Principles and Applications of Microwave Kinetic Inductance Detectors

Sunil Golwala

June 25, 2013

LTD15 - Pasadena

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Overview

- Tutorial/introduction, not a review

- Summary of electrodynamics of superconductors: kinetic inductance
- Monitoring complex conductivity of large numbers of detectors with resonator circuits
- Expected responsivity and noise
- Applications you will hear about later

- Won't cover nonlinear kinetic inductance
  - Nonlinearity becomes important when magnetic energy comparable to pairing energy:
  $$L_k\, I^2 \sim 2\, N_0\, V\, \Delta^2$$
  - Offers prospect of parametric amplification with minimal dissipation
  - Discussed fully in talks and posters by Klapwijk, Gao, Kher, Day, de Visser, Bockstiegel

Quasiparticles to Conductivity

- Conductivity from microscopic BCS theory by Mattis and Bardeen
  - Use perturbation theory to calculate response of BCS superconductor to EM field
  - M&B assume extreme anomalous limit, but analysis can also be used for local limit with appropriate modification (see, e.g., Gao thesis Ch 2).
  - Yields complex conductivity:

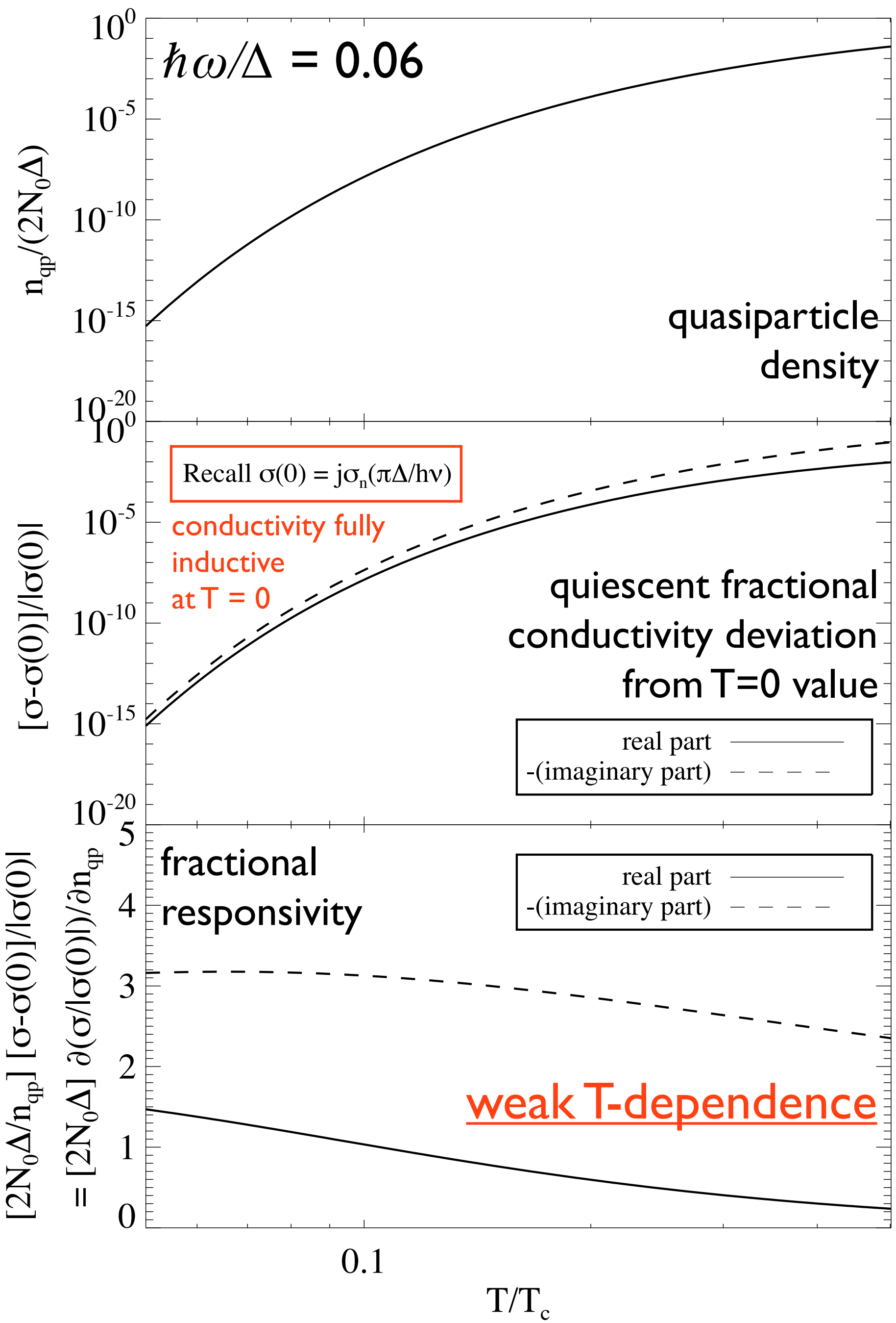
$$\frac{\sigma_1}{\sigma_n} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty} d\epsilon \frac{[f(\epsilon) - f(\epsilon + \hbar\omega)]\,(\epsilon^2 + \Delta^2 + \hbar\omega\epsilon)}{\sqrt{\epsilon^2 - \Delta^2}\sqrt{(\epsilon + \hbar\omega)^2 - \Delta^2}}$$ resistive

$$f(\epsilon) = 1/[e^{\epsilon/k_B T} + 1]$$

$$\frac{\sigma_2}{\sigma_n} = \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{\Delta} d\epsilon \frac{[1 - 2f(\epsilon + \hbar\omega)]\,(\epsilon^2 + \Delta^2 + \hbar\omega\epsilon)}{\sqrt{\Delta^2 - \epsilon^2}\sqrt{(\epsilon + \hbar\omega)^2 - \Delta^2}}$$ reactive

  - Two-fluid model: imaginary (reactive) part scales with Cooper pair component, real (resistive) part scales with quasiparticle density
  - Quasiparticle/Cooper pair population change $\Rightarrow$ conductivity change
- T. Klapwijk and others: "engineering" model insufficient due to non-BCS density of states, effects of readout power
- For clarity here, stick with engineering model: changes in quasiparticle number completely characterize effect of energy input

Quasiparticles to Conductivity



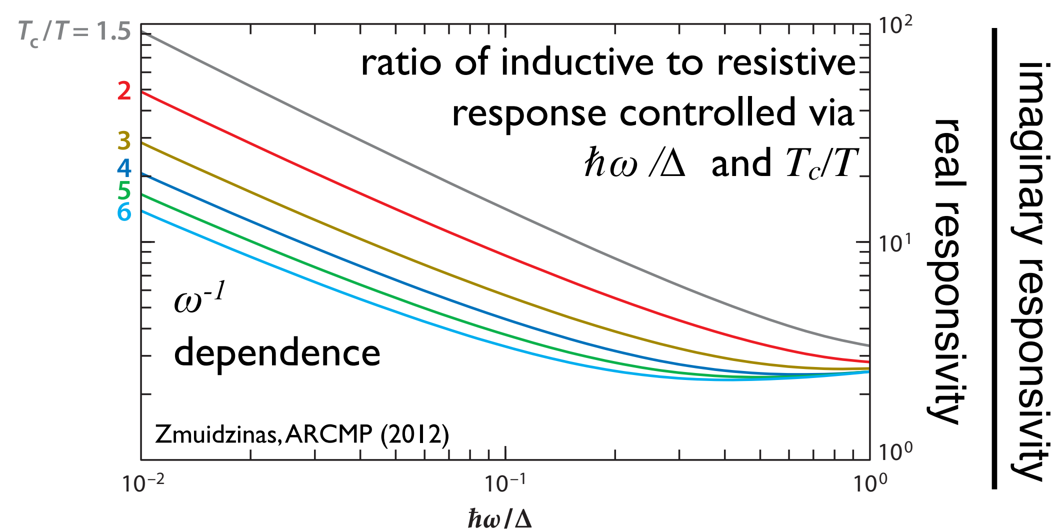
- MB gives characteristic temperature and $\hbar\omega/\Delta$ dependence

$$\frac{\sigma_1}{|\sigma(0)|} = \frac{4}{\pi}\frac{n_{qp}}{2N_0\Delta}\frac{1}{\sqrt{2\pi\frac{kT}{\Delta}}}\sinh\left(\frac{\hbar\omega}{2kT}\right)K_0\left(\frac{\hbar\omega}{2kT}\right)$$

