Two Level System Noise (TLS) and RF Readouts

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Two Level System (TLS) and Superconducting Resonators

Have well known effects in superconducting resonator applications

- Energy dissipation – limits Q’s of devices (Q-bits, MKIDS, etc)
- Frequency shift – small shifts in resonant frequency
- Add Frequency Noise

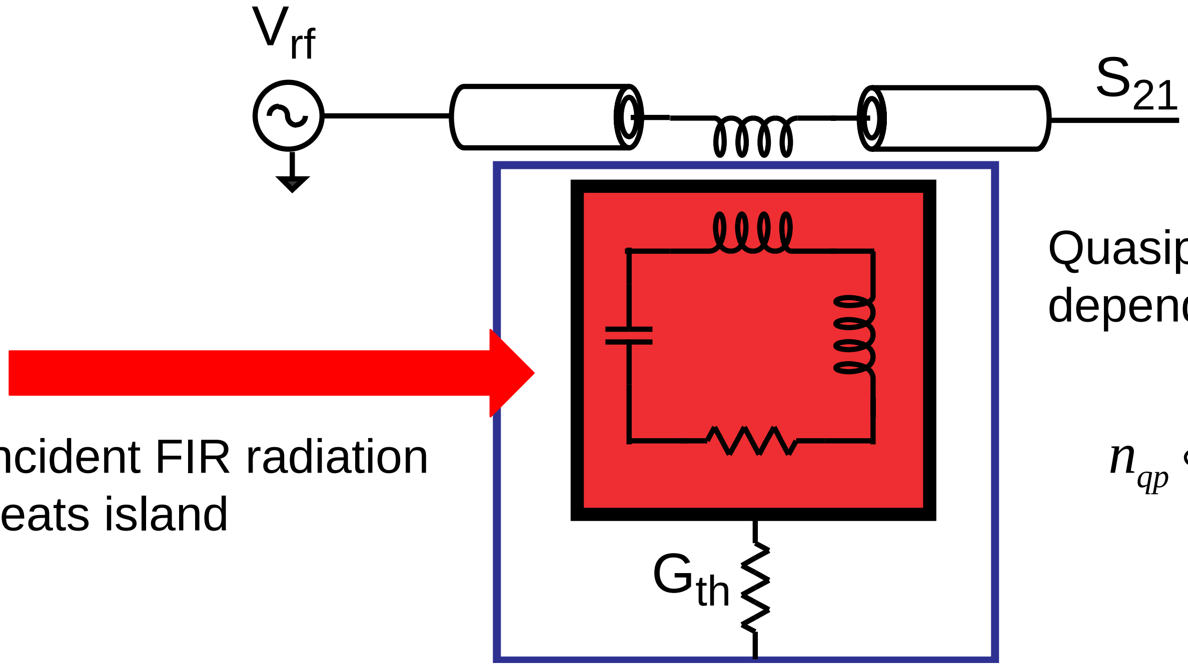
No clear theoretical understanding of noise

- Temperature power power dependence well mapped
- Limited exploration of variation with resonator frequency
- Some TLS physics suggest lower noise as hf << kT

Kinetic Inductance Thermometry And Radio-Frequency Readouts

Possible use of LC resonators at Kinetic Inductance Thermometers (KITs)

- FIR radiation absorbed by suspended bolometer island
- Temperature read out via RF-KIT
- RF - Require large capacitors with amorphous dielectrics (TLS noise)



Incident FIR radiation heats island

Quasiparticle density (therefore L) depends on temperature:

$$n_{qp} \propto \sqrt{\frac{2\pi k_B T}{\Delta}}\, e^{-\Delta/k_B T}$$

Kinetic Inductance Thermometry And Radio-Frequency Readouts

TLS Noise - potentially limiting factor in this FIR detection scheme

Need TLS Noise < Photon Noise

$$S_{TLS} < \frac{\beta^2}{4Q_\sigma^2}\frac{1+n}{n\Delta\nu}$$

β – ratio of frequency to dissipation response
n – optical efficiency ~ 1
$\Delta\nu$ – optical bandwidth

$$\beta = \frac{\delta\sigma_2}{\delta\sigma_1} \sim 1-10$$

Noise for a FIR spectrometer detector with typical values:
$n = 1$, $\beta = 10$, $Q_i = 10^5$, $\Delta\nu = 0.3$ GHz: $S_{TLS} < 2\times10^{-17}$ / Hz

Is this achievable with radio-frequency readouts?

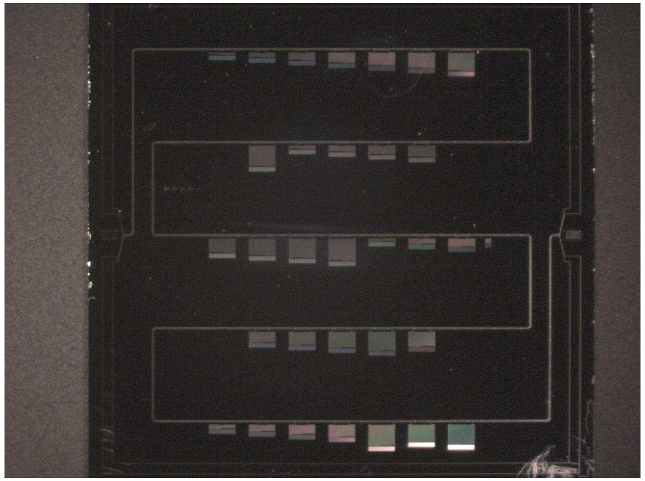
Exploration of TLS effects at Radio-Frequency

Lumped LC resonators spanning wide frequency range

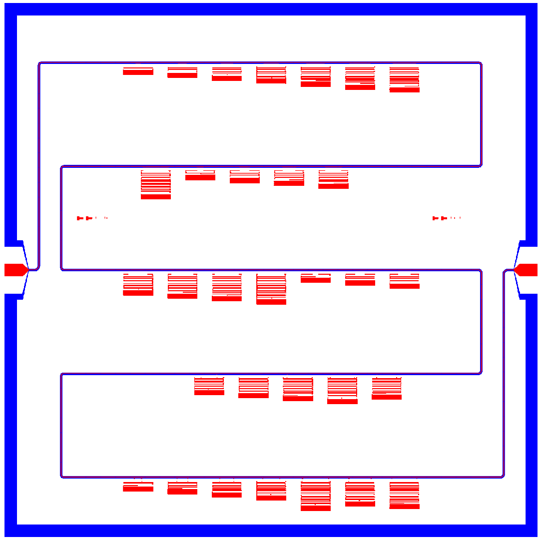
Inductance
- High α materials – TiN, NbTiN
- Vary frequency of resonators by adjusting length of meander inductors

