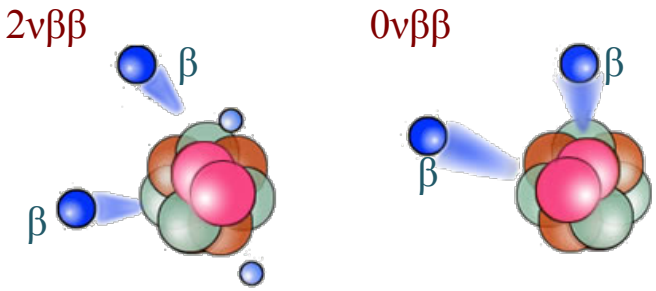
CUORE: Large Mass Bolometers for Neutrinoless Double Beta Decay Searches

Ke Han, Berkeley Lab

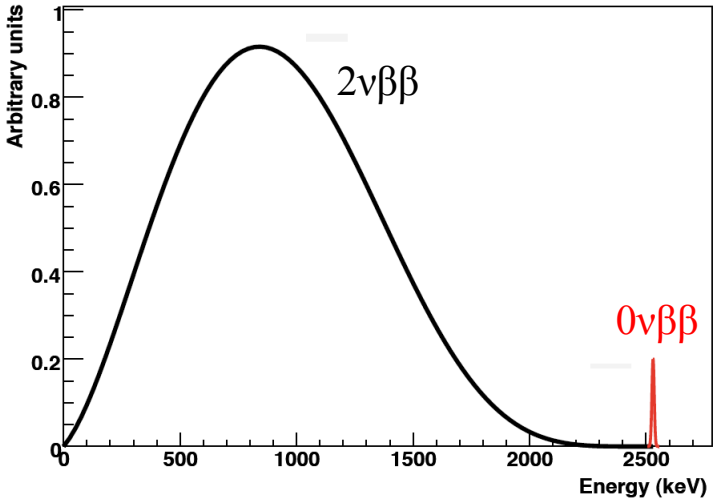
2nd International Conference on Technology and Instrumentation in Particle Physics

June 13, 2011

Neutrinoless double beta decay

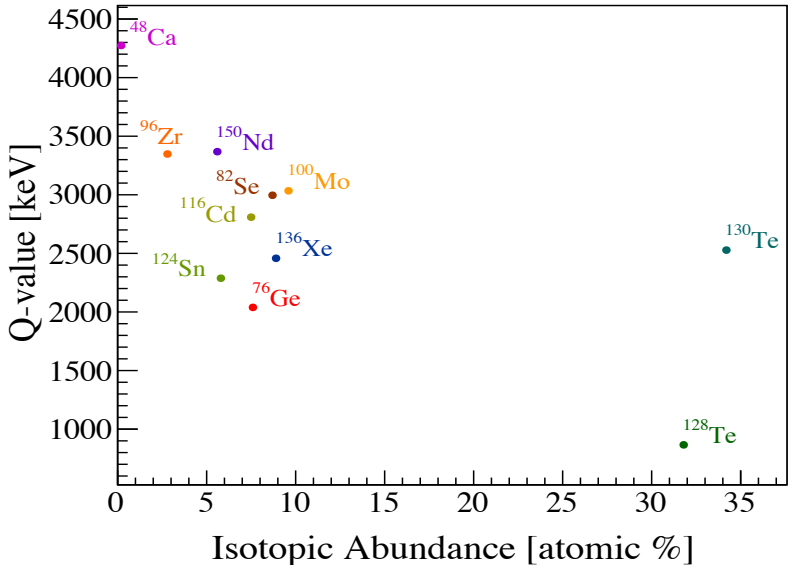


- $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

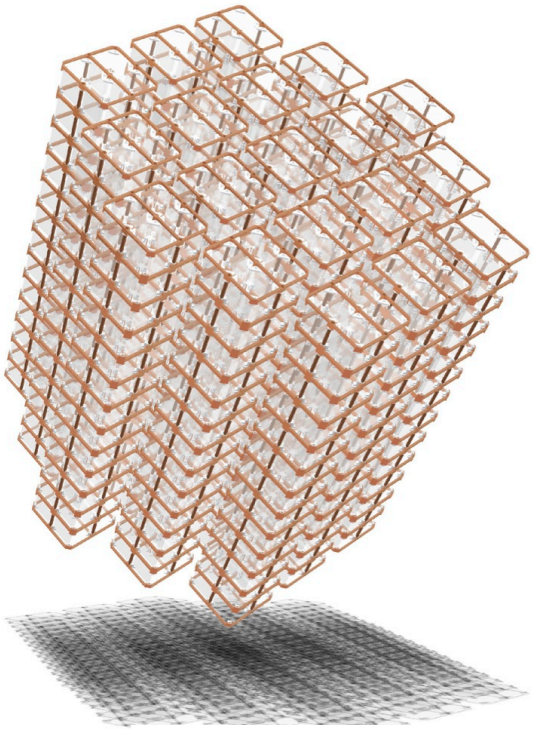


- $0\nu\beta\beta \Leftrightarrow E_{sum}$ of $2e$ = Q-value

- Extremely rare ($T^{0\nu}_{1/2} > 10^{24}$ y), only if ν is Majorana particle
- Candidate nuclei: ^{48}Ca, ^{76}Ge, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, . . .
- Large natural I. A., cost effective
- Q-value (2528 keV) above most of the γ backgrounds



Cryogenic Underground Observatory for Rare Events

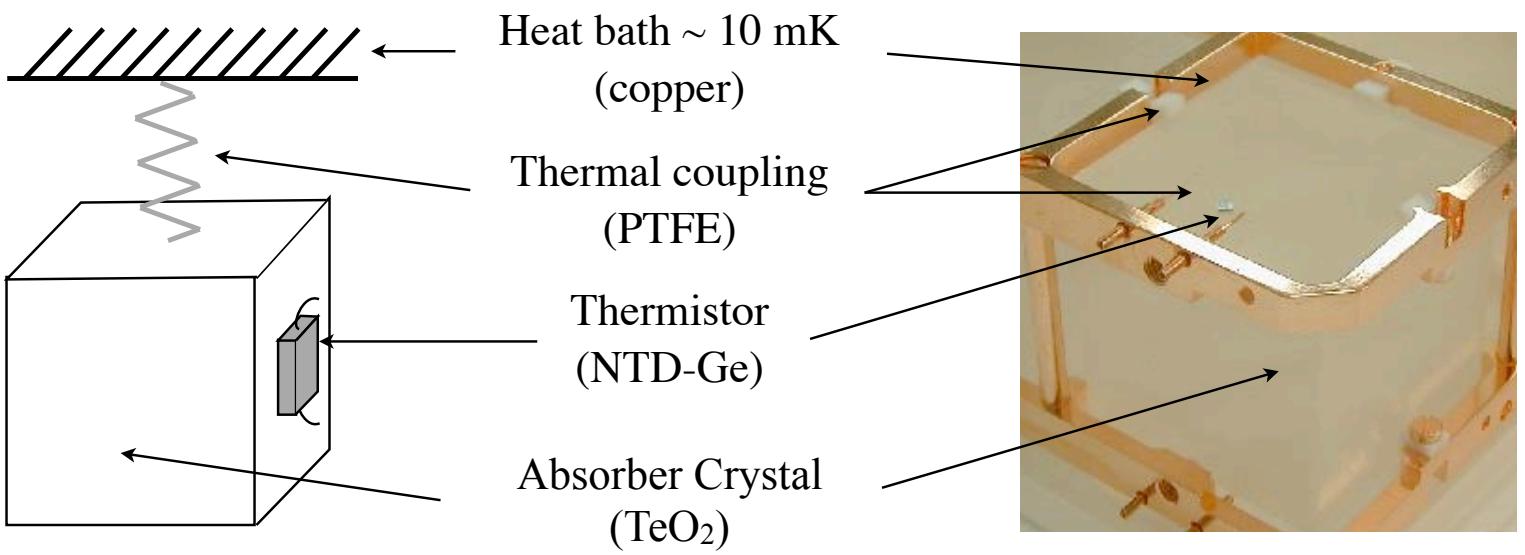


- at Gran Sasso National Lab, Italy
- 988 bolometers at 10 mK.
  - 19 towers $\times$ 13 floors $\times$ 4 TeO_2 crystals
  - each crystal: 5x5x5 cm^3, 750g
- 206 kg ^{130}Te; 741 kg crystals total
- Source = Detectors
  - high detecting efficiency at $\sim$ 87%.
- Excellent energy resolution: 5 keV @ ROI.

