Northwestern

Characterization of the TES sensors for the Ricochet experiment

Ran Chen
for the Ricochet Collaboration

Requirement for Low Thresholds

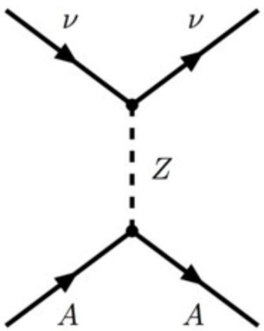
CEvNS: Coherent Elastic Neutrino-Nucleus Scattering

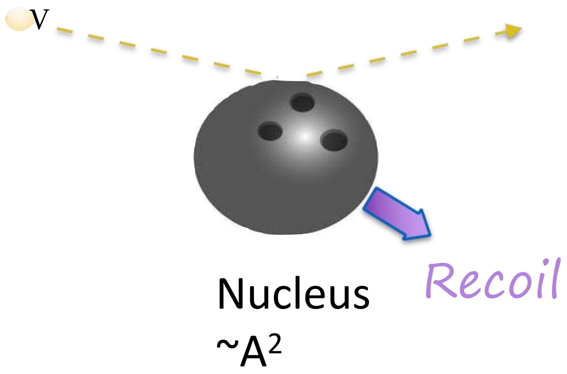
CEvNS:

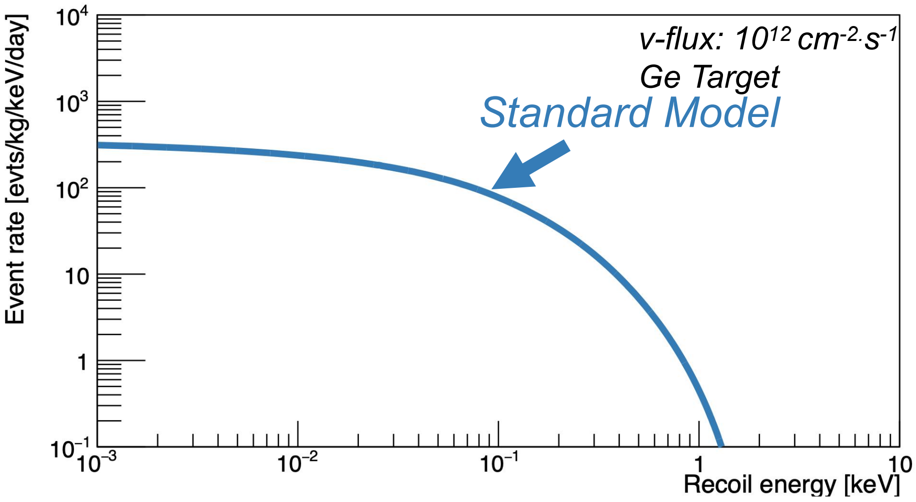
- Coherent Elastic Neutrino-Nucleus Scattering
- 2017: Observed via neutrinos of tens of MeV at SNS.
- 2022: Observed at reactors.

Ricochet goals:

- First, 5σ observation of low-energy CEvNS
- Then, precision measurement of spectrum







Requirement for Low Thresholds

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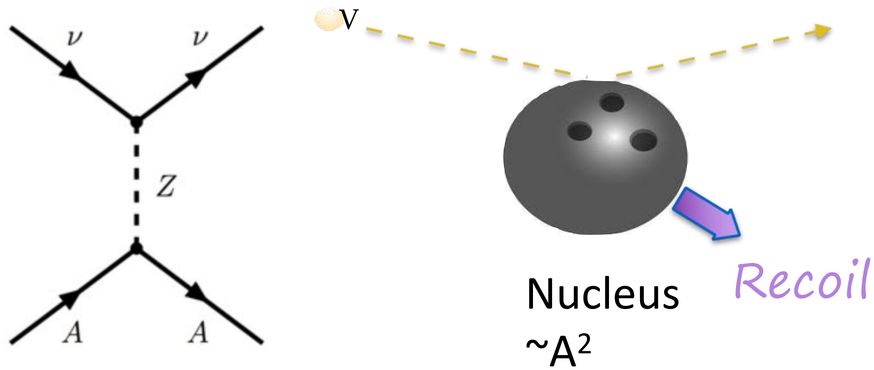

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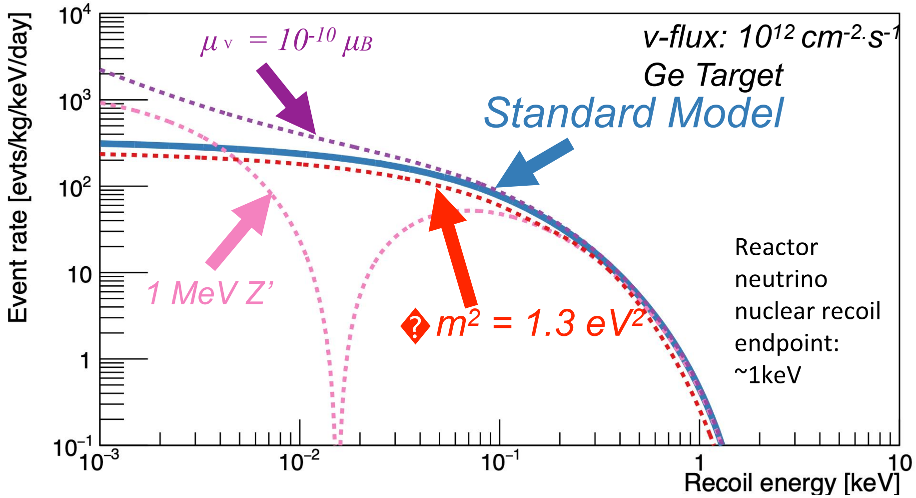
Sensitive to new physics, including

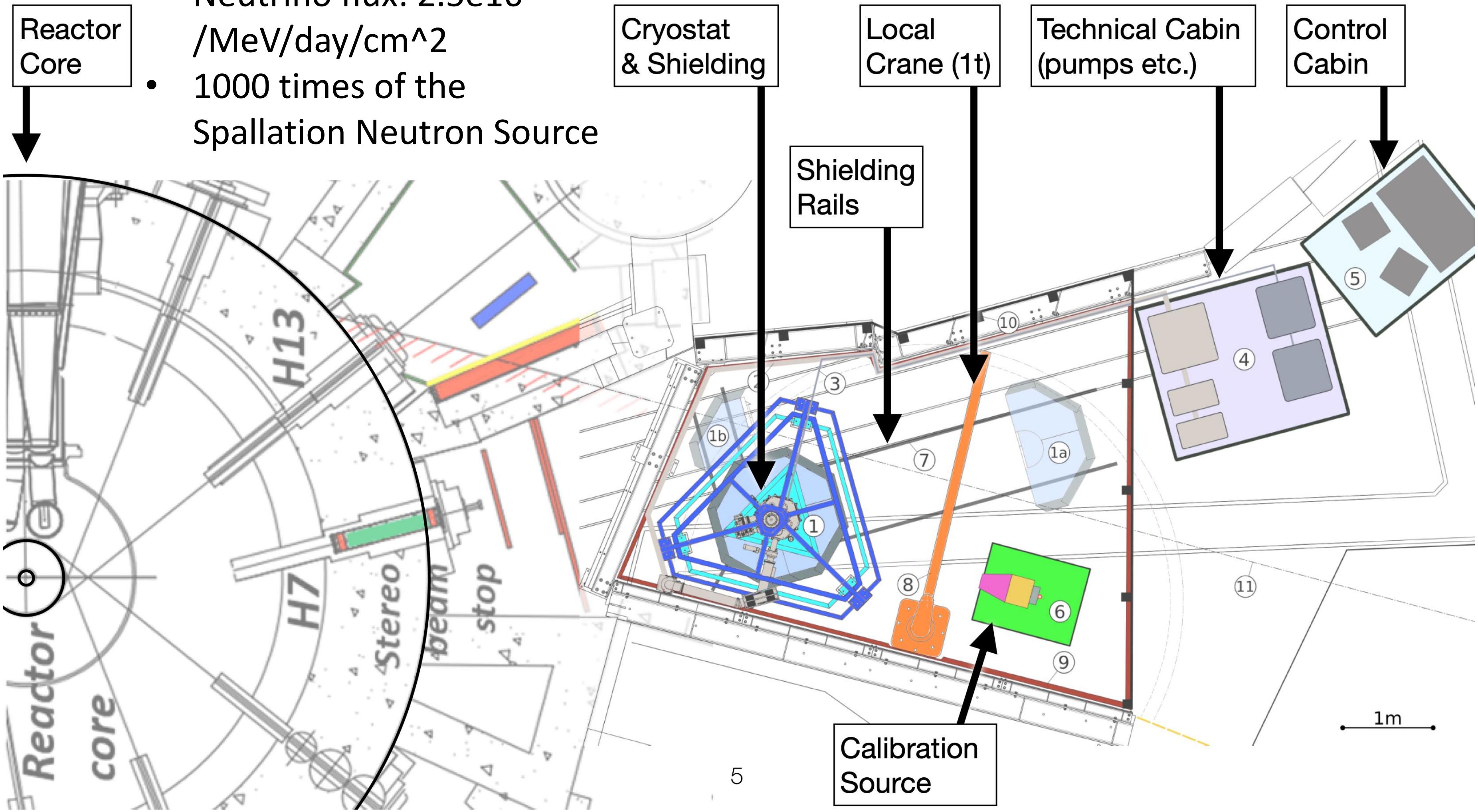
- neutrino mag. moment
- sterile neutrinos
- new force mediators



The ILL Reactor in Grenoble, France

RICOCHET

- Reactor Power: 58 MW
- Neutrino flux: 2.5e16 /MeV/day/cm^2
- 1000 times of the Spallation Neutron Source



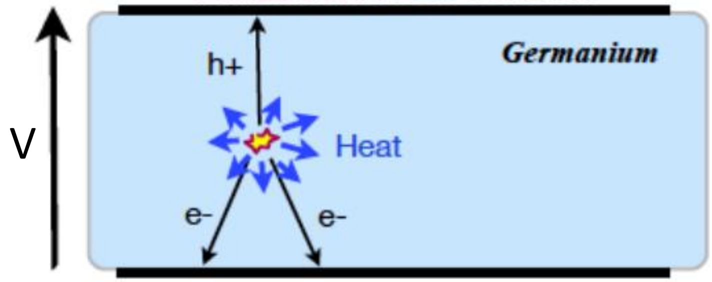
Ricochet Detector Technologies

RICOCHET

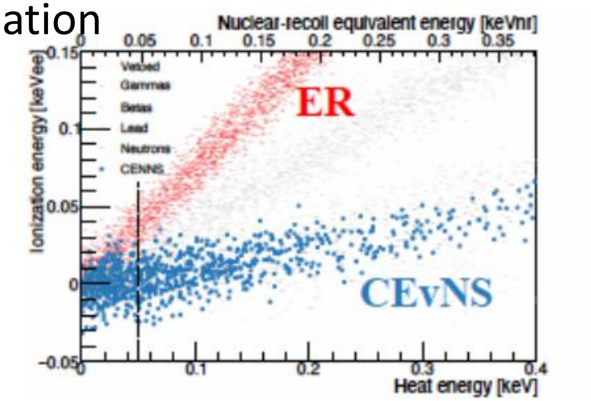
"CryoCube"

