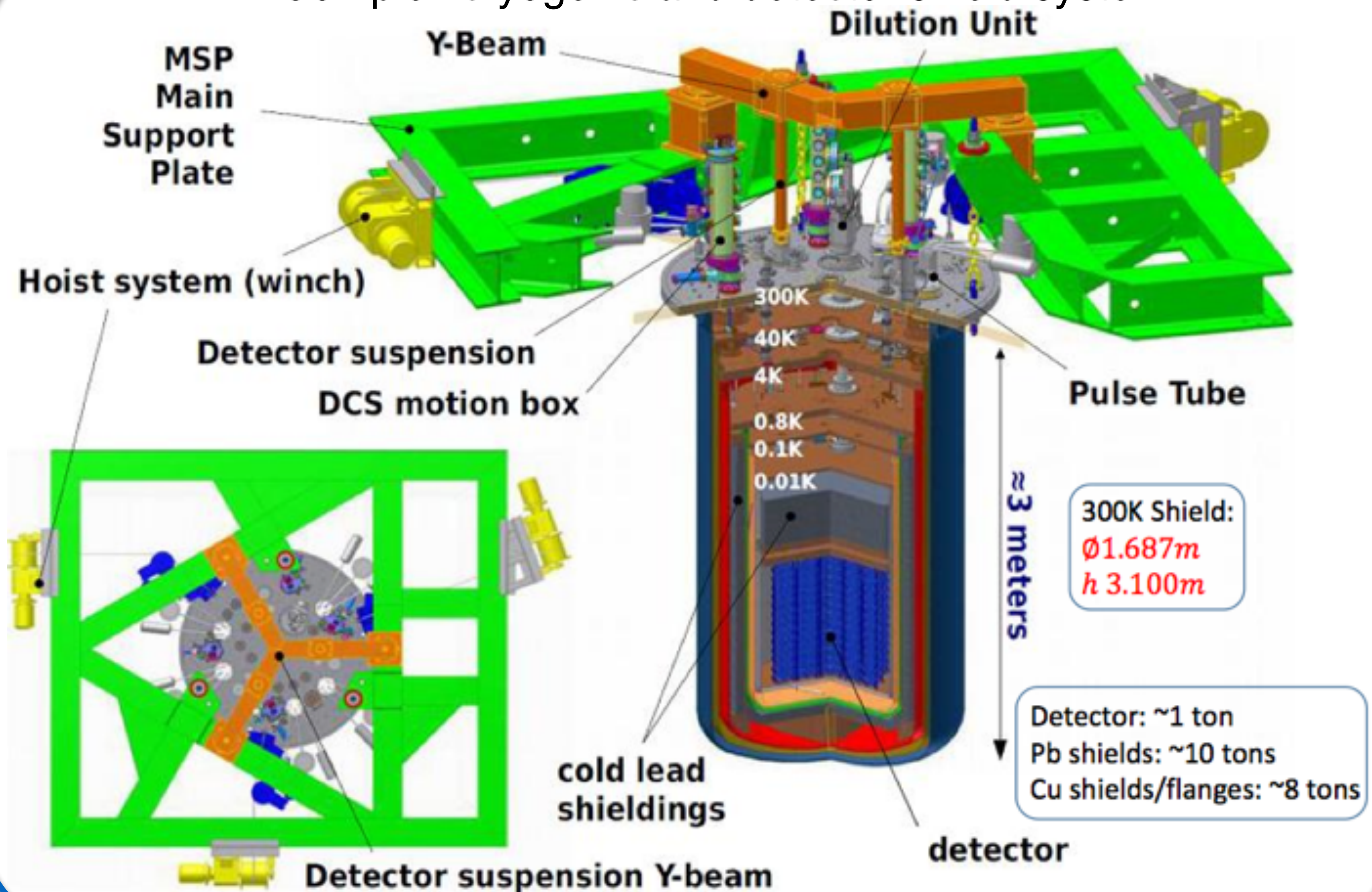
- CUORE will run in Hall A of Gran Sasso National Lab in Italy

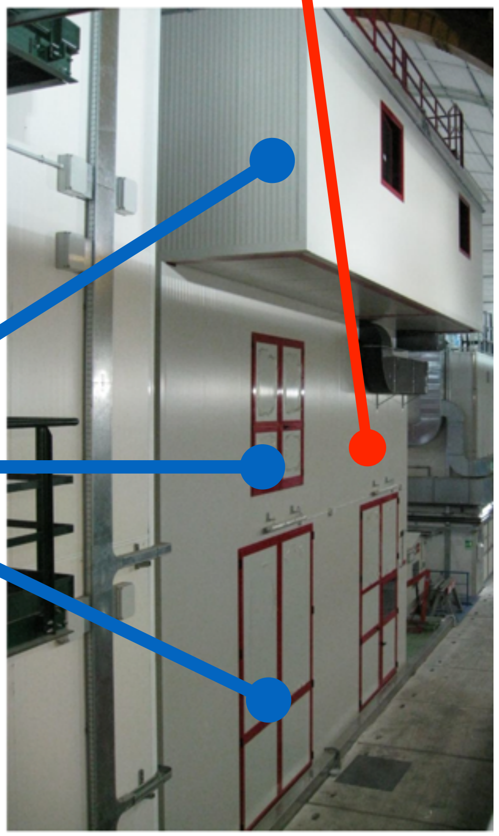


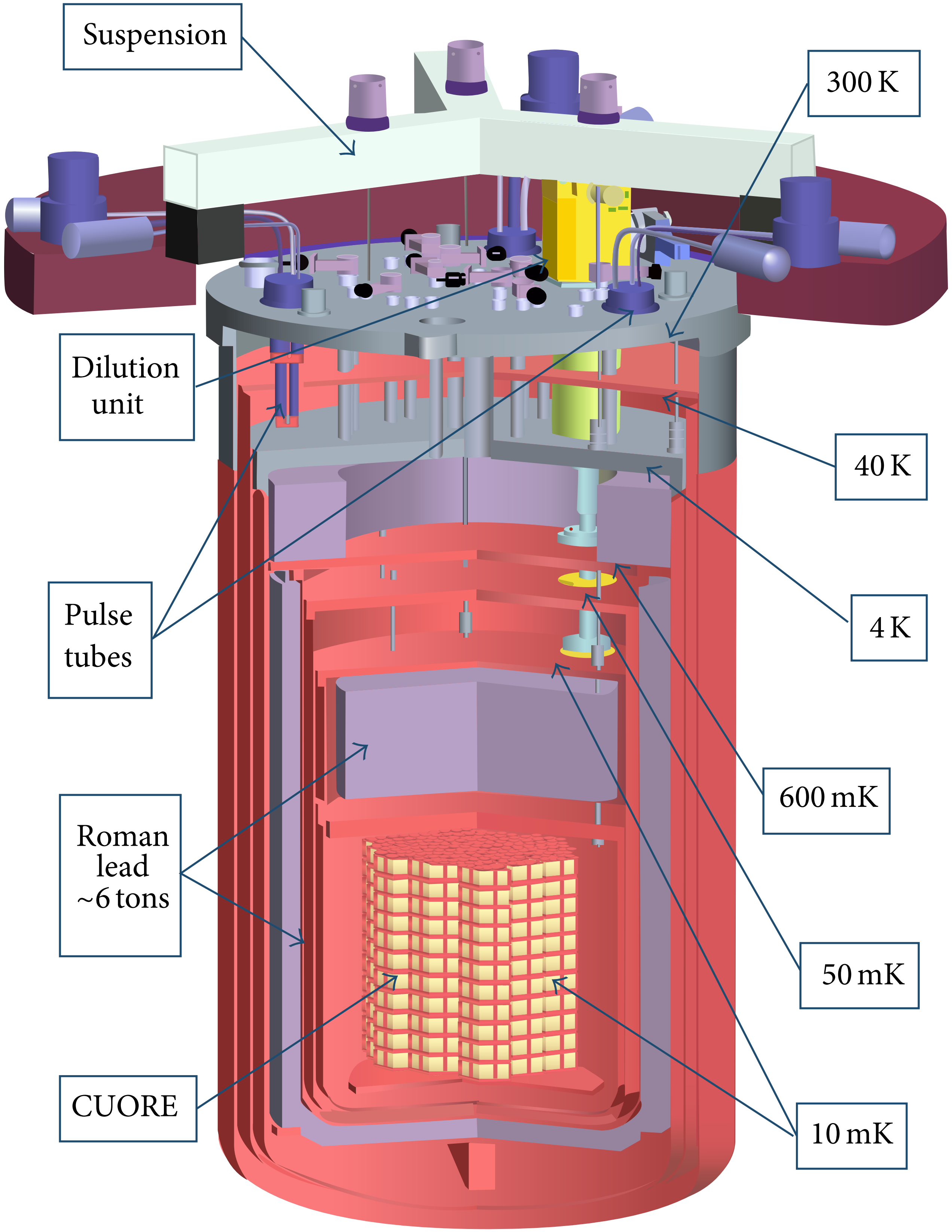


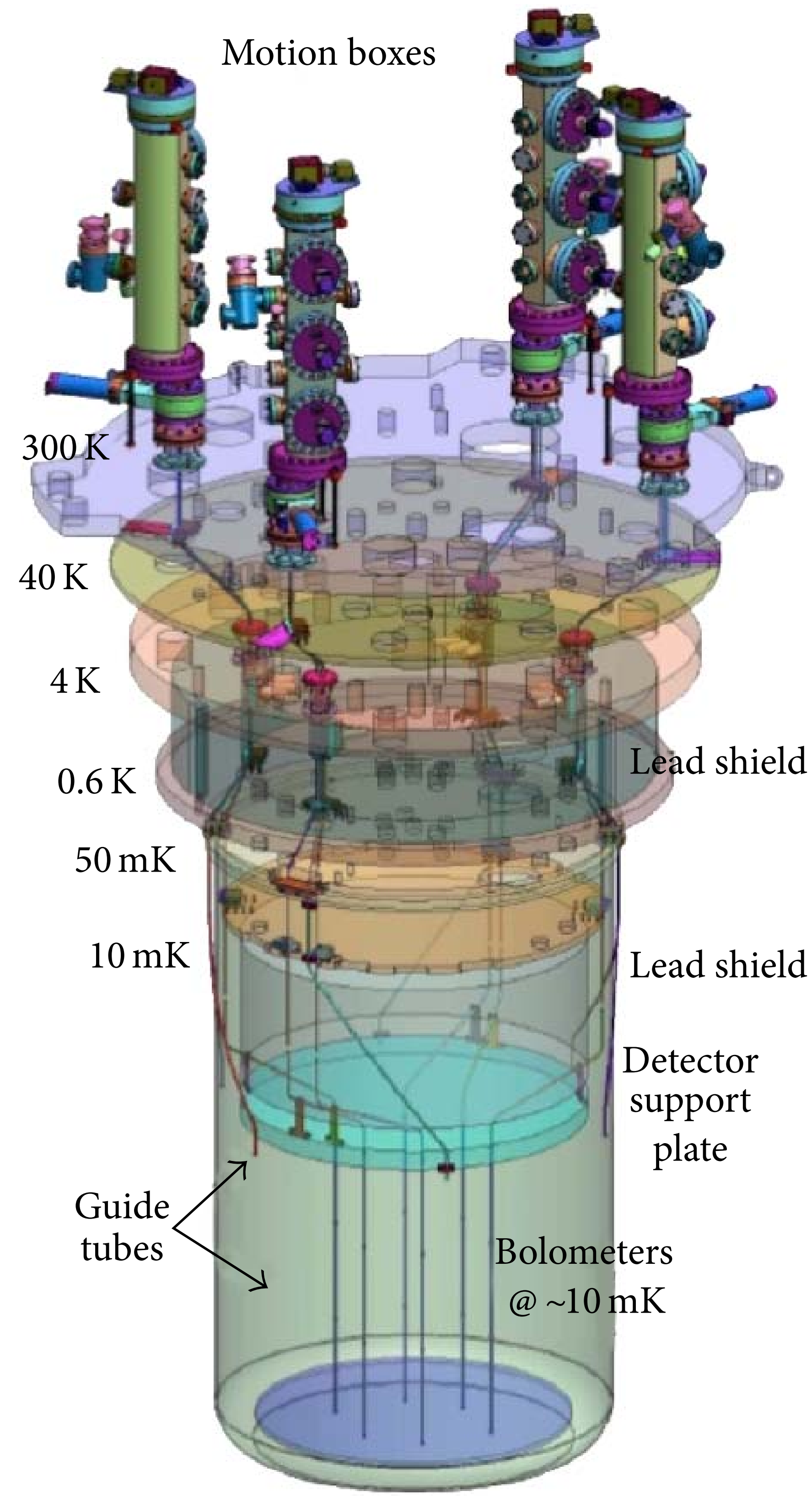
Class 1000 Clean Room for Detector Assembly and Storage

Complex cryogenic and detector shield system



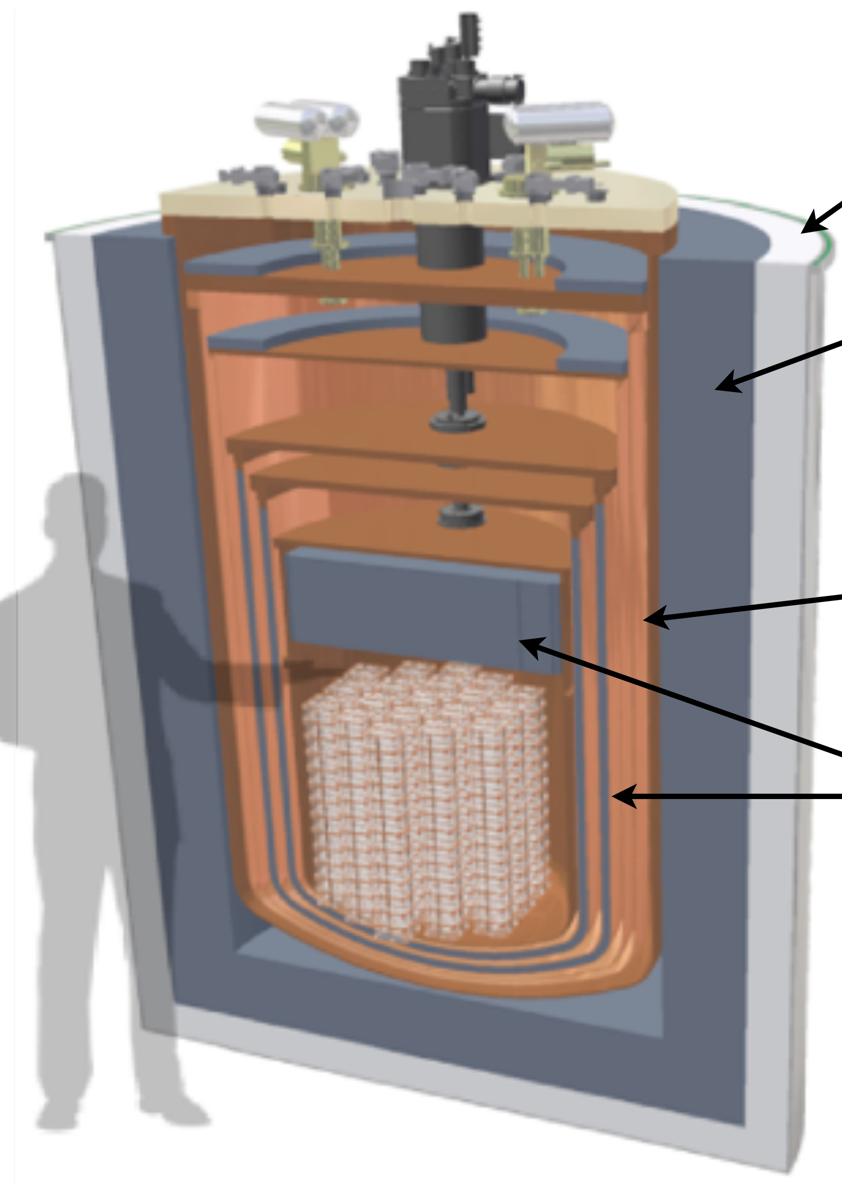



Suspension
300 K
Dilution unit
40 K
4 K
Pulse tubes
600 mK
Roman lead ~6 tons
50 mK
CUORE
10 mK


