Counting quasiparticles: generation-recombination noise in microwave resonators

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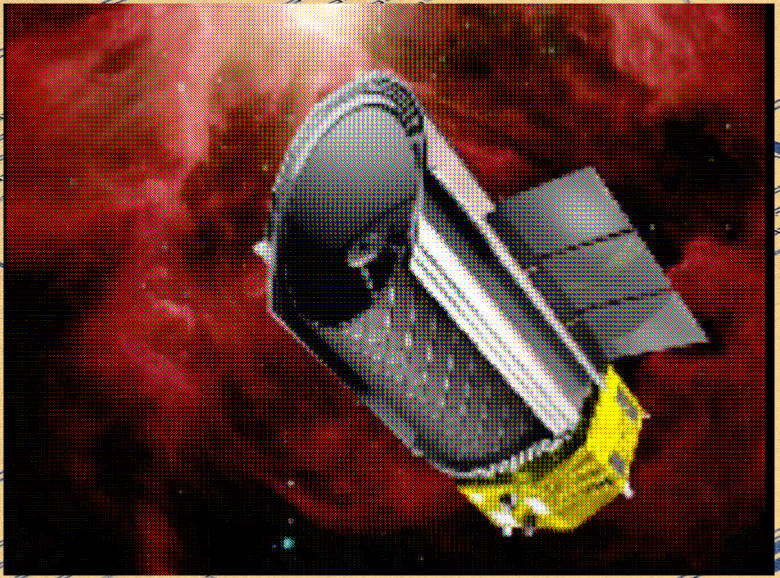
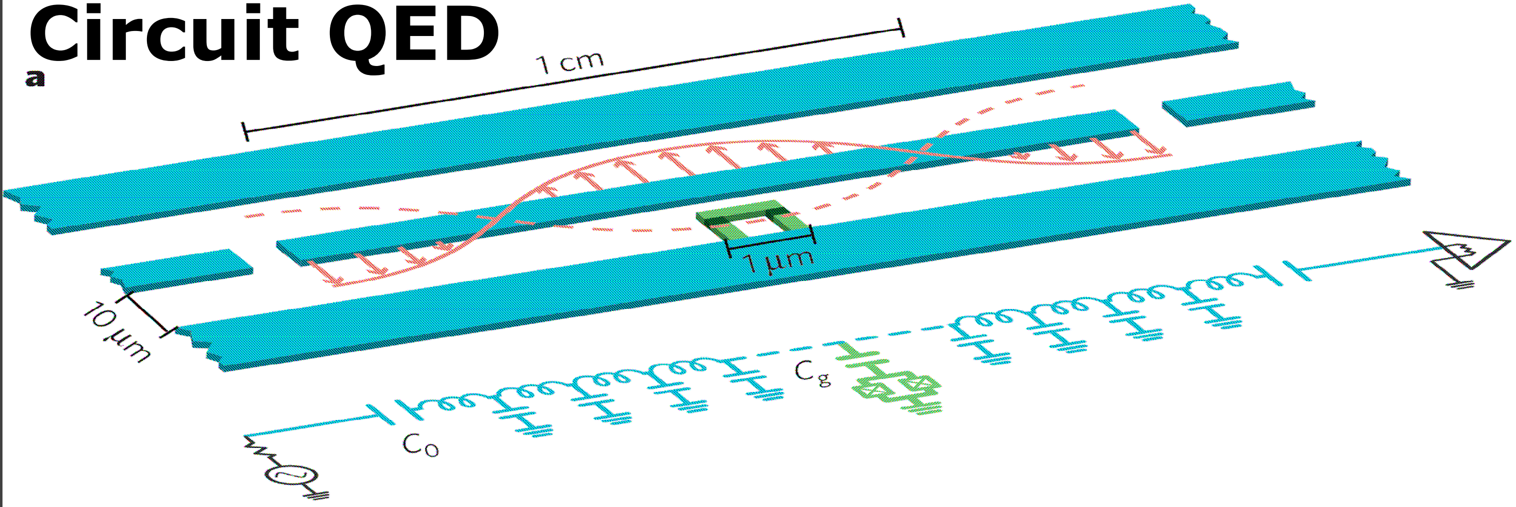
Space / ground based astronomy

