Are you MKIDing me?!

The Story of MUSIC's Detectors

Seth Siegel

Outline

- Introduction to Microwave Kinetic Inductance Detectors (MKIDs)
- Recap of the 2010 DemoCam Observing Run
- The problem of dark response
- The problem of low optical efficiency
- Results from the latest 6x6 (4 Color) Array
- Future work

MUSIC

- **576 spatial pixels**, simultaneously sensitive to **4 spectral bands**

ν (GHz)	150	230	290	350
Δν (GHz)	34	45	34	21

- 14 arcminute FOV
- **Primary science goals:**
  - Pointed observations of galaxy clusters through the tSZ Effect
  - Wide blank-field surveys of dusty, star-forming galaxies
- First camera at any wavelength to use MKIDs as detectors
- Scheduled to be commissioned at the CSO in the winter of 2011/2012

Photo courtesy of Matt Hollister

Introduction to MKIDs

Superconductivity

- A Cooper pair consists of two electrons bound together by the electron-phonon interaction. The energy of the Cooper pair is below the Fermi energy.

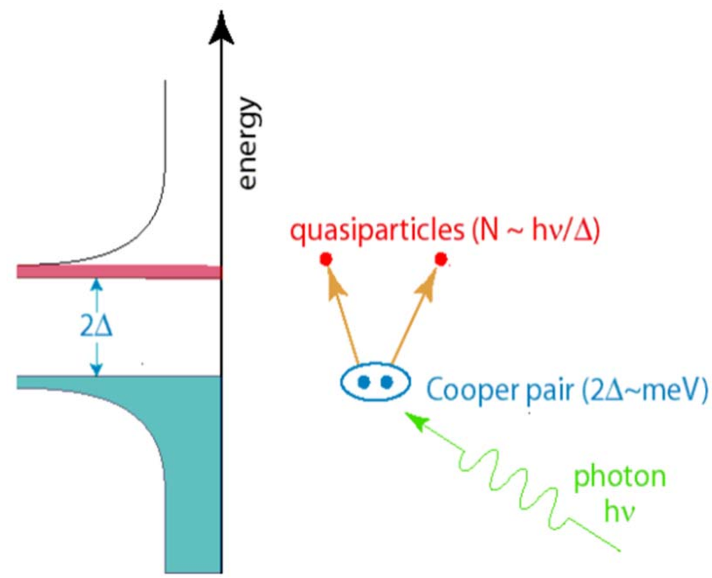
- Binding energy is weak.

Aluminum:	$\Delta \approx 0.18\ \mathrm{meV}$	$\frac{2\Delta}{h} \approx 80\ \mathrm{GHz}$
Niobium:	$1.45\ \mathrm{meV}$	$700\ \mathrm{GHz}$

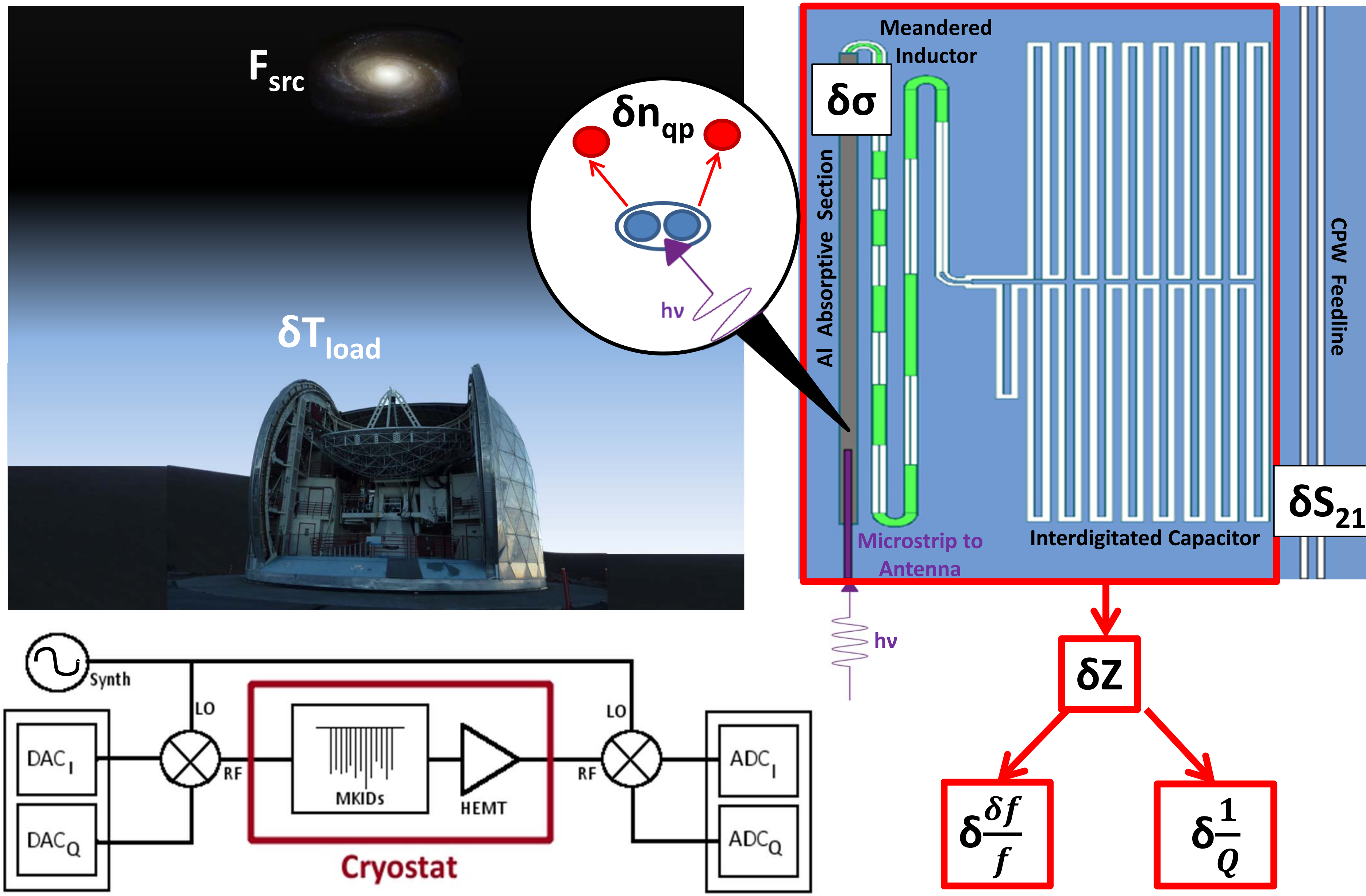
- Still, prevents inelastic scattering resulting in zero DC resistance.

- But Cooper pairs have inertia. Results in a "phase-lag" between current and an AC electric field that has a form equivalent to an inductance:

Kinetic Inductance

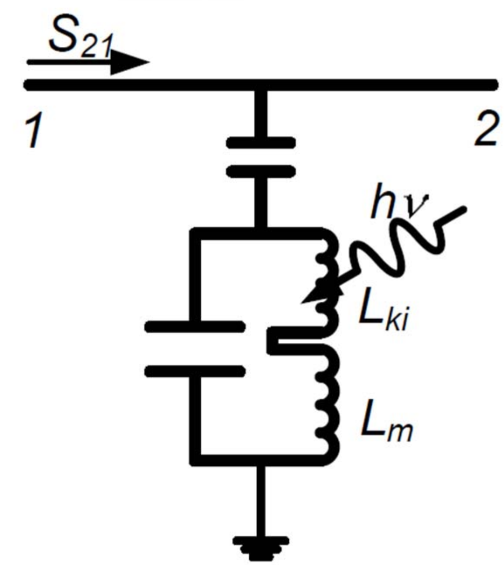


Principle of Detection



Basics

- MKIDs are **superconducting RLC circuits**, capacitively coupled to a feedline.



- Near the resonant frequency the complex transmission S_{21} of a microwave probe signal sweeps out a circle

$$S_{21}(f) = 1 - \frac{Q/Q_c}{1 + 2iQ\frac{f-f_0}{f_0}}$$

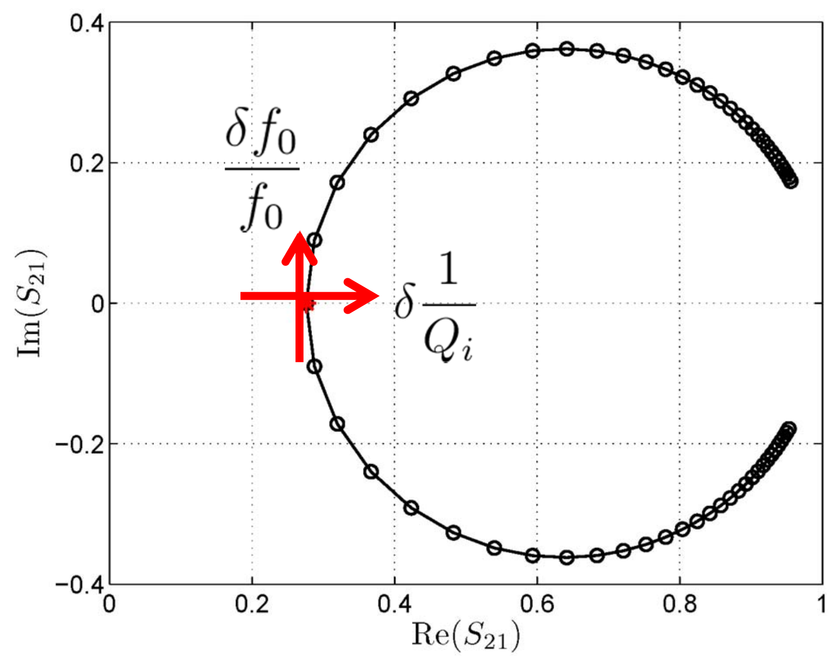
where

$$\frac{1}{Q} = \frac{1}{Q_i} + \frac{1}{Q_c}$$

- Consider small perturbations in frequency and loss, this results in perturbations in the transmission **on resonance** given by

$$\delta S_{21} = \frac{Q^2}{Q_c}\left(\delta\frac{1}{Q_i} - 2i\frac{\delta f_0}{f_0}\right)$$

Amplitude **Phase**



Basics

- The frequency f and loss 1/Q are determined by the impedance of the circuit

$$Z = R + i\omega L + \frac{1}{i\omega C}$$

Quasi-particles

Cooper Pairs
+ Geometry

Geometry

- Define the ***kinetic inductance fraction***

$$\alpha = \frac{L_k}{L} = \frac{L_k}{L_k + L_m}$$

- Frequency and loss then given by

$$f_0 \propto \frac{1}{\sqrt{LC}}$$

$$\delta f_0 = f_0 \left(\frac{\sqrt{L}}{\sqrt{L + \delta L}} - 1 \right) = -\frac{f_0}{2} \frac{\delta L}{L}$$

$$\frac{\delta f_0}{f_0} = -\frac{\alpha}{2} \frac{\delta L_k}{L_k}$$

$$\frac{1}{Q_i} = \frac{R}{\omega L}$$

$$\delta \left(\frac{1}{Q_i} \right) = \alpha \frac{\delta R}{\omega L_k}$$

Basics

- Changes in resistance and inductance of the resonator due solely to changes in the complex conductivity of the superconductor

$$\sigma = \sigma_1 - i\sigma_2$$

- For a superconducting thin film

$$\frac{\delta Z_s}{Z_s} = \frac{\delta\sigma}{\sigma}$$

- Lets measure relative to the values at zero temperature, so that

$$\sigma_1(0) = 0 \qquad\qquad R(0) = 0$$

and

$$\frac{\delta R}{\omega L_k(0)} = \frac{\delta\sigma_1}{\sigma_2(0)} \qquad\qquad \frac{\delta L_k}{\omega L_k(0)} = -\frac{\delta\sigma_2}{\sigma_2(0)}$$

- Now just need a theory for the complex conductivity of a thin superconducting film under an AC electromagnetic field.

Mattis - Bardeen Theory

- In 1958, D.C. Mattis and J. Bardeen use BCS theory to derive an expression for the complex conductivity

$$\sigma = \sigma_1 - i\sigma_2$$

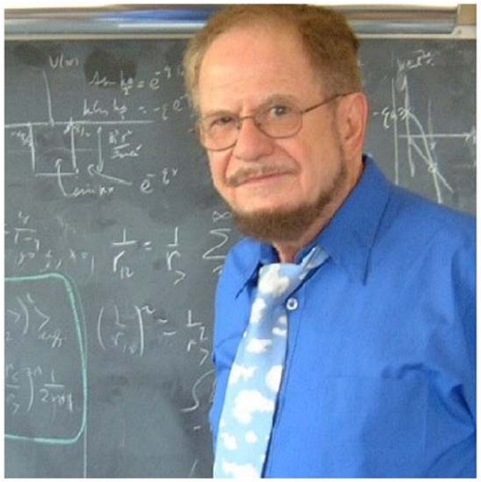
of a superconducting thin film:

$$\begin{aligned}
\frac{\sigma_1}{\sigma_n} &= \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}\frac{[f(E)-f(E+\hbar\omega)](E^2+\Delta^2+\hbar\omega E)}{\sqrt{E^2-\Delta^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}dE \\
&+\frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{-\Delta}\frac{[1-2f(E+\hbar\omega)](E^2+\Delta^2+\hbar\omega E)}{\sqrt{E^2-\Delta^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}dE \\
\frac{\sigma_2}{\sigma_n} &= \frac{1}{\hbar\omega}\int_{\max\{\Delta-\hbar\omega,-\Delta\}}^{\Delta}\frac{[1-2f(E+\hbar\omega)](E^2+\Delta^2+\hbar\omega E)}{\sqrt{\Delta^2-E^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}dE.
\end{aligned}$$

- Here f(E) is the Fermi distribution

$$f(E;\mu^*,T) = \frac{1}{1+e^{\frac{E-\mu^*}{kT}}}$$

John Bardeen



Daniel Mattis

Mattis – Bardeen Theory

- In the limits applicable to our detectors $\hbar\omega \ll \Delta$ and $kT \ll \Delta$ the first order approximation is valid

