CPAD 2021

LOW-TC TES AS SENSORS FOR FUNDAMENTAL PHYSICS

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U.S. DEPARTMENT OF ENERGY

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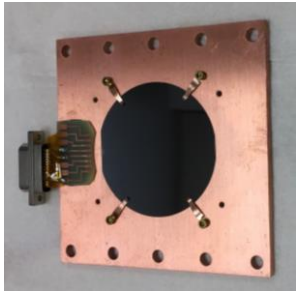
CONTENT

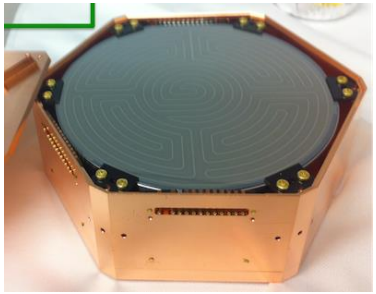
- Low-Tc TES motivations (ANL)
- Neutrinoless double beta decay (CUORE/CUPID)
- Large area light detector for $0\nu\beta\beta$ experiment (CUPID)
  - Design/modeling/testing
  - Low-Tc IrPt films
  - Thermal characterization of IrPt TES devices

LOW-TC TES @ ANL

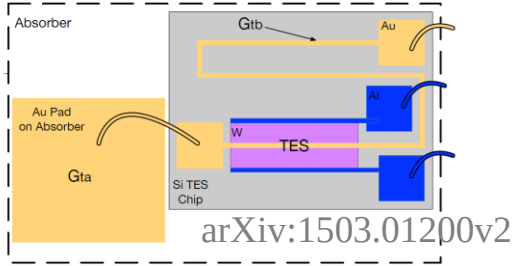
- Neutrinoless double beta decay ($0\nu\beta\beta$)
  - Large area thermal light detector for CUPID



- Low mass dark matter
  - CDMS style athermal phonon detector

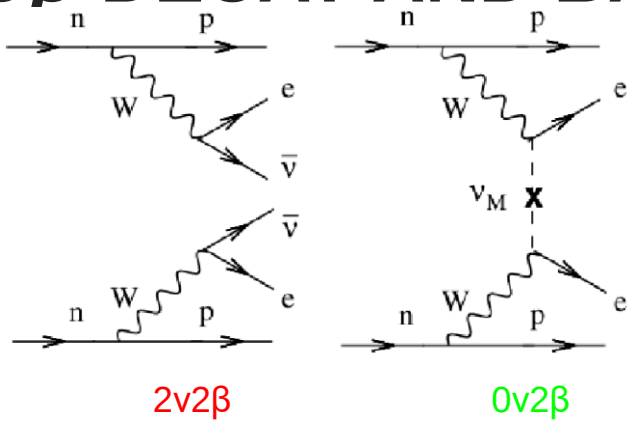


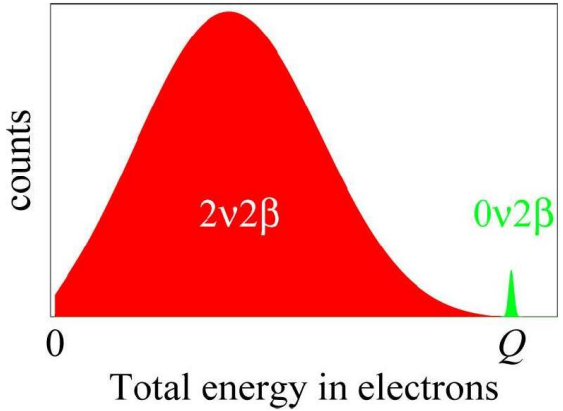
- Coherent neutrino nucleus scattering
  - Attachable TES sensor chip



