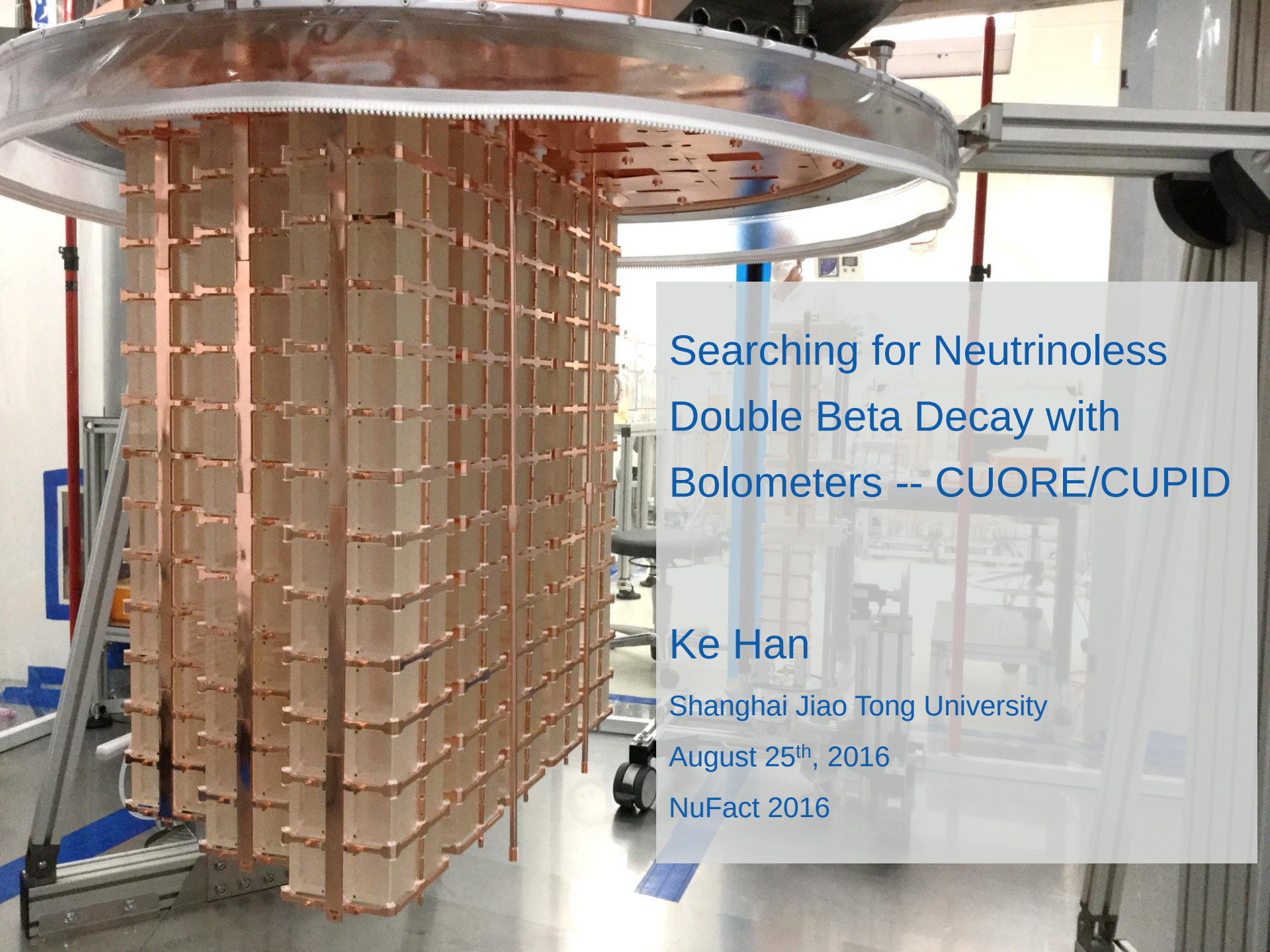


Searching for Neutrinoless Double Beta Decay with Bolometers -- CUORE/CUPID

Ke Han

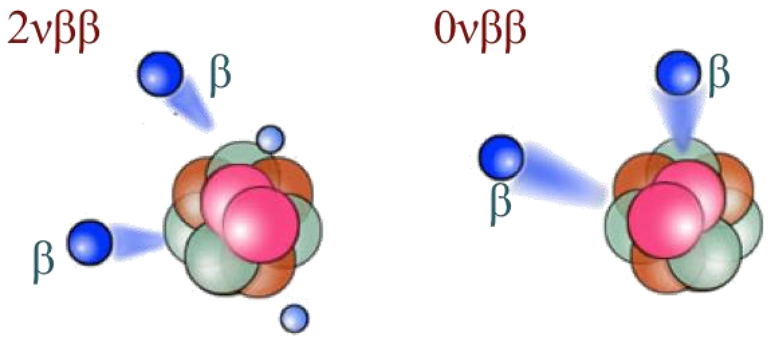
Shanghai Jiao Tong University

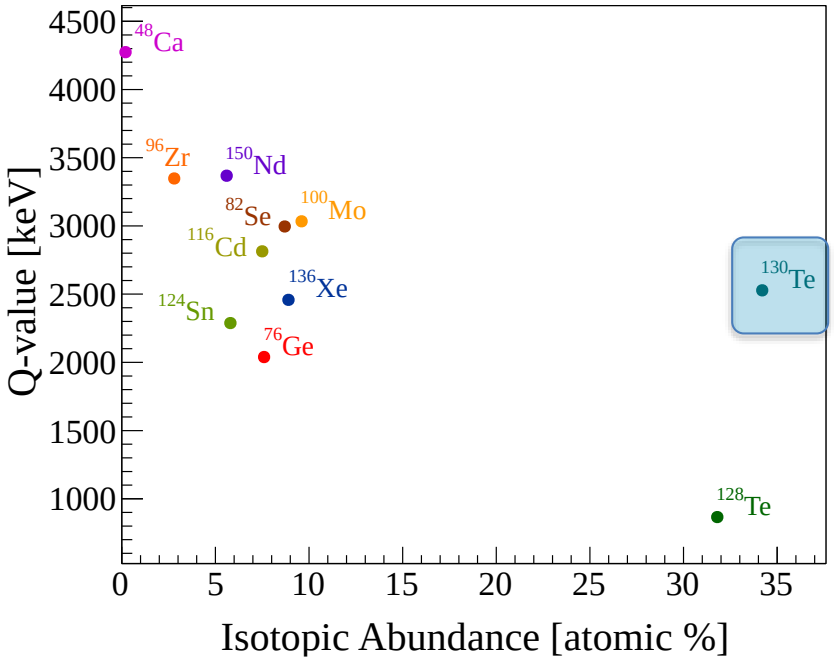
August 25th, 2016

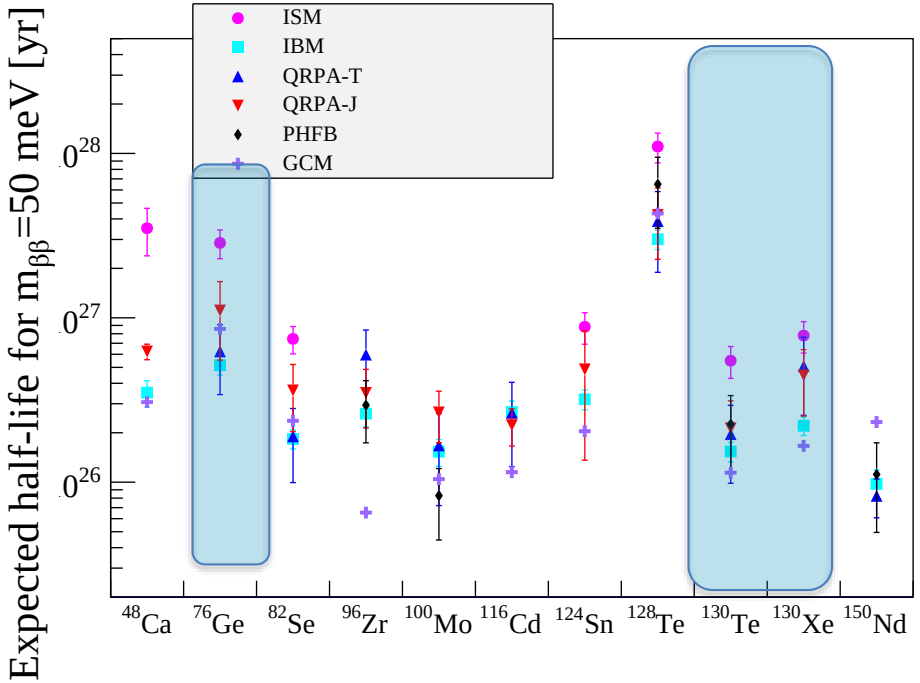
NuFact 2016

Double beta decay in experiments

- Extremely rare events $T_{1/2} > 10^{24}$ year.
- Experimentally try to search for a peak on the spectrum of total energy of electrons.
- ^{130}Te: isotopically abundant and favorable in terms of half-life requirement



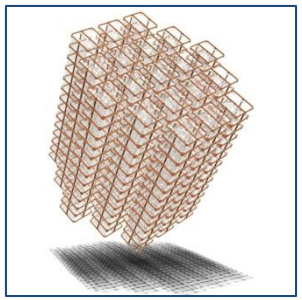




Detection channels

$$(T_{1/2}^{0\nu})^{-1} = F_N \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

Phonons



CUORE

AMoRE

CUPID

Electrons/holes

GERDA

Majorana

COBRA

PandaX-III

EXO

NEXT

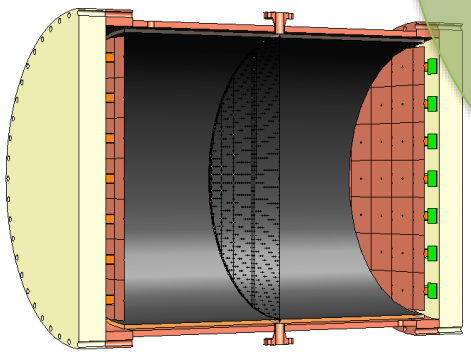
SuperNEMO

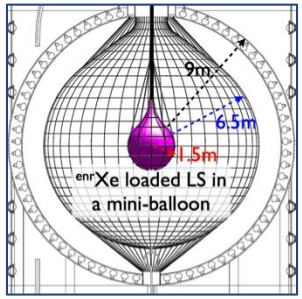
KamLAND-Zen

SNO+

CANDLES

Photons

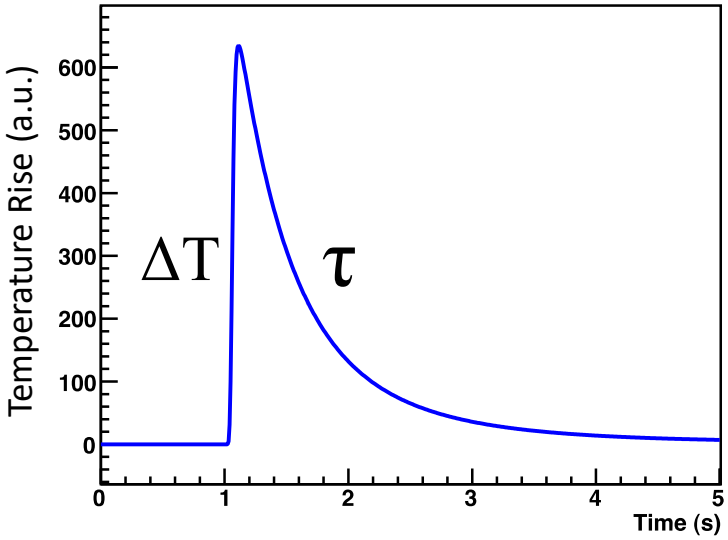




Large mass bolometer

Bolometer: measure energy via temperature change

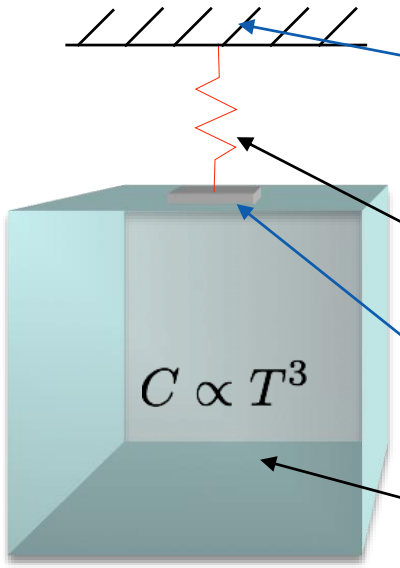
$$\Delta T = \frac{E}{C} \qquad t \sim \frac{C}{G}$$



CUORE: TeO_2 crystals

$5\times5\times5$ cm^3, 750 g

ΔT = 0.1 mK/MeV at 10 mK base temperature

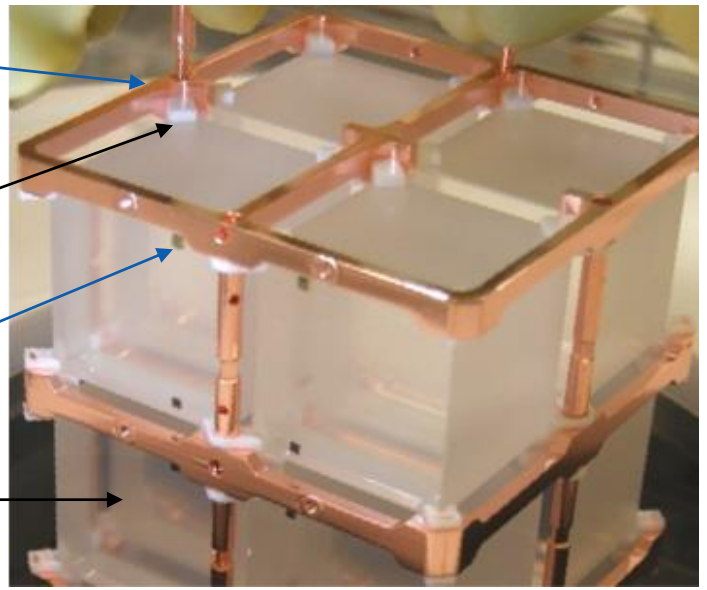


Heat bath (~10mK): Cu frames

Thermal coupling: PTFE supports

Ge-NTD Thermistor

Absorber TeO_2 crystal



Arrays of TeO_2 bolometers

Cuoricino
(2003-2008)

