The search for $0\nu\beta\beta$ decay with CUORE and next generation bolometric detector R&D

Alexey Drobizhev
Physics 290E
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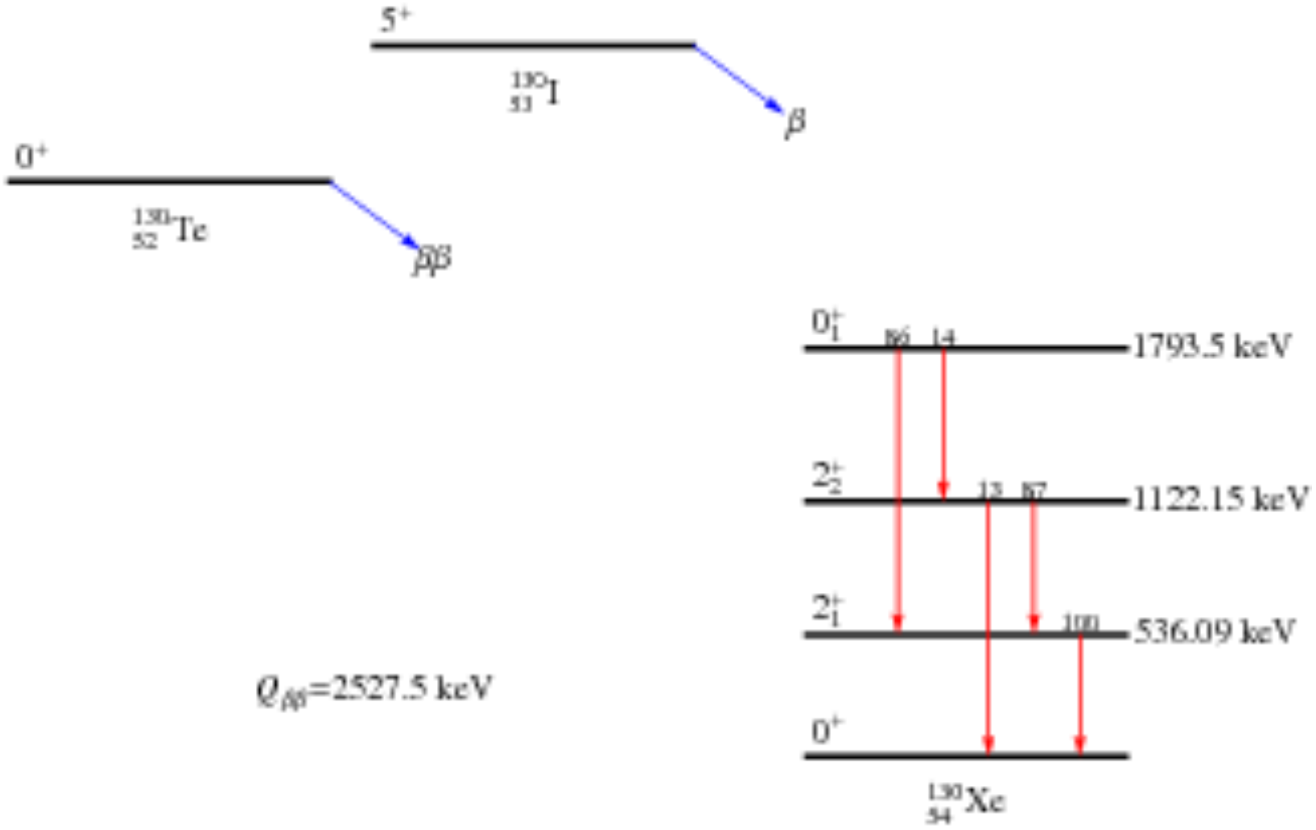
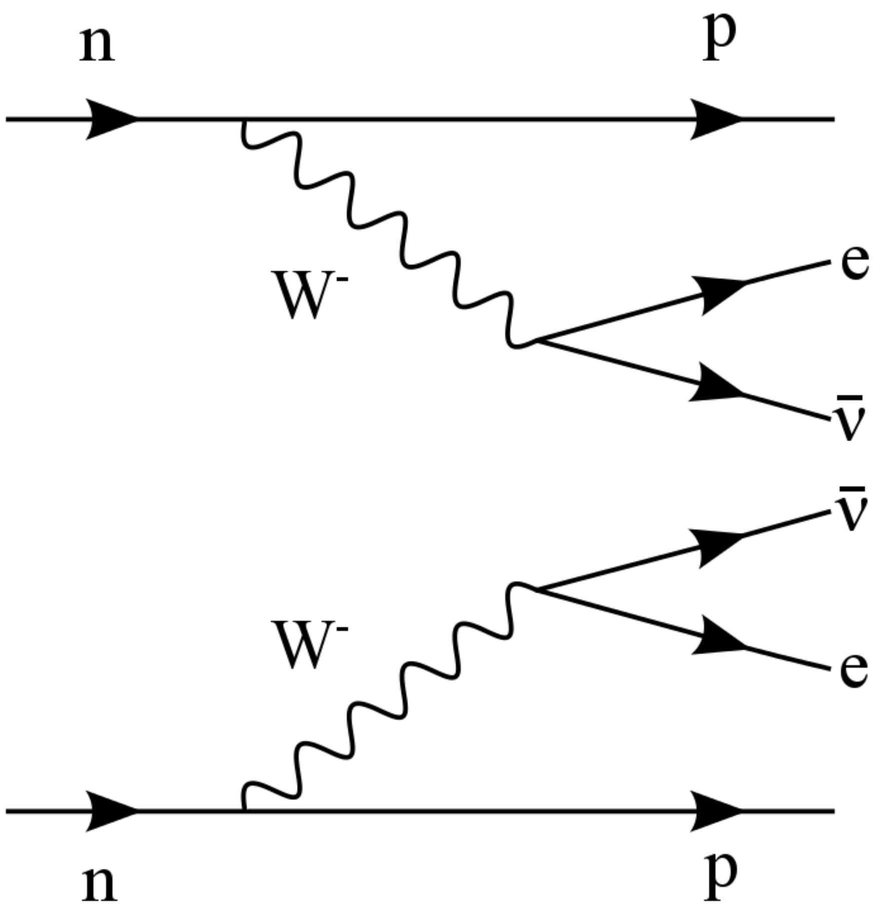
Outline

- Introduction
  - 2νββ
  - 0νββ
  - Detecting ββ
- CUORE-0 and CUORE
  - Bolometric detection
  - CUORE and CUORE–0 overview.
  - CUORE and CUORE–0 measurements.
  - CUORE and CUORE-0 results, projections, performance.
  - Anticoincidence background reduction.
- CUPID and R&D
  - CUPID overview
  - Effects of alpha background rejection
  - Cherenkov light bolometers
  - Transition edge sensors
  - Berkeley TES light detector R&D right now.

Ordinary Double Beta Decay ($2\nu\beta\beta$)





- 1935—Maria Goeppert-Mayer, 1937—Ettore Majorana

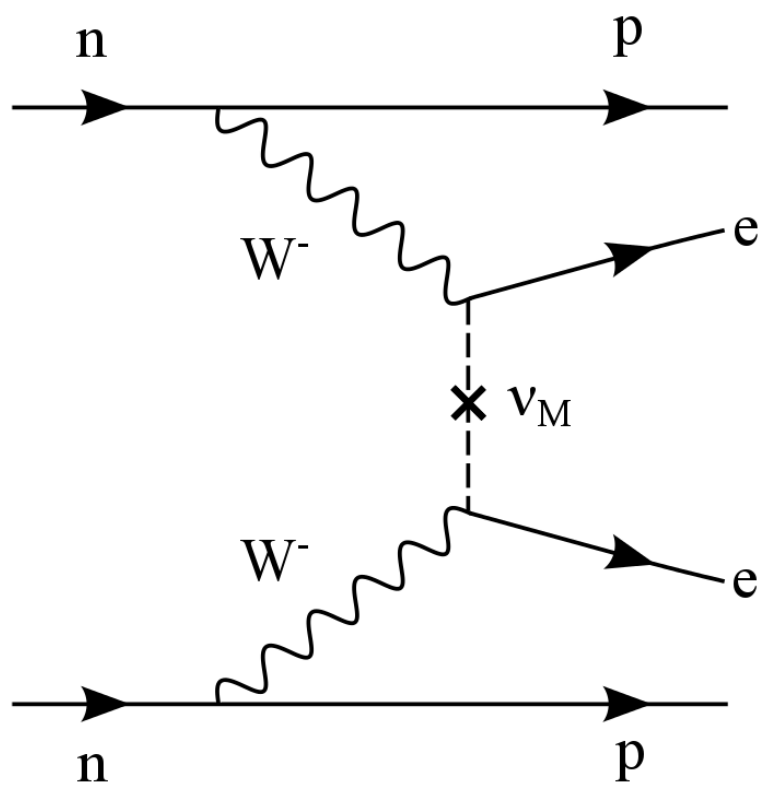
- Can be thought of as two single beta decays occurring simultaneously:

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

- Occurs when the single beta decay is forbidden by energy conservation.
- Slowest observed natural process ($t_{1/2} \approx 10^{19\text{–}21}$ y)
- Observed since the 1980s in Even-Z, Even-N nuclei (^{130}Te, ^{76}Ge, ^{136}Xe, others…) — stable due to spin coupling.

Neutrinoless Double Beta Decay (0νββ)

- Double beta decay with virtual annihilation of the neutrinos.
- Possible if the neutrino is a Majorana fermion—its own antiparticle:
  - Must be a fundamental neutral fermion.
  - Mass from Majorana mechanism.
  - Only 2 states, defined by helicity: left-handed antineutrino *is* the neutrino and vice-versa.
- Would be much more rare than even 2νββ — $t_{1/2} > 10^{24}$ y



$$\mathcal{L}_{M+D} = \overbrace{\frac{1}{2} m_L \underset{\uparrow}{\nu_L^T} C^\dagger \underset{\uparrow}{\nu_L}}^{\text{Majorana}} - \overbrace{m_D \underset{\uparrow}{\bar{\nu}_R} \underset{\uparrow}{\nu_L}}^{\text{Dirac}} + \overbrace{\frac{1}{2} m_R \underset{\uparrow}{\nu_R^T} C^\dagger \underset{\uparrow}{\nu_R}}^{\text{Majorana}} + h.c.$$

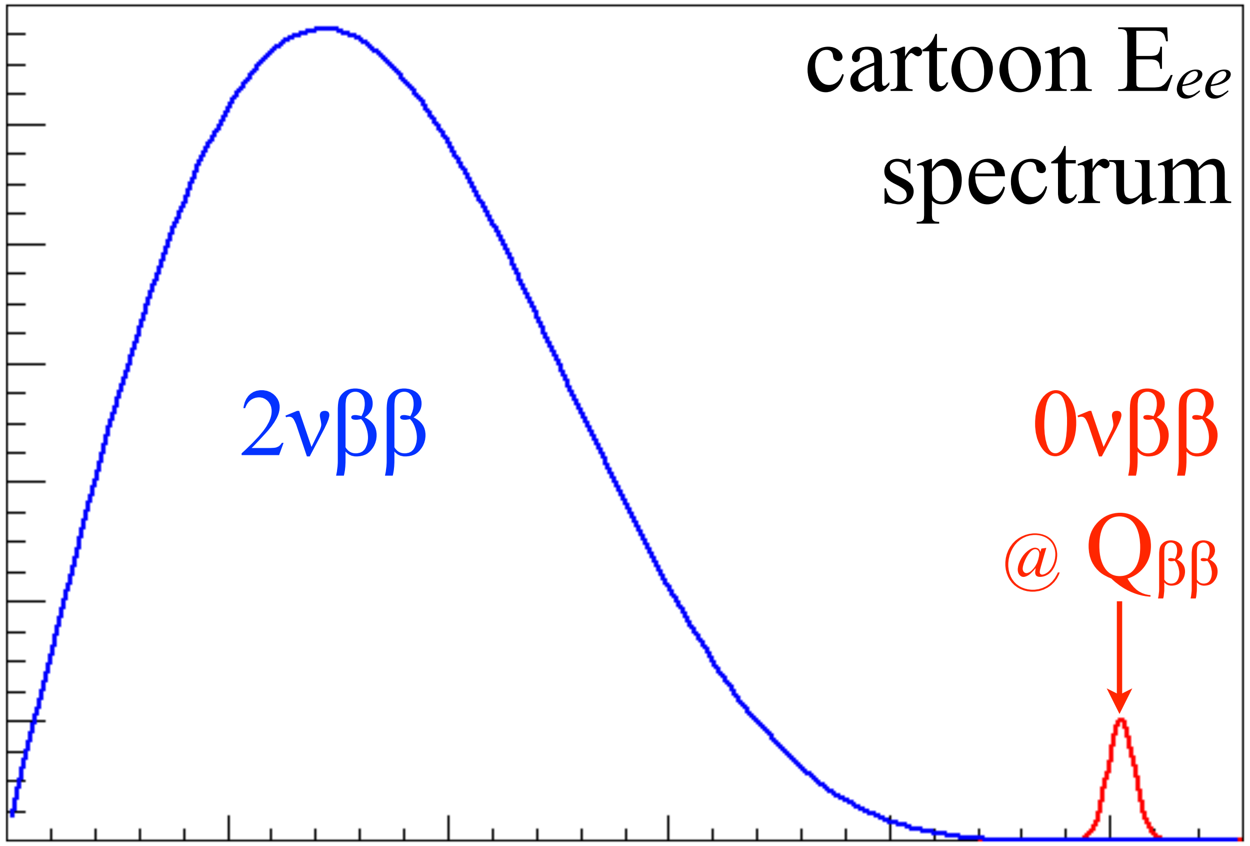
not independent independent not independent

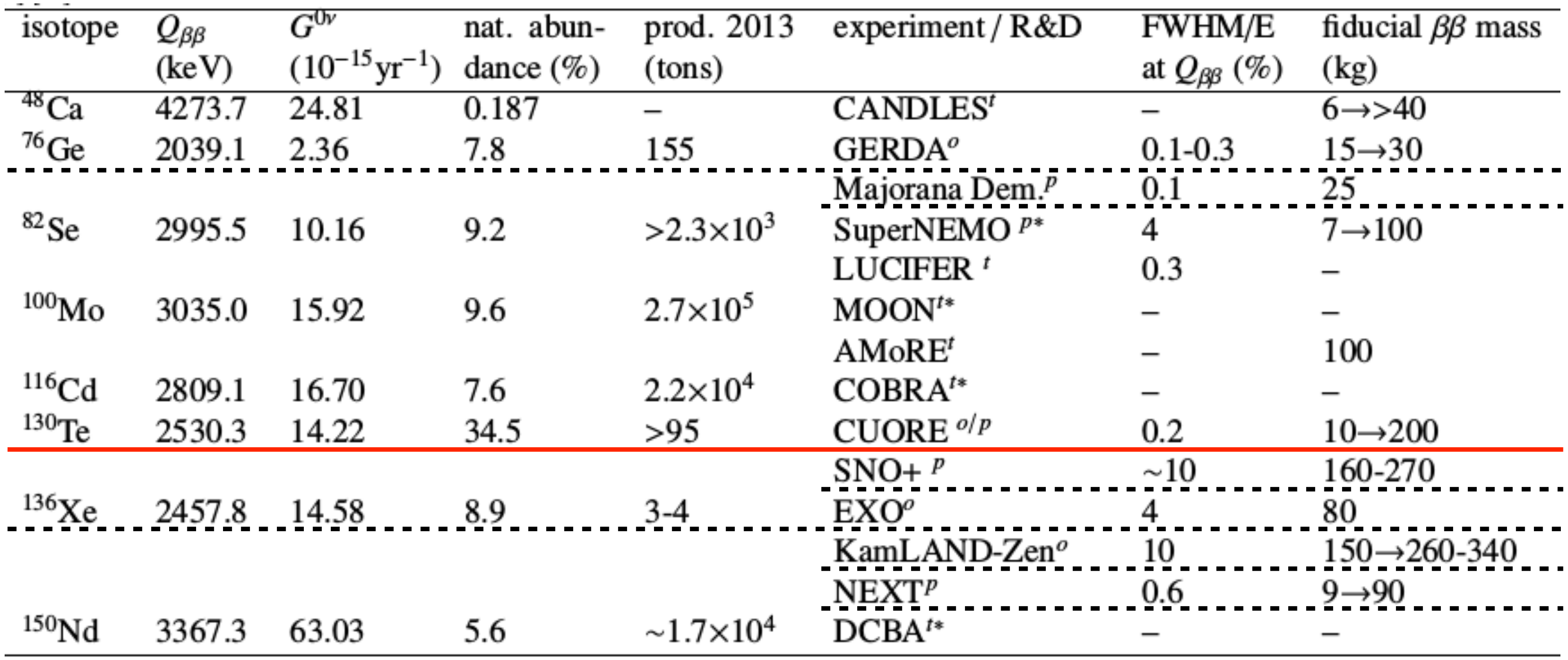
- L_M violates U(1) symmetry by two units → Lepton Number violation!

