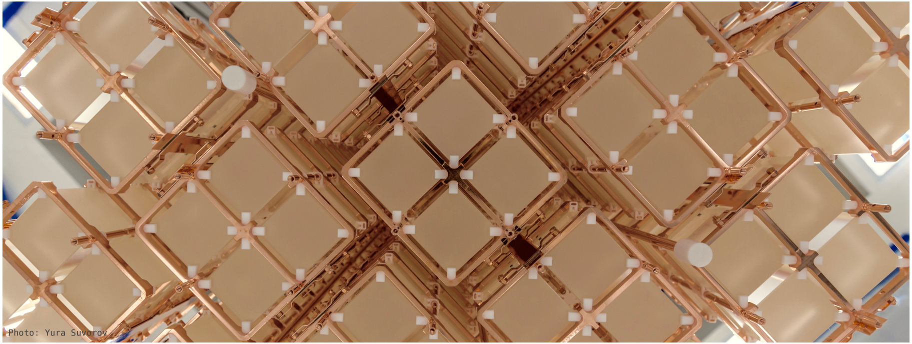
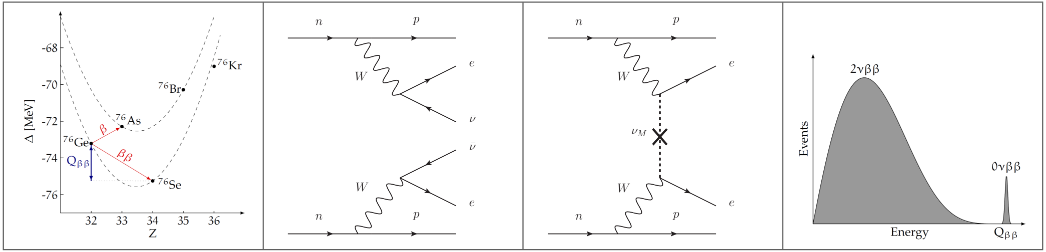


Status and results of the CUORE experiment

Giovanni Benato

MEDEX'19

$0\nu\beta\beta$ decay: what and why?



$\beta\beta$ decay signature

- Continuum for $2\nu\beta\beta$ decay, peak at $Q_{\beta\beta}$ for $0\nu\beta\beta$ decay
- Additional signatures from signal topology, pulse shape discrimination, . . .

$0\nu\beta\beta$ decay rate

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot \frac{|f|^2}{m_e^2}$$

- $T^{0\nu}_{1/2}$ = $0\nu\beta\beta$ decay half life
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element (NME)
- f = new physics

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CSNSM

Yale

INFN Istituto Nazionale di Fisica Nucleare

BERKELEY LAB

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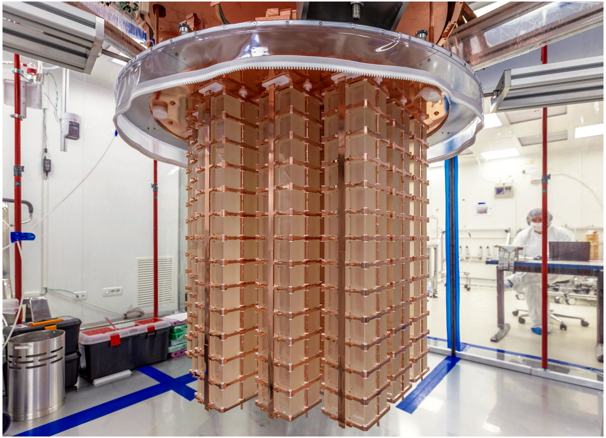

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CUORE

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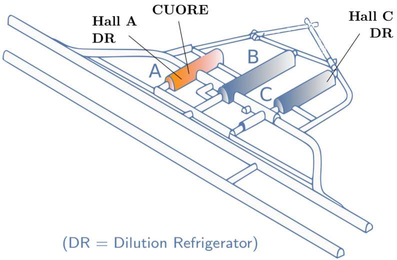
CUORE: the Cryogenic Underground Observatory for Rare Events

- TeO_2 crystals are source and detector for $0\nu\beta\beta$ decay of ^{130}Te
- First ton scale array of cryogenic calorimeters (bolometers)
- Located at the Laboratory Nazionali del Gran Sasso (LNGS) of INFN, Italy
  - ⇒ Natural shielding of $\sim$ 3600 mwe
  - ⇒ Also on google maps!



(DR = Dilution Refrigerator)

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Advantages

- Decoupling of infrastructure and detectors
  - ⇒ Multi-isotope approach possible
  - ⇒ Ideal for confirming eventual discovery
- High energy resolution
- Ultra-low background achievable with particle identification
- Granular geometry
  - ⇒ Rejection of high-multiplicity events
  - ⇒ Self-shielding

Why ^{130}Te?

