Bolometric Measurement of Neutrinoless Double Beta Decay

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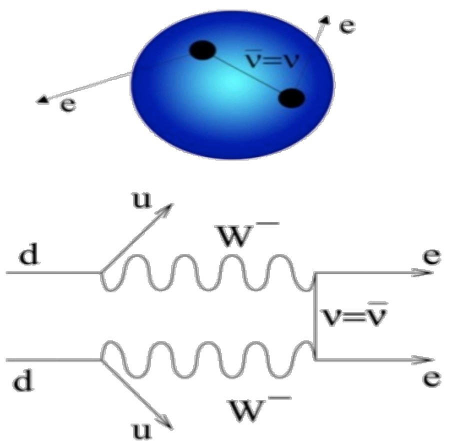
Outline

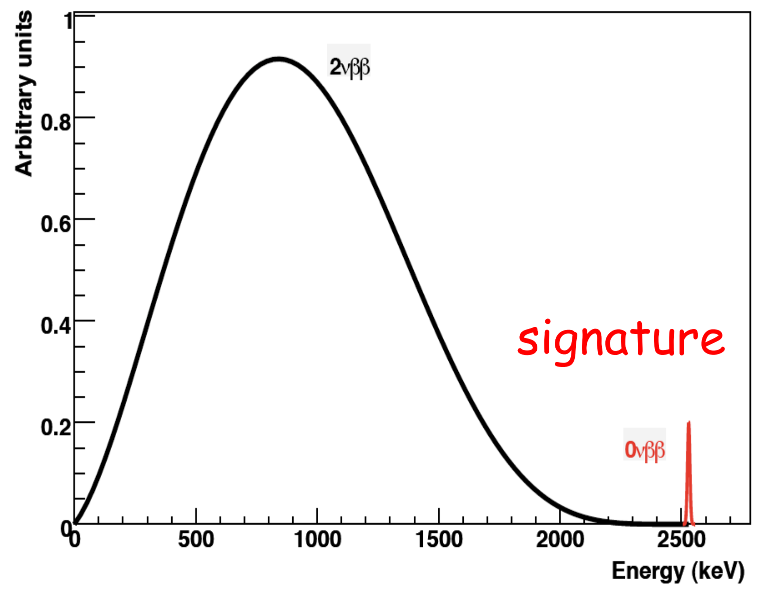
- A brief introduction to COURE – Cryogenic Underground Observatory for Rare Events
- Event by event based background discrimination with simultaneous measurements of heat and light – a roadmap to exploring the neutrino mass hierarchy
- Transition Edge Sensor (TES) R&D at ANL for both heat and light measurements
- Summary

COURE — An Experimental Searching for Neutrinoless Double Beta Decay (0vDBD)

- Two simultaneous electrons with summed kinetic energy $Q_{\beta\beta}$ *~2.527 Mev*. Measuring event rate at the expected energy.
- In inverted hierarchy, Majorana neutrino mass >= 10 meV.

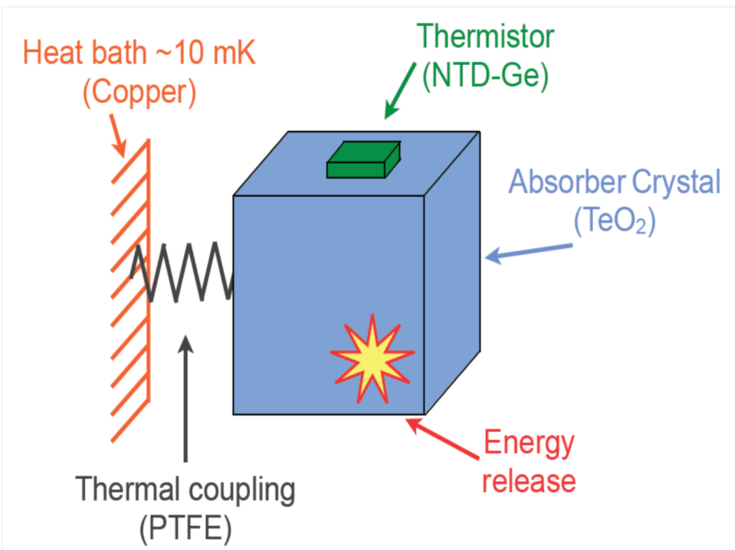
$^{130}Te \rightarrow ^{130}Xe + 2e^{-}$

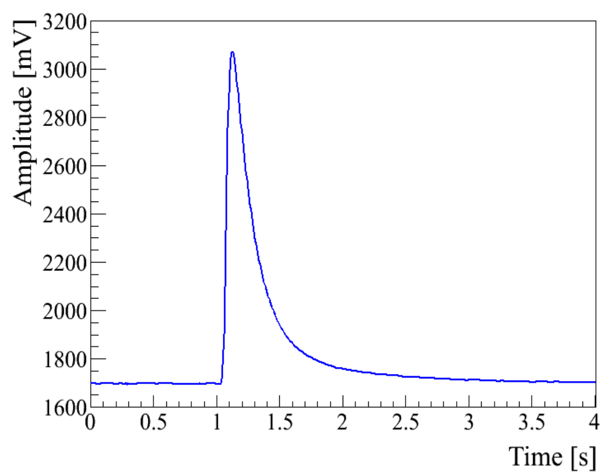




Bolometric Measurement

- 5cm by 5cm by 5cm (750g) TeO_2 Crystals
- Cooled to ~10 mK inside a dilution refrigerator cooled cryostat
- Such a small heat capacity (C proportional to T^3) that the released energy in 0vDBD produces a measurable rise in temperature





$$\Delta T(t) \approx \frac{E}{C} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C}{G}$$