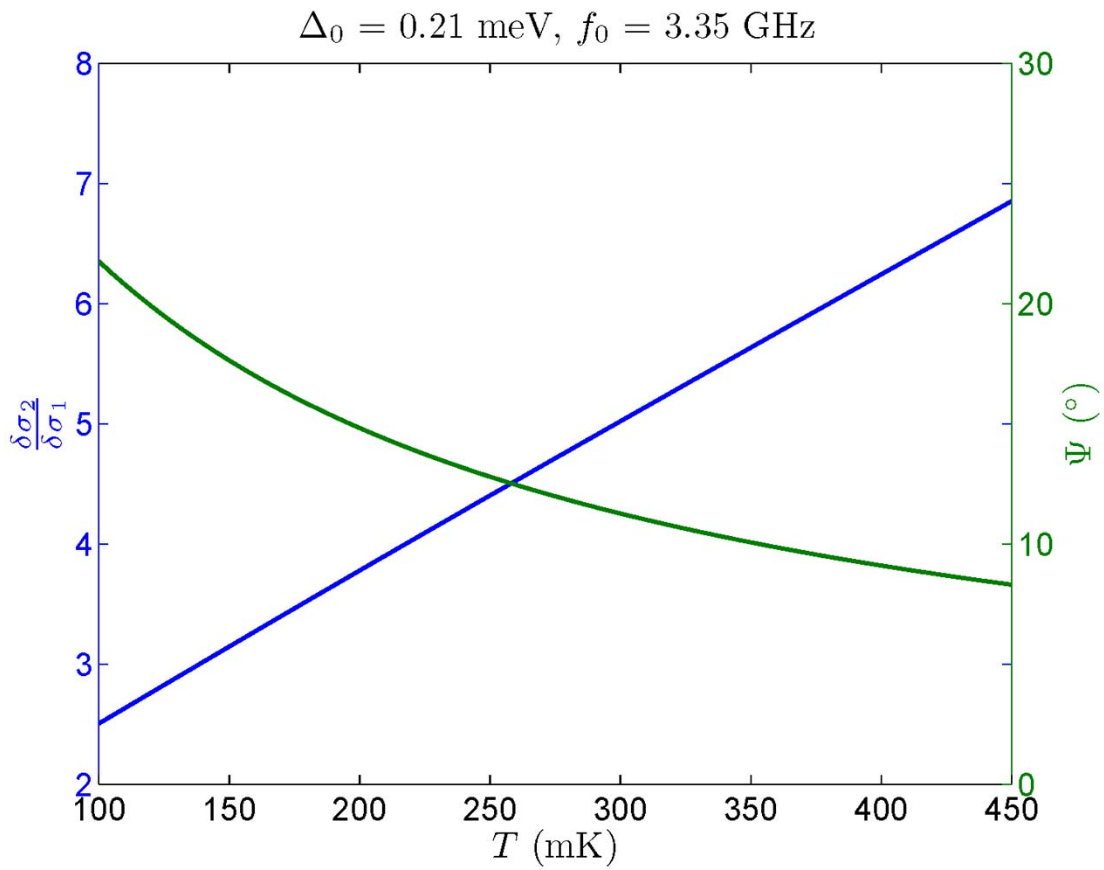
$$\frac{\delta\sigma_1}{\sigma_2(0)} = \frac{1}{\pi N_0}\sqrt{\frac{2}{\pi kT\Delta_0}}\sinh\left(\frac{\hbar\omega}{2kT}\right)K_0\left(\frac{\hbar\omega}{2kT}\right)n_{qp} = \boxed{\kappa_1(\omega, T, \Delta_0)\; n_{qp}}$$

$$\frac{\delta\sigma_2}{\sigma_2(0)} = -\frac{1}{2\Delta_0 N_0}\left[1+\sqrt{\frac{2\Delta_0}{\pi kT}}\,e^{-\frac{\hbar\omega}{2kT}}\;I_0\left(\frac{\hbar\omega}{2kT}\right)\right]n_{qp} = \boxed{\kappa_2(\omega, T, \Delta_0)\; n_{qp}}$$

- Hence, complex conductivity is proportional to quasi-particle density

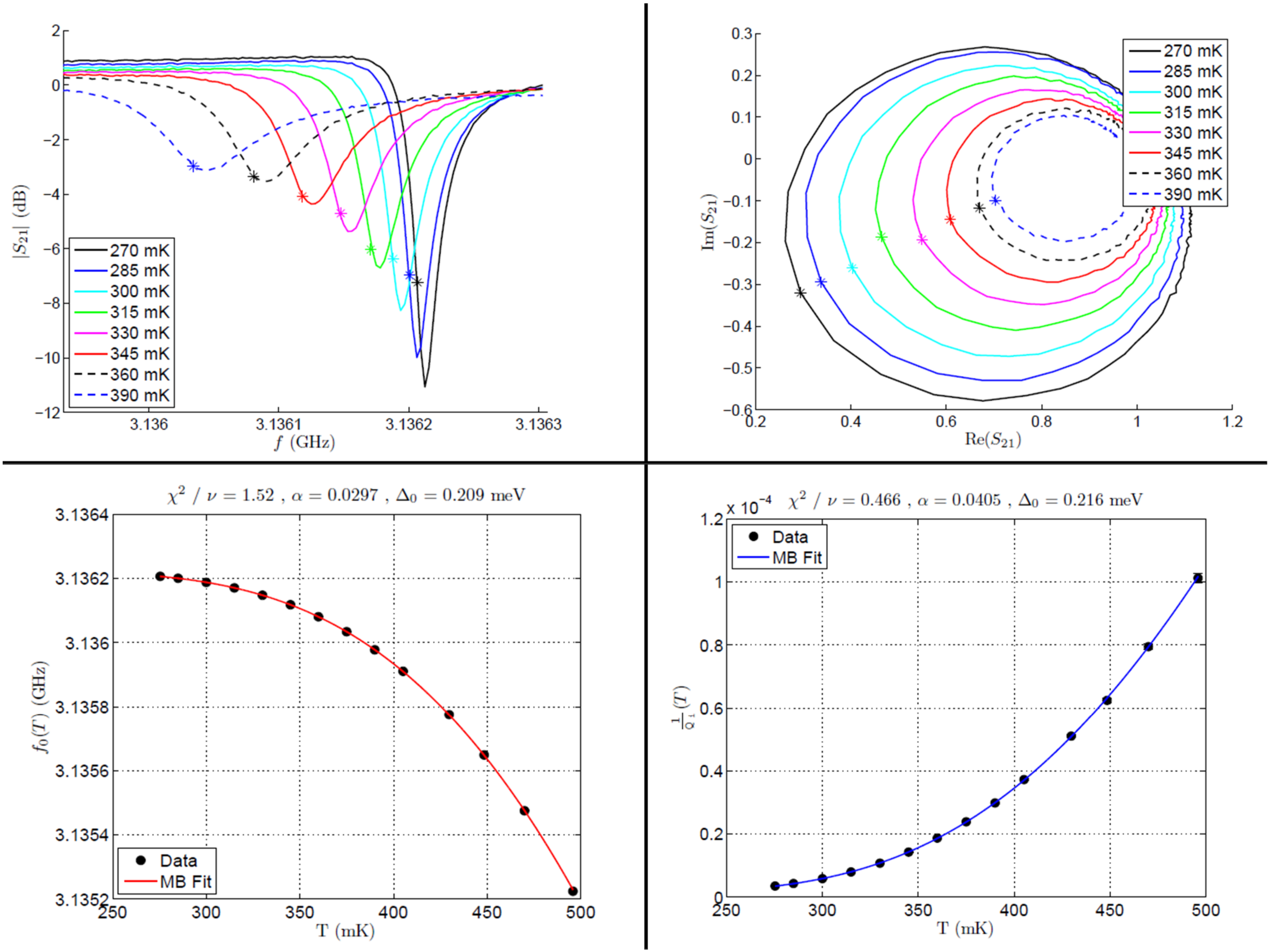
$$n_{qp} = 2N_0\sqrt{2\pi kT}\; e^{\frac{\Delta-\mu^*}{kT}}$$

Mattis – Bardeen Theory



- Frequency response inherently larger than dissipation response

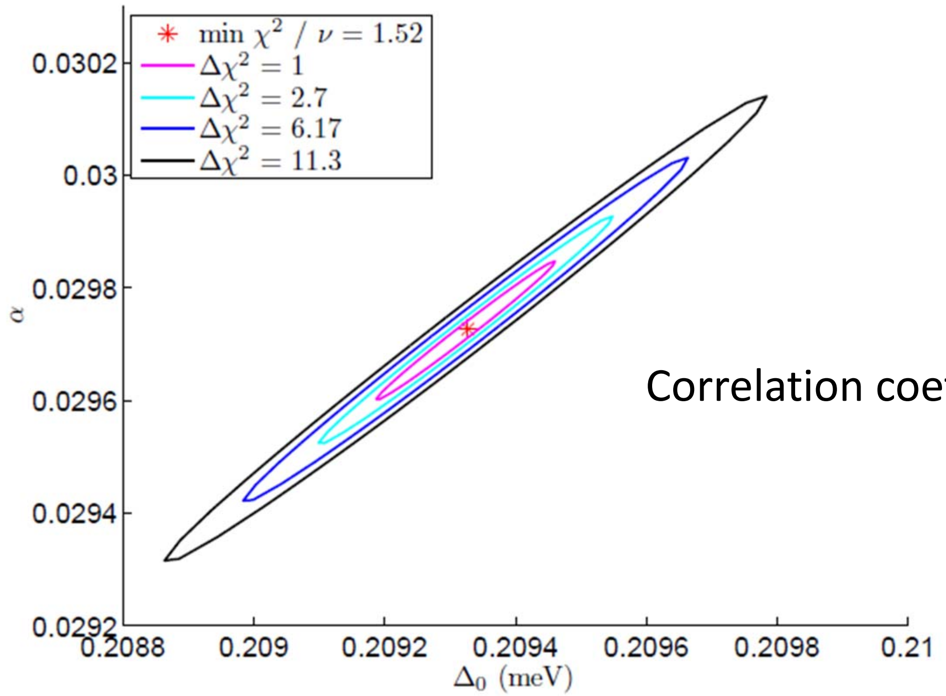
$$\frac{\delta\sigma_1}{\delta\sigma_2} = \frac{\kappa_1(\omega, T, \Delta_0)}{\kappa_2(\omega, T, \Delta_0)} = \tan(\Psi)$$



270 mK
285 mK
300 mK
315 mK
330 mK
345 mK
360 mK
390 mK
$|S_{21}|$ (dB)
f (GHz)
3.136
3.1361
3.1362
3.1363
Im(S_{21})
Re(S_{21})
χ^2 / ν = 1.52 , α = 0.0297 , Δ_0 = 0.209 meV
$f_0(T)$ (GHz)
T (mK)
Data
MB Fit
x 10^{-4}
χ^2 / ν = 0.466 , α = 0.0405 , Δ_0 = 0.216 meV
$\frac{1}{Q_i}(T)$
T (mK)
Data
MB Fit

Mattis - Bardeen Theory

- Obtain very good estimates of **α** and **Δ_0** from MB fits to dark temperature sweeps

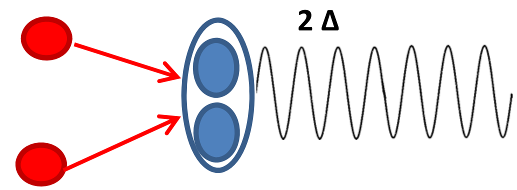


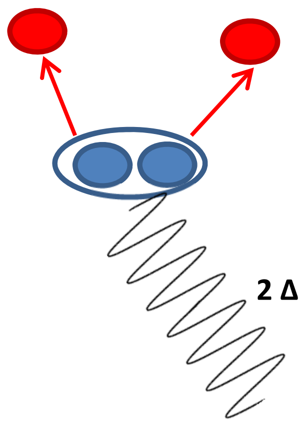
Correlation coefficient $\rho \approx 0.99$

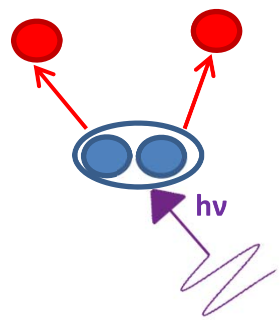
- However, results from fits to frequency and loss inconsistent.

The G-R Equation

In a steady state $$\Gamma^G_{th} + \Gamma^G_{opt} = \Gamma^R$$







Recombination

$$\Gamma^R = \frac{V n_{qp}}{\tau}$$

where

$$\frac{1}{\tau} = R n_{qp} + \frac{1}{\tau_0}$$

$$n_{qp} = n_{qp,opt} + n_{qp,th}(T, \alpha, \Delta_0)$$

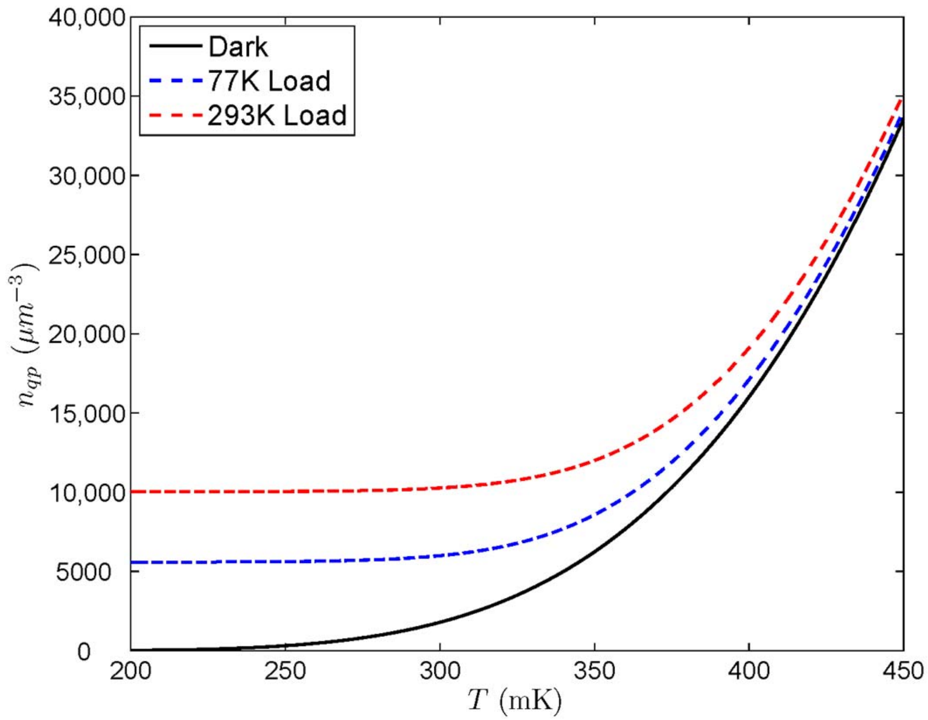
Optical Generation

$$\Gamma^G_{opt} = \frac{\eta P}{\Delta} = \frac{\eta k (T_{load} + T_{exc}) B}{\Delta}$$

$$\Rightarrow \quad \Gamma^G_{th} + \frac{\eta k (T_{load} + T_{exc}) B}{\Delta} = R V n_{qp}^2 + \frac{V n_{qp}}{\tau_0}$$

- Obtain the following quadratic equation for quasi-particle density

$$\frac{\eta k(T_{load}+T_{exc})B}{RV\Delta} = n_{qp}^2 - n_{qp,th}^2 + \frac{1}{R\tau_0}(n_{qp}-n_{qp,th})$$



- Taking the derivative with respect to T_{load}

$$\frac{dn_{qp}}{dT_{load}} = \frac{\eta k B}{RV\Delta\left(2n_{qp}+\frac{1}{R\tau_0}\right)}$$

Responsivity

$$\text{Responsivity} = \left[\frac{dS_{21}}{d(\frac{\delta f}{f})}\right]\left[\frac{d(\frac{\delta f}{f})}{d(\frac{\delta\sigma_2}{\sigma_2})}\right]\left[\frac{d(\frac{\delta\sigma_2}{\sigma_2})}{dn_{qp}}\right]\left[\frac{dn_{qp}}{dT_{load}}\right]\left[\frac{dT_{load}}{dF_{src}}\right]$$

$$\frac{dS_{21}}{d(\frac{\delta f}{f})} = \frac{2Q^2}{Q_c}$$

$$\frac{d(\frac{\delta f}{f})}{d(\frac{\delta\sigma_2}{\sigma_2})} = \frac{\alpha}{2}$$

$$\frac{d(\frac{\delta\sigma_2}{\sigma_2})}{dn_{qp}} = \frac{1}{2N_0\Delta_0}\left[1+\sqrt{\frac{2\Delta_0}{\pi kT}}e^{-\frac{\hbar\omega}{2kT}}I_0\left(\frac{\hbar\omega}{2kT}\right)\right] = \kappa_2(\omega, T, \Delta_0)$$

$$\frac{dn_{qp}}{dT_{load}} = \frac{\eta\ k\ B}{RV\Delta_0(2n_{qp}+\frac{1}{R\tau_0})}$$

$$2kT_{src}\Delta\nu = F_{src}A_{tel}\eta_{tel}\Delta\nu \quad\Longrightarrow\quad \frac{dT_{load}}{dF_{src}} = \frac{\eta_{tel}A_{tel}}{2k}$$

What makes for a responsive MKID?