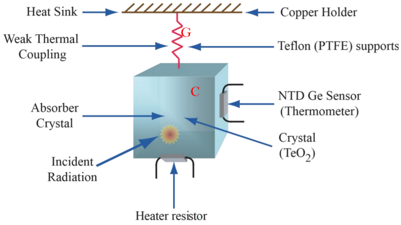
- Q-value: 2528 keV
  ⇒ Above most natural radioactive background
  ⇒ Between ^{208}Tl line and its Compton edge
- Natural abundance: 34.2%
  ⇒ No enrichment needed. At least not yet.
- TeO_2 crystals can easily be produced in large size and amount
- Source = detector
  ⇒ High containment efficiency ($\varepsilon_{MC} \sim 90\%$)
- Relatively large phase space
  ⇒ Shorter $0\nu\beta\beta$ half life

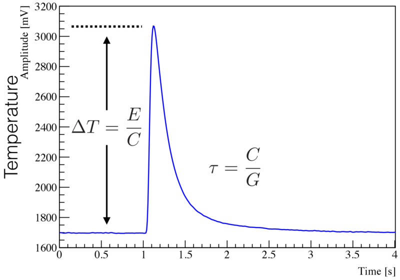
Why cryogenic calorimeters?

- Detect temperature variation due to phonon contribution of released energy
  $\Rightarrow$ High energy resolution: currently $\sim 0.2\%$, with room for improvement
- Allow to change crystal and isotope

How do cryogenic calorimeters work?

- Heat capacity: $C = C(T) \propto T^3 \Rightarrow$ Need to work at $\sim$ 10 mK
- Temperature response (pulse height): $\Delta T = \Delta E / C$
- Relaxation through weak link with thermal conductivity G
- Pulse decay constant: $\tau = C / G$





Crystals

- $5 \times 5 \times 5$ cm^3, ~ 750 g
- 988 crystals $\Rightarrow$ Cut coincidences

Temperature readout

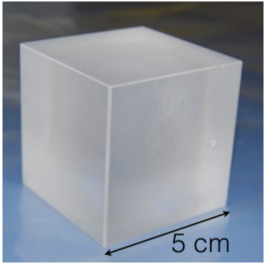
- NTD germanium thermistors
- $R(T) = R_* \cdot \exp\left(T_* / T\right)^{1/2}$
- $3.0 \times 2.9 \times 0.9$ mm^3

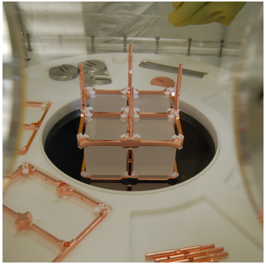
Crystal holders and readout

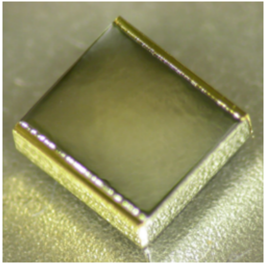
- Copper frames, PTFE holders
- Cu-PEN flat cables
- 19 towers, 52 crystals per tower

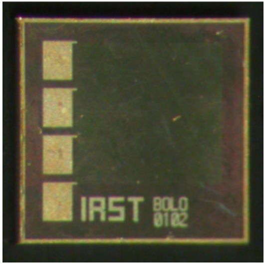
Stabilization

- Silicon heaters as pulser
- $2.3 \times 2.4 \times 0.5$ mm^3









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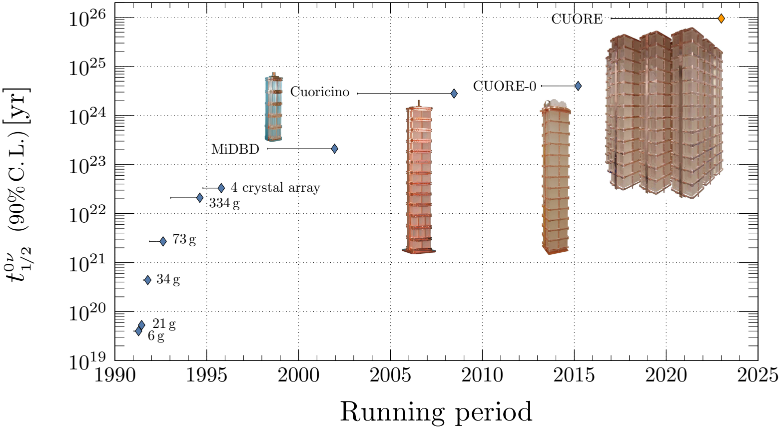
Hall A dilution refrigerator

- crystals (1991-1995)
- MiDBD (1998-2001)
- Cuoricino (2003-2008)
- CUORE-0 (2013-2015)
- CUPID-0 (2017-now)

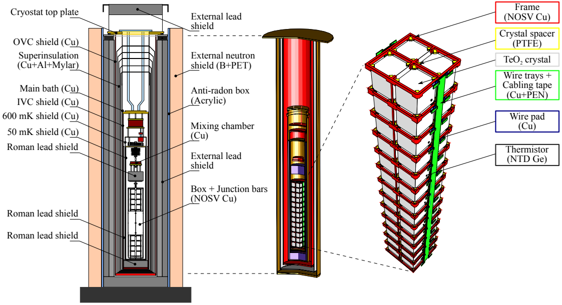
CUORE cryostat

- CUORE (2017-now)

