CPAD Workshop

Low Tc Thin Film Superconducting detectors

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University of Chicago

SLAC
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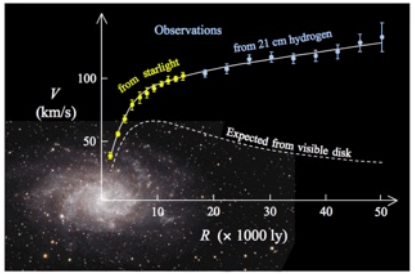
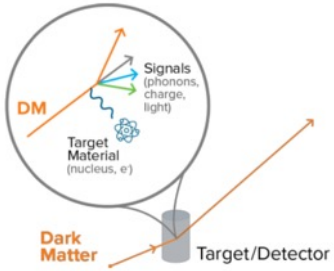
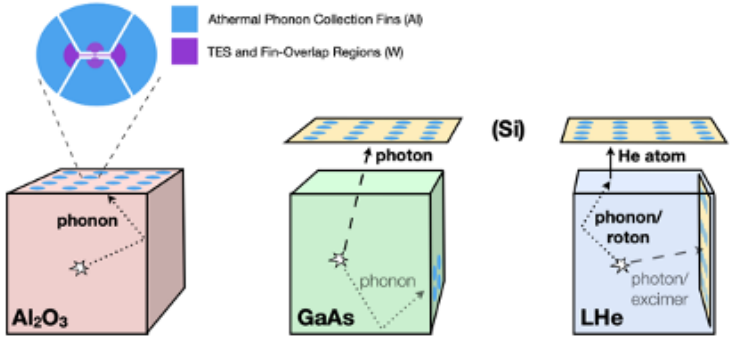
New physics via Rare event searches

Dark Matter

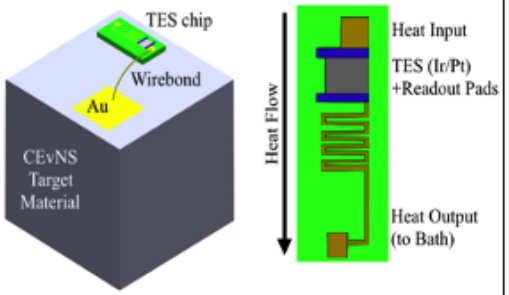






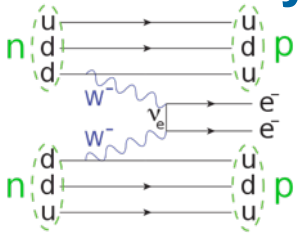
TESSERACT

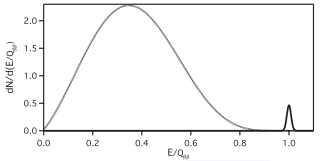
Coherent Elastic Neutrino-Nucleus Scattering

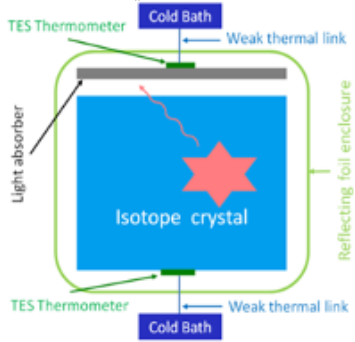


RICOCHET

Neutrinoless Double-beta Decay



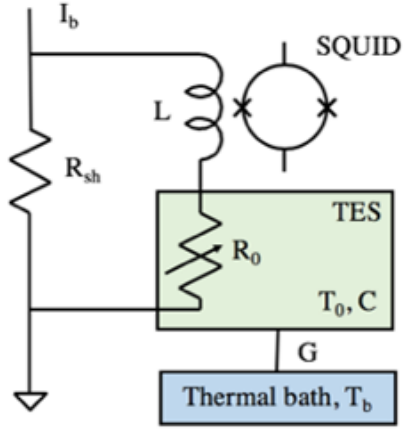


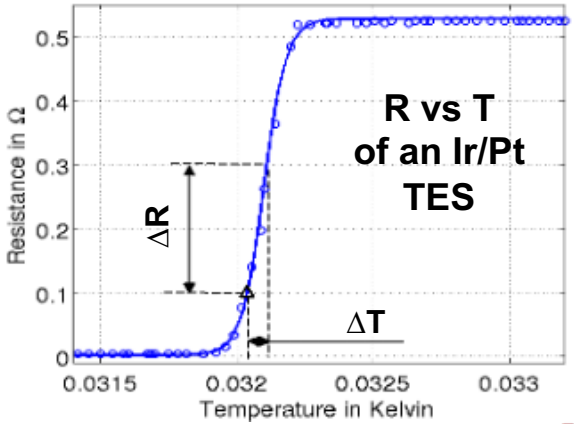


CUPID

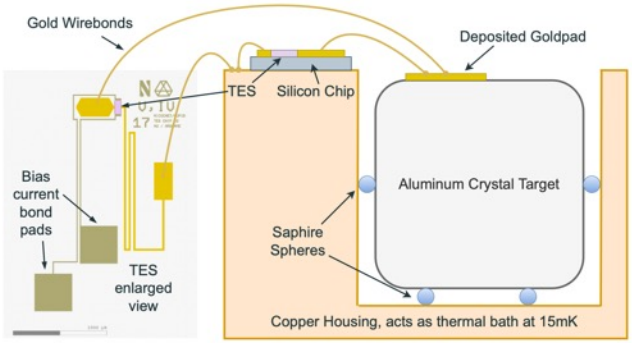
Transition Edge Sensor (TES)

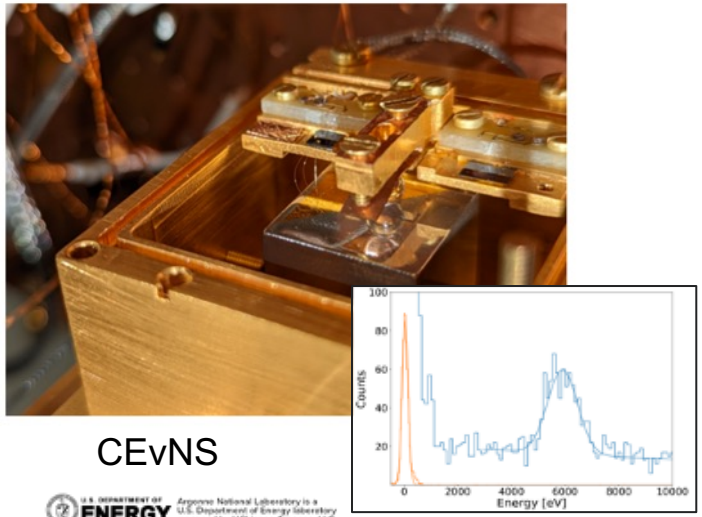
- Thermal detector
  - Versatile coupling
  - Well understood theory of performance
- Voltage-bias establishes negative feedback
  - linearizes response,
  - increase bandwidth
  - suppresses readout noise
- Noise comes from thermal fluctuations
- Multiplexable
- Sensitivity and threshold improves with lower Tc
  - Target Tc~20-60 mK