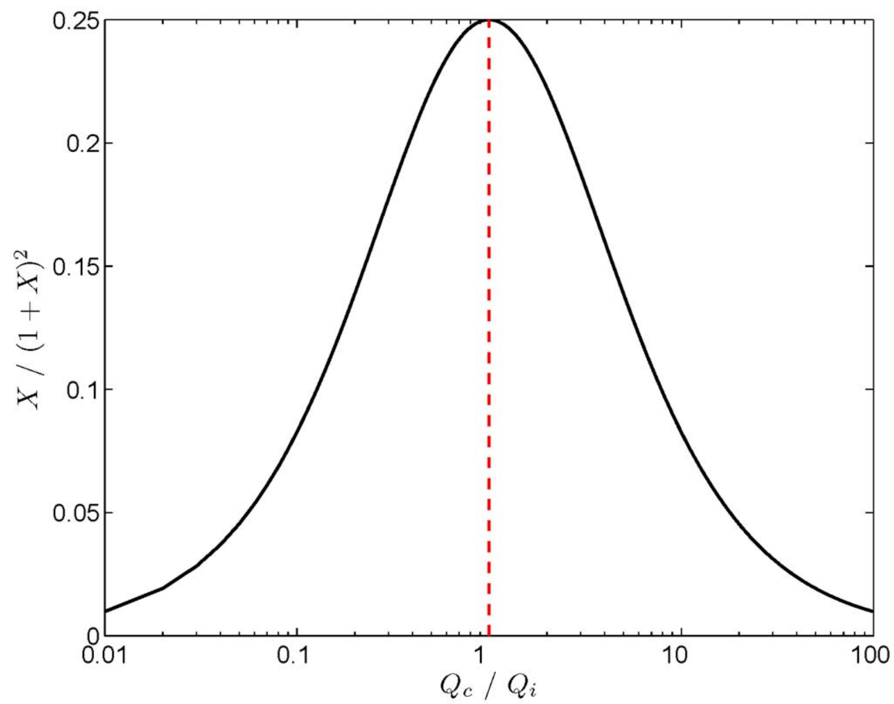
$$\text{Responsivity} = \frac{\kappa_2(\omega, T, \Delta_0)}{\Delta_0}\left(\frac{\eta_{tel}A_{tel}}{2}\right)\left(\frac{\alpha}{V}\frac{\eta B}{(2Rn_{qp}+\frac{1}{\tau_0})}\right)\left(\frac{Q^2}{Q_c}\right)$$

Under typical loading conditions and bath temperatures $Rn_{qp} \gg \frac{1}{\tau_0}$

Neglecting the factors intrinsic to the material we are using (i.e. R, N_0, Δ_0) we obtain the following simplified expression:

$$\text{Responsivity} \propto \frac{\eta B \alpha^2 Q_i^2}{V}\frac{X}{(1+X)^2}$$

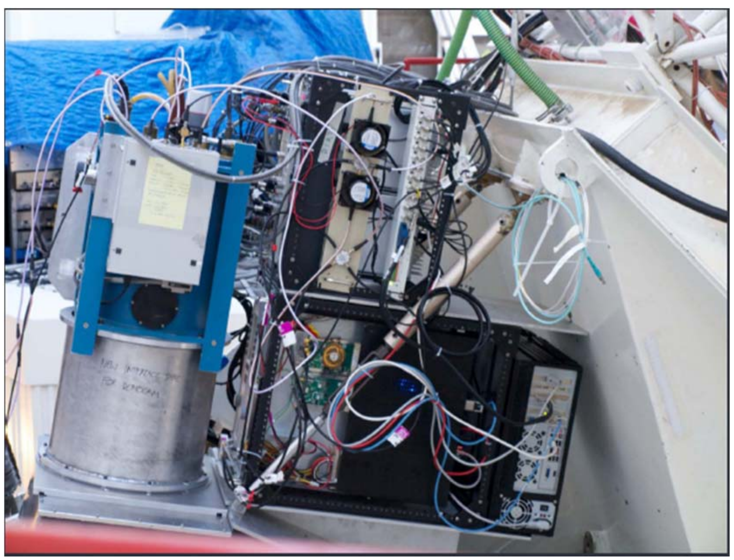
where $X = \frac{Q_c}{Q_i}$

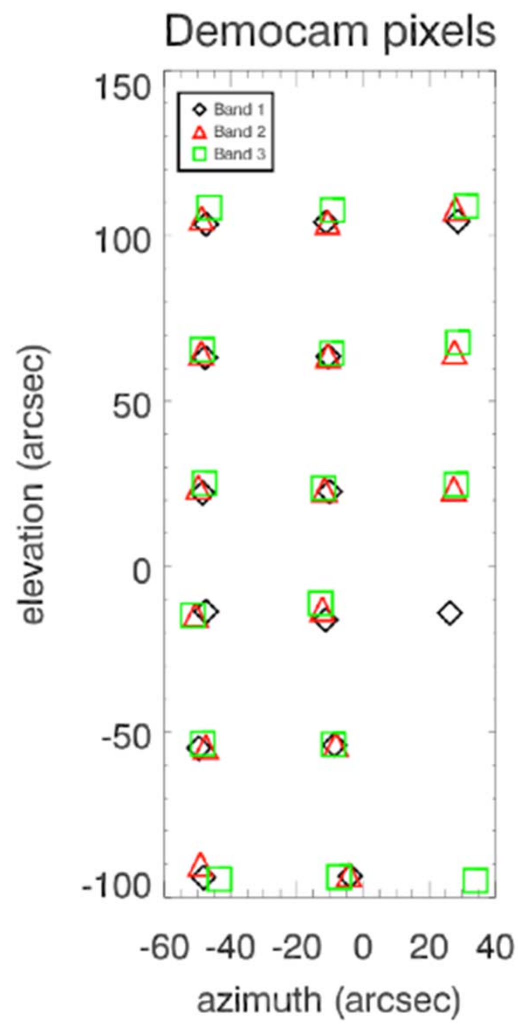


One year ago…

2010 Observing Run

- Beam shapes and locations matched expectations
- Successfully read out **100+ carriers (60 resonators)**
- Demonstrated a path to the full-scale camera
- Plagued by low-frequency electronics noise
- Sensitivity 200-500 mJy $s^{1/2}$
- Factor of 10-100 above BLIP





Credit: Jack Sayers

The Problem of Dark Response

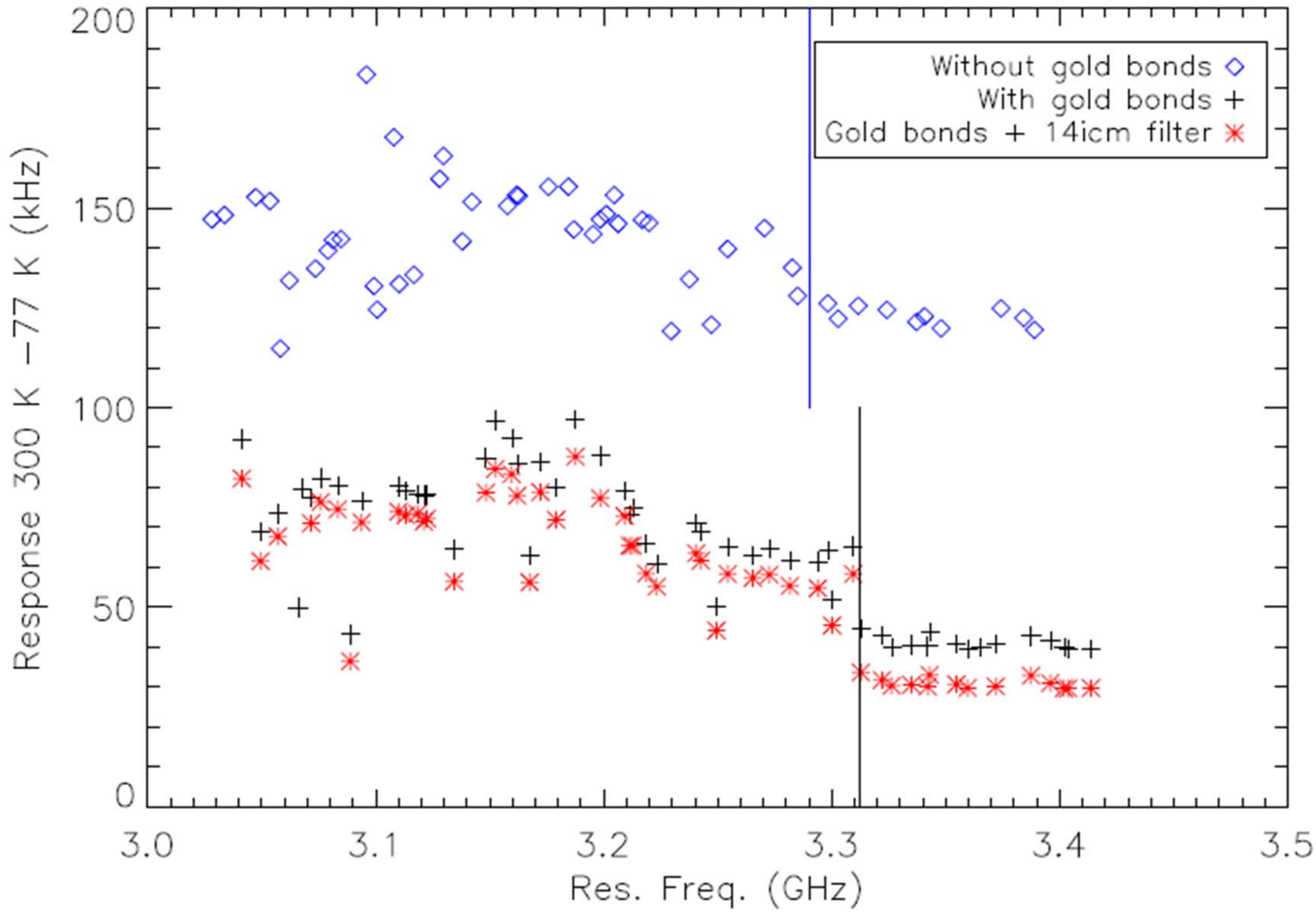
Resonators not-coupled to an antenna show significant response to outside-the-dewar loading.

Possible causes?

- **Heating of the substrate**
- **Direct pick-up**
  - Direct absorption in the aluminum section
  - Coupling through the interdigitated capacitor (IDC)

Substrate Heating

Result of adding gold wire bonds and 14 icm (420 GHz low-pass) filter

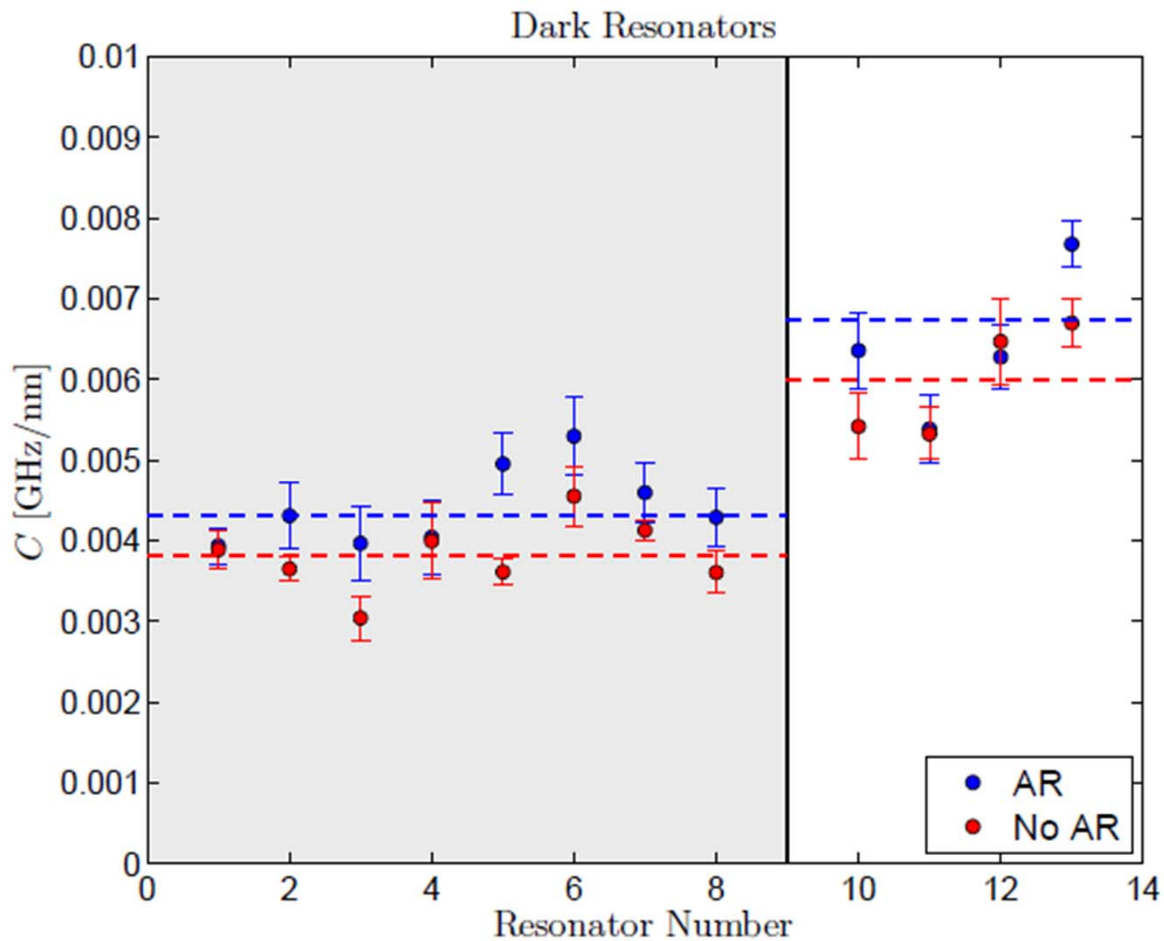


Credit: James Schlaerth

Half - Aperture Test

Placed aluminum aperture over half of the array. Measured efficiency of the non-antenna coupled resonators.