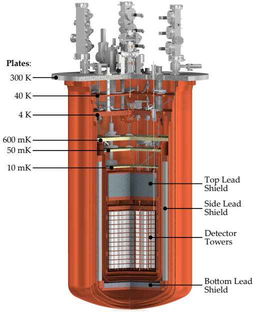


(Recent) history of TeO_2 $0\nu\beta\beta$ decay experiments

Cuoricino/CUORE-0 cryostat

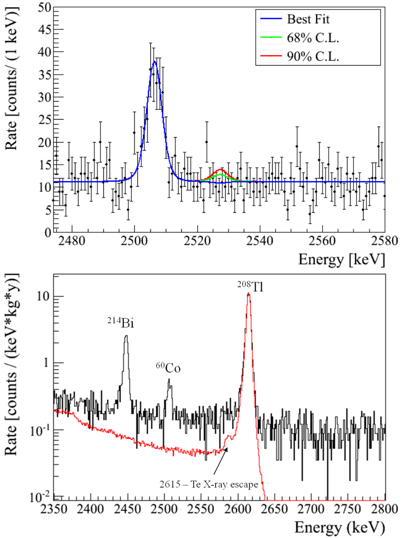


CUORE cryostat



Experiment	^{130}Te Mass [kg]	FWHM [keV]	*BI* [cts/(keV·kg·yr)]	$T^{0\nu}_{1/2}$ 90% CL Limit [yr]
Cuoricino	11.3	6.3	0.169(6)	$> 2.8 \cdot 10^{24}$
CUORE-0	11	5.1	0.058(4)	$> 4.0 \cdot 10^{24}$
CUORE	206	~ 8	0.014(2)	$\sim 9 \cdot 10^{25\,\dagger}$

† projected sensitivity with 5 years of live time



Cuoricino background

- $\sim$ 65% α particles from crystal and copper surfaces due to U/Th contamination
  $\Rightarrow$ Minimize support structure; material selection; minimize exposure to radon
- $\sim$ 35% external γ's from ^{232}Th contamination in cryostat
  $\Rightarrow$ Material selection; shielding

CUORE-0: from Cuoricino to CUORE

- Test tower assembly and installation procedure for CUORE
- Goal: reduce α background (2700-3900 keV) by a factor $\sim$ 10
- Minimize crystal contamination, reduce copper mass in support structure; clean cryostat inner surface.

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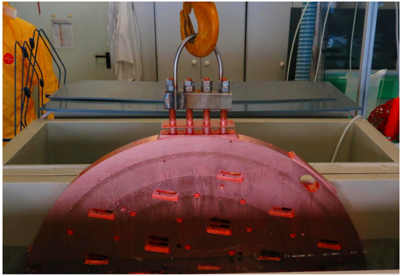
Copper cleaning procedure[1]

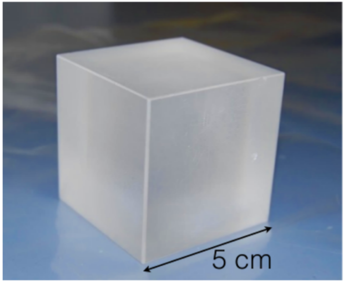
- Precleaning: tetrachloroethylene, acetone and ethanol to remove machining residuals.
- Tumbling and smoothing (removes $\sim 1\ \mu$m).
- Electropolishing: controlled oxidation of the copper surfaces and dissolution of the so-formed oxide by applying a positive anode potential in a bath of phosphoric acid and butanol (removes $\sim 100\ \mu$m).
- Chemical etching and passivation with sulfuric acid (removes $\sim 10\ \mu$m).
- Plasma etching: surface erosion produced by plasma in vacuum (removes 2μm). Vacuum prevents recontamination and promotes desorption of contaminants.
- Yields $< 1.3 \cdot 10^{-7}$ Bq/cm^2 (90% C.L.) for both ^{238}U and ^{232}Th



[1] F. Alessandria et al., Astropart. Phys. 45 (2013) 13-22.

TeO_2 crystal production for CUORE-0/CUORE[5]

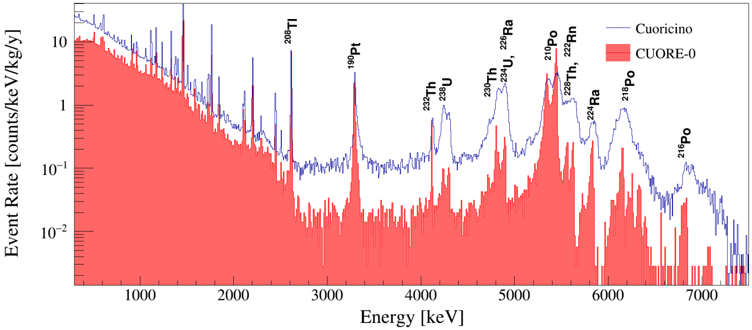
- TeO_2 crystals produced by SICCAS in Shanghai, China.
- ^{238}U and ^{232}Th contamination of raw metallic Te and TeO_2 powder (screened with germanium spectrometers and ICP-MS): $< 2 \cdot 10^{-10}$ g/g (90% C.L.).
- Crystals produced with Bridgman growth using platinum crucibles.
- Crystals shipped to Italy by sea to minimize cosmic activation, then stored underground in nitrogen atmosphere.
- Final crystal contamination in table.



