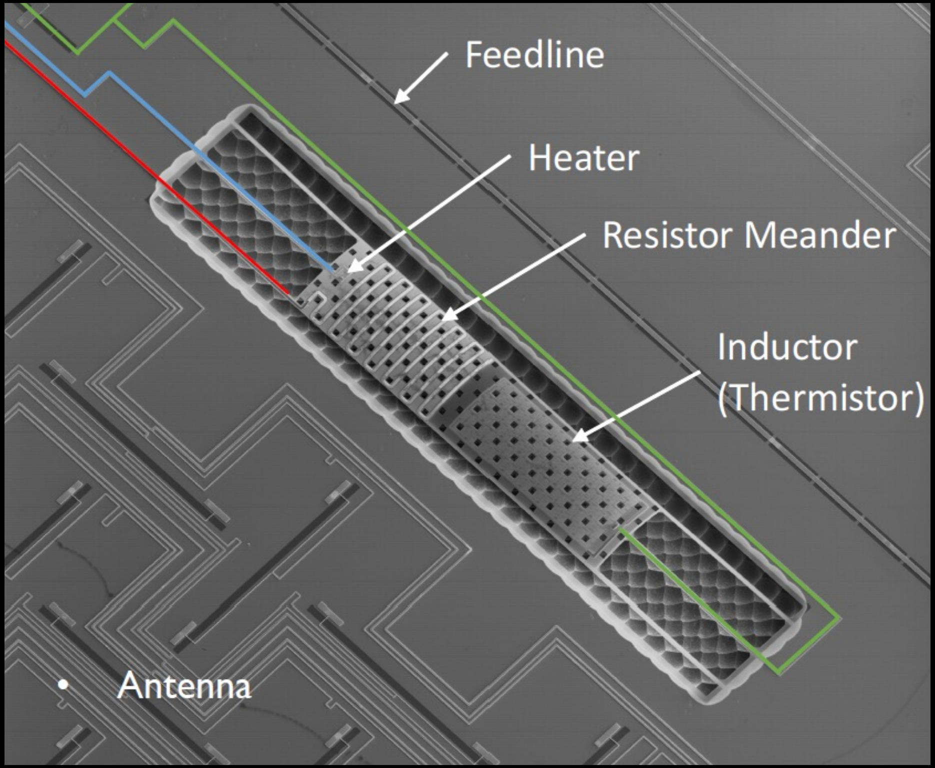
TKIDs for CMB and millimeter wave astrophysics



Roger O'Brient

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CPAD 2023- SLAC

Team Members

Albert Wandui

Lorenzo Minutolo

Bryan Steinbach

- Cliff Frez- JPL
- Anthony Turner- JPL
- Sophia Fatigoni Caltech
- Kenny Lau- Caltech
- Jamie Bock- Caltech
- Jonas Zmuidzinas- Caltech

- Zoe Smith- Stanford
- Taj Dyson- Stanford
- Shawn Henderson- SLAC
- Shub Agriwal- UPenn
- Katie Hughes- UChicago

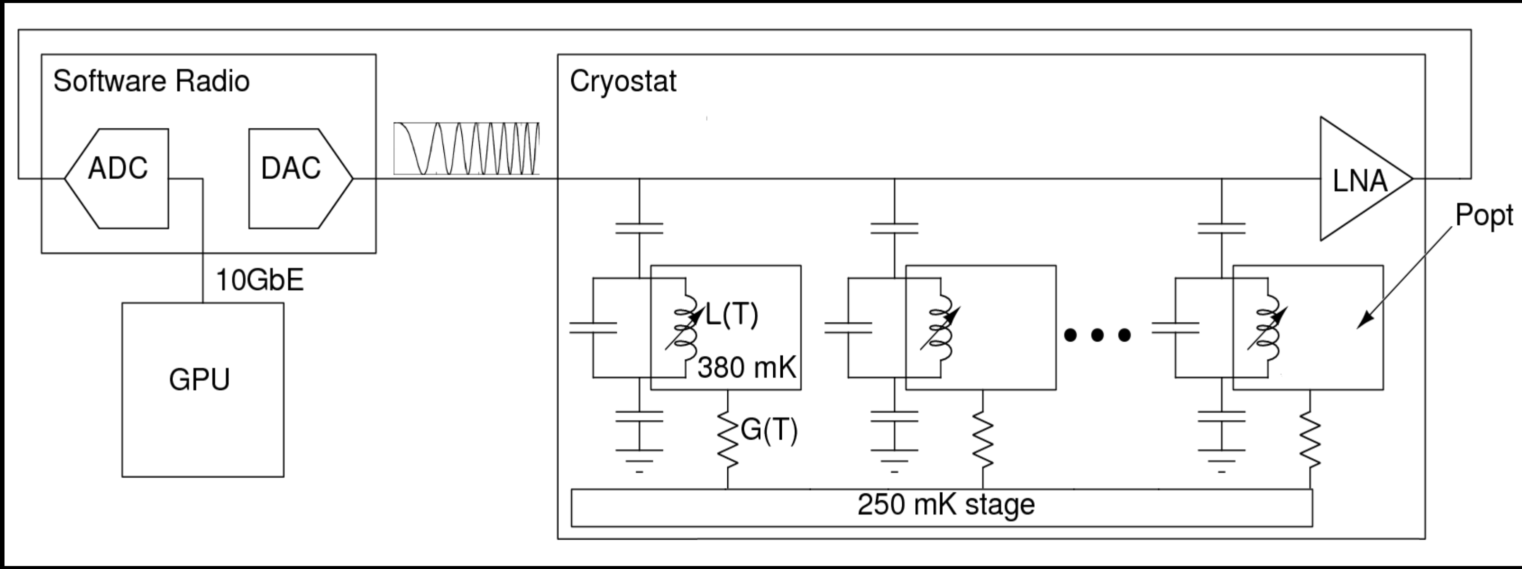
Outline

- Motivations
- Designs
- Performance
- What’s next?

Scientific Applications

- Millimeter waves are crucial for cosmology
- Cosmic Microwave Background: post-S4 larger field maps
- Intensity line mapping:
    - CII to trace reionization
    - CO to trace cosmic expansion history through dark energy dominance
- All require large arrays of detectors

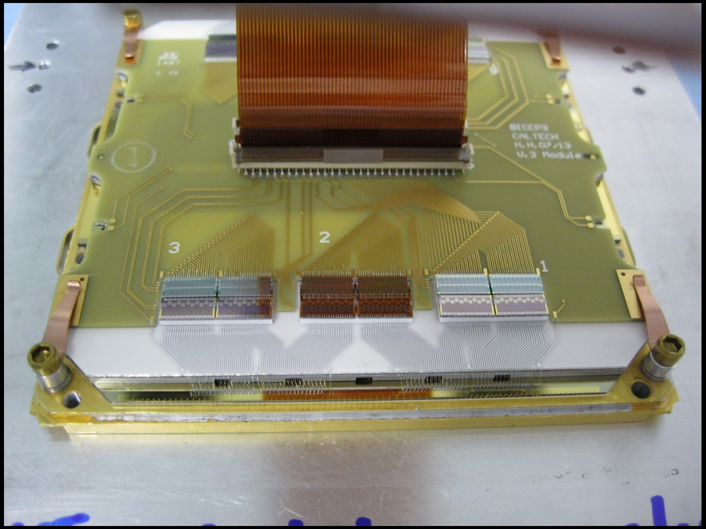
Thermal Kinetic Inductance Detectors



- Bolometer with kinetic inductance thermometer
- Inductors are in high-Q resonators, each with unique resonant frequency
- All inductors are in parallel from a common transmission line
- Fundamental detector noise is phonons in the legs, *not* GR

The merits of TKIDs

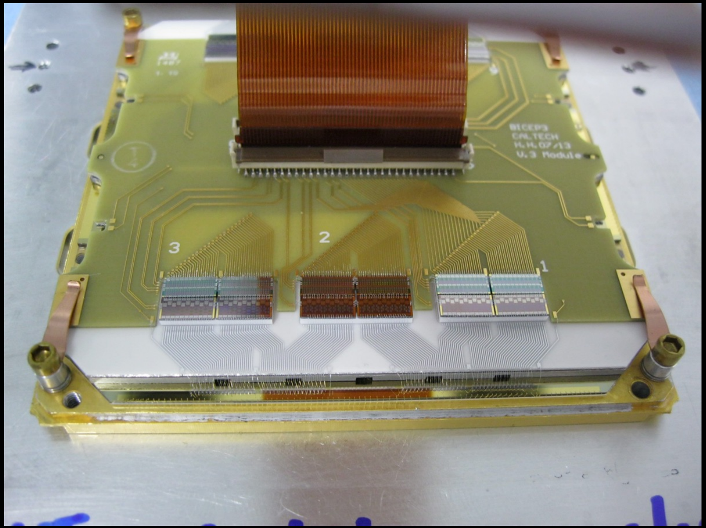
- No SQUIDs- simplified readout



Note all the ~1mm 3-D wirebonds (Nightmare fuel!)

The merits of TKIDs

- No SQUIDs- simplified readout
- Retain many valuable bolometer features:
  - Ease of optical coupling
  - Natural radiation hardening
  - Can be background noise limited
  - Calibration of responsivity



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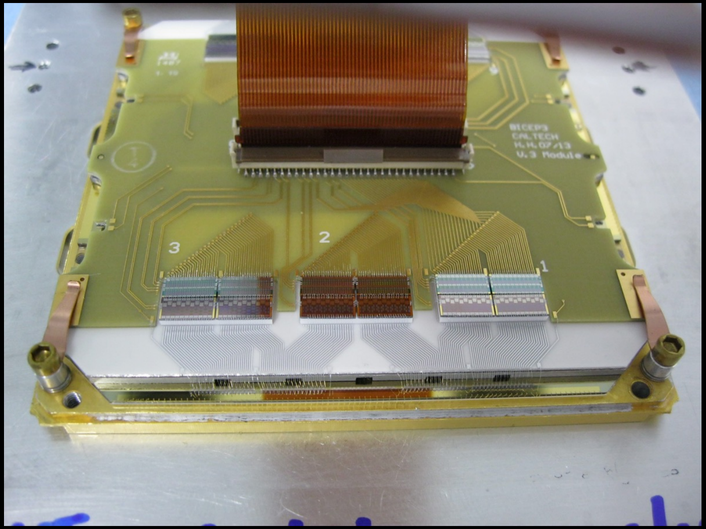
The merits of TKIDs

- No SQUIDs- simplified readout
- Retain many valuable bolometer features:
  - Ease of optical coupling
  - Natural radiation hardening
  - Can be background noise limited
  - Calibration of responsivity
  - Myriad design parameters:
    - T_c
    - T_{bath}
    - Inductor volume
    - T_{island}
    - Bolometer G
    - Inductor optical absorption efficiency



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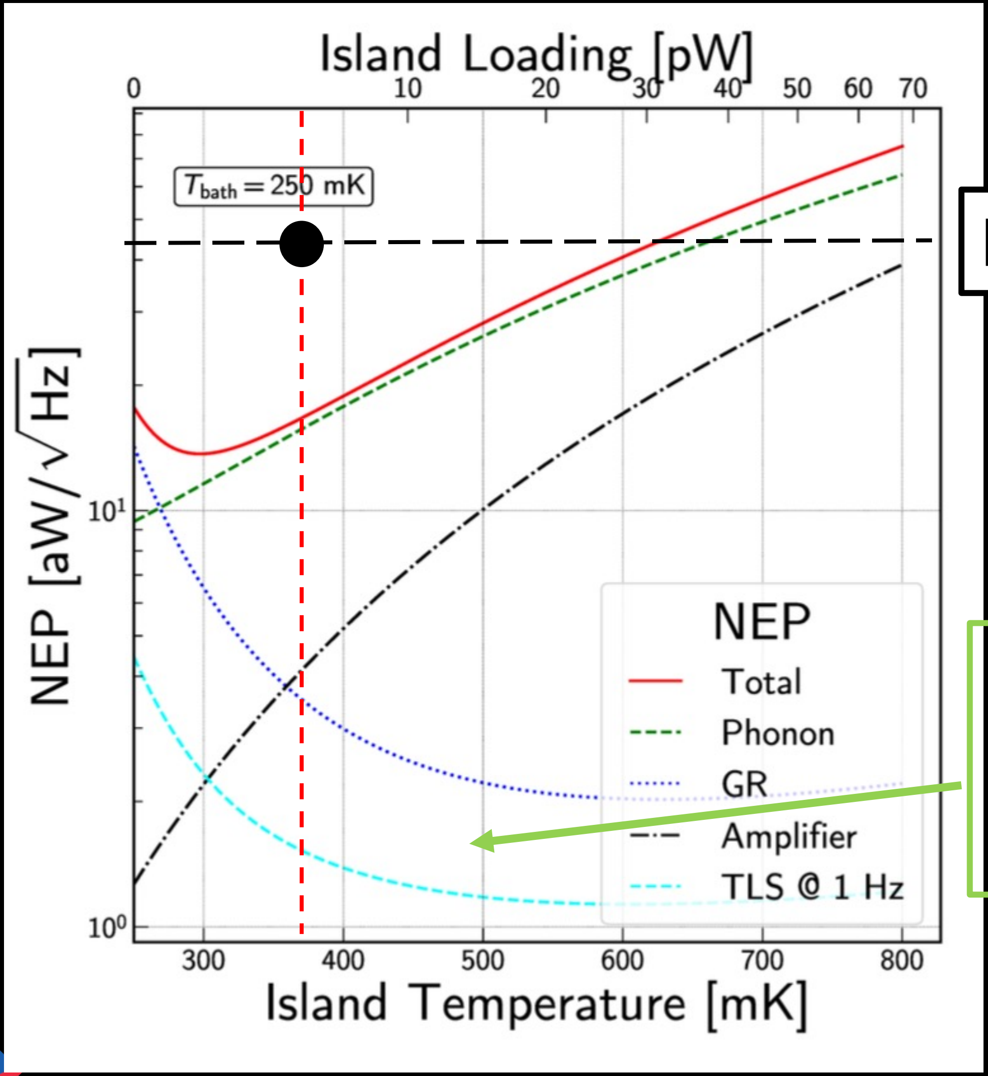
Sensitivity



$$S = \frac{\partial f_r}{\partial P} = f_r(T)\frac{\beta(\omega,T)\kappa(T)}{2Q_iG(T)T}$$

