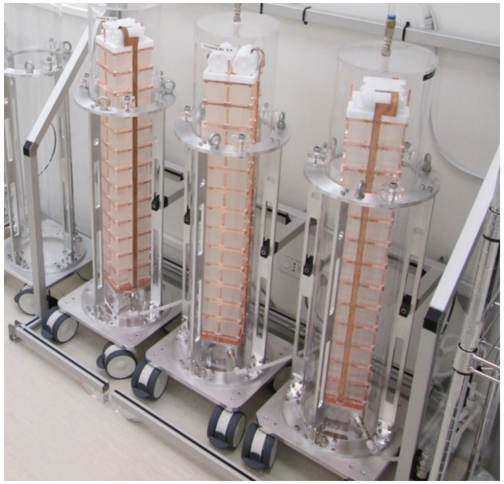
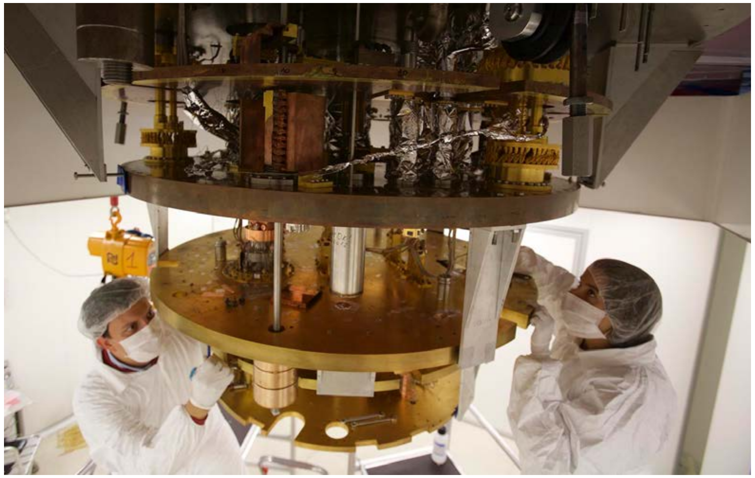
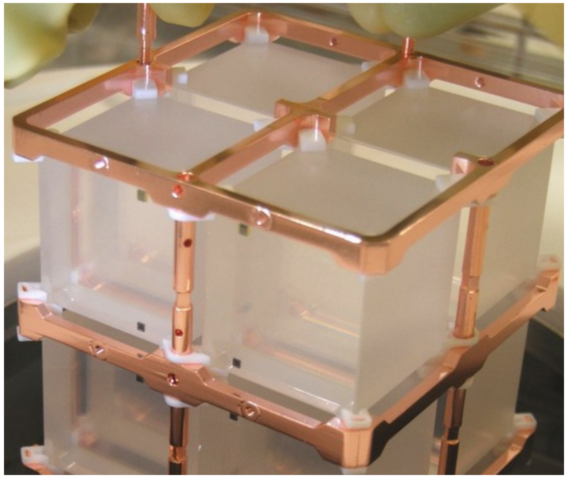
Investigation of 0νββ with Bolometers

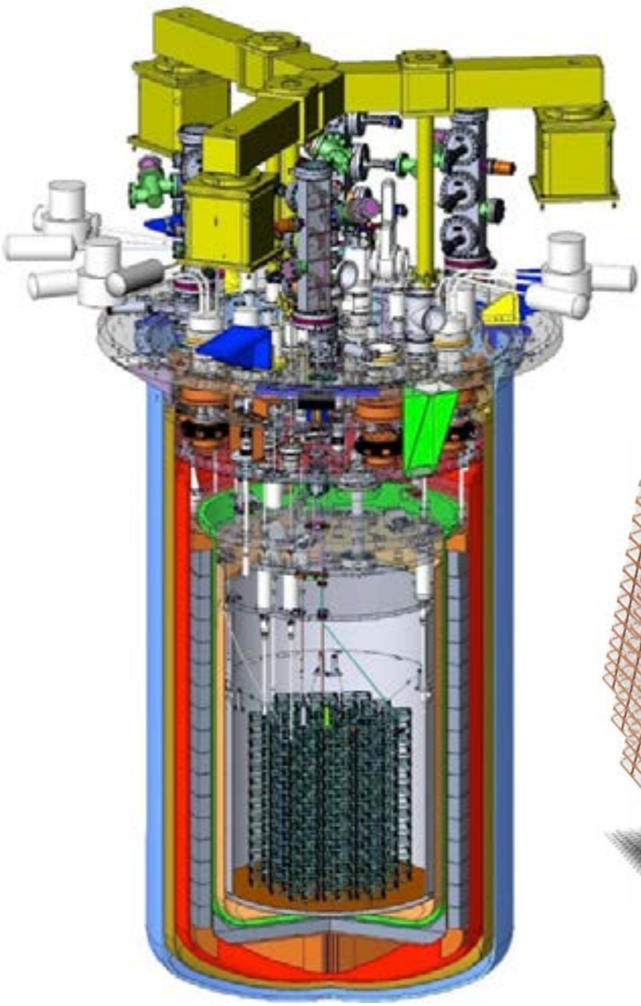
CUORE and Beyond

Karsten Heeger
Yale University

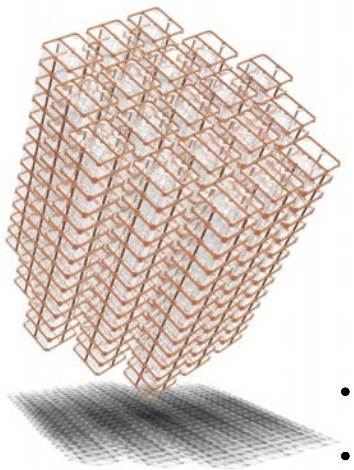
on behalf of the CUORE Collaboration

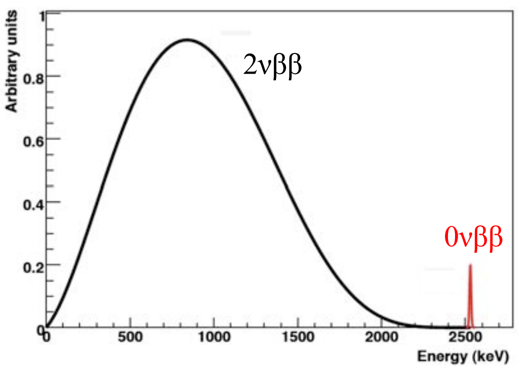
CUORE

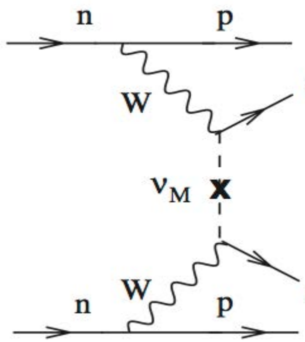


Cryogenic Underground Observatory for Rare Events

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







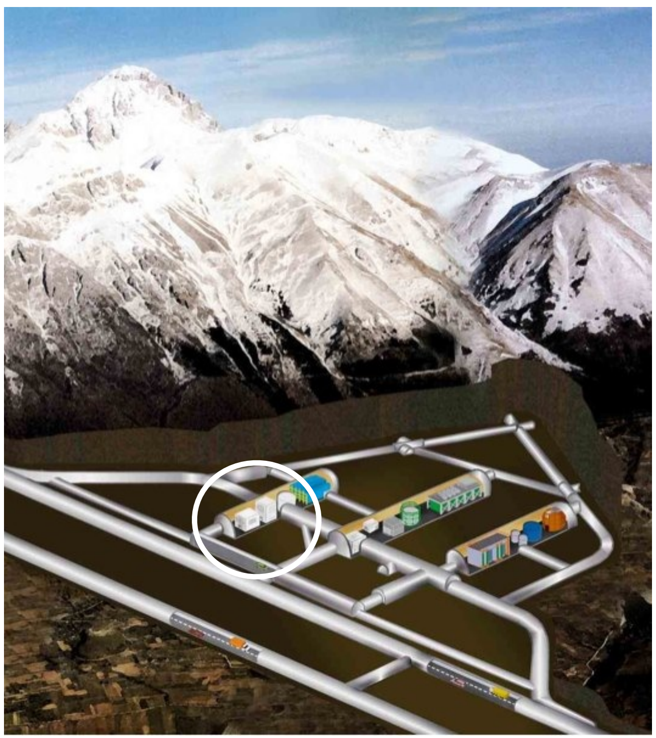
- Excellent energy resolution of bolometers
- New pulse tube dilution refrigerator and cryostat
- Radio-pure material and clean assembly to achieve low background at region of interest (ROI)