Isot.	Contamination[6] [Bq/kg]
^{210}Po	$2.39(11) \cdot 10^{-6}$
^{210}Pb	$1.37(19) \cdot 10^{-6}$
^{232}Th (only)	$7(3) \cdot 10^{-8}$
^{228}Ra-^{208}Pb	$< 3.5 \cdot 10^{-8}$
^{238}U-^{230}Th	$< 7.5 \cdot 10^{-9}$
^{230}Th (only)	$2.8(3) \cdot 10^{-7}$
^{226}Ra-^{210}Pb	$< 7.0 \cdot 10^{-9}$
^{40}K	$5.1(14) \cdot 10^{-6}$
^{60}Co	$< 5.1 \cdot 10^{-7}$
^{125}Sb	$9.6(4) \cdot 10^{-6}$
^{190}Pt	$2.00(5) \cdot 10^{-6}$

[5] C. Arnaboldi et al., J. Cryst. Growth 312 (2010) 2999-3008.
[6] C. Alduino et al., Eur. Phys. J. C (2017) 77:13.

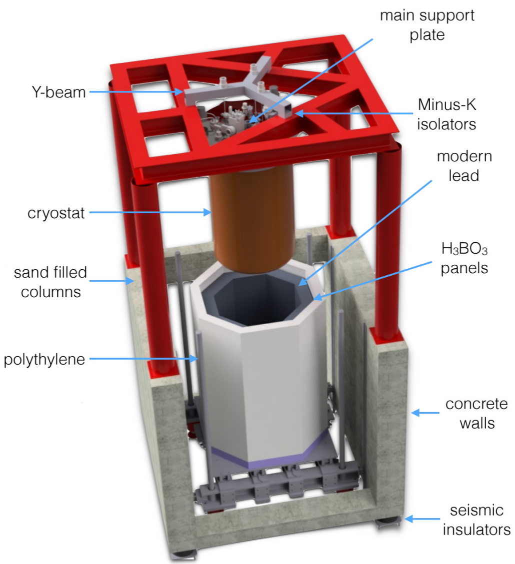
CUORE-0 vs Cuoricino



Experiment	BI at $Q_{\beta\beta}$ cts/(keV·kg·yr)	BI in [2.7, 3.9] MeV cts/(keV·kg·yr)
Cuoricino	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

Mitigation of external background

- Underground location: $3 \cdot 10^{-8}\ \mu/\text{cm}^2/\text{s}$
- Polyethilene and H_3BO_3 neutron shieldings
- 70 tons of external lead shielding
- 6.5 tons of Roman Pb inside the cryostat
- Copper cryostat absorbs Pb X-rays



How to avoid recontamination?

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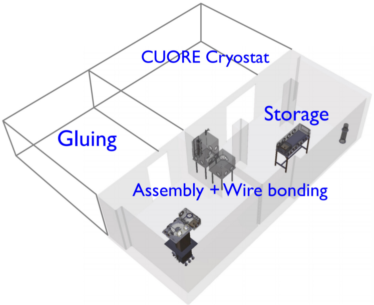
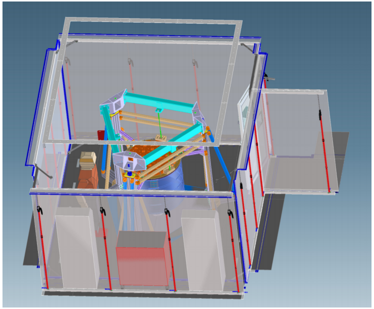
- Screening of all parts
- Underground storage to avoid cosmic activation
- Tower assembly in underground class 1000 clean room (CR)
- Towers stored in N_2 athmosphere to minimize Rn contamination
- Dedicated CR with Rn-free air for tower installation



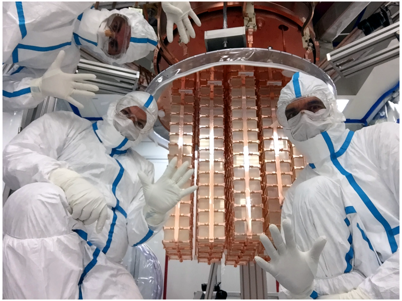


Installation history

- Jul. 27, 2016: first tower installed
- Aug, 28, 2016: installation complete
- Sep. - Nov. 2016: cable routing, electronics and DAQ tests, cryostat closure
- Dec. 5, 2016: cool-down started
- Jan. 27, 2017: first pulse!

Preservation of crystal radio-purity

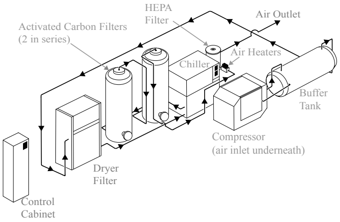
- Dedicated temporary clean room (CR6) flushed with radon-free air
- Towers in N_2 atmosphere overnight for additional safety
- Rn level kept $\lesssim 50$ mBq/m^3 for the entire duration of the installation



Radon abatement and monitoring[4]

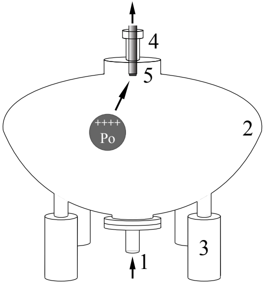
Radon Abatement System

- Provides ~ 120 m^3/hr of low-radon air
- Radon level at output: < 5 mBq/m^3
- Factor ~ 35 reduction wrt LNGS lab
- Compressed air $\Rightarrow$ dryer $\Rightarrow$ chiller $\Rightarrow$ active carbon filter $\Rightarrow$ heater $\Rightarrow$ HEPA filters $\Rightarrow$ CR6