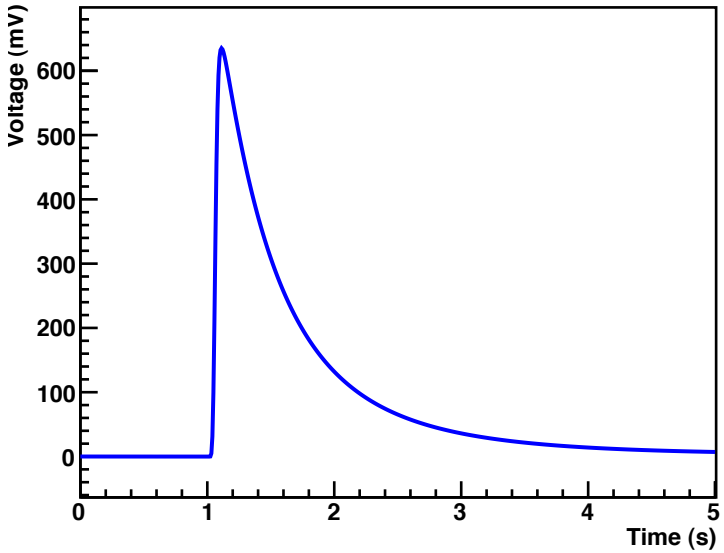
$$\text{Half life sensitivity} \propto \eta \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

- Isotopic abundance
- Detecting efficiency
- Detector mass
- Background rate
- Energy resolution
- Measuring time

A large mass bolometer module



- Energy measurement from corresponding temperature rise.
  - Small phonon excitation energy; excellent intrinsic energy resolution
  - Resolution dominated by vibrational noise
- Slow process, $\tau = \frac{C}{G} \sim 1\,second$



Crystal – the absorber

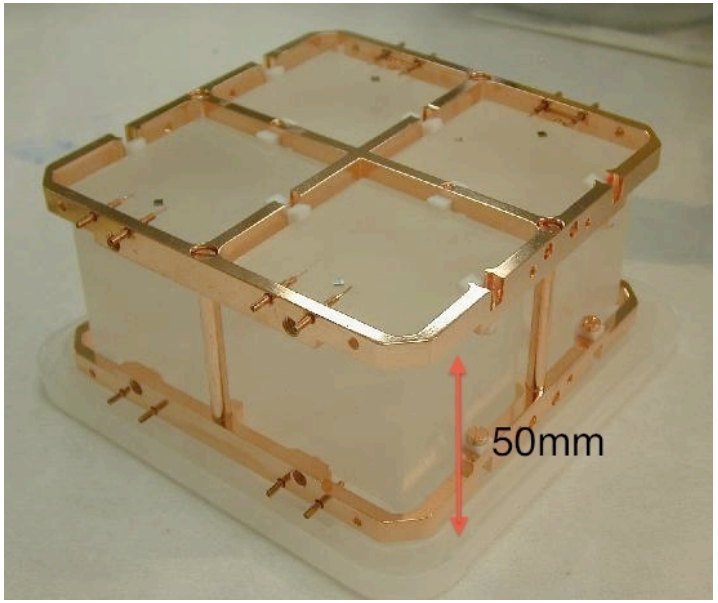
- Material choice:

$$c(T) = c_r(T) + \cancel{c_e(T)}$$

- High Debye temperature

$$c_r(T) = \frac{12}{5}\pi^4 k_B N_A \left(\frac{T}{\Theta_D}\right)^3$$

- Low working temperature
- Large crystals desired but still cost effective to grow.
  - 5x5x5 cm^3, 750g
  - had 3x3x6; tried 6x6x6

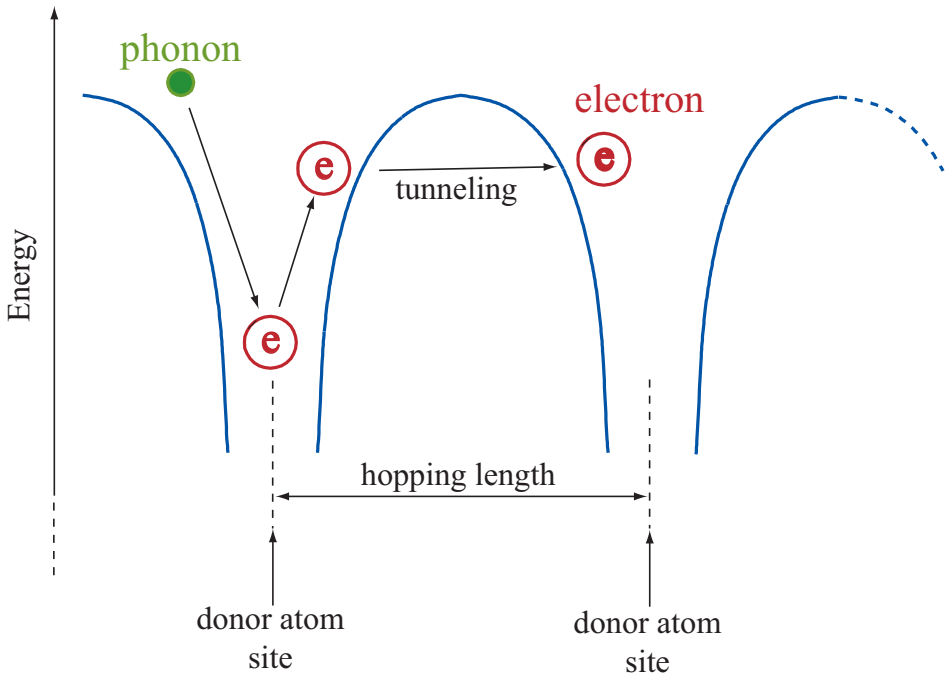


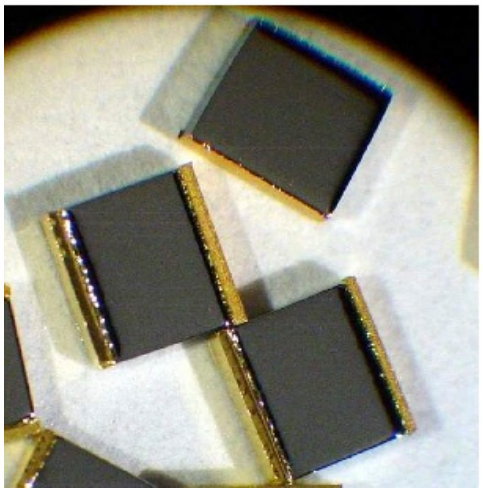
- $C_r = 2.3 \times 10^{-3} T^3$ J/K
  - ΔT=0.1 mK/MeV at 10mK
- Survives the heat cycling.

  $\surd$ TeO_2 $\times$ Te
- radiopure

CUORE Thermistors

- Neutron Transmutation Doped (NTD) germanium thermistor
- Phonon induced tunneling (hopping) between impurity sites.
- $R = R_0 e^{\sqrt{T_0/T}}$; R_0, T_0 determined by dosage.
- $R_0 \sim 1\Omega$, $T_0 \sim 3$K for CUORE thermistor
- 100 MΩ at 10 mK.





$3 \times 3 \times 1$ mm^3

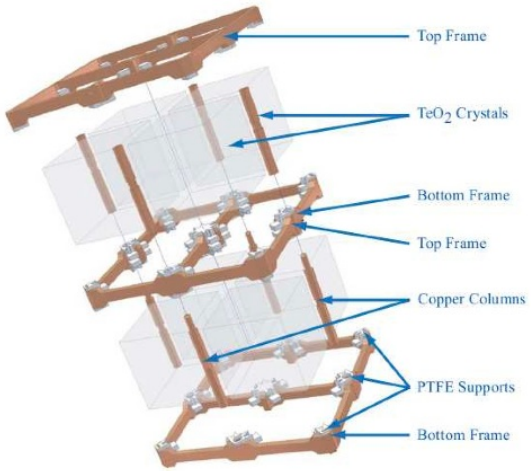
Copper Frame and Teflon Holders

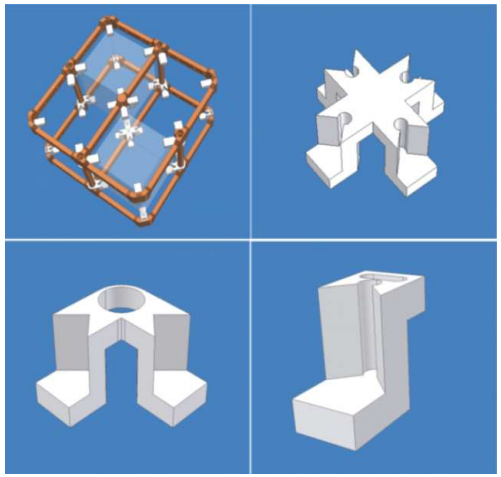
Copper Frame:

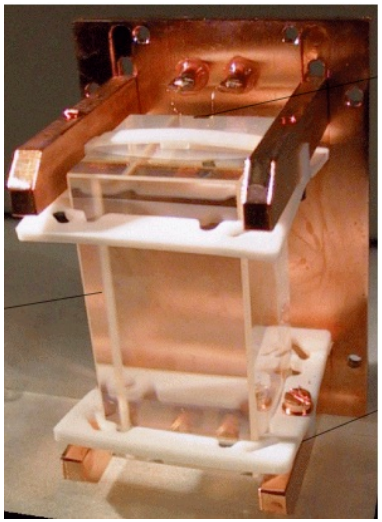
- Heat bath
- Background source

Teflon holders

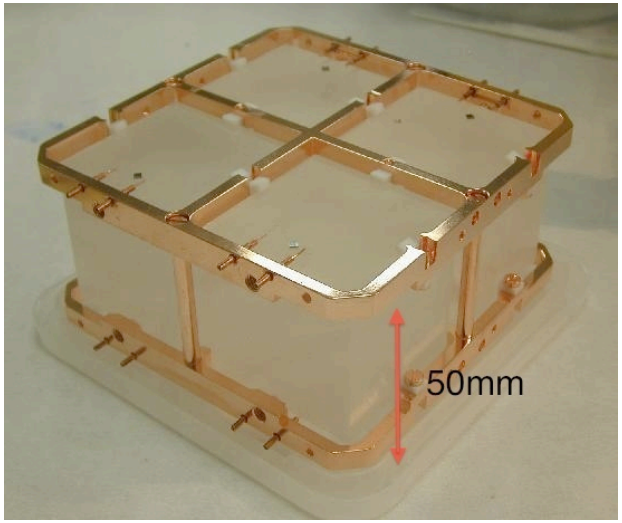
- The weak thermal link
- Reduce vibration noise



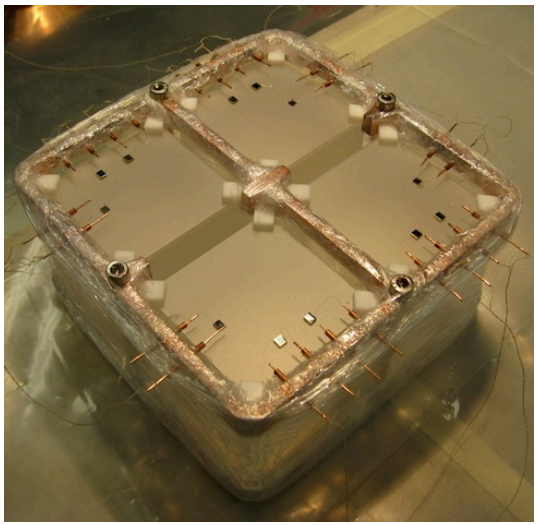




MiDBD

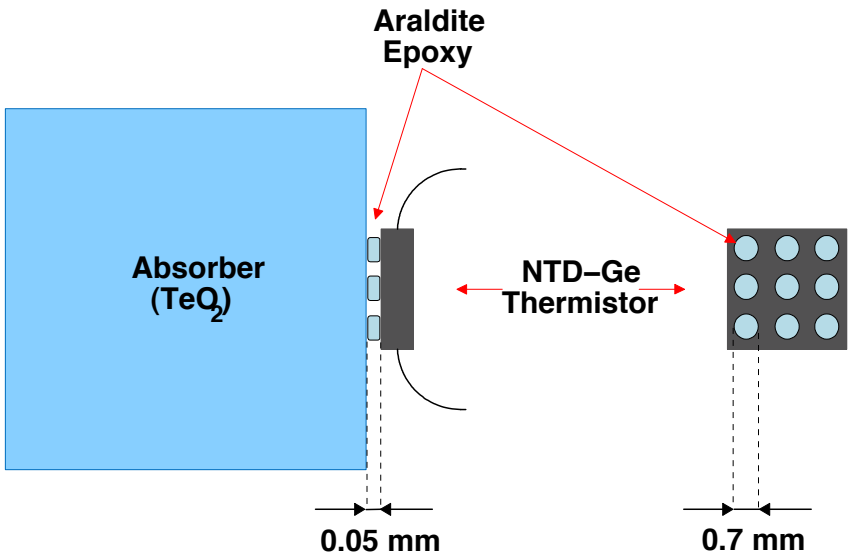


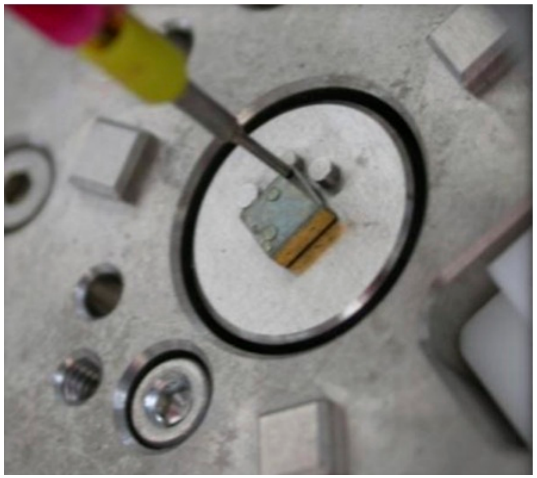
CUORICINO

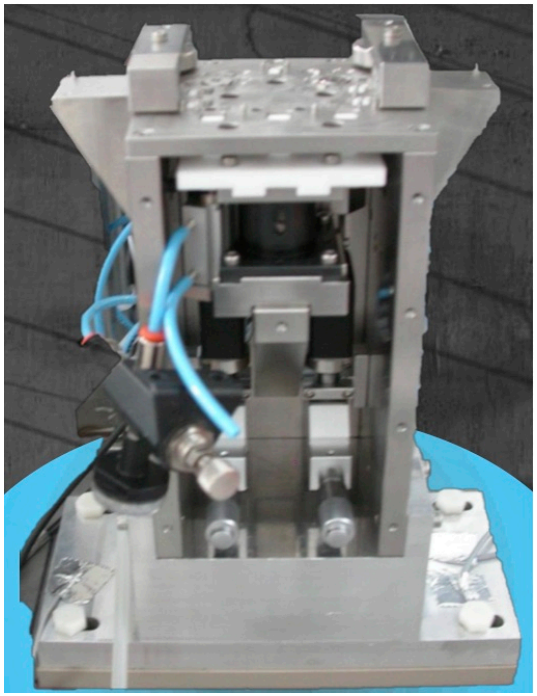


CUORE

Gluing


Araldite
Epoxy
Absorber
(TeO_2)
NTD–Ge
Thermistor
0.05 mm
0.7 mm





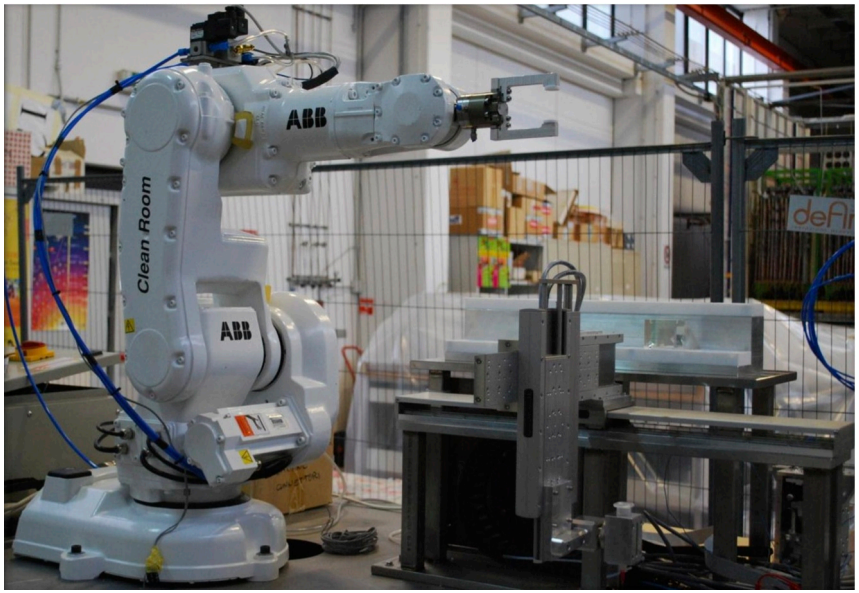
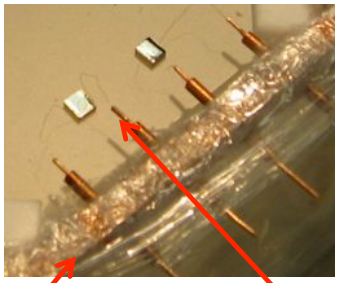