arXiv:1503.01200v2

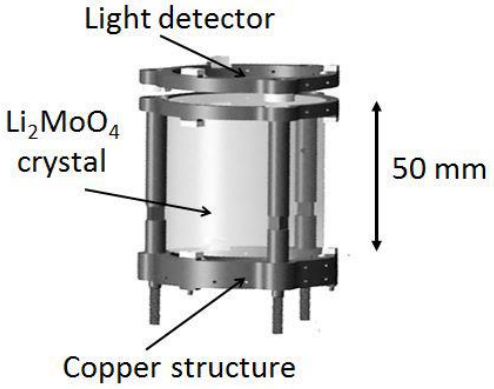
$0\nu\beta\beta$ DECAY AND BACKGROUND



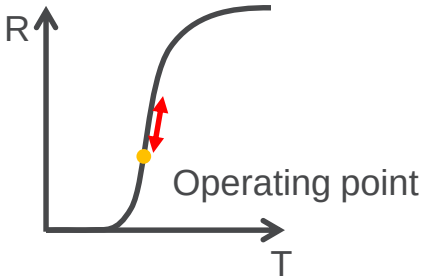


- $(A,Z) \rightarrow (A,Z+2) + 2e + 2\overline{\nu_e}$: 2ν2β
  - Ge, Se, Mo, Te, Xe, …
  - ^{100}Mo $T_{1/2}$ > 7.1×10^{18} yr (90% CL) (NEMO-3)
- $(A,Z) \rightarrow (A,Z+2) + 2e$: 0ν2β
  - Never observed
  - ^{100}Mo $T_{1/2}$ > 1.1×10^{24} yr (90% CL) (NEMO-3)
- Physics of 0ν2β decay
  - Nature of neutrino mass, Dirac or Majorana
  - Absolute neutrino mass scale
- Backgrounds
  - Partially contained alphas are the dominant background for CUORE
  - ^{100}Mo 2ν2β pileups for CUPID

LD FOR CUPID BACKGROUND REJECTION



CUPID detector concept

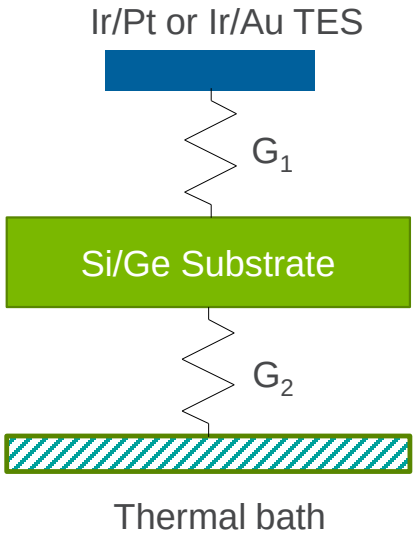


TES electrothermal feedback

- CUPID (CUORE Upgrade with Particle ID) detector
  - Sensitive thermometer (NTD/TES) on Li_2MoO_4 for heat signal
  - Light detector for scintillation light, enabling event-by-event background rejection
  - Li_2MoO_4: ~3 keV scintillation light, 100 eV baseline resolution and O(10) μs timing resolution to reject 2ν2β pileups
  - (TeO_2: 20 eV baseline resolution to reject alphas)

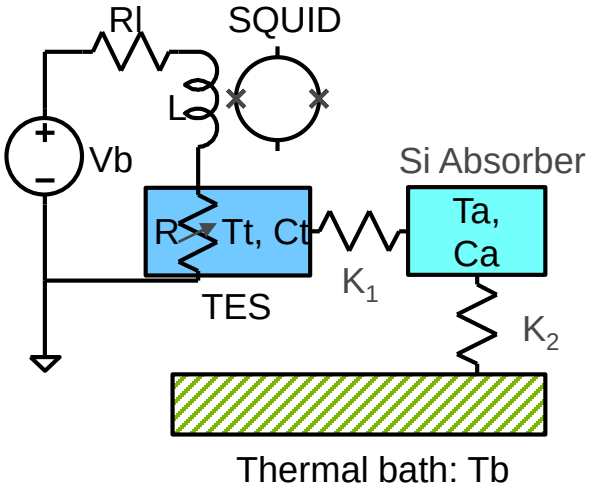
- Transition Edge Sensors (TES) LDs are an excellent choice
  - High energy resolution → Low T_c
  - Fast response time → Negative electrothermal feedback
  - Large scale multiplexing

PATH TO A LOW T_C TES LIGHT DETECTOR



- Low T_c Superconducting films: Ir/Pt or Ir/Au bilayers, T_c tunable between 20-110 mK.
- Light absorber: 2” Si/Ge wafer
- Detector dynamics modeled with TES physics
- Fabrication at ANL, characterization at ANL and UCB