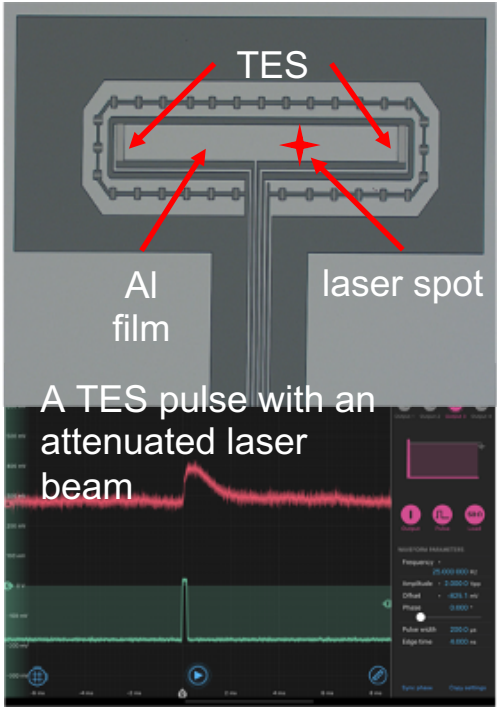


TES for rare event searches

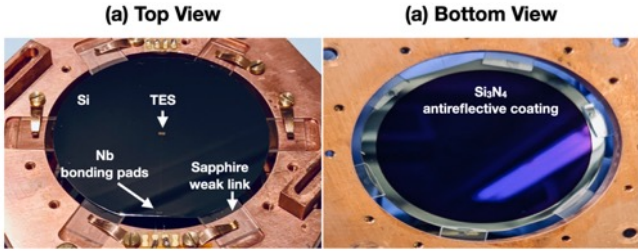


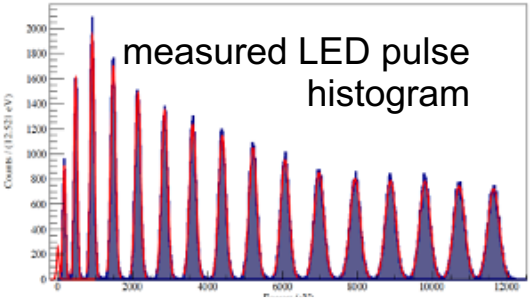


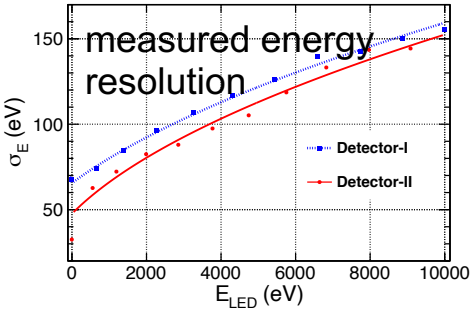
CEvNS



Dark Matter

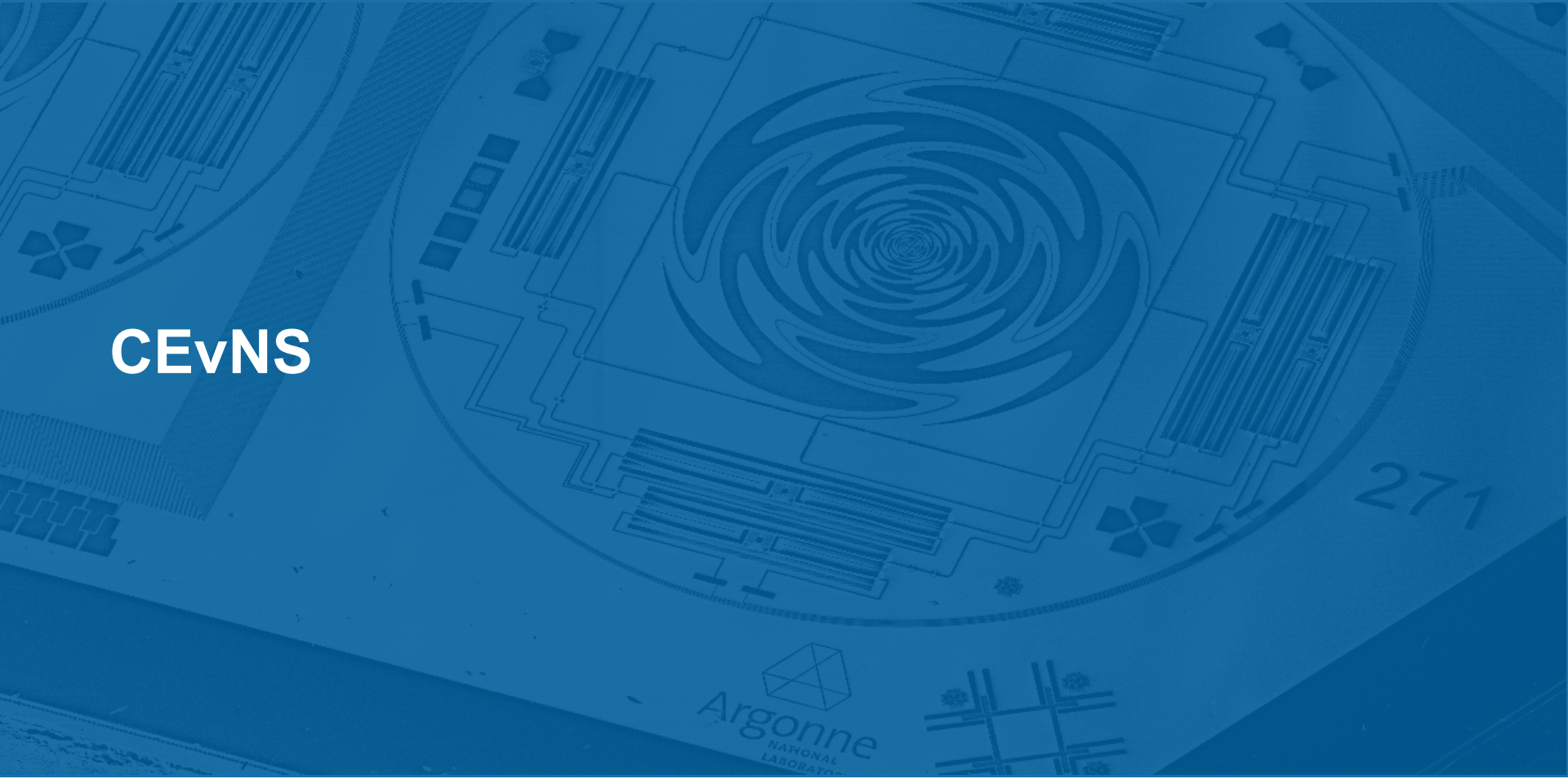






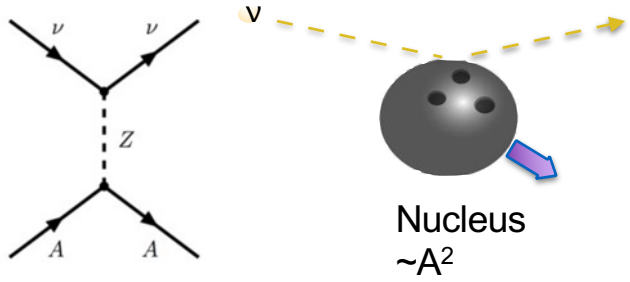
NLDBD

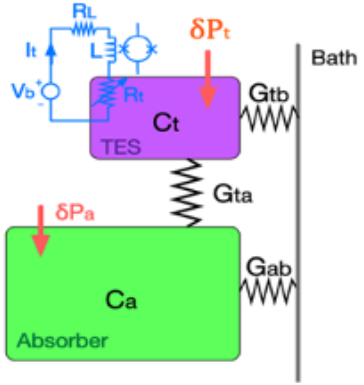
CEvNS

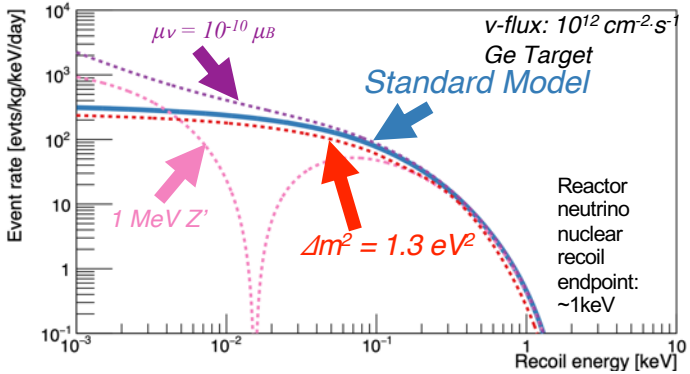


Ricochet

- Measure low energy reactor neutrino spectra via Coherent Elastic Neutrino-Nucleus Scattering
- Thermal detector measuring heat with a TES thermometer
  - Large particle and radiation collection volume