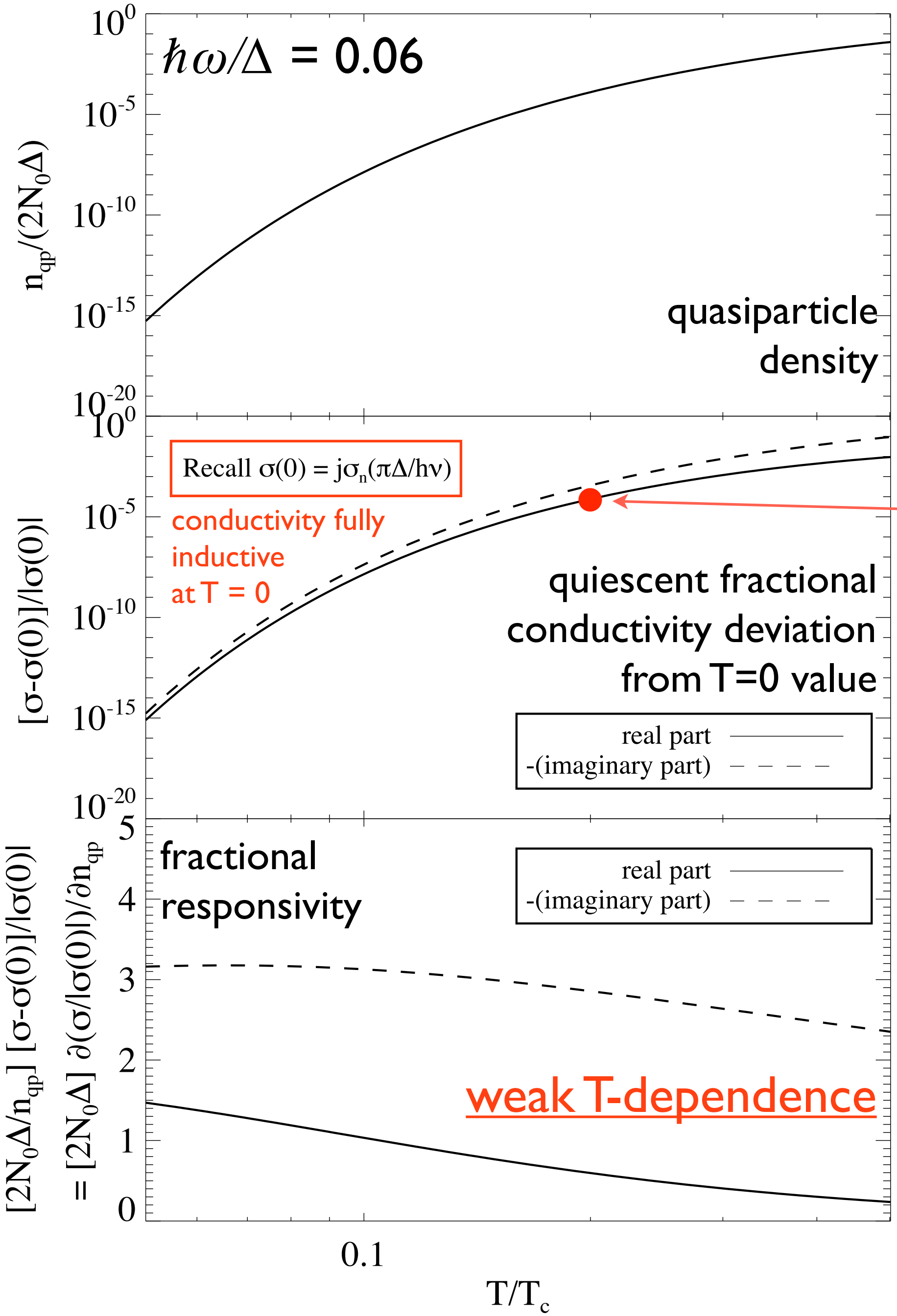
$$\frac{\sigma_2}{|\sigma(0)|} = 1 - \frac{n_{qp}}{2N_0\Delta}\left[1 + \sqrt{\frac{2\Delta}{\pi kT}}\exp\left(-\frac{\hbar\omega}{2kT}\right)I_0\left(\frac{\hbar\omega}{2kT}\right)\right]$$

$$2N_0\Delta\left.\frac{\partial(\sigma_1/|\sigma(0)|)}{\partial n_{qp}}\right|_T = \frac{2N_0\Delta}{n_{qp}}\frac{\sigma_1}{|\sigma(0)|}$$

$$2N_0\Delta\left.\frac{\partial(\sigma_2/|\sigma(0)|)}{\partial n_{qp}}\right|_T = \frac{2N_0\Delta}{n_{qp}}\frac{\sigma_2 - \sigma_2(0)}{|\sigma(0)|}$$



Quasiparticles to Conductivity



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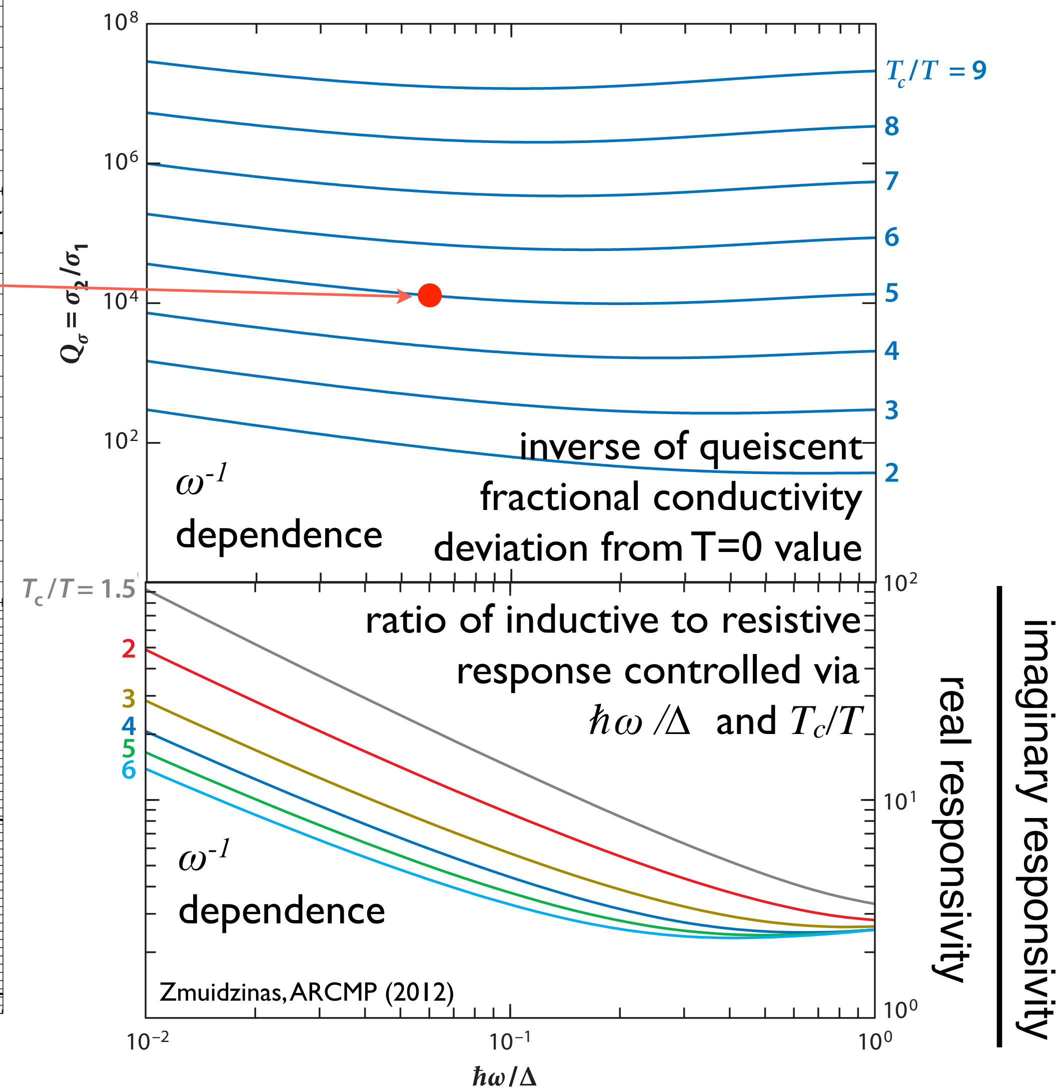


Conductivity to Observables

- Observables
  - Surface impedance is $Z_s = E / H$ for EM wave propagating normal to surface
  - For thin films (thickness t, therefore local limit; $\gamma = -1$):

$$Z_s = R_s + i\,X_s \approx \frac{1}{(\sigma_1 - i\,\sigma_2)\,t}$$

$$\begin{aligned} Z_s \to i\,X_s(T=0) &= i\,\omega\,L_s(T=0) \\ &\propto -\left[\sigma(T=0)\right]^{-1} = i\left[\sigma_2(T=0)\right]^{-1} \end{aligned}$$

σ_2 dominates for $T << T_c$, so X_s dominates

  - Relate fractional changes in σ to fractional changes in Z_s (thin film limit)

$$\frac{\delta Z_s}{Z_s(T=0)} = \frac{\delta\sigma}{\sigma(T=0)}$$

"kinetic impedance"

$$\frac{\delta L_s}{L_s} = \frac{\delta\sigma_2}{\sigma_2(T=0)} > 0$$

"kinetic inductance"

$$\frac{\delta R_s}{\omega L_s} = \frac{\delta\sigma_1}{\sigma_2(T=0)} > 0$$

"kinetic resistance"

Recall that the fractional conductivity change shows weak temperature dependence.