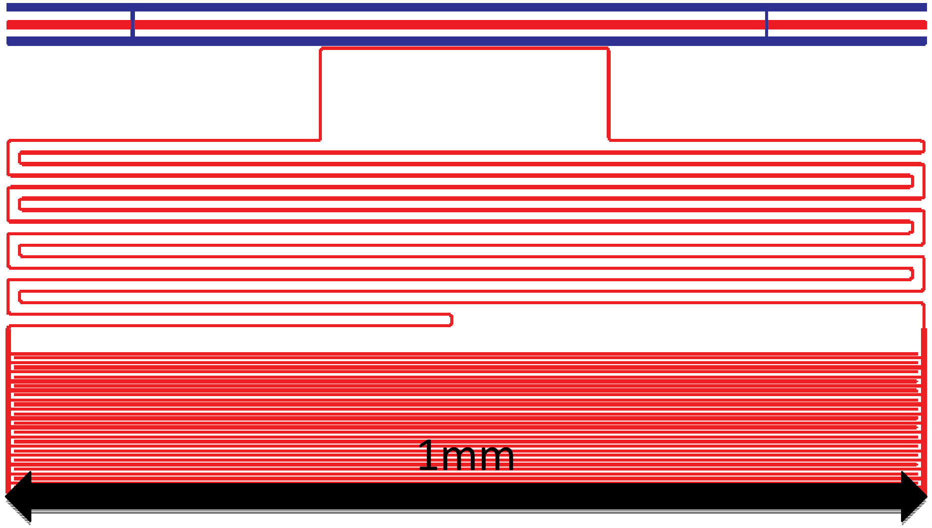
Capacitance – goals:
- Interdigitated Capactiors – 250 MHz – 3 GHz
- Parallel Plate – 50 MHZ – 1 GHz
- Multiple dielectrics – SiO2, SiN, Si, SOI

Fabricated our first device:
- **28 Resonators**
- **IDC, 250 MHz – 1 GHZ**



Devices: Lumped LC resonators spanning wide frequency range



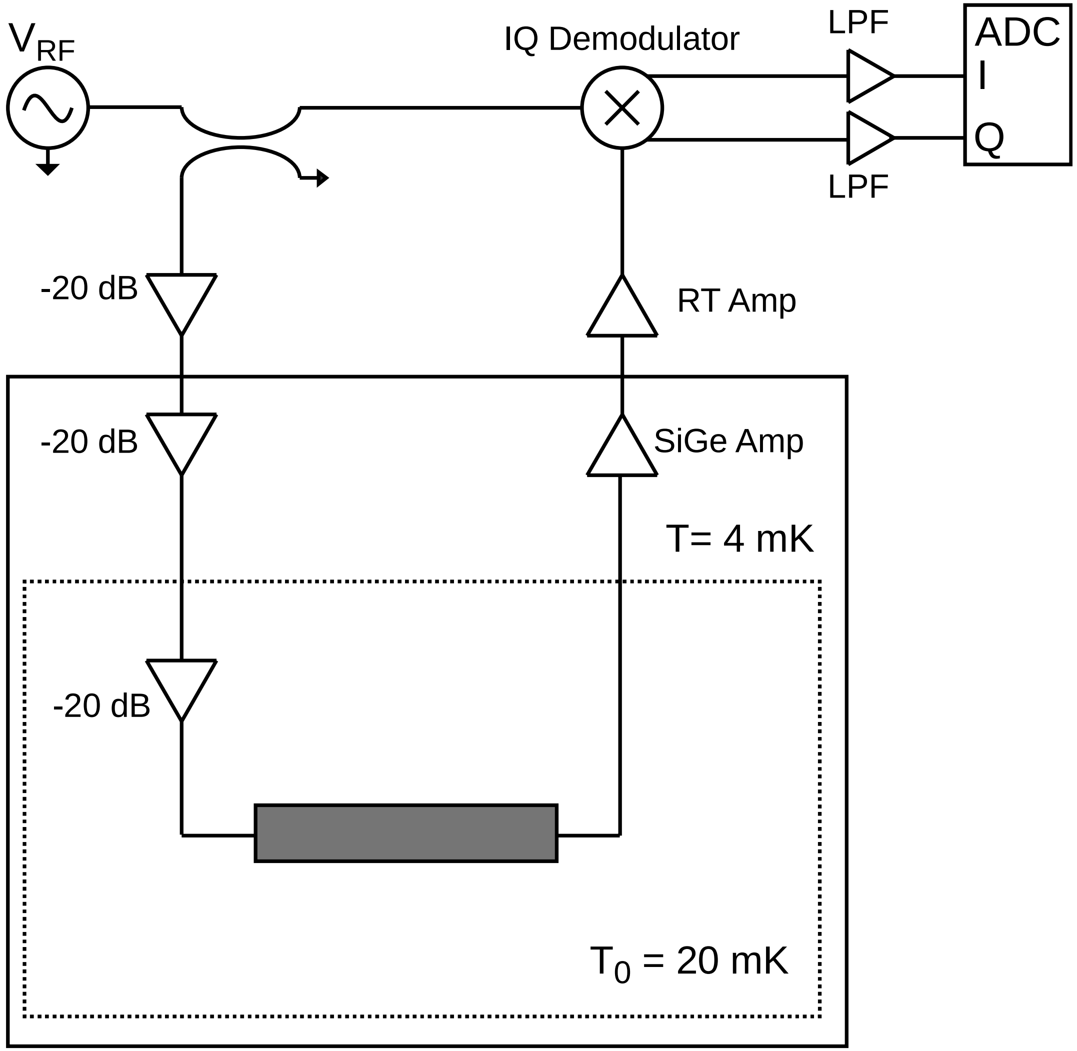


Device design:
31 Resonators
Resonator + CPW center conductor:
NbTiN (Tc ~ 14 K)
Ground Planes: Nb
Dielectric coating: 200nm SiO2
Frequency: 250 MHz – 1 GHz

IDC:
Fingers 2µm wide, 2µm spacing
32 Fingers total (~ 160 µm long)
Finger length: 1mm
Capacitance ~ 2 pF