DETECTOR MODELING



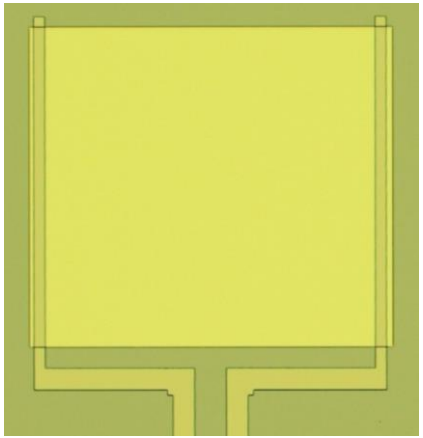
$$C_t \frac{dT_t}{dt} = I^2 R(T_t, I) - K_1(T_t^n - T_a^n)$$

$$C_a \frac{dT_a}{dt} = K_1(T_t^n - T_a^n) - K_2(T_a^m - T_b^m)$$

$$L \frac{dI}{dt} = V_b - IR(T_t, I) - IR_l$$

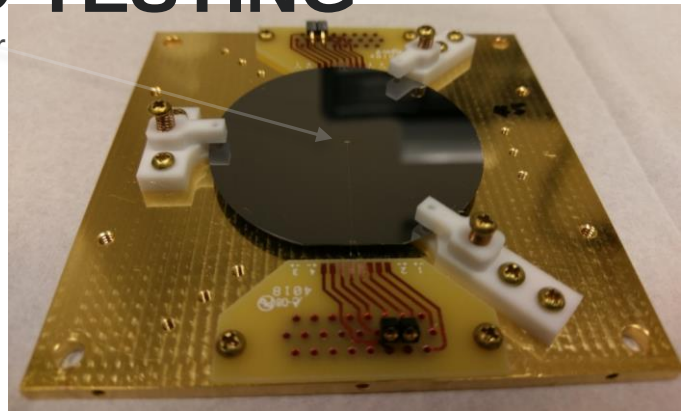
- Detector modeled with established TES physics
  - TES resistance $R(T, I)$ constrained by two fluid model
  - Measured parameter values fed into the model
- Preferred T_c range 40-60 mK
- E-ph coupling needs to be strengthened to improve detector responsivity
- Wafer-bath thermal conductance needs to be carefully engineered

