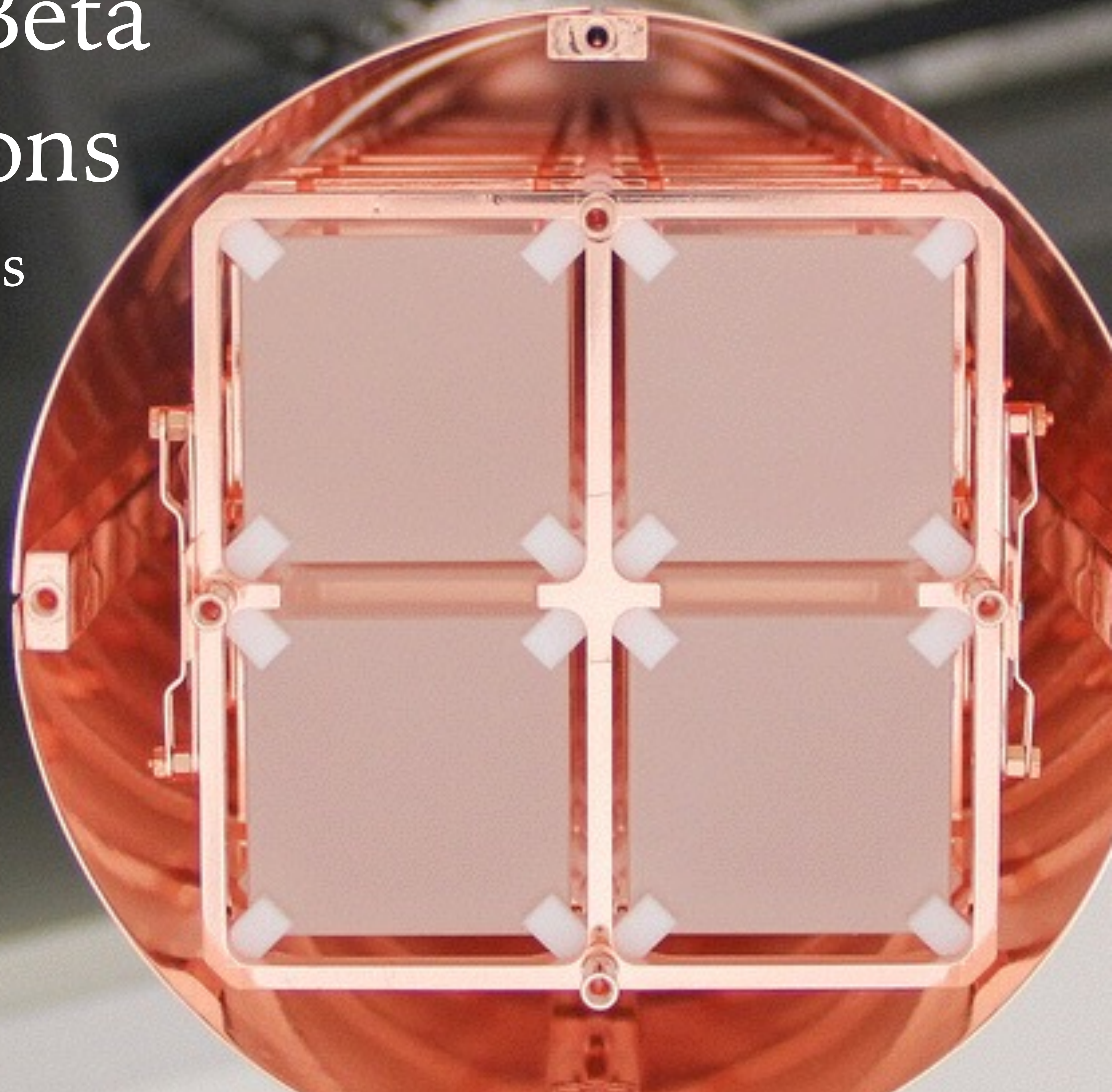
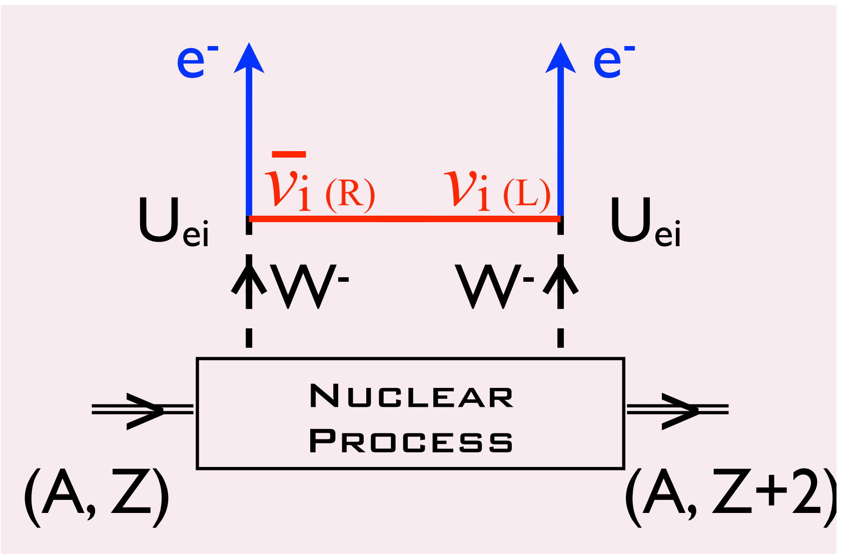
TES for Double Beta Decay Applications

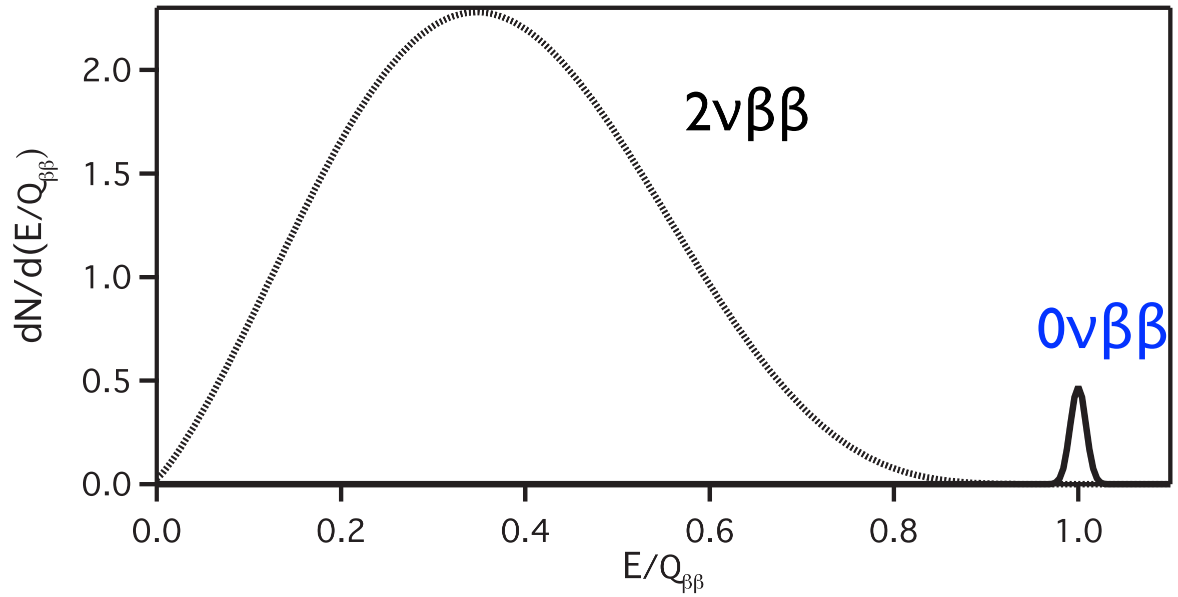
Raul Hennings Yeomans
UC Berkeley



Neutrino-less Double Beta Decay

- Hypothetical ββ decay mode allowed if neutrinos are Majorana particles, i.e $\bar{\nu}_i \equiv \nu_i$





Phase space factor

Nuclear matrix element

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Decay half-life

Effective Majorana ν mass: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$

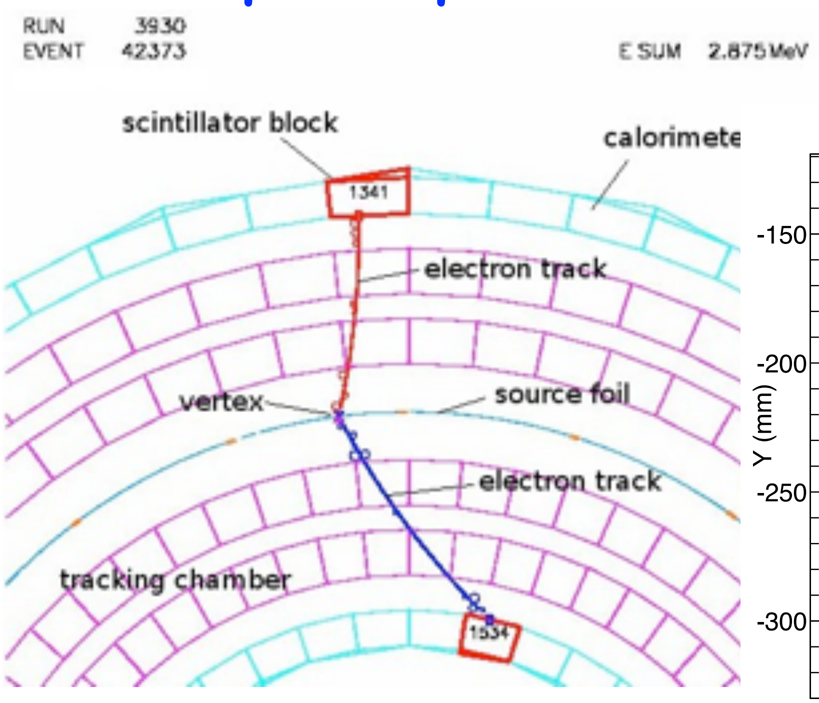
- For $m_{\beta\beta}$ = 15 meV estimated half lives 10^{27} - 10^{28} years, depending on the nuclear system

- ***Observation of 0νββ would mean***
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate measures (effective) electron neutrino mass

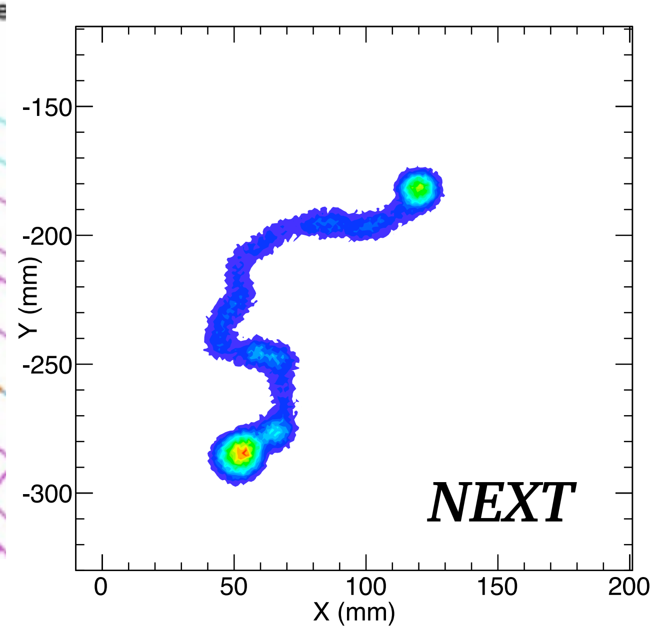
Experimental approaches to 0νββ

Source external to detector

Example: SuperNEMO



Nemo



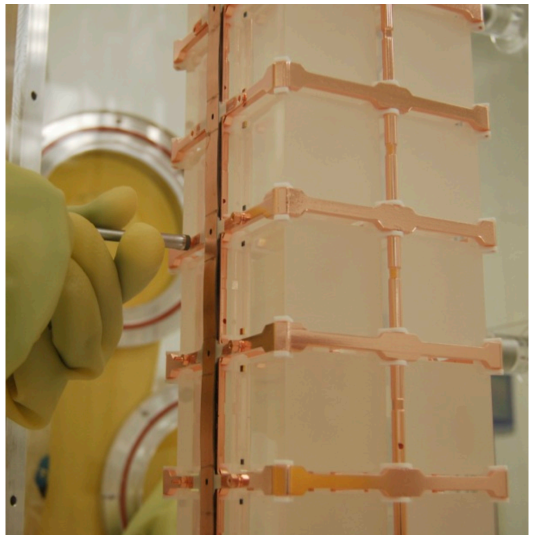
Plus: event topology, background rejection, multiple isotopes possible.
Cons: detector mass, resolution, acceptance.
Technology: typically tracking detectors.

Tecnology: Pressurized TPC (10-16 atm)

May prove invaluable to test models once 0νββ is discovered

Source internal to detector

Example: MAJORANA, EXO, CUORE, SNO+, Kamland-Zen, etc.



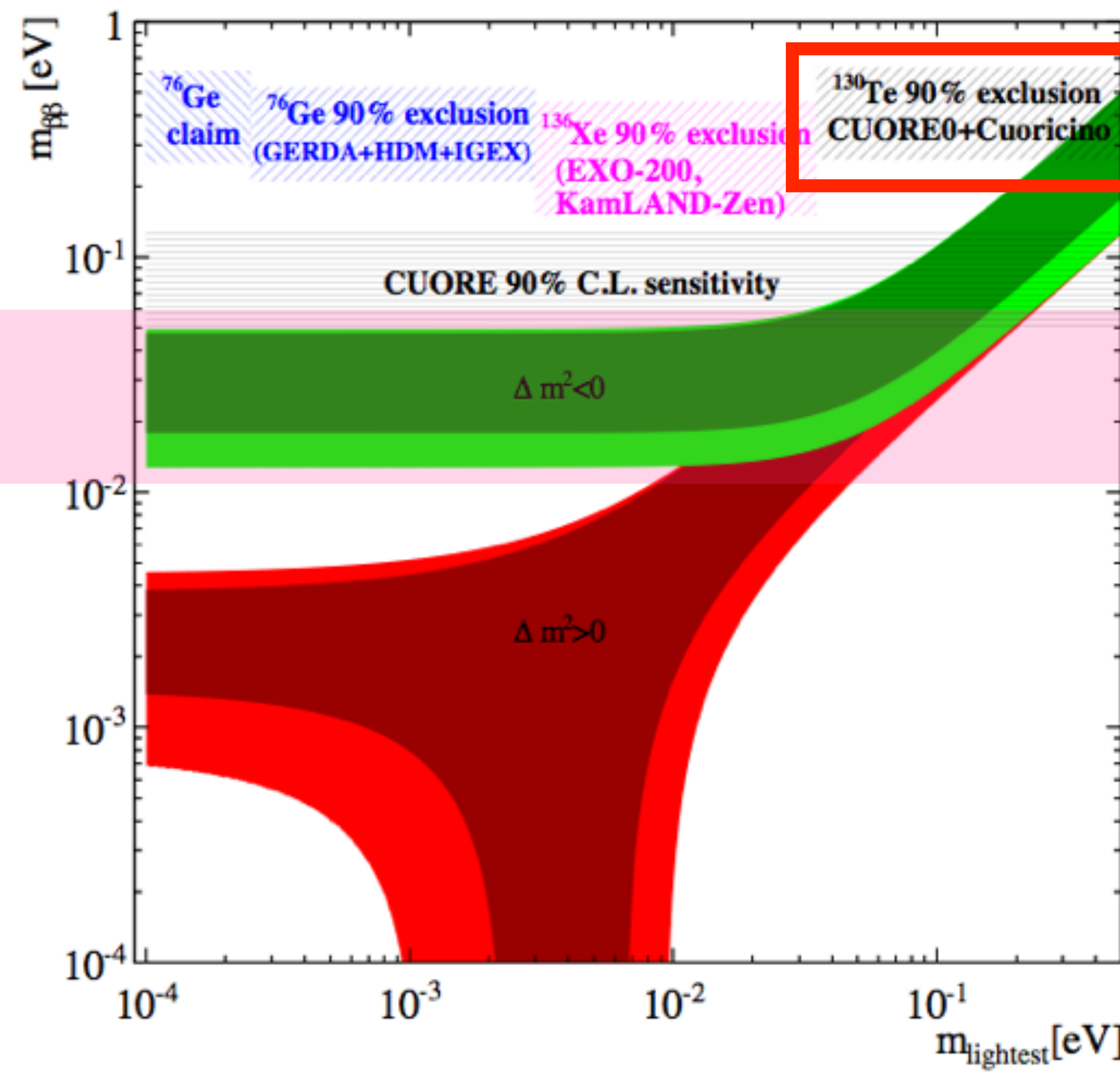
CUORE

SNO+

Plus: detector mass, energy resolution, acceptance
Cons: event topology, background rejection
Technology: calorimeters (bolometers, ionization, scintillation), tracking