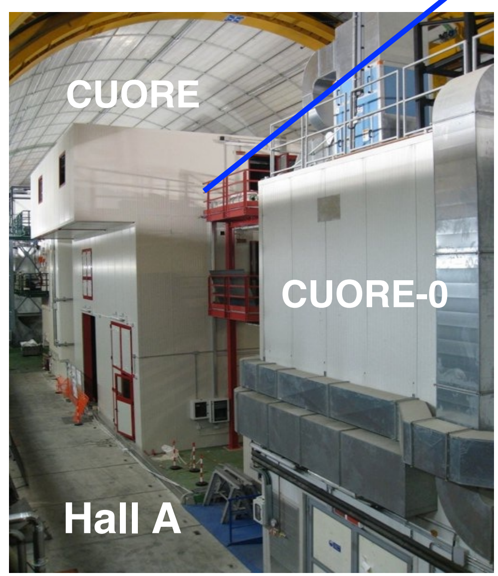
CUORE at LNGS

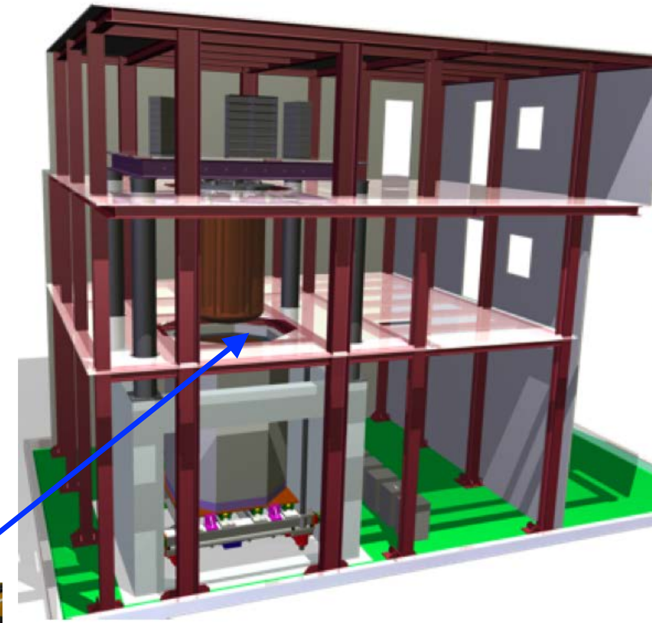
Gran Sasso National Laboratory

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

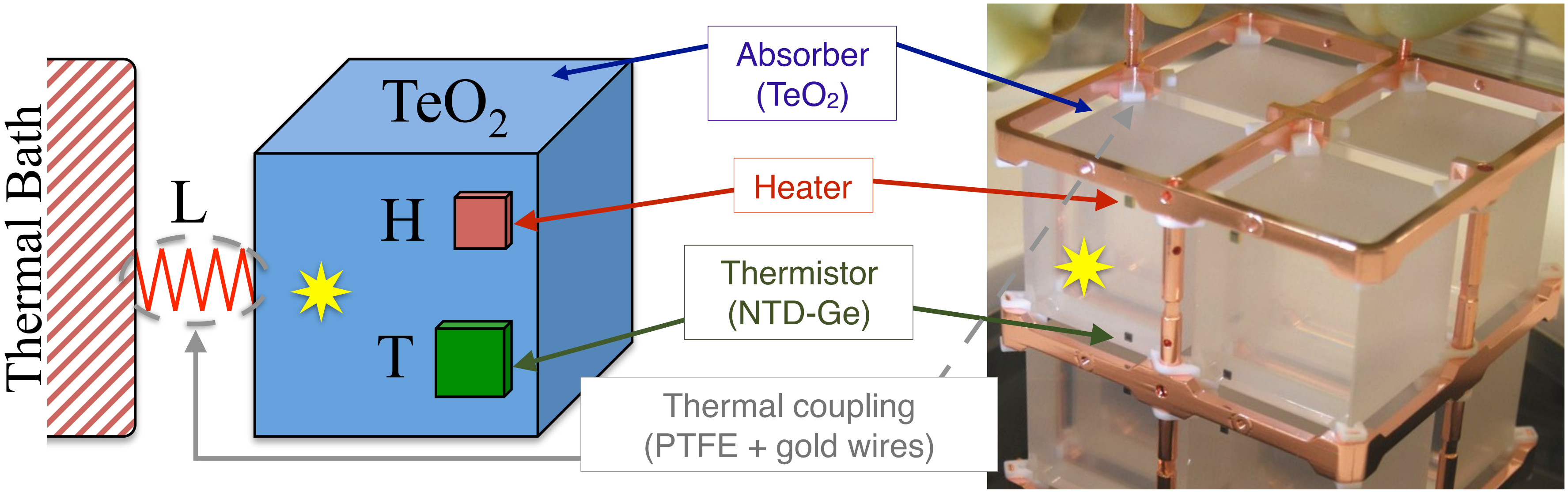






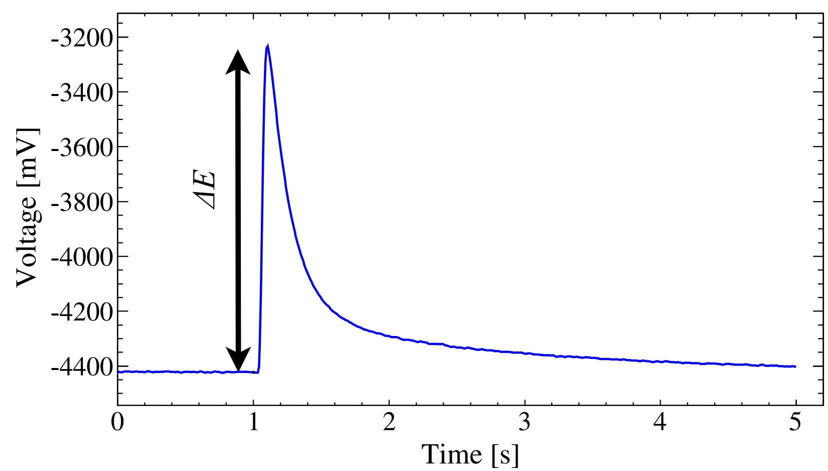
CUORE Hut

TeO_2 Bolometers for 0νββ Search



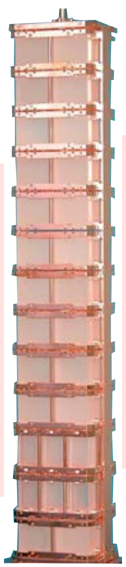
$\Delta T_{crystal}$ ~ 10 - 20 μK/MeV

- ^{130}Te is a good 0νββ source
  - high isotopic abundance
  - high Q-value
- TeO_2 bolometer provides excellent energy resolution (0.2% at Q-value)



CUORE 0νββ Search

Cuoricino
(2003-2008)



Astropart. Phys. 34 (2011) 822–831

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

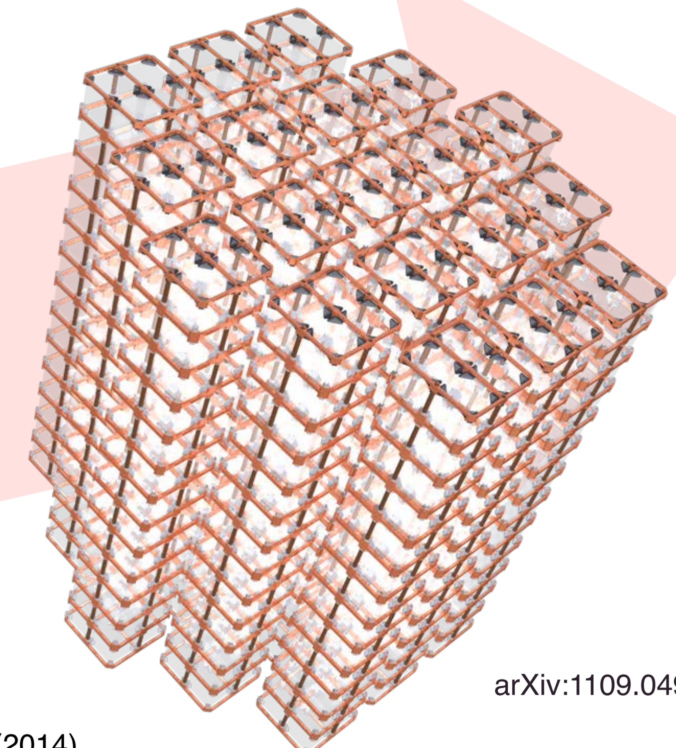
$$\langle m_{\beta\beta}\rangle_{90\%\ \mathrm{C.L.}} = 300 - 710\ \mathrm{meV}$$

CUORE-0
(2013-2015)

EPJC 74, 2956 (2014)

Surpass Cuoricino w/ ~1-yr data

CUORE
(2015-2020)