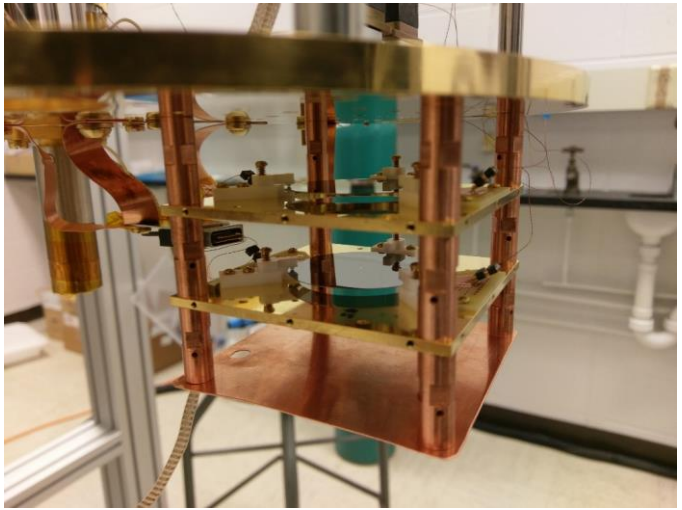
DETECTOR FABRICATION AND TESTING



300 um x 300 um
50 nm Pt/100 nm Ir TES
and Nb leads

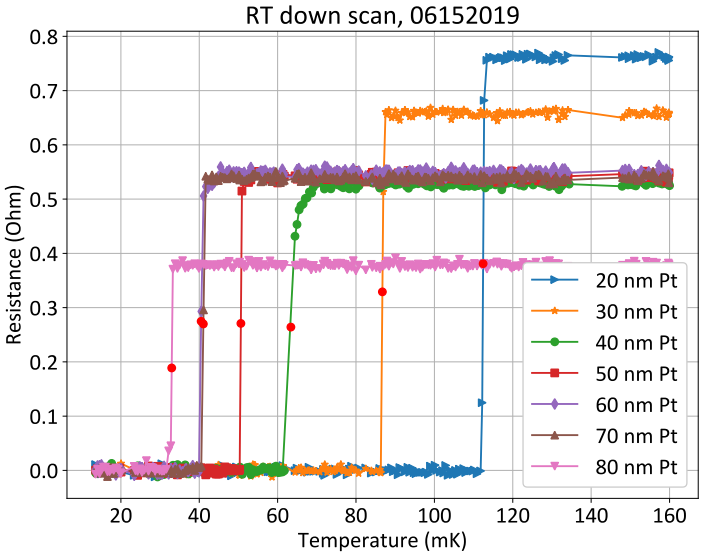
TES in the center





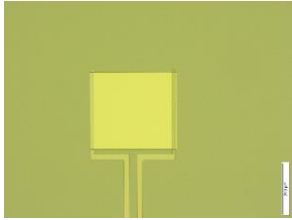
- Detector fabrication at ANL
- Detector testing at ANL and UCB
  - Dilution refrigerators with sub 10 mK base temperature
  - ANL: Tc, IV, time constants, complex impedance, and X-ray calibration
  - UCB DR additionally quipped with optical fibers

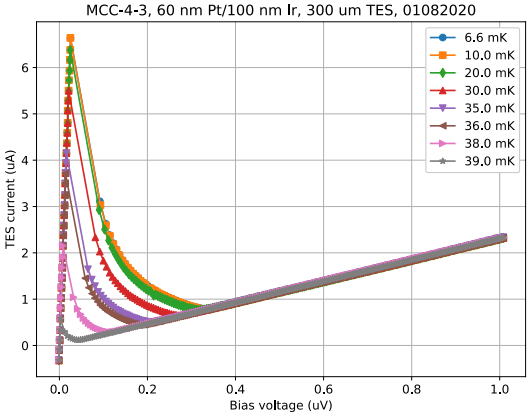
FILM T_C TUNING

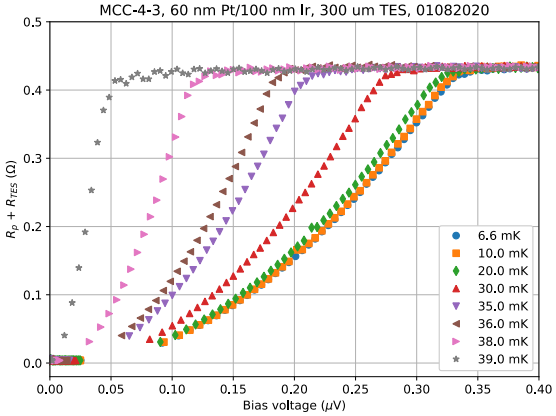


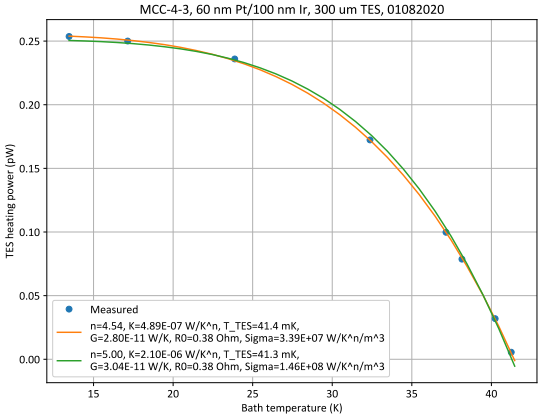
- T_c tuning using proximity effect between Ir and Pt/Au
- T_c range 20-110 mK demonstrated with Ir/Pt bilayers and Au/Ir/Au trilayers
- Good T_c repeatability demonstrated