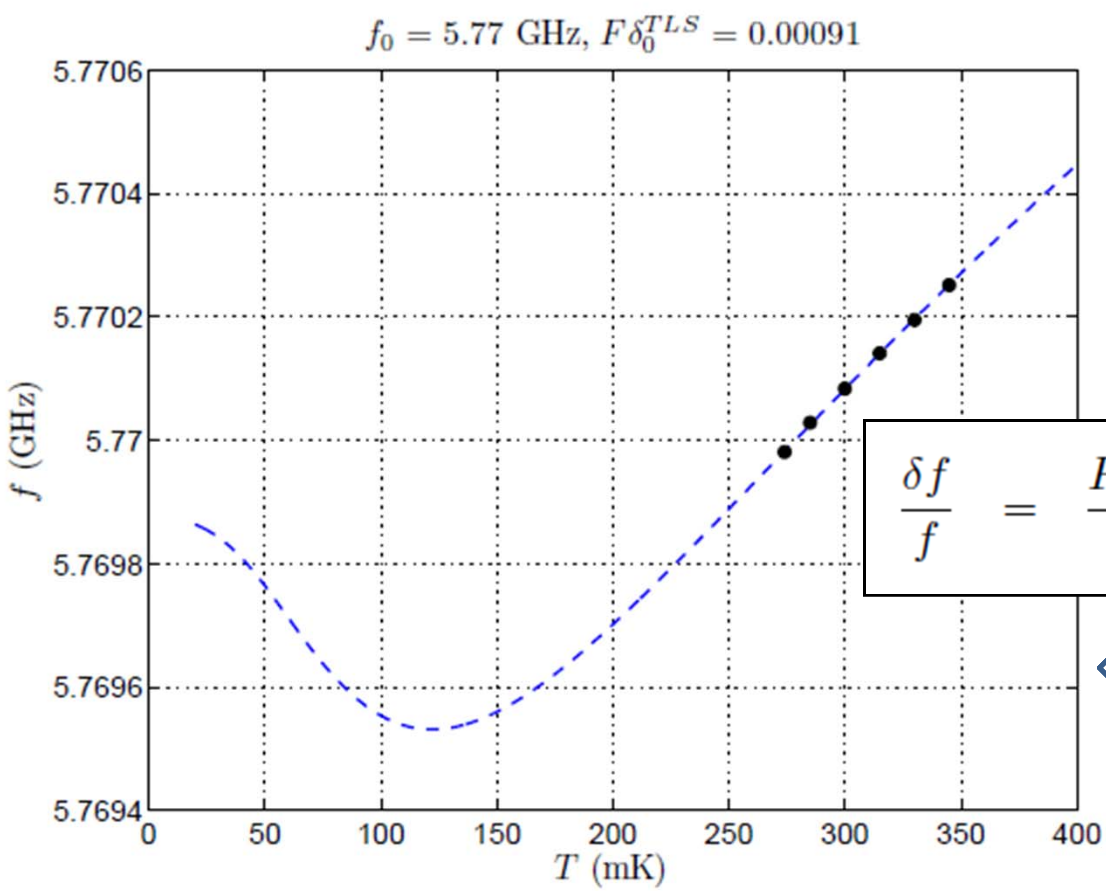
$$C = \frac{\eta B}{d}$$



Ɛ Test Devices

All Niobium ⟹ $T_c = 9.2$ K $\quad \frac{2\Delta}{h} \approx 700$ GHz

- Cannot absorb mm –radiation (no direct pick-up)
- Thermal quasi-particle density negligible

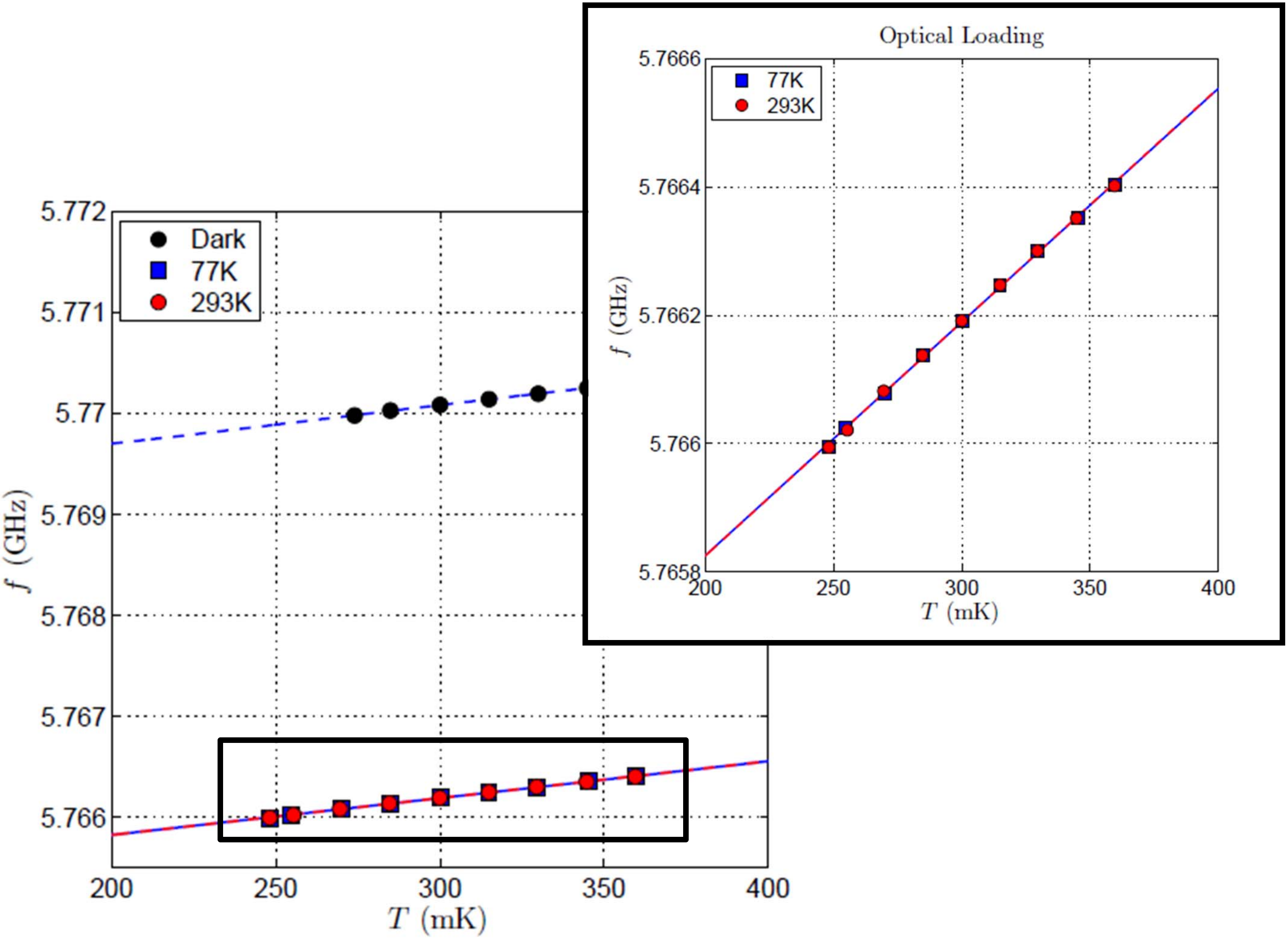


Resonator frequency determined by TLS effects

Use as a TLS thermometer

$$\frac{\delta f}{f} = \frac{F\delta_0^{TLS}}{\pi}\left[\mathrm{Re}\Psi\left(\frac{1}{2} - \frac{\hbar f_0}{ikT}\right) - \log\frac{\hbar f_0}{kT}\right]$$

⟸ Dark calibration



Dark
77K
293K
5.772
5.771
5.77
5.769
5.768
5.767
5.766
f (GHz)
200
250
300
350
400
T (mK)
Optical Loading
5.7666
5.7664
5.7662
5.766
5.7658

Ɛ Test Devices

- No change in the resonant frequency between 77K and 293K loads. Places tight upper-limit on the change in substrate temperature:

$$T_{293K} - T_{77K} \leq 1.0 \text{ mK}$$

- The large response in our normal resonators between hot/cold loads simply cannot be explained by such a small change in substrate temperature.

⇨ **It's Direct Pick-Up**

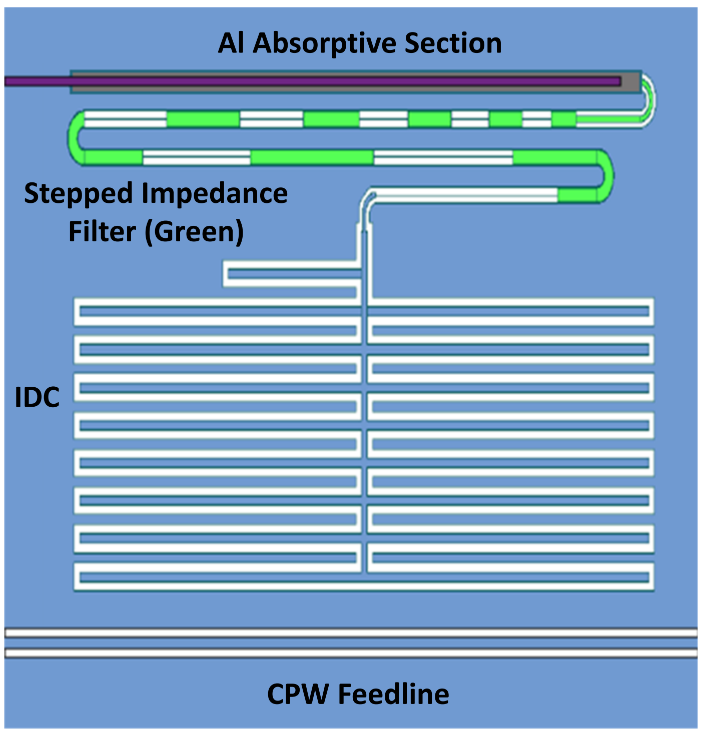
- Epsilon test devices also provide us with an estimate of the loss tangent of the dielectric

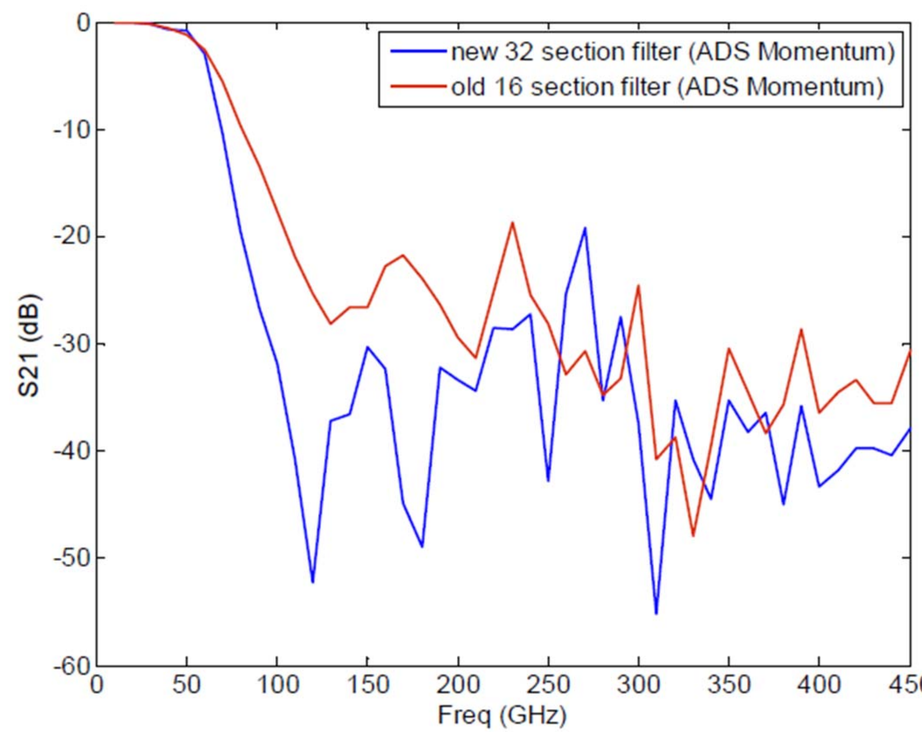
$$F\delta_0^{TLS} = 0.00085$$

- And an estimate of the dielectric constant after simulating the magnetic inductance L_m.

Coupling through the IDC

- Originally implemented IDC to reduce TLS noise
- Observed large increase in direct pick-up. Due to the geometry of the capacitor coupling to broadband radiation.
- Stepped impedance filter introduced between IDC and Al section to block frequencies **80 GHz < ν < 700 GHz**





Credit: Omid Noroozian

Direct Pick-Up Device

- Currently testing a device without antennas
- Contains three groups of five resonators:
  1. IDC with 16-element stepped impedance filter
  2. IDC with new 32-element stepped impedance filter
  3. CPW
- In each group the Al absorptive section is varied in length between 0 mm and 1 mm with the remainder Nb.
- If pick-up is through the aluminum, the response should have some dependence on Al length.
- If there is still pick-up through the IDC we should see drastic differences in the response between the three groups with **CPW < IDC-32 < IDC-16**

The Problem of Low Optical Efficiency

Not so much a problem as an insufficient understanding of the factors that effect the overall absorption of power in our detectors.