C = heat capacity
G = thermal conductance

~20 μK / MeV

Experimental Event Rate of 0νDBD

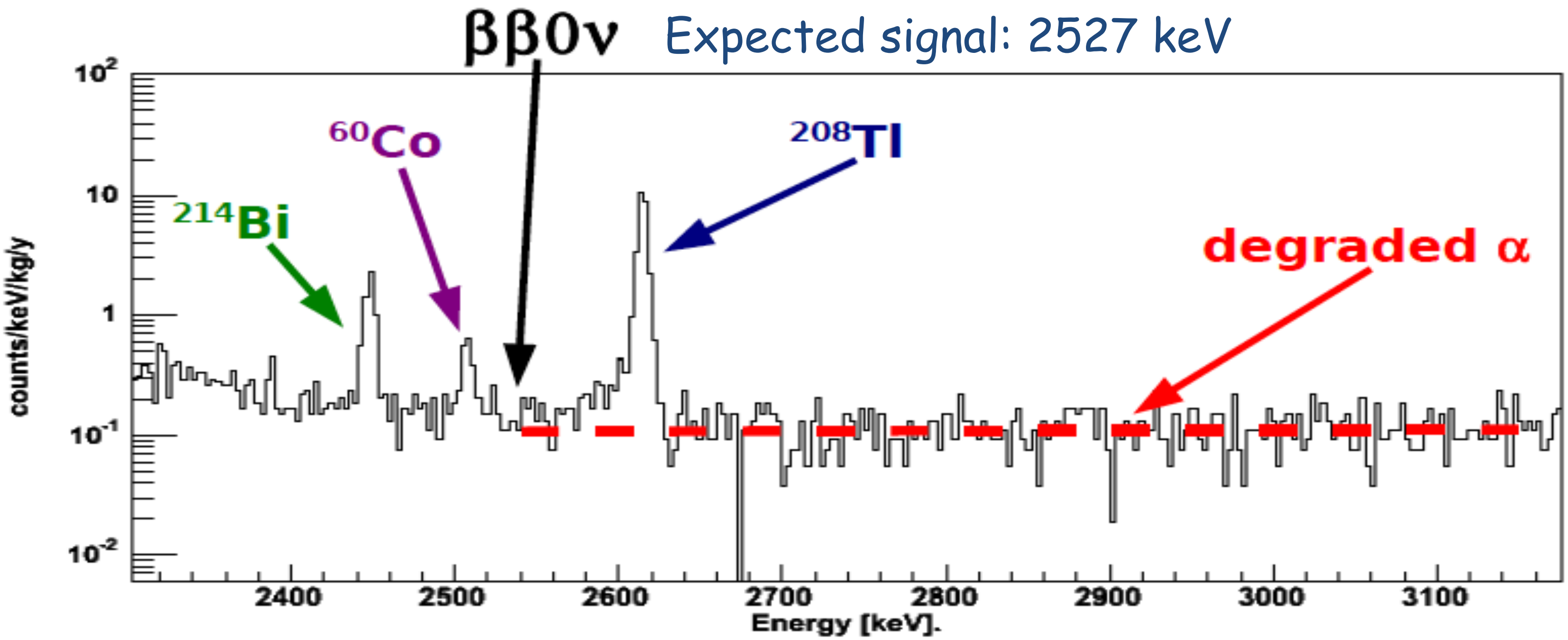
The measured 0νDBD half-life corresponds to the maximum signal that could be detected in a experiment

$$1/T_{1/2}^{0\nu} \propto \frac{a \cdot \eta \cdot \varepsilon}{A} \cdot \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

- a : isotopic abundance
- η : stoichiometric coefficient
- ε : detector efficiency
- A : molecular weight of the active mass

- M : detector mass [kg]
- T : measurement live time [y]
- B : background [c/keV/kg/y]
- ΔE : energy resolution [keV]

Normalized Background Spectrum



- ^{60}Co from cosmogenic activation: ~small amount
- Compton edge from ^{208}Tl (daughter of ^{228}Th): ~40%
- Alphas from crystal surfaces (^{232}Th and ^{238}U): ~10%
- Alphas from Cu holders surfaces (^{232}Th and ^{238}U): ~50%

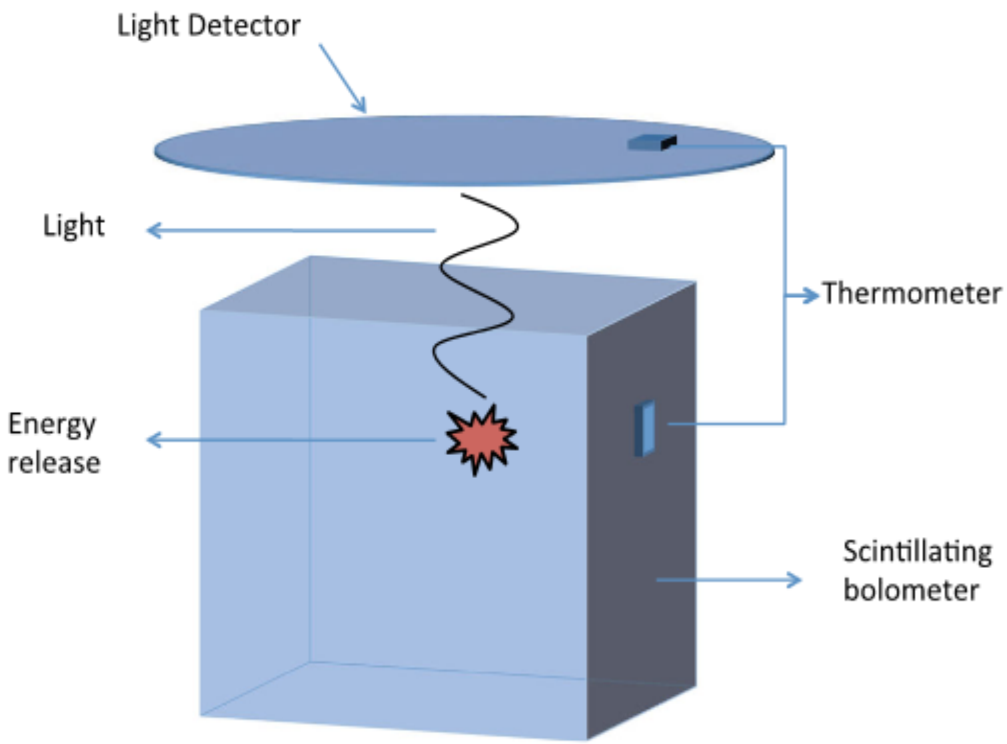
CUORE Results

- CUORE-0
  - ΔE=5.1 keV, B=0.058 counts/keV·kg·year, 10 kg·year of total Te low background data, $T_{1/2}^{0\nu} > 2.7 \cdot 10^{24}$ yr
  - CUORICINO and CUORE-0, $T_{1/2}^{0\nu} > 4.0 \cdot 10^{24}$ yr
- CUORE
  - Introducing pulse shape discrimination parameters and with improved materials handling
  - B=0.010 counts/keV · kg · year
  - 988 TeO_2 crystals in 5 years, $T_{1/2}^{0\nu} \sim 6 \cdot 10^{25}$ yr
- CUPID (Cuore Upgrade with Particle IDentification)
  - An interest group working on a new generation large scale bolometric 0vDBD experiment beyond CUORE