  - So, given a measurement of surface impedances in a thin film, we can infer changes in conductivity and thus qp density.

KID Readout and Multiplexing

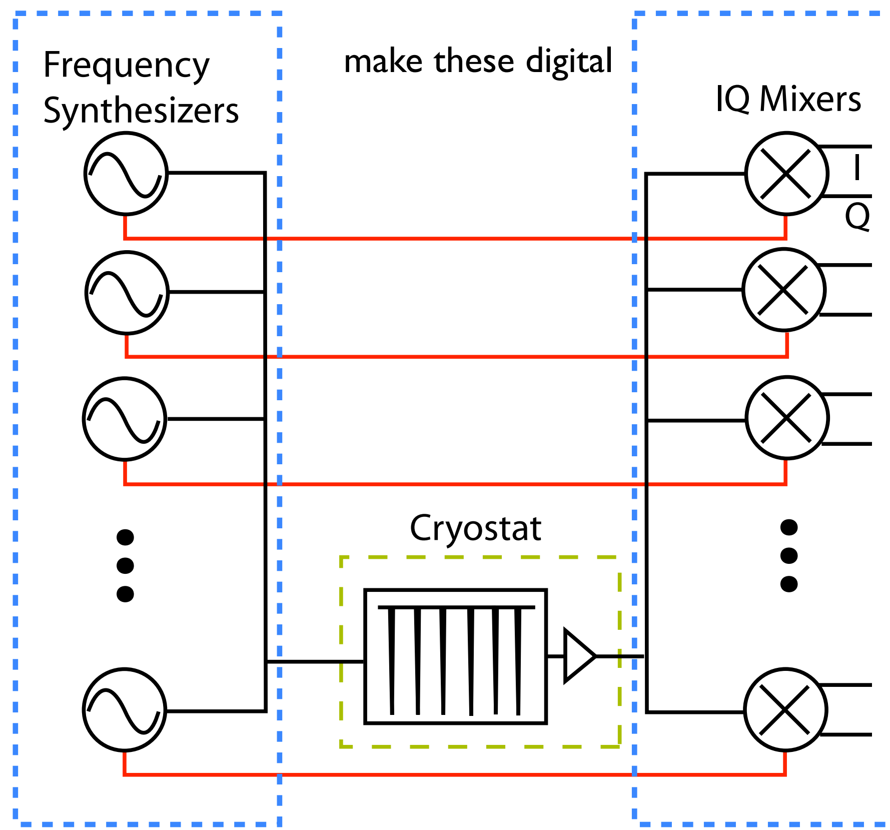
- KIDs response in both reactance and resistance
- High Q_σ suggests KIDs can be incorporated into high-Q resonant circuits; yields frequency and Q response
- High-Q circuits lend themselves to frequency-domain multiplexing
  - Principle identical to AM/FM radio: frequency → phase (FM), Q → amplitude (AM)
  - Don't forget resonator bandwidth! $f_{qp} < f_r / 2Q_r$
- Ever-growing capabilities in GHz digital electronics:
  - Fully digital generation, reception, and demodulation now possible

kinetic inductance fraction

$$\frac{1}{Q_{i,qp}} = \frac{R_s}{\omega\left(L_m + L_s(T=0)\right)} = \alpha \frac{R_s}{\omega L_s(T=0)}$$

$$\frac{f_r - f_r(T=0)}{f_r(T=0)} = -\frac{1}{2}\,\alpha\,\frac{L_s - L_s(T=0)}{L_s(T=0)}$$

$$\delta S_{21}\big|_{f=f_r} = \frac{Q_r^2}{Q_c}\left(\delta\frac{1}{Q_{i,qp}} - 2\,i\,\frac{\delta f_r}{f_r}\right)$$



Mazin (2004)

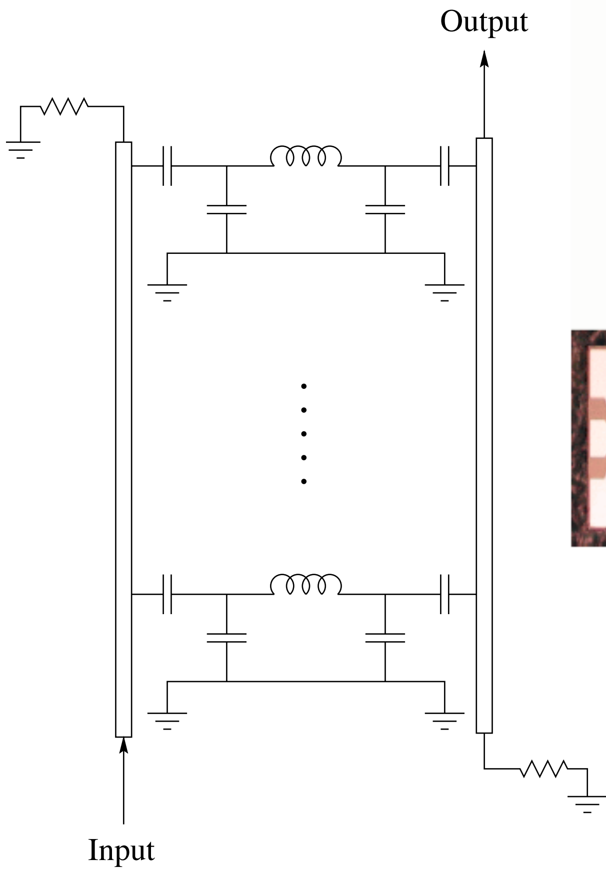
Materials

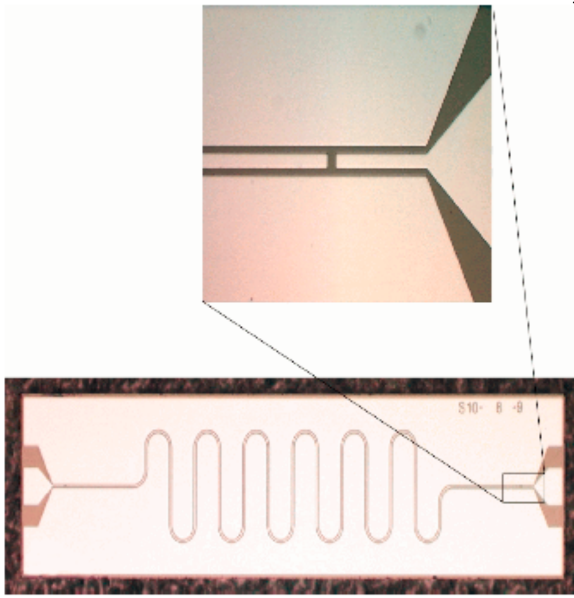
- Aluminum
  - Workhorse of superconductivity
  - Seems to follow Mattis-Bardeen well
  - Difficult to get high kinetic inductance fraction in a range of geometries due to short penetration depth (low resistivity)

- Titianium nitride and other nitrides, silicides, etc.
  - High resistivity! Yields very large penetration depth and KI fractions almost unity in films of tens of nm thickness
  - T_c controllable
  - But does not follow Mattis-Bardeen; obtaining physics-based understanding of response is critical.

