Status and Prospects of CUORE & CUPID

Reina Maruyama
Yale University

INT Program INT-17-2a
Neutrinoless Double-beta Decay
University of Washington
Seattle, WA USA

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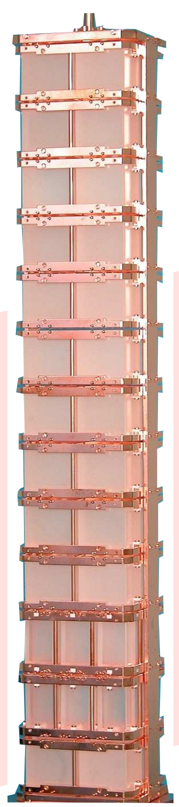
The CUORE $0\nu\beta\beta$ Search

Cuoricino
(2003 – 2008)



Astropart. Phys. 34 (2011) 822–831

$T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24}$ y (90% C.L.)

CUORE-0
(2013 – 2015)

EPJC 74, 2956 (2014)
arXiv:1504.0245

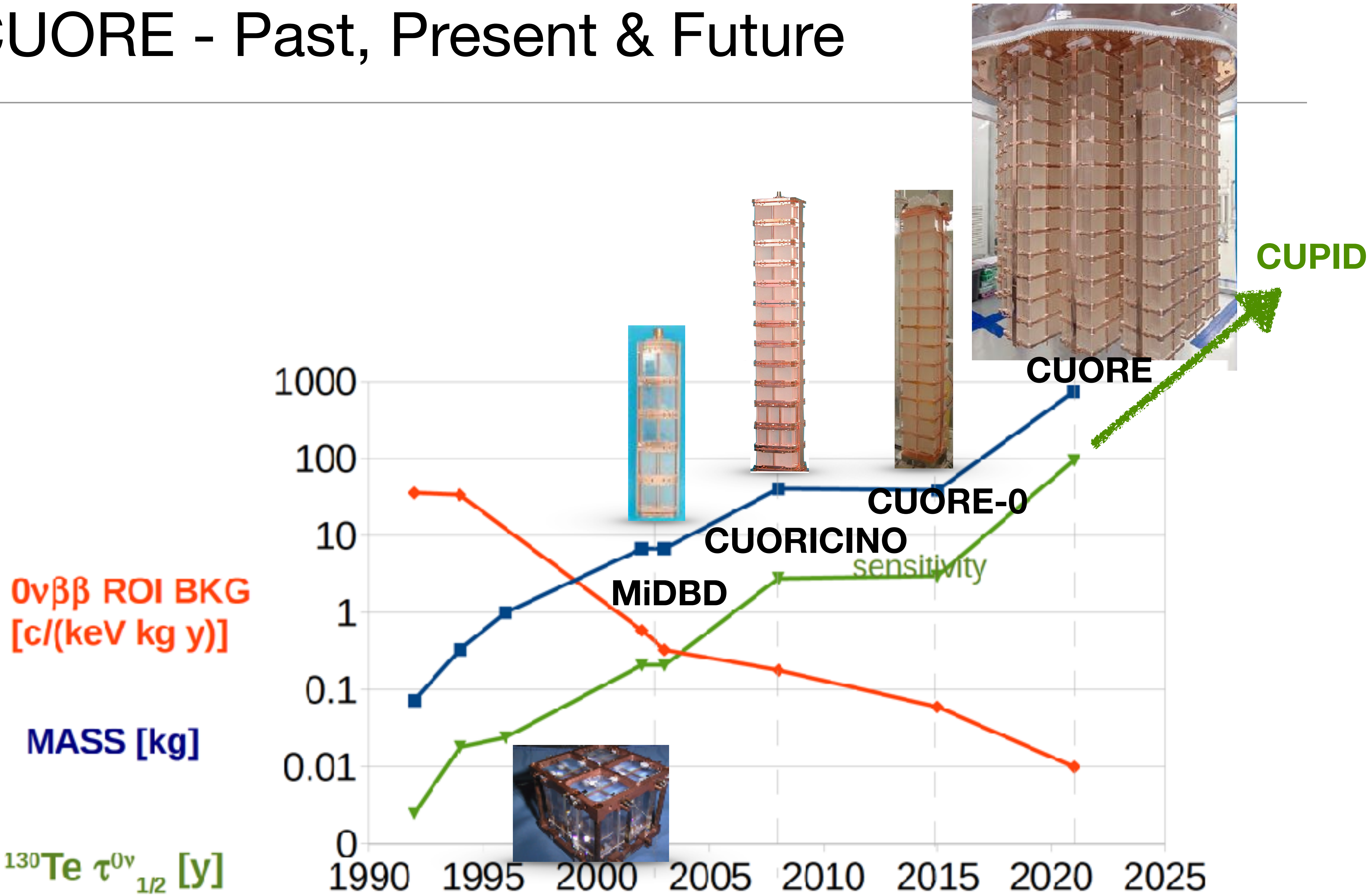
$T_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24}$ y (90% C.L.)

CUORE
(2017 –)

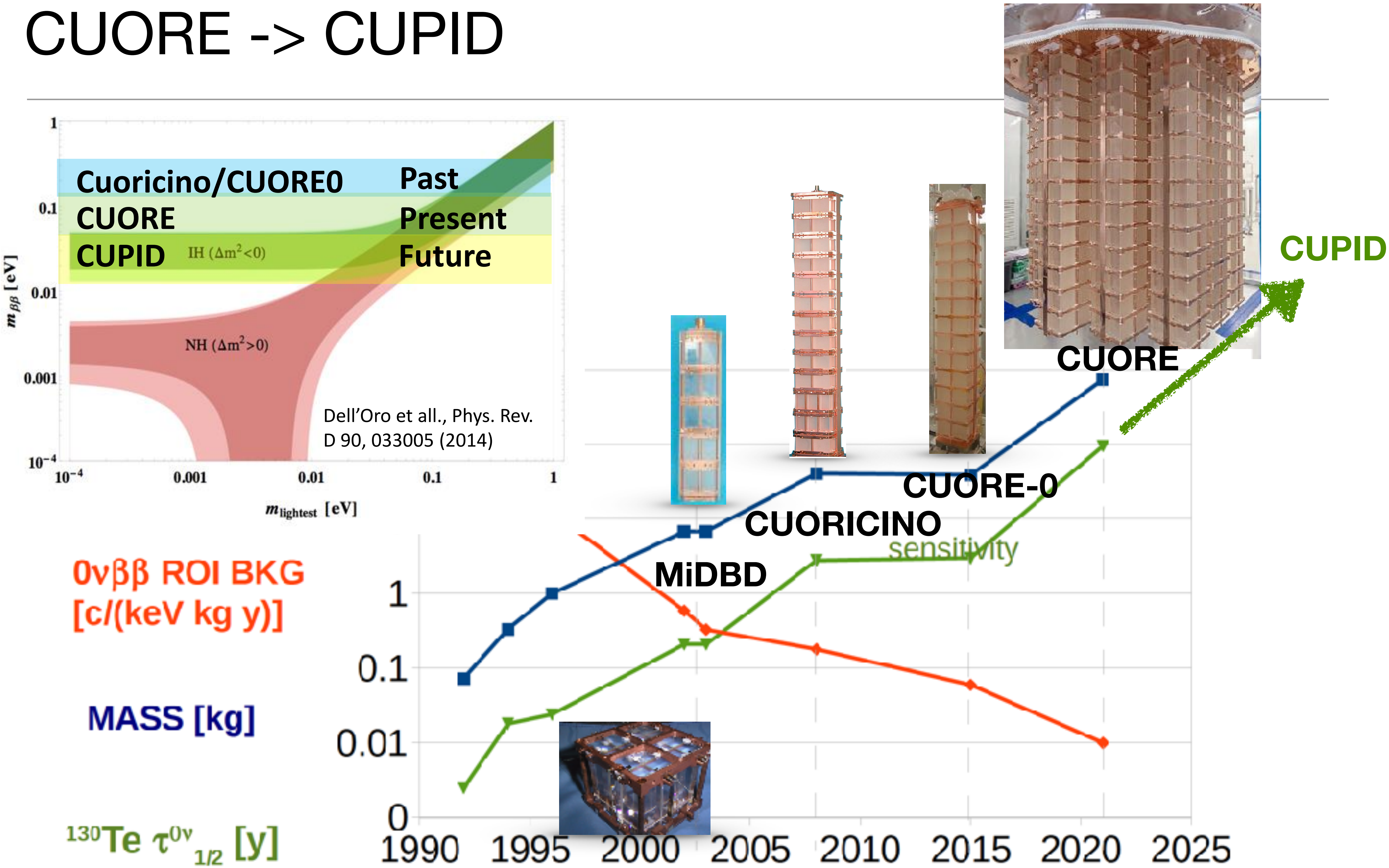
arXiv:1109.0494
arXiv:1705.10816

Projected
$T_{1/2}^{0\nu\beta\beta} \sim 9 \times 10^{25}$ yr (90% C.L.)

CUORE - Past, Present & Future



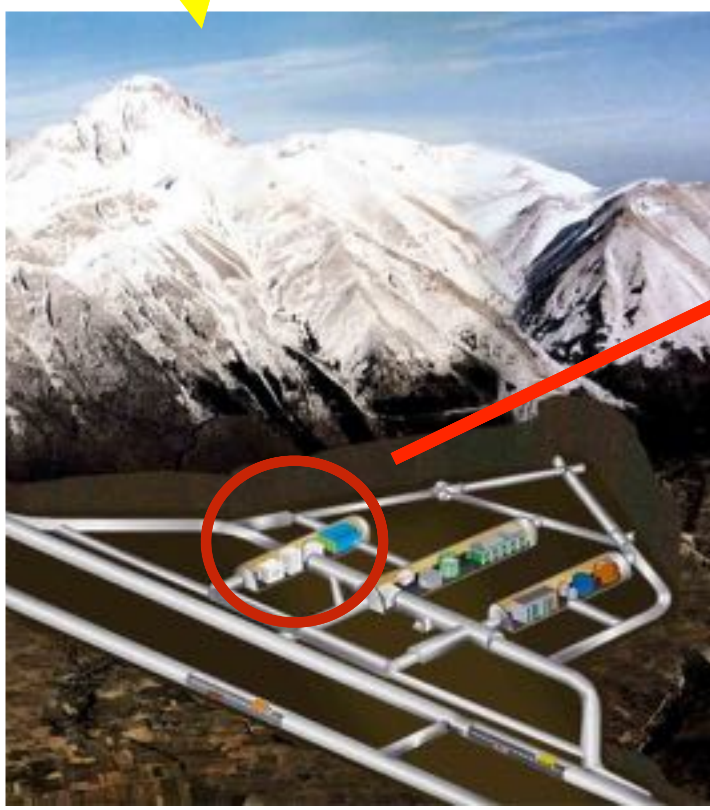
CUORE -> CUPID



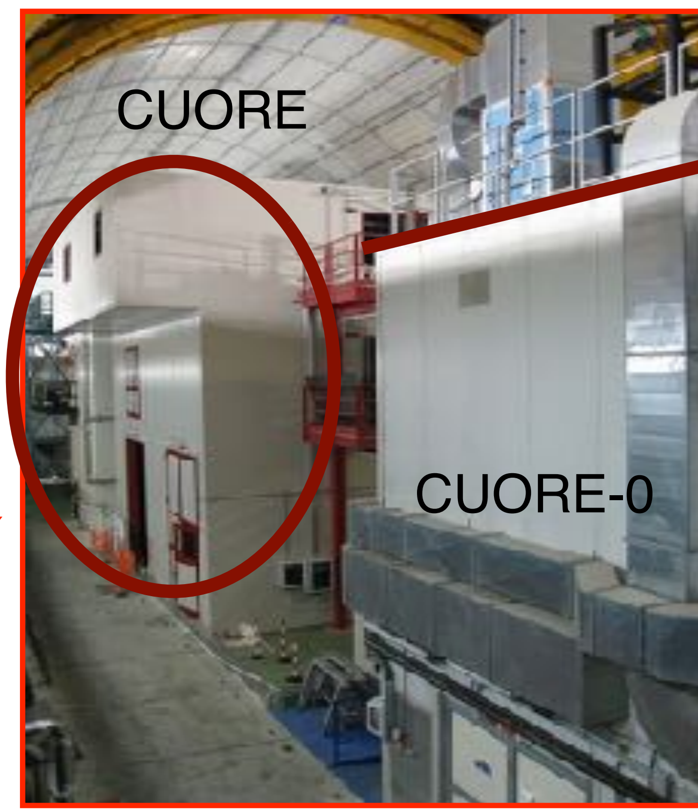
Cuoricino/CUORE0 Past
CUORE Present
CUPID Future
IH (Δm²<0)
NH (Δm²>0)
Dell'Oro et all., Phys. Rev. D 90, 033005 (2014)
m_ββ [eV]
m_lightest [eV]
0νββ ROI BKG [c/(keV kg y)]
MASS [kg]
130Te τ0ν1/2 [y]
CUPID
CUORE
CUORE-0
CUORICINO
MiDBD
sensitivity
1
0.1
0.01
0
1990 1995 2000 2005 2010 2015 2020 2025

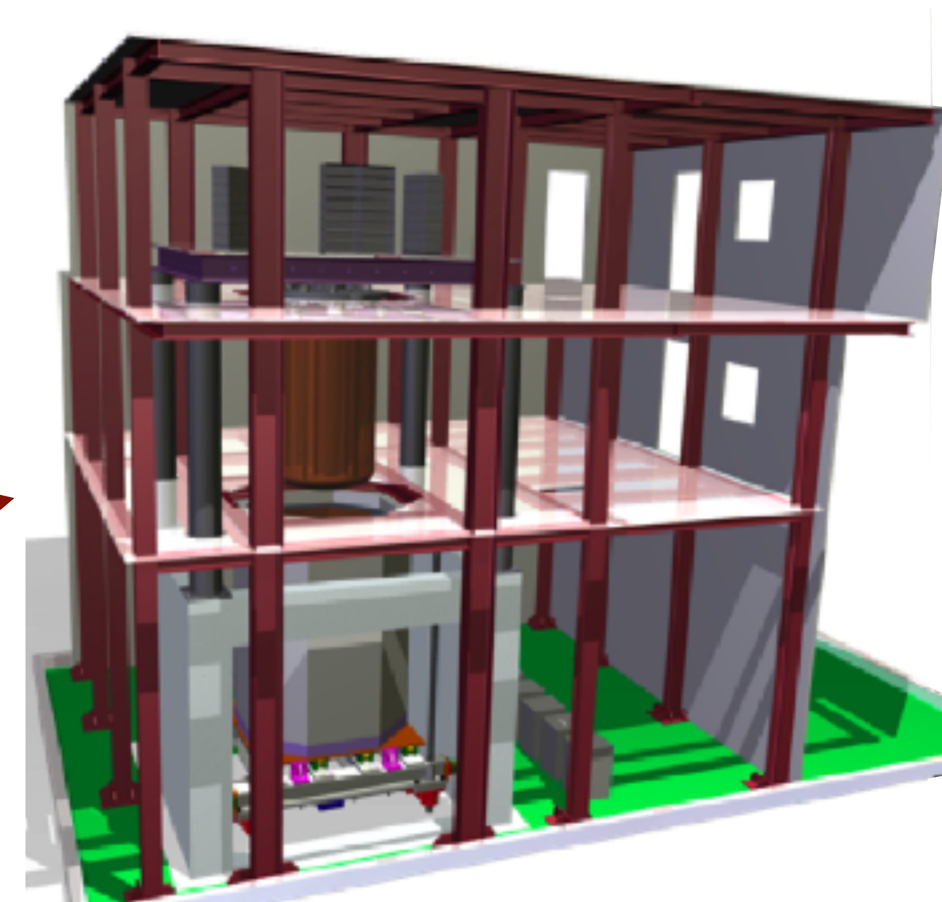
CUORE at LNGS

Gran Sasso National Laboratory



Hall A





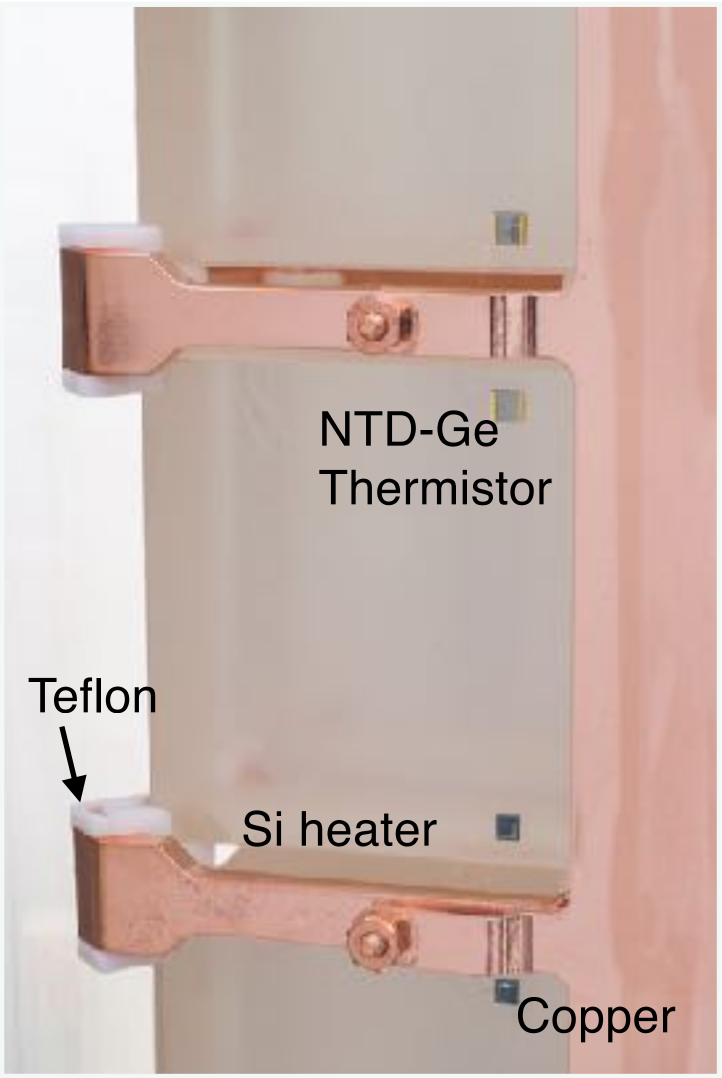
CUORE Hut

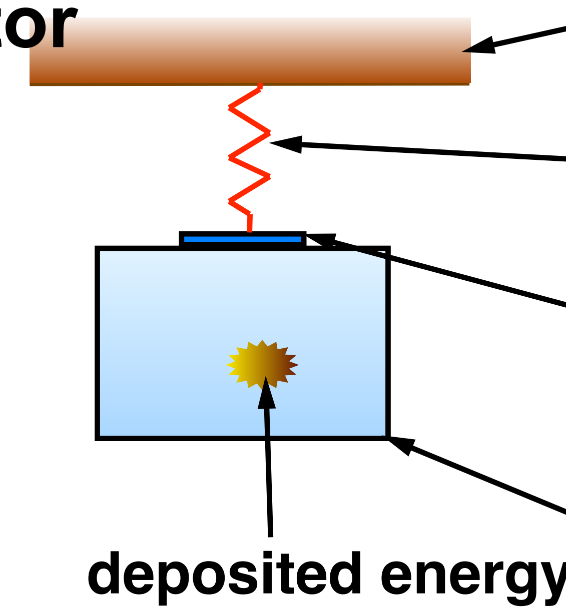
Average depth ~ 3600 m.w.e.