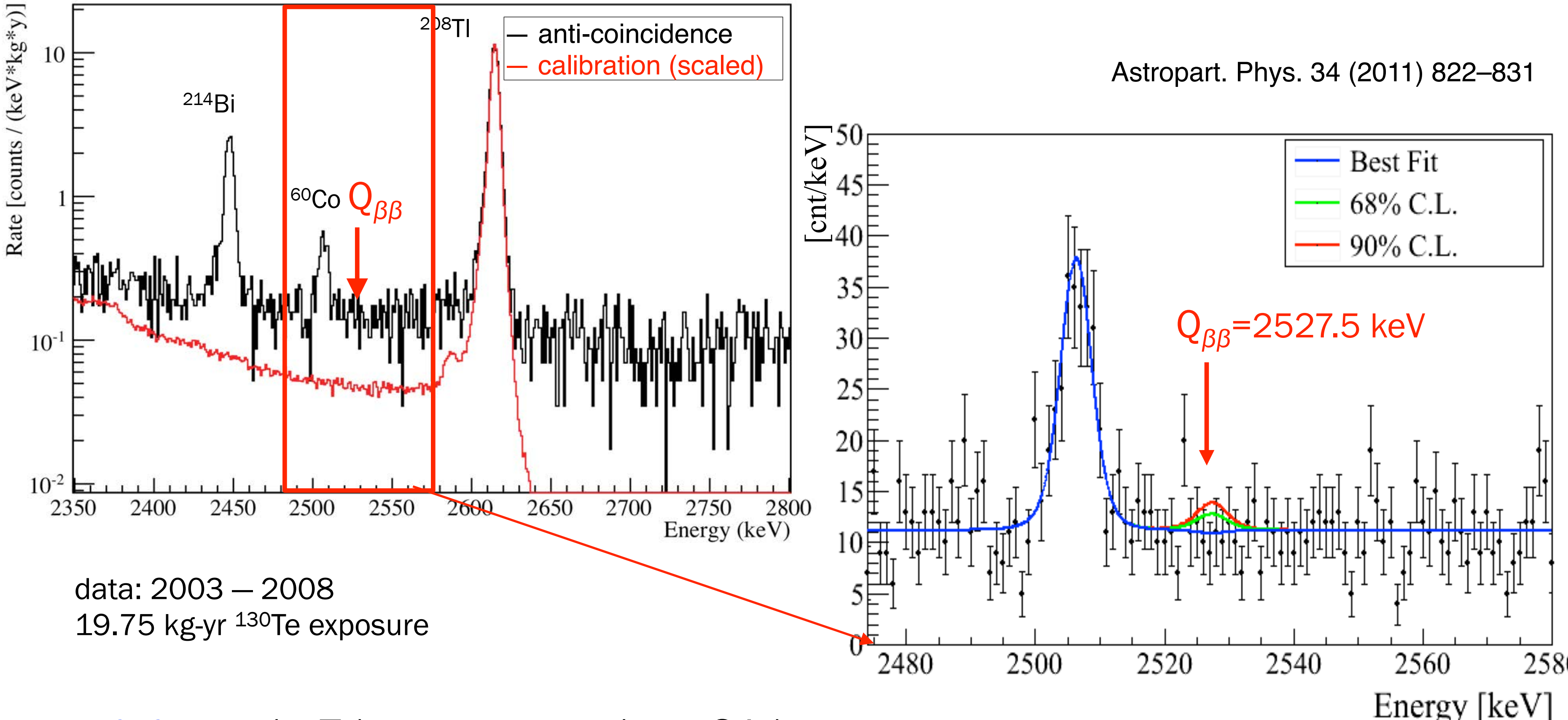
arXiv:1109.0494

Projected

$T_{1/2}^{0\nu\beta\beta}$ > 9.5 x 10^{25} yr (90% C.L.)

$$\langle m_{\beta\beta}\rangle_{90\%\ \mathrm{C.L.}} = 51 - 133\ \mathrm{meV}$$

CUORICINO Result



data: 2003 – 2008
19.75 kg-yr ^{130}Te exposure

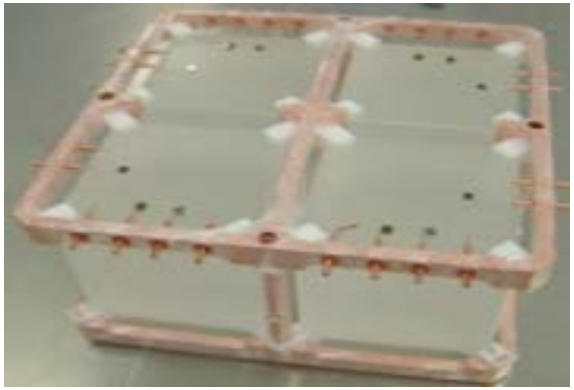
Half-life limit (^{130}Te) ≥ 2.8×10^{24} y (90% C.L.)

Background: 0.169 ± 0.006 counts/keV/kg/y

No evidence of neutrinoless double beta decay in ^{130}Te.

Upper limit, Majorana mass: $m_{\nu_e} < 300 - 710$ meV

CUORE: An ultrapure TeO_2 Crystal Array

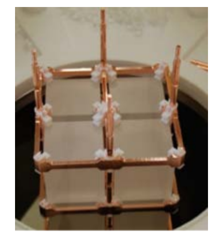


Bulk activity 90% C.L. upper limits:

$8.4 \cdot 10^{-7}$ 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:

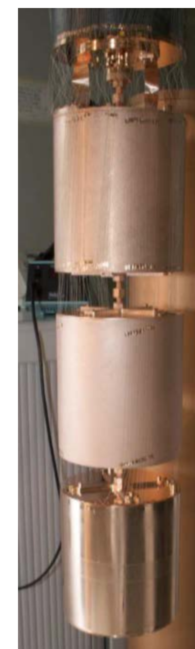
$2 \cdot 10^{-9}$ Bq/cm^2 (^{232}Th), $1 \cdot 10^{-8}$ Bq/cm^2 (^{238}U), $1 \cdot 10^{-6}$ Bq/cm^2 (^{210}Po)



- 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

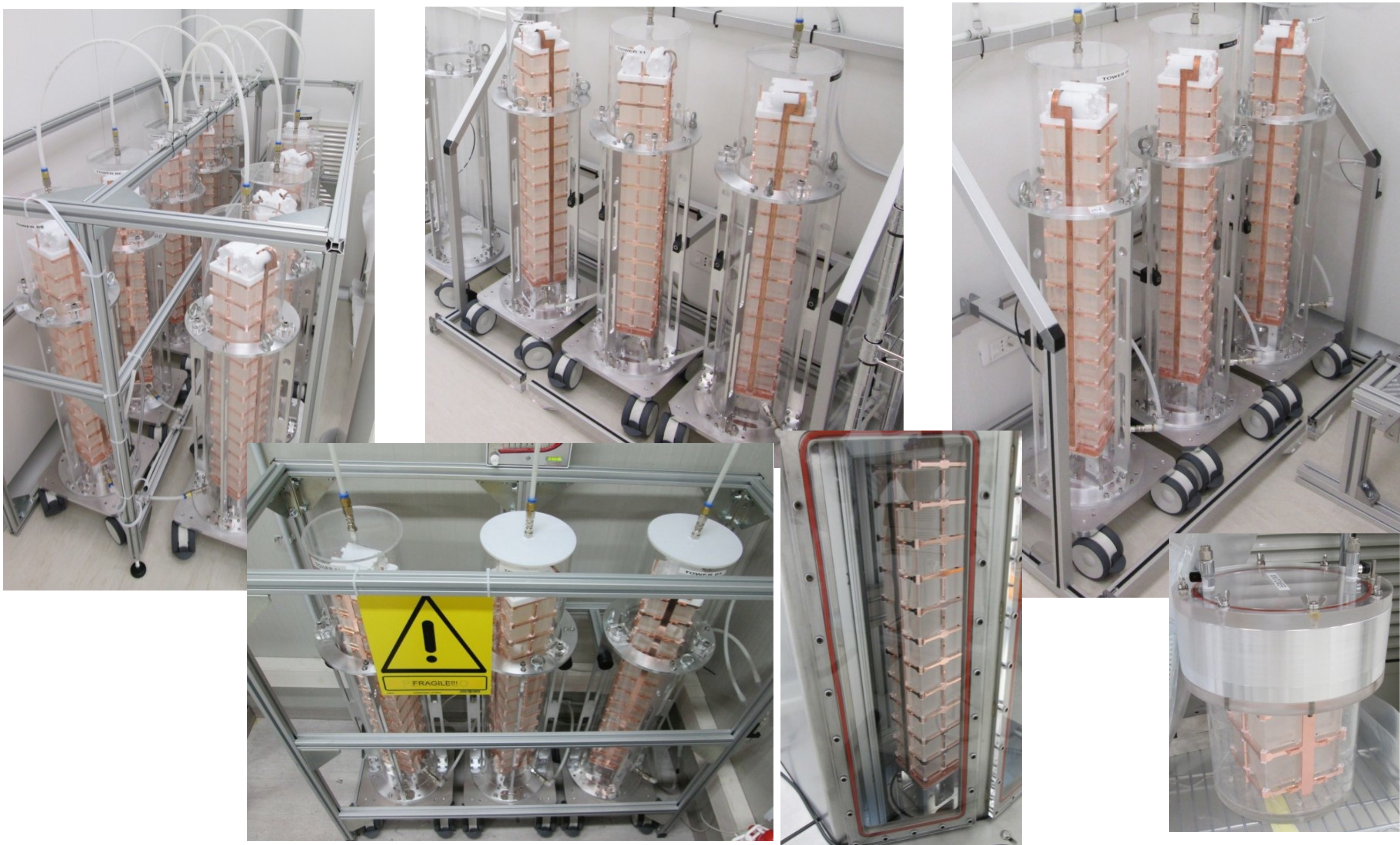


- Benchmarked in dedicated bolometer run at LNGS
  - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2
- Validated by CUORE-0