Ionization+Heat in Ge

Sensors: NTDs and HEMTs



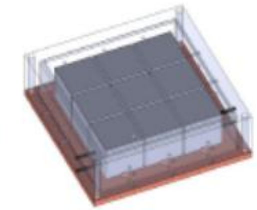
Simulation

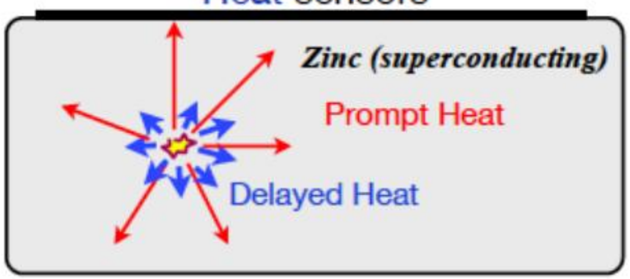


"Q-Array"

Heat Pulse Timing in Zn

Sensors: TESs





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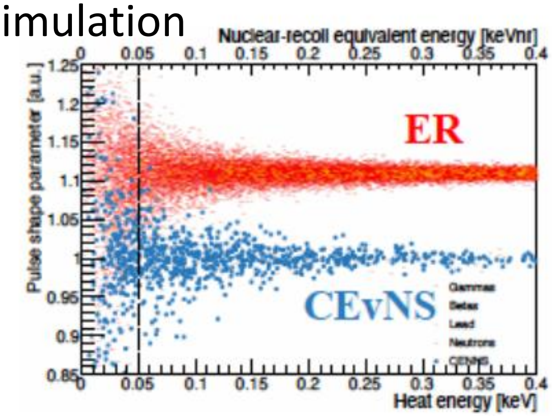

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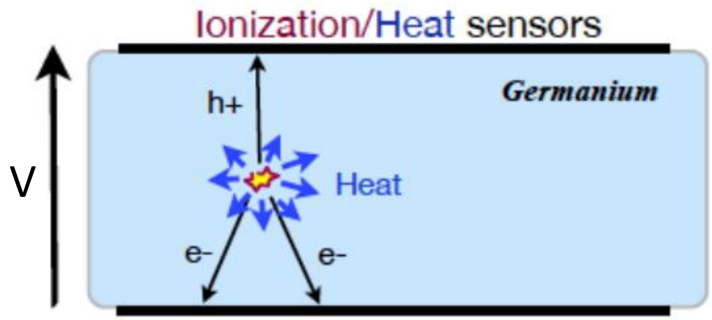

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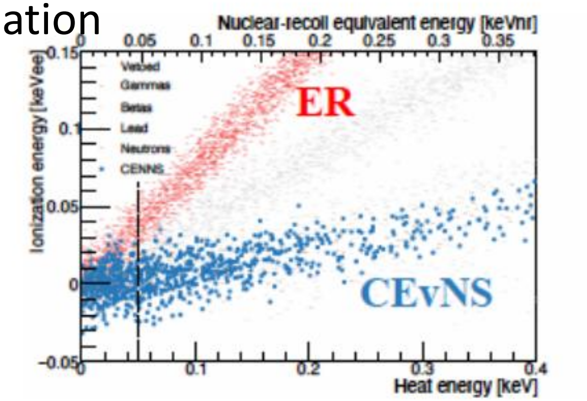

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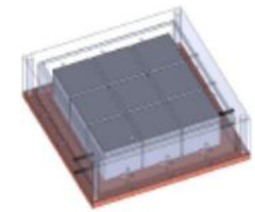

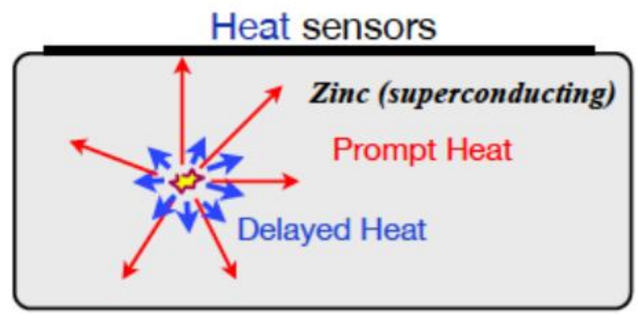

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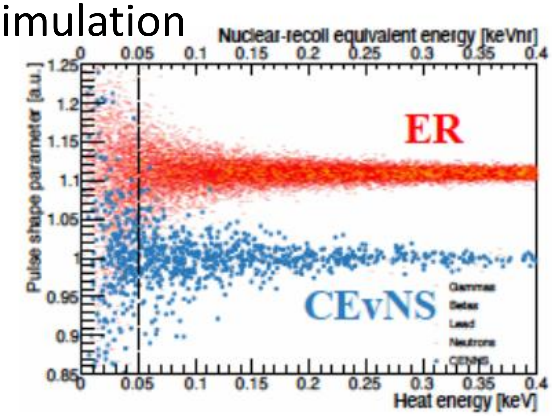
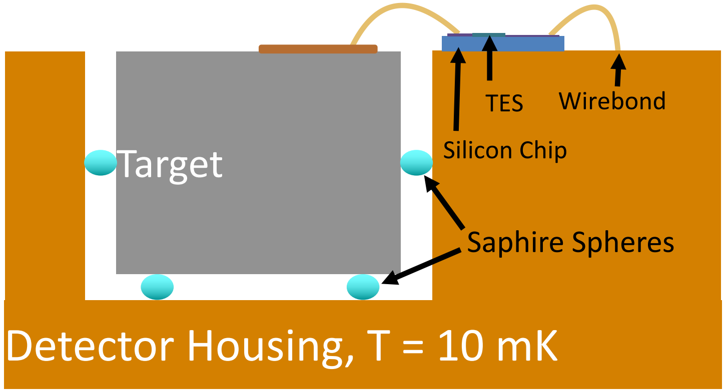
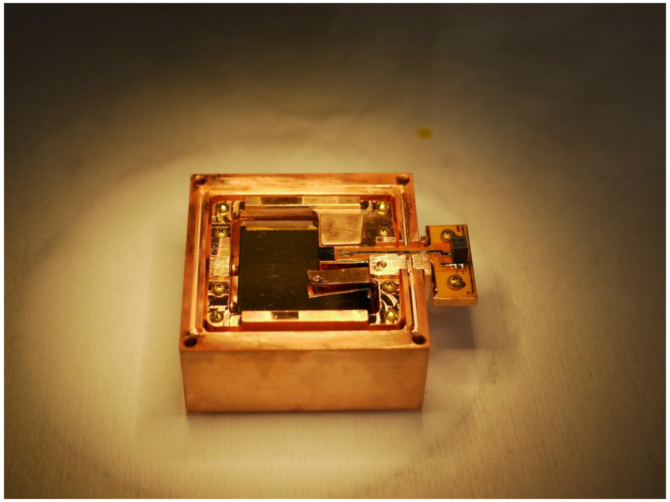


A New Architecture for Modular Cryogenic Detectors

- New modular sensor design using Al/ Mn Transition Edge Sensors (TES)
- Scalable architecture decoupling target from thermometer
- Designs for both Ricochet (reactor coherent neutrino scattering) and CUPID (neutrinoless double beta decay) experiments underway



Detector Housing



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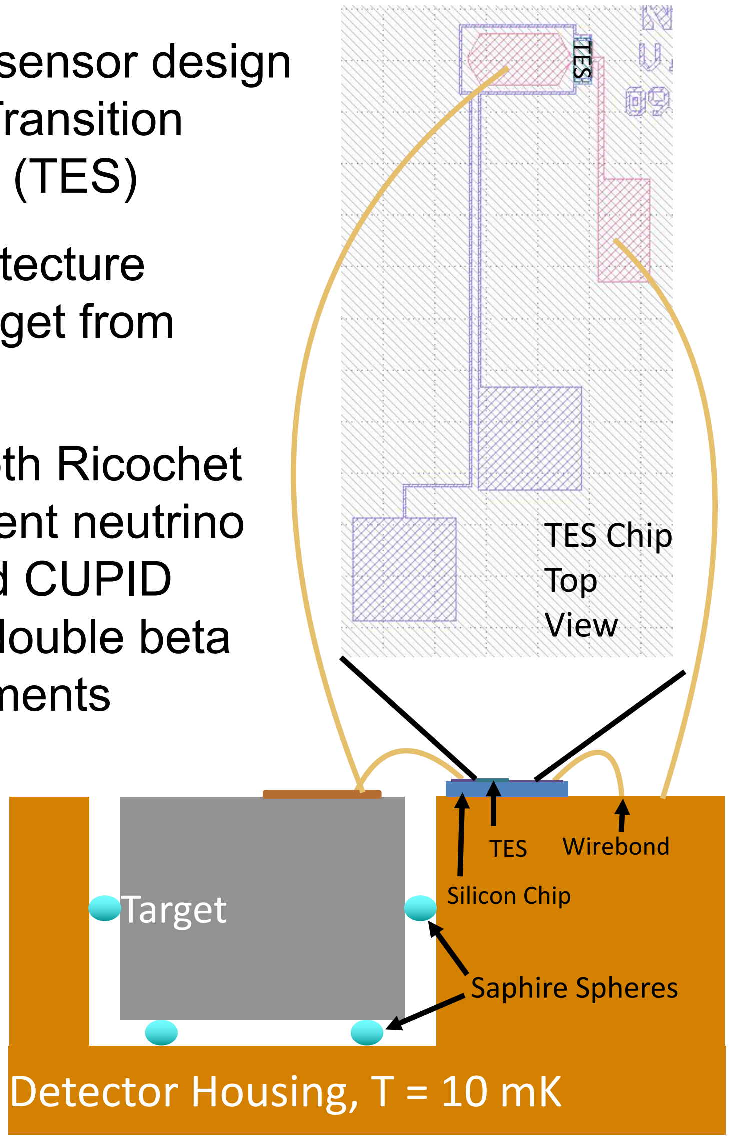

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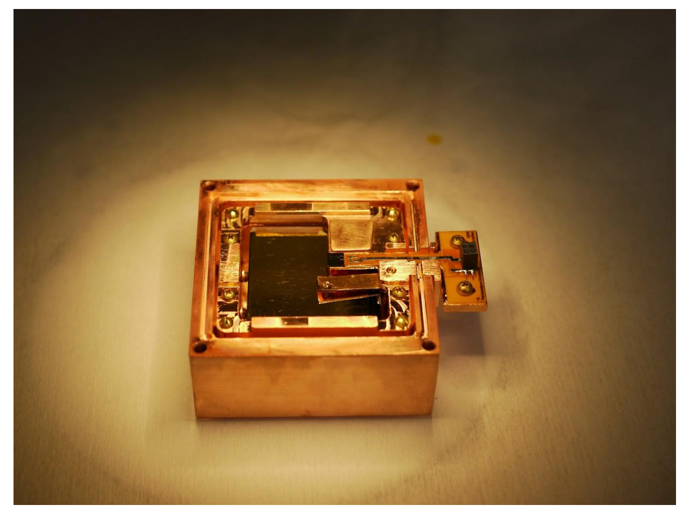