- **μ: 3 x 10^{-8} μ/s/cm^2**
- **n < 10 MeV: 4 x 10^{-6} n/s/cm^2**
- **γ < 3 MeV: 0.73 γ/s/cm^2**

CUORE Bolometer

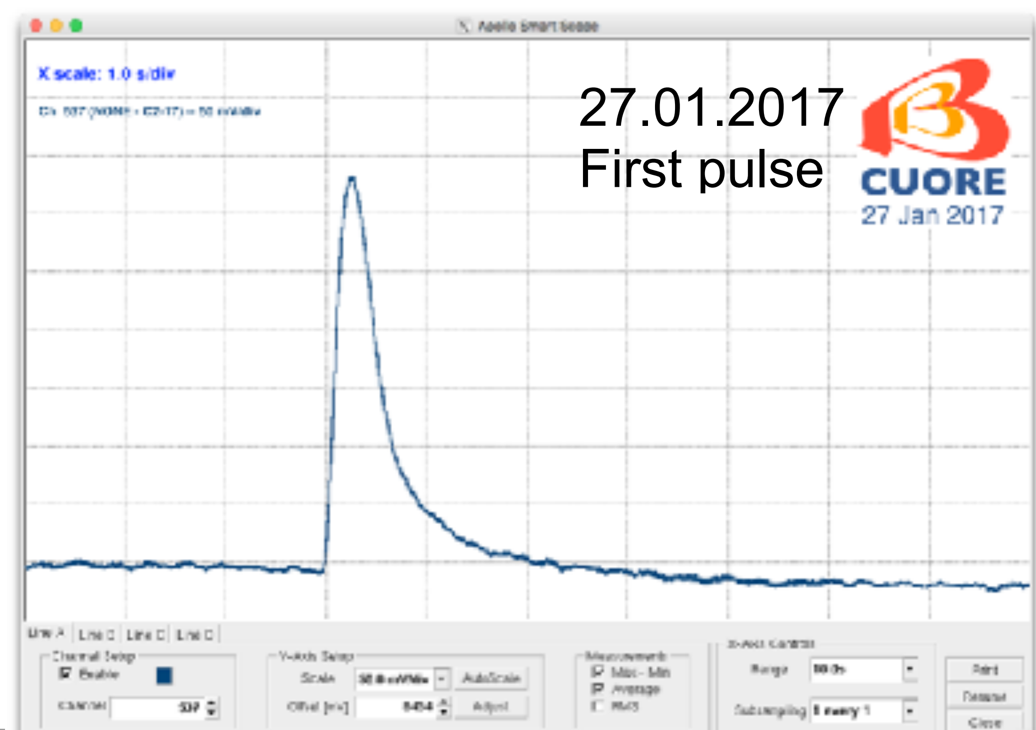
TeO_2 Bolometer: Source = Detector





Heat sink:
Cu structure (10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor (100 kΩ/μK)
Absorber:
TeO_2 crystal
(C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

main candidate isotope: ^{130}Te
Q-value: 2526.515 ± 0.013 keV
Isotopic abundance: 34%



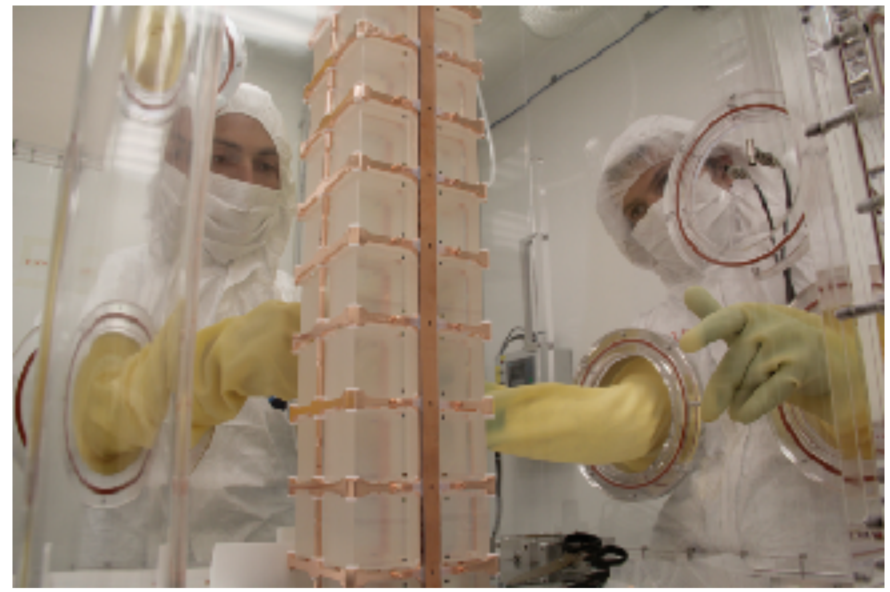
For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK
Signal size: 1 mV

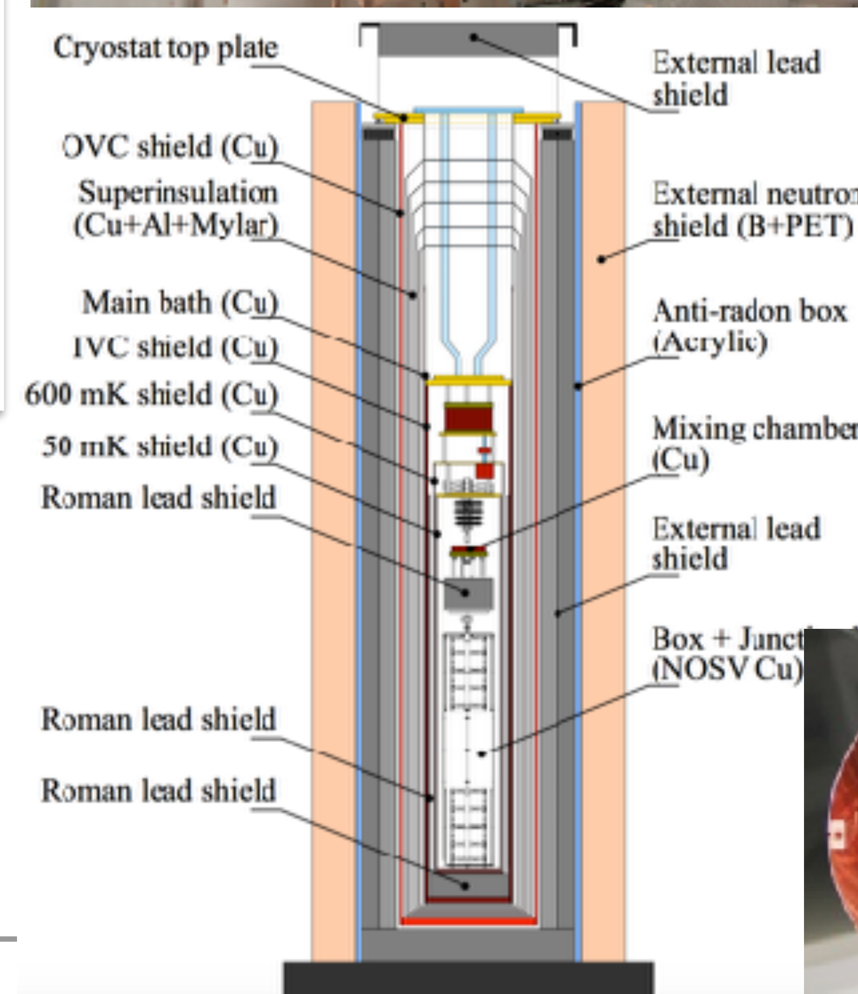
Time constant: $\tau = C/G = 0.5$ s
Energy resolution: ~ 5-10 keV at 2.5 MeV

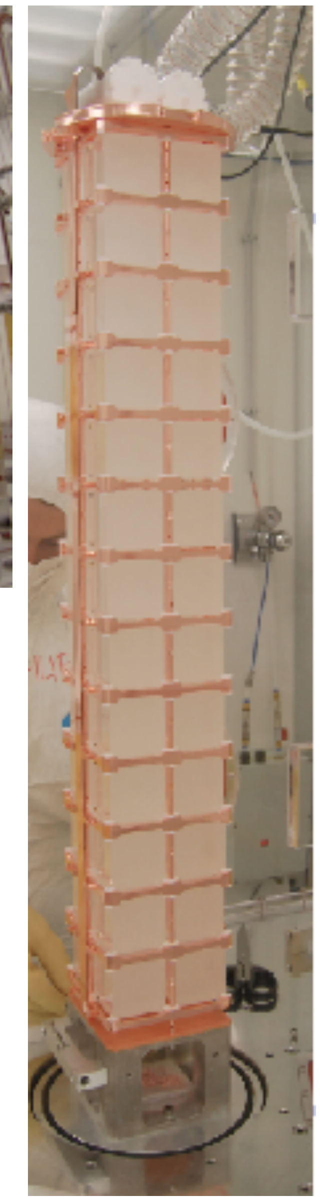
CUORE-0

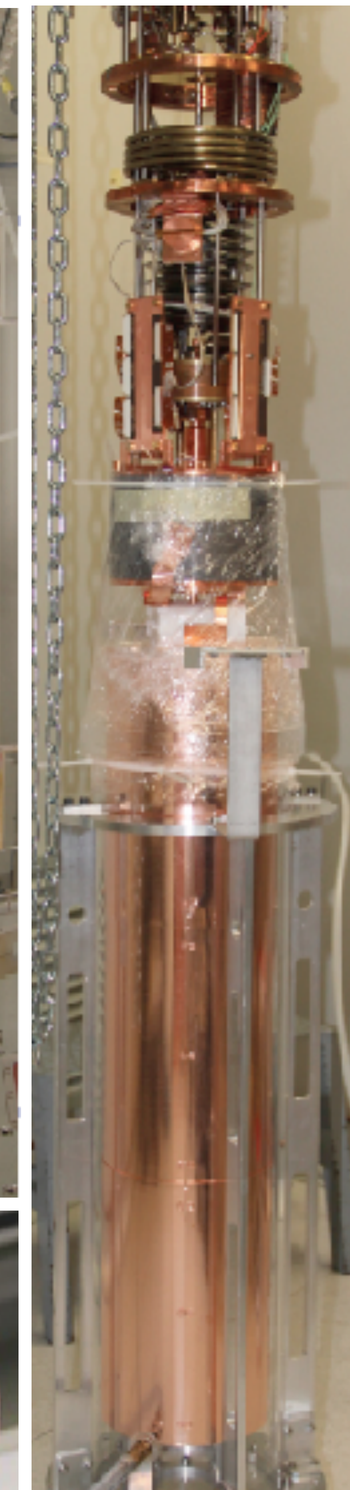
Test & verify projected background & assembly for CUORE

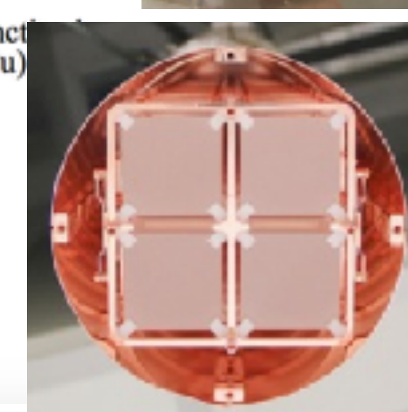
- Data taking: March 2013 to Aug 2015.
- 9.8 kg·yr ^{130}Te exposure
- 5 keV FWHM @ Q-value
- 52 crystals, total mass 39 kg
- 11 kg of ^{130}Te
- Shielding limited by Cuoricino cryostat.









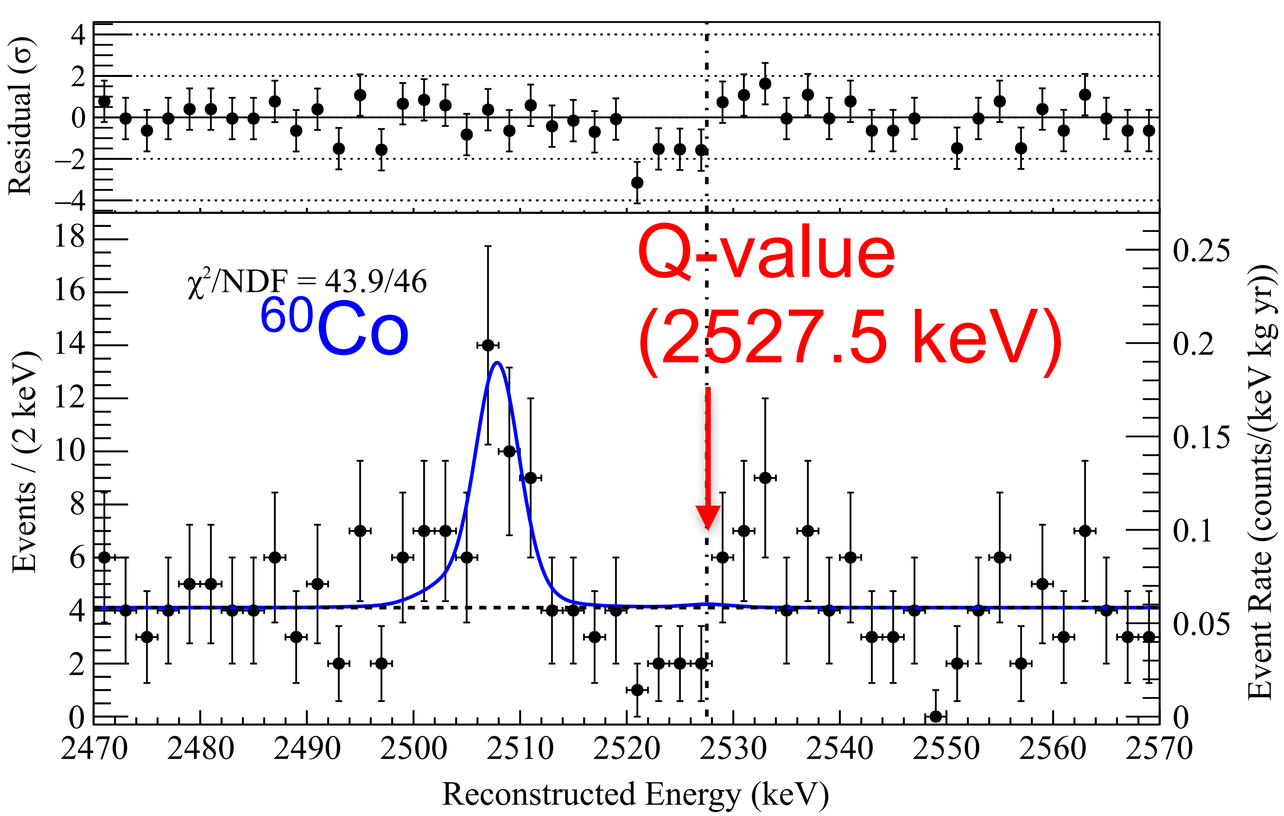


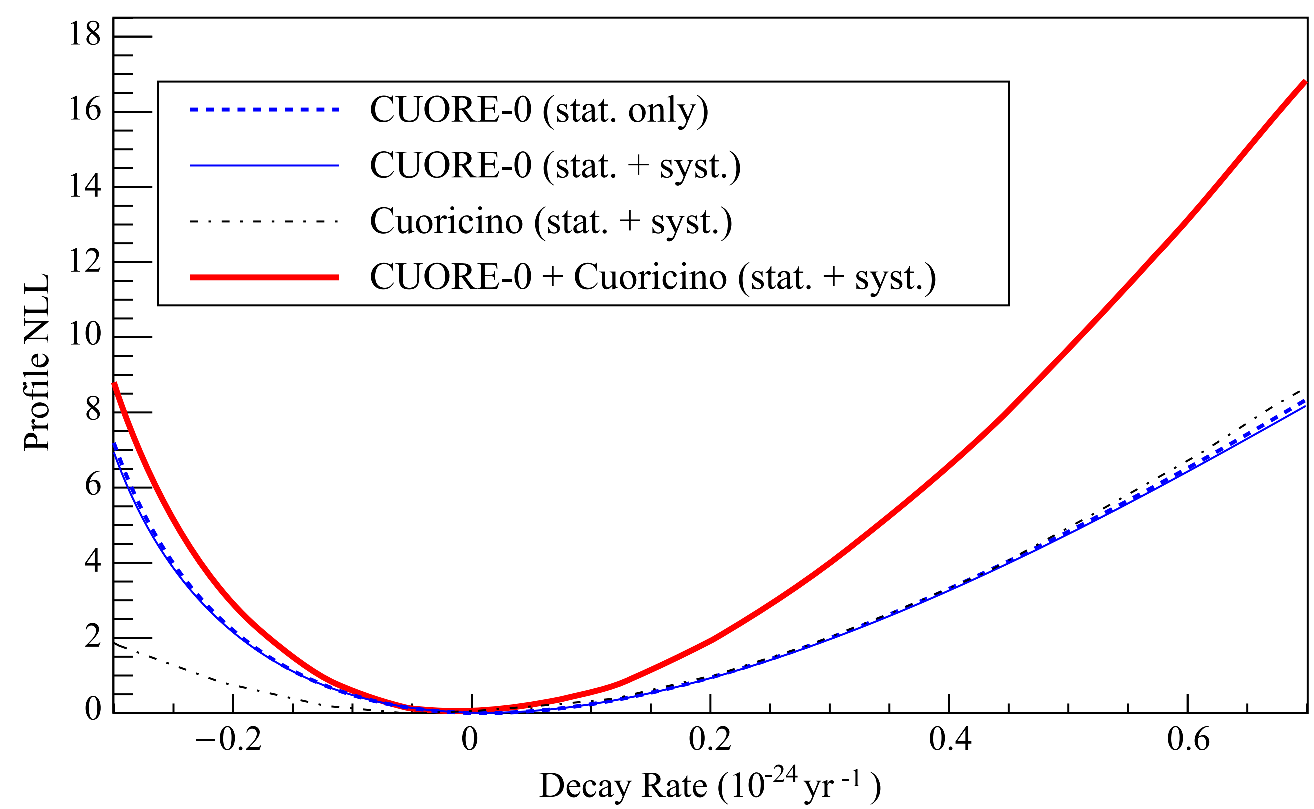
EPJC **74,** 2956 (2014)
PRL **115,** 102502 (2015)
PRC **93**, 045503 (2016)
EPJC **77,** 13 (2017)

