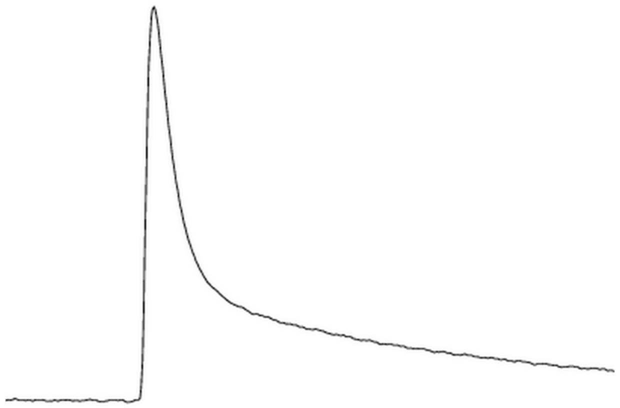


Detecting rare events using optical bolometers with transition edge sensors.

Alexey Drobizhev
Physics 290E
Wednesday 14 October 2015
UC Berkeley

Outline

- Overview of bolometric detection principles
- CUORE experiment as state of the art large conventional bolometric detector
  - overview
  - measurements
  - energy resolution
  - backgrounds
  - limited capacity for active background rejection (anticoincidence)
- Transition Edge Sensors (TES's)
  - overview
  - operation theory
  - tungsten TES's
  - multilayer TES's
  - bilayer TES R&D by Kolomensky group at UC Berkeley
- Optical bolometers
  - Scintillating bolometers
    - overview
    - CRESST II as state of the art example
  - Cherenkov light bolometers
  - Neganov-Luke amplification for light detectors

Bolometers: general principles

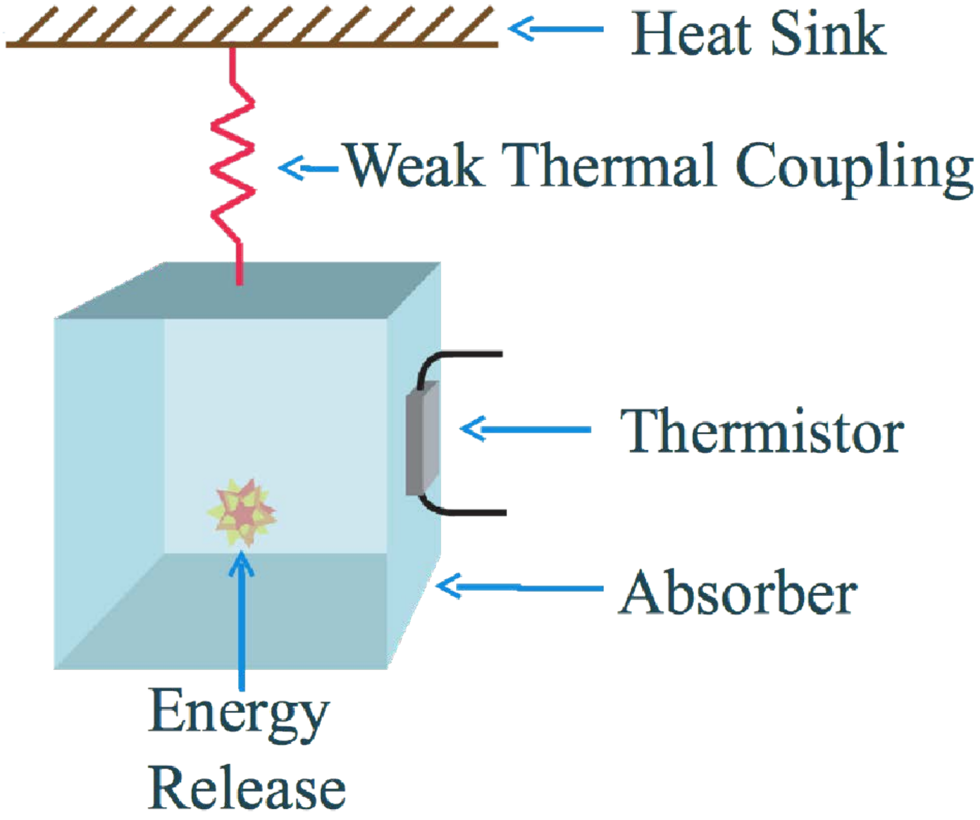
- Detection of thermal signatures of absorbed particles:

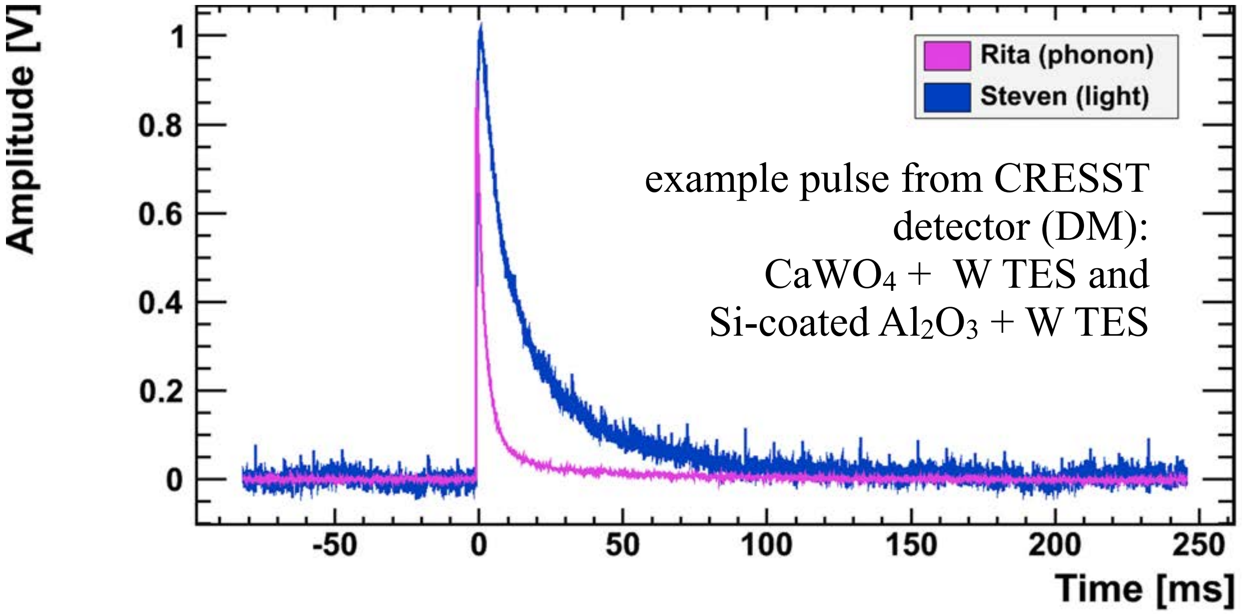
$$\Delta T = \frac{E_{event}}{C_{absorber}}$$

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

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

- Attractive for low-background, rare event searches like Dark Matter and 0νββ.





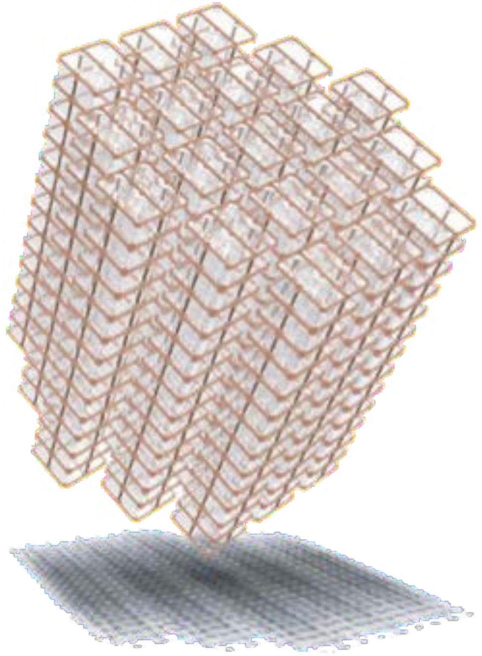
example pulse from CRESST detector (DM): $CaWO_4$ + W TES and Si-coated Al_2O_3 + W TES

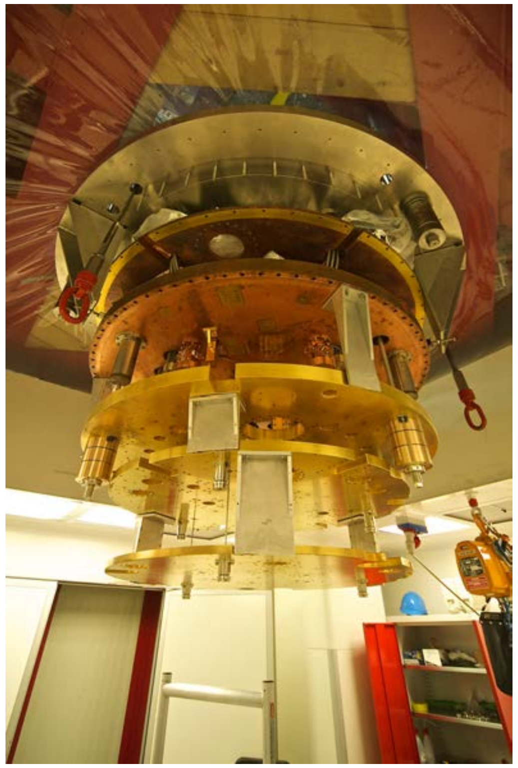
CUORE: example of modern day "traditional" bolometric detector

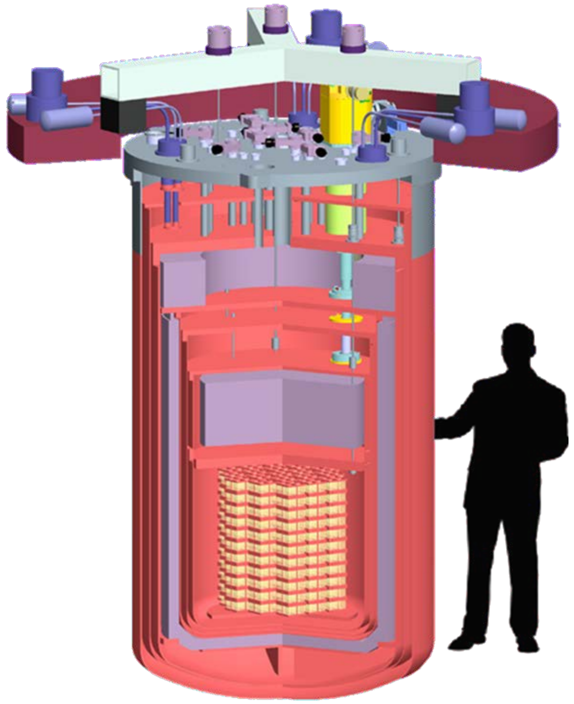
(w/o TES or optical channel)

CUORE

- Cryogenic Underground Observatory for Rare Events.
- Bolometric search for 0νββ in ^{130}Te (with secondary topics 2νββ, axions, and others).
- A good practical example of currently-running/ soon-to-run practical ton-scale bolometric detector with *only a thermal channel*.
- 988 TeO2 5x5x5cm^3 crystals in 19 towers of 52: source and absorber, $m_{isotope} = 204$kg.
- $T_{base} \leq 10$mK
- Commissioning ongoing, data in 2016.
- CUORE-0—single CUORE tower, turned off summer 2015, results spring 2015 (2y data).