Motion boxes
300 K
40 K
4 K
0.6 K
Lead shield
50 mK
10 mK
Lead shield
Detector support plate
Guide tubes
Bolometers @ ~10 mK

CUORE: Path to lower background

- Improved shielding

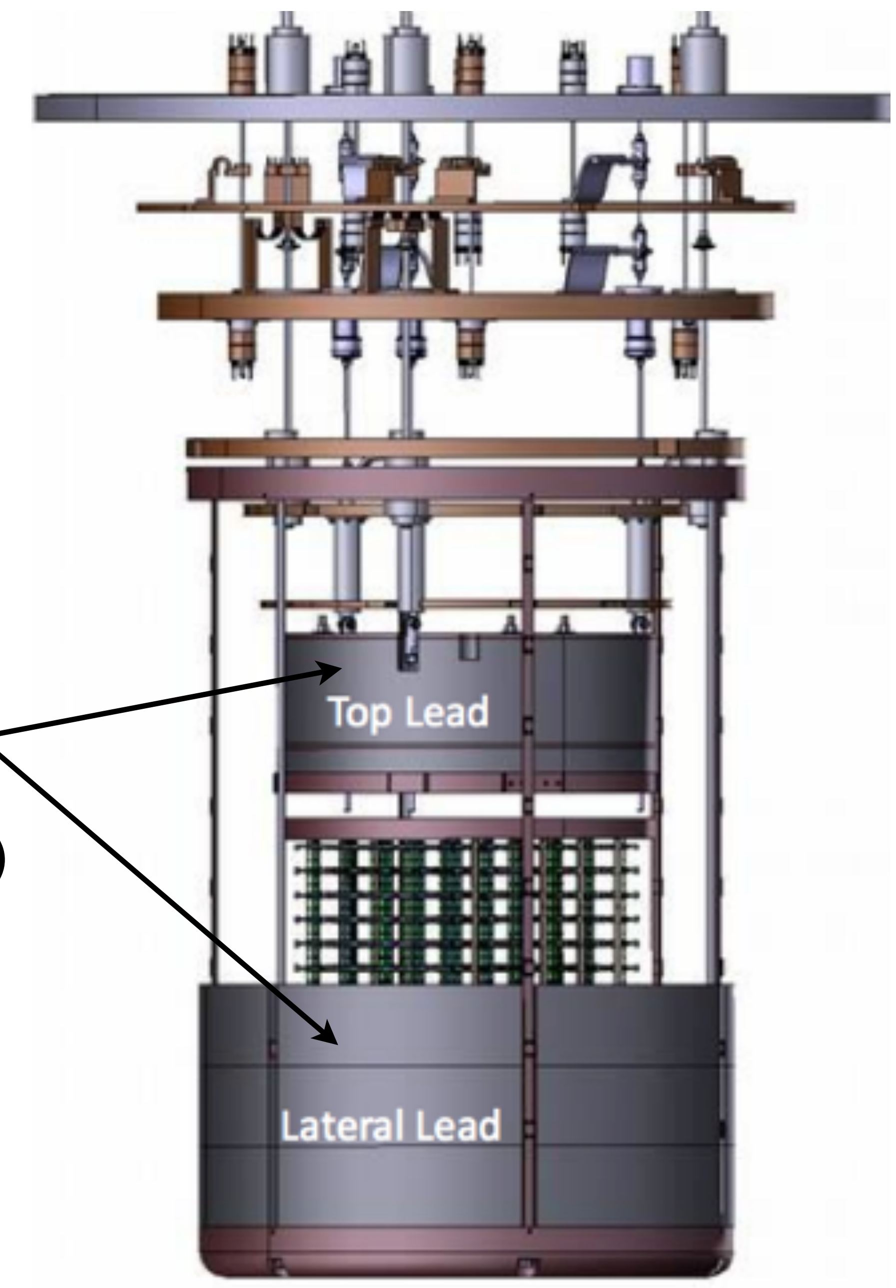


Neutron shield
(18 cm PET + 2cm of H_3BO_3)

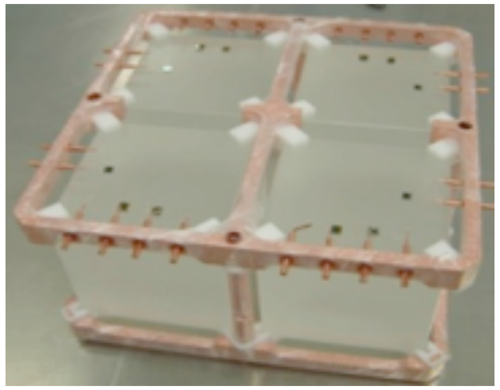
External lead shield
(thickness >35 cm)

Low-radioactivity copper for
cryostat vessels and flanges

Internal lead shield
(low-radioacivity/ancient lead)



CUORE: Path to lower background



Ultra-pure TeO2 crystal array

Bulk activity 90% C.L. upper limits:

$8.4 \cdot 10^{-7}$ Bq/kg (^{232}Th), $6.7 \cdot 10^{-7}$ Bq/kg (^{238}U), $3.3 \cdot 10^{-6}$ Bq/kg (^{210}Po)

Surface activity 90% C.L. upper limits:

$2 \cdot 10^{-9}$ Bq/cm^2 (^{232}Th), $1 \cdot 10^{-8}$ Bq/cm^2 (^{238}U), $1 \cdot 10^{-6}$ Bq/cm^2 (^{210}Po)

- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals

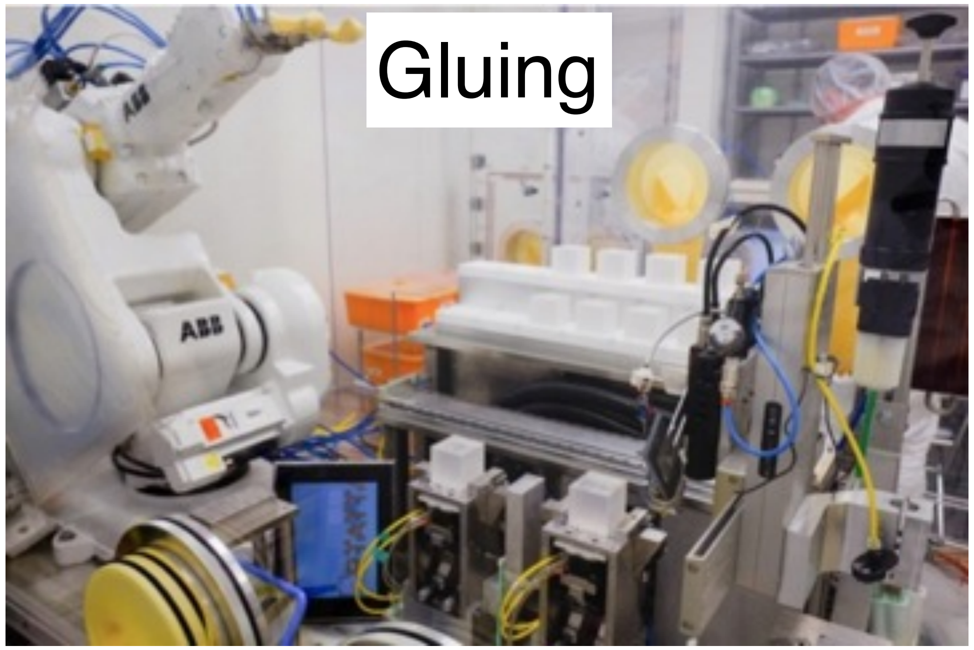
- Developed ultra-cleaning process for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching

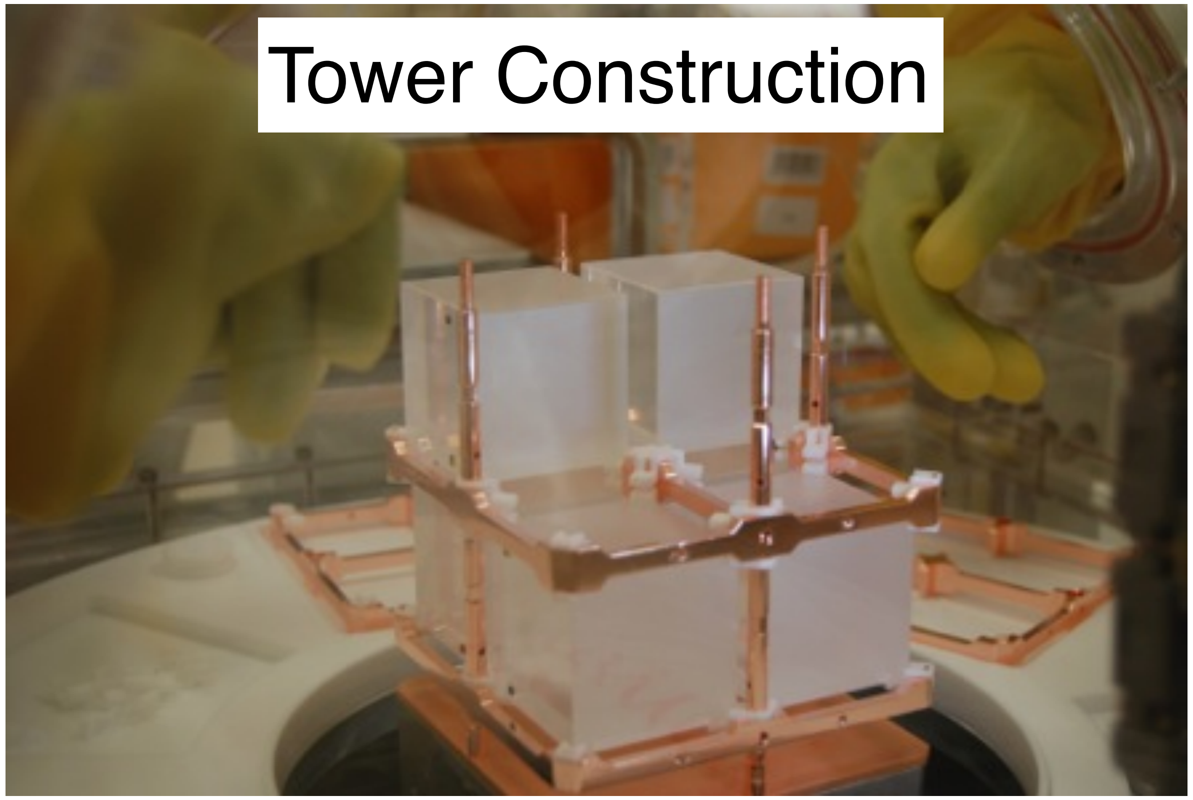
T1 T2 T3

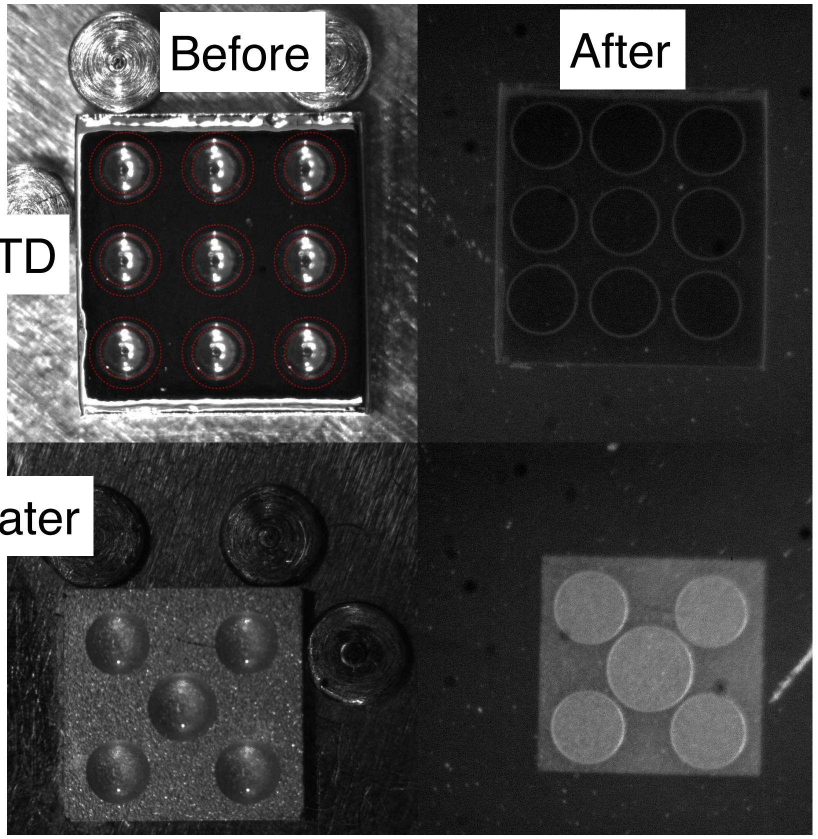
- Benchmarked in dedicated bolometer run at LNGS
  - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2