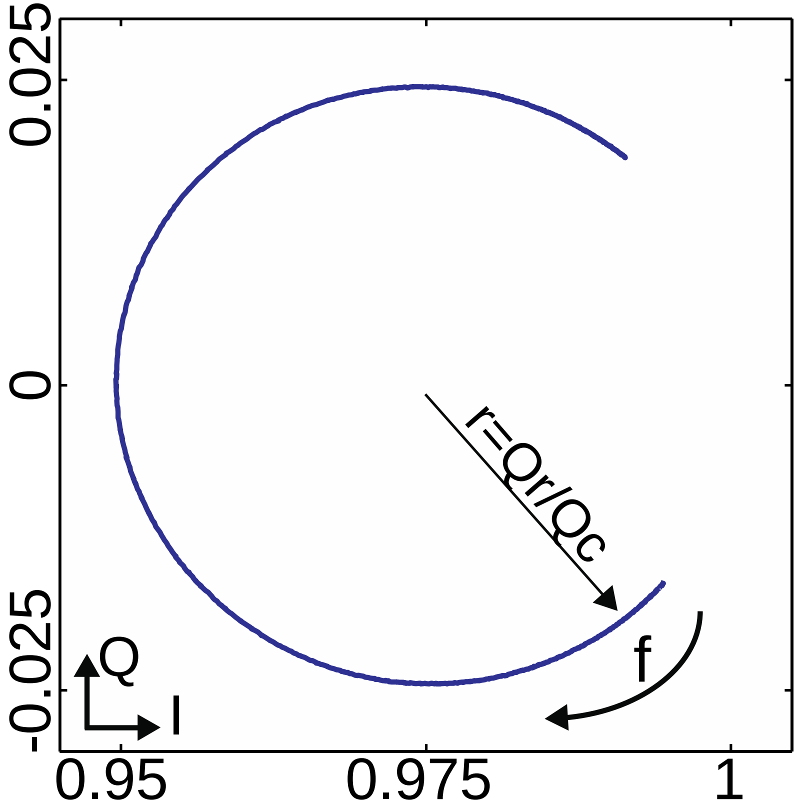
Inductor:
NbTiN ~ 6 pH / square

Probe devices by measuring forward transmission (S21)



Device response plots a circle in the IQ plane:

For the resonator with fres = 813 MHz:



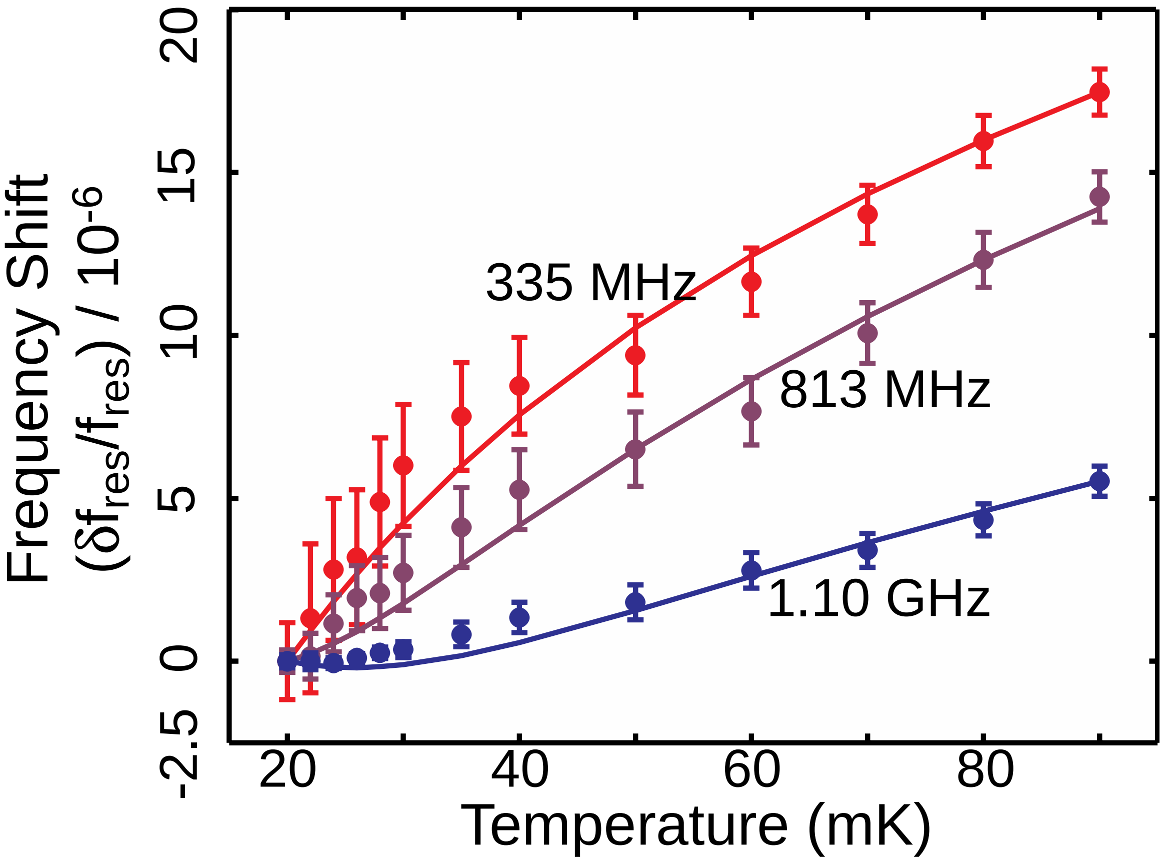
$$S_{21} = 1 - \frac{Q_r}{Q_c} \frac{1}{1 + 2i\delta x Q_r}$$

Fits yield:

Qi = 1.0x10^5
Qc = 3.8x10^6

Devices are undercoupled!