E-Ph COUPLING IN IrPt



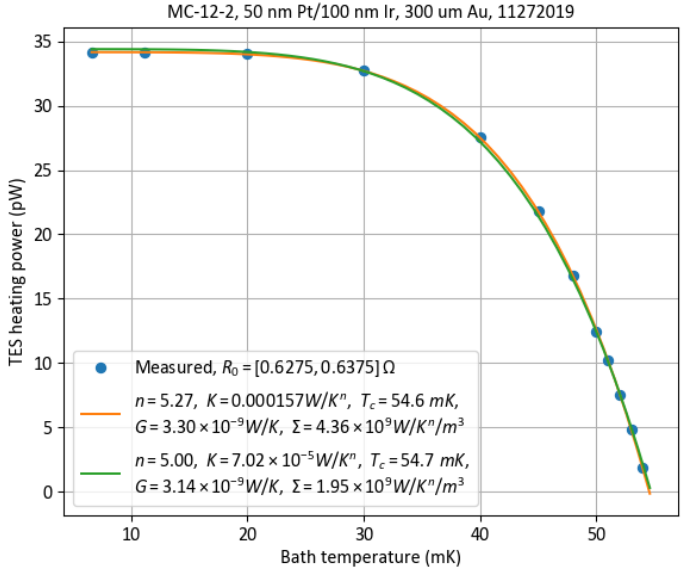


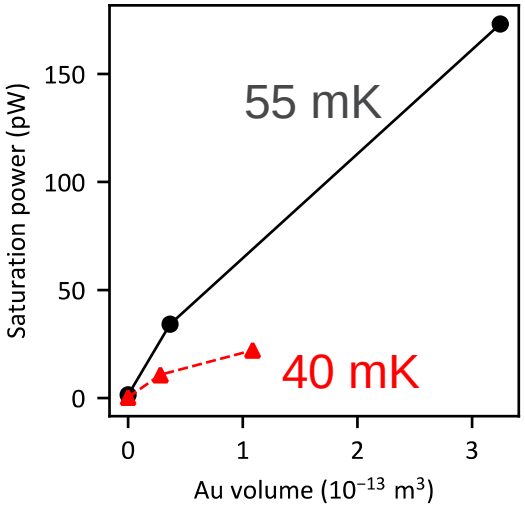


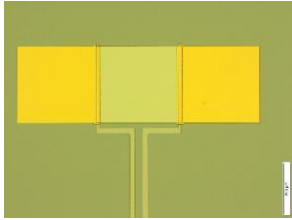


- Prototype TES devices fabricated to characterize the TES-Si wafer thermal coupling
- IV curves for bare IrPt TESs and TESs with gold pads are taken at different bath temperatures
- E-ph coupling constant Σ extracted from $n = 5$ power law fit. $\Sigma(\mathrm{IrPt}) = 1.2 - 2.7 \times 10^8 \mathrm{WK}^{-5}\mathrm{m}^{-3}$

E-Ph COUPLING FOR Au

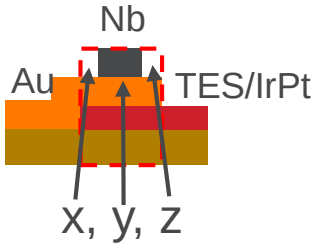






- P-T curve largely described by single-block T^5 power law
- Psat-V shows saturation effects at large Au volume
- Additional weak thermal link presents in the TES

EFFECTS OF TES-Au INTERFACE



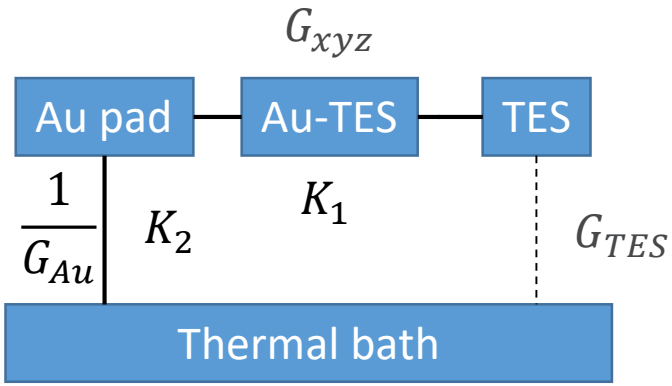
60 nm Pt/100 nm Ir, 300 um x 300 um TES

Device	Tc (mK)	Au Pad (um^2)	x/y/z (um)	Psat (pW)
MCC-4-10	39.3	900x300	5/10/5	22
MCC-4-11	41.0	900x300	5/10/10	29
MCC-4-12	41.8	900x300	5/5/5	32

- Increasing TES/Au overlap increases Psat
- Decreasing Nb width increases Psat
- TES-Au interface is a weak thermal link