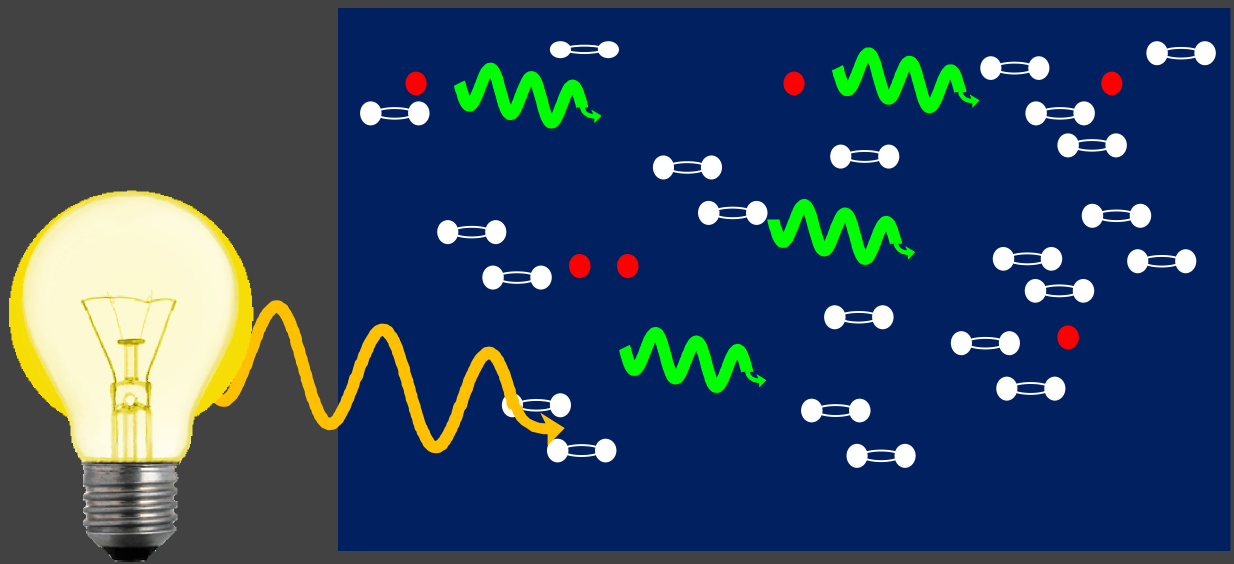


Circuit QED



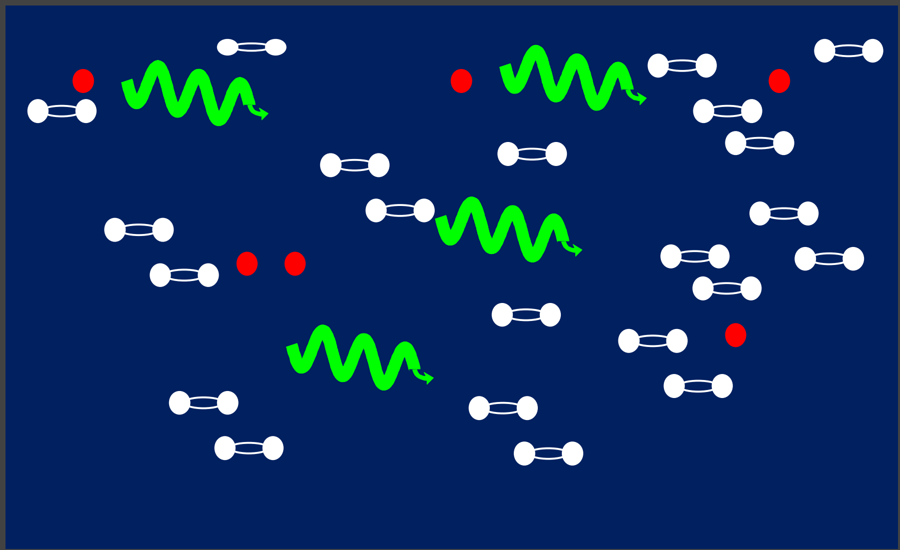
Detection by pair breaking

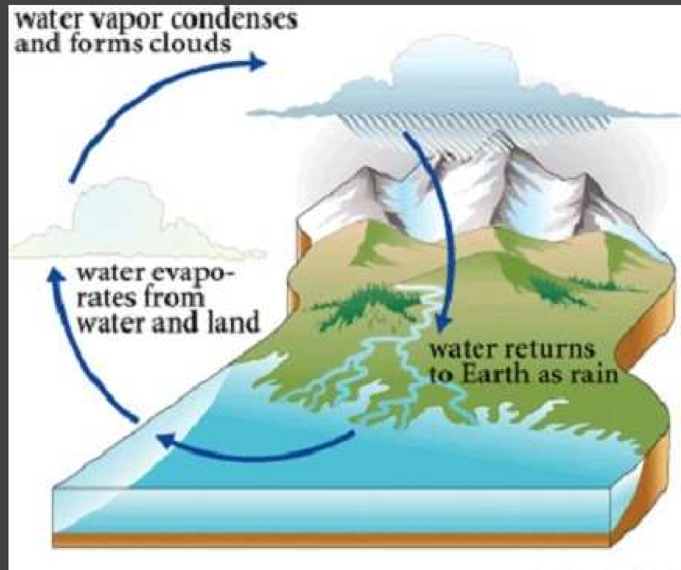
1. Most electrons are paired in equilibrium
2. A photon breaks a pair
3. Resistance increases
4. Detection with microwave resonator



Quasiparticle number fluctuations

In equilibrium: generation and recombination balanced





Number of excitations fluctuates: fundamental noise!