CUORE: measurements

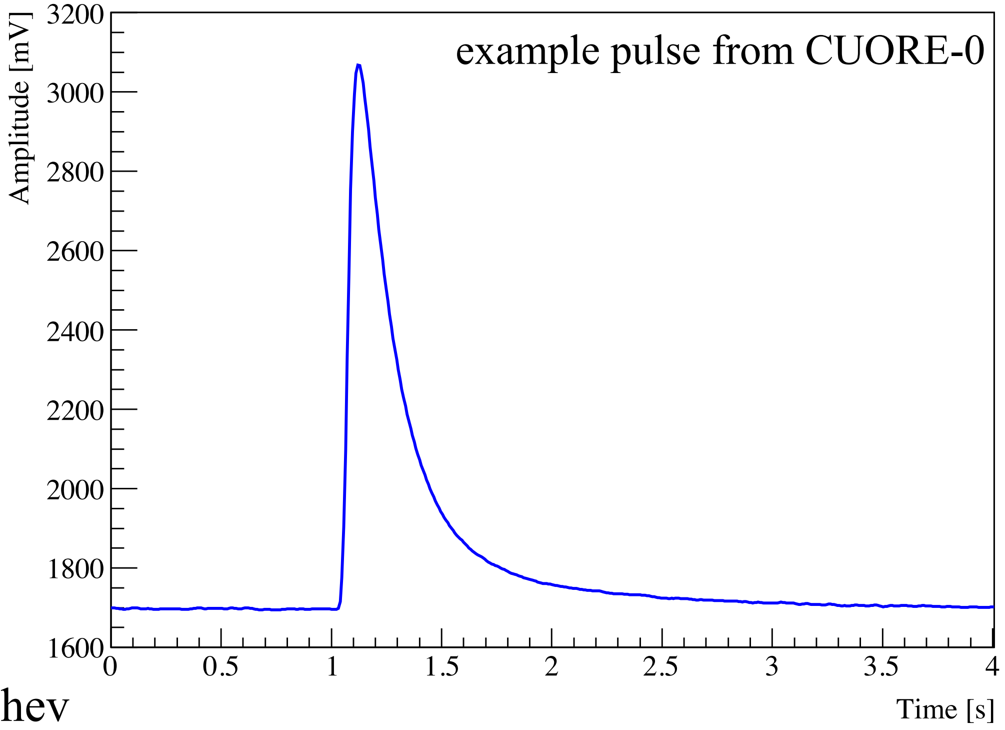
- $5x5x5cm^3$ TeO_2 at 10mK:

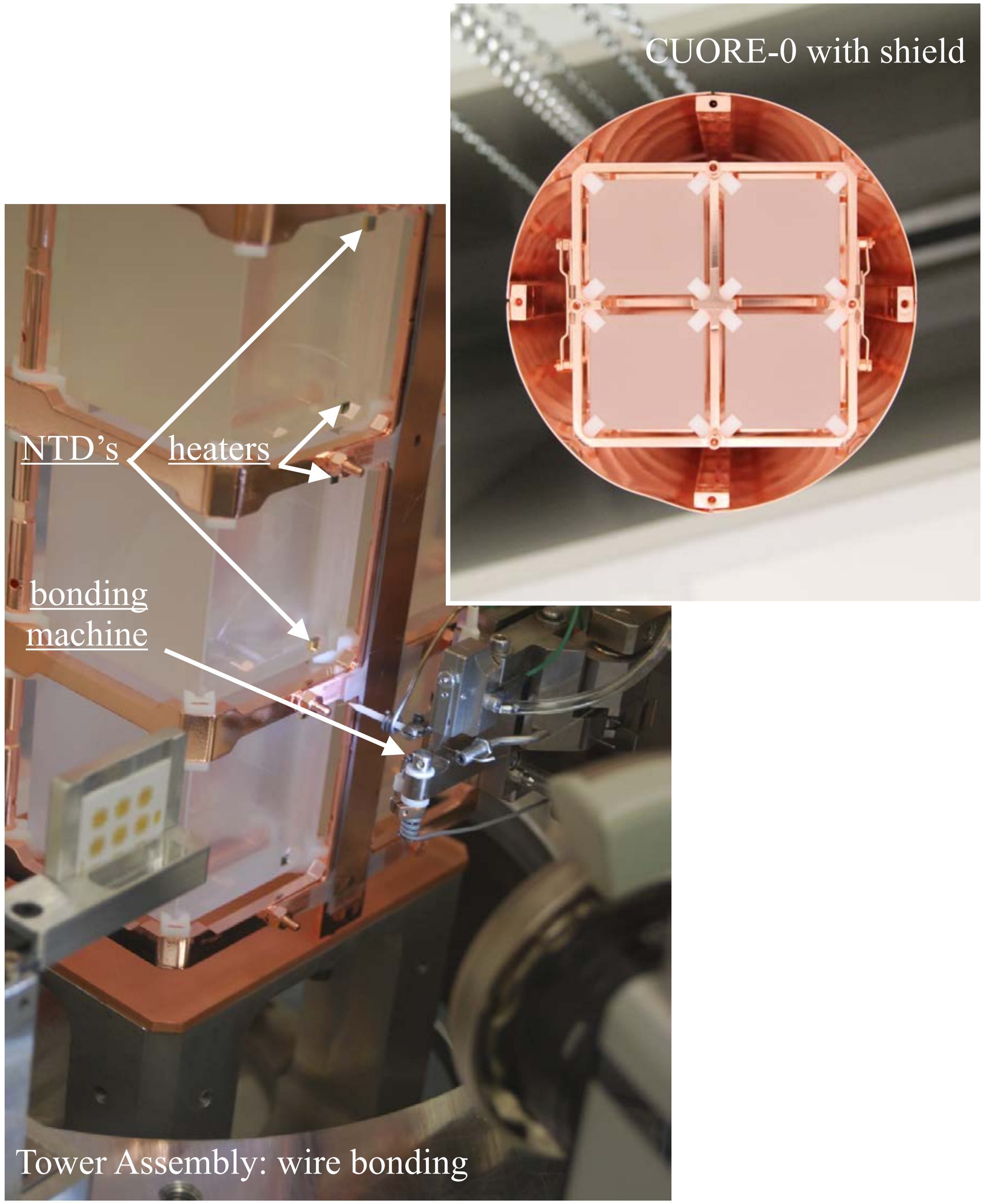
$$\Delta T_{event} = \frac{E_{event}}{C_{crystal}}$$

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

- Readout with Ge NTD thermistor:

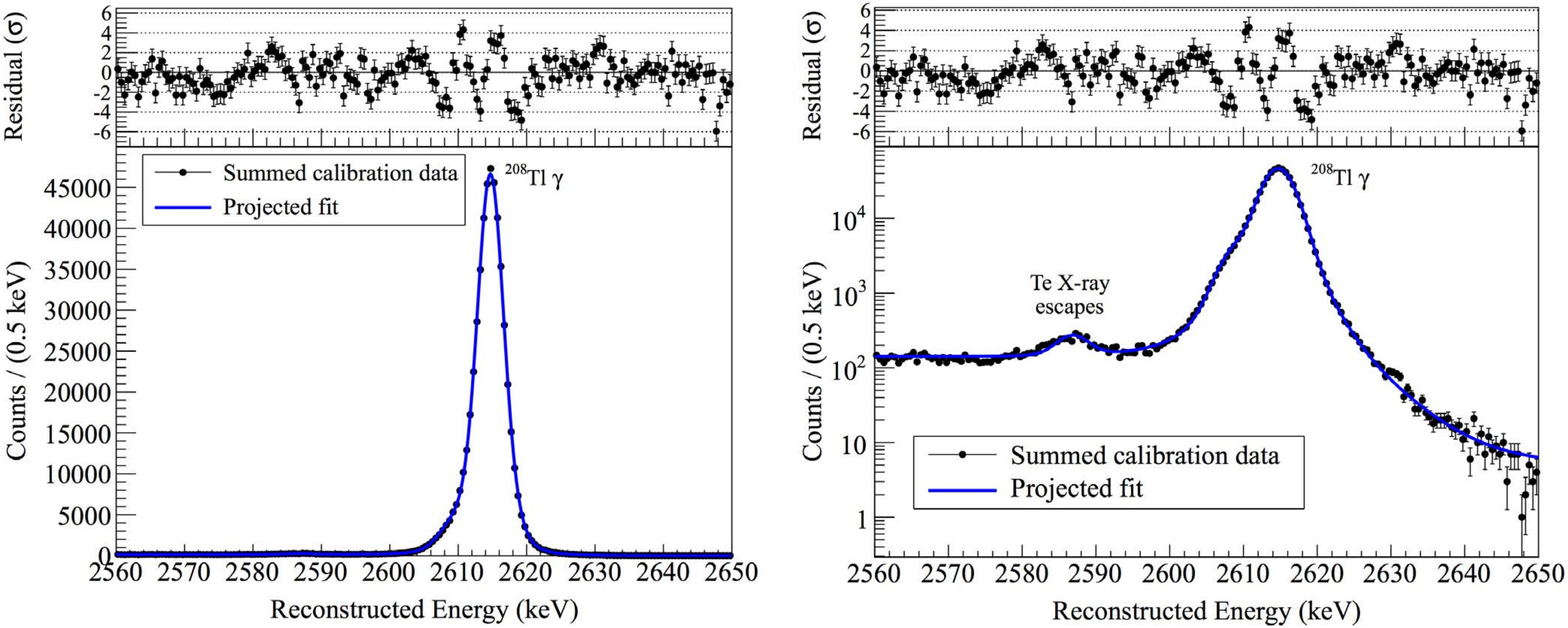
$$R_{NTD} = R_0 e^{\sqrt{T_0/T}}$$





Tower Assembly: wire bonding

CUORE: energy resolution performance



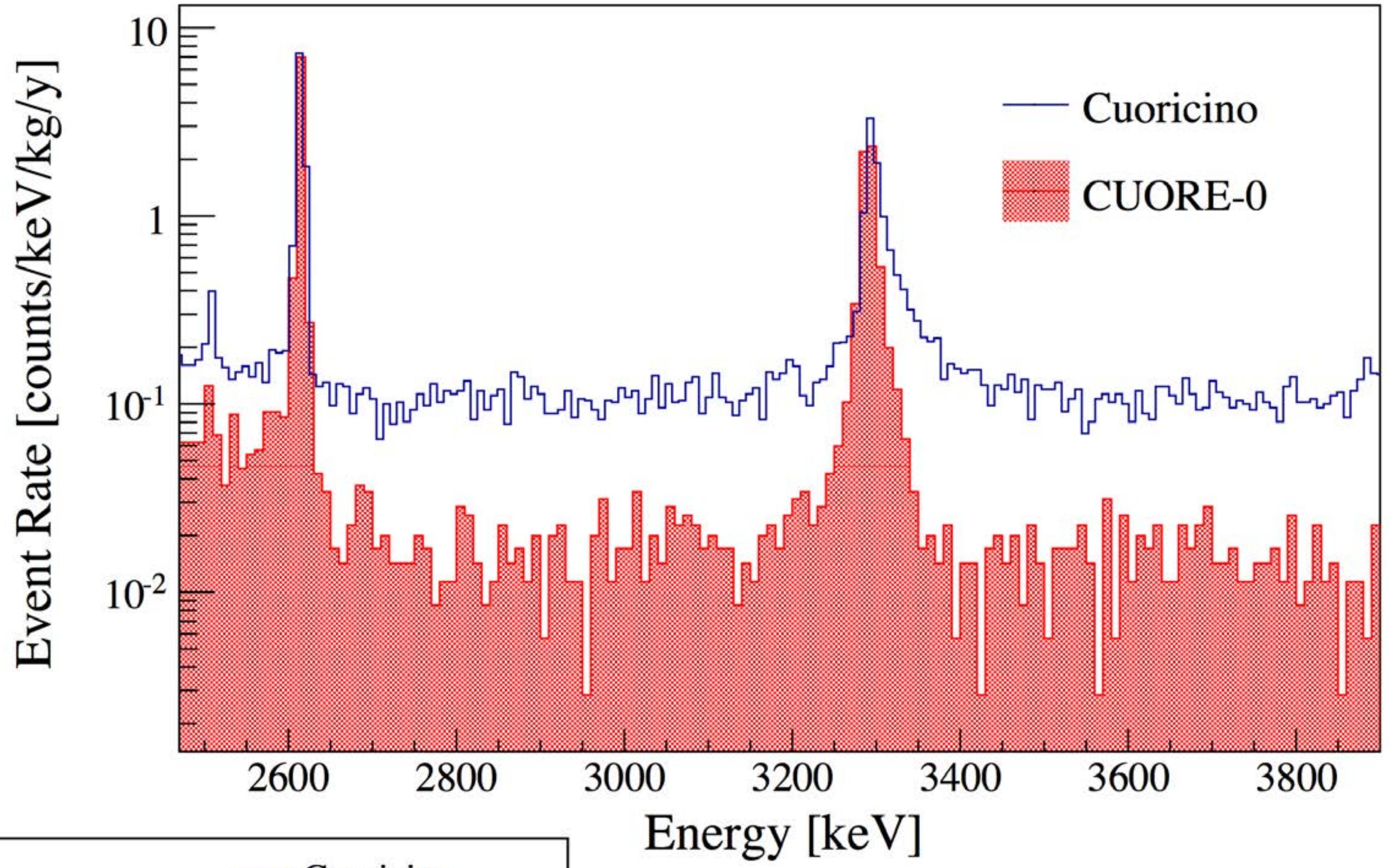
$$\Delta E_{limit} \sim \sqrt{kCT^2} \sim 10eV \quad \Delta E_{CUORE-0} \sim 5keV\ FWHM$$