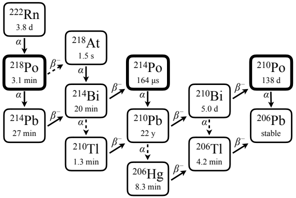
Radon Monitor

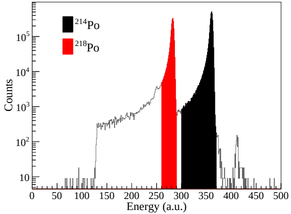
- Borrowed from MPI-HD (Thanks!!)
- ~ 700 L volume flushed at 7 L/min
- Sensitive to ^{214}Po and ^{218}Po (Si diode)
- Total efficiency: $\sim 30\%$
- Internal background: $\sim 300\ \mu$Bq/m^3
- Sensitivity for CUORE measurement: $\lesssim 5$ mBq/m^3 (integrating for 30 min)

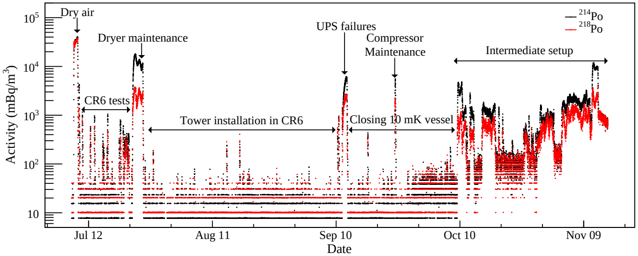


[4] G. Benato et al., JINST 13 (2018) P01010

Radon abatement and monitoring[4]







[4] G. Benato et al., JINST 13 (2018) P01010

The CUORE cryostat

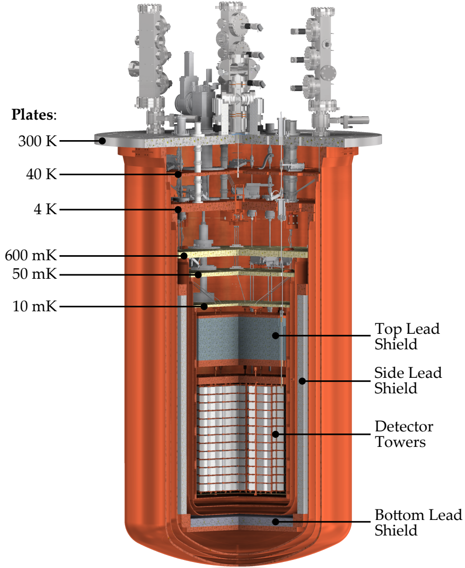
Temperature [K]	Mass [ton]
300	~ 3.5
40	~ 1
4	~ 7.5
0.600	~ 0.8
0.050	~ 3
0.010	~ 1.5

Requirements

- Cool down in $\lesssim 1$ month
- Stay stable at ~ 10 mK for 5 yr

Solutions

- Cryogen free cryostat $\Rightarrow$ Lower down time
- Fast cooling with He vapor down to ~ 40 K
- 5 Pulse Tubes (PT) down to ~ 4 K
- Dilution Unit (DU) down to ~ 10 mK



First science run

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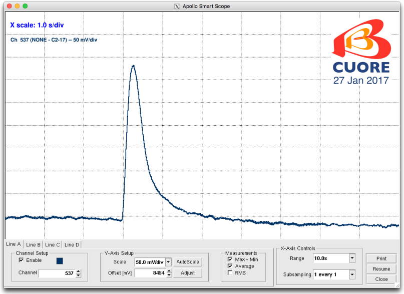
Apr. 17: first physics data

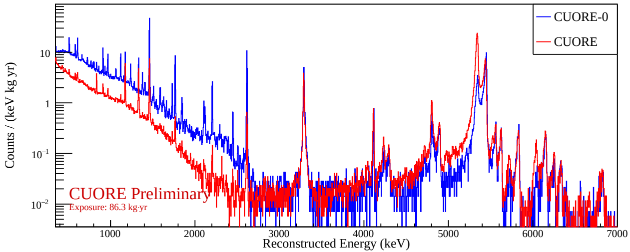
- Working T set at 15 mK
- Dataset 1: 3 weeks
- Further optimization campaign
- Dataset 2: 5 weeks
- Exposure: 86.3 kg·yr

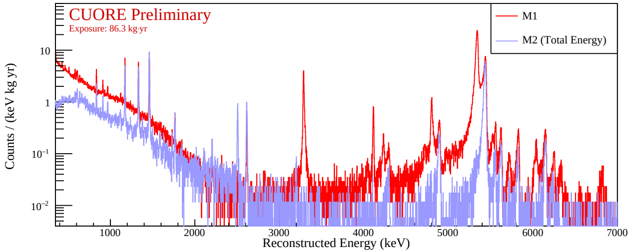


Operational performance

- 99.6% of channels operative (984/988)
- Energy resolution at $Q_{\beta\beta}$: 7.7 keV (FWHM)
- Signal efficiency: $\sim$ 80%

The CUORE background





- α contamination comparable to CUORE-0
- γ contamination reduced by factor ~ 6
- Unexpected surface ^{210}Po recontamination of crystal surface (estimated contribution at ROI: $\sim 10^{-4}$ cts/(keV·kg·yr))
- α contribute to $\sim 90\%$ of background at $Q_{\beta\beta}$