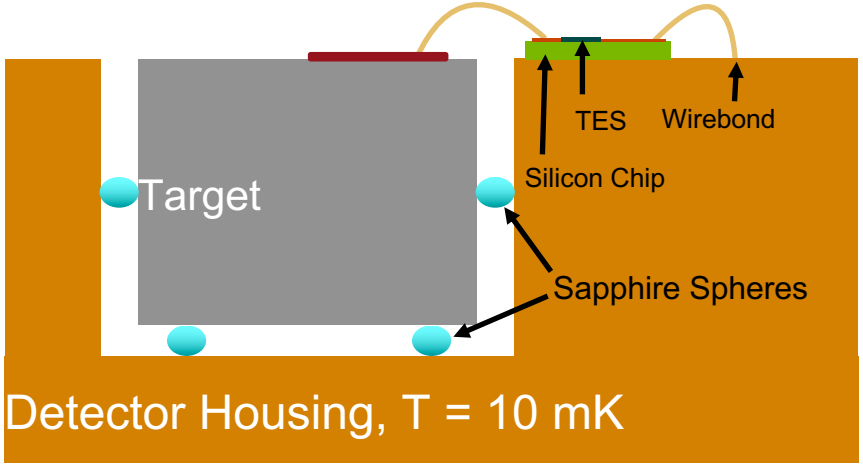


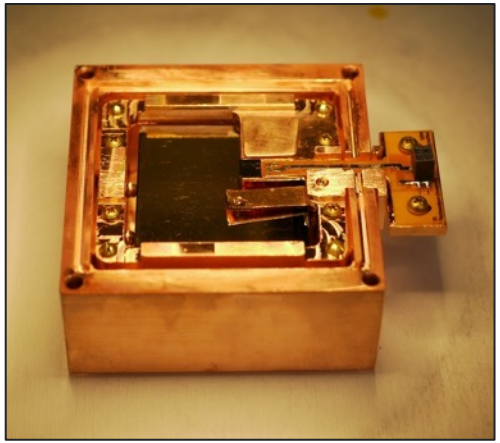


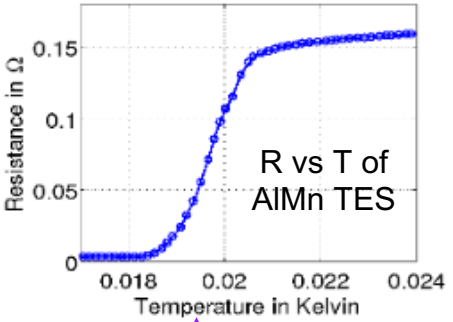
M. Pyle et al. arXiv:1503.01200v2

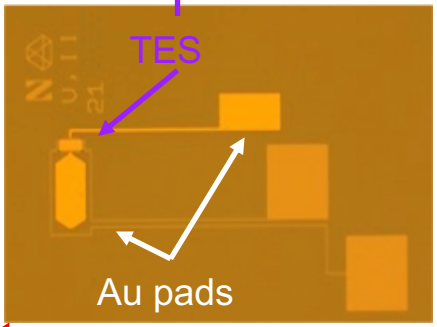
Thermal Detector Using AlMn TES

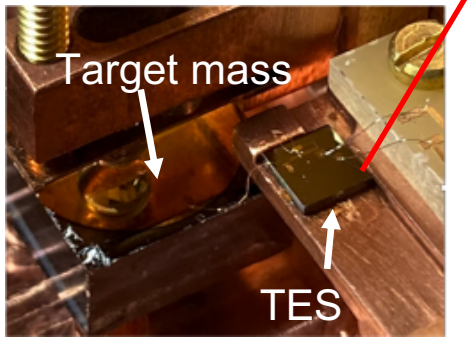
Collaborating with UMass, MIT and Northwestern

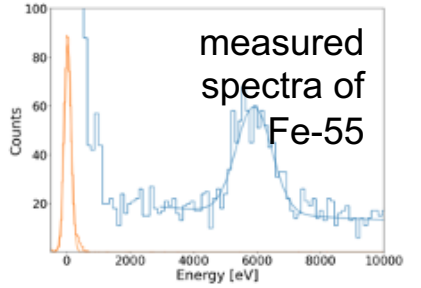






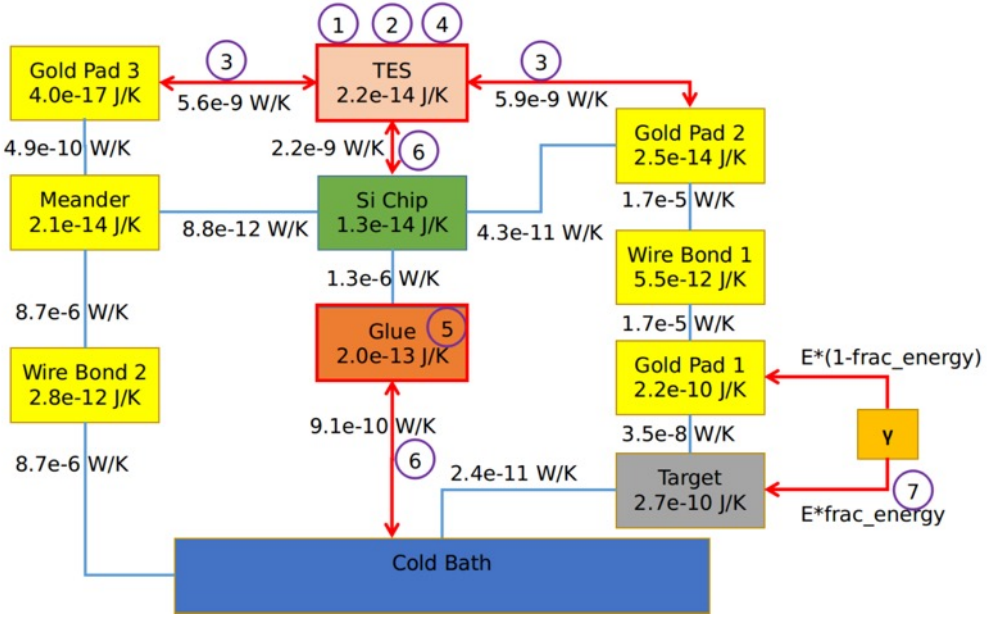


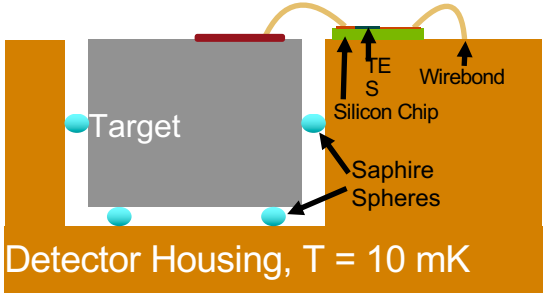




https://doi.org/10.1016/j.nima.2023.168765

Thermal modeling

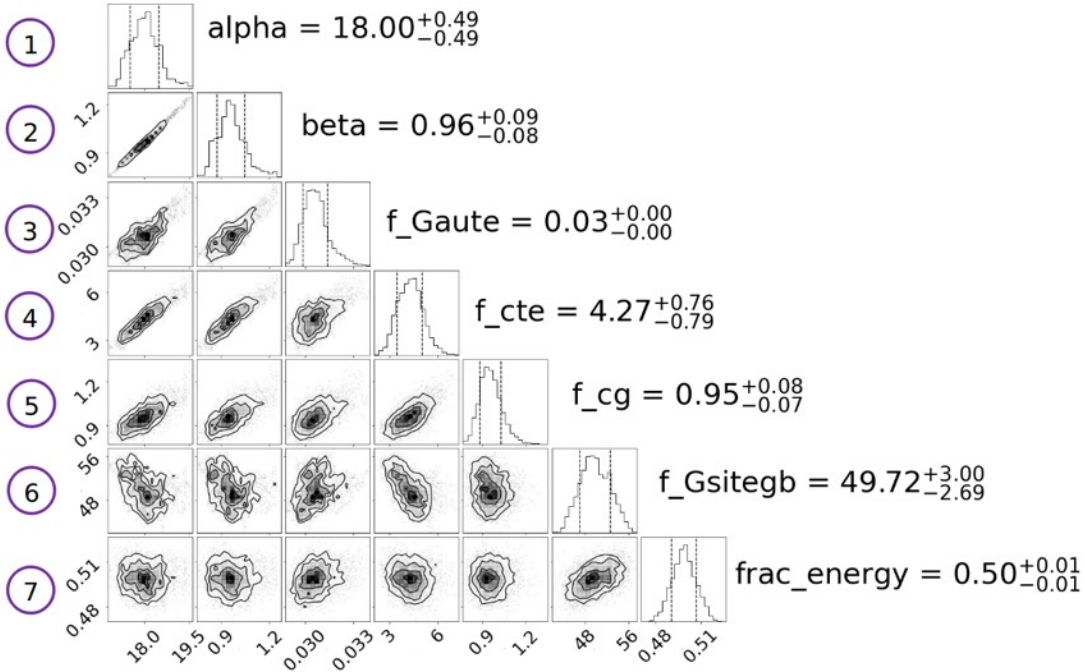


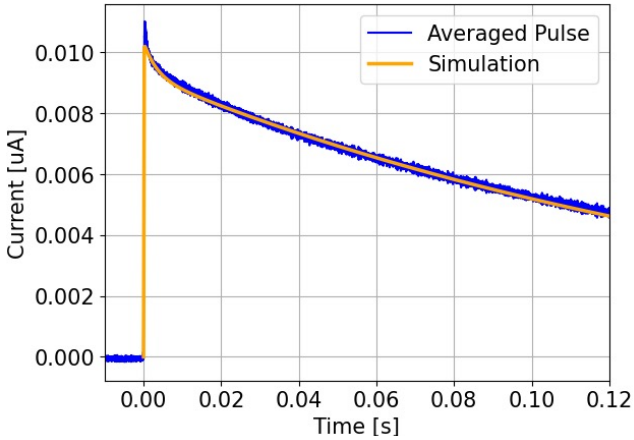


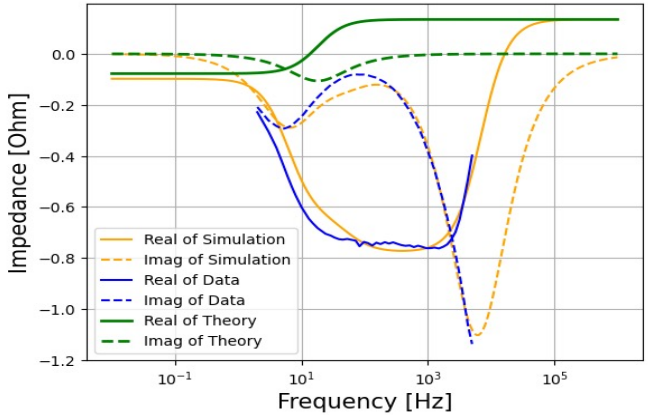
- Thermal model
  - Separate into multiple isothermal heat capacities
  - Connect blocks with therma conductances
- Measure through temporal/frequency response to energy injection
  - Bias modulation
  - Pulse shape