CUORE-0: 0νββ decay results

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

- CUORE-0 regained the Cuoricino sensitivity in 40% of the lifetime
- Combined with Cuoricino: $\mathbf{T_{1/2}^{0\nu\beta\beta}}$ **(^{130}Te)> 4.0 × 10^{24} y (90% CL)**
- Effective Majorana mass: **$m_{\beta\beta}$ <(270-650) meV**
- CUORE analysis testbed





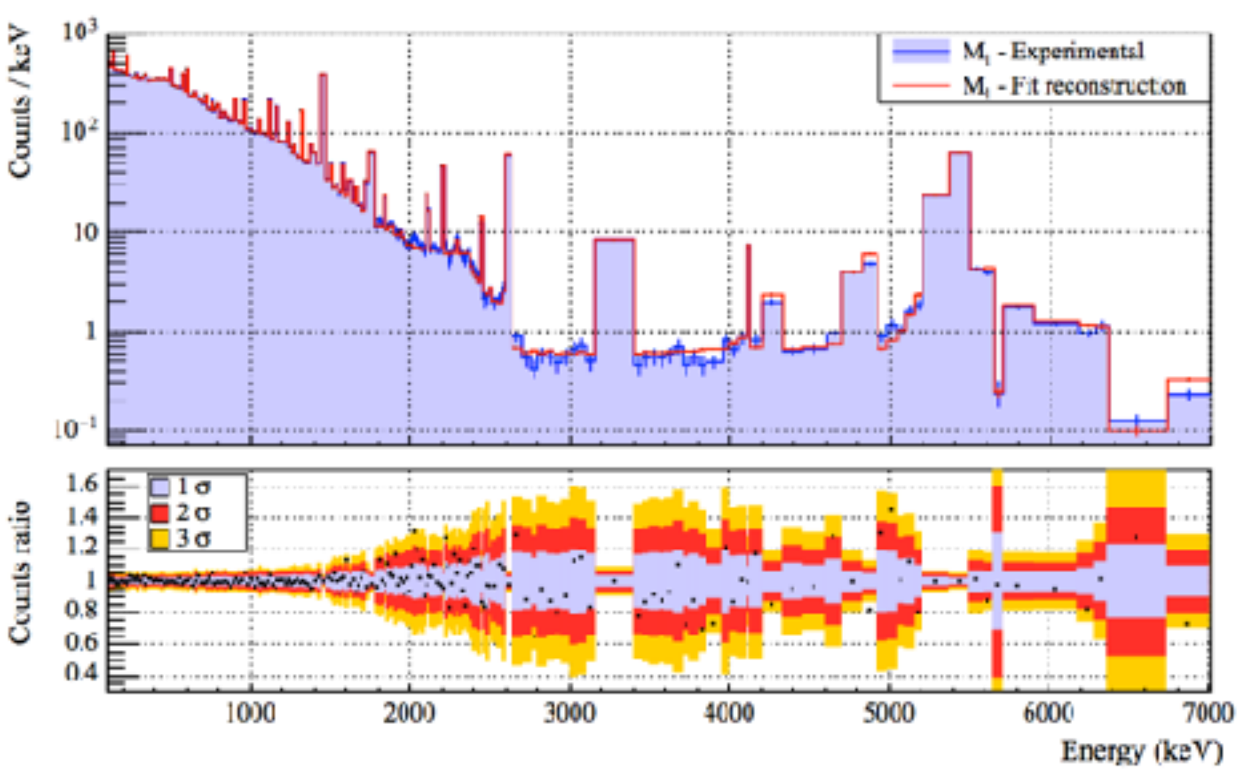
CUORE-0 backgrounds and 2νββ

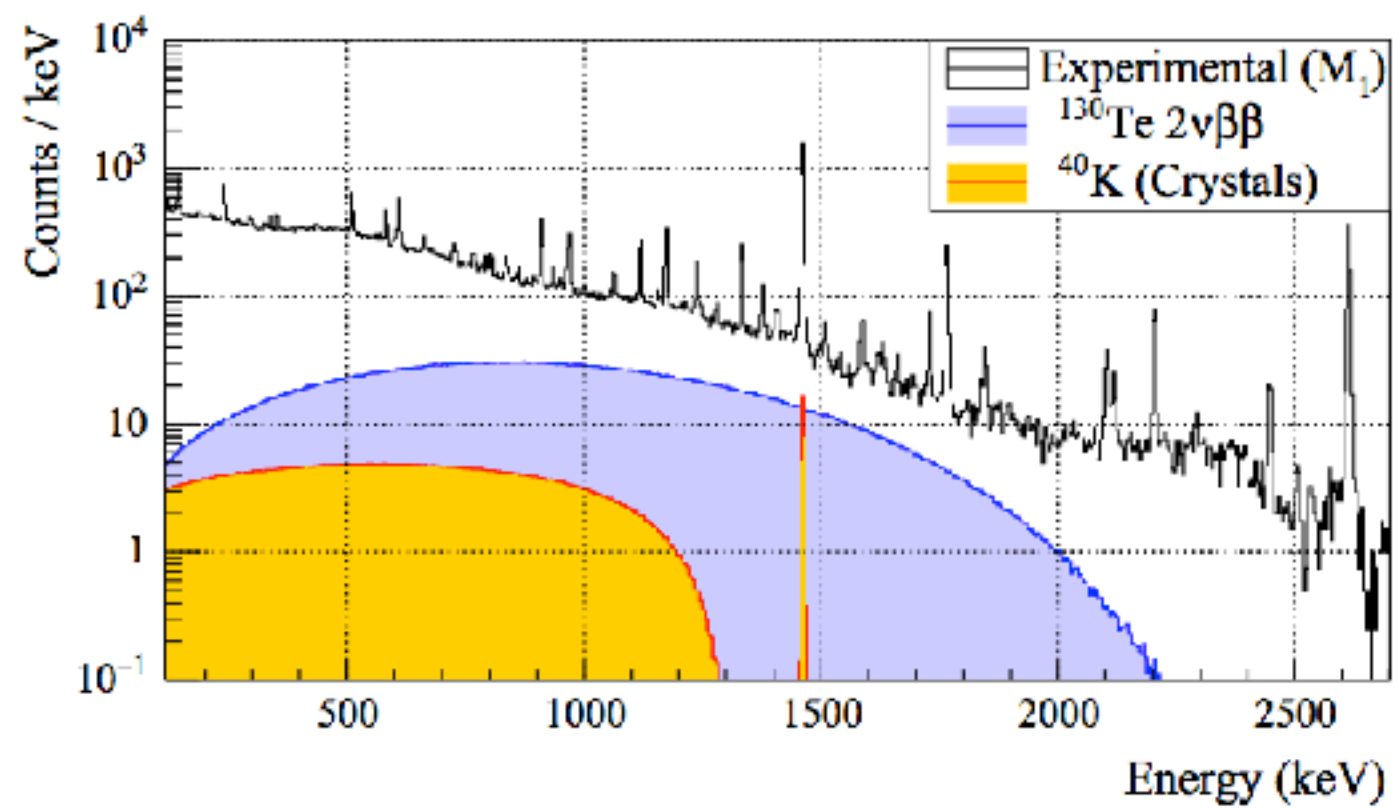
Eur. Phys. J. C **77,** 13 (2017)

MC-background model

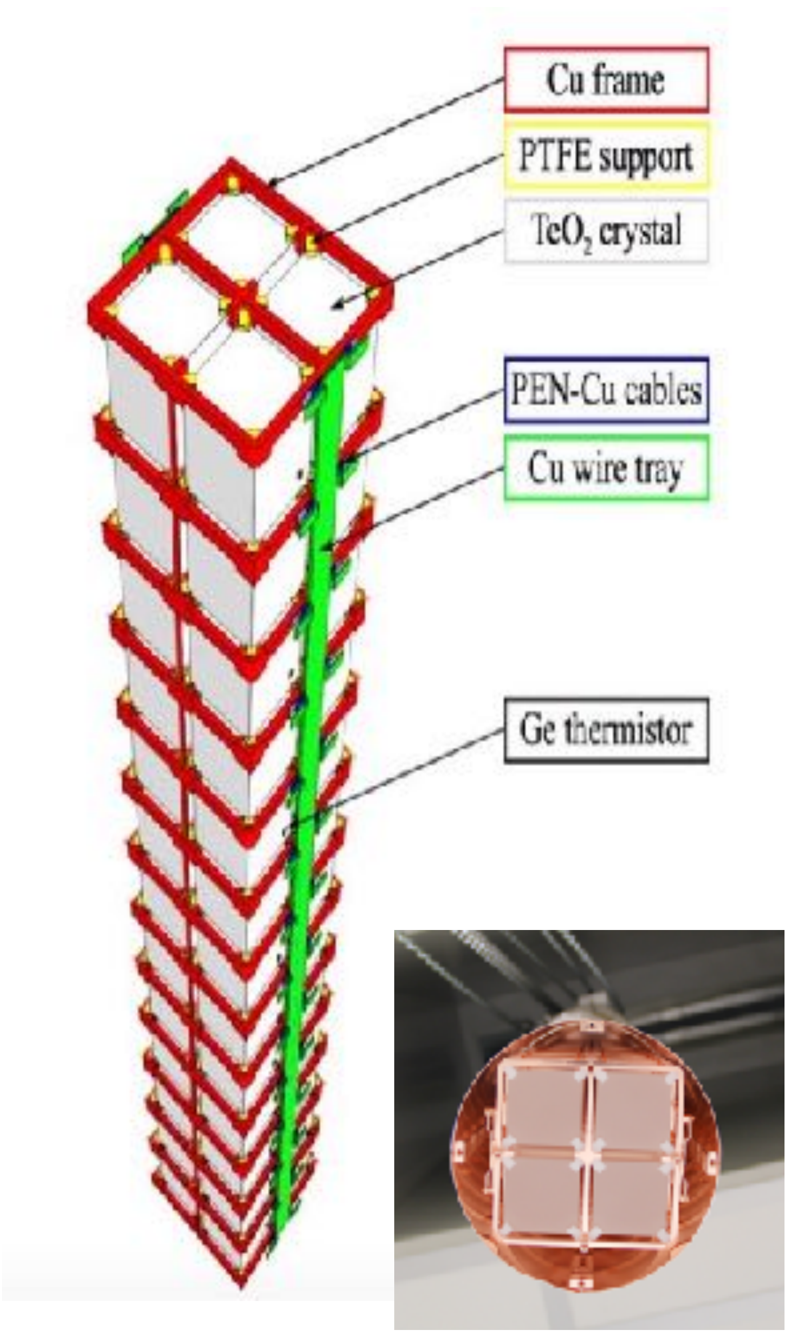
- surface & bulk contaminations included
- environmental γ's, μ's and n's
- Bayesian fit to CUORE-0 data with priors from material screening w/ ICPMS, HPGe, neutron activation analysis

$$T_{1/2}^{2\nu\beta\beta} = [8.2 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})] \cdot 10^{20}\text{y}$$

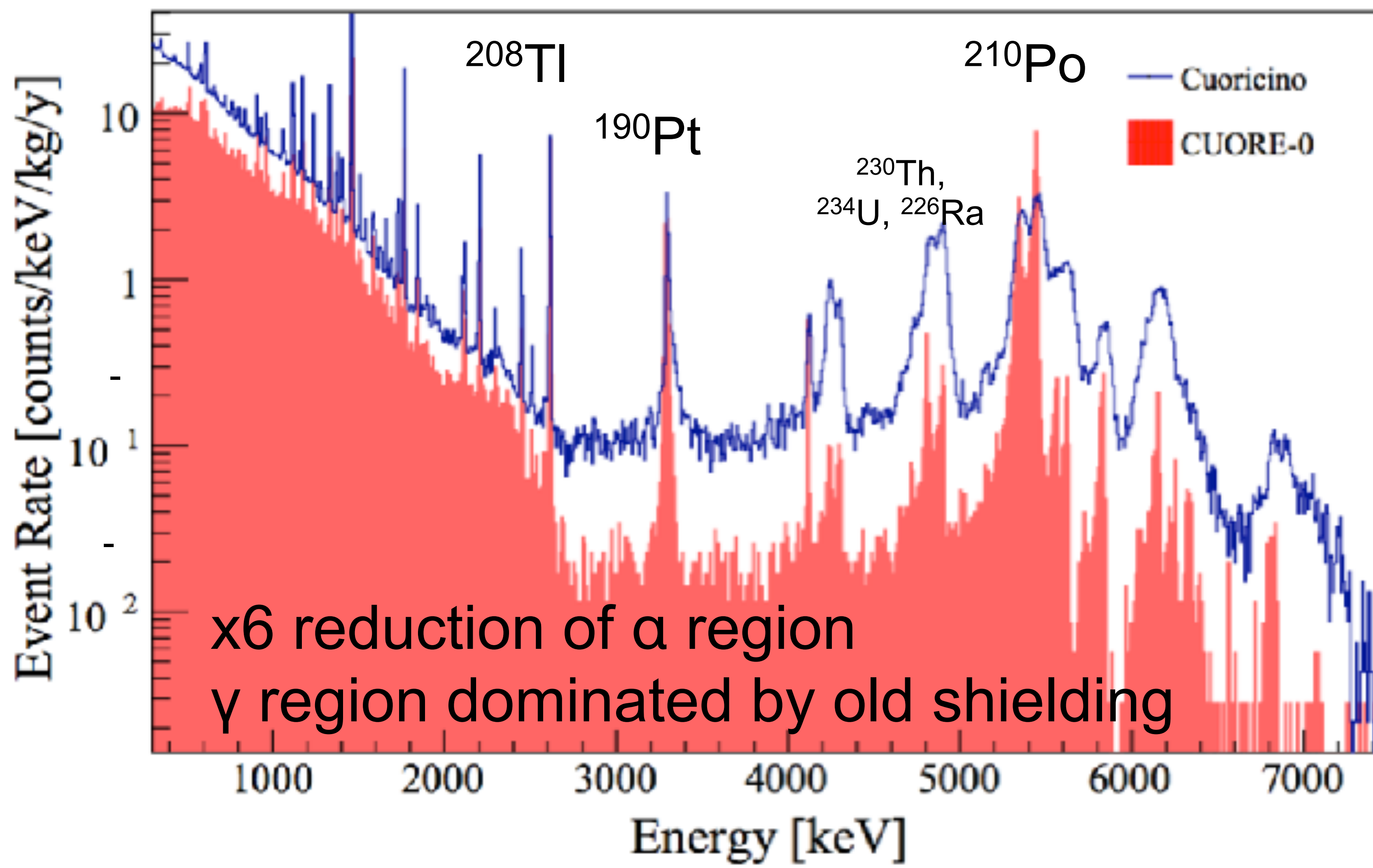




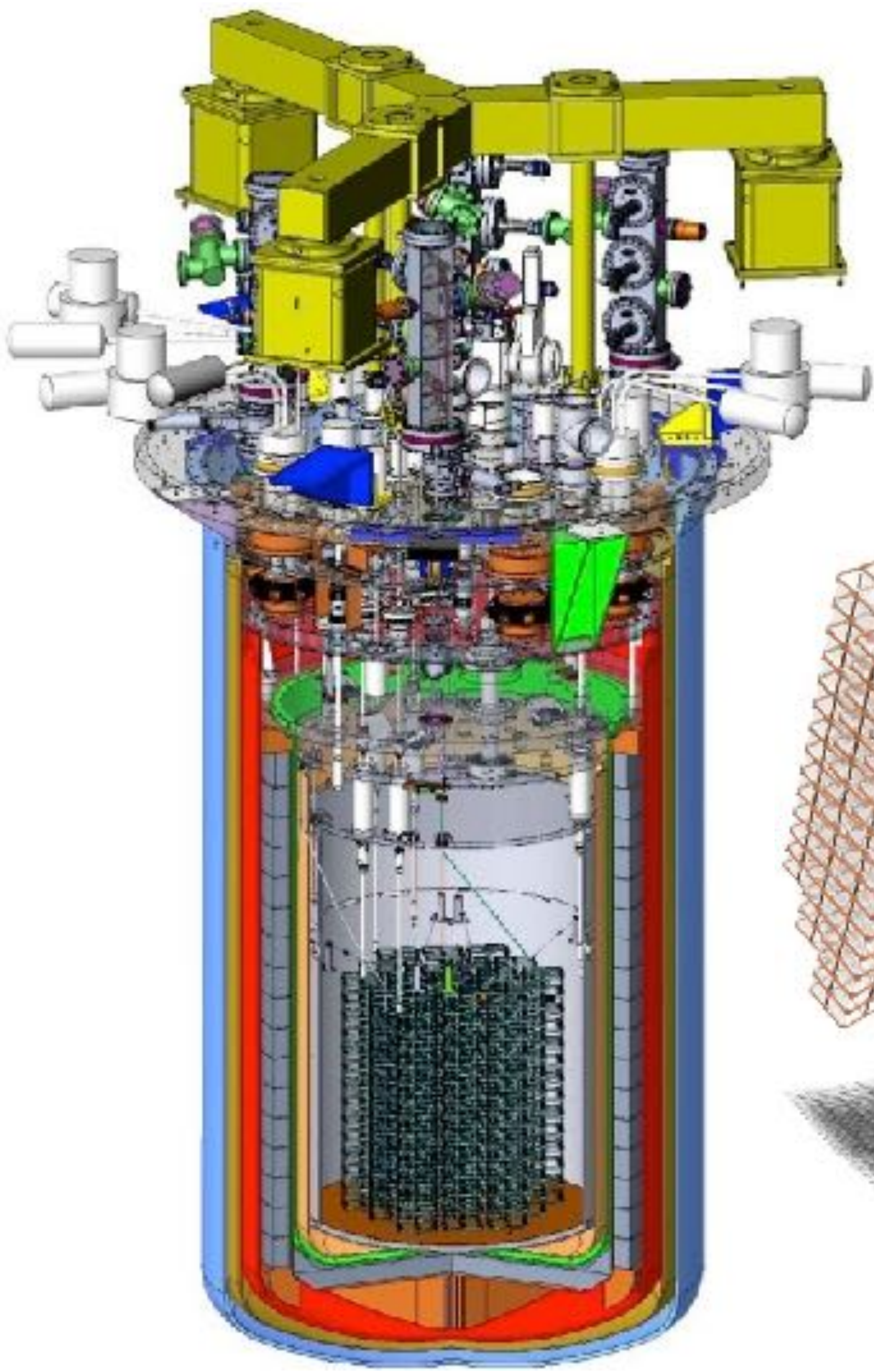
CUORE-0 backgrounds



Surface cleaning procedures results in background reduction in [2.7,3.9] MeV:
0.016 ± 0.001 c/keV/kg/y (CUORE-0)
0.110 ± 0.001 c/keV/kg/y (CUORICINO)

