The CUORE experiment at LNGS

Brian Fujikawa (Lawrence Berkeley National Lab)

16-22 July 2017 Rencontres du Vietnam Neutrinos

https://cuore.lngs.infn.it/

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

Outline

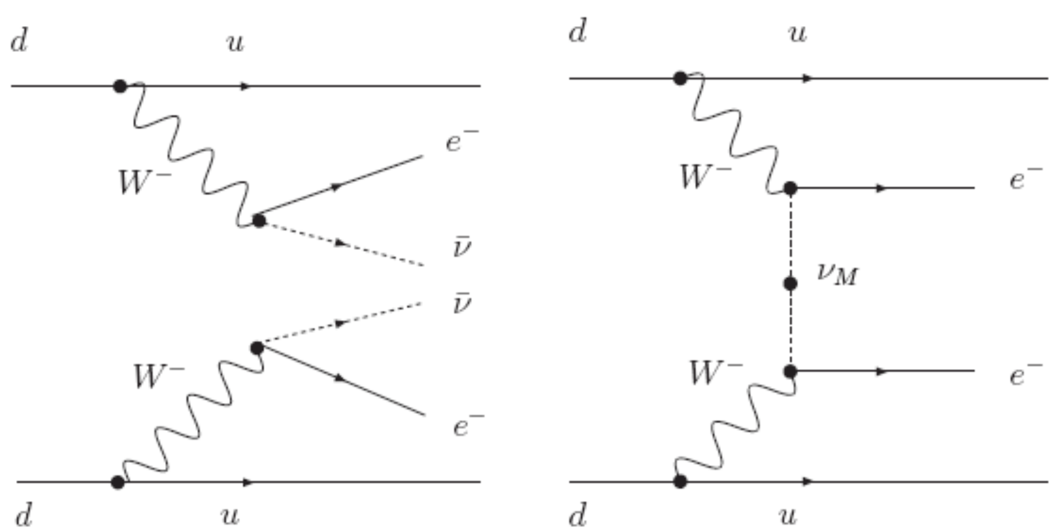
- Neutrinoless Double Beta Decay

- CUORE Experiment
  - Bolometric detectors
  - Construction
    Background mitigation
  - Status

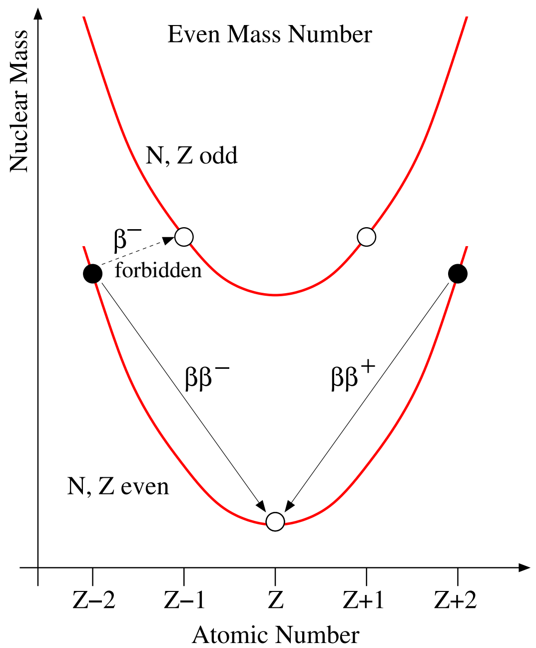
- CUORE-0
  - $0\nu\beta\beta$ & $2\nu\beta\beta$ Analysis
  - Projected CUORE performance

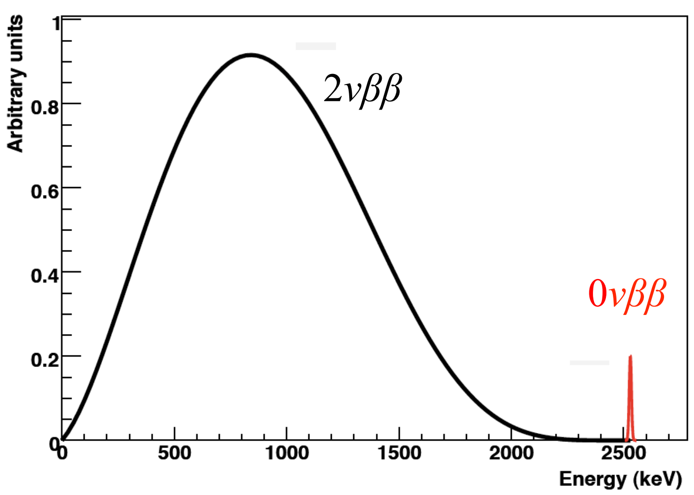
- Beyond CUORE: CUPID

Double Beta Decay



2νββ   0νββ





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

$$(A, Z-2) \rightarrow (A, Z) + 2e^-$$

<u>Two Neutrino Double Beta Decay</u> (2νββ)

- Rare, but allowed by the Standard Model
- Has been experimentally observed in several isotopes
- $T_{1/2}^{2\nu} \geq 10^{18}$ y

<u>Neutrinoless Double Beta Decay</u> (0νββ)

If observed, then:

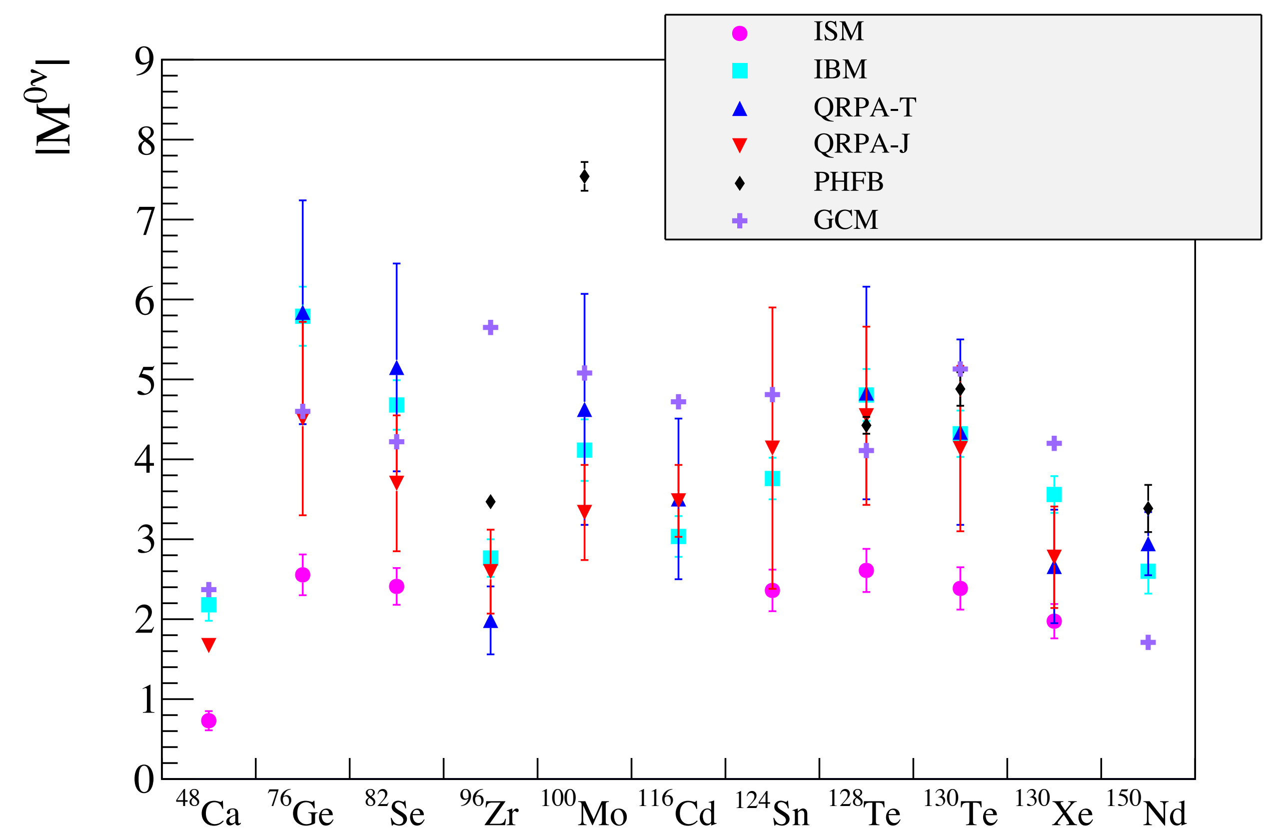
- Establish ΔL = 2 Lepton Number Violation
- Establish the Majorana nature of the neutrino (Schechter & Valle "Black Box")
- Determination of the absolute neutrino mass scale
- Possible determination of the neutrino mass hierarchy

Neutrinoless Double Beta Decay (0νββ)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{m^2_{\beta\beta}}{m^2_e}$$

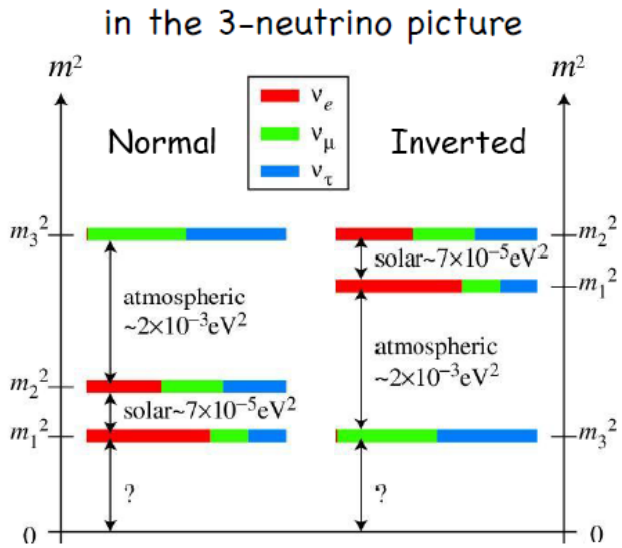
Phase Space Factor (calculated, reasonably precisely)

Nuclear Matrix Element (calculated, factor of a few uncertainty)



Neutrinoless Double Beta Decay (0νββ)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \frac{m^2_{\beta\beta}}{m^2_e}$$



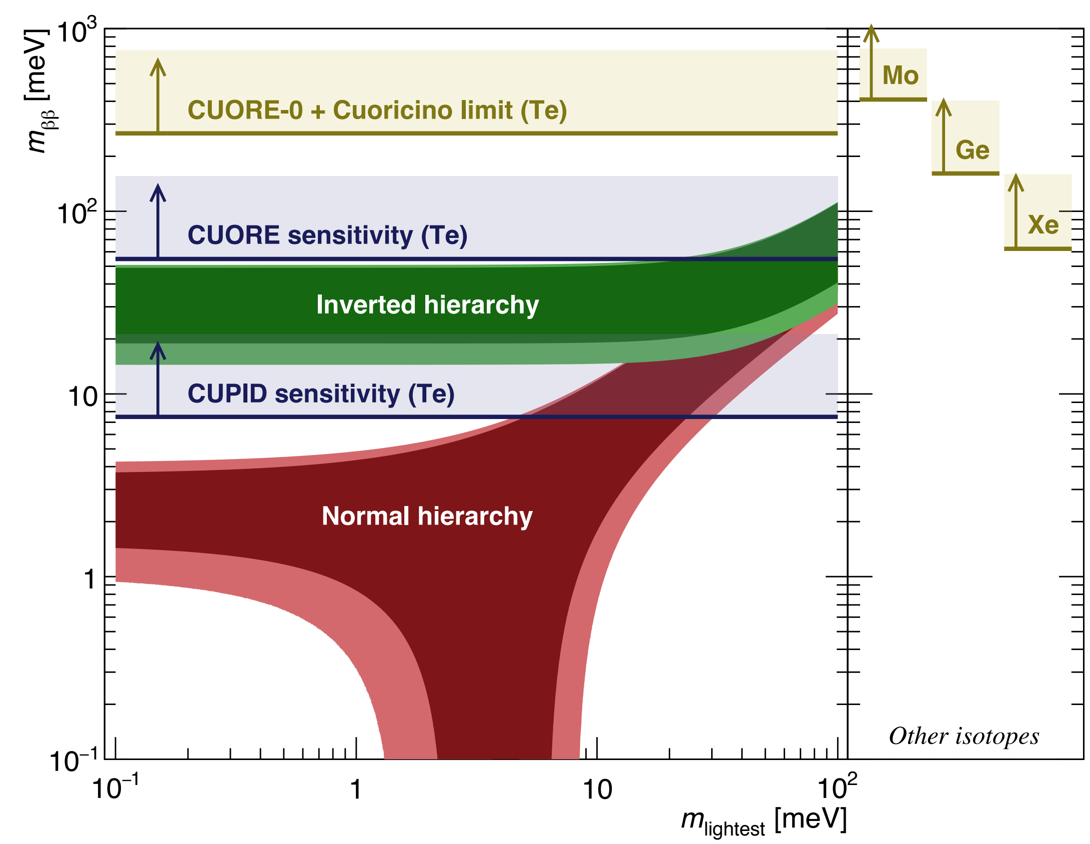
$U_{\alpha i}$, Δm_{ij} from measurements of:

- Solar neutrinos
- Reactor neutrinos
- Atmospheric neutrinos
- Long Baseline Accelerator neutrinos

Effective Majorana Mass of the Neutrino

$$m_{\beta\beta} = |\sum_i U^2_{ei} m_i|$$

"Lobster Plot"



Sensitivity to $m_{\beta\beta} \sim 100\,\text{meV}$ requires

sensitivity to $T^{0\nu}_{1/2} \gtrsim 10^{26}\,\text{years}$

Neutrinoless Double Beta Decay F.O.M.

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

- a: isotopic abundance
- ε: detection efficiency
- M: source mass
- t: exposure time
- b: ROI background rate
- δE: ROI energy resolution

Goal: sensitivity to $T^{0\nu}_{1/2} \gtrsim 10^{26}\,\text{years}$

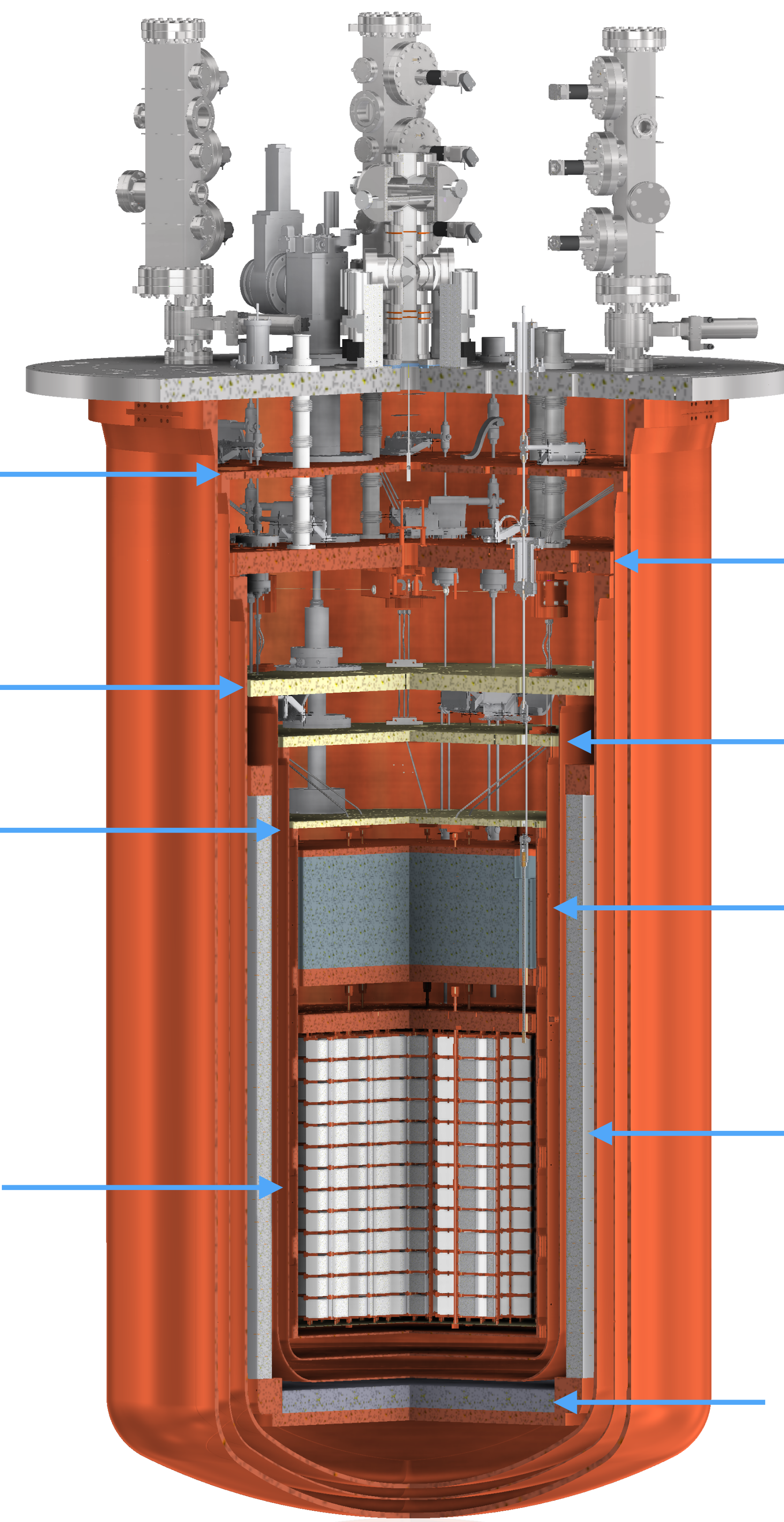
Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