Expected Photon Noise

High responsivity suppresses GR and TLS noise at higher loading

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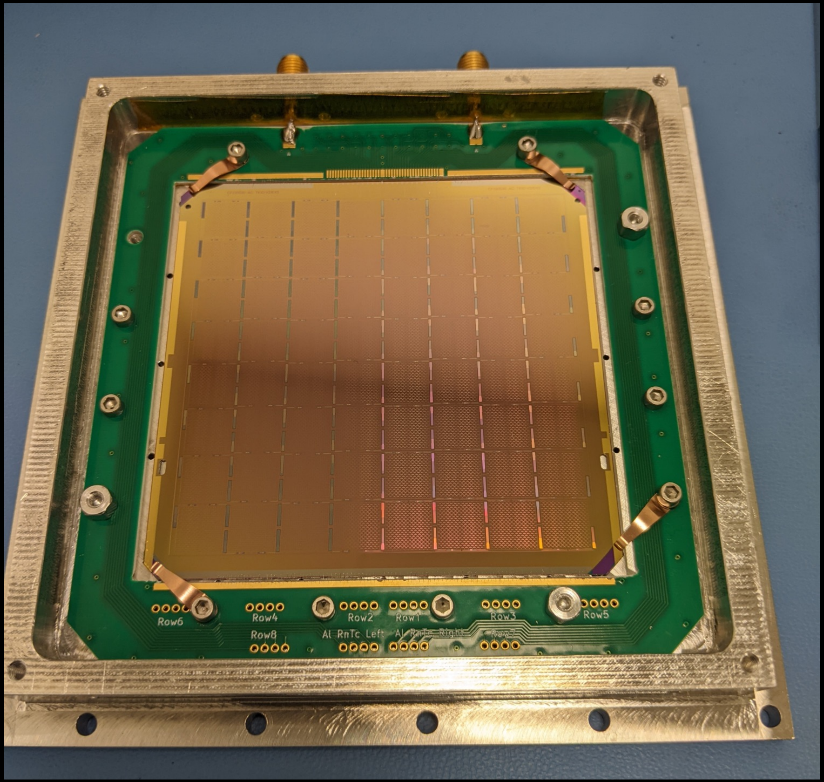
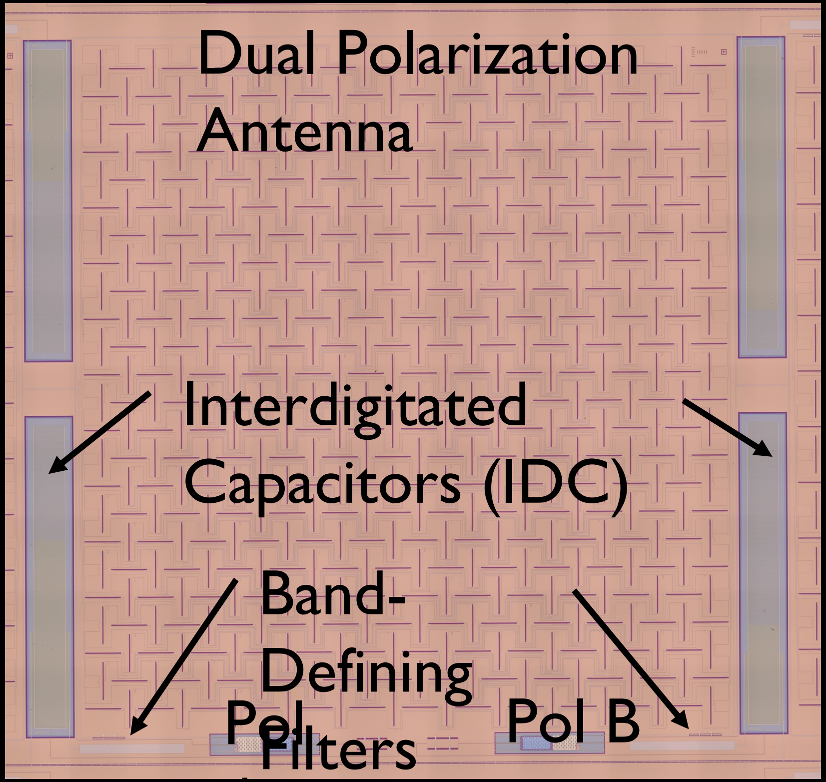
Detector Design





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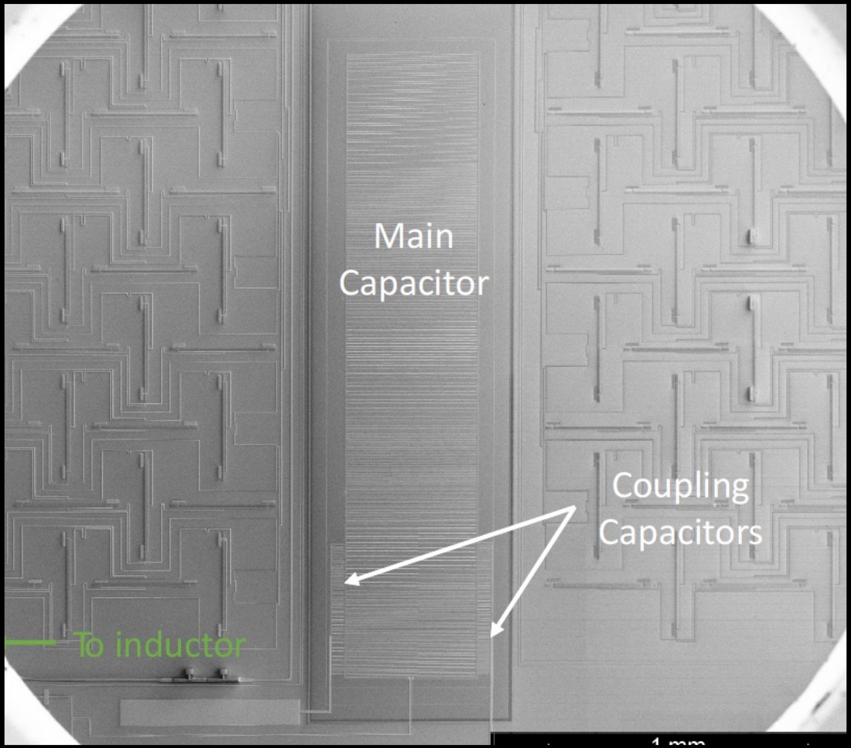
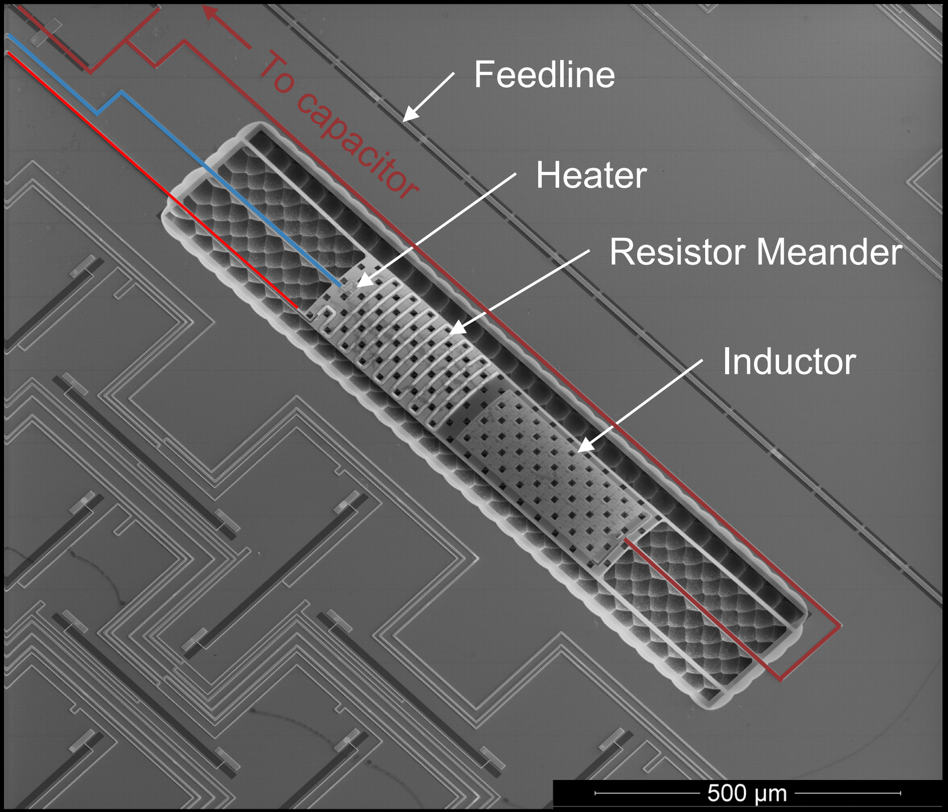
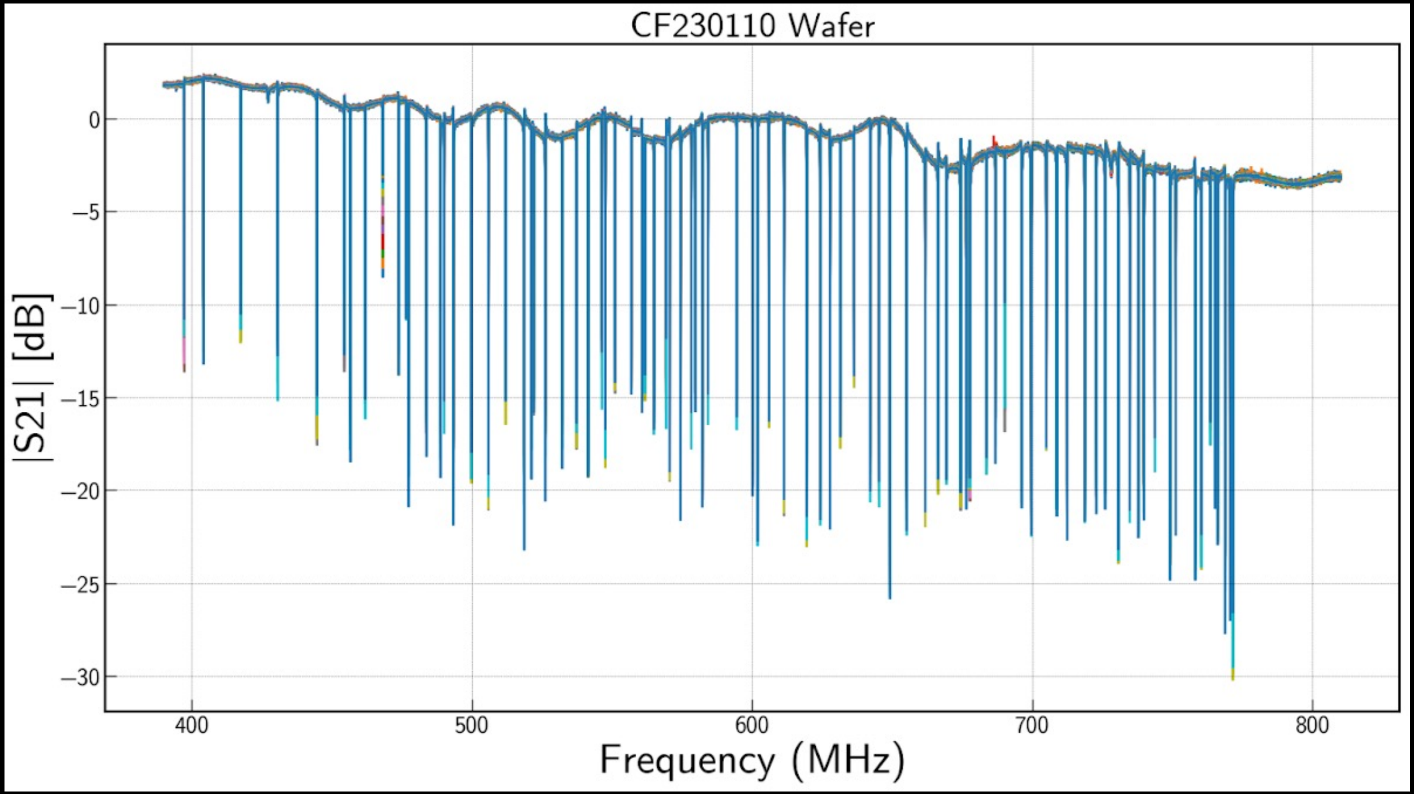
Detector Design