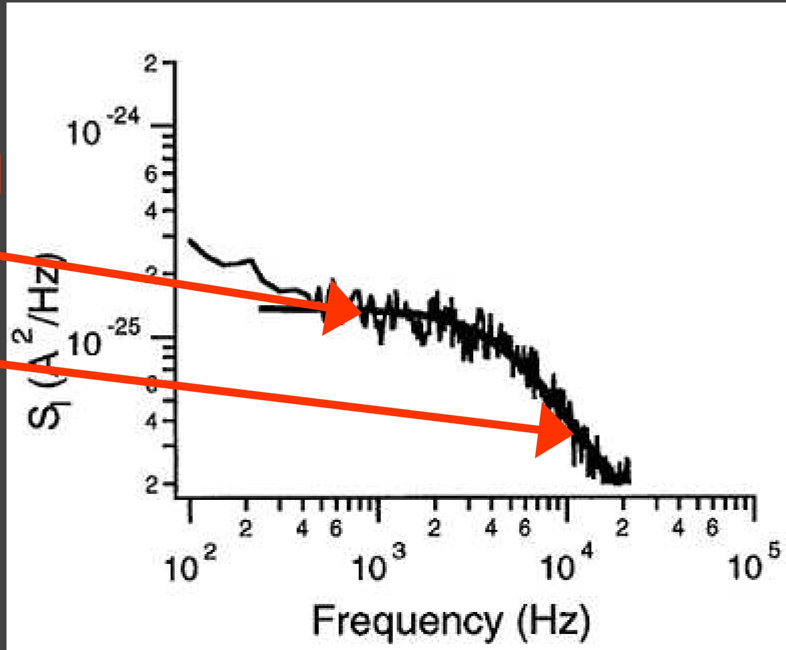
Quasiparticle number fluctuations in equilibrium

Power spectrum:

$$S_N = \frac{4 < N^2 > \tau}{1+\omega^2\tau^2} = \frac{4N\tau}{1+\omega^2\tau^2}$$

Noise level

Roll-off



$$N_{qp} = 2N_0\sqrt{2\pi kT\Delta}\exp(-\Delta/kT)$$

$$\tau = \frac{\tau_0}{\sqrt{\pi}}\left(\frac{kT_c}{2\Delta}\right)^{5/2}\sqrt{\frac{T_c}{T}}\exp(\Delta/kT)$$

$$N_{qp}\tau = 2\tau_0 N_0 V \frac{(kT_c)^3}{(2\Delta)^2}$$

Noise level constant as a function of temperature!!

Wilson and Prober, PRB **69**, 094524 (2004)