COMBINATION OF G

- $\frac{1}{\frac{1}{G_{xyz}}+\frac{1}{G_{Au1}}} + G_{TES} = G_{T1}$
- $\frac{1}{\frac{1}{G_{xyz}}+\frac{1}{G_{Au2}}} + G_{TES} = G_{T2}$
- $G_{Aui} = 5\Sigma_{Au}\Omega_i T_{ci}^4$
- G_{TES}, G_{Ti}, T_{ci} are measured
- G_{xyz} and Σ_{Au} are two knowns



50 nm Pt/100 nm Ir, 300 um x 300 um TES

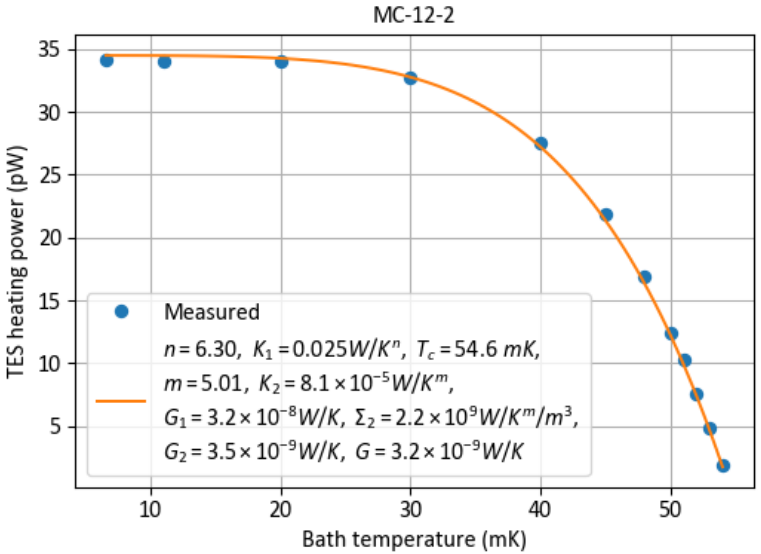
(nW/K)	Au (um x um x nm)	Tc (mK)	G_tot	G_xyz	G_Au	G_TES
MC-12-2	300x300x200	54.6	3.3	32.0	3.5	0.12
MC-12-4	900x900x200	55.0	16.2	32.0	32.2	0.12

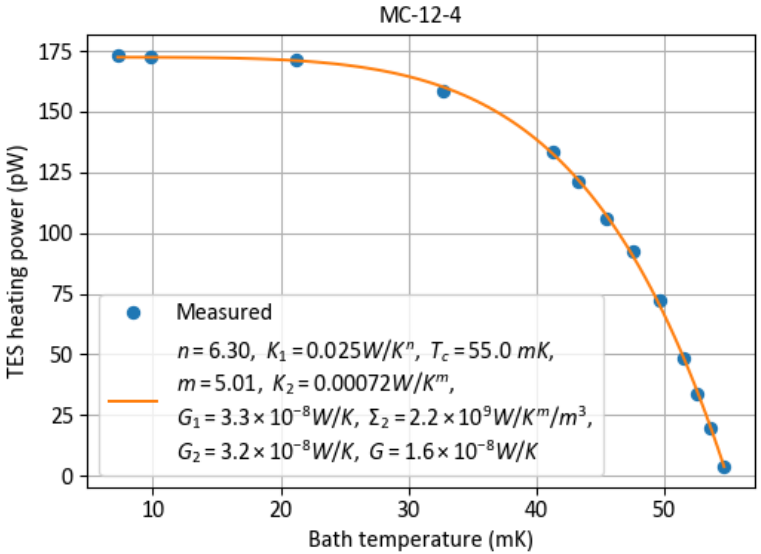
Σ = 2.2E+09 W/K^5/m^3

Two-block model:

$$P = K_1(T^n - T_a^n) = K_2(T_a^m - T_b^m)$$

2-BLOCK FITS





Simultaneous 2-block fits for MC-12-2 and MC-12-4. Tc's are fixed. K_1, Σ_{Au}, n and m are fit parameters.
n=6.3, m=5.0, Σ = 2.2E+09 W/K^5/m^3