CUPID — A way to lead

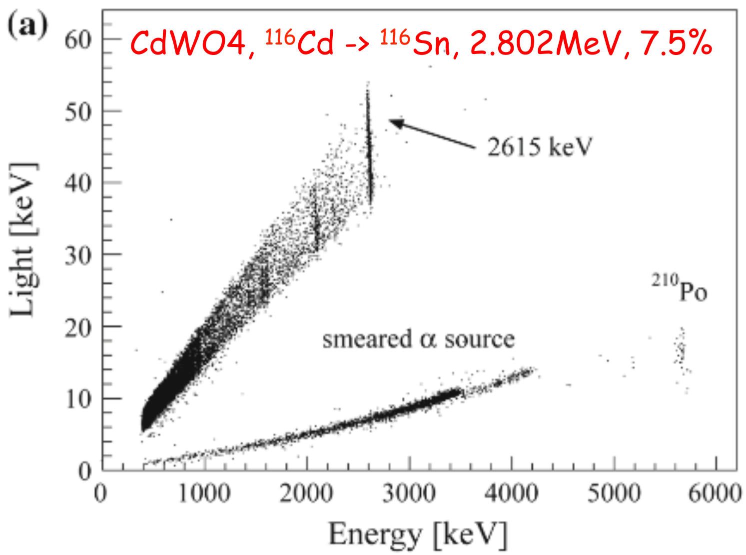
- Other neutrinoless double beta decay experiments
  - GERDA (^{76}Ge), 2013, $T_{1/2}^{0\nu} > 3 \cdot 10^{25}$ yr
  - EXO (^{136}Xe), 2014, $T_{1/2}^{0\nu} > 1.1 \cdot 10^{25}$ yr
  - Future scalable experiments: nEXO (^{136}Xe) and SNOplus (^{130}Te)
- To scale bolometric experiment up
  - Enriched isotopes (^{130}Te, ^{82}Se, ^{116}Cd and ^{100}Mo)
  - Large number of bolometric detectors with multiplexing capability (using superconducting electronics)
- Near-zero background experiment
  - ROI above ^{208}Tl gamma line (^{82}Se, ^{116}Cd and ^{100}Mo)
  - Event by event background discrimination with simultaneous measurements of heat and light.
  - $\Delta E = 2.0$ keV energy resolution by using TES
  - B=0.0001 counts/keV · kg · year
- Science goal of $T_{1/2}^{0\nu} \sim 10^{28}$ y & $m_\nu \sim 10$ meV