Typically aimed at 0νββ discovery

Beyond CUORE: towards covering the IHE



Goal of next generation experiments

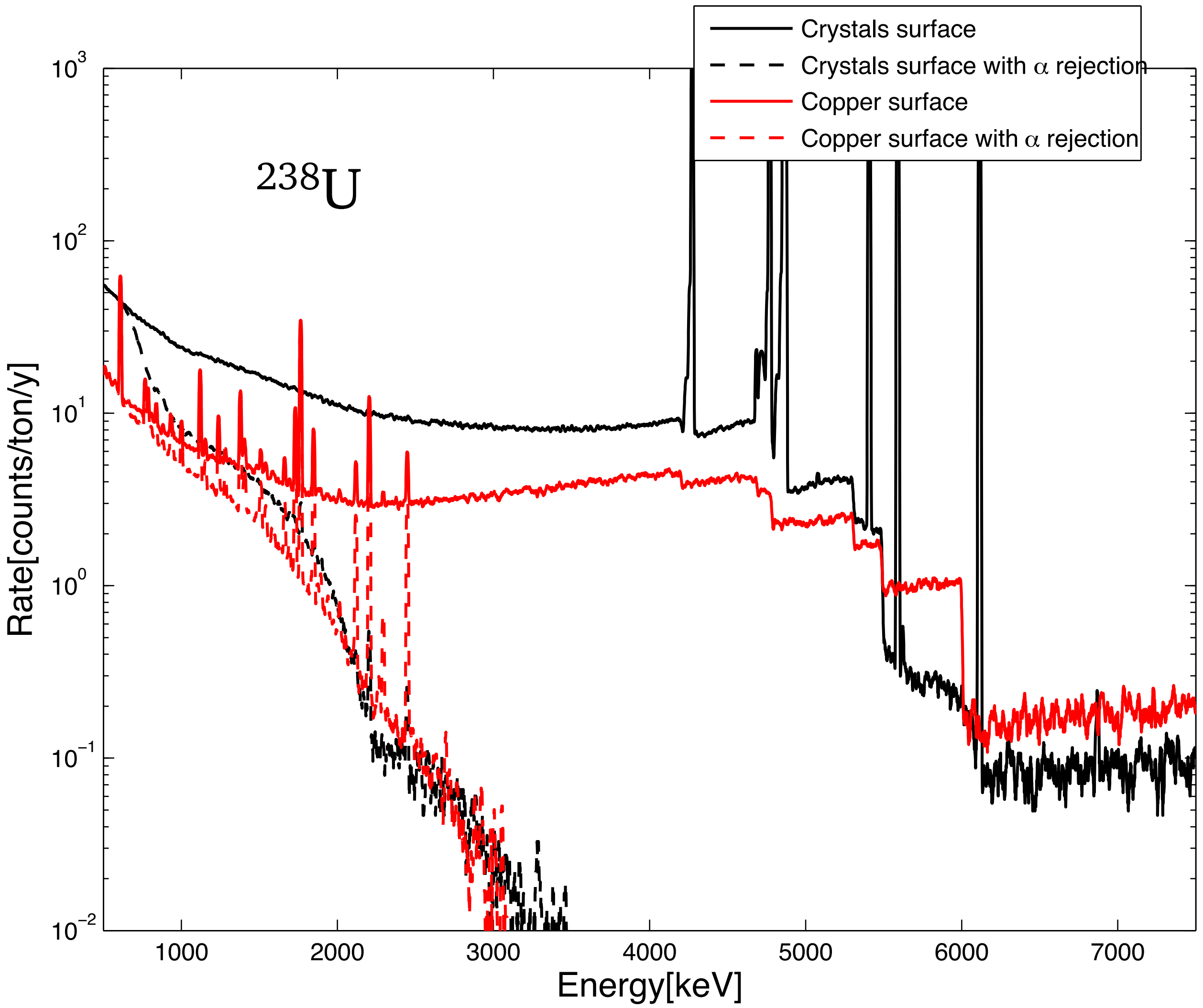
$$m_{\beta\beta} \sim \frac{m_e}{\sqrt{F_N \cdot \varepsilon \cdot \eta \sqrt{\frac{M \cdot t}{b \cdot \delta E}}}}$$

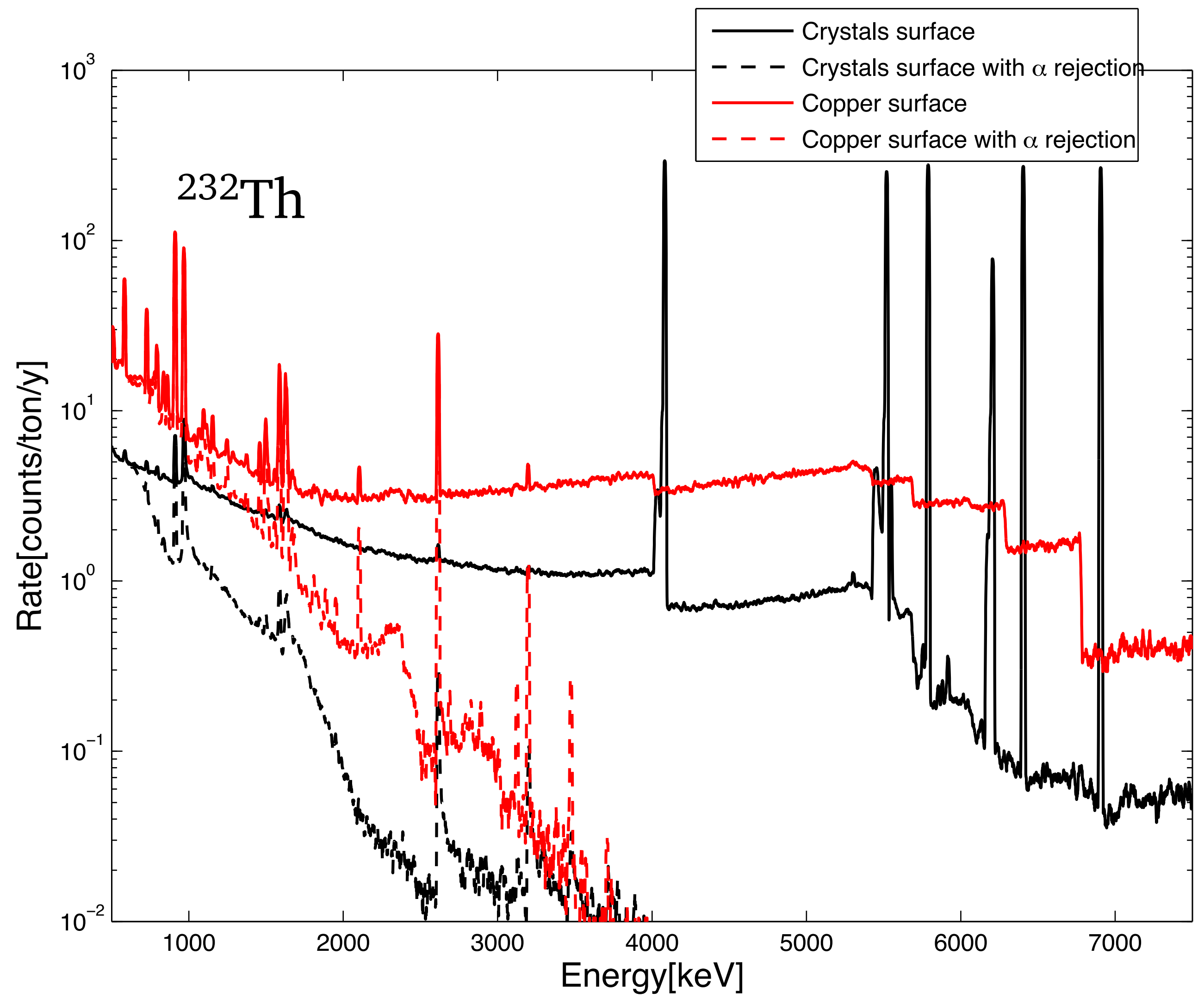
For a zero background experiment $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$

With background subtraction $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

Beyond CUORE: effect of alpha background rejection

Simulation of surface contamination with an exponential depth profile and a mean depth of 5 μm. Dashed histograms are without α's

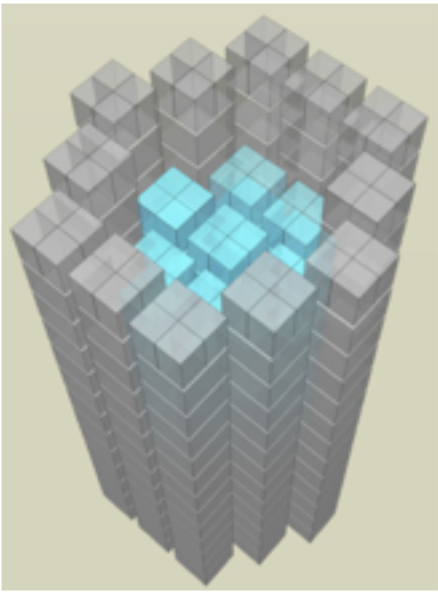




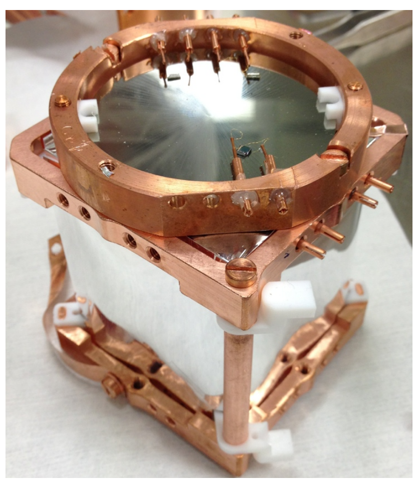
CUORE Collaboration Eur.Phys.J. C74 (2014) 10, 3096

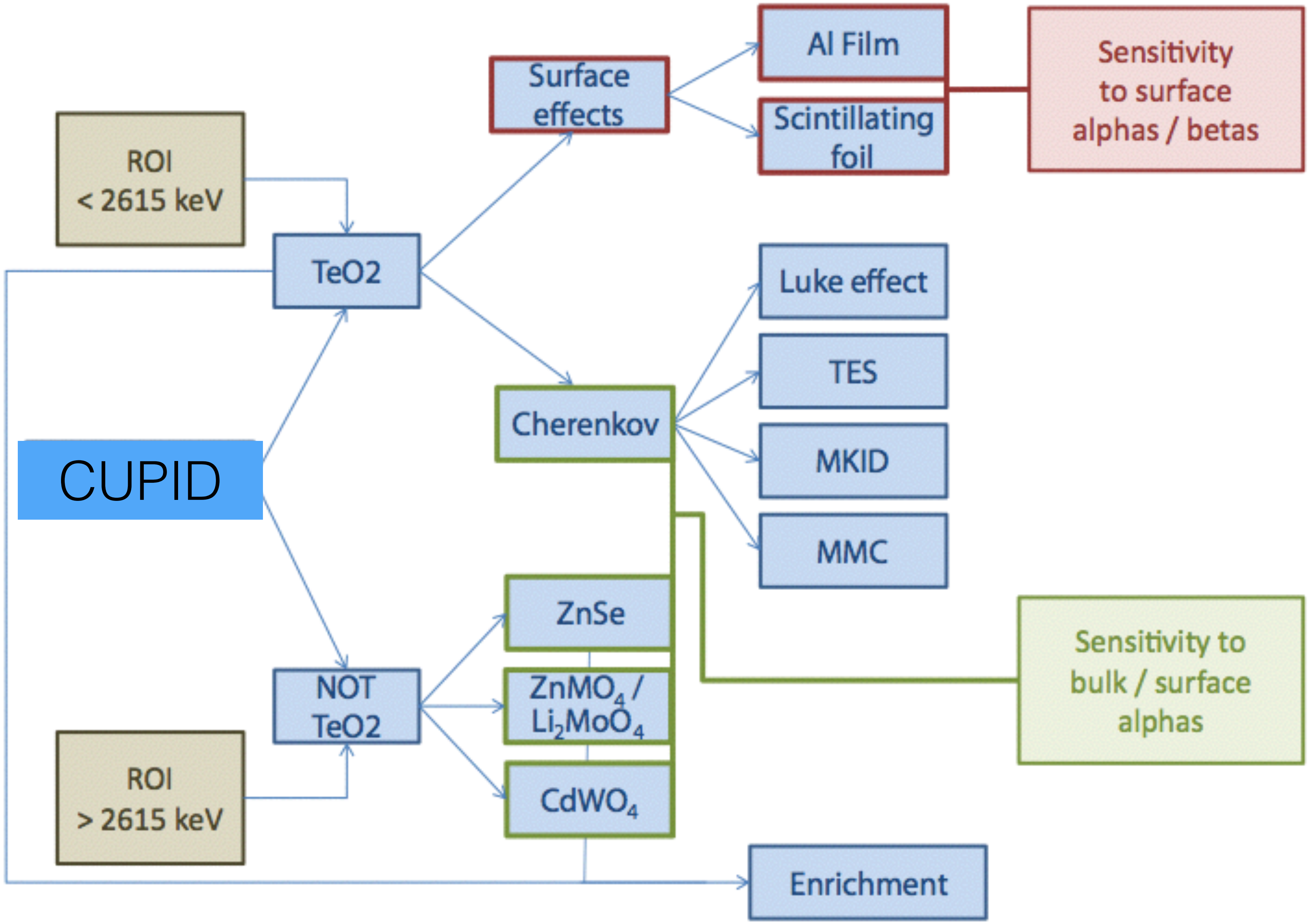
CUPID: Cuore Upgrade with Particle ID

Te-130 enrichment



Particle ID



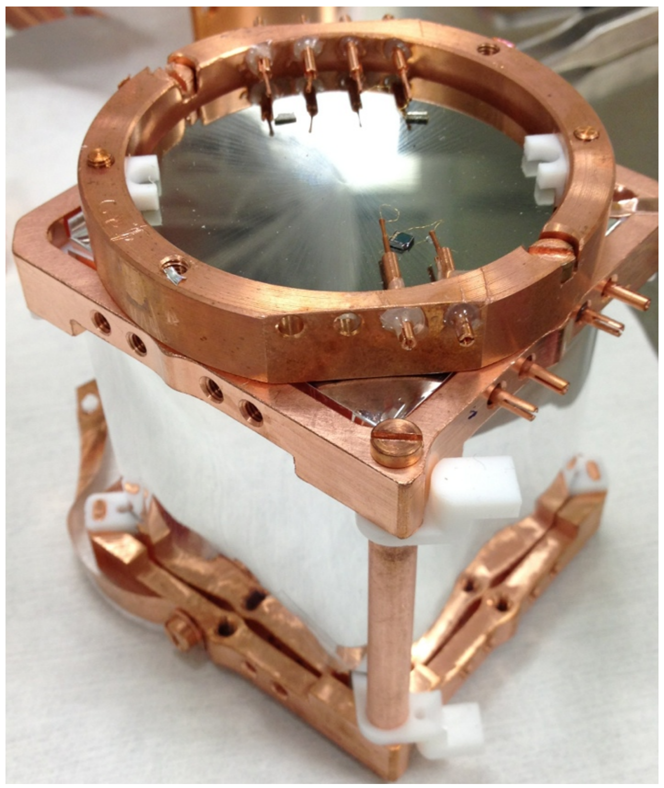


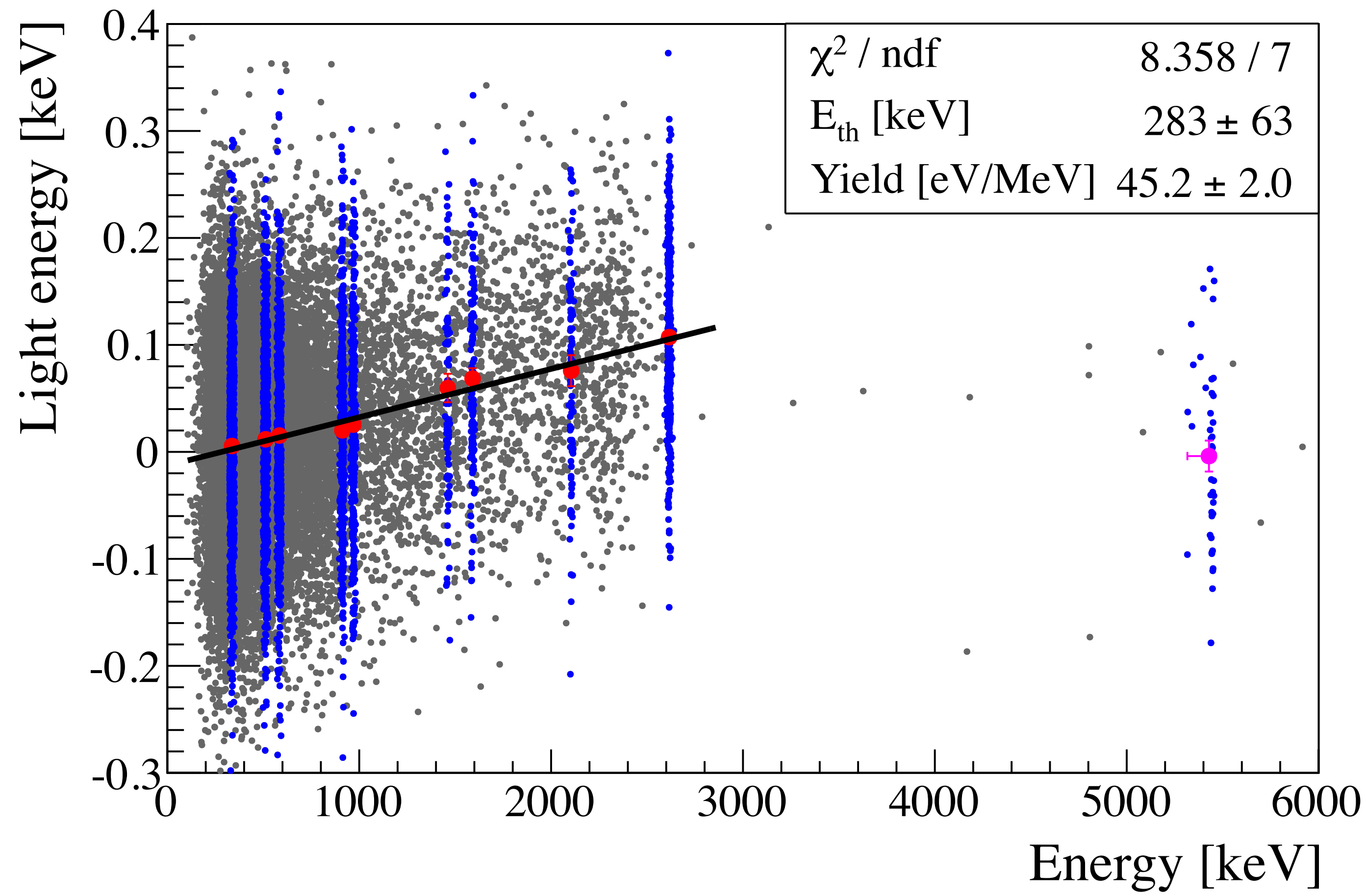
Bolometer R&D:

- CALDER
- Cherenkov/TeO_2
- LUCIFER
- LUMINEU

Particle ID via a the Light channel

Cherenkov light from a full 750g TeO_2 crystal





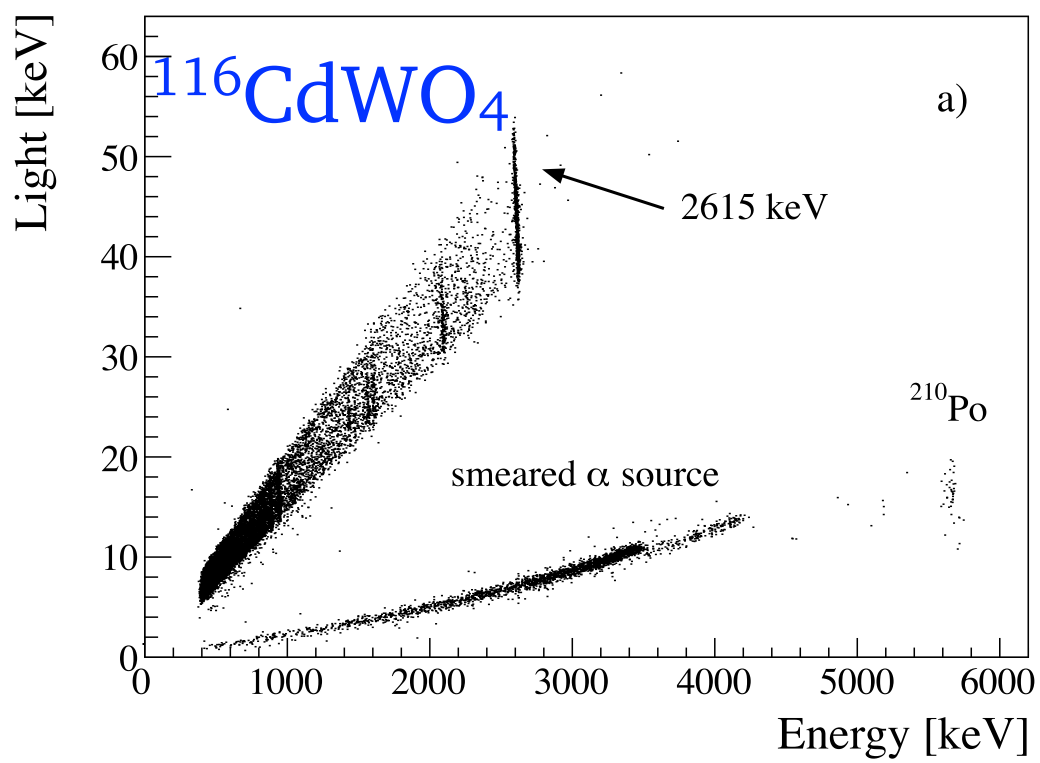
Casali et al. Eur. Phys. J. C75 (2015), 1, 12

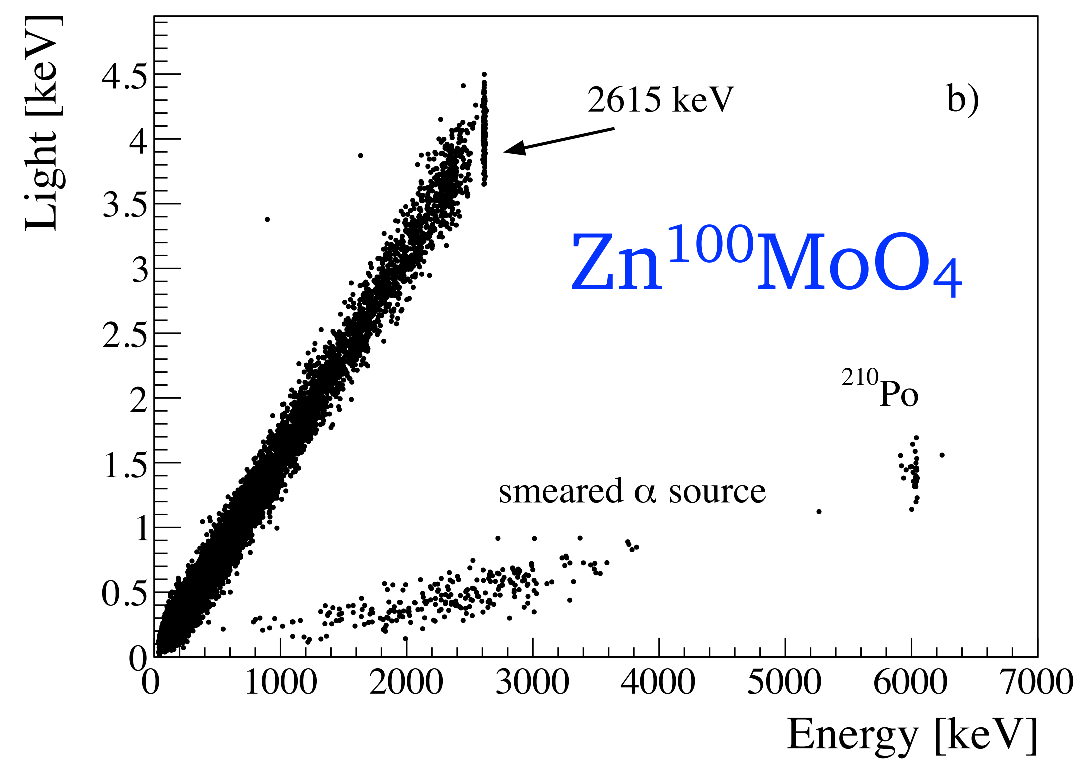
101+/- 3.4 eV of light for a β/γ event with energy 0νββ value

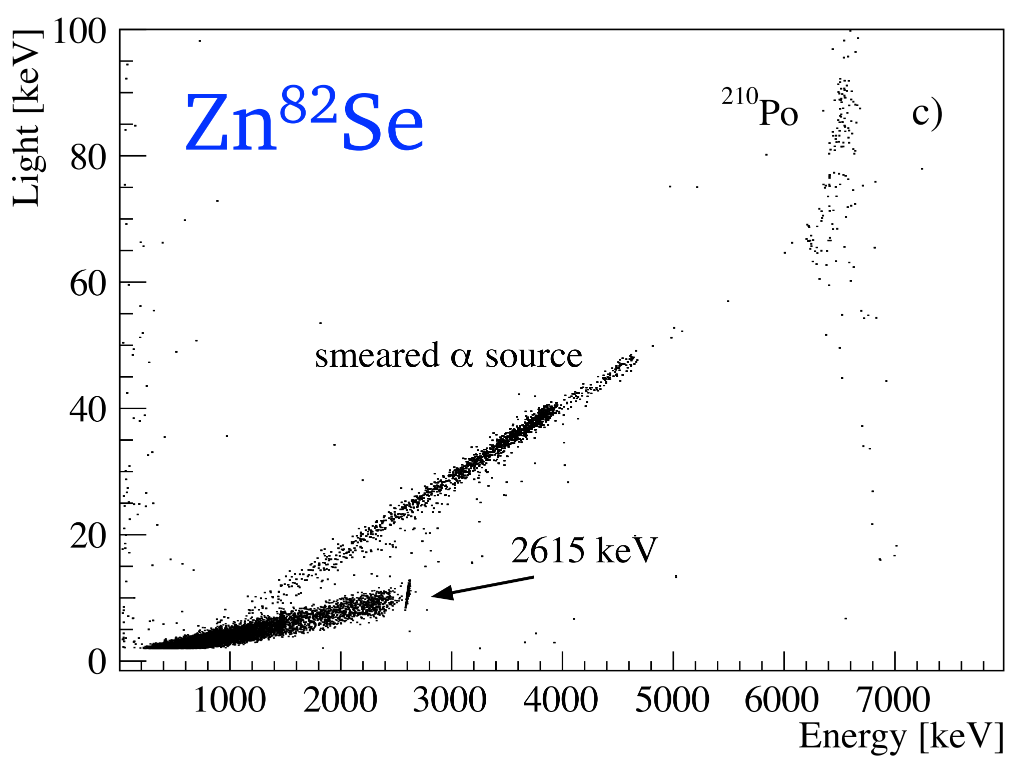
R&D on improved light detectors currently ongoing:
MKIDs, TES, Neganov-Luke assisted, MMCs

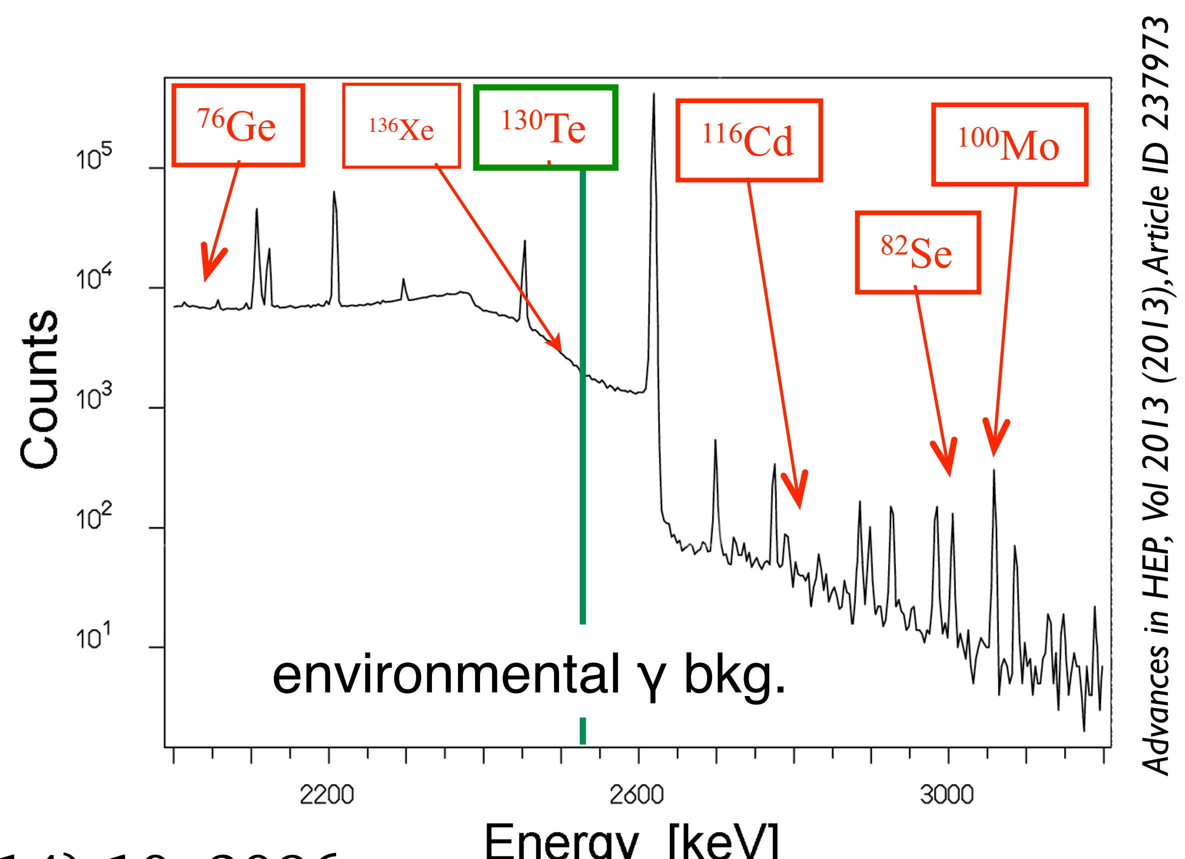
We need to discriminate between α and β/γ at 5σ, ie 99.9% rejection α's with 90% efficiency.
For a light yield of 100 eV implies resolution need of better than 20eV.

Scintillating crystals





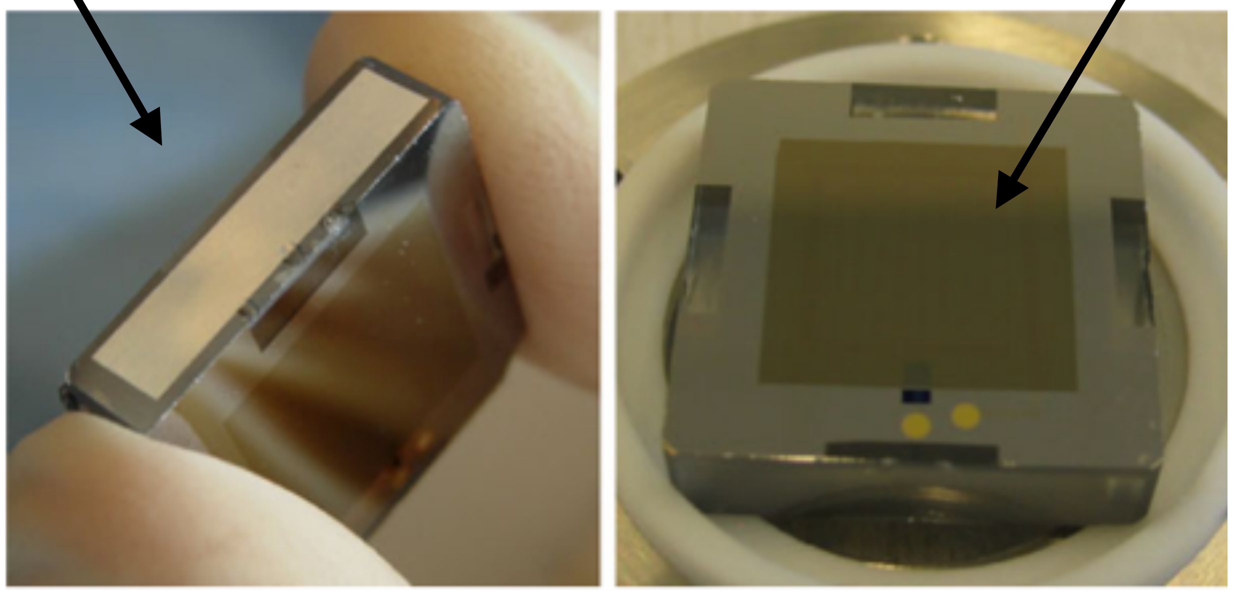




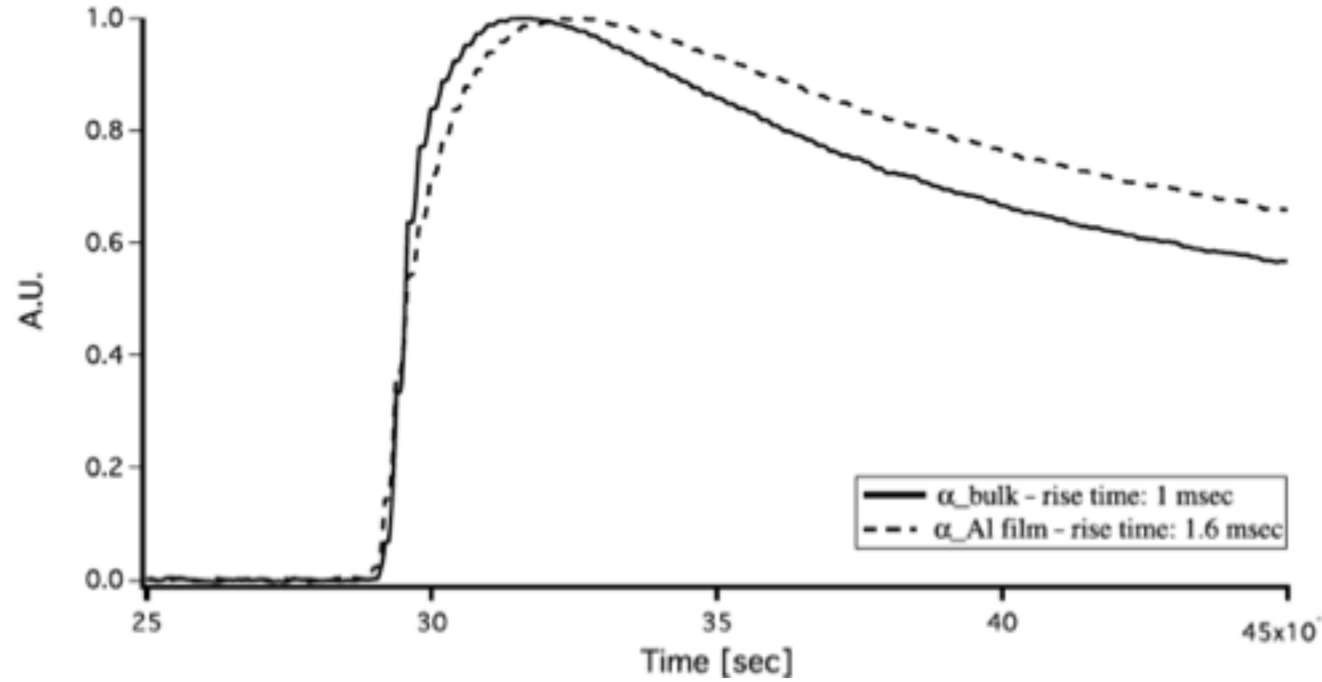
Cuore Collab. Eur. Phys. J. C74 (2014) 10, 3096