ABB
Clean Room
ABB

Thermal Model



Copper

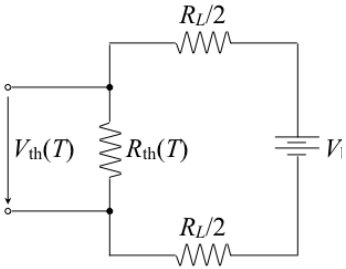
Wires

P_e

electrons

$P_{f,e}$

Bias

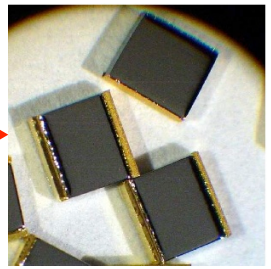


heat sink T_0

P_{rb}

P_{er}

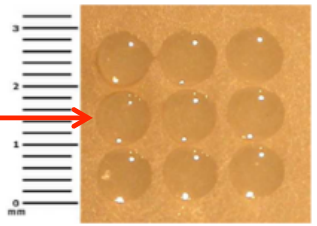
Thermistor



lattice

P_{ra}

Epoxy



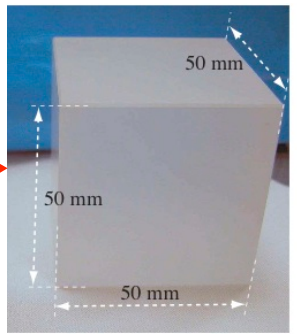
P_{ab}

$P_{f,a}$

Teflon

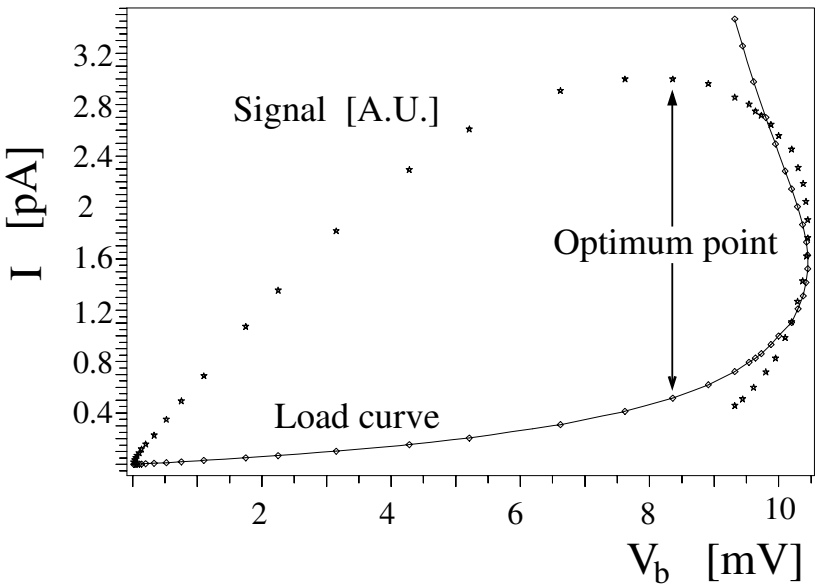
absorber

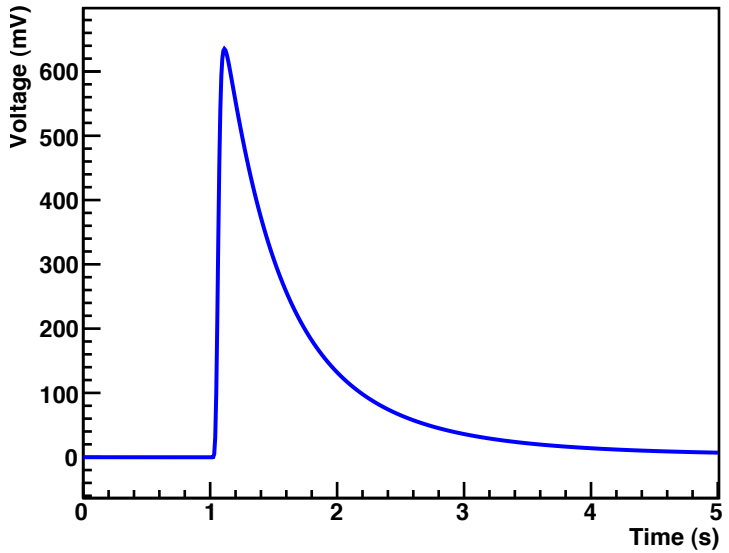
Crystal



Bias Circuit and DAQ

- Programmable bias voltage and load resistance.
- $R_L \gg R_{th}$, constant current bias $\Rightarrow$ Electrothermal feedback.
- Optimum point (with max S/N) is close to maximum signal pulse height point.





- 18-bit high accuracy M series digitizer from NI
- 125 Hz sampling rate
- 5s pulse window, 1s pre-trigger
- Continuous data also recorded for offline triggering

Calibration

^{232}Th source:

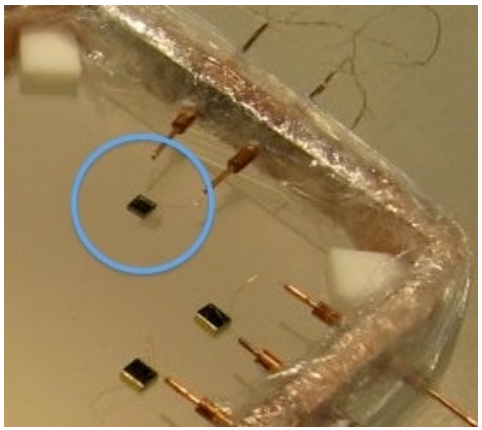
- once per month
- 2615 keV γ

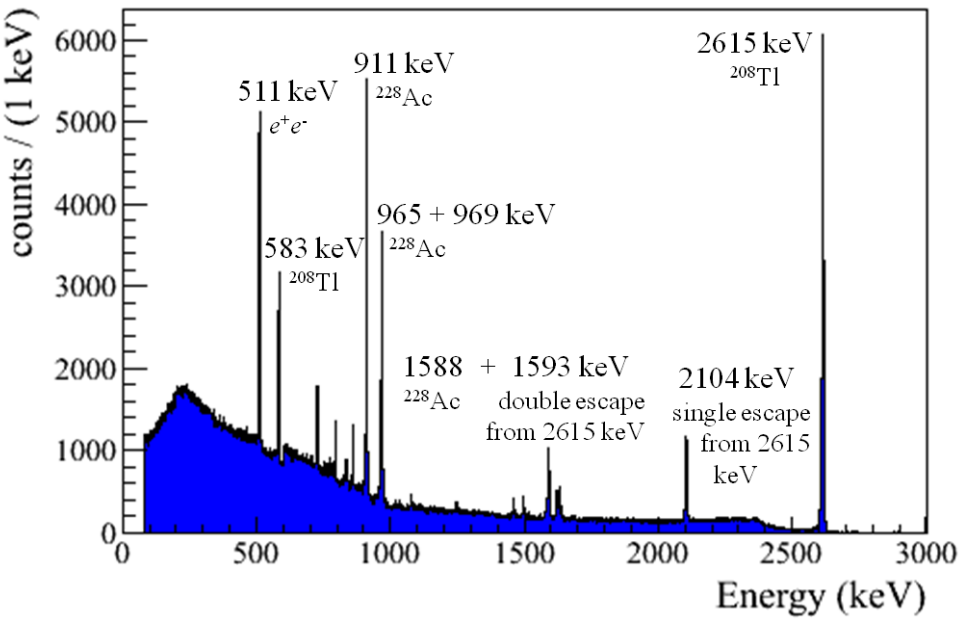
Radio-impurity

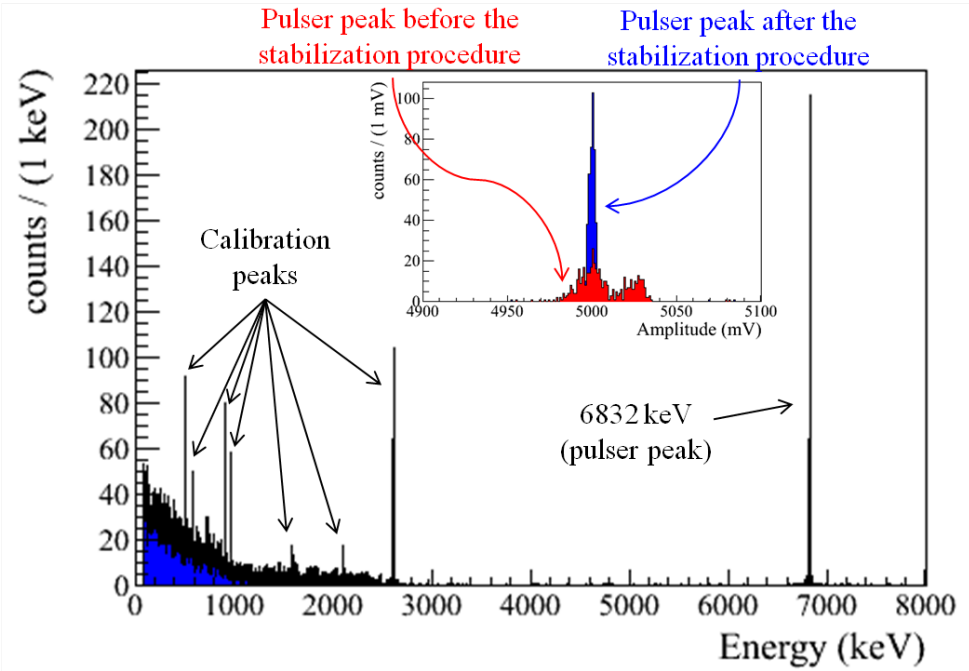
- ^{210}Po: α; ^{40}K: γ

Reference Si heater:

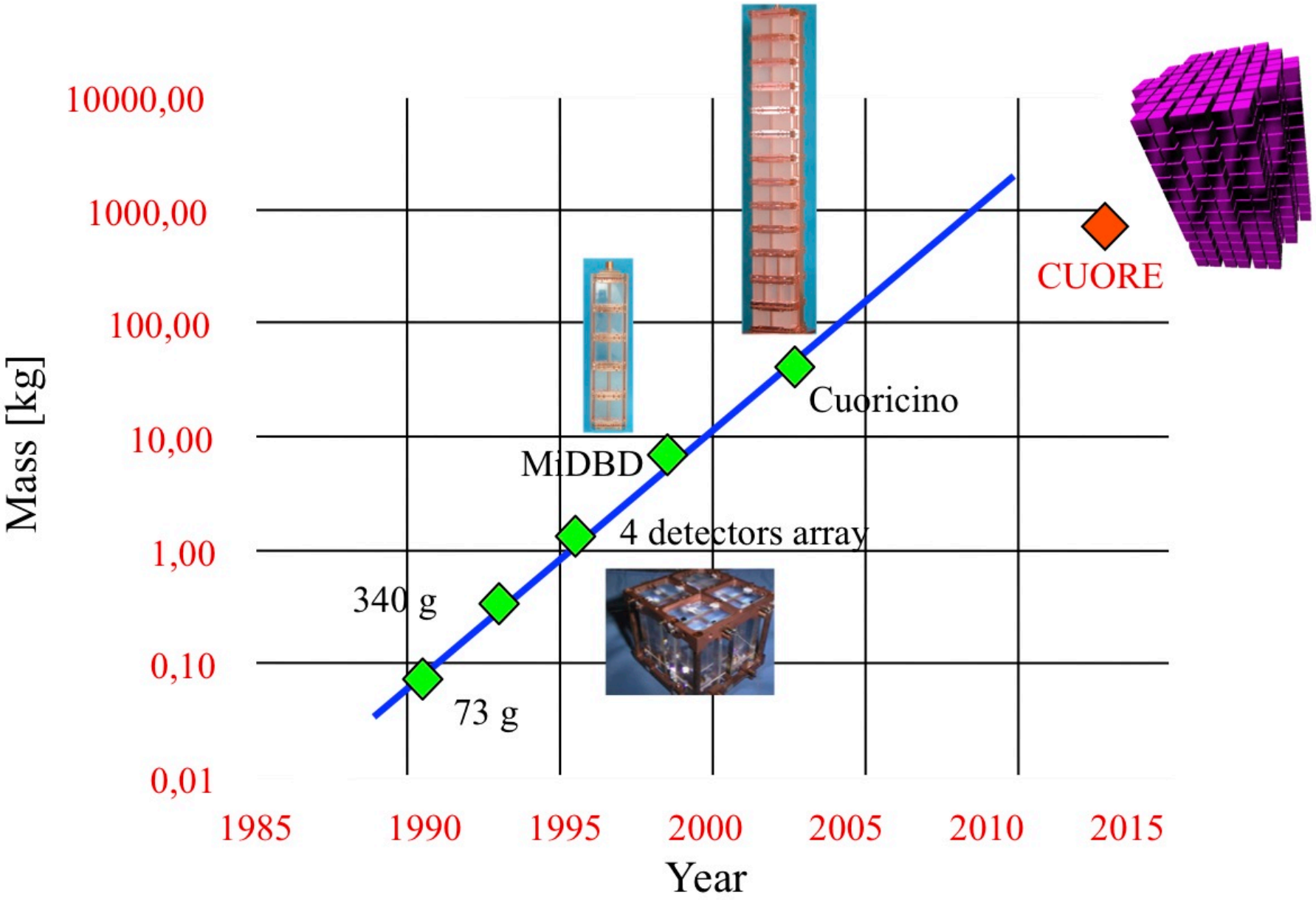
- One pulse per 5 min
- Negligible heat capacity
- Constant R over T
- Programmable pulser in FEE