High yield arrays



- We use LED arrays to identify detectors with their resonance
- Capacitor trimming to avoid collisions
- Then release bolometers

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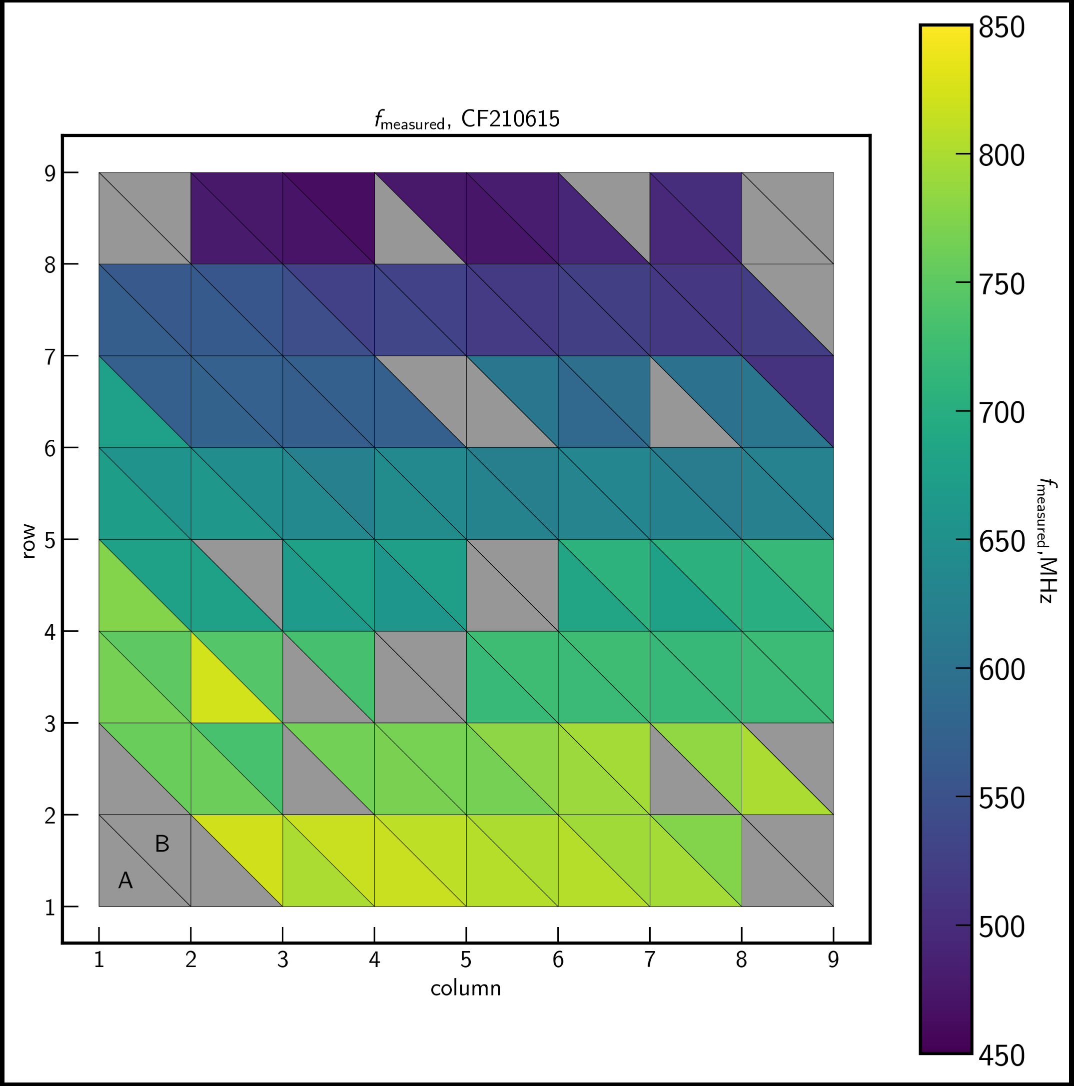
Yield

- Best yield on TKID tile: 112/128 detector pairs
- Have estimated defect density on capacitors through optical inspection: 0.299/mm^2 +/- 0.063
- Feedline defects can be fatal.



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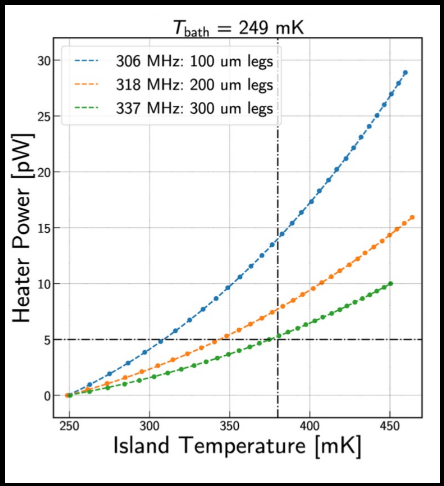
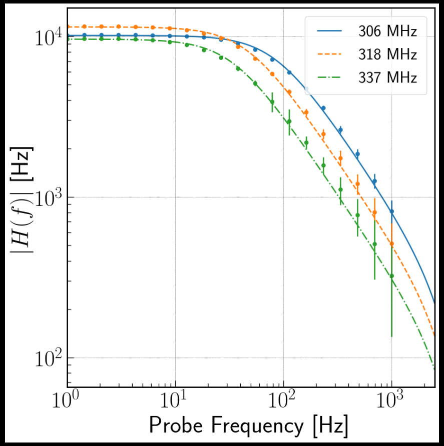
Bolometer & Inductor Properties



- Use calibration heater to vary island temperature
- Leg Thermal Conductivity G consistent with TES experience
- Temperature index n~3.



- Roll-off of transfer function from AC drive on heater
- Time constant set by island heat capacity as well as G
- Independent of island temperature
- No electrothermal feedbackl

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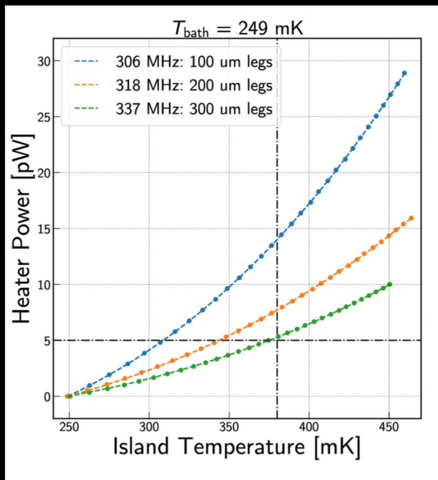

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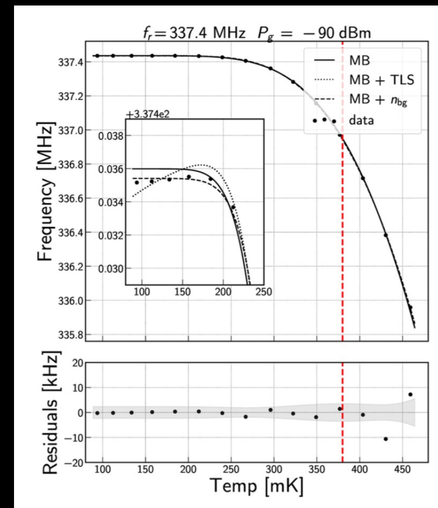
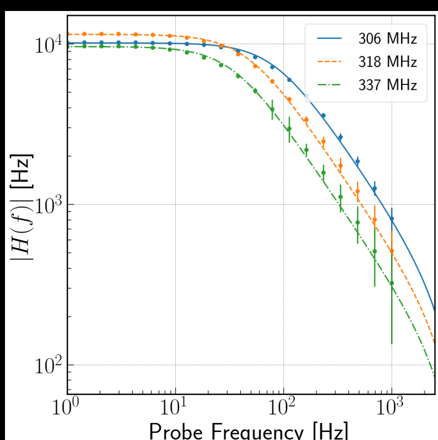


- Resonator Q and fr vary with temperarture
- Well described by Mattis Bardeen Theory on Aluminum
- There is a background quasiparticle background that limits Qi
- Red line is intended operating temperature. Thermal quasiparticles dominate there



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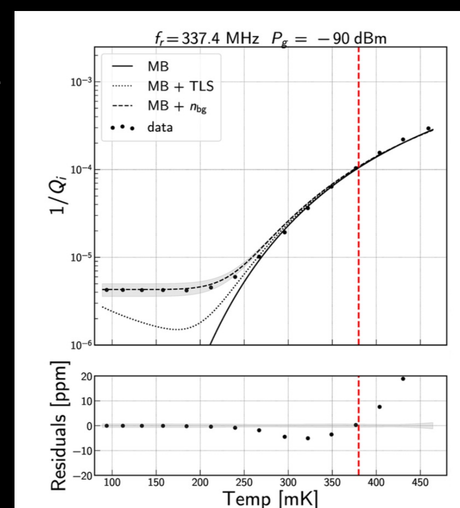
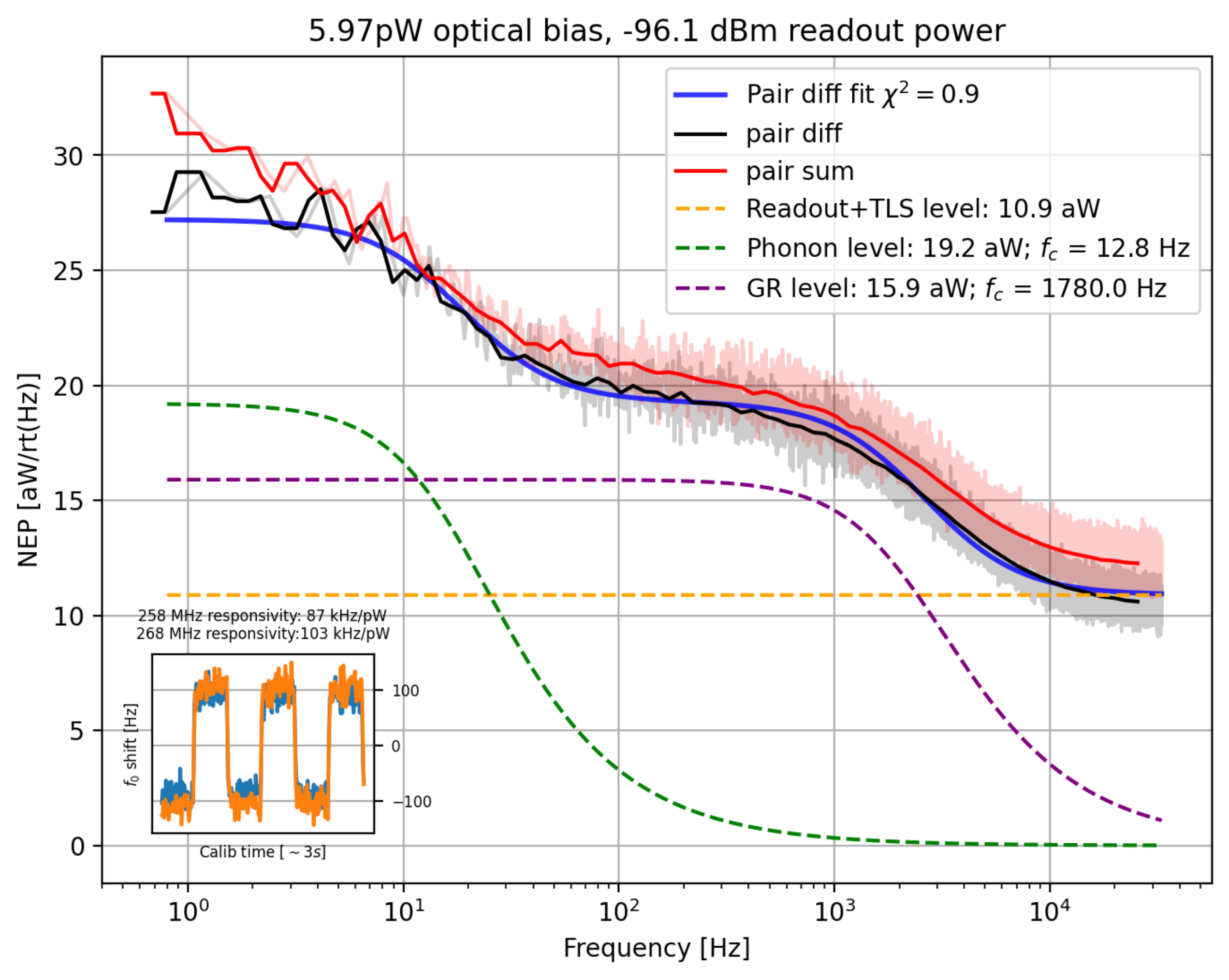


Noise Studies



- We expect 6pW power for 150GHz at the South Pole.
- So bias heaters to provide that in lab
- Total noise is below the expected photon NEP~45aW/rtHz
- Pair difference is stable to low frequencies
- Dashed lines show model, with higher than expected GR noise, and longer lifetimes.