Particle ID via Pulse Shape with Aluminum coating

Aluminum film NbSi sensor



J. Low Temp. Phys (2012) 167:1029-1034



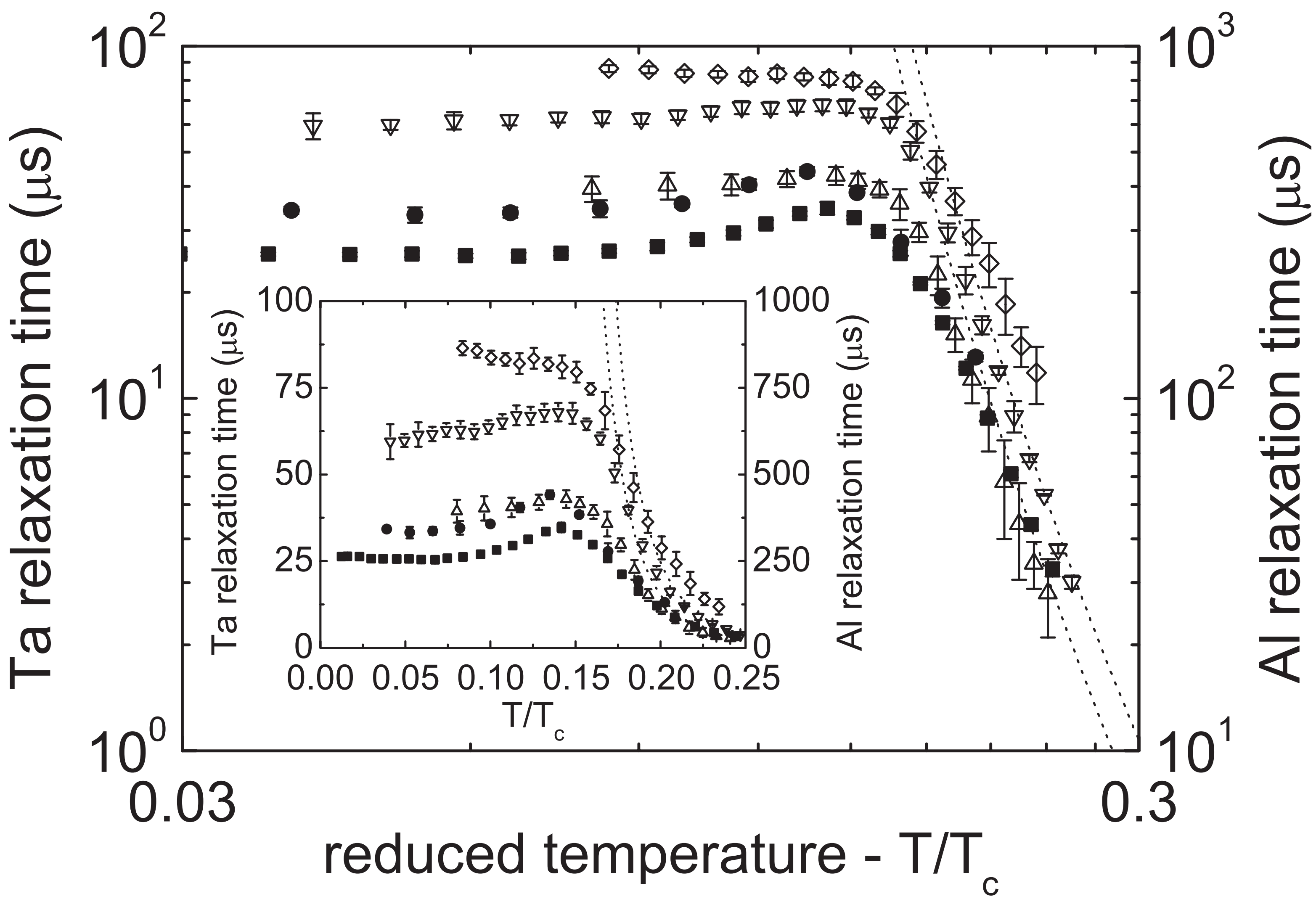
Quasiparticles "recombination" time:

$$\frac{1}{\tau_{\mathrm{rec}}} = \frac{1}{\tau_0}\sqrt{\pi}\left(\frac{2\Delta}{kT_c}\right)^{5/2}\sqrt{\frac{T}{T_c}}e^{-\Delta/kT}$$

for example, for 1µm of Al on sapphire τ_{rec}~1.5 µsec from J. Shnagl NIMA 444 (2000)245-248

Quasiparticles recombination time τ_R

$$\frac{1}{\tau_{\text{rec}}} = \frac{1}{\tau_0}\sqrt{\pi}\left(\frac{2\Delta}{kT_c}\right)^{5/2}\sqrt{\frac{T}{T_c}}e^{-\Delta/kT}$$

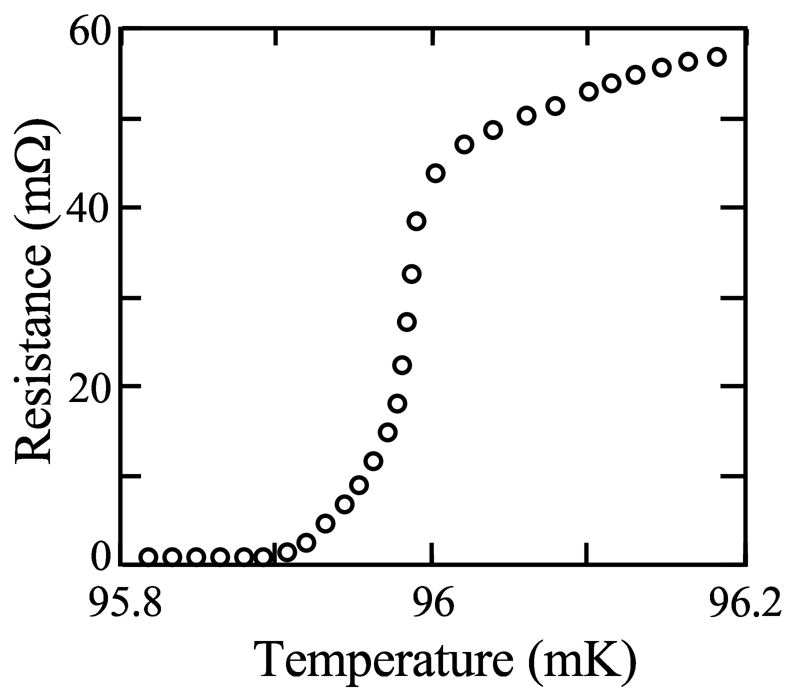


Film (substrate)	Thickness [nm]	τ_R [μsec]
Al(Si)*	100	390
Al(Si)*	250	600
$Al(Al_2O_3)$*	250	860
$Al(Al_2O_3)$**	1000	1530 +/- 350

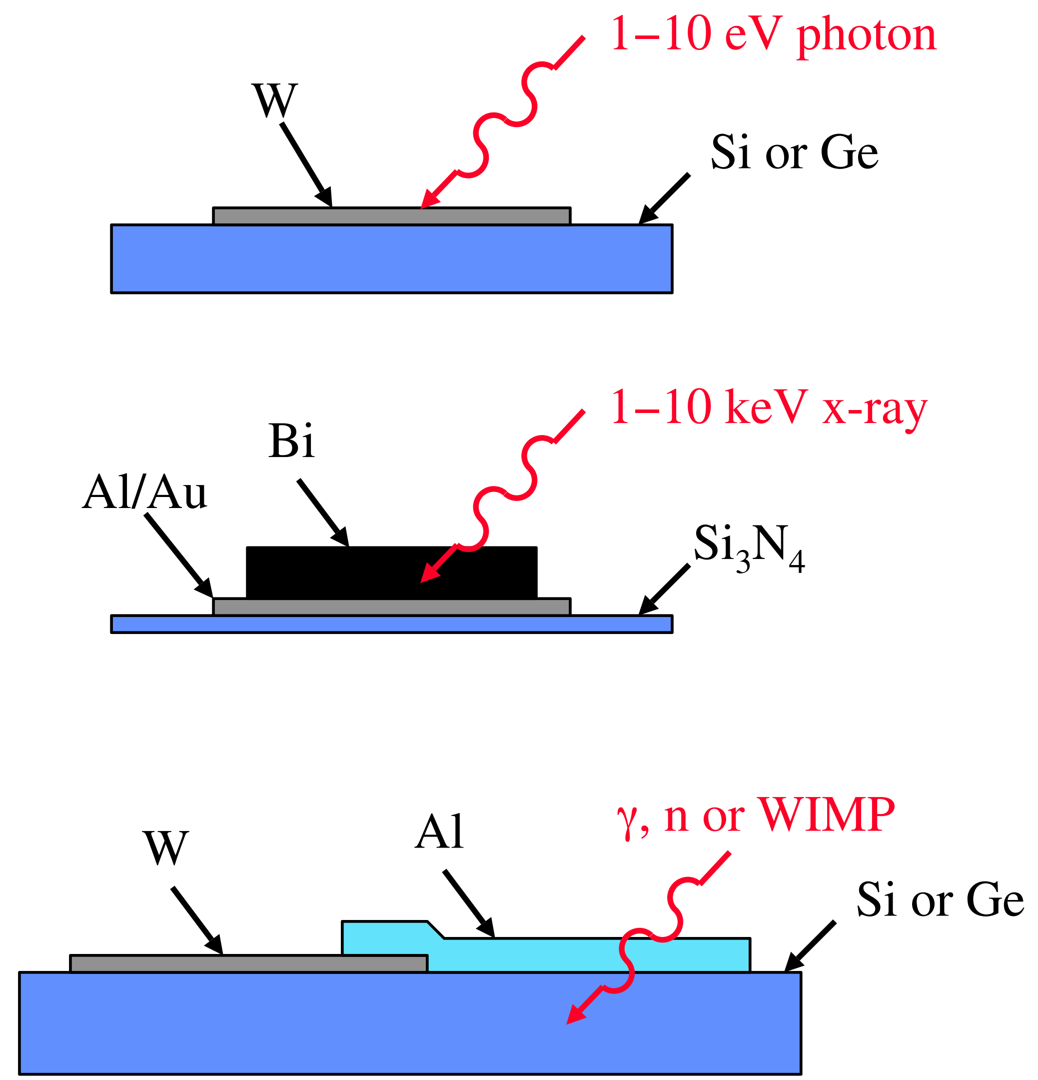
τ_R ~ √(thickness)
τ_R independent of Temp for T/Tc < 0.1
τ_R depends on substrate

* R. Barends et al. PRL 100, 257002(2008)
** J. Schnagl NIMA 444 (2000)245-248

Transition Edge Sensors



Topics Appl. Phys. 99, 63-149 (2005)



B. Cabrera, J. Low Temp. Phys. (2009) 151:82-93

$$\Delta E_{\mathrm{rms}} = \sigma_E \approx \sqrt{\frac{4k_B T^2 C_{\mathrm{tot}}}{\alpha}\sqrt{\frac{\beta + 1}{2}}},$$

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

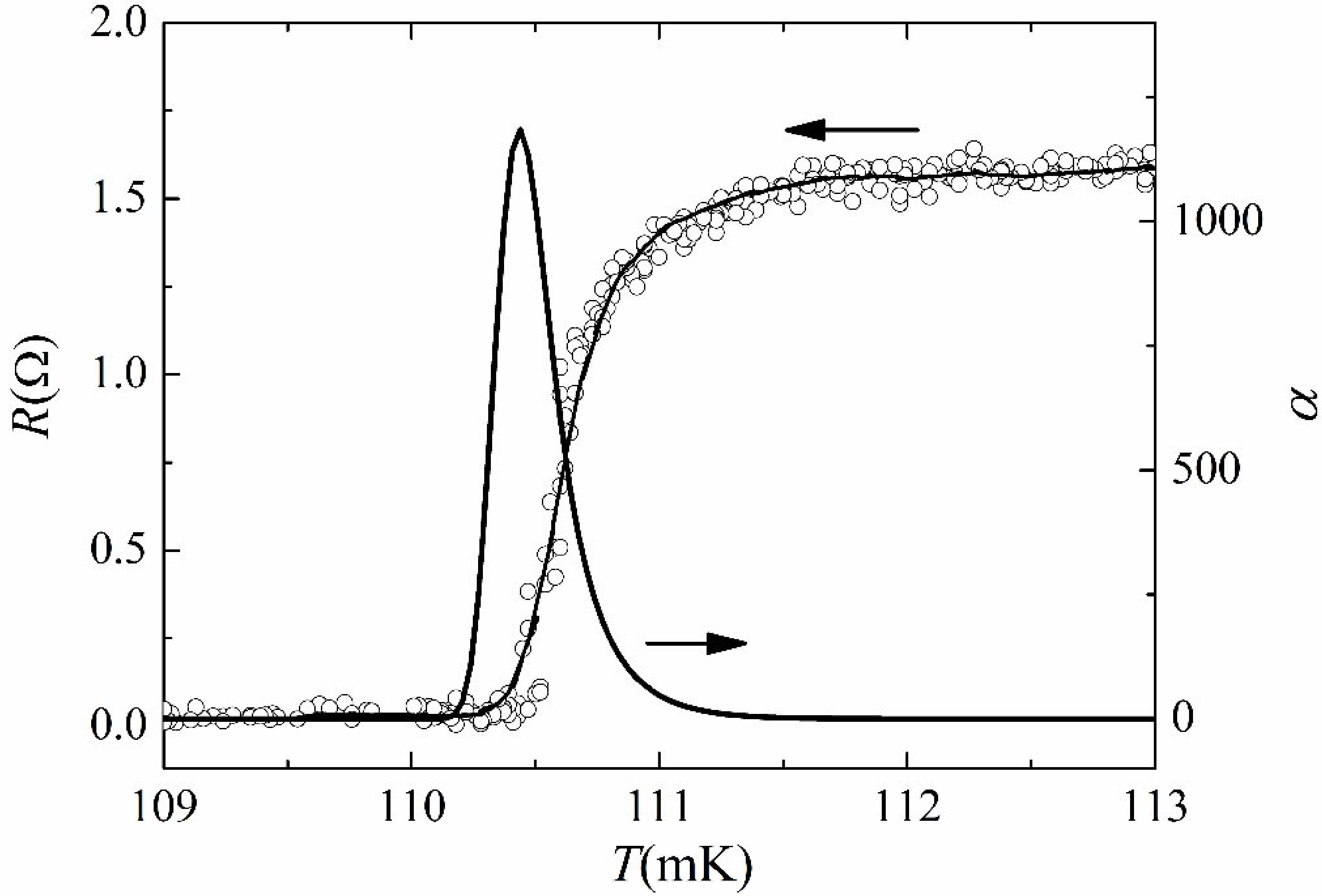
β: determined by thermal conductivity between the TES and absorber/heat-bath

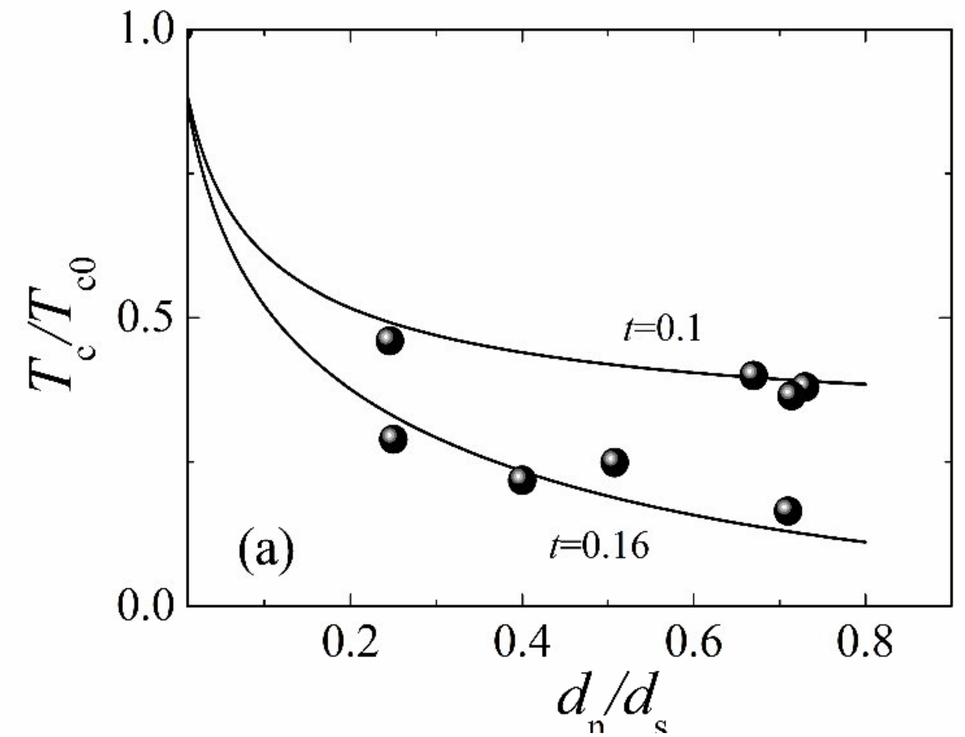
$C_{tot} = C_{bolo}$ ($\sim T^3$) + C_{TES} ($\sim T$) + C_{other} (e.g. caused by impurities in the crystal)