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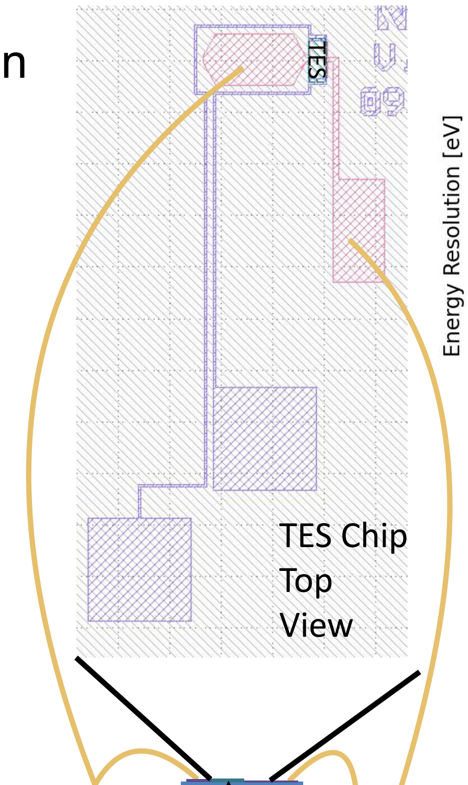
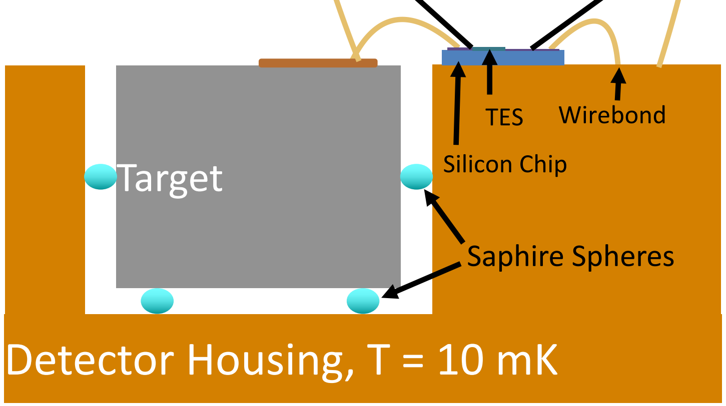
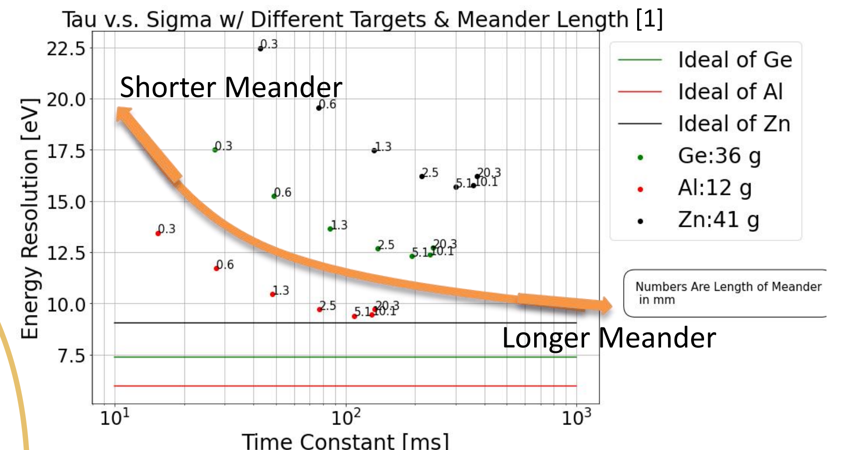
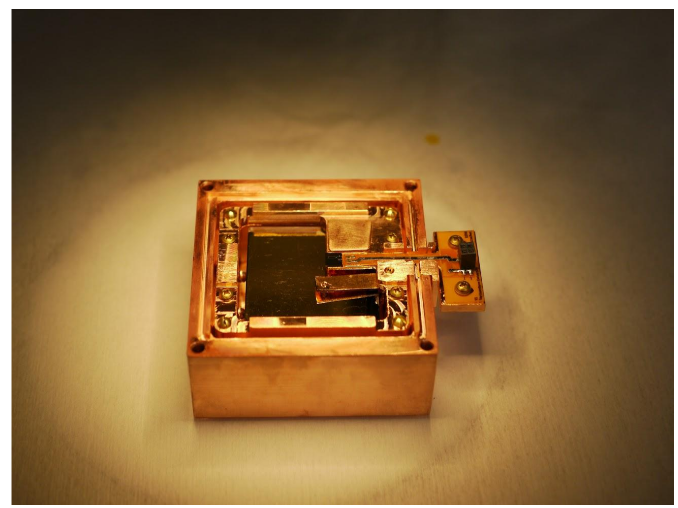






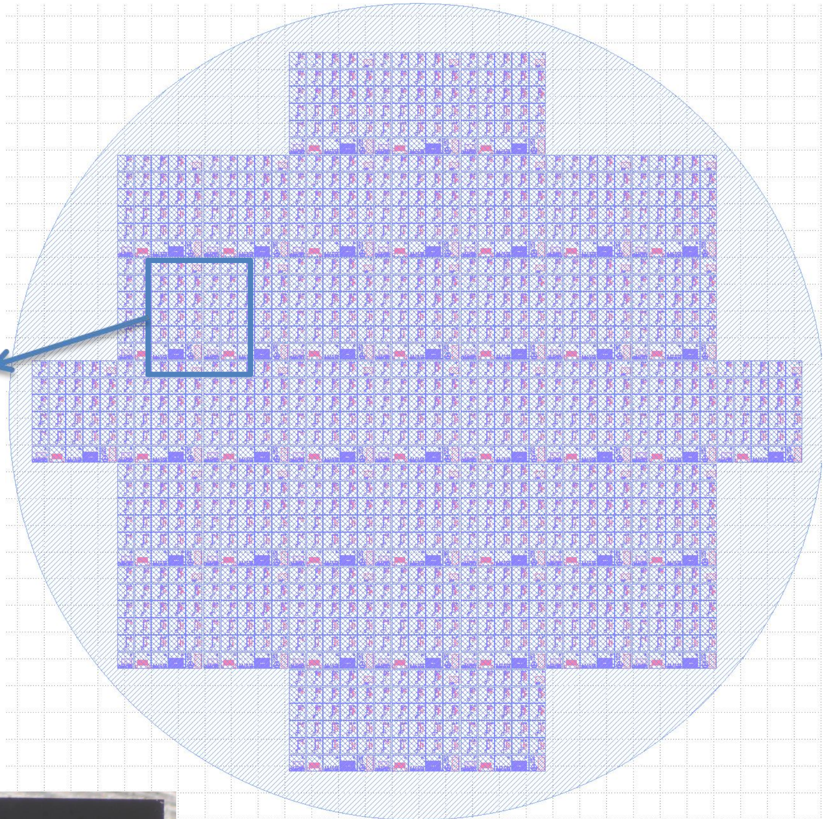
[1]: Transition Edge Sensor Chip Design of Modular CEvNS Detector for the Ricochet Experiment. R. Chen, et al. https://arxiv.org/abs/2111.05757

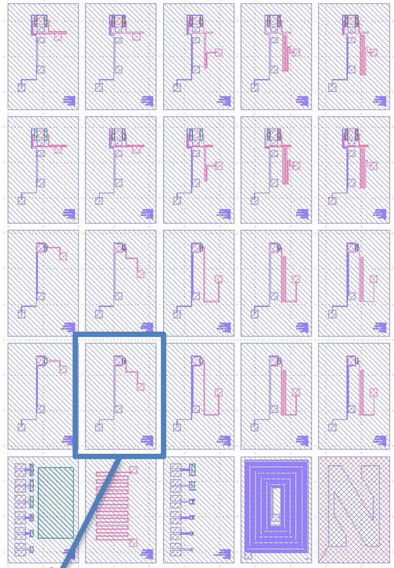
Detector Housing

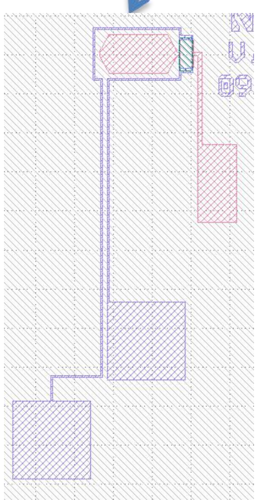


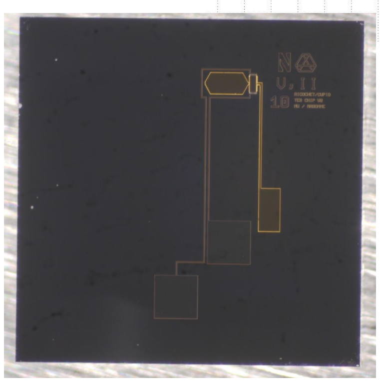
Ricochet Modular Sensor Design

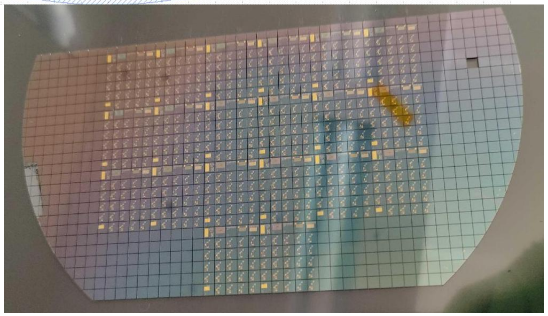
- Al/Mn TES with tunable Tc fabricated at Argonne National Laboratory
- More than 1000 chips from a single wafer
- Easy to change design and re-fabrication
- Already got a whole wafer.