$$\nu_L \rightarrow e^{i\phi} \nu_L \qquad \mathcal{L}_M \rightarrow e^{i2\phi} \mathcal{L}_M$$

Detecting 0νββ

- Neutrinos annihilate virtually—100% of energy in β's.
- Manifests in E_{ee} spectrum as small peak at $Q_{\beta\beta}$ given sufficient sensitivity (right).
- Isotope chosen based on abundance and $Q_{\beta\beta}$ value.
- Techniques and technologies:
  - Liquid scintillator
    - SNO+, KamLAND-Zen
  - Liquid Xe TPC
    - EXO
  - Xe gas TPC
    - NEXT
  - Dual phase TPC
    - PandaX
  - HPGe detector
    - Majorana, GERDA
  - Bolometer
    - CUORE/Lucifer/CUPID





isotope	$Q_{\beta\beta}$ (keV)	$G^{0\nu}$ (10^{-15}yr^{-1})	nat. abundance (%)	prod. 2013 (tons)	experiment / R&D	FWHM/E at $Q_{\beta\beta}$ (%)	fiducial $\beta\beta$ mass (kg)
^{48}Ca	4273.7	24.81	0.187	–	CANDLES^{t}	–	6→>40
^{76}Ge	2039.1	2.36	7.8	155	GERDA^{o}	0.1-0.3	15→30
					Majorana Dem.^{p}	0.1	25
^{82}Se	2995.5	10.16	9.2	>2.3×10^{3}	SuperNEMO ^{p*}	4	7→100
					LUCIFER ^{t}	0.3	–
^{100}Mo	3035.0	15.92	9.6	2.7×10^{5}	MOON^{t*}	–	–
					AMoRE^{t}	–	100
^{116}Cd	2809.1	16.70	7.6	2.2×10^{4}	COBRA^{t*}	–	–
^{130}Te	2530.3	14.22	34.5	>95	CUORE $^{o/p}$	0.2	10→200
					SNO+ ^{p}	~10	160-270
^{136}Xe	2457.8	14.58	8.9	3-4	EXO^{o}	4	80
					KamLAND-Zen^{o}	10	150→260-340
					NEXT^{p}	0.6	9→90
^{150}Nd	3367.3	63.03	5.6	~1.7×10^{4}	DCBA^{t*}	–	–

The CUORE and CUORE–0 experiments

Bolometers: general principles

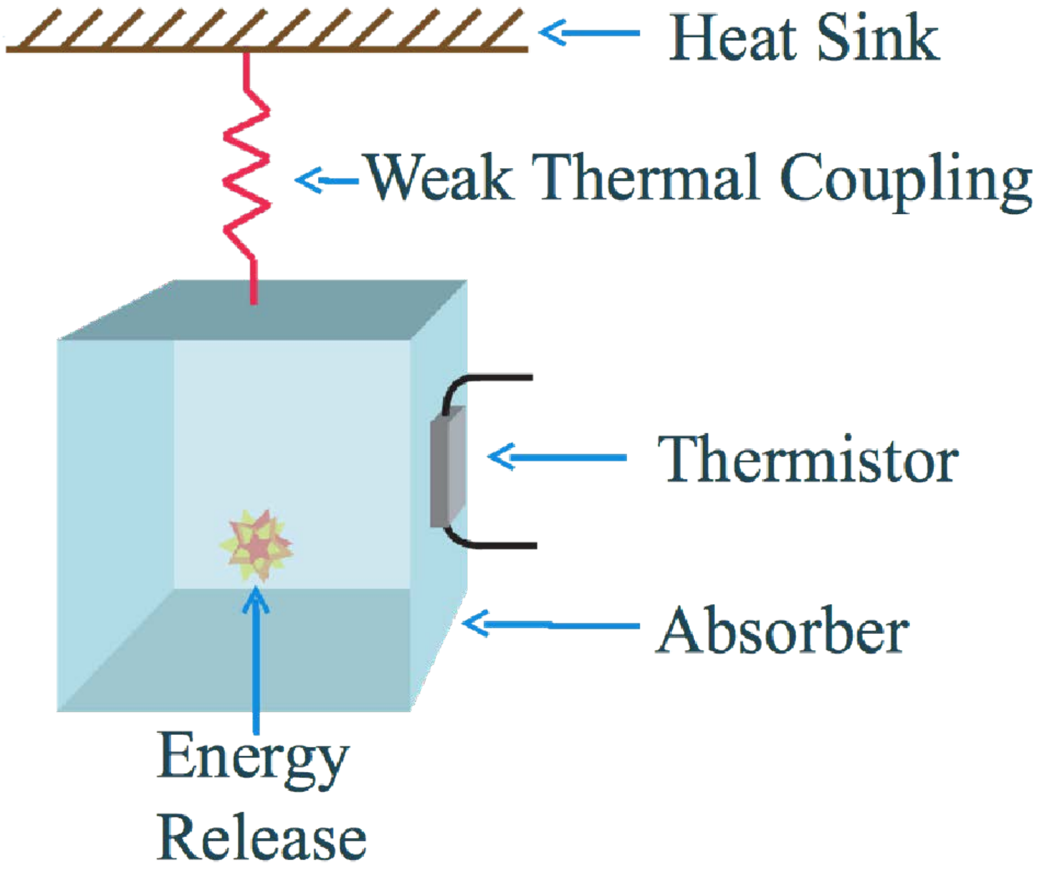
- Detection of thermal signatures of absorbed particles:

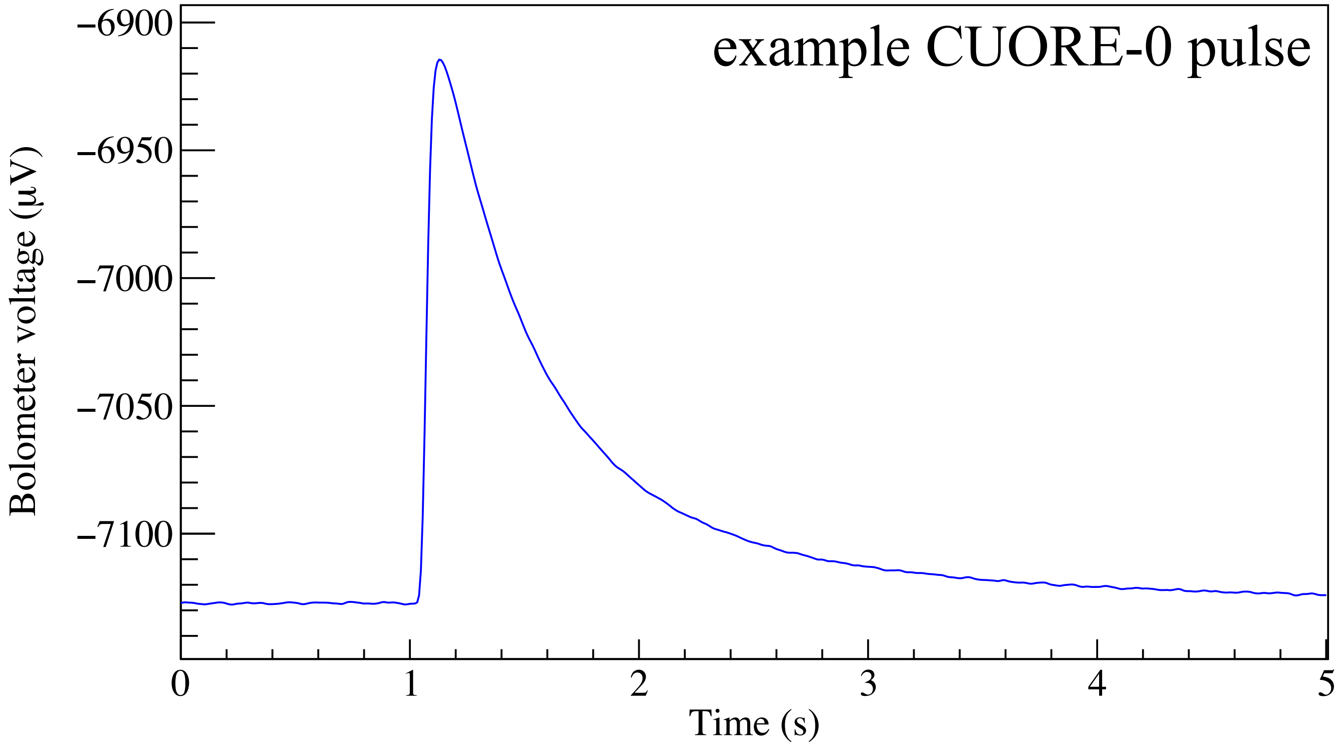
$$\Delta T = \frac{E_{event}}{C_{absorber}}$$

- Low T (10mK–100mK):
  - minimization of $C_{absorber}$
  - achieved using Dilution Refrigerator
- Scaleable
- Fundamental limit on energy resolution very low:

$$\Delta E_{limit} \sim \sqrt{kCT^2}$$

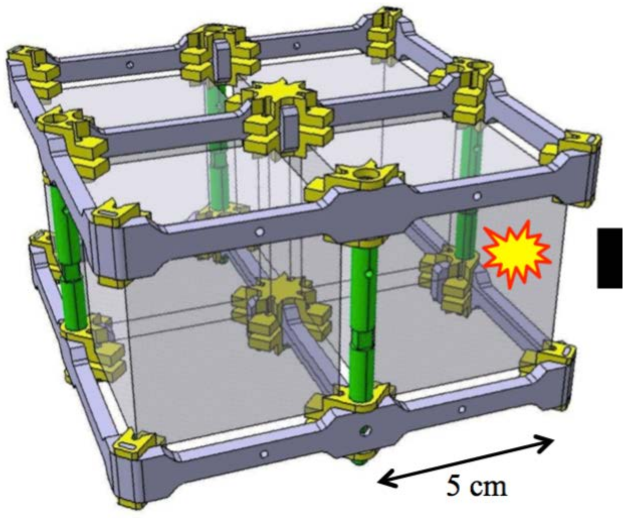
- Wide range of absorber materials can be used—some flexibility in isotope choice.
- Can be augmented with scintillation or Cherenkov optical channel or ionization (as in CDMS).

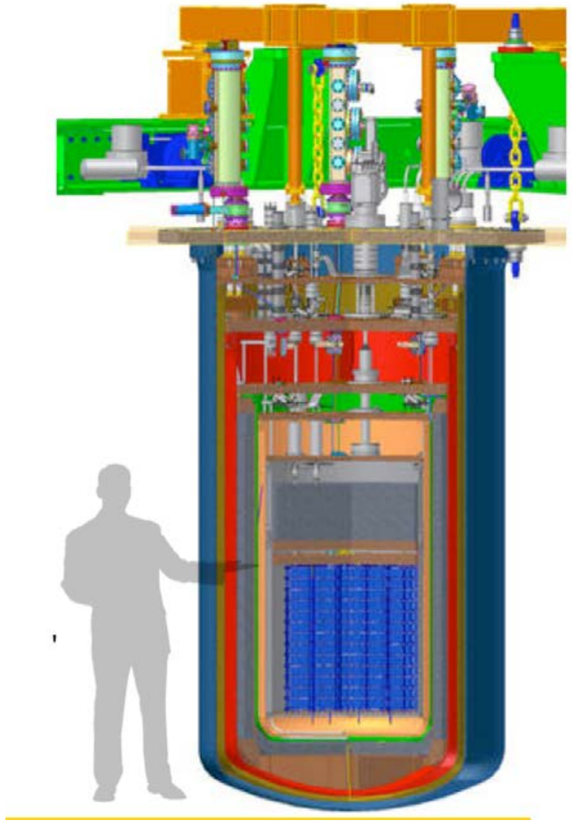


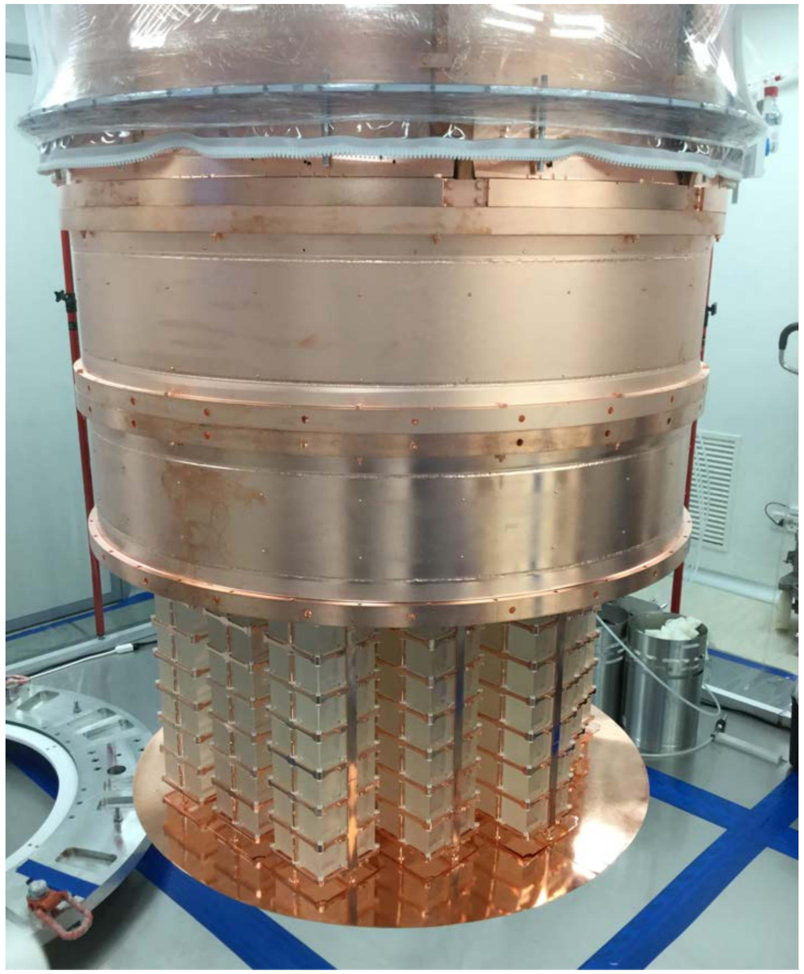


CUORE

- **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents.
- Bolometric search for 0νββ in ^{130}Te (with secondary topics 2νββ, other isotopes, axions…).
- An example of state of the art ton-scale bolometric detector.
- 988 TeO_2 5 × 5 × 5 cm^3 crystals in 19 towers of 52: source and absorber, $m_{isotope} = 206$ kg.
- $T_{base} \leq 10$mK
- First cooldown as we speak. Data this winter.
- CUORE-0—single CUORE tower, operated 2013–2015.