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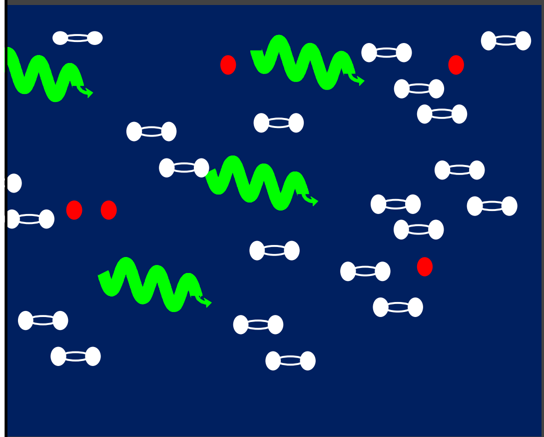
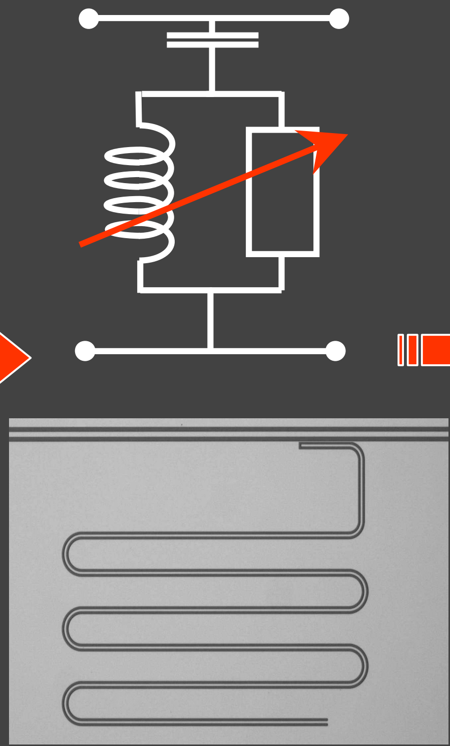
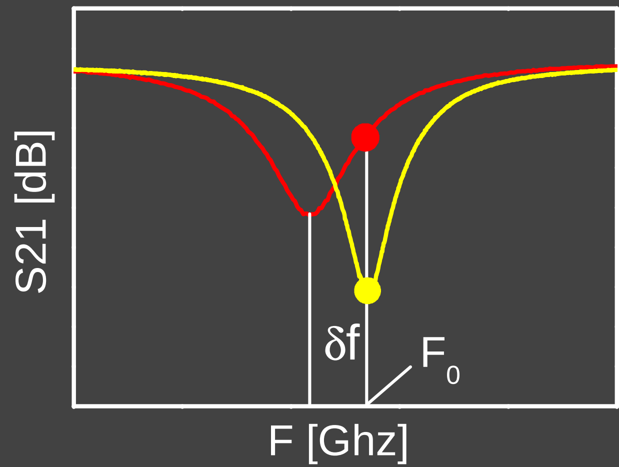
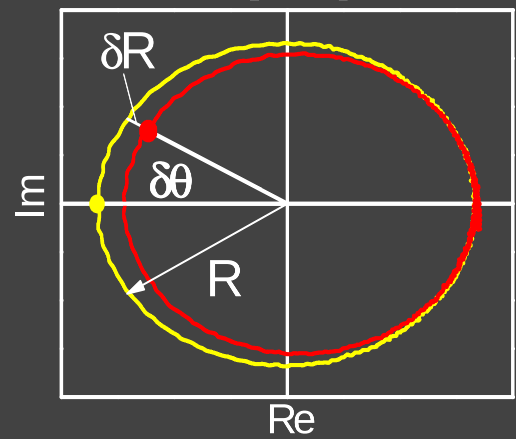
KID: superconducting resonator









Probe the complex conductivity ($\sigma_1+i\sigma_2$) of the resonator

Dip depth / amplitude: dissipation response σ_1

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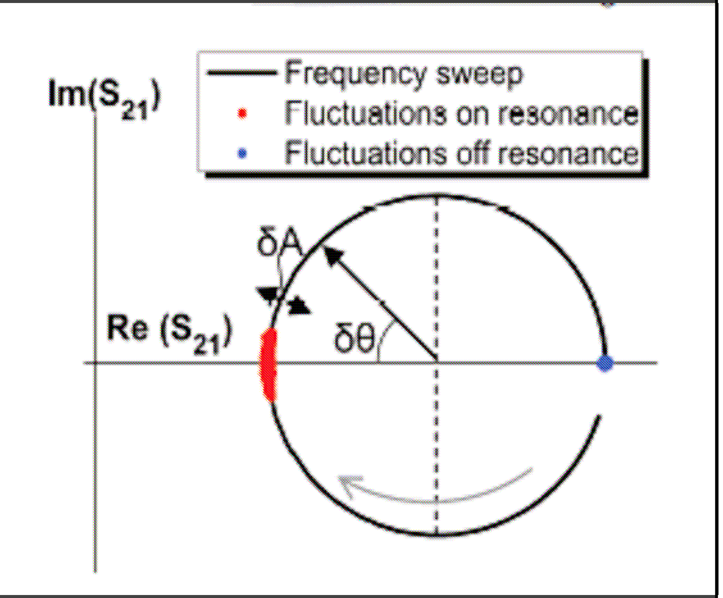
P. Day, et al., Nature 425, 817 (2003).

Quasiparticle fluctuations in a resonator

$$S_A = S_N \left(\frac{dA}{dN_{qp}} \right)^2 = \frac{4N_{qp}\tau}{1+\omega^2\tau^2} \left(\frac{dA}{dN_{qp}} \right)^2$$



Amplitude noise = number fluctuations * response

Responsivity is the phase/radius change per quasiparticle

Observing this noise => fundamental sensitivity reached!