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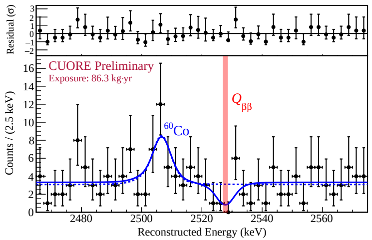
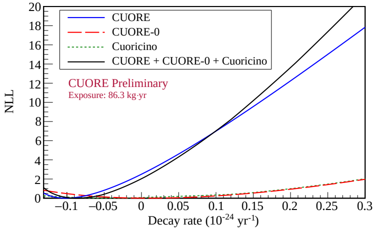
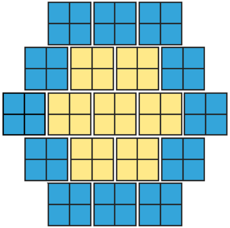
Limit on $T_{1/2}^{0\nu}$ and $|m_{\beta\beta}|$

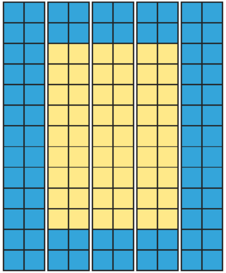
- Integrate profile likelihood in the physical region ($\Gamma_{0\nu} > 0$)
- For bkg-dominated case, equivalent to Bayesian construction with flat prior on all rates
- CUORE only: $T_{1/2}^{0\nu} > 1.3 \cdot 10^{25}$ yr (90% C.I.)
- With Cuoricino and CUORE-0: $T_{1/2}^{0\nu} > 1.5 \cdot 10^{25}$ yr (90% C.I.)
- Median sensitivity: $\hat{T}_{1/2}^{0\nu} = 7.4 \cdot 10^{24}$ yr
- 2% probability of obtaining more stringent limit
- Limit on effective mass: $m_{\beta\beta} < (110 - 520)$ meV (90% C.I.)





[4] CUORE Collaboration, arXiv:1710.07988



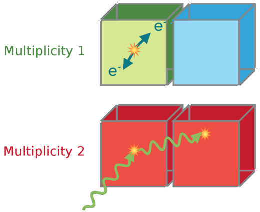


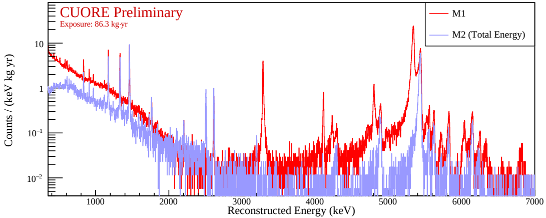
Maximize use of available information

- Split the data into inner and outer layers
- Split data into Multiplicity 1 (M1), Multiplicity 2 (M2), Multiplicity 2 Sum ($\Sigma 2$)

Background model

- Geant4 simulation of contaminants in different cryostat components ($\sim$ 60 independent fit parameters)
- Bayesian fit using a MCMC Gibbs sampler (JAGS)
- Flat priors for all parameters except muons





Building the CUORE background model

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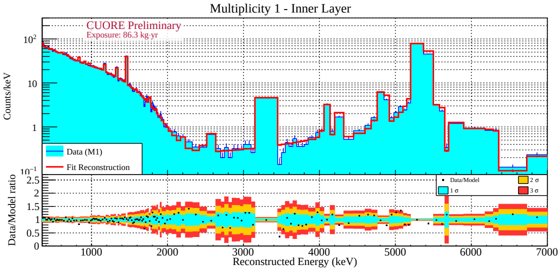
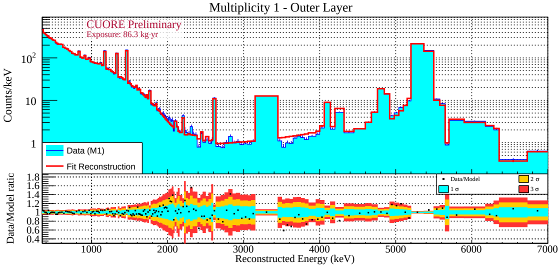
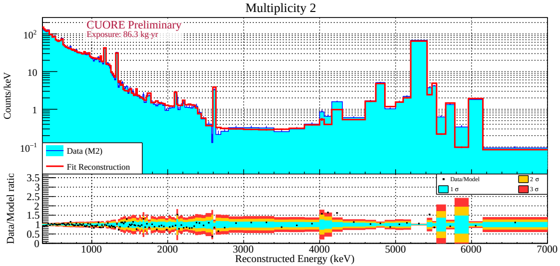




Why separate spectra?

- Inner layer very sensitive to signal (lower background)
- Outer layer sensitive to external backgrounds
- M2 and Σ2 spectra constrain a subset of the backgrounds



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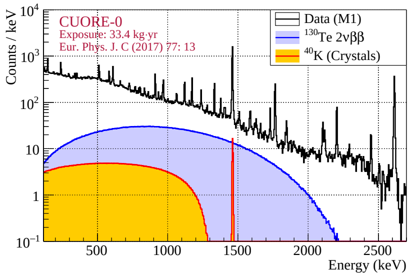
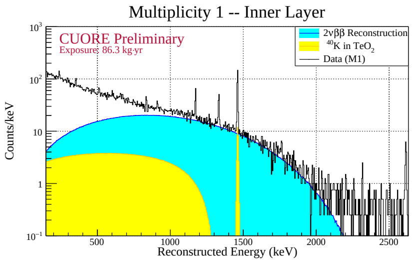
Results