Astropart. Phys. **34**, 822–831 (2011)

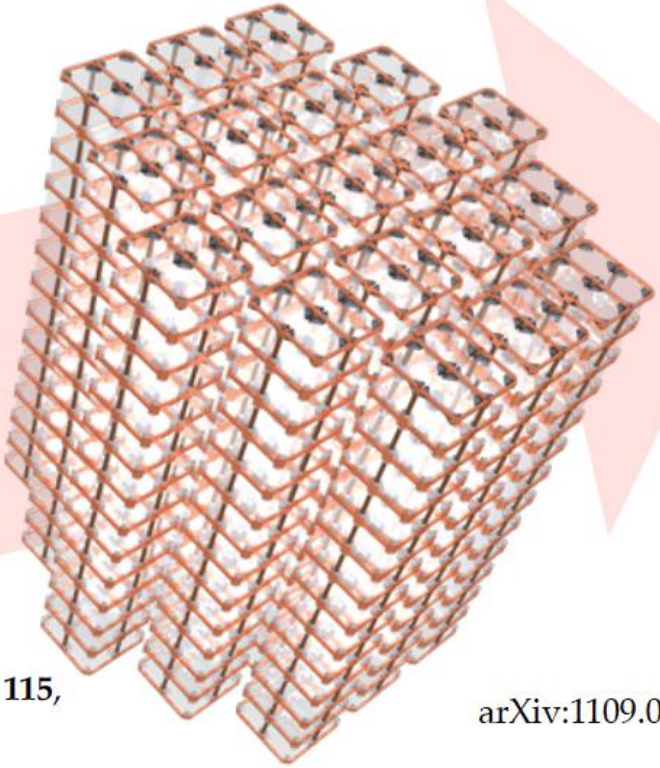
+

CUORE-0
(2013-2015)

Phys. Rev. Lett. **115**, 102502 (2015)

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

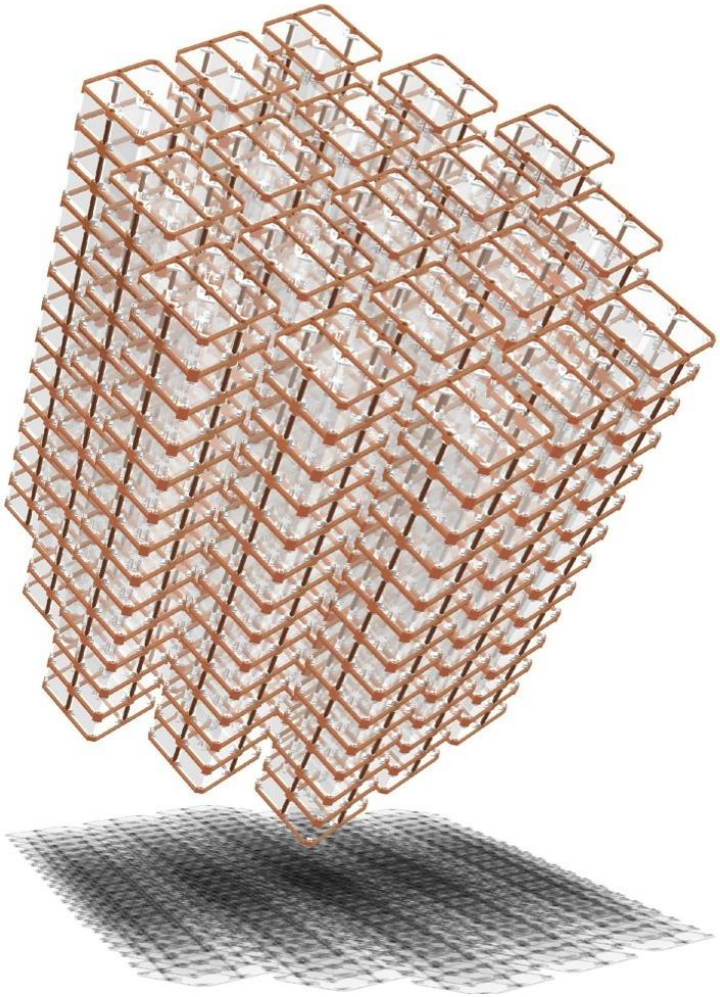
CUORE
(2016-2020)



arXiv:1109.0494

Projected:
$T_{1/2}^{0\nu\beta\beta} > 9.5 \times 10^{25}$ yr (90% C.L.)
$m_{\beta\beta} < 50 - 130$ meV

CUORE (Cryogenic Underground Observatory for Rare Events)



- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 19 Towers
  - 13 floors
  - 4 modules per floor
  - 741 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- 10 mK base temperature in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy

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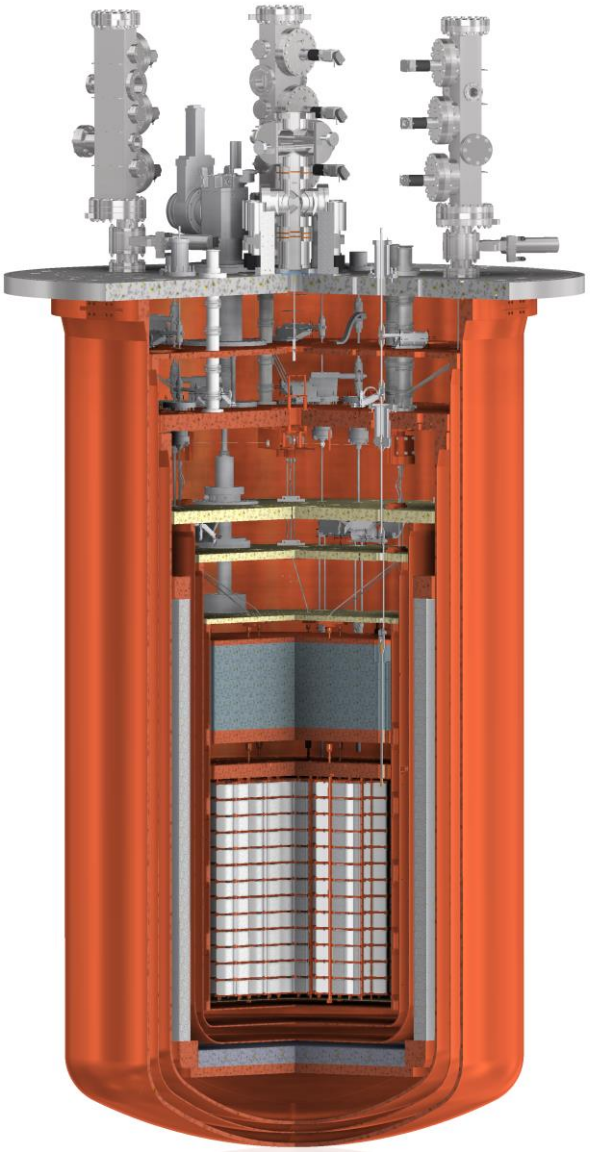

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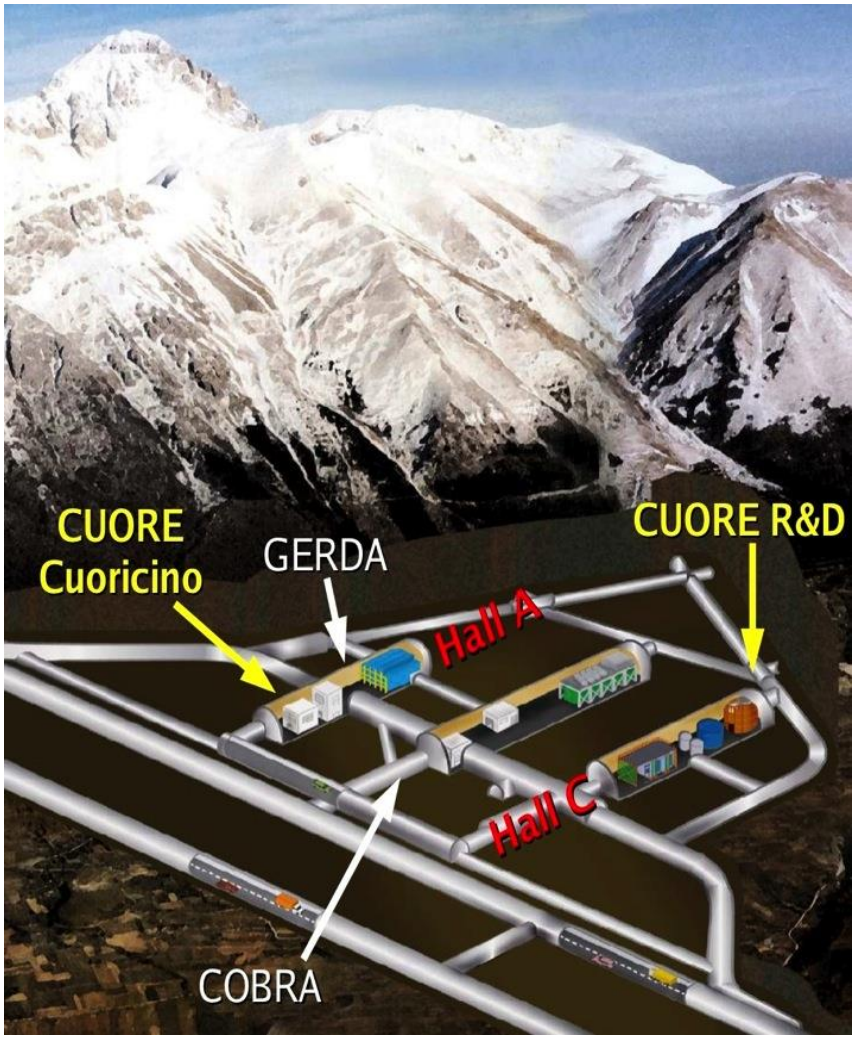

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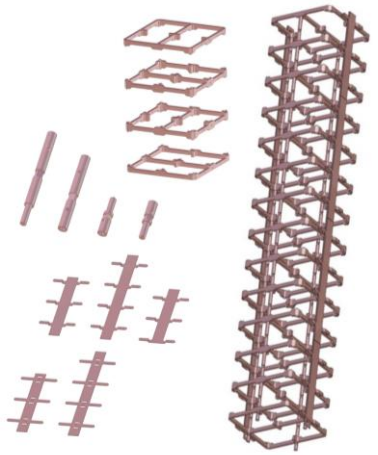
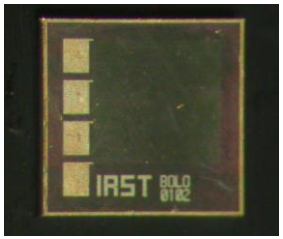
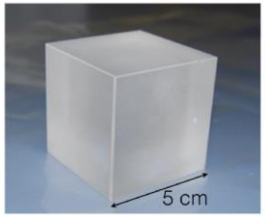
CUORE-module: a tower