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

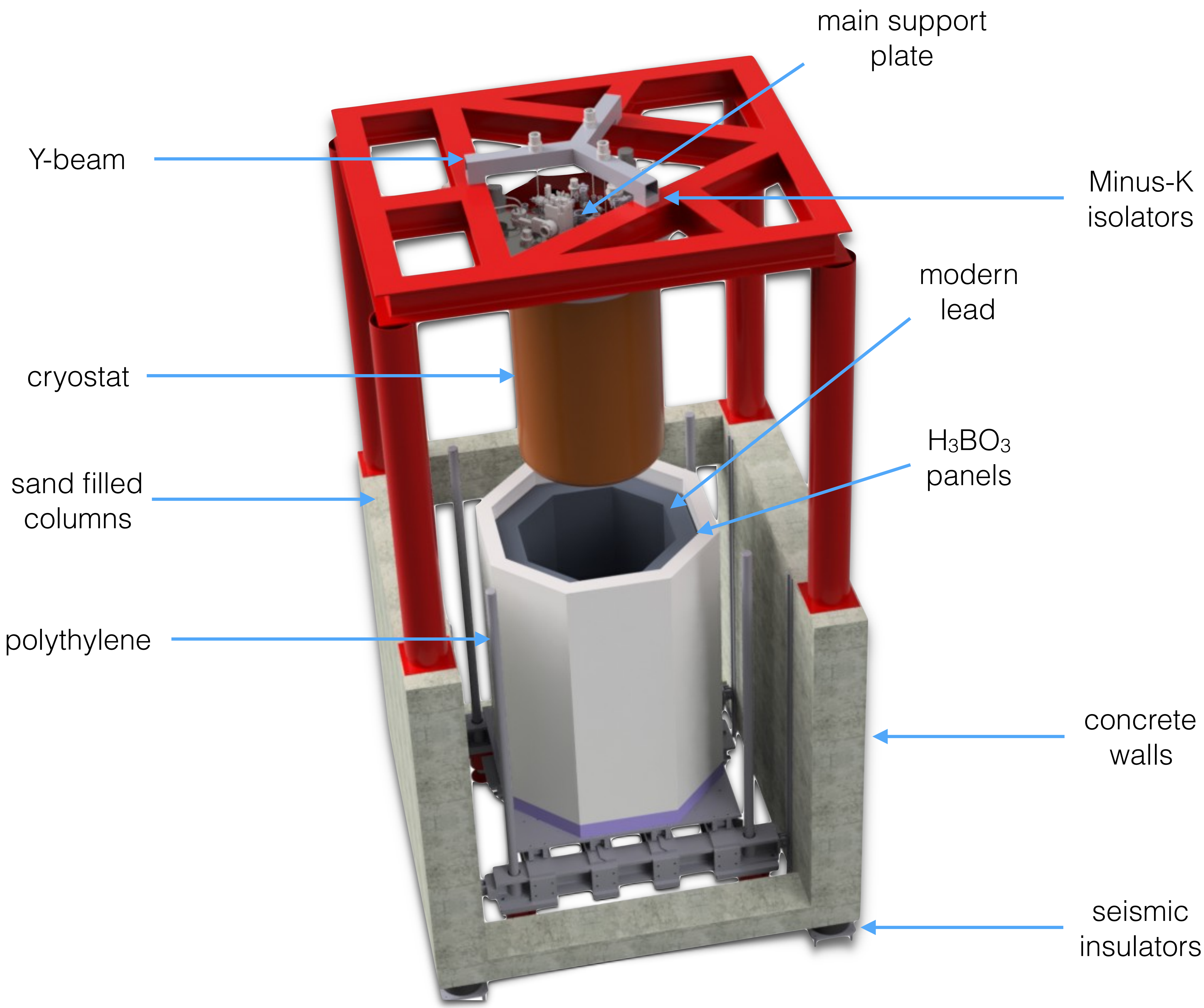
increase livetime

low down time vs "wet" refrigerators

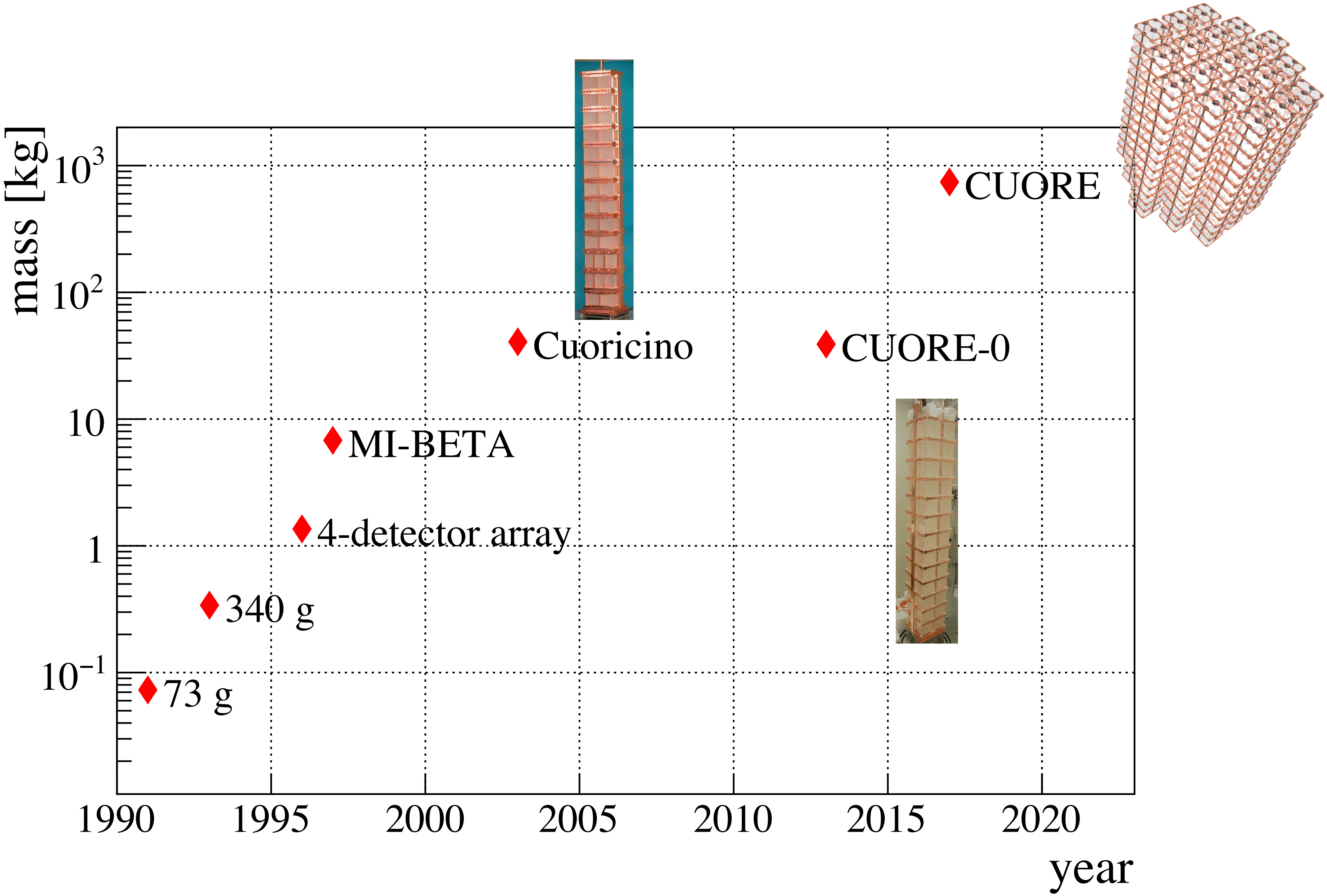
- cryogen free cryostat
- fast cooling (He vapor) to ~40 K
- 5 Pulse Tubes down to ~4 K
- dilution refrigerator down to ~10 mK
  nominal cooling power: 3 μW
- total mass: ~30 tons
- mass cooled < 4 K: ~15 tons
- mass cooled < 50 mK: ~3 tons
  (Pb, Cu, and TeO2)



Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

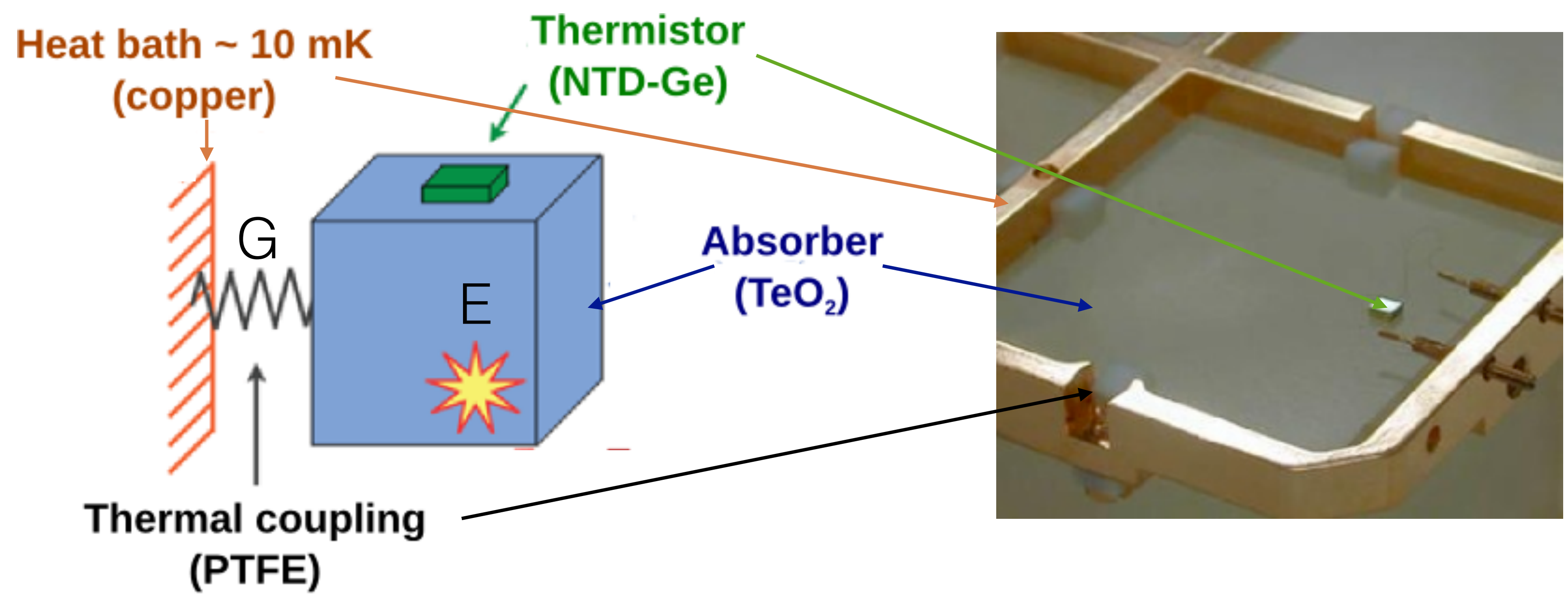


Timeline of TeO_2 Bolometric Detectors

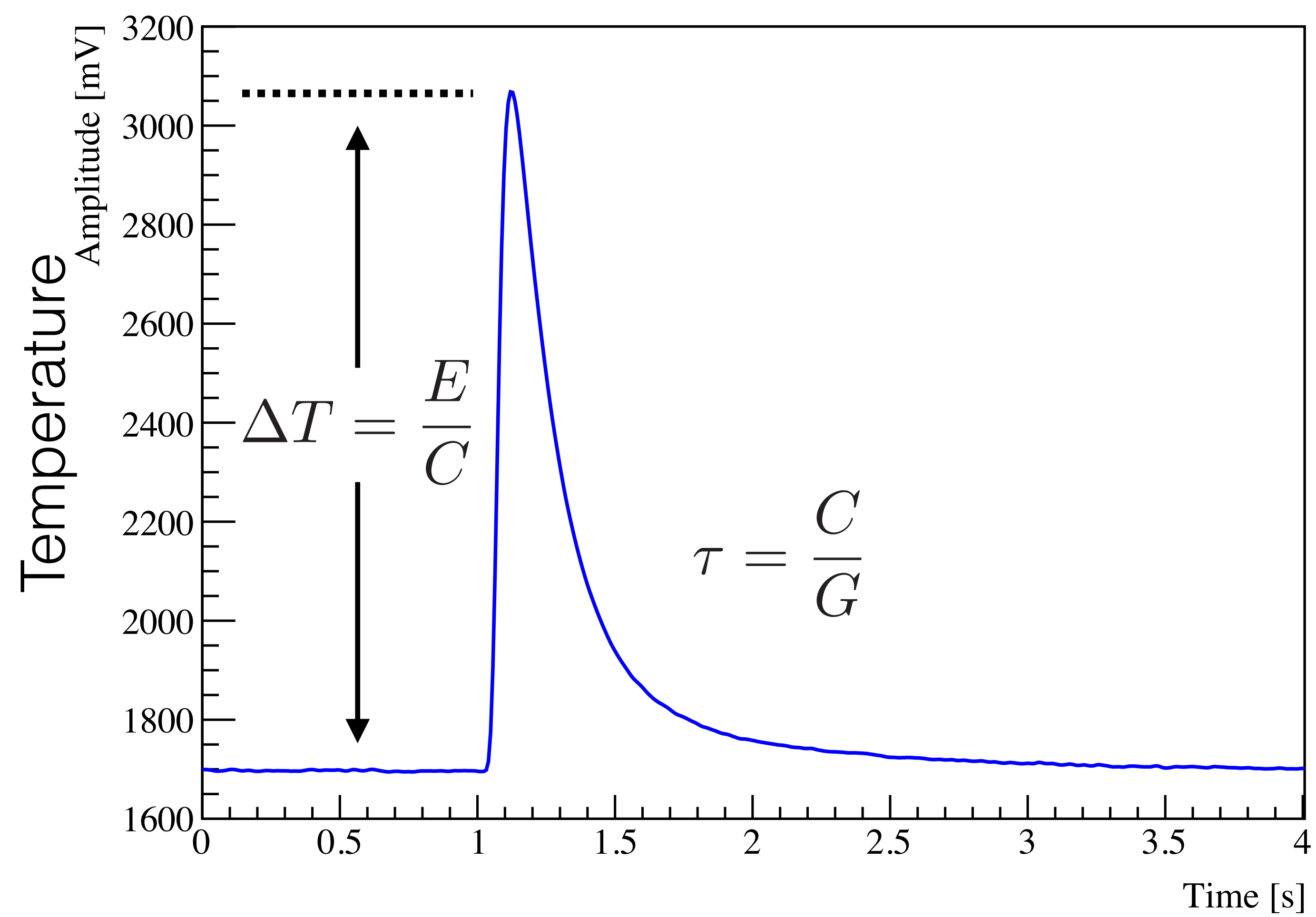


CUORE is the latest in the series

Bolometric Detectors



- Energy Deposited: E
- Temperature: T
- Heat Capacity: C = C(T) $\propto T^3$
  (Need to operate at ~10 mK)
- Conductivity of the Thermal Link: G
- Typical TeO_2 ΔT ~ 0.1 mK/MeV



Bolometric Detector Performance

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

Advantage: excellent energy resolution

	Technology	**ROI $\delta E/Q_{\beta\beta}$ (FWHM)**
GERDA	Ge Diode	0.13 to 0.30%
CUORE-0	TeO_2 Bolometer	0.20%
EXO-200	Liquid Xe TPC	3.6%
KamLAND-Zen	^{136}Xe loaded liquid scintillator	10 to 11%

Mod. Phys. Lett. A **31**, 1630017 (2016)

Isotope Choice: ^{130}Te

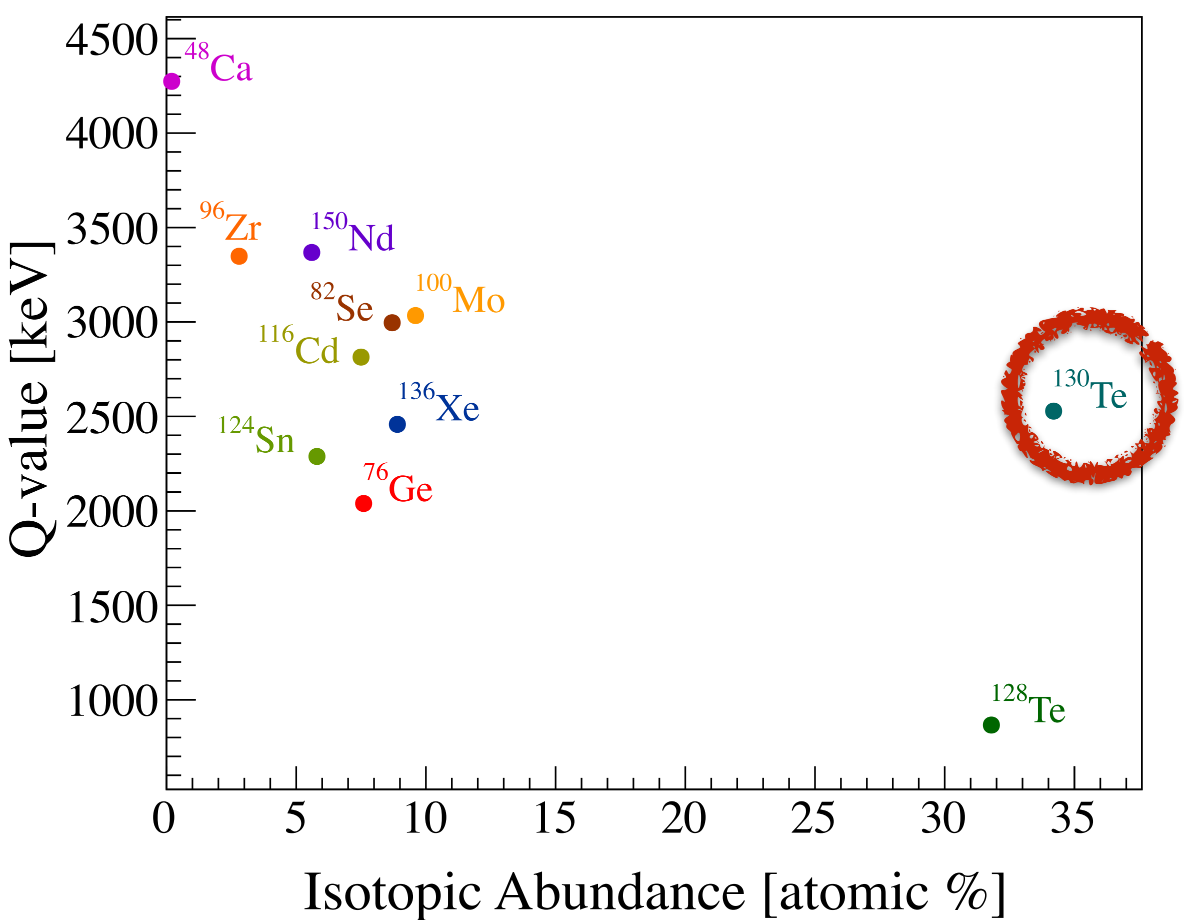
$$T^{0\nu}_{1/2}(\text{FOM}) \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

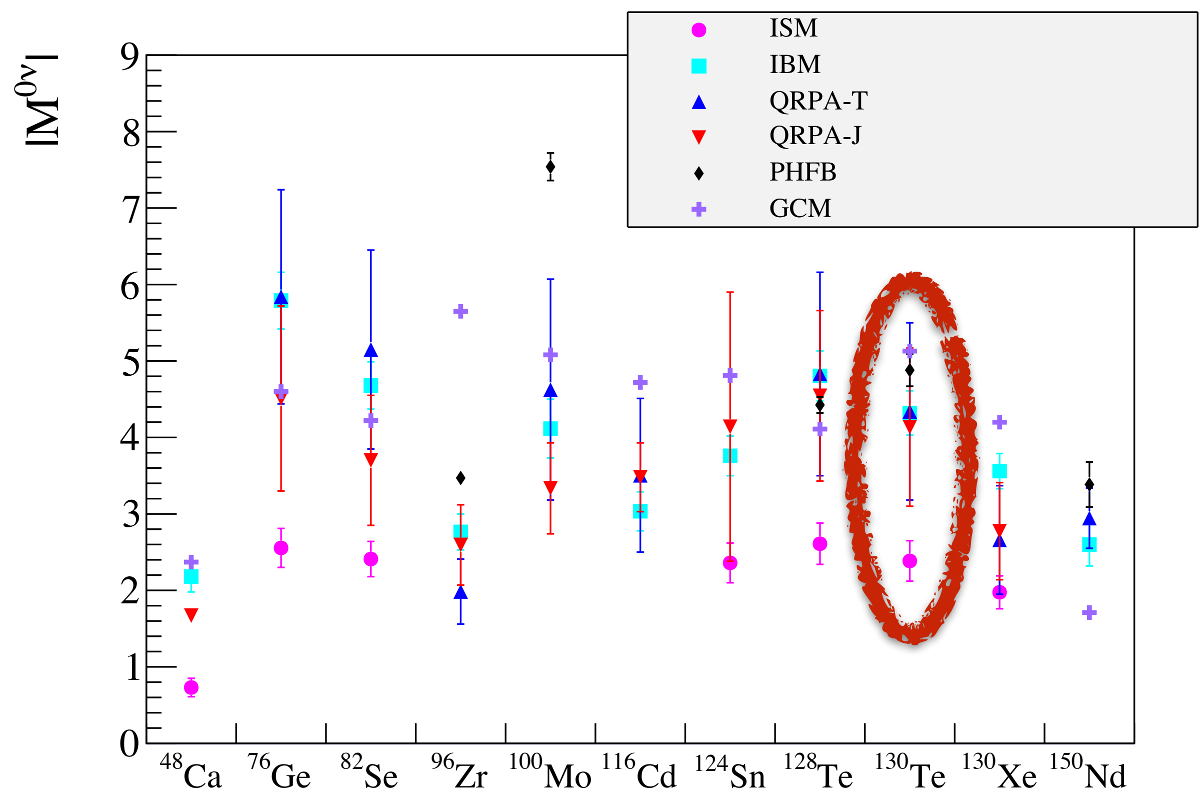
^{130}Te:

$Q_{\beta\beta}$ = 2528 keV

a(natural) = 34.2%

- High natural abundance
- Enrichment is not necessary for the current generation of $0\nu\beta\beta$ searches