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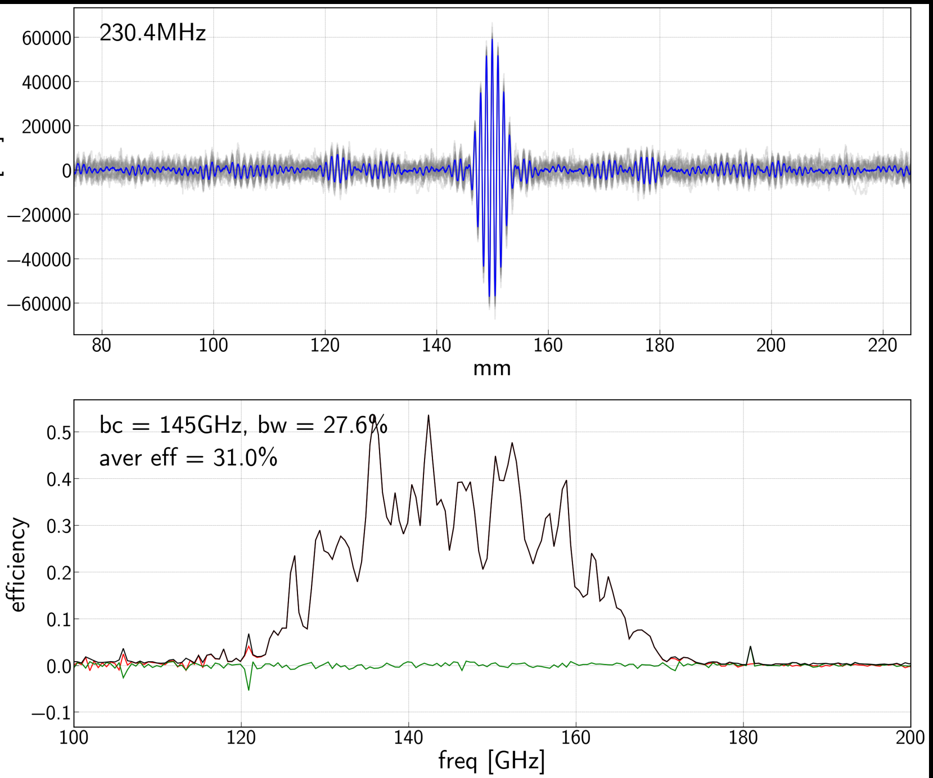
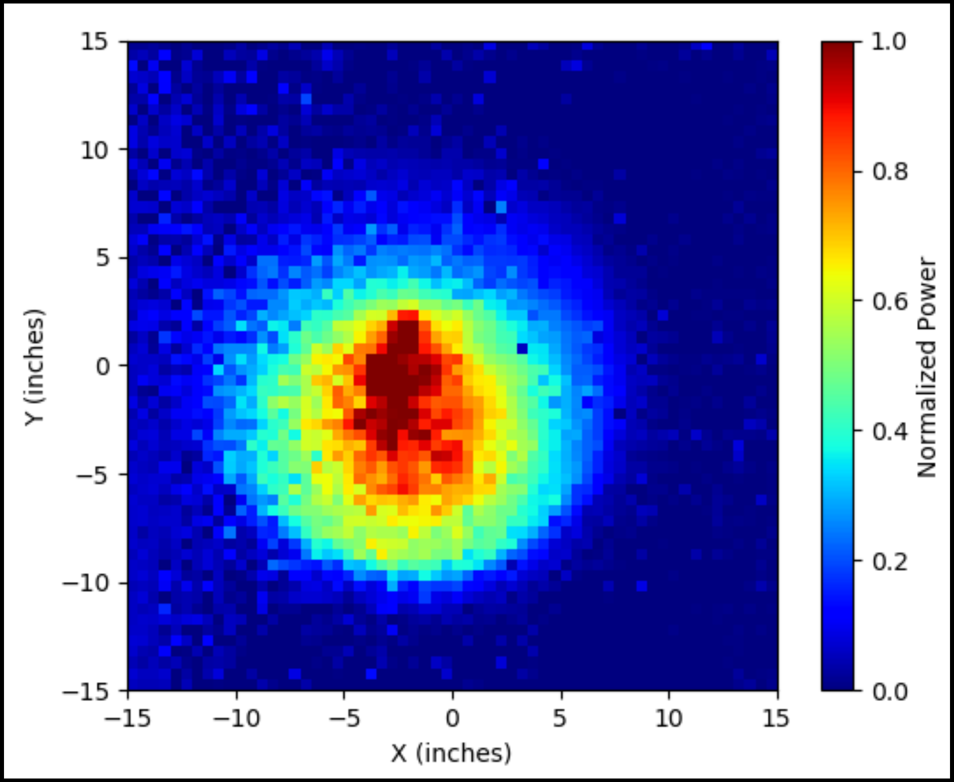
Optical Responsivity





- Bands are as consistent with design, limited out of band response
- Camera Optical efficiency of ~30% (includes optical filters and window)

- Beams are roughly gaussian.
- Distortion at peak is due to internal reflections in the optics.

- Lines shift several line widths
- So we use a chirped readout

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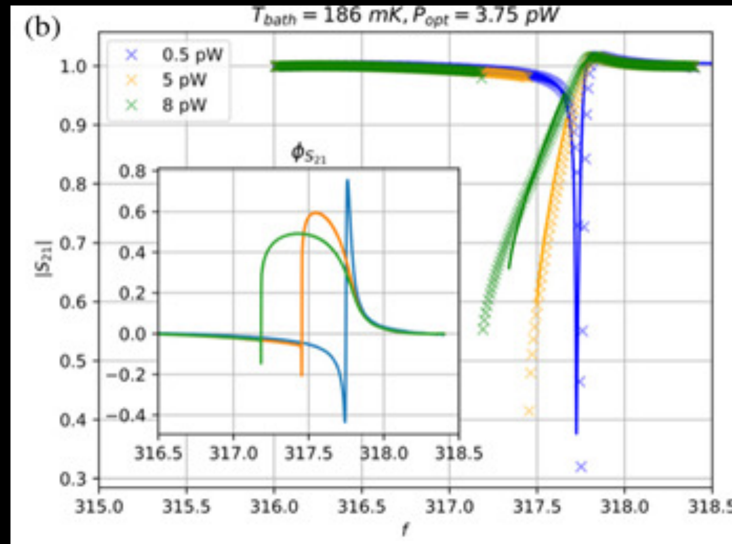
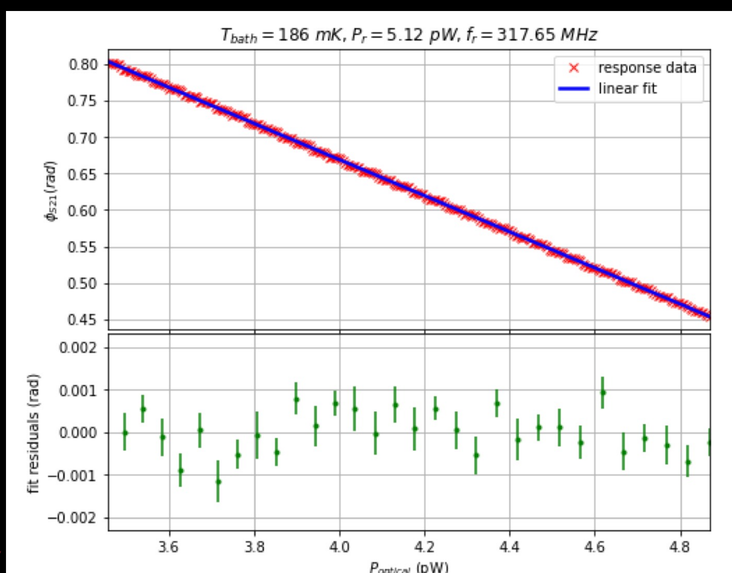
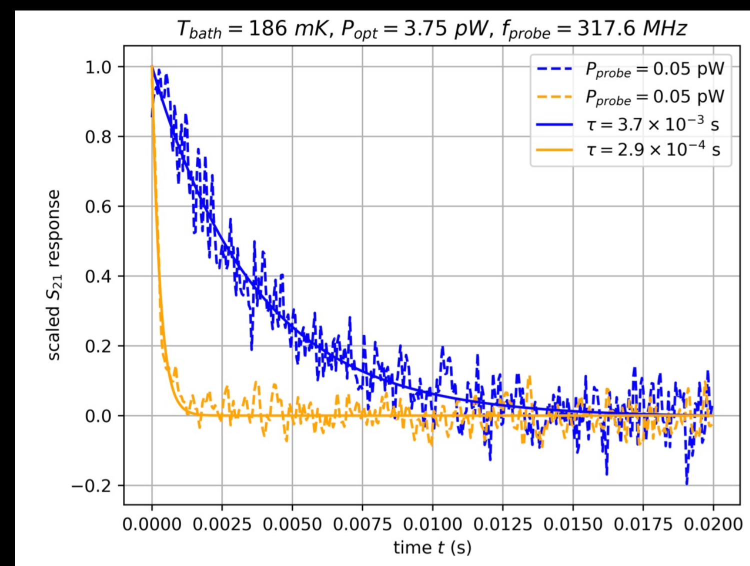
Electrothermal Feedback



arXiv: 2107.12493





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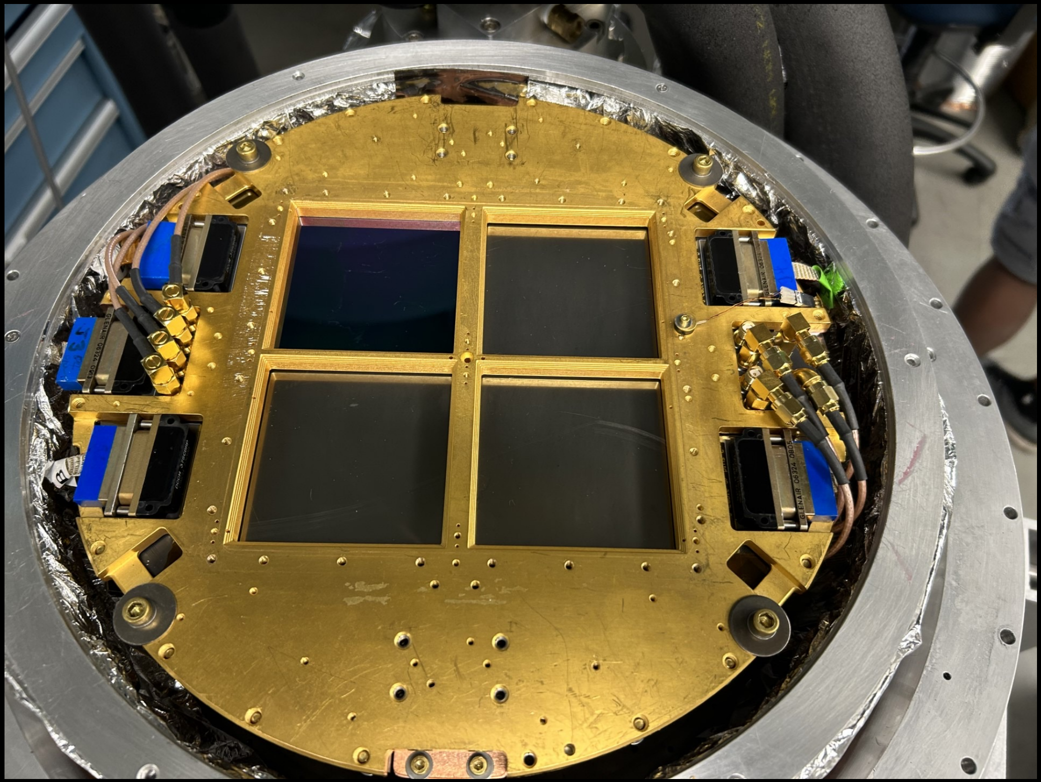
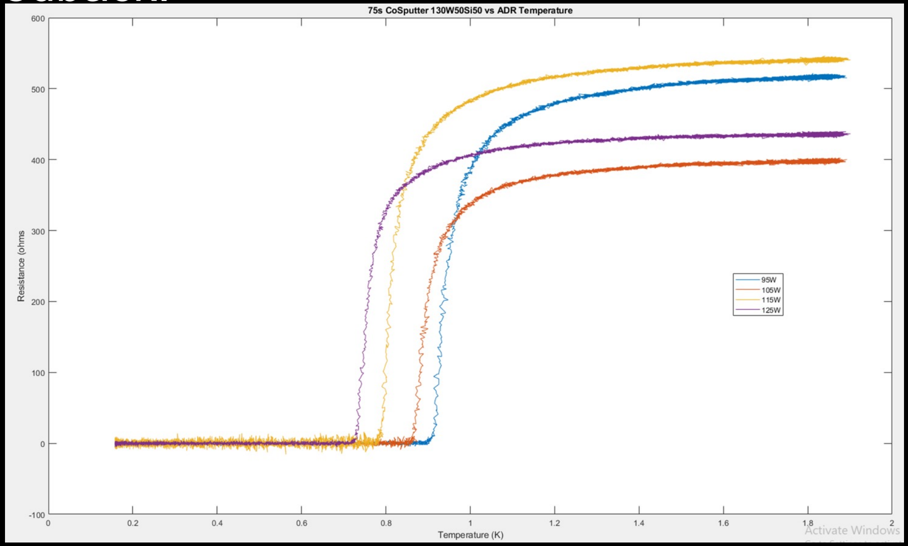
Field Demonstration

- Possible BICEP field demonstration
- We have four tiles of high yield arrays, and still testing others
- Retrofitted Keck Array Camera
- Have been conducting system level studies of the camera in the lab
- NSF has some infrastructure challenges to work through



Lower loading TKIDs

- A CMB space observatory loading lower an order of magnitude lower than through atmosphere: 0.5-2pW
- Ground based spectrometers with R~100 have similarly reduced loading compared to CMB photometric experiments
- We know we can build bolometers with leg G to be background noise limited
- Need to contain GR noise:
  - WSi T_c can be adjusted by varying film content with co-sputtering
- Lower G requires lower C to maintain similar time constants
- High resistivity inductor films are key to limiting island size. (ρ_{WSI}~100 Ω/□)
- EletrothermalFeedback.