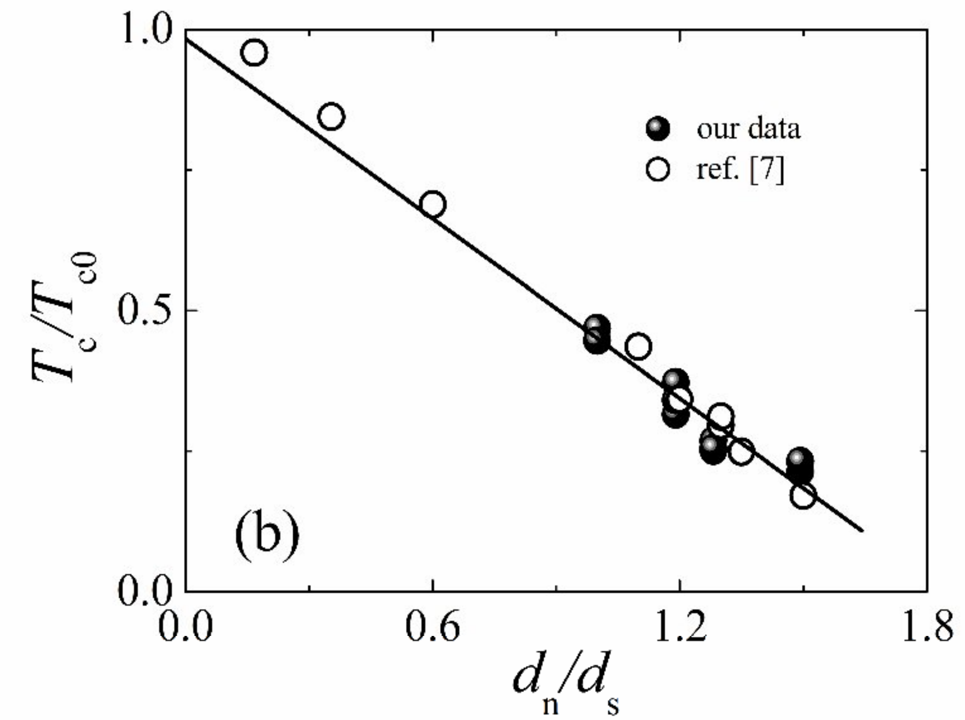
K.D. Irwin, Appl. Phys. Lett. Vol. 66, 1998 (1995)

Example of Ti/Pd bilayer TES

Journal of Physics: Conference Series **150** (2009) 052168







$$\Delta E_{\mathrm{rms}} = \sigma_E \approx \sqrt{\frac{4k_B T^2 C_{\mathrm{tot}}}{\alpha}\sqrt{\frac{\beta+1}{2}}},$$

K.D. Irwin, Appl. Phys. Lett. Vol. 66, 1998 (1995)

TES scalability and low Tc

Tc tunning through $^{56}Fe^{+}$ implantation

Large quantity (hundreds) production:

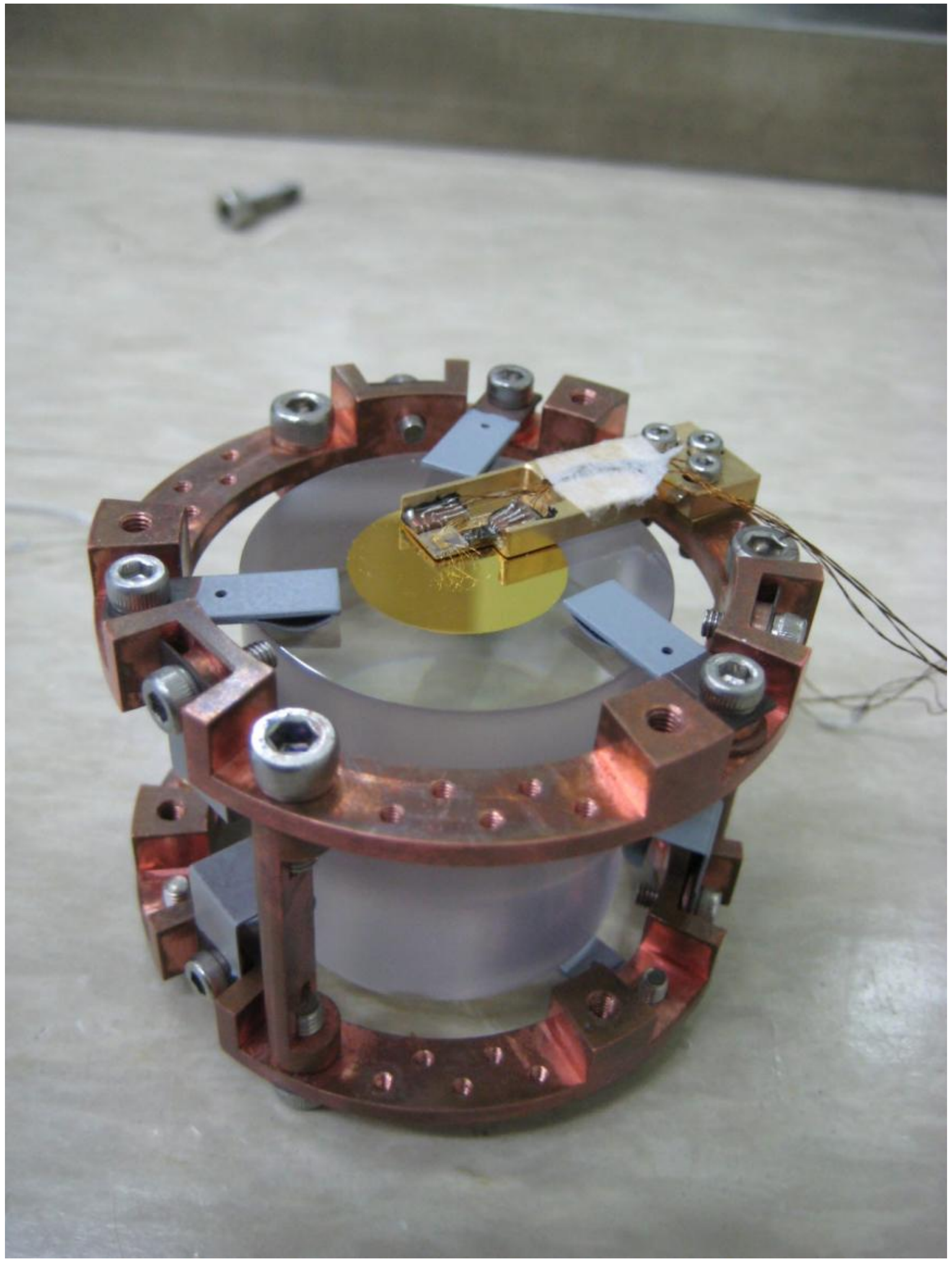
- Minimize # TES and SQUIDs on detector
- Simplify and tune thermal coupling TES/ crystal-absorber
- Could the TES sit on the thermal bath?
- SQUIDs can be readout in arrays al large as up to 10,000

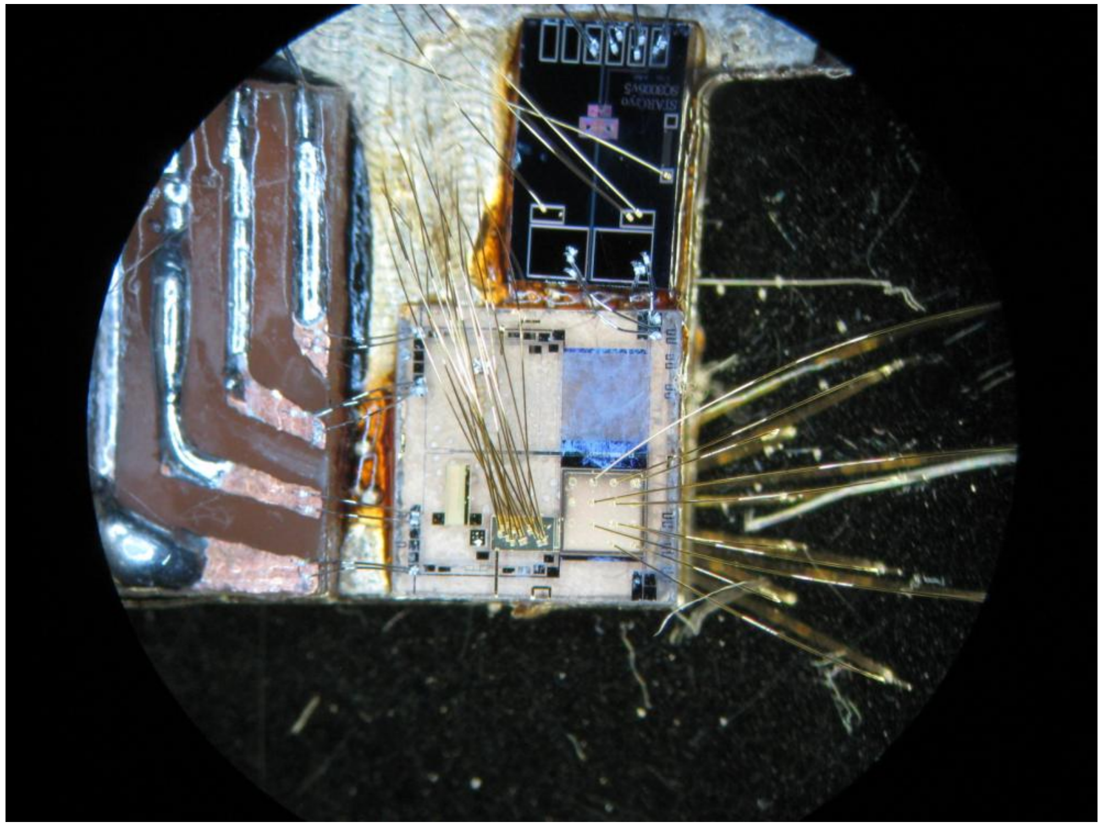
W-alpha phase for low Tc

Low Tc TES fabrication:

- CDMS W-TES through ion implantation, cryogenic testing
- CRESST W-alpha phase TES
- Or we can utilize superconducting bilayers as TES (proximity effect)

AMORE prototype from 2012: Au patch coupled via gold wires to a floating MMC - ***scalability***

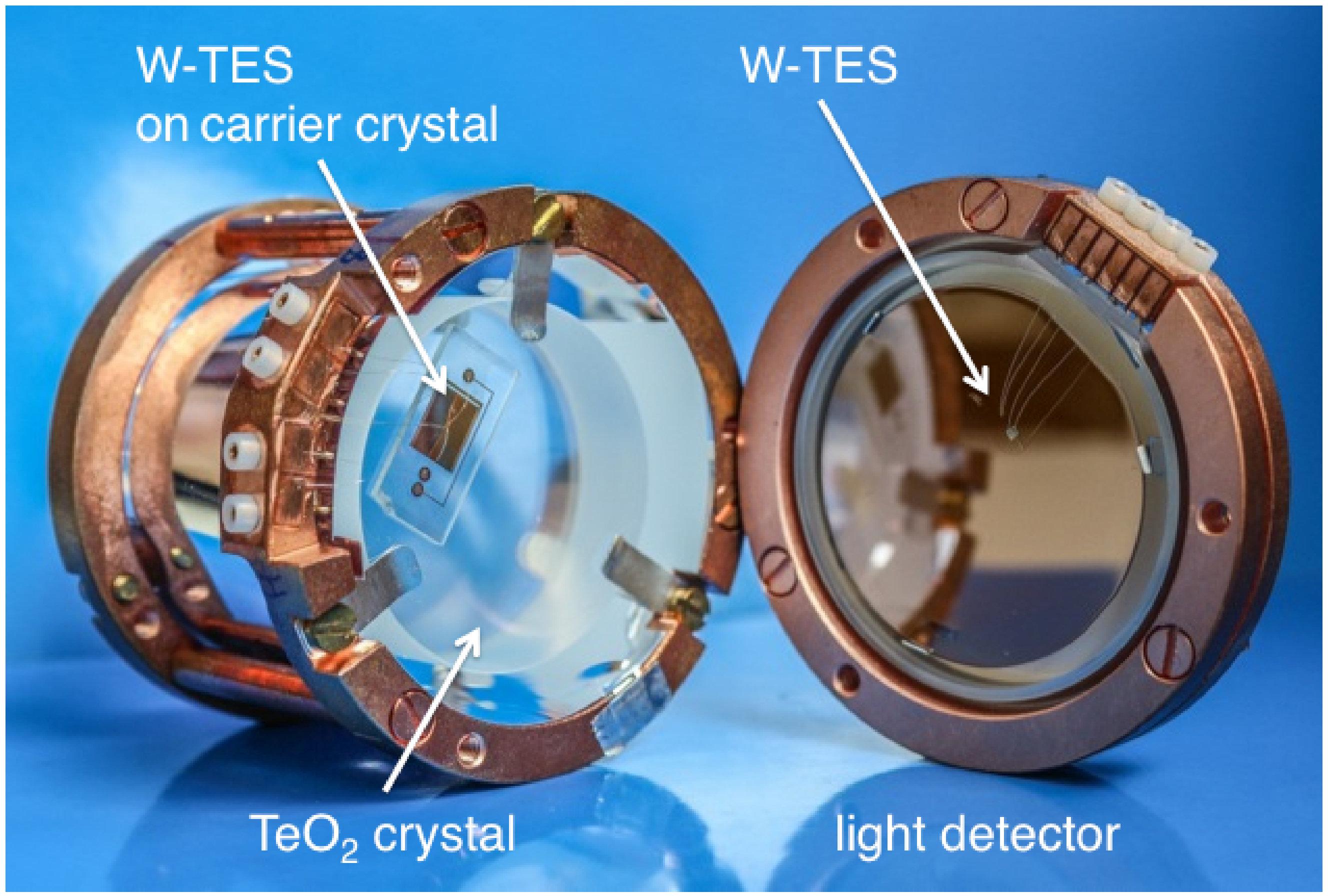




- 2cm diameter, 200nm thickness gold film is evaporated on the center of the crystal top surface.
- Meander chip is placed on the brass support and it is connected to the gold film by ~10 gold wires of 25um diameter.

For CUPID we need O(1000) channels

CRESST-II technology as Light Detector for TeO_2



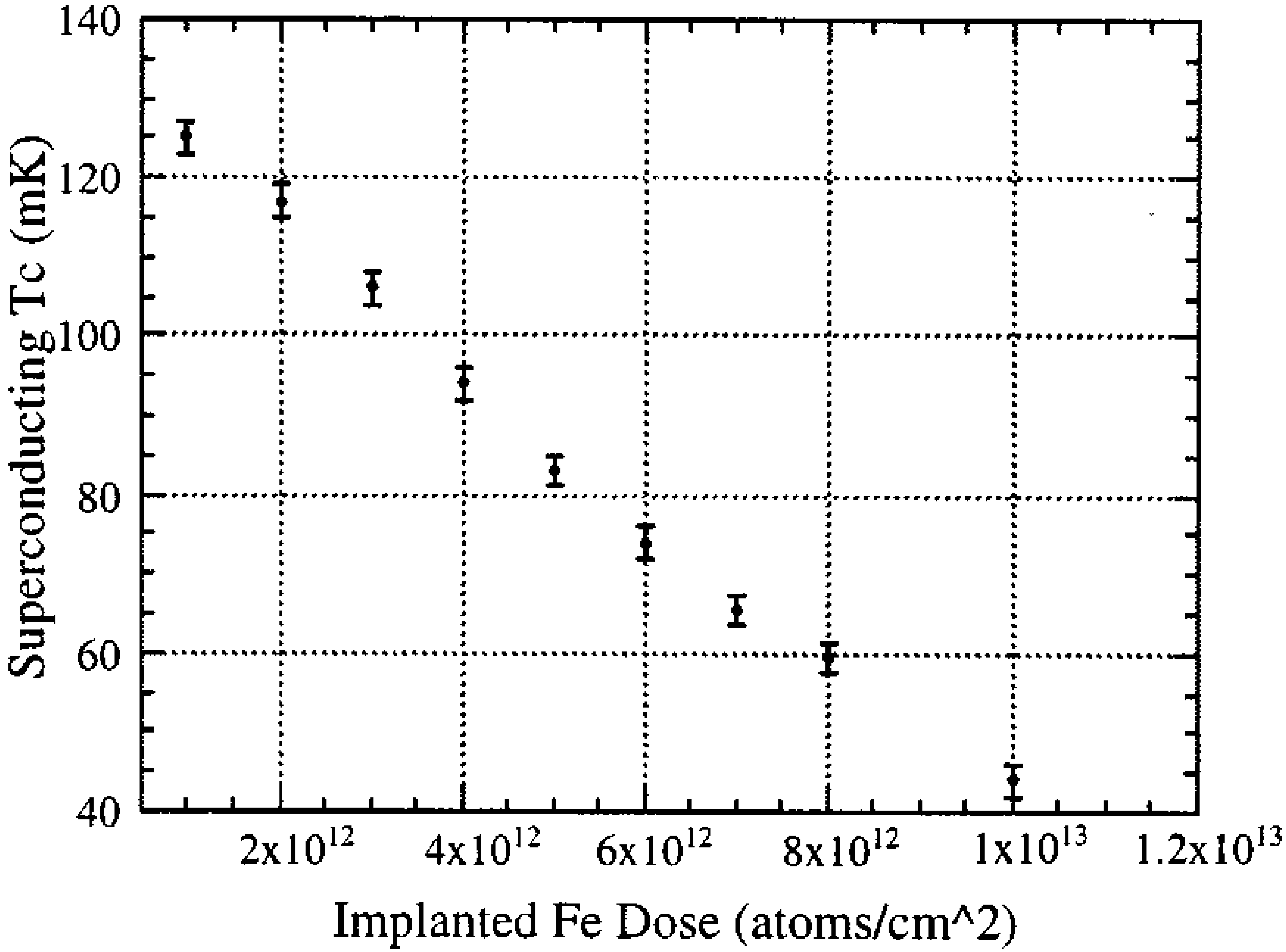
K. Schaffner et al. Astroparticle Physics (2015), pp. 30-36