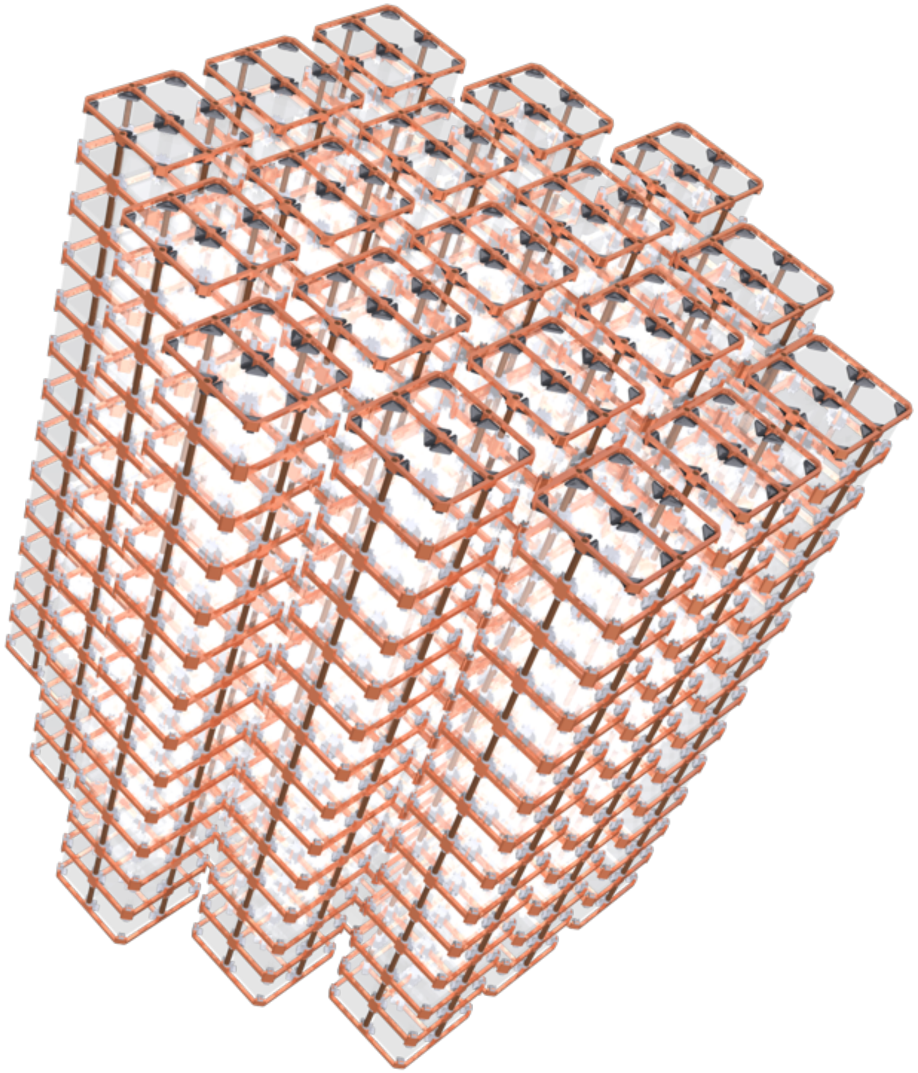




The CUORE Detector

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

- 19 towers
- 52 TeO_2 bolometers per tower
- 988 TeO_2 bolometers
- 742 kg TeO_2 mass
- ^{130}Te mass: 206 kg



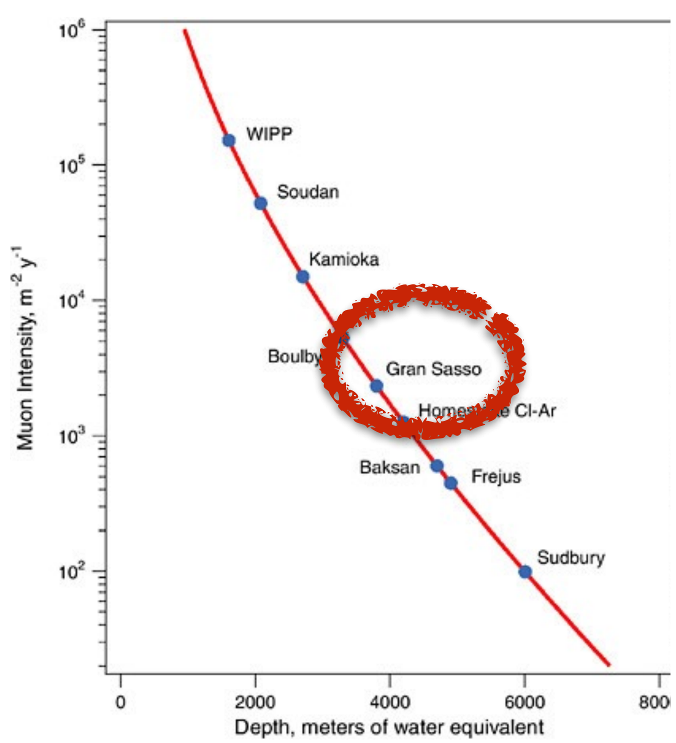
- near "ton-scale" experiment
- highly segmented

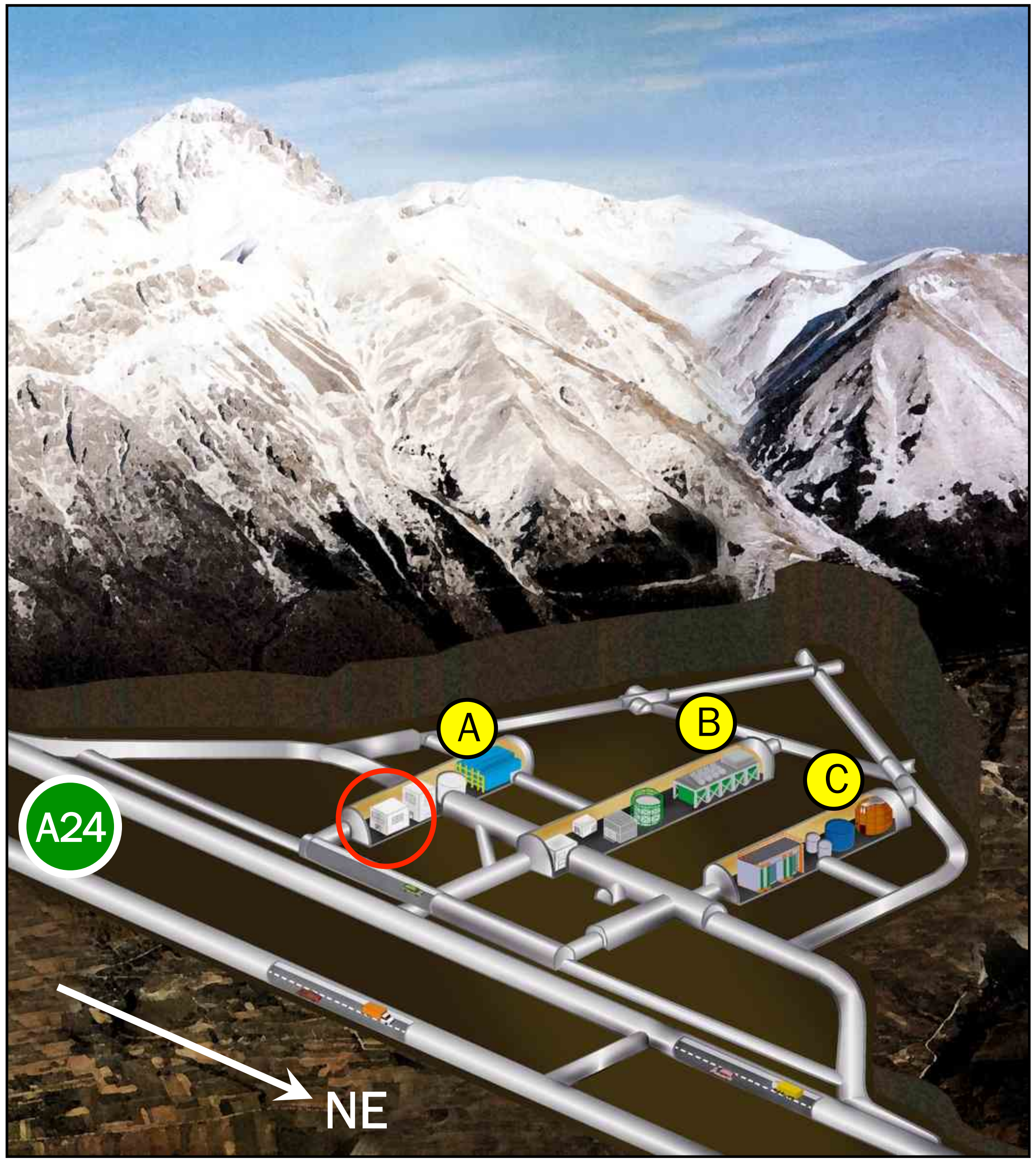
Backgrounds from Cosmic Rays

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

CUORE goal: b ≤ 10^{-2} counts/keV/kg/year

Cosmic Rays:
- Direct interactions
- Spallation products
- Activation



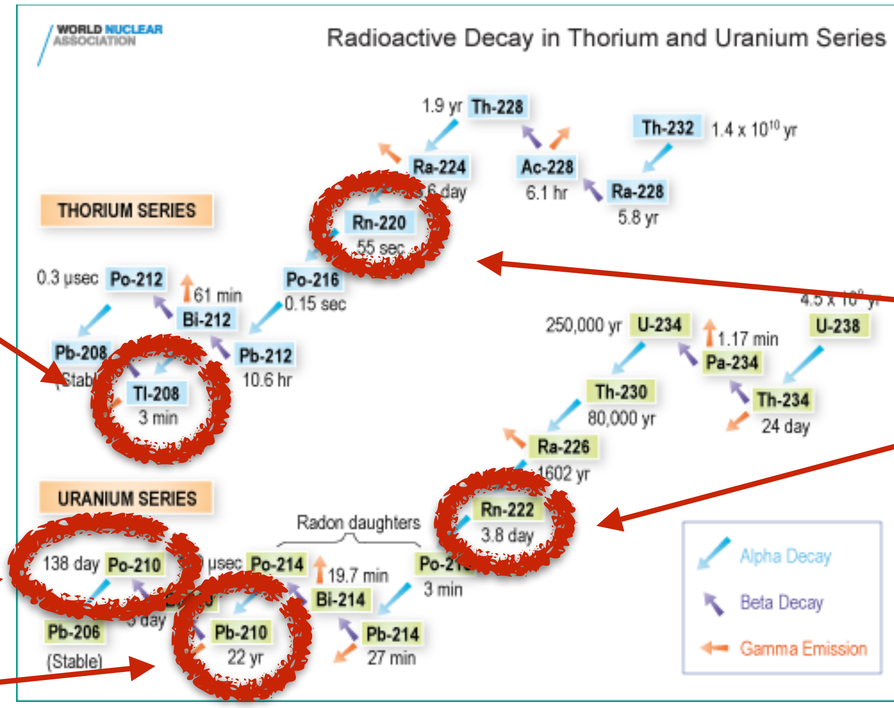


LNGS Average depth: ~3600 m.w.e.
Muon Flux at LNGS: ~3x10^{-8} μ/(s cm^2)
(factor ~ ×10^6 reduction from the surface)

Backgrounds from Natural Radioactivity

U/Th typically ~1 ppm level in dust, etc.

^{208}Tl E_γ = 2.6 MeV > $Q_{\beta\beta}$



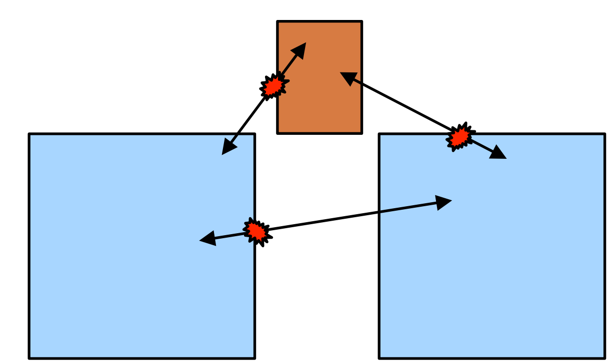
^{220}Rn & ^{222}Rn
inert gas

^{210}Pb & ^{210}Po
long half-live

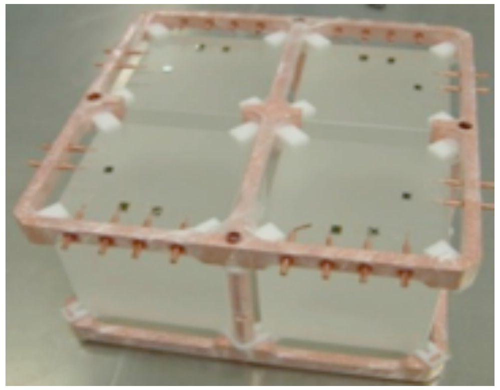
external:
- neutrons
- high energy γ-rays
  n-capture
  ^{208}Tl, ^{214}Bi, etc.

background mitigation:
- external shielding:
  - archeological & modern Pb
  - polythylene & boron-loaded
- start with clean parts
- contamination prevention:
  - underground storage in flowing N2
  - class 1000 clean room
  - glove box with flowing N2
  - final assembly in low Rn air

degraded α's
energy loss can put events in 0νββ ROI



Clean Detector Components



Ultra-pure TeO2 crystal array

Bulk activity 90% C.L. upper limits:

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

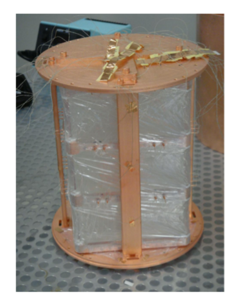
Surface activity 90% C.L. upper limits:

1.9×10^{-9} Bq/cm^2 (^{232}Th), 8.9×10^{-9} Bq/cm^2 (^{238}U), 9.8×10^{-7} Bq/cm^2 (^{210}Po)

(arXiv:1704.08970)

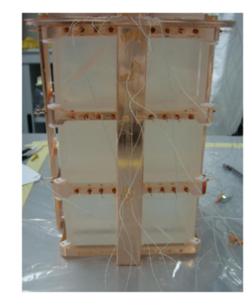
- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals

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

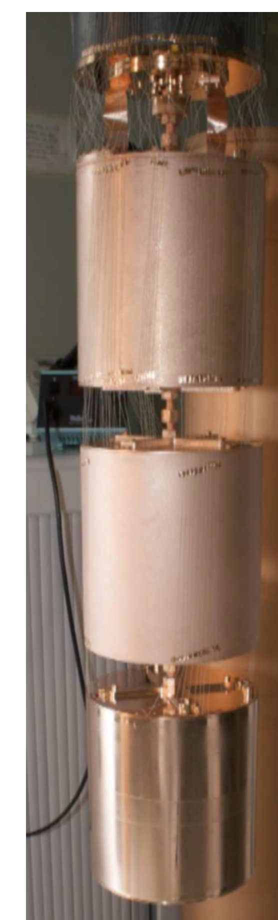


T1

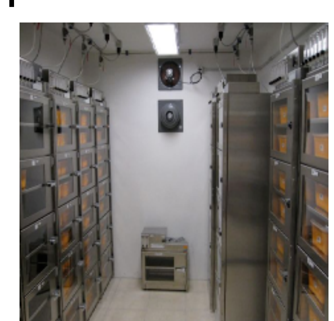
T2



T3



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

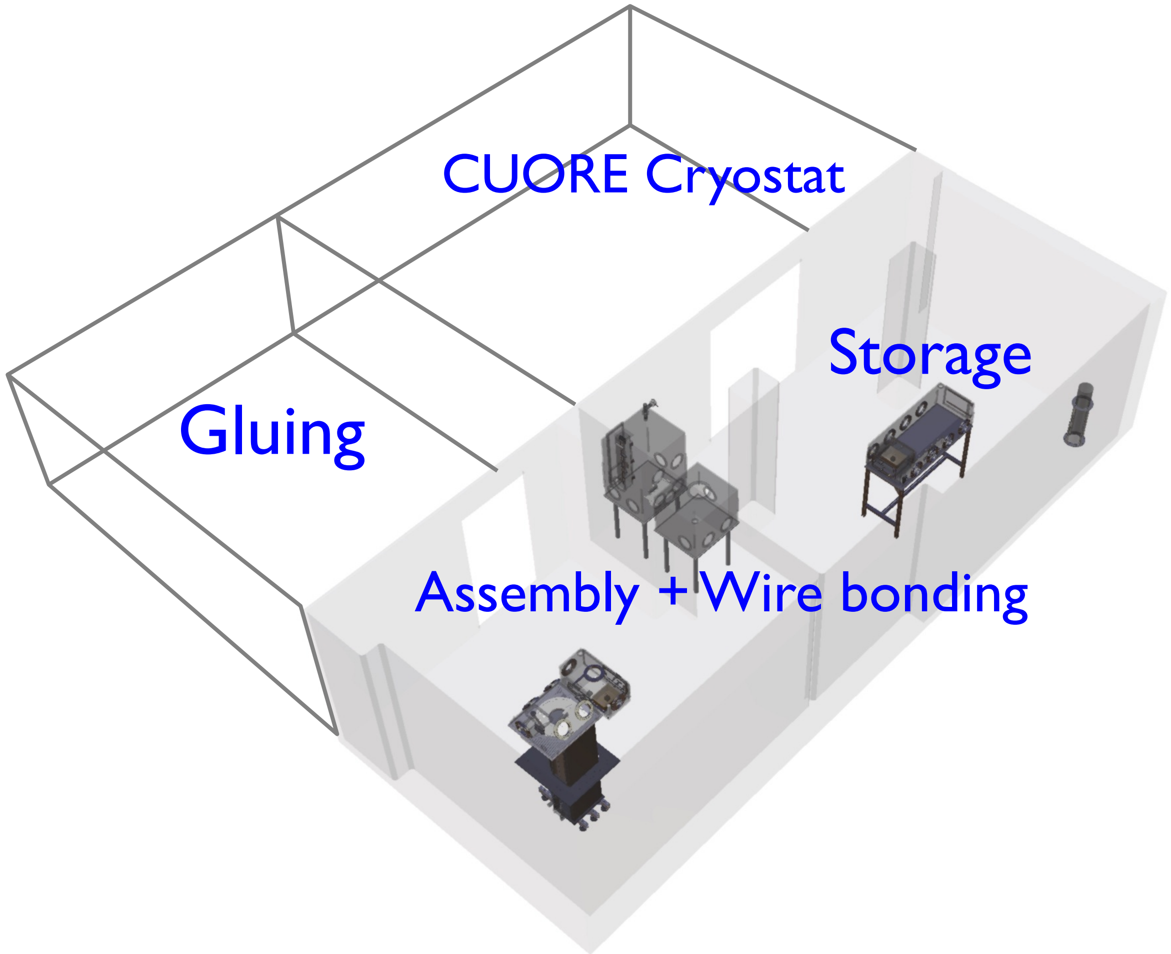


- All parts stored underground, under nitrogen after cleaning

Tower Assembly

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

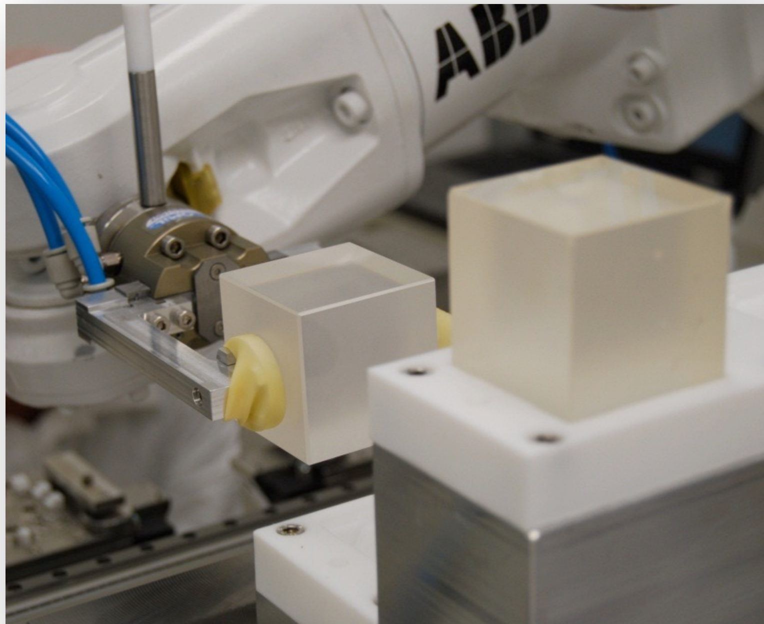


CUORE Gluing Line

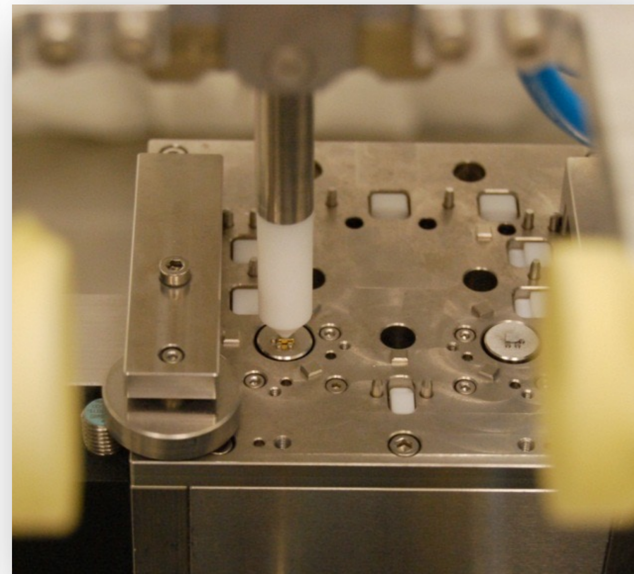
$$T^{0\nu}_{1/2}(\text{FOM}) \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Important for energy resolution