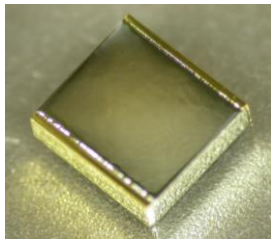
~2000 Cu NOSV components



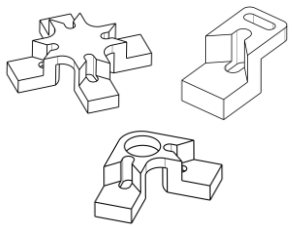
52 Si heaters



52 TeO_2 crystals



52 Ge thermistors

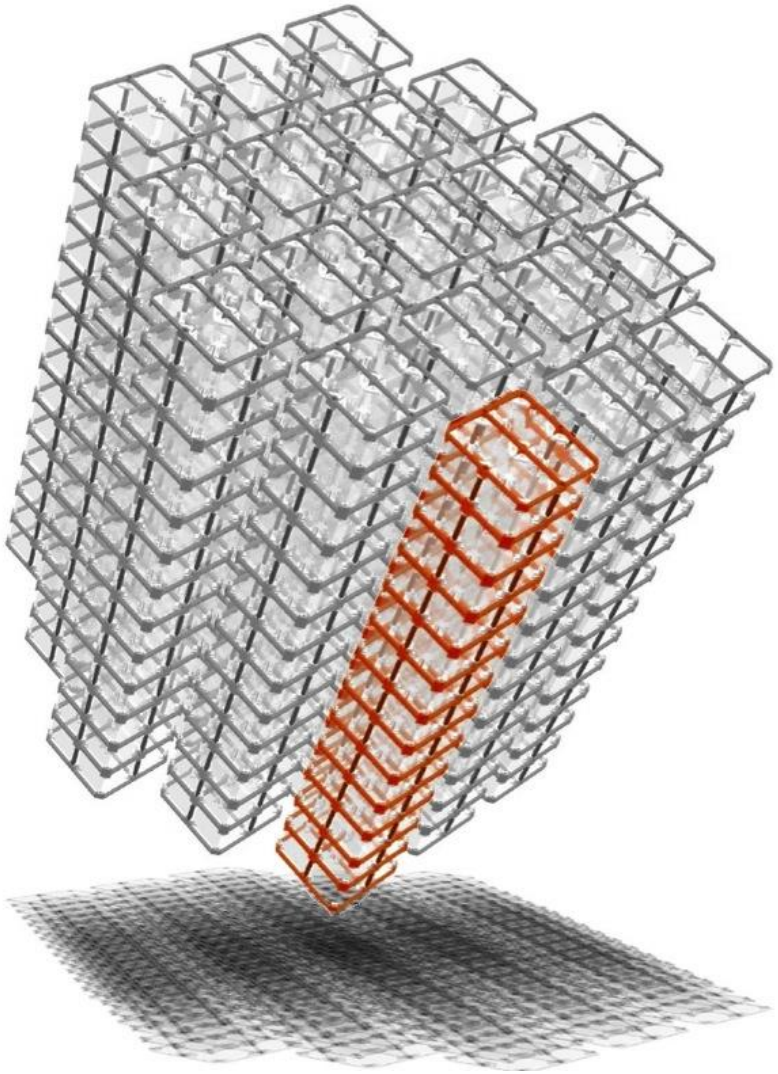


234 PFTE holders

8 Cu-PEN cables

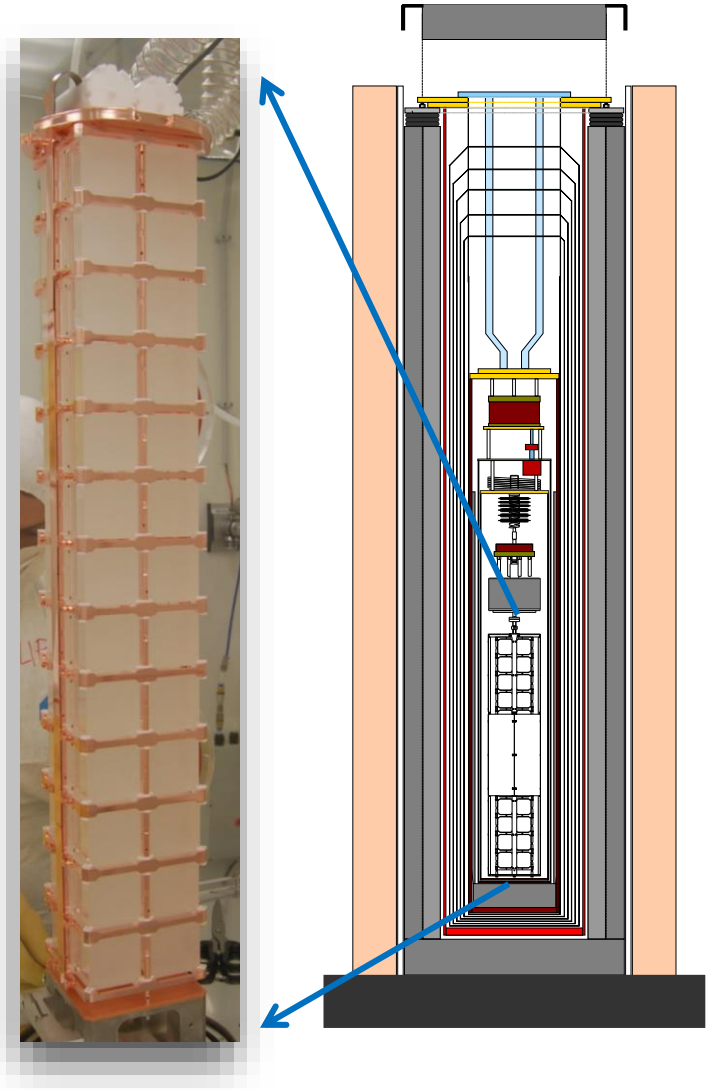
- New detector design structure
- Strict material selection (e.g. raw materials)
- Strict surface cleaning technique for Cu and TeO_2
- Minimization of Rn exposure (Glove Box assembly)

CUORE-0



- The first CUORE tower assembled with CUORE standards
  - Cleaning components
  - Assembly procedure
- Tower Properties
  - 52 crystals, total mass 39 kg
  - Total ^{130}Te mass 11 kg
- CUORE-0 tower was installed in the original Cuoricino cryostat.
- Data taking: March 2013 to Aug 2015.
- 9.8 kg · yr of ^{130}Te exposure
- Reached CUORE goal of 5 keV FWHM around Q-value

CUORE-0



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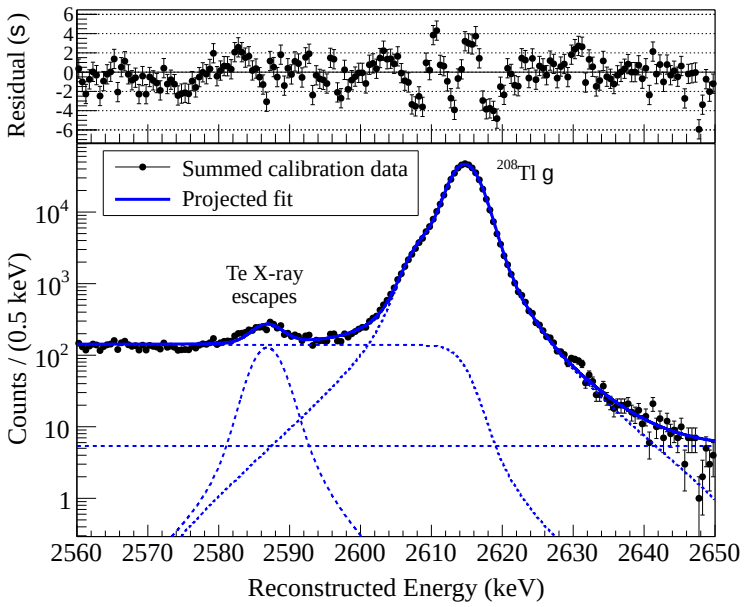
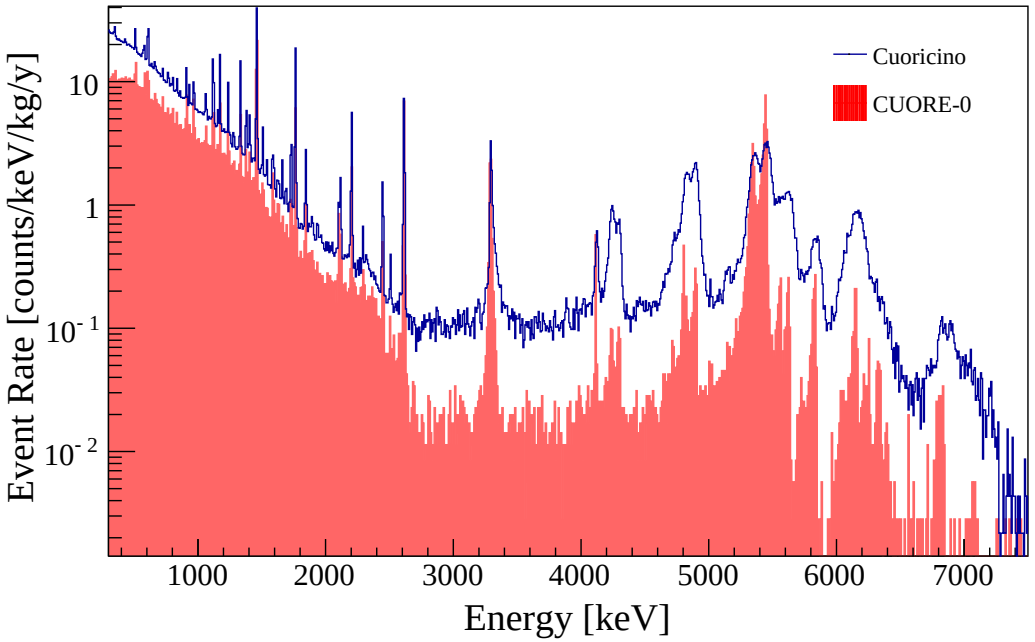
Detector performance: CUORE-0 vs. Cuoricino





keV	Average FWHM	RMS of FWHM
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

c/keV/kg/y	2.7-3.9 MeV	ROI
Cuoricino	0.110 ± 0.001	0.169 ± 0.006
CUORE-0	0.016 ± 0.001	0.058 ± 0.004

- Channel and dataset independent fit
- The 5 keV CUORE goal has been reached

~ ×6 reduction in the alpha continuum region

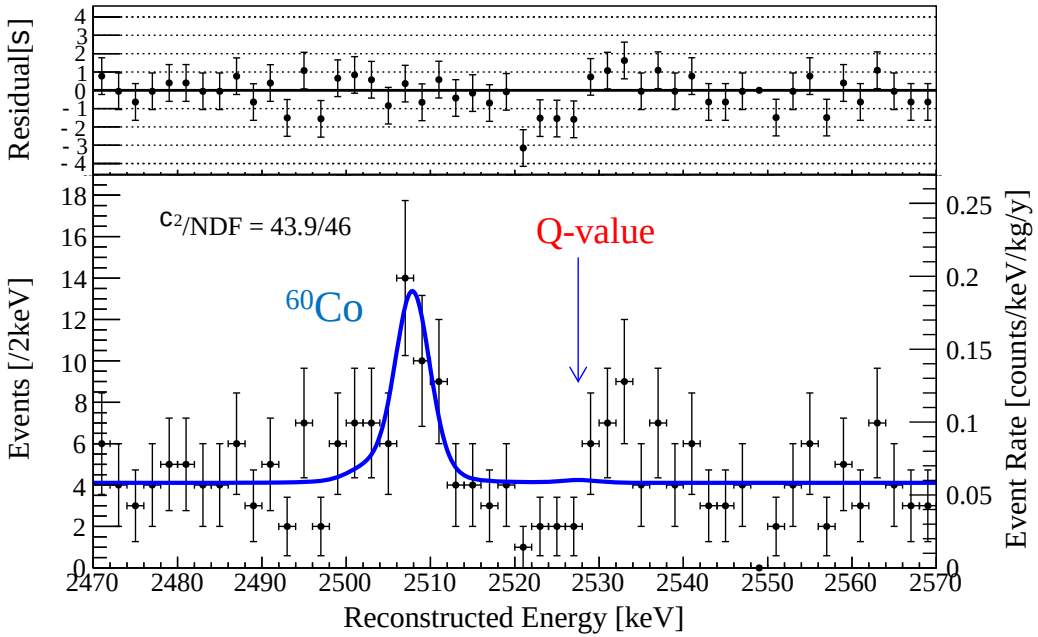
CUORE-0 $0\nu\beta\beta$ results

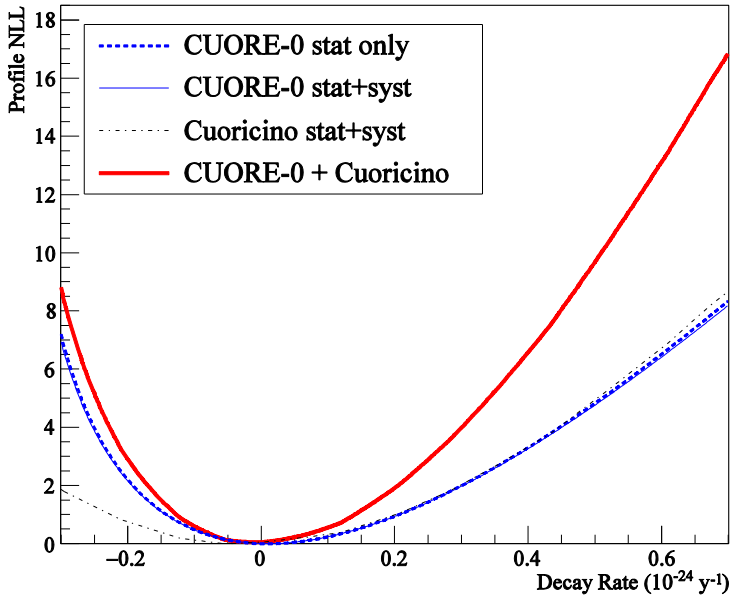
We find no evidence for $0\nu\beta\beta$ decay of ^{130}Te: $T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{24}$ yr (90% C.L.)