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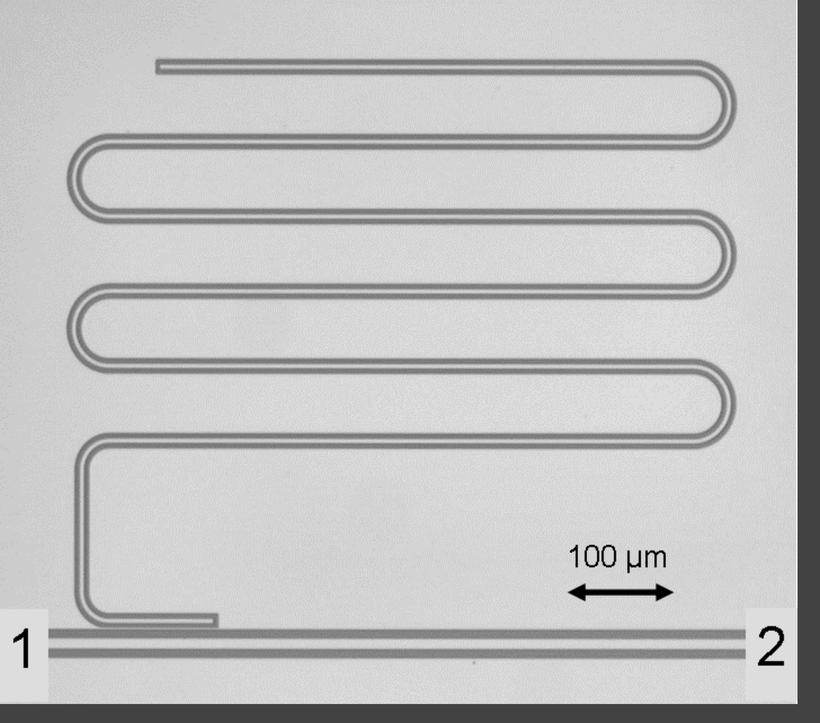
Measurement: alumumium resonator

- 50 nm Al film, sputtered on sapphire
- T_c=1.1 K
- Half wave CPW resonators
- Resonant at 6.6 GHz, Q~40k, Qi~160k