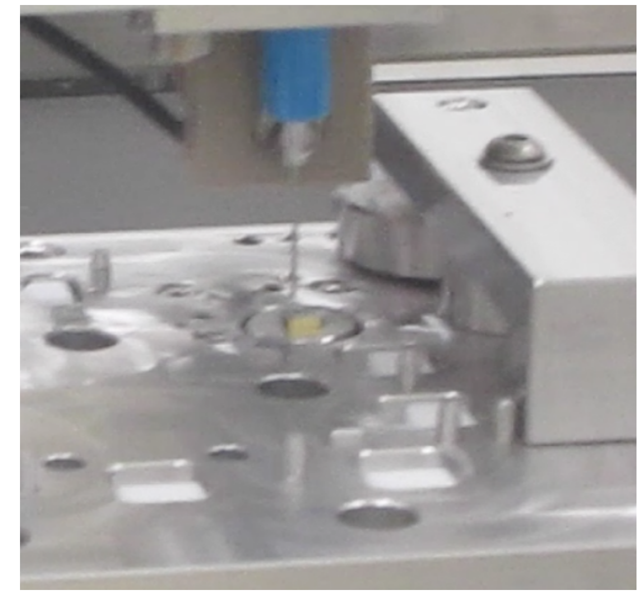
Robotic Arm



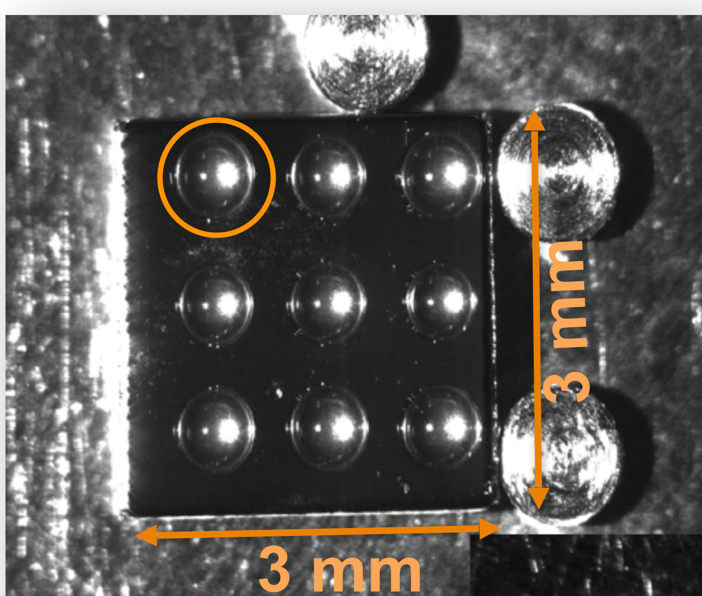
Position Sensors



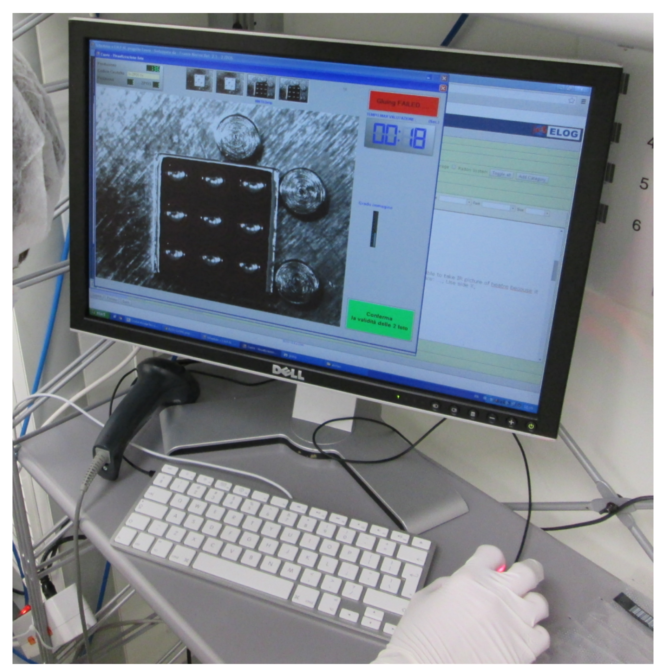
Print Glue Matrix



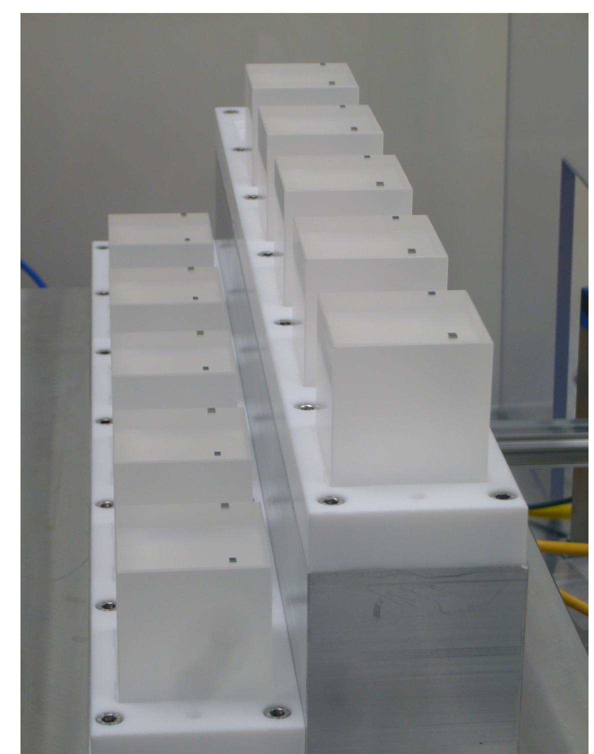
Inspection



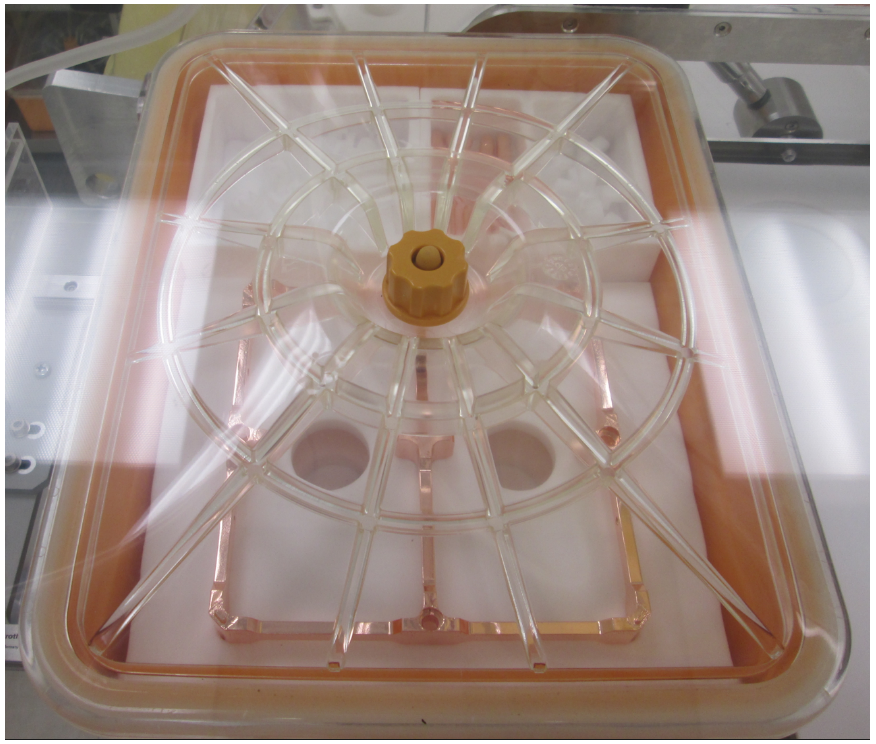
Quality Control

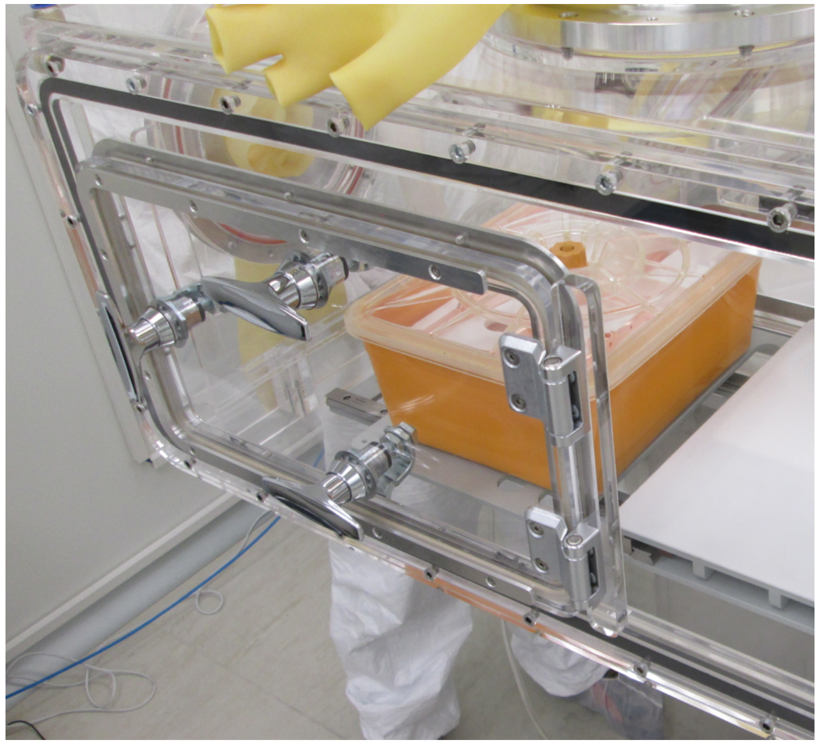


Glued Crystals



Mechanical Assembly

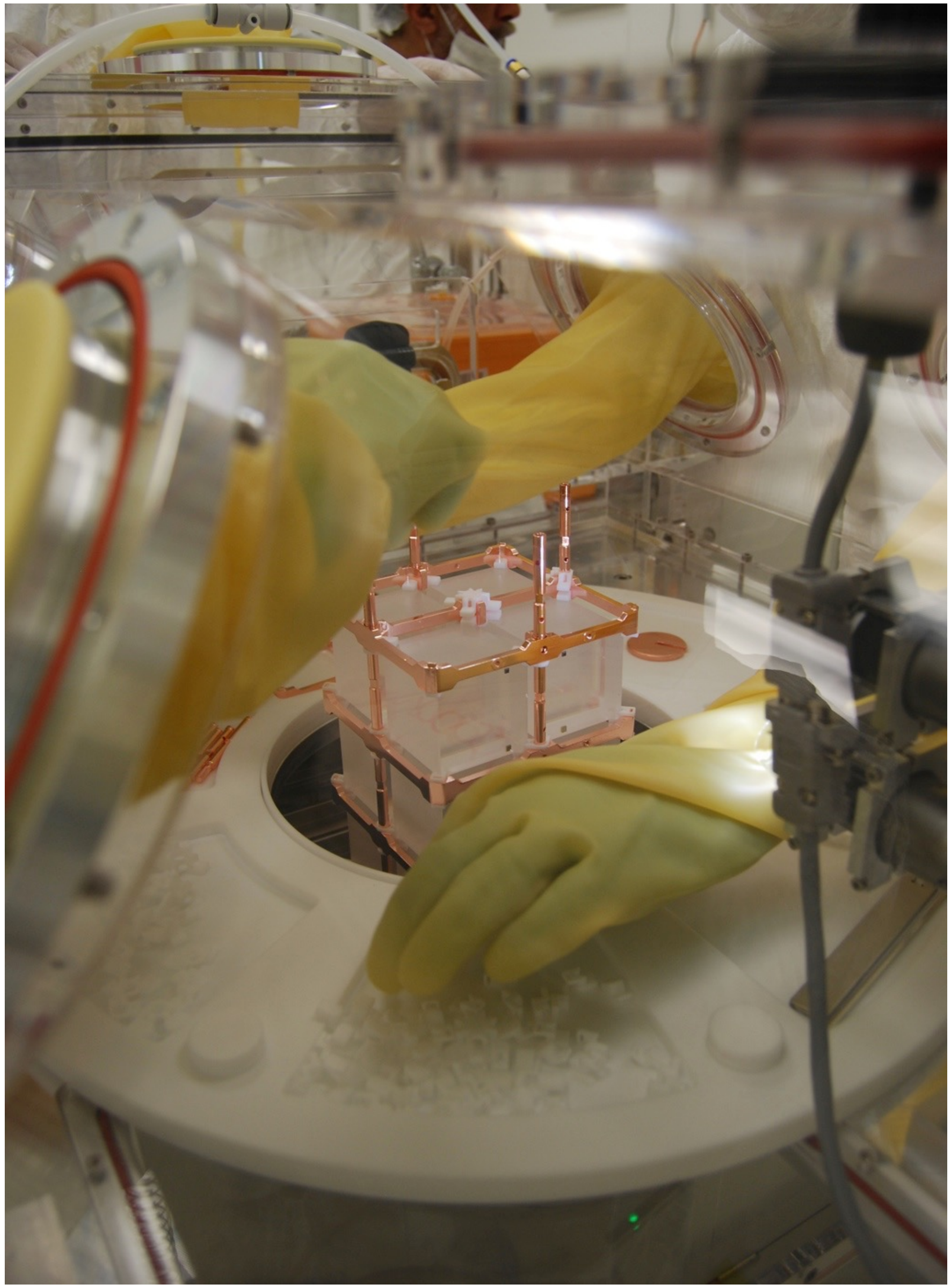


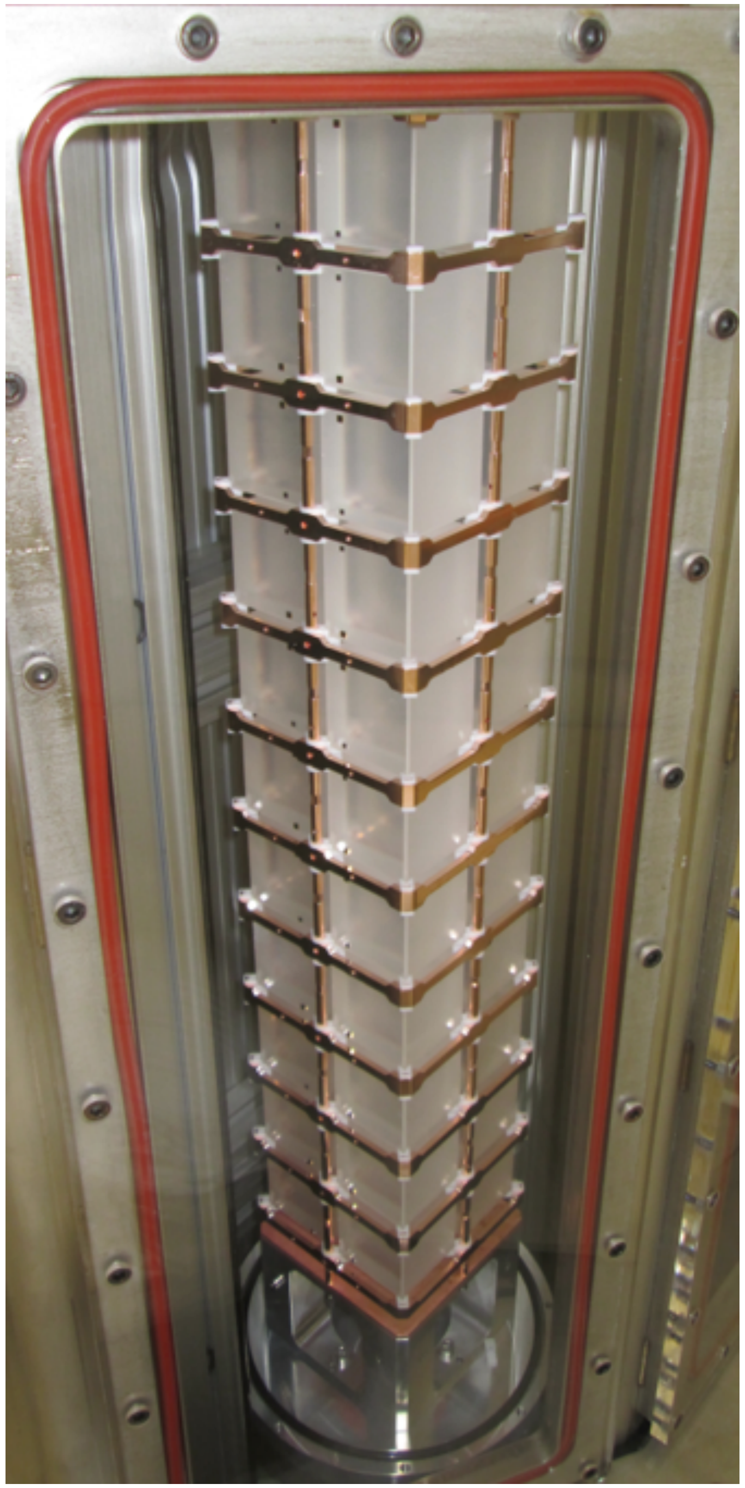


Parts are stored in nitrogen flushed boxes

And, transfered in vacuum boxes to nitrogen flushed glove boxes…

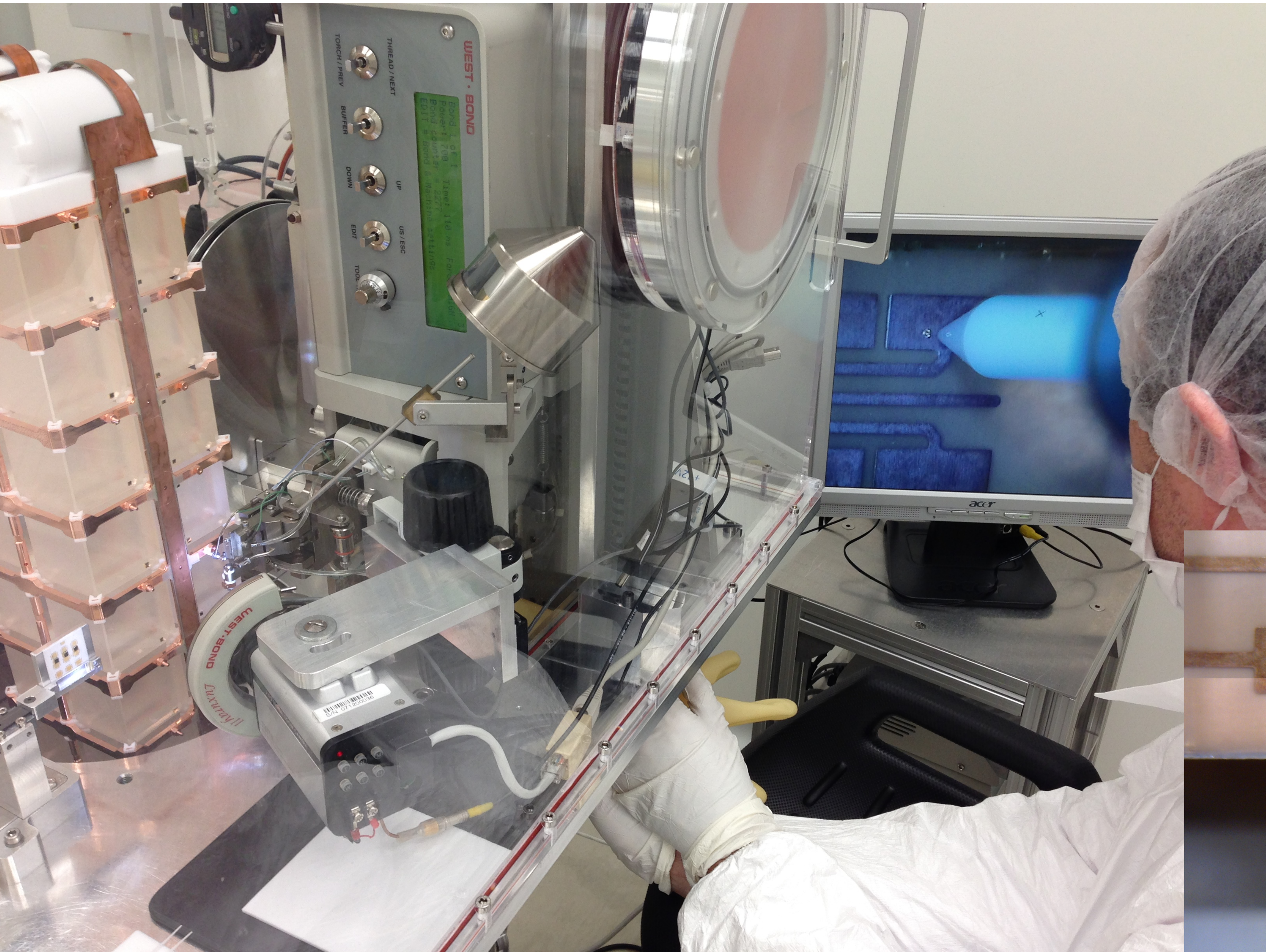
Mechanical Assembly

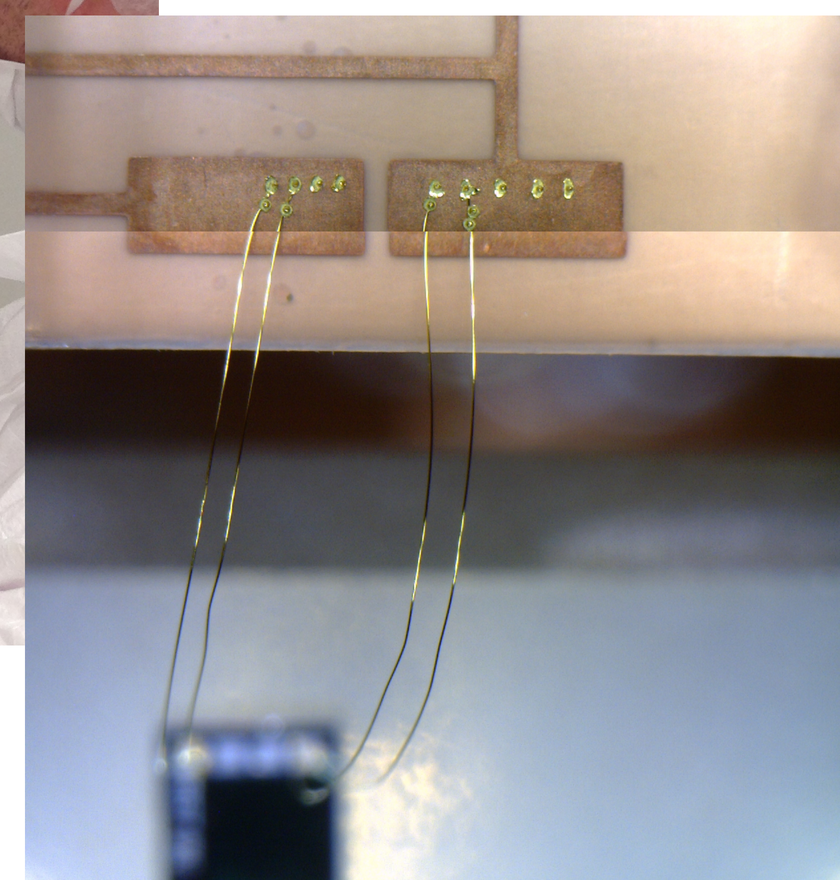




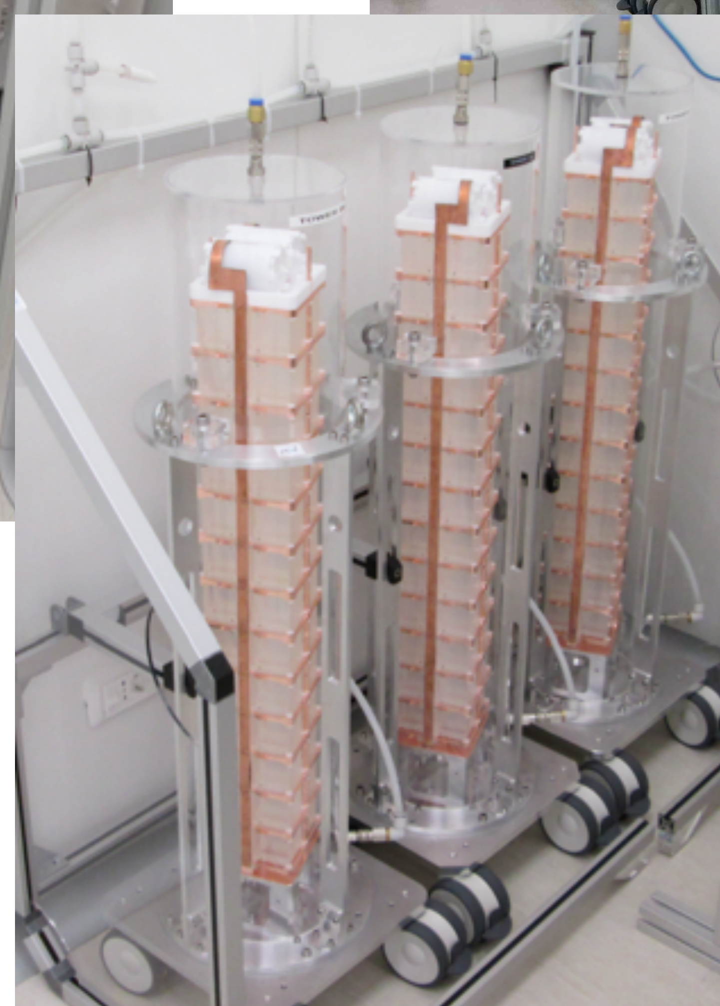