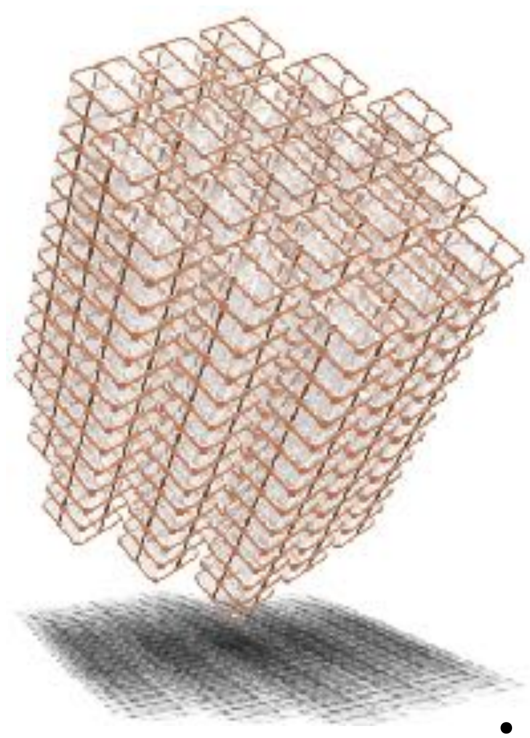


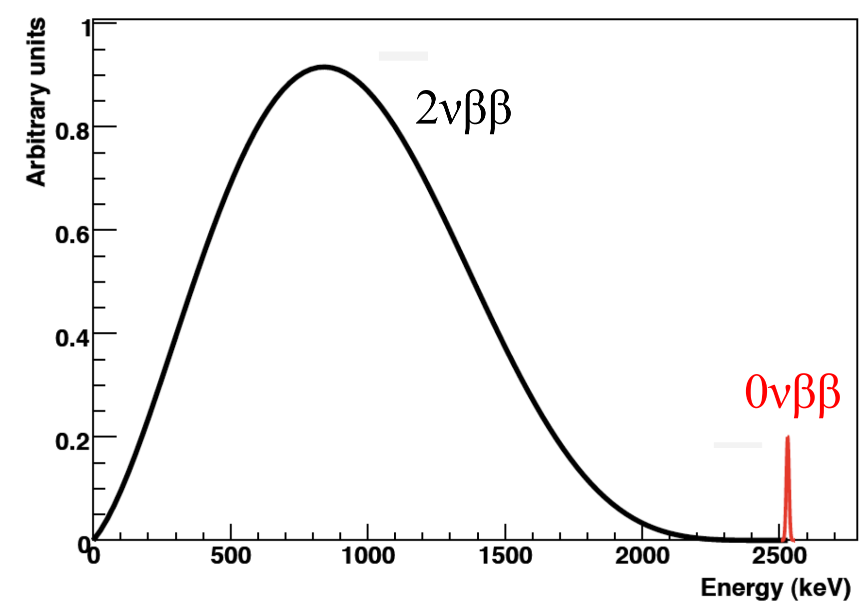
CUORE



Cryogenic Underground Observatory for Rare Events

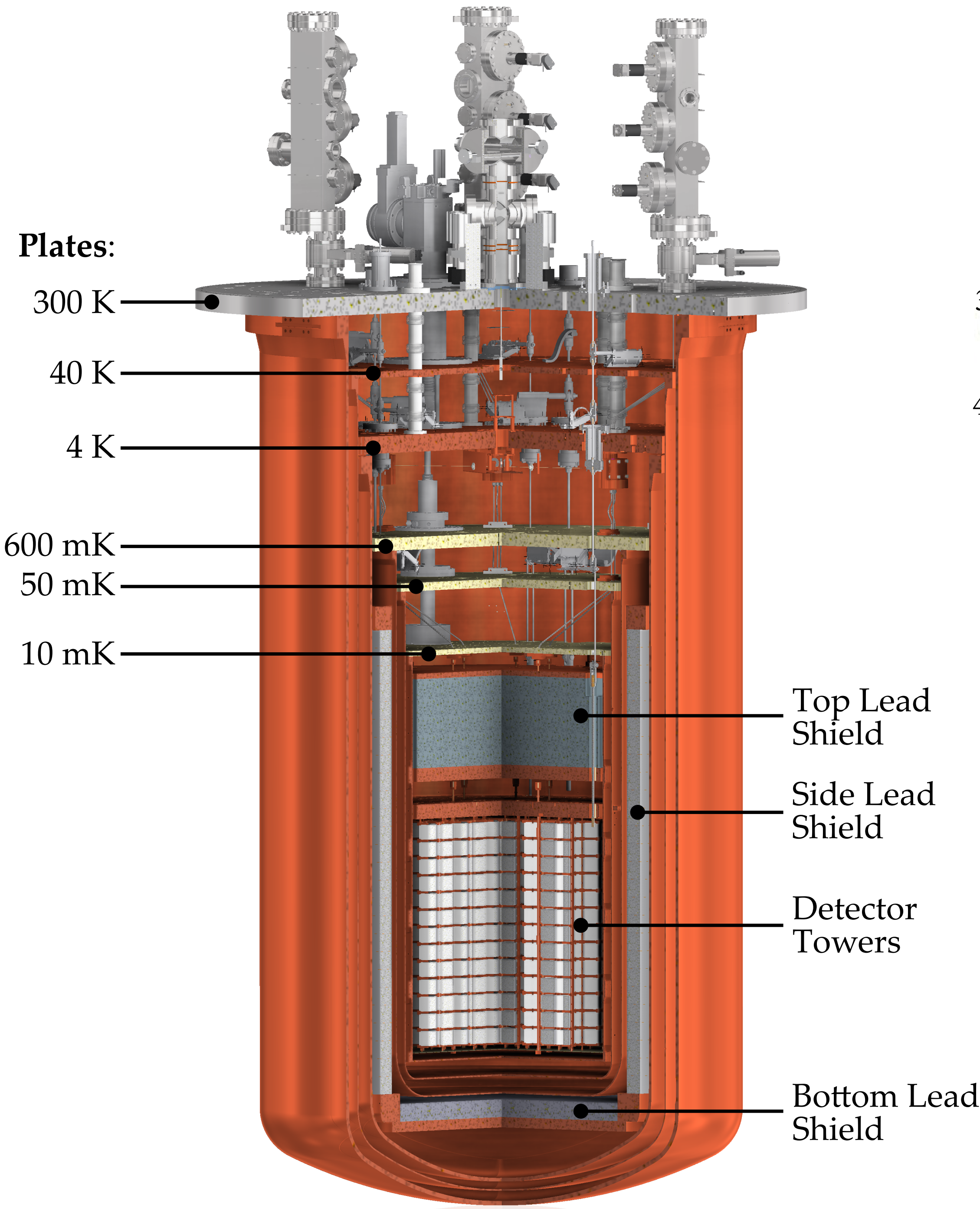
- 988 TeO_2 crystals run as a bolometer array
  - 5x5x5 cm^3 crystal, 750 g each
  - 19 Towers; 13 floors; 4 modules per floor
  - 742 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei

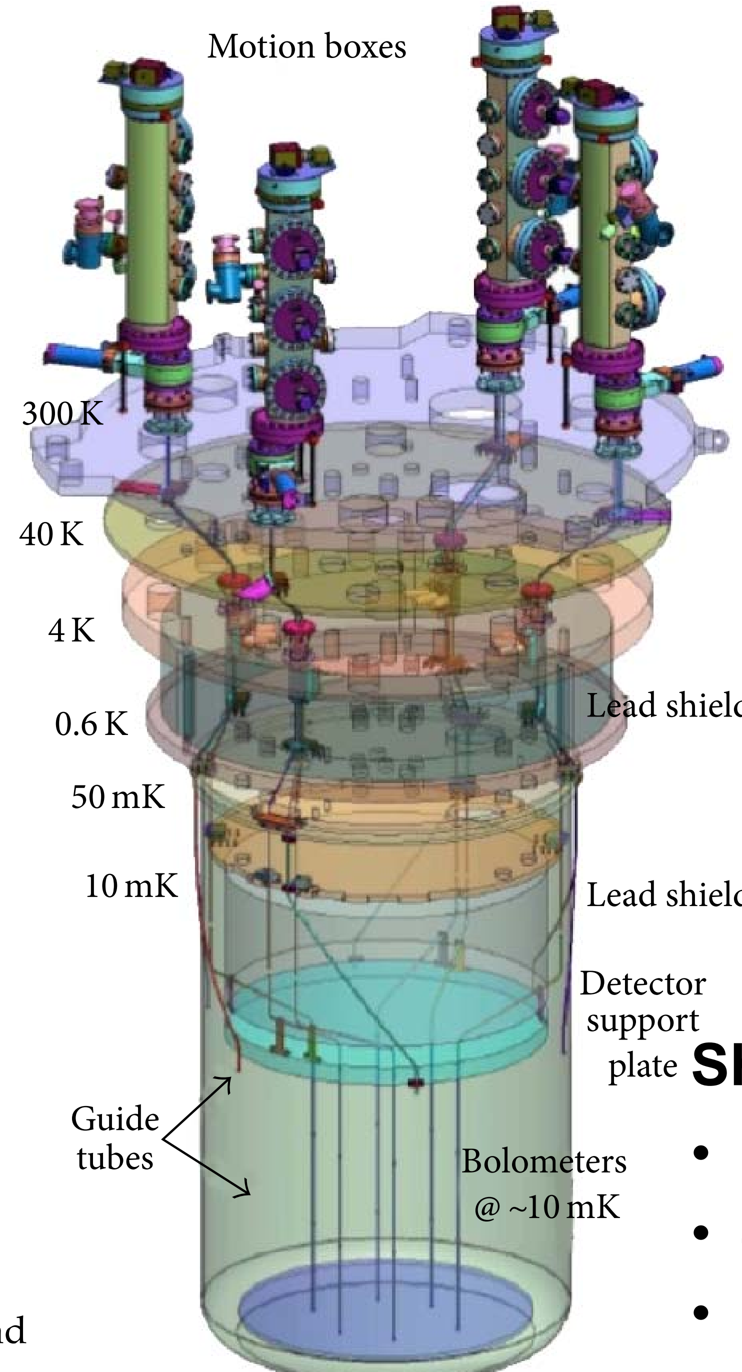




- New pulse tube dilution refrigerator and cryostat
- Radio-pure material and clean assembly to achieve low background in region of interest (ROI)

CUORE Cryostat

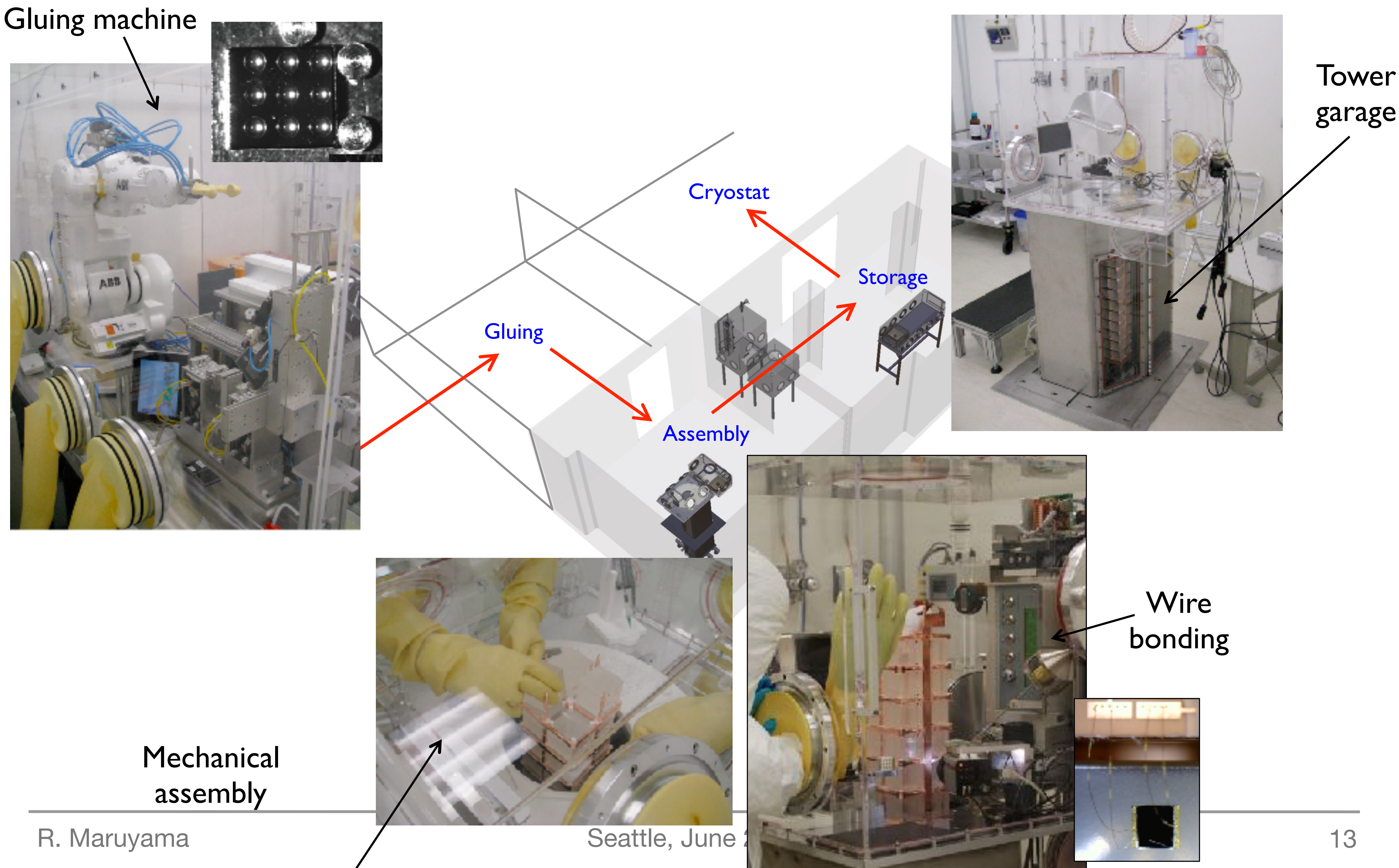




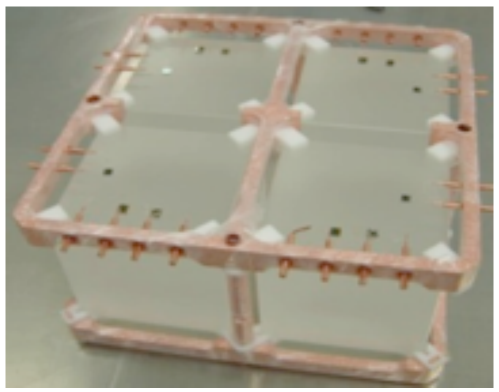
Shielding

- 2.1t modern lead @ 50 mK
- 4.6 t roman lead @ 4 K
- 35 cm external lead
- 18 cm PET + 2 cm H_3BO_3

CUORE Detector Assembly



Lowering Background: Crystals & Copper



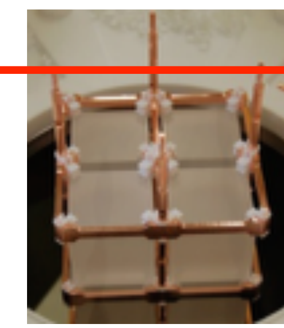
Ultra-pure TeO2 crystal array

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)

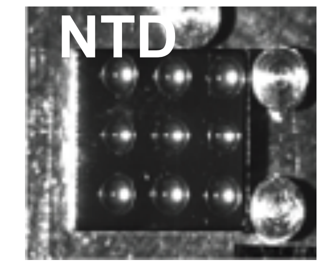


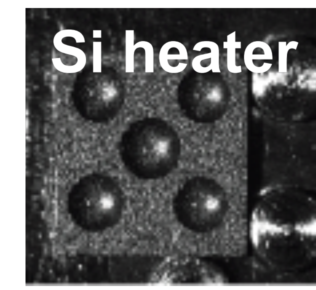
- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals
- Developed ultra-cleaning process for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching

T1 T2 T3

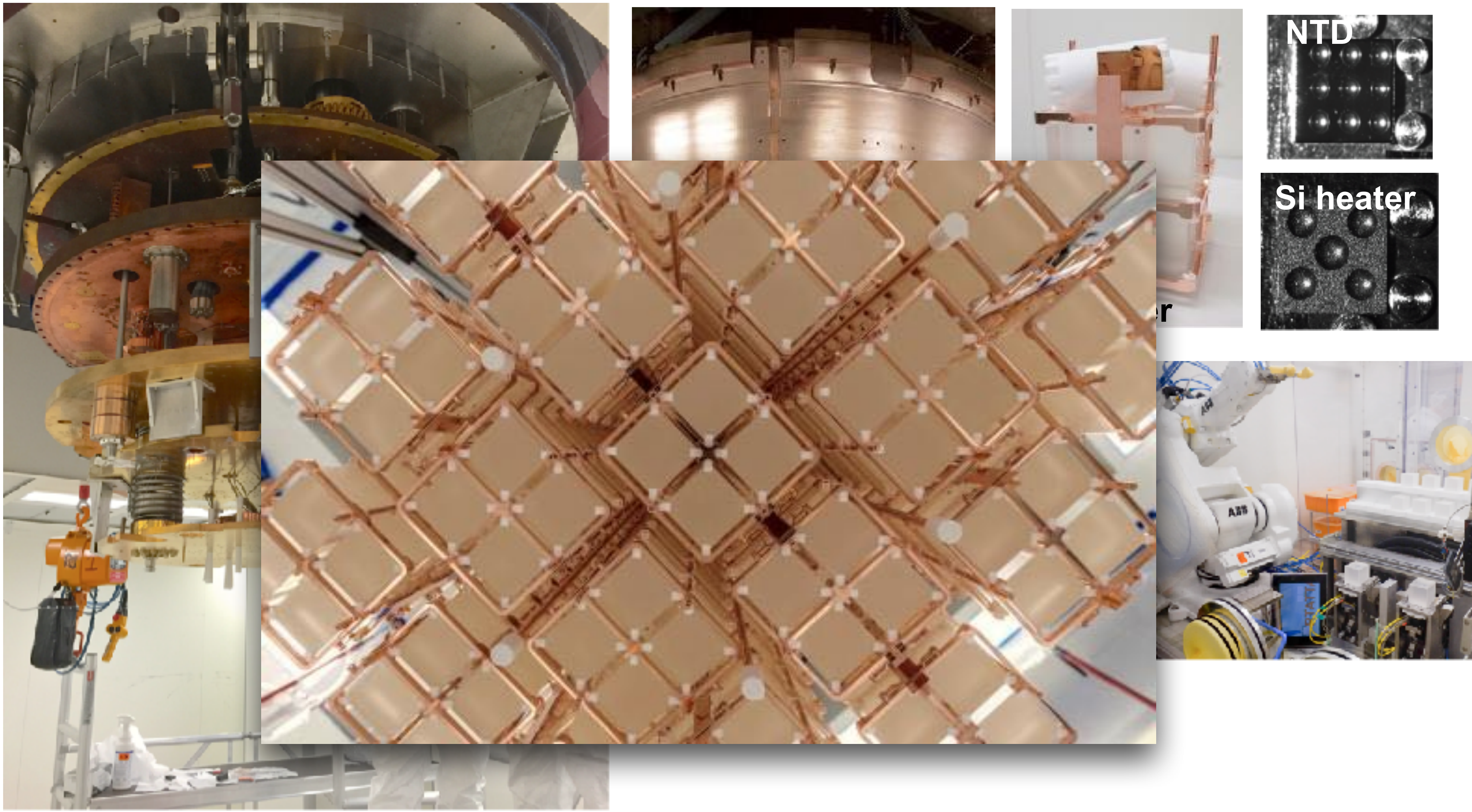
- Benchmarked in dedicated bolometer run at LNGS
  - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2
- Validated by CUORE-0
- All parts stored underground, under nitrogen after cleaning