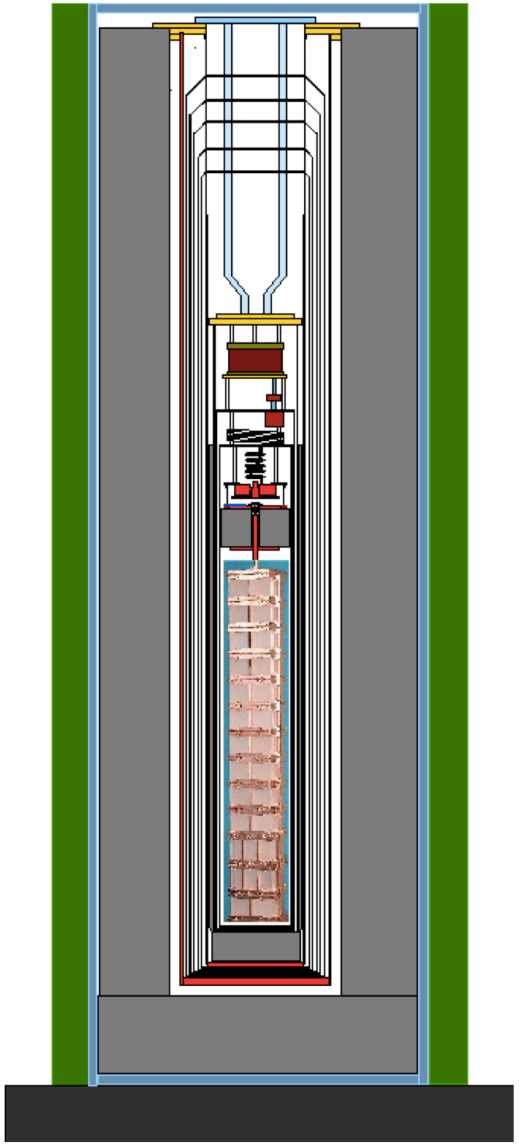


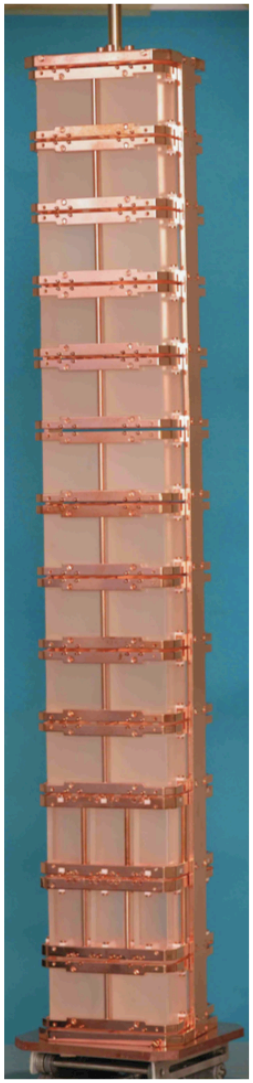


Pursuit of rare decay events with bolometers

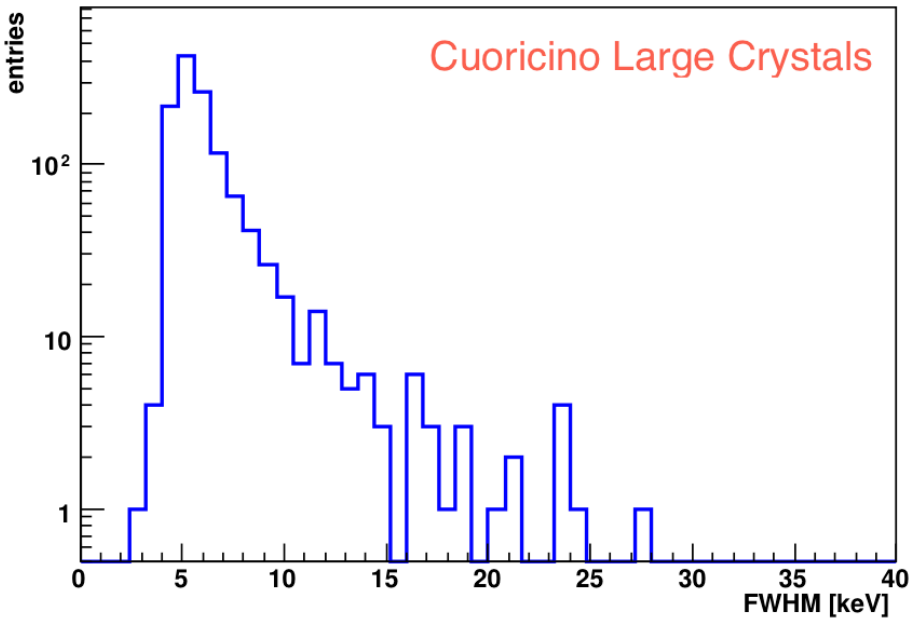


Cuoricino – little CUORE





- March 2003 to May 2008
- 11.3 kg of ^{130}Te out of 40.7 kg of TeO_2
- Total exposure 19.75 kg·y.
- Average resolution 6.3 keV at $Q_{\beta\beta}$



Improving energy resolutions

Maximizing S/N:

Signal pulse height

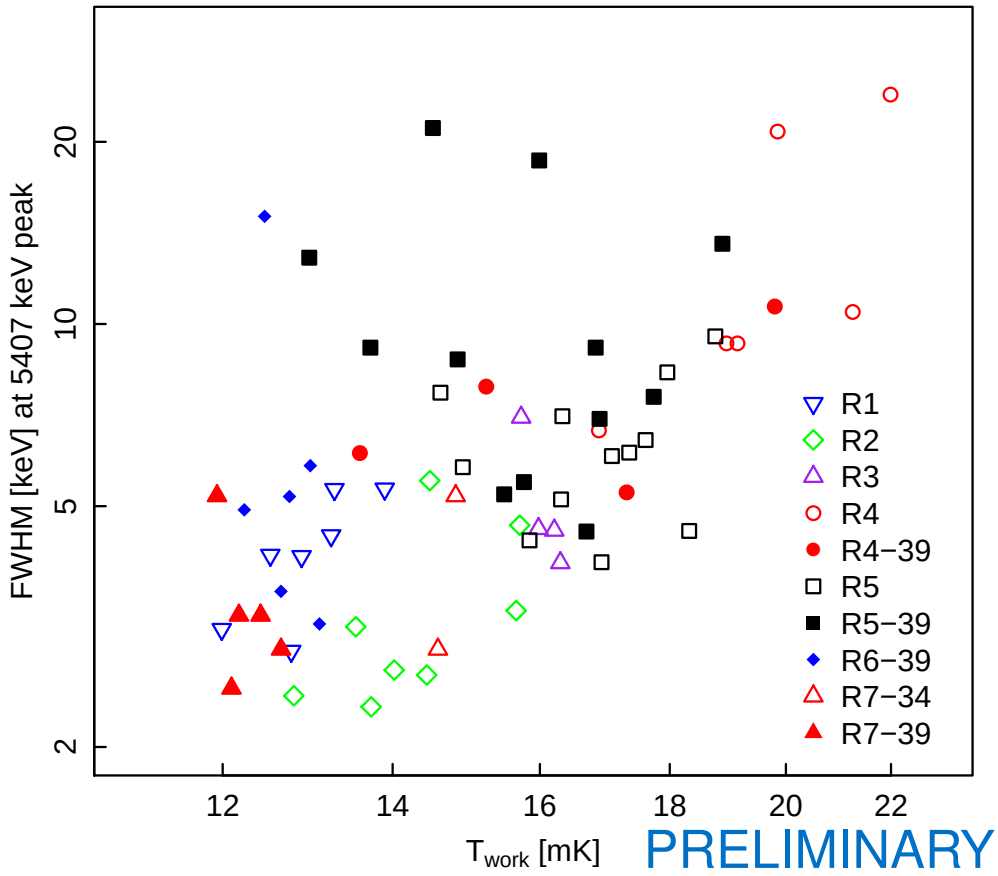
- Cryostat temperature
- Thermistor response
- Gluing
- Bias voltage

Noise

- Vibrations
- Microphonics
- Pre-Amp noise

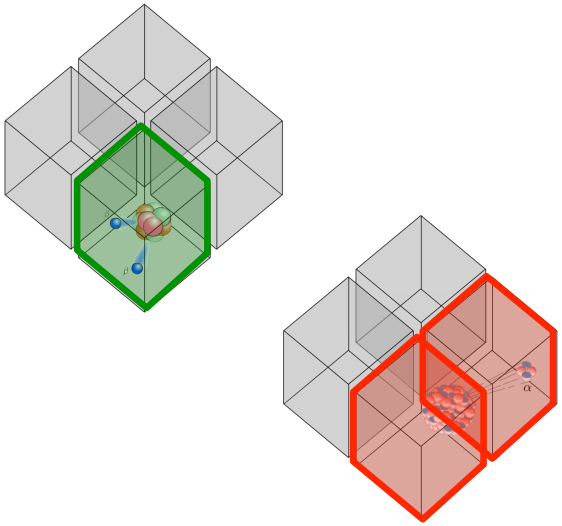
CUORE baseline is certainly within reach; will aim for better

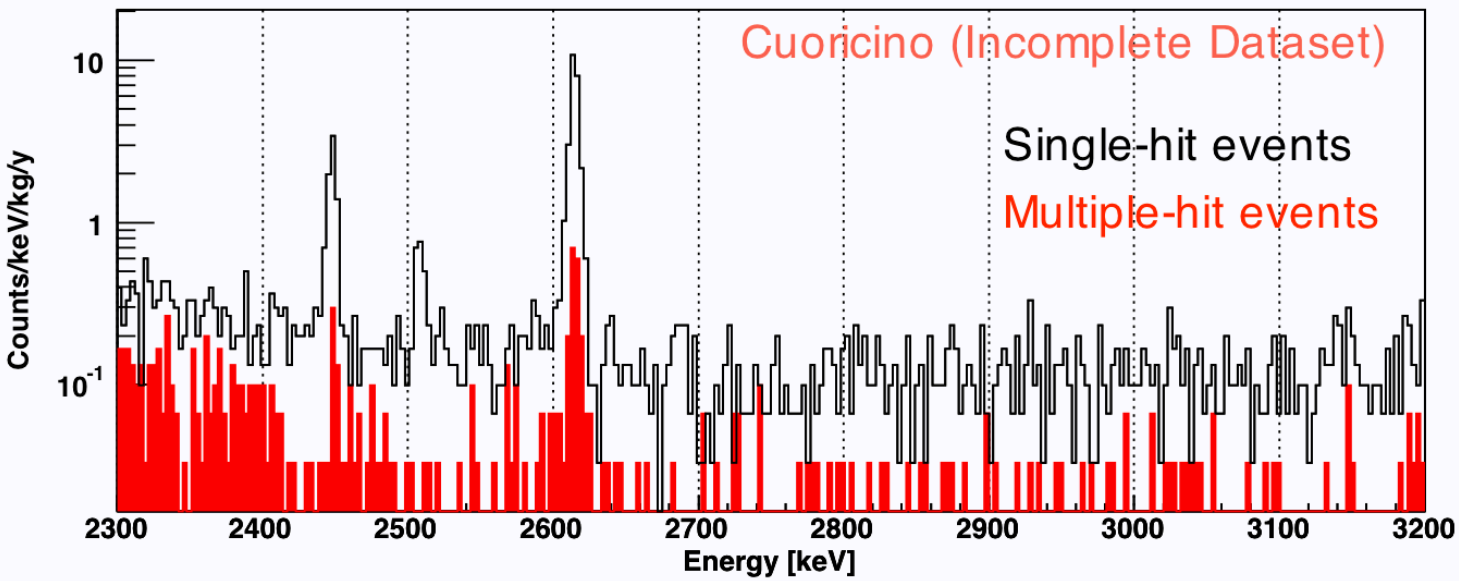
- Cuoricino: long term stability
- CCVR (best): 3keV FWHM at 5.4MeV
- CUORE baseline: 5 keV at ROI