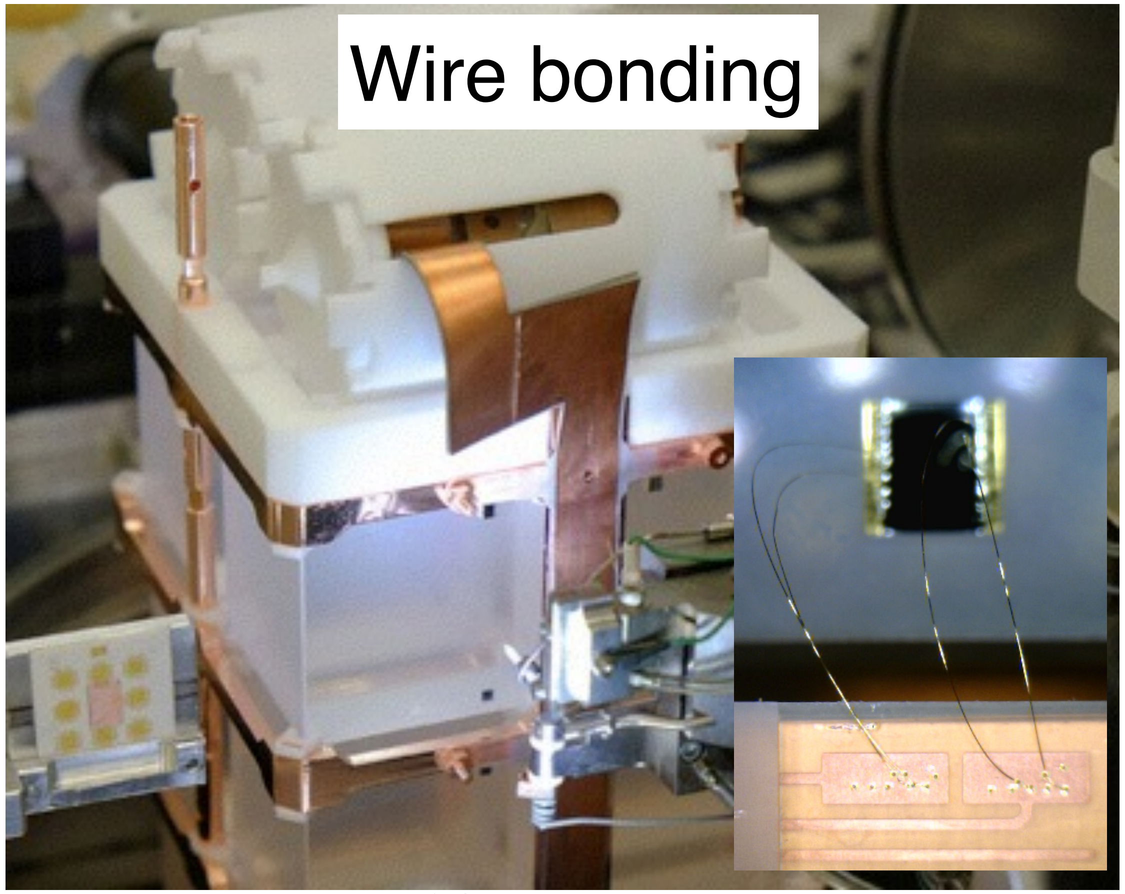
- All parts stored underground, under nitrogen after cleaning

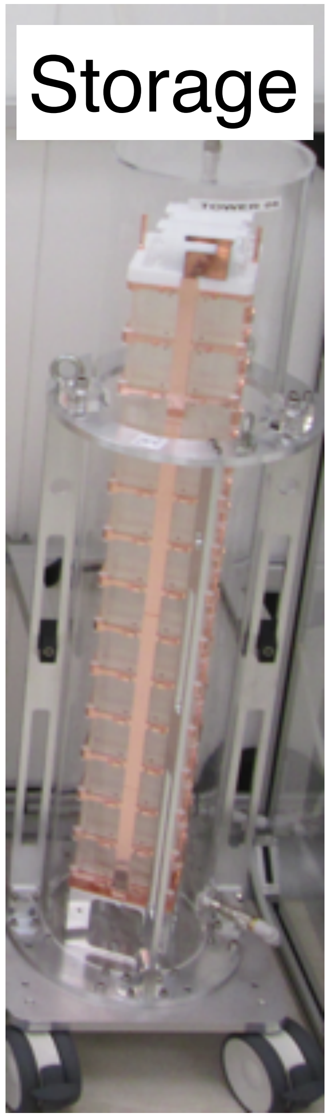
CUORE: Tower Assembly Steps



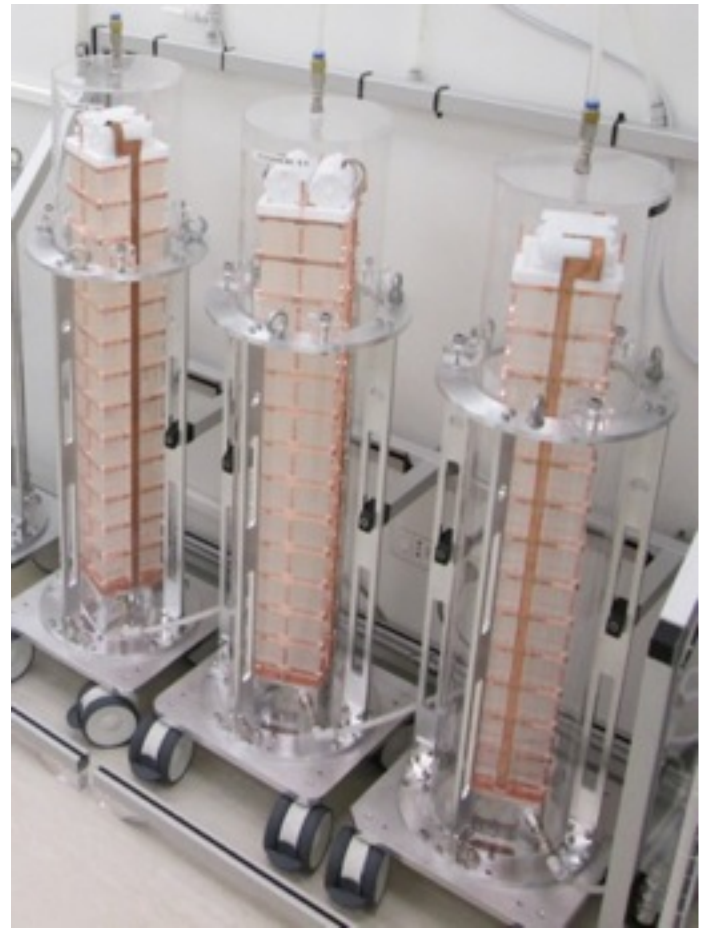


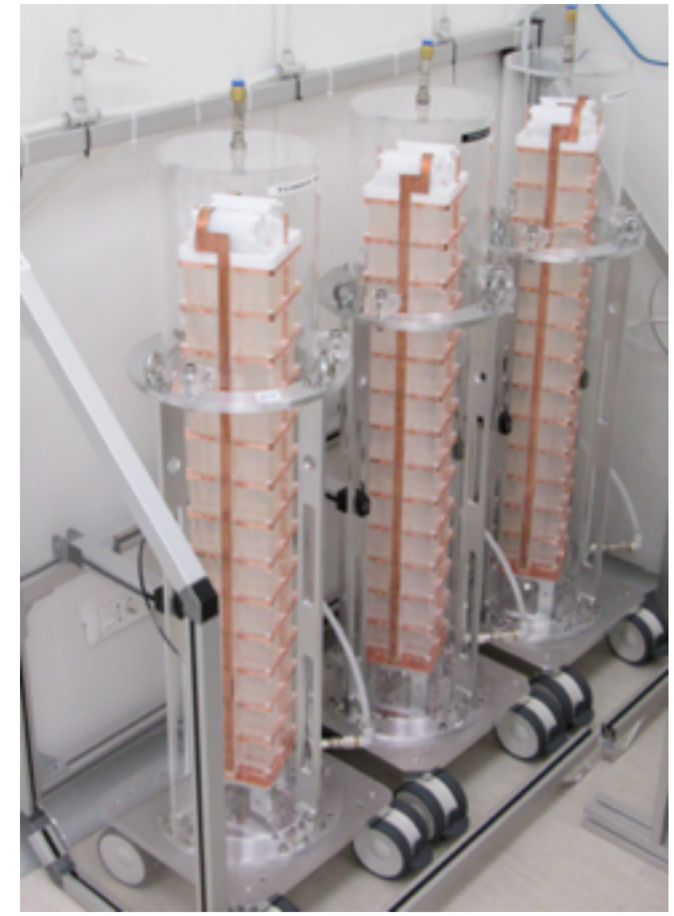


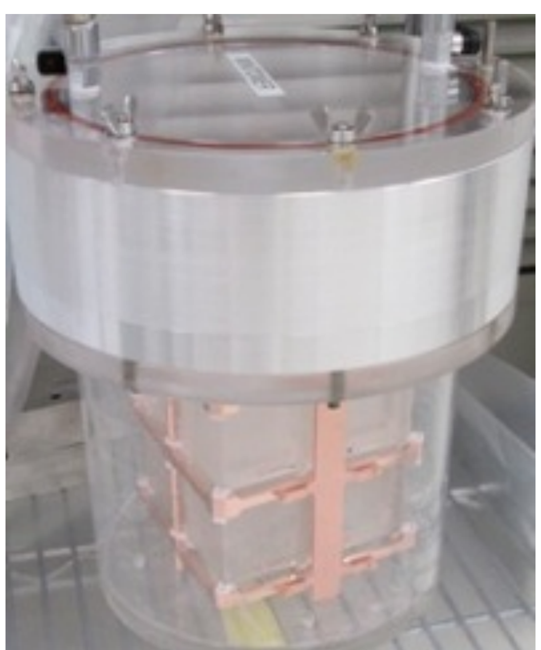




Assembly of all 19 towers is complete

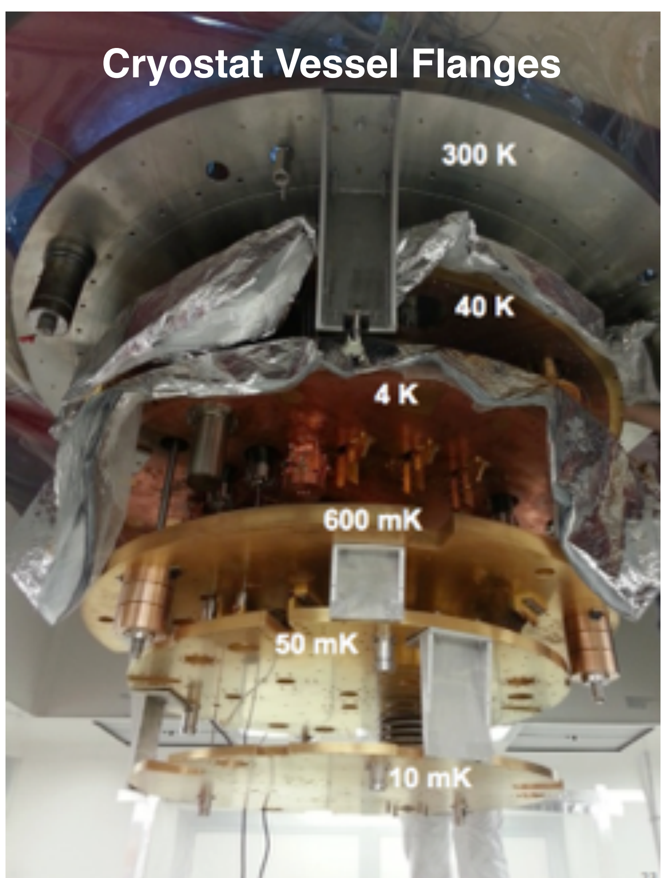


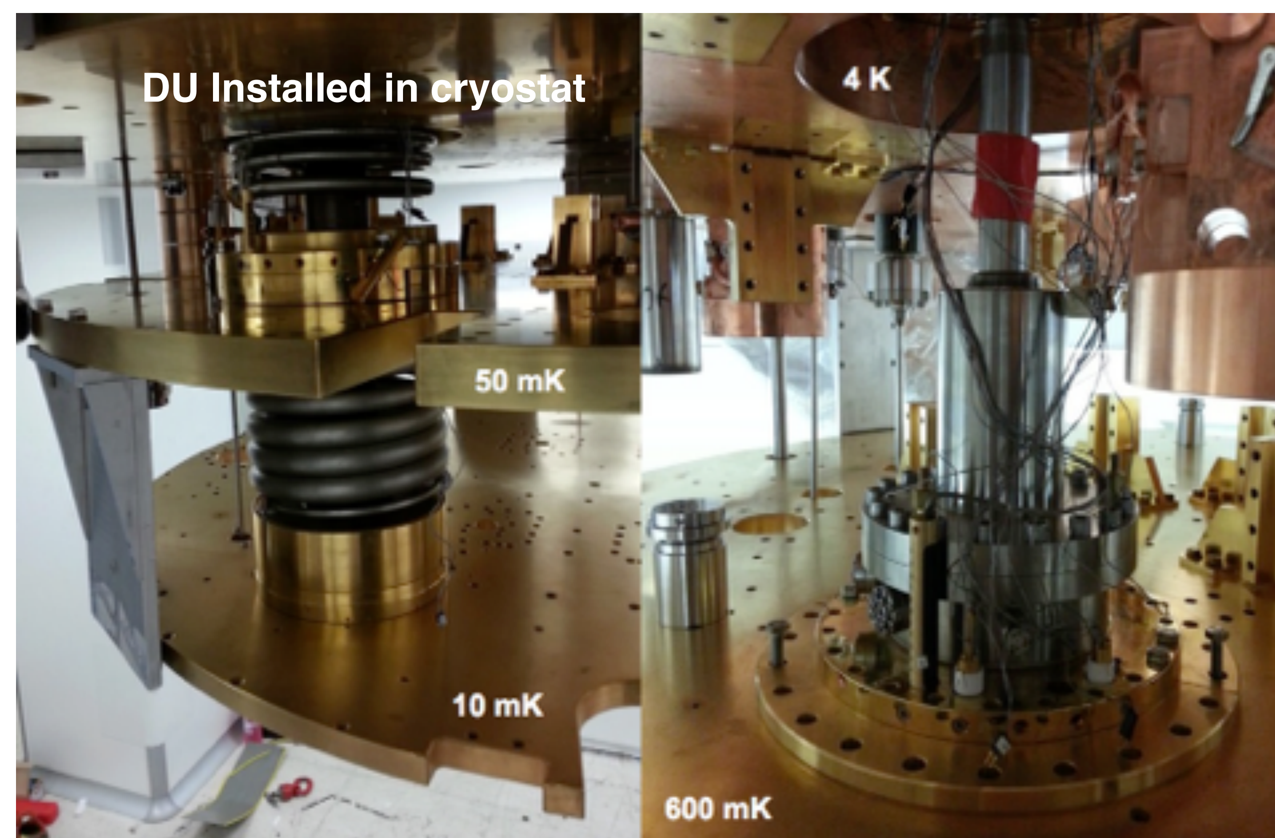




CUORE: Cryogenic system commissioning

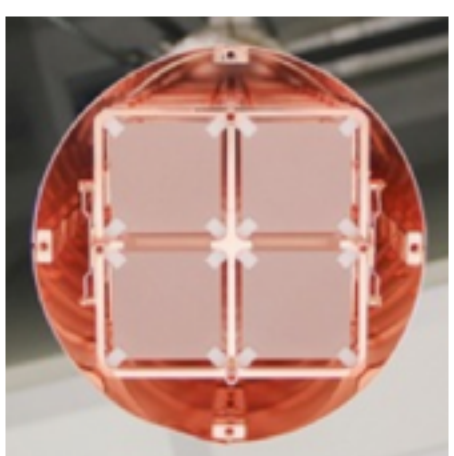
- ☑ Cryostat assembled, passed 4K commissioning test
- ☑ Dilution unit delivered to LNGS, able to maintain ~5mK in commissioning tests
- ☐ Full integration of DU in cryostat ongoing
  - ☑ first integration run already reached 14mK base T