Transition Edge Sensor Chip Design of Modular CEvNS Detector for the Ricochet Experiment, Ricochet Collaboration, R. Chen et al.
DOI: 10.1007/s10909-022-02927-1

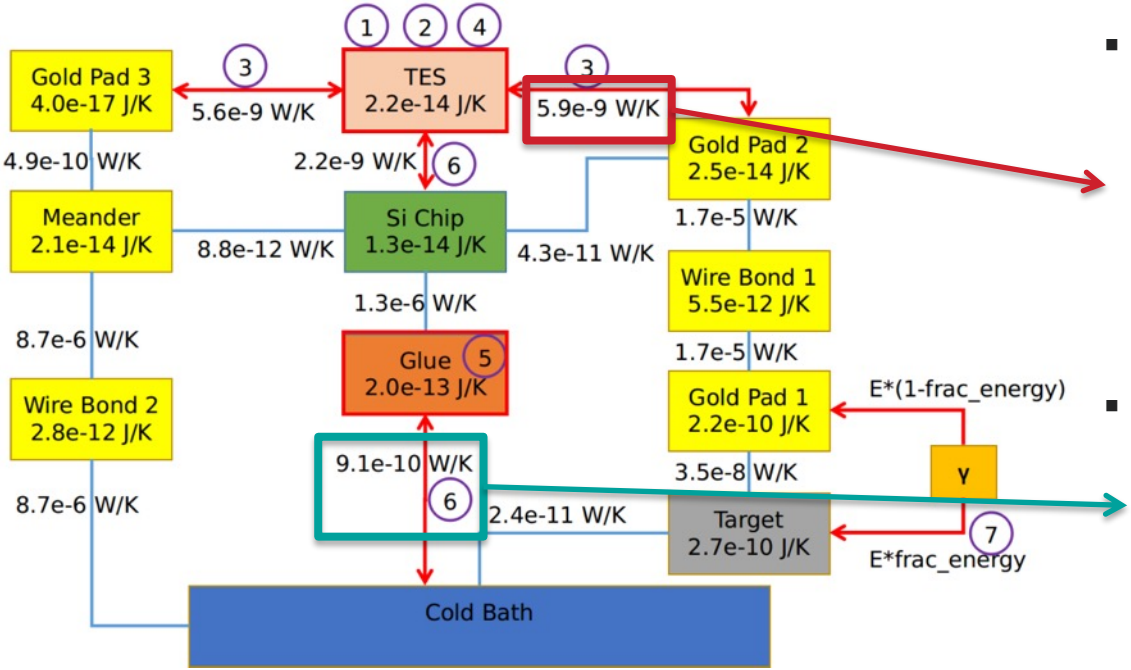
MCMC analysis





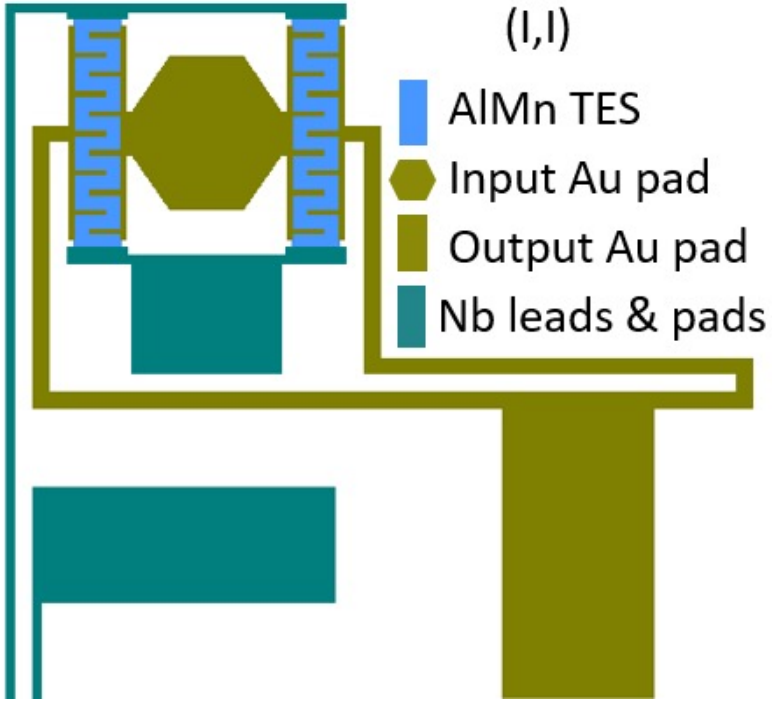


Directions for optimization



- Conductance from Gold Pad 2 to TES is much smaller than expectation. This could point to an issue with fab and/or design.
- Thermal link through the TES chip and glue is significantly larger than we intended in the device we tested.

Improving thermal performance

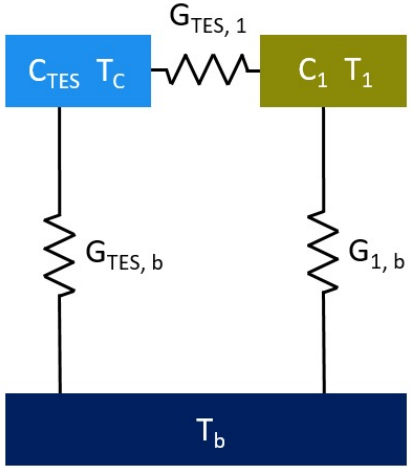


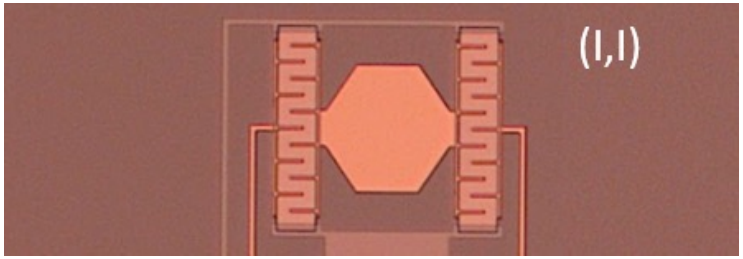
- ”Split TES”
  - Same electrical circuit
  - Thermal transport across TES reduced by 2x
- “Zebra stripes”
  - Provide additional thermal conductance across TES

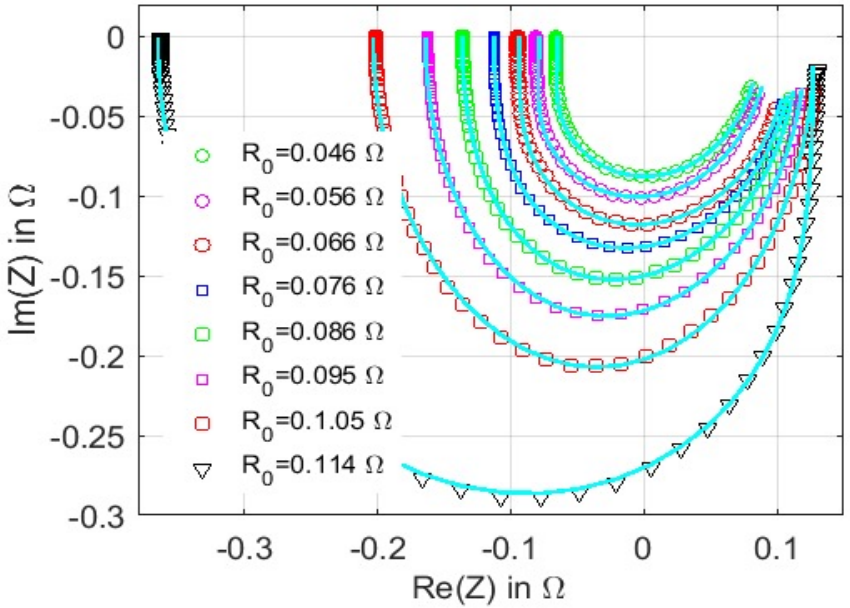
Thermal modeling

Study & measure TES chip alone

- Complex impedance (“transfer function” measurement)
- 2-block model (TES and Au pad)