- All parts stored underground, under nitrogen after cleaning

CUORE Detector Towers

Assembly of all 19 towers is complete



CUORE: Cryogenic Systems & Commissioning

Phased Commissioning

Phase I: 4K system check

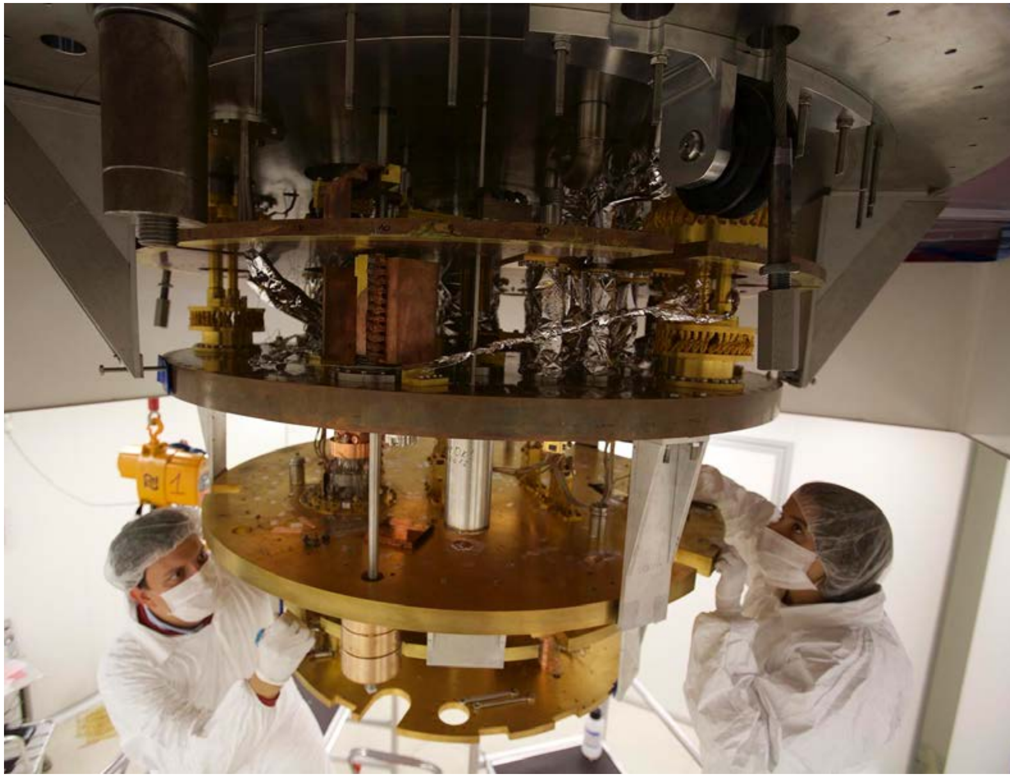
- Outer/Inner vacuum chamber test
- Cryogenic verification of detector calibration system
- Commissioning test of DU

Phase II: full cryostat vessel check

- Full assembly of cryostat
- Cool down of cryostat
- Integration of test tower
- Detector wiring
- calibration system

Preparing for Phase III: integrated cryogenic test

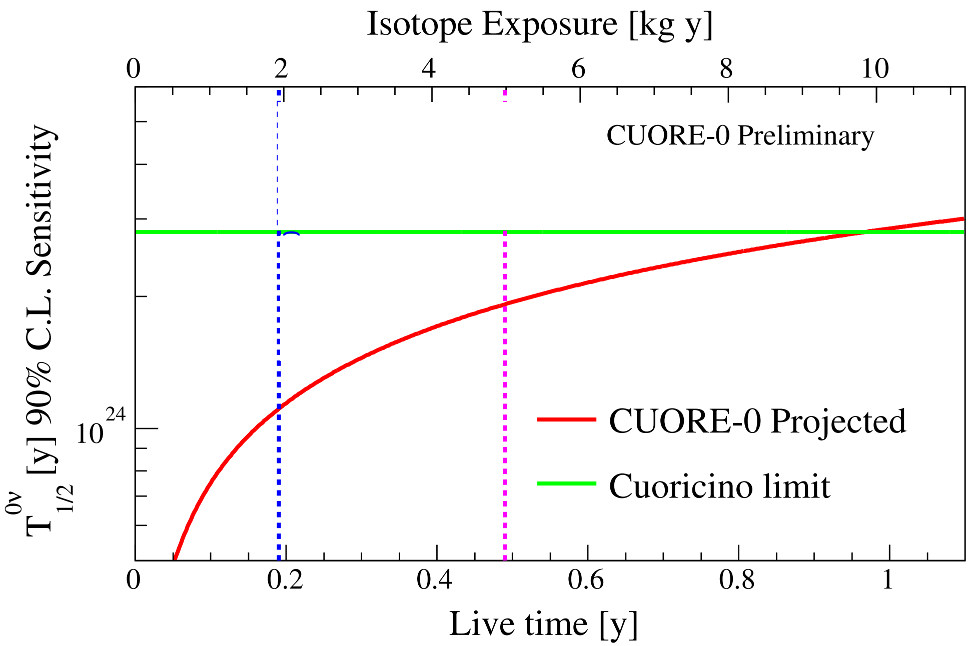
- with lead shields
- wiring
- full calibration system

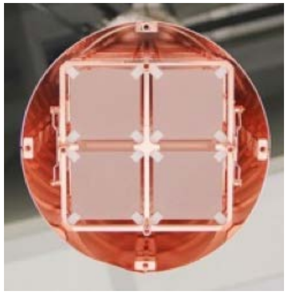


6mK stable base temperature achieved in October 2014

CUORE-0 Status and Projections

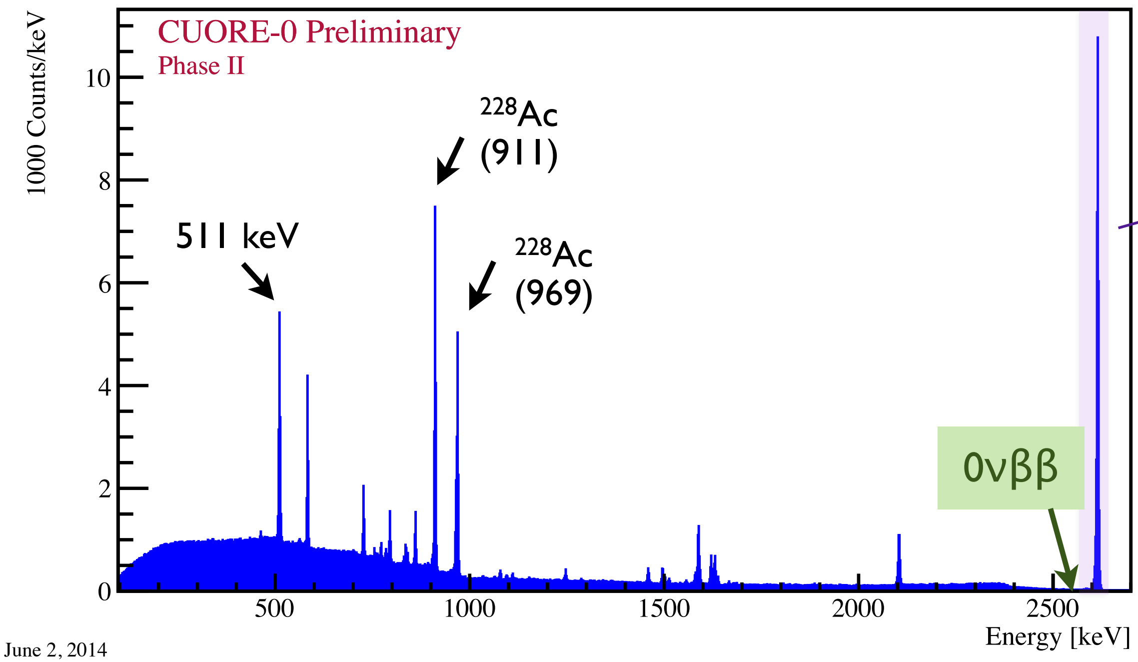
- **CUORE-0**
  - single CUORE-like tower ~11 kg of ^{130}Te running in CUORICINO shielding & cryostat since March 2013
  - Validate new cleaning and assembly procedures for CUORE
  - stand-alone DBD experiment
- **CUORE-0 phase I:** first results in EPJC 74, 2956 (2014).
- **CUORE-0 phase II:** data taking w/ improved detector operation condition, improved analysis.
- Reach CUORICINO sensitivity with ~ 1yr lifetime (unblind in spring 2015)

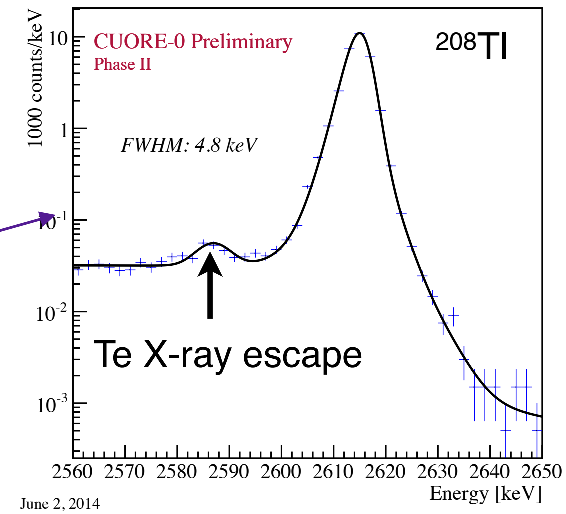




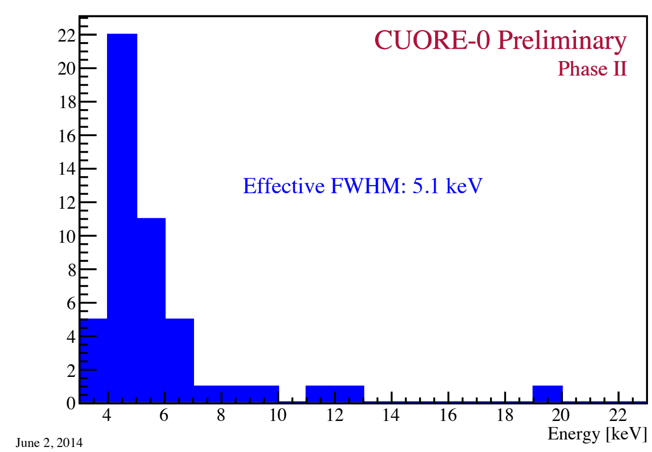
CUORE-0 Energy Resolution

CUORE-0 Calibration Spectrum (Phase II)