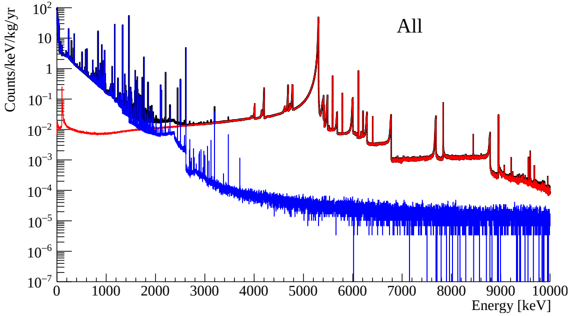
- Almost all events in 1-2 MeV range are $2\nu\beta\beta$ events (compare to $\sim$ 20% in CUORE-0)
- $T^{2\nu}_{1/2} = [7.9 \pm 0.1(\text{stat}) \pm 0.2(\text{syst})] \cdot 10^{20}$ yr (PRELIMINARY)
- CUORE-0: $T^{2\nu}_{1/2} = [8,2 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})] \cdot 10^{20}$ yr
- NEMO: $T^{2\nu}_{1/2} = [7.0 \pm 0.9(\text{stat}) \pm 1.1(\text{syst})] \cdot 10^{20}$ yr

Systematics

- Primary systematic from geometric splitting
- No dependence on fit threshold over the range 100-750 keV







Lessons learned from CUORE

- 90% of background at ^{130}Te $Q_{\beta\beta}$ induced by degraded α from crystal, PTFE or copper surfaces
- Need to discriminate between α and β/γ or between surface and bulk
- β/γ background "naturally" lower above the ^{208}Tl line at 2615 keV
- Provided that an isotope with $Q_{\beta\beta} > 2615$ keV is used, a background $\lesssim 10^{-4}$ cts/(keV·kg·yr) is achievable with the CUORE infrastructure

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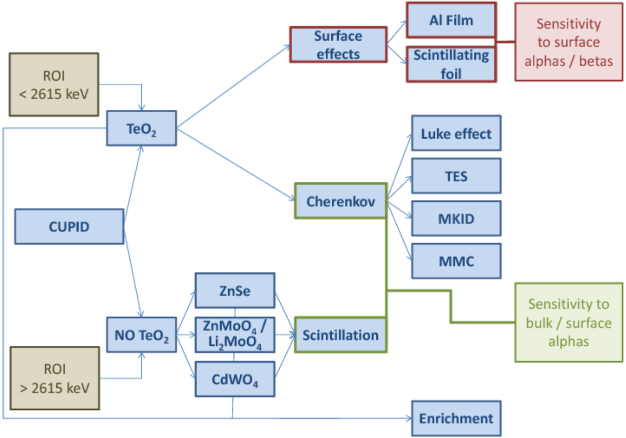
Optimize chances of discovery

- Isotope with high $Q_{\beta\beta}$
- Discriminate α from β/γ
  $\Rightarrow$ Scintillation or Cherenkov light
- Discriminate bulk from surface events

Possible isotopes

Isotope	$Q_{\beta\beta}$ [keV]	Res. [keV]	Scalable	Scint.
^{130}Te	2525	5–8	Yes	No
^{82}Se	2997	23	Maybe	Yes
^{100}Mo	3034	6	Yes	Yes



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Mission

- Discover $0\nu\beta\beta$ decay if $m_{\beta\beta} > 10$ meV ($T_{1/2}(^{100}\text{Mo}) > 10^{27}$ yr)

CUORE achievements

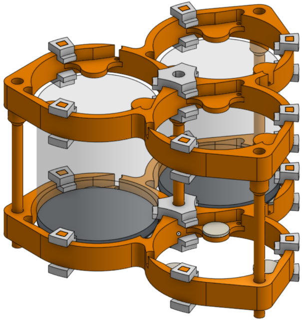
- Ton-scale bolometric detector is technically feasible
- Analysis of 1000 channels demonstrated
- Reliable data-driven background model constructed
- Infrastructure for next generation experiment exists

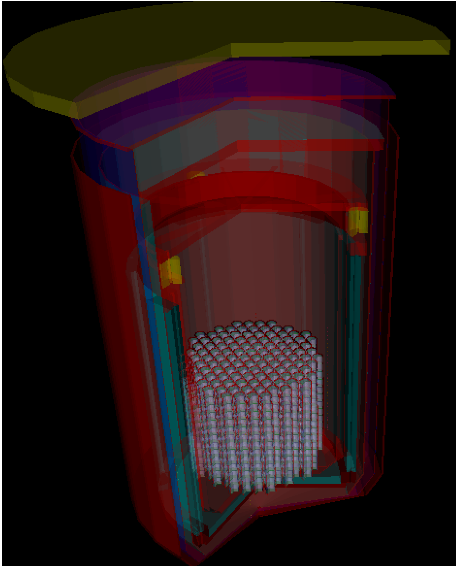
Scintillating bolometers R&D (CUPID-0, Lumineu, CUPID-Mo)

- Demonstrated large-scale enriched crystal production capability
- Internal radiopurity target met
- Demonstrated active background rejection
- Demonstrated ~ 5 keV resolution
- Total background of $\sim 10^{-4}$ cts/(keV·kg·yr)achievable