CUORE and CUORE-0: measurements

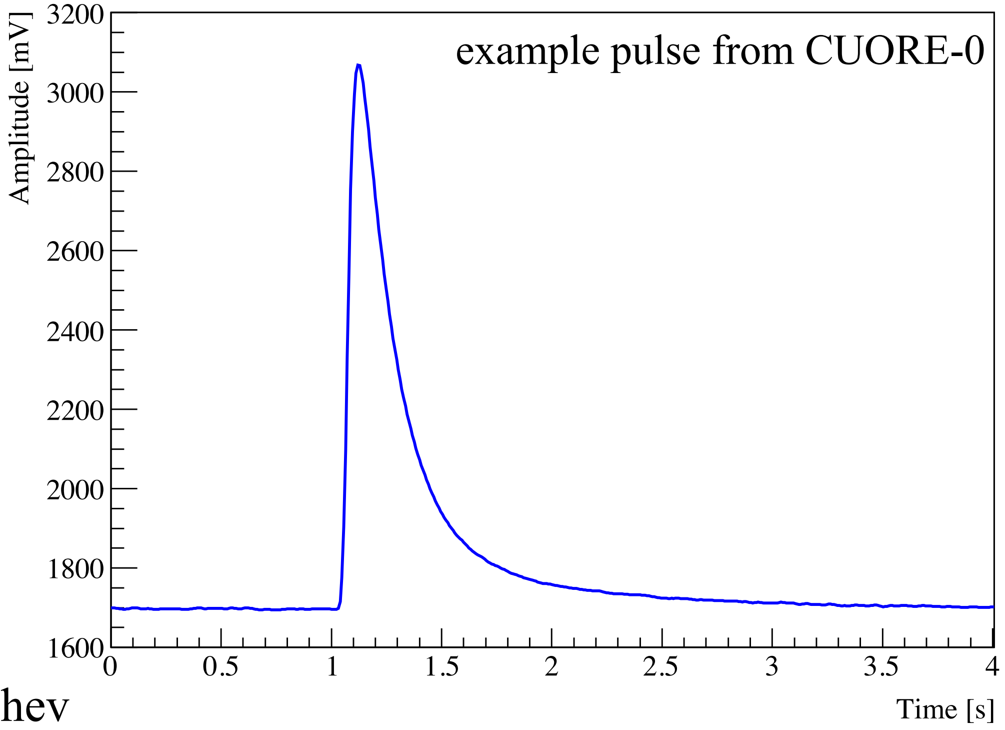
- 5x5x5cm^3 TeO$_2$ at 10mK:

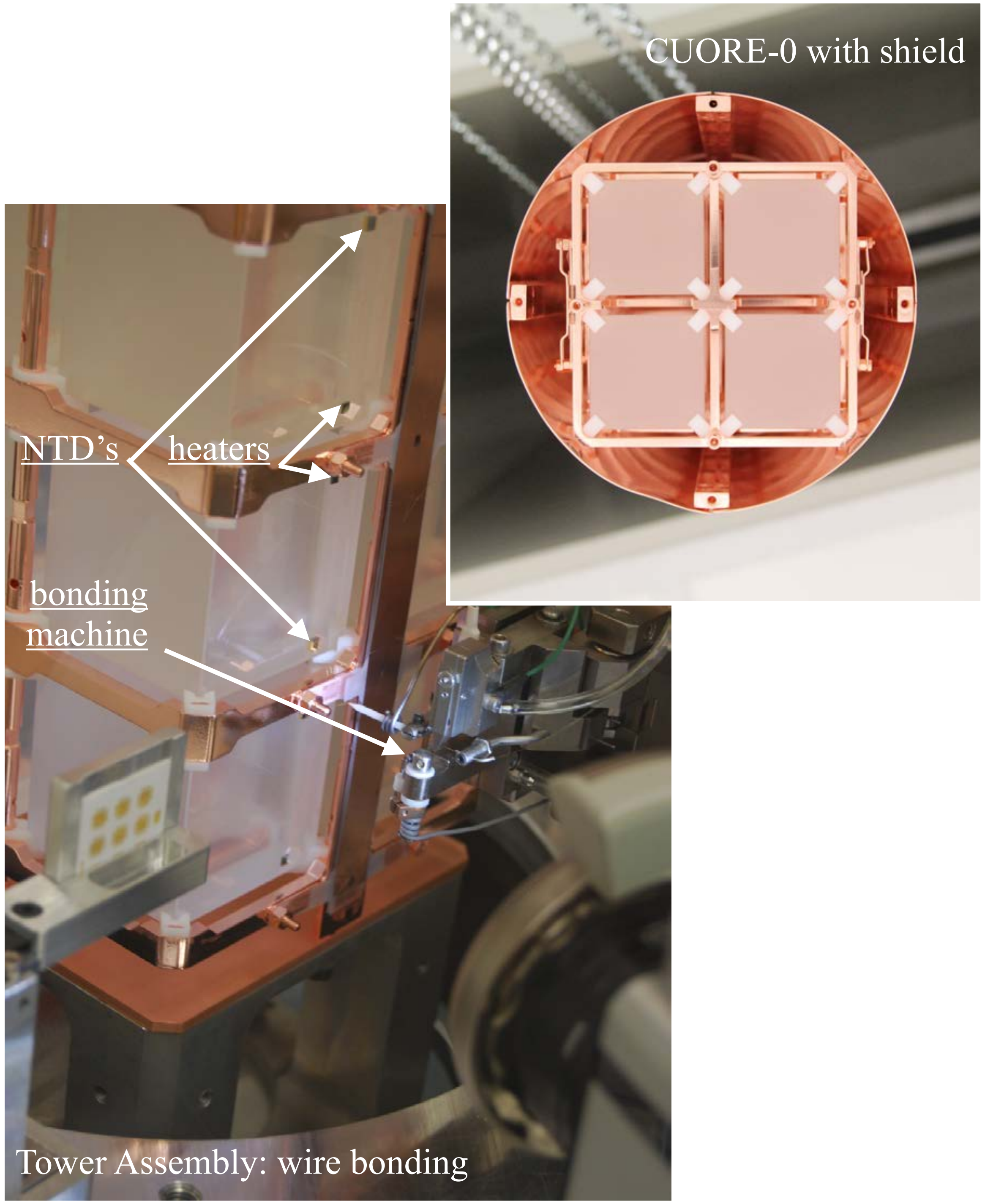
$$\Delta T_{event} = \frac{E_{event}}{C_{crystal}}$$

with $C^{-1}_{crystal} \approx 100 \mu K/MeV$

- Readout with Ge NTD thermistor:

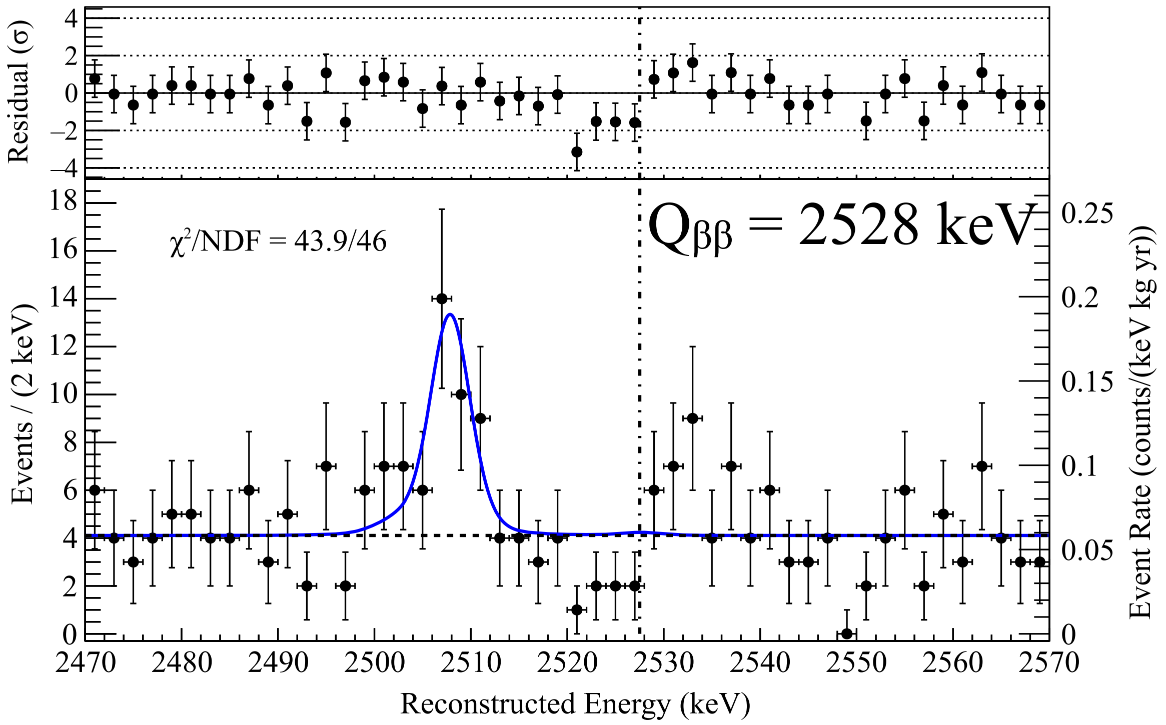
$$R_{NTD} = R_0 e^{\sqrt{T_0/T}}$$

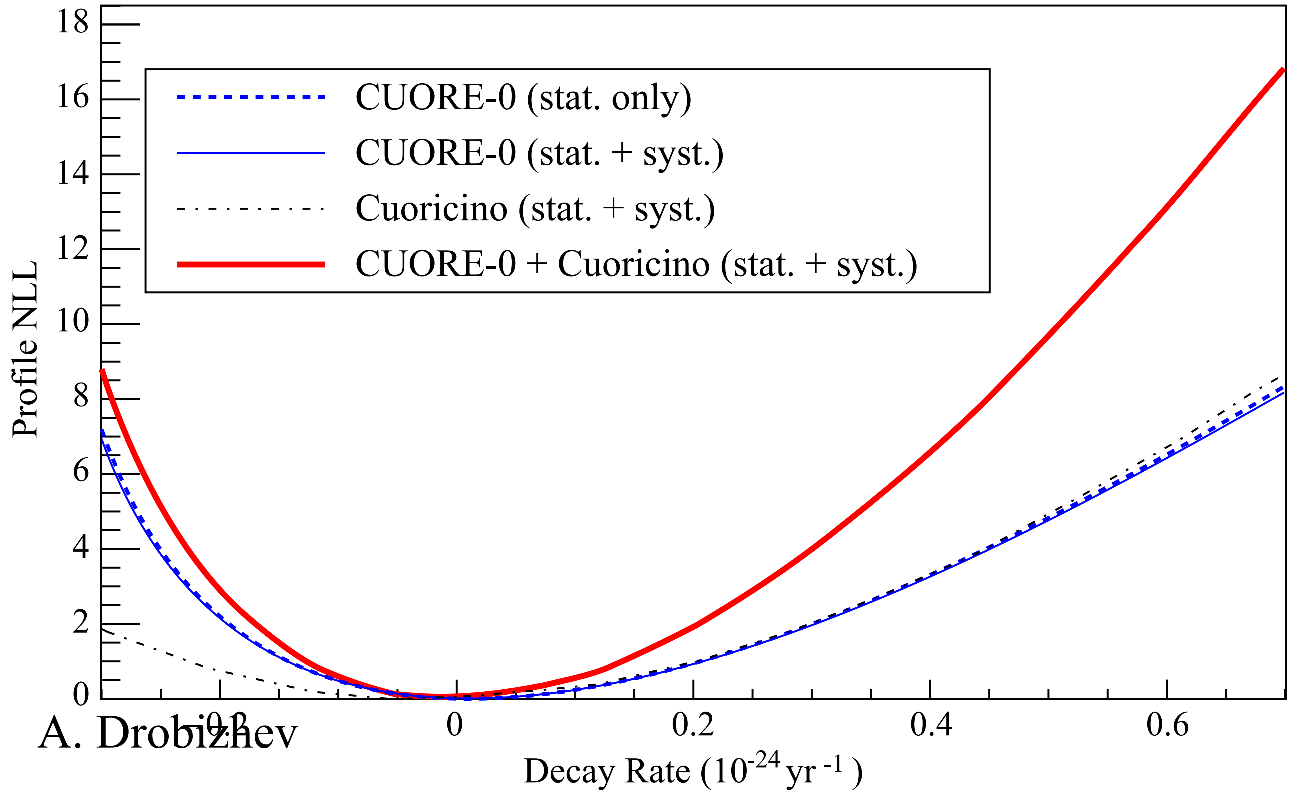


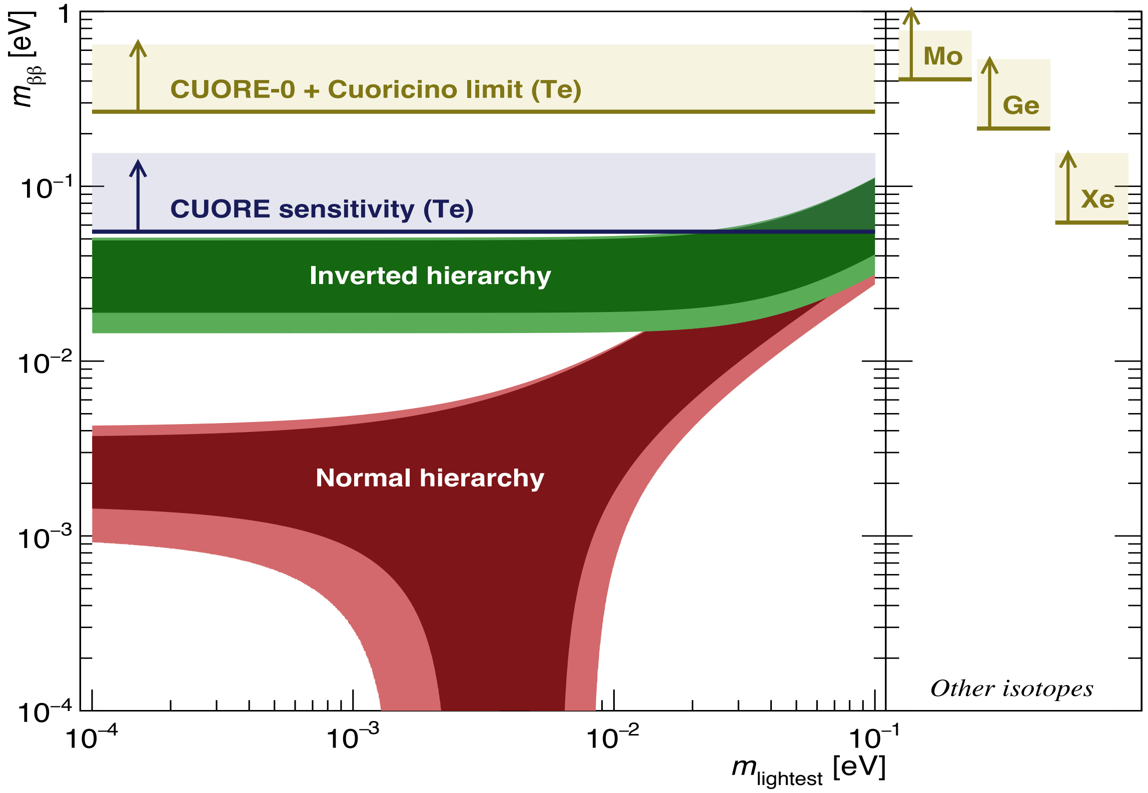


CUORE–0 results and CUORE projections

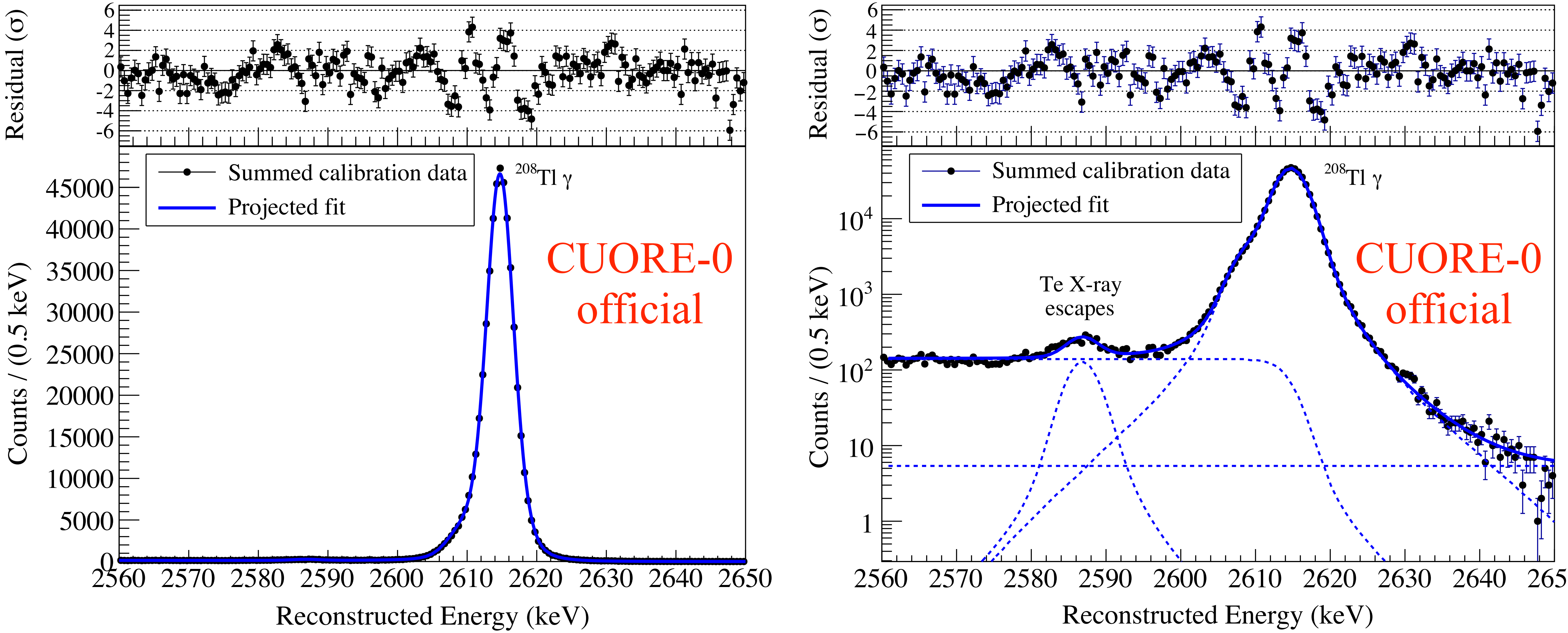
- CUORE-0:
  - 9.8 kg•yr ^{130}Te exposure.
  - Sensitivity: 2.9×10^{24} y.
  - Limit (Bayesian 90% C.L.): 2.7×10^{24}
  - Limit including Cuoricino: 4.0×10^{24} y.
  - $t_{1/2}$ ($2\nu\beta\beta$) = [8.2 ± 0.2 (stat.) ± 0.6 (syst.)] $\times 10^{20}$ y
- CUORE:
  - ~5 years of data w/ > 200 kg of ^{130}Te.
  - Sensitivity: 9.5×10^{25} y.







Energy Resolution

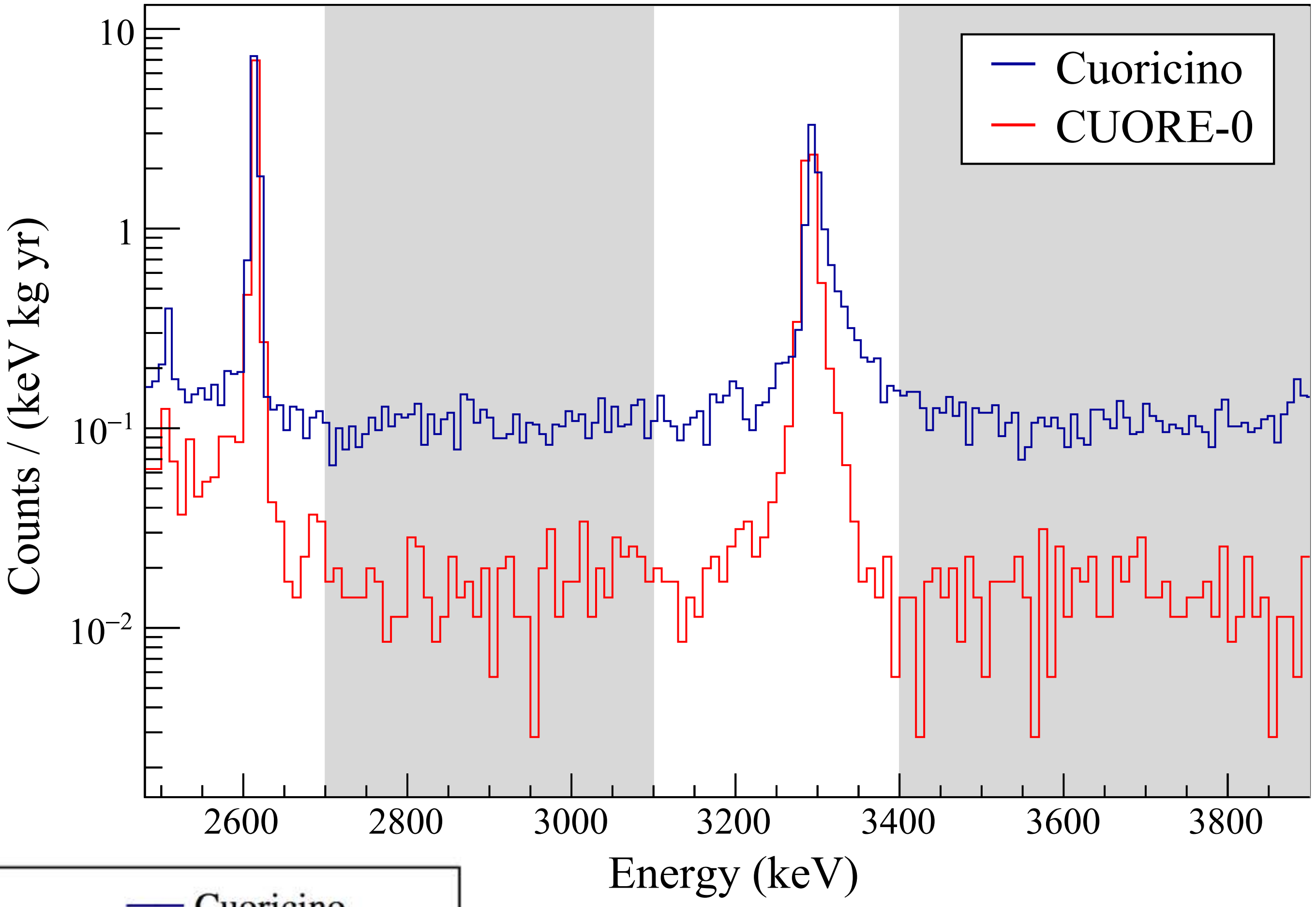


$$\Delta \mathrm{E}_{CUORE-0} = 5.1 \pm 0.3 \text{ keV FWHM @2615 keV (background)}$$
$$\Delta \mathrm{E}_{CUORE-0} = 4.9 \text{ keV FWHM @2615 keV (calibration)}$$

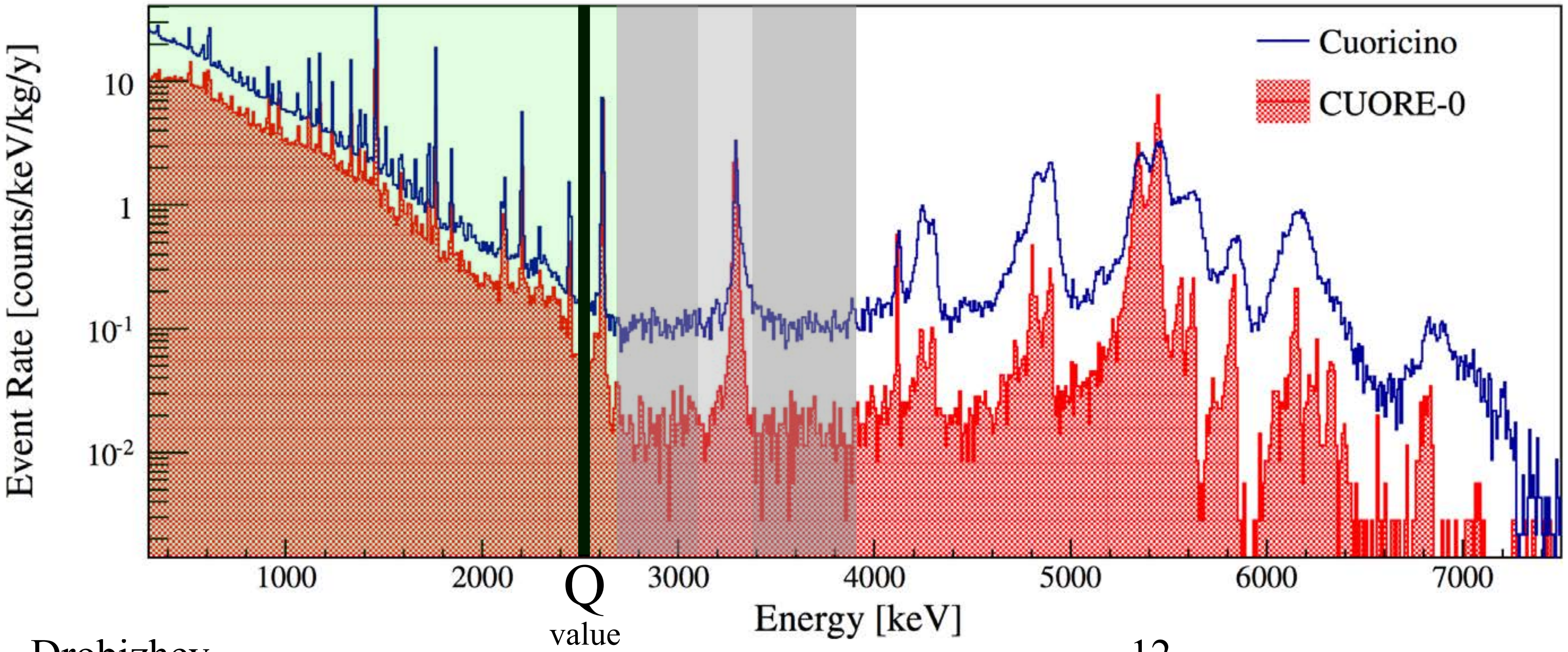
- CUORE is expected to exhibit comparable resolution

Backgrounds

- CUORE-0:
  - 0.058 ± 0.004 (stat.) ± 0.002 (syst.) counts/keV/kg/y in ROI.
  - 0.016 ± 0.001 counts/keV/kg/y in α region.
- CUORE expected: ≤ 0.01 counts/keV/kg/y (ROI).
- Q = 2528 keV—high energy edge of γ region, but away from major peaks due to good energy resolution.