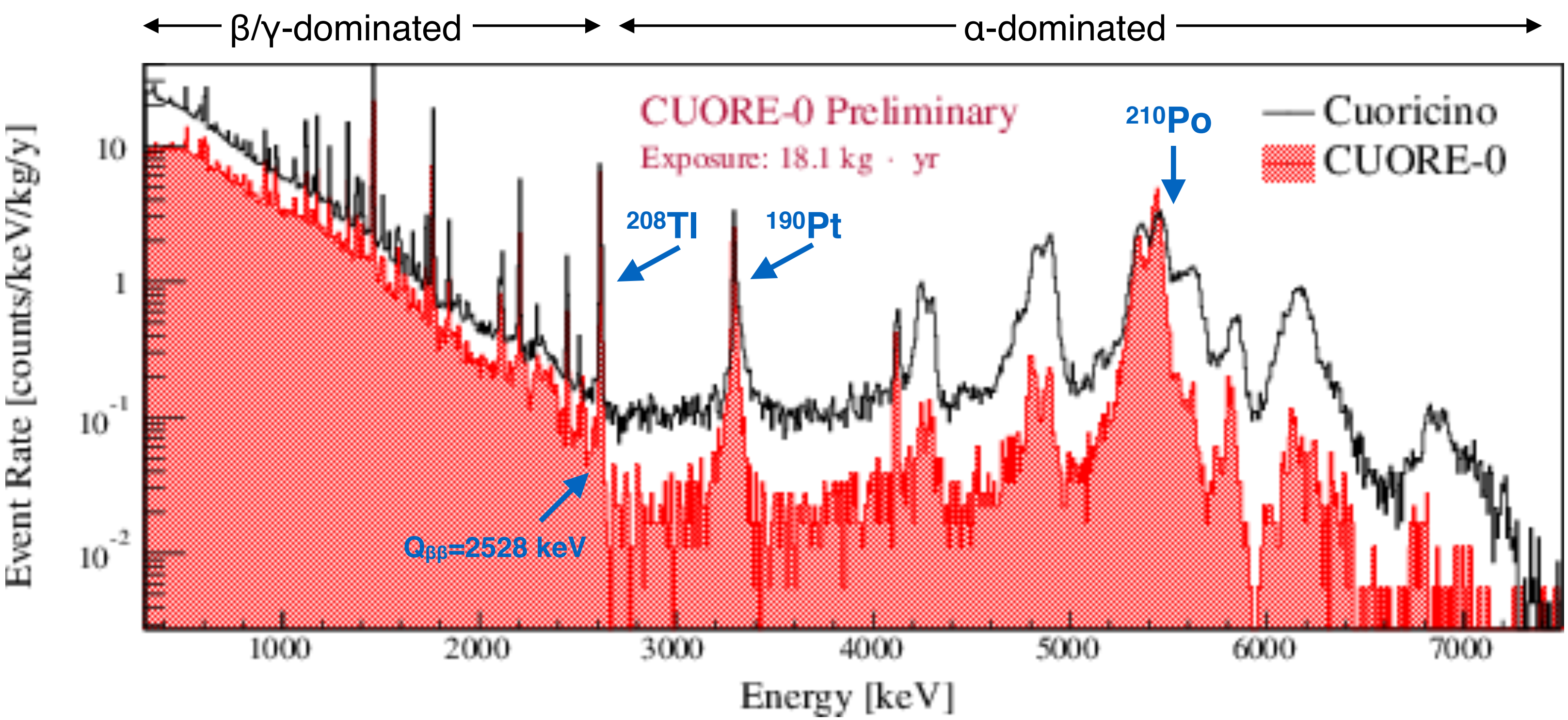
CUORE-0 Calibration Resolution by Channel (Phase II)



- Total ^{232}Th activity of 100 Bq via two thoriated wires outside the cryostat
- Improved detector operation in Phase II. CUORE goal of 5 keV FWHM near ROI achieved. Previously 5.7 keV.

CUORE-0 Background Measurement

Eur. Phys. J. C 74, 2956 (2014)



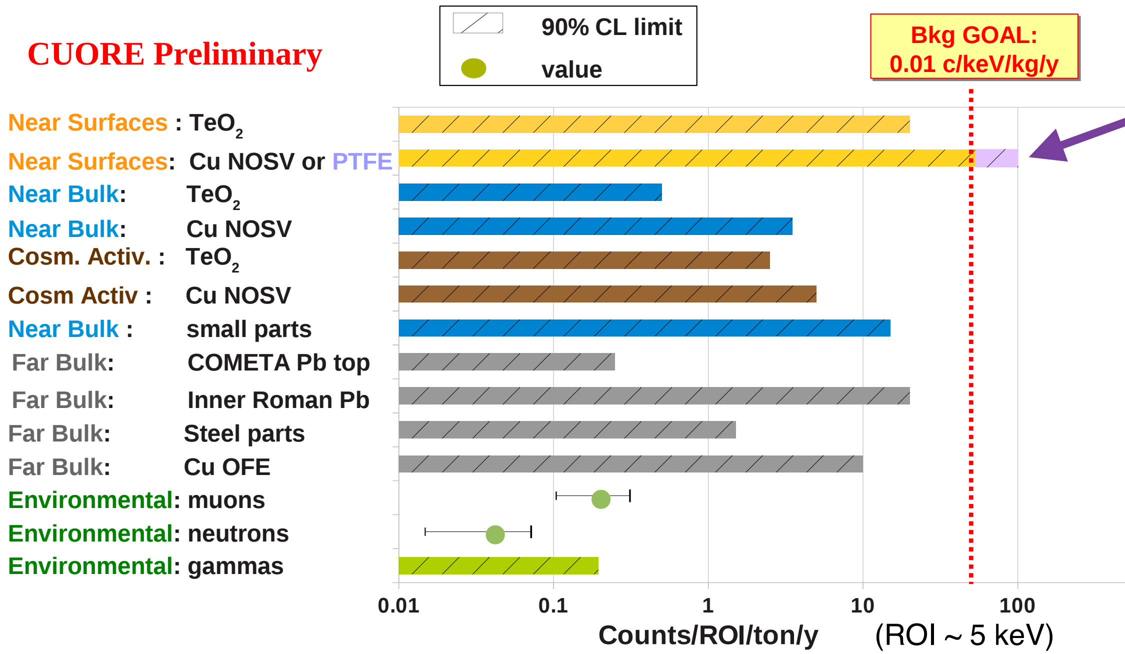
	0νββ region [c/keV/kg/yr]	2700-3900 keV * [c/keV/kg/yr]
CUORICINO ε=83%	0.153 +/- 0.006	0.110 +/- 0.001
CUORE-0 ε =78%	**0.063 +/- 0.006**	**0.020 +/- 0.001**

* excluding the ^{190}Pt peak region

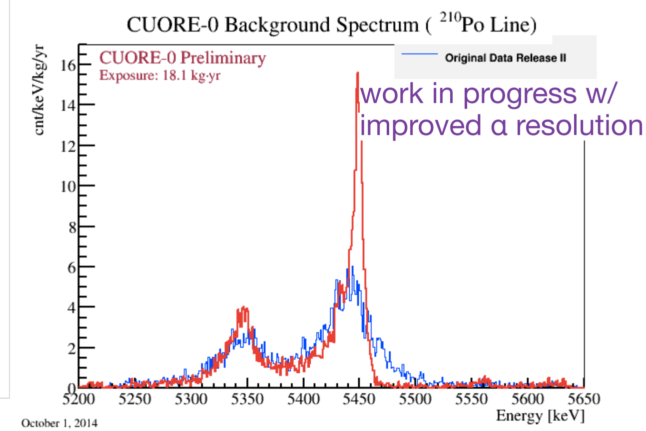
- α-dominated bkg: 6-fold reduction
  - Ultra-cleaning of CUORE-0 Cu surfaces
- 2.5-fold reduction of bkg in ROI
  - stringent radon control in COURE-0
- β/γ bkg from cryostat ^{232}Th remains the same
- **Consistent with the Cuoricino bkg model**

CUORE Background Projections

- **CUORE-0:** provides bench mark for remaining background with new assembly & crystal/Cu cleaning protocols
- **CUORE projections:** results of CUORE-0 + screening campaign results ->