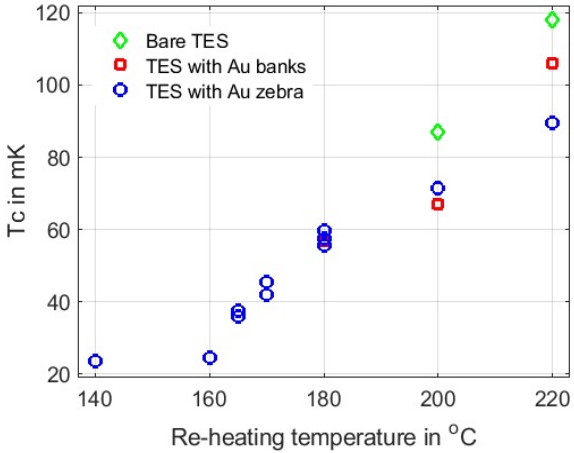


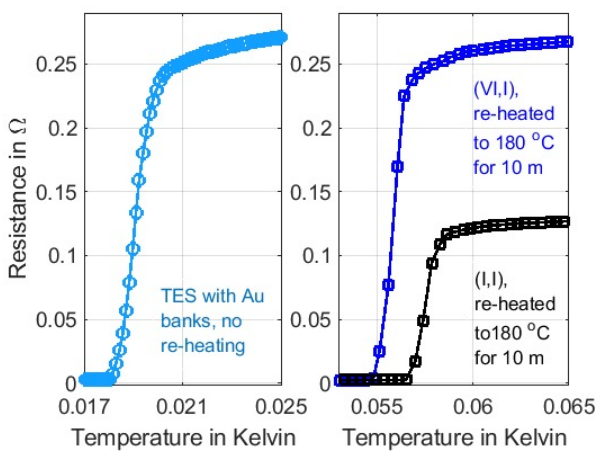


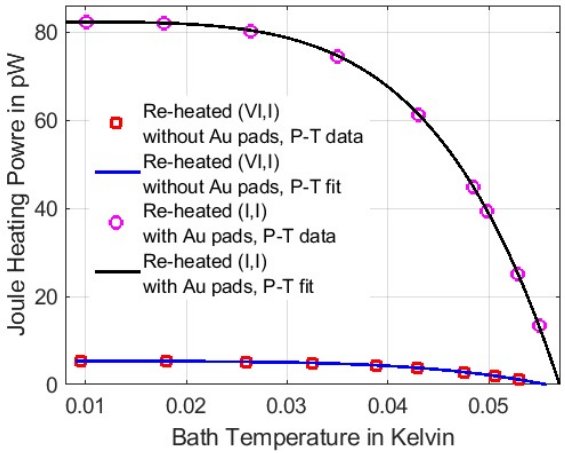
New approaches to tuning Tc

Tc control

- AlMn Tc is sensitive to heat treatment
  - Film Tc changes at “low” temperatures
- For this design, can reheat individual chips and further tune Tc



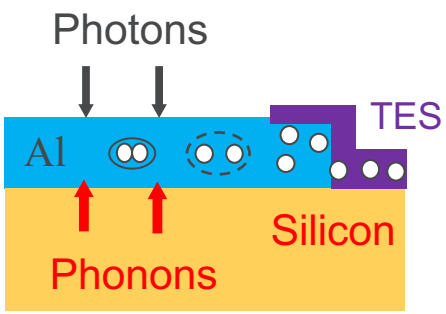


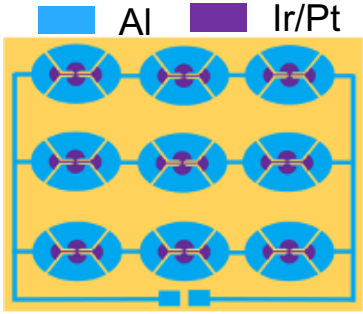


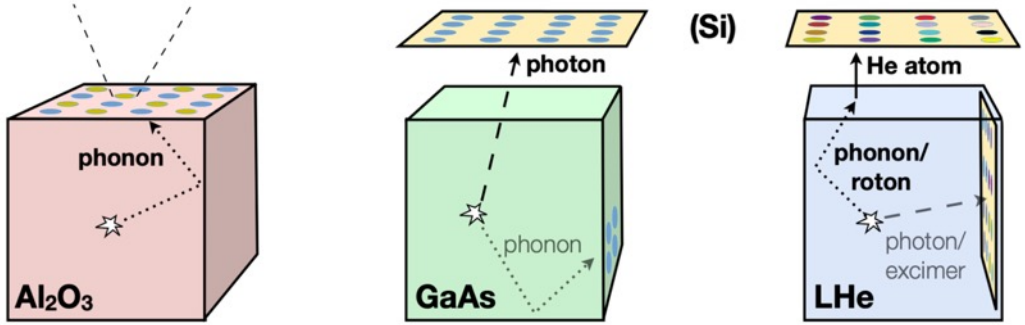
Dark Matter

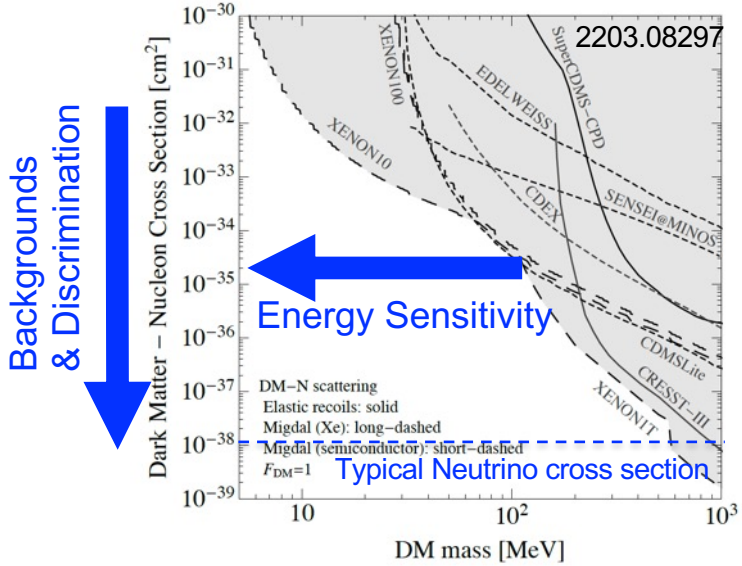
Dark Matter including SPICE/HeRALD (TESSERACT)

- Athermal detector measuring quasiparticles from Al photon/phonon collection fins with TES sensors
  - Large photon/phonon collection area
- Searches for low mass particle dark matter using various targets





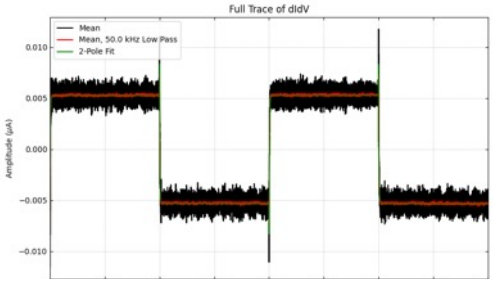


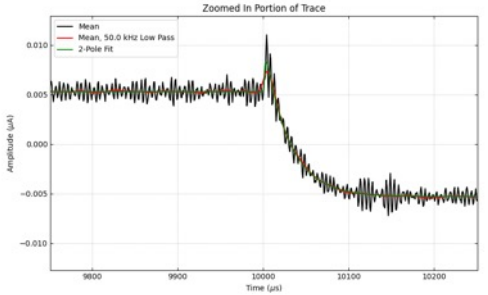


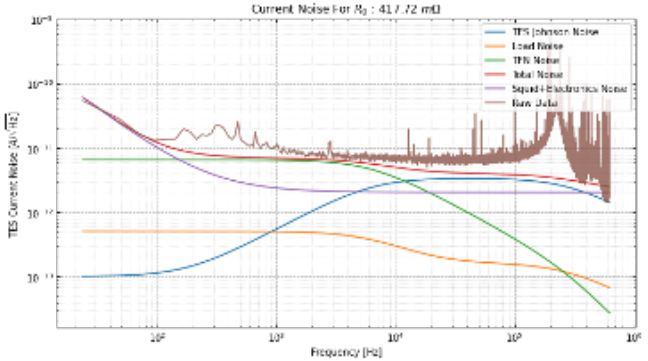
Device modeling

UC Berkeley

- $Z(\omega) = R_{sh} + R_p + j\omega L + Z_{TES}(\omega)$
- $Z_{TES}(\omega) = R_0(1+\beta) + \frac{R_0\mathcal{L}}{1-\mathcal{L}} \frac{2+\beta}{1+\frac{j\omega\tau_0}{1-\mathcal{L}}}$
- $\frac{\partial I}{\partial P}(\omega) = [I_0 \left(1 - \frac{1}{\mathcal{L}}\right)\mathrm{e}\left(1 + \frac{j\omega\tau_0}{1-\mathcal{L}}\right) Z(\omega)]^{-1}$
- $S_P(\omega) = S_I(\omega) \left|\frac{\partial I}{\partial P}(\omega)\right|^{-2}$
- $\sigma_E = [\int_0^\infty \frac{d\omega}{2\pi} \frac{4}{S_P(\omega)}]^{-1/2}$ = 76 meV