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G COMPARISON

G's from G combination					
(nW/K)	Tc (mK)	G_tot	G_xyz	G_Au	G_TES
MC-12-2	54.6	3.3	32.0	3.5	0.12
MC-12-4	55.0	16.2	32.0	32.2	0.12
Σ = 2.2E+09 W/K^5/m^3					

G's from the 2blk fits					
(nW/K)	Tc (mK)	n	G_tot	G_xyz	G_Au
MC-12-2	54.6	6.3	3.2	32.1	3.5
MC-12-4	55.0	6.3	16.4	33.3	32.1
Σ = 2.2E+09 W/K^5/m^3					

- 2-block fits recover G and Σ values from G combination formulas
- N=6.3 signals G_{xyz} may have to do weakened e-ph coupling

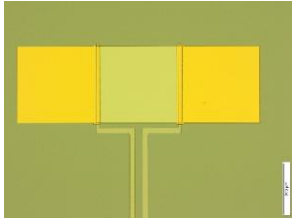
G COMPARISON: MCC-4

G's from G combination						
(nW/K)	Tc (mK)	x/y/x (um)	G_tot	G_xyz	G_Au	G_TES
MCC-4-8	42.5	5/10/5	1.3	7.4	1.5	0.03
MCC-4-10	39.6	5/10/5	2.8	7.4	4.3	0.03
MCC-4-11	41.2	5/10/10	3.6	12.4	5.0	0.03
MCC-4-12	42.0	5/5/5	3.9	13.2	5.4	0.03
Σ = 3.2E+09 W/K^5/m^3						

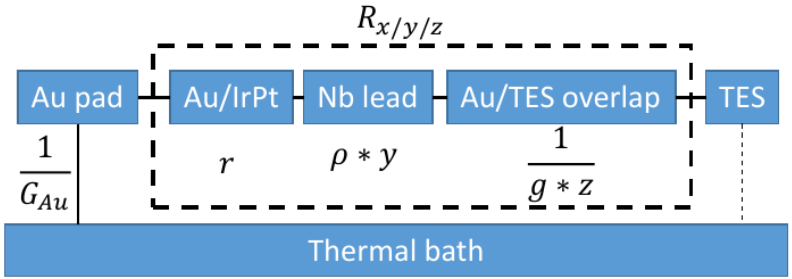
G's from the 2blk fits					
(nW/K)	Tc (mK)	n	G_xyz	G_Au	G_tot
MCC-4-8	42.5	1.8	7.4	1.5	1.3
MCC-4-10	39.6	1.8	7.0	4.5	2.7
Σ = 3.1E+09 W/K^5/m^3					

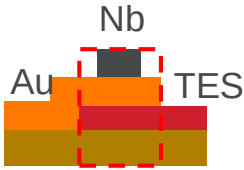
- 2-block fits recover G and Σ values from G combination formulas
- N=1.8, partially due to weaker constraining power on G_{xyz}, some other impedance may play a role too

INTERFACIAL THERMAL IMPEDANCE



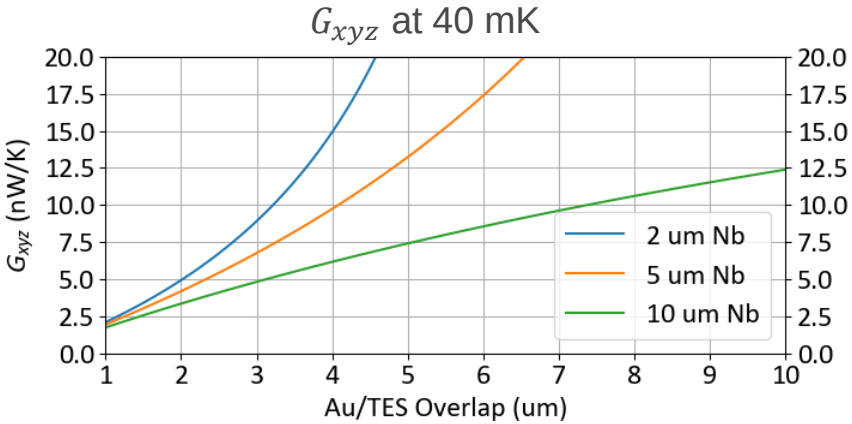
- Linear dependence of thermal G/R assumed in x/y/z regions of TES-Au interface.