To this end we pursued:

1. A systematic characterization of all sources of loss in our system.

2. Extensive hot/cold measurements, an **improved model** of our detectors, and a **robust fitting procedure** to obtain better estimates of the actual system efficiency.

Expected Efficiency

DemoCam

Band	Filters	Lyot Stop	Antenna Efficiency	Fringing Efficiency	Reflection at MKID	Phonon Emission	Overall Efficiency
0	0.73	0.18	0.42	0.69	1.0	0.66	**0.025** +/- 0.005
1	0.76	0.36	0.47	0.68	1.0	0.58	**0.05** +/- 0.01
2	0.73	0.52	0.49	0.76	1.0	0.58	**0.08** +/- 0.02
3	0.68	0.63	0.41	0.96	1.0	0.58	**0.10** +/- 0.02

MUSIC

Band	Filters	Lyot Stop	Antenna Efficiency	Fringing Efficiency	Reflection at MKID	Phonon Emission	Overall Efficiency
0	0.73	0.28	0.65	0.69	1.0	0.66	**0.06** +/- 0.01
1	0.74	0.51	0.58	0.68	1.0	0.58	**0.09** +/- 0.01
2	0.67	0.68	0.61	0.76	1.0	0.58	**0.12** +/- 0.01
3	0.58	0.76	0.54	0.96	1.0	0.58	**0.13** +/- 0.01

Full Model

Data

Hot /cold measurements of resonator frequency and quality factor made over a wide range of base temperatures (200 – 400 mK)

Model

Mattis-Bardeen Theory + Generation-Recombination Equation

Fit To

Frequency Shift

$$\Delta f(T) = f(T, 293\mathrm{K}) - f(T, 77\mathrm{K})$$

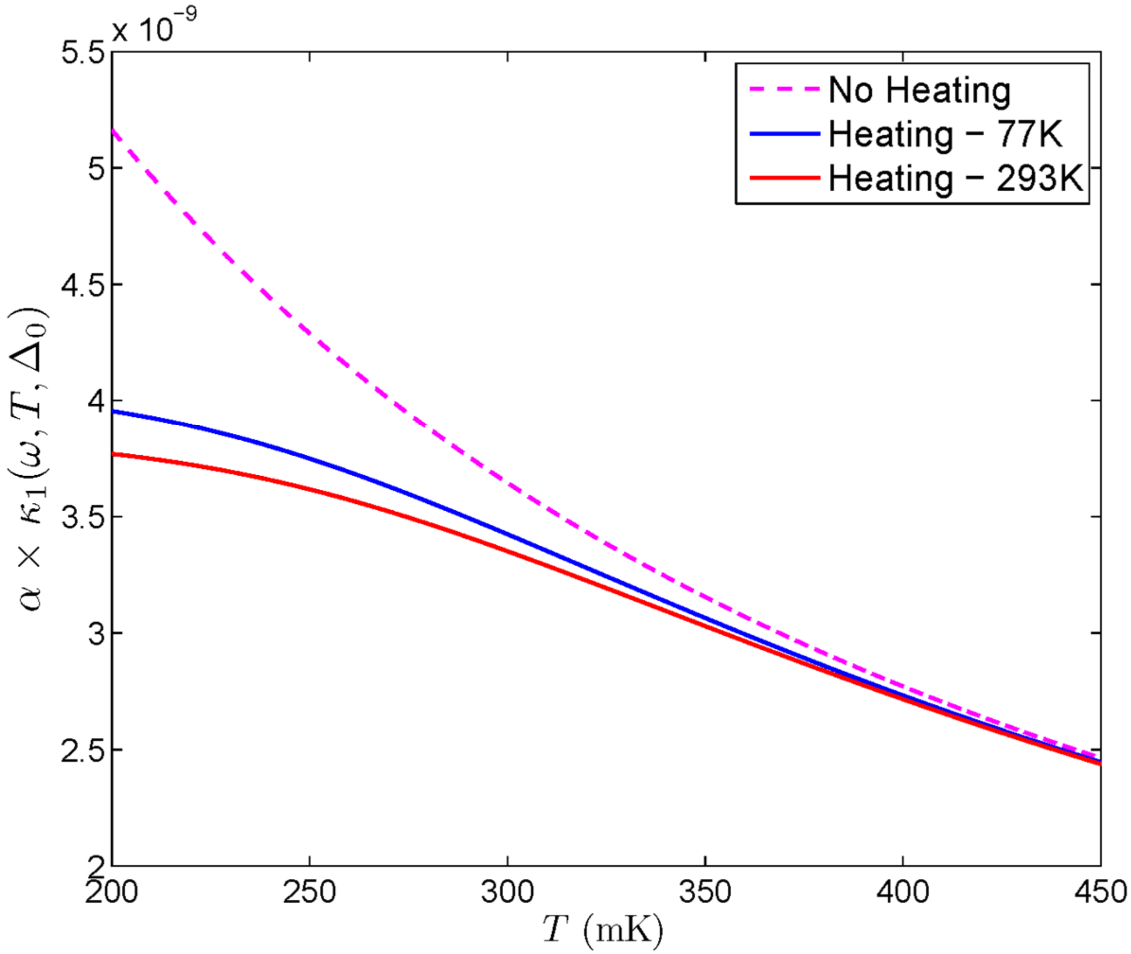
and Naïve Excess Load

$$T_{exc}^{naive} = \frac{293/Q_i^2(T, 77\mathrm{K}) - 77/Q_i^2(T, 293\mathrm{K})}{1/Q_i^2(T, 293\mathrm{K}) - 1/Q_i^2(T, 77\mathrm{K})}$$

Full Model

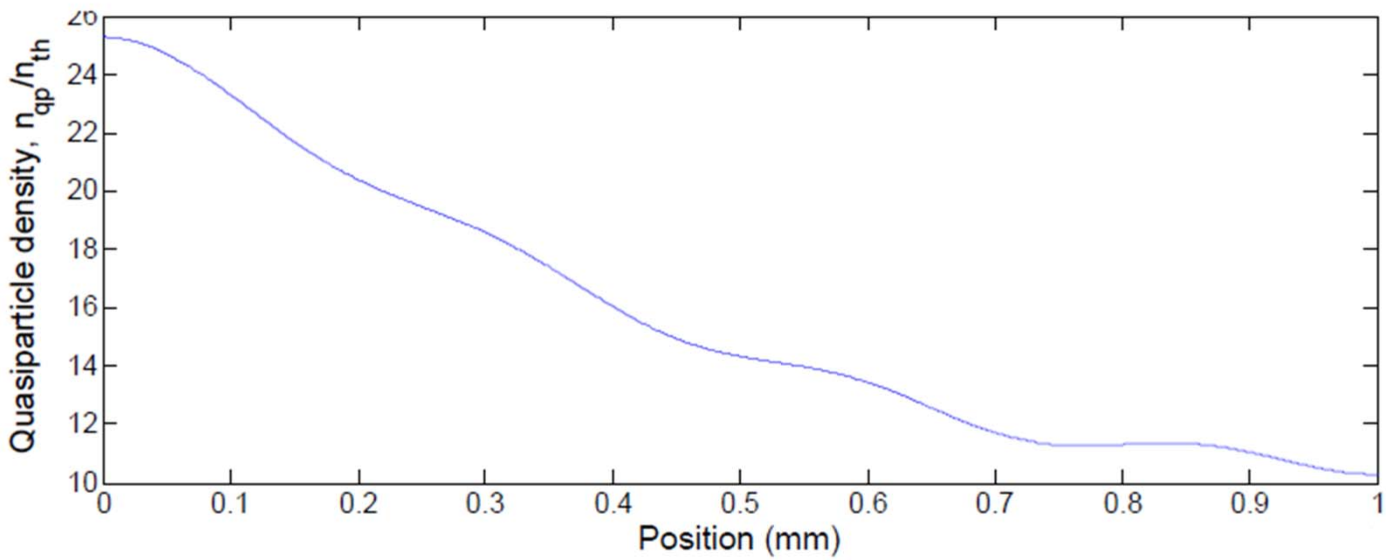
- Allow for an elevated "effective temperature" T_{eff}, parameterized by a conductance law of the form

$$P = g\left(T_{eff}^{\beta} - T^{\beta}\right)$$



Full Model

- **Do not** take into account non-uniform absorption of radiation



Credit: Jonas Zmuidzinas

- Instead include a **1.15** correction factor to the efficiency obtained from the fit

Fitting Procedure

- Total of 9 parameters, 3 have prior information from dark Mattis-Bardeen fits

$$\frac{\eta B}{d}, \quad T_{exc}$$

$$\tau_0, \quad \beta, \quad \frac{P_{77K}}{g}, \quad \frac{P_{293K}}{g}$$

Nuance

$$\alpha, \quad \Delta_0, \quad \frac{1}{Q_{i,0}}$$

Well-constrained
by priors

- Implement a MCMC using the **Metropolis Algorithm** and **simulated annealing** to efficiently explore the parameter space and search for global minimum of the likelihood function
  - Accounts for uncertainty in bath temperature, loading conditions, etc.
  - Correctly capture the large correlation between $\boldsymbol{\alpha}$ and $\boldsymbol{\Delta_0}$

Most Recent Results

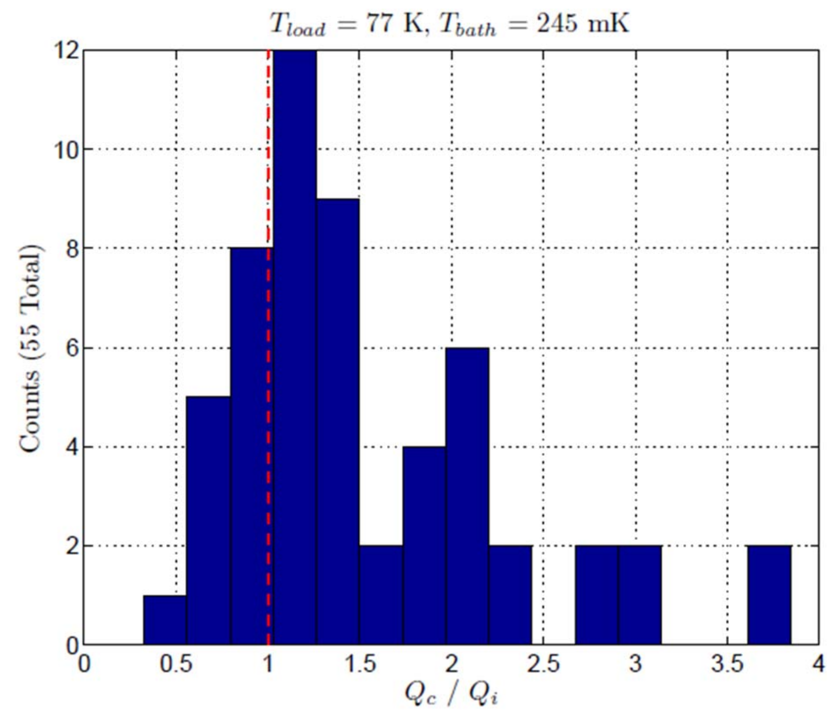
Array Description

Changes Made

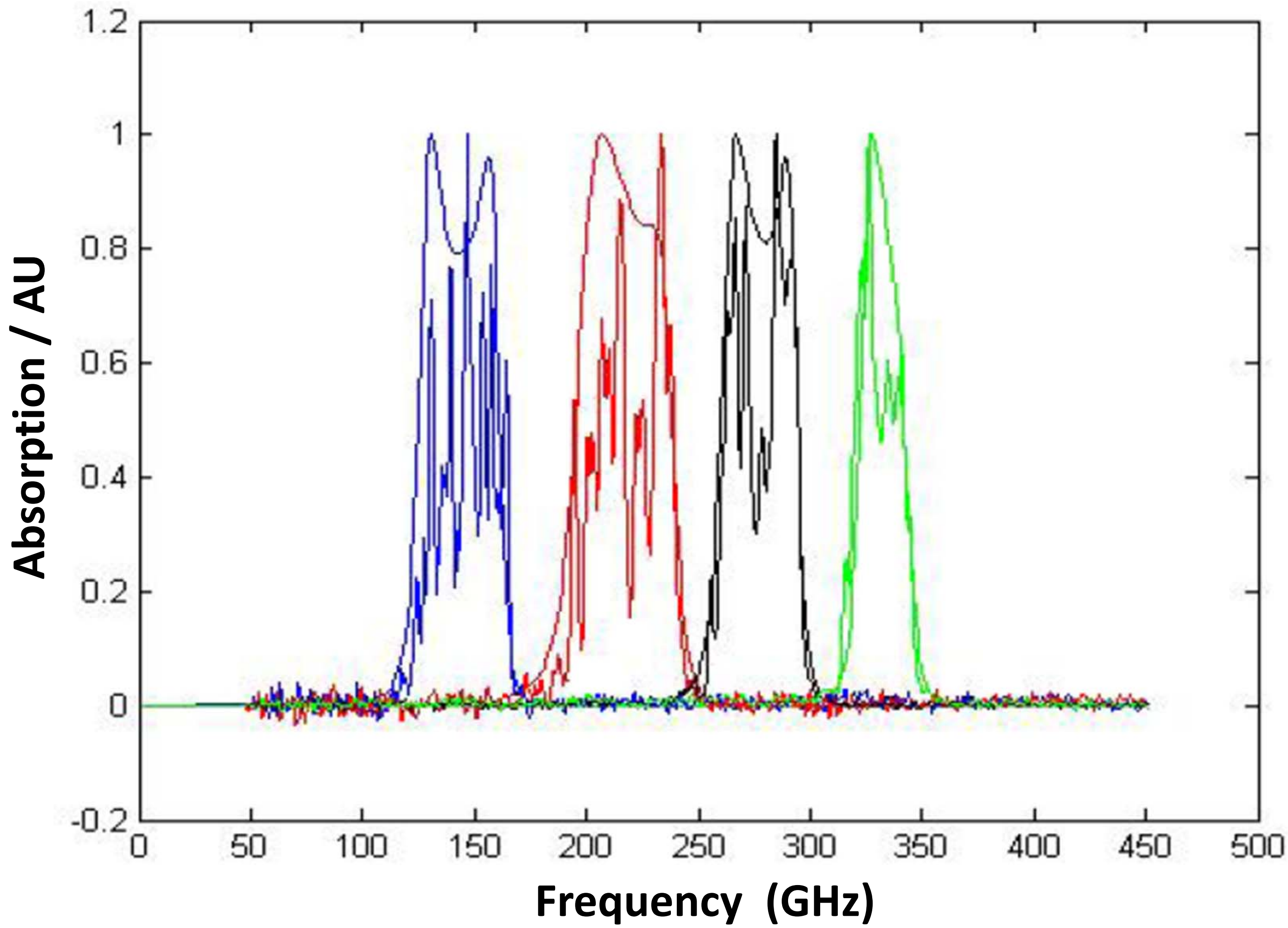
- Switched dielectric in microstrip and bandpass filters from SiO_2 to Si_3N_4
- Increased antenna slot and tap impedance for improved efficiency in lower frequency bands
- Included "index" and "loss" test devices to measure the phase velocity and loss in the microstrip
- Added a **fourth band at 150 GHz** (Band 0)

Broad Characteristics

- Approximately 100 out of 144 resonators survived **(70% yield)**
- Internal and coupling Q's well matched at base temperature under 77K load (comparable to sky loading at CSO).