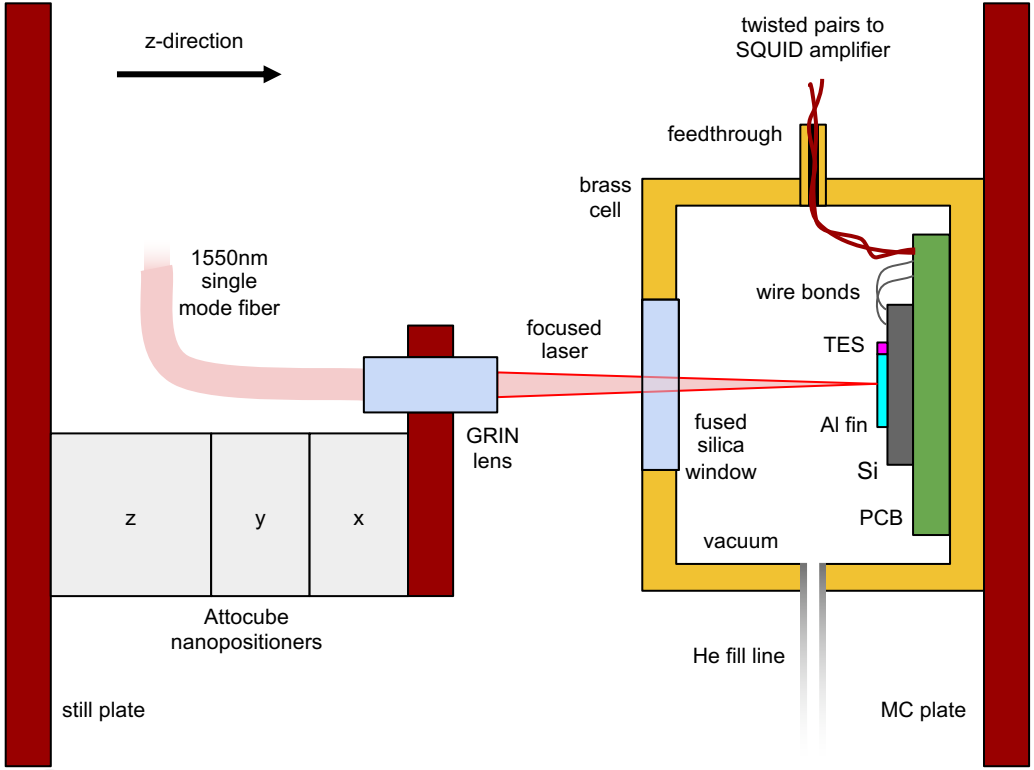


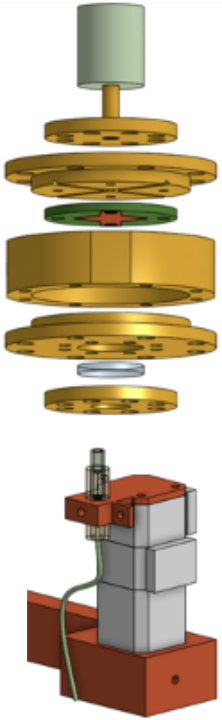


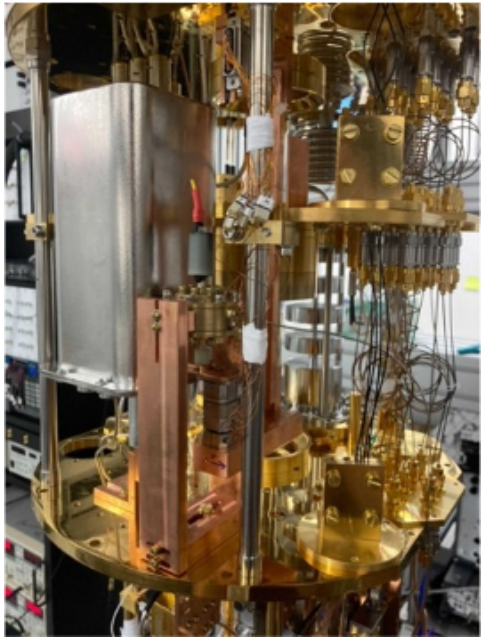


QP diffusion measurement

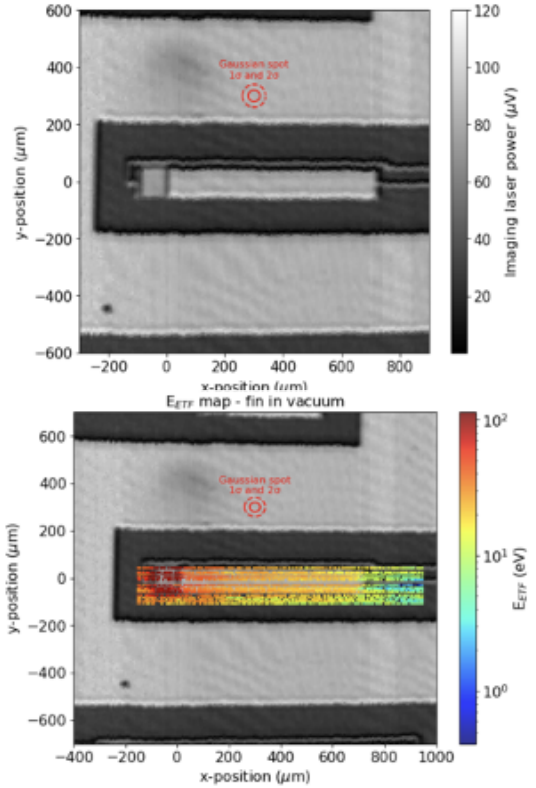
UMass



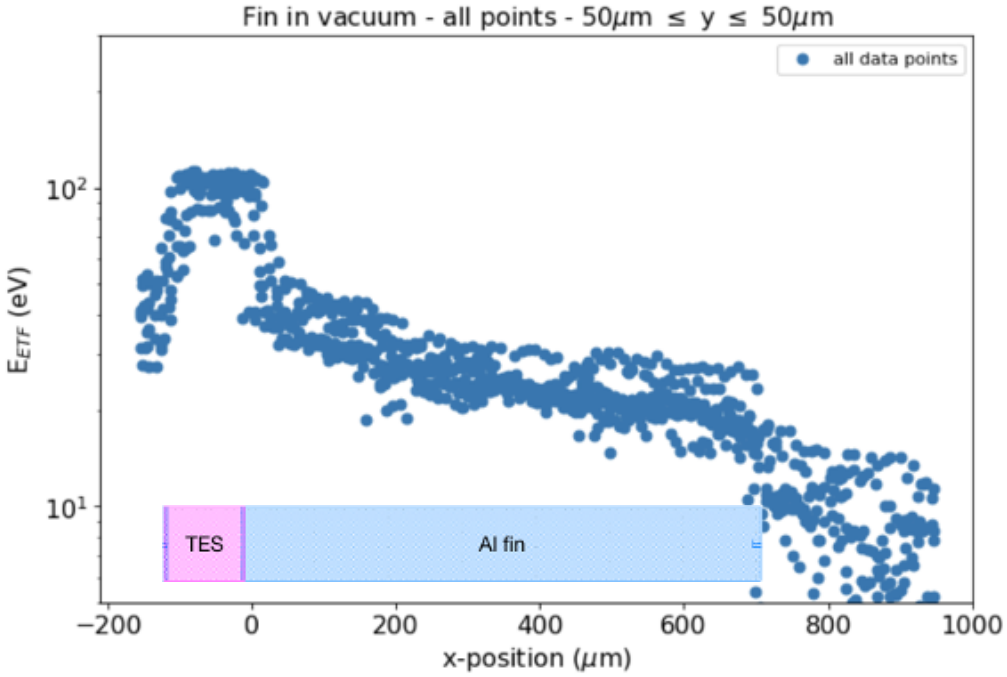




QP propagation along Al fin into TES

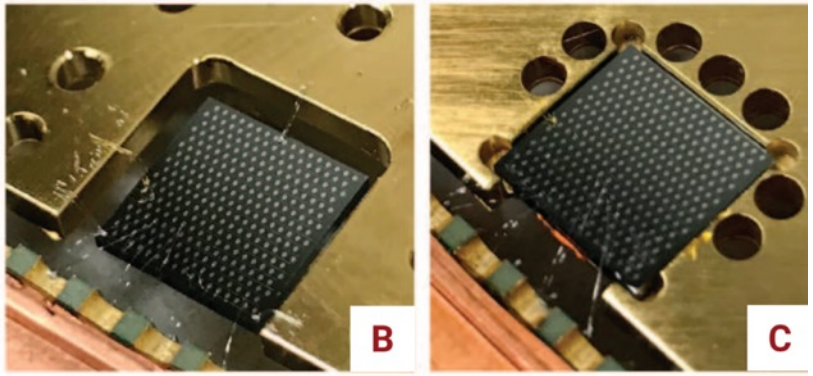


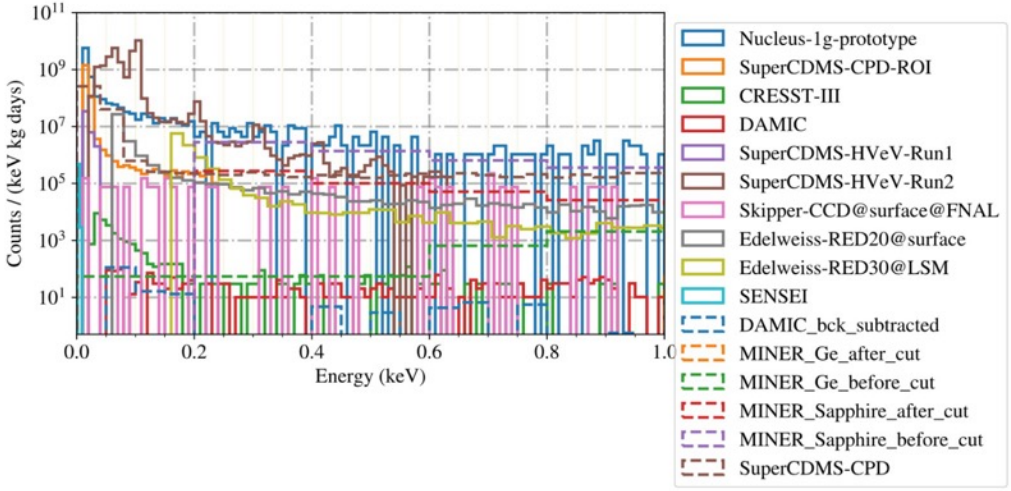
Preliminary

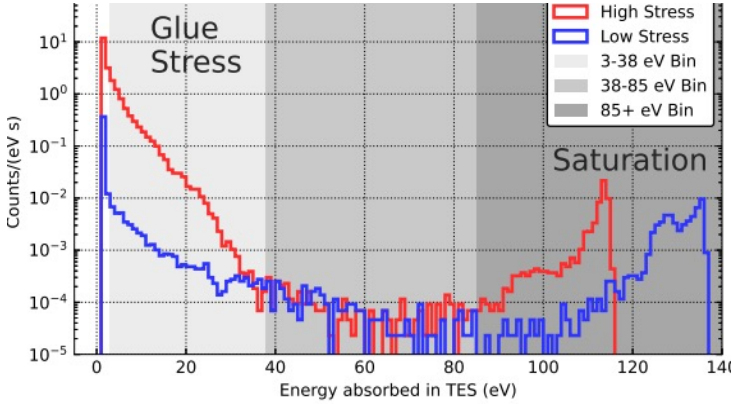