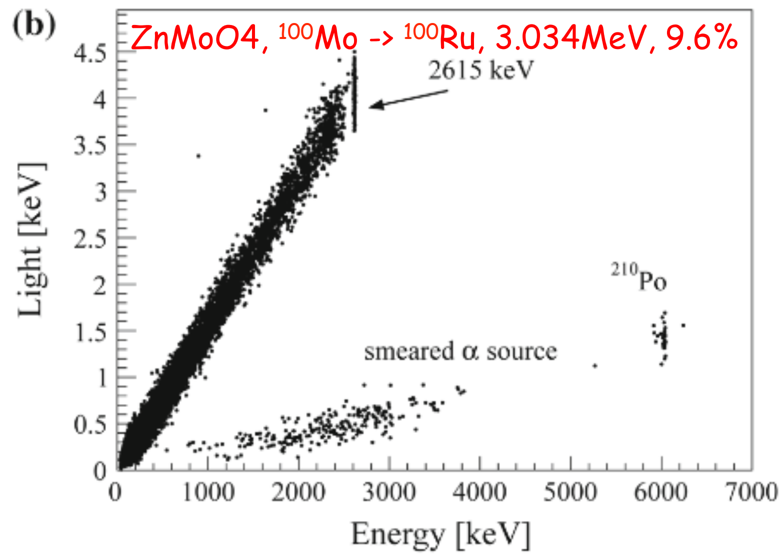
Measuring both Heat and Light

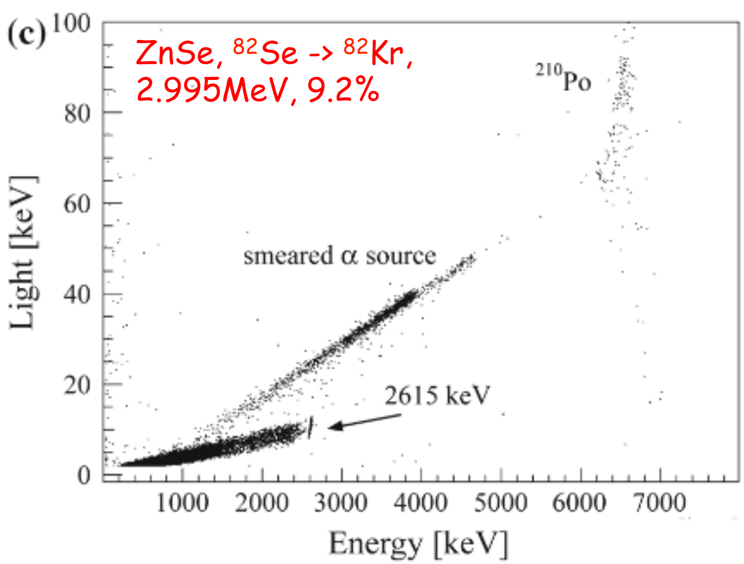


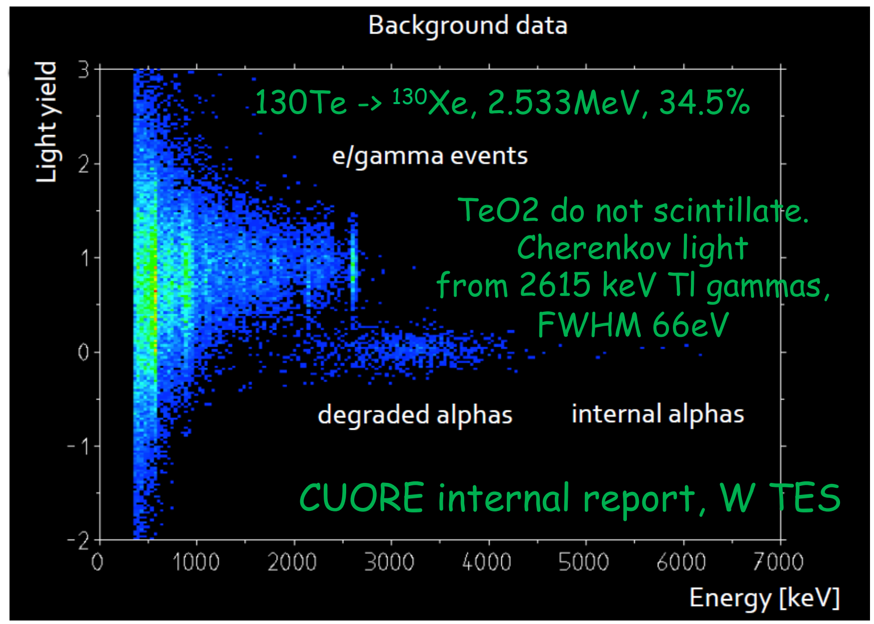
- Ge NTD
- High impedance thermometer
- Long electric time constant (RC)
- Alternative – TES

Surface event rejection – light yield







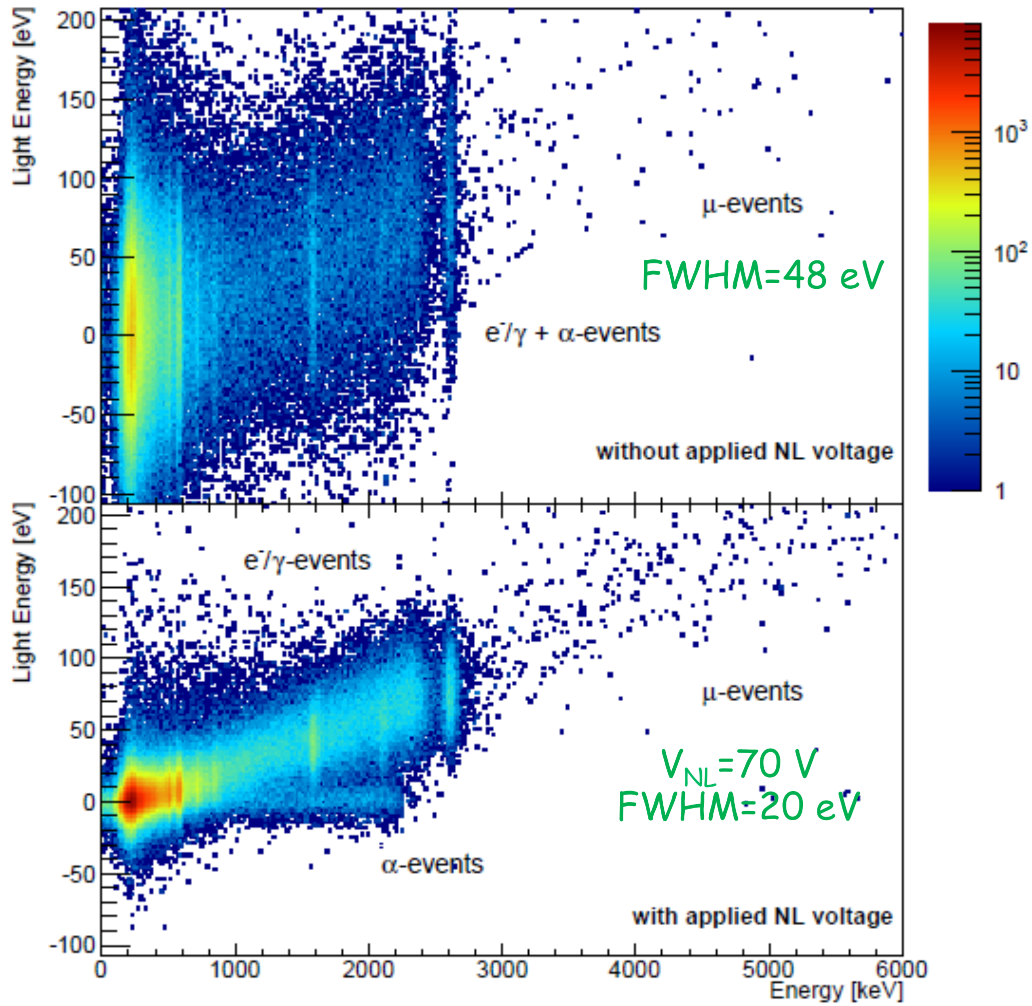


D. R. Artusa et al., Eur. Phys. J. C (2014) 74:3096

Light Detector with Internal Gain

- 500 μm crystalline silicon
- Al superconducting electrodes
- Photons create ionization charges
- Electric charges are converted to heat under high voltage (Neganov-Luke effect)
- TES thermometer measures temperature change due to the primary photons and the Neganov-Luke phonons