- 280g TeO_2 crystal, 40mm diameter and height
- A small (20x10x2)mm3 CdWO4 carrier crystal, equipped with the W-TES was attached on one of the flat surfaces of the TeO2 by vacuum grease
- Light Detector CRESST-II type, saphire disc (Silicon on Saphire) readout by W-TES
- Light Detector reached RMS baseline σ=24eV, although CRESST-II has obtained σ=5eV

Absorber signal and sensor bandwidth mismatch minimization may improve energy resolution in this type of detectors as predicted by model in Pyle et al. arXiv:1503.01200

Tc tunning in W for TES applications in CDMS

J. Appl. Phys., Vol. 86, No. 12, 15 December 1999



Measured superconducting transition temperature for 350 A-thick W films implanted with Fe-56 ions at 50 keV kinetic energy

Tc calculation for a superconducting bilayer using Usadel model

NIM A Vol. 444 (2000) 23-27

For thin films:

$$T_C = T_{C0}\left[\frac{d_s}{d_0}\frac{1}{1.13(1+1/\alpha)}\frac{1}{t}\right]^{\alpha}$$

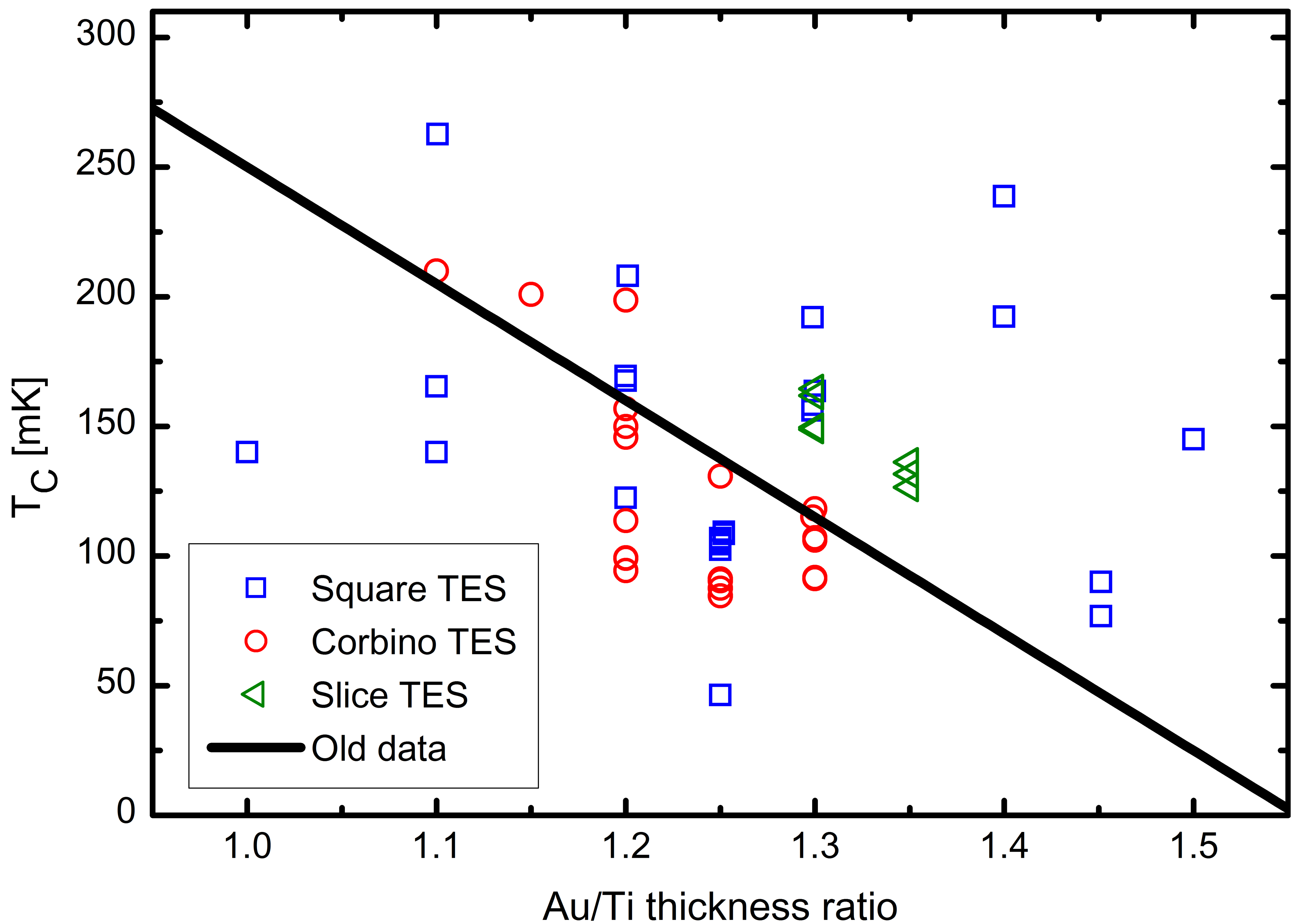
$$1/d_0 = (\pi/2)k_B T_{C0}\lambda_f^2 n_s$$

$$\alpha = d_n n_n / d_s n_s.$$

For a MoCu bilayer, d0=1.18 μm, nn/ns=0.431, λf=0.464nm.
From data they obtained t=0.21

Although experimentally is a very challenging task

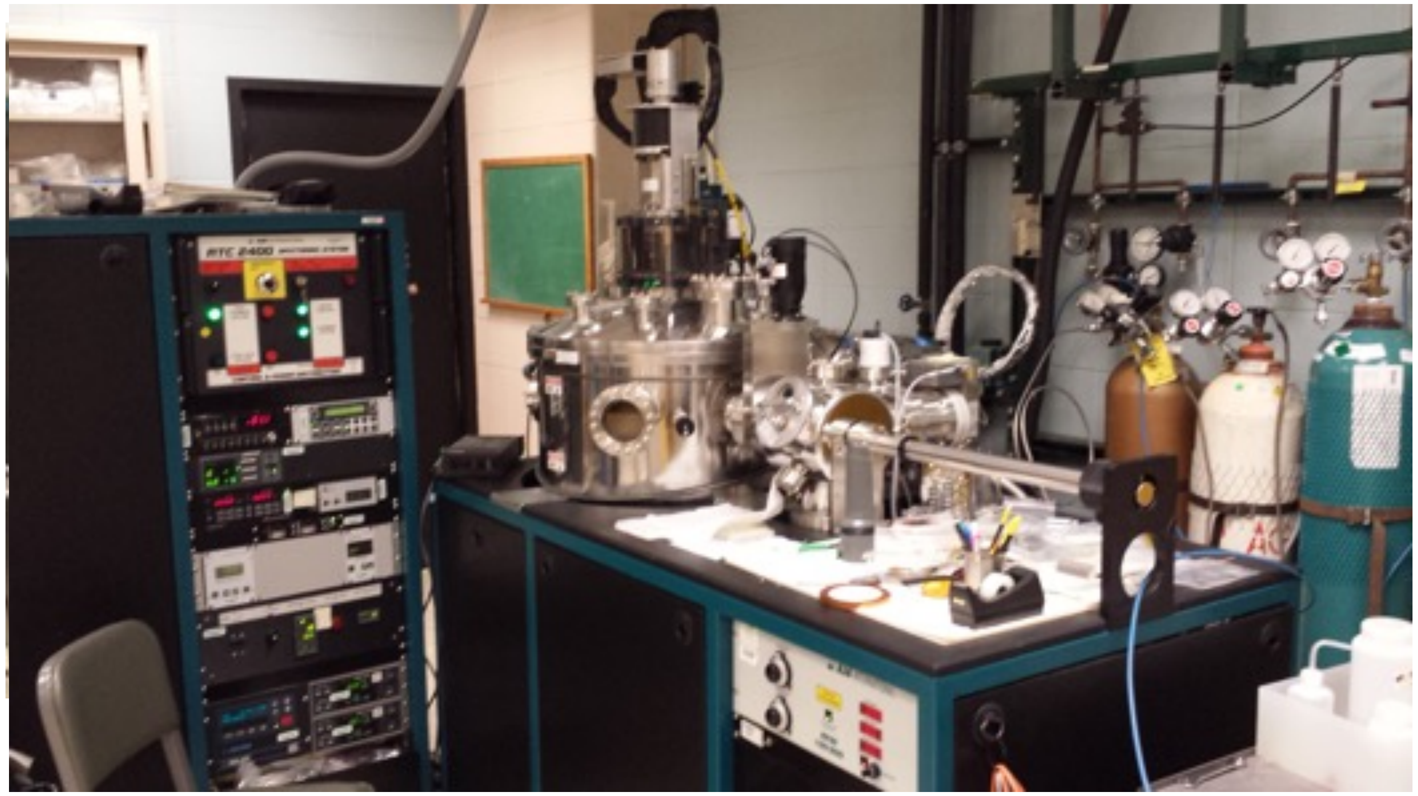
Kinnunnen PhD Thesis



Sample production at ANL and testing at Berkeley

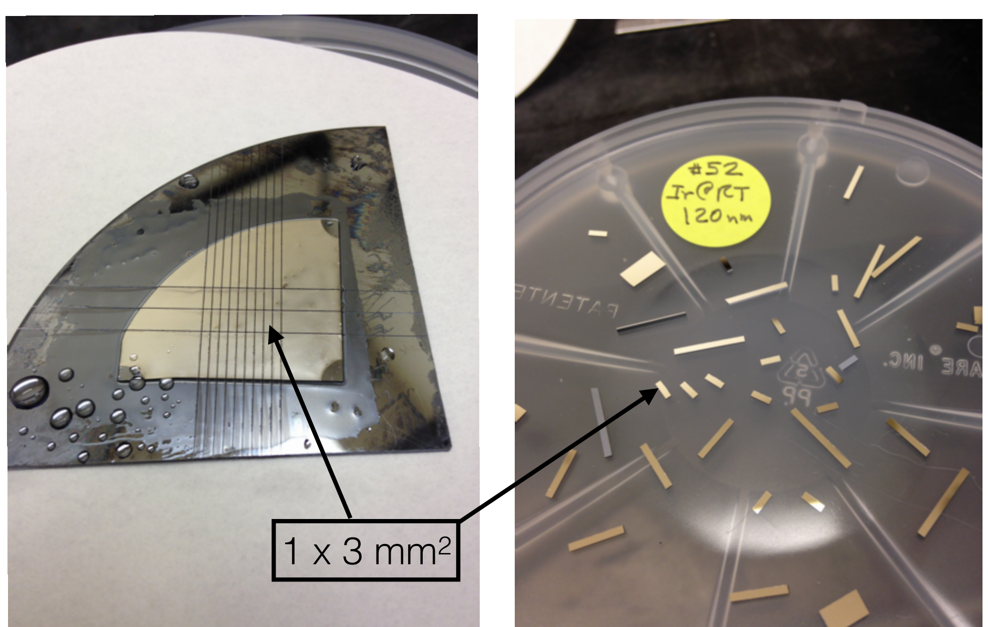
Collaborating at ANL with G. Wang, V. Novosad, V. Yefremenko and C. Chang

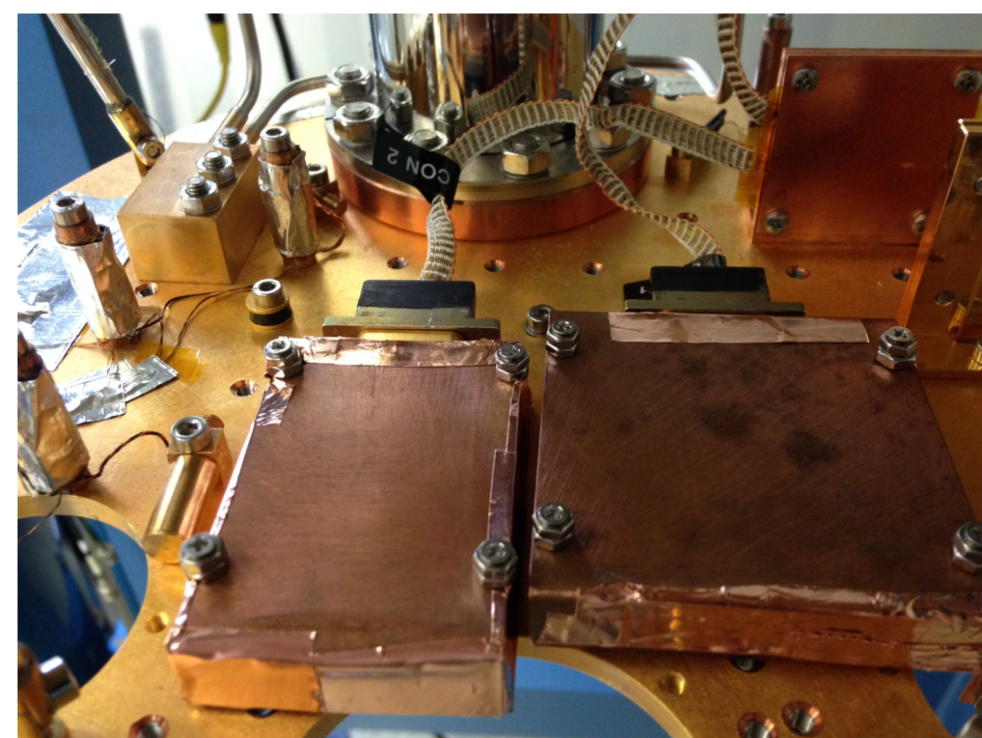
Cryogen free DR and Co-60 thermometry down to ~7mK