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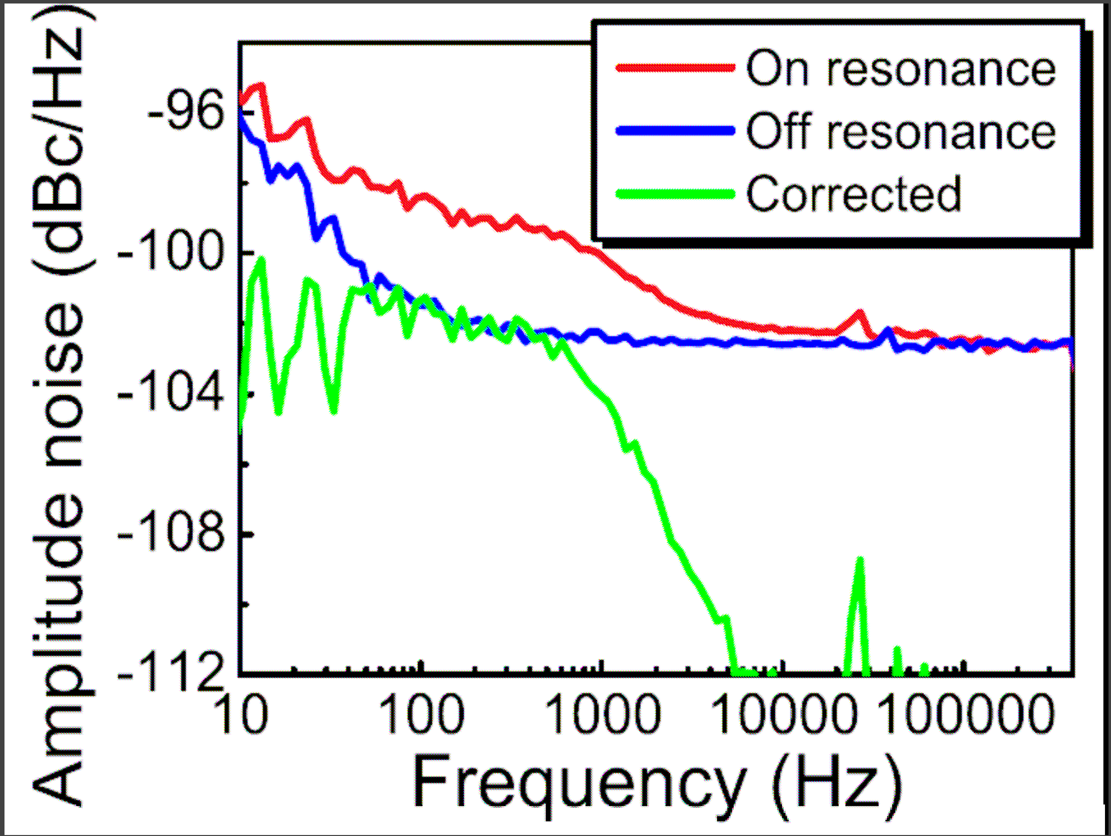
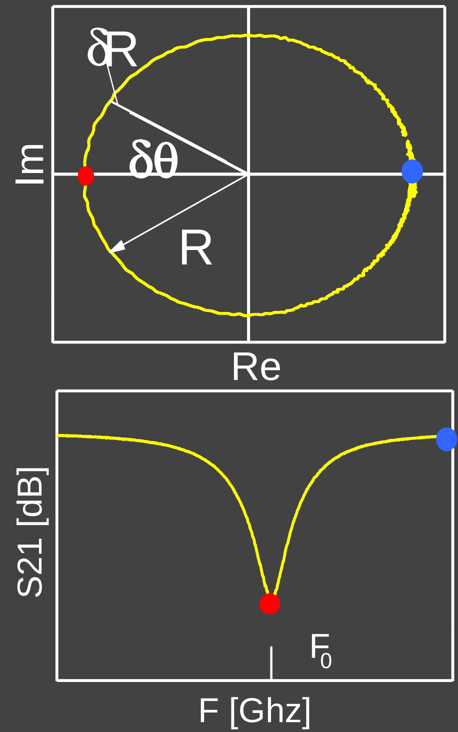
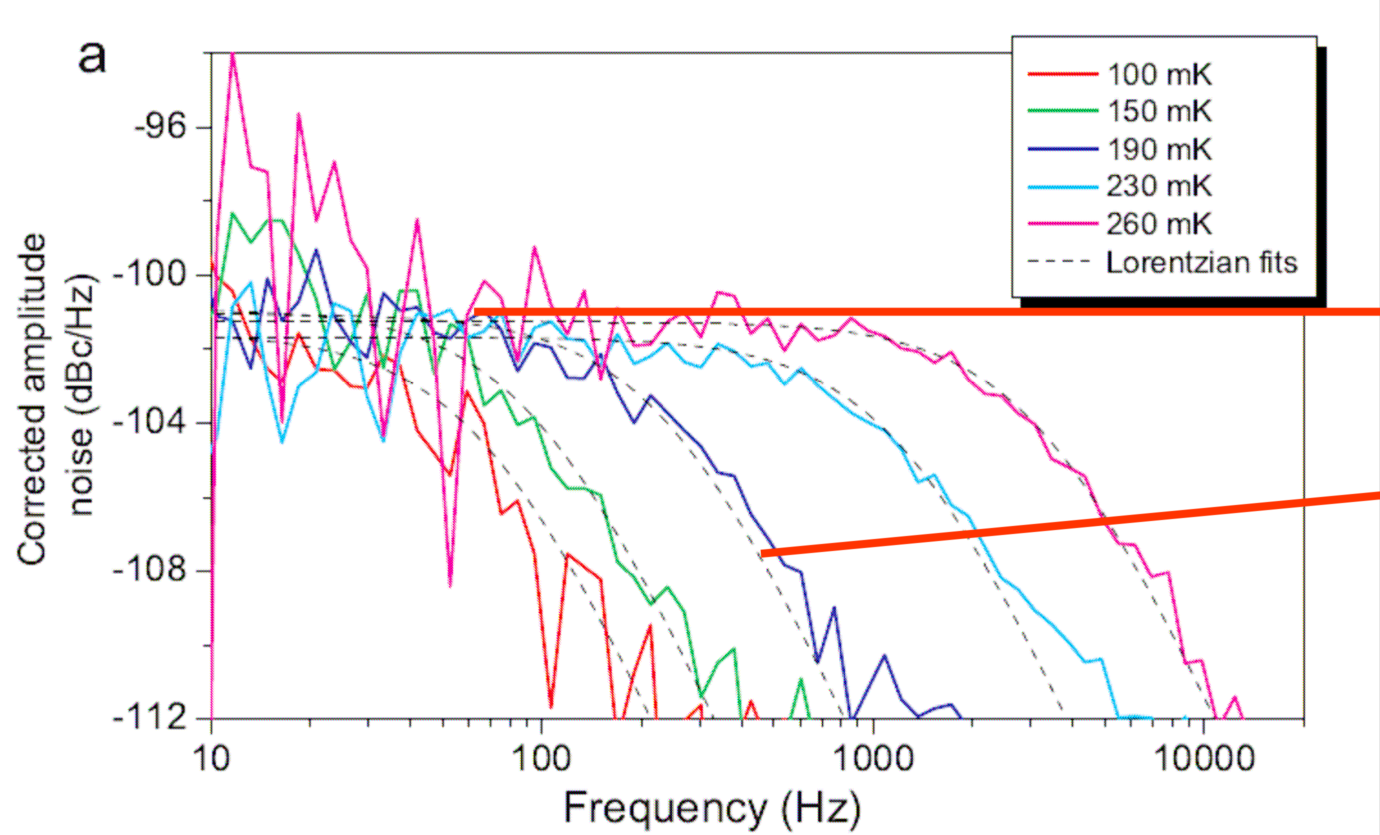
Calibration: subtract system noise