Resonator Readout Architectures

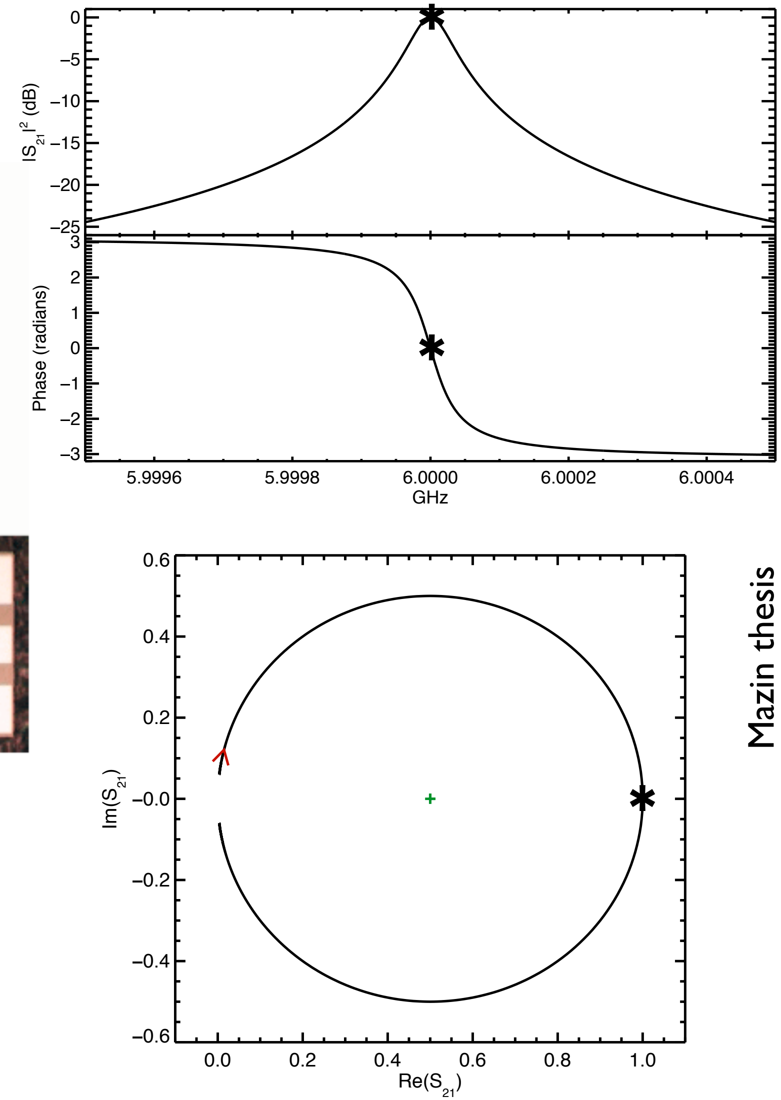
- Half-wave through
  - $\lambda/2$-length of transmission line acts like a through short on-resonance
  - disfavored architecture;
    has no off-resonance transmission





responsivity ∝ I^2, peaks at center, vanishes at ends

Mazin et al., Proc. SPIE (2002)

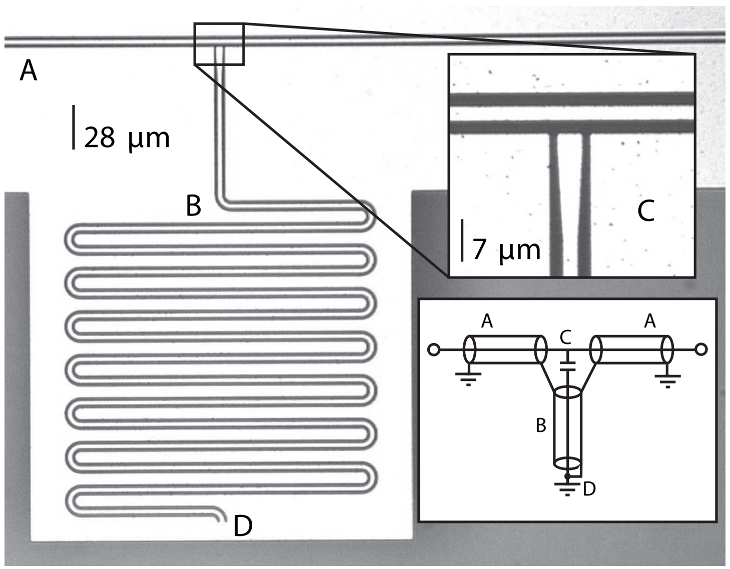


Mazin thesis

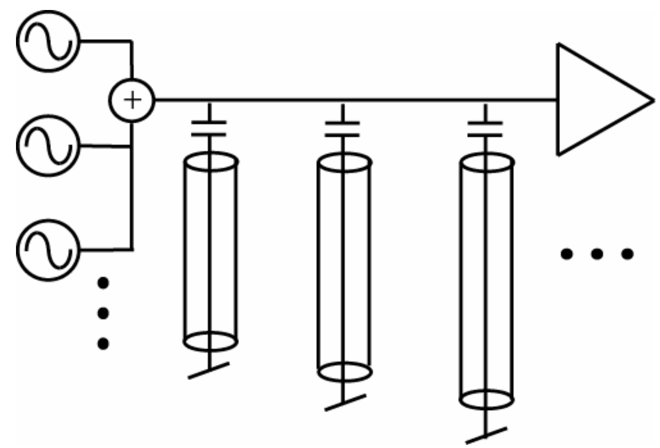
Resonator Readout Architectures

- Quarter-wave shunt
  - λ/4-length of transmission line acts like a short to ground on-resonance

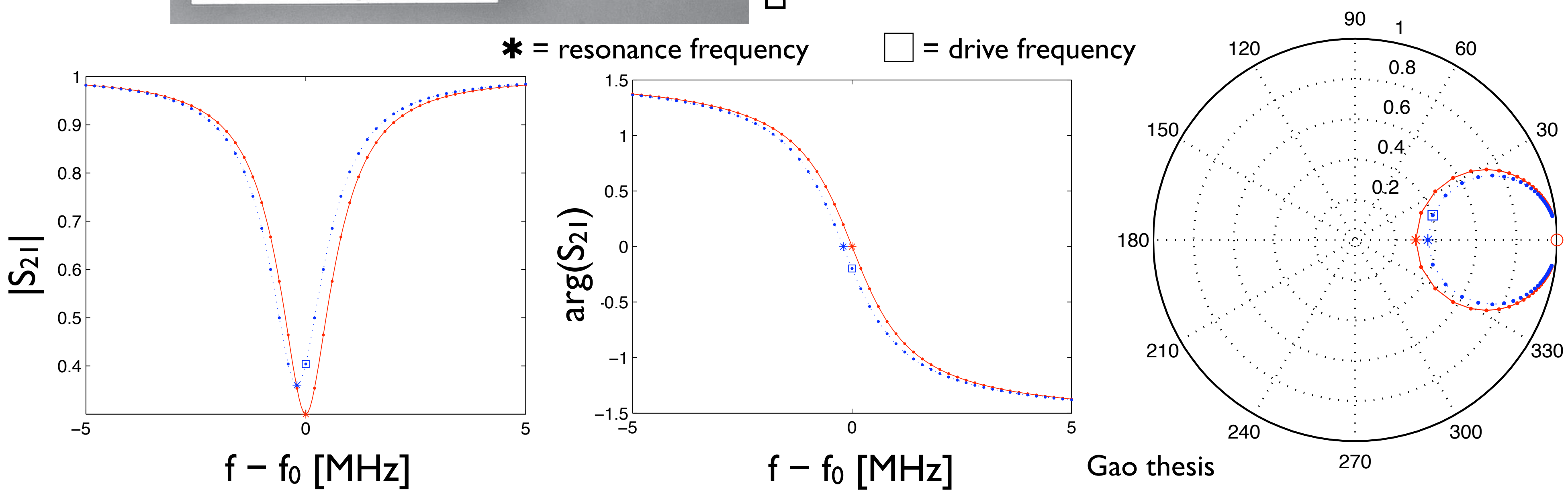
responsivity ∝ I^2, peaks at shorted end, vanishes at open end



Day et al. Nature (2003)