CUORE fabrication & cryostat commissioning



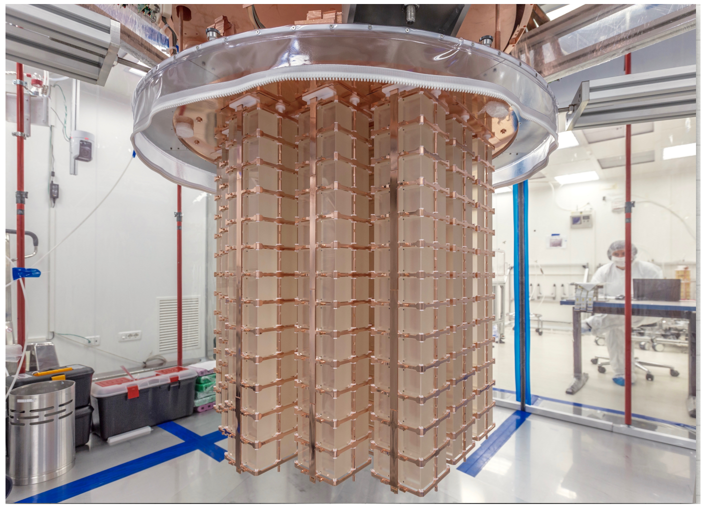


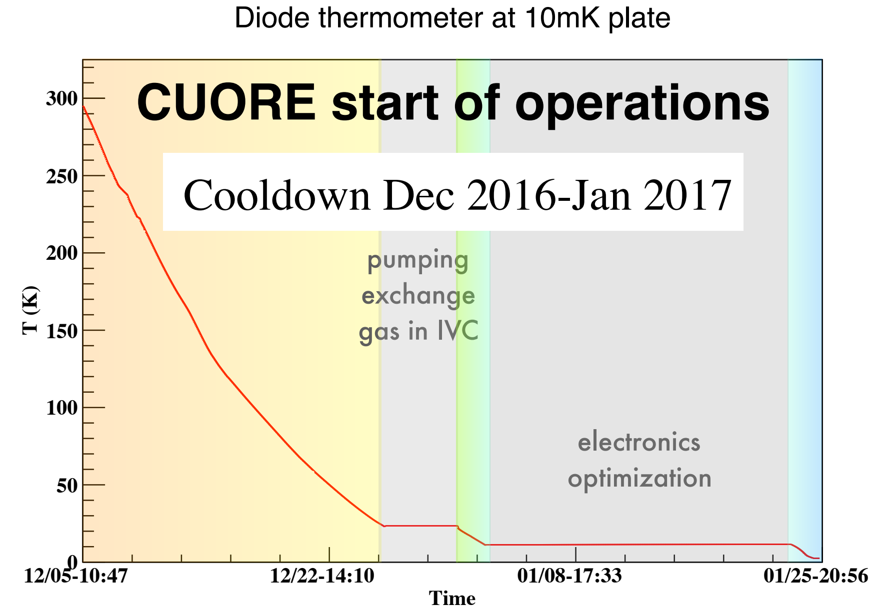
CUORE fabrication & cryostat commissioning

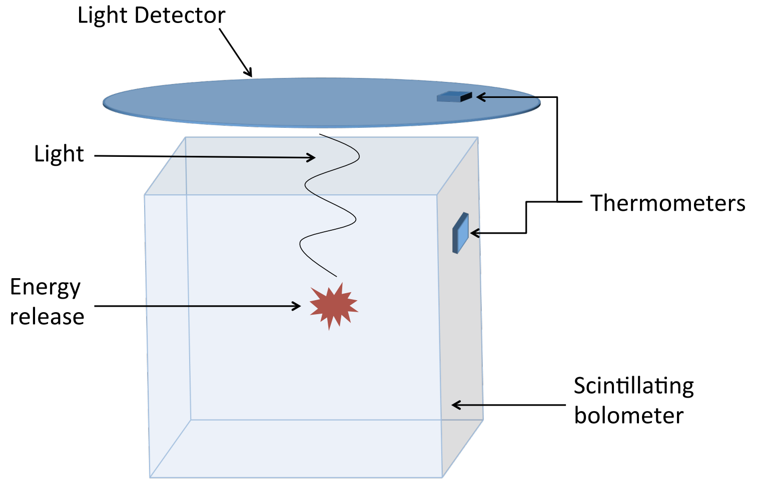


^{130}Te CUORE/CUPID

CUORE detectors installed







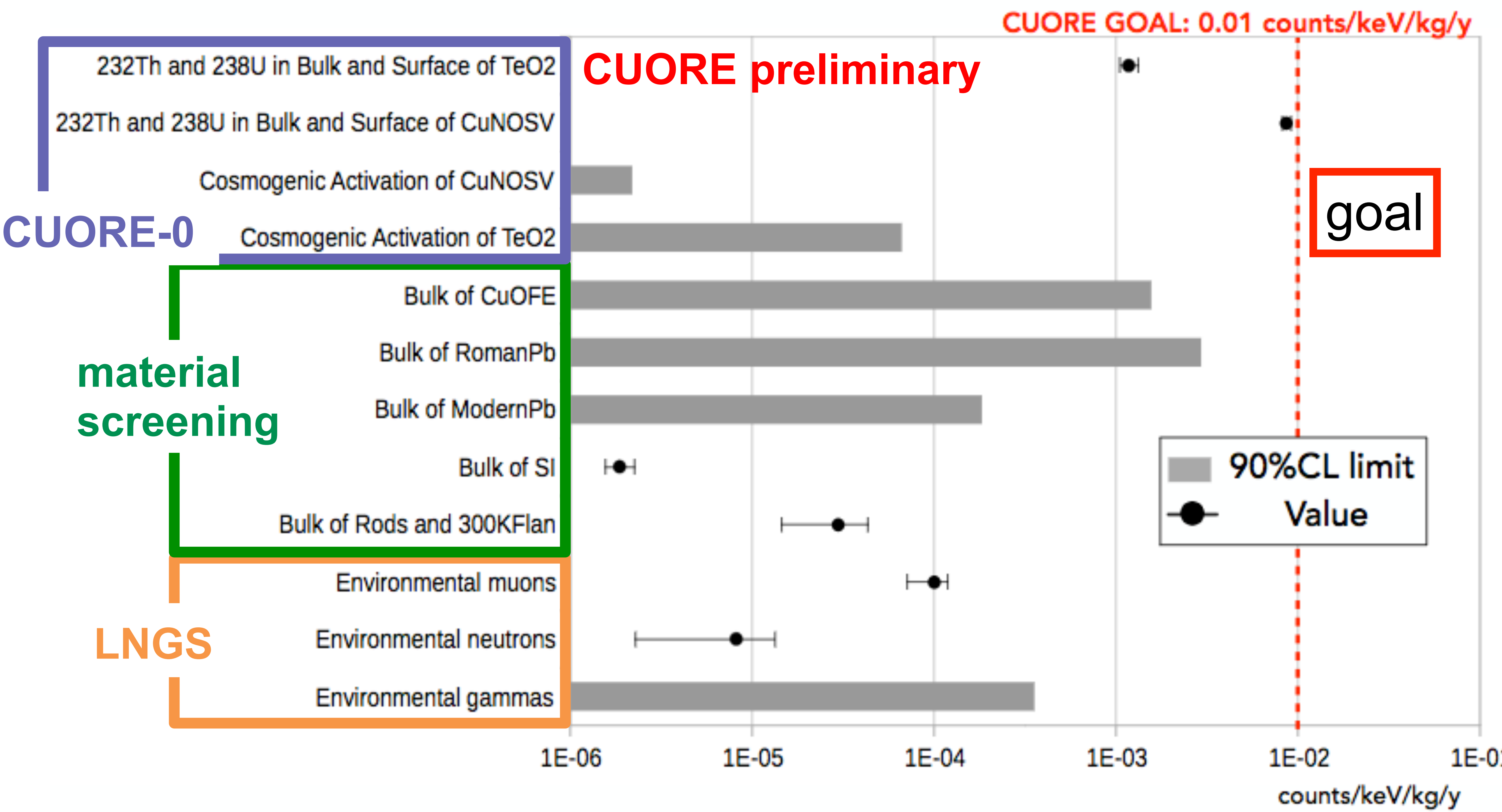
Next-generation bolometric tonne-scale experiment based on the CUORE design, proven CUORE cryogenics

- CUORE Milestones:
  - Tower installation: Jul-Aug 2016
  - Cryostat closeout: Nov 2016
  - Cooldown: Dec-Jan 2016
  - Commissioning and initial performance optimization: Jan-May 2017
  - First science run: May 2017
- Cryostat performs very well: base T < 7 mK
- >95% of detectors operational
- First data to be reported in Summer 2017

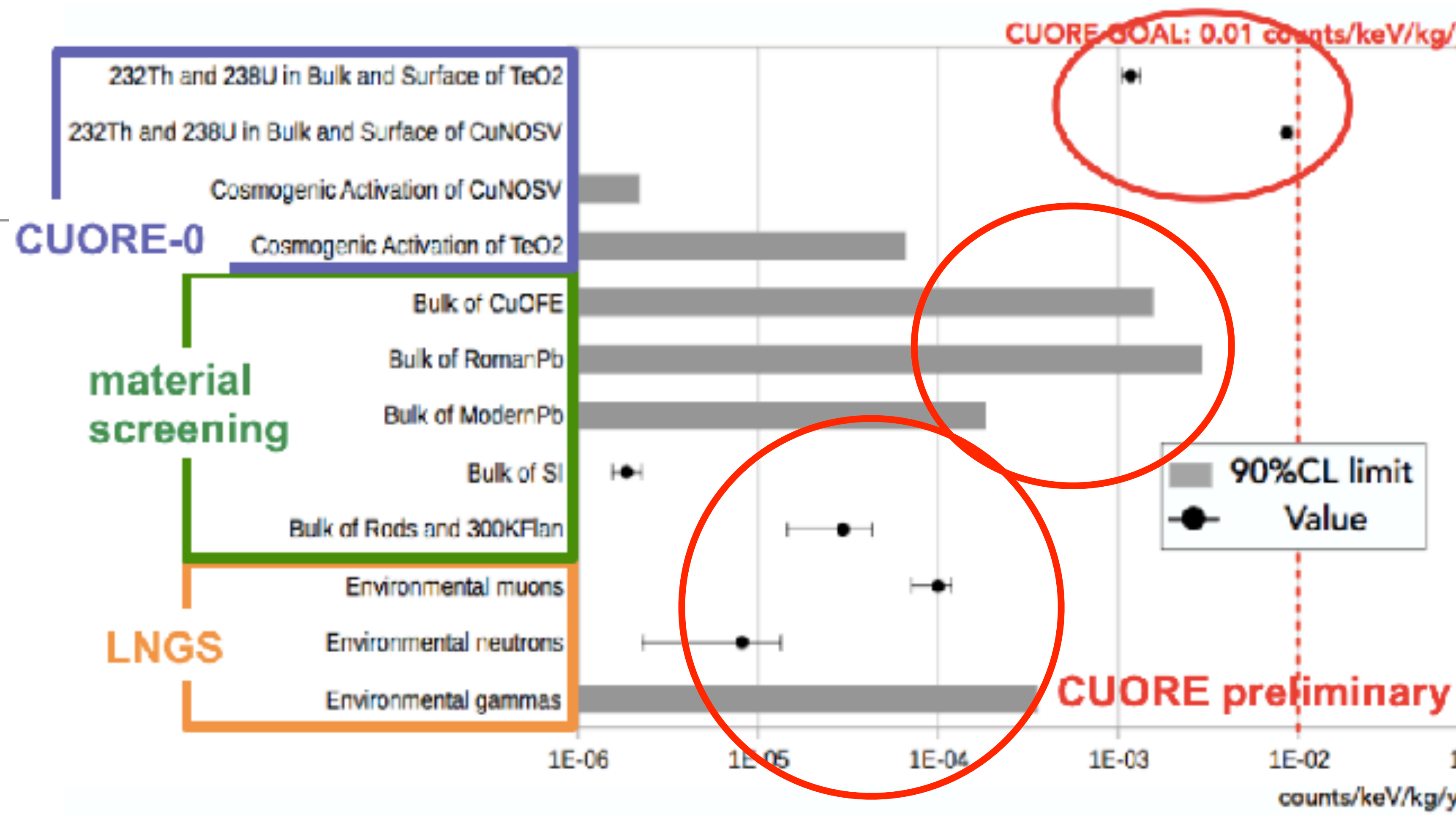
- Intense CUPID R&D effort in the next 2-3 years
  - ☞ US focus: $^{130}TeO_2$ enrichment and purification, high-resolution sensors for Cherenkov light
  - ☞ Complementary European efforts
  - ☞ Background goal is 0.1 cts/ROI-t-yr; achieve sensitivity to the full Inverted Hierarchy
  - ☞ Other important R&D: detailed background analysis, cosmogenic backgrounds @ LNGS — to be addressed before downselect
  - ☞ Worldwide efforts: 8 countries, 32 institutions
  - ☞ Data from CUORE and pilot detectors will drive technology and isotope choice

CUORE background budget

arXiv:1704.08970

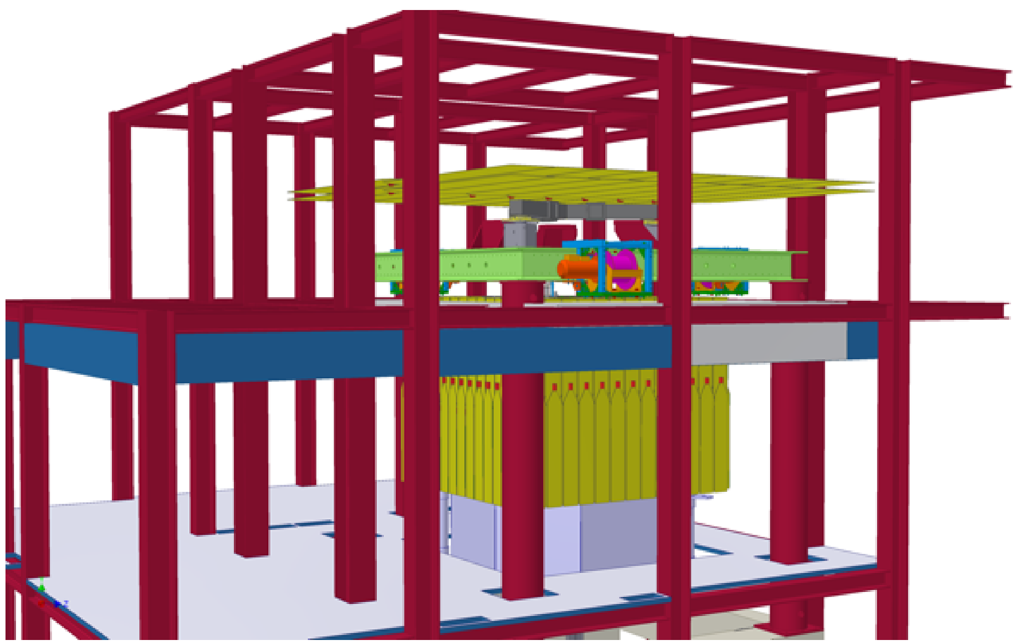


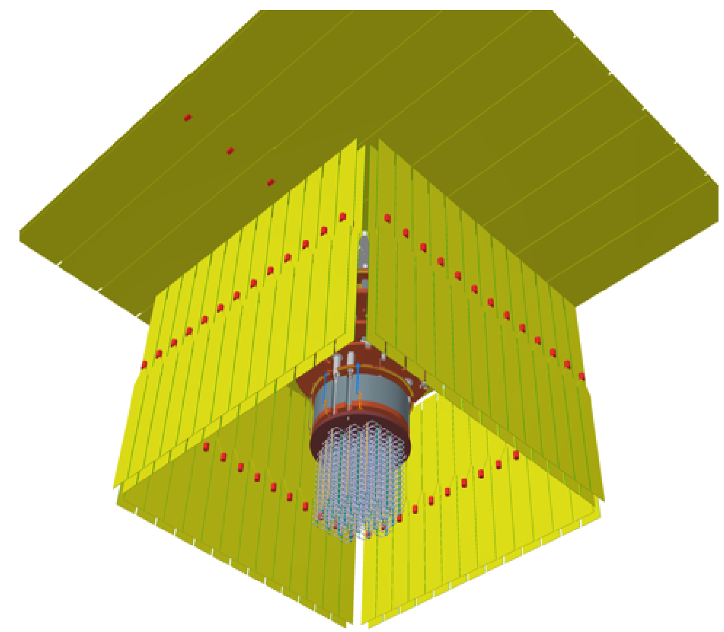
Towards CUPID

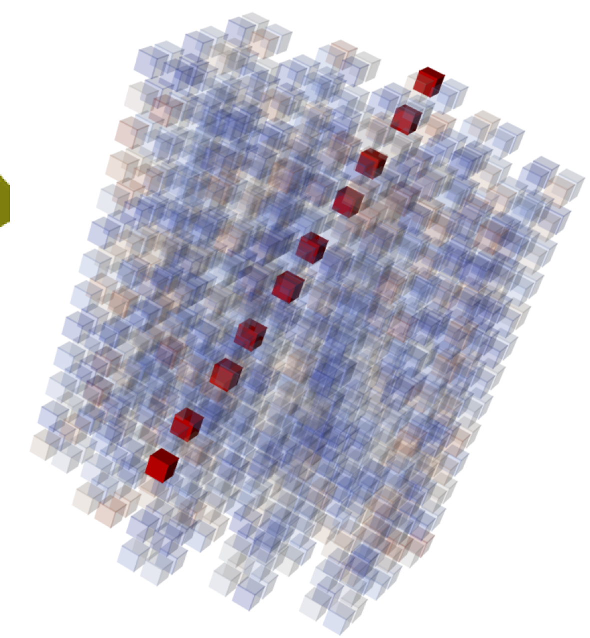


- α/β discrimination
- surface/bulk discrimination
- Reduction of surface/bulk contamination
- reduce γ
- cosmogenic backgrounds
- Isotopic enrichment
- Crystal production