Courtesy of Andrew Beyer/ Sahil Patel

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Thanks for your attention

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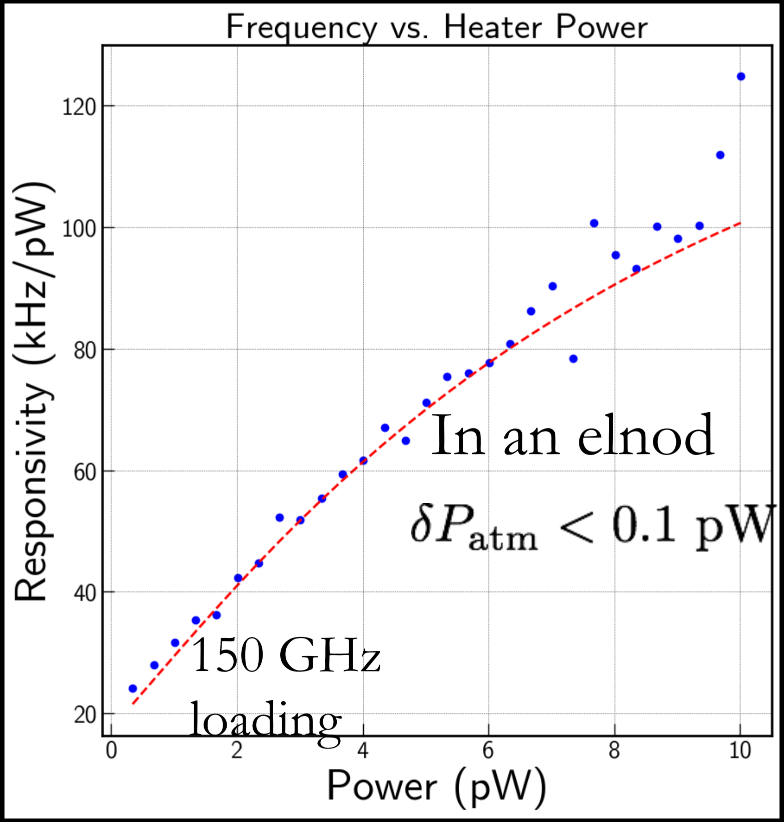
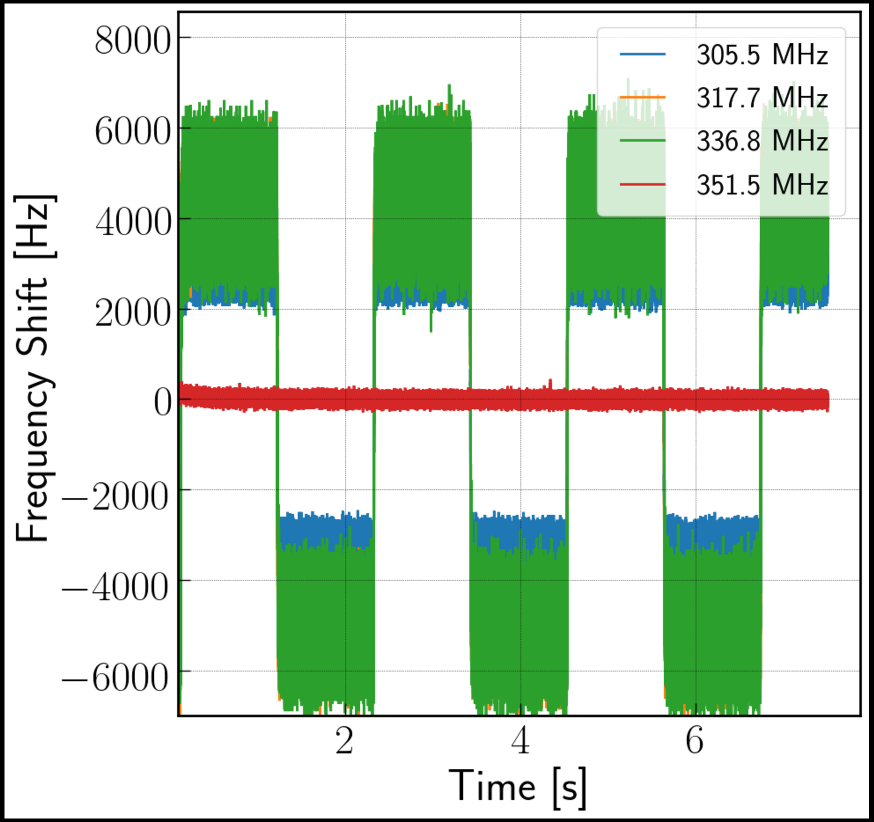
Extra slides

Responsivity





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GR Noise

$$\mathrm{NEP}_{gr}^2 = \frac{1}{V_{sc}^2 \cdot \left(\partial n_{qp}/\partial P_{opt}\right)^2} S_{gr}$$

$$\mathrm{NEP}_{gr}^2 = 4G(T_0)k_B T_0^2 \cdot \left(\frac{G(T_0)}{k_B \cdot \kappa(T_0)^2 n_{qp}(T_0)^2} \cdot \frac{1}{R^* V_{sc}} \right)$$

$$\mathrm{NEP}_{\mathrm{ph}}^2 = 4G(T_0)k_B T_0^2 \cdot F(T_0, T_{\mathrm{bath}})$$

- QP density has an exponential dependence on temperature.
- At high enough temperature system reduces to a single-link system
- Qi drops at higher temperatures. Multiplexing sets a lower bound on Qi at operating temperature

TLS and Amp Noise

$$\mathrm{NEP}^2_{\mathrm{TLS}} = \frac{1}{(\partial x/\partial P)^2} S_{\mathrm{TLS}}$$

$$\mathrm{NEP}_{\mathrm{amp}} = \frac{1}{\partial x/\partial P_{\mathrm{opt}}} \cdot \frac{2}{Q_i \chi_c \chi_g} \cdot \sqrt{\frac{k_B T_N}{P_g}}$$

$$S_{\mathrm{TLS}}\left[\mathrm{Hz}^{-1}\right] = \kappa_{\mathrm{TLS},0} \left(\frac{\nu}{1\mathrm{Hz}}\right)^{-1/2} \left(\frac{T}{380\mathrm{mK}}\right)^{-2} (1 + N/N_c)^{-1/2}$$

$$N = \frac{E_{\mathrm{stored}}}{h f_r}$$

Microwave photon number given by energy stored and resonance frequency

$$S_{\mathrm{TLS}} \ll 2.7 \times 10^{-17}\ \mathrm{Hz}^{-1}$$

At T=380 mK, responsivity is 331 ppm/pW

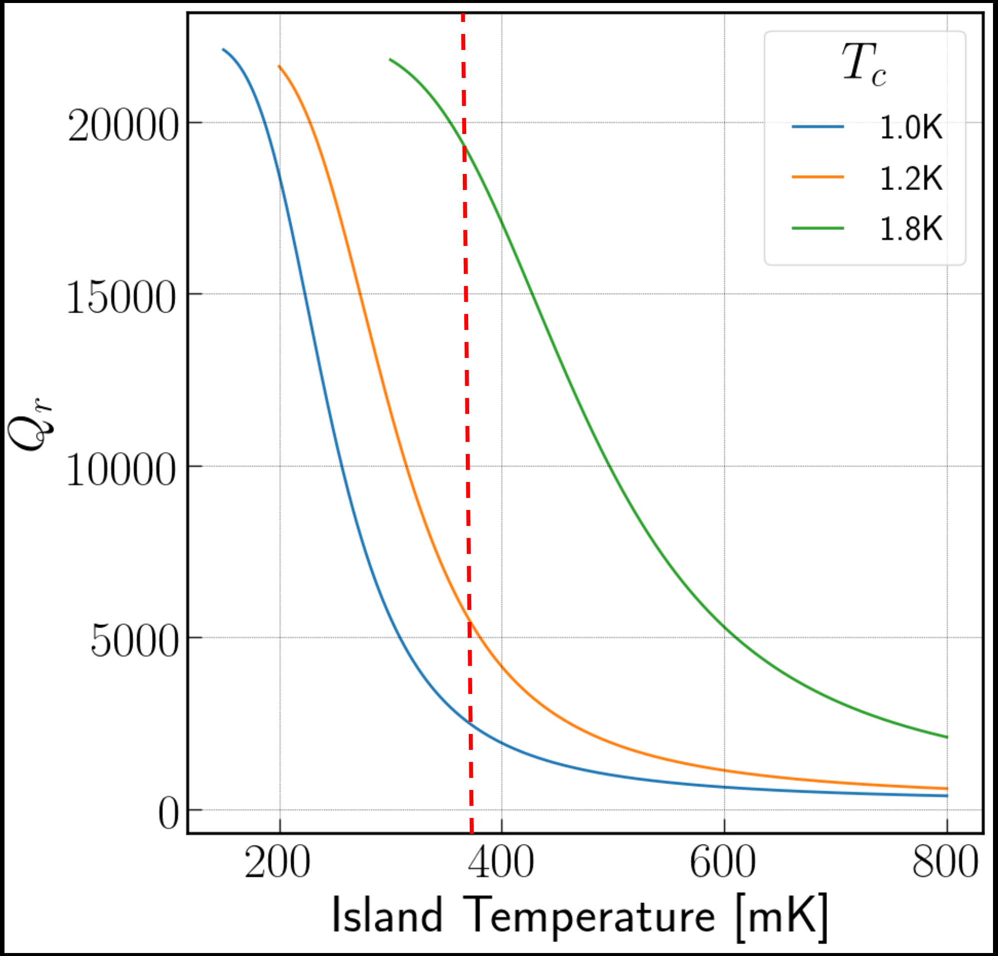
- Cryogenic amplifier at 4K. Measured noise temperature of ~5K.
- Relation above is true even when the resonator is asymmetric.

Readout Requirements

- Dynamic Range Requirement: -95dBc/Hz
- Bandwidth requirements: 256 devices across an octave of BW.
- To multiplex N=256 channels over m=1 octaves with ξ=0.5% cross talk, we require:

$$Q_r \approx N\xi_{max}^{-1/2}2^m$$

- Requirements for warm lab testing set how tightly we can pack the resonators



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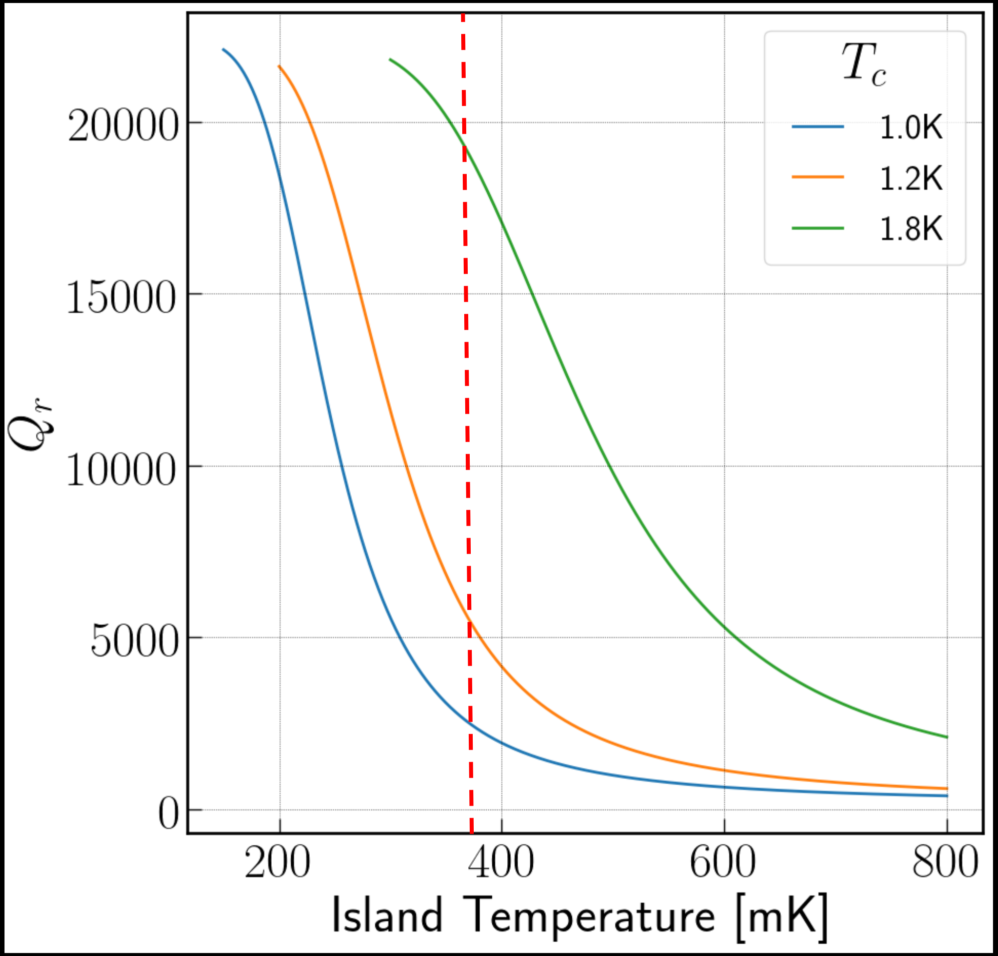