Bandpasses

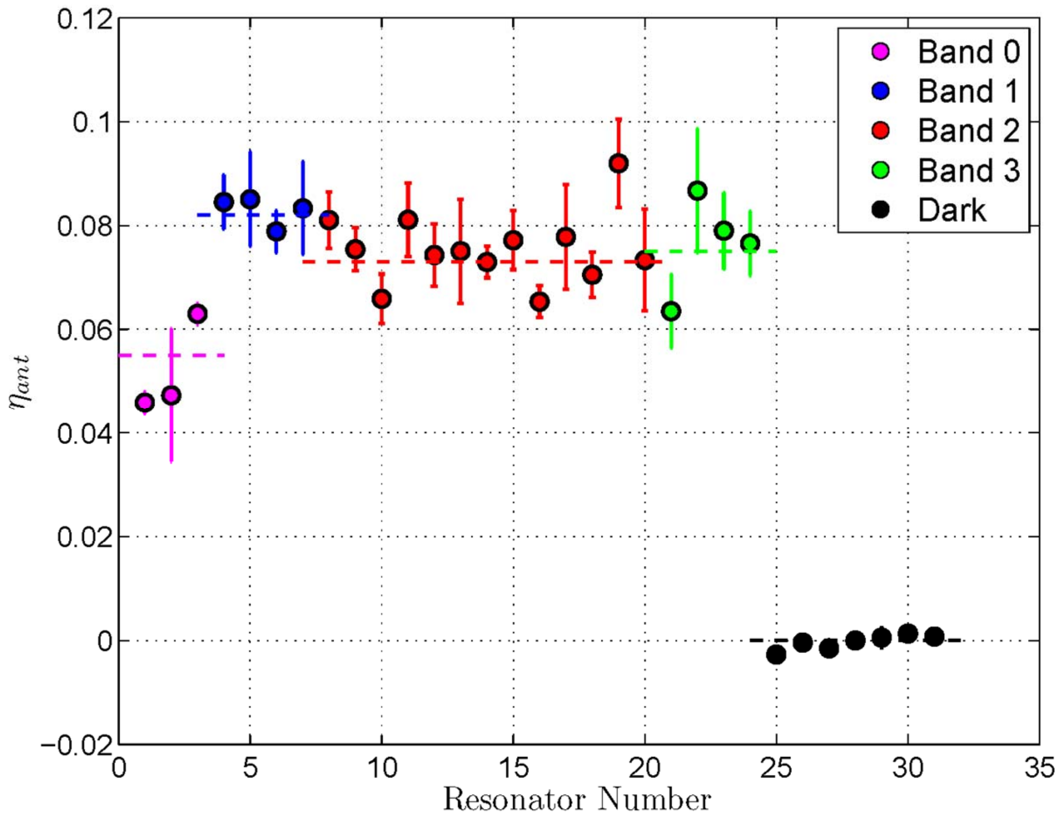


Epsilon of Si_3N_4 : 7.0

Credit: Ran Duan

Optical Efficiency

Band	Expected Efficiency	Measured Efficiency
0	**0.025** +/- 0.005	**0.055** +/- 0.002
1	**0.05** +/- 0.01	**0.082** +/- 0.003
2	**0.08** +/- 0.02	**0.073** +/- 0.001
3	**0.10** +/- 0.02	**0.075** +/- 0.004



Note: Quoted uncertainties are only statistical. **Actually sensitive to**

$$\frac{\eta}{RV}$$

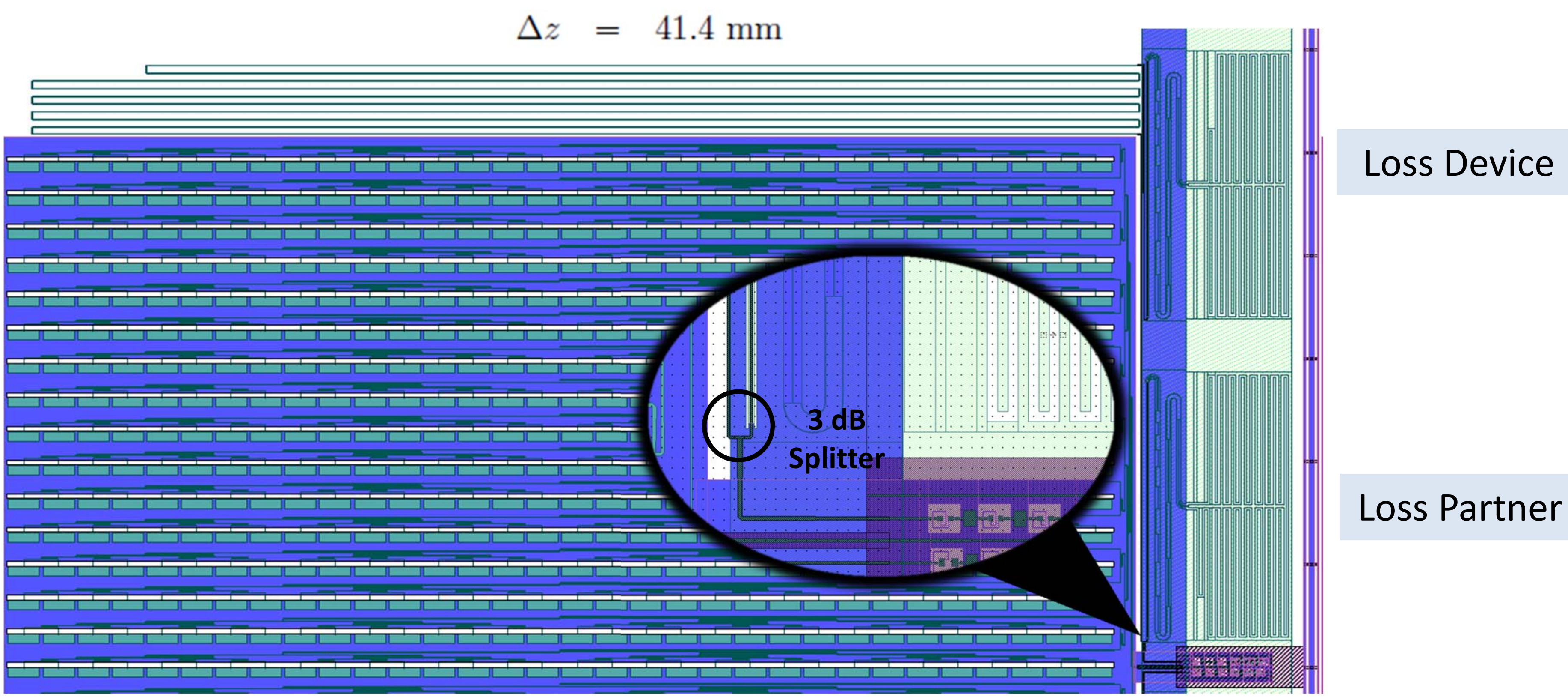
Assume that

$$R = 9.4\ \mu\mathrm{m}^3\ \mathrm{s}^{-1}$$

and

$$V = 1000\ \mu\mathrm{m}\ \times\ 6\ \mu\mathrm{m}\ \times\ (55\ \mathrm{nm})$$

Loss Test Devices



Latest mask contained devices designed to measure the loss tangent of Si_3N_4. These are based on devices designed by Chao-Lin Kuo for CMB polarization experiments, scaled to higher frequencies.

Loss Partner -- Loss Device efficiency ratio: $\eta_{LP} \; / \; \eta_L = 3.9 \pm 0.4$

Loss tangent defined as the angle in the complex plane between the resistive component of an EM field and the reactive component

$$\tan\delta = \frac{\omega\epsilon'' + \sigma}{\omega\epsilon'}$$

Power dissipated in microstrip as:

$$P = P_0 \, e^{-\delta k z} \quad \Rightarrow \quad \delta = \frac{\ln\left(P_{LP}/P_L\right)}{k \, \Delta z}$$

Loss tangent of Si_3N_4 :

$$\delta = 0.0016$$

8.4 mm of microstrip between antenna and device

Band	Transmission
0	0.88
1	0.83
2	0.79
3	0.75

- From epsilon test devices $F\delta_0^{TLS} = 0.00085$
- Roughly equal to previously measured values for SiO_2
- Factor of 2.25 larger than value measured in BICEP2 for Si_3N_4

Credit: Sunil Golwala

Excess Load

- Load from the dewar being absorbed by our dark detectors:

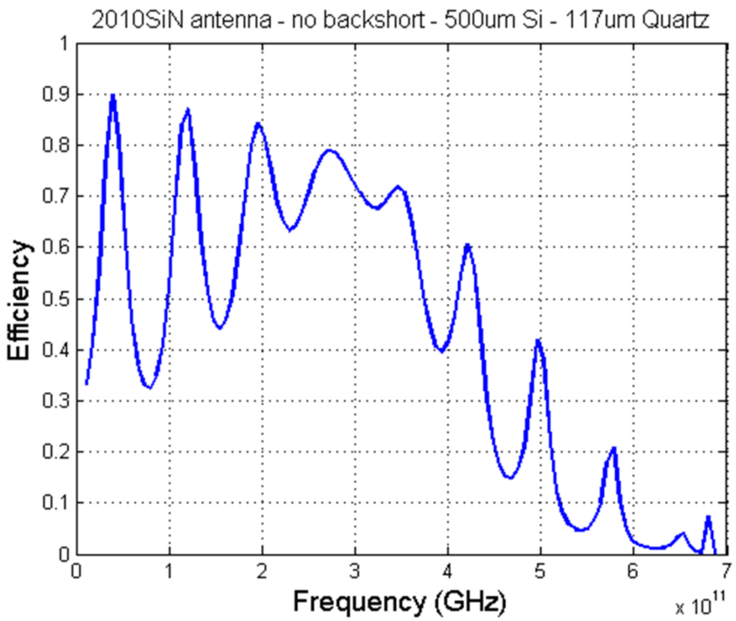
  $\mathbf{P_{dewar} = 0.4\ pW}$

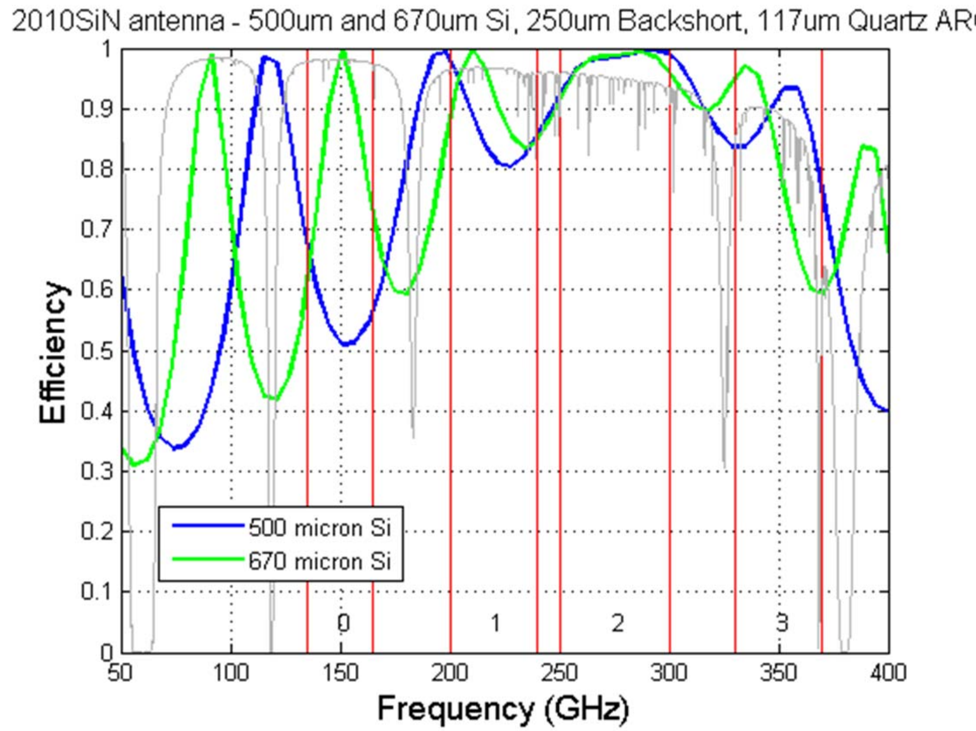
- Load from the dewar being absorbed by our antenna coupled detectors:

  $\mathbf{P_{dewar} = 1.0 – 1.5\ pW}$ (depending on band)

  - Corresponds to an excess load of 30 - 40 K
    - 10 – 15 K due to direct pick-up
    - 20 – 25 K due to antenna beam spilling onto inside of dewar

Nb Backshort



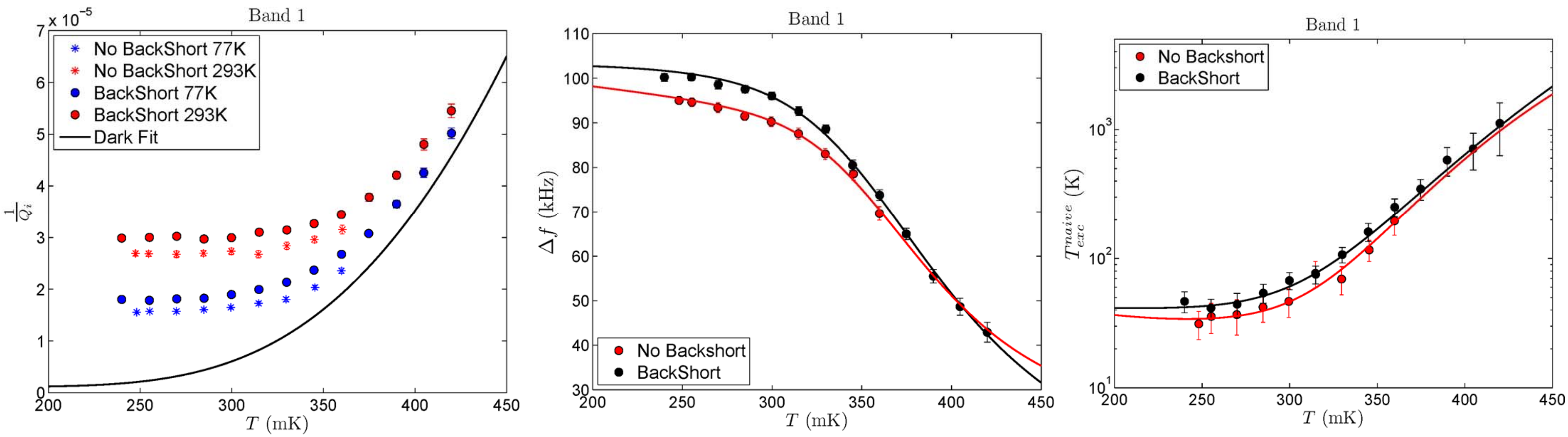


Credit: Peter Day

Current array has **500 µm Si** with **117 µm Quartz AR Coat**.