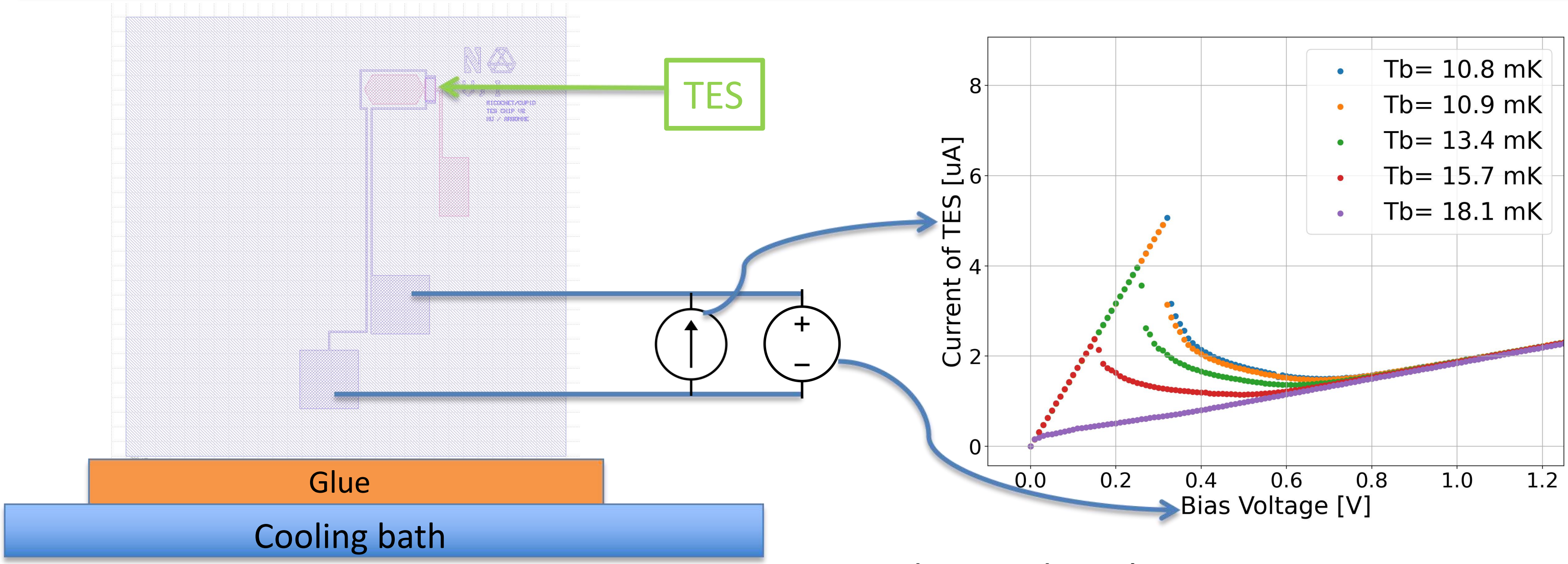


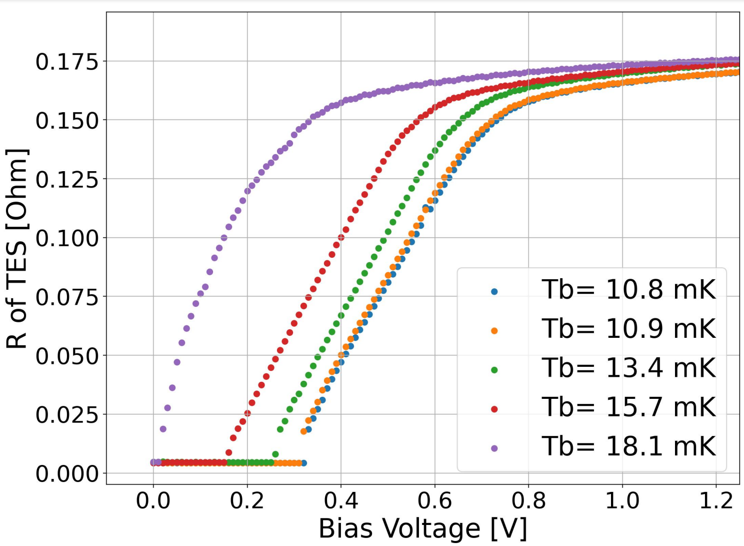




A 6-inch test wafer

TES Characterization





- Understanding the TES parameters is one of the first steps in understanding the full detector performance.
- To measure TES parameters, we attached a TES chip to the cooling bath without any target.
- IV curves are usually the first measurement made in characterizing a TES.

- Measured Tc is ~ 20 mK for this wafer.

TES Characterization

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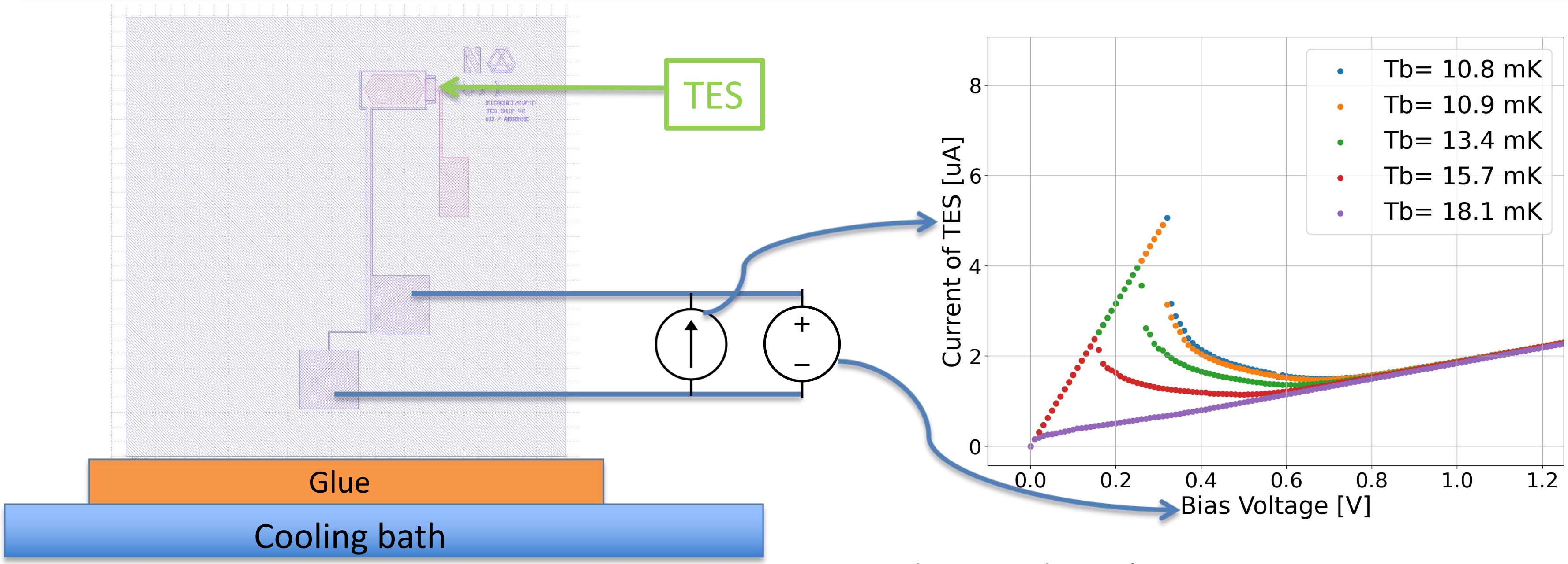

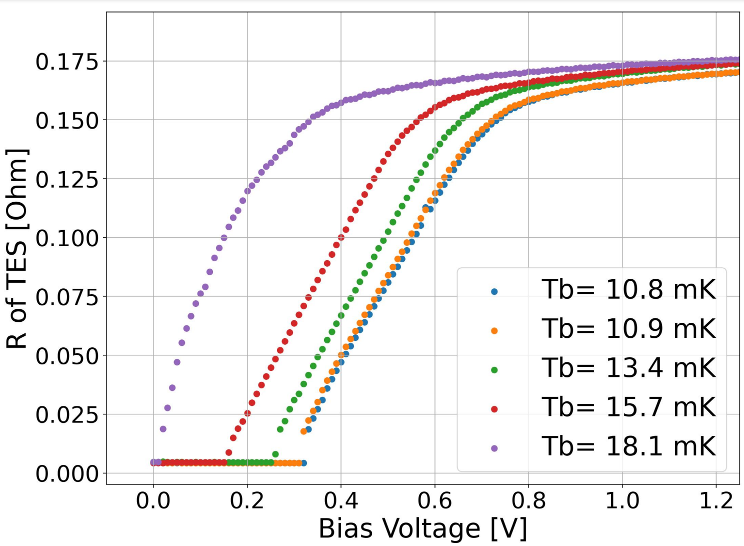

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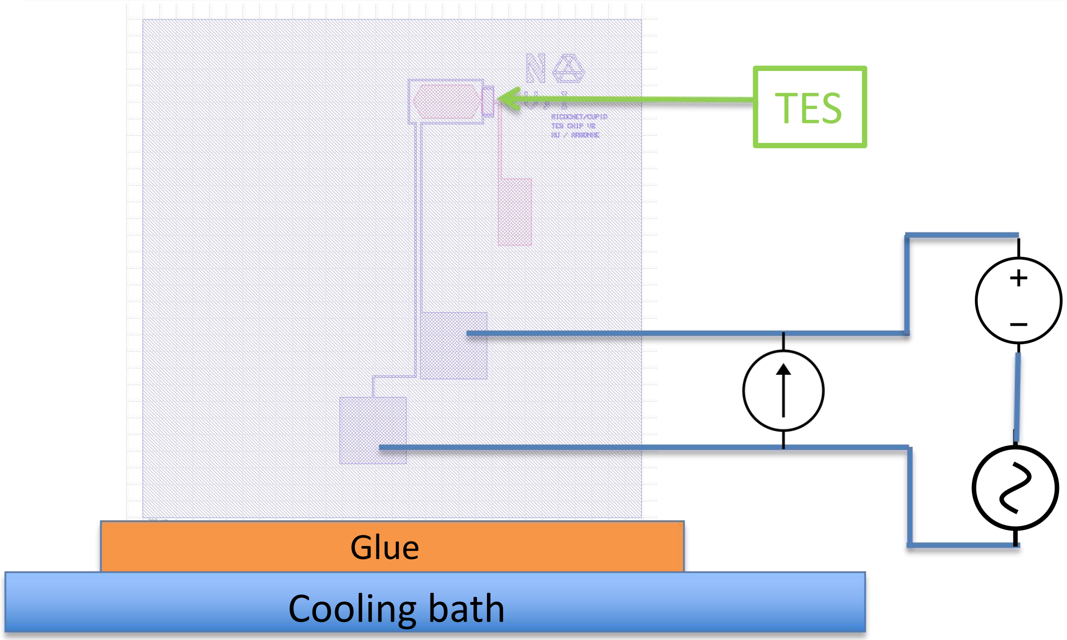
- To measure TES parameters, we attached a TES chip to the cooling bath without any target.
- IV curves are usually the first measurement made in characterizing a TES.
- IV curve tells us the static response.

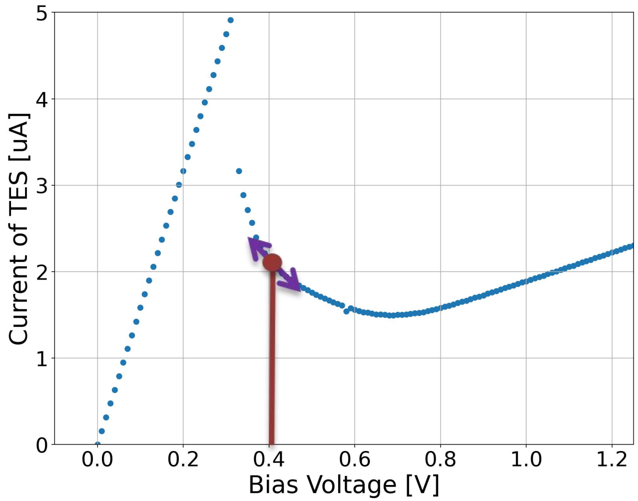
Furthermore, we want the dynamic response!

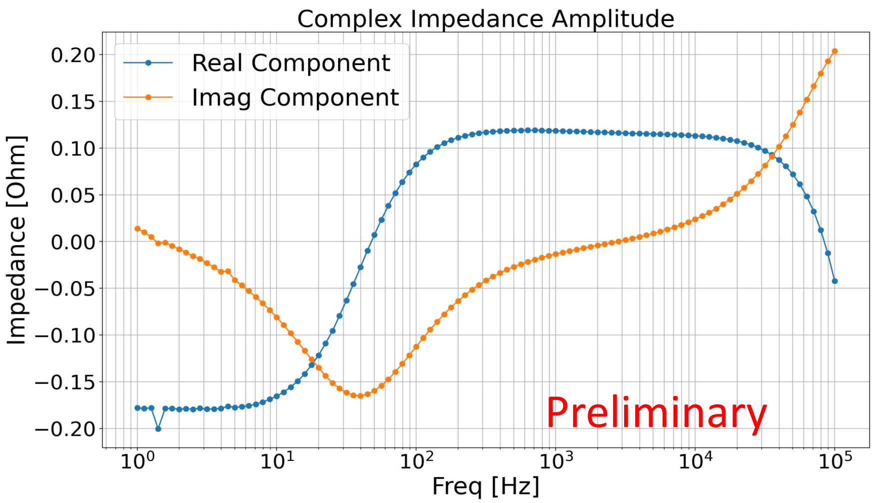
Complex Impedance of TES chip



DC source to bias TES at a certain working point.

AC source provides a sine wave of different frequency and amp ~ 1% of DC.