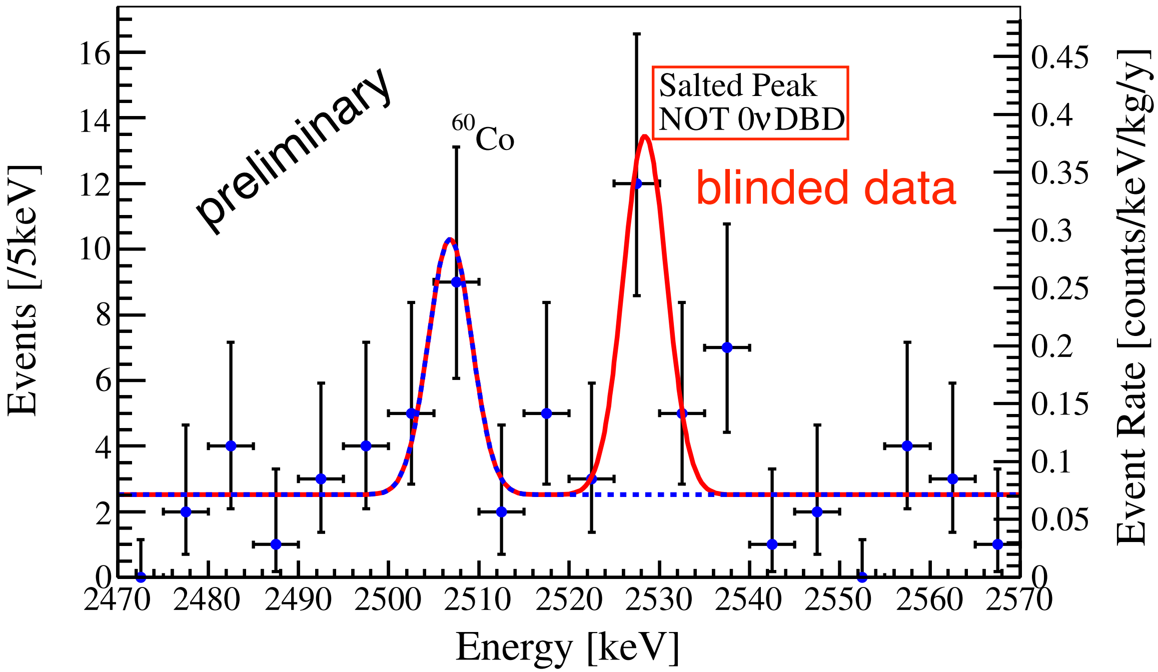


Detailed studies of surface vs. bulk contamination underway



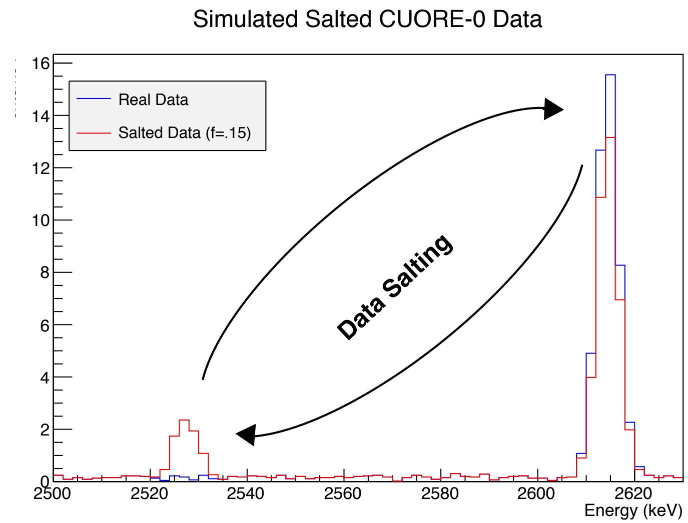
Conservatively extrapolate measured α-region bkg from CUORE-0 assuming all bkg is from ^{238}U/^{232}Th/^{210}Po individually

CUORE-0 0νββ Region



EPJC 74, 2956 (2014)

- Region of Interest was blinded by "salting": exchange a small (and ***blinded***) fraction of the events in ^{208}Tl peak with events in the 0vDBD region to produce an artificial peak.



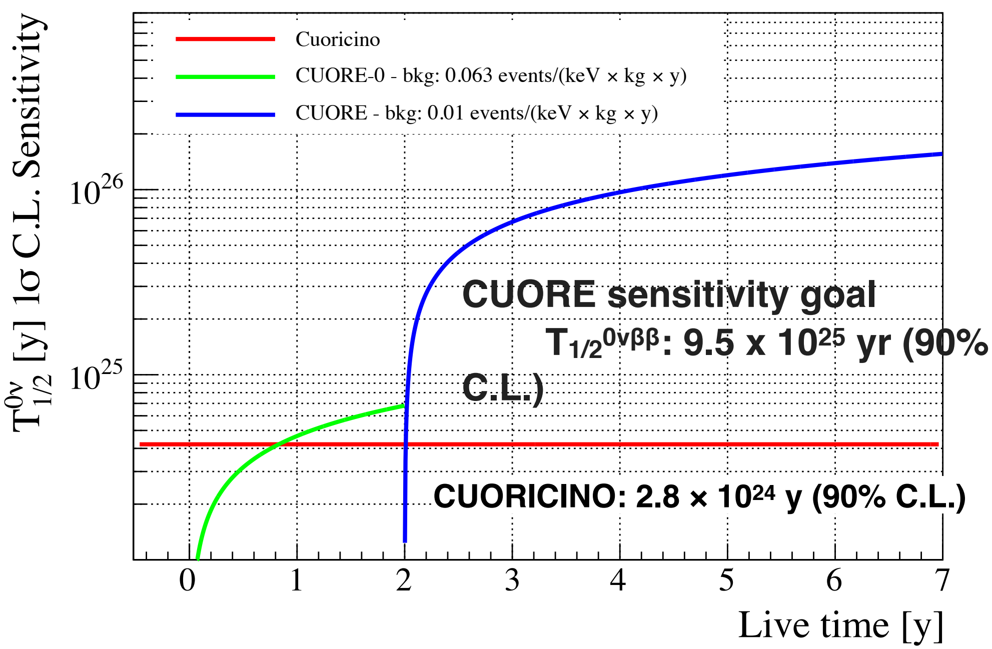
Analysis improvements underway

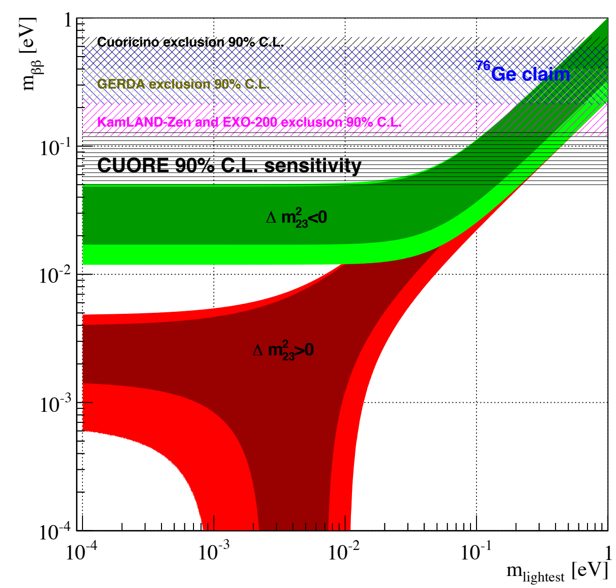
- noise reduction - decorrelation
- heater-less gain stabilization
- calibration, pulse-shape, and multiplicity-cuts
- background model
- low-energy PSA for dark matter searches

Unblinding in Spring 2015

CUORE Sensitivity

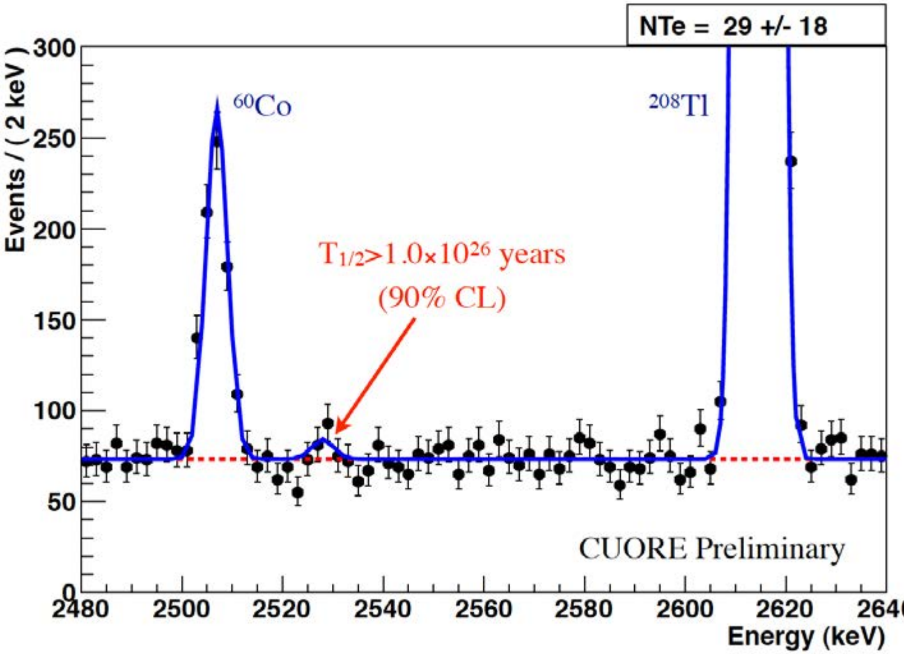
- CUORE sensitivity goal $\mathbf{T_{1/2}^{0\nu\beta\beta}}$ **> 9.5 x 10^25 yr** @ 90% C.L.
- Effective Majorana mass 51 - 133 meV @ 90% C.L.
    - Assumptions: 5 keV FWHM ROI resolution (δE), background rate (b) of 0.01 counts/(keV·kg·yr), 5 years of live time.