At ANL with sputtering chamber on the back

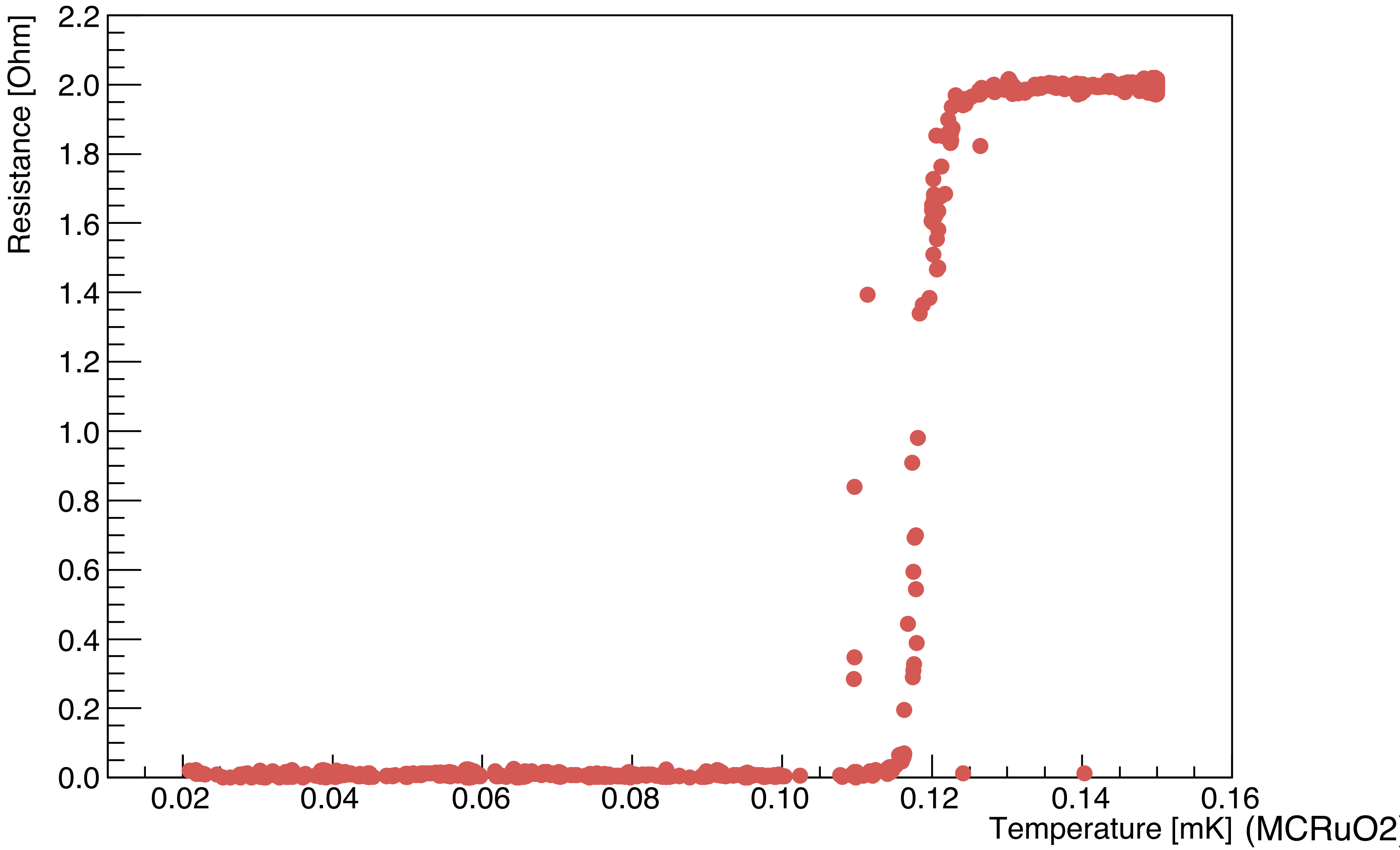
Iridium bilayers





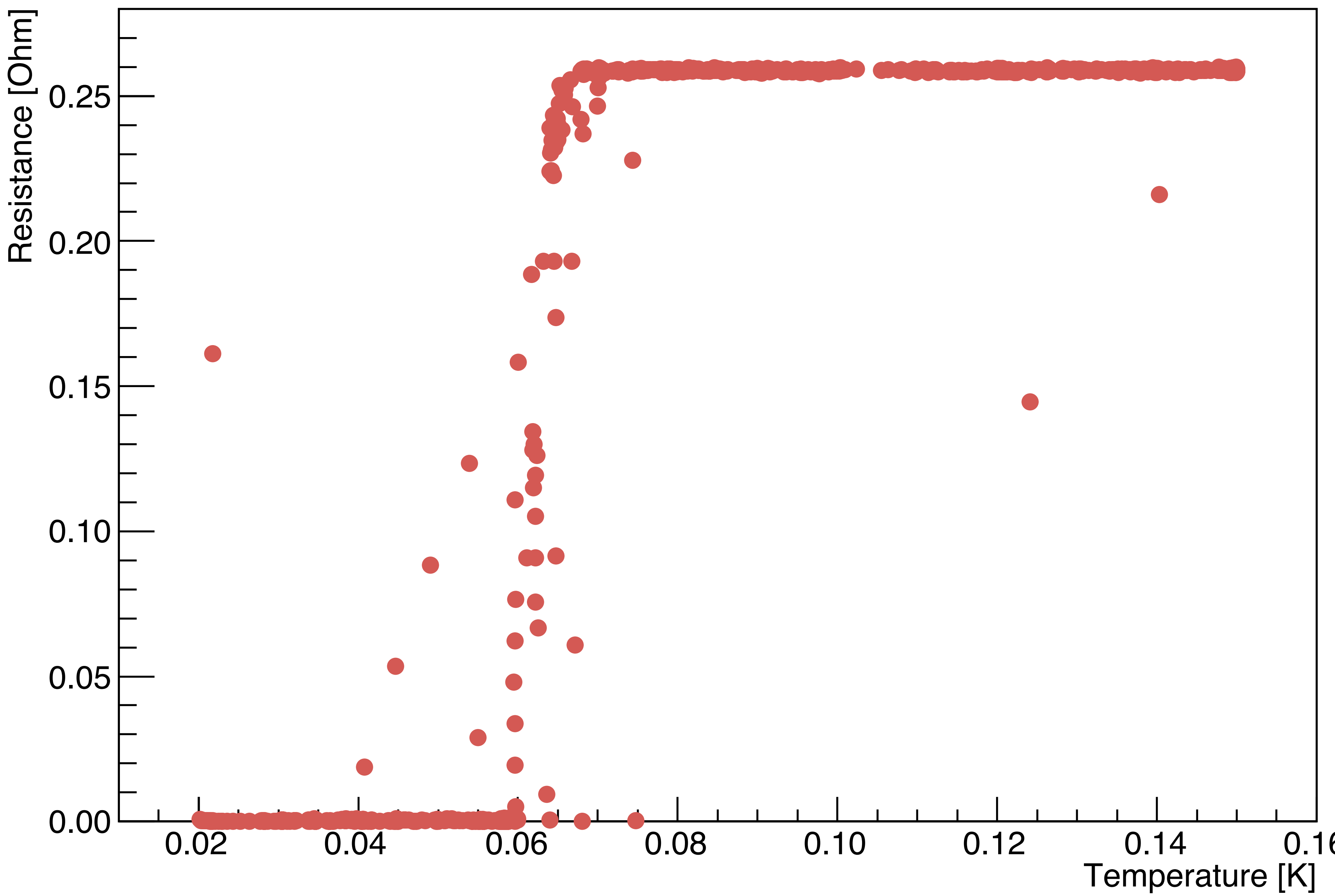
Ir at RT / Au
Ir = 80 nm
Au = 120 nm

T_C = 120 mK
Channel 07



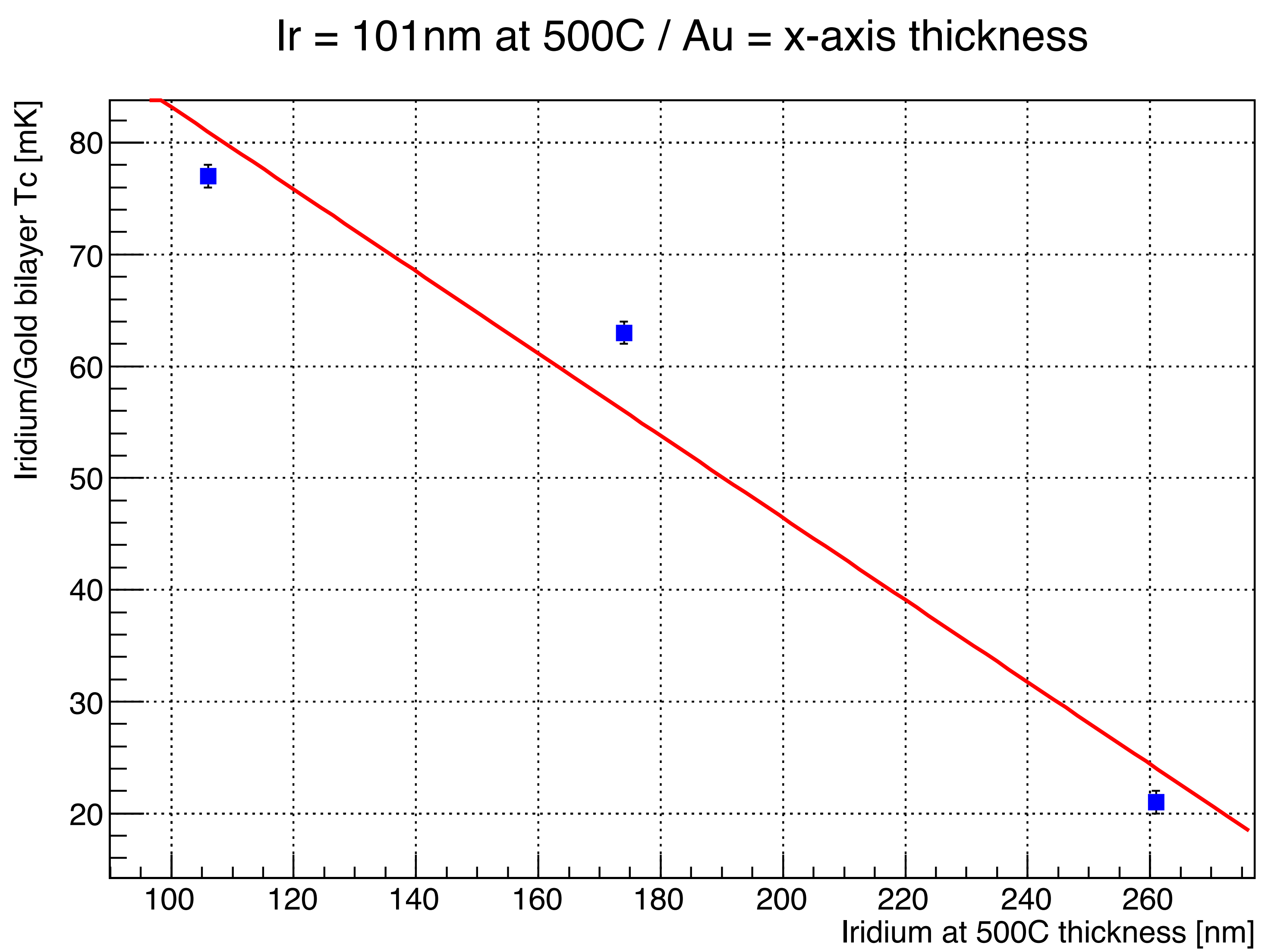
Ir at 600 °C / Au
Ir = 80 nm
Au = 120 nm

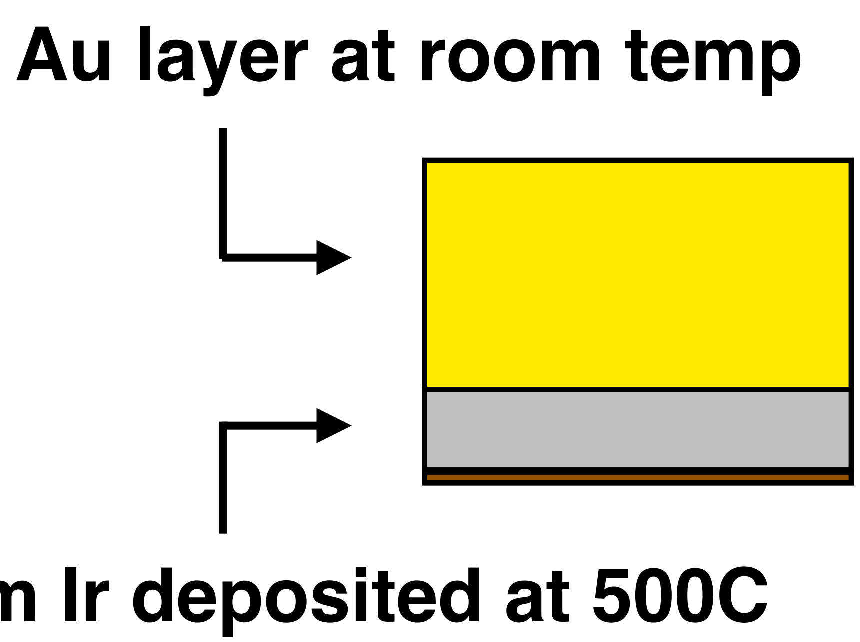
T_c = 60 mK
Channel 06



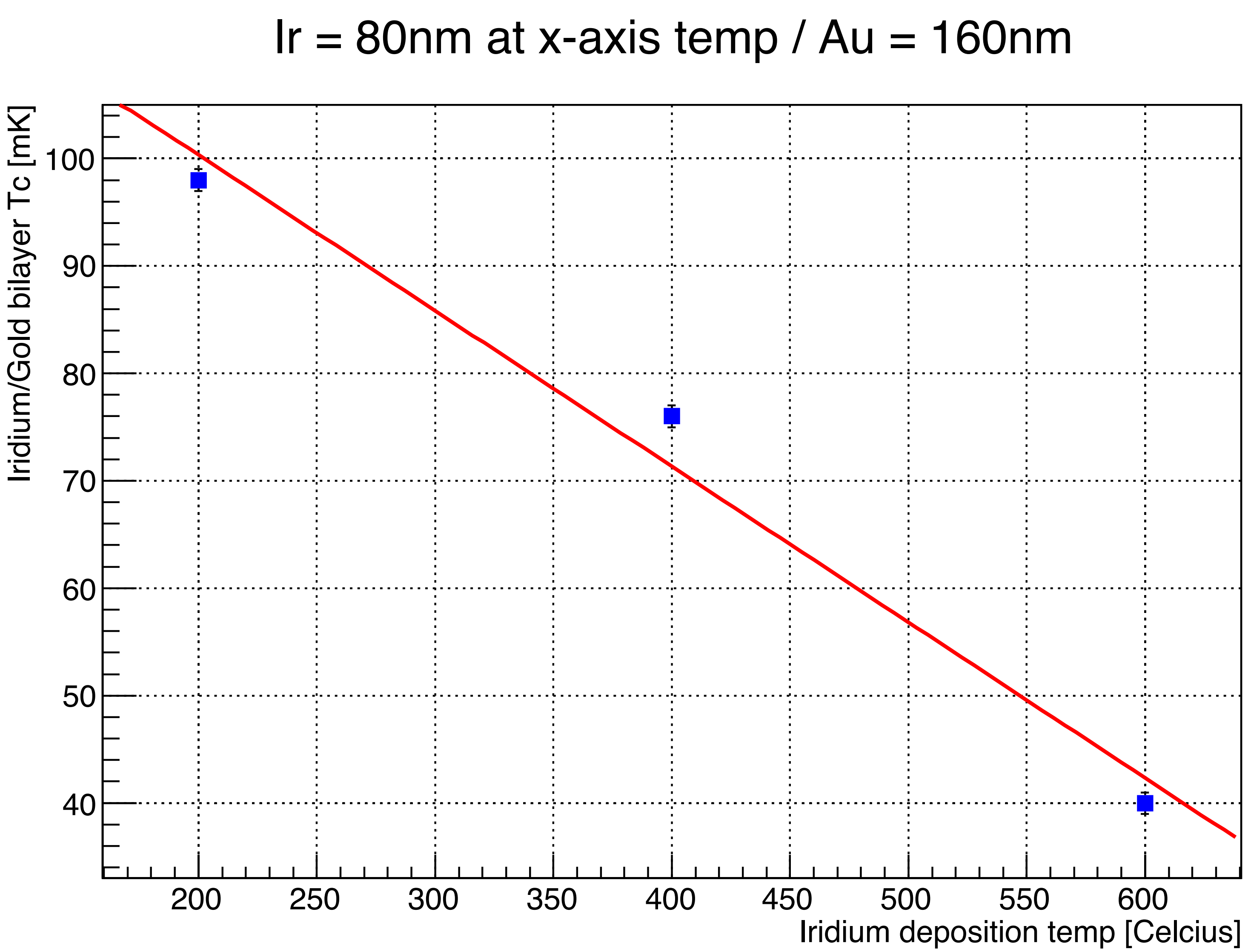
(MCRuO2)