$$at\ \sim 2.6MeV\ (^{208}Tl\ \gamma\ line)$$

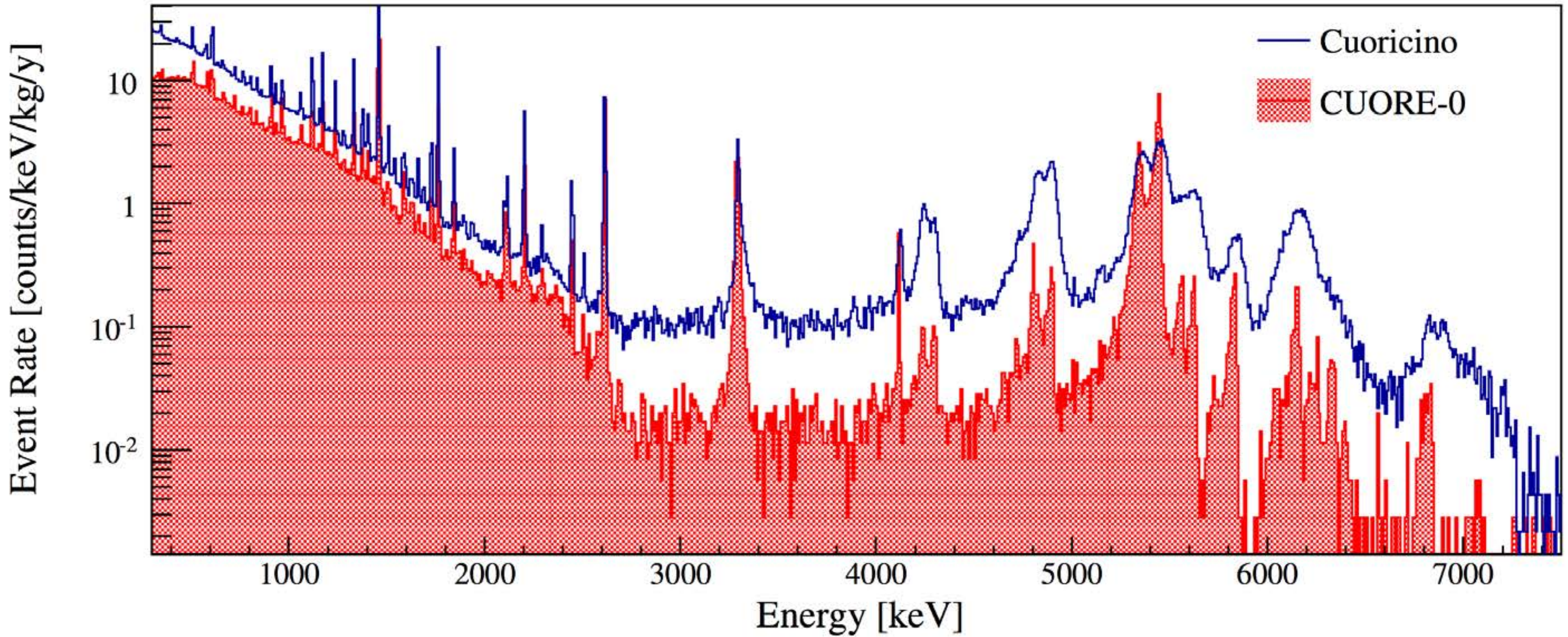
K. Alfonso et al. arxiv: 1504.02454

CUORE: background performance

- Passive suppression to 0.02 counts/keV/kg/y (CUORE-0), expected 0.01 counts/keV/kg/y for CUORE.
- Q=2527 keV—high energy edge of γ region, but away from major peaks due to good energy resolution.
- Primary background is degraded α's.



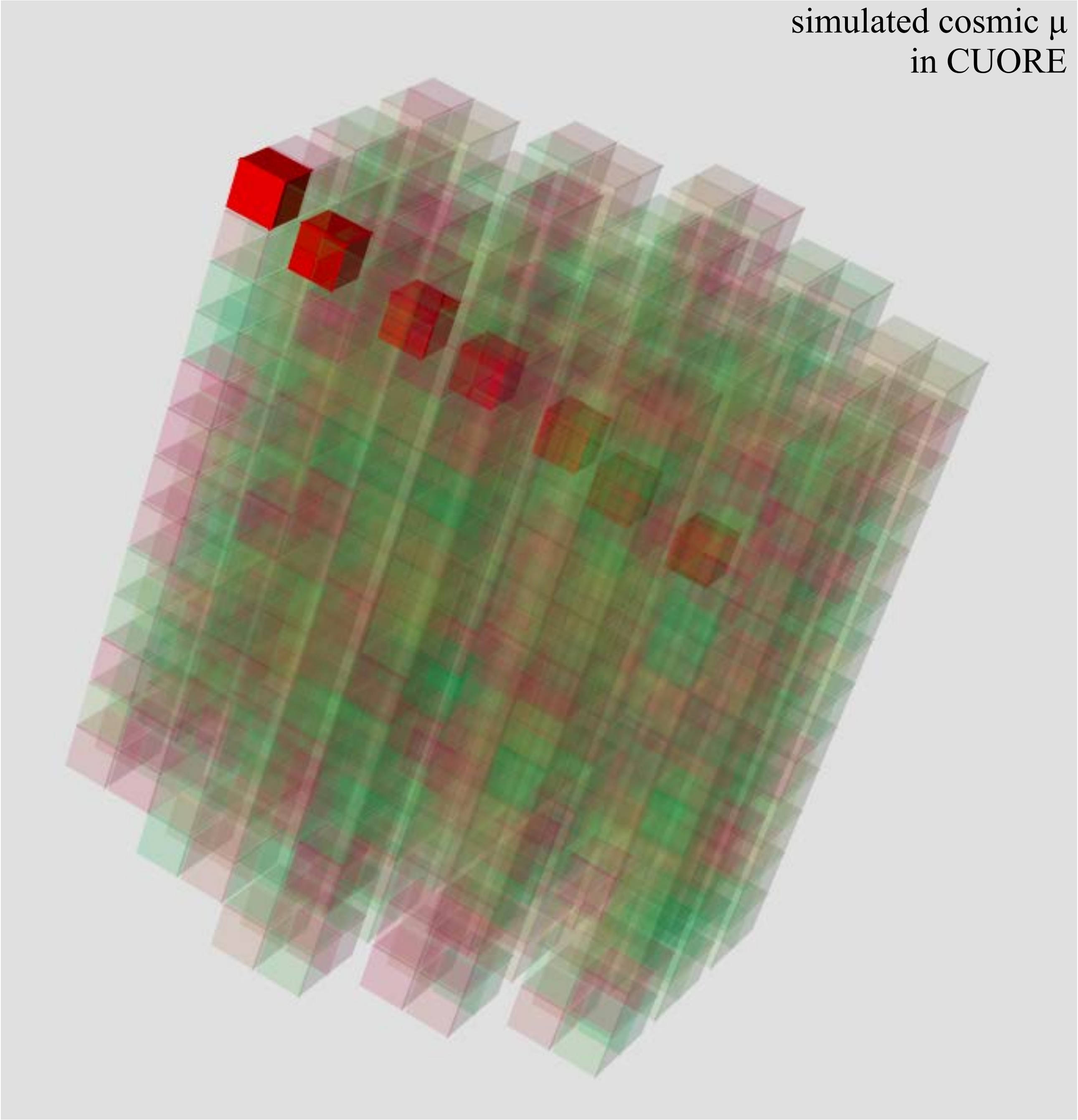
↑ α region



← full spectrum

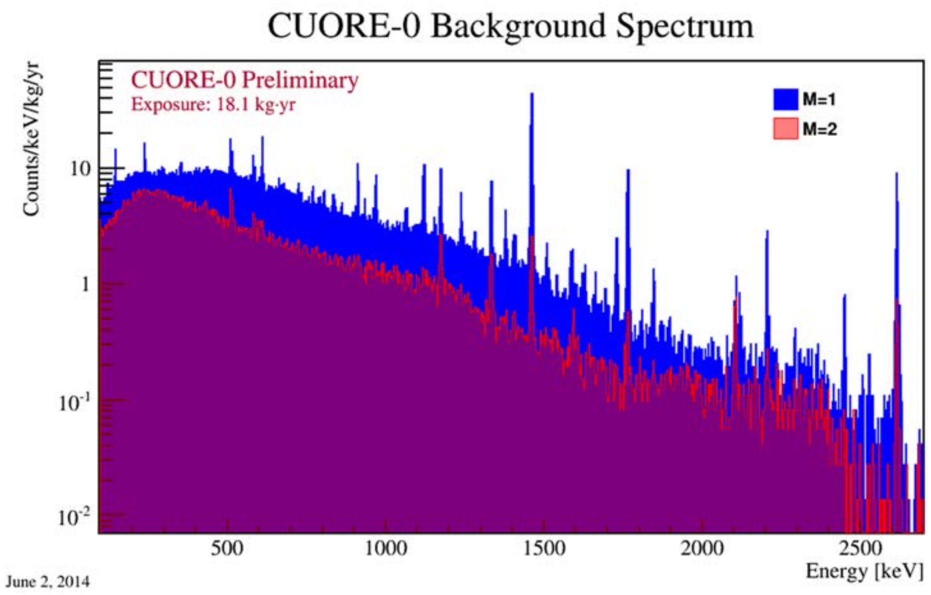
CUORE: anti-coincidence background rejection

- Only thermal channel, NTD readout ⇒ only energy measurement ⇒ not possible to distinguish α, β, γ, μ, etc.
- Anti-coincidence:
  - 2νββ, 0νββ events — 1 crystal.
  - Some surface α's — 2 crystals— nuclear recoil back into crystal, α absorbed on adjacent crystal.
  - Some γ's — multiple crystals (Compton length 10-20cm).
  - Cosmic μ's— multiple crystals.

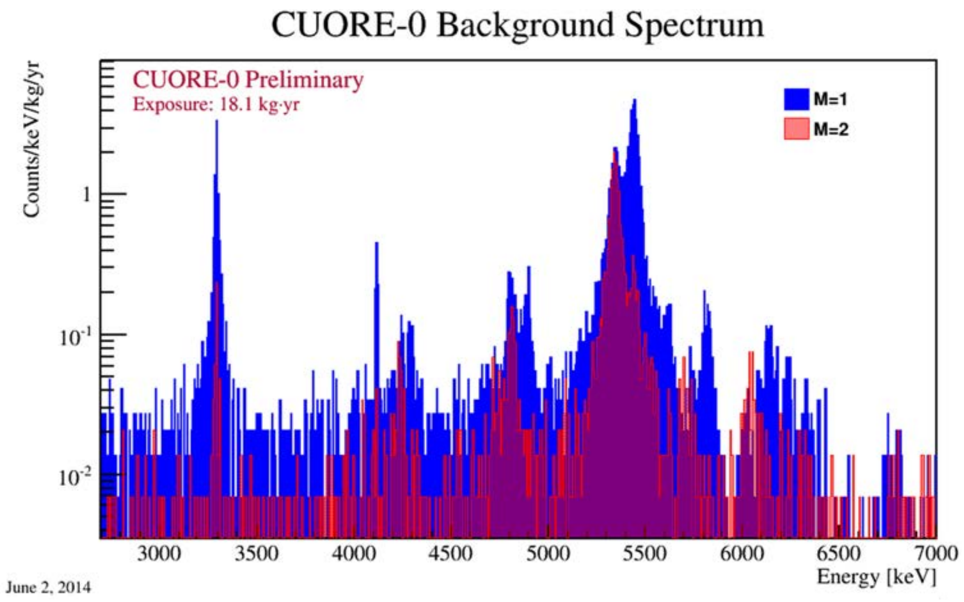


simulated cosmic μ in CUORE

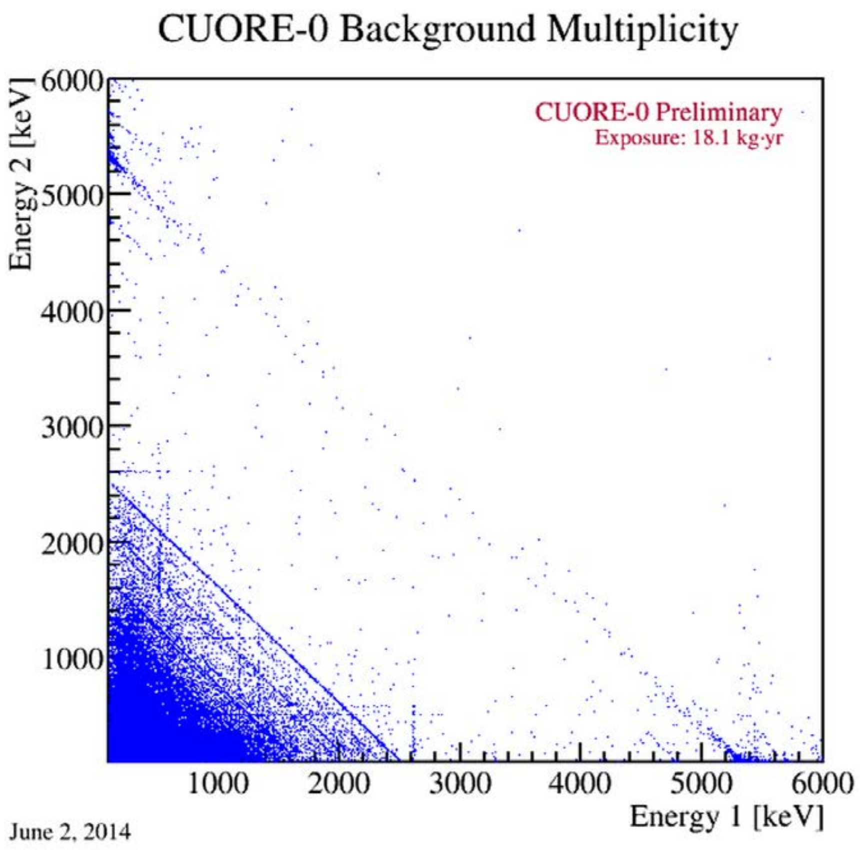
CUORE: anti-coincidence background rejection