…where the towers are assembled.

Wire Bonding



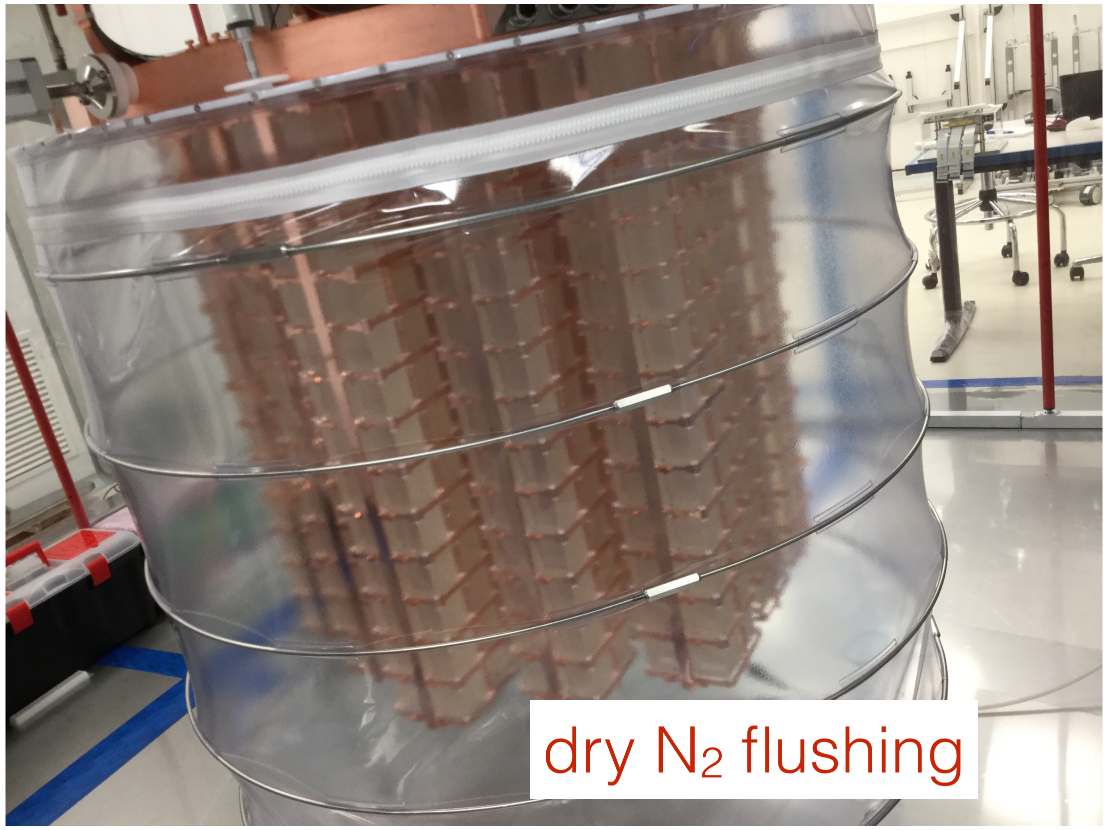


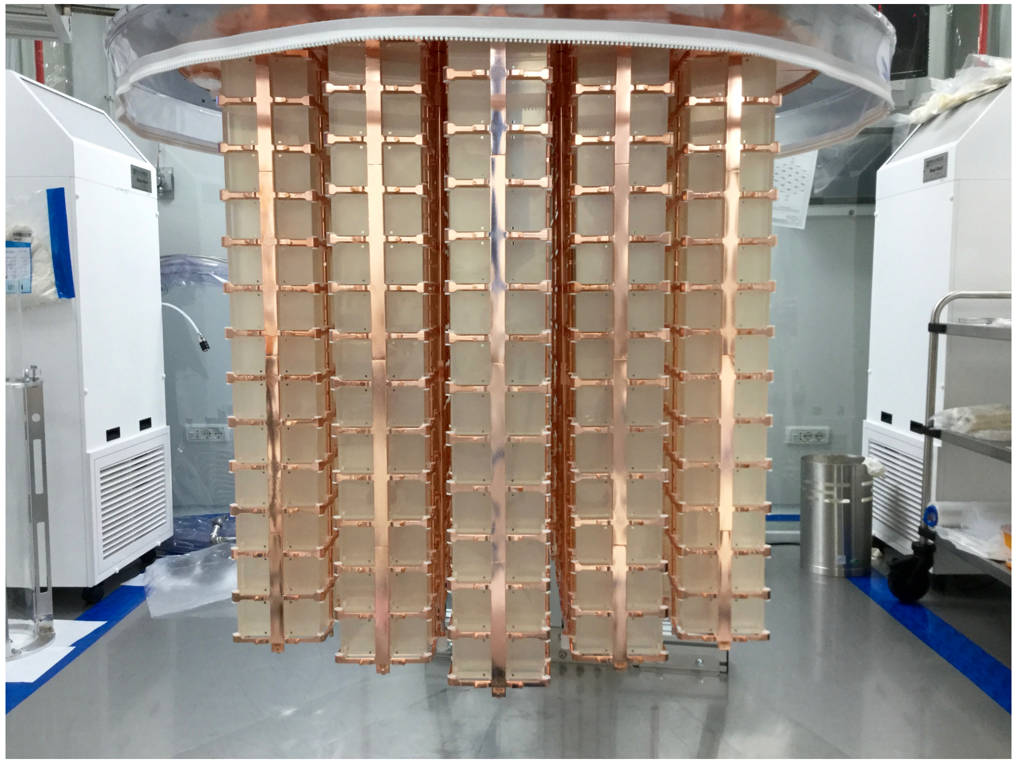
19 (+1) Towers Assembled



(flushed nitrogen storage)

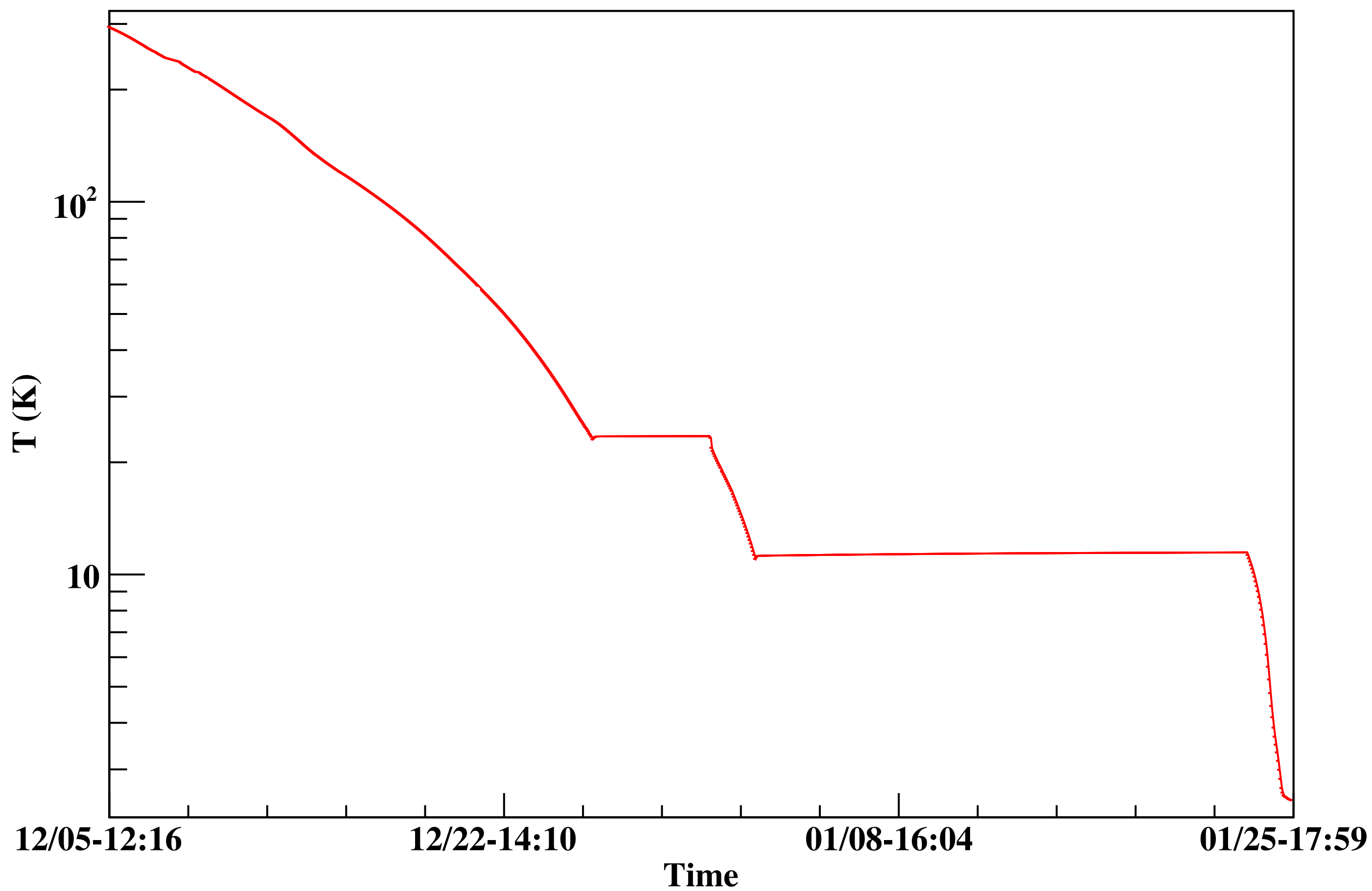
Tower Installation



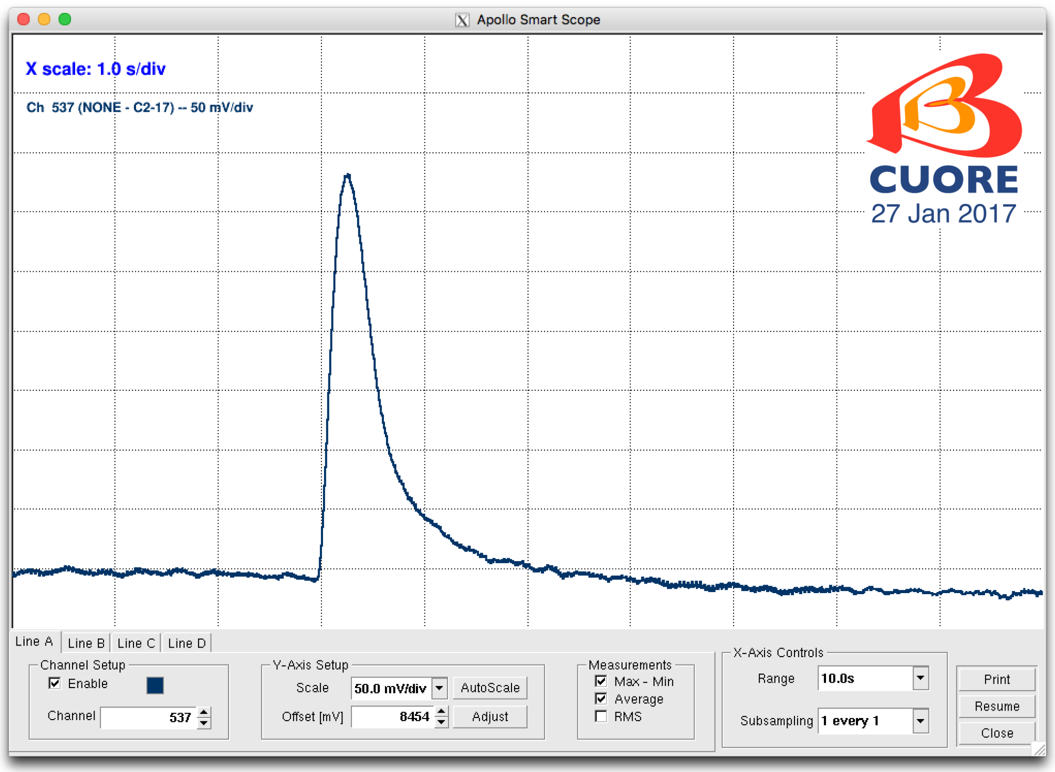


CUORE is cold and running!

Diode thermometer at 10mK plate



Reached 8 mK: 26 Jan 2017



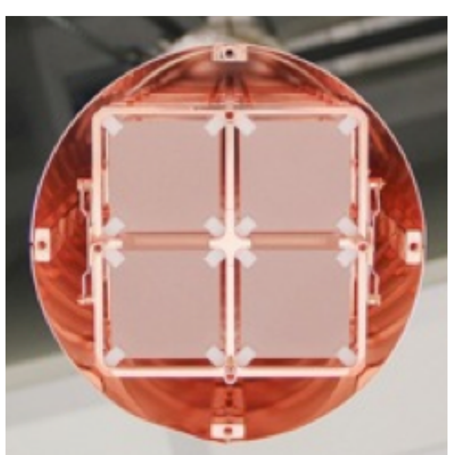
First pulse: 27 Jan 2017

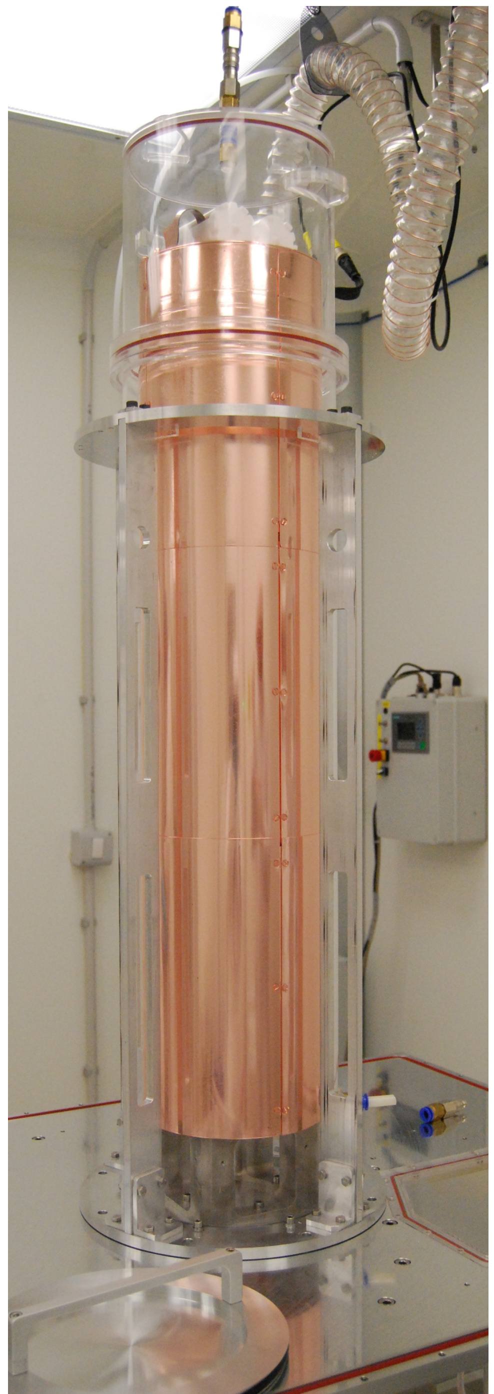
<u>Current status of CUORE</u>:

- End of commissioning and beginning of data-taking: April 2017
- Blind analysis currently in progress
- Expect first results within the next few months