- System noise measured off-resonance
- System noise subtraction





Measurement: Noise at different temperatures



$$S_N = \frac{4N\tau}{1+\omega^2\tau^2}$$

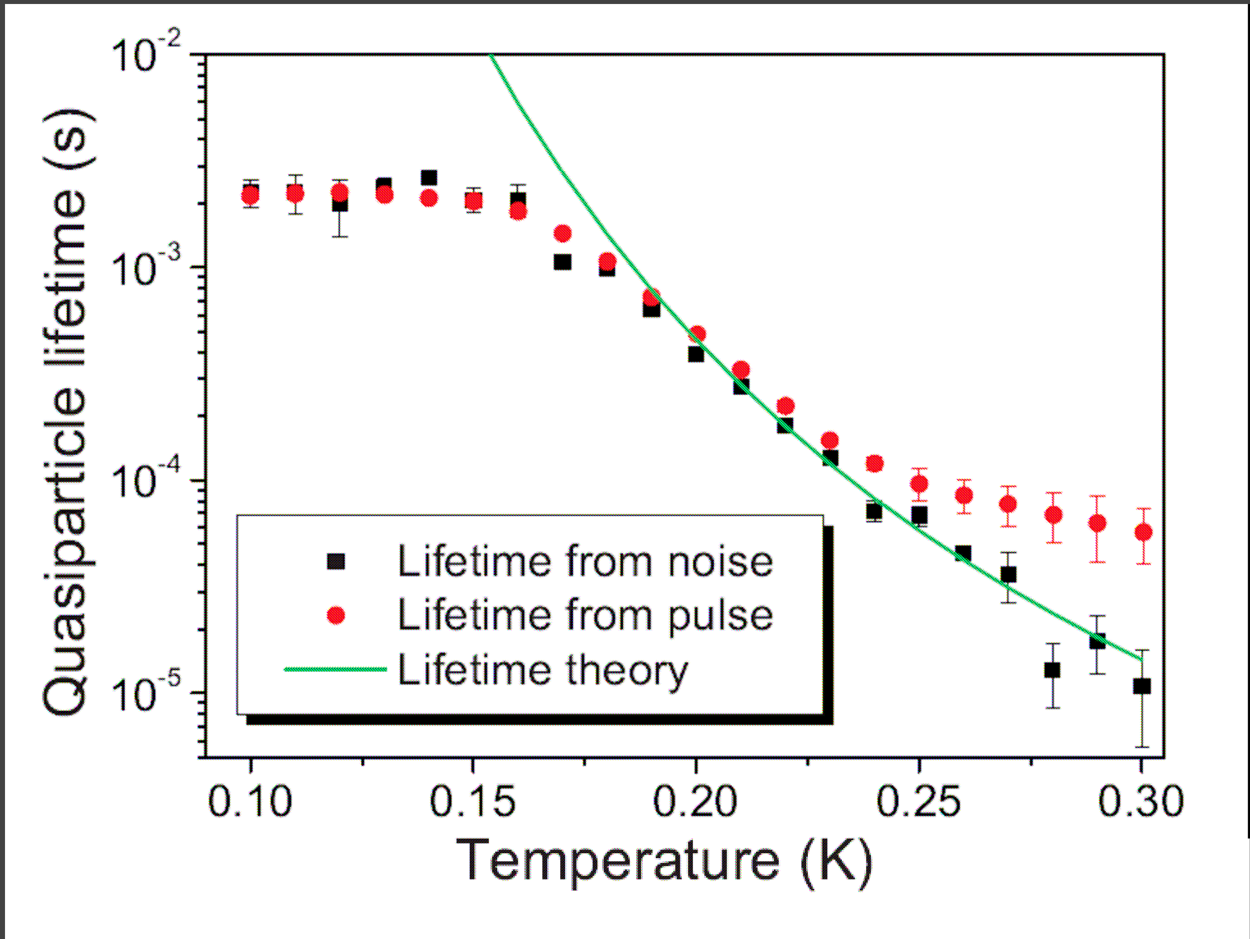
$$N_{qp} \propto \exp(-\Delta / kT)$$

$$\tau \propto \exp(\Delta / kT)$$

Clear sign of quasiparticle number fluctuations!!

Fundamental noise reached!