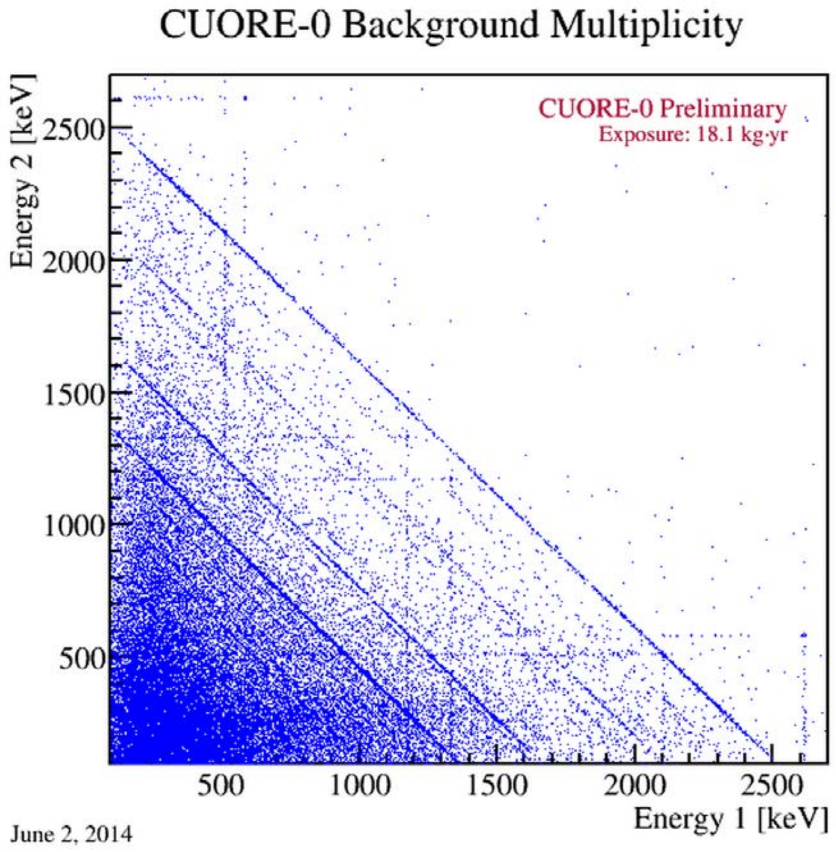
CUORE-0 Background Spectrum



CUORE-0 Background Spectrum



CUORE-0 Background Multiplicity

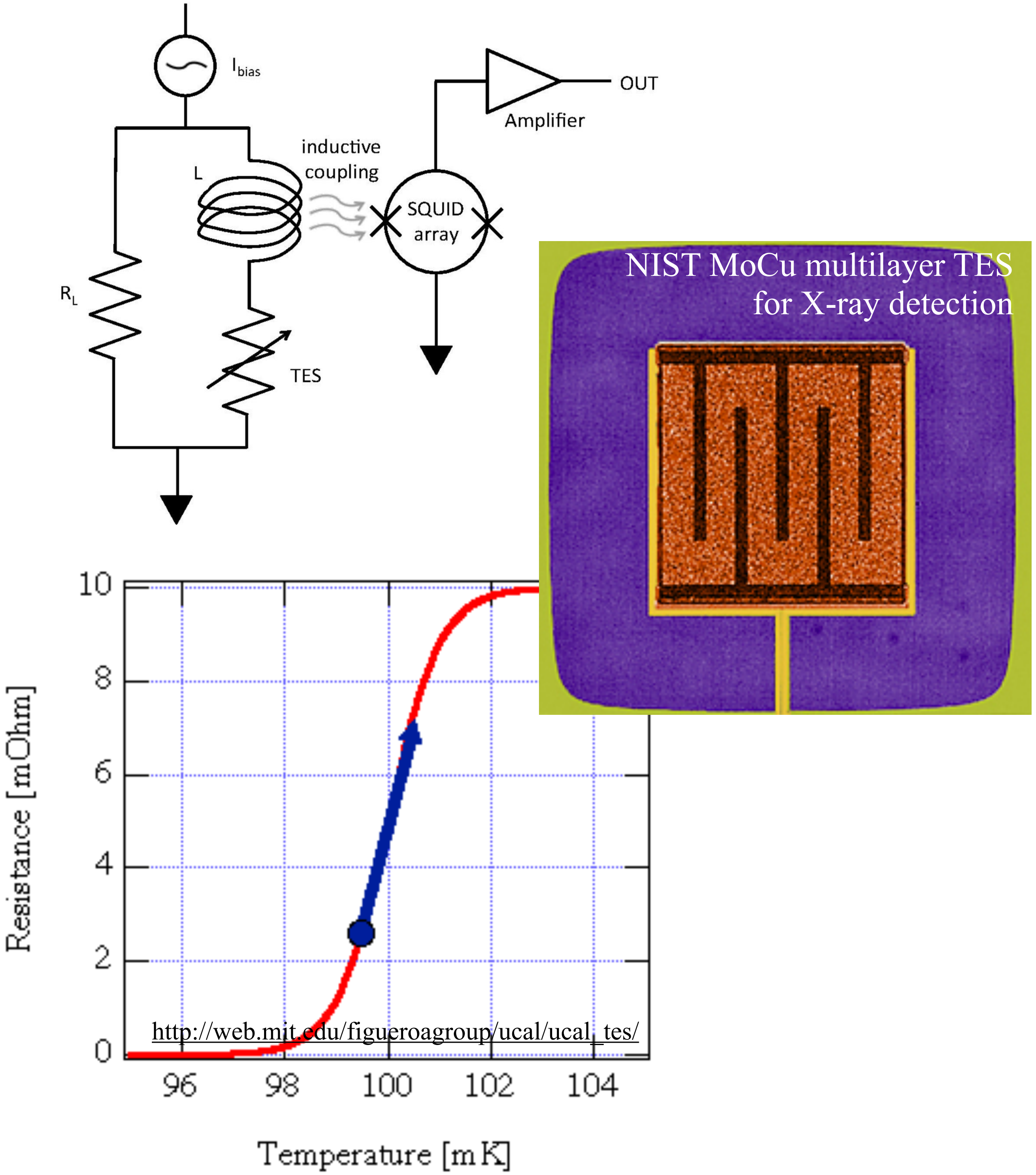


CUORE-0 Background Multiplicity

Transition Edge Sensors (TES’s): improved phonon signal readout

Transition Edge Sensors: overview

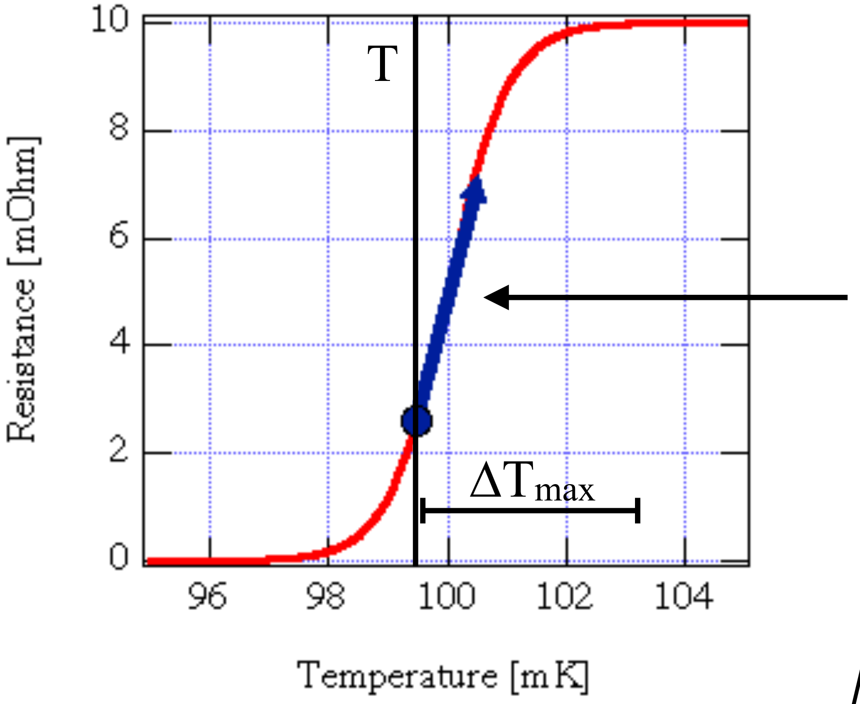
- Temperature sensor based on superconducting transition of a metal or alloy.
- In narrow region around T_C, R(T) much more sensitive than exponential.
- Typically read out by SQUID ⇒ low-T preamp ⇒ lower noise (than room-T preamp).
- 2 primary types in use:
  - W (tungsten) (α and β phases)
  - Bilayer or multilayer sample of superconducting and non-superconducting metals (e.g. Ir/Au).
- Main challenge/compromise for rare event bolometers: sufficiently low T_C for low temperature operation.
- Long history of use outside rare event searches for photon detection.



NIST MoCu multilayer TES for X-ray detection

http://web.mit.edu/figueroagroup/ucal/ucal_tes/

Transition Edge Sensors: operation theory



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

$$\Delta E = 2.35\sqrt{4kT^2\frac{C}{\alpha}}$$

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

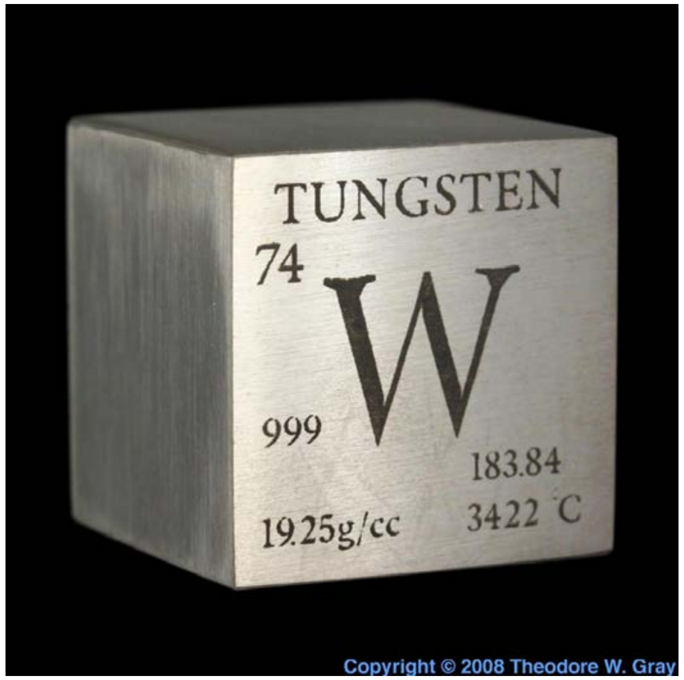
$$\Delta E \simeq 2.35\sqrt{4kT^2 E_{max}}$$

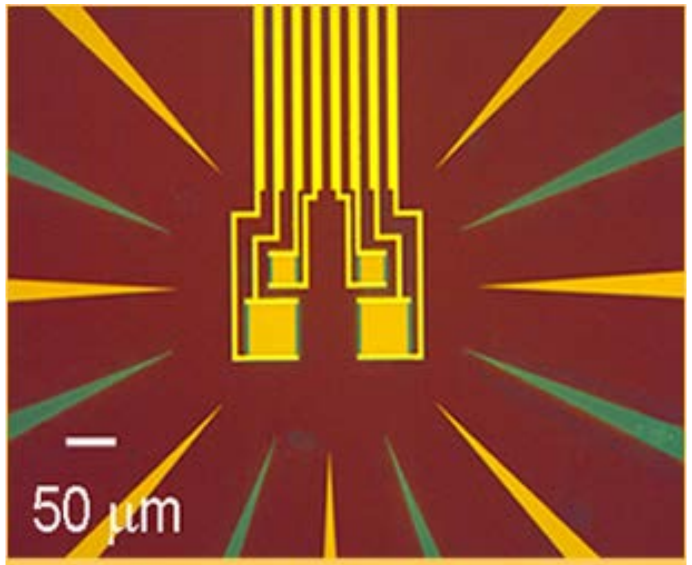
- figure of merit α—steepness of transition
- low operating T, low C of absorber (interconnected), large α improve energy resolution ΔE.
- low C and large α also lower bandpass ⇒ best performing TES must be very well tuned for precise application.
  - Example: typical X-ray TES @ 100mK has badpass ~0.1keV - ~10keV w/ΔE ~ 1.5eV FWHM (plot)
- low R (+ electrothermal feedback) ⇒ possibility of larger signal bandwidth (than NTD) ⇒ possibility of pulse shape discrimination

http://web.mit.edu/figueroagroup/ucal/ucal_tes/

Tungsten (W) TES's

- 2 crystalline forms:
  1. α: BCC structure, isometric grains. $T_C \sim 10\text{mK} - 15\text{mK}$
  2. β: A15 cubic, columnar habit. $T_C \sim 1\text{K} - 4\text{K}$
- 2 forms can be mixed to achieve intermediate T_C's.
- Pure α (or β) sample very hard to fabricate:
  - Most examples' T_C >15mK necessitates higher operating temperature.
  - Irregularity/high rejection rate
    - ⇒ O.K. for small detectors like CRESST II; problematic for ton-scale experiments like CUPID (planned CUORE successor) or EURECA (planned CRESST successor).
- Examples of use:
  - CRESST II (close to pure α-W; main and light bolometers)
  - CDMS ($T_C \approx 90\text{mK}$, mixed phases; in athermal phonon collector of Ge detector)





Four tungsten transition-edge sensors with aluminum wiring. The upper two are 25 μm by 25 μm. The lower two sensors are 50 μm by 50 μm.