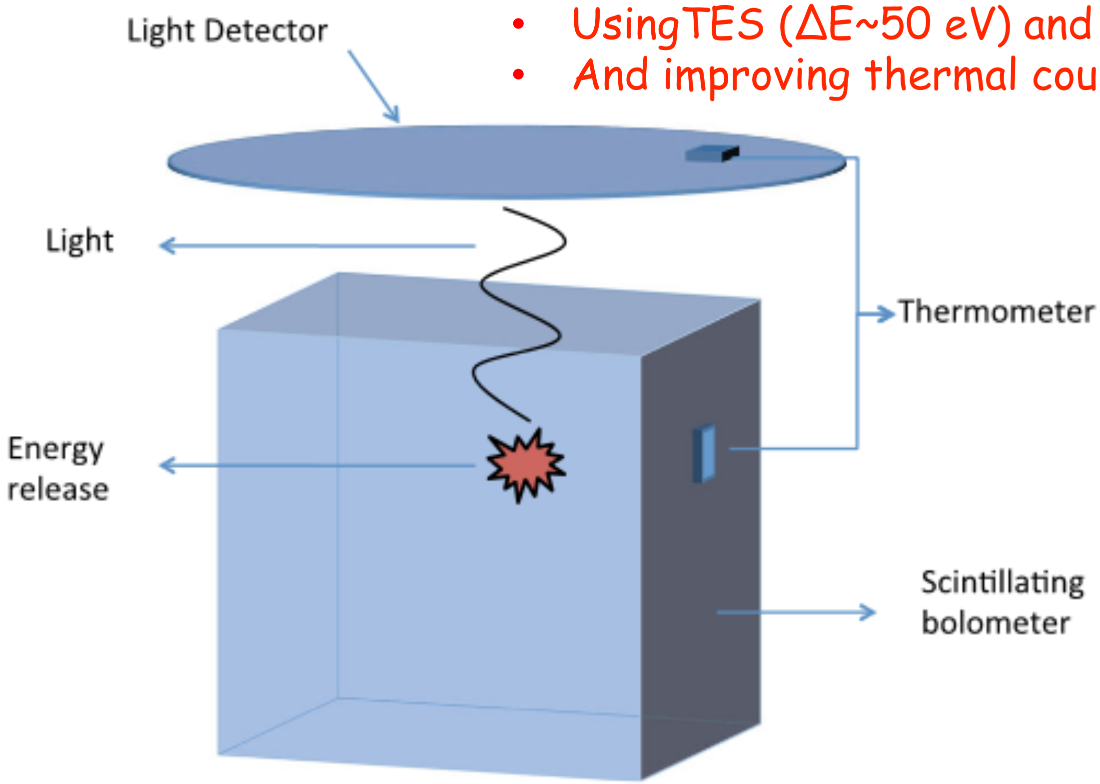
$$G = 1 + \frac{e \cdot V_{NL}}{E_g / \eta}$$



M. Willers et. al., JINST 10 (2015) P03003

Measuring both Heat and Light with TESs

- Heat capacitance < 1pJ/K, 1.6μK@10eV, expected thermodynamic ΔE=1.0eV, measured with NTD ΔE=150eV
- UsingTES (ΔE~50 eV) and thermal gain, ΔE~20 eV
- And improving thermal coupling, ΔE<10 eV



- TES
- Fast thermometer, pulse shape information at the rising edge
- Low impedance
- Multiplexing with SQUID electronics
- Multiplexing with superconducting kinetic inductance sensor
- Scaling the experiment to one ton active mass and more

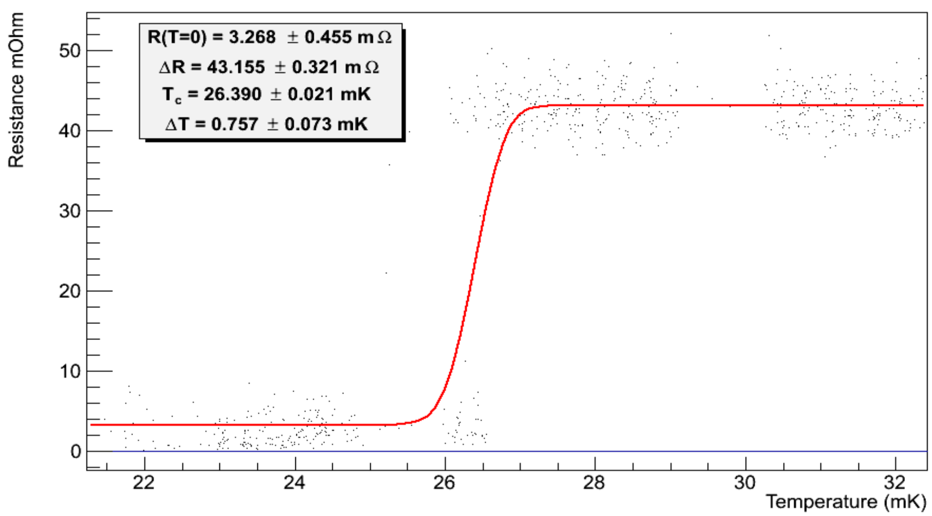
- Heat capacitance < 100nJ/K, 50μK@2.6MeV, expected thermodynamic ΔE=0.3 keV, measured with NTD ΔE=5.1 keV
- Using TES and improving thermal coupling, ΔE<2 keV

Low-Tc Transition Edge Sensor (TES) at Argonne

- Low-Tc (below 30 mK) TES using proximity effect
- Ir/Au (or Ir/Pt) bilayer TESs were fabricated at Argonne
- Tested at Berkeley using a dilution refrigerator with a base temperature of ~ 8 mK