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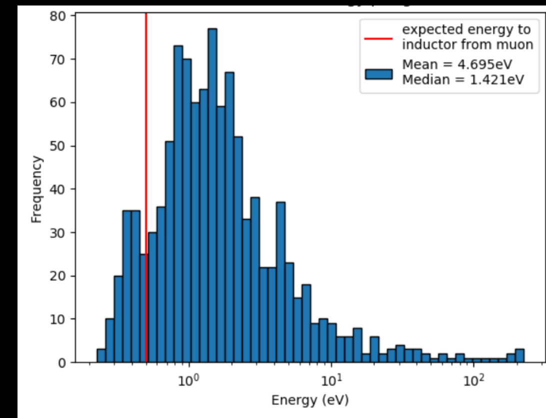
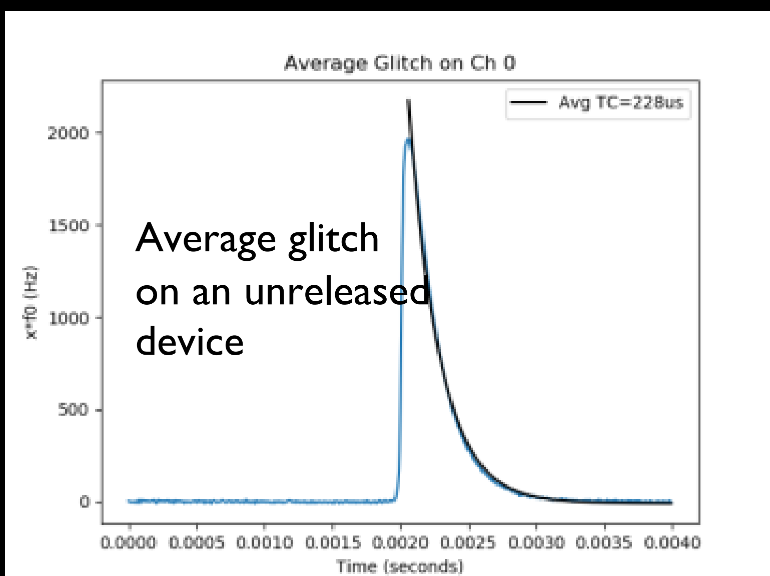
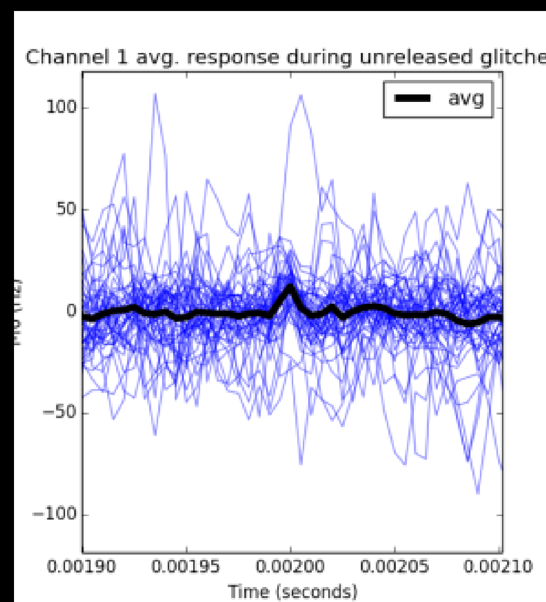
Cosmic Ray Testing

- Expected muon hit rate: 1 per second
- Can compare the glitch rate on the released vs. unreleased devices
- Checked for coincident cosmic ray hits using a scintillator
- Cosmic ray hits to measure qp time constants



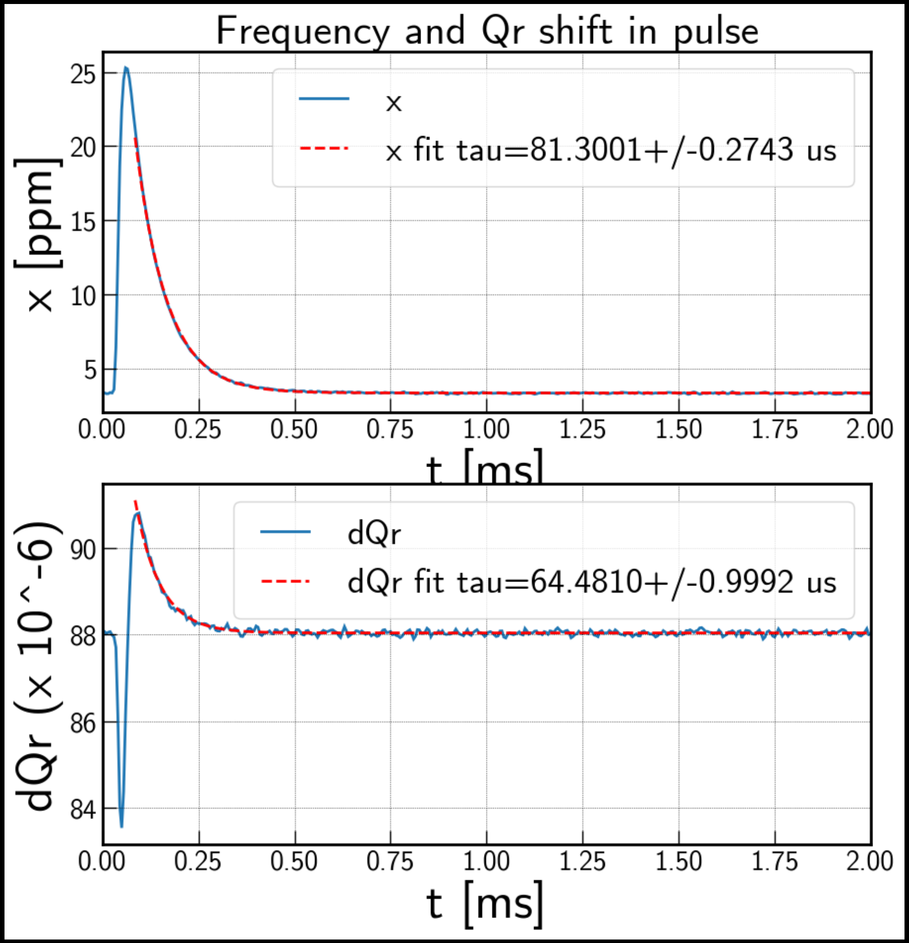


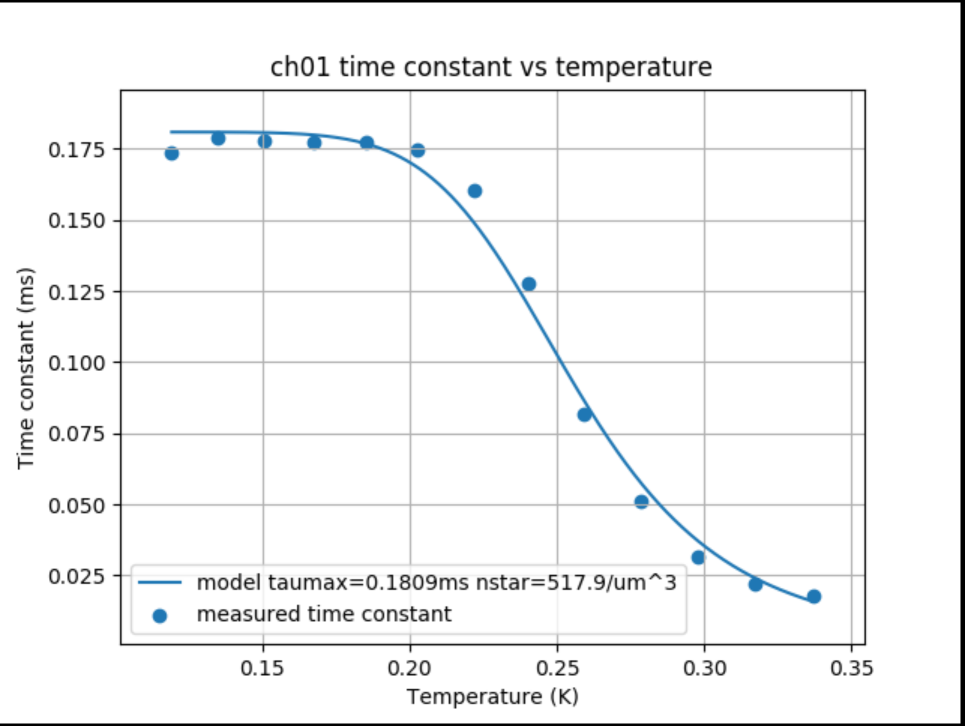


Stacked timestreams of a released device during glitches in an unreleased device

Credit: Katie Hughes

Quasiparticle Lifetimes





$$n^* = 517.9 \pm 40/\mu m^3$$
$$\tau_{max} = 0.1809 \pm 0.0025 ms$$

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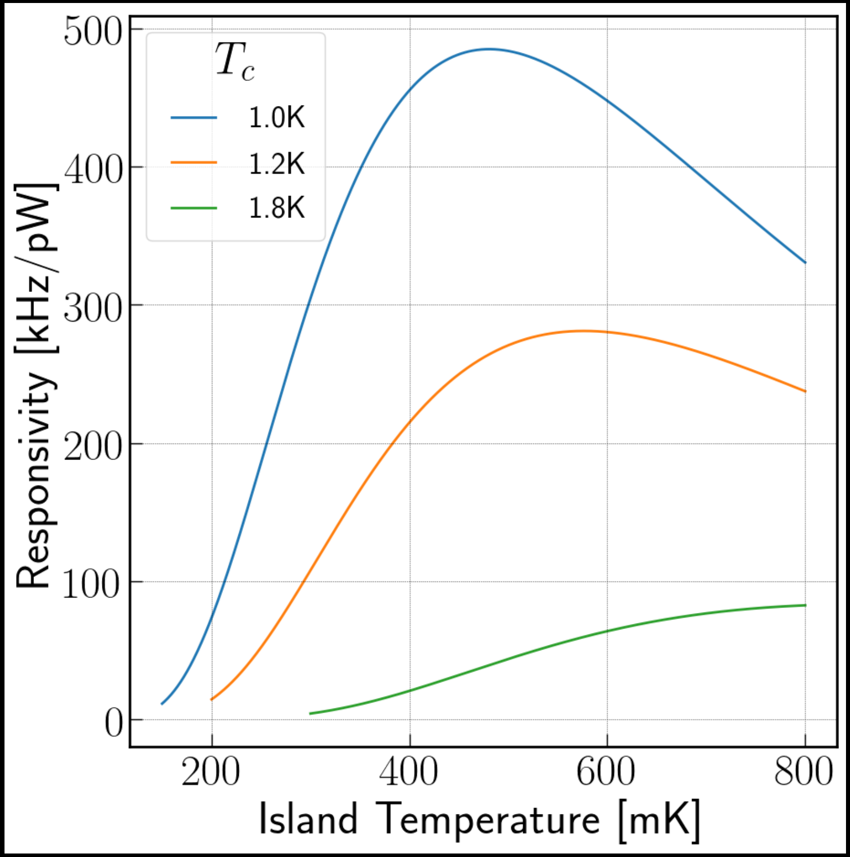
Responsivity Details

$$S = \frac{\partial f_r}{\partial P} = \frac{\partial f_r}{\partial n_{qp}} \frac{\partial n_{qp}}{\partial T} \frac{\partial T}{\partial P}$$

$$S = \frac{\partial f_r}{\partial P} = f_r(T) \frac{\beta(\omega, T)\kappa(T)}{2Q_i G(T) T}$$

$$\kappa(T) = \frac{1}{2} + \frac{\Delta}{k_B T}$$

$$\beta(f,T) = \frac{1 + \sqrt{\frac{2\Delta}{\pi k_B T}} \exp\left[-\frac{hf}{2k_B T}\right] \mathrm{I}_o\left[\frac{hf}{2k_B T}\right]}{\frac{2}{\pi}\sqrt{\frac{2\Delta}{\pi k_B T}} \sinh\left[\frac{hf}{2k_B T}\right] \mathrm{K}_o\left[\frac{hf}{2k_B T}\right]}$$