Multilayer TES's

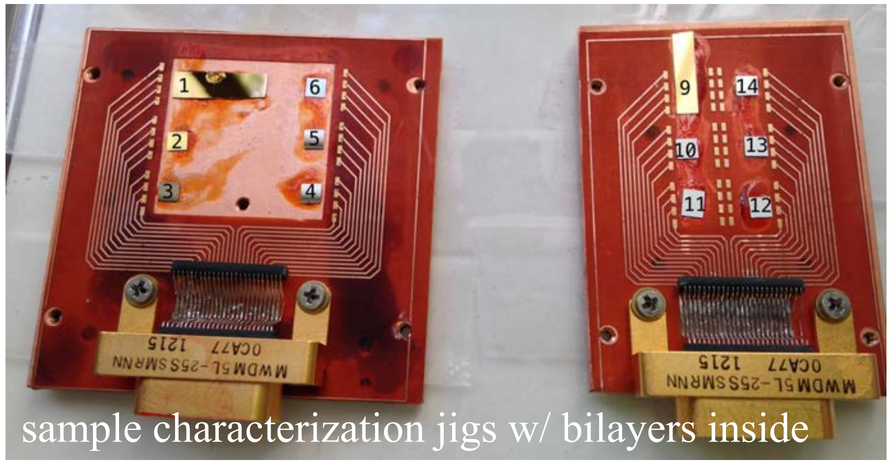
- 2+ O(100μm) layers of superconducting and normal metals sputtered or atomic-deposited on substrate.
    - Ir/Au, Ir/Pt, Ir/IrMn/Au, Ir/Pd/Au, Mo/Au, Mo/Cu, Mo/Ti, Al/Au, Al/Ti/Au, others…
- T_C of superconducting metal is suppressed by leakage of carriers from normal metal layer.
- Usadel theory (right) to estimate T_C of bilayer—impossible to get transmission parameter, empirical methods are necessary.
- Motivations for developing multilayer TES's :
    - Theoretically possible to set T_C precisely, including very cold <15mK transitions (no need to compromise like with W).
    - Dedicated clean, high vacuum, high precision fabrication facility should allow for cheaper and more robust production than W TES's for large detectors.
- Most practical examples now: T_C's ~100mK; used for X-rays, cosmology, nonproliferation R&D, etc.
- No workable examples with T_C < 20mK – 30mK

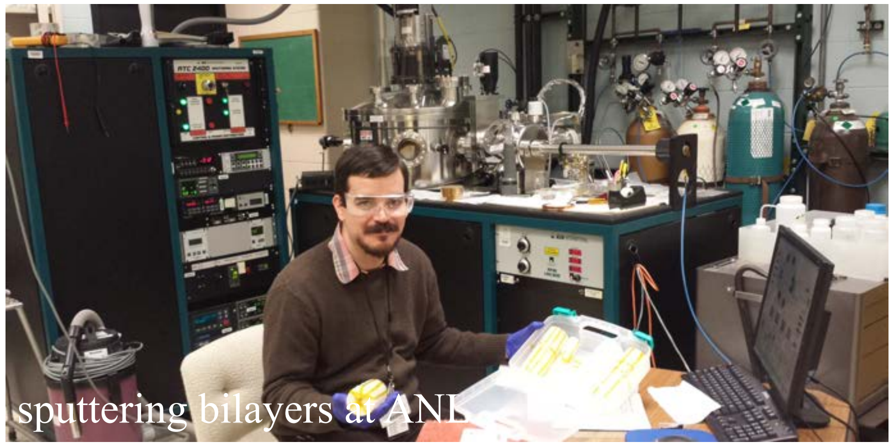
$$\begin{aligned} T_{\mathrm{c}} &= T_{c_0}\left[\frac{d_s}{d_0}\frac{1}{1.13(1+1/\alpha)}\frac{1}{t}\right]^{\alpha} \\ \frac{1}{d_0} &= \frac{\pi}{2}k_{\mathrm{B}}T_{c_0}\lambda_f^2 n_s, \\ \alpha &= d_n n_n / d_n n_s. \end{aligned}$$

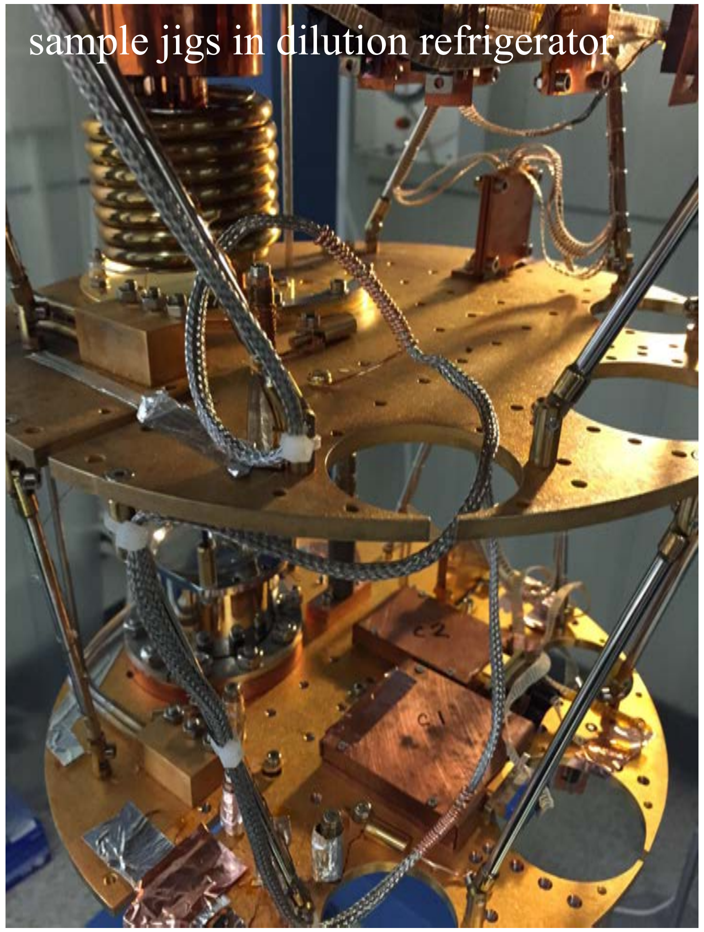
n_n, n_s — densities of states
d_n, d_s — film thicknesses
T_{C_0} — natural s.c. layer T_C
λ_f — Fermi λ in normal metal
t — unitless interface transmission parameter $O(1)$

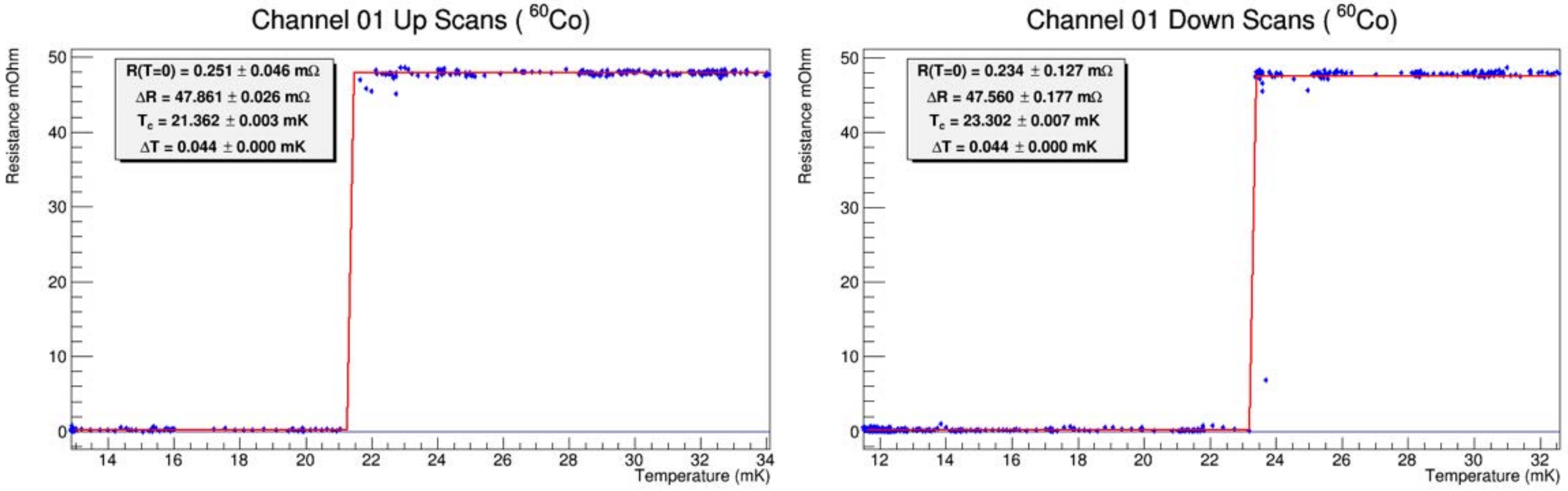
K.D. Irwin, G.C. Hilton. Transition-Edge Sensors. Chapter - Cryogenic Particle Detection Volume 99 of the series Topics in Applied Physics pp 63-150

Low-T_C bilayer TES R&D at Berkeley


sample characterization jigs w/ bilayers inside


sputtering bilayers at ANL


sample jigs in dilution refrigerator



Ir/Au bilayer w/ $T_C \approx 22$mK (hysteresis effect in plots from AC bridge readout)

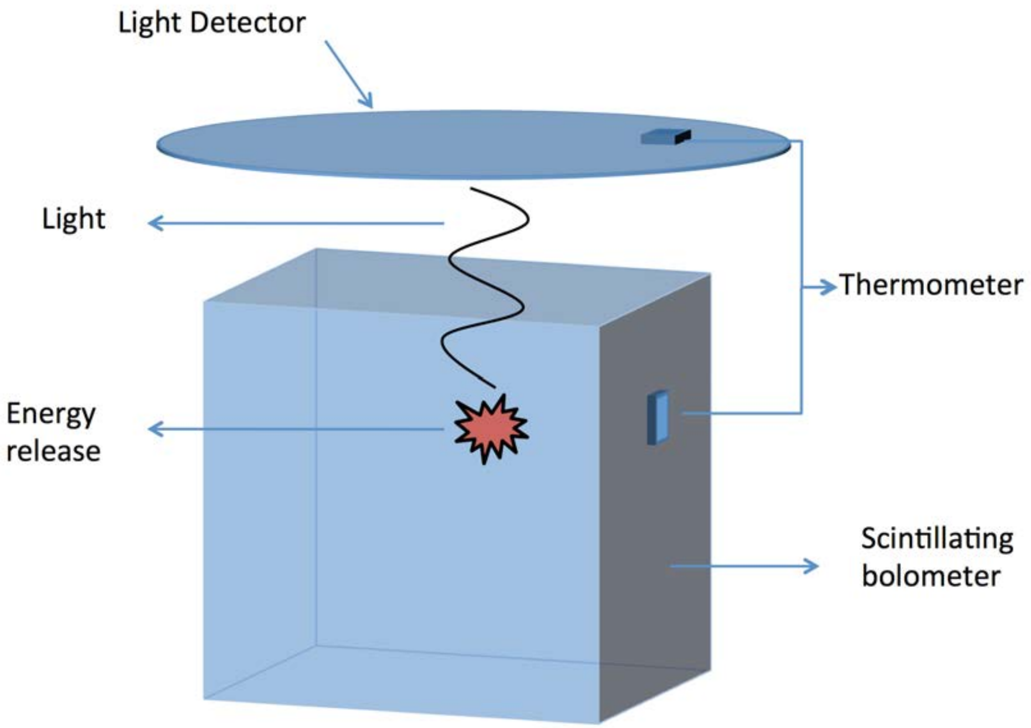
- Dilution refrigerator facility:
  - Oxford Instruments cryogen-free DR:
    - $P_{cooling}$(100mK) ≥ 400μW (record ~450μW)
    - $T_{base} \leq$ 10mK (record ~6mK)
  - Readout:
    - AC370 resistance bridges
    - new Magnicon SQUID electronics
  - Thermometry:
    - RuO_2 resistance thermometers down to 20mK – 30mK
    - ^{60}Co nuclear orientation thermometer down to base temperature
    - new Magnicon noise thermometer down to base temperature.
- Ir/Au, Ir/Pt, Ir/IrMn/Au, Ir/Pd/Au bilayers being fabricated and tested in collaboration with ANL.
- Next step: light detector w/ meandered bilayer TES with semiconductor absorber.