CUORE-0

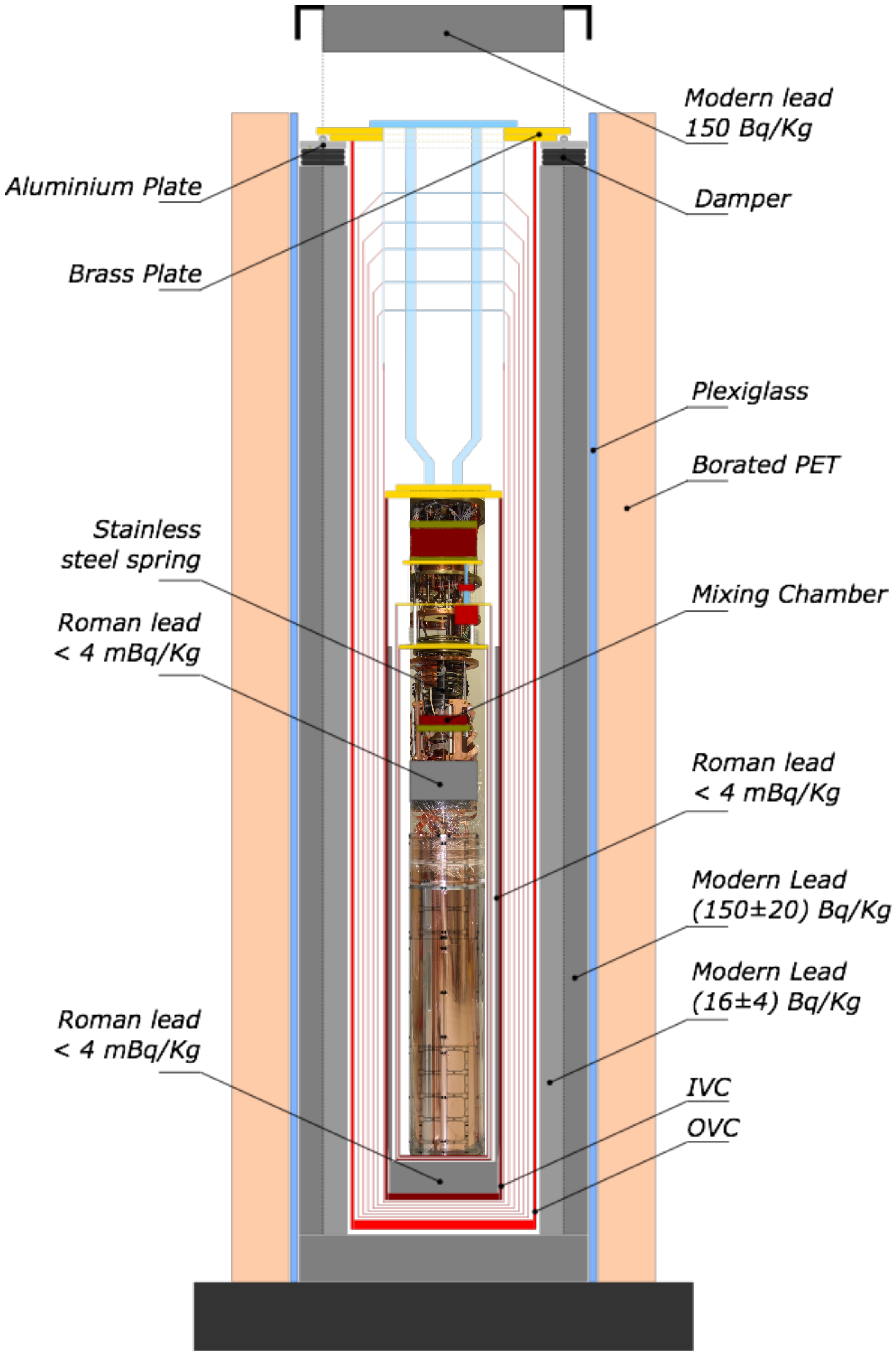
- A total of 19 + 1 CUORE towers were assembled
- CUORE-0 is the “0th” tower





- CUORE-0 tower running in Cuoricino cryostat
- Base temperature (10 mK) achieved in Mar 2013

CUORE-0

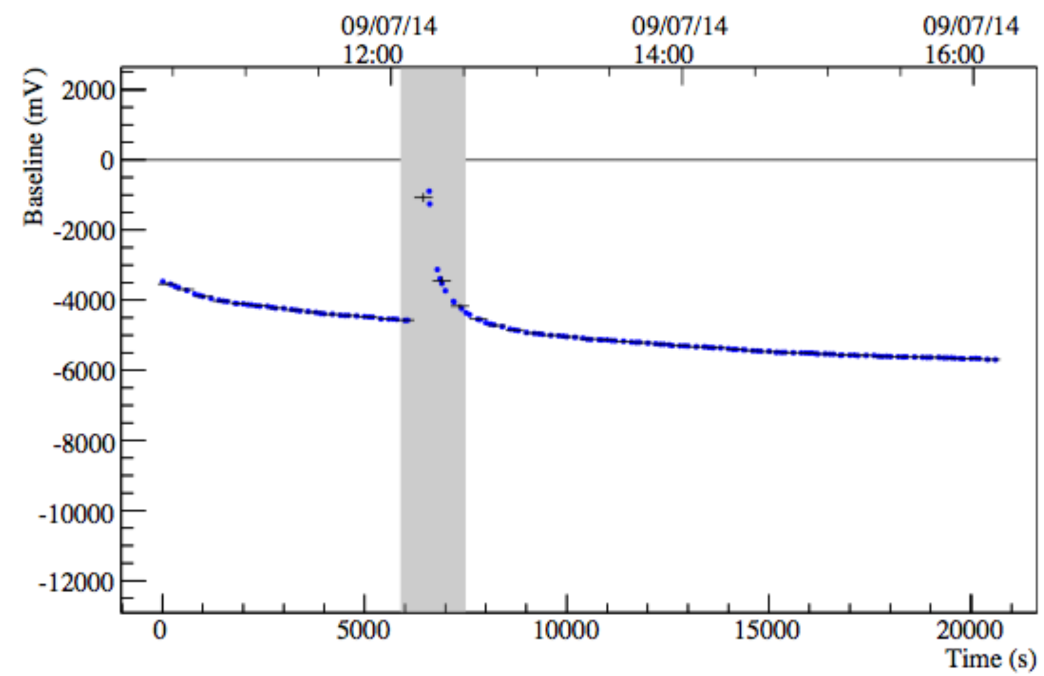


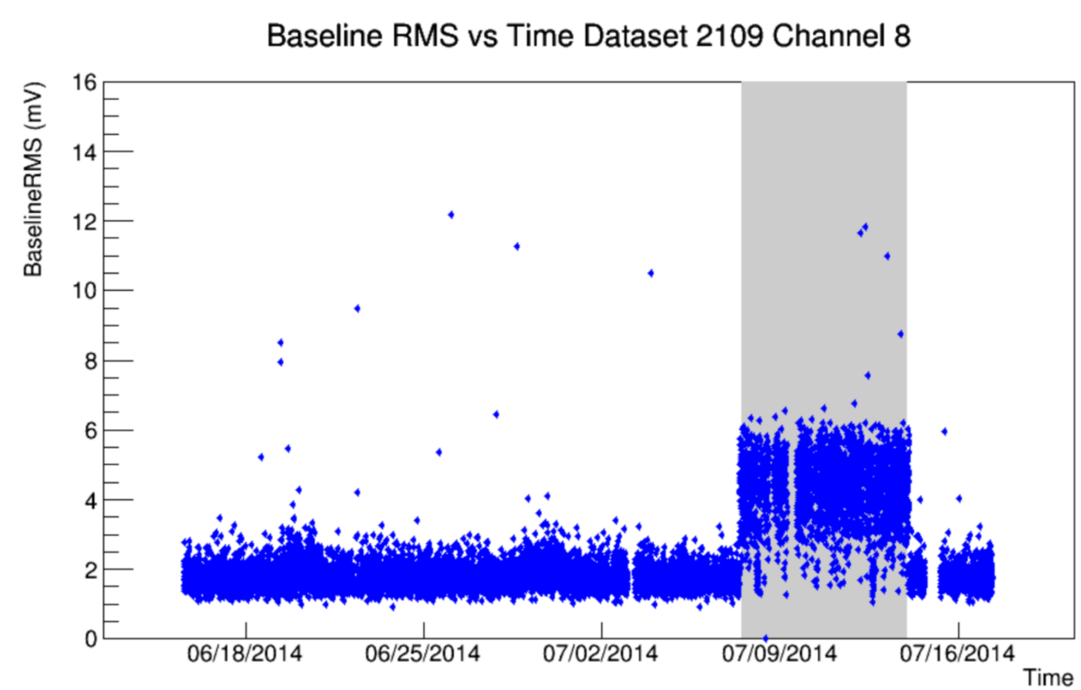
- Uses the old Cuoricino cryostat
- Electronics from Cuoricino
- Shielding from Cuoricino
  - Inner lateral shield of Roman lead (1cm)
  - Inner top/bottom cap of Roman lead (20 cm)
  - Outer shield:
    - low-activity modern lead (10 cm)
    - regular modern lead (10 cm)
  - Borated PET neutron shield
  - Enclosed in Faraday cage and flushed with N2 for radon suppression
- Cooled to base T (~10 mK) March 2013
- Ran through March 2015

CUORE-0: Simplified Analysis Chain

DAQ continuously samples the NTD thermistor voltage at 125 Hz

1. Software trigger identifies waveforms
2. **<u>Data quality inspection</u>**
3. Apply optimal filter
4. Apply thermal gain stabilization
5. Energy calibration
6. Apply blinding
7. 0νββ candidate event selection
    1. Reject pileup events
    2. Apply pulse shape cut
    3. Apply anti-coincidence cut
8. Unblind the data



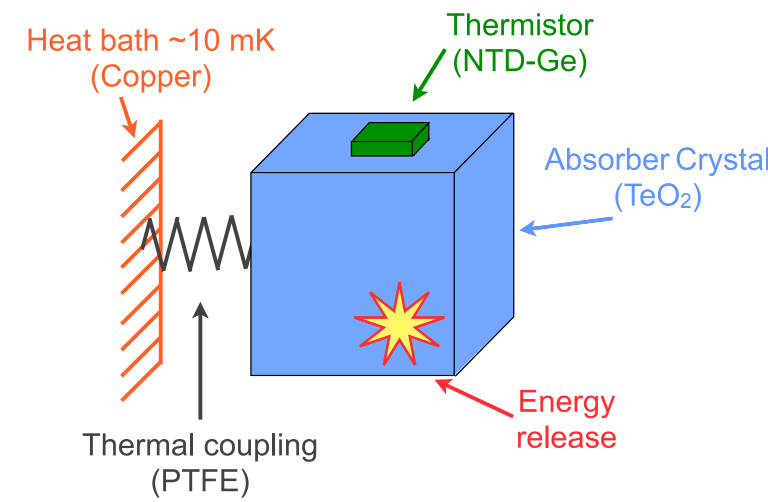


CUORE-0: Simplified Analysis Chain

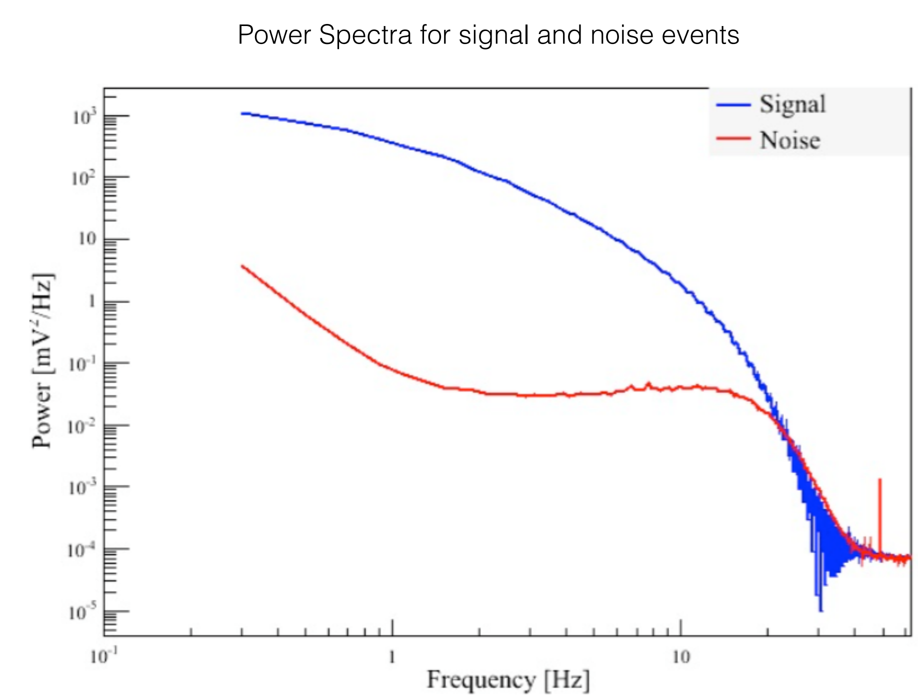
DAQ continuously samples the NTD thermistor voltage at 125 Hz

1. Software trigger identifies waveforms
2. Data quality inspection
3. **<u>Apply optimal filter</u>**
4. Apply thermal gain stabilization
5. Energy calibration
6. Apply blinding
7. 0νββ candidate event selection
    1. Reject pileup events
    2. Apply pulse shape cut
    3. Apply anti-coincidence cut
8. Unblind the data

Johnson noise



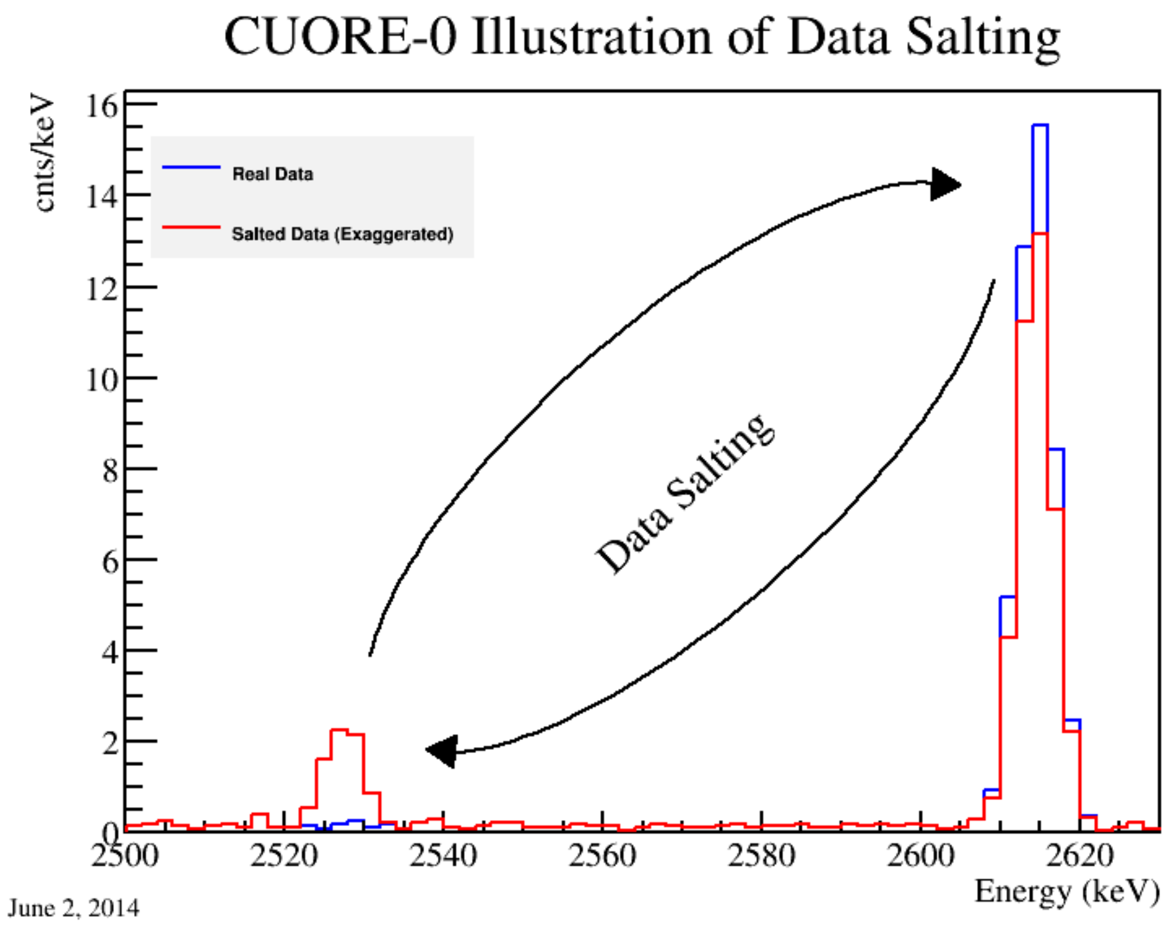
thermodynamic fluctuations



CUORE-0: Simplified Analysis Chain

DAQ continuously samples the NTD thermistor voltage at 125 Hz

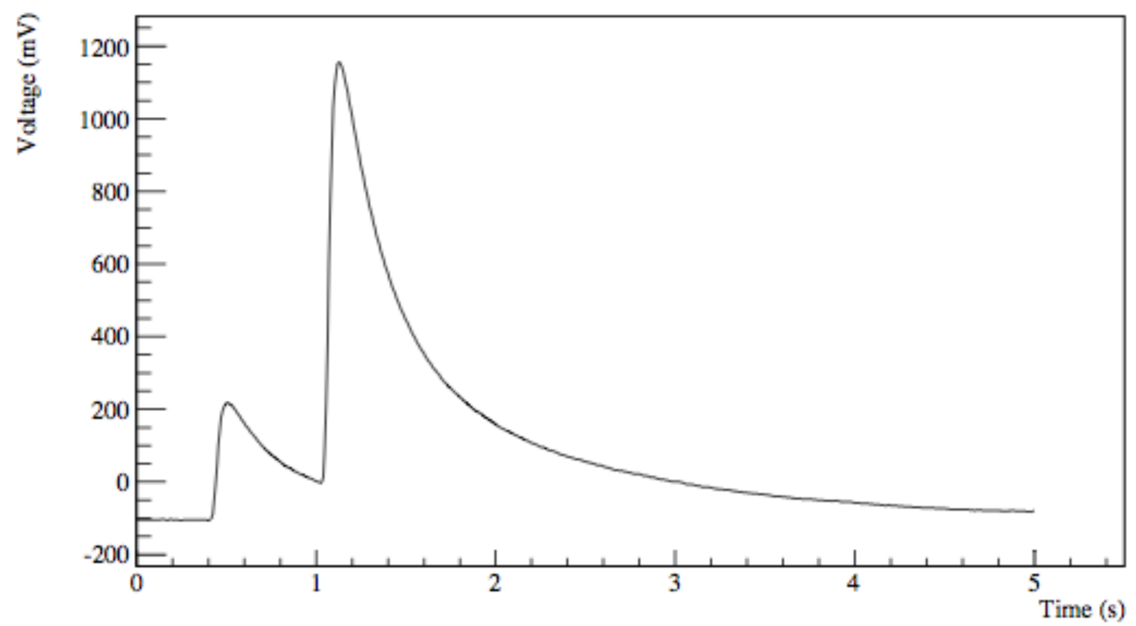
1. Software trigger identifies waveforms
2. Data quality inspection
3. Apply optimal filter
4. Apply thermal gain stabilization
5. Energy calibration
6. **Apply blinding**
7. $0\nu\beta\beta$ candidate event selection
    1. Reject pileup events
    2. Apply pulse shape cut
    3. Apply anti-coincidence cut
8. Unblind the data



CUORE-0: Simplified Analysis Chain

DAQ continuously samples the NTD thermistor voltage at 125 Hz

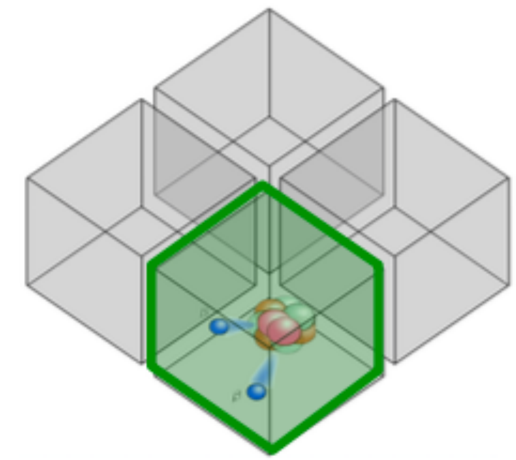
1. Software trigger identifies waveforms
2. Data quality inspection
3. Apply optimal filter
4. Apply thermal gain stabilization
5. Energy calibration
6. Apply blinding
7. $0\nu\beta\beta$ candidate event selection
    1. **Reject pileup events**
    2. Apply pulse shape cut
    3. Apply anti-coincidence cut
8. Unblind the data