Environmental Backgrounds







CUORE will improve **γ rate estimates**: limited by available data and MC statistics
μ rate may need to be reduced (by ~*10): μ veto at LNGS or deeper site

Cosmogenic activation of near detector elements (Te and Cu): minimize by storing both underground quickly. Most dominant backgrounds from

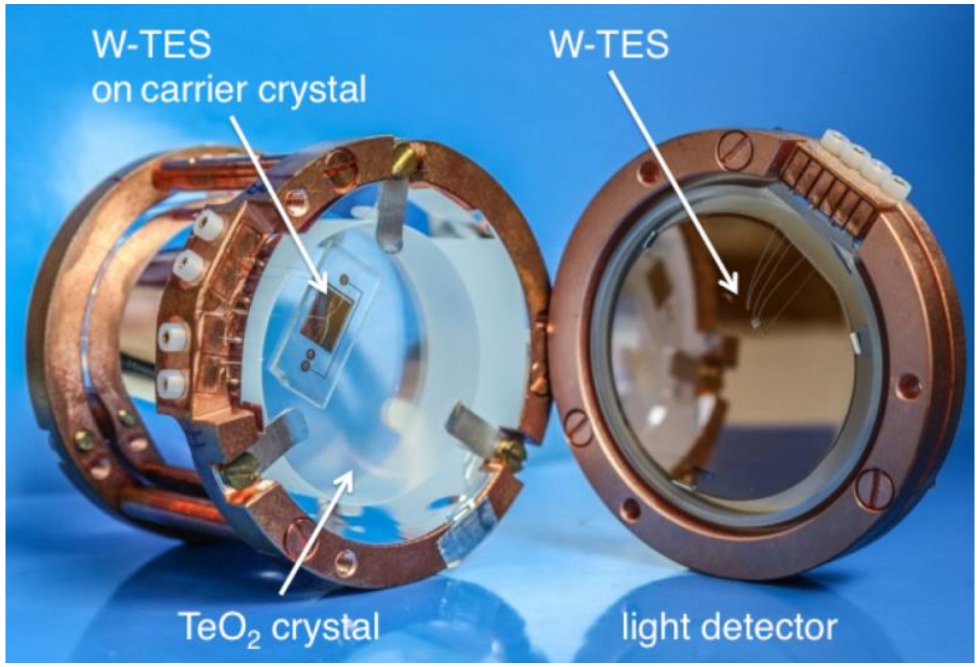
- ^{60}Co in Cu structures: <50 μBq/kg → <5×10^{-1} counts/(ton keV year) in ROI
- Other contributions negligible → will measure Cu activation in CUORE and reassess

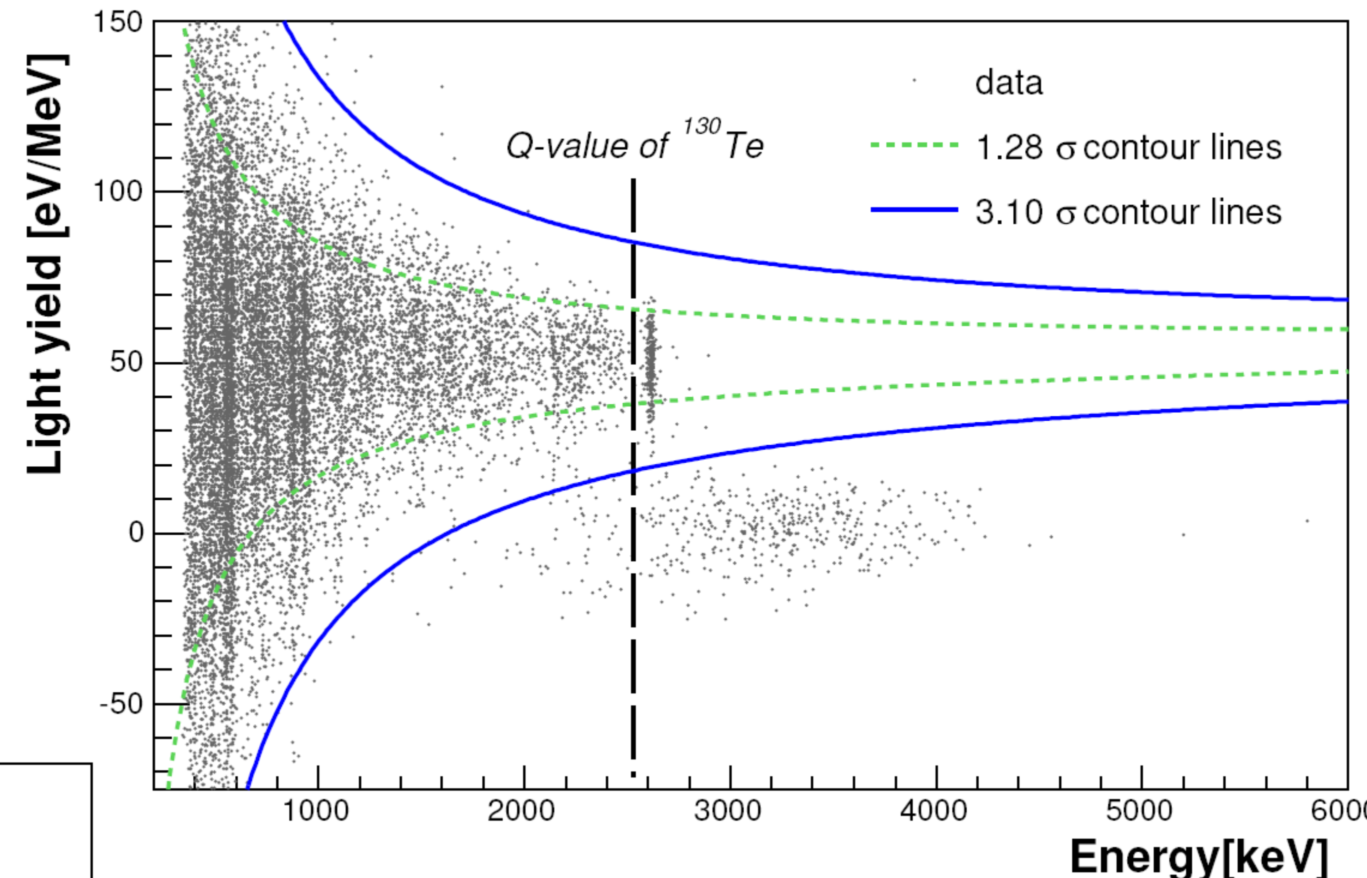
^{130}Te Isotopic Enrichment and Crystal Production

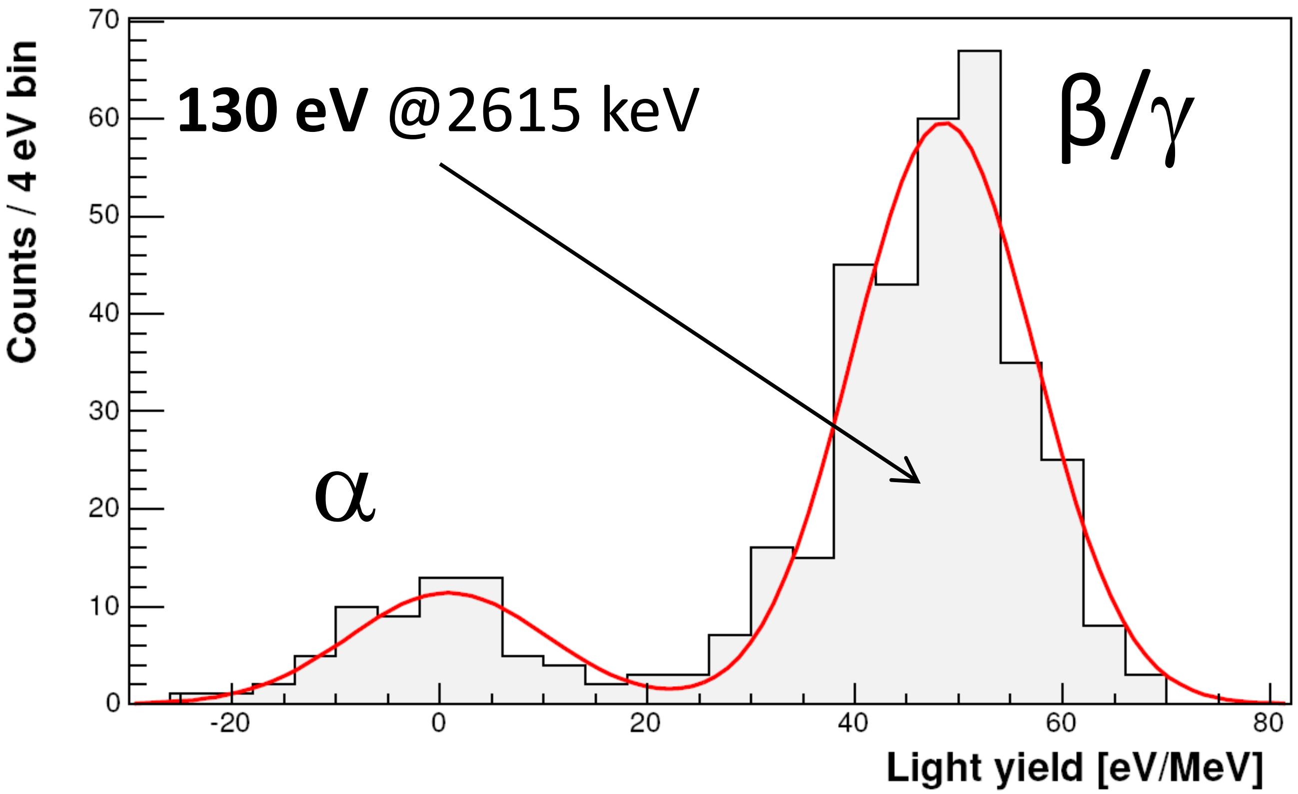
USC/Berkeley

- 10 kg of 92% enriched ^{130}Te procured
  - ☞ NSF grant to USC
- 2 crystals with 40% enrichment grown at SICCAS
  - ☞ Single-pass crystallization (to conserve enriched material)
  - ☞ Show relatively high level of impurities (residual from enrichment process)
  - ☞ High bulk activity, compromised bolometric performance
- Further development needed
  - ❑ Zone refining and/or chemical purification
    - ☞ Benefit from SNO+ process (BNL)
  - ❑ Optimization of crystal production

Cherenkov Detection in TeO_2 Y. Kolomensky







K. Schaeffner et al, Astrop. Phys. 69, 30 (2015)

Event-by-event α/β discrimination requires light detectors with ~15-20 eV resolution

TES-based light detectors: promising start

CRESST/LUCIFER: W-based detectors

US (Berkeley/Argonne): bilayer TES

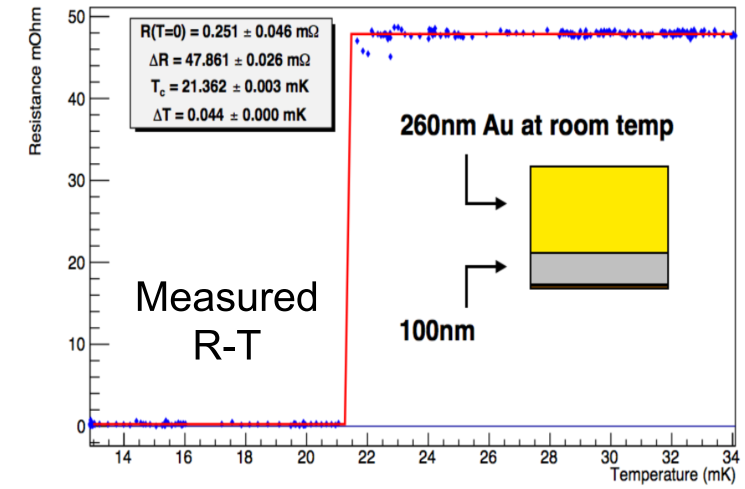
US (MIT/UCLA): anti-reflective coating

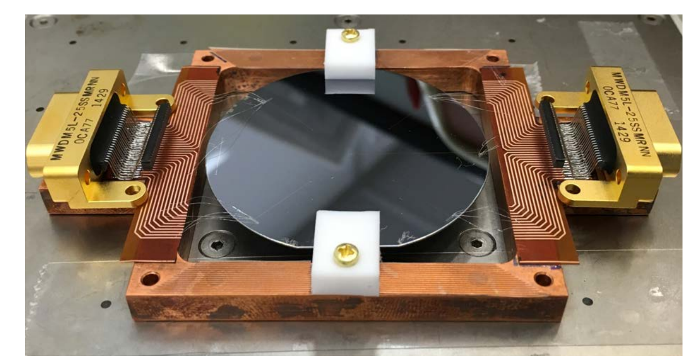
(a) C. Arnaboldi et al., **34**, 143 (2010)
(b) J. Beeman et al., Phys. Lett. B **710**, 318 (2012
(c) C. Arnaboldi et al., **34**, 344 (2011)
(d) N. Casali et al., Eur. Phys. J. C**75**, 12 (2015)

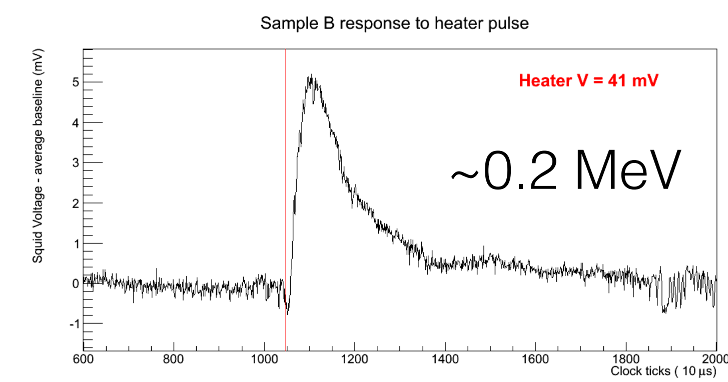
TeO_2+Light R&D in the US

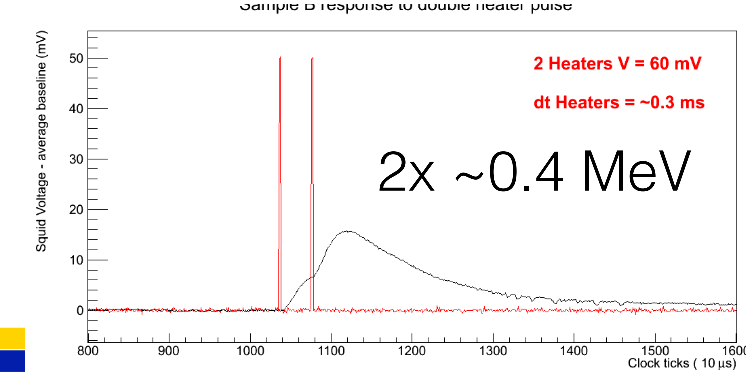
- TES sensor operates at transition temperature T_c
  - Should be near base T~10 mK
  - Europe: W-TES, lowest T_c=15 mK
    - ☞ Difficult to produce reliably
- US: TES based on superconducting bilayer films
  - Argonne, UCB/LBNL, MIT/UCLA
  - Already candidates with T_c~20 mK
  - Milestones:
    - ☞ 2016: prototype LD; demonstrate α/β discrimination in small crystal (surface)
    - ☞ 2017: α/β discrimination in CUORE-sized crystals (underground)
    - ☞ 2018: single-tower TeO_2 demonstrator with dual readout

Berkeley/ANL







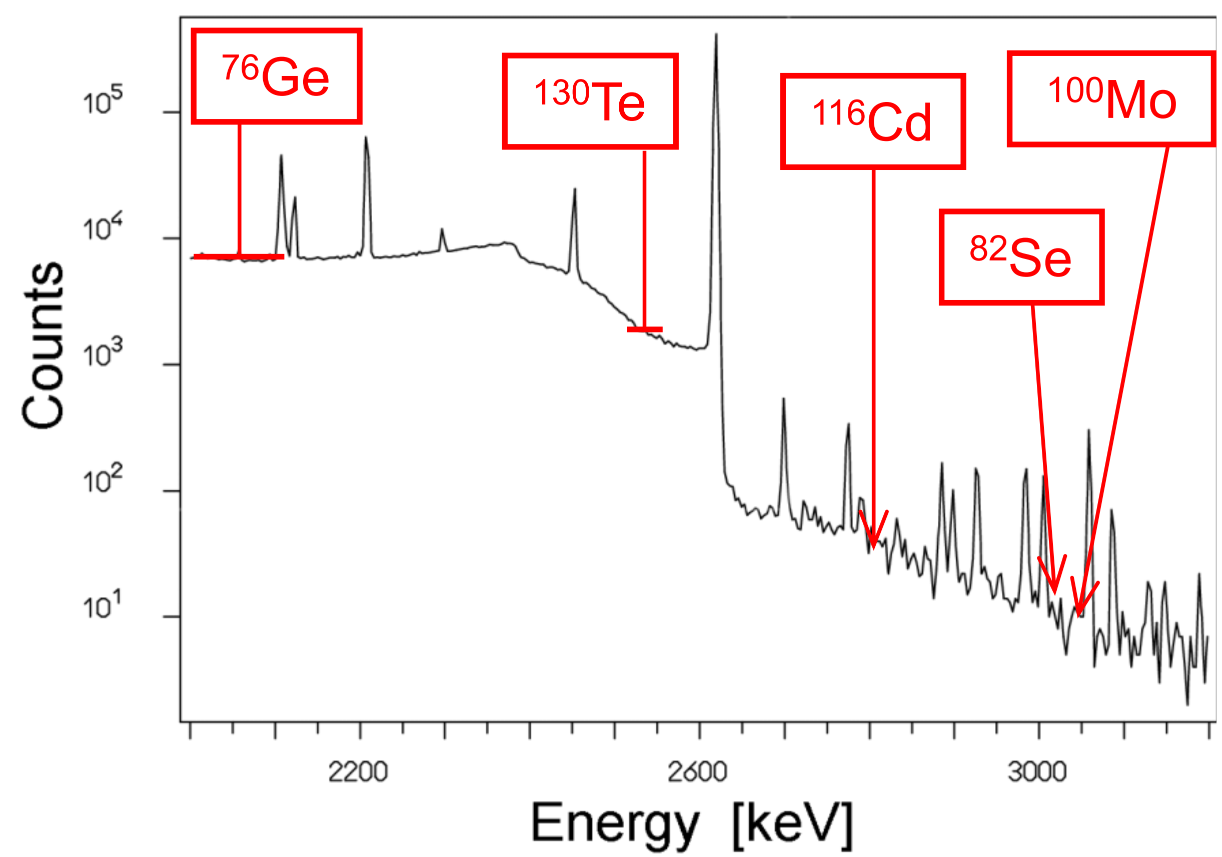


Multi-Isotope Possibilities in Bolometers

- Q > 2.6 MeV dramatically lower in background in 0νββ ROI
- High-resolution detectors → minimize 2νββ