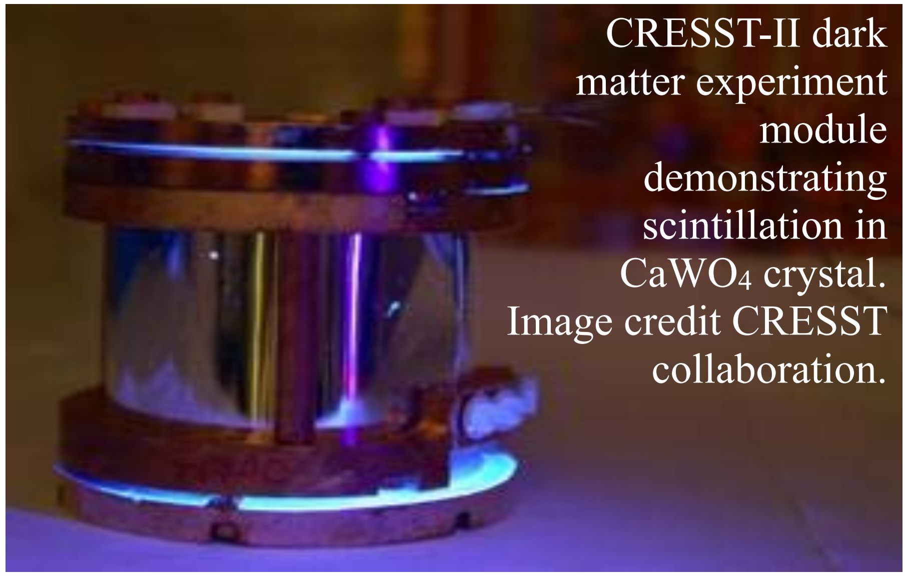
Optical bolometers:

active background discrimination

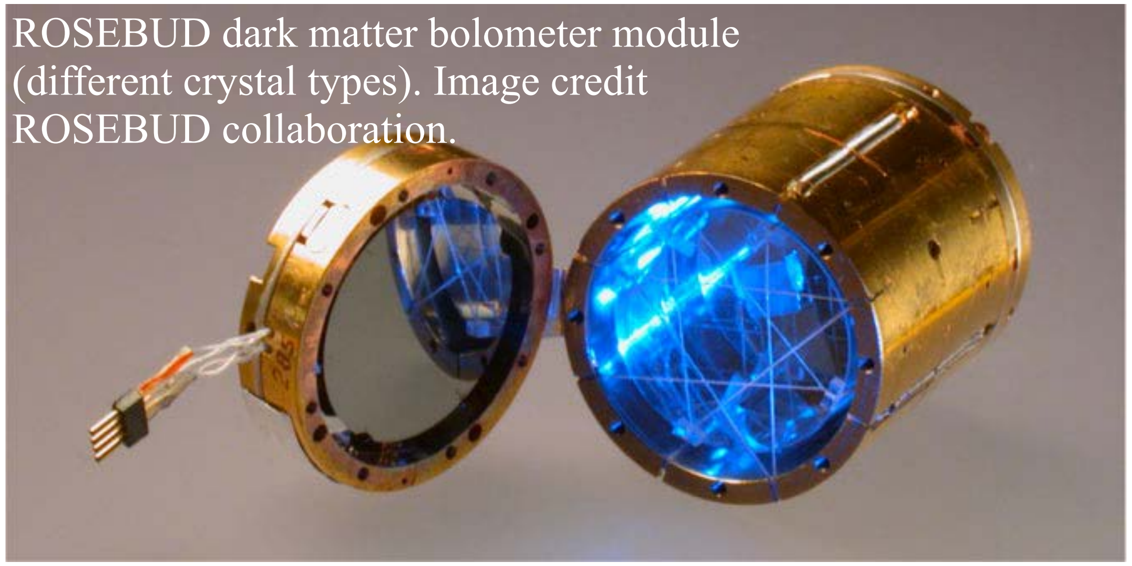
Scintillating bolometers

- Secondary bolometer w/thin wafer as absorber to detect scintillation light from main bolometer crystal.
- Heat signature + light collection:
  - phonons: best E resolution
  - photons: separation of nuclear recoil (α, n or WIMP) from electron recoil (γ or β) via light yield, quenching.





CRESST-II dark matter experiment module demonstrating scintillation in $CaWO_4$ crystal. Image credit CRESST collaboration.

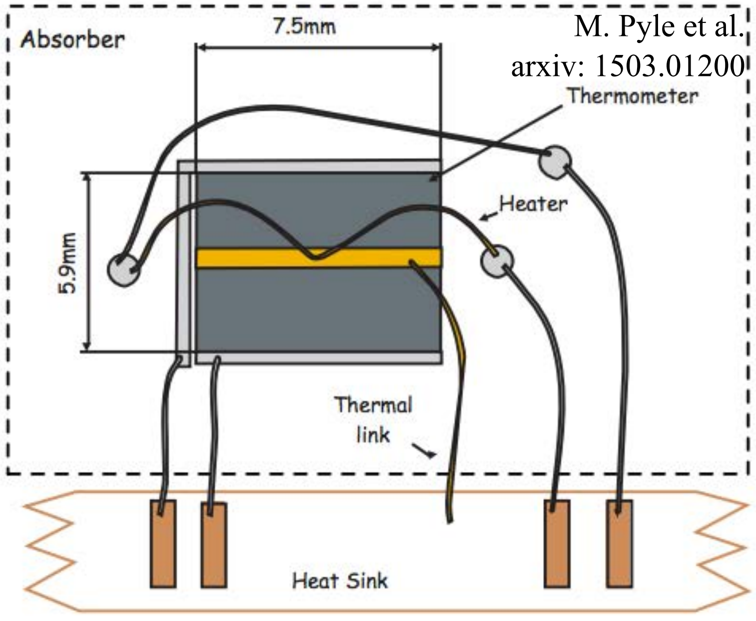


ROSEBUD dark matter bolometer module (different crystal types). Image credit ROSEBUD collaboration.

Scintillating bolometers: CRESST II

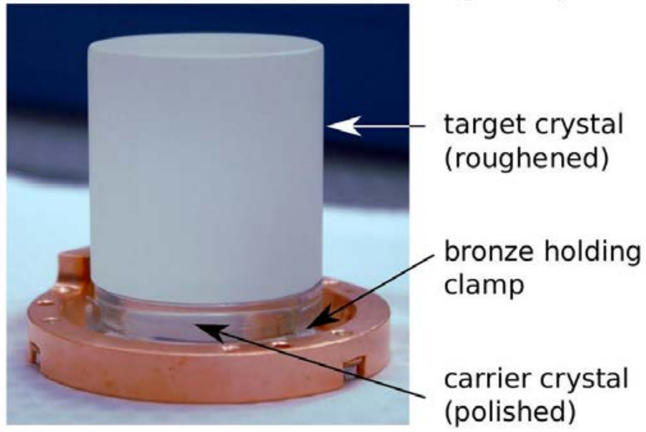
- Cryogenic Rare Event Search with Superconducting Thermometers II
- European Dark Matter experiment at Gran Sasso.
- Main strength: low WIMP mass sensitivity.
- 18 modules:
  - clean Cu structure
  - scintillating 3M reflector
  - phonon detector: 300g $CaWO_4$ scintillating crystal (total 5.4kg)
  - photon detector: Si-coated Al_2O_3 or Si absorber.
  - readout: W TES w/ $T_C \sim$ 10mK (closer to ~13mK, pure α W)
  - Variations in crystal attachment module to module.

http://www.cresst.de/material.html



M. Pyle et al. arxiv: 1503.01200

- ▨ W
- ▨ Al
- ▨ Au
- ▨ Cu-Kapton-Cu

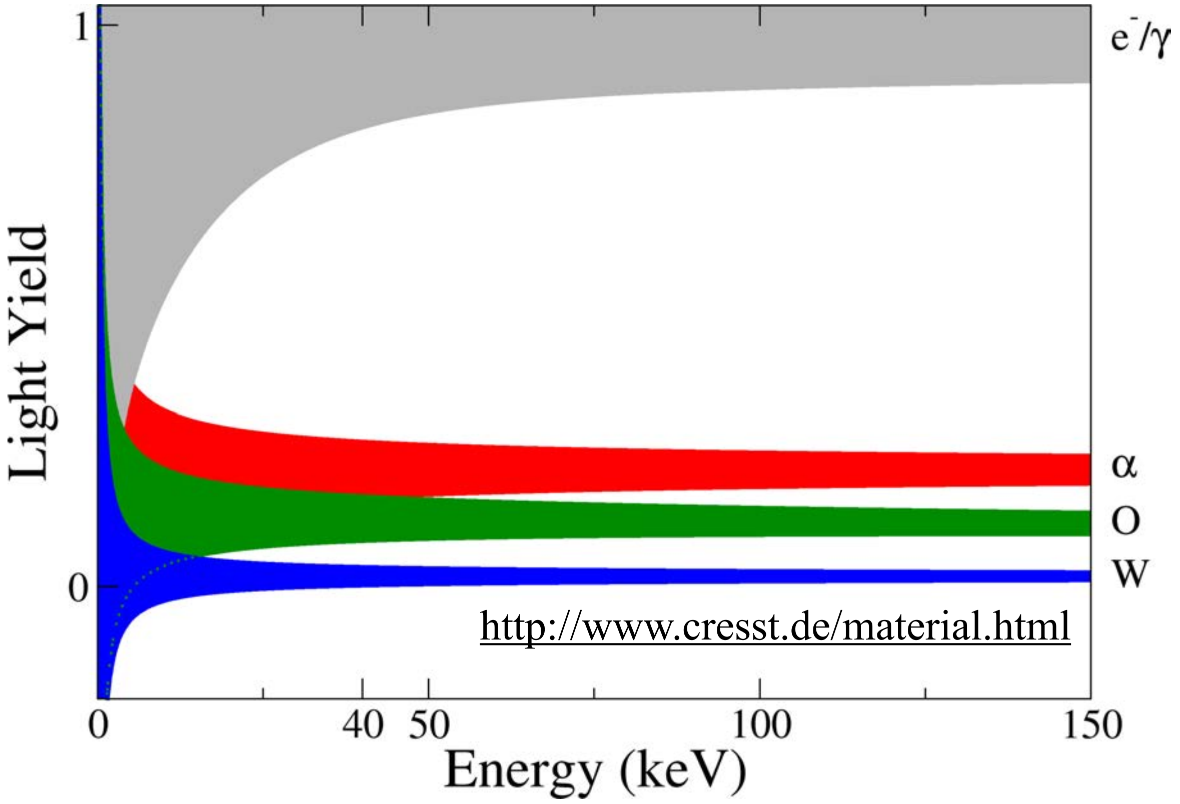


Schematic of the TES and its connections on the original CRESST-II phonon detector

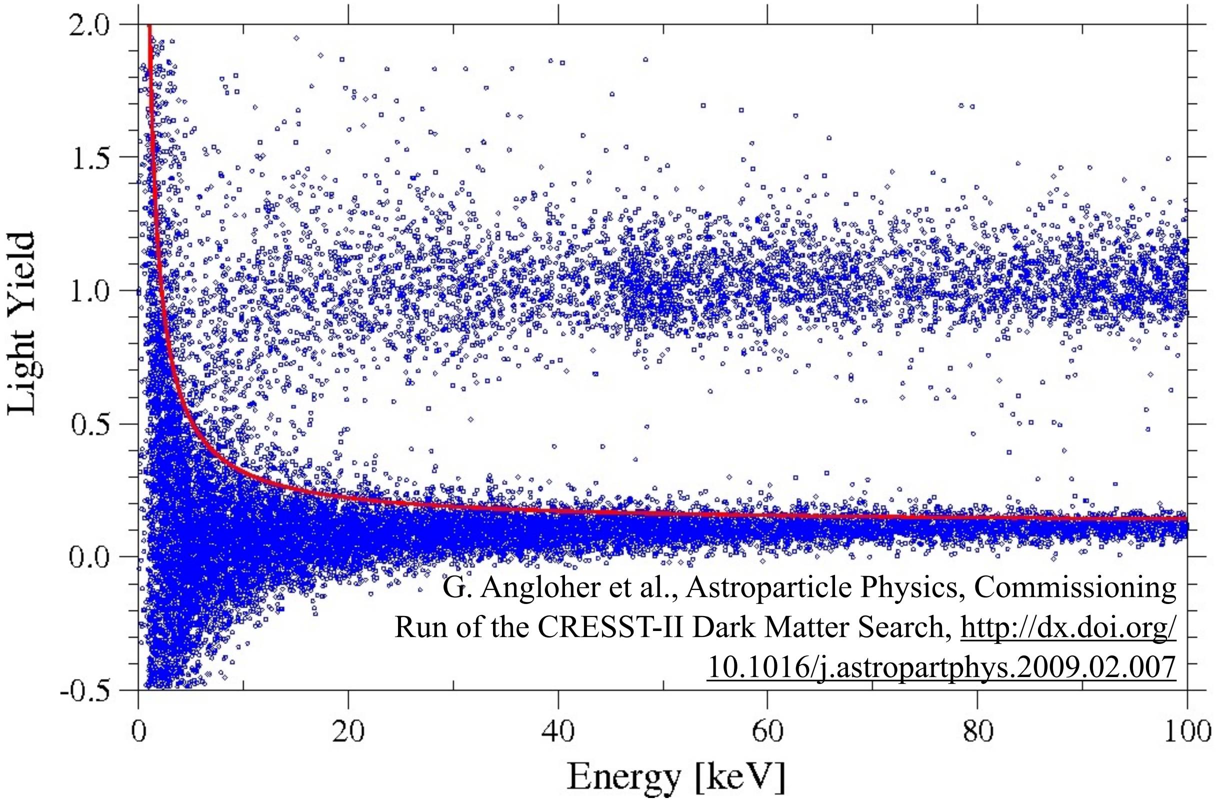
Scintillating bolometers: CRESST II

- Example from CRESST II : less light from nuclear recoil (from WIMP, α, n) than from electron recoil (from γ or β) in $CaWO_4$ crystals (readout w/ W TES; light detection w/ Si-coated sapphire absorber and W TES).

  Left: schematic of bands. Right: data from calibration with neutrons.



http://www.cresst.de/material.html



G. Angloher et al., Astroparticle Physics, Commissioning Run of the CRESST-II Dark Matter Search, http://dx.doi.org/10.1016/j.astropartphys.2009.02.007

** negative light yield values stem from amplitude fitting procedure that allows for negative amplitudes for unbiased treatment of noise. Phenomenon not unique to CRESST II.*

Scintillating bolometers: CRESST II

- Example from CRESST II : dark matter data.