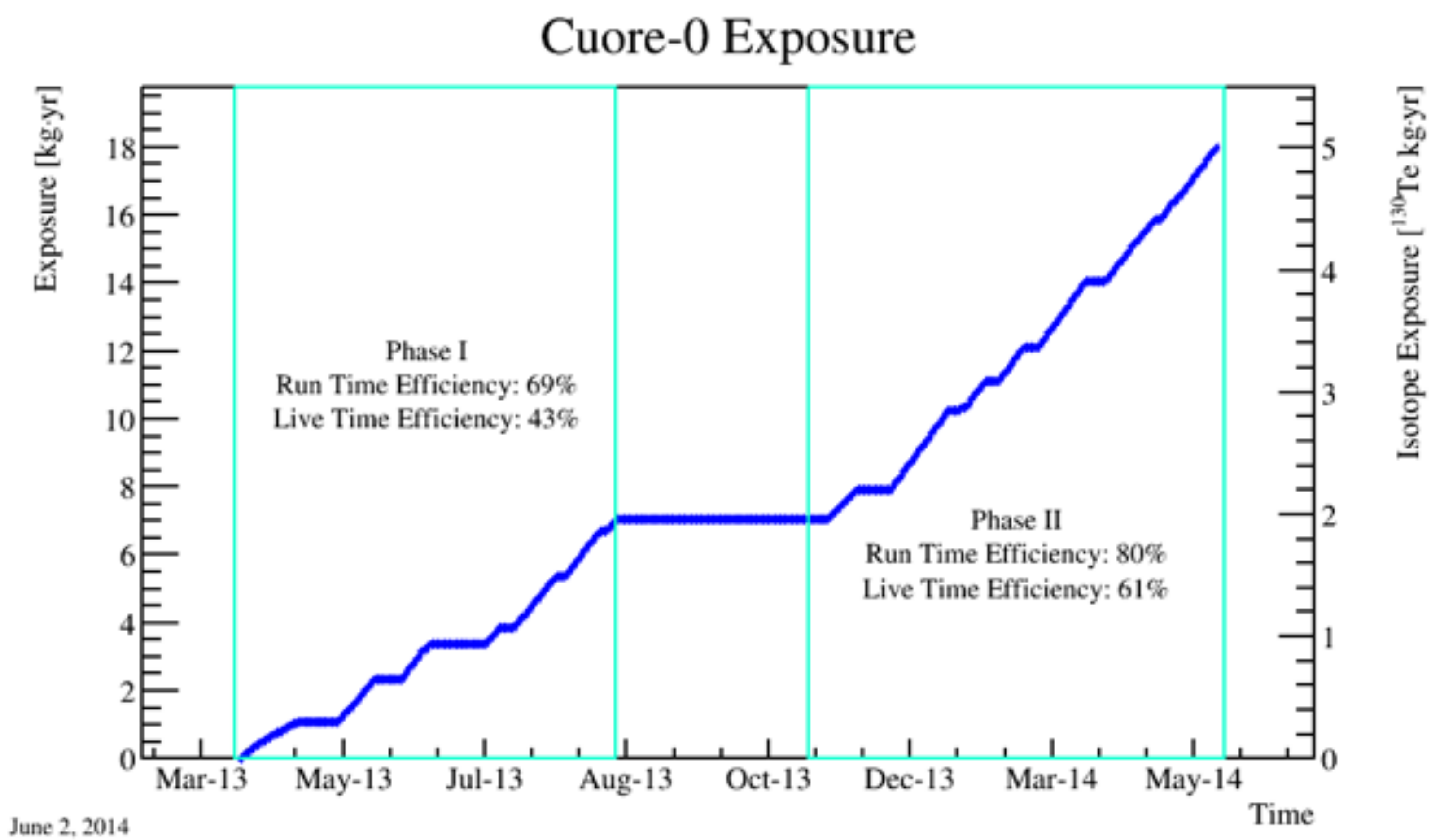




CUORE-0

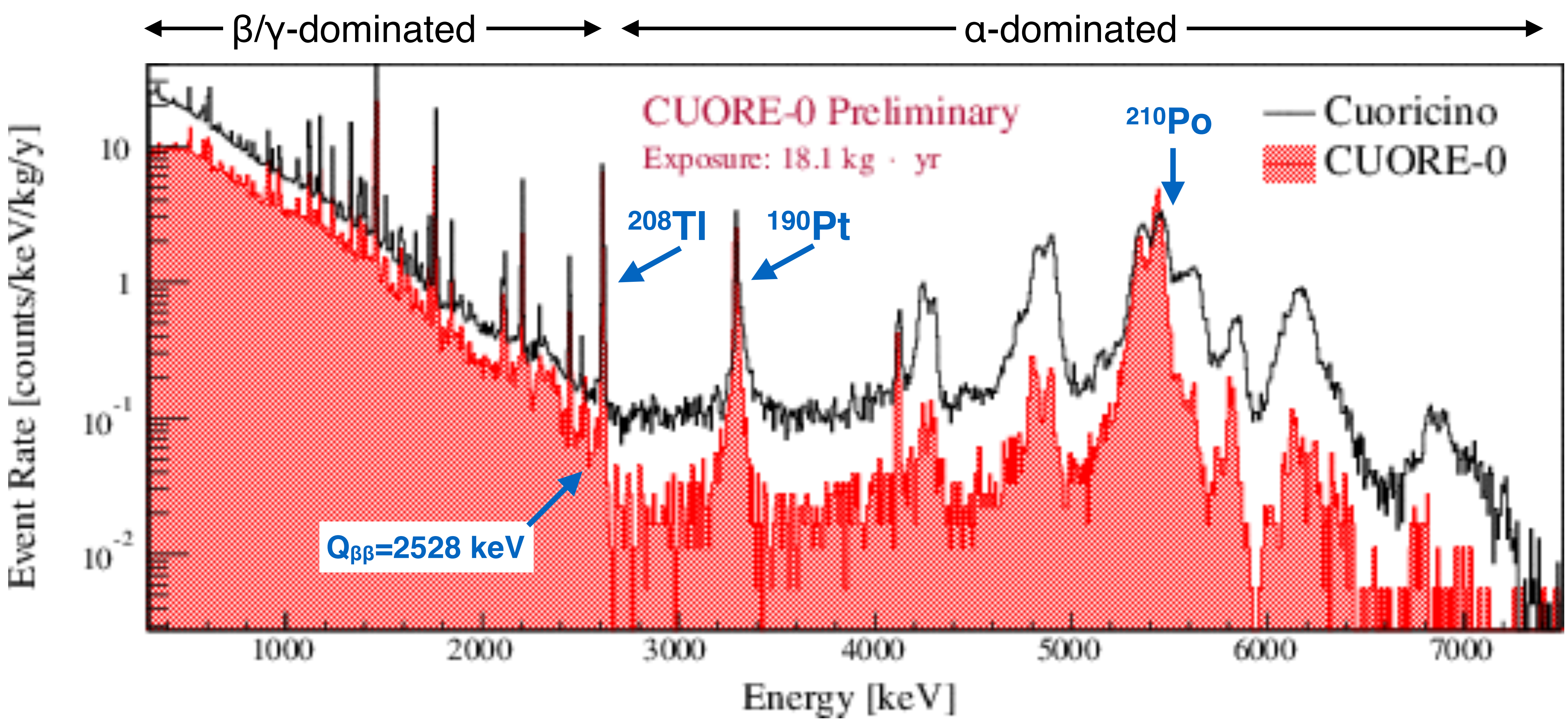
- A single CUORE-like tower ~11 kg of ^{130}Te
- Assembly followed the new procedures and protocols for CUORE
- Currently deployed in the old CUORICINO cryostat in HallA of LNGS





- Importance experience for CUORE collaboration
- Competitive 0νββ search in its own right

CUORE-0 Background Measurement

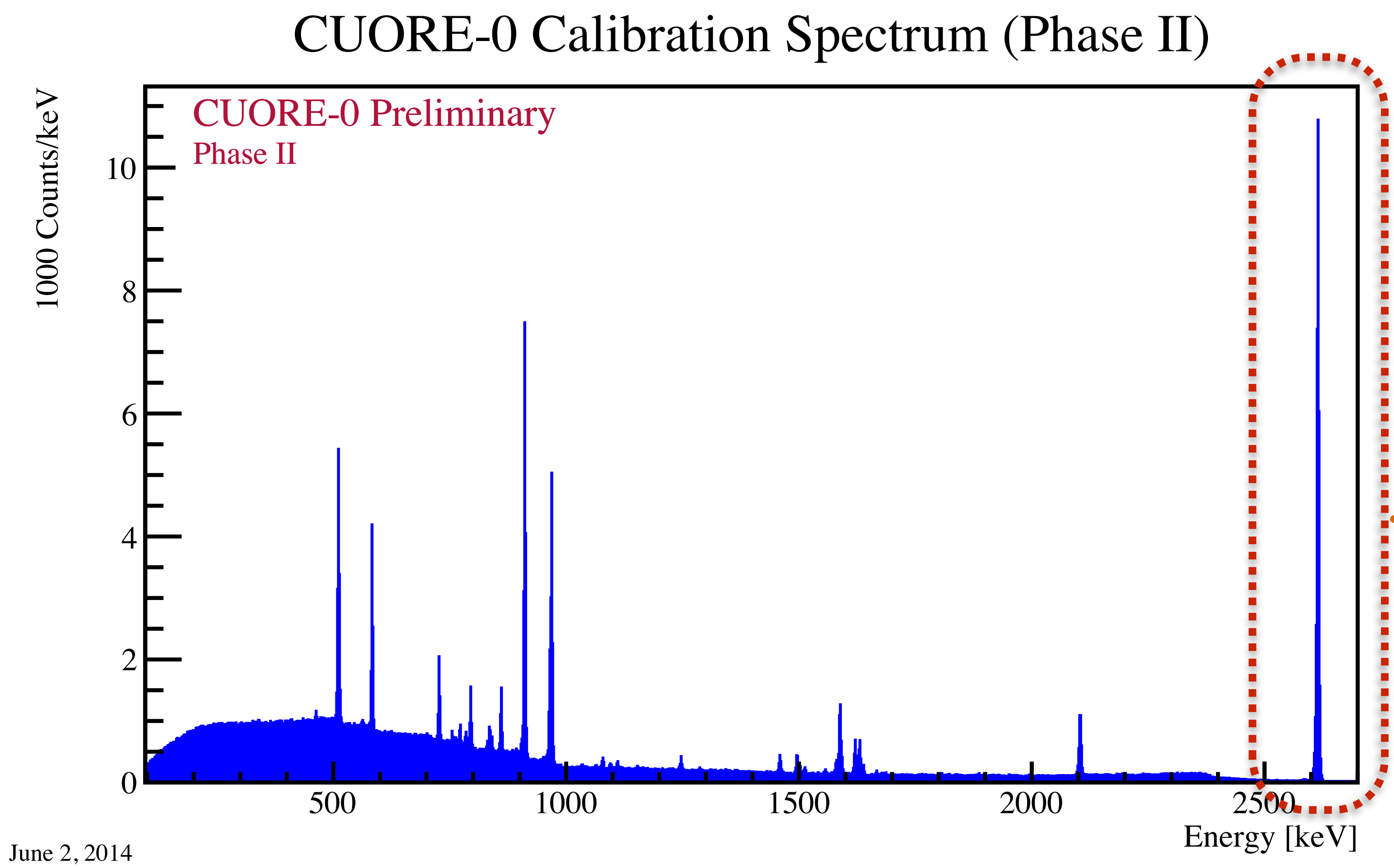


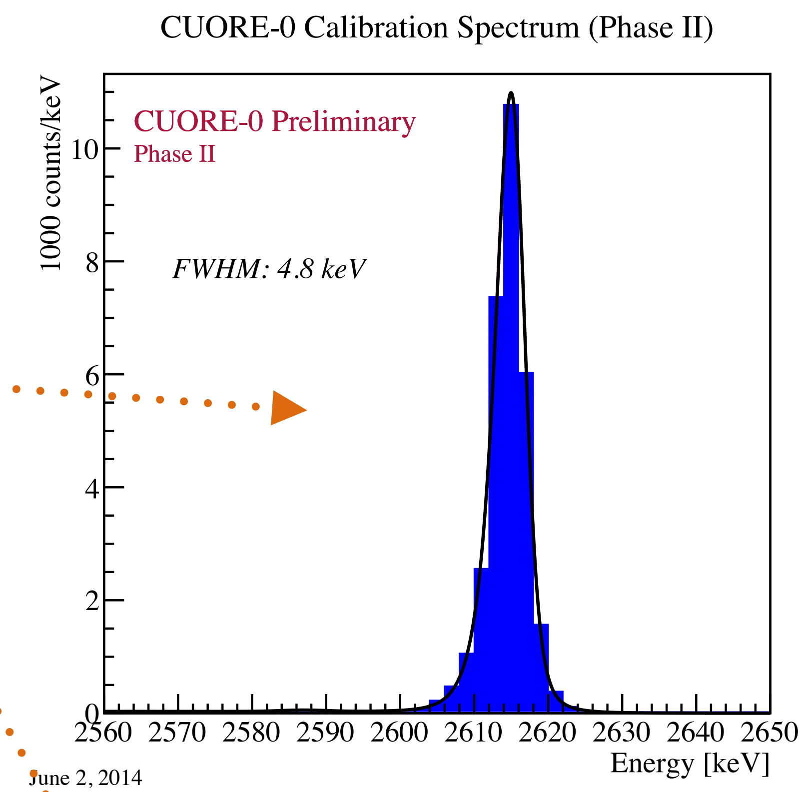
	0νββ region [c/keV/kg/yr]	2700-3900 keV * [c/keV/kg/yr]
CUORICINO ε=83%	0.153 +/- 0.006	0.110 +/- 0.001
CUORE-0 ε =78%	0.063 +/- 0.006	0.020 +/- 0.001