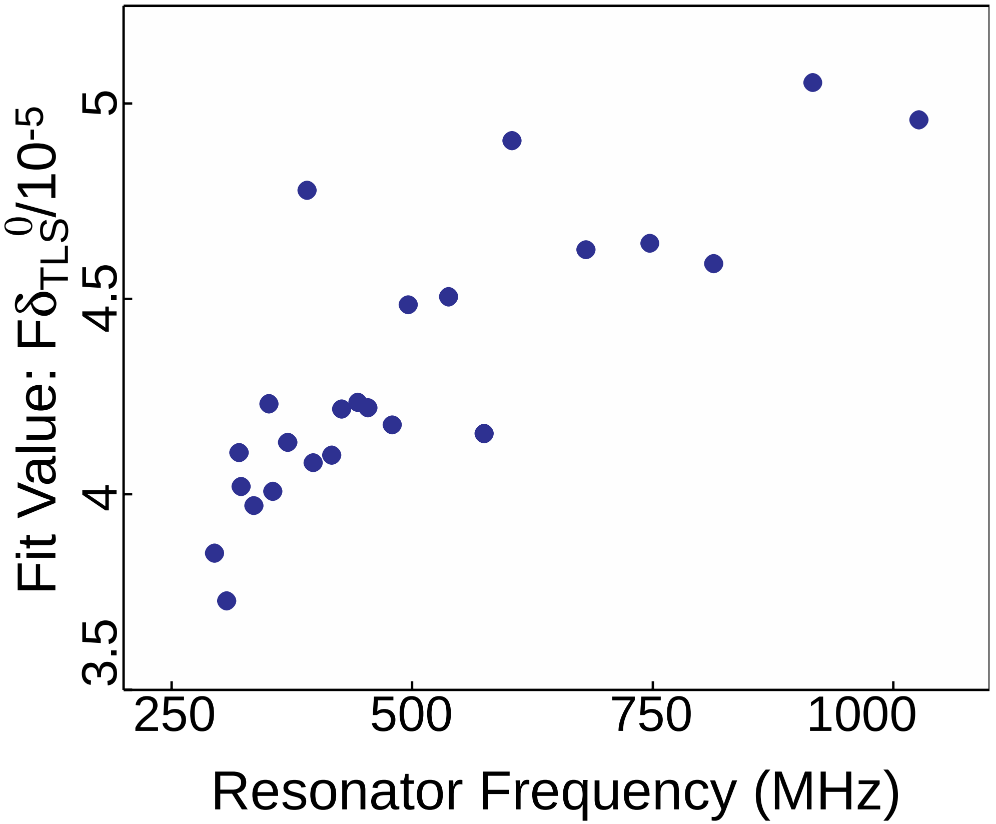
Shift in resonant frequency – Matches TLS predictions



Lines are fits to:

$$\frac{f_R - f_0}{f_0} = \frac{F\delta^0_{TLS}}{\pi}\left[\mathrm{Re}\left(\frac{1}{2} - \frac{\hbar\omega}{2j\pi k_B T}\right) - \ln\left(\frac{\hbar\omega}{2k_B T}\right)\right]$$

Loss tangent fit over 28 resonators:

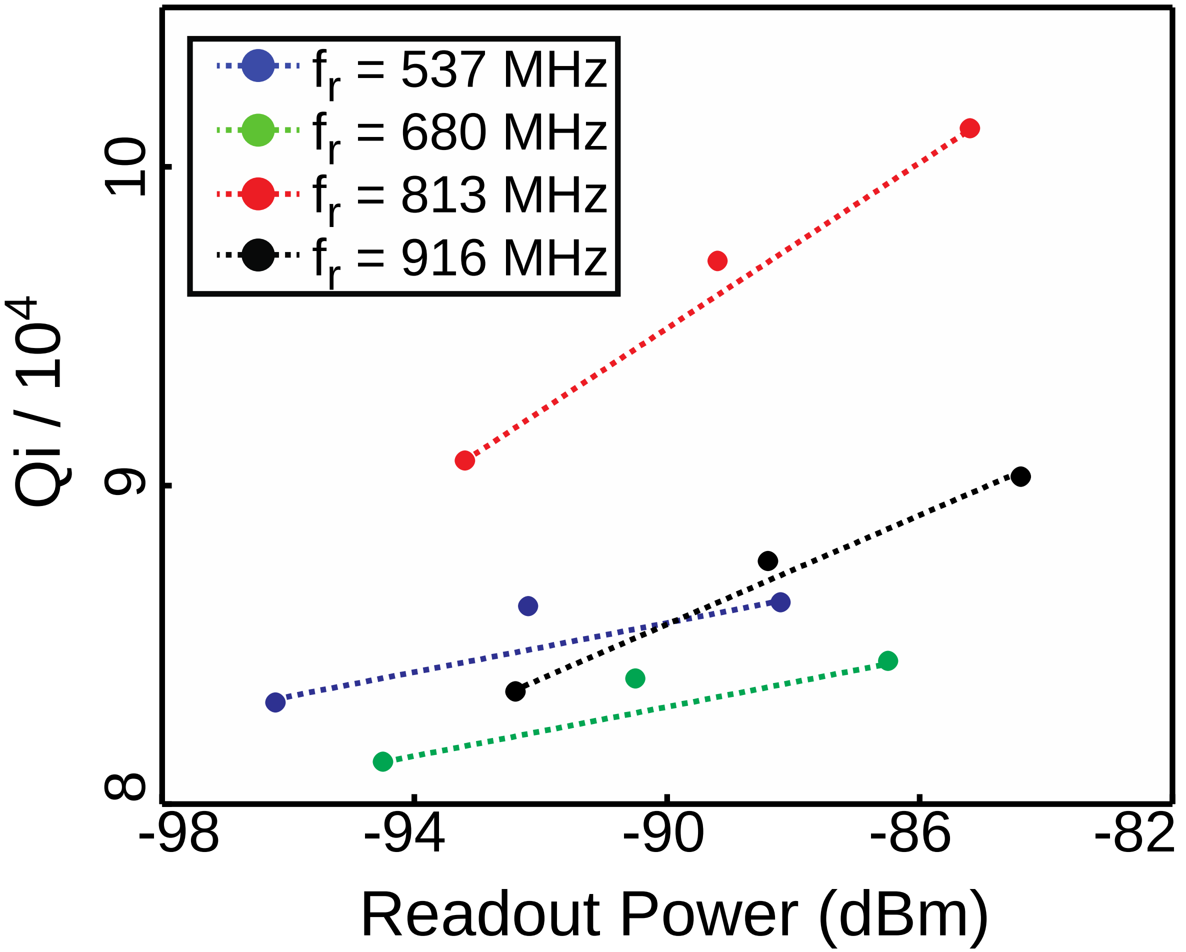


Very little change as frequency varies ~ 20%

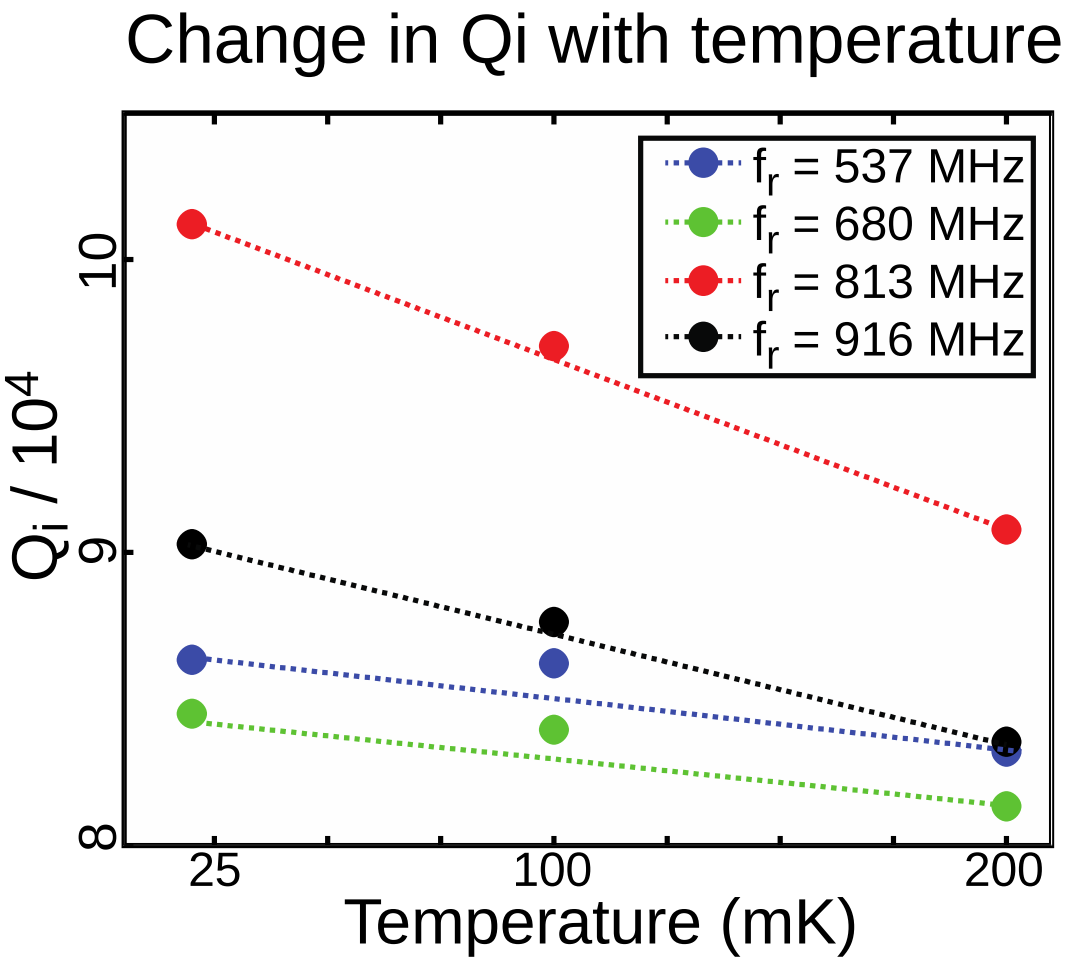
Sonnet simulations indicate F ~ 0.035 for our geometry

Q_{TLS} ~ 800 for this amorphous SiO2

TLS saturates with increasing power – T = 100 mK



Observe decreasing Qi with temperatures



Internal Qi depends strongly on electric field and temperature
Weak Fields – TLS saturates as temperature increases

$$\delta_{TLS} = \delta_{TLS}^{0} \tanh\left(\frac{\hbar\omega}{2kT}\right)$$

Under Bloch model TLS saturation condition

$$\Omega^2 T_1 T_2 >> 1$$

$$\Omega = \vec{d} \cdot \vec{E} / \hbar$$

For SiO2 – $E_{critical} \approx 2.6\left(\frac{f}{GHz}\right)^{3/2} \coth^{1/2}\left(\frac{hf}{2kT}\right)\left(\frac{T}{200\mathrm{mK}}\right)^{0.75}$

4 GHz, 200 mK: Ecrit ~ 30 V/m
500 MHz, 100mK: Ecrit ~ 1 V/m
Our fields ~ 10^3 V/m, well above critical field

Internal Qi depends strongly on electric field and temperature
Weak Fields – TLS saturates as temperature increases

$$\delta_{TLS} = \delta_{TLS}^{0} \tanh\left(\frac{\hbar\omega}{2kT}\right) \quad \Longrightarrow \quad \delta_{TLS}^{0}\left(\left|\vec{E}\right|\right) = \frac{\delta_{TLS}^{0} \tanh\left(\frac{\hbar\omega}{2kT}\right)}{\sqrt{1-\left|\left|\vec{E}\right| / Ec\right|^{2}}}$$

Under Bloch model TLS saturation condition

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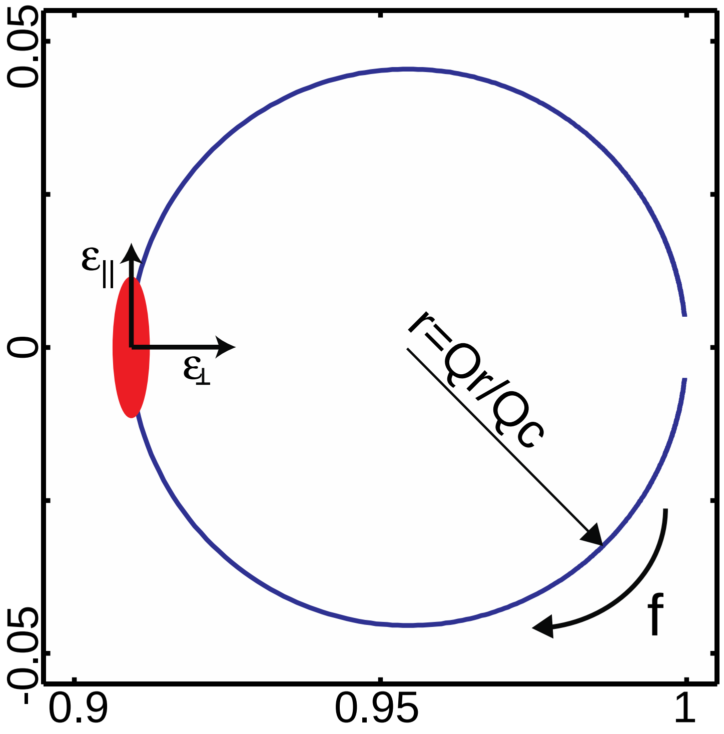
Measure noise as S21 fluctuations
(I) Amplitude and Frequency (Q) components