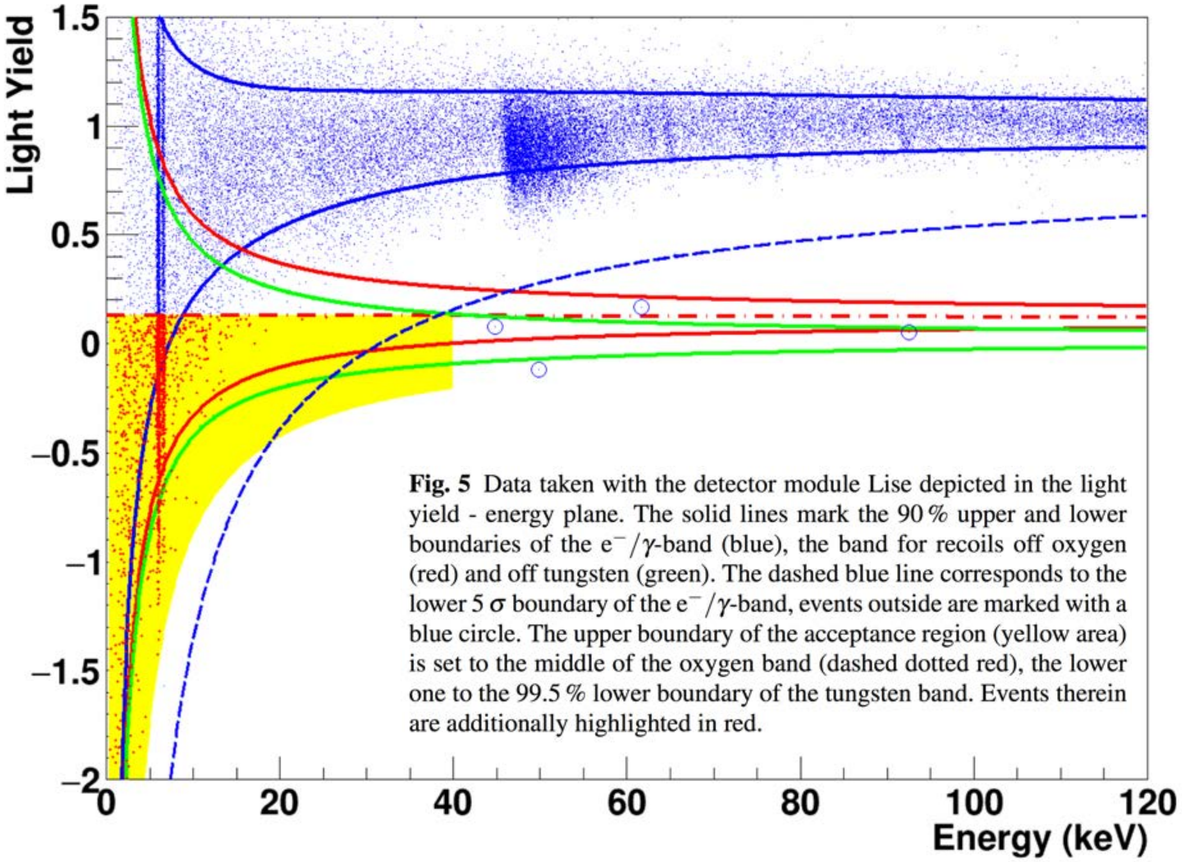
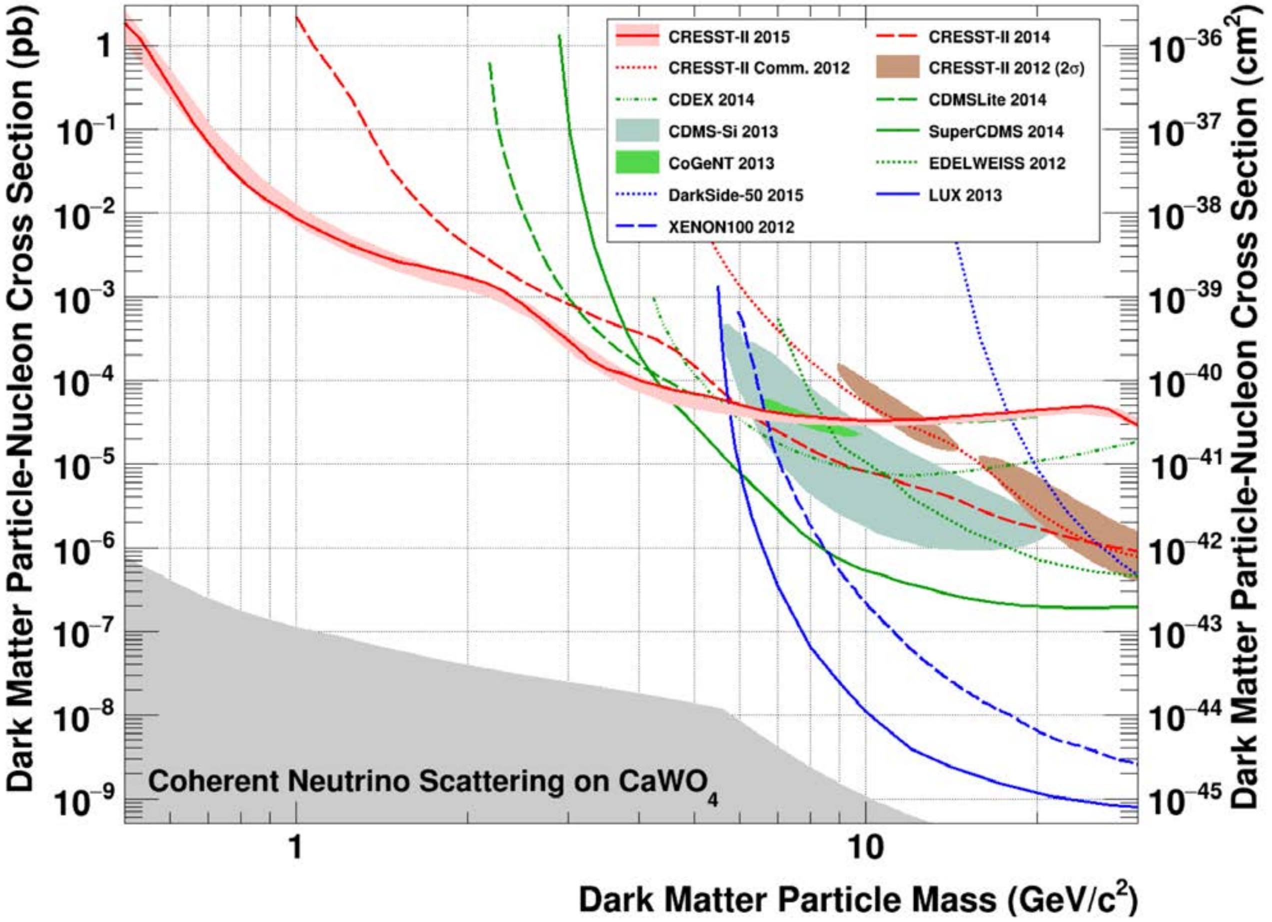


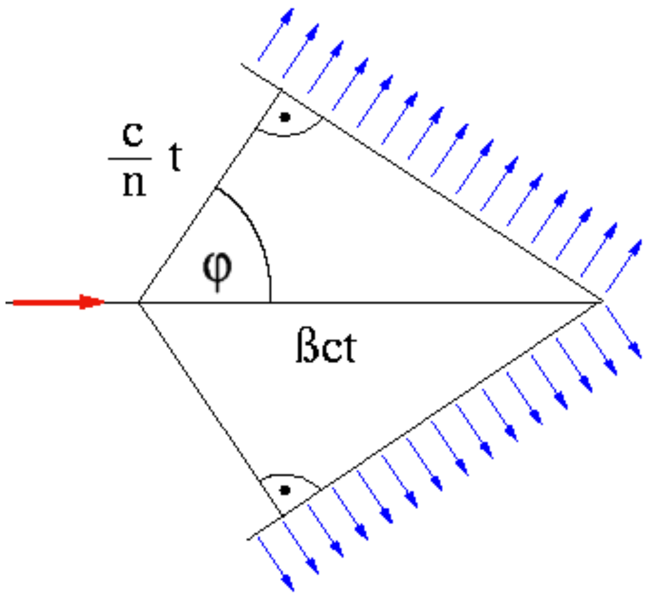
Fig. 5 Data taken with the detector module Lise depicted in the light yield - energy plane. The solid lines mark the 90 % upper and lower boundaries of the e^-/γ-band (blue), the band for recoils off oxygen (red) and off tungsten (green). The dashed blue line corresponds to the lower 5 σ boundary of the e^-/γ-band, events outside are marked with a blue circle. The upper boundary of the acceptance region (yellow area) is set to the middle of the oxygen band (dashed dotted red), the lower one to the 99.5 % lower boundary of the tungsten band. Events therein are additionally highlighted in red.

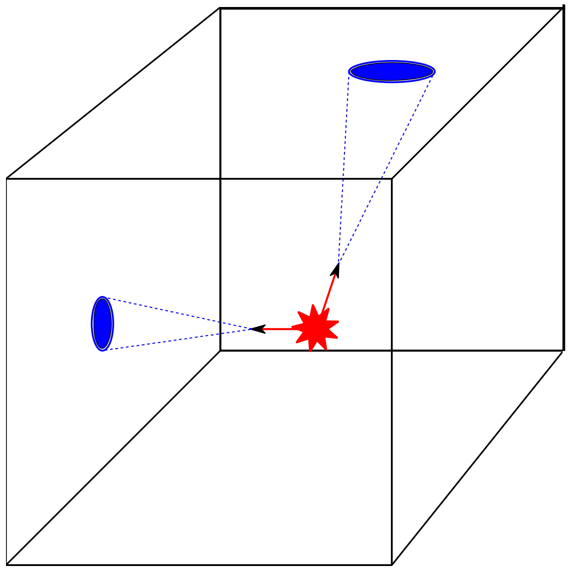


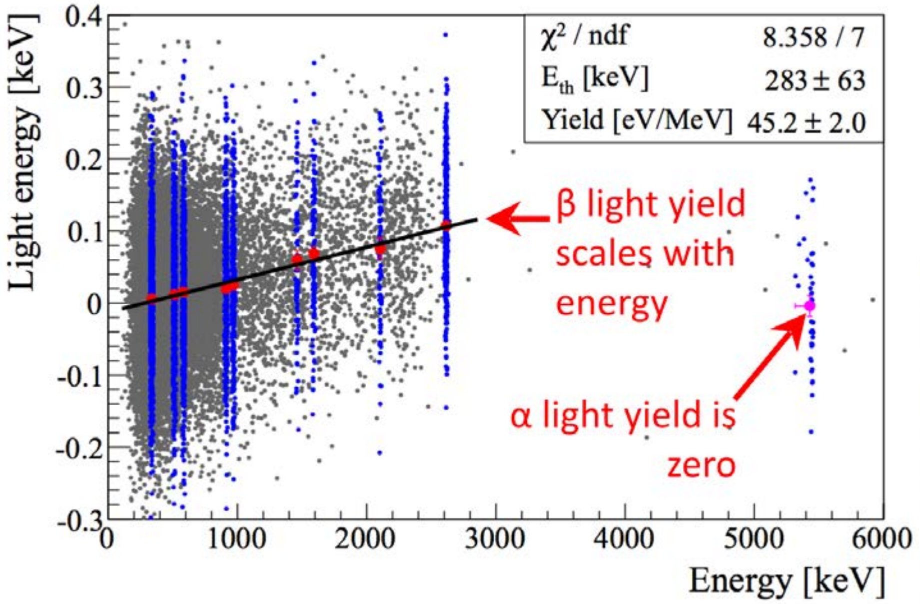
G. Angloher et al. arXiv:1509.01515v1

Cherenkov bolometers

- Analogous hardware configuration to scintillating bolometers
- Instead of scintillation photons, Cherenkov photons are detected:
    - β's radiate; slow α's and many n's do not.
    - ⇒ WIMPS would not radiate
- degraded α's a major background in cryogenic detectors ⇒ Cherenkov detectors not very useful for DM searches.
- Active interest from 0νββ researchers due to necessity of including isotope of interest in crystal (difficult w/ scintillators) and simple binary discrimination
    - challenging weak signals (10's of photons, thresholds as low as 10eV).