Fitted background: 0.058 ± 0.004 (stat.) ± 0.002 (syst.) c/(keV kg y)

Combined with Cuoricino: $T_{1/2}^{0\nu\beta\beta}$ (^{130}Te)$> 4.0 \times 10^{24}$ yr (90% CL)

Effective Majorana Mass: $m_{\beta\beta}$ <(270-650) meV





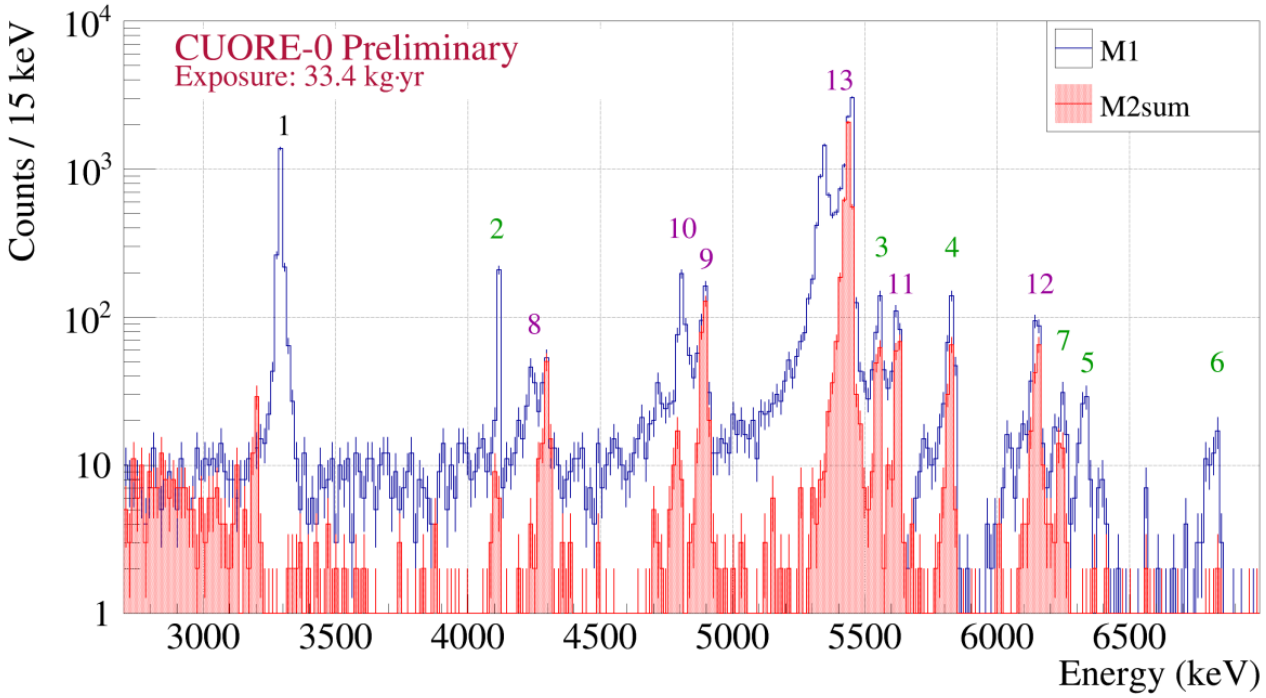
Phys. Rev. Lett. 115, 102502 (2015);
Phys. Rev. C 93, 045503 (2016)

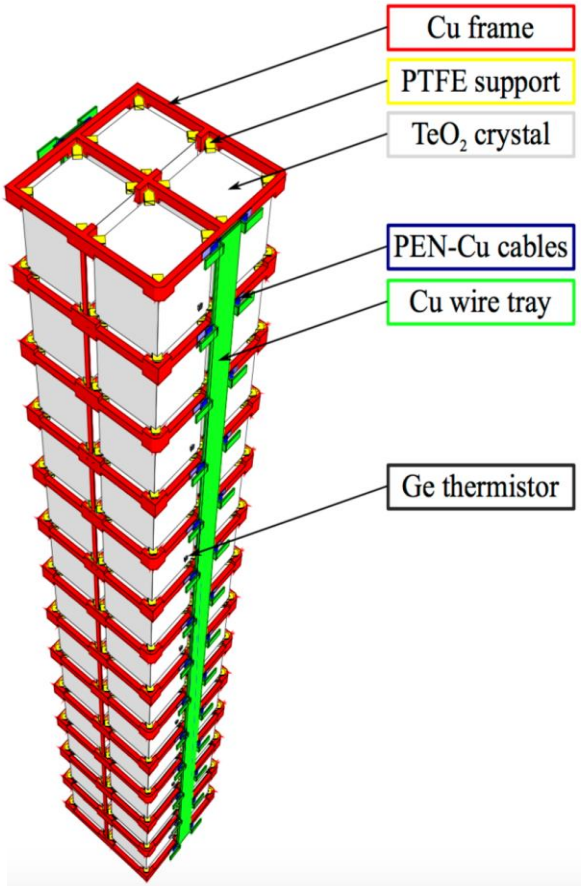
CUORE-0 background model

Identification of the background sources:

- CUORE-0 analysis
- radio-assay measurements
- cosmogenic activation analysis

Taking into account all detector/cryostat components

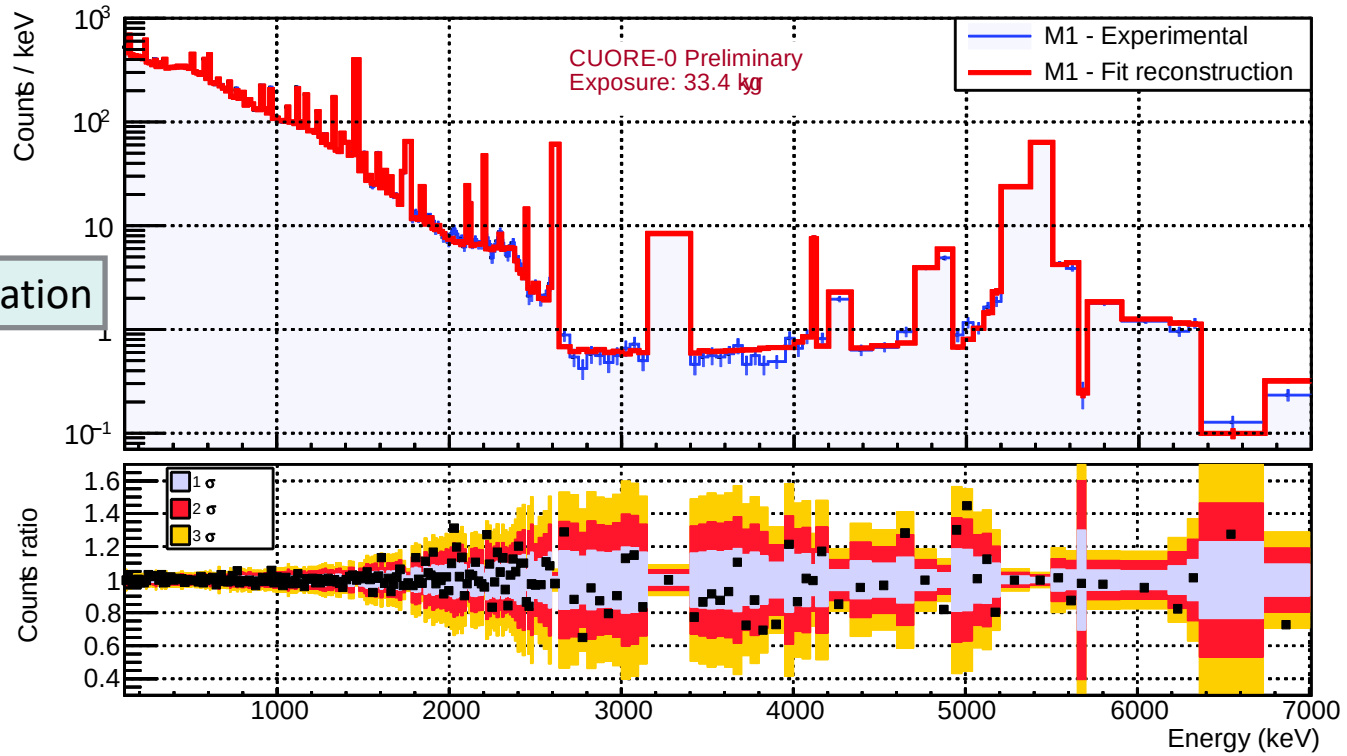


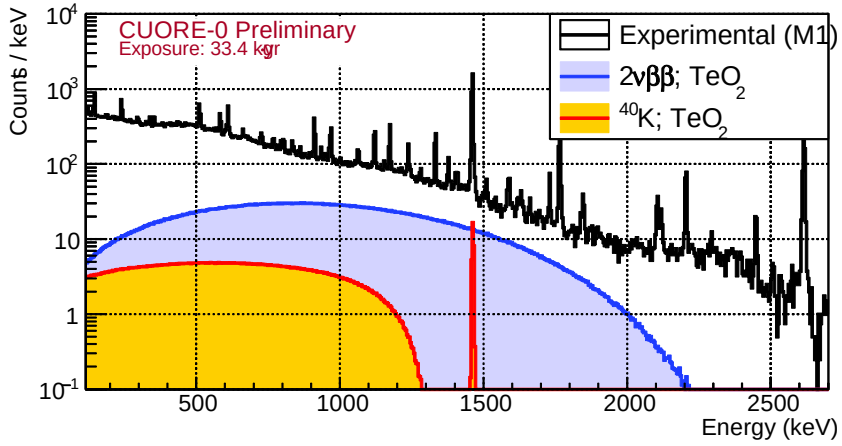


1-7 ^{232}Th decay chain
8-13 ^{238}U decay chain

Fit spectrum with 2νββ

paper in preparation





May-13-2016

$$\text{CUORE-0: } T^{2\nu}_{1/2} = [8.2 \pm 0.2\ (\text{stat.}) \pm 0.6\ (\text{syst.})] \times 10^{20}\ \text{y}$$

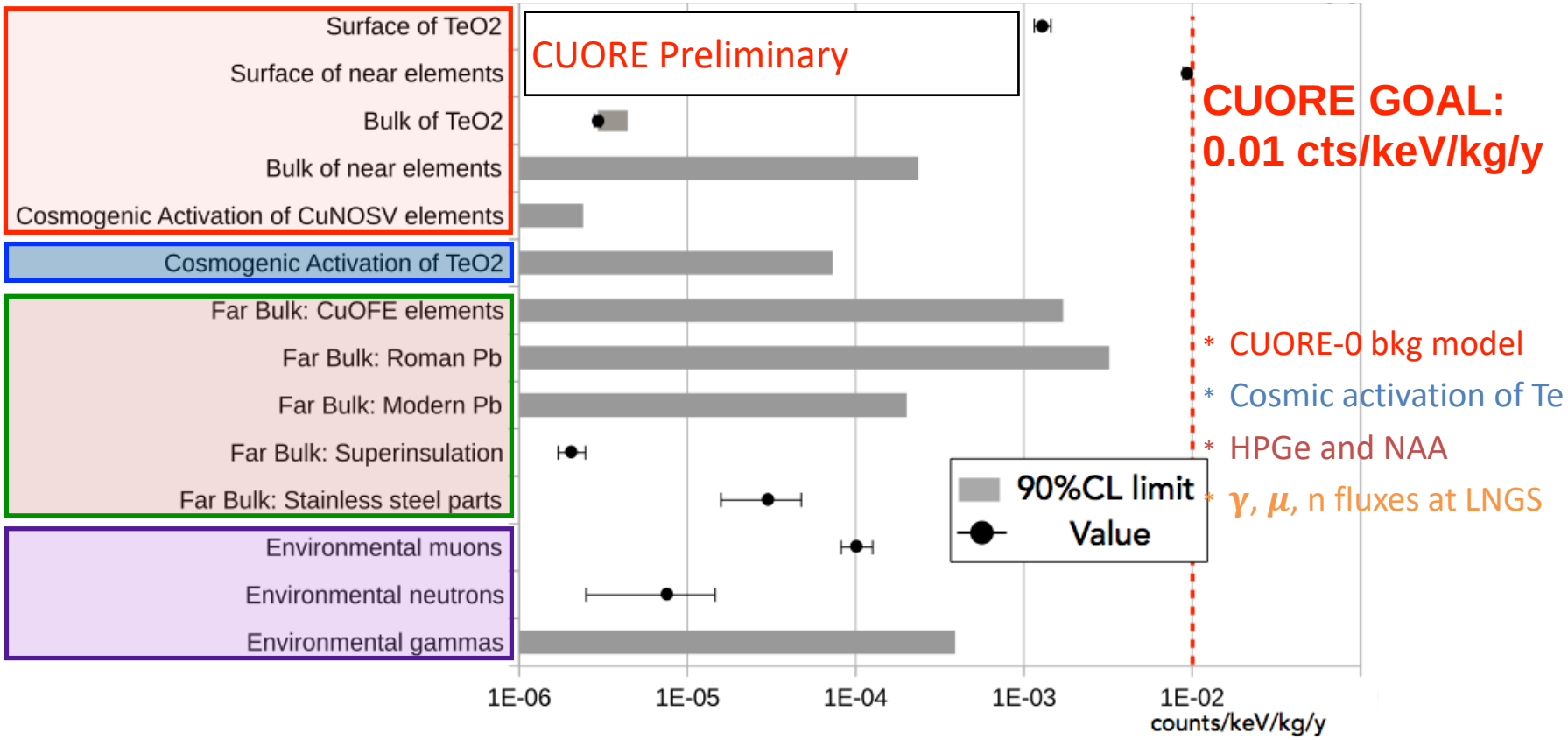
$$\text{NEMO: } T^{2\nu}_{1/2} = [7.0 \pm 0.9\ (\text{stat.}) \pm 1.1\ (\text{syst.})] \times 10^{20}\ \text{y}$$

$$\text{MiDBD: } T^{2\nu}_{1/2} = [6.1 \pm 1.4\ (\text{stat.})\ ^{+2.9}_{-3.5}\ (\text{syst.})] \times 10^{20}\ \text{y}$$

NEMO-3 Collaboration, Phys. Rev. Lett., 107, 062504 (2011).
C. Arnaboldi et al., Phys. Lett. B, 557, 167 (2003).