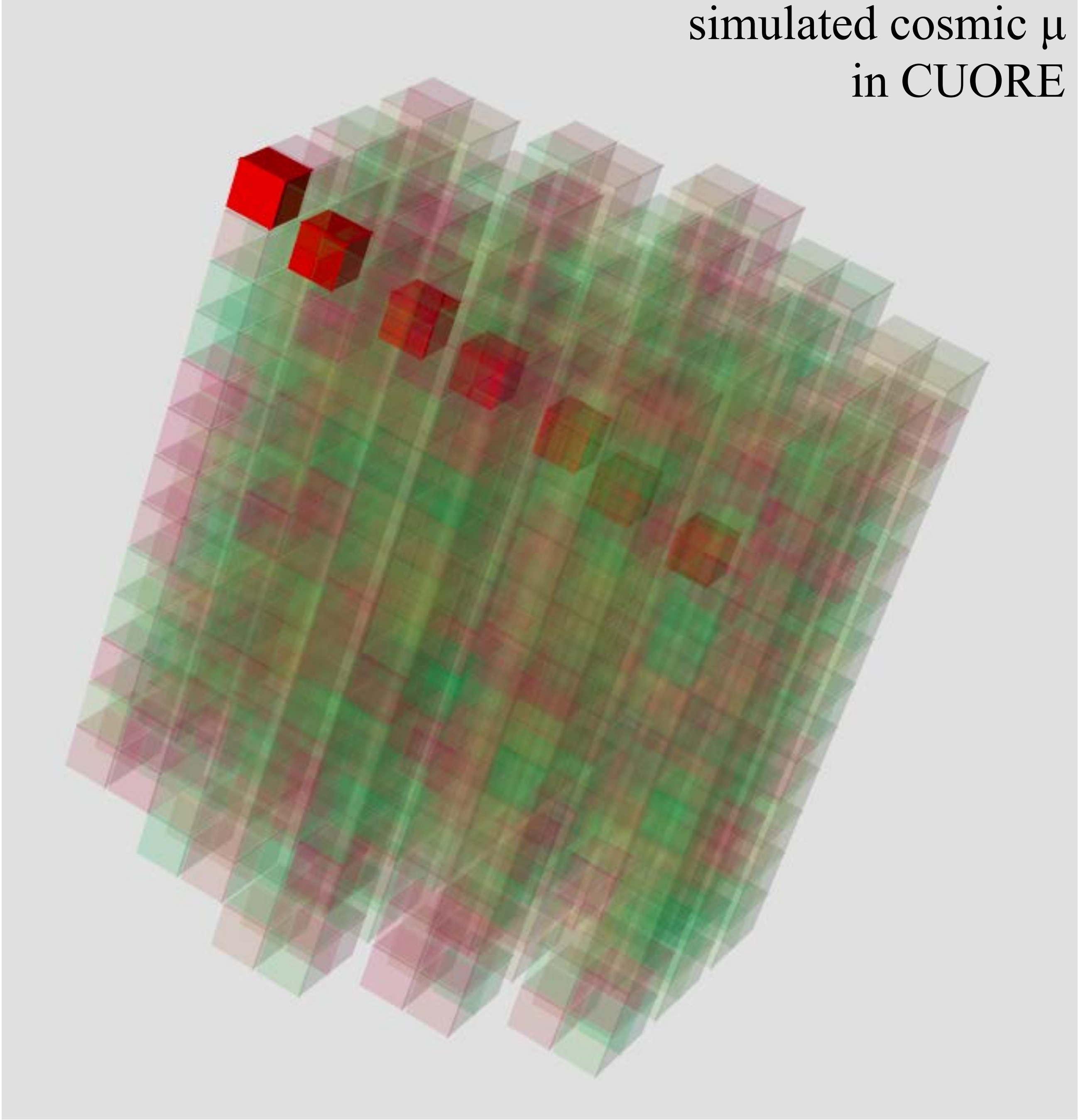
↑ α region



← full spectrum

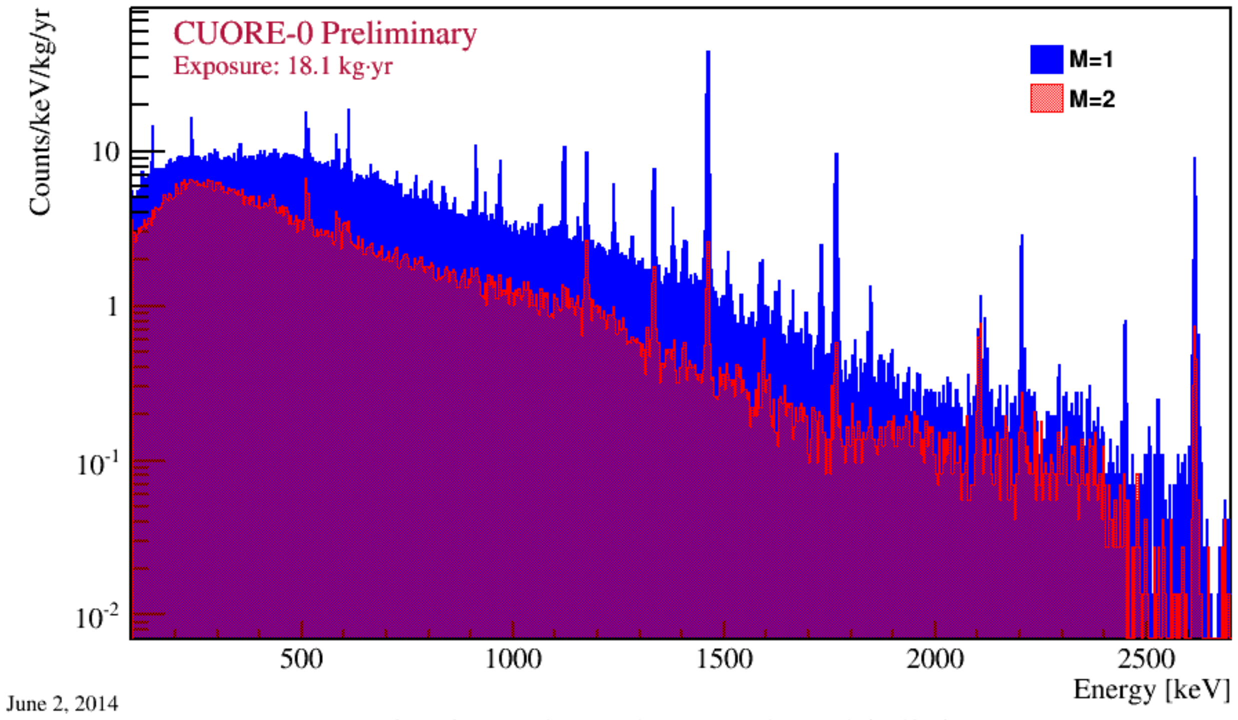
Anti-coincidence background rejection

- Only thermal channel, NTD readout ⇒ only energy measurement ⇒ not possible to distinguish individual α, β, γ, or μ events.
- Anti-coincidence:
  - 2νββ, 0νββ events — 1 crystal.
  - Some surface α's — 2 crystals— nuclear recoil into source crystal, α absorbed on adjacent crystal.
  - Some γ's — multiple crystals (Compton length 5-20cm).
  - Cosmic μ's— multiple crystals.