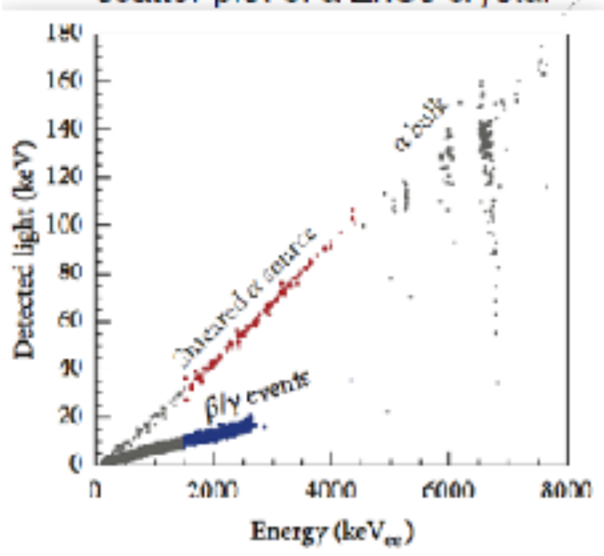
Isotope	Q [keV]	a [%]	$T^{2\nu}_{1/2}$ 10^{19} [y]
^{48}Ca	4274	0.2	$4.4^{+0.5}_{-0.4}$
^{76}Ge	2039	7.6	160^{+13}_{-10}
^{82}Se	2996	8.7	9.2±0.7
^{96}Zr	3348	2.8	2.3±0.2
^{100}Mo	3034	9.6	0.71±0.04
^{116}Cd	2814	7.5	2.85±0.15
^{130}Te	2528	34.2	69±13
^{136}Xe	2458	8.9	220±6
^{150}Nd	3368	5.6	0.82±0.9

$Q_{\beta\beta}$ above ^{208}Tl

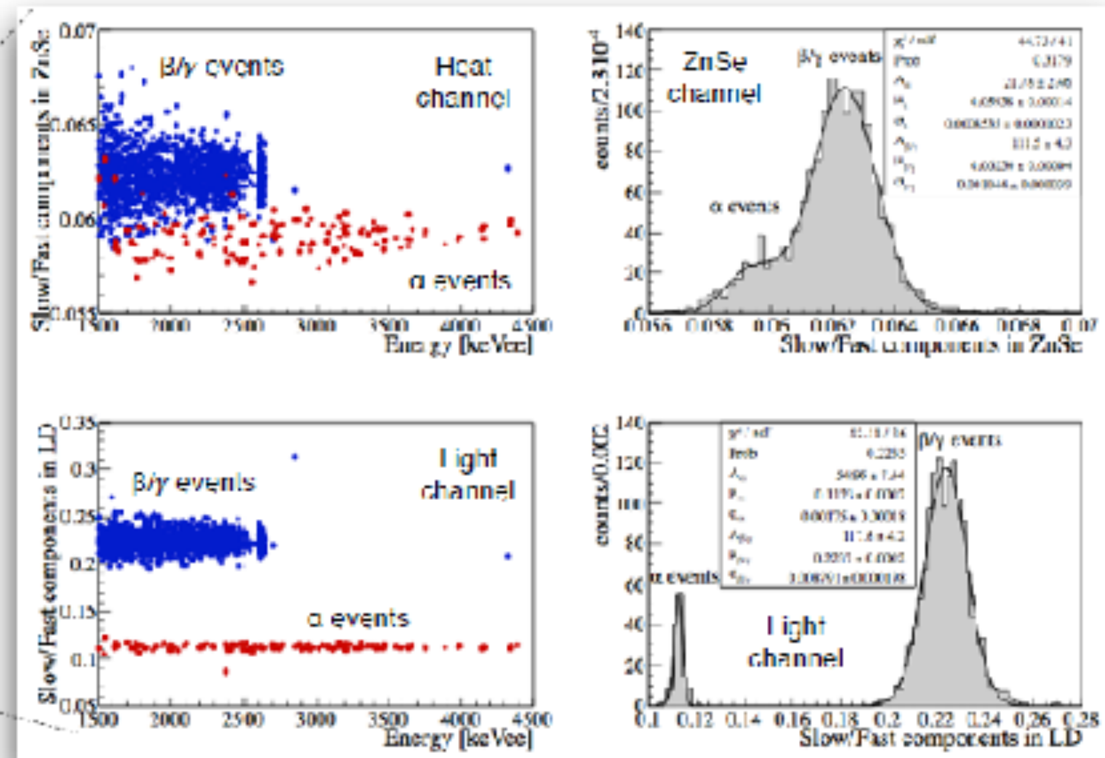


ZnSe Scintillating Bolometers

Calibration Light VS Heat scatter plot of a ZnSe crystal



Particle identification using Pulse Shape Parameters (decay time)



Discrimination potential @ ROI:

$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta\gamma}^2(E)}}$$

Heat channel
DP@ROI – 2

Light channel
DP@ROI – 11

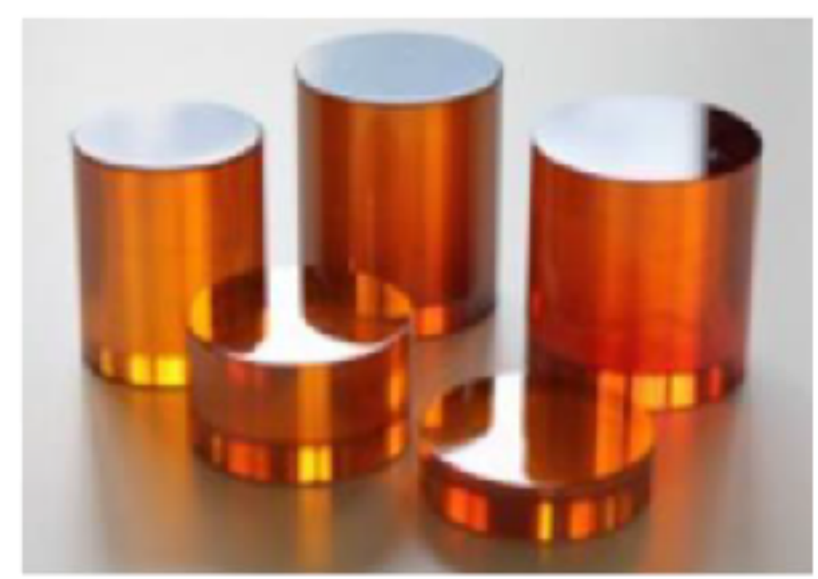
Full rejection of α events
shapeHEAT+shapeLIGHT+light

For CUPID-0 experiment

^{82}Se enriched @URENCO(96%)

Enriched powder activity (HP-Ge)	
Isotope	Upper limit 90% CL (μBq/kg)
^{232}Th	<61
^{238}U	<110
^{235}U	<74

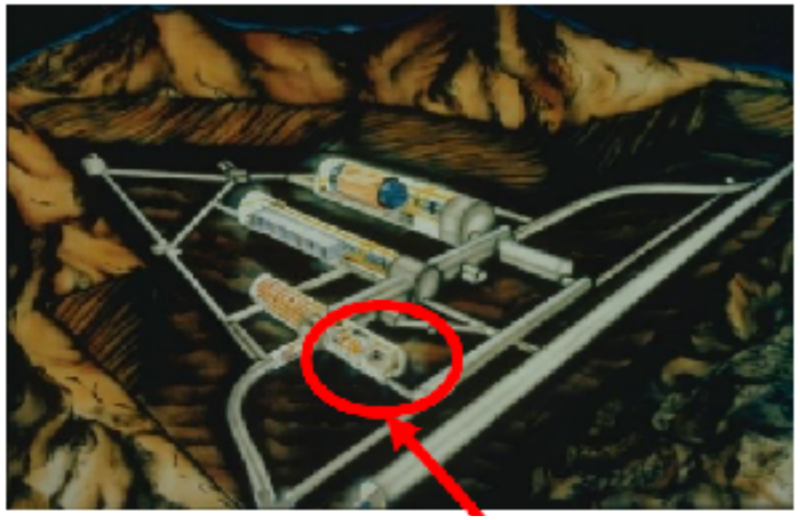
Zn^{82}Se grew @ISMA (Ukraine)
Final enrichment 95% in ^{82}Se



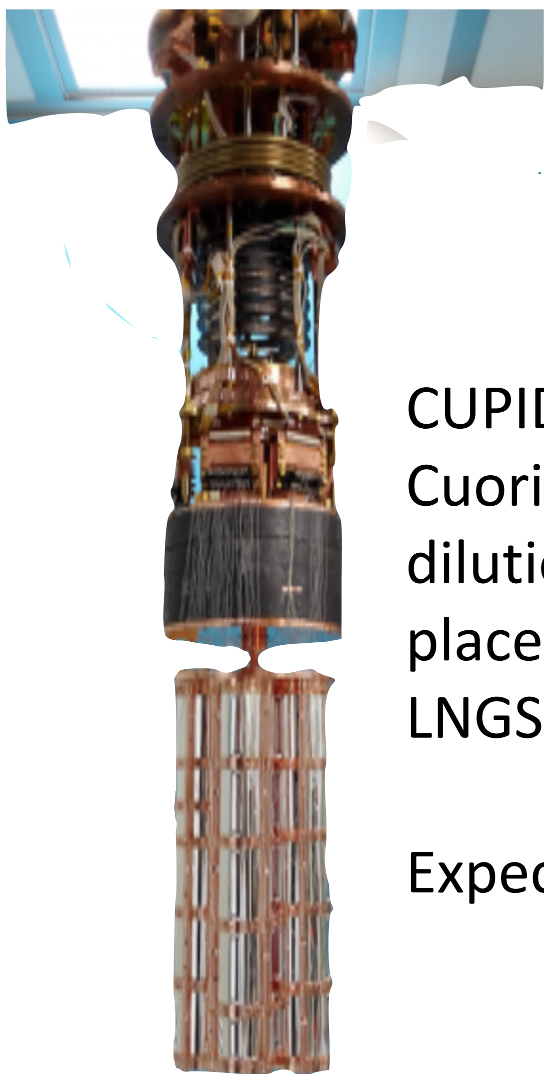
ZnSe crystals show:

- Excellent light/heat discrimination - **α scintillates more then β**
- Excellent pulse shape discrimination - **especially on light signal**

CUPID-0 Experiment

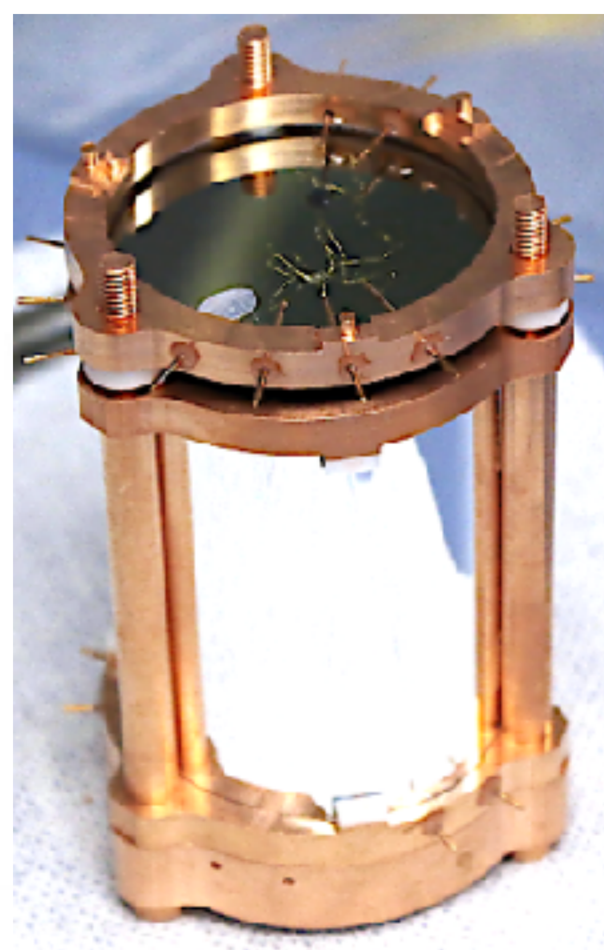


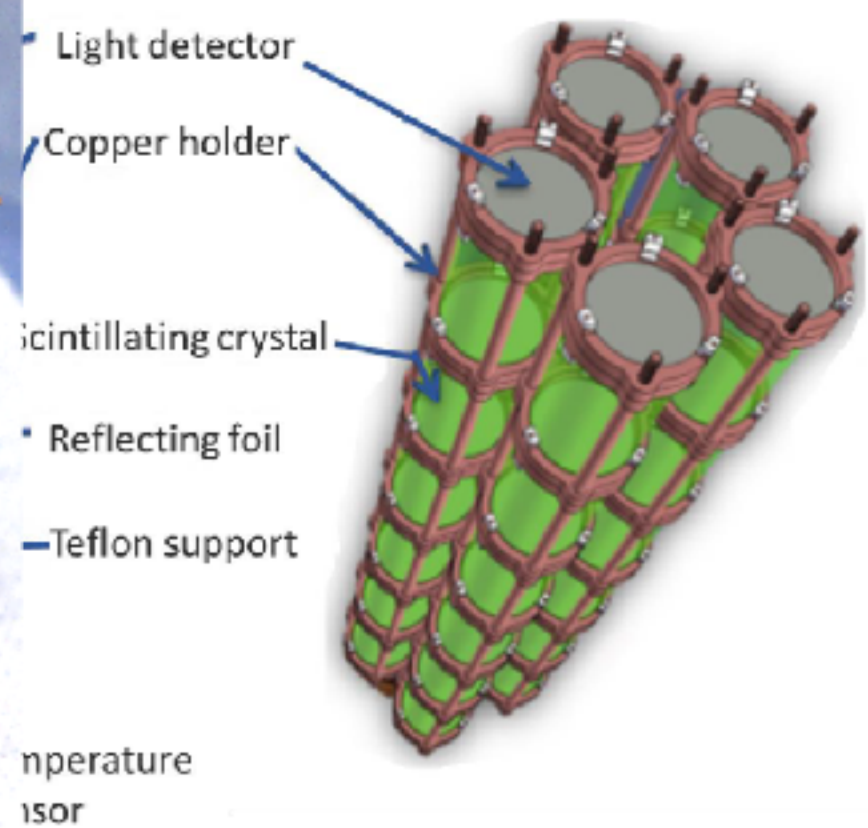
24 **$Zn^{82}Se$** bolometers, for a total mass **≈ 5.1 kg of ^{82}Se**
2 ZnSe bolometer ≈400 g each, not enriched in ^{82}Se
$Q_{\beta\beta}(^{82}Se)$ = 2996 keV
Light detectors high purity Ge wafers with antireflecting coating
Thermal sensors made with NTD thermistors
Detector assembled in 5 towers in Cuoricino/CUORE-0 cryostat
Total active **mass of the detector ~10.5 kg**
Expected background @ ROI 10^{-3} count/(keV kg year)
Expected FWHM energy resolution @ ROI 20 keV



CUPID-0 is installed in the Cuoricino-CUORE-0 dilution refrigerator placed in the Hall A of LNGS

Expect first results soon





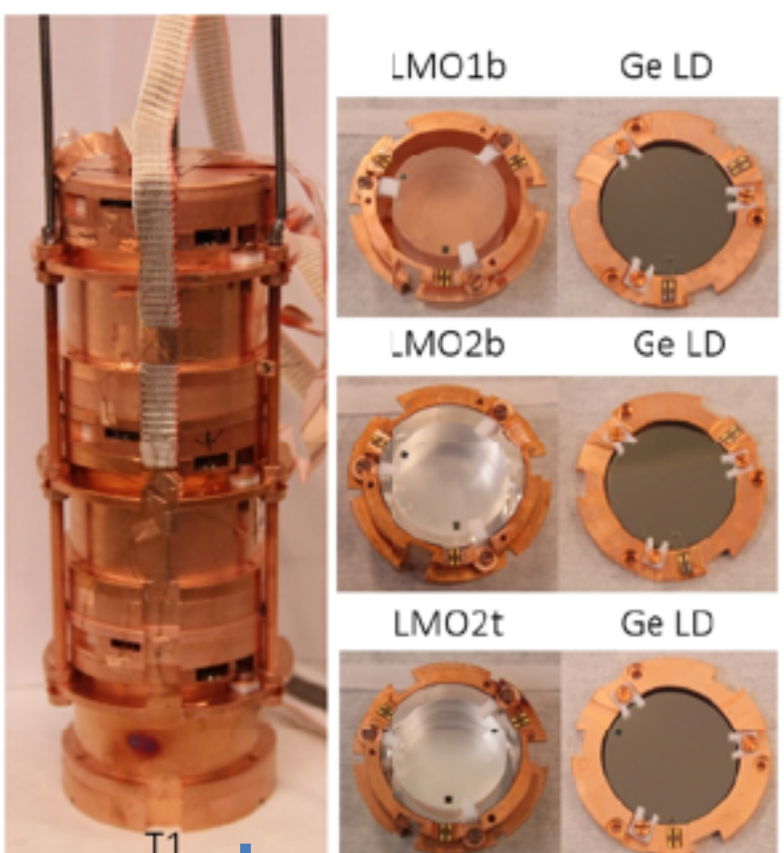
A. Giuliani

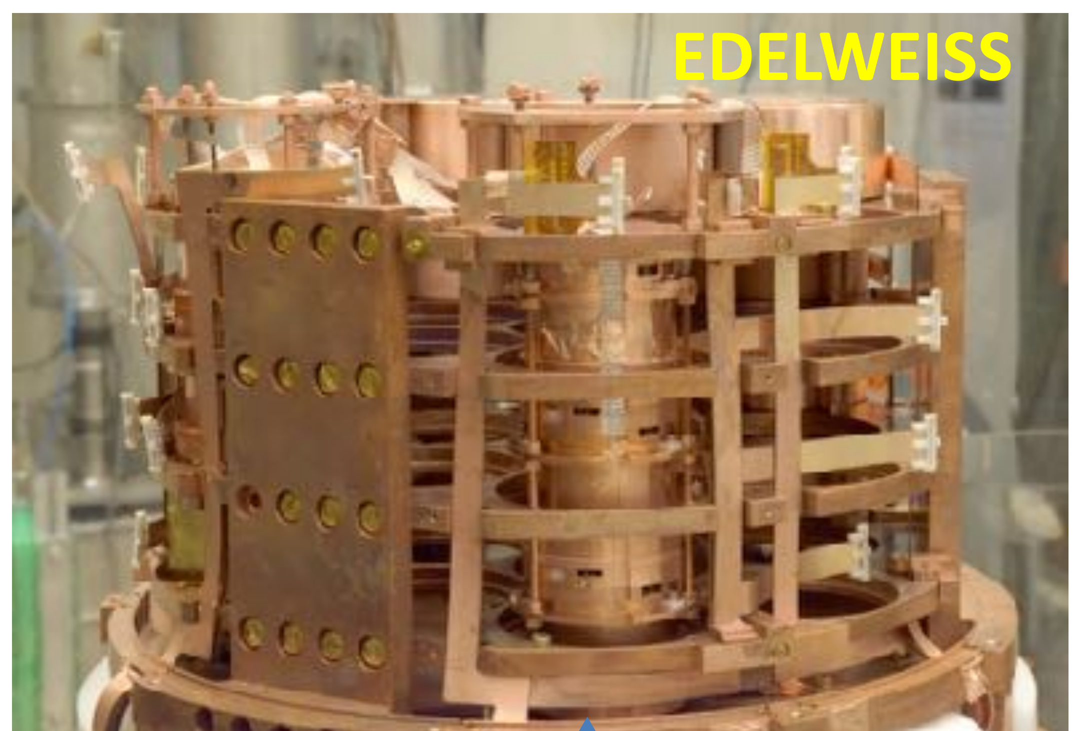
$Li_2{}^{100}MoO_4$ scintillating bolometers: a mature technology