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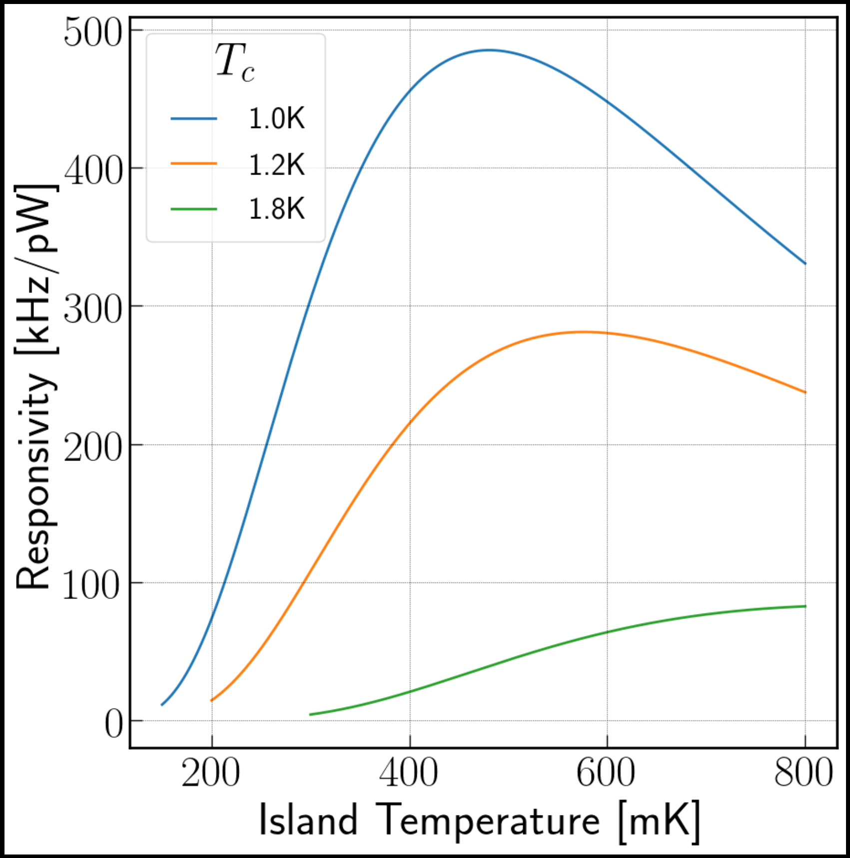

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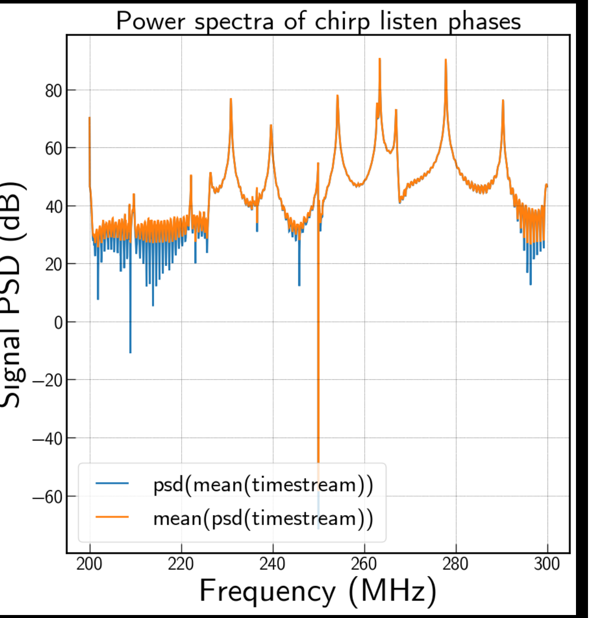
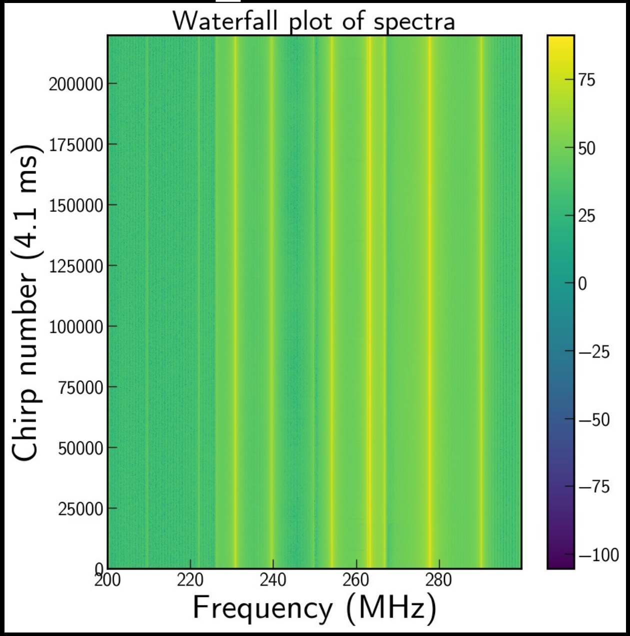
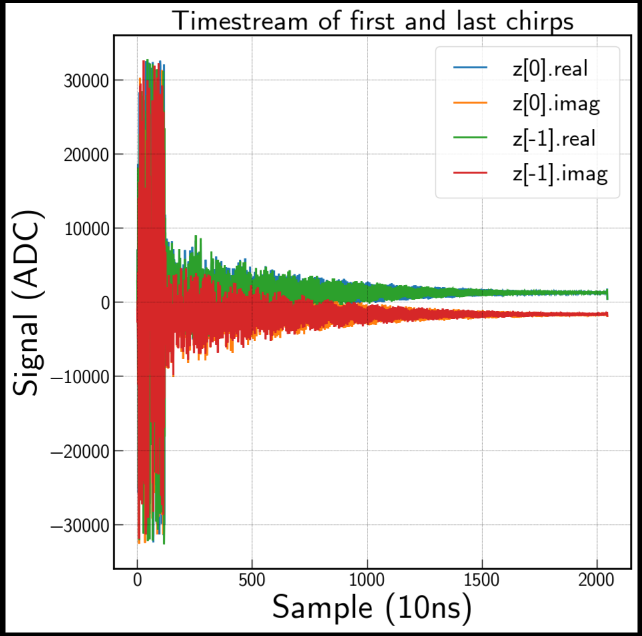
Chirped Readout

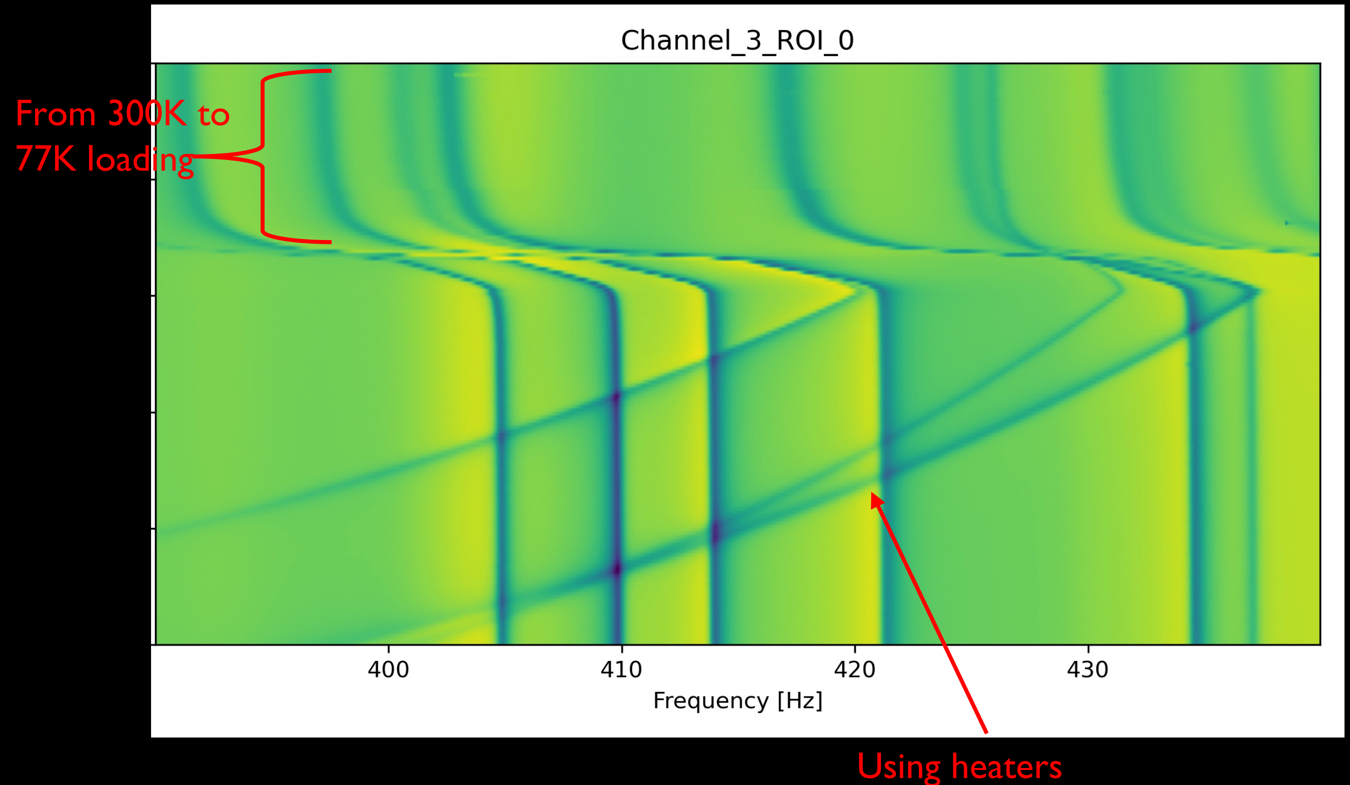






- Changes in optical loading during lab measurements shift the resonators by many line-widths
- In place of single-tone readout, we use a pulsed readout scheme
- Excite the resonators by applying a short chirp sweeping from high to low frequency
- Disable the transmit amplifier and listen to the resonator ringdown response.

Chirped Readout



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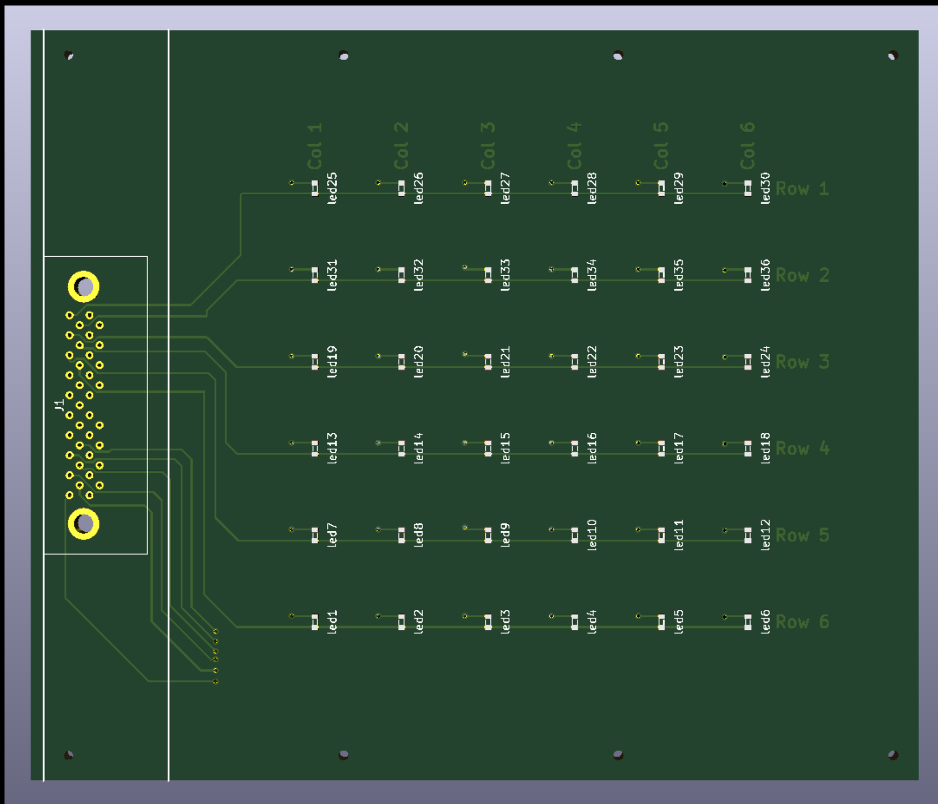
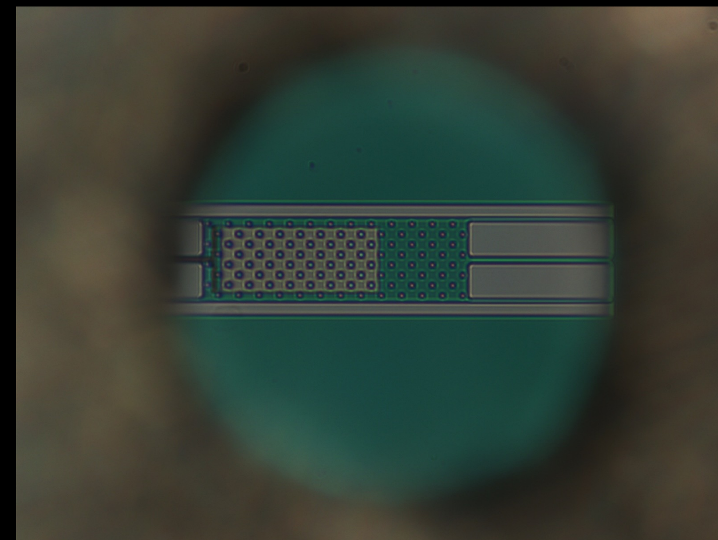
LiteBrite® Testing