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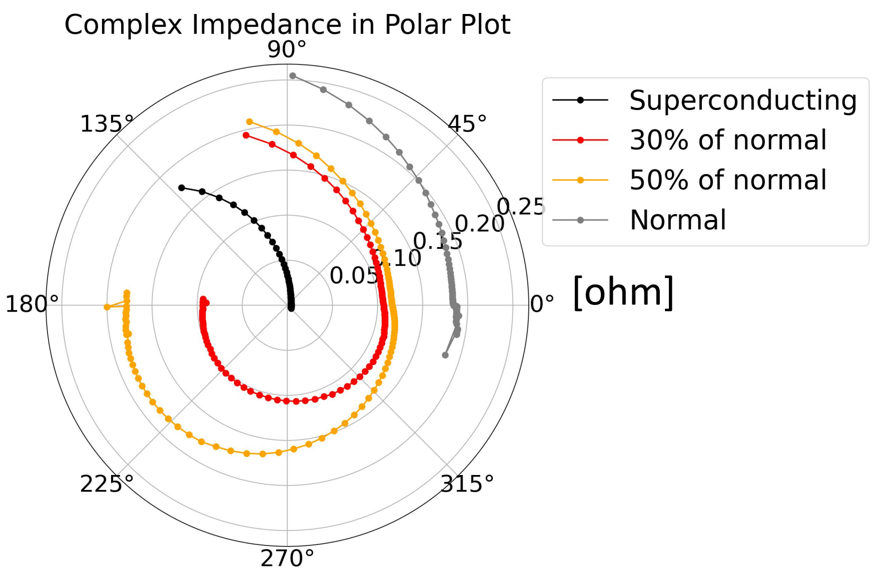

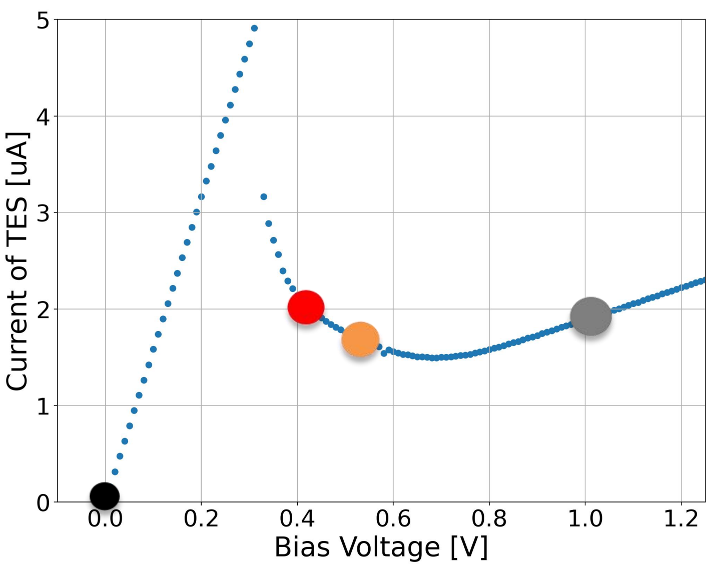

- Repeat the same measurement at different bias point:
  - 30%: Resistance of TES is ~ 30% of normal resistance
  - 50%: Resistance of TES is ~ 50% of normal resistance

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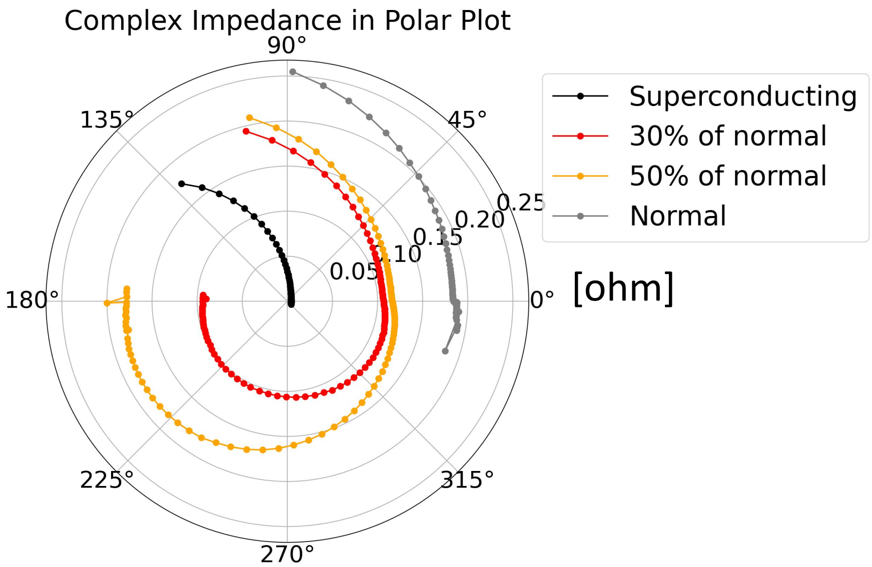

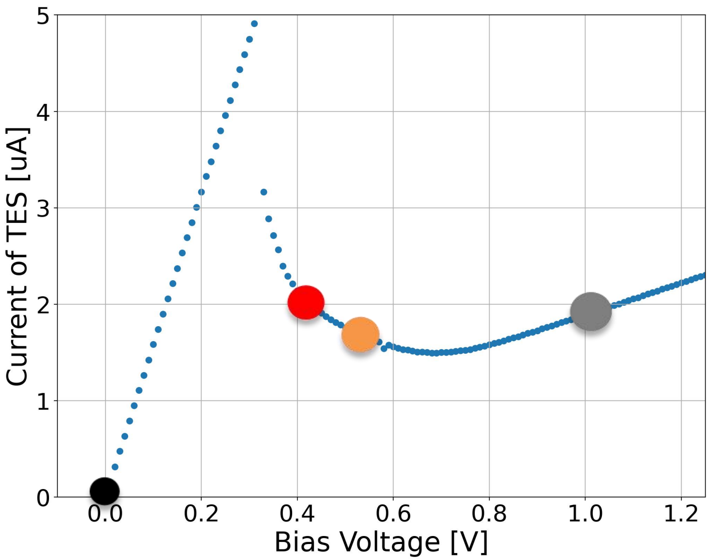

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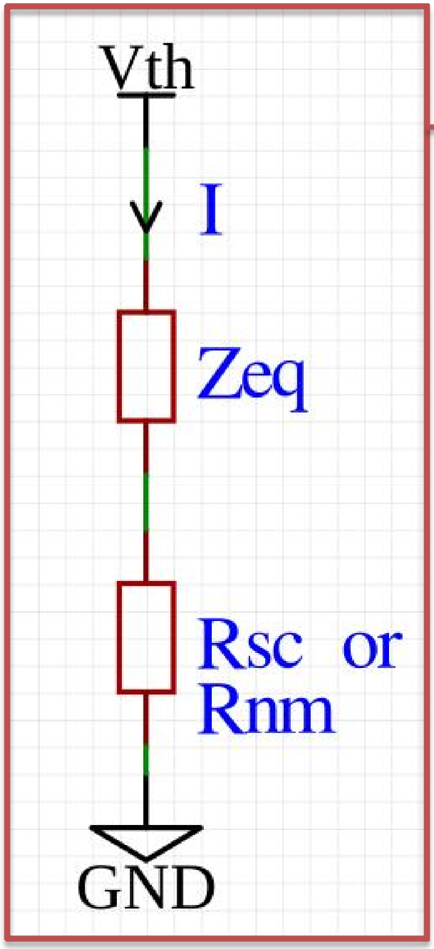
- This still contains the impedance of the bias circuit!
- Superconducting and normal results are used to characterize the bias circuit.
  - Superconducting: No bias voltage
  - Normal: Apply large bias so that TES is totally normal.
  - When superconducting or normal, the TES is just a resistor and we know the resistance.

Characterization of the Bias Circuit



- Assume the bias circuit does not change with bias current:
  - Thevenin equivalent of the bias circuit.
  - Vth and Zeq represent the voltage and impedance of the bias circuit.

[1]: Impedance measurements and modeling of a transition-edge-sensor calorimeter.
M. A. Lindeman, et al.
https://doi.org/10.1063/1.1711144

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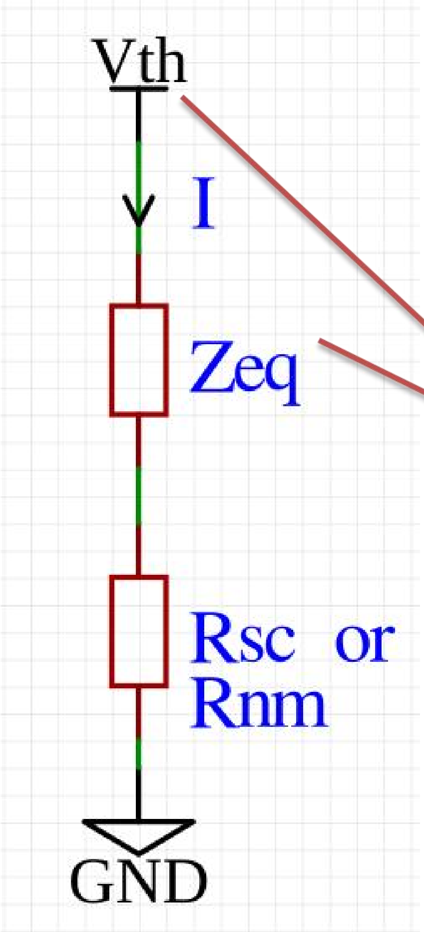

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  - Superconduction (SC) and normal (NM) response --> Vth(f) and Zeq(f)

$$I_{sc/nm}^{-1}(f) = \frac{R_{sc/nm}(f)+Z_{eq}(f)}{V_{th}(f)}$$

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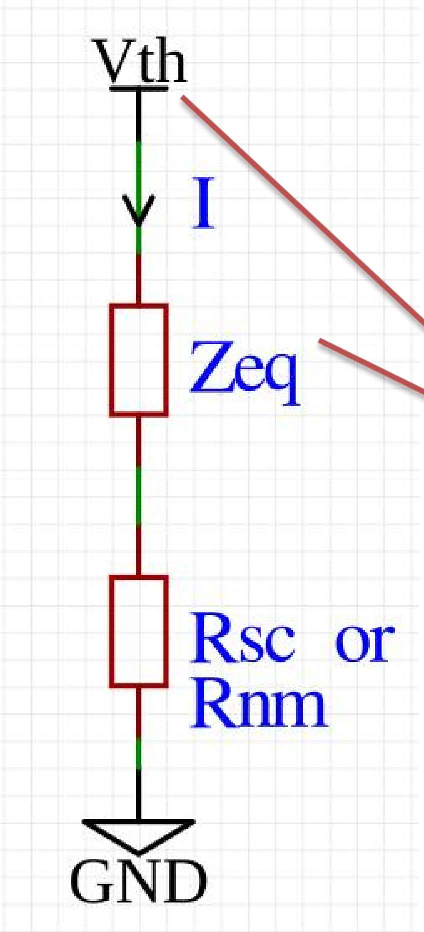

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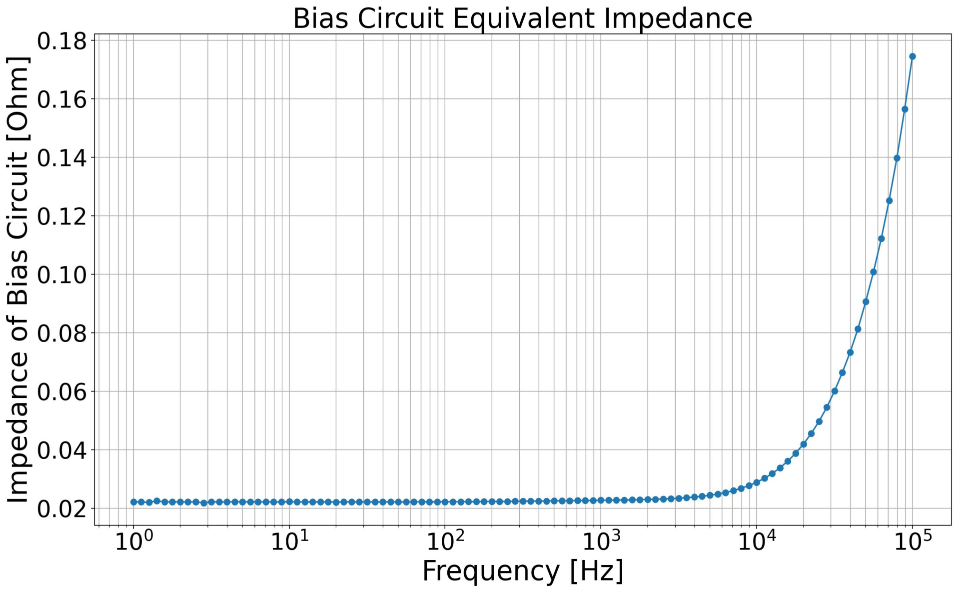

- The impedance of bias circuit is similar to a resistor + inductor.
- Match our expectation!