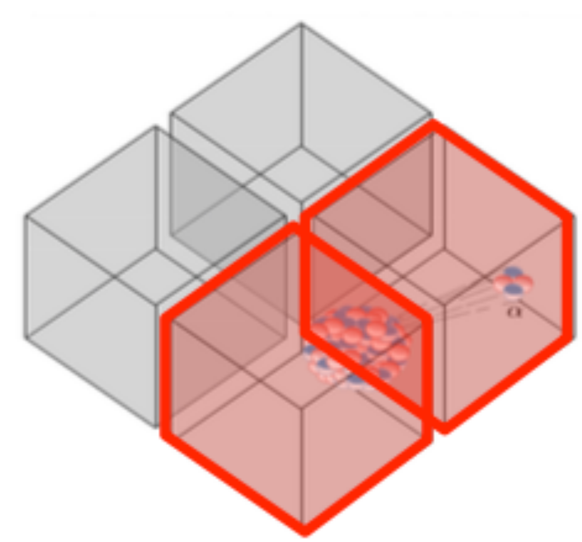
CUORE-0: Simplified Analysis Chain

DAQ continuously samples the NTD thermistor voltage at 125 Hz

1. Software trigger identifies waveforms
2. Data quality inspection
3. Apply optimal filter
4. Apply thermal gain stabilization
5. Energy calibration
6. Apply blinding
7. 0νββ candidate event selection
    1. Reject pileup events
    2. Apply pulse shape cut
    3. **Apply anti-coincidence cut**
8. Unblind the data

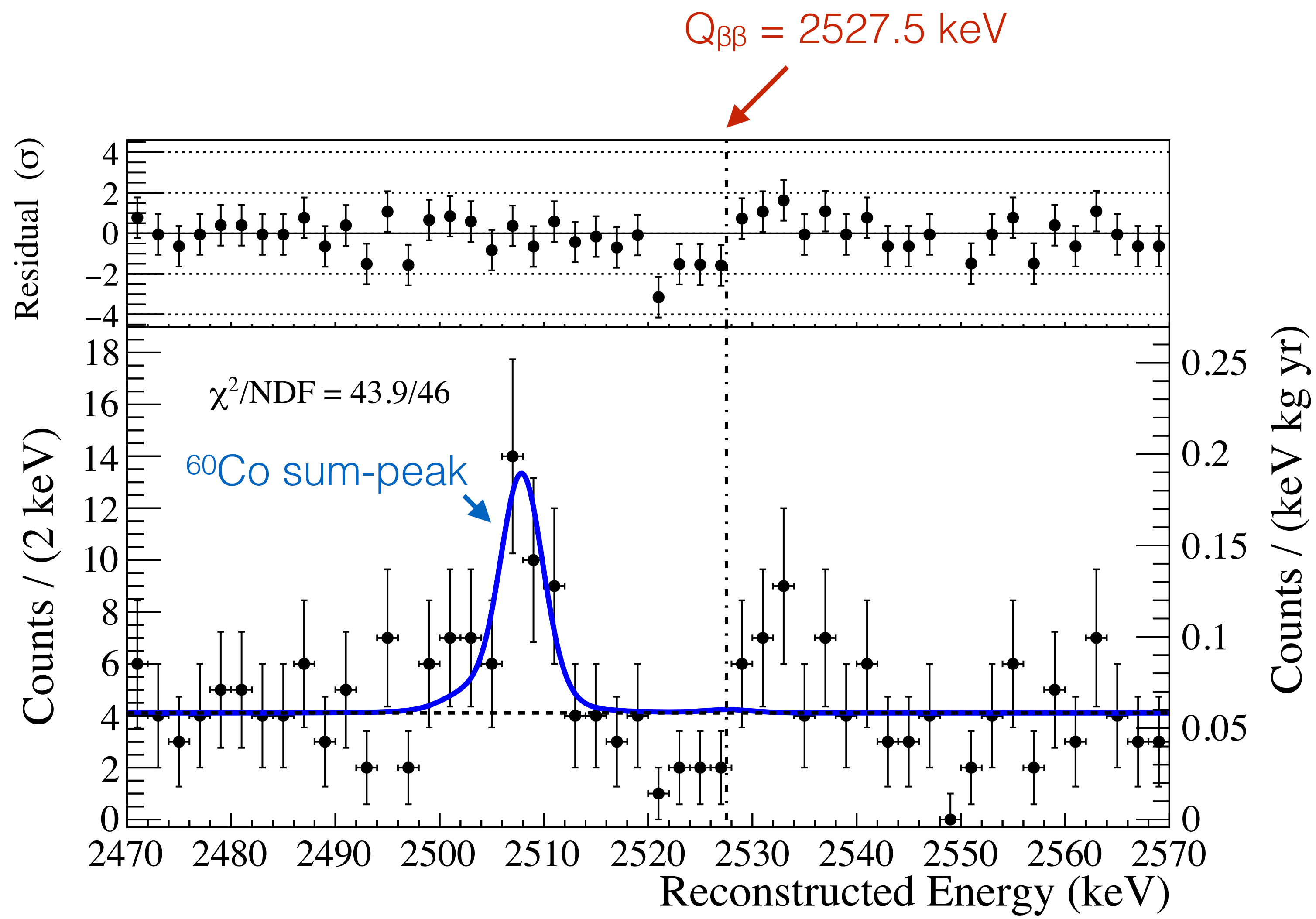


~88% of 0νββ decays confined to single bolometer



Continuum background from multi-Compton scatters and degraded alphas are mostly multisite events

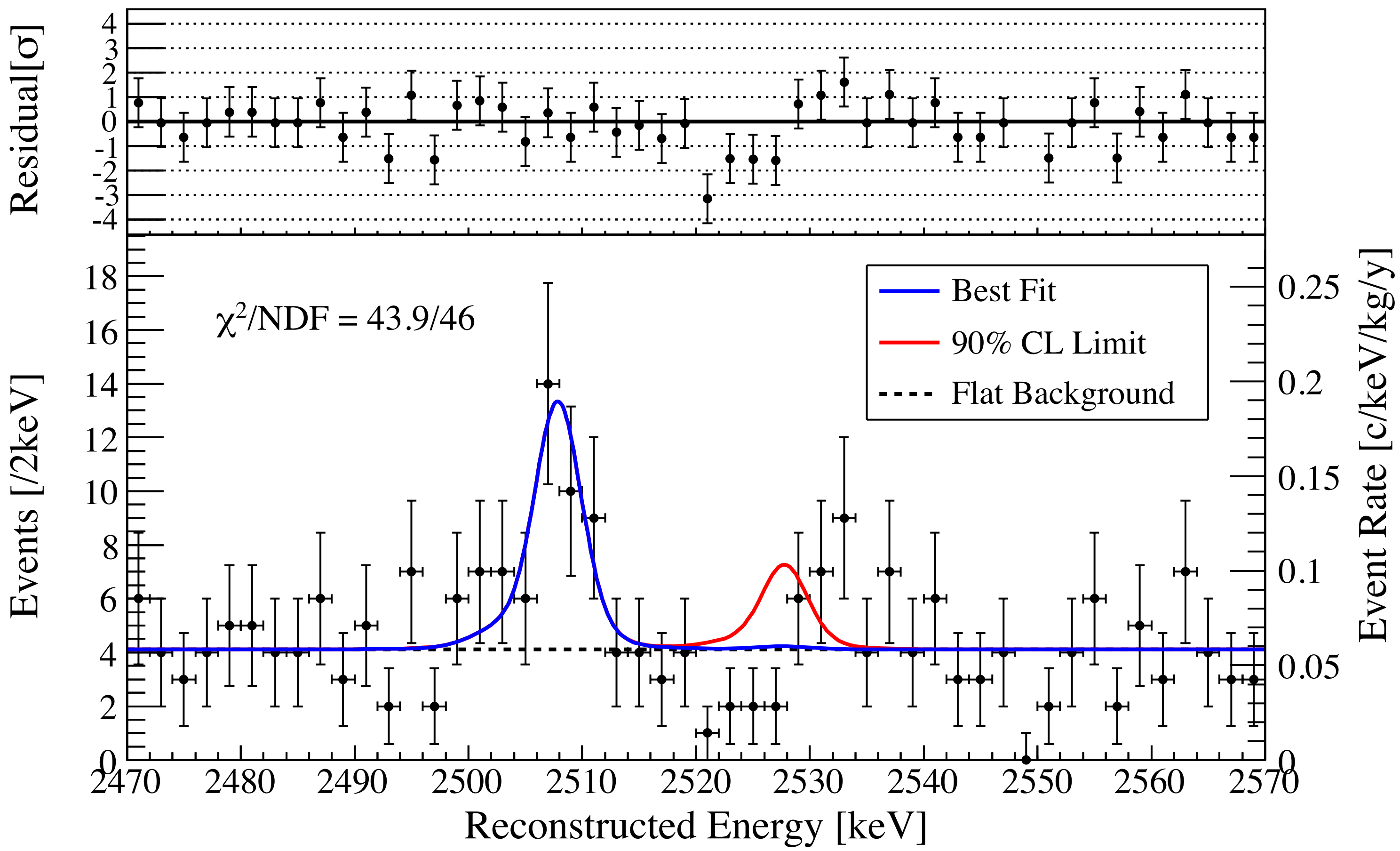
CUORE-0 0νββ ROI (unblinded)



Simultaneous un-binned extended ML fit to range [2470,2570] keV
Fit function has 3 components:

1. Calibration-derived line shape modeling posited fixed at 2527.5 keV
2. Calibration-derived line shape modeling ^{60}Co sum-peak floated around 2505 keV
3. Continuum background

CUORE-0 0νββ Results



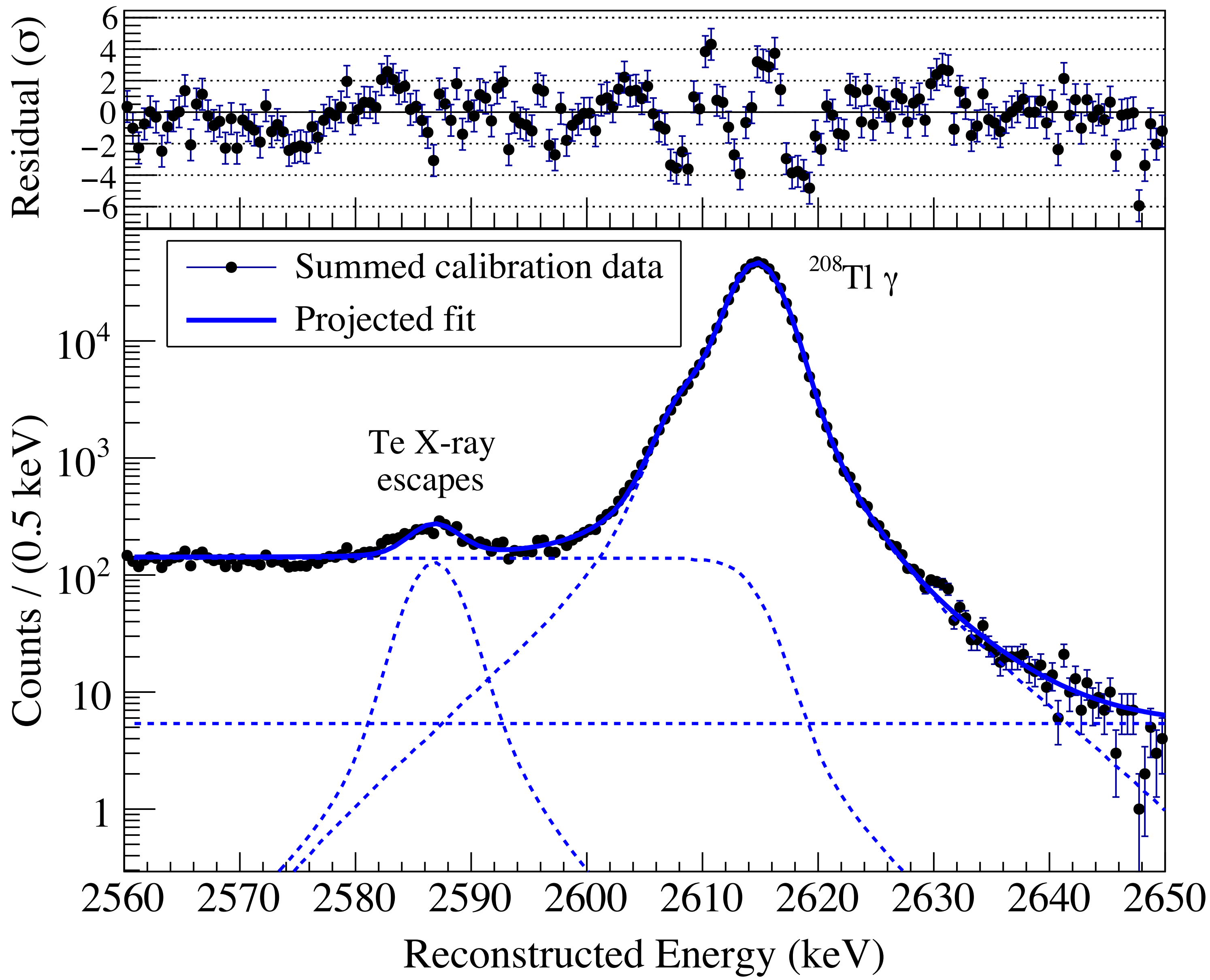
	Additive (10^{-24} yr^{-1})	Scaling (%)
Line shape	0.004	1.3
Energy resolution	0.006	2.6
Fit bias	0.006	0.15
Energy scale	0.006	0.4
Bkg function	0.004	0.7
Selection efficiency	0.7%	

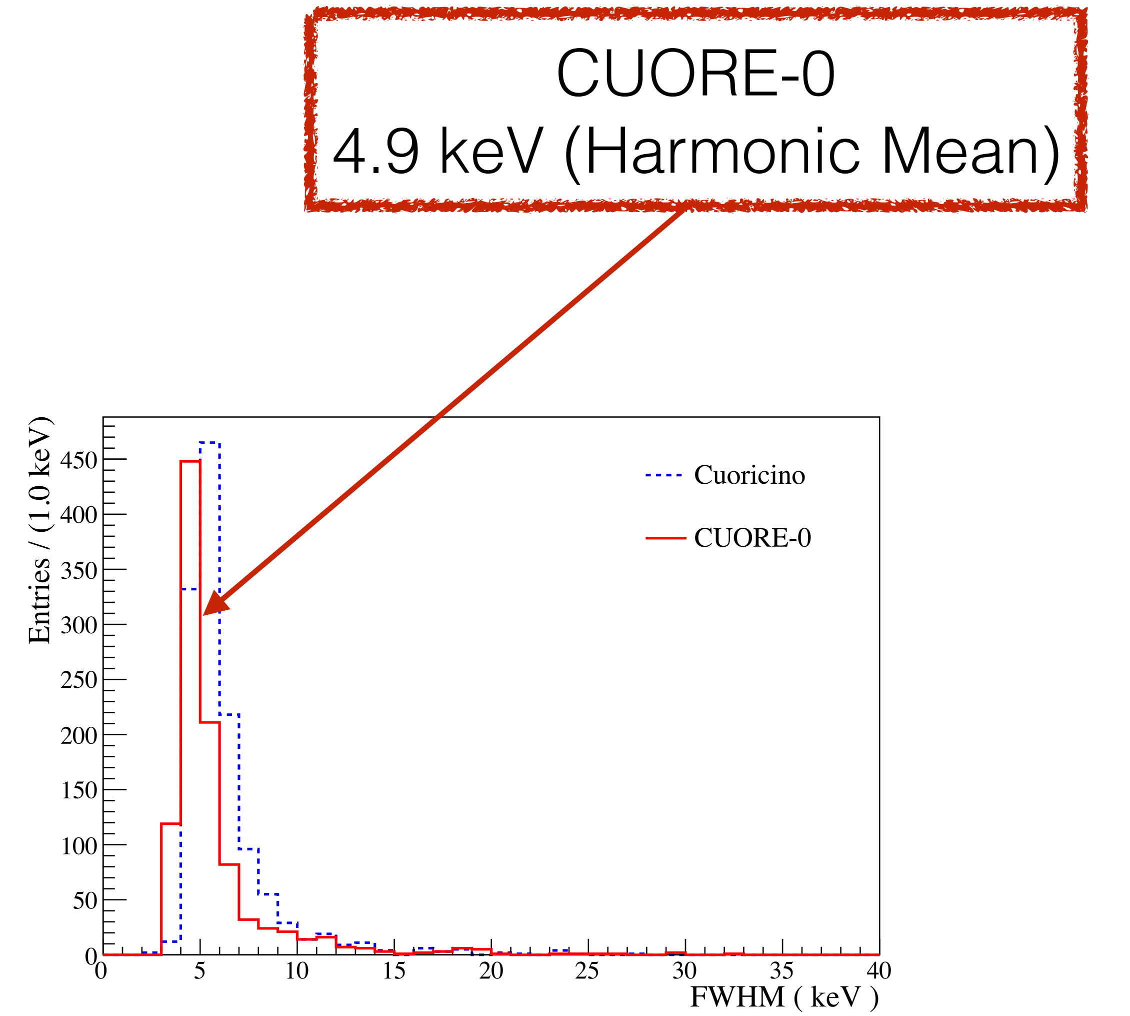
CUORE-0 only: $T^{0\nu}_{1/2}(^{130}Te) > 2.7 \times 10^{24}\, y\, (90\%\, C.L.)$

Combined CUORE-0 & Cuoricino: $T^{0\nu}_{1/2}(^{130}Te) > 4.0 \times 10^{24}\, y\, (90\%\, C.L.)$

Phys. Rev. Lett. **115**, 102502 (2015)
Phys. Rev. C **93**, 045503 (2016)

CUORE-0 Energy Resolution at ^{208}Tl 2615 keV



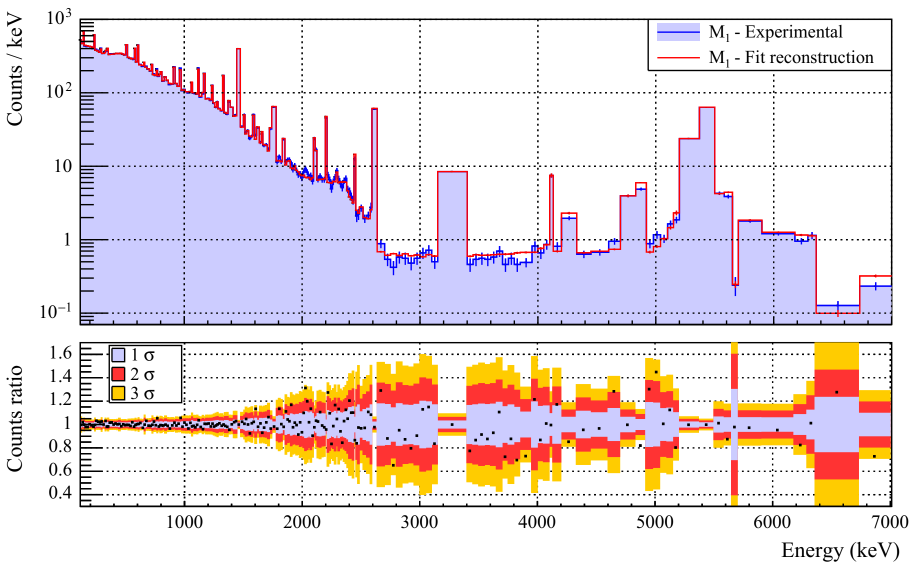


Achieved the 5 keV resolution goal of CUORE

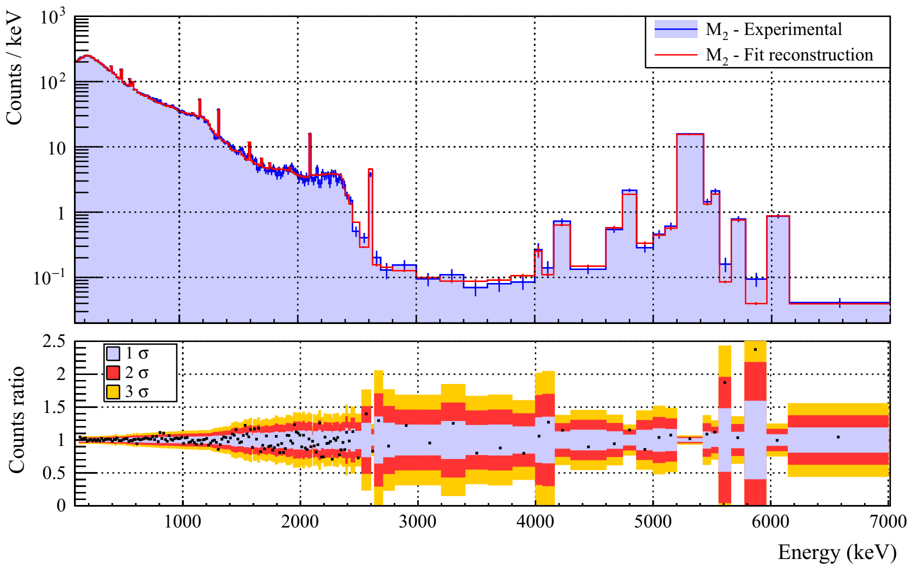
CUORE-0 2νββ Analysis

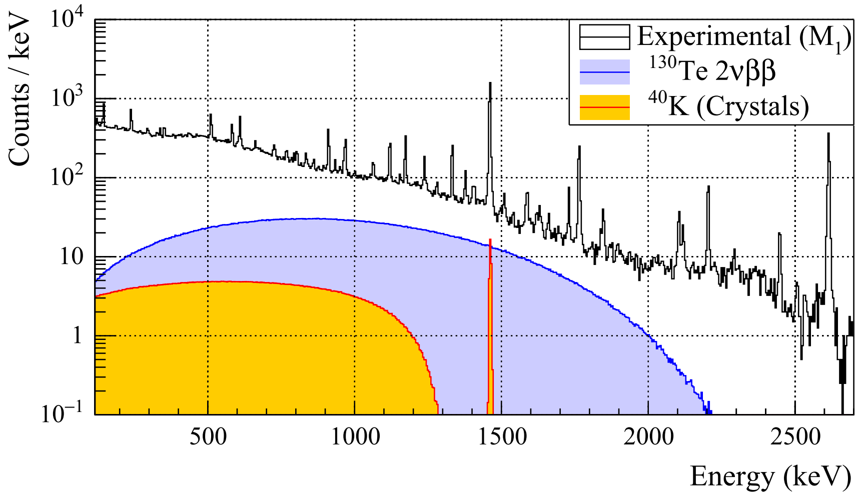
- Geant4-based CUORE MC
- Bayesian JAGS Fit
- Material assay
  (a priori constraints)