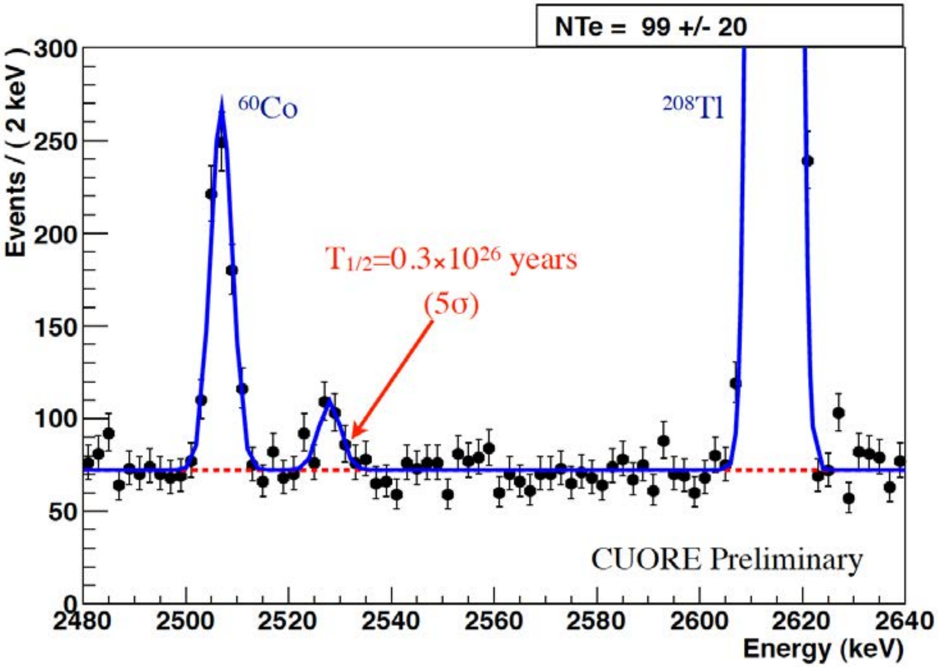




arXiv:1109.0494

CUORE - What a signal might look like…

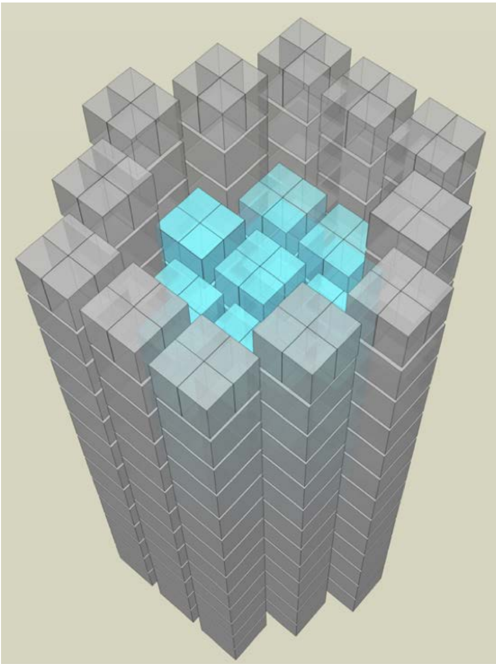




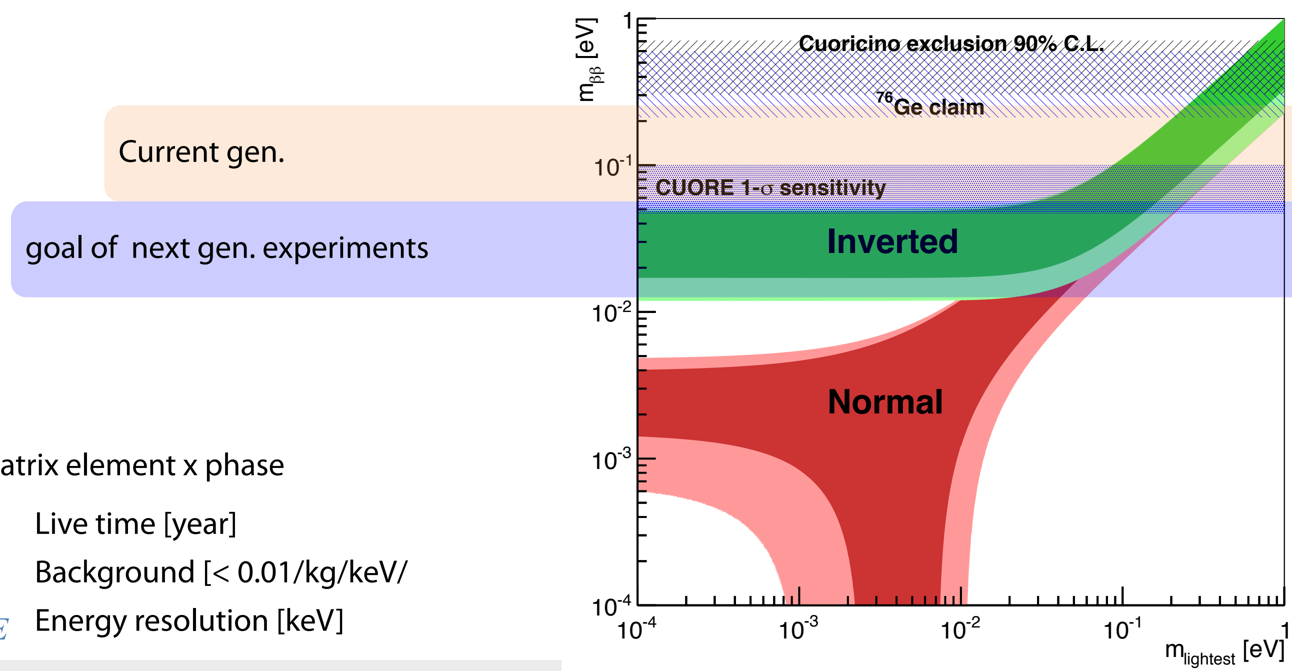
5 years lifetime of CUORE, assuming a background index of 0.01 counts/kg/keV/y,

spectrum is fitted with a flat background plus 3 peaks (^{60}Co, 0νββ and ^{208}Tl).

Beyond CUORE: ^{130}Te Enrichment



- Natural next step for CUORE
  - Increase # of parent nuclei, not the detector mass (# of background events)
- ^{130}Te enrichment is relatively cheap at $17K/kg
  - Compared to ^{76}Ge enrichment at $100/g
- 500 gram of enriched ^{130}Te metal is sent to SICCAS for enriched crystal growth.

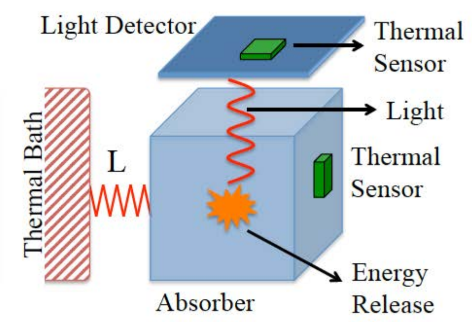


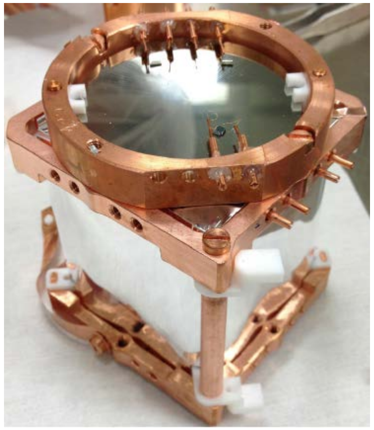
$$m_{\beta\beta} \sim \frac{m_e}{\sqrt{F_N \cdot \varepsilon \cdot \eta \sqrt{\frac{M\cdot t}{b\cdot \delta E}}}}$$

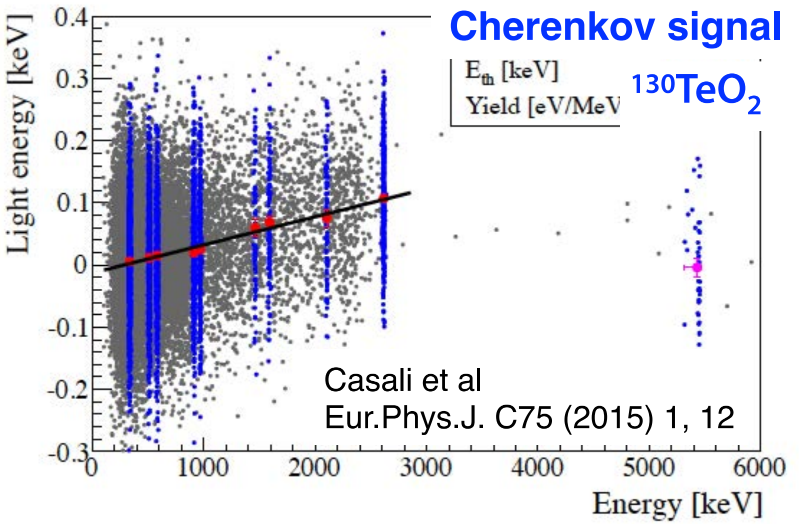
F_N	Nuclear figure of merit: nuclear matrix element x phase		
ε	Detection efficiency	t	Live time [year]
η	Isotopic abundance	b	Background [< 0.01/kg/keV/
M	Detector total mass [kg]	δE	Energy resolution [keV]