[1]: Impedance measurements and modeling of a transition-edge-sensor calorimeter.
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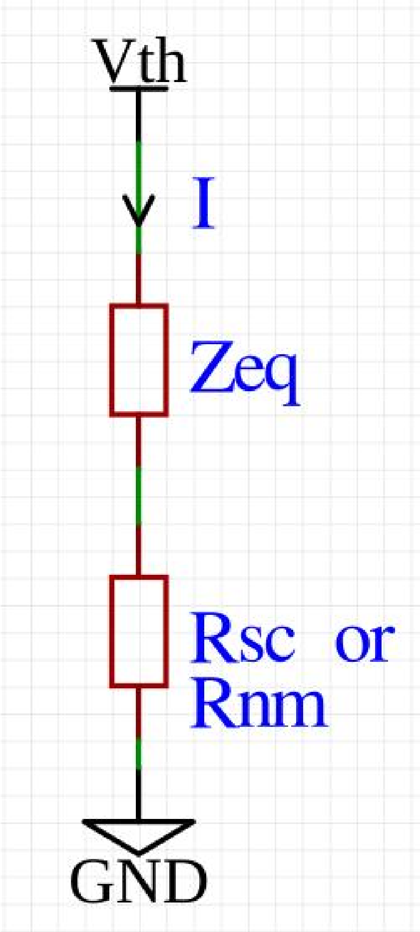

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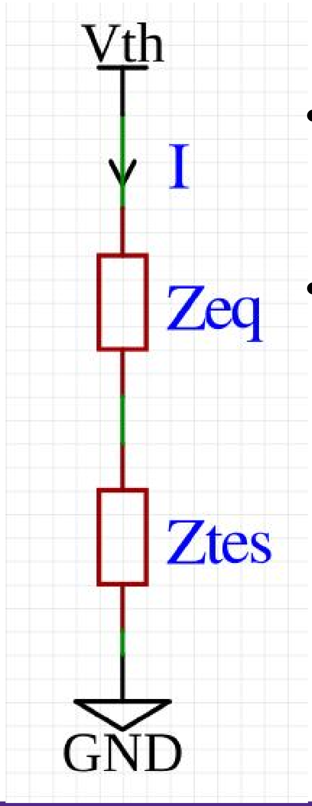

- $$Z_{tes}(f, I_{bias}) = \frac{V_{th}(f)}{I(f, I_{bias})} - Z_{eq}(f)$$

- 30% and 50% response, Vth(f) and Zeq(f)
  --> Ztes

[1]: Impedance measurements and modeling of a transition-edge-sensor calorimeter.
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Complex Impedance of TES chip

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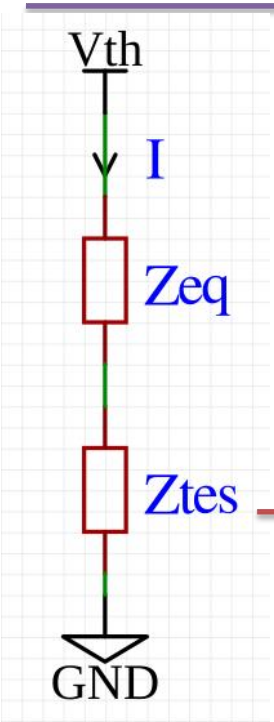
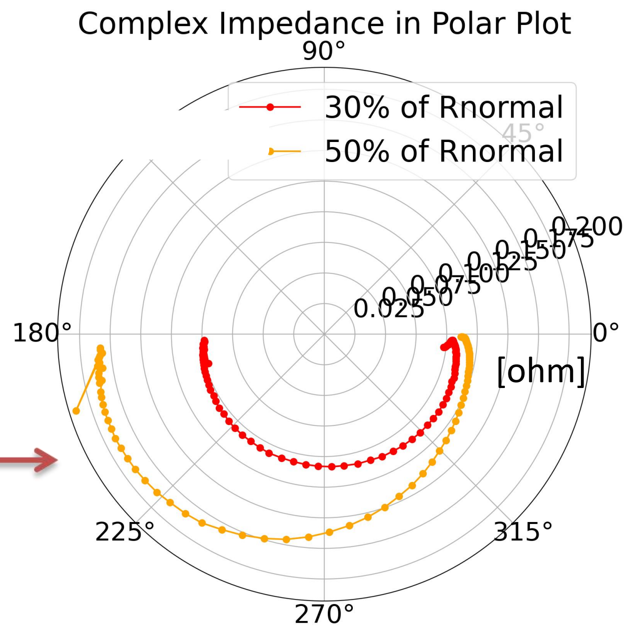
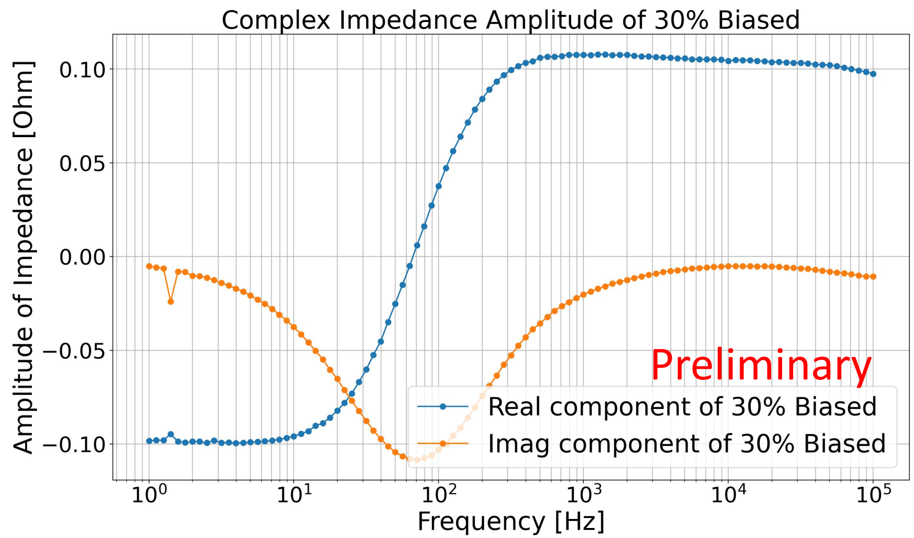
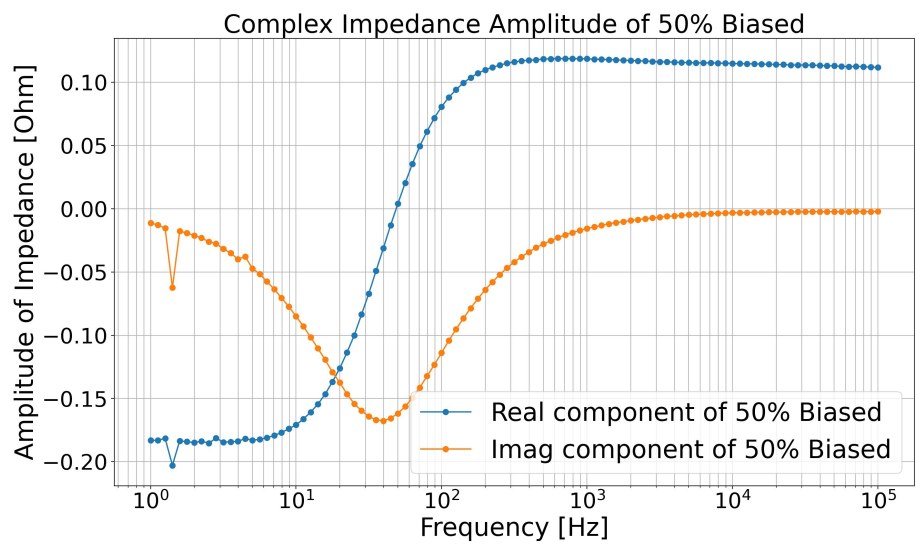








Model for Complex Impedance of TES

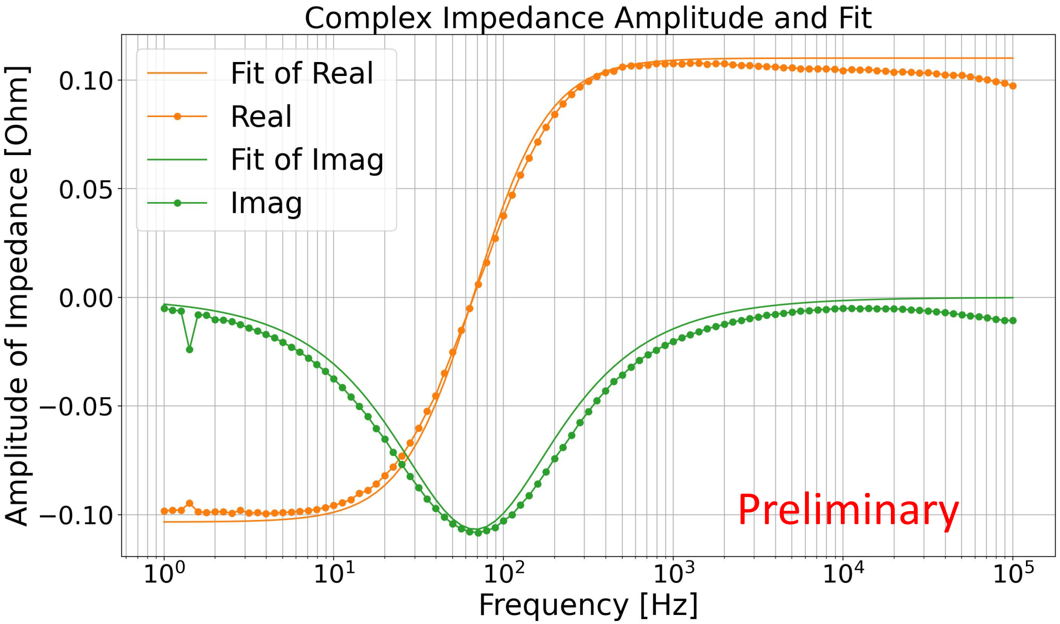
- Model: $$Z_{\text{tes}}(f) = R_0 \frac{(1+\beta)(1+i2\pi f\tau)+\mathcal{L}}{1-\mathcal{L}+2i\pi f\tau}$$ [1]
- R_0 is the resistance of TES at biased point. Depends on how TES biased.