Multiplicity 1



Multiplicity 2





$$T_{1/2}^{2\nu} = [8.2 \pm 0.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})] \times 10^{20}\ \mathrm{years}$$

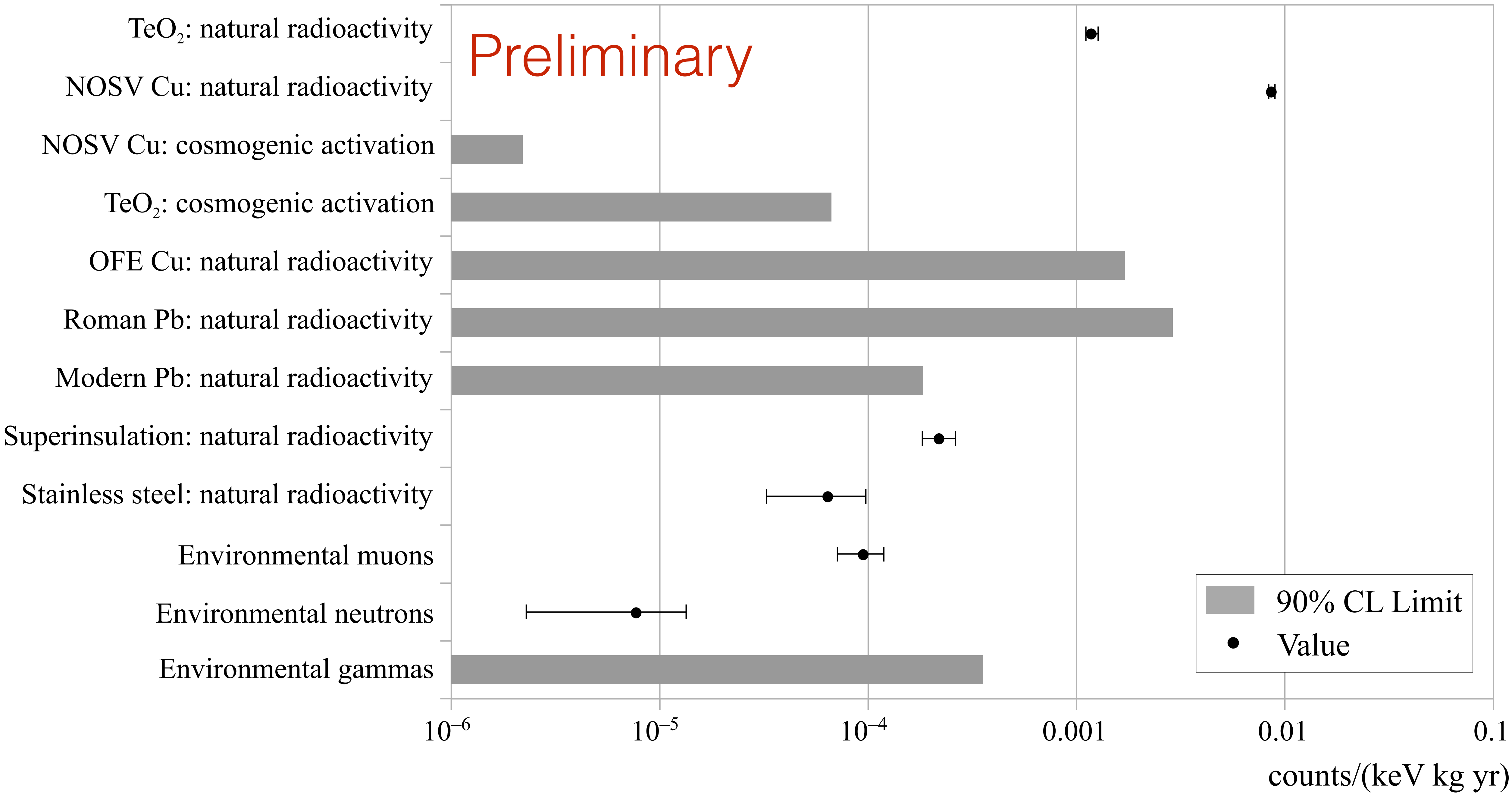
$$T_{1/2}^{2\nu} = [7.0 \pm 0.9(\mathrm{stat}) \pm 1.1(\mathrm{syst})] \times 10^{20}\ \mathrm{years}$$ (NEMO-3)

Eur. Phys. J. C **77** 13 (2017)

Projected CUORE Backgrounds

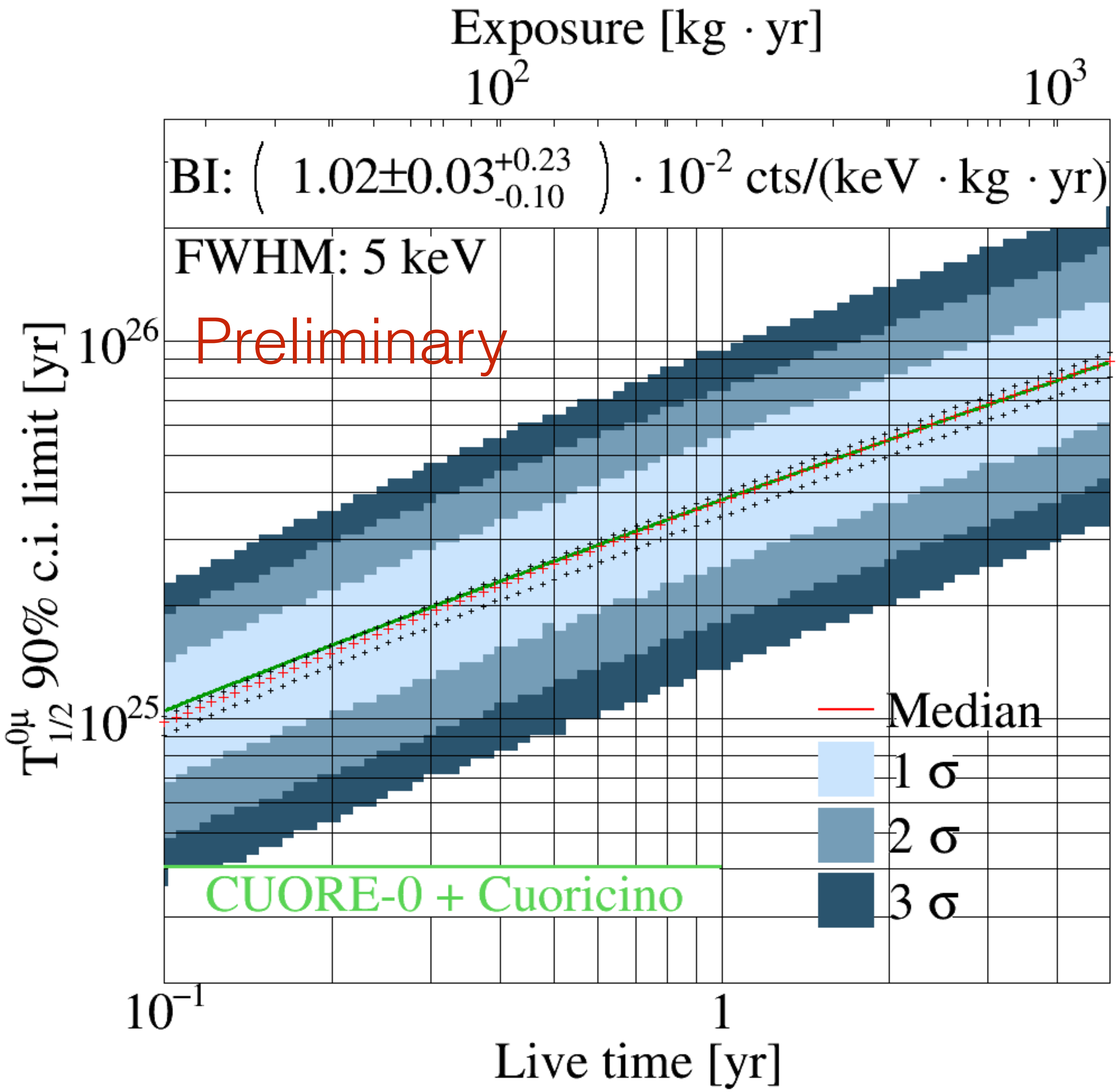
- "Radio-assay" by CUORE-0
  from 2νββ analysis
- Material assay
- Geant4-based CUORE MC

$$b = [1.02 \pm 0.03(\mathrm{stat})^{+0.23}_{-0.10}(\mathrm{syst})] \times 10^{-2}\ \mathrm{counts/keV/kg/year}$$



arXiv:1704.08970

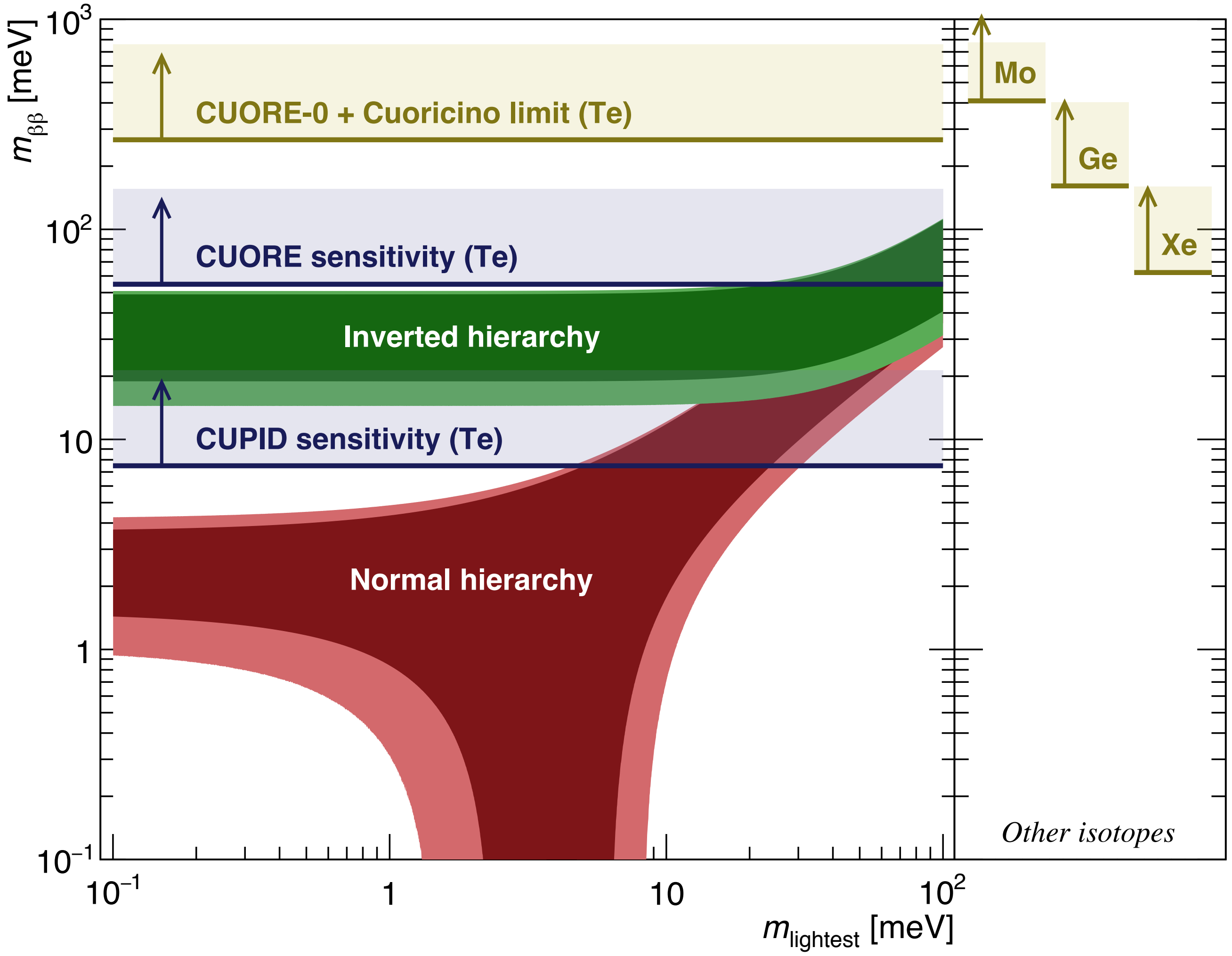
Projected CUORE Sensitivity



arXiv:1705.10816

Beyond CUORE: CUPID

CUPID: **C**UORE **U**pgrade with **P**article **ID**



- Goal: sensitivity to the full IH region

$$T^{0\nu}_{1/2} \sim 10^{27} - 10^{28}\,\text{years}$$

- Requires:
  - ≳1 ton of ββ isotope
  - CUORE-like energy resolution

$$\delta E/Q_{\beta\beta} \sim 0.2\%\,(\text{FWHM})$$

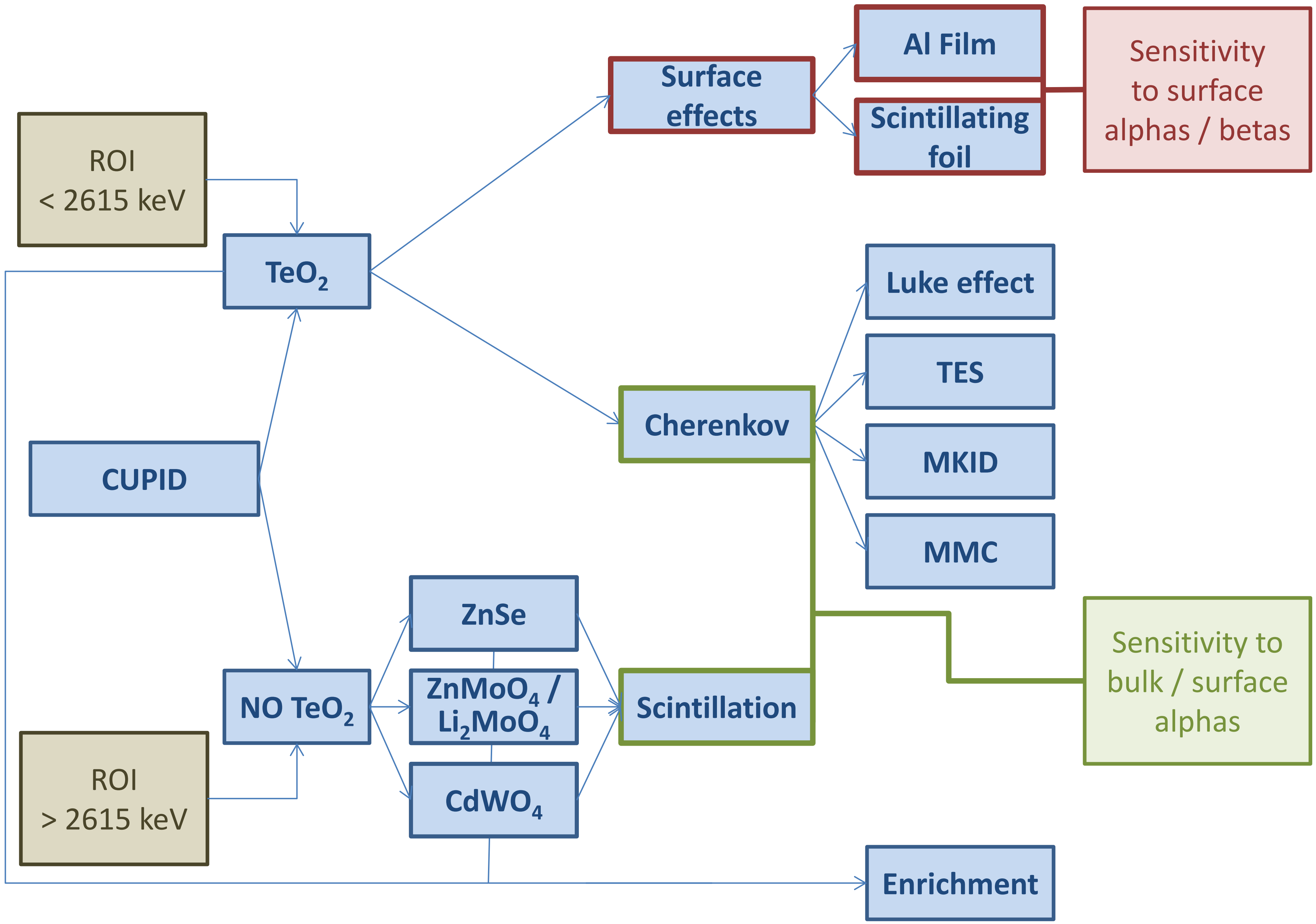
  - Background index

$$b \lesssim 10^{-1}\,\text{counts}/(\text{keV} \cdot \text{ton} \cdot \text{year})$$

  - ≥×10^3 reduction relative to CUORE

The CUPID Interest Group: arXiv:1504.03599 & arXiv:1504.03612

CUPID R&D



Surface effects
Al Film
Scintillating foil
Sensitivity to surface alphas / betas
ROI
< 2615 keV
TeO2
Luke effect
TES
Cherenkov
MKID
CUPID
MMC
ZnSe
Sensitivity to bulk / surface alphas
NO TeO2
ZnMoO4 / Li2MoO4
Scintillation
ROI
> 2615 keV
CdWO4
Enrichment

R&D Towards CUPID

Please see the related talks at this conference:

<u>Wednesday 19 July 2017</u>:

- Laura Cardani (morning session)
  Innovative light detectors for background rejection in CUORE and CUPID

<u>Thursday 20 July 2017</u>:

- Claudia Nones (09:30, next talk)
  Scintillating bolometers for the study of double beta decay
- Nicola Casali (10:00)
  CUPID-O Cryogenic calorimeter with particle ID for double beta decay
- Andrea Giuliani (11:00)
  A ^{100}Mo pilot experiment with scintillating bolometers (CUPID activities)

The CUORE Collaboration

Università degli Studi di Milano Bicocca

CSNSM

SINAP

Universitas Studii Paduani MCCXXII

INFN Istituto Nazionale di Fisica Nucleare

Cal Poly San Luis Obispo

Lawrence Livermore National Laboratory

VirginiaTech Invent the Future® 1872

Alma Mater Studiorum Università di Bologna A.D. 1088

Università degli Studi di Cassino e del Lazio Meridionale 1979 Sol per noctem

Sapienza Università di Roma Studium Urbis

Yale

Shanghai Jiao Tong University 1896

Massachusetts Institute of Technology

Berkeley Lab

University of South Carolina 1801

UCLA

The University of California 1868 Let there be light

CUORE