✱ = resonance frequency   □ = drive frequency

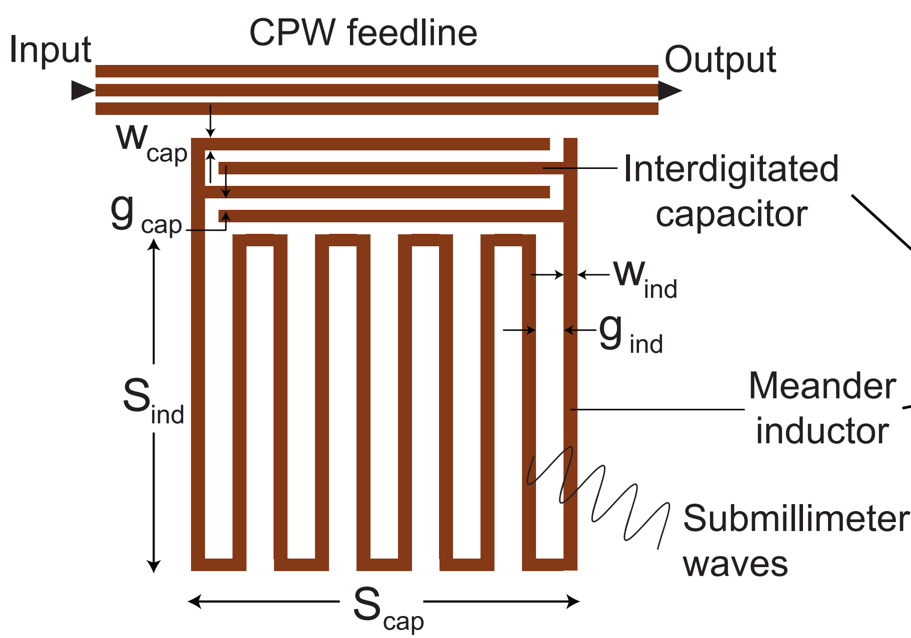


Gao thesis

Resonator Readout Architectures

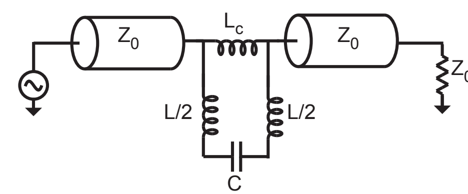
- Lumped element
  - Can be designed to eliminate dependence of responsivity on current distribution
    - Energy can be usefully absorbed anywhere
    - No insensitive volume for quasiparticles to diffuse to
  - Decouples size of resonator from readout frequency
  - Many implementations!

Capacitive coupling

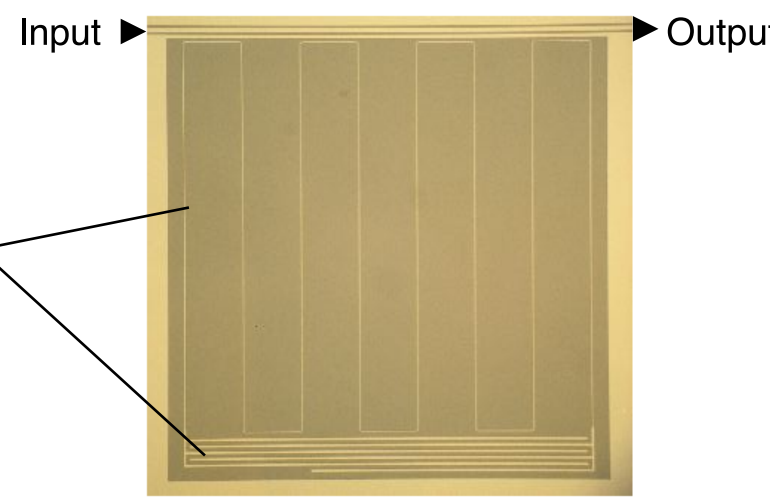


Noroozian thesis (2012)

Inductive Coupling



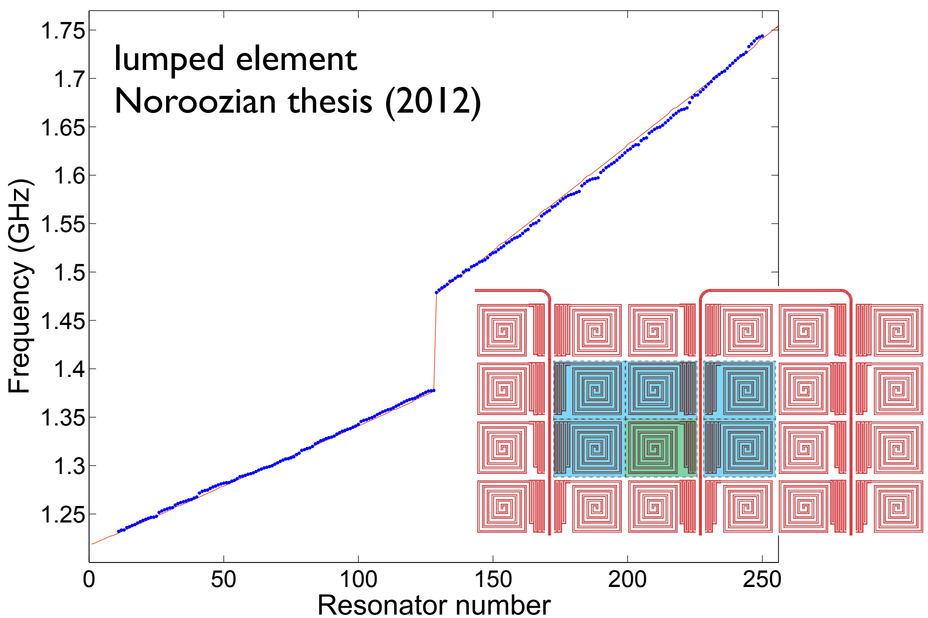
McKenney et al., Proc. SPIE (2012)

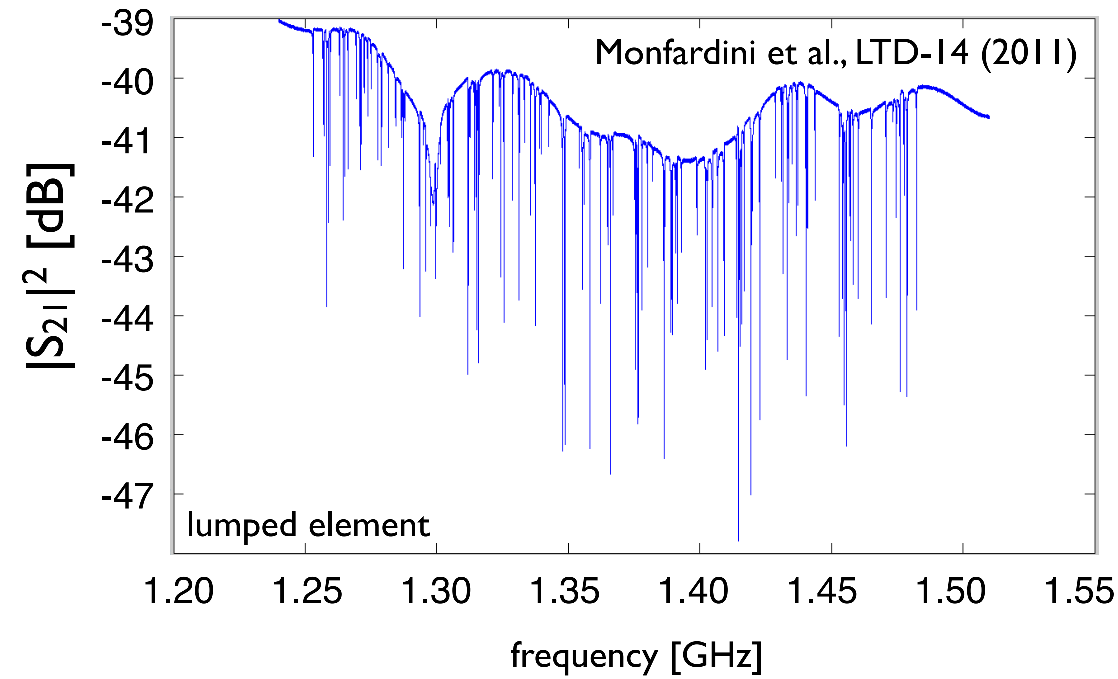


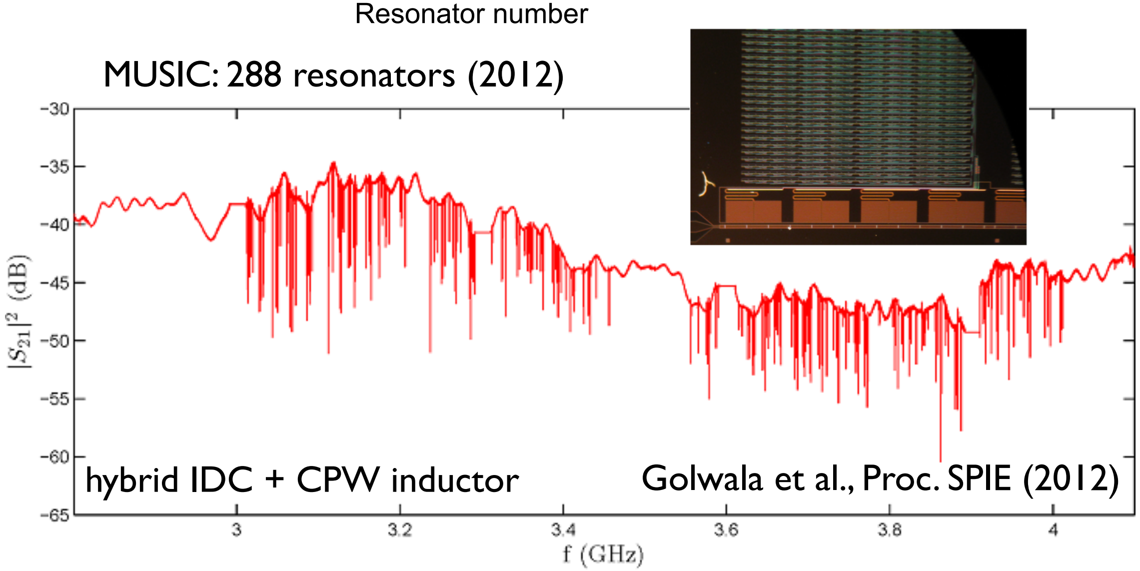
Monfardini et al., LTD-14 (2011)