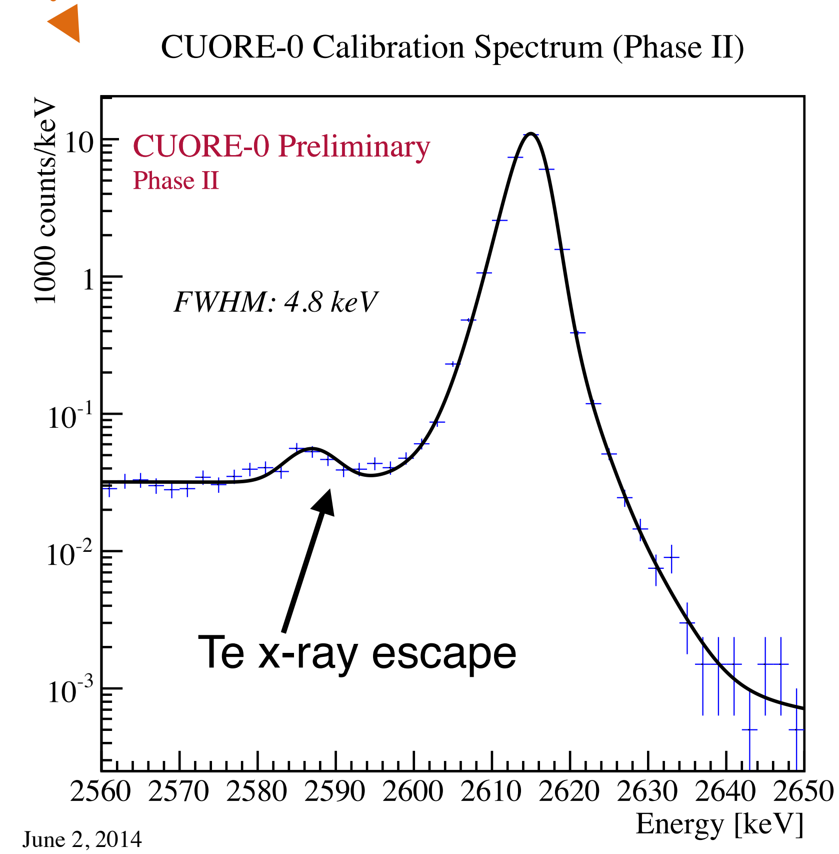
- ~6-fold reduction α-dominated bkg
  - ☑ Ultra-cleaning of CUORE-0 Cu surfaces
- ~2.5 fold reduction of bkg in ROI
  - ☑ Better radon control in COURE-0
    - β/γ bkg from cryostat ^{232}Th remains the same
- **Consistent with the Cuoricino bkg model**

* excluding the ^{190}Pt peak region

CUORE-0 Energy Resolution

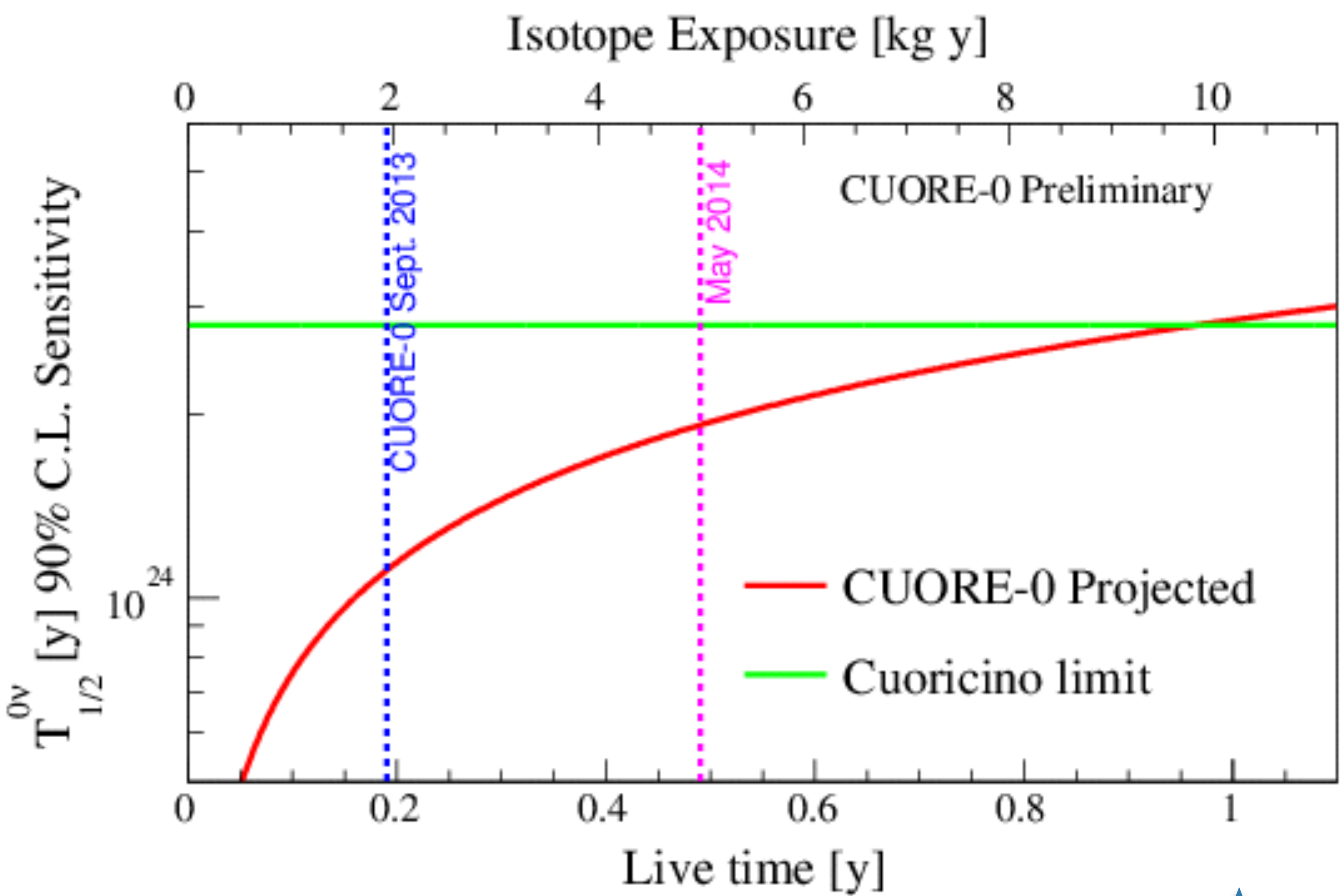






- Two thoriated strings are deployed just outside OVC of cryostat
- ☑ With improved running conditions of phase 2 CUORE target ~5keV energy resolution near the ROI is demonstrated

CUORE-0 Sensitivity



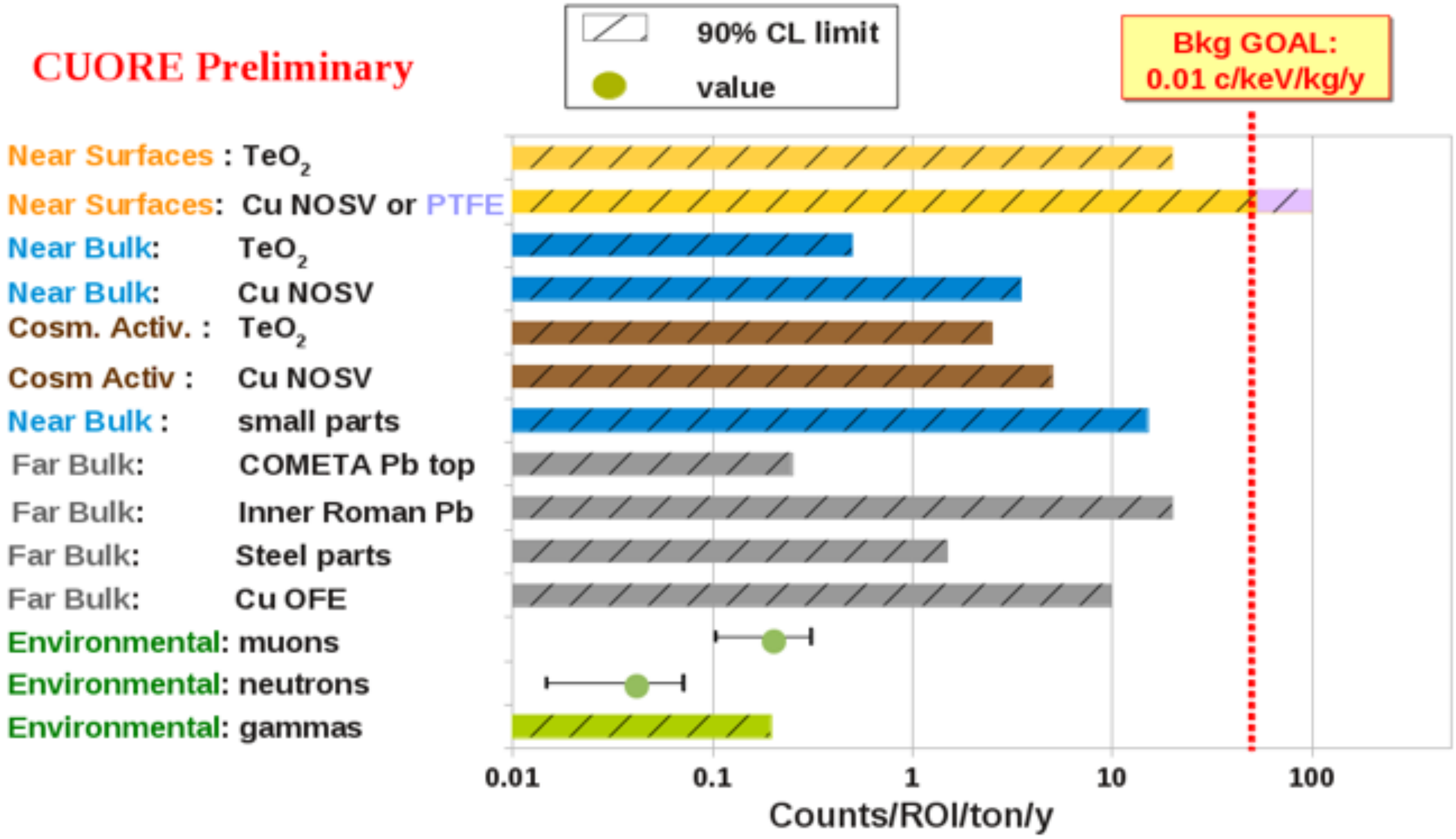
Assumptions:

- δE = 5.2 keV FWHM at 2615 keV
- b = 0.063±0.006 counts/(keV · kg · yr)

- CUORE-0 is the most sensitive ^{130}Te 0νββ expt **running**
- Expect to surpass CUORICINO with ~ 1yr lifetime

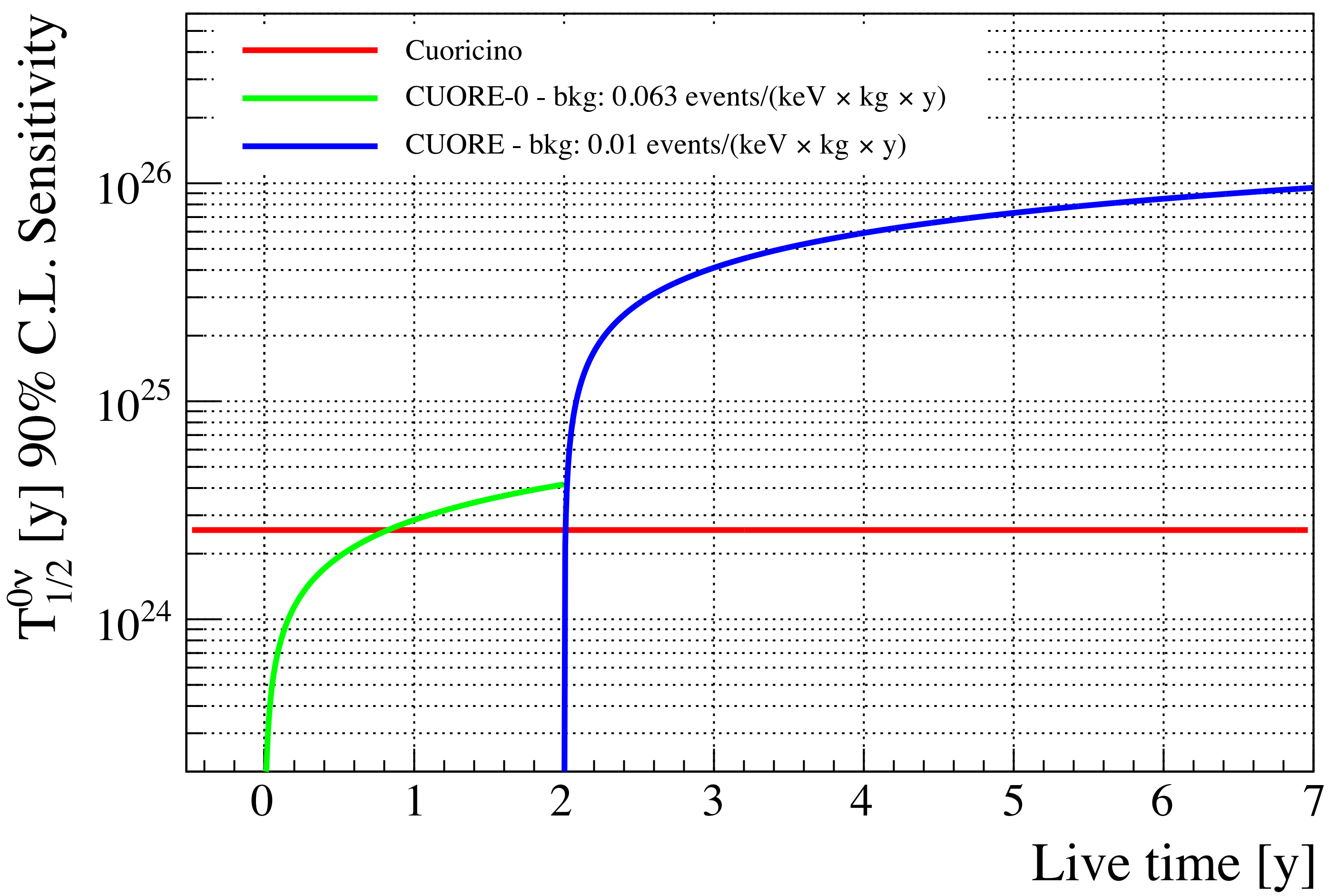
Projection to CUORE Bkg

- CUORE-0 provides benchmark of bkg remaining after the new assembly and Cu ultra-cleaning protocols
- Using measurements and limits from materials screening campaign we project bkg to CUORE using full geometry simulation