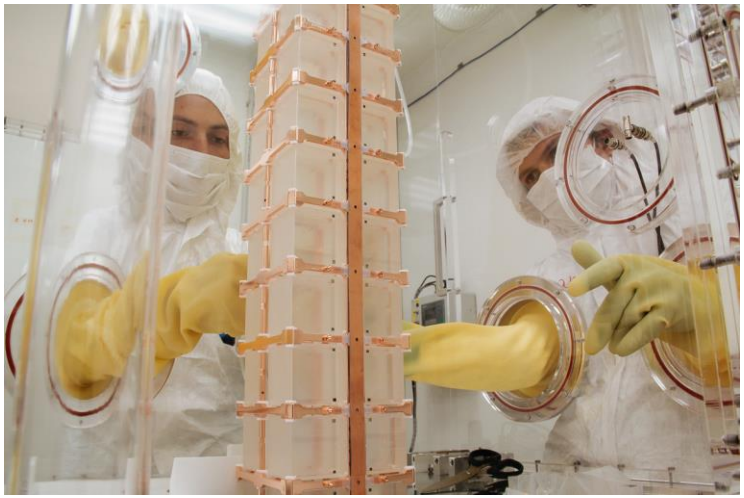
CUORE background Budget

Geometry in the MC simulations was updated to the final CUORE design

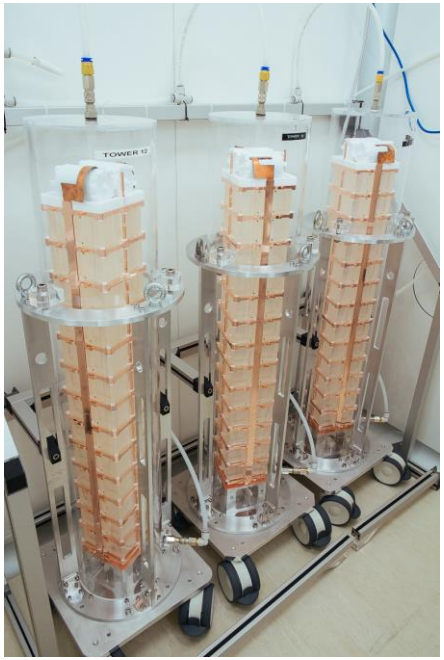


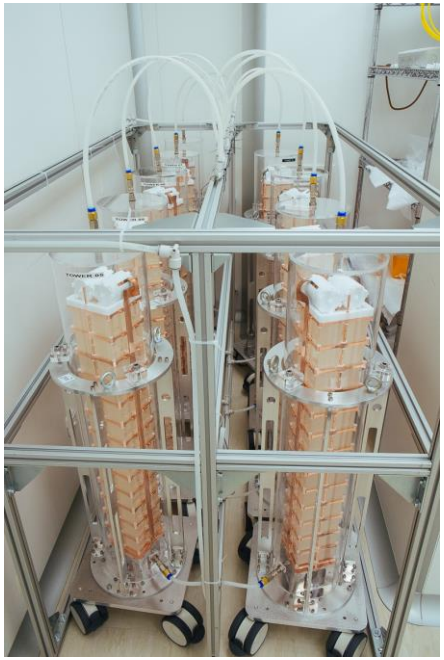
paper in preparation

Building CUORE: detector array assembly

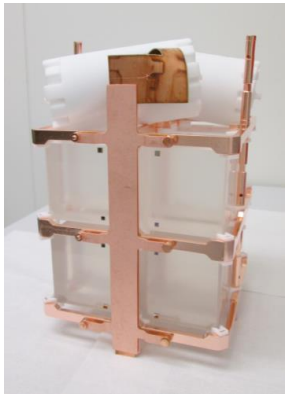


- All 19 ultraclean towers assembled by summer 2014.
- From ~10000 components
- Inside 5 glove boxes (N_2)





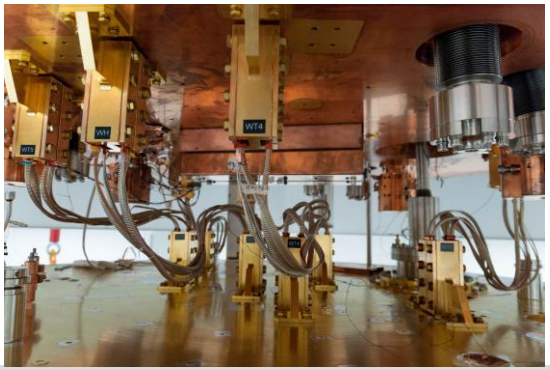
Cryogenic system commissioning

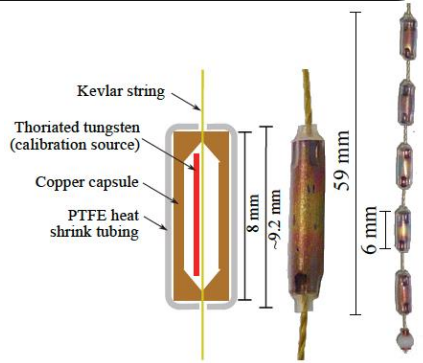


Attaching a mini-tower

Cryostat + Dilution Unit → Wiring → Top Pb shield, Towers support plate, Fast Cooling System, Calibration System → Side Roman Pb shield

- Cooling power: 3μW @ 10 mK
- Stable base T @ 6.3 mK for 70+ days

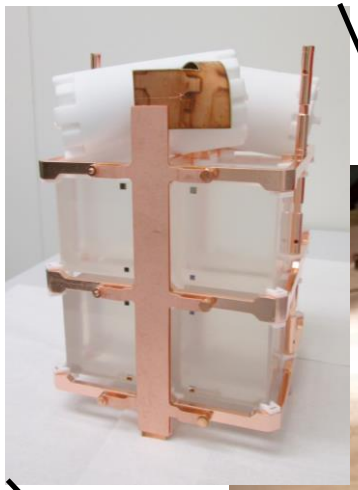


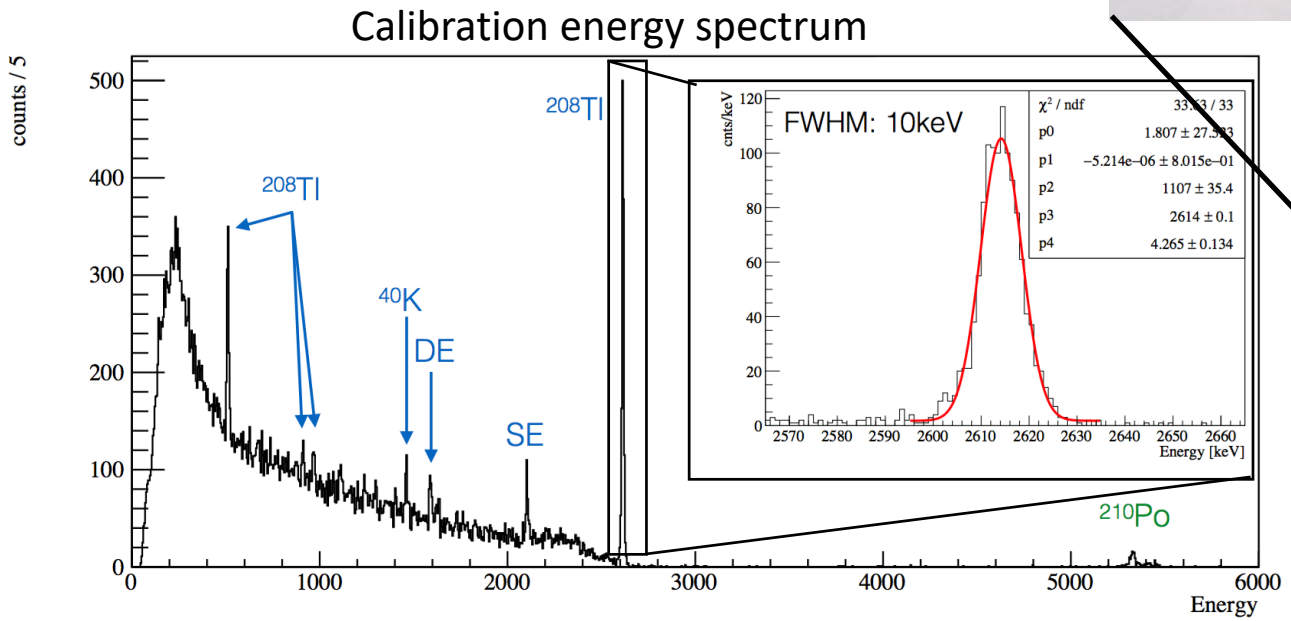


^{232}Th calibration sources deployed from 300 K to 10 mK

Mini Tower Test Run

- 8 TeO_2 bolometers (Mini-Tower)
- Stable base temperature
- Good energy resolution.
- No unexpected background sources.
- Validation of the electronics, DAQ, temperature stabilization, and calibration systems.