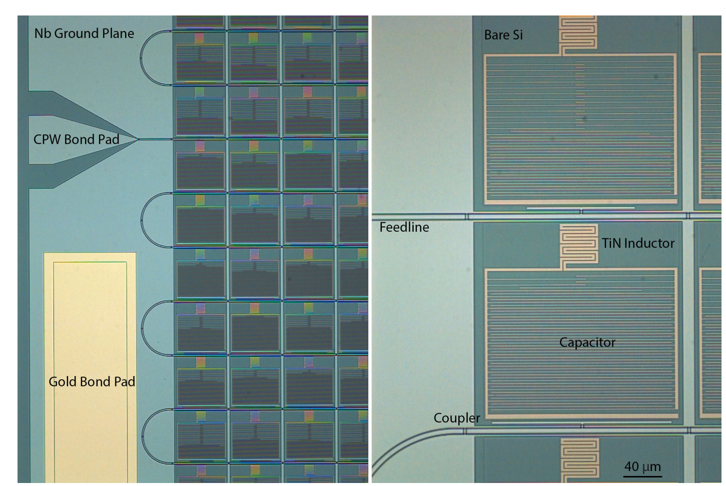
Multiplexing and Readout

- Fulfilling the KID dream! But there are challenges: collisions, cross-coupling, scatter.







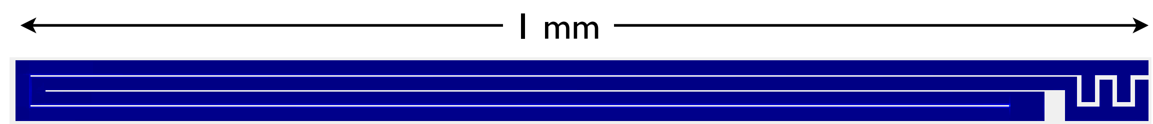


~1000 pixels/line + microlens array

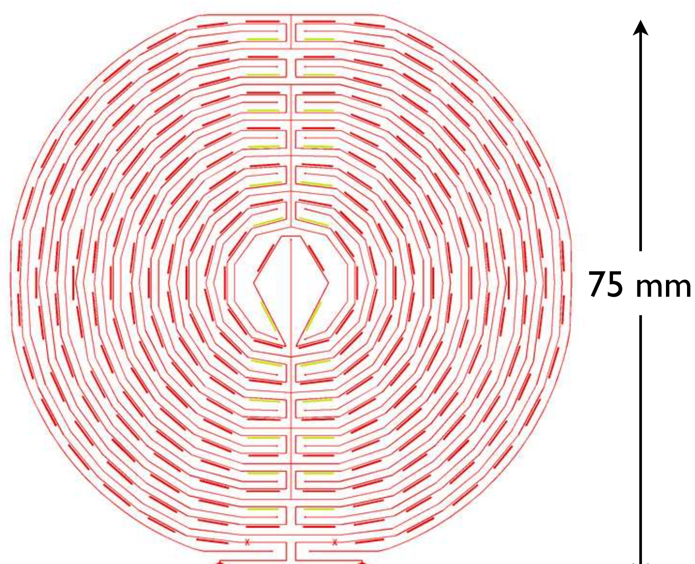
ARCONS; Mazin et al (2013)

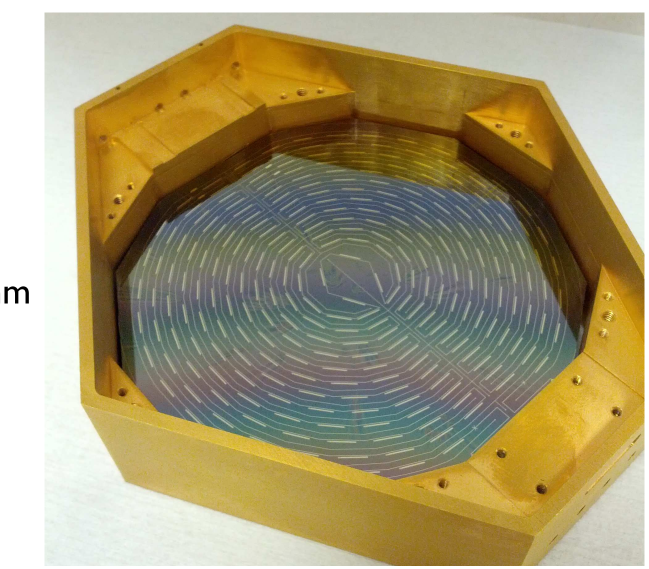
Energy Coupling Architectures

- Direct absorption of X-ray, optical, submm, mm photons in KID
  - Microlenses can be used to decouple KID size from diffraction spot size (MAKO, ARCONS); high resistivity material can match free space; also via feedhorn
- Antenna (and feedhorn) coupling
  - SRON: lens coupling to twin-slot antenna at end of CPW KID
  - MUSIC: phased array antennas coupling to hybrid IDC/inductor KID



- Phonon absorption
  - Direct absorption of phonons in lumped element KIDs
  - Phonon-mediated detection of particles, γ's





Cornell, Moore et al.