Ir@500C/Au bilayer Tc as a function of Au thickness

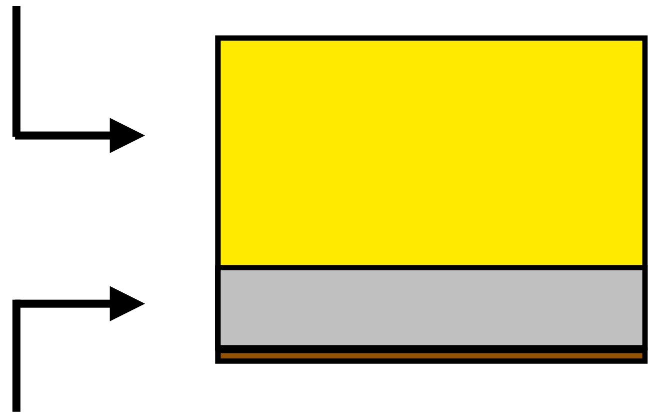




Ir/Au bilayer Tc as a function of Ir temp

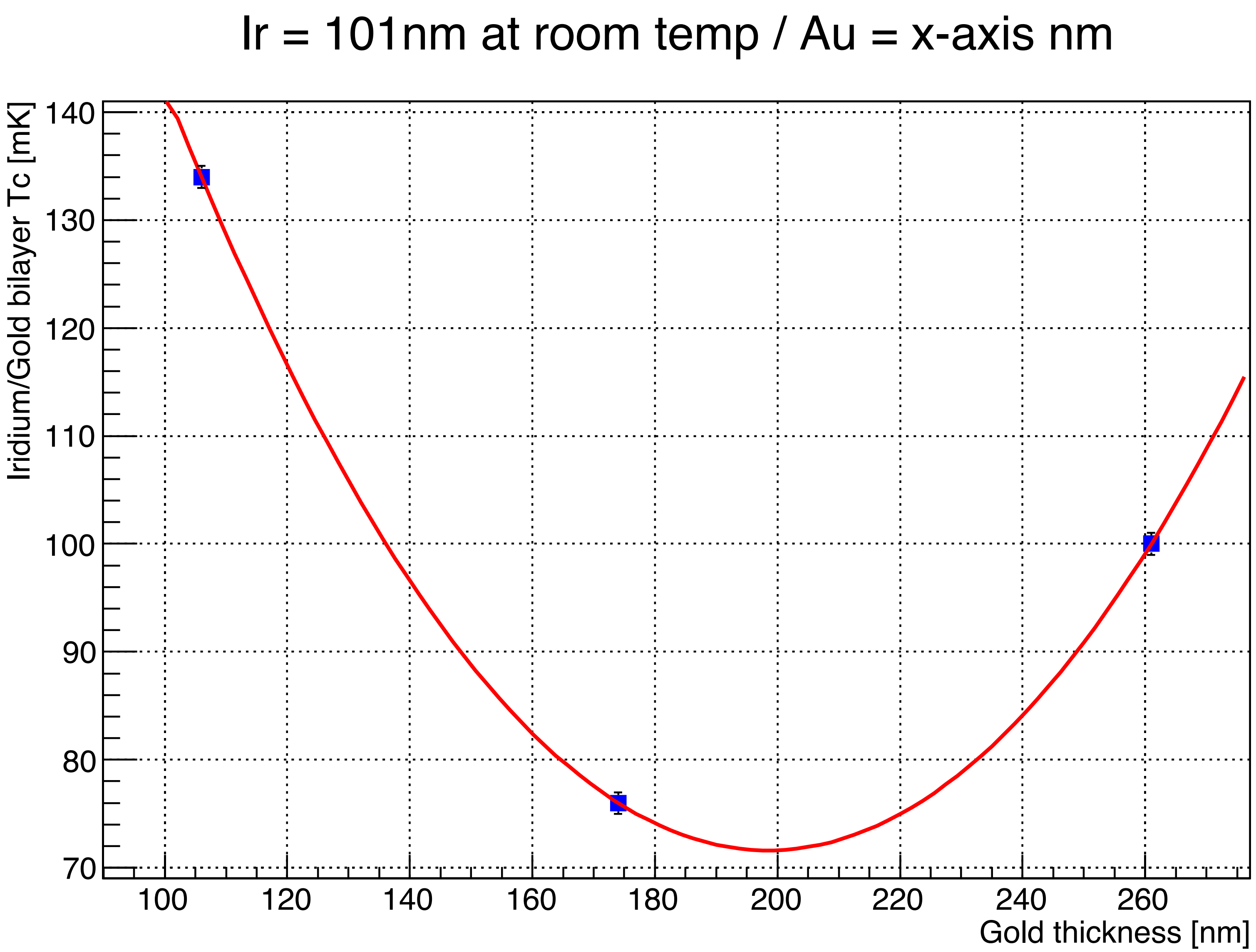


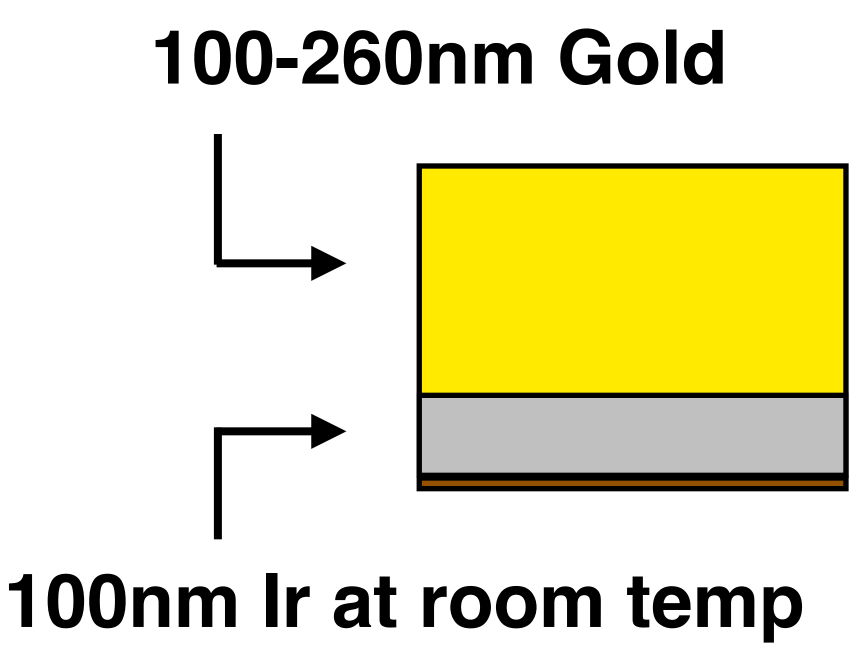
260nm Au at room temp



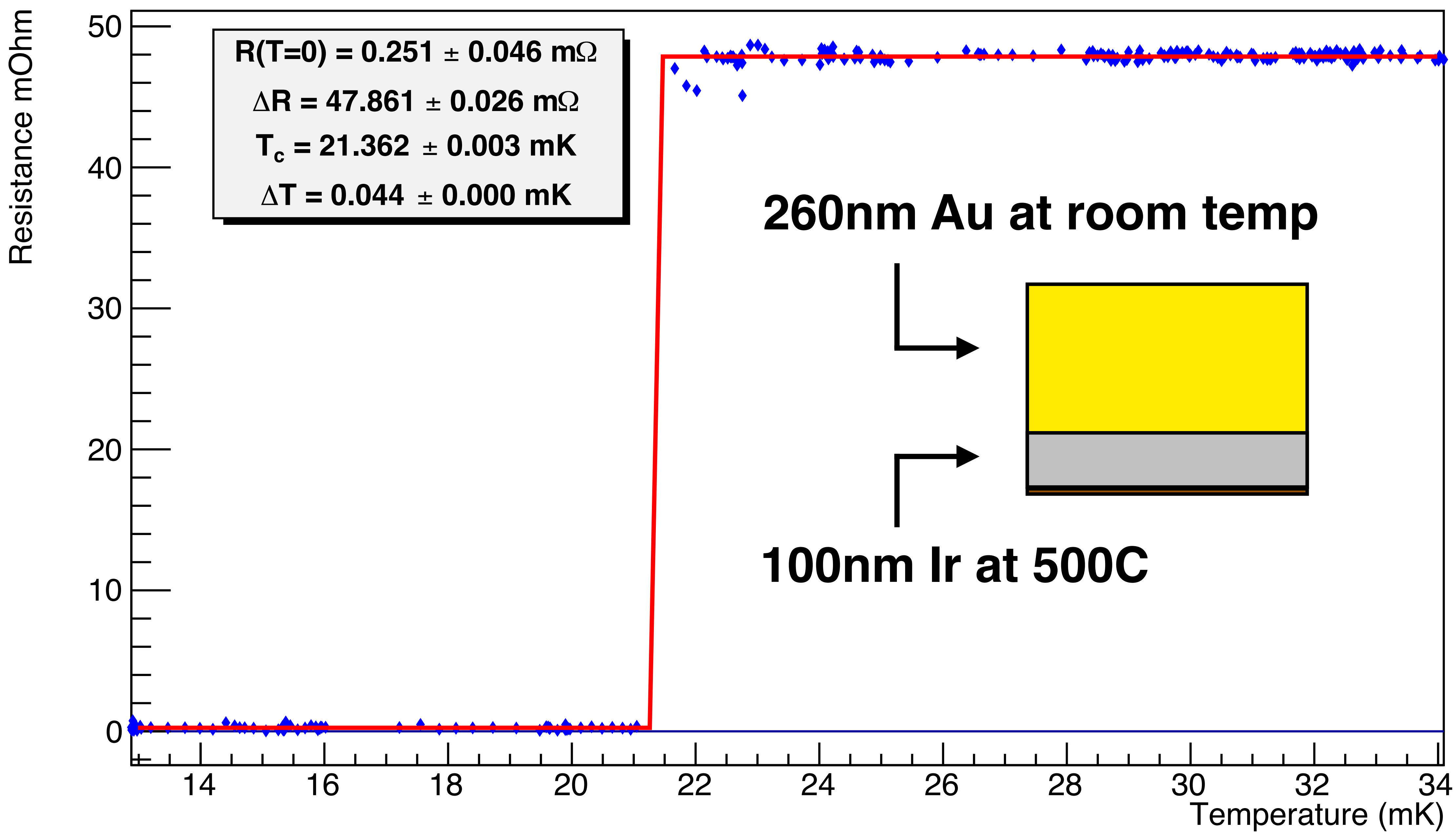
100nm Ir annealed at different temperatures

Ir/Au at Room Temperature was discarded



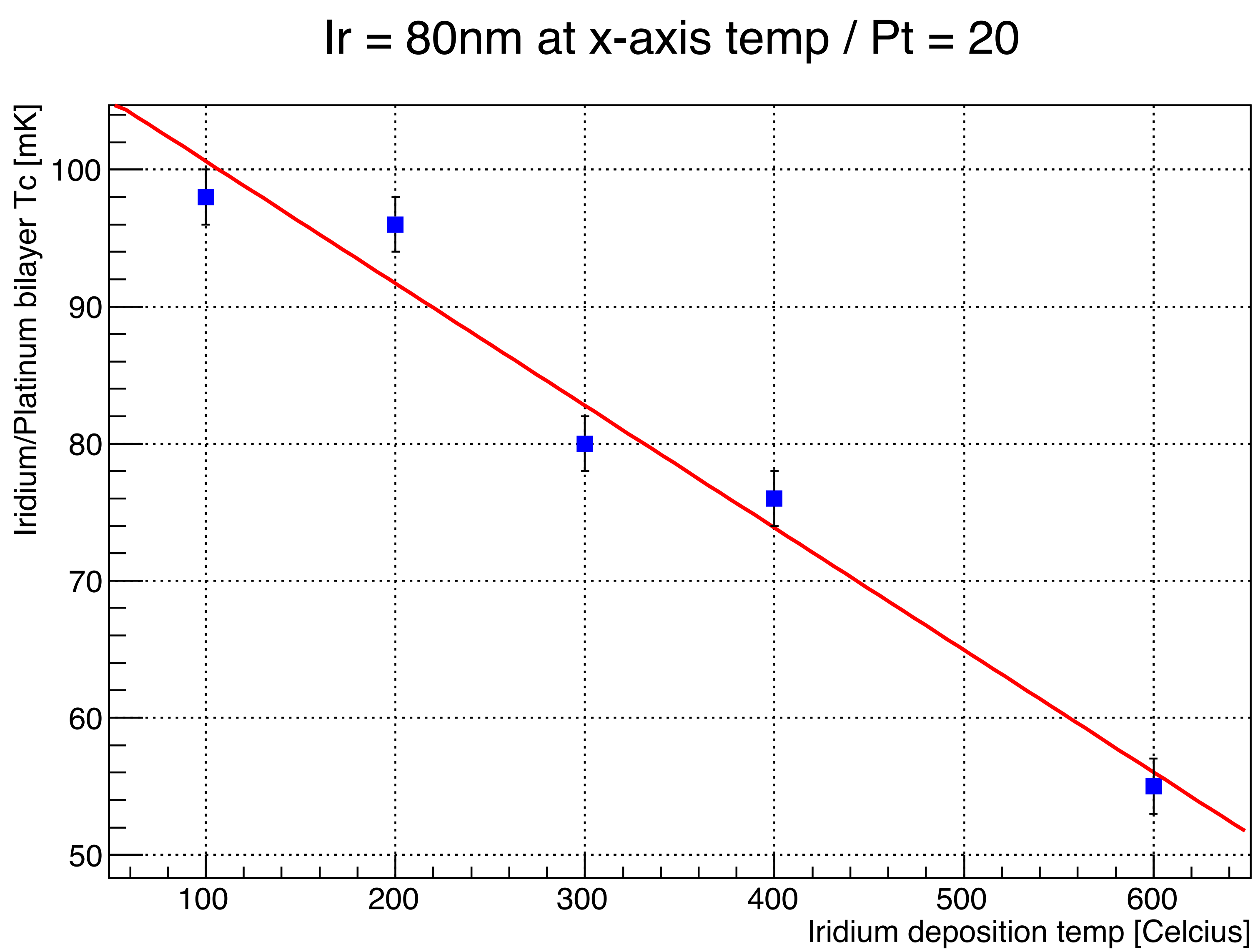


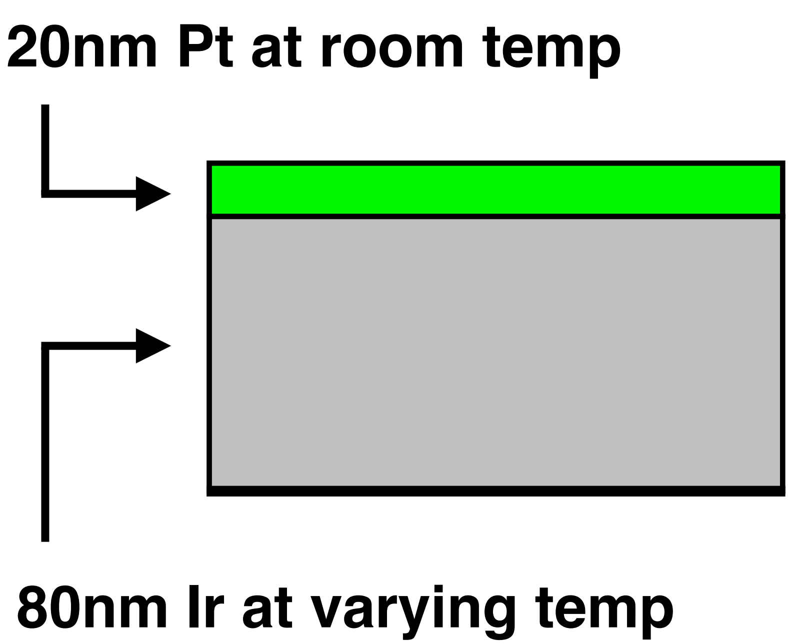
Our lowest **Ir/Au** bilayer Tc=21.4 mK



A promising new bilayer for Low Tc TES: **Ir/Pt**

Tc dependence on Iridium deposition temperature for an Ir/Pt

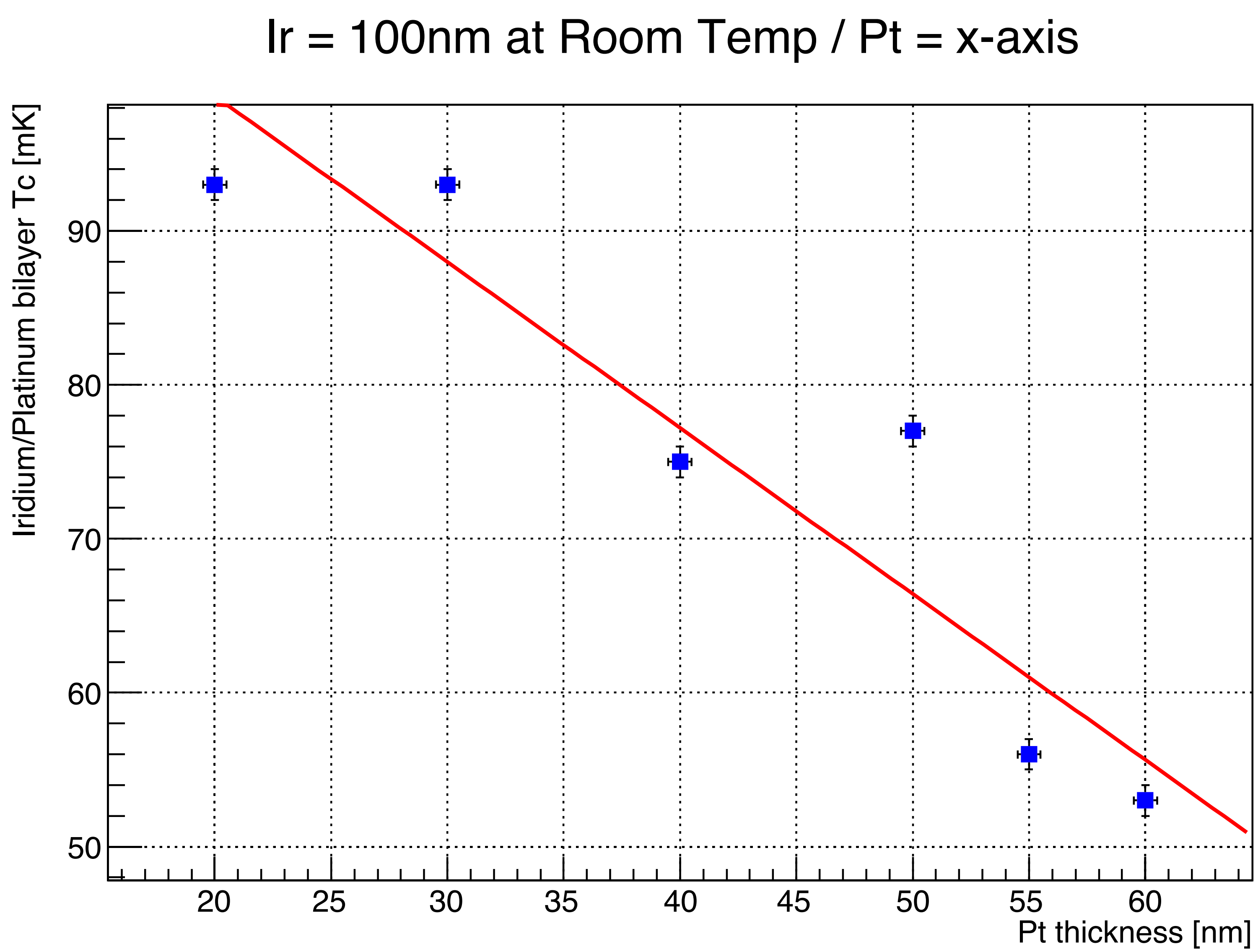


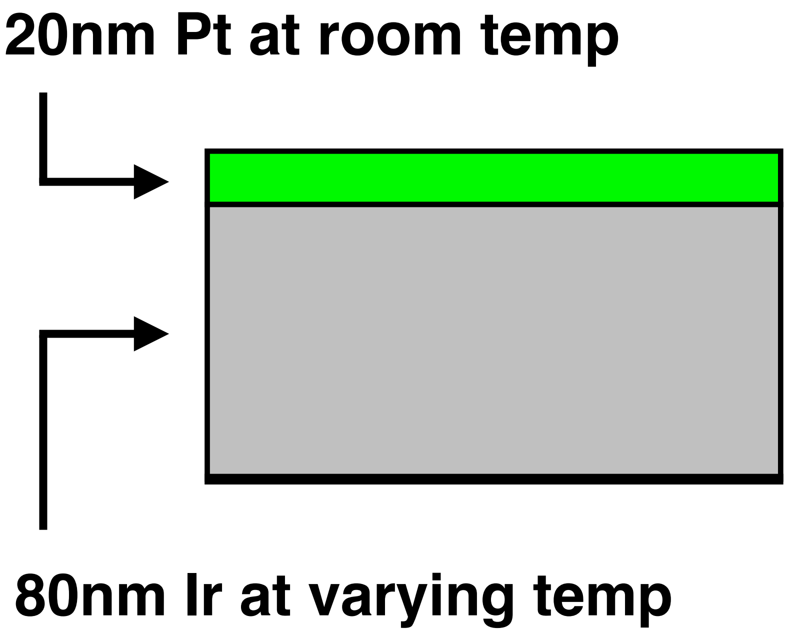


Normal resistance ~10x of IrAu for same Tc

Ir/Pt at room temperature

Tc dependence on Platinum thickness





Room tempearature deposition of TES would make application to large crystals possible

Summary

- TES technology for Double Beta Decay may be applicable in order to improve energy resolution and reduce backgrounds
- TES as light detectors for macro-bolometers in large quantities O(1000) remains to be demonstrated for the future of double beta decay with bolometers
- Low Tc material for TES with fast fabrication time may be achievable utilizing Iridium/Gold and Iridium/Platinum
- Ir/Au only works if we heat Ir and let it anneal to room temperature before depositing Au at room temperature
- We have found a new promising bilayer, Ir/Pt that works both with Ir annealing and at room temperature. It also shows large R(normal) compared to Ir/Au (~10x).
- Large Tc suppression (reproducibility) remains an issue without dedicated film deposition chambers
- SQUID multiplexing may be required, although the channel number has been already accomplished by other experiments in CMB community