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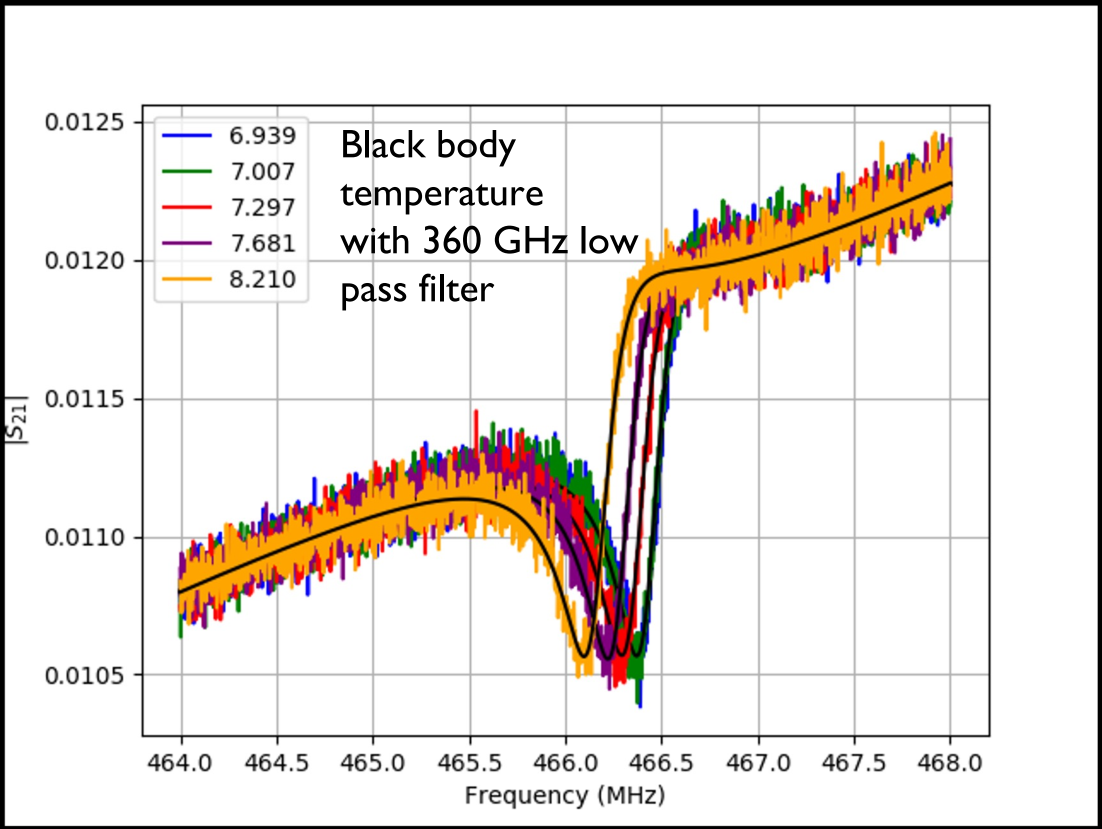
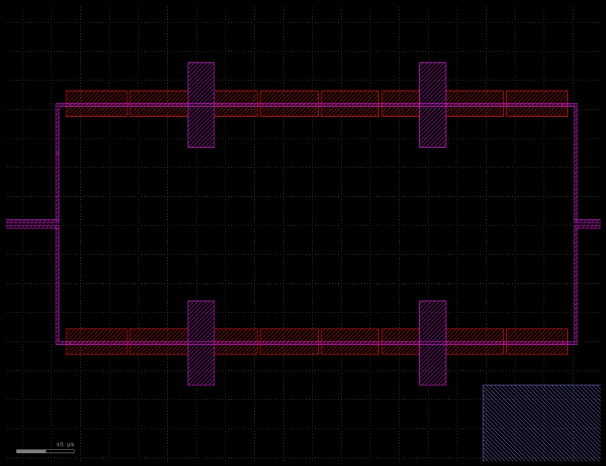
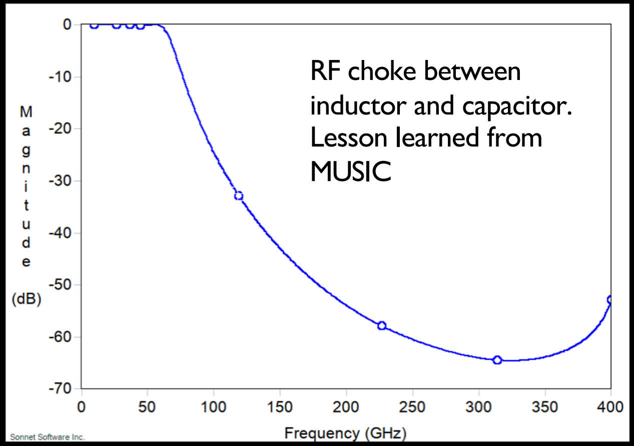
RF Choke







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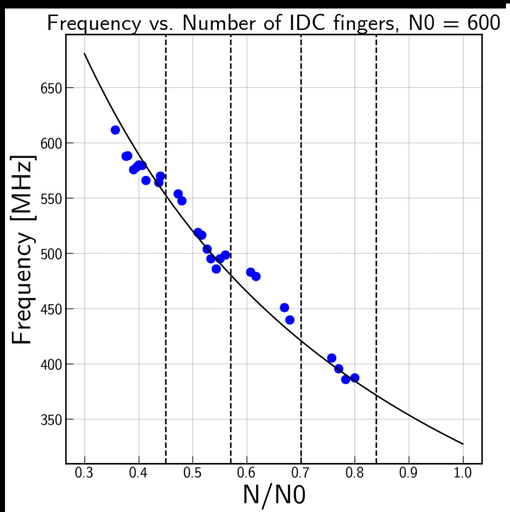
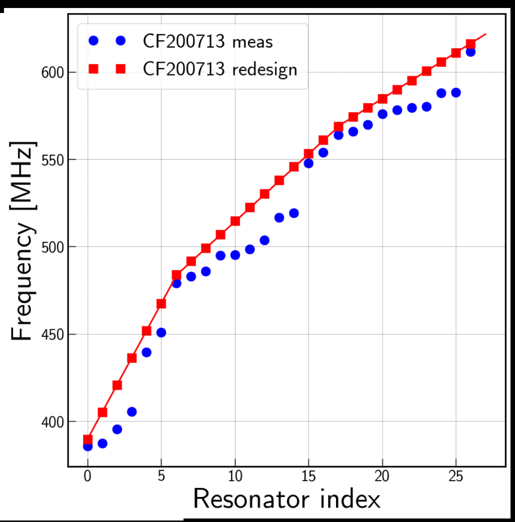
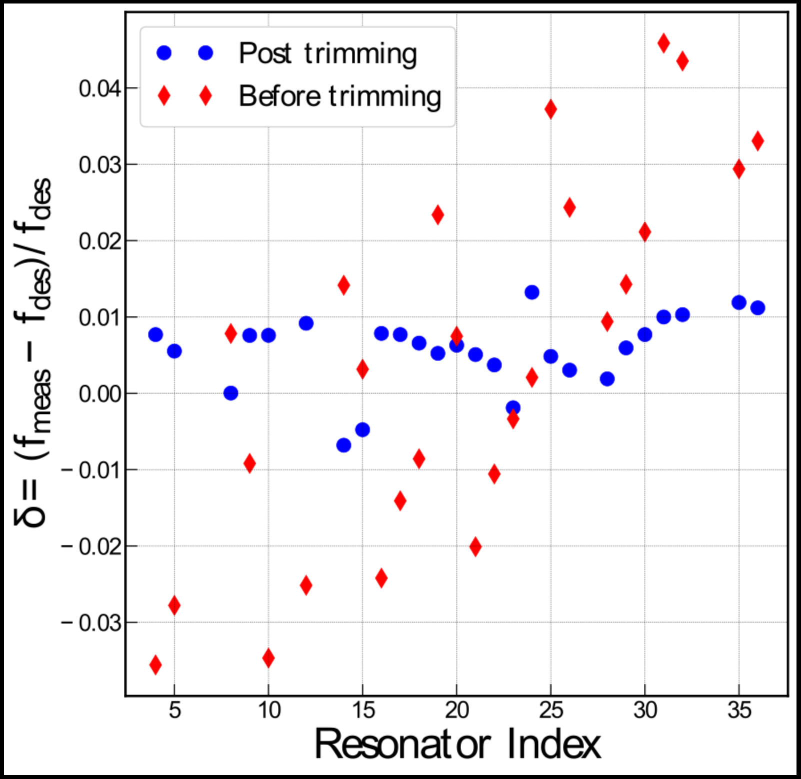
Trimming Capacitors







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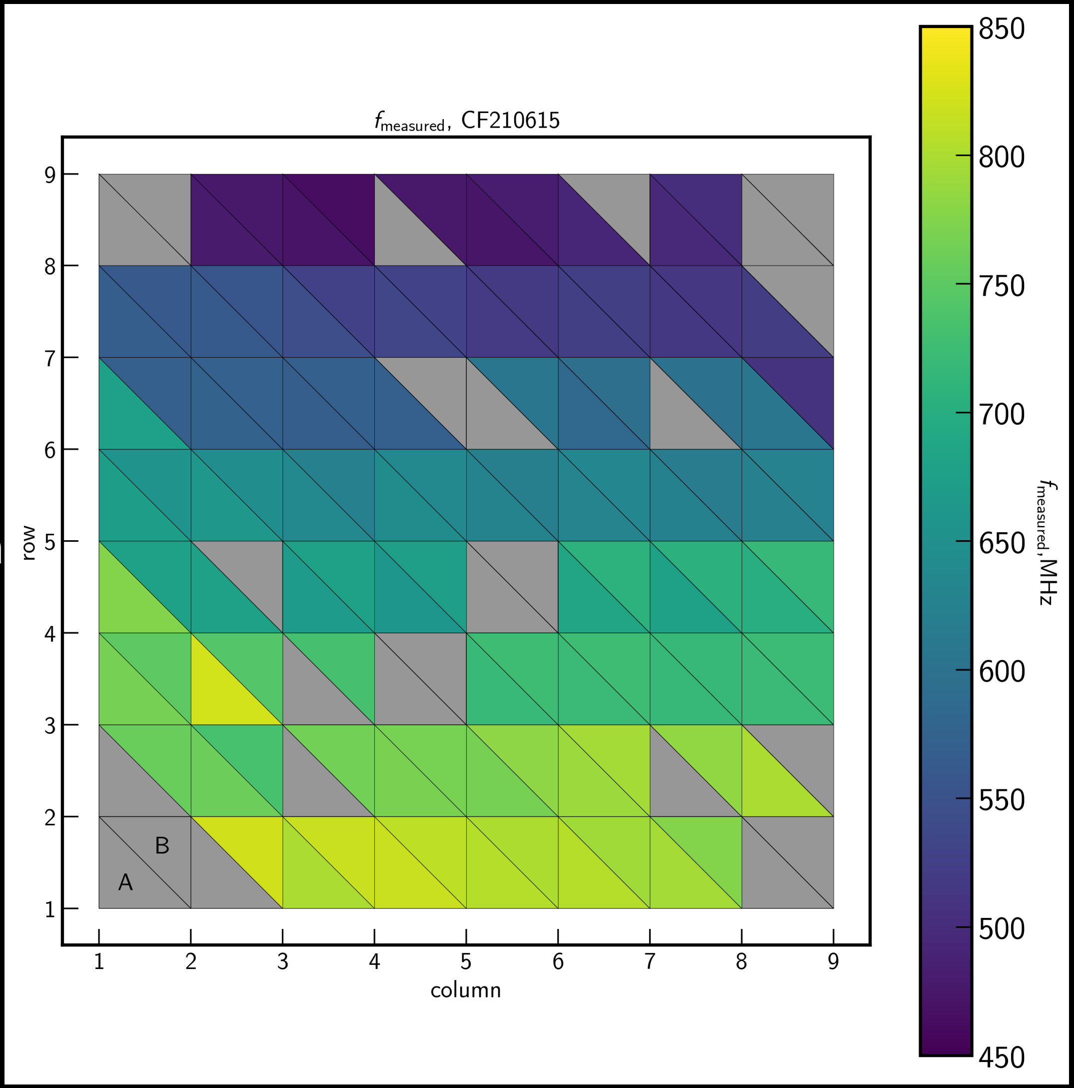
Yield

- Best yield on TKID tile: 112/128 detector pairs
- Eliminated vias to GND in the design of the Antenna-Coupled TKID chips
- Have estimated defect density on capacitors through optical inspection: 0.299/mm^2 +/- 0.063
- Feedline defects can be fatal.



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