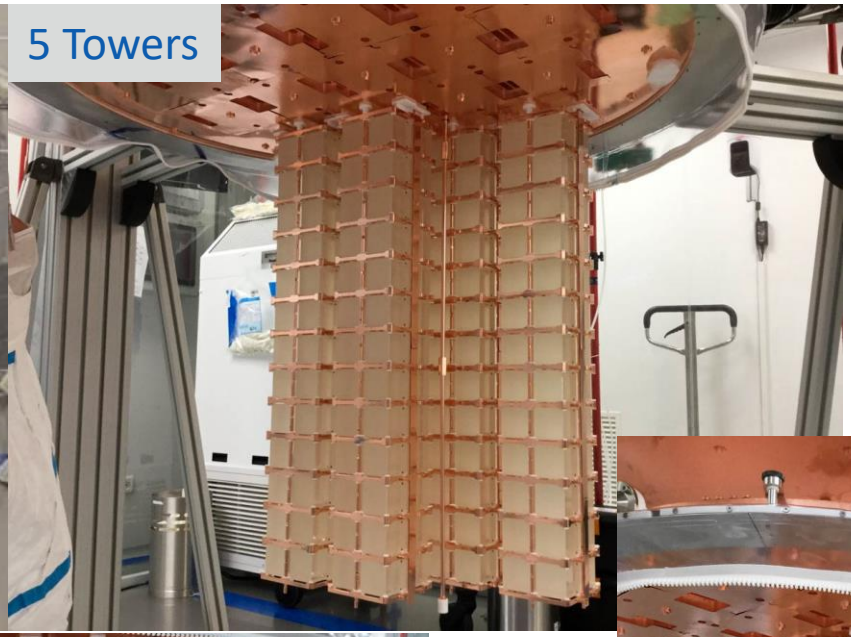




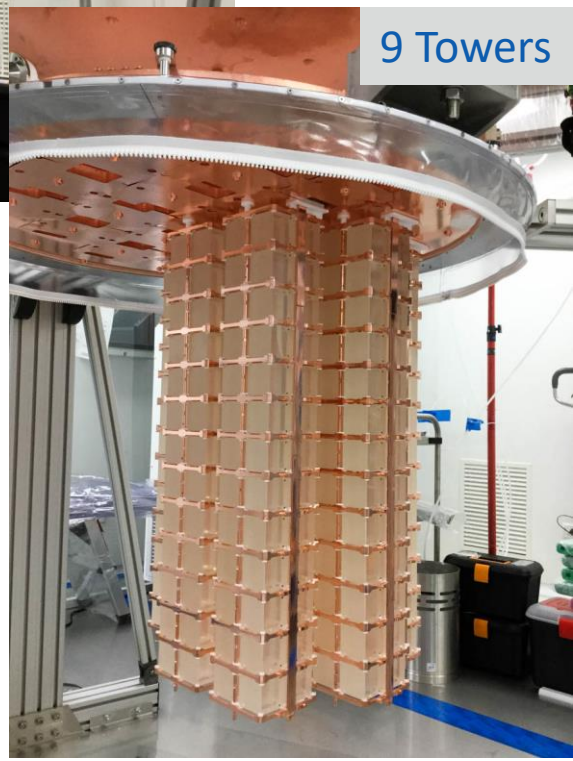
Detector installation

First Tower

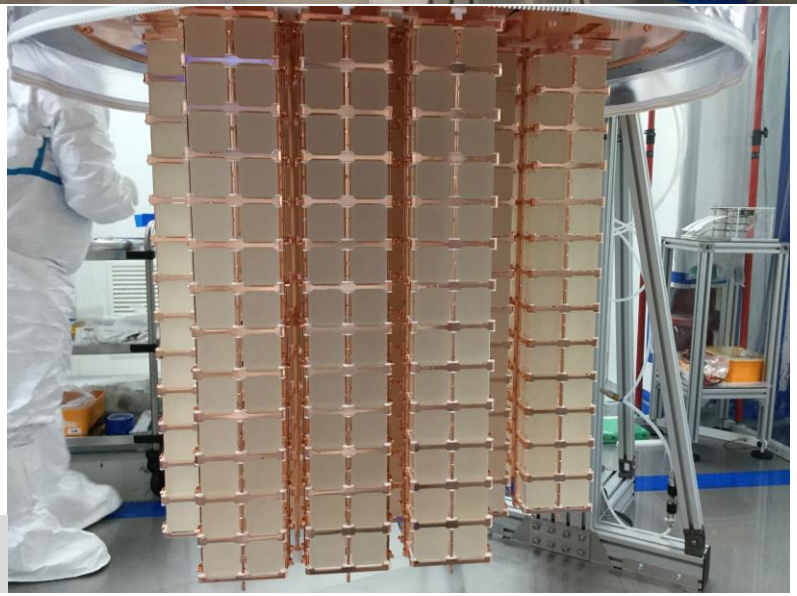
5 Towers



9 Towers



15 Towers

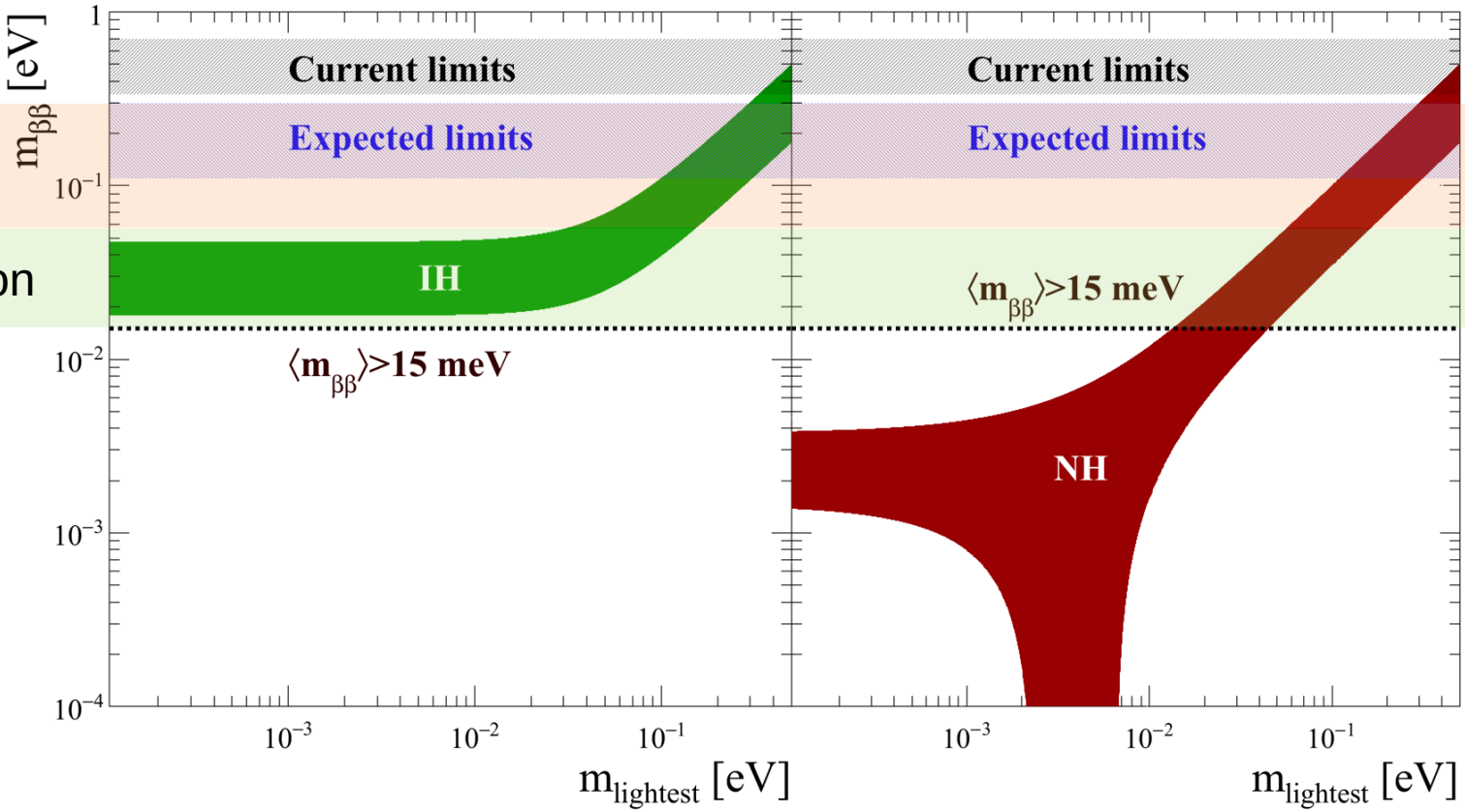


From CUORE to CUPID (CUORE Upgrade with Particle ID)

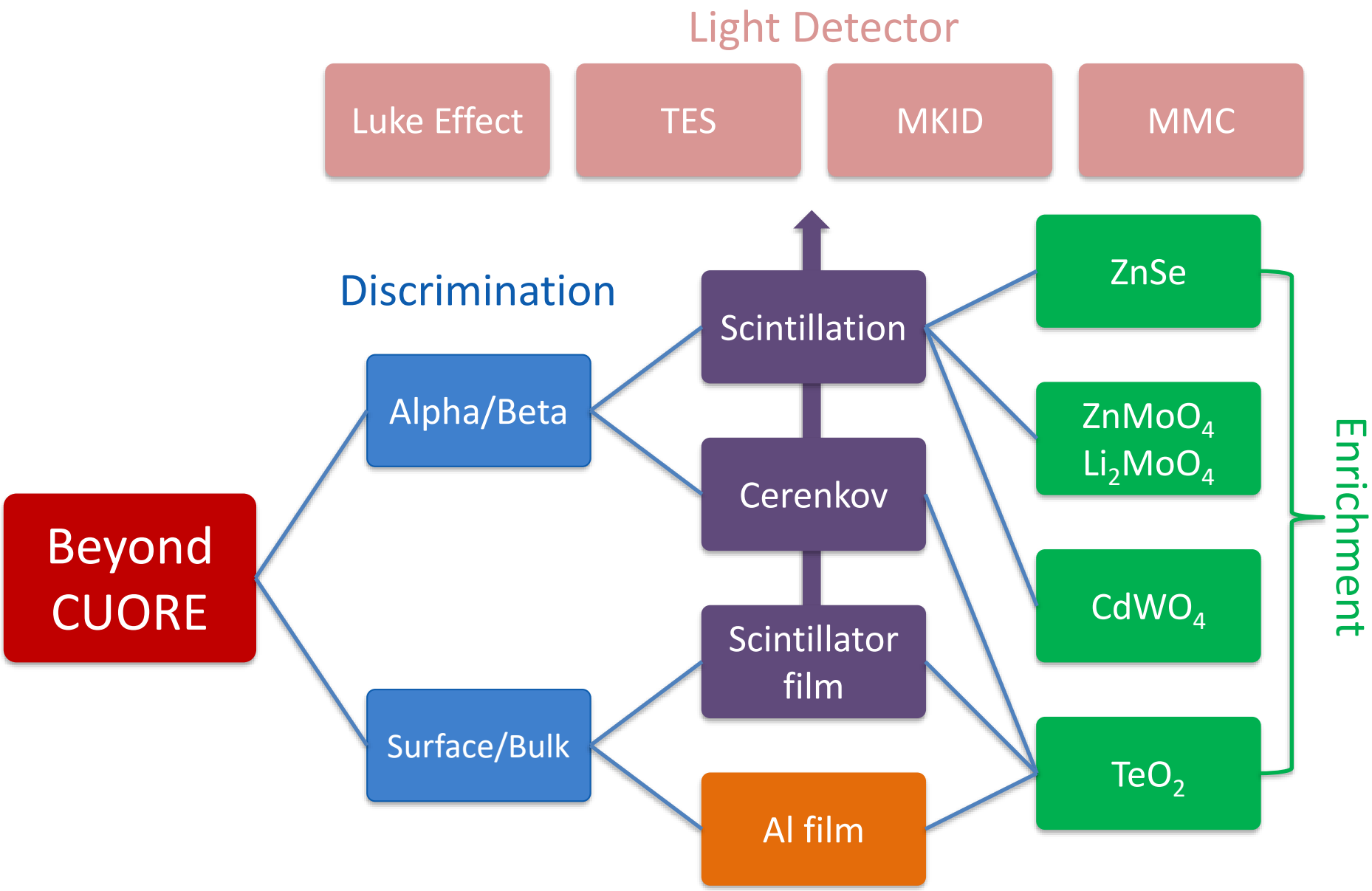
- CUORE sensitivity $T_{1/2}^{0\nu\beta\beta} = 9.5 \times 10^{25}$ y (90% CL)
- Effective Majorana mass down to 50-130 meV.
- CUPID to cover the IH region

Near future

Next Generation



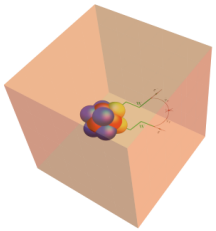
CUPID R&D options



Possibility to search 0νββ of different isotopes

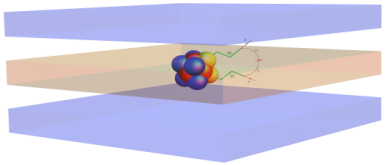
High efficiency

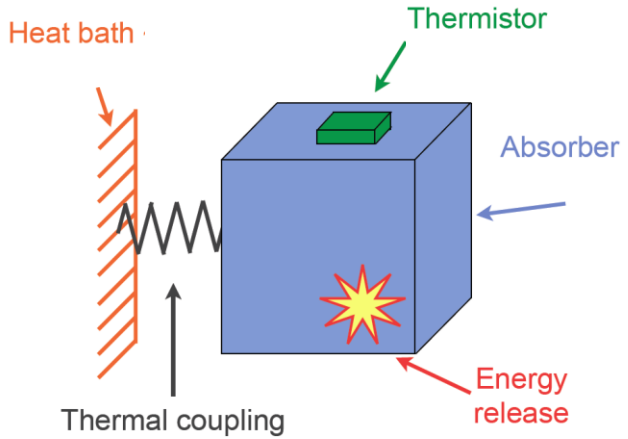
Source = Detector



Flexibility in isotope choice

Source ≠ Detector



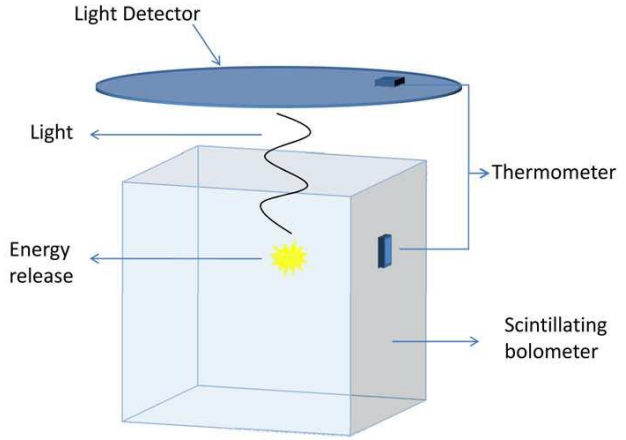


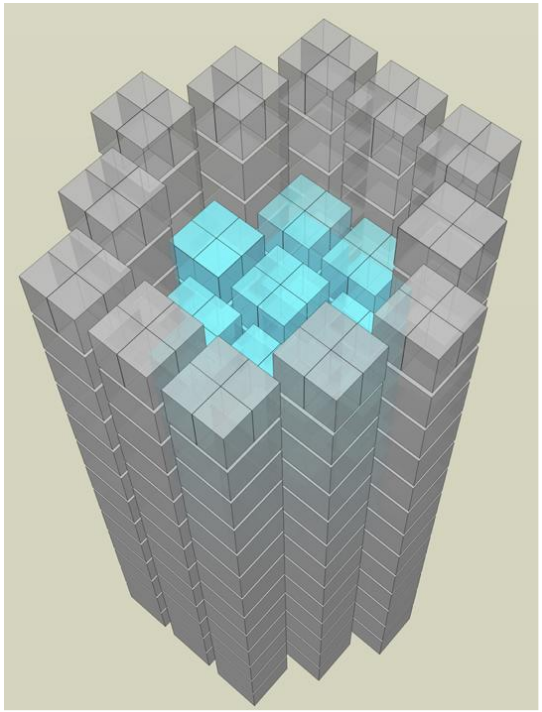
Bolometry - best of both worlds

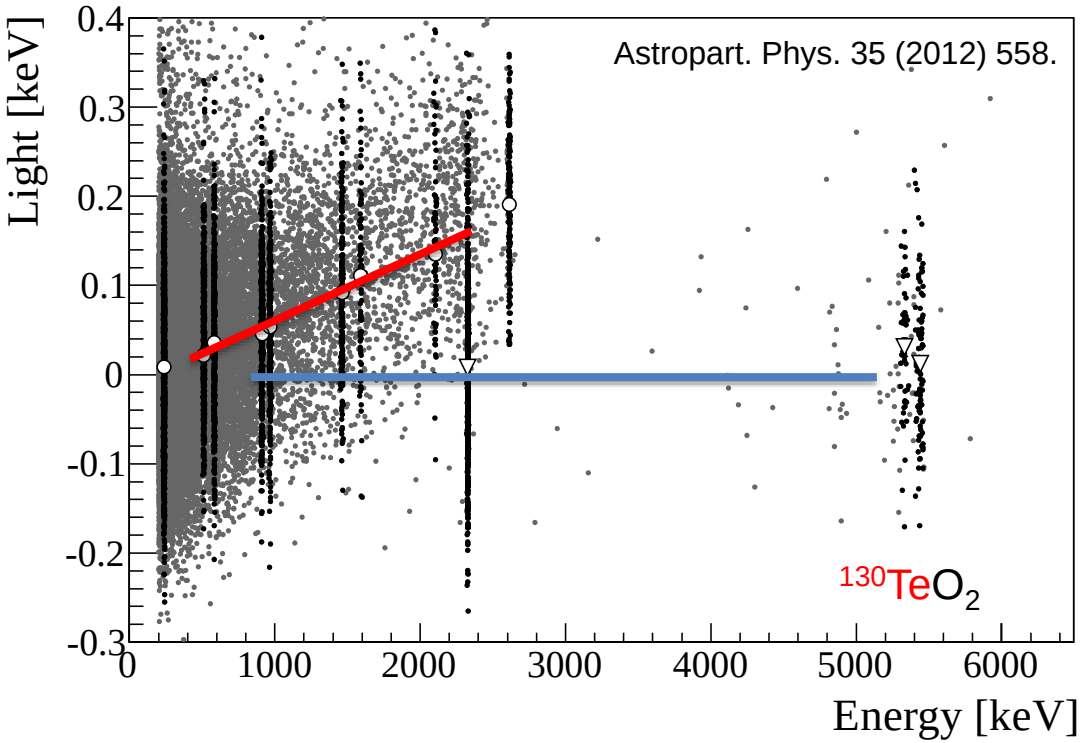
- Bolometer utilizes only the low heat capacity of dielectric crystal.
- High efficiency and flexibility in candidate isotope choices.
- Especially valuable for discovery confirmations in different isotopes.