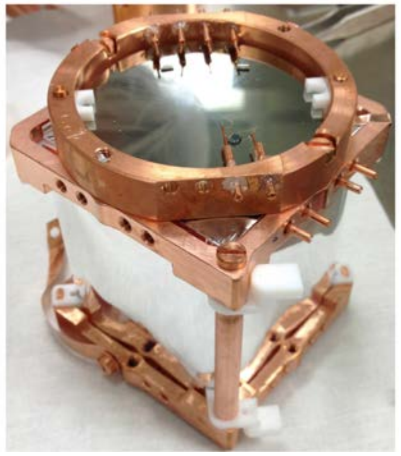




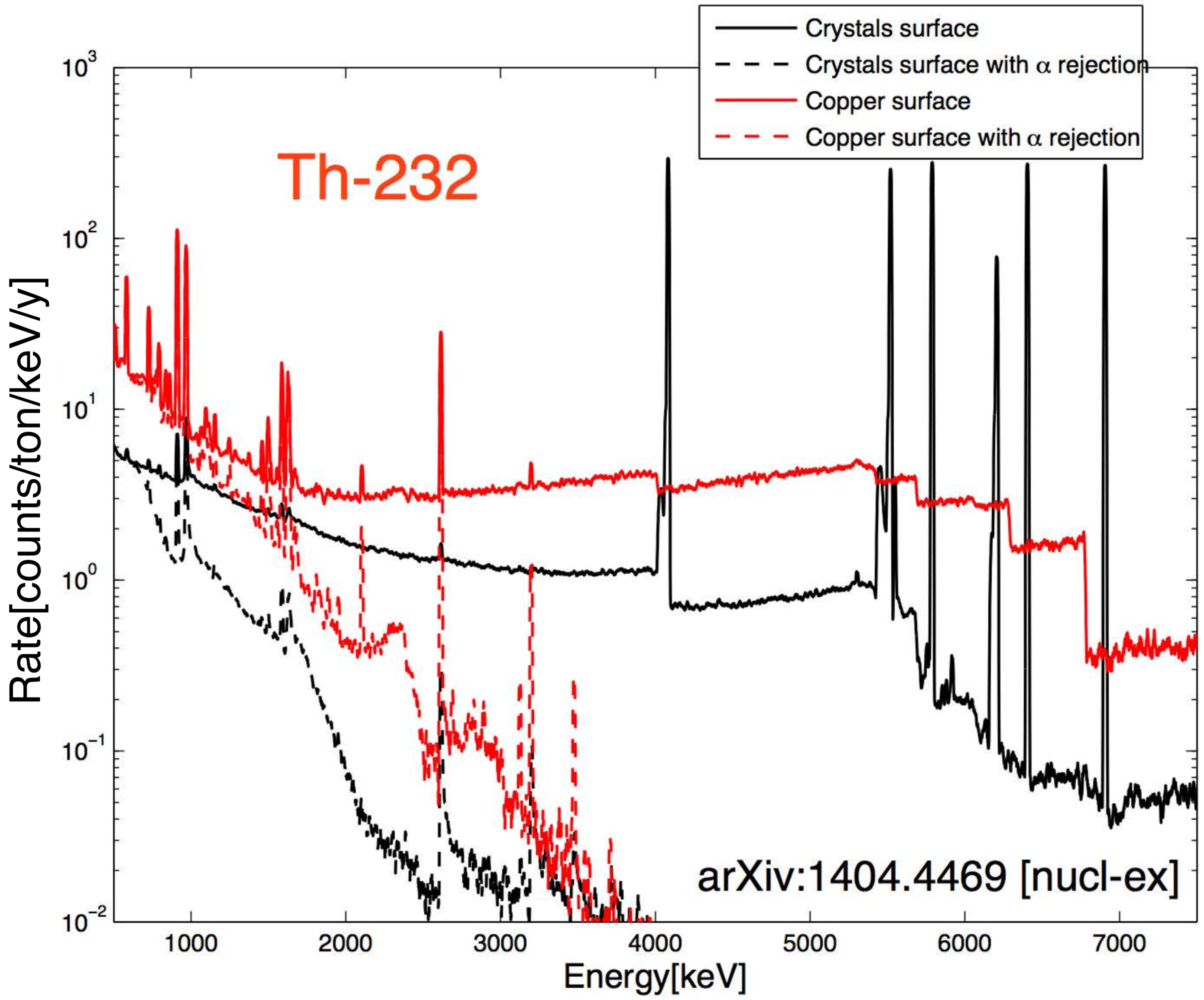


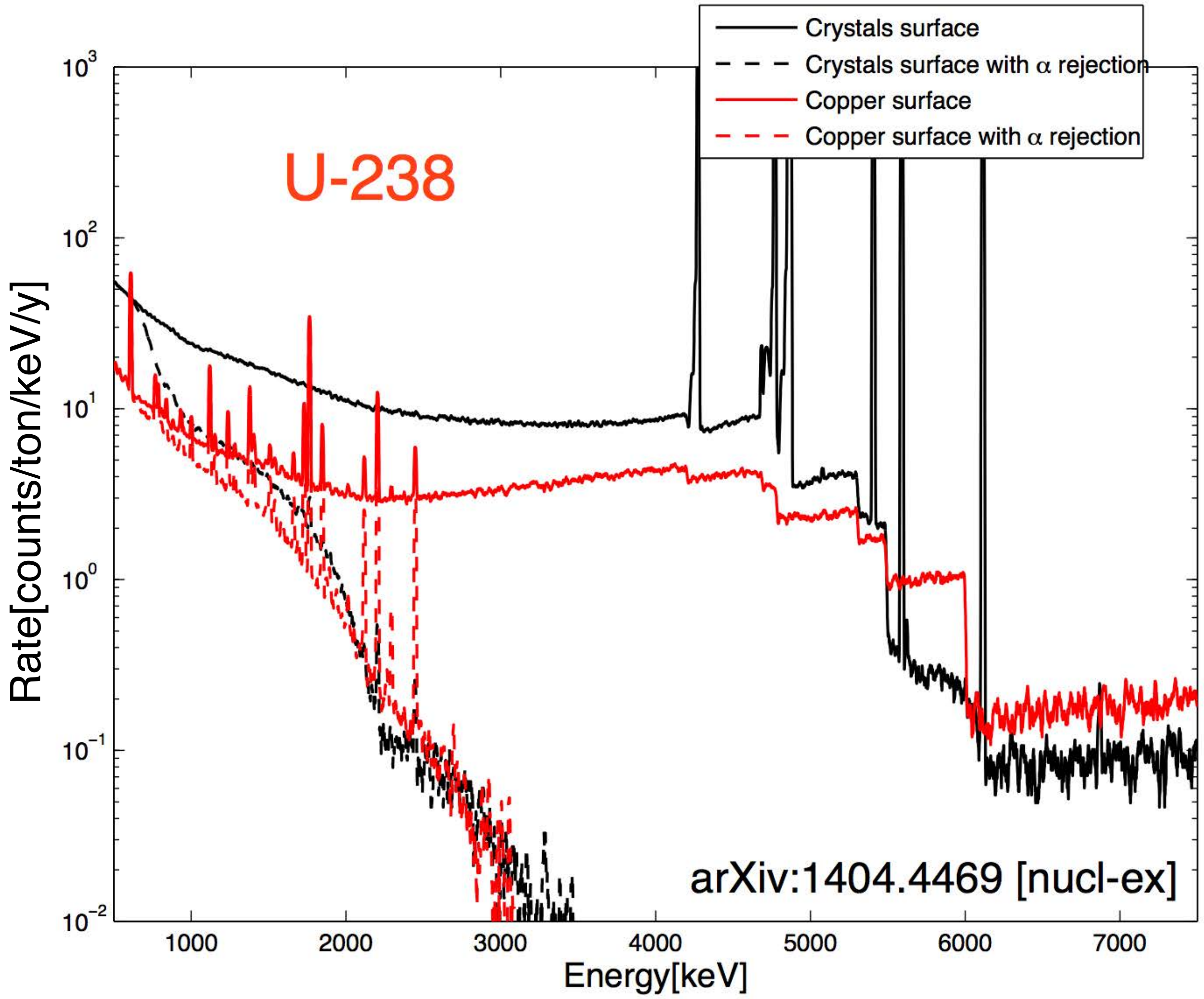
β light yield scales with energy

α light yield is zero



Improvement of CUORE performance with complete rejection of α background (simulation)





Neganov-Luke amplification

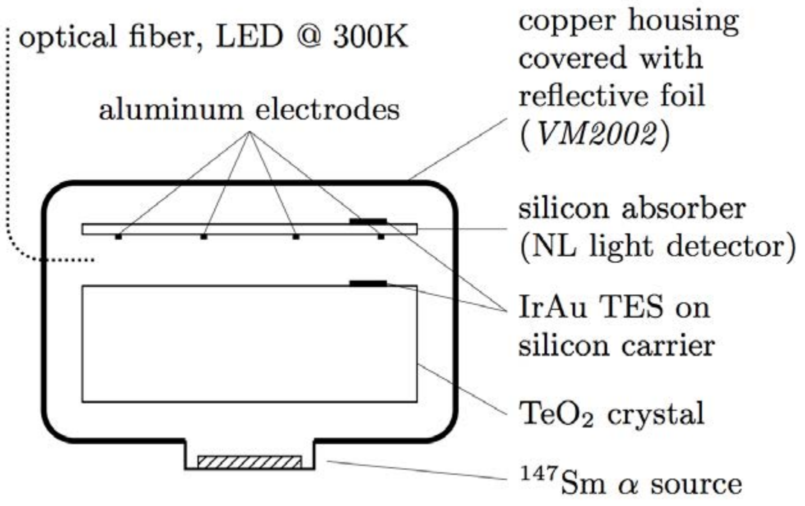
- Devices being developed in framework of both direct DM searches (EURECA) and $0\nu\beta\beta$ searches (CUPID).
- Semiconductor absorber equipped with electrodes, biased.
- Created electrons & holes drifted to create stronger thermal signal:

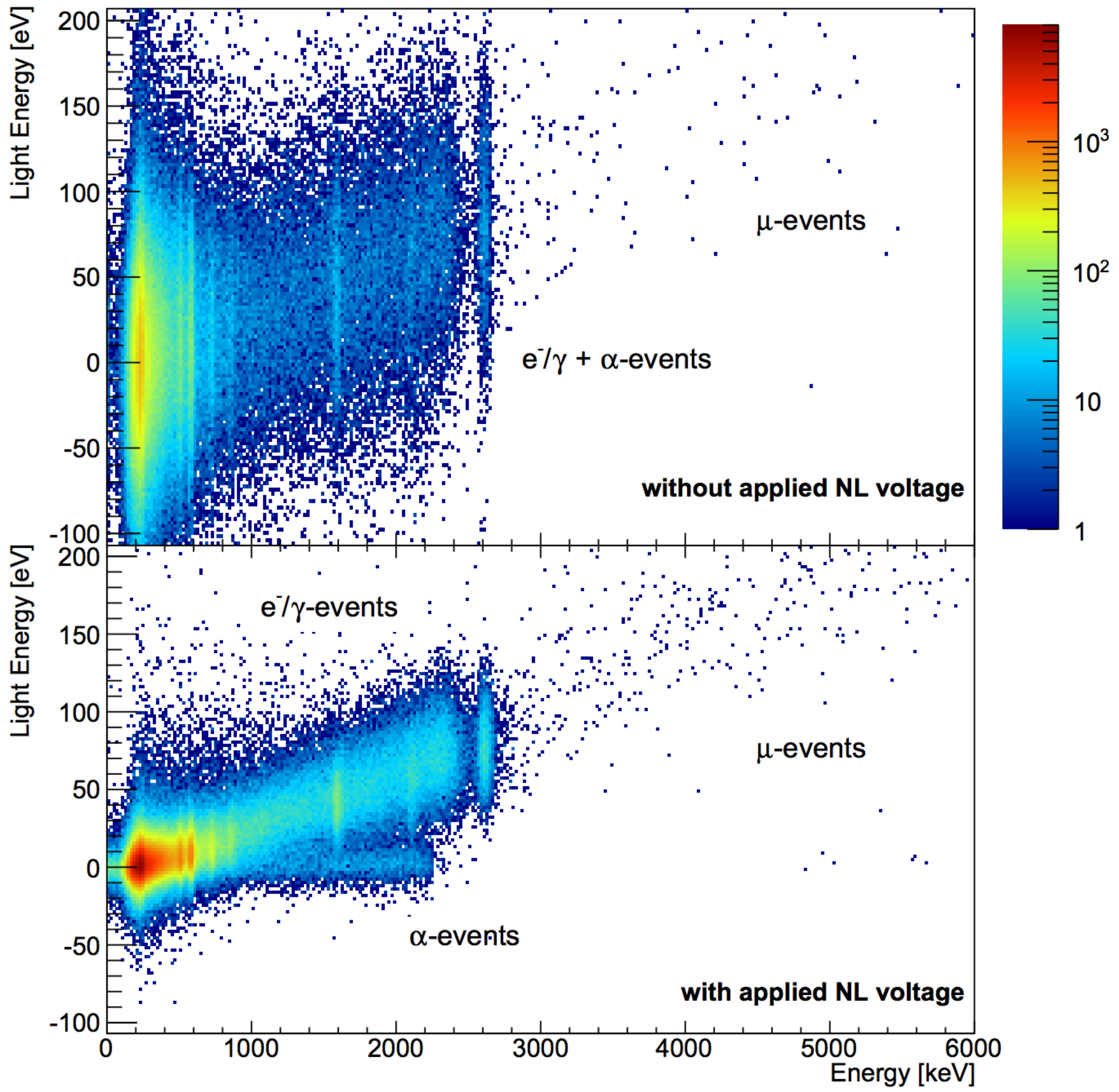
$$G = 1 + \frac{e \cdot V_{NL}}{E_{ph}/\eta}$$

η—quantum efficiency of electron-hole pair production, E_{ph}—photon energy, V_{NL}—applied voltage

- Likely essential for Cherenkov bolometers for $0\nu\beta\beta$.
- Also seriously improves $CaWO_4$ scintillating bolometer performance.

M. Willers et al.
arxiv: 1407.6516v2





thank you for your attention