- Conservatively extrapolate measured α-region bkg from CUORE-0 assuming all bkg is from $^{238}U/^{232}Th/^{210}Po$ individually

CUORE Sensitivity



Assumptions:

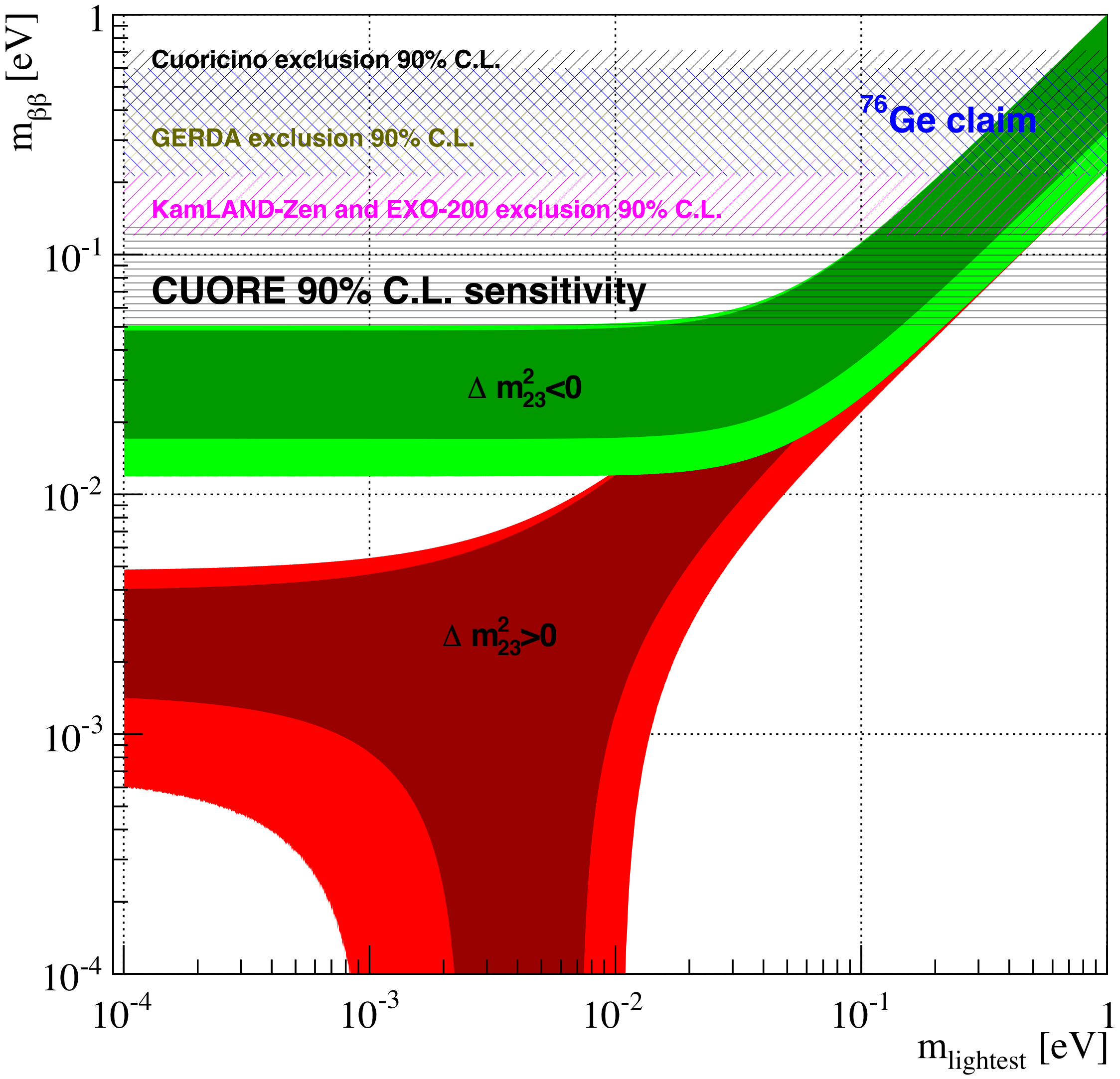
- δE = 5 keV FWHM at 2615 keV
- b = 0.01 counts/(keV · kg · yr)

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

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

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

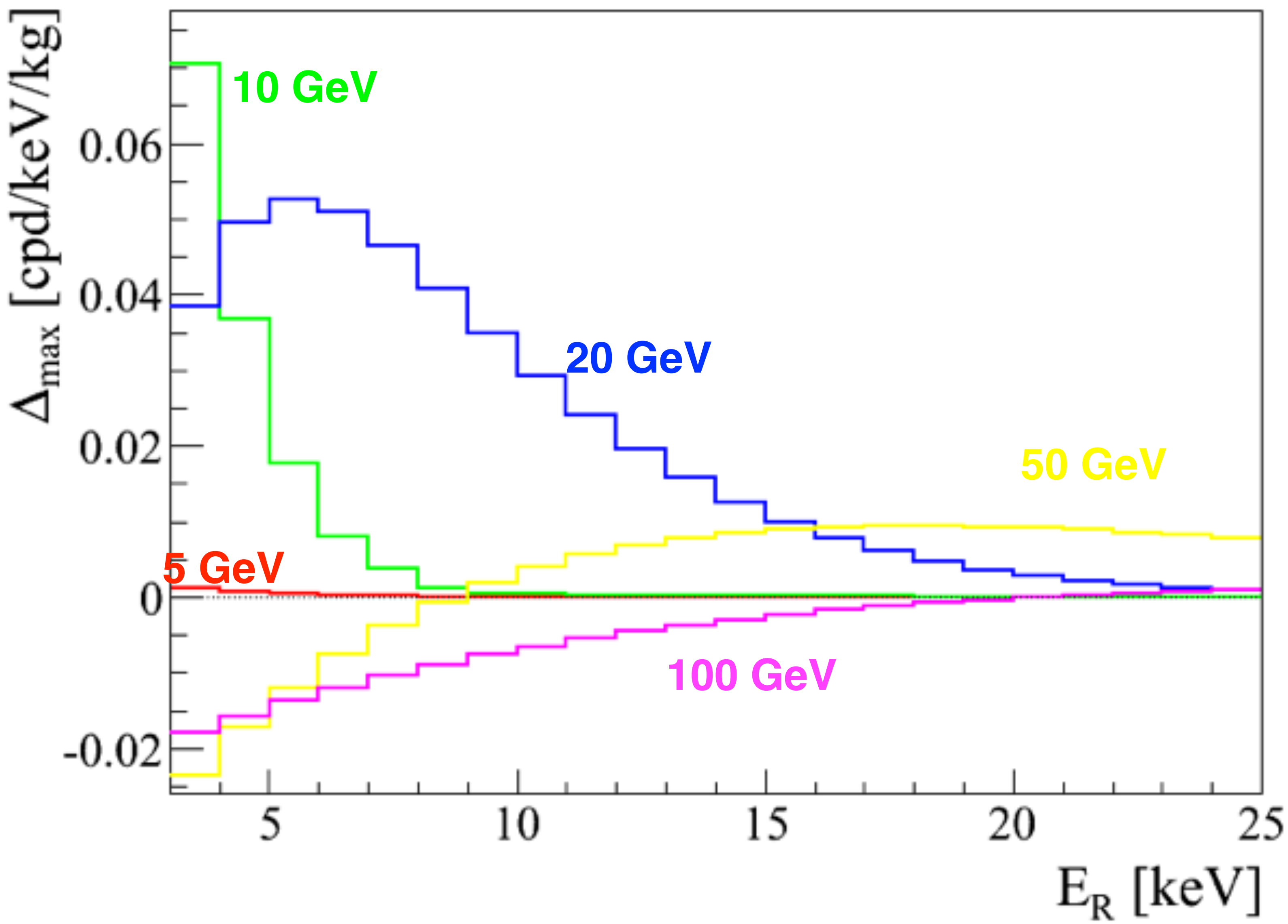
- CUORE will start to explore the inverted-hierarchy (depending on the NME)

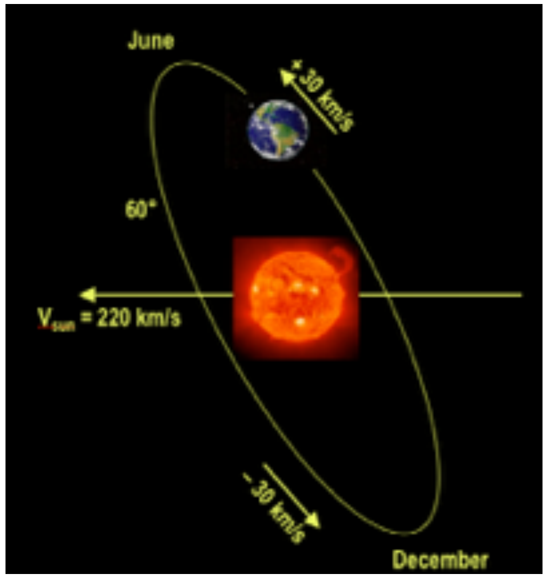


WIMP Dark Matter with CUORE ?

What would WIMP recoil modulation signal look like in CUORE (TeO_2) ?

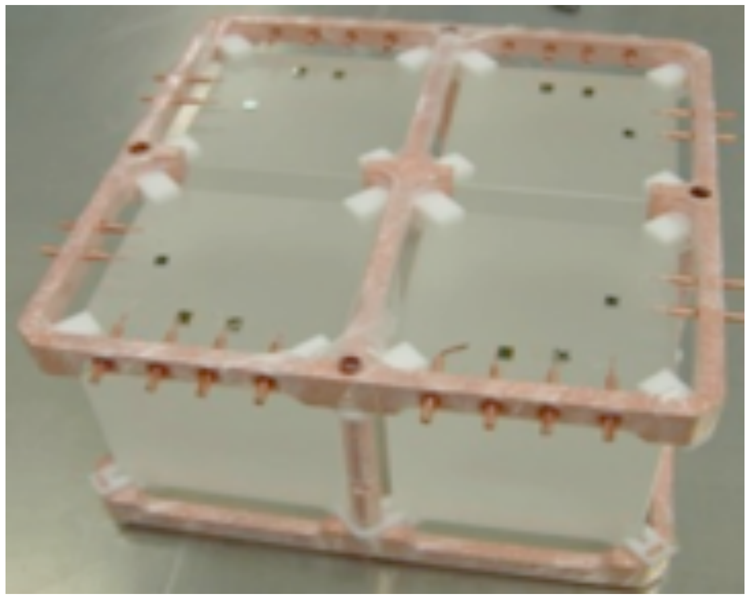
Max-min modulated rate vs recoil energy for $\sigma_{SI/nucleon} = 10^{-41} cm^2$





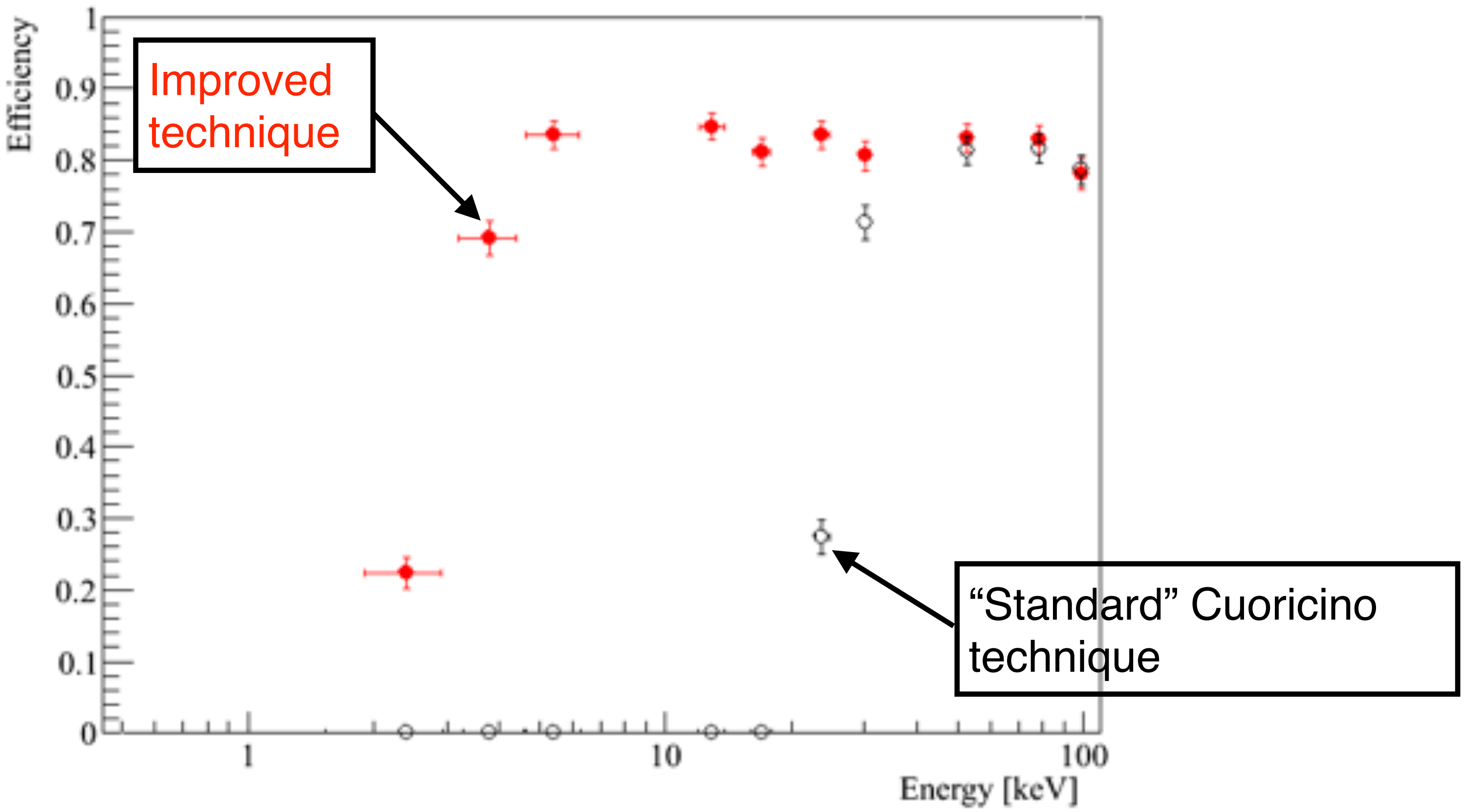
- Requires low threshold ~10keV (not typically interesting domain for 0νββ searches)
- Requires low background

Can threshold of CUORE-style modules be lowered ?