Enriched TeO_2 crystals with Cerenkov light

- Active R&D on light collectors for better resolution
  - 99.9% α background suppression
- Testing 4 enriched crystals
  - Crystal lattice quality
  - Bolometric performance

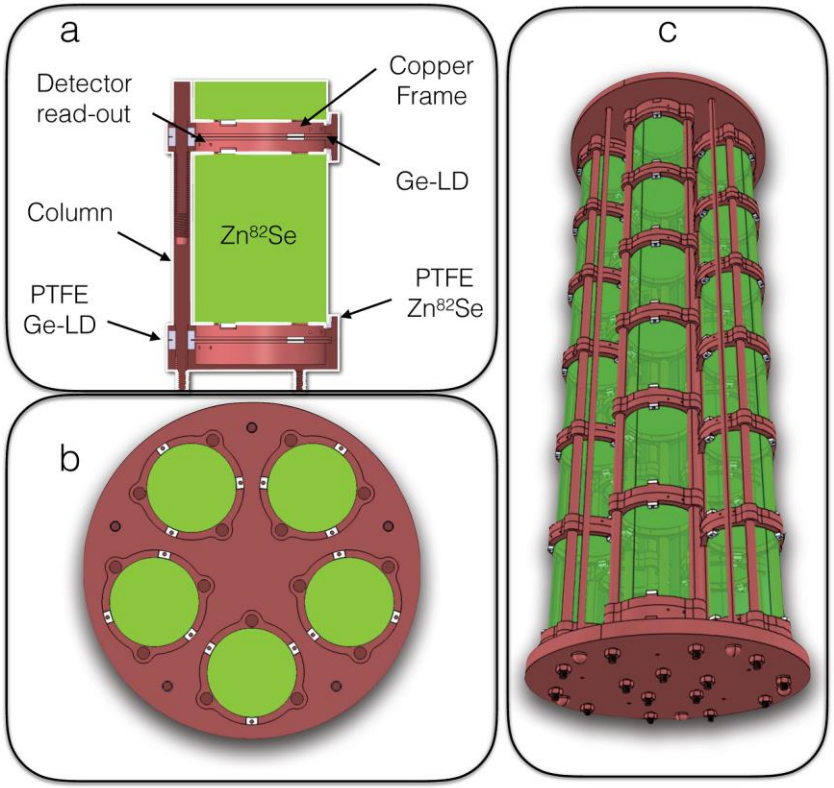


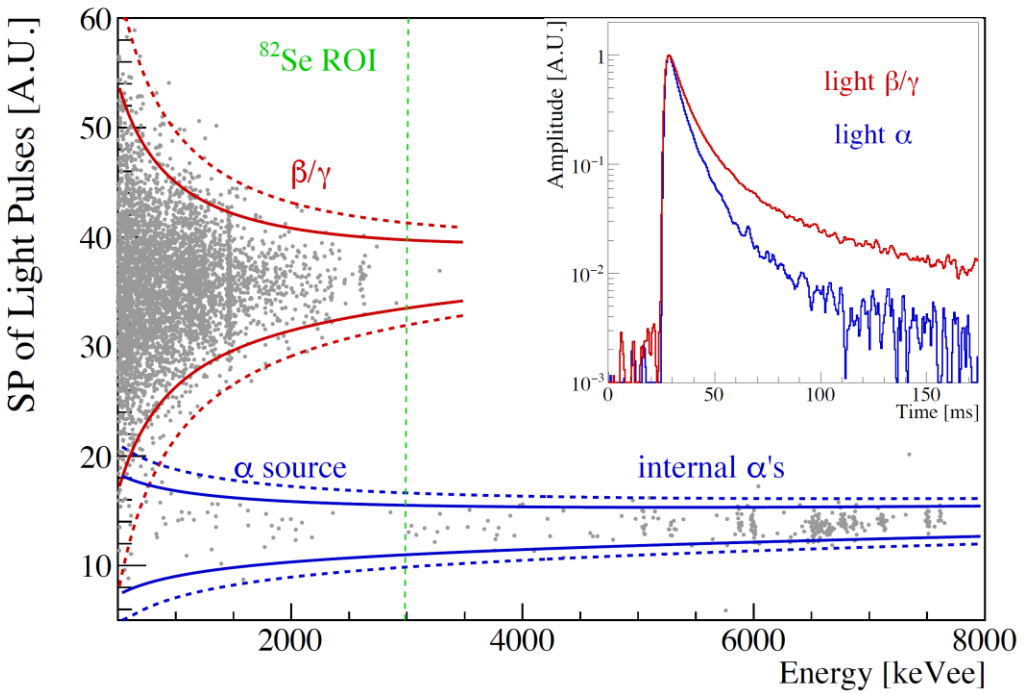




The ZnSe tower

- Search for 0νββ of ^{82}Se
- Will be installed in the Cuoricino/CUORE-0 cryostat
- Great background rejection power
- CUPID-0



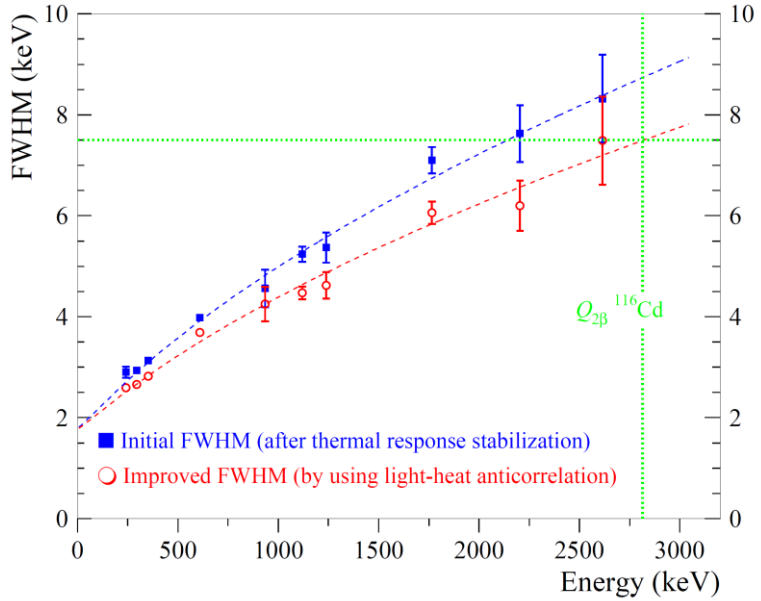


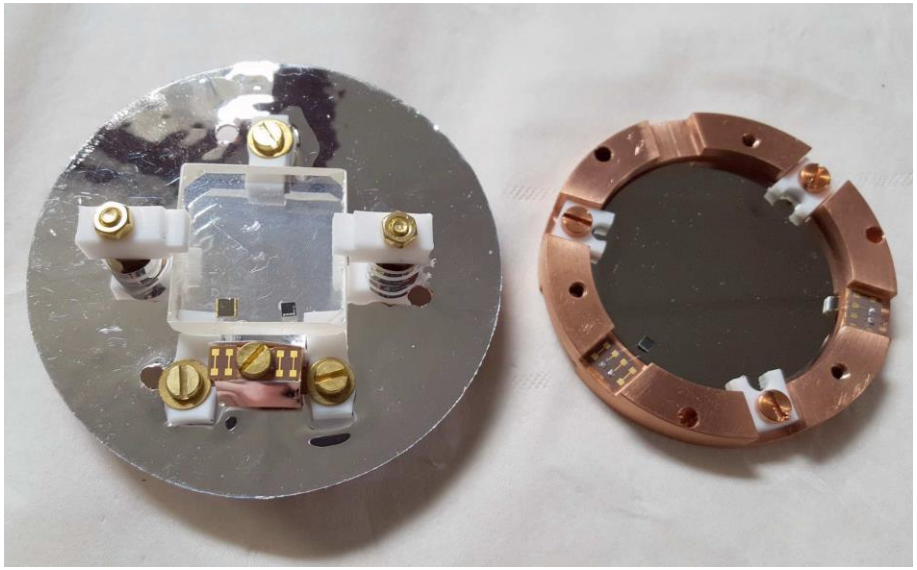
Eur. Phys. J. C (2016) 76: 364. arXiv:1605.05934

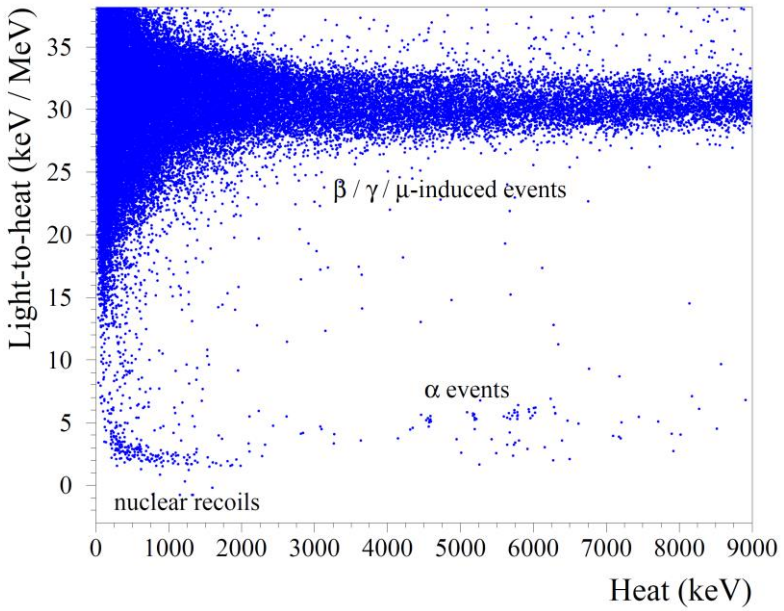
$CdWO_4$ bolometer for 0νββ

- Search for 0νββ of ^{116}Cd
- Great background rejection power via the light channel

- arXiv: 1606.07806



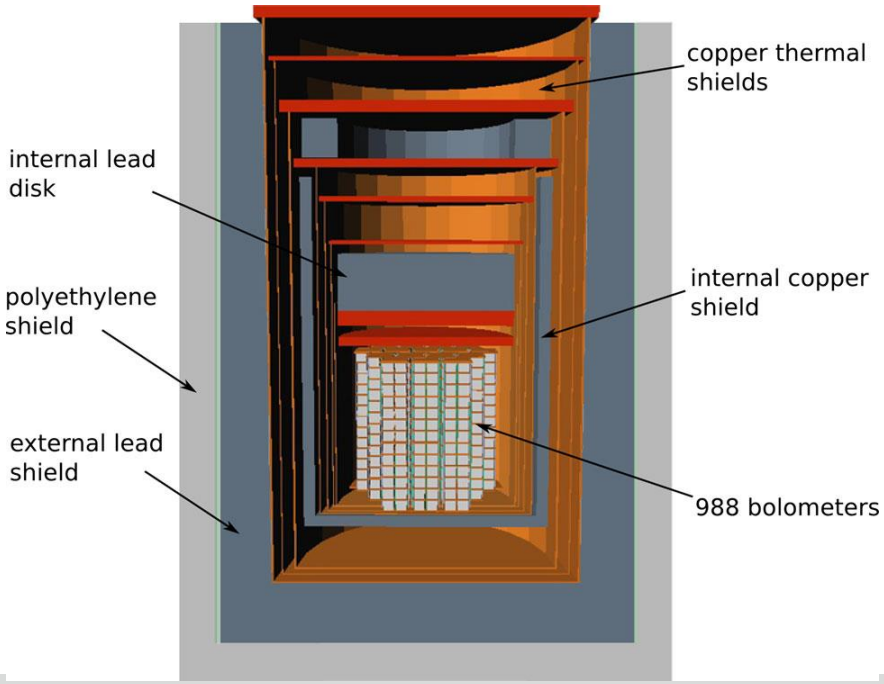




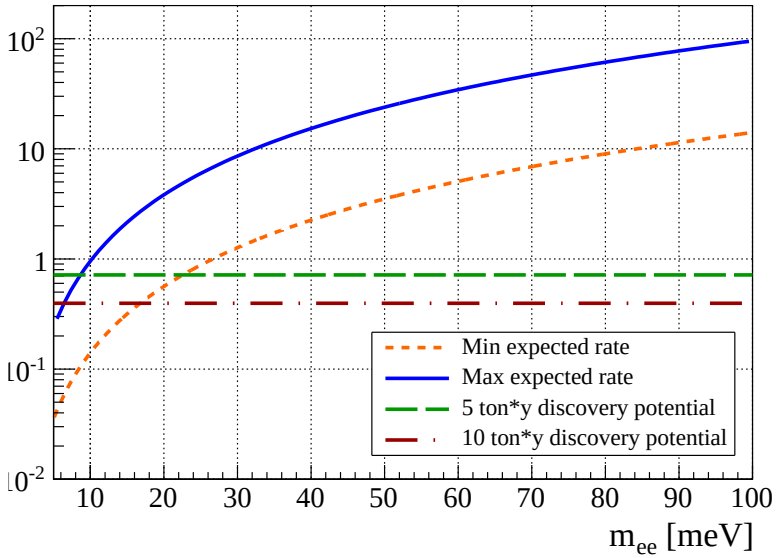
CUPID sensitivity studies

- Based on the CUORE design, CUORE cryogenics
- Enriched crystals with background rejection
- Active vetoes

Eur. Phys. J. C (2014) 74: 3096.