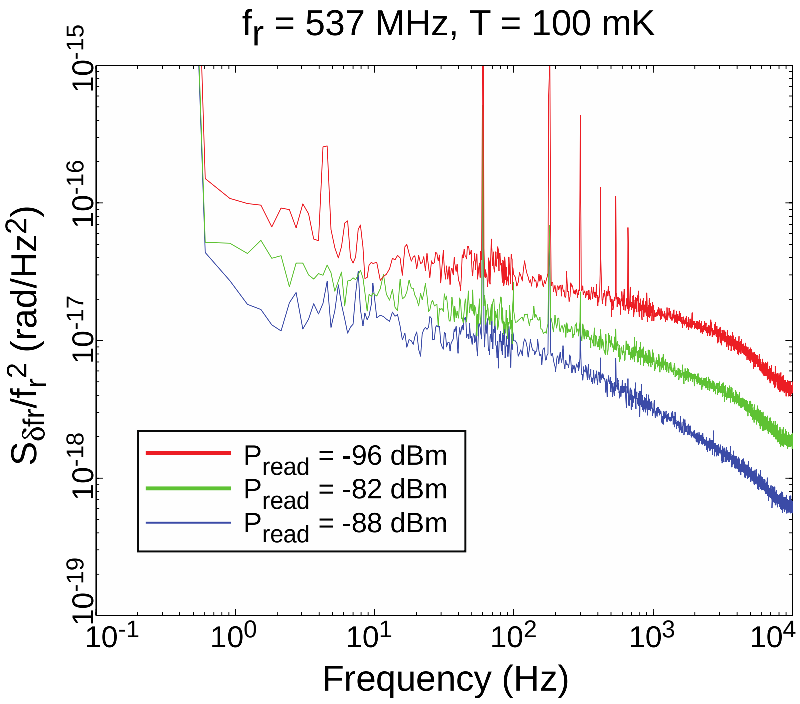
- Decompose noise spectra (S) into parallel and perpendicular components
- Fractional Frequency Noise Spectrum

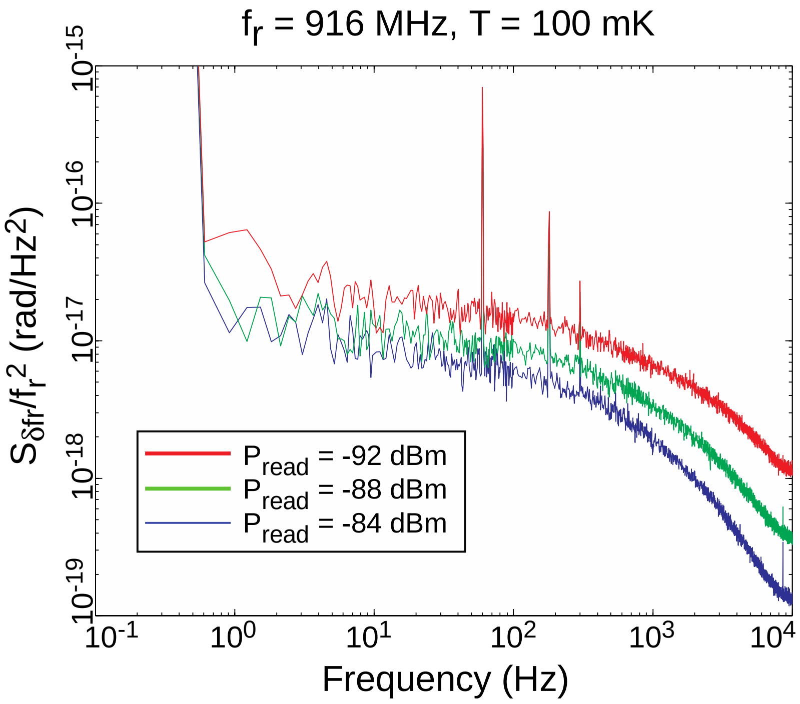
$$\frac{S_{\delta fr}(\nu)}{f_r^2} = \frac{S_{||}}{16Q^2r^2}$$

- Our devices – undercoupled (Qc/Qr < 0.05)
- TLS fluctuations not far above amplifier noise
- Phase noise ~ 2-4x amplifier noise
- Measuring at internal powers not far below critical power in NbTiN

Fractional Frequency Noise Spectra - Power dependence

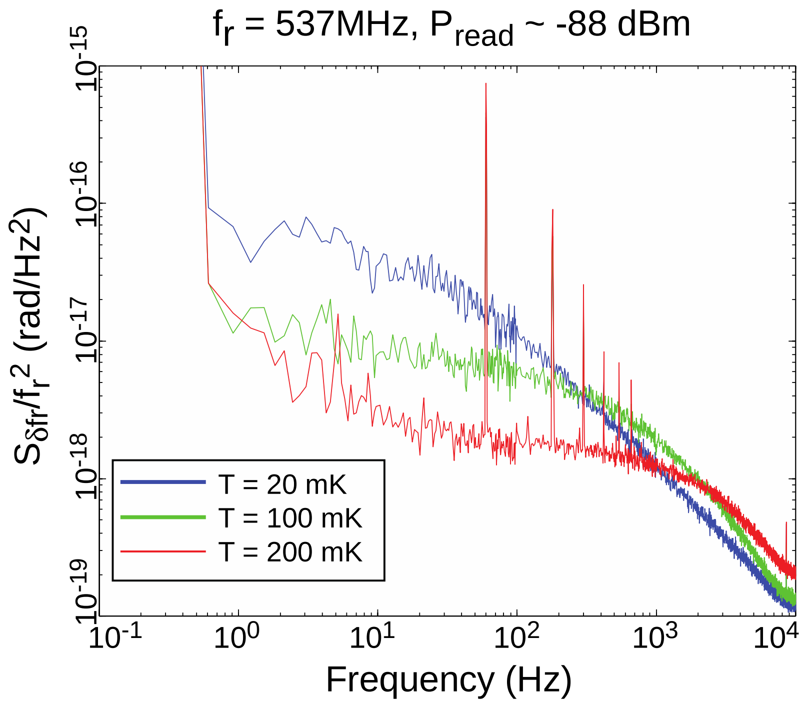
- Increasing power saturates TLS
- Observe near $P^{-1/2}$ dependence Indicative of TLS
- Observed from ~ 500 MHz – 1 GHz