Implemented a **250 µm Nb backshort**.

No Backshort vs. Backshort



- Improvement in optical efficiency

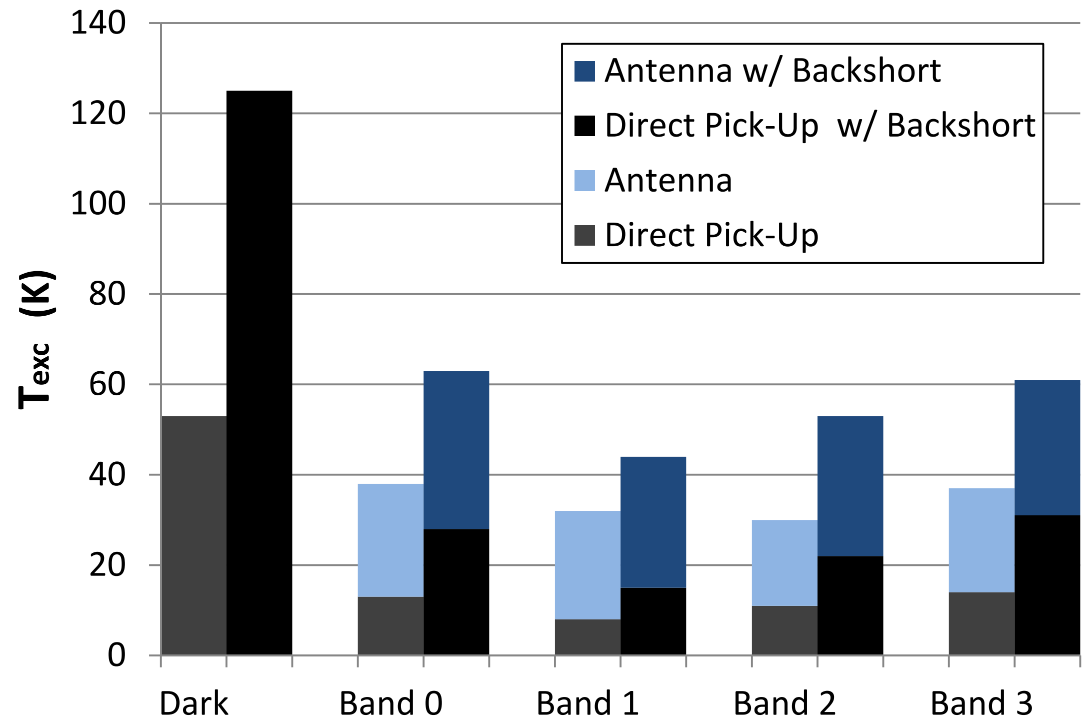
Band	Measured Efficiency	Measured Improvement	Expected Improvement
0	**0.060**	9%	-8%
1	**0.099**	21%	32%
2	**0.085**	17%	26%
3	**0.093**	24%	29%

- Efficiency of direct pick-up remained the same

No Backshort vs. Backshort

- Note that with the addition of the back short, we also **blackened the inside of the magnetic shield**

- We saw a large increase in excess load
  - P_{dewar} doubled for both dark resonator and antenna coupled resonators

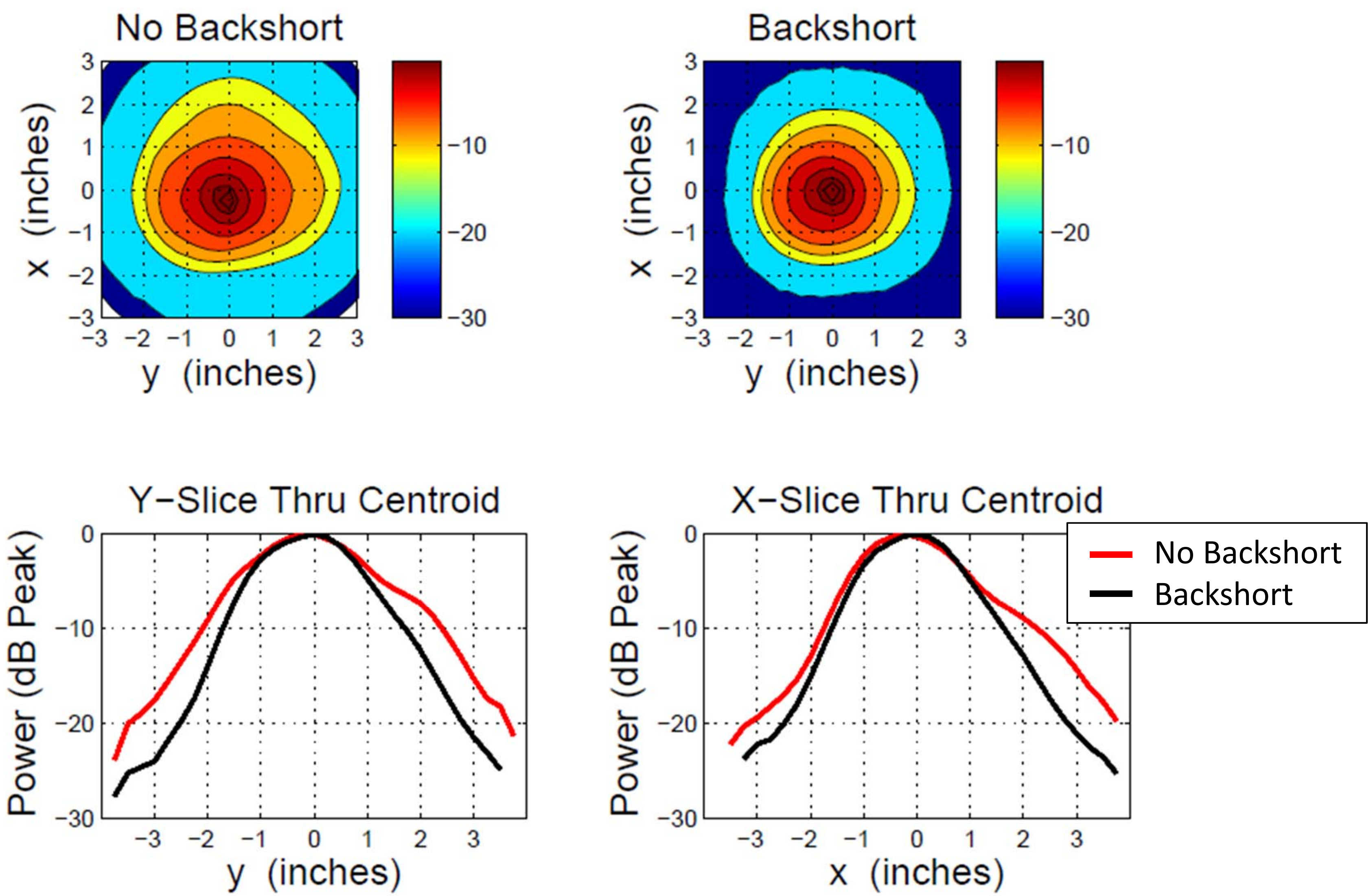


- Could be due to two competing effects

1. Increased efficiency for direct absorption due to the backshort (increases η_{dir}).
2. Decreased coupling to outside world due to blackening of the mag shield. Large angle response now terminates inside dewar (decreases η_{dir}).

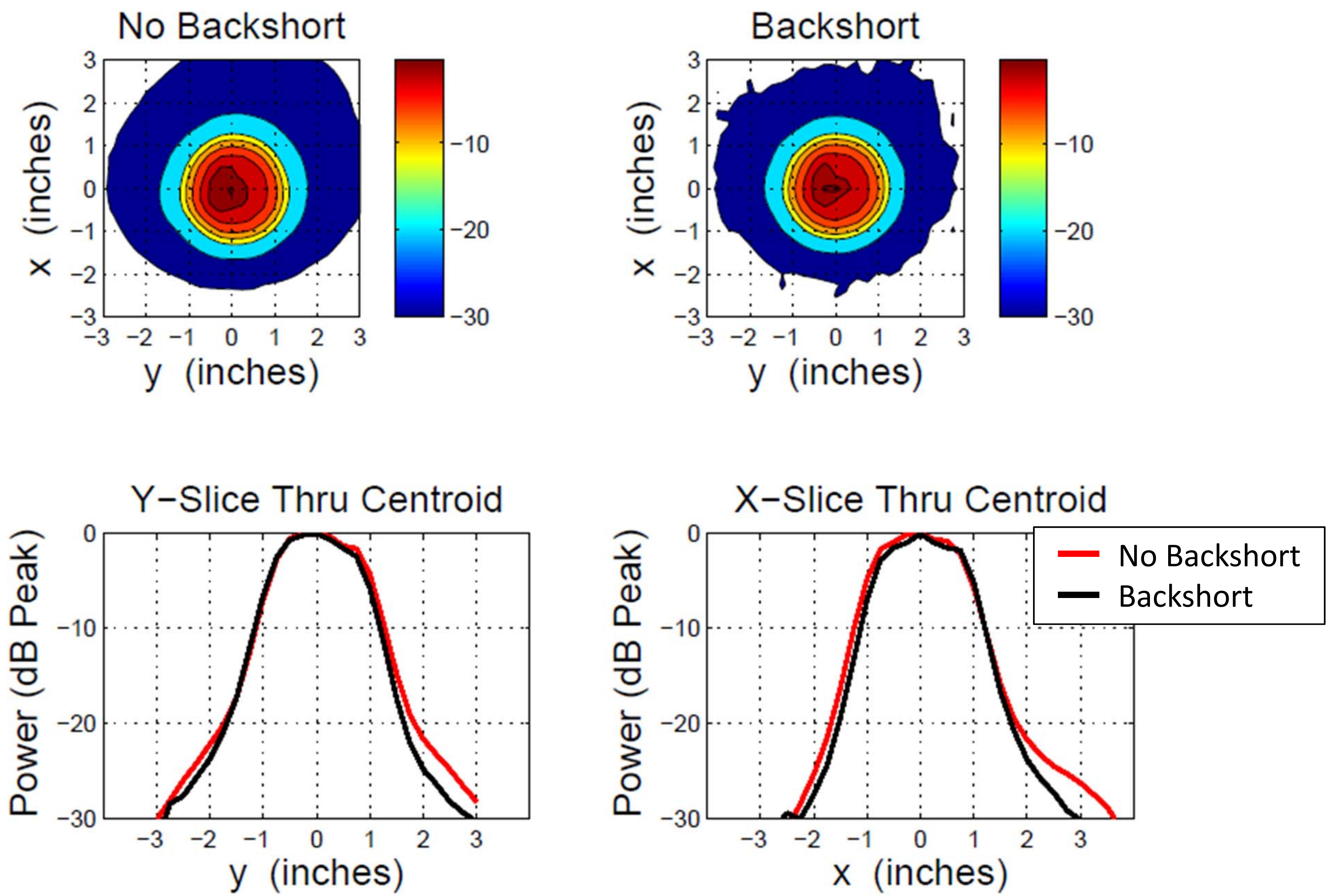
Beammaps

Stacked Map for Non-Antenna Coupled Resonators



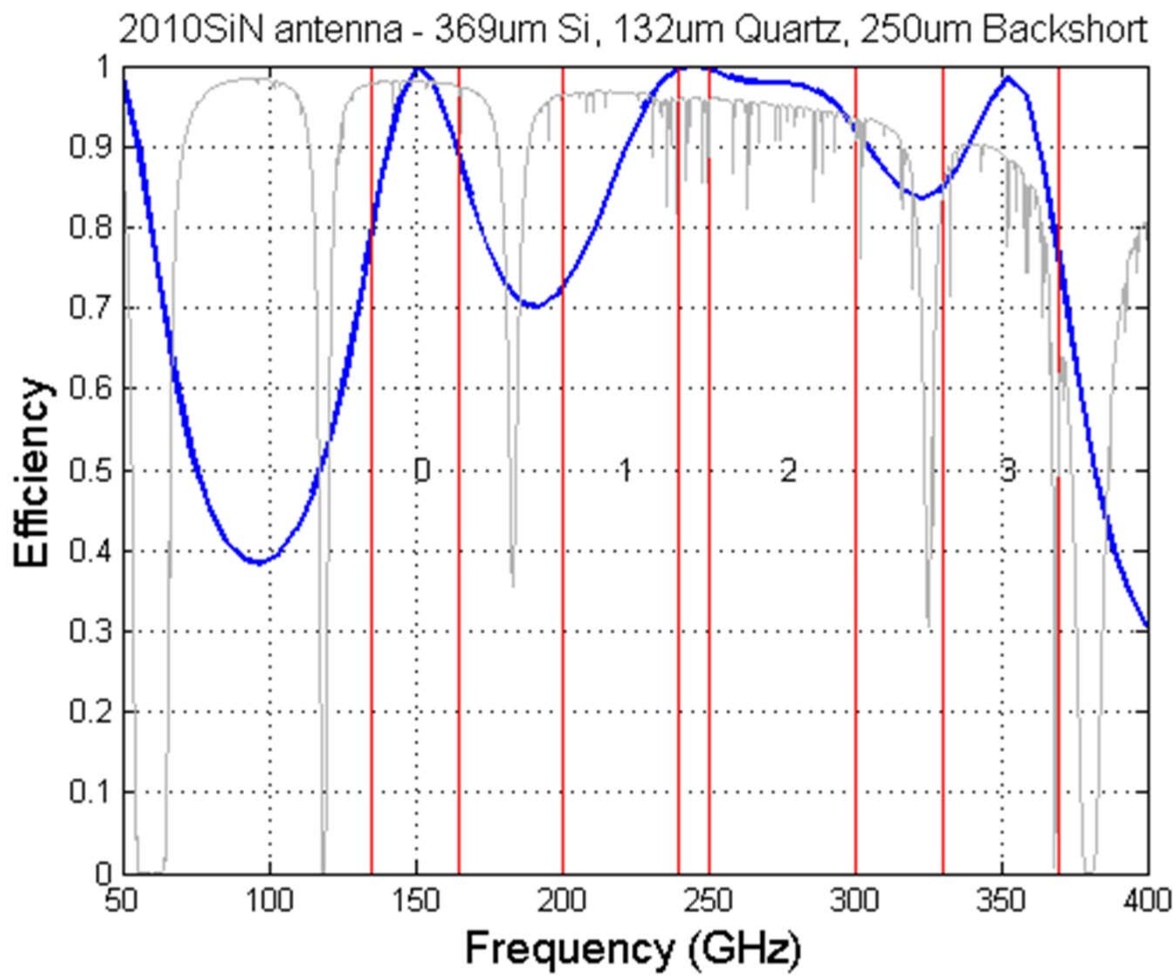
Beammaps

Stacked Map for Band 3 Resonators



Nb Backshort

Room for improvement, particularly in Band 0.
Transmission for optimized Si and AR thickness:



Credit: Peter Day

NEP

Defined as the signal power required to achieve a signal-to-noise ratio of 1.

$$\mathrm{NEP}(\tilde{f}) = \sqrt{S_X(\tilde{f})}\,\left|\frac{dX}{dP_{\mathrm{opt}}}\right|^{-1}$$

Dominant Sources of Noise:

- Photon: $$\mathrm{NEP}_\gamma^2 = 2P_{\mathrm{opt}}h\nu_0 + \frac{2P_{\mathrm{opt}}^2}{\Delta\nu}$$

- Two Level System (TLS) noise: $$S_{\delta f/f}^{\mathrm{TLS}}(\tilde{f}) \;\propto\; T^{-2}\; P_{\mathrm{read}}^{-1/2}\; \tilde{f}^{-1/2}$$

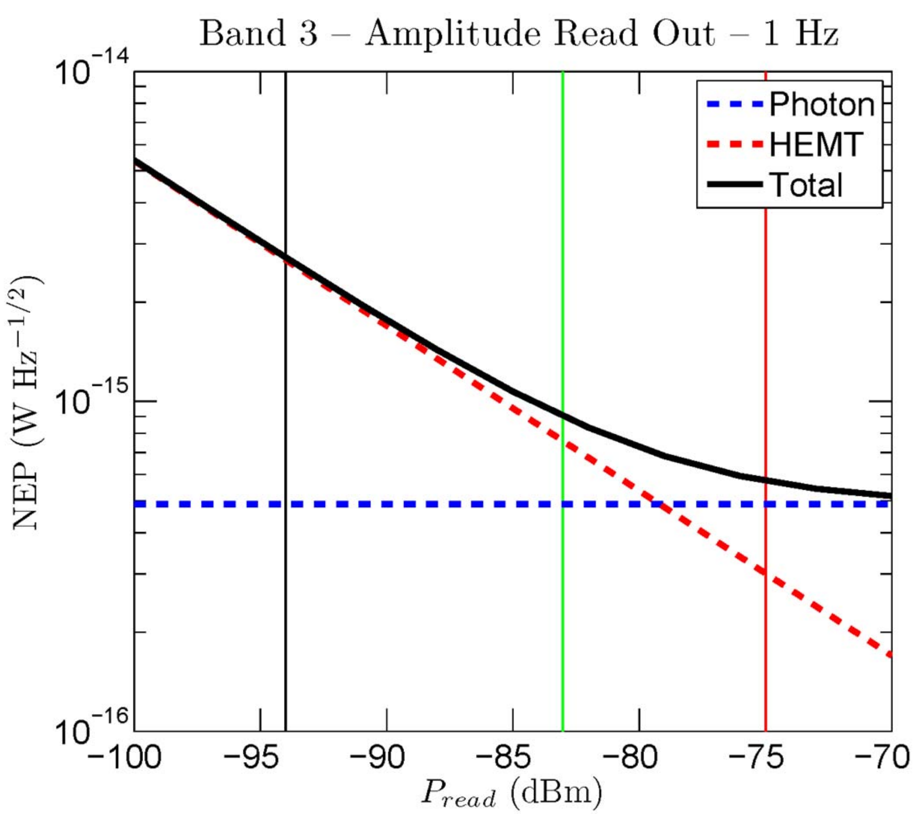
- HEMT noise: $$S_{\delta \mathrm{S}21}^{\mathrm{HEMT}}(\tilde{f}) \;=\; \frac{kT_n}{2P_{\mathrm{read}}}$$ where $$T_n = 5\ \mathrm{K}$$

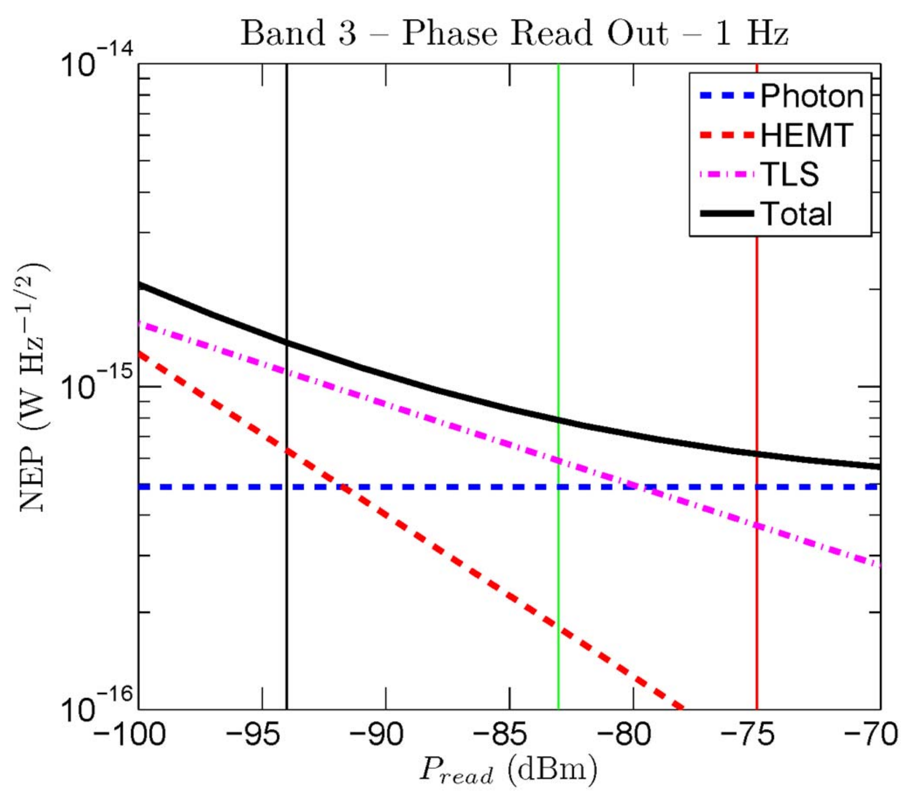
- Loading at CSO with MUSIC will be different from in lab, 77K load

Band	Atmospheric Load
0	16 K
1	27 K
2	42 K
3	80 K

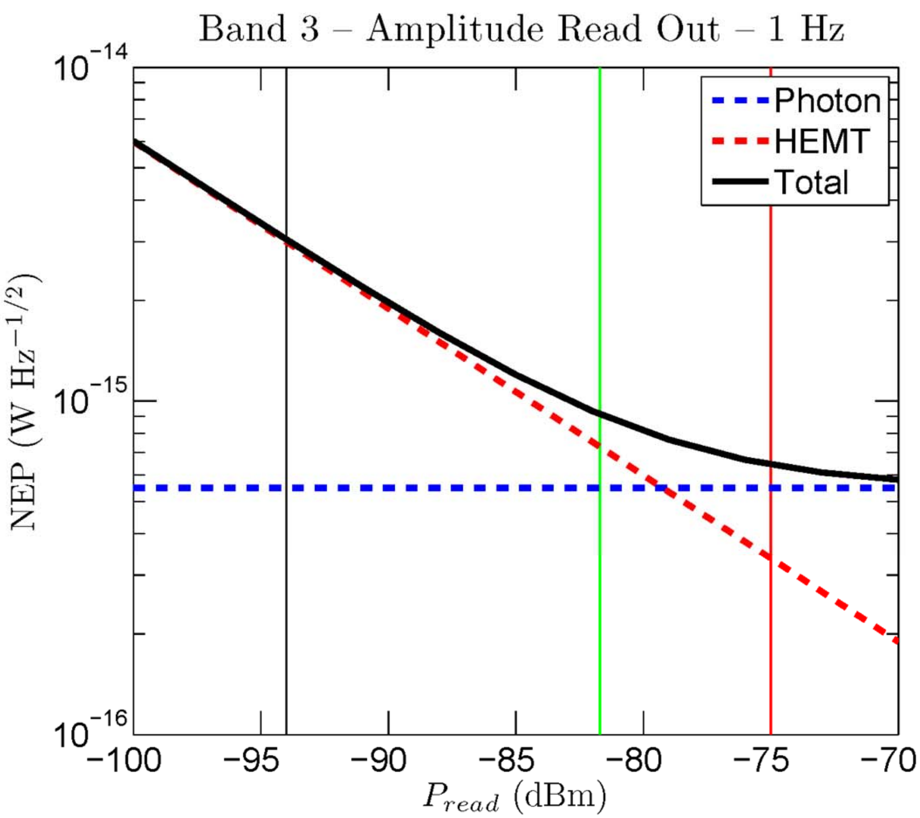
Credit: Jack Sayers

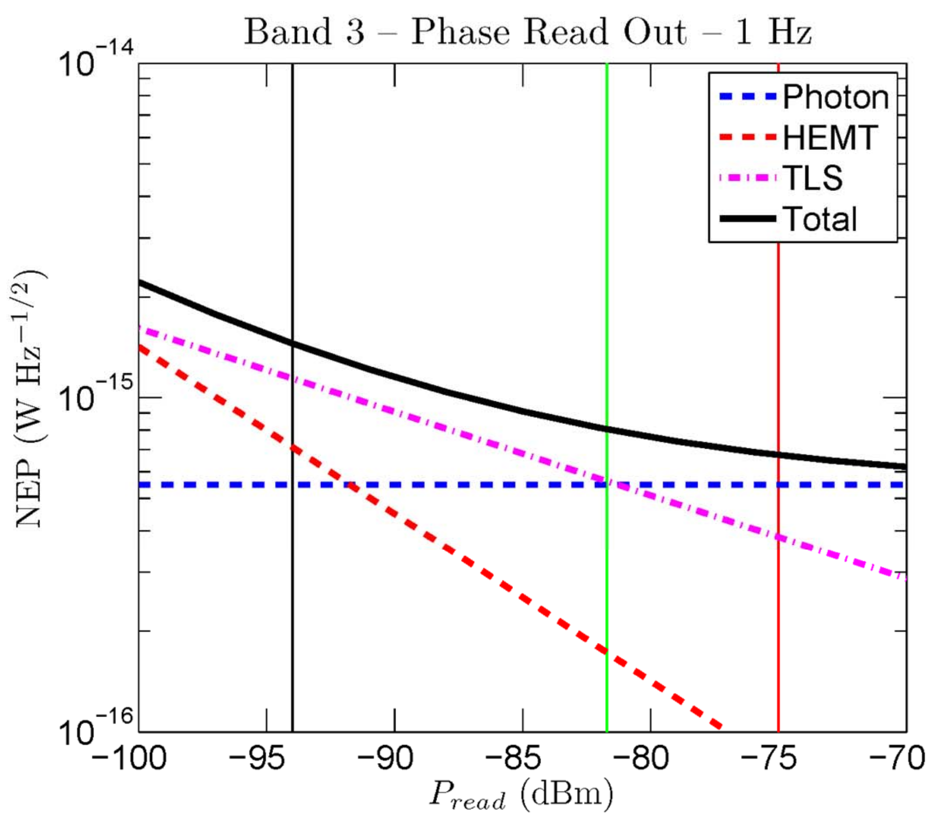
DemoCAM NEP -- No Backshort





DemoCAM NEP -- Backshort





In Conclusion…

Accomplishments

- Reduction of substrate heating (through the addition of gold wire bonds) to a negligible level (as measured by epsilon test devices).
- Better understanding of our optical efficiency.
  Measurements roughly match expectations!
- 15-25% improvement in efficiency with the introduction of a Niobium back-short (at the cost of increased excess load).
- Experimental results point to physics that we do not fully understand:
  - Anomalous frequency-to-dissipation ratio
  - Quasi-particle heating

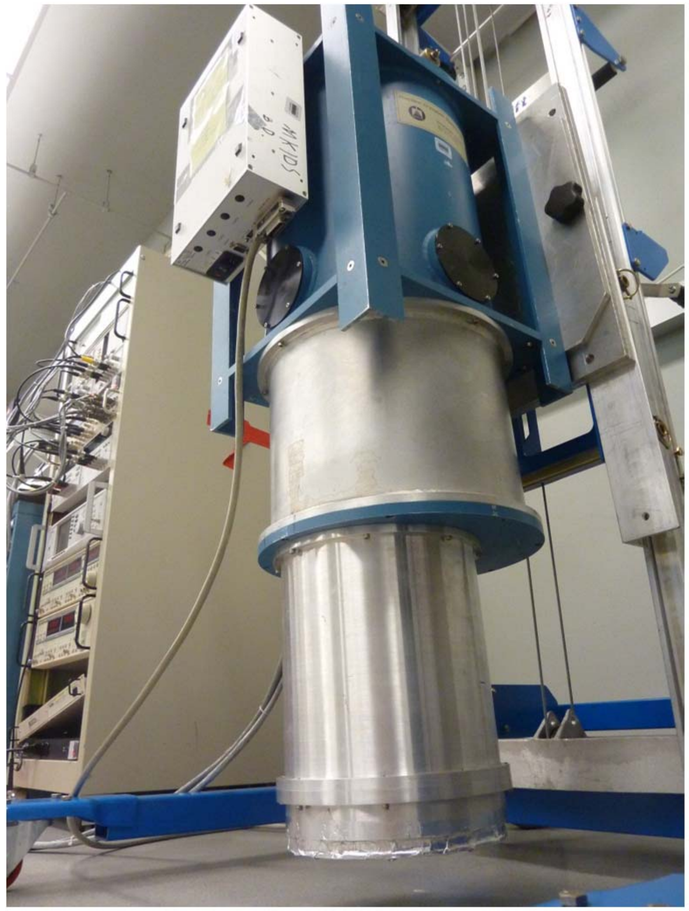
Challenges

- Understanding the mechanism for direct pick-up
  - New “direct pick-up” mask currently being tested

- Optimizing MKID read-out power

- Removing correlated, low-frequency electronics noise

- Characterizing and reading out 2304 MKIDs


MKIDS