100 nm Ir/xxx nm Au bilayer

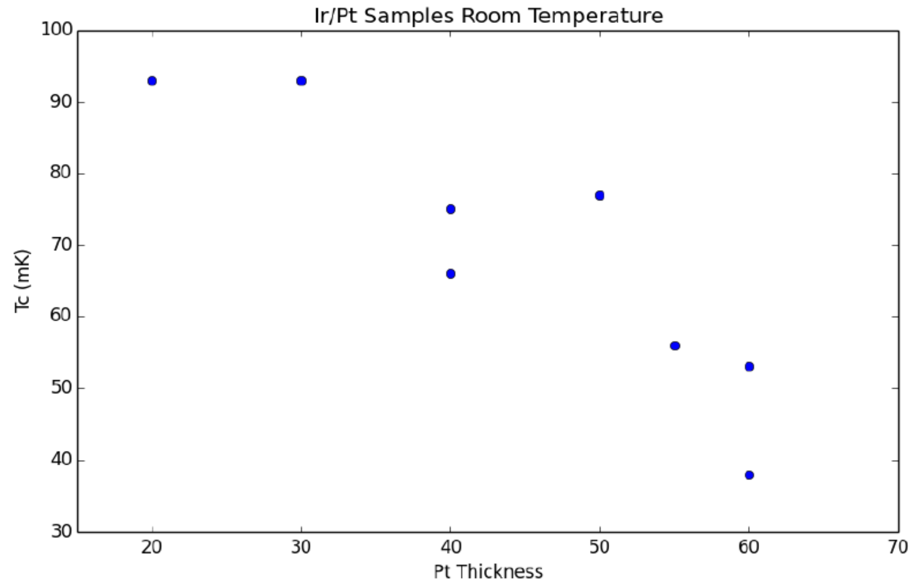
Channel	ANL Sample	Film	Au (nm)	Ir Aneal (° C)	R(1K) (mΩ)	T_c (mK)
1	12	Ir/Au	261	500	47.6	**21-23**
2	15	Ir/Au	106	500	153	78
3	17	Ir/Au	174	-	81	65
4	19	Ir/Pt	20	500	1000	93
6	16	Ir/Au	261	-	?	?
10	15	Ir/Au	106	500	99	77
12	12	Ir/Au	261	500	35	32
13	12	Ir/Au	261	500	33	26-27
14	12	Ir/Au	261	500	25.2	**23-25**



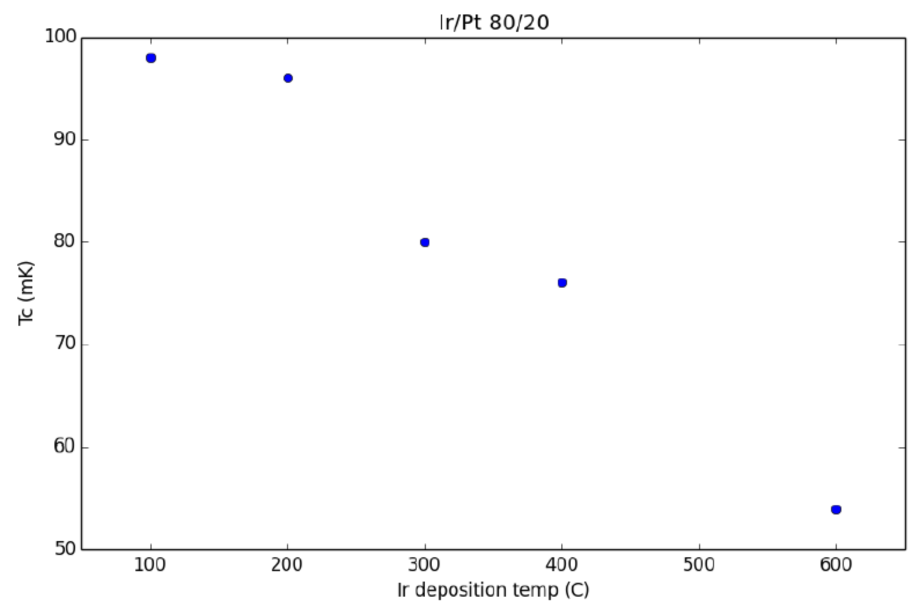
Ir was sputtering deposited at 500 ^{0}C on silicon wafer. Au was sputtering deposited after the wafer cooled to room temperature.

Ir/Pt bilayer

Room temperature sputtering deposition. 80 nm Ir. Change Pt thickness.



80 nm Ir / 20 nm Pt . Change wafer temperature during Ir sputtering deposition.



Low-Tc TES for 0vDBD search at Argonne

TES for light measurements using Neganov-Luke effect, high purity crystalline Si disks

TES for heat measurements, reducing the accoustic phonon mismatch

Low-Tc TES with low noise, batch fabrication repeatability, and wafer uniformity

1. Understanding the proximity effect between a superconductor and a normal metal for a low-Tc
2. Understanding characteristics of film structure, composition, and surface morphology under fabrication settings
3. Correlating the measured cryogenic performances with fabrication parameters

TES for heat measurements, TeO_2, $ZnSe$, $ZnMoO_4$, $CdWO_4$

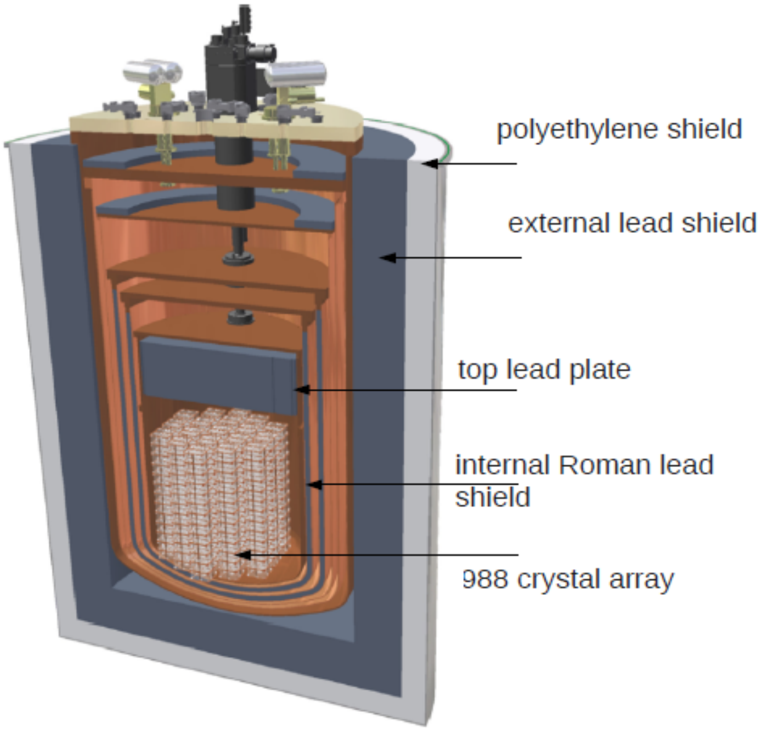
TES for light measurements, reducing the accoustic phonon mismatch