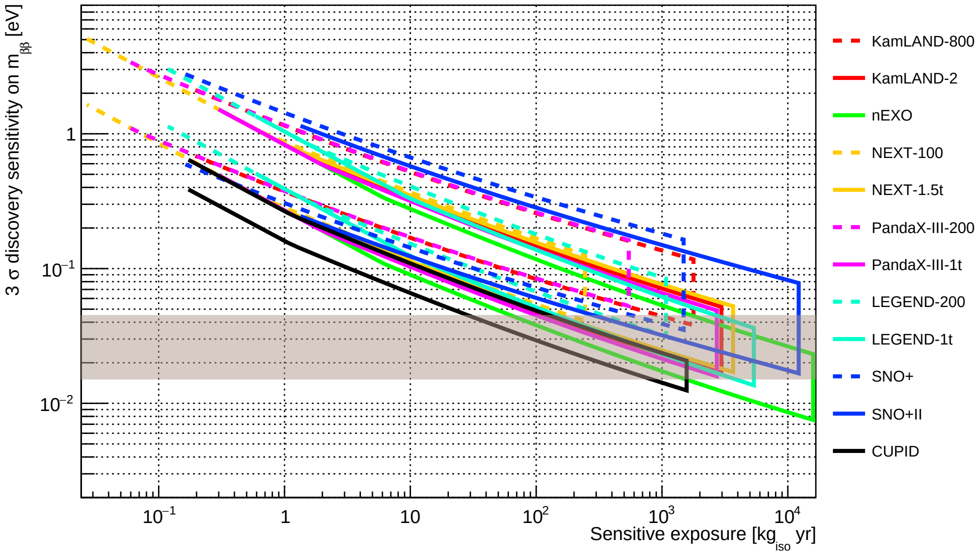
CUPID conceptual design

- Re-use CUORE cryogenic infrastructure at LNGS
- $Li_2^{100}MoO_4$ scintillating crystals
- $\sim$ 1500 crystals for 270 kg of ^{100}Mo
- Active background rejection using light and heat signals
- Options for multiple isotopes possible
- TDR and construction readiness in 2021





Discovery potential



CUPID collaboration

High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA
Materials Science Division, Argonne National Laboratory, Argonne, IL, USA
INFN - Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Department of Nuclear Engineering, University of California, Berkeley, CA, USA
Department of Physics, University of California, Berkeley, USA
Università di Bologna and INFN Bologna, Bologna, Italy
Massachusetts Institute of Technology, Cambridge, MA, USA
Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
Technische Universität München, Physik-Department E15, Garching, Germany
Dipartimento di Fisica, Università di Genova and INFN - Sezione di Genova, Genova, Italy
Institute for Nuclear Research, Kyiv, Ukraine
INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
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Sobolev Institute of Geology and Mineralogy, SB RAS, Novosibirsk, Russia
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INFN - Sezione di Padova, Padova, Italy
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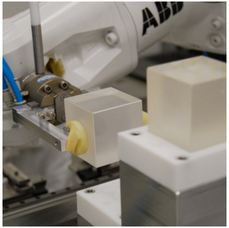
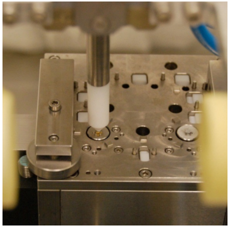
Shanghai Institute of Applied Physics (SINAP), China
Institut de Physique Nuclèaire de Lyon, Universitè Claude Bernard, Lyon 1, Villeurbanne, France
Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA
Laboratorio de Fisica Nuclear y Astropartculas, Universidad de Zaragoza, Zaragoza, Spain

Backup: How to glue 10^3 heaters and NTDs?

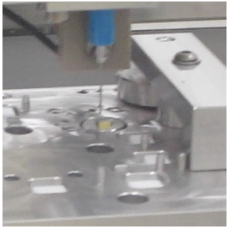
Robotic arm



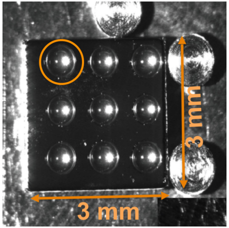
Position sensor



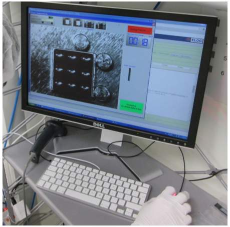
Print glue matrix



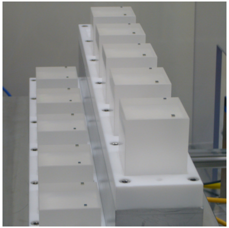
Inspection glue



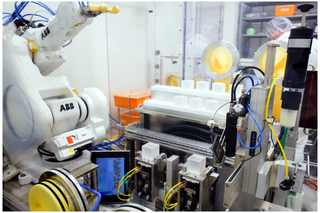
Quality control



Glued crystals

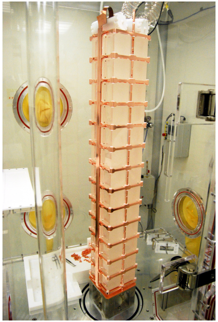


Gluing setup

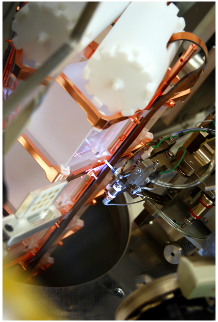


Tower assembly

Finished tower



Wire bonding



Tower storage