Backgrounds

Stress & Low Energy Excess





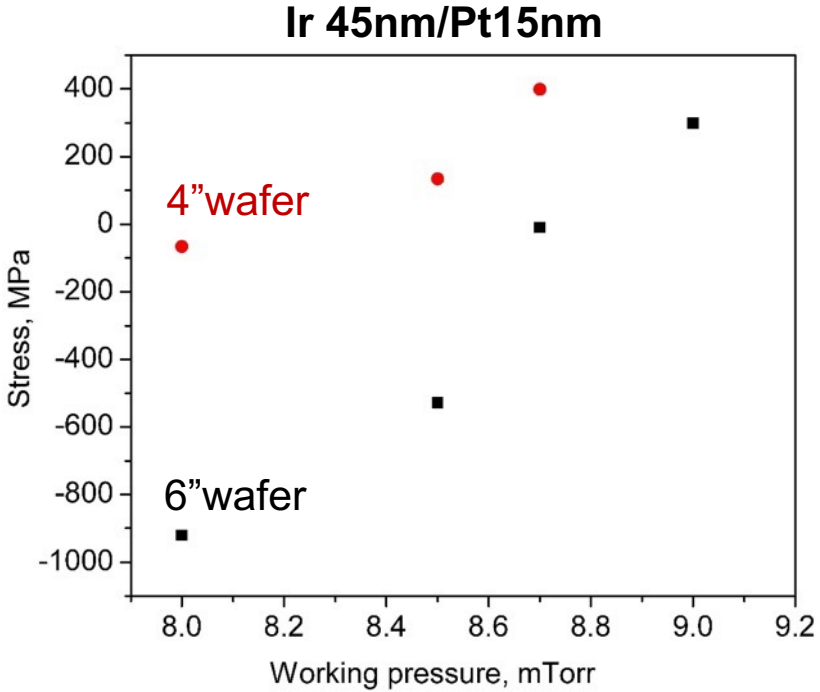


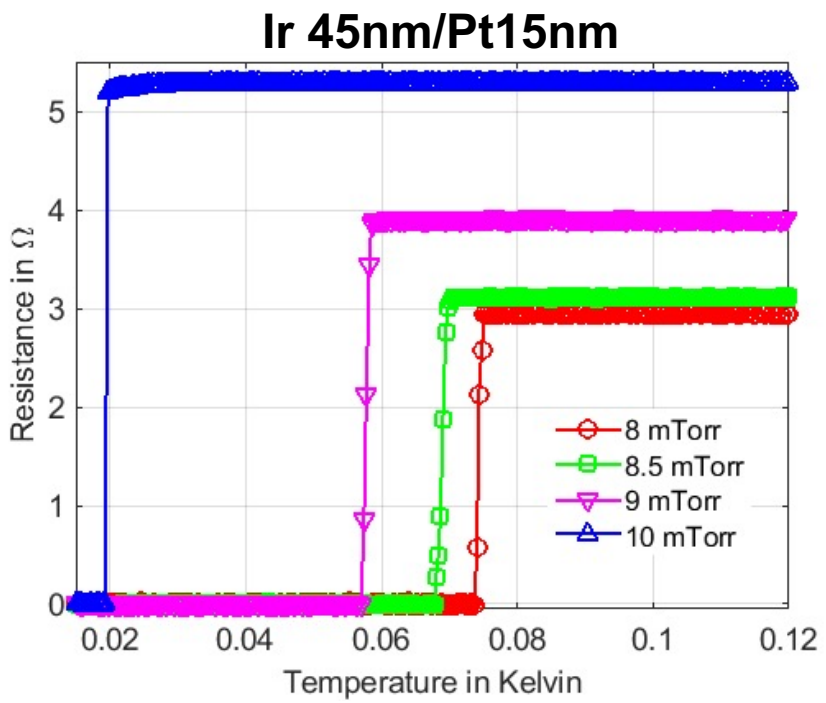
- Measurements with “external” sources of stress exhibit excess low-E background events
  - Low-E background reduces when stressors are removed

arXiv:2208.02790

Near zero stress Ir bilayers

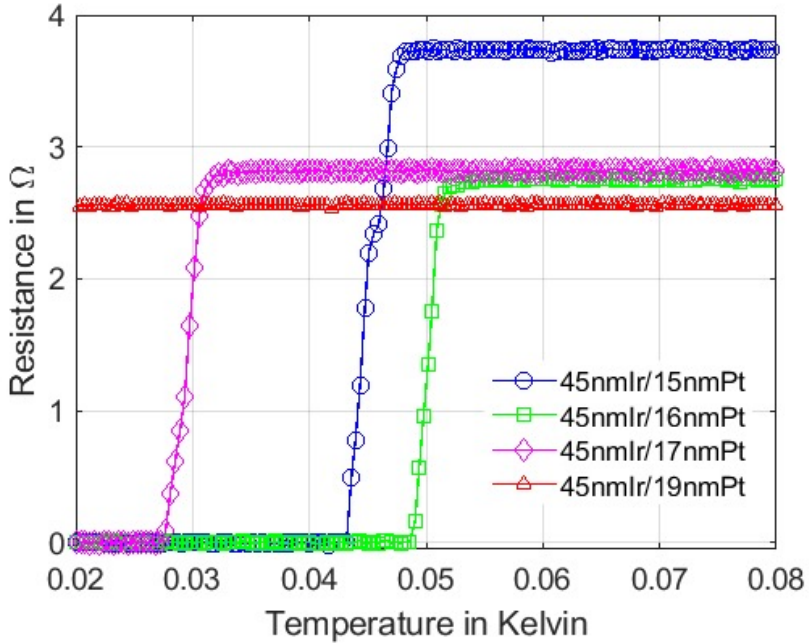
Can tune stress by adjusting working pressure for Ir film dep