simulated cosmic μ
in CUORE

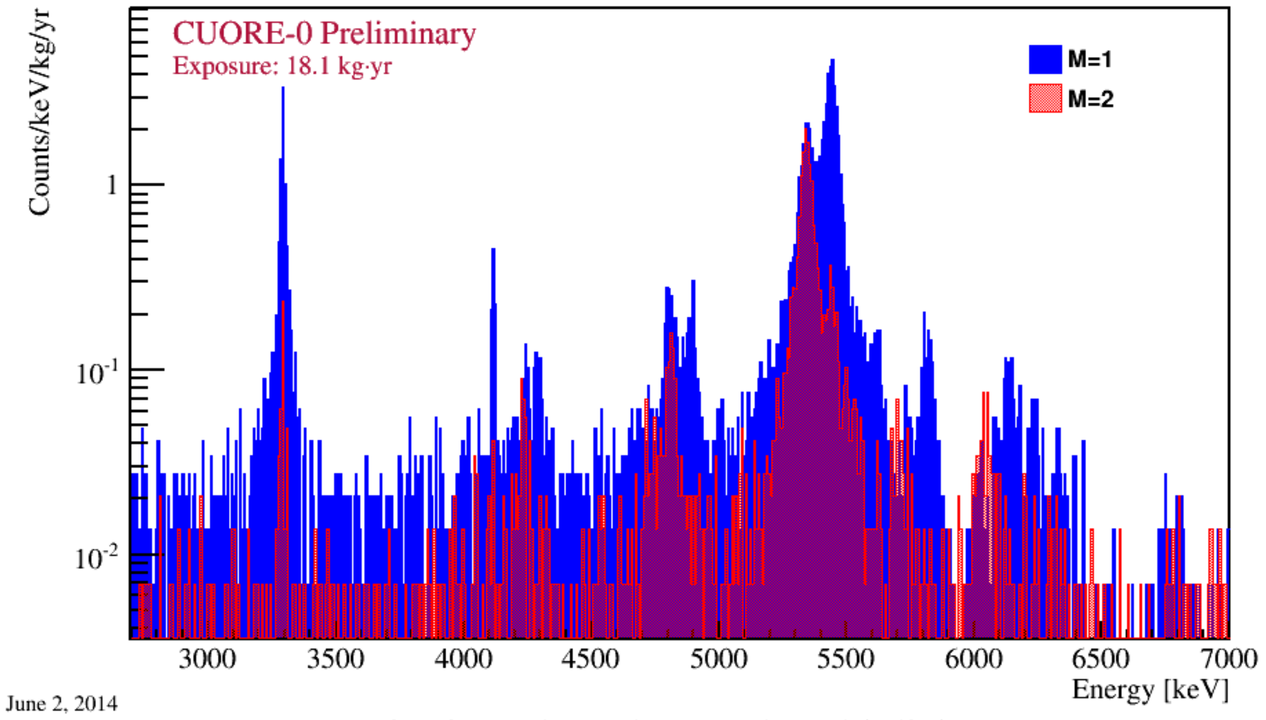
Anti-coincidence background rejection

CUORE-0 Background Spectrum



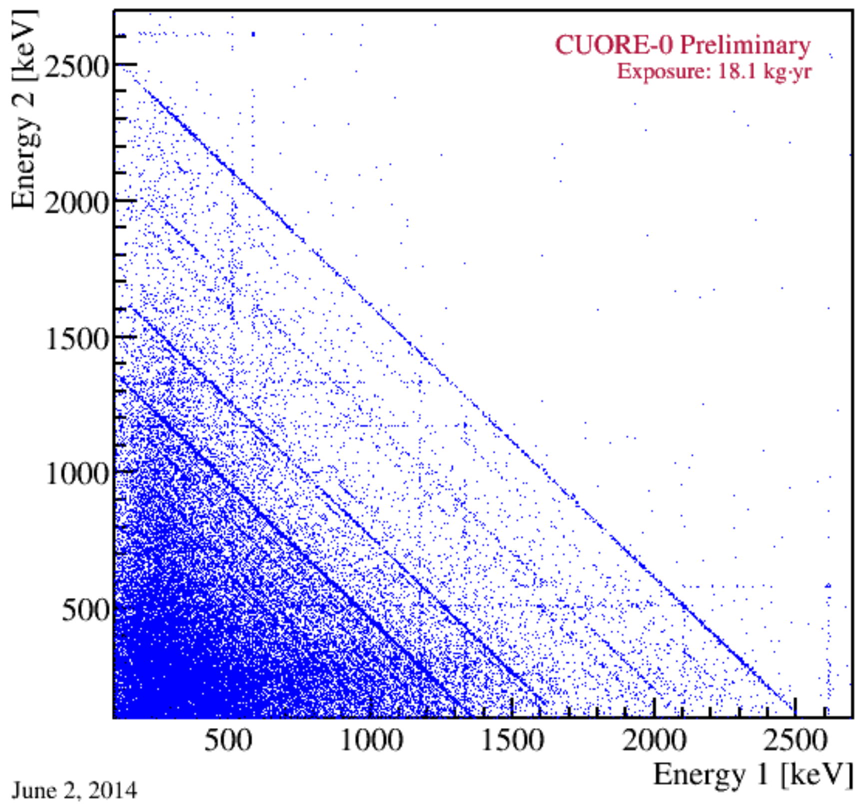
June 2, 2014

CUORE-0 Background Spectrum



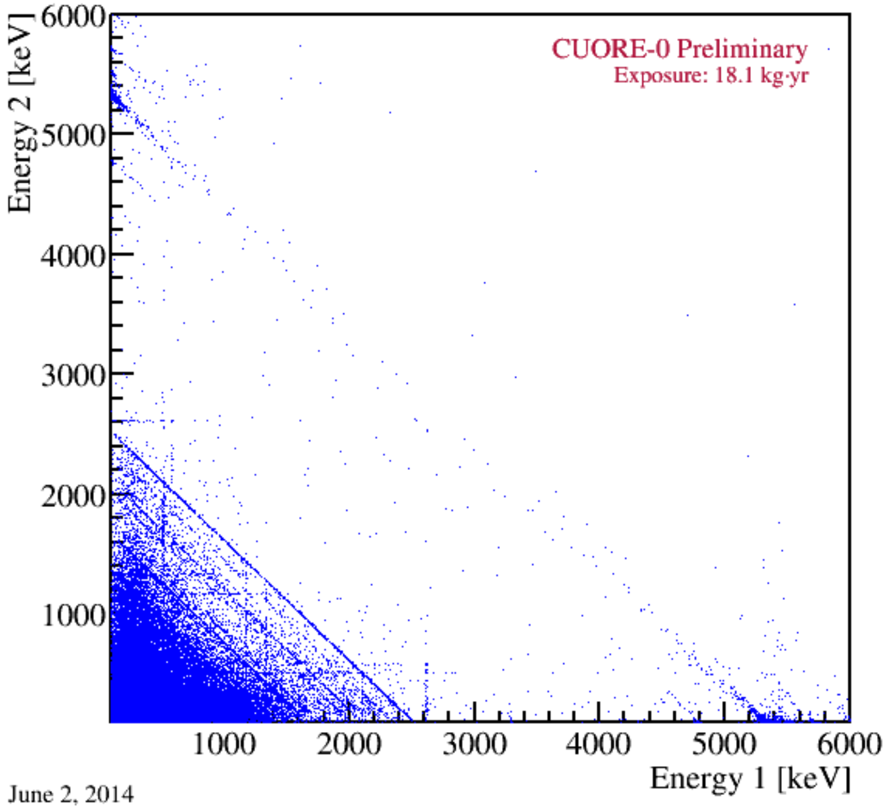
June 2, 2014

CUORE-0 Background Multiplicity



June 2, 2014

CUORE-0 Background Multiplicity

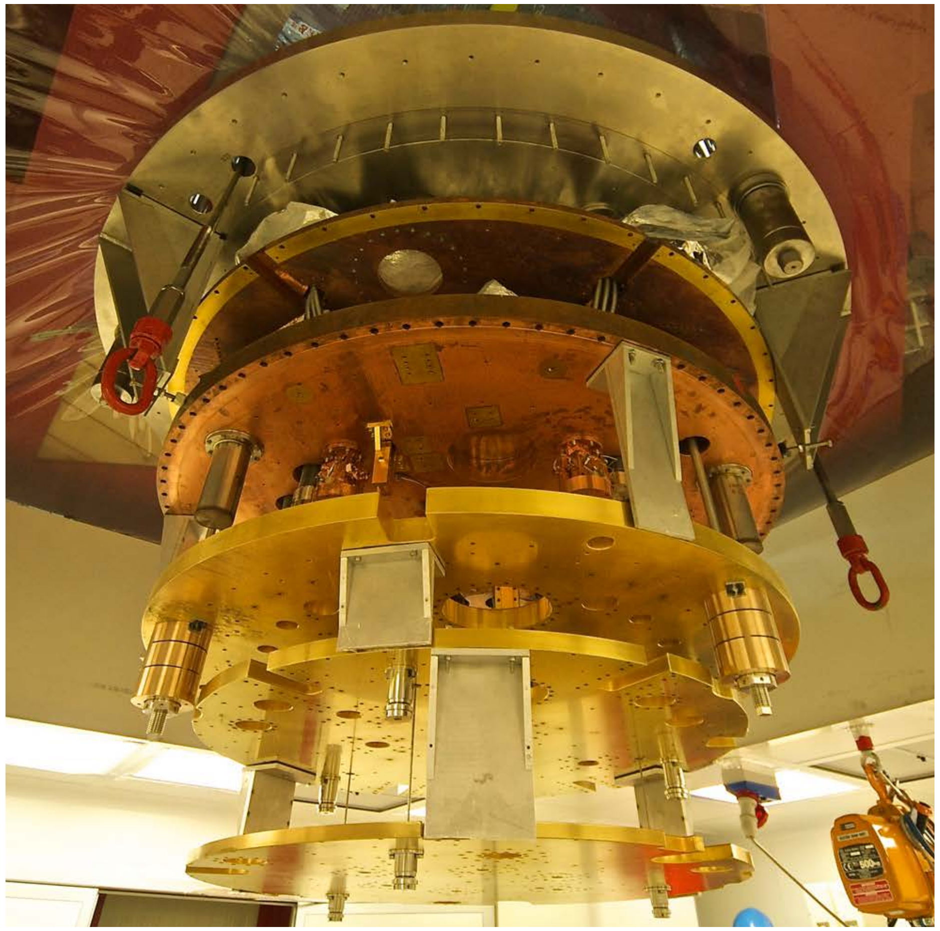


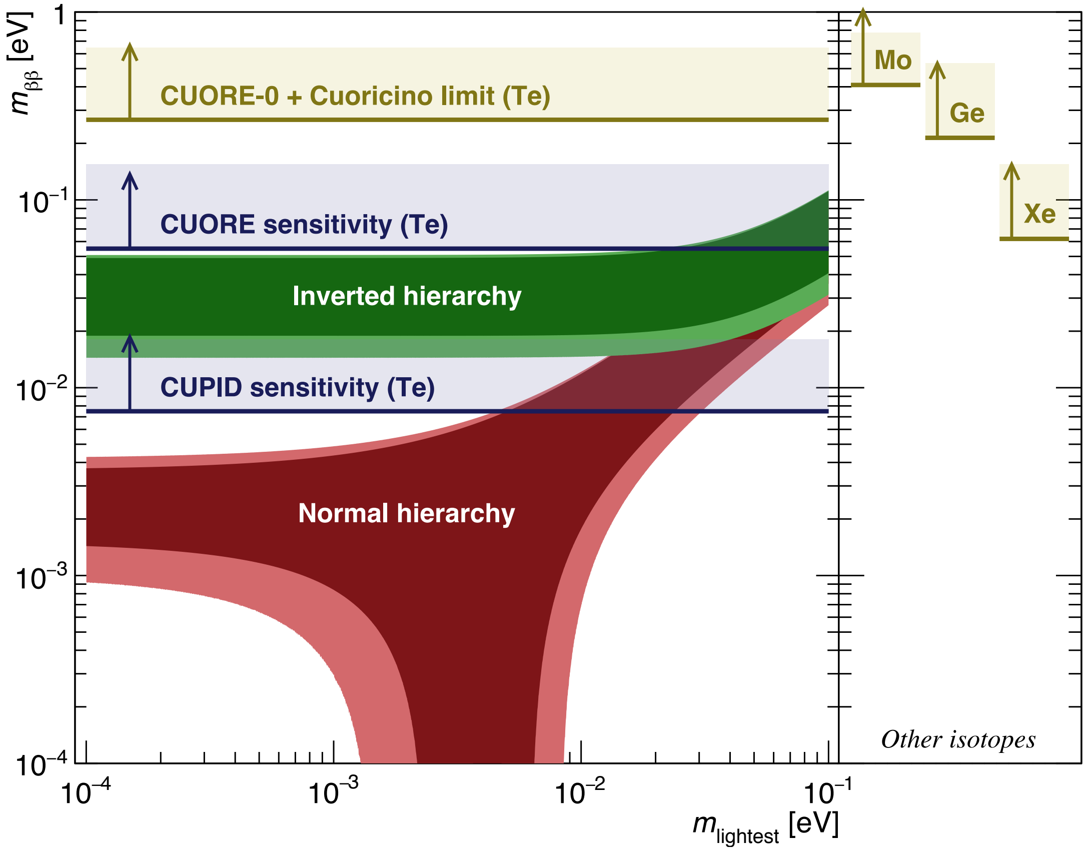
June 2, 2014

CUPID and next generation bolometer R&D at Berkeley

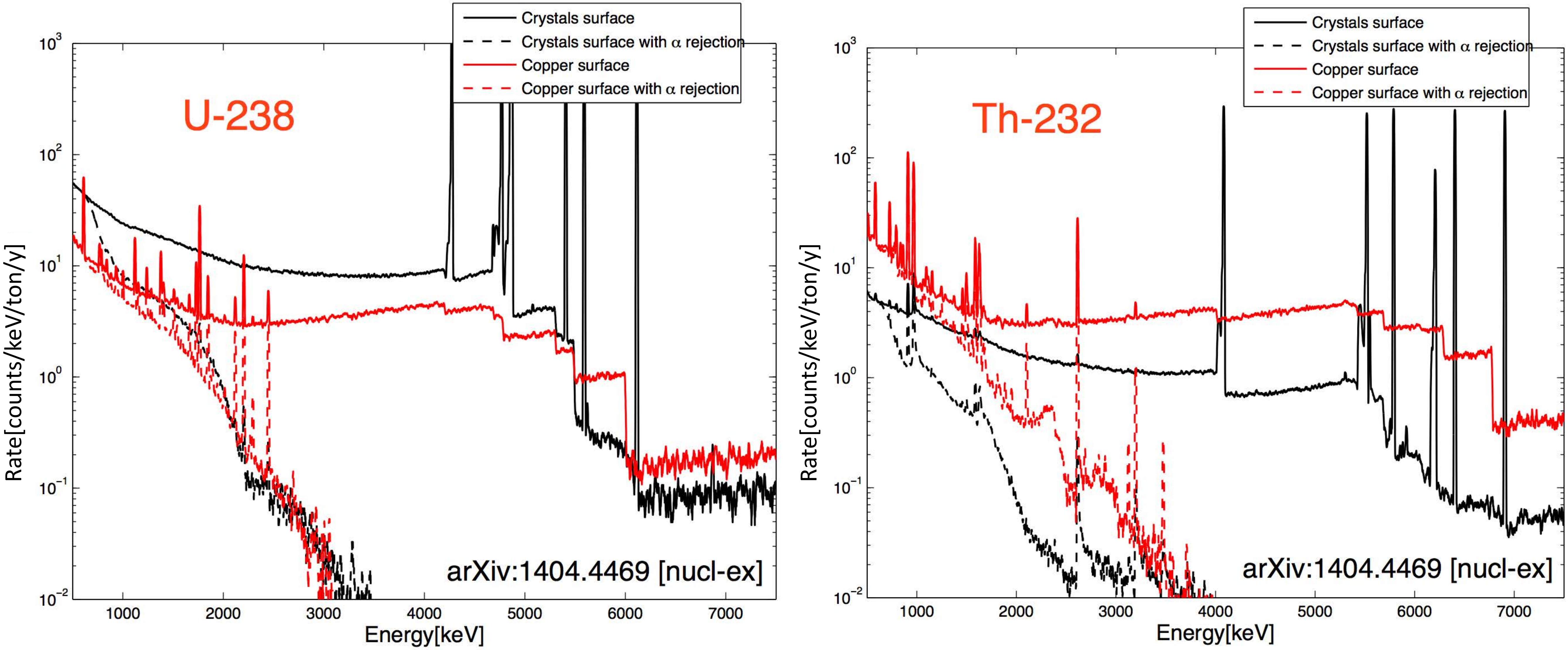
CUPID

- **C**UORE **U**pgrade with **P**article **I**dentification.
- CUORE scale and geometry, same cryostat, same backgrounds.
- Add optical channel for active discrimination—“best of both worlds.”
  - Option 1: Scintillating crystal (“Lucifer/CUPID-0 style”)
    - ZnSe, $ZnMoO_4$, Li_2MoO_4, or $CdWO_4$
    - ^{82}Se (Q = 2995.5 keV, NA = 9.2%), ^{100}Mo (Q = 3035 keV, NA = 9.6%), ^{116}Cd (Q = 2809 keV, NA = 7.6%)
    - Strong light signal.
    - Difficult and expensive to grow crystals in large amounts.
  - Option 2: Cherenkov light w/ TeO_2
    - Enrichment to >90% ^{130}Te (33.8% natural in CUORE)—nearly triple isotope mass without increasing background and bulk mass.
    - Well understood and affordable crystals.
    - Weak, challenging to detect light signal.
- Surface/bulk discrimination with scintillating or superconducting (pulse shape) films.
- 10 y live time w/ sensitivity goals:
  - $t_{1/2}$: $(2–5)\times10^{27}$ y (3σ)
  - $m_{\beta\beta}$: 6–15 meV (90% CL)





Effect of α background rejection (simulation)

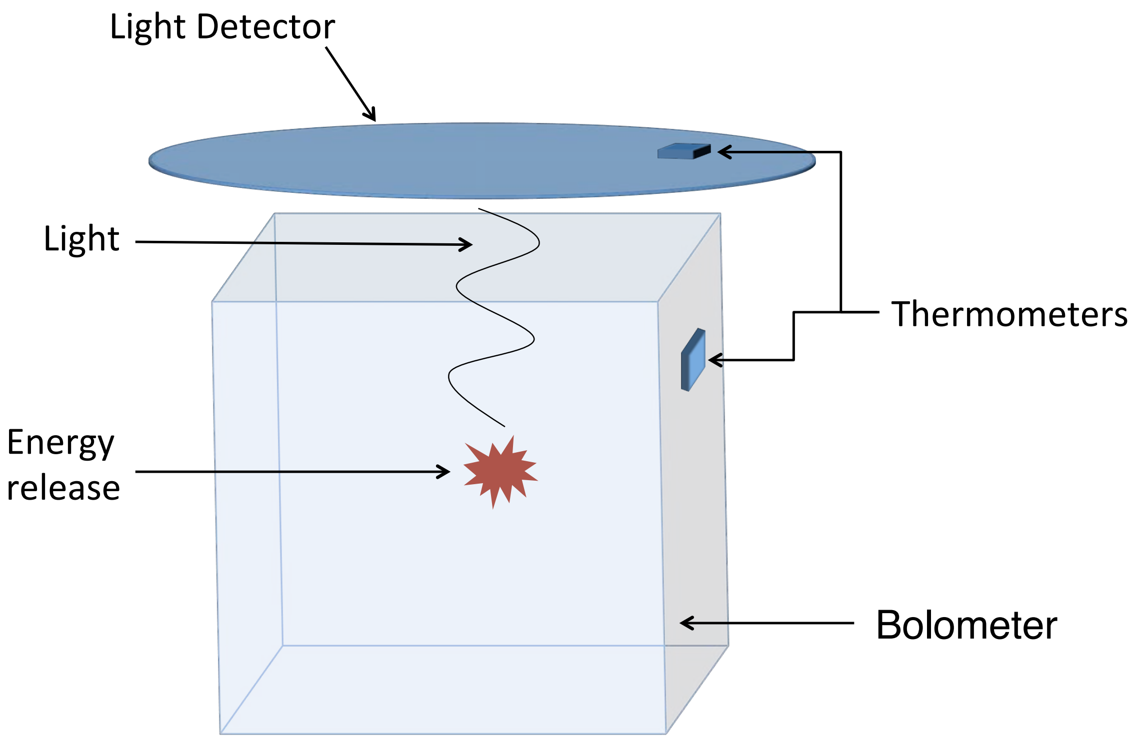


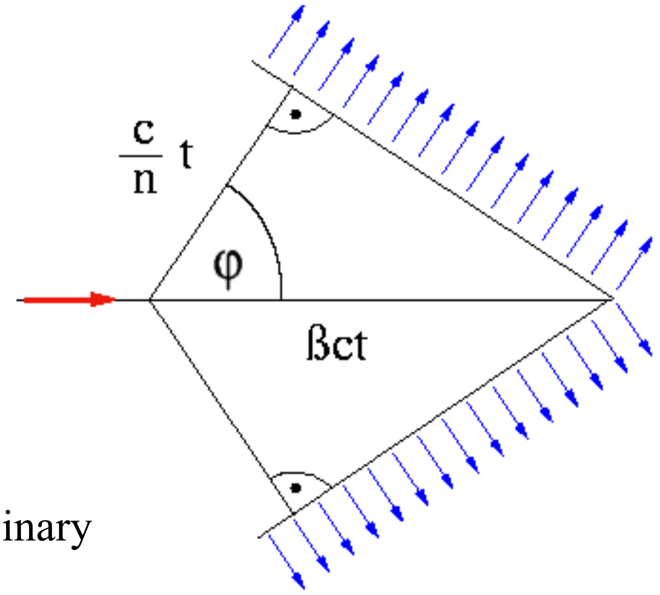
arXiv:1404.4469 [nucl-ex]

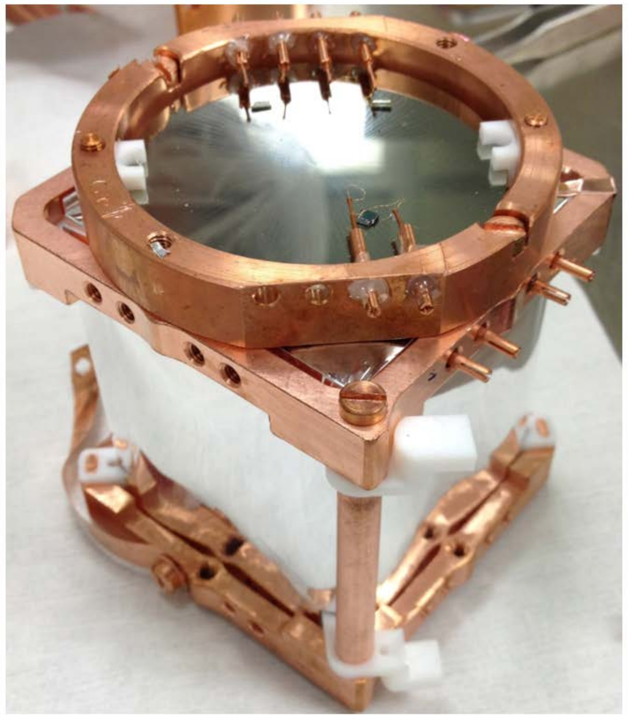
Simulated CUORE backgrounds from ^{238}U and ^{232}Th chain contaminants on crystal and copper (structure) surfaces.

Cherenkov light bolometers

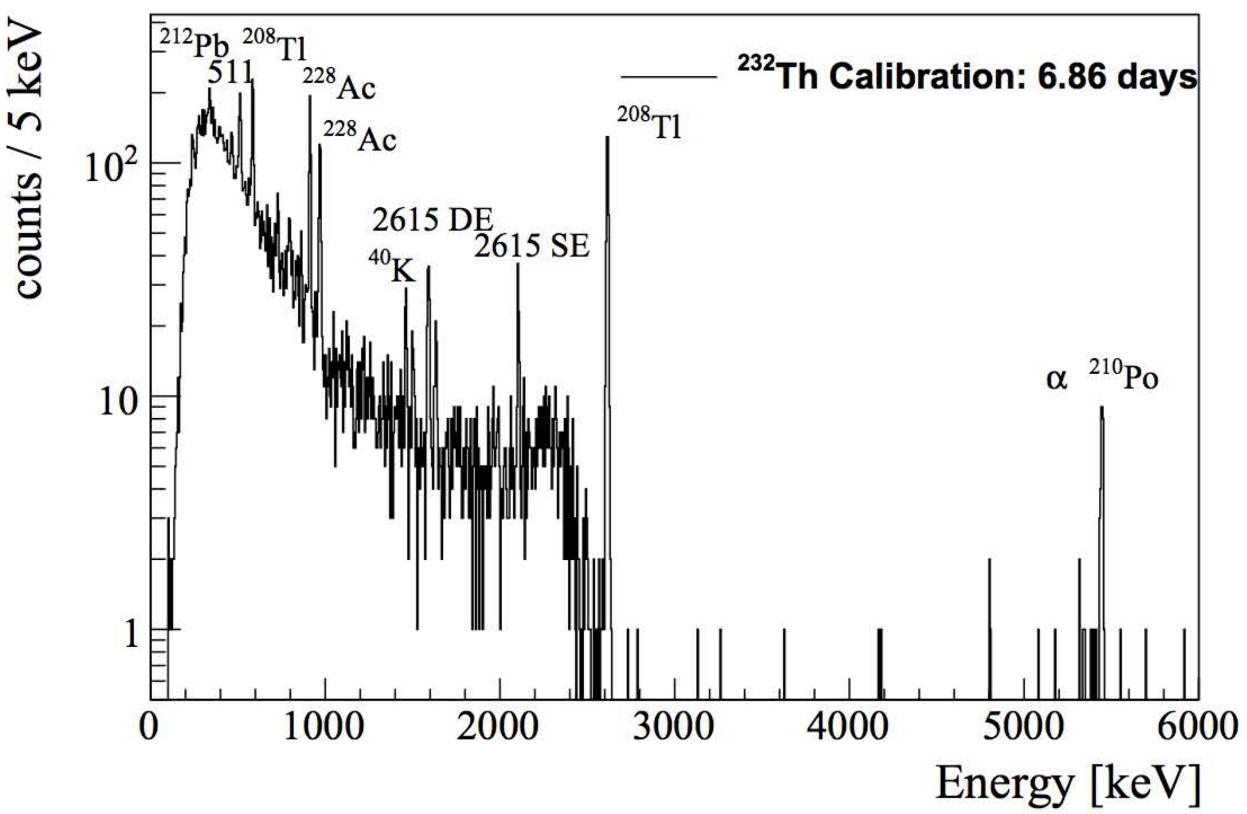
- Primary energy readout is still the conventional bolometer.
- A second bolometer detects Cherenkov radiation from the crystal to identify particles.
- Motivation and advantages:
  - Cherenkov light is generated by β particles moving faster than c/n.
  - No Cherenkov light from α's: binary discrimination.
  - Allows us to have optical channel with non-scintillating TeO_2 crystals.
  - Growing scintillating crystals with ββ isotopes has proven difficult.
- Challenges and Research Opportunities:
  - Low light yield.
  - High rate of total internal reflection in TeO_2.
  - Detector ideally must have ≤ 10 eV threshold,
  - Dynamic range, however, is not prioritized because of binary nature of signal.