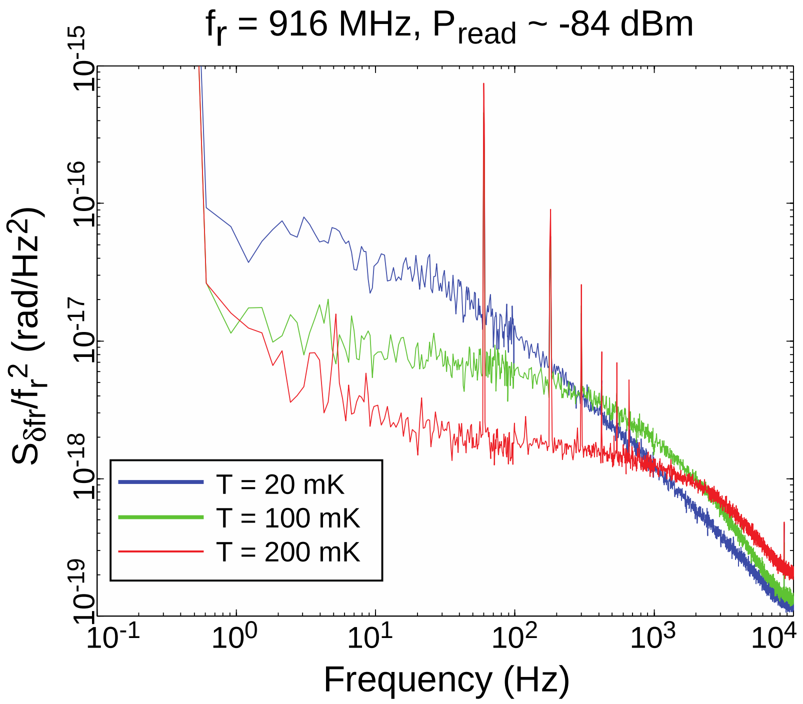


Fractional Frequency Noise Spectra

- Increasing Temperature saturates TLS
- Observe ~ T^{-2} dependence – characteristic of TLS
- Observed from ~ 500 MHz – 1 GHz
- Unusual slope is clear on temperature plot – usually $S_{TLS} \sim \nu^{-1/2}$



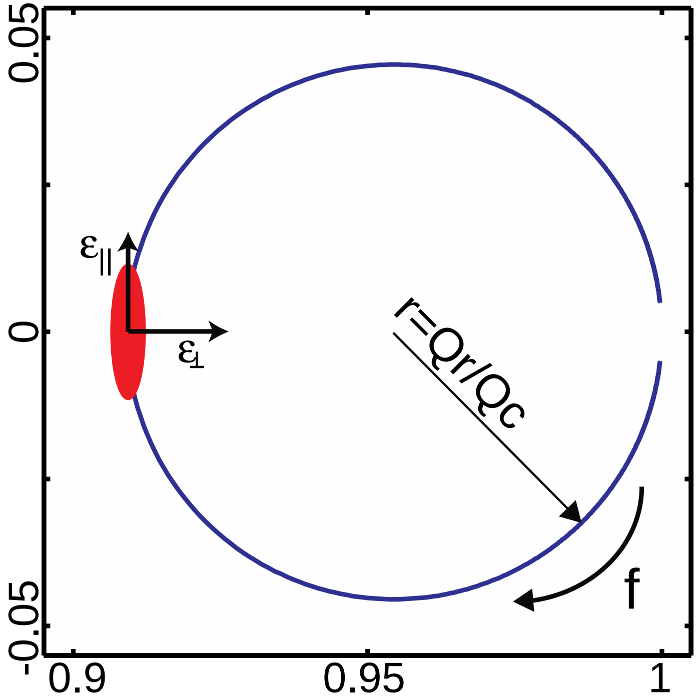
f_r = 537MHz, P_{read} ~ -88 dBm

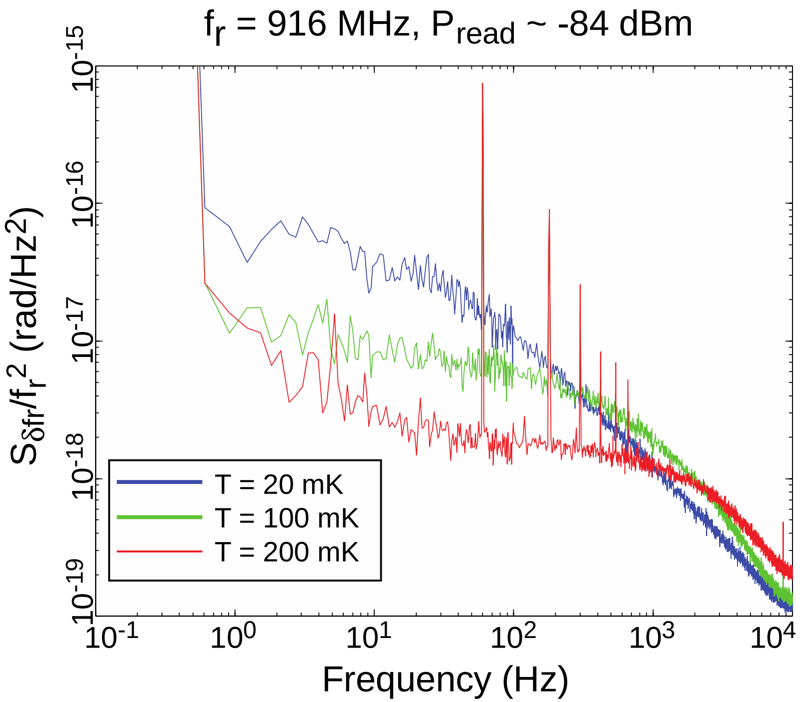


f_r = 916 MHz, P_{read} ~ -84 dBm

Observed slope deviation from $\nu^{-1/2}$

- Operating about 10 dB below critical current – nonlinearities
- Severely undercoupled
  - Noise is large compared to radius of curvature
  - Phase noise is 2-4x amplifier noise
  - Mixing of I & Q components?





FIR Applications:

- What is the TLS noise under conditions FIR detection?