- Need $G_{xyz} > 10\ \mathrm{nW/K}$

- G_{xyz} temperature dependence under investigation, data signals e-ph coupling dependence



SUMMARY

- Iridium based low T_c TES detectors are an excellent choice for cryogenic rare event searches: $0\nu2\beta$, dark matter, CEvNS…
- Substantial progress made in developing the $0\nu2\beta$ LD
  - Ir based low T_c film recipe
  - Detector fabrication and testing infrastructures at ANL and UCB
  - TES thermal properties and couplings to Si substrate characterized
- Currently optimizing the TES-Si thermal conductance and developing Si-bath thermal link
- Demonstration of a full LD in the near future.

BACKUP SLIDES

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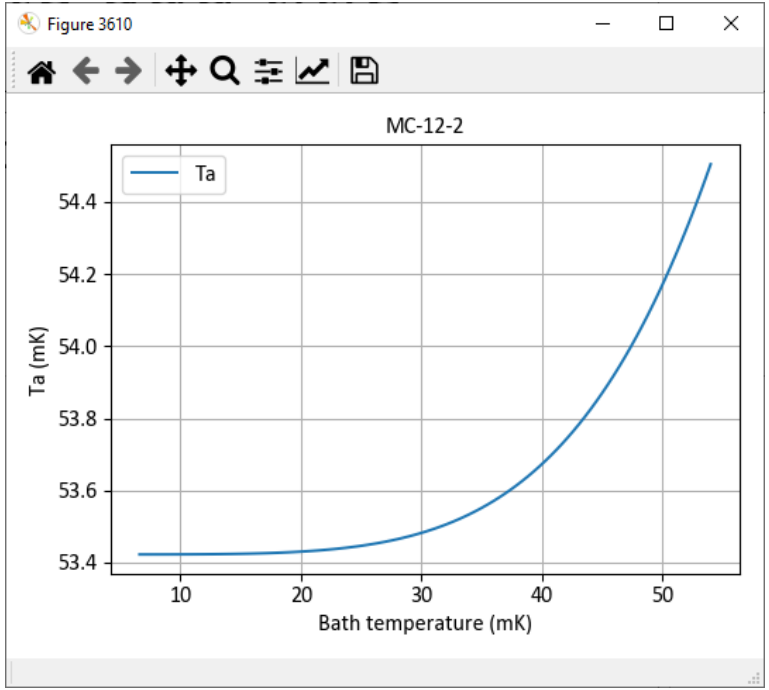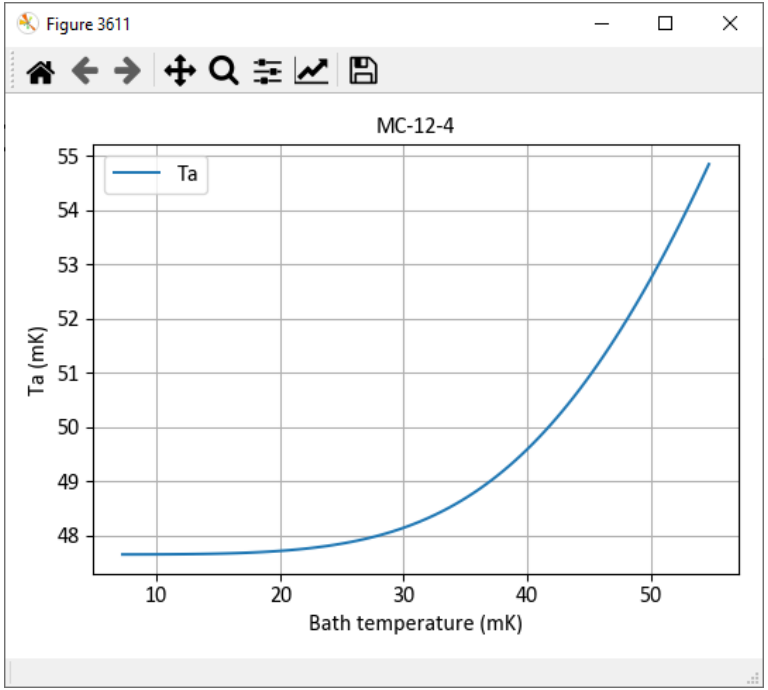
TA DETERMINED FROM TB AND TC