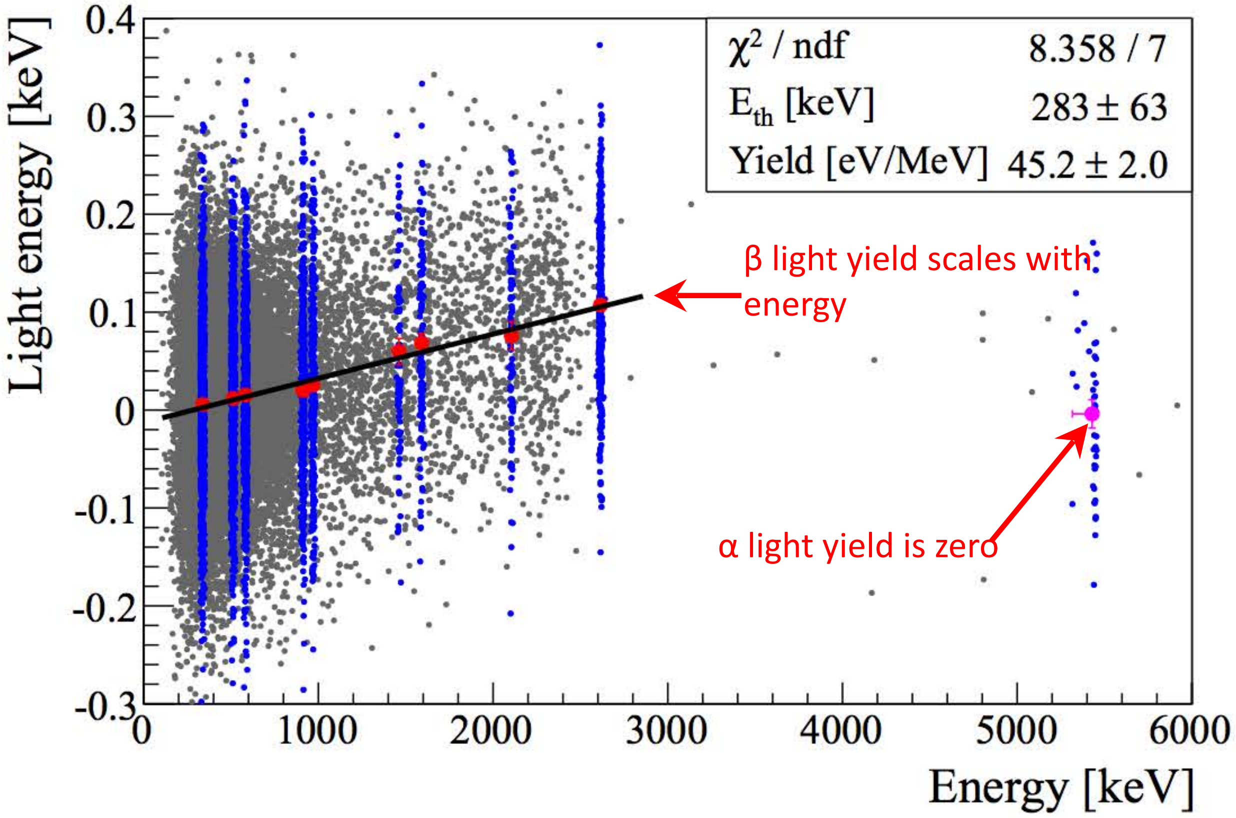






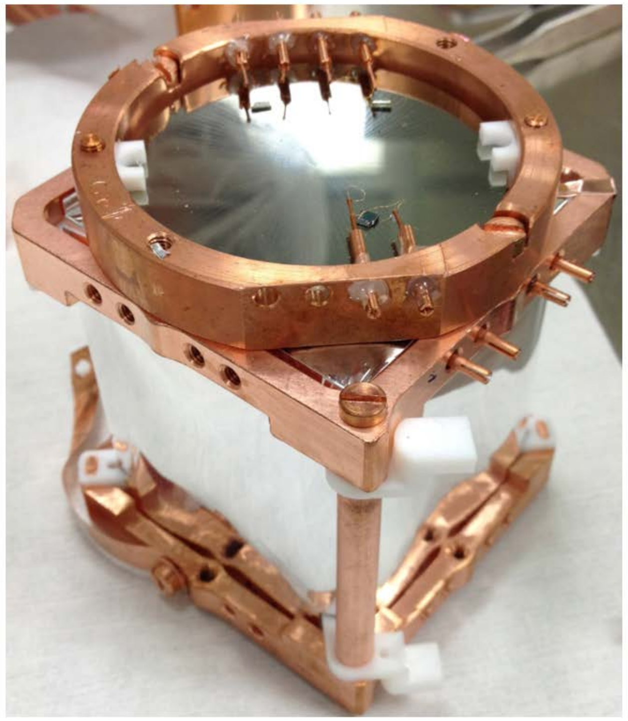
Cherenkov particle ID: LNGS prototype





β light yield scales with energy

α light yield is zero



- CUORE-type TeO2 crystal.
- Ge bolometric light detector with NTD readout.
- 3M VM2002 reflector.
- Successful proof of concept.
- Insufficient for complete alpha rejection—light detector baseline noise < 20eV (3–4× less) needed.
- New light detector development is necessary.

Transition Edge Sensors

- **T**ransition **E**dge **S**ensor—based on superconducting transition of a metal or alloy.
- In narrow region around T_C, R(T) much more sensitive than exponential.
- Typically read out by SQUID
- Our TES's are bi-/trilayers of superconducting and normal metals (e.g. Ir/Pt or Au/Ir/Au).
- Main challenge: sufficiently low T_C.

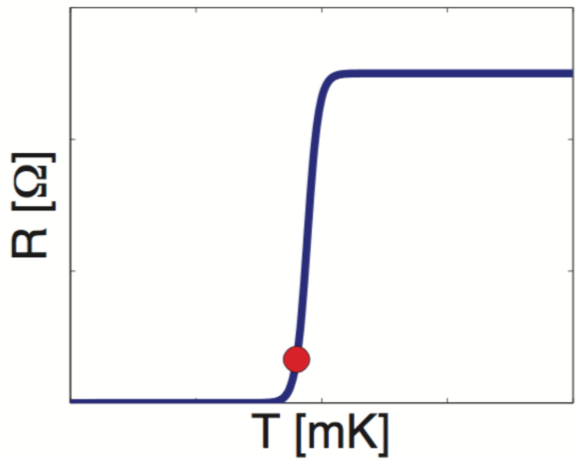
$$\sigma_E = \sqrt{\frac{4k_BT^2C_{tot}}{\alpha}\sqrt{\frac{\beta+1}{2}}}$$

$$\alpha \equiv \frac{T}{R}\frac{dR}{dT}$$

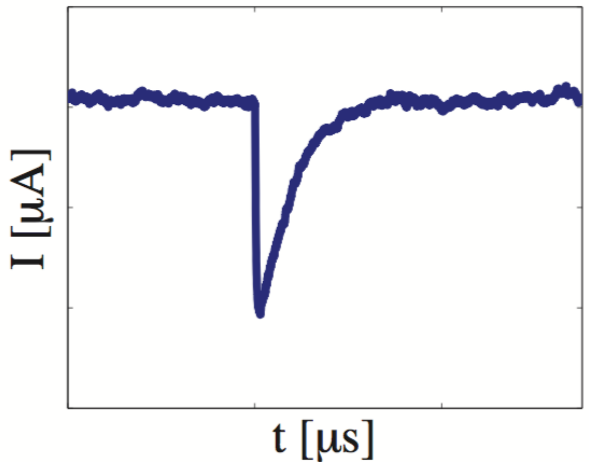
$$C_{tot} = C_{bol}(\propto T^3) + C_{TES}(\propto T) + C_{other}$$

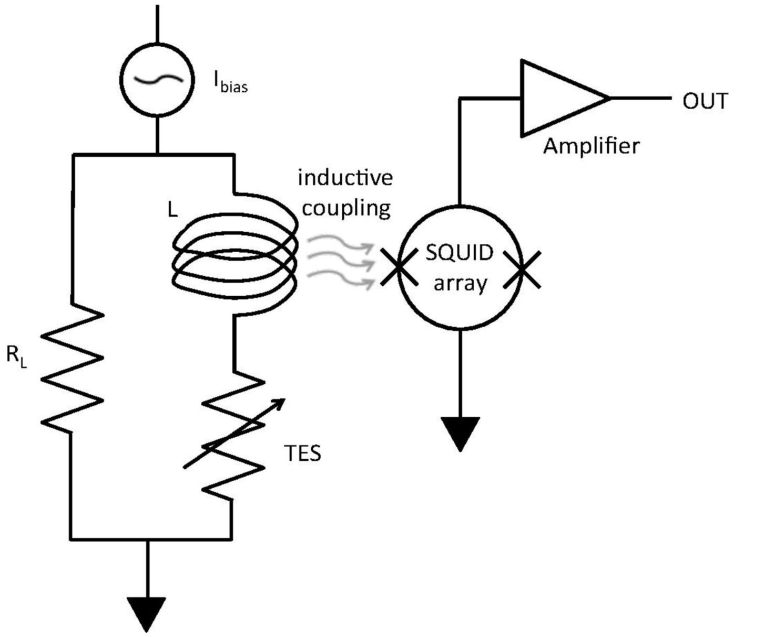
$$E_{max} = C\Delta T_{max} \simeq \frac{C}{\alpha}T$$