Quasiparticle Response to Energy Input

- Quasiparticle response governed by quasiparticle lifetime, observed to follow

$$\tau_{qp} = \frac{\tau_{max}}{1 + n_{qp}/n_*}$$

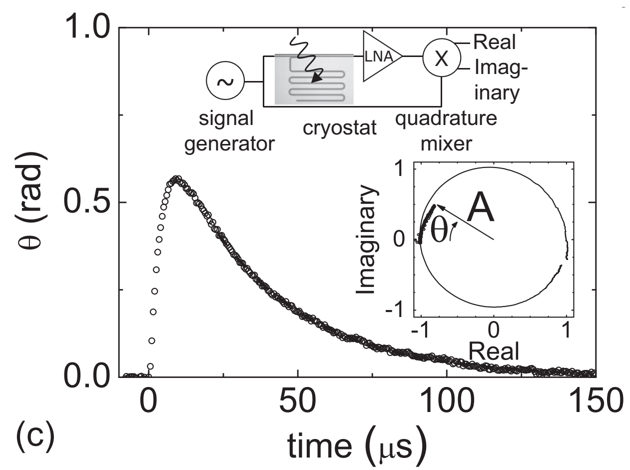
where n_* may be a limiting qp density

- Frequently written as

$$\frac{1}{\tau_{qp}} = 2\,R\,n_{qp} + \frac{1}{\tau_{max}}$$

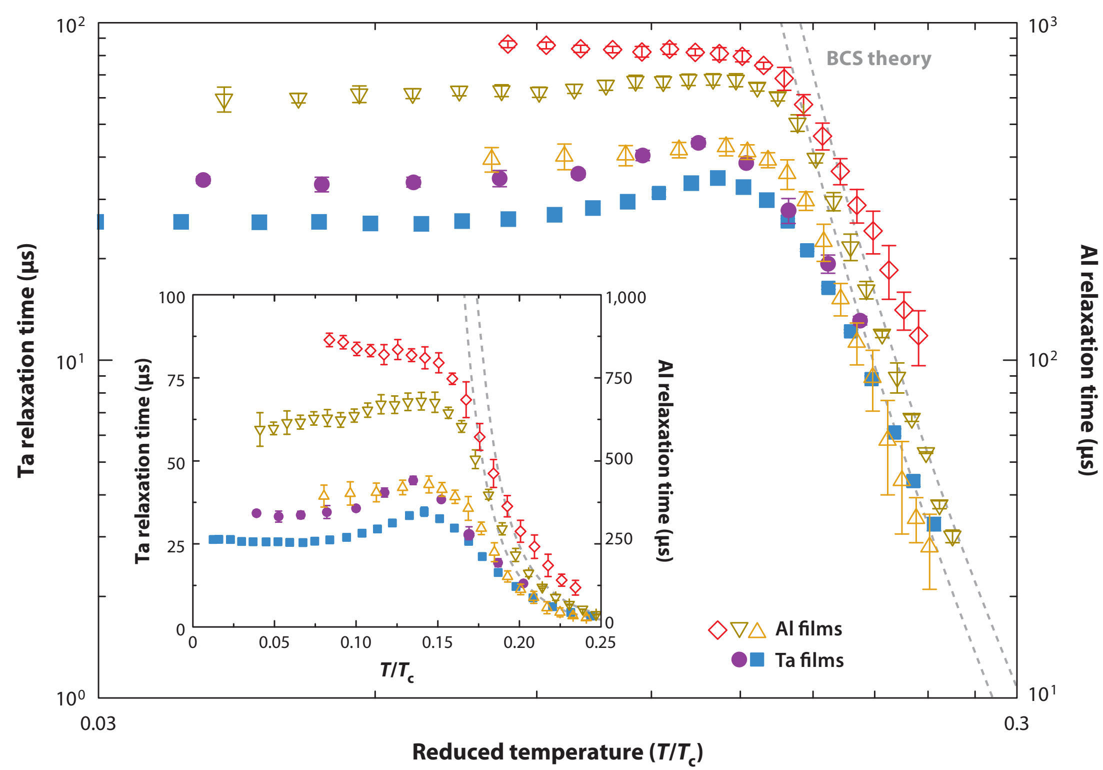
with the recombination constant

$$R = (2\,n_*\,\tau_{max})^{-1}$$



Barends et al PRL (2008)

asymptotic regime; limiting excess qp density n_*, or something else? related to disorder? (Barends et al implantation experiment)



Barends et al PRL (2008)
as reproduced in Zmuidzinas, ARCMP (2012)

Quasiparticle Response to Energy Input

- queiscent point (τ_{qp} and n_{qp}) set using g-r equation to balance qp generation by power (optical, readout, and stray) and qp decay:

$$\frac{\eta P}{\Delta} = N_{qp}\left(\frac{1}{\tau_{max}} + R\,\frac{N_{qp}}{V}\right) \qquad N_{qp} = n_{qp}\,V \qquad N_* = n_*\,V$$

$$\Longrightarrow \quad \tau_{qp} = \frac{\tau_{max}}{\sqrt{1 + 2\,(\eta\,P/\Delta)\;\tau_{max}/N_*}} \qquad \frac{N_{qp}}{N_*} = \sqrt{1 + 2\,(\eta\,P/\Delta)\,\tau_{max}/N_*} - 1$$

  In absence of known power, $\tau_{qp} \rightarrow \tau_{max}$, $N_{qp} \rightarrow N_*$, and $\eta P \rightarrow N_* \Delta/\tau_{max}$

- Dynamic response: use dynamic g-r equation to obtain

$$\frac{\delta N_{qp}(f)}{N_{qp}} \propto \frac{1}{1 + 2\,\pi\,i\,f\,\tau_{qp}}\,\frac{\delta P(f)}{P}\,\frac{1 + N_{qp}/N_*}{1 + N_{qp}/2\,N_*}$$

  - Bolometric mode: simple proportionality with "bolometer time constant" τ_{qp}
  - Calorimetric mode: $\delta P(f) = \delta E$: exponentially decaying pulse response with pulse height $\delta n_{qp} = \eta \delta E/\Delta$ and decay time τ_{qp}

- Use relations between δn_{qp} and observables to obtain expected signal
- Don't forget resonator bandwidth! $f_{qp} < f_r\,/\,2Q_r$

Noise

photon noise · generation-recombination noise · thermal qp generation rate · amplifier noise temperature

$$\mathrm{NEP}^2_{\mathrm{diss}} = \boxed{2P_o h\nu(1+n_o)} + \boxed{\frac{4\eta_a\chi_{qp}\Delta_0}{\eta_o^2}P_a + \frac{4\Gamma_{th}\Delta_0^2}{\eta_o^2} + \frac{2N_{qp}\Delta_0^2}{\eta_o^2}(\tau_{\max}^{-1}+\tau_{qp}^{-1})} + \boxed{\frac{8N_{qp}^2\Delta_0^2}{\eta_o^2\chi_c\chi_{qp}^2\tau_{qp}^2}\frac{kT_a}{P_a}}$$

$$\mathrm{NEP}^2_{\mathrm{freq}} = 2P_o h\nu(1+n_o) + \boxed{\mathrm{NEP}^2_{\mathrm{g-r}}} + \boxed{\frac{8N_{qp}^2\Delta_0^2}{\beta^2\eta_o^2\chi_c\chi_{qp}^2\tau_{qp}^2}\frac{kT_a}{P_a}} + \frac{8N_{qp}^2\Delta_0^2 Q_i^2}{\beta^2\eta_o^2\chi_{qp}^2\tau_{qp}^2}S_{\mathrm{TLS}}$$

amplifier noise · two-level system noise

$P_a = (\chi_c/2)\,P_g$ — absorbed readout power; P_g: feedline readout power

P_o: optical power; ν: optical photon frequency; n_o: optical photon occupation number

η_o — efficiency for creation of qps from optical power

$\eta_a = (\Delta_0/\chi_{qp})\partial\Gamma/\partial P_a$ — differential efficiency for creation of qps from readout power

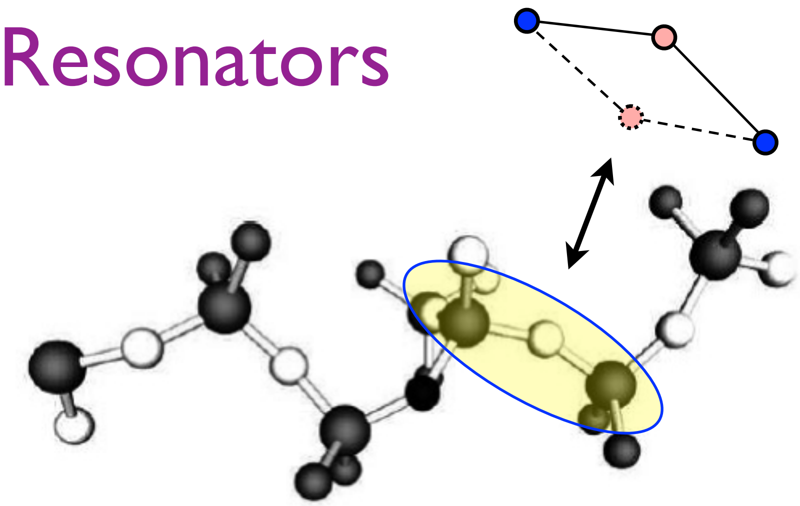
$\beta = \dfrac{\delta\sigma_2}{\delta\sigma_1}$ — ratio of imaginary (frequency) to real (dissipation) response

$\chi_c = \dfrac{4Q_cQ_i}{(Q_c+Q_i)^2} \leq 1$ — resonator-feedline coupling efficiency

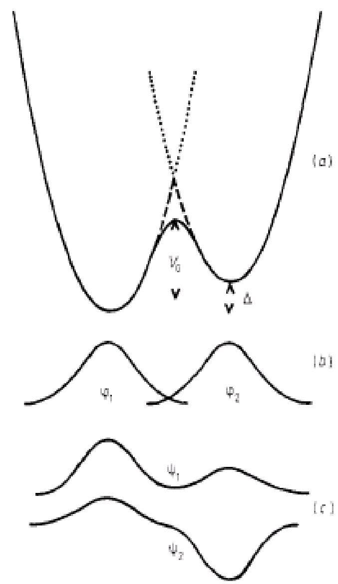
$\chi_{qp} = Q_i/Q_{qp} \leq 1$ — quasiparticle quality factor efficiency (Q_i: total internal quality factor; Q_{qp}: qp internal quality factor)

- g noise for qps created by readout and thermally; g noise for optically created qps already in photon noise term; r noise for all qps
- Amplifier noise reduced by factor β in frequency direction
- In submm/mm, approaching or achieving bgnd limit; see talks/posters

Two-Level Systems in Resonators

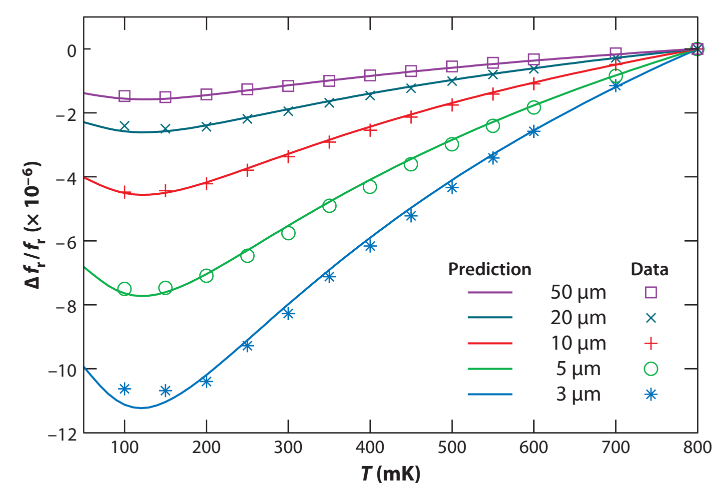


- Amorphous oxides on resonator metal film and bare substrate
- Amorphous materials have large population of "two-level systems"
  - Defect states in materials present opportunity for tunneling between two configurations
  - Theory of two-level systems in NMR applies



- TLS interacts with resonator via electric dipole moment
  - Trades energy with resonator's RF EM field.
  - But can also emit to substrate via phonons.
  - Loss (dissipation) → noise in the coupling.