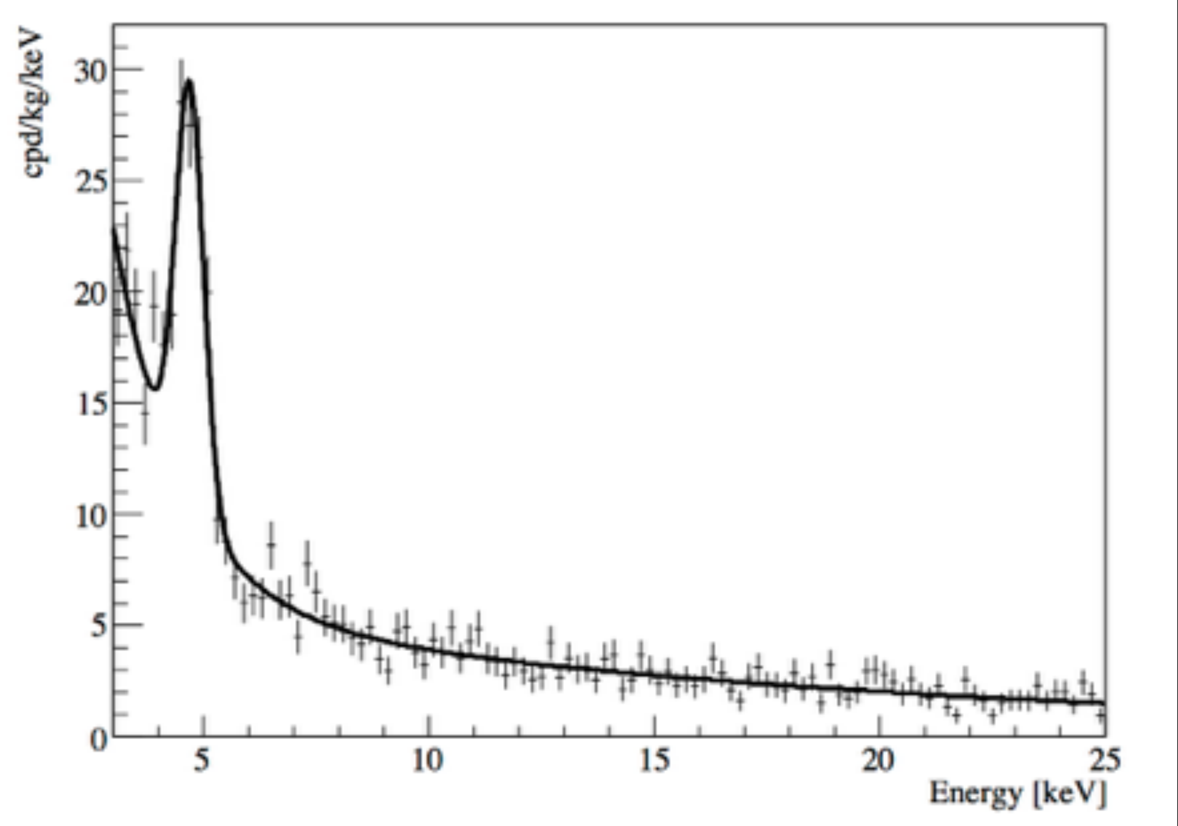


- Cuore Crystal Validation Run 2 (CCVR2)
- 4 CUORE crystals operated in test run for QA
- Improved analysis techniques achieved lower threshold:
- Achieved a threshold of ~3keV with 3 out of 4 crystals

Trigger threshold Scan



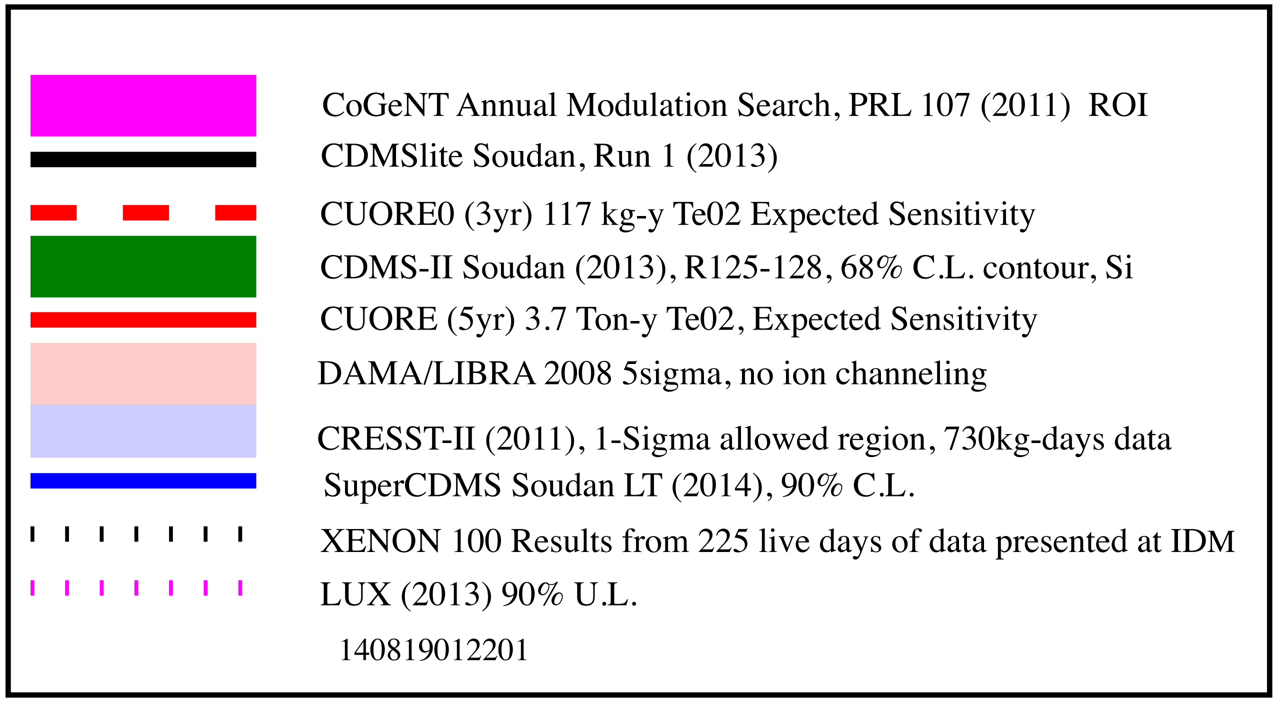
Summed spectrum of the 3 low-theshold crystals

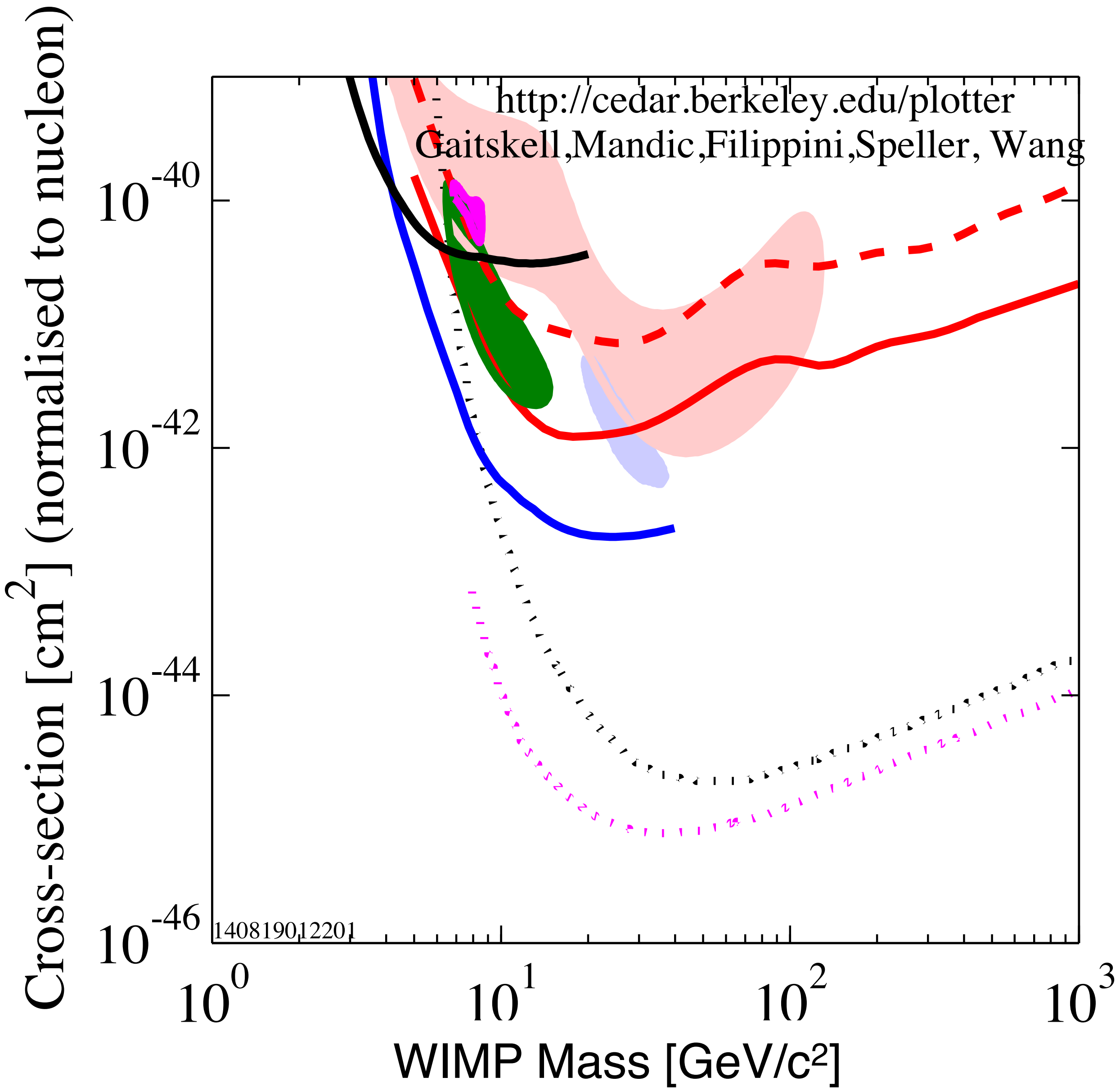


Sensitivity to annual modulation in CUORE-0 and CUORE

Assumptions:

- Energy threshold: 3keV
- Background: sampled from CCVR2
- Halo model: Isothermal sphere, ρ_w=0.3GeV/cm^3, v_0=220km/s, v_{esc} =600 km/s
- Q_{NR/e^-R} =1





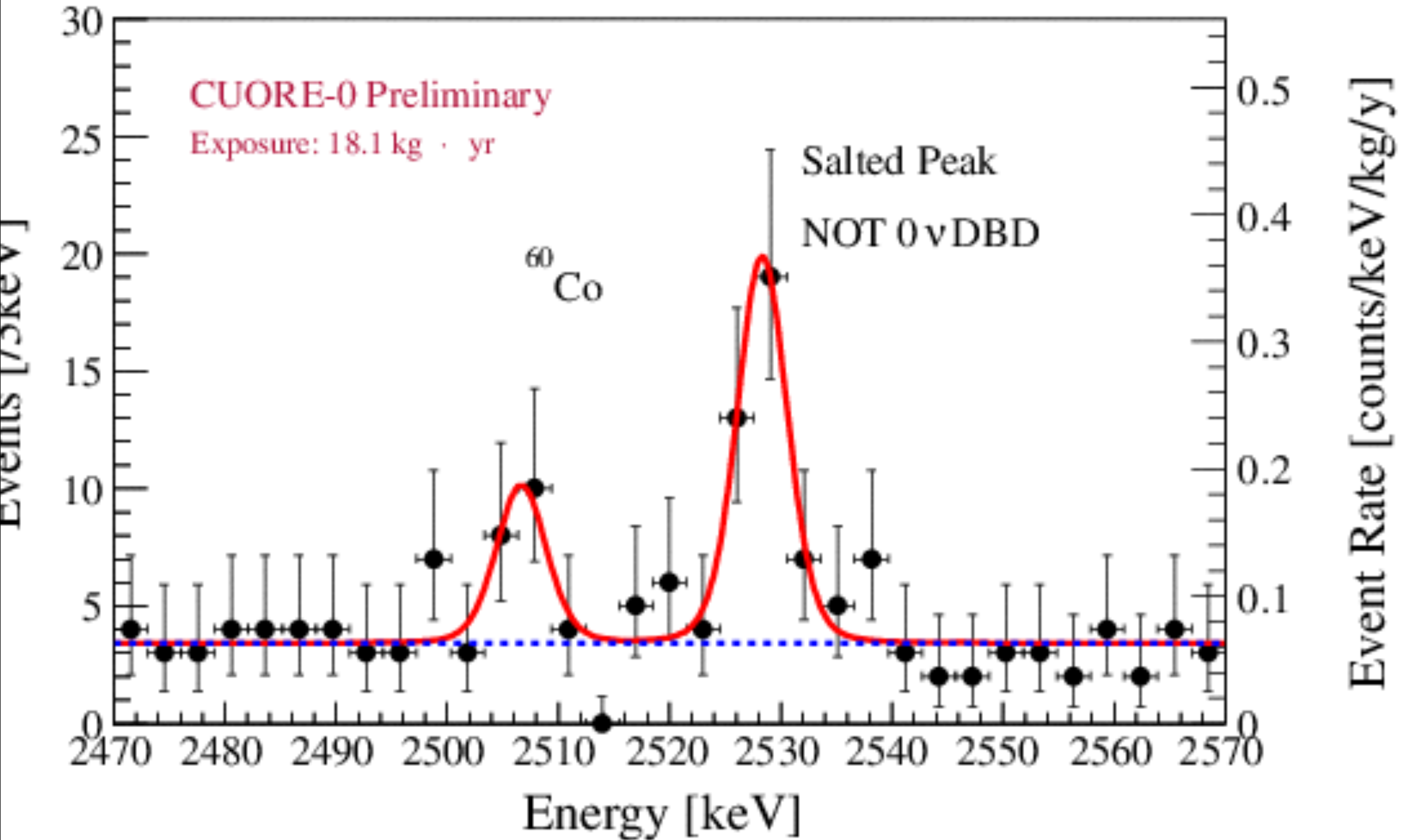
- CUORE-0 is now taking data, low-threshold analysis is ongoing
- For sure, CUORE is not as sensitive as dedicated DM experiments but may provide constraints in an interesting region of parameter space