$^{130}TeO_2$ 5σ discovery potential



90% sensitivity limits

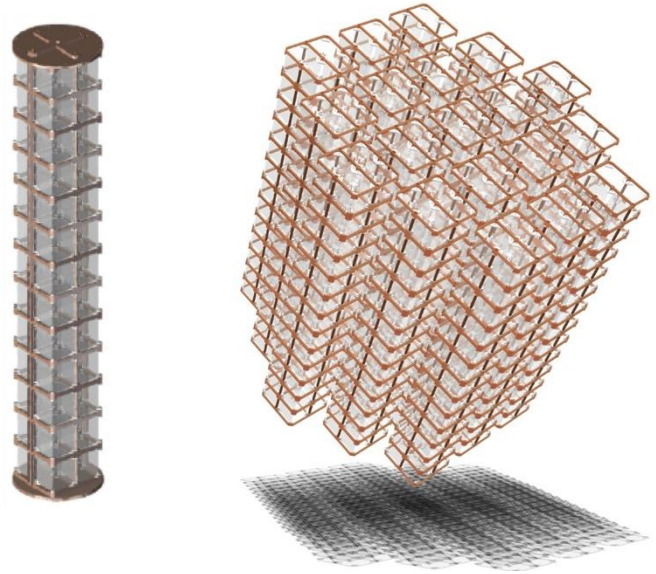
Crystal	Exposure [ton·y]	$T^{0\nu}_{1/2S}$ [10^{27}y]	$\lvert m_{ee}\rvert_S$ [meV]
ZnSe	5	3.3	8–22
	10	6.5	5–15
$CdWO_4$	5	1.5	12–22
	10	3.0	8–15
$ZnMoO_4$	5	0.9	9–27
	10	1.4	8–21
TeO_2	5	3.4	7–18
	10	6.8	5–13

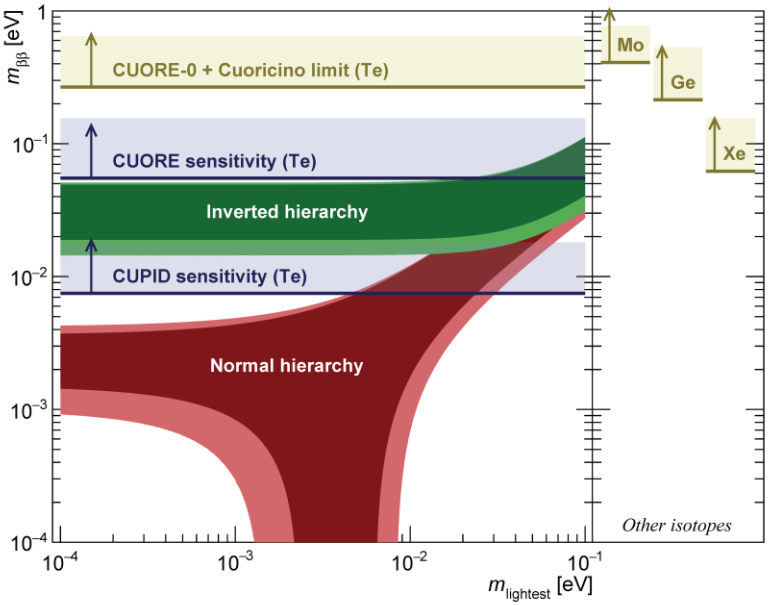
Summary and outlook

- CUORE-0 reached energy resolution and background rate requirement.
- Null $0\nu\beta\beta$ result published in PRL.
- $2\nu\beta\beta$ analysis recently presented.

- CUORE, with 206 kg of ^{130}Te and 5 keV resolution, is able to reach 50-130 meV effective Majorana mass.
- Detector installation is under way.
- Detector operations will start by the end of this year.

- CUPID, CUORE upgrade with particle ID will cover the inverted hierarchy band.





The CUORE Collaboration

Systematics

TABLE I. Systematic uncertainties on $\Gamma_{0\nu}$ in the limit of zero signal (Additive) and as a percentage of nonzero signal (Scaling).

	Additive ($10^{-24}\,\mathrm{y}^{-1}$)	Scaling (%)
Lineshape	0.007	1.3
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Signal normalization	0.7%	

- For each systematic, we run toy MC expts to evaluate bias on fitted $0\nu\beta\beta$ decay rate
- Bias is parameterized as p0 + p1×Γ, where p0="additive" and p1="scaling"
- Signal lineshape: Used variety of different lineshapes to model signal
- Energy resolution: Apply 1.05±0.05 correction to calibration-derived resolution
- Fit bias: Effect of using unbinned extended ML fit to extract values
- Energy scale: Assign 0.12 keV uncertainty derived from peak residuals in physics spectrum
- Bkg function: Treated choice of 0-, 1-, 2-order polynomial as discrete nuisance parameter

Systematics

TABLE I. Systematic uncertainties on $\Gamma_{0\nu}$ in the limit of zero signal (Additive) and as a percentage of nonzero signal (Scaling).

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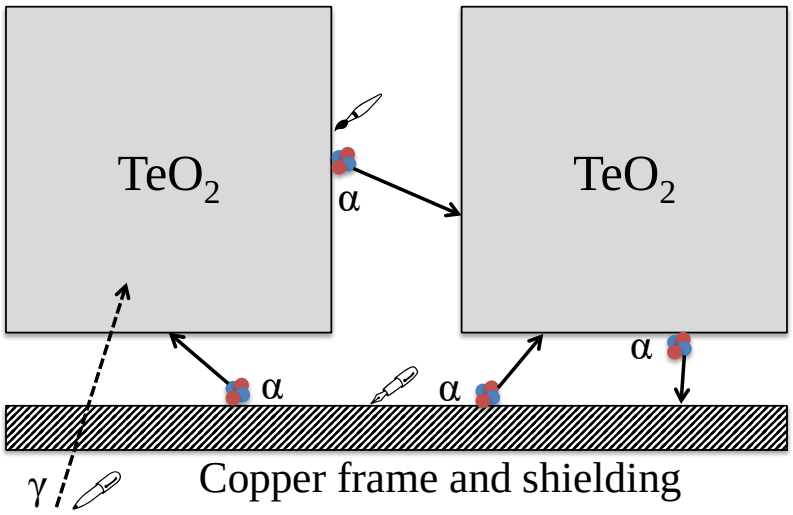
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Signal normalization	0.7%	

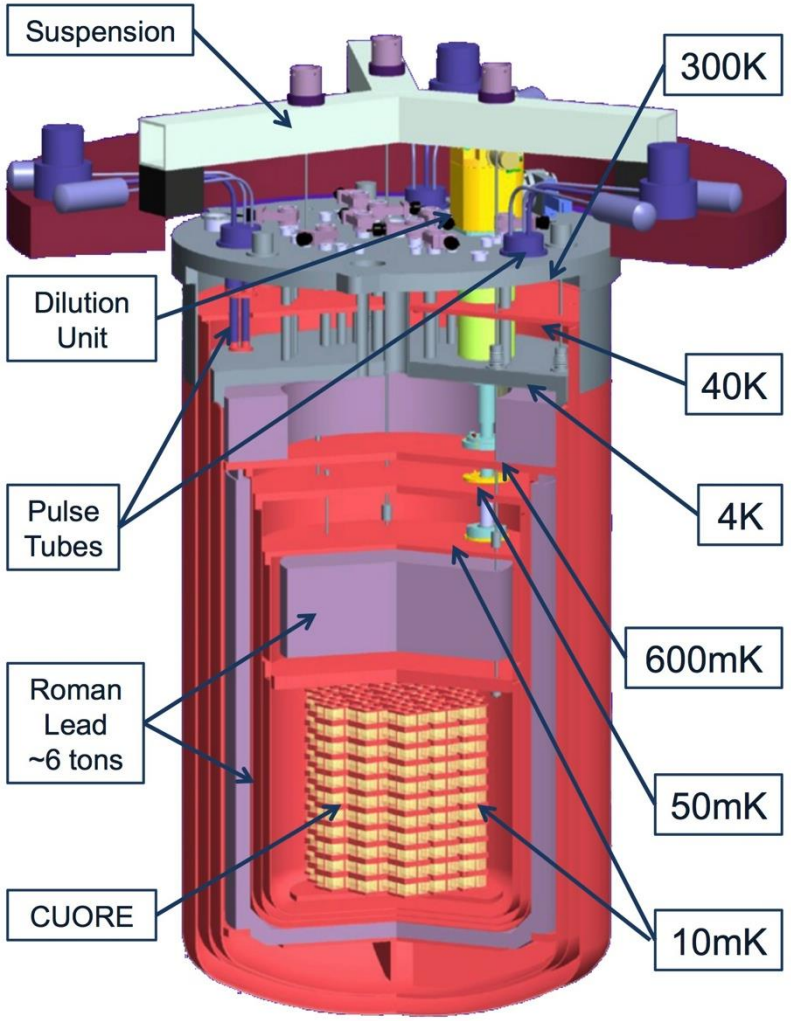
After accounting for systematic uncertainties we report the Bayesian limits:

$\Gamma^{0\nu\beta\beta}$ (^{130}Te) < 0.25 × 10^{-24} yr^{-1} (90% C.L., stat.+syst.)

$T_{1/2}^{0nbb}$(^{130}Te) > 2.7 × 10^{24} yr (90% C.L., stat. + syst.)

Background reduction: from CUORE-0 to CUORE

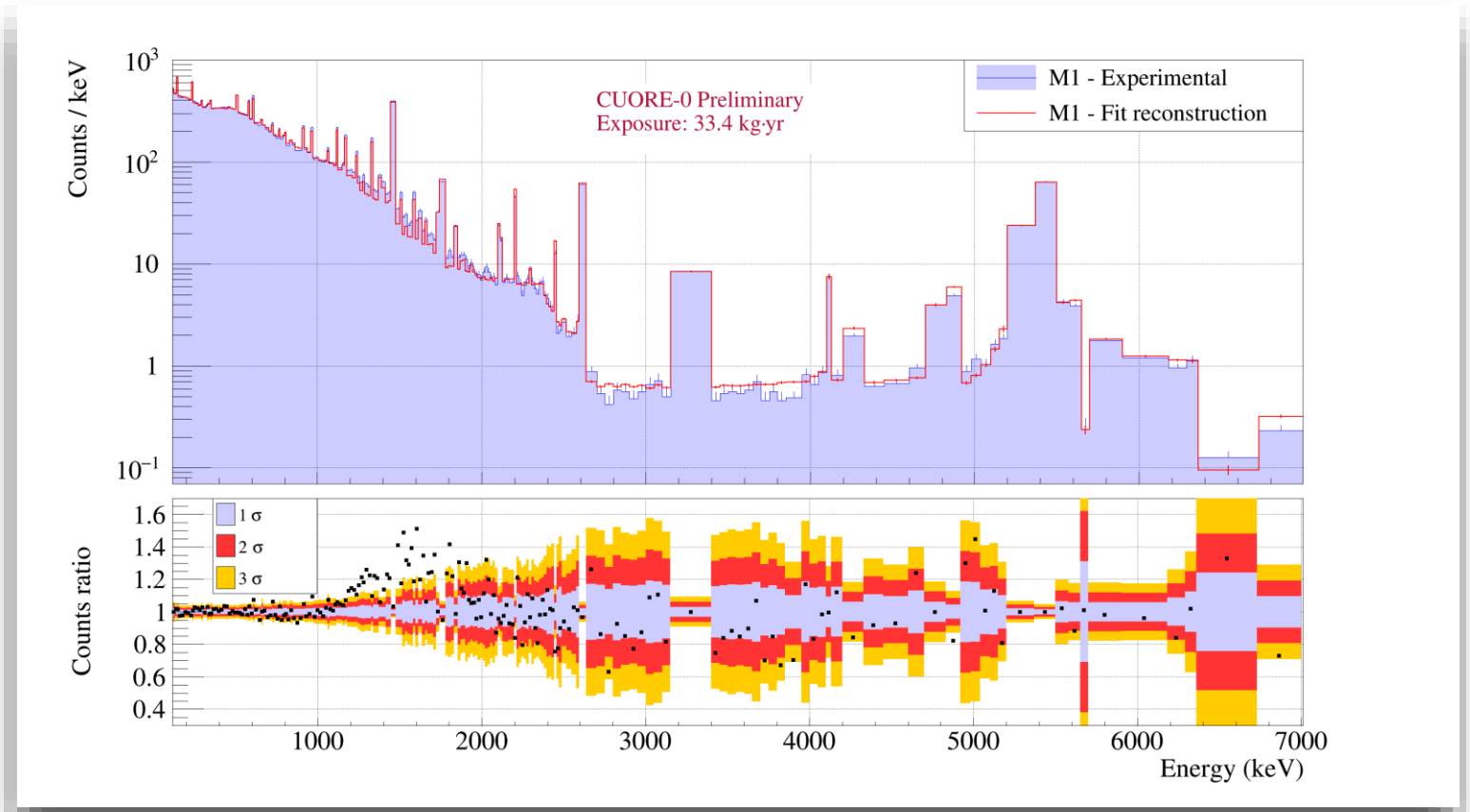




CUORE background in ROI

1. New cryostat with radio-pure materials
   → negligible gamma contributions
2. More effective self-shielding
   → Copper surface background can be reduced below background goal.
3. More effective anti-coincidence
   → negligible surface alpha from crystals.

Fit spectrum w/o 2νββ



Full reconstruction between: 118 keV - 7 MeV

Reconstruction within 3σ range for most of bins (also in multiplicity 2 spectra)