Frequency shift scales with temperature and dimensions as expected from phenomenological theory

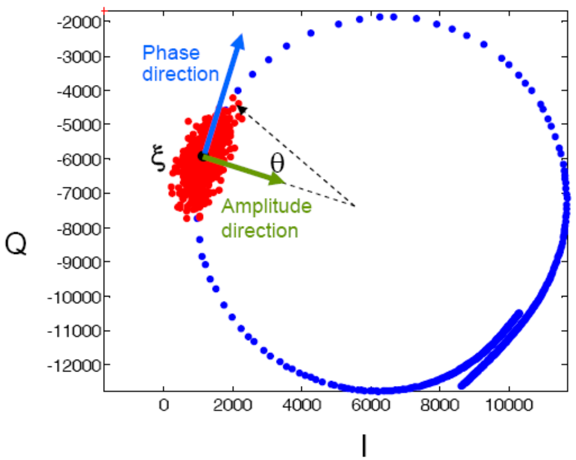


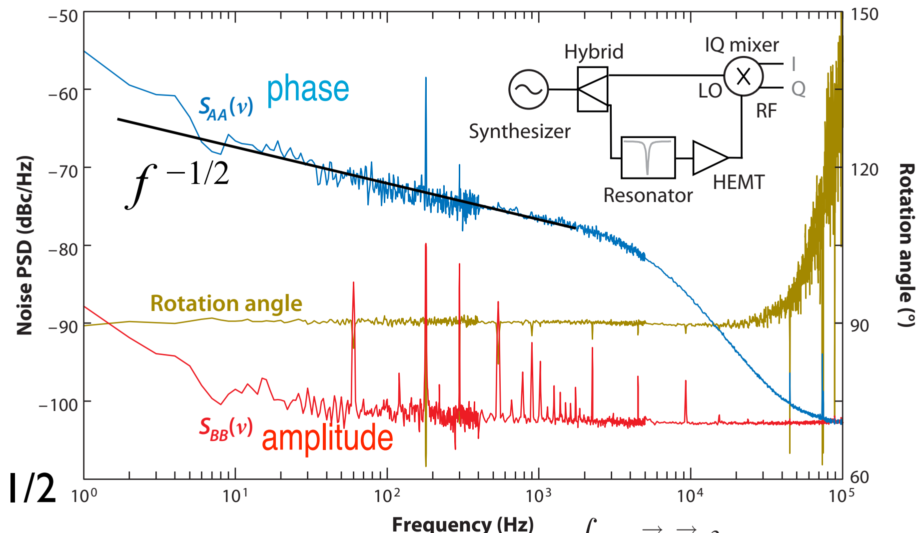
Gao et al APL (2008) as reproduced in Zmuidzinas, ARCMP (2012)

- Coupling to dipole moments in substrate = dielectric constant
  Fluctuations in TLSs = dielectric constant fluctuations

Two-Level System Noise Characteristics

- Noise only in phase direction to high precision, $f^{-1/2}$ spectrum

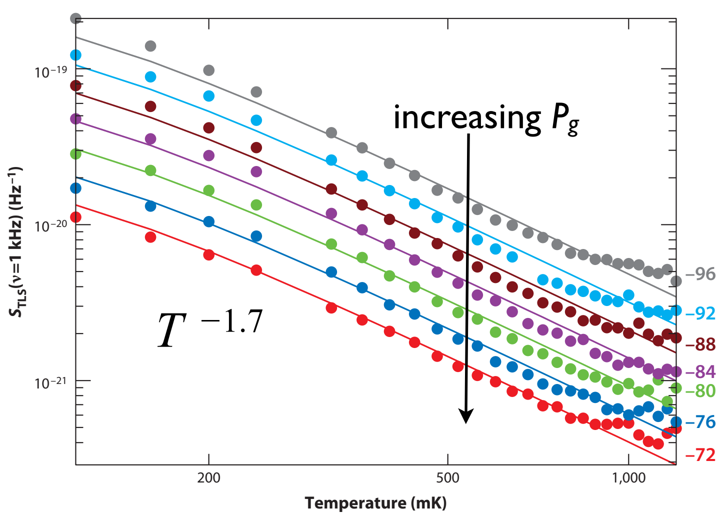




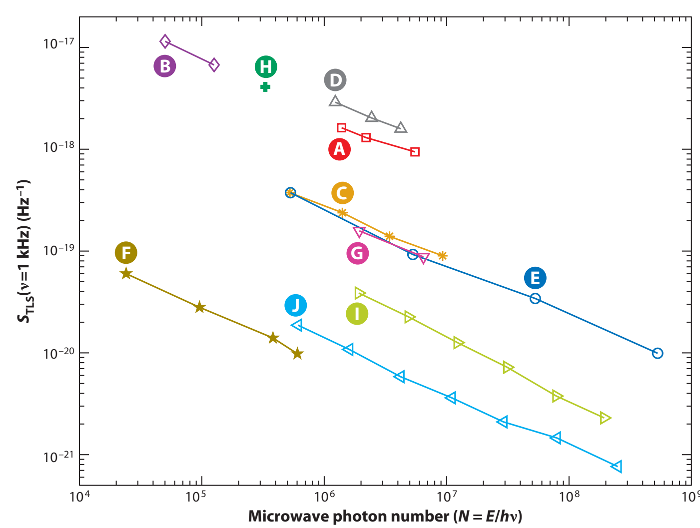
Gao et al APL (2007) as reproduced in Zmuidzinas, ARCMP (2012)

- Noise varies as $T^{-1.7}$ and $P_{stored}^{-1/2}$

$$S_{\mathrm{TLS}}(\nu) = \kappa(\nu,\omega,T)\,\frac{\int_{V_{\mathrm{TLS}}} |\vec{E}(\vec{r})|^3 d^3\vec{r}}{4\left(\int_V |\epsilon(\vec{r})\vec{E}(\vec{r})|^2 d^3\vec{r}\right)^2}$$



Kumar et al APL (2008) as reproduced in Zmuidzinas, ARCMP (2012)



literature compilation in Zmuidzinas, ARCMP (2012)

- Engineering: reduce E where TLS are get away from amorphous materials

Applications: So Many!

- submm/mm
  - imaging: MAKO (McKenney, Swenson), BLAST-POL+ (Hubmayr), NIKA (Doyle, Monfardini, Calvo(P)), lens-coupled twin-slot antenna (Yates), GroundBIRD (Tajima, Watanabe(P)), MUSIC (Sayers, Gill(P), Siegel(P)), A-MKID (Baryshev(P), Baselmans(P)), polarization-sensitive KIDs (Tartari(P))
  - spectroscopy: DESHIMA (Endo), SuperSpec (Shirokoff, Barry(P), Hailey-Dunsheath (P))
  - membrane-isolated resonator (Wernis(P), Lindeman(P), Thomas(P))
- optical: ARCONS (Mazin, Marsden(P), Meeker(P))
- X-ray: membrane-isolated resonator (Ulbricht, Cecil(P), Miceli(P))
- Phonon-mediated detection (Cornell, Ishino(P))
- Materials development: Giachero(P), Vissers(P), Koga(P), Bueno(P)
- Noise: Lindeman(P), Lovitz(P)
- Current-biased KID: Yoshioka(P)
- Assorted talks/posters on readouts

Conclusion

- Kinetic inductance detectors are an exciting application of the physics of superconductivity yielding high readout multiplex factors
- The fundamental response and noises can be understood and tested (at least for M-B material, and hopefully soon for high-resistivity non-M-B materials).
- They are applicable in a wide variety of circumstances for energy detection.
- Thanks to the many LTD participants who supplied input to this talk.