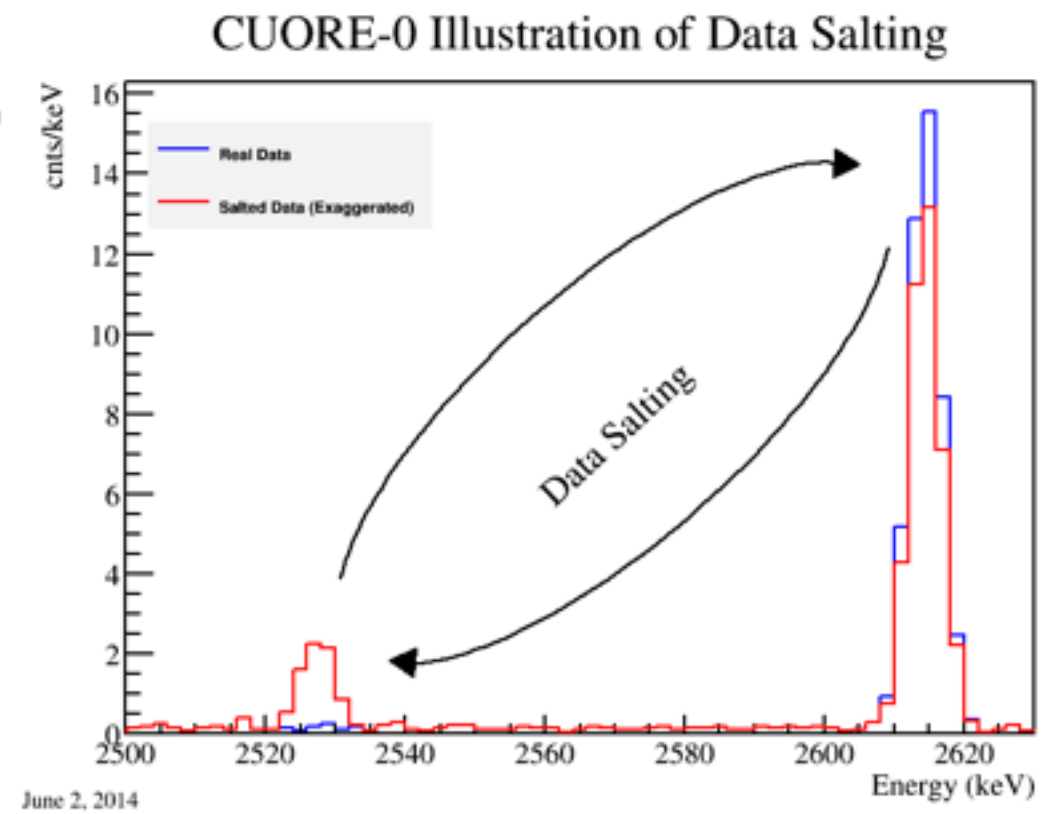
Conclusion

- The CUORE program has made a lot of progress in the last decade
- Lessons learned from CUORICINO have guided the CUORE design
- Data from CUORE-0 verifies that the assembly line, materials selection, and ultra-cleaning protocols are effective in reducing the leading background
- CUORE detector array is now ready and cryogenic system commissioning is advancing
- Expect array to be deployed in cryostat in 2015
- Large mass and low-background array has potential for other rare event searches unrelated to $0\nu\beta\beta$

Extra Material

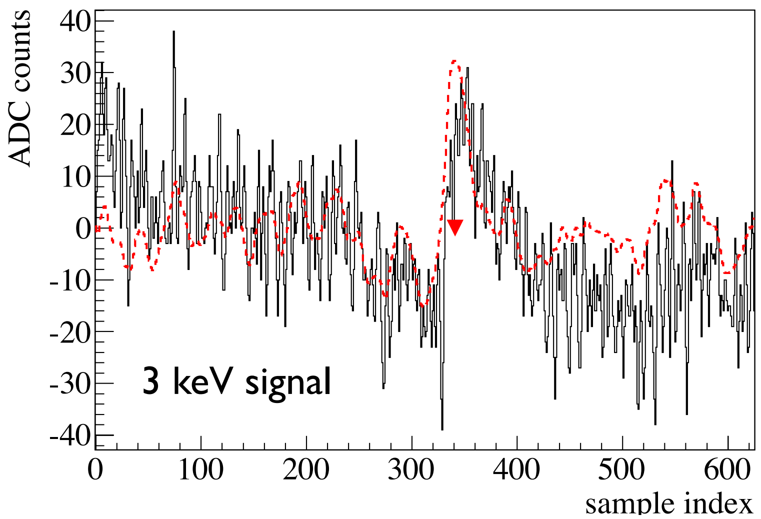
CUORE-0 Blinding Procedure

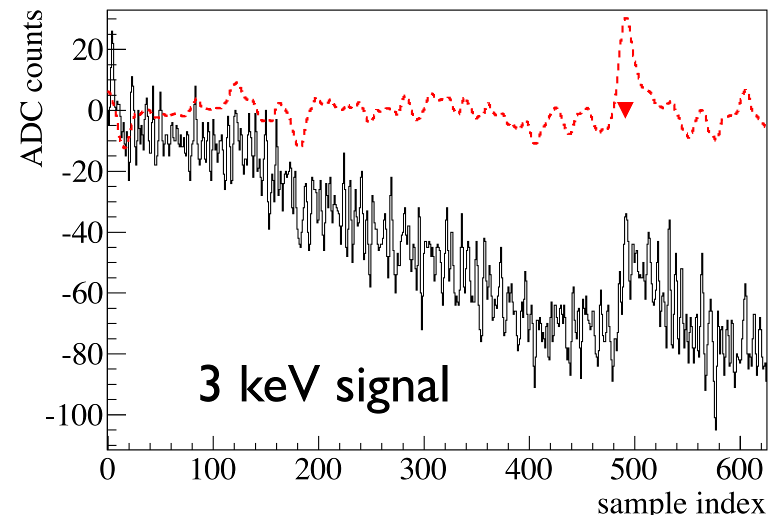




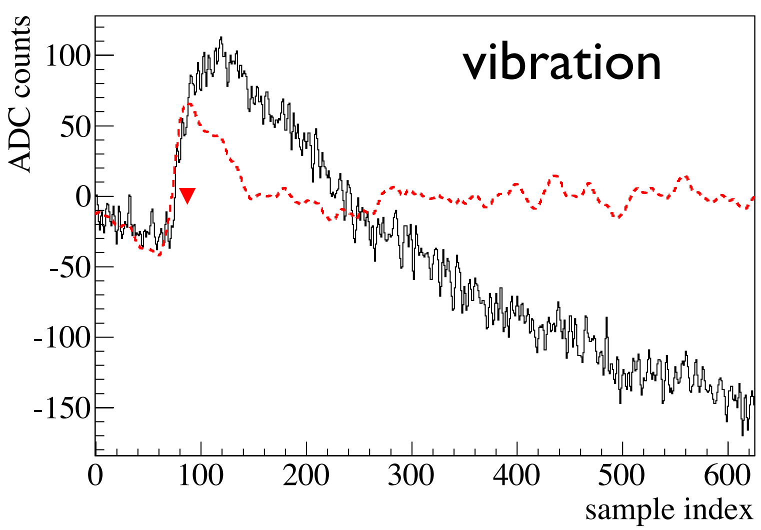
- Produce an artificial peak in the ROI
  A small blinded fraction of events within ±10keV of 2615keV peak are exchanged with events within ±10 keV of Q-value
- Plan to unblind when CUORE-0 sensitivity exceeds CUORICINO

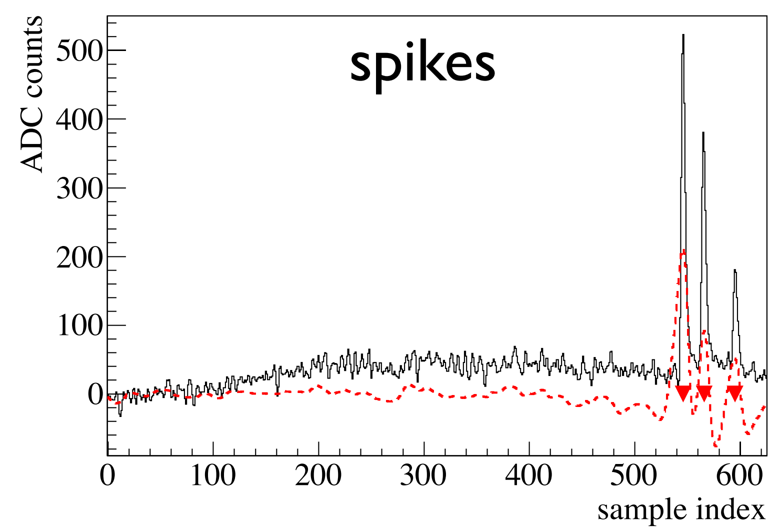
Improvements for lowering threshold

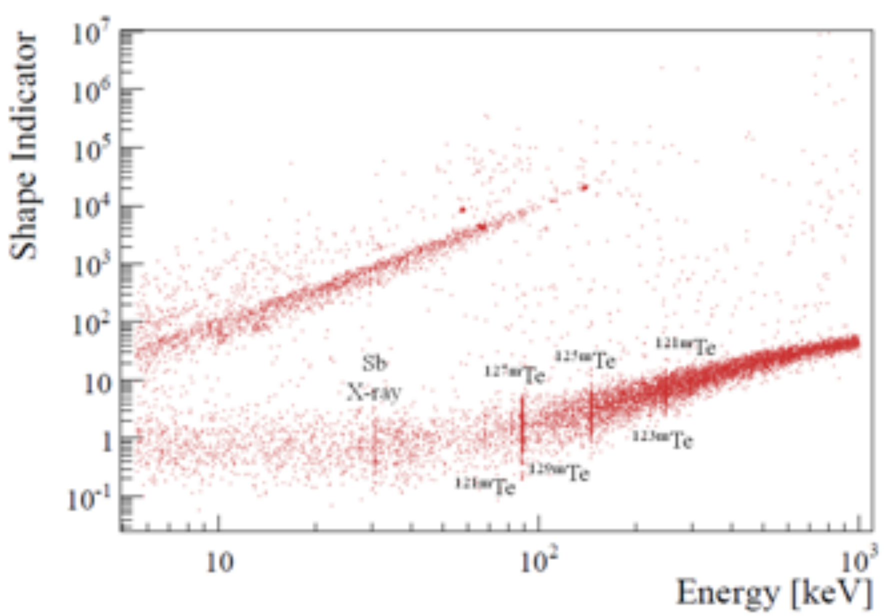




- Offline filter of continuously sampled raw data with offline trigger



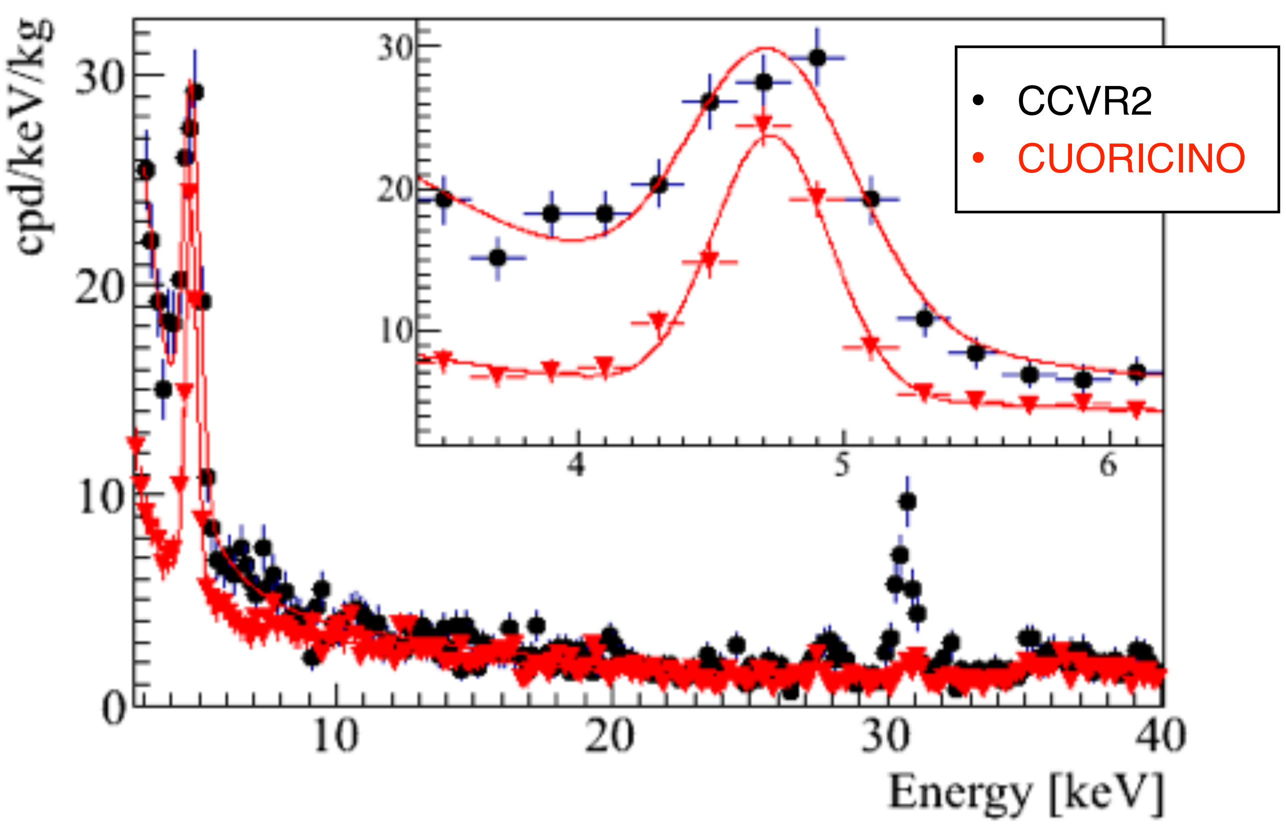




- Pulse-shape analysis to distinguish physical and non-physical pulses

4.7 keV peak in CCVR2

- This peak was also confirmed in a re-analysis of CUORICINO data
- Was only possible for the last 2 months of data-taking
- Only 4 channels reached threshold below 4.7keV



- Origin of the peak is not understood
- 4.7 keV coincides with L_1 atomic shell of antimony (Sb)
- Data are not consistent with known decays to Sb
  - ^{121m}Te, ^{121}Te EC to ^{121}Sb ($T_{1/2}$ =154 d and 17 d) but the intensity of the L1/K lines are inconsistent with our data
  - Other EC metastable Te isotopes have half-lives < 4.7 days. Peak rate is constant over 20 days.