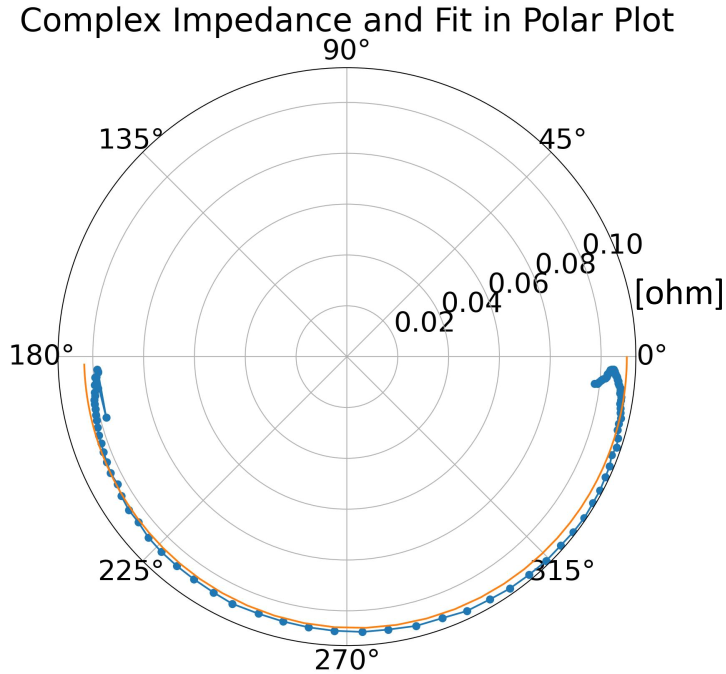
- $$\beta = \frac{I_0}{R_0}\frac{\partial R}{\partial I}\bigg|_{T_0}$$ is the current sensitivity of the TES.
- $$\mathcal{L} = \frac{\alpha}{n}\left(1-\left(\frac{T_b}{T_c}\right)^n\right)$$ Loop Gain. n=5 determined by the coupling type.
  - $$\alpha = \frac{T_0}{R_0}\frac{\partial R}{\partial T}\bigg|_{T_0}$$ is the temperature sensitivity of the TES.
- $$\tau = \frac{C_{\text{TES+Au}}}{G_{\text{TES+Au}}}$$ time constant of the TES.

What used to fit

[1]: Complex impedance of a transition-edge sensor with sub-µs time constant
https://doi.org/10.1063/1.5127100