Bias point

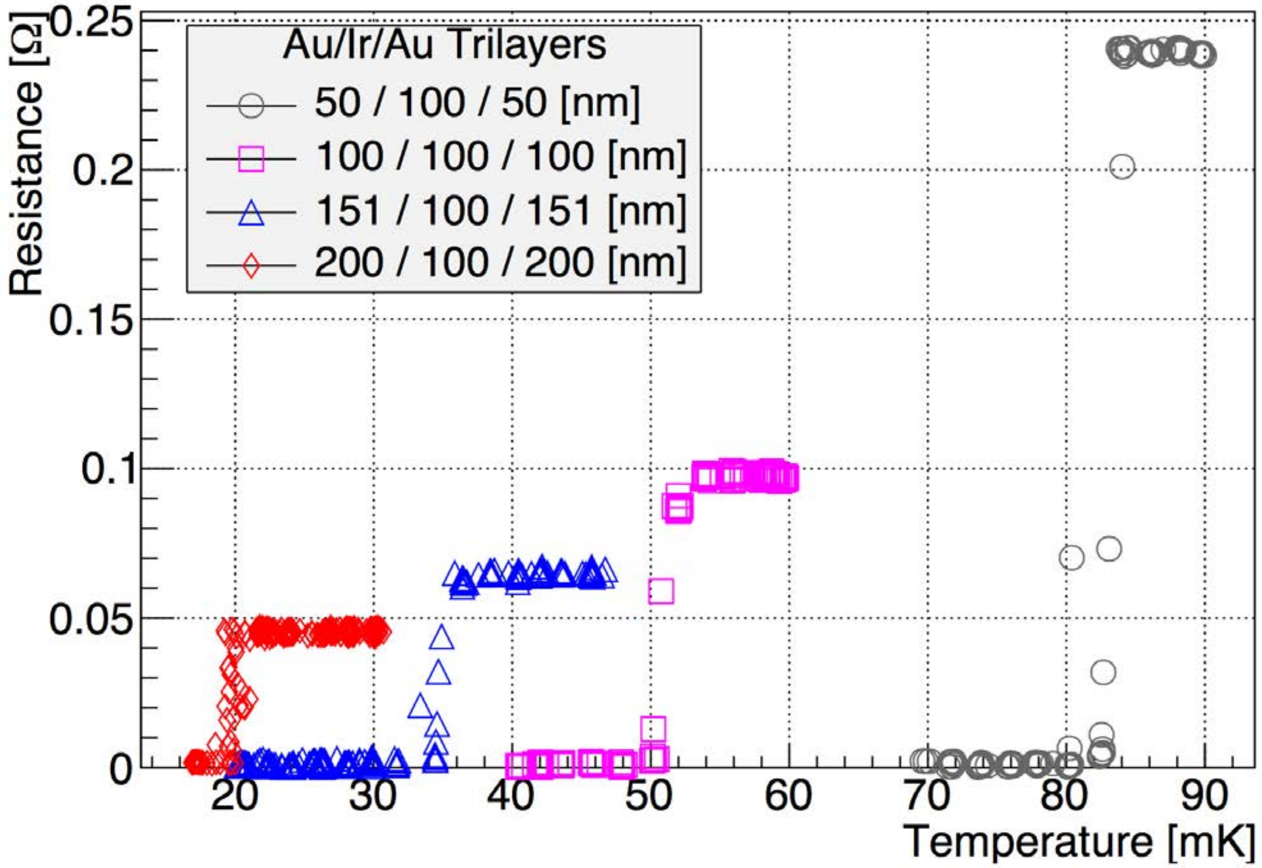


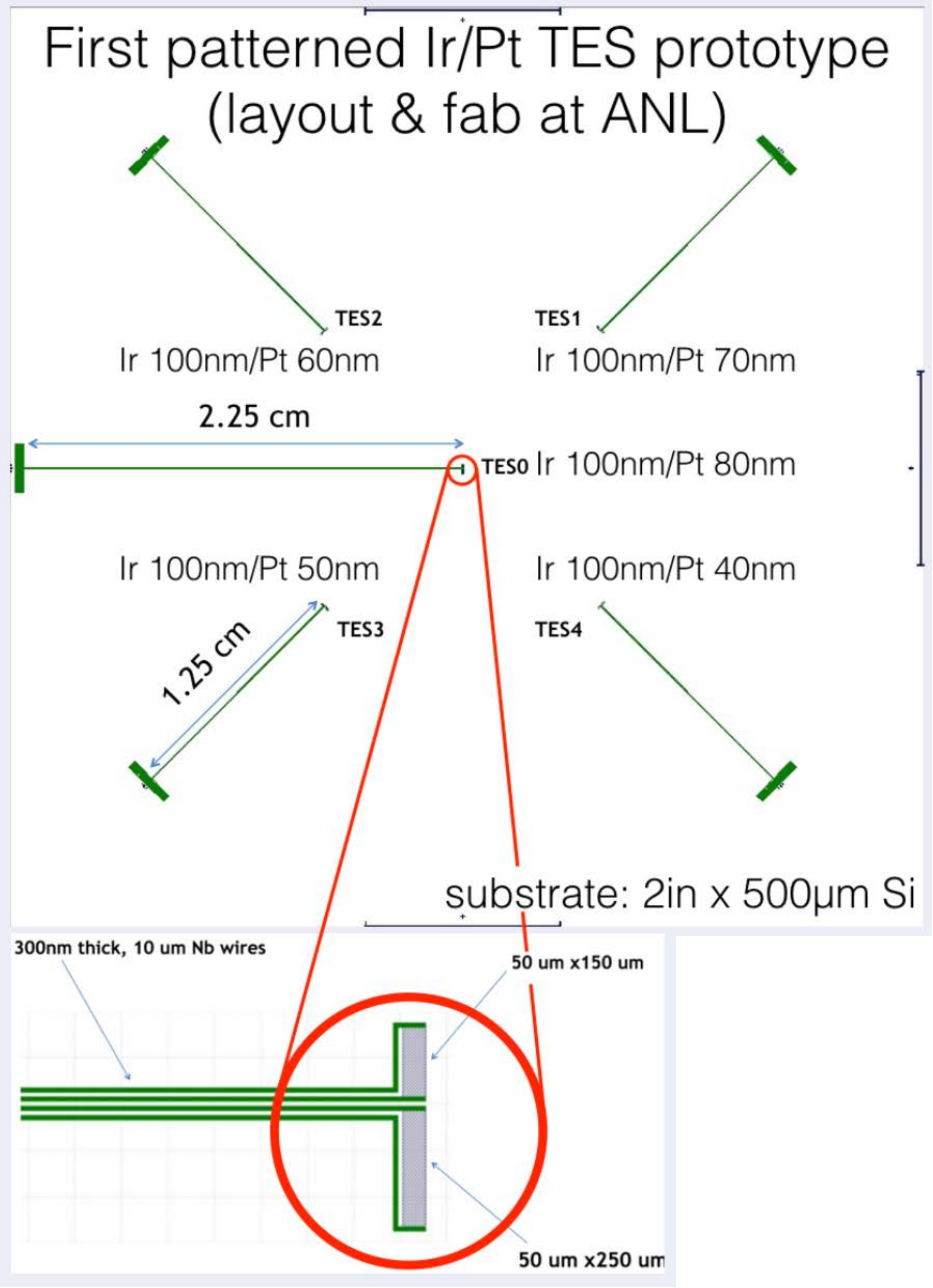
Signal out

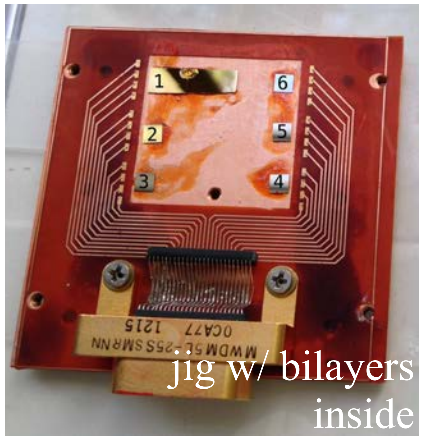




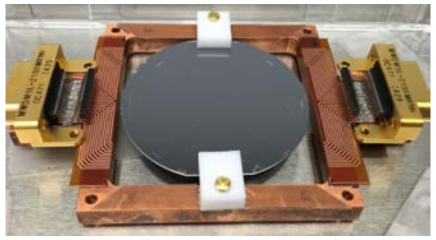
Light detector TES R&D at Berkeley

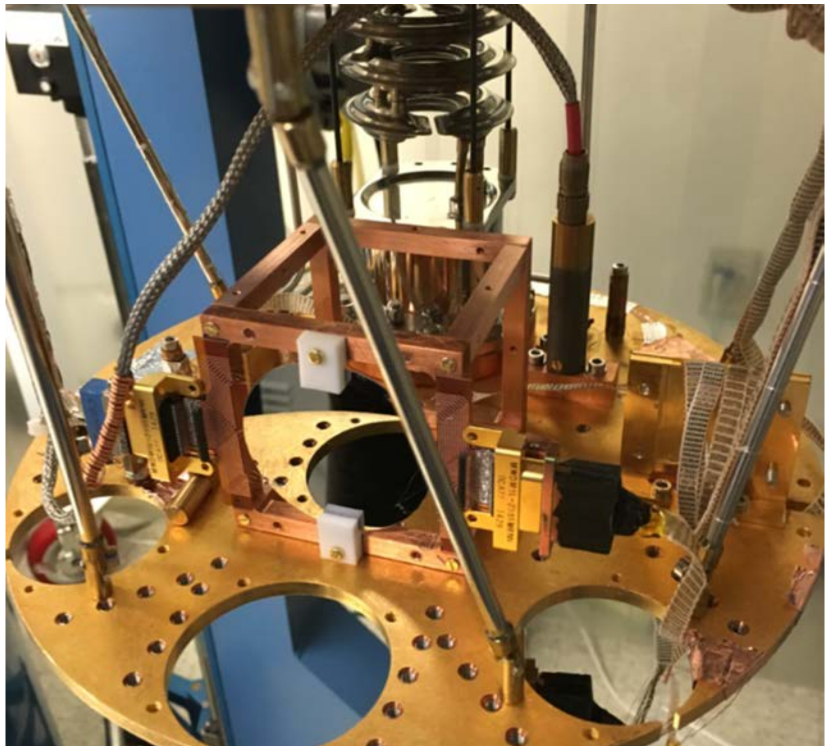



First patterned Ir/Pt TES prototype (layout & fab at ANL)



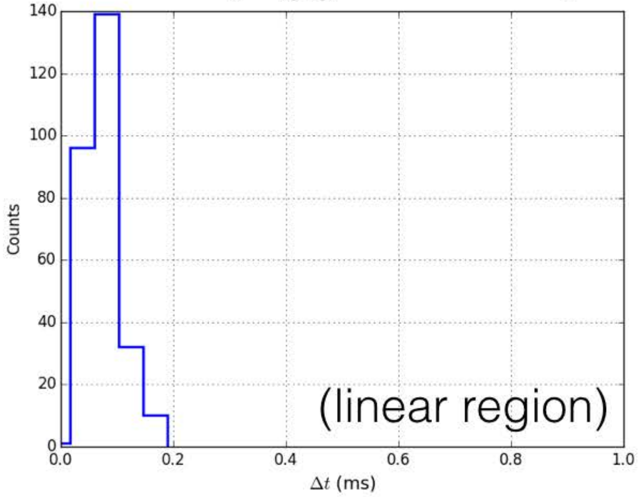
jig w/ bilayers inside



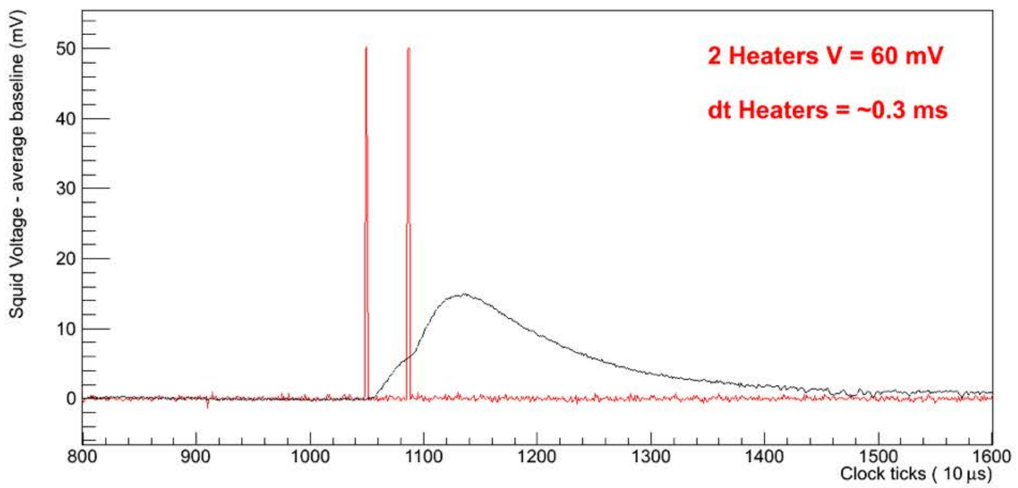


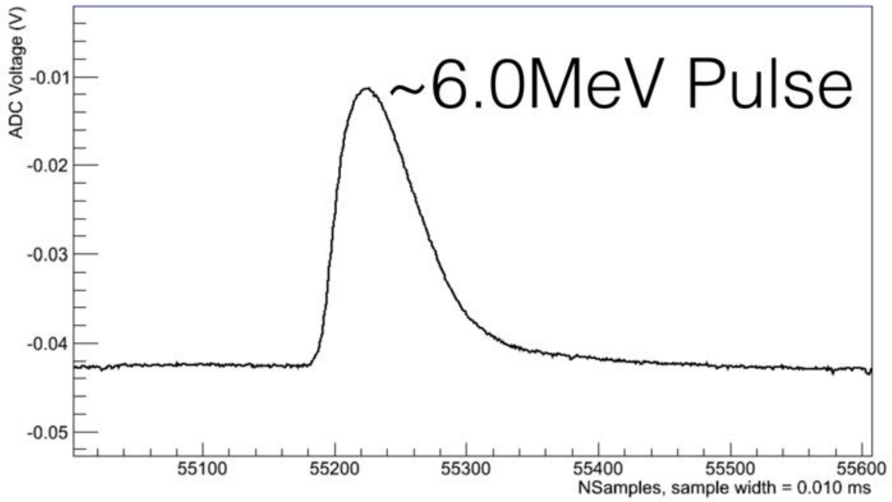
Our first TES bolometer test jig

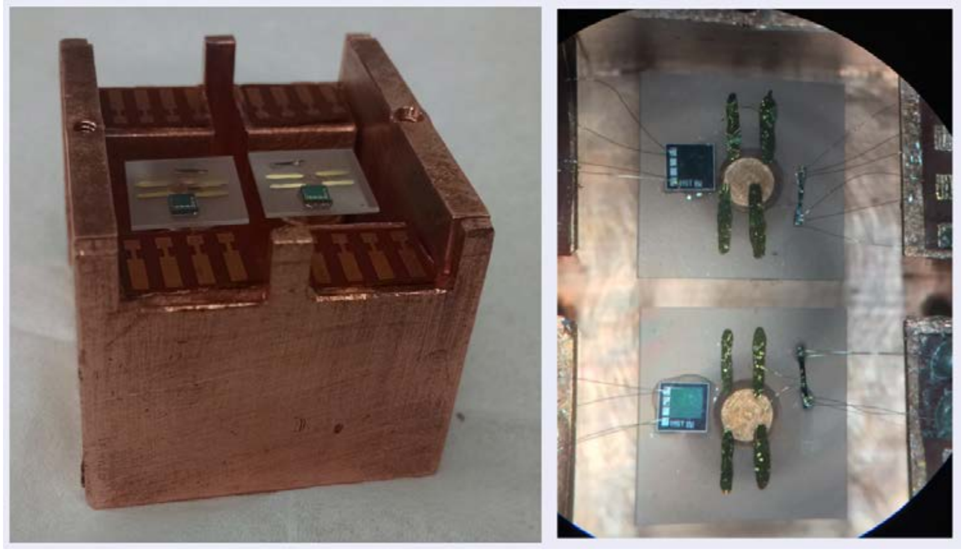
Δt (trigger – heater)

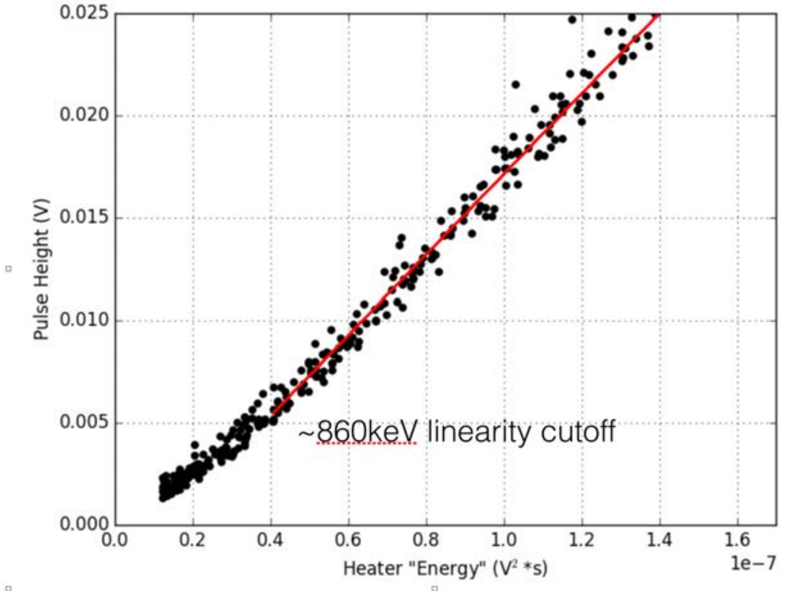


raw double pulse response







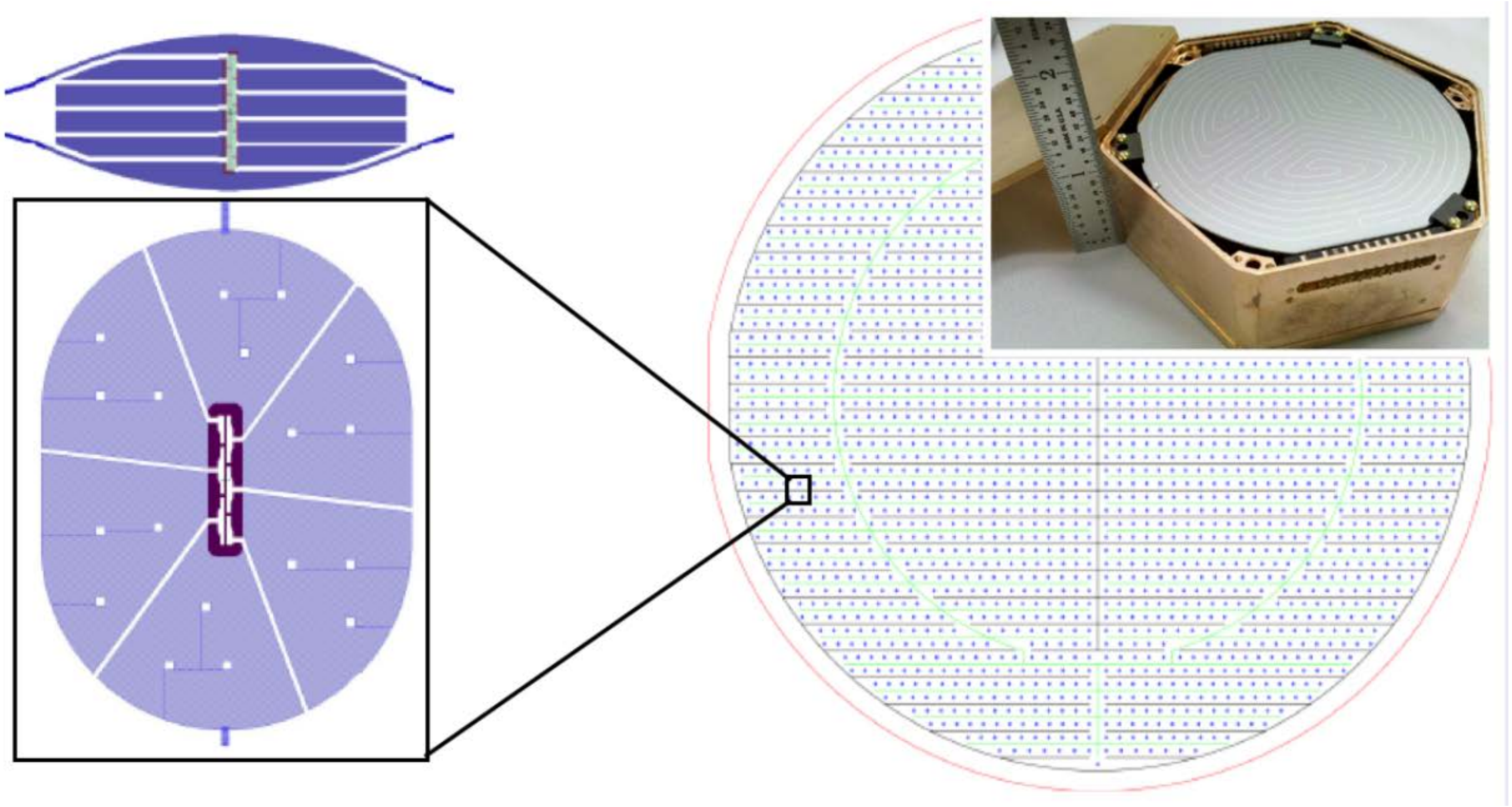


- 3mm×0.25mm Ir/Pt bilayer (80nm/20nm @ 600◦C; $T_C \approx$ 56mK) and 300kΩ CUORE heater glued on 1cm×1cm×0.5mm single-crystal Al_2O_3.

- SQUID readout.
- Al bonds for electrical connections

- Au bonds for thermal connections
- Operated at 53–55 mK

Athermal phonon light detector



- Being developed in collaboration with Berkeley CDMS group (Matt Pyle).
- “Super CDMS-style”: 1030 W tes’s with aluminum collector fins on 3” Si wafer.
- Being developed in parallel with standard “thermal” designs.

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