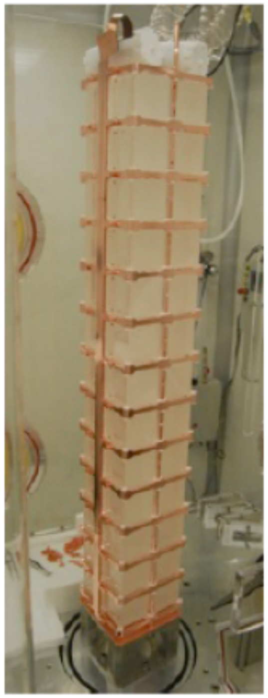
Summary

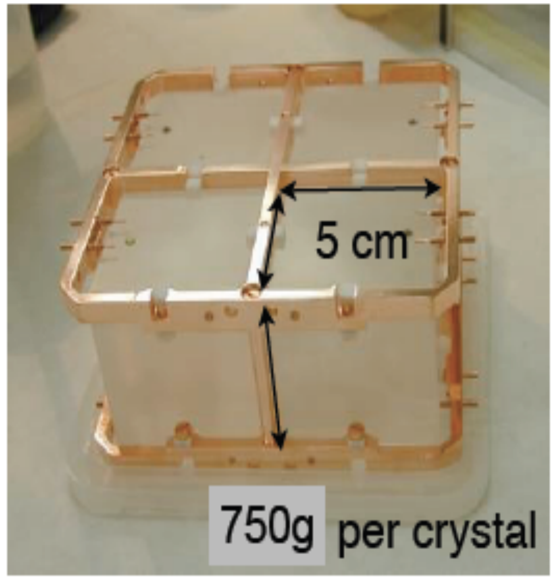
- CUORE is a 0vDBD search experiment using sensitive bolometric technique
- CUPID will be the successor of CUORE with enriched isotopes and TESs (which can be multiplexed)
- ANL contributes a new generation 0vDBD search technology by collaborating with Berkeley group
  - Low-Tc TESs for both heat and light measurements
- Background reduction
  - Using Neganov-Luke effect to increase the signal to noise ratio for Cherenkov light detection in case of TeO_2 — reducing B
  - Taking advantage of the scintillation light and using isotopes with larger $Q_{\beta\beta}$ values of ZnSe, $ZnMoO_4$, $CdWO_4$, but at a higher cost
  - Exploring techniques to improve the thermal coupling between a target crystal and a TES thermometer — reducing ΔE

COURE Experiment

- 19 towers, 13 floors each tower, 4 750g TeO_2 crystals each floor
- Cooled down to 10 mK with a dilution refrigerator in a shielded cryostat in LNGS







Expected Event Rate of 0vDBD

neutrinoless Double Beta Decay rate

Phase space

Nuclear matrix elements

Effective **Majorana mass**

$$1/T^{0\nu}_{1/2} = G(Z,Q)\left|M_{nucl}\right|^2 \left\langle M_{\beta\beta}\right\rangle^2 / M_e^2$$

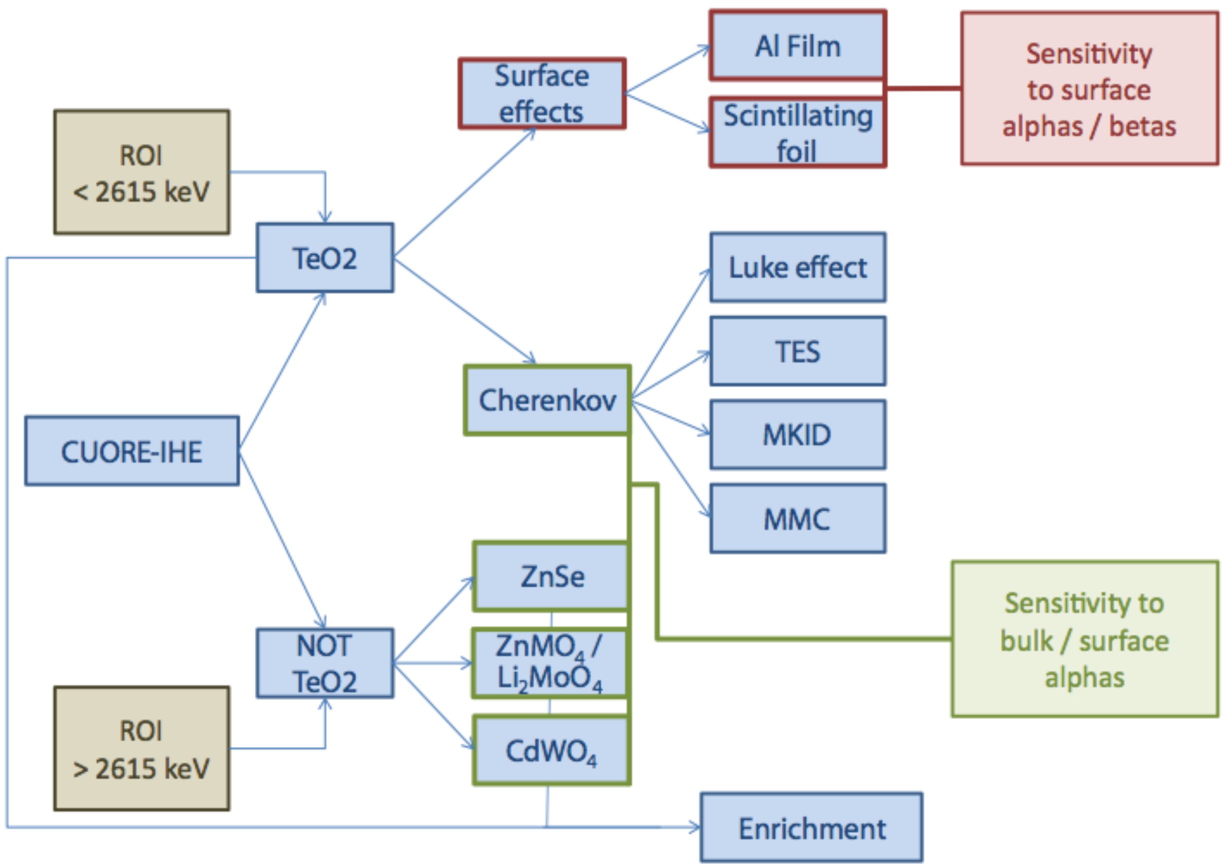
what the experimentalists try to measure