Beyond CUORE: Particle ID with Light Detectors

phonon+photon

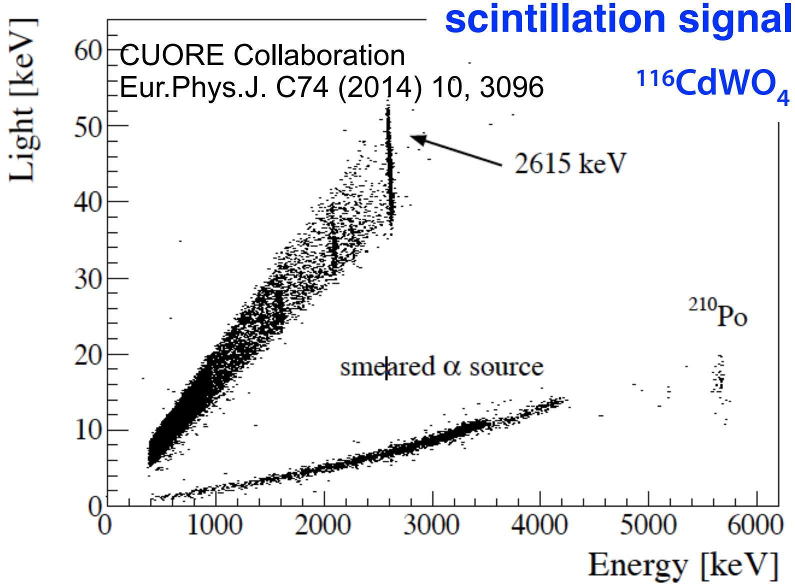






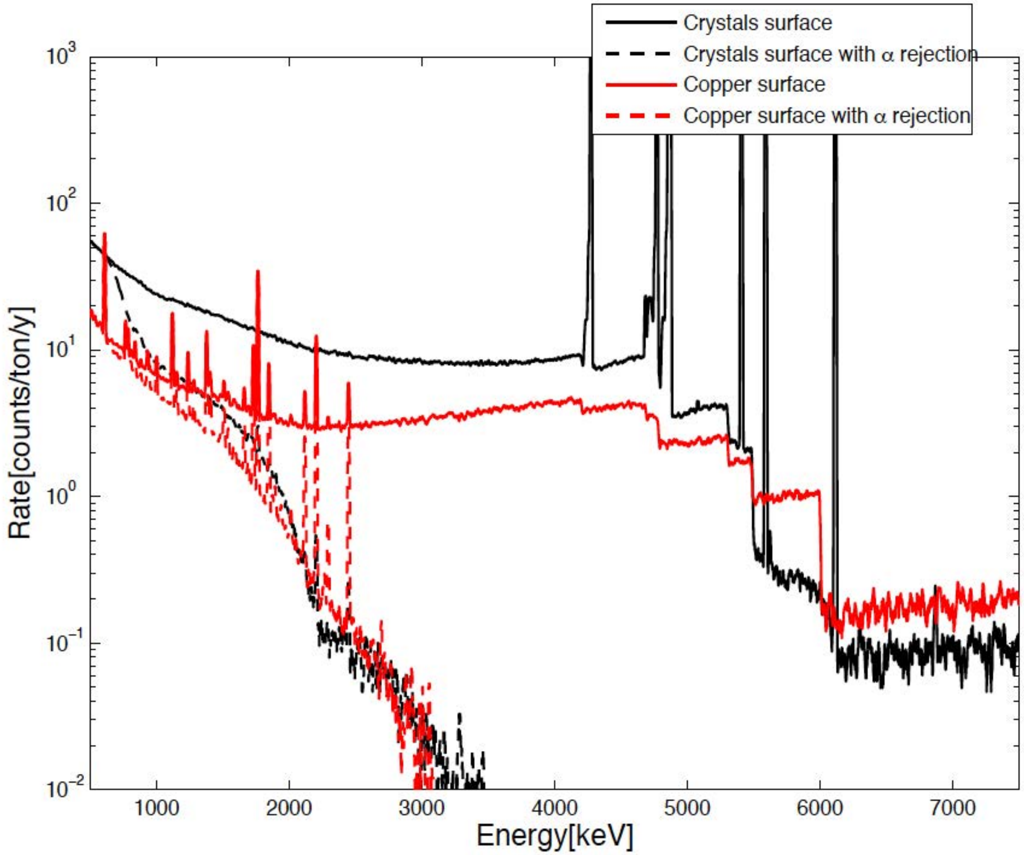
- Cherenkov light or scintillation to distinguish α from β/γ ($^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO_4$, and $Zn^{100}MoO_4$)
- More rejection power needed: 99.9% α background suppression. Light detector R&D for better resolution.
  - –R&D on TES in US
  - –R&D on MKID in Italy
  - –R&D on NTD/Luke effect in France/LNGS
- Background free search.

$$m_{\beta\beta} \sim (M \cdot t)^{-1/2}, \text{ not } (M \cdot t)^{-1/4}$$



Beyond CUORE: Particle Identification

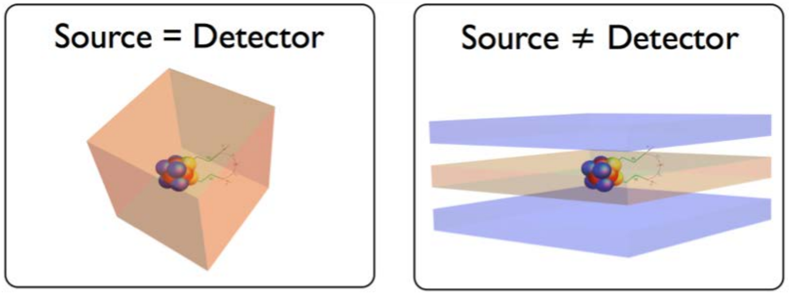
Background Rejection with Particle ID



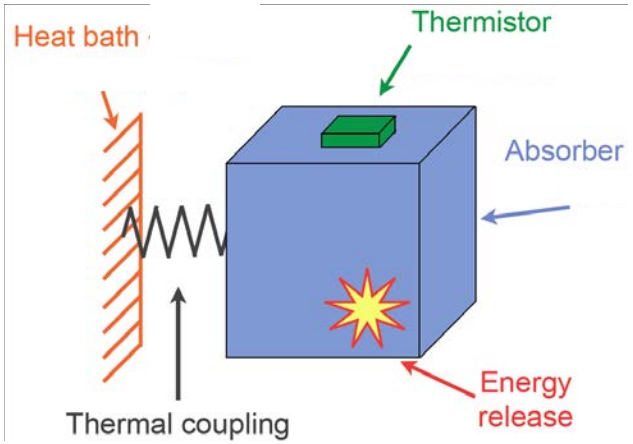
CUORE Collaboration
Eur.Phys.J. C74 (2014) 10, 3096

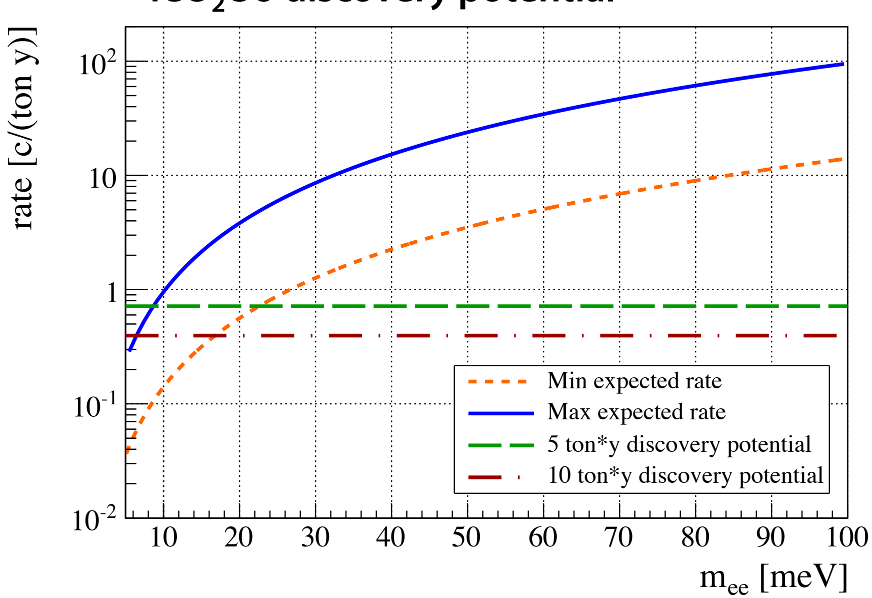
^{238}U with 5μm depth profile on TeO_2 and detector copper surfaces; assume 5σ α-β separation

Beyond CUORE: Different Isotopes



- Bolometer utilizes only the low heat capacity of dielectric crystal.
- High efficiency and flexibility in candidate isotope choices.
- Especially valuable for discovery confirmations in different isotopes.





90% sensitivity limits

Crystal	Exposure [ton·y]	half-life sensitivity [10^{27}y]	$\lvert m_{ee}\rvert_S$ [meV]
ZnSe	5	3.3	9 - 26
	10	6.5	6 - 18
$CdWO_4$	5	1.5	14 - 26
	10	3.0	10 - 18
$ZnMoO_4$	5	0.9	11 - 32
	10	1.4	9 - 25
TeO_2	5	3.4	8 - 22
	10	6.8	6 - 16

Summary & Outlook

CUORE builds on the success of CUORICINO and its predecessors

- **CUORE-0** has been running since March 2013
  - confirms the Cuoricino background model and successful background mitigation
  - goal of < 5 keV FWHM for ROI energy resolution reached
  - data taking for $0\nu\beta\beta$
- **CUORE**
  - tower assembly is complete and cryogenic system commissioning underway.
  - physics data taking expected to start in late 2015.
  - with 206 kg of ^{130}Te and 5 keV energy resolution, is able to reach 51-133 meV effective Majorana mass.
- **Beyond CUORE**: R&D effort is underway. Large bolometers offer path towards exploring the inverted hierarchy.
  - enrichment
  - light detection
  - different isotopes
  - muon veto
  - materials screening

CUORE Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

SAPIENZA UNIVERSITÀ DI ROMA

Lawrence Livermore National Laboratory

Universidad Zaragoza

UNIVERSITY OF SOUTH CAROLINA

CSNSM

SINAP

BERKELEY LAB

UCLA