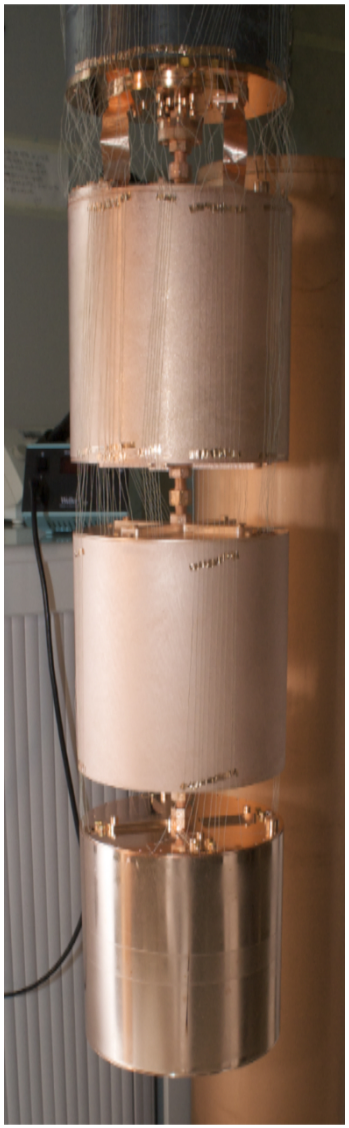
Reducing background: anti-coincidence cuts

- Anti-coincidence cut (100 ms) window rejects α from crystal surfaces.
- In the ROI, the reduction is about 20%.
- Does not work for α from copper
- The array does self-shield some surfaces from copper





Reducing background: copper cleaning



- Cuoricino total BG: 0.169 ± 0.006 cts/keV/kg/y
  - (~40%) Compton events from 2615 keV γ (cryostat).
  - (~50%) Degraded α from ^{238}U, ^{232}Th (copper).
  - (~10%) Degraded α from ^{238}U, ^{232}Th (crystal).
- Copper cleaning comparison: Three Tower Test
  - Comparable γ bg at $Q_{\beta\beta}$
  - $\times 3$ reduction for α at 3 to 4 MeV
  - 0.06 cts/keV/kg/y

For CUORE, factoring in:

- New radiopure cryostat
- More anti-coincidence and self-shielding
- Target at 0.01 cts/keV/kg/y for CUORE.

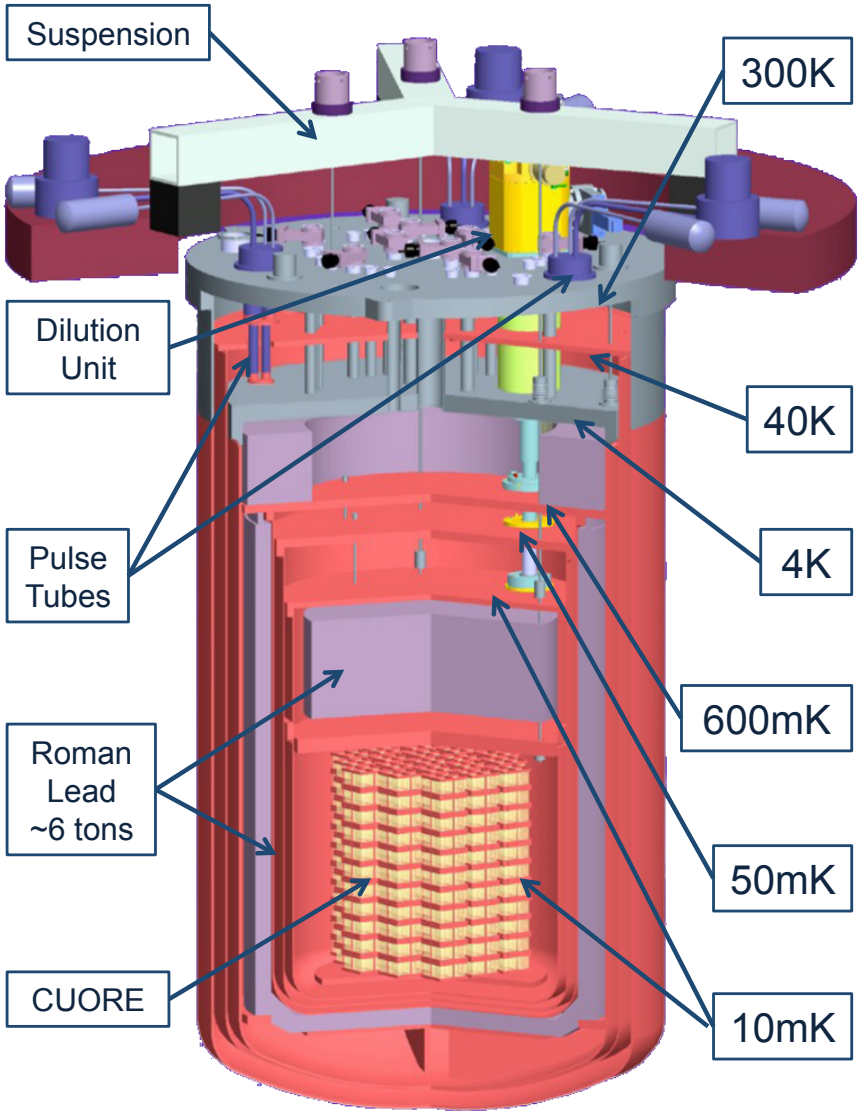
CUORE

CUORE data taking in 2014

- Custom-built cryostat
  - ~ 1 ton bolometers at 10 mK
  - ~ 20 tons at various T
- Calibration system
- Detector assembly

Meanwhile, CUORE-0

- One tower in Cuoricino cryostat
- Now under construction
- Data taking start Nov 2011.



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  - $\sim$ 20 tons at various T
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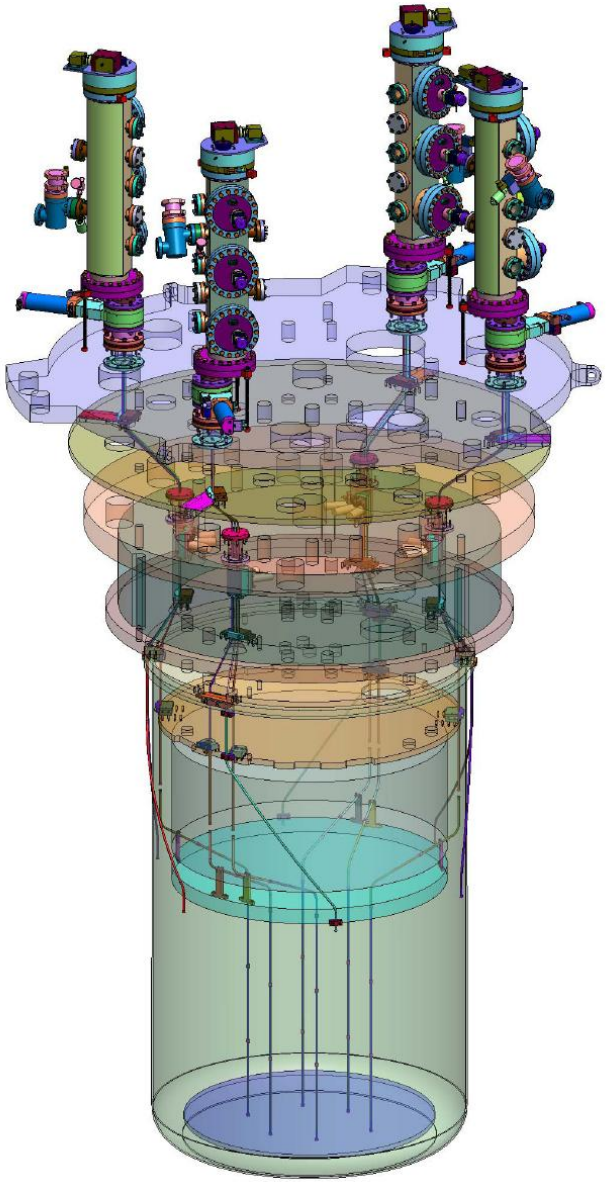