$$Popt \sim Pdiss$$

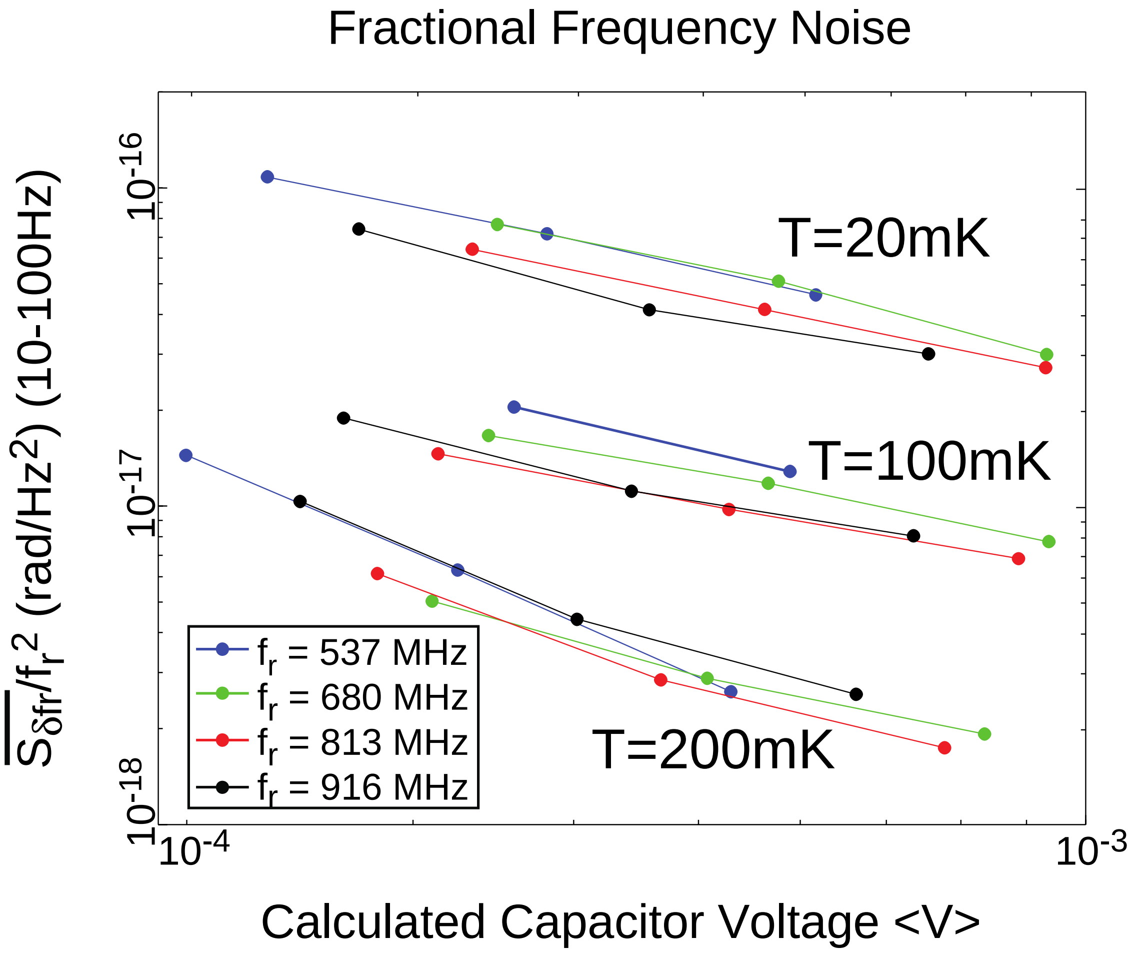
$$P_{opt} = (\hbar \nu_{opt})\Delta \nu \qquad P_{diss} = \frac{\omega_{RF} E_{res}}{Q_i} \qquad E = \frac{1}{2} C V^2$$

Readout: Qi ~ 10^5, ωRF ~ 100 MHz, C ~ 10 pF

Spectroscopy: ν = 300 GHz, Δn = 0.3 GHz – V ~ 1.3 mV

Photometry: ν = 300 GHz, Δn = 100 GHz – V ~ 25 mV

S_{TLS} versus applied voltage to IDC capacitor:



$$\frac{S_{\delta fr,TLS}}{f_r^{\,2}} < \frac{\beta^2}{4Q_i^2}\frac{(1+n)}{n\Delta\nu} \sim 10^{-17}$$

Conclusions

Measured TLS noise from 500 MHz – 1 GHz

- TLS noise may be suitable for FIR detection with RF readout schemes
- No clear readout frequency dependence noticed

Remaining goals:

- Measure over wider frequency range and lower powers
    - Improve coupling – measure at lower powers
    - Improve electronics – measure noise at lowest resonator frequencies
- More device geometries: Parallel plate, different size IDC, etc

Thanks

Rick LeDuc

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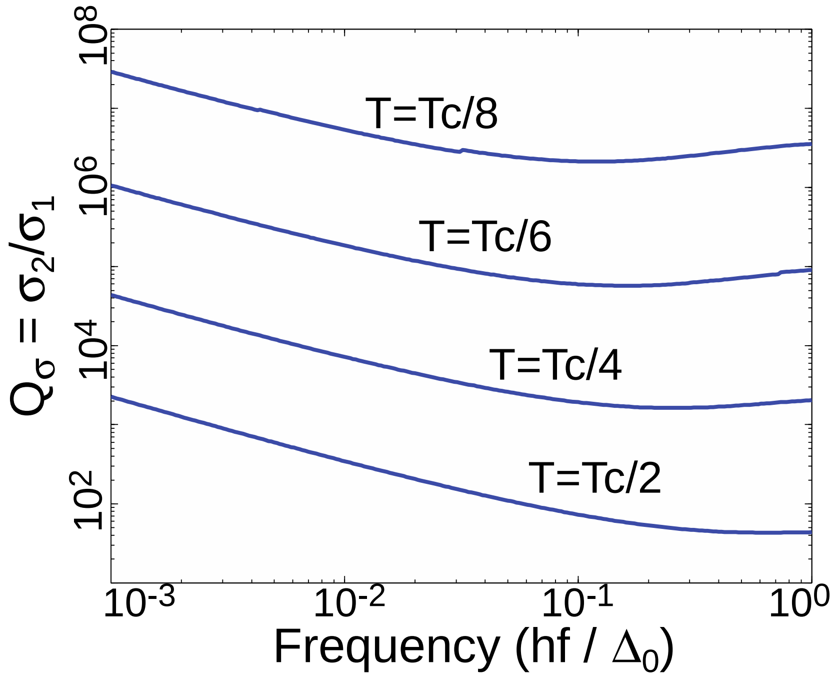
Kinetic Inductance Thermometry And Radio-Frequency Readouts

Frequency dependence of response

Mattis-Bardeen: Surface impedance

$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty} dE \frac{E^2 + \Delta^2 + \hbar\omega E}{\left(\sqrt{E^2 - \Delta^2}\right)\sqrt{((E + \hbar\omega)^2 - \Delta^2}} [f(E) - f(E + \hbar\omega)]$$

$$\frac{\sigma_2}{\sigma_N} = \frac{1}{\hbar\omega}\int_{\Delta}^{\Delta+\hbar\omega} dE \frac{E^2 + \Delta^2 - \hbar\omega E}{\left(\sqrt{E^2 - \Delta^2}\right)\sqrt{\Delta^2 - ((E + \hbar\omega)^2}} [1 - 2f(E)]$$



High Qi’s and responses possible

Working at RF makes electronics simpler

Easily multiplex large number of detectors