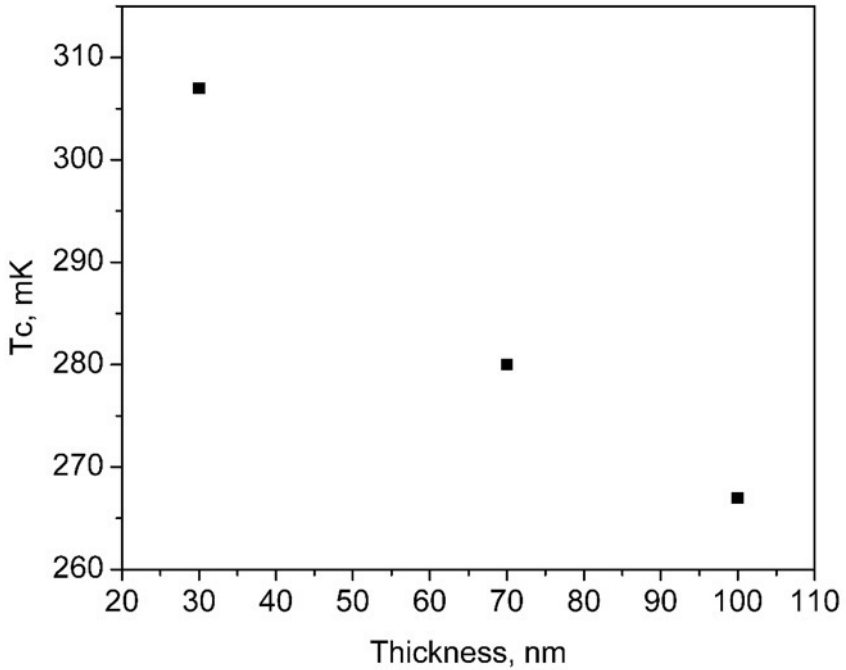




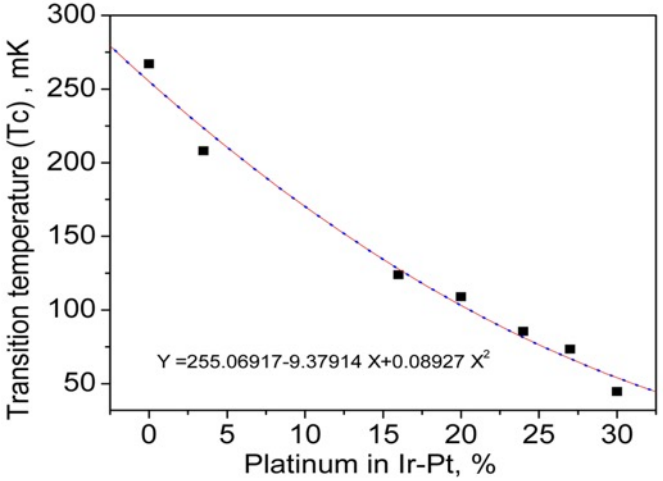
Improving Tc control

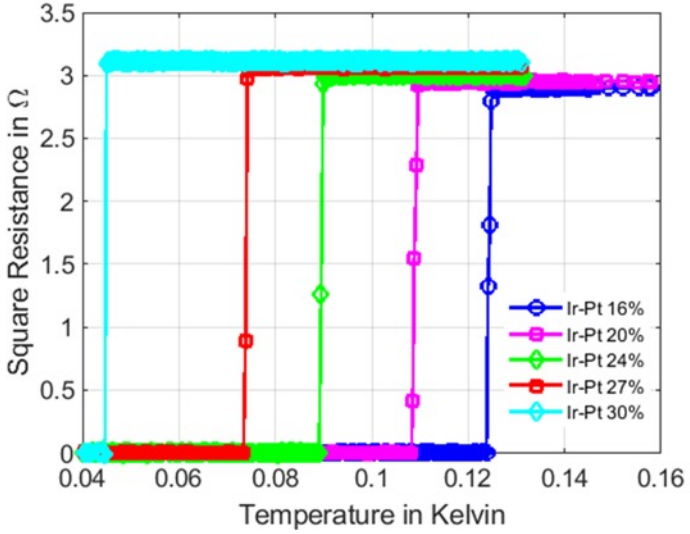
Pursue very thin films to realize very small volumes

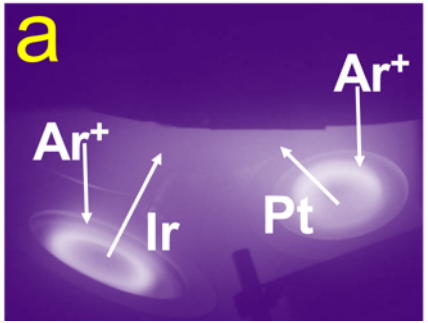


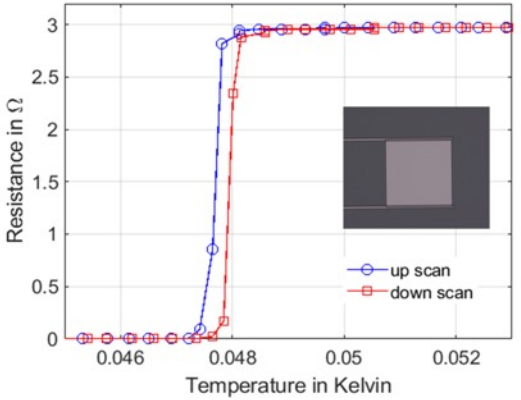


Co-sputtering Ir w/ Pt





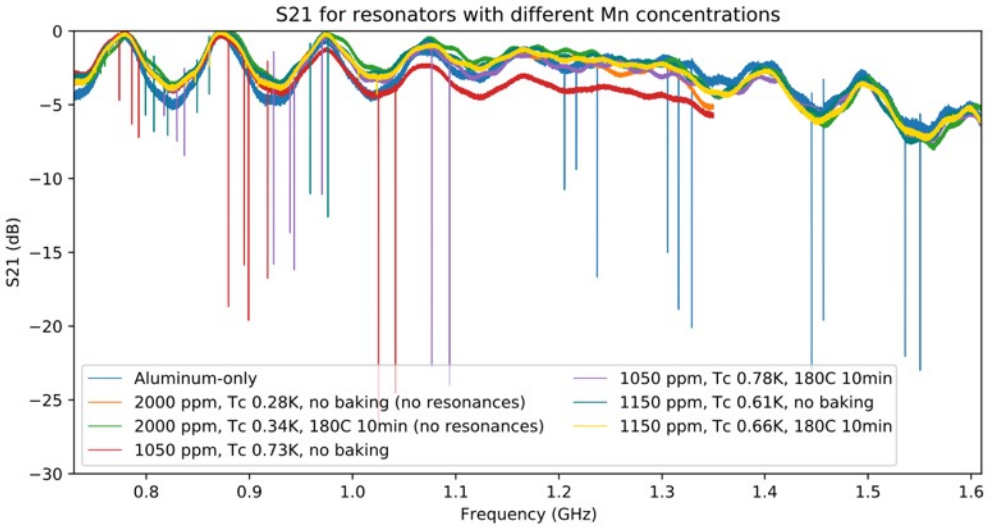


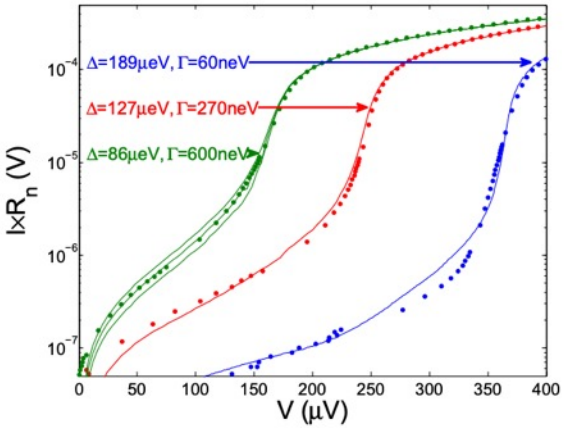


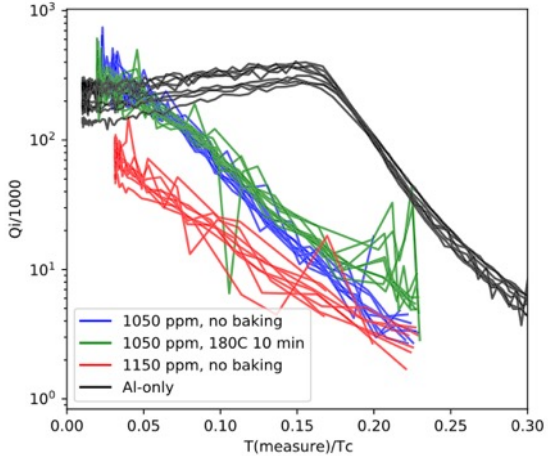
Moving beyond low Tc TES

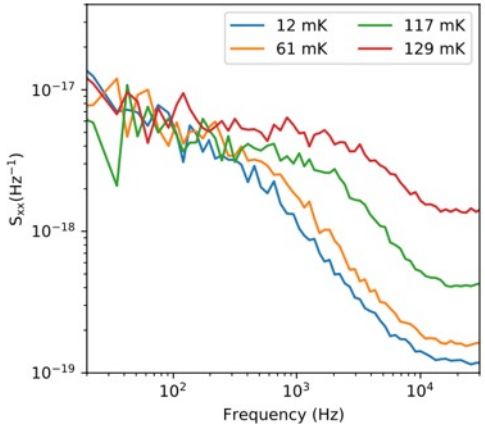
AlMn MKIDs

- Studied AlMn resonators
  - Reduced Tc
  - Qi vs T/Tc is not universal, suggests superconductivity not just rescaled gap
- Sub-gap DOS?









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Summary

- For most superconducting detectors, lower Tc enables lower noise/threshold
- Research and development of new materials and corresponding detector designs for low Tc detectors enables new science.
- New approaches to low Tc materials
  - Post-fab reheating of AlMn
  - Co-sputtered Ir-Pt w/ tunable stress
- Evolving thermal (bolometric) designs
- Validating athermal (qp/phonon) designs
- Exploring low Tc for non-TES detectors
  - Need a better understanding of the underlying physics of materials properties