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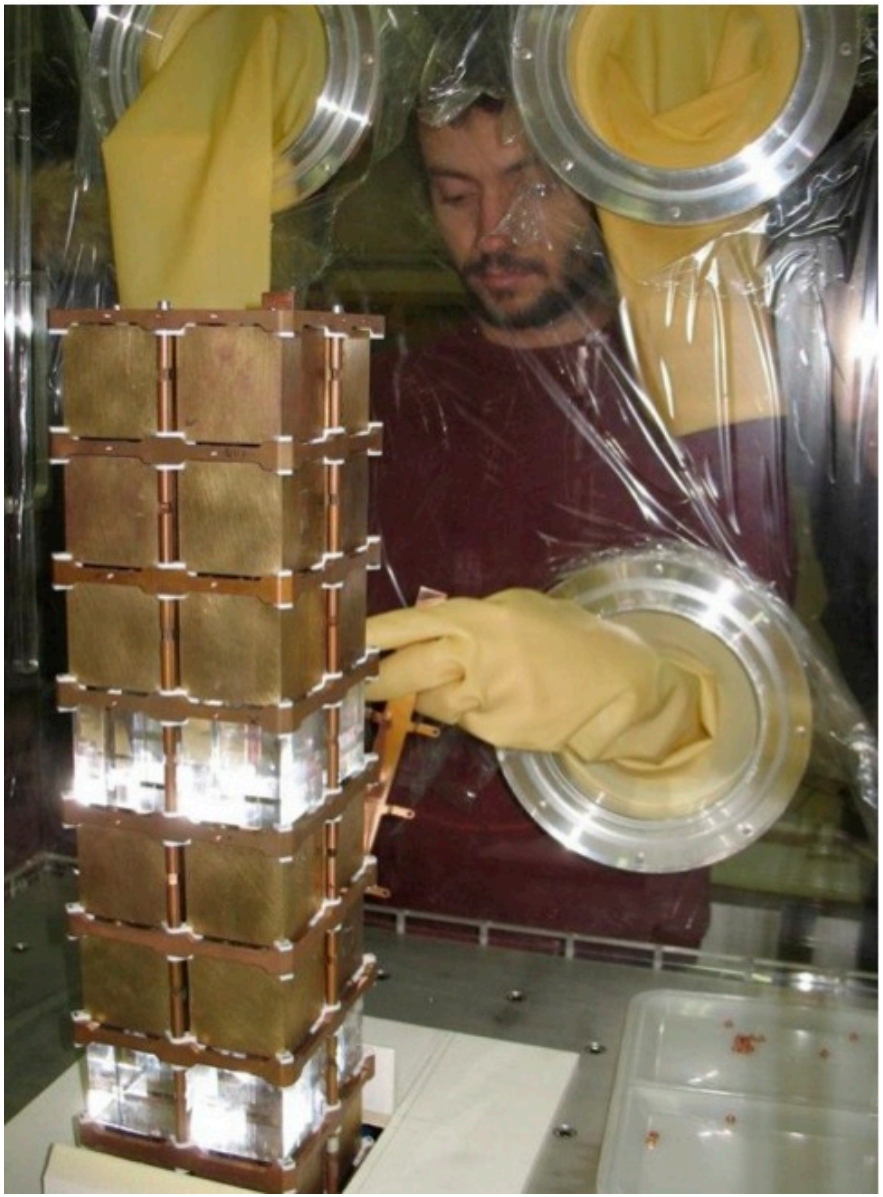

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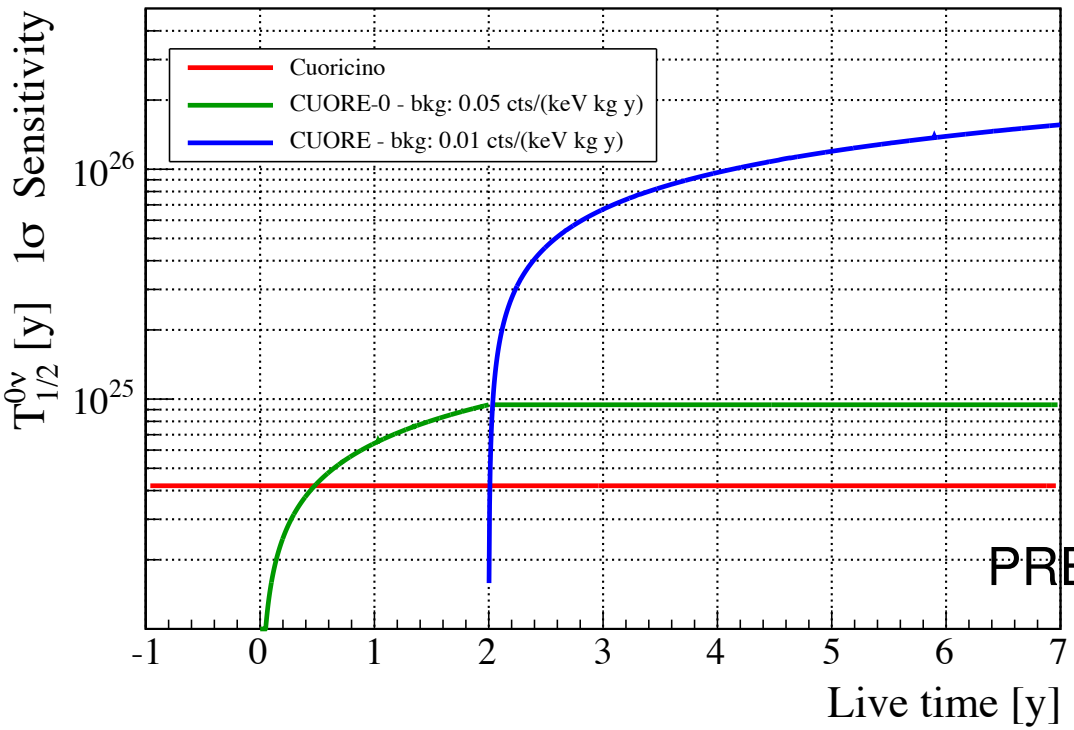
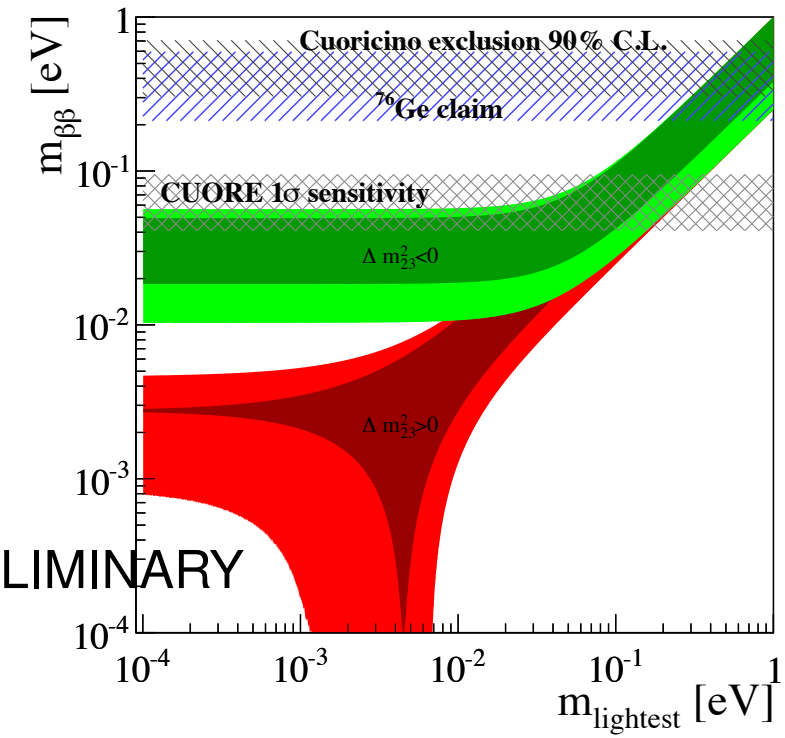
CUORE sensitivities

- $m_{\beta\beta} \approx 40 - 100$ meV for 5 yrs live time [PRELIMINARY]





PRELIMINARY


unige

CAESAR AVGVSTANAE STVDIVM GENERALE CIVITATIS

INFN
Istituto Nazionale
di Fisica Nucleare

ACADEMIA LUGDUNO BATAVA
15
75
PRAESIDIUM LIBERTATIS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FLORENTINA STUDIORUM UNIVERSITAS

THE UNIVERSITY OF CALIFORNIA BERKELEY
LET THERE BE LIGHT
1868

THE UNIVERSITY
of
WISCONSIN
MADISON

UNIVERSITY OF
SOUTH
CAROLINA