Fit Results for 30% Bias TES





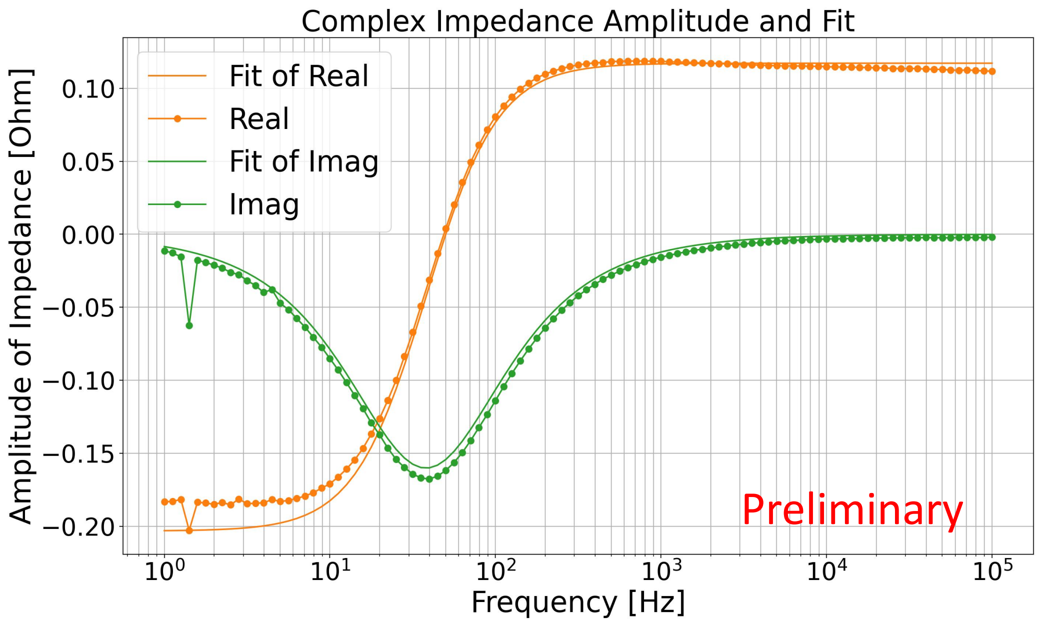
$$\mathcal{L} = 4.4 \pm 0.3$$

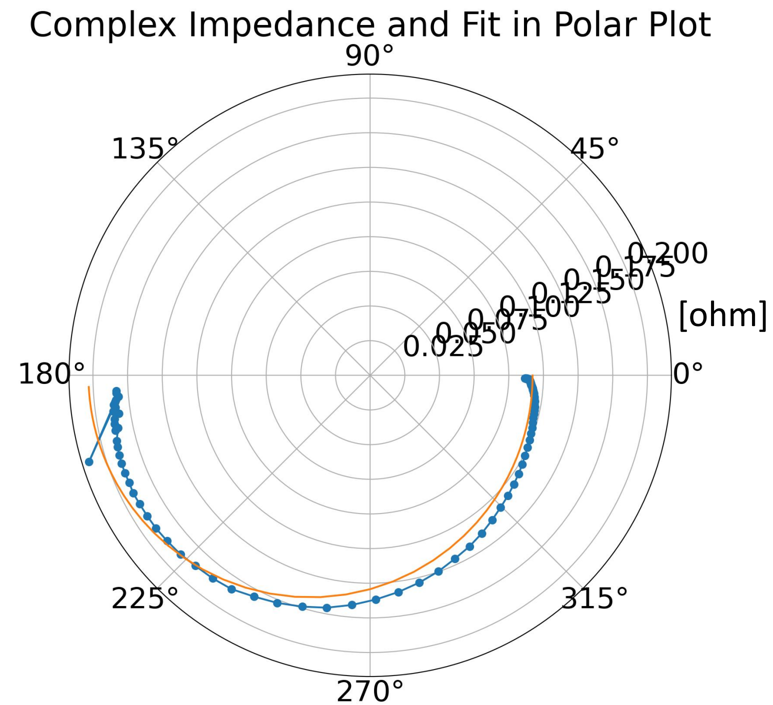
$$\beta = 0.92 \pm 0.03$$

$$\tau = 8.0 \pm 0.6\ ms$$

- Rn = 185 mOhm
- TES bias @ 30 % of Rn
- α estimated by $\mathcal{L}$: 24

Fit Results for 50% Bias TES





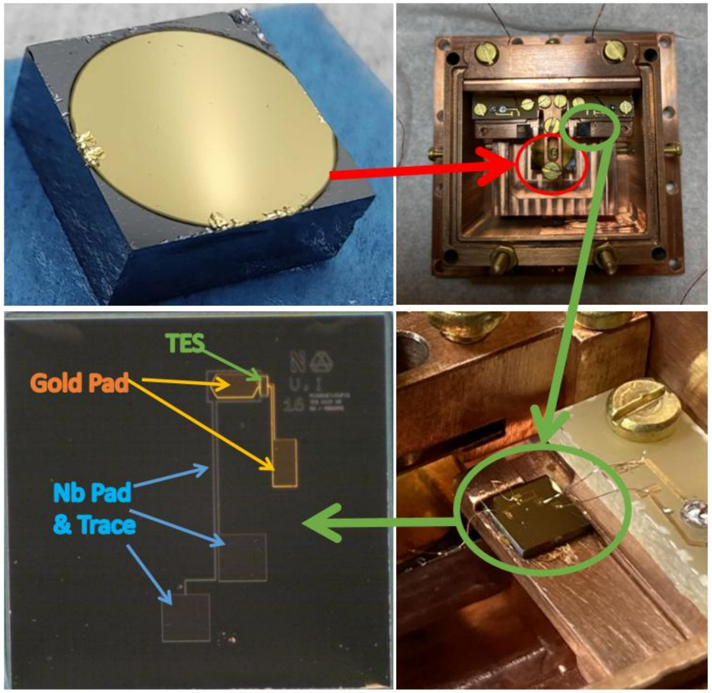
$$\mathcal{L} = 2.17 \pm 0.03$$

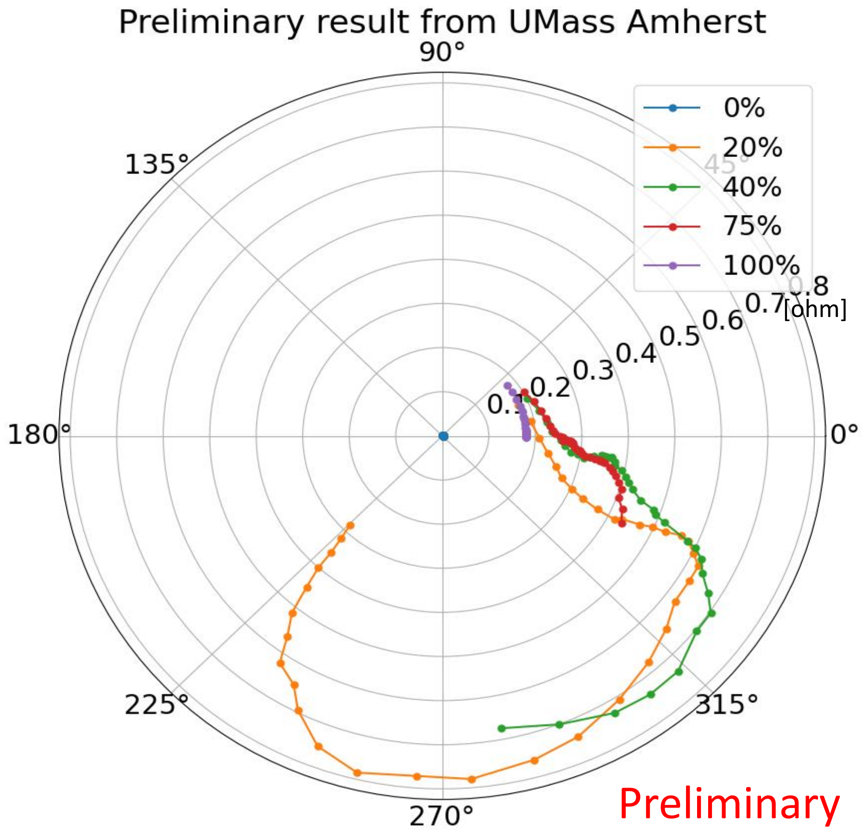
$$\beta = 1.10 \pm 0.01$$

$$\tau = 4.9 \pm 0.1\ ms$$

- Rn = 185 mOhm
- TES bias @ 50 % of Rn
- α estimated by $\mathcal{L}$: 12

Next Steps



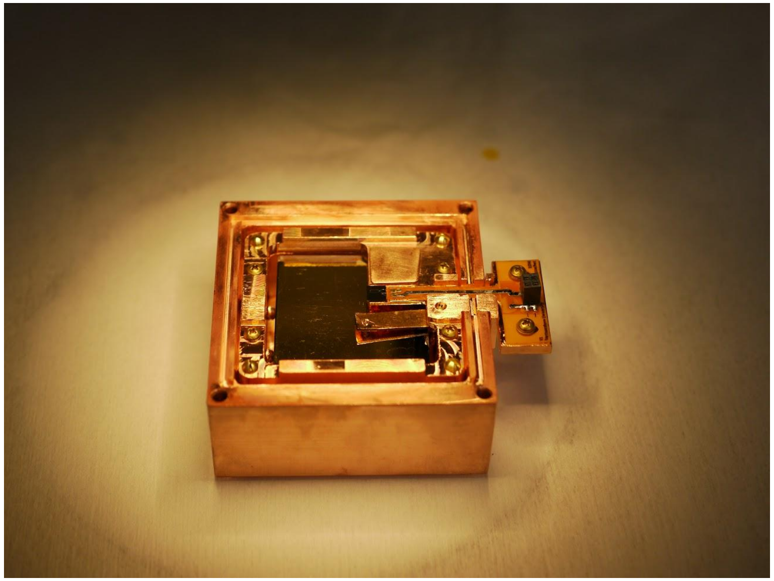


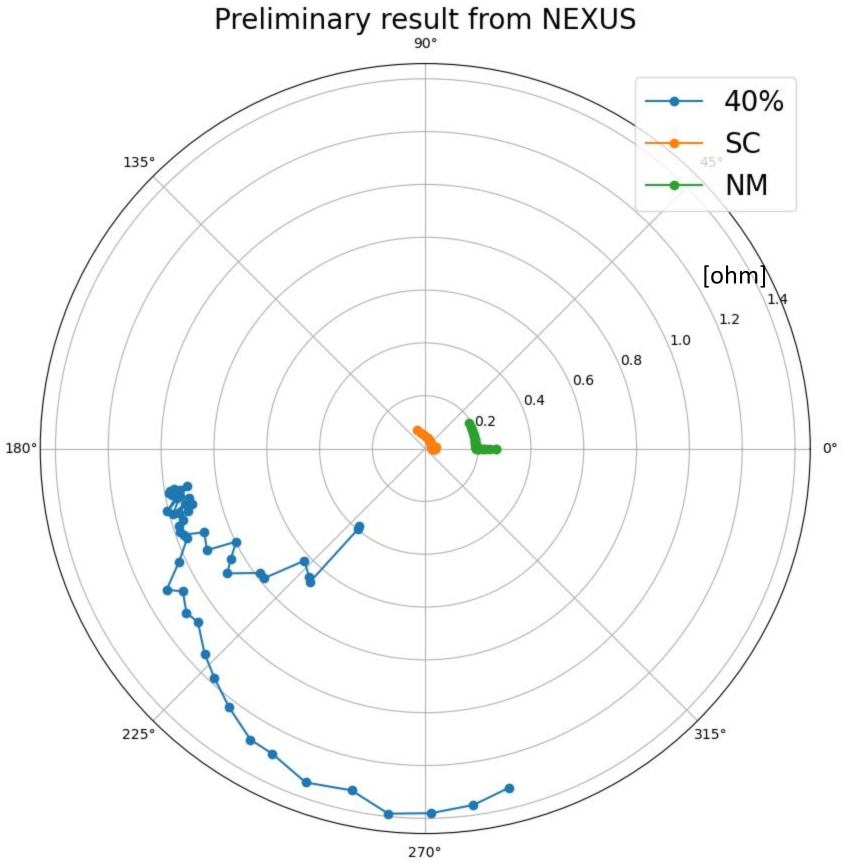
- A detector with 1 gram Silicon target has been built up at UMass Amherst

- The complex impedance measurement is ongoing!

- More info will be presented on Dec 1, 2022, 11:15 AM ET by Luke Chaplinsky

Next Steps

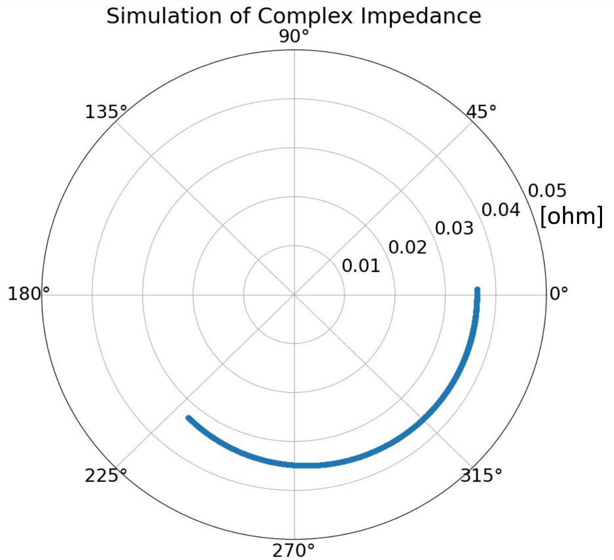


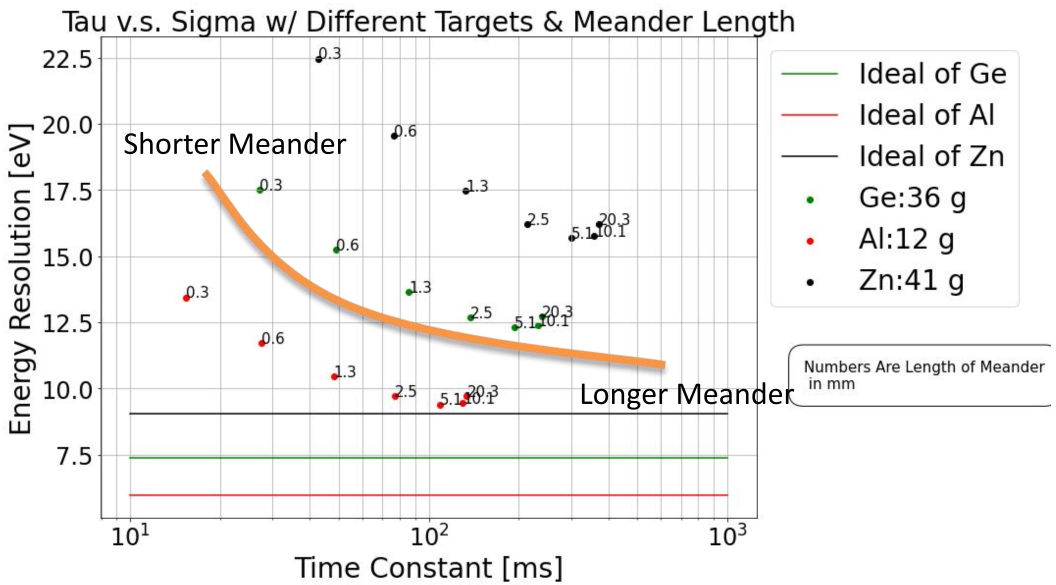


- A detector with 36 gram Germanium target is installed at NEXUS (Northwestern EXperimental Underground Site) of Fermi National Laboratory.

- The complex impedance measurement is also on going!

Next Steps

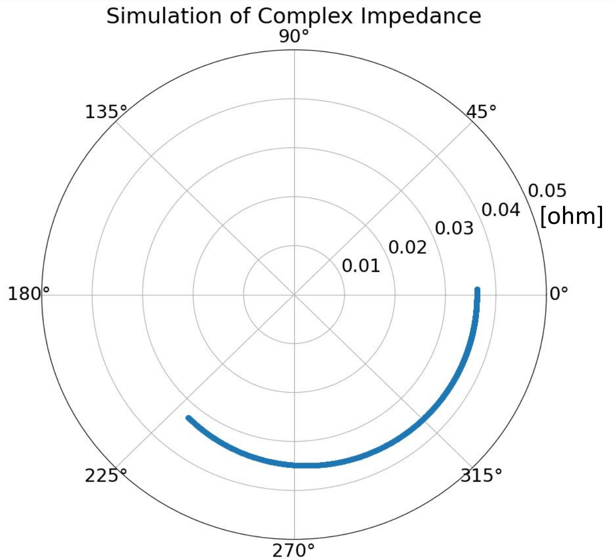


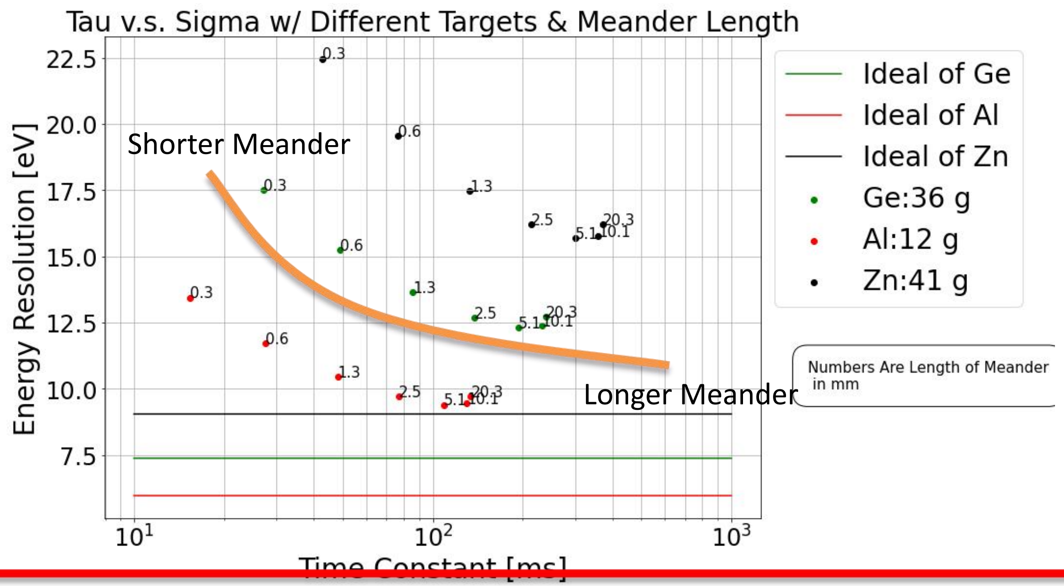


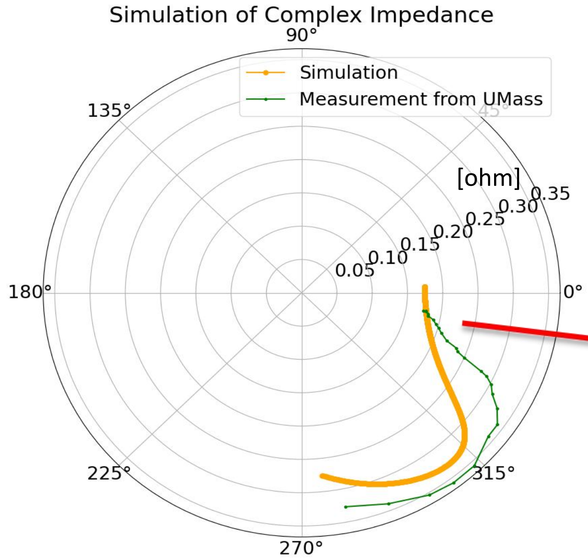
- In our previous simulation [1], some parameters were assumed from other kinds of TES detectors:
  - α = 100, β = 1
- Using these parameters, the simulation behaves as a semi-circle on the complex plane which does not match our measurement at UMass.

[1]: Transition Edge Sensor Chip Design of Modular CEvNS Detector for the Ricochet Experiment
R. Chen, et al.
https://arxiv.org/abs/2111.05757

Next Steps







- Improving the simualtion by adding parameters measured from the Al/Mn TES chip.
- Our model can now produce similar complex impedance curves!
- Fitting UMass measurements using new TES parameters underway.
- A better model of Ricochet detectors will come out!

Q&A