what the nuclear theorists try to calculate

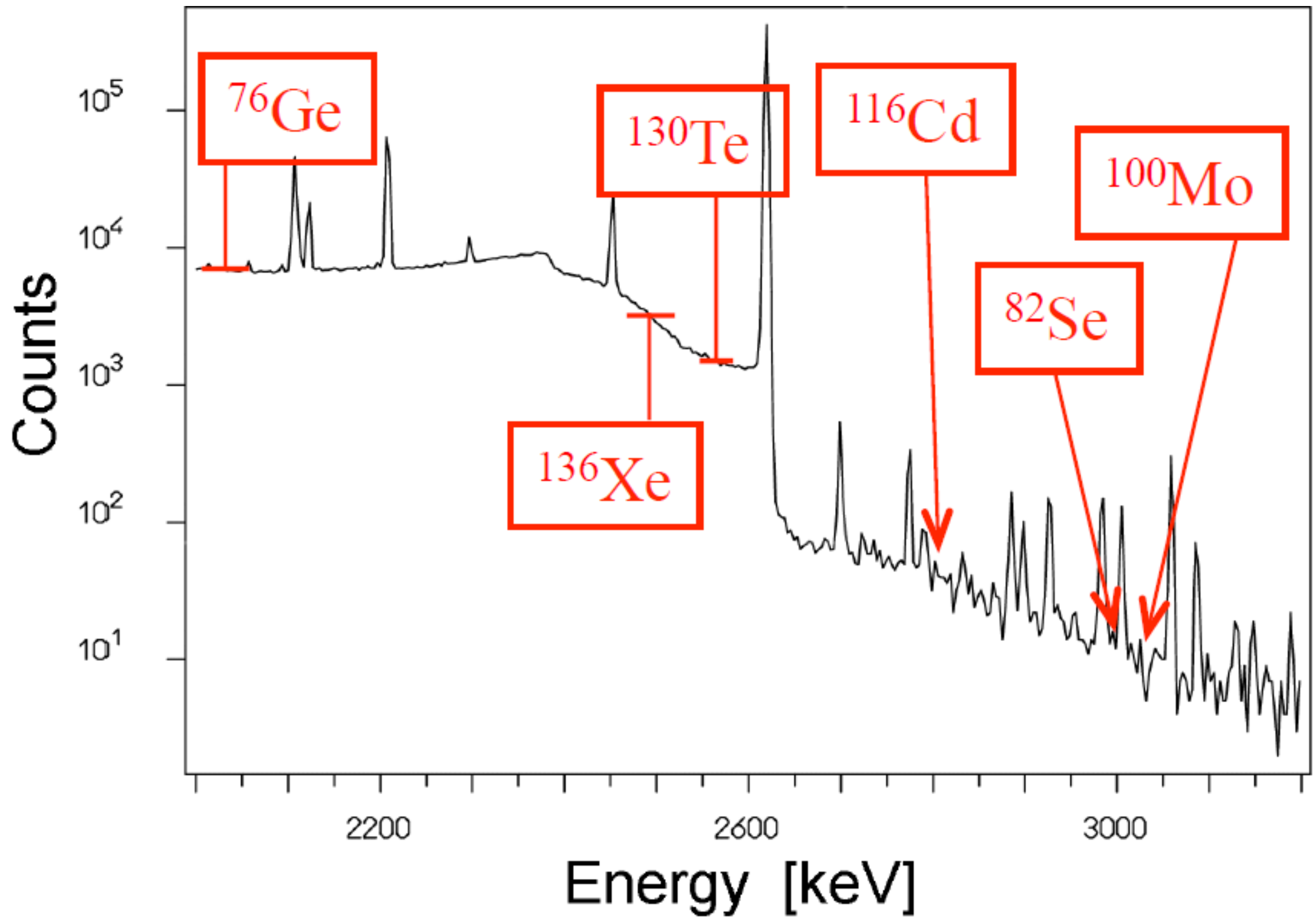
parameter containing the physics: **Effective Majorana mass**

$$\langle M_{\beta\beta}\rangle = |\,|U_{e1}|^2 M_1 + e^{i\alpha 1}\,|U_{e2}|^2 M_2 + e^{i\alpha 2}\,|U_{e3}|^2 M_3\,|$$

Techniques to a bolometric 0vDBD experiment



Background vs ROI



Isotopes for 0vDBD

Isotope	$Q_{\beta\beta}$ (keV)	I.A.(%)	$G^{0\nu}$	$H^{0\nu}$
^{48}Ca	4272	0.187	24.81	826.2
^{76}Ge	2039	7.8	2.36	49.6
^{82}Se	2995	8.73	10.16	198.1
^{96}Zr	3350	2.8	20.58	342.7
^{100}Mo	3034	9.63	15.92	254.5
^{110}Pd	2018	11.72	4.82	70.0
^{116}Cd	2814	7.49	16.70	230.1
^{124}Sn	2287	5.79	9.04	116.5
^{128}Te	866	31.69	0.59	7.4
^{130}Te	2527	33.8	14.22	174.8
^{136}Xe	2458	8.9	14.58	171.4
^{148}Nd	1929	5.76	10.10	109.1
^{150}Nd	3371	5.64	63.03	671.7
^{154}Sm	1215	22.7	3.02	31.3
^{160}Gd	1730	21.86	9.56	95.5
^{198}Pt	1047	7.2	7.56	61.0