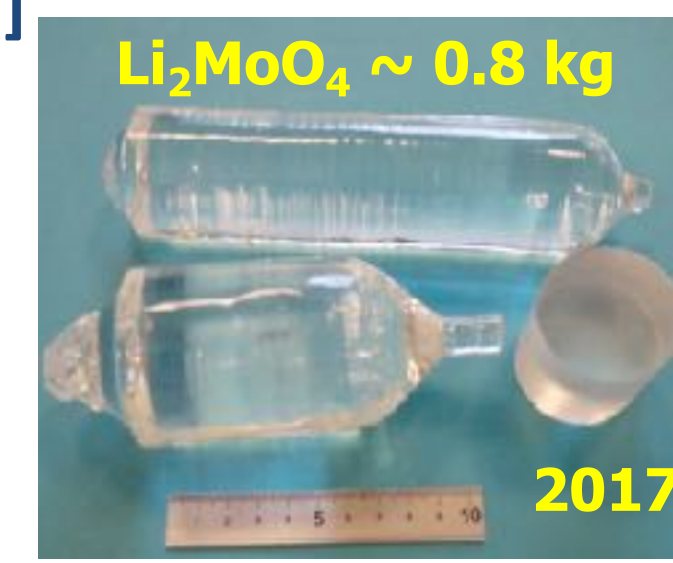
Multiple tests with **natural and enriched crystals** (2014-2017) in LSM and LNGS with outstanding results in terms of: *http://arxiv.org/abs/1704.01758*

Reproducibility	→	excellent performance uniformity
Energy resolution	→	~ **4-5 keV FWHM** in RoI
α/β separation power	→	**> 99.9 %**
Internal radiopurity	→	**< 5 μBq/kg in ^{232}Th, ^{238}U**; < **5 mBq/kg in ^{40}K**

→ Compatible with ***b*** **≤ 10^{-4} [counts/(keV kg y)]**

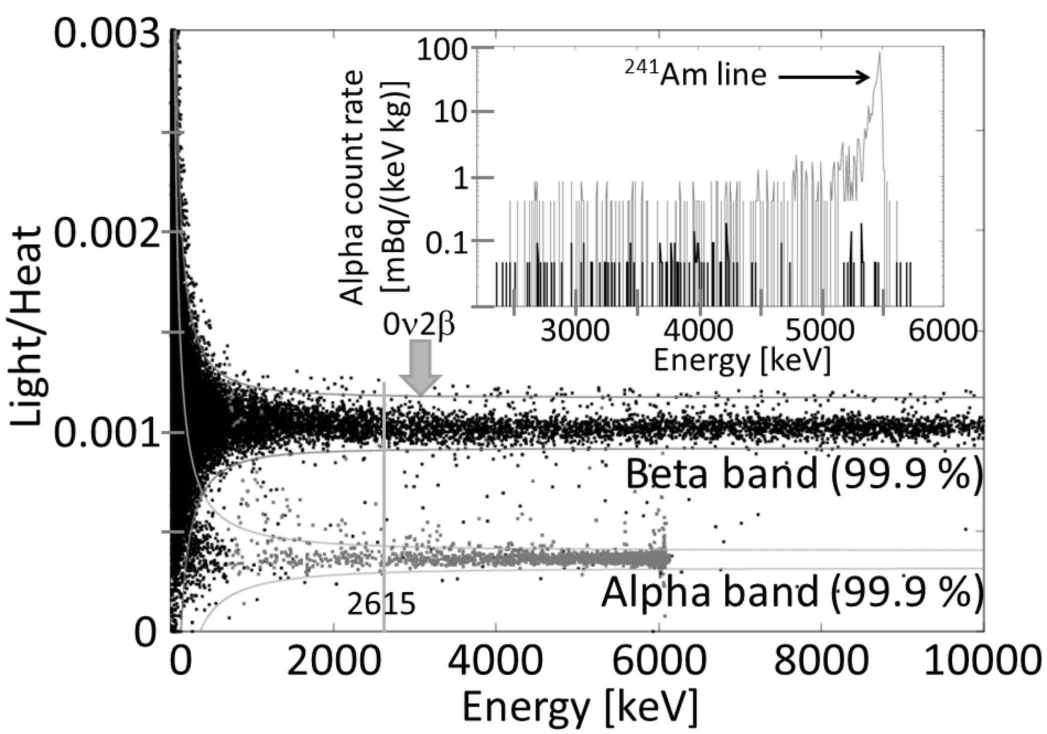






NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)
arXiv:1704.01758 (EPJC)

Scintillating Bolometer R&D



Crystal Production has been the focus of the U.S. Groups:

- We partnered with RMD Inc. in Watertown, MA due to their experience growing low background crystals.
- ZnMoO4, $Na_2Mo_4O_{13}$, and Li_2MoO_4 crystals have been grown.
- SBIR Phase 2 just awarded!

A. Giuliani

CUPID-0/Mo pilot experiments

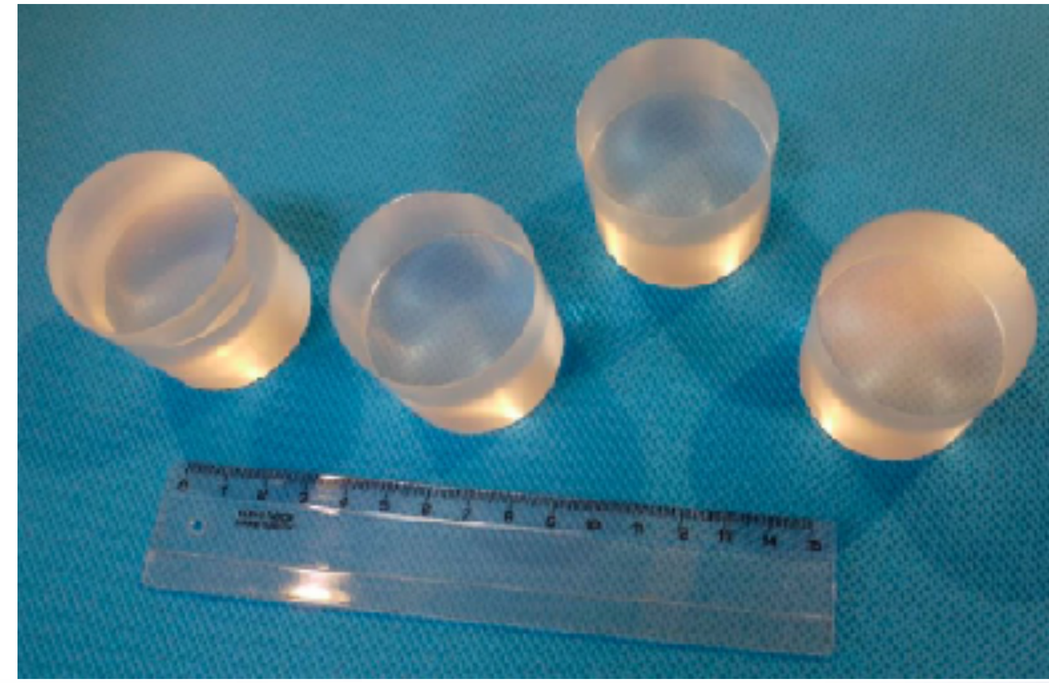
CUPID-0/Mo Phase I (20 crystals already delivered):

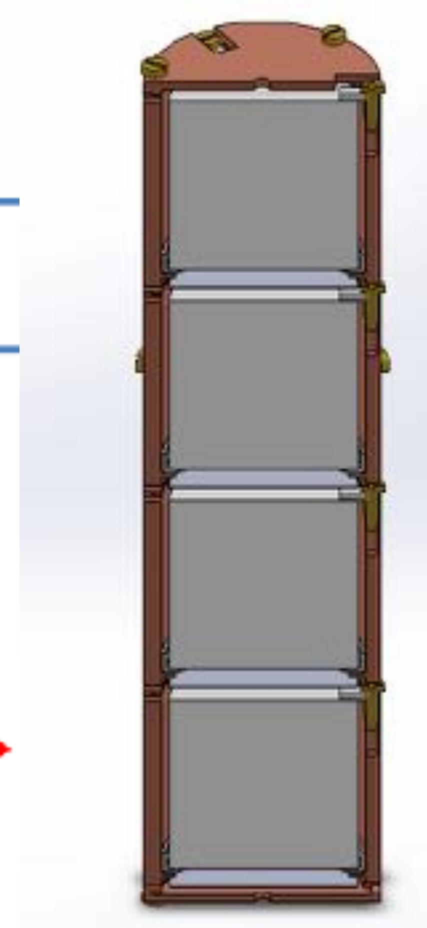
- **20 ^{100}Mo-enriched (97%) Li_2MoO_4**
  (∅44×45 mm, 0.21 kg each; 4.18 kg total)
  ⇒ 2.34 kg of ^{100}Mo (1.37×10^{25} ^{100}Mo nuclei)
- **20 Ge light detectors** (∅44×0.175 mm)+SiO
- **EDELWEISS set-up** @ LSM (France)
- $T_{1/2}$ of O(10^{24} yr)

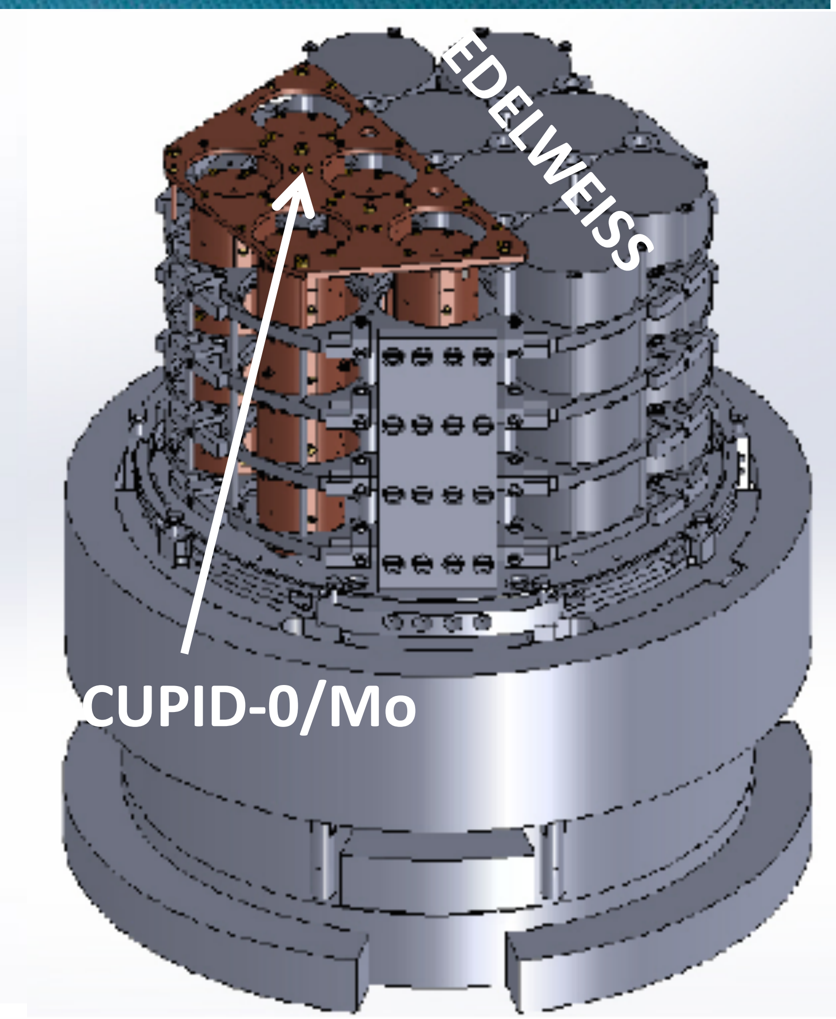
START DATA TAKING: December 2017

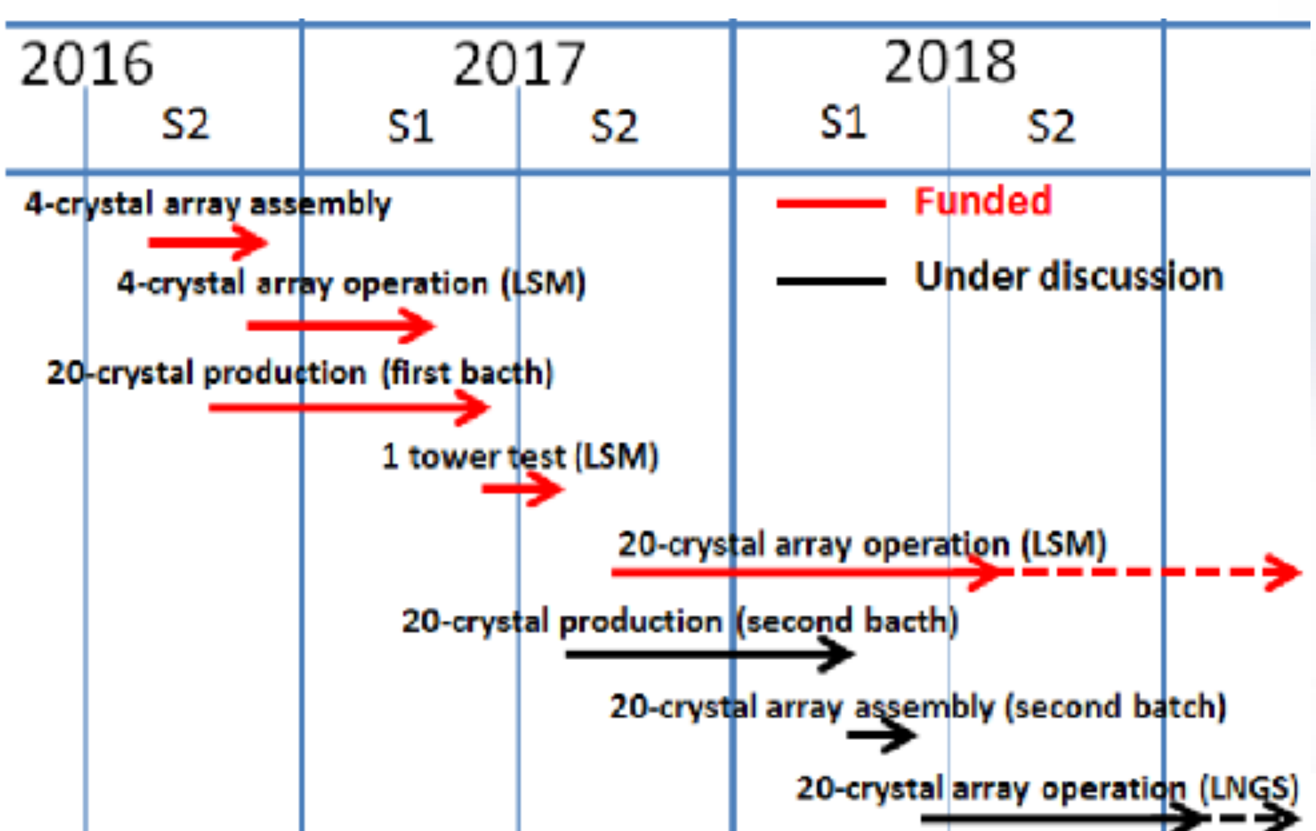
CUPID-0/Mo Phase II (20+20 - or more - crystals):

- At least additional **20 $Li_2{}^{100}MoO_4$**
- **CUPID-0 set-up** @ LNGS (Italy, under discussion)
- $T_{1/2}$ of O(10^{25} yr)

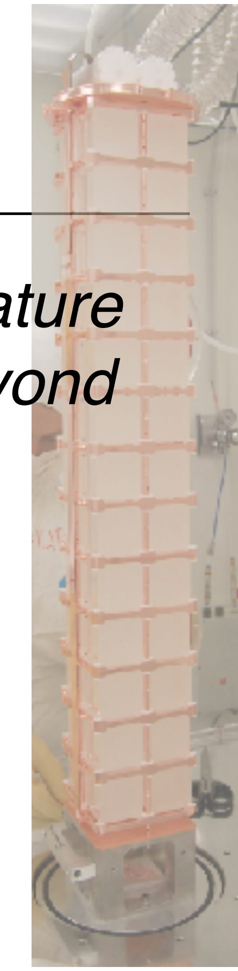








Conclusions



Neutrinoless double beta (0νββ) is the only method for probing the Majorana nature neutrinos. Observation would establish lepton number violation and physics beyond Standard Model.

CUORE program builds on the success of CUORICINO and predecessors

- **CUORE-0** (2013 - 2015)
  - CUORE & CUORE-0 successful background mitigation and modeling
  - energy resolution of < 5 keV FWHM for ROI reached
  - $T_{1/2}^{0\nu\beta\beta}$ (^{130}Te) > 4.0×10^{24} y (90% CL)
  - $T_{1/2}^{2\nu\beta\beta}$ (^{130}Te) = [8.2±0.2(stat)±0.6(syst.)] x 10^{20} y
- **CUORE**
  - projected $T_{1/2}^{0\nu\beta\beta}$ ~ 9 x 10^{25} yr (90% C.L.)
  - started operations and is going through detector optimization
  - expect to report initial data this summer
- **Beyond CUORE**: R&D effort is underway. Large bolometers offer path towards exploring the inverted hierarchy.