Quasiparticle lifetime

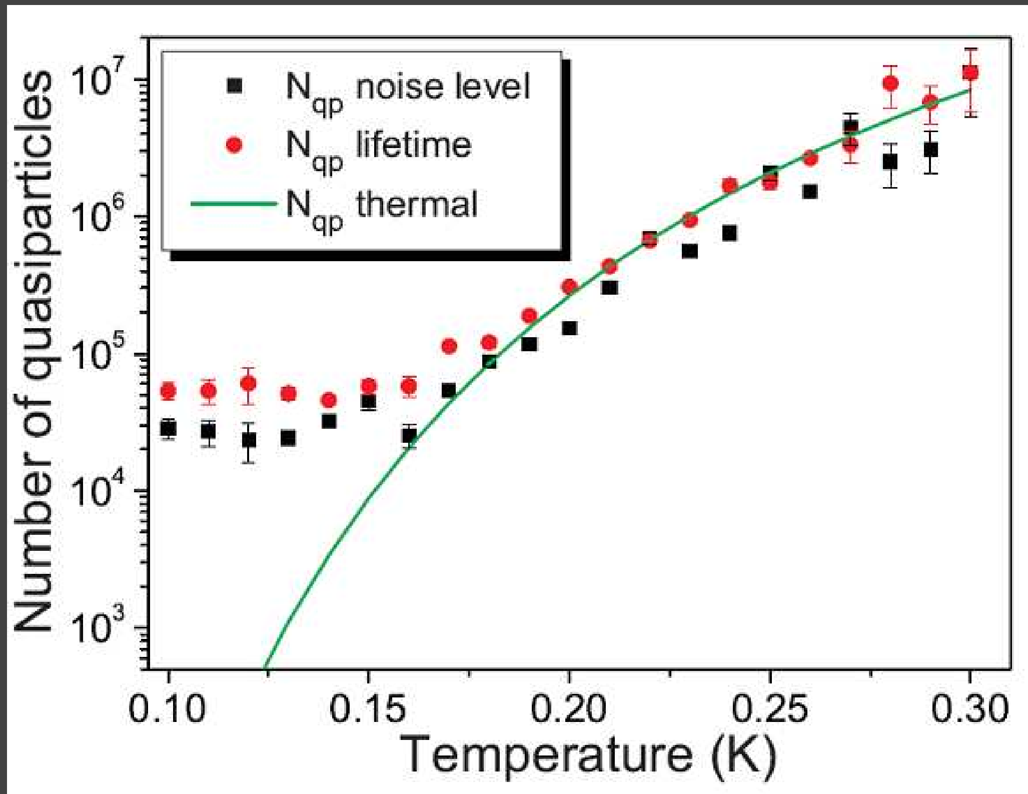


$$S_N = \frac{4N\tau}{1+\omega^2\tau^2}$$

2 methods: consistent lifetime
But it saturates at low Temperature

Noise is a signal!

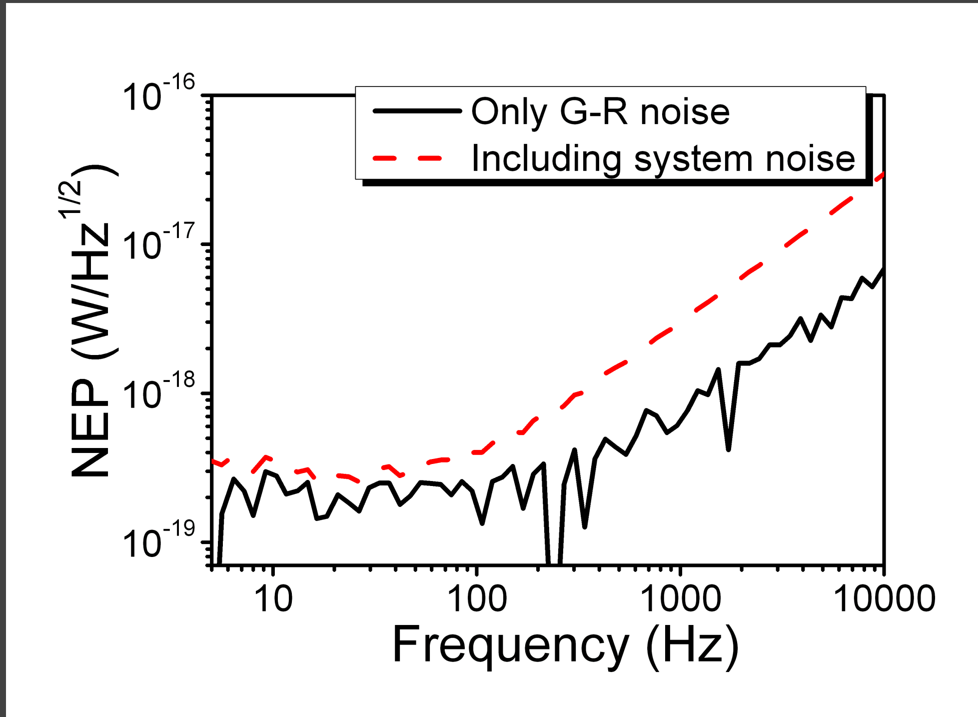
Counting quasiparticles with microwave resonators



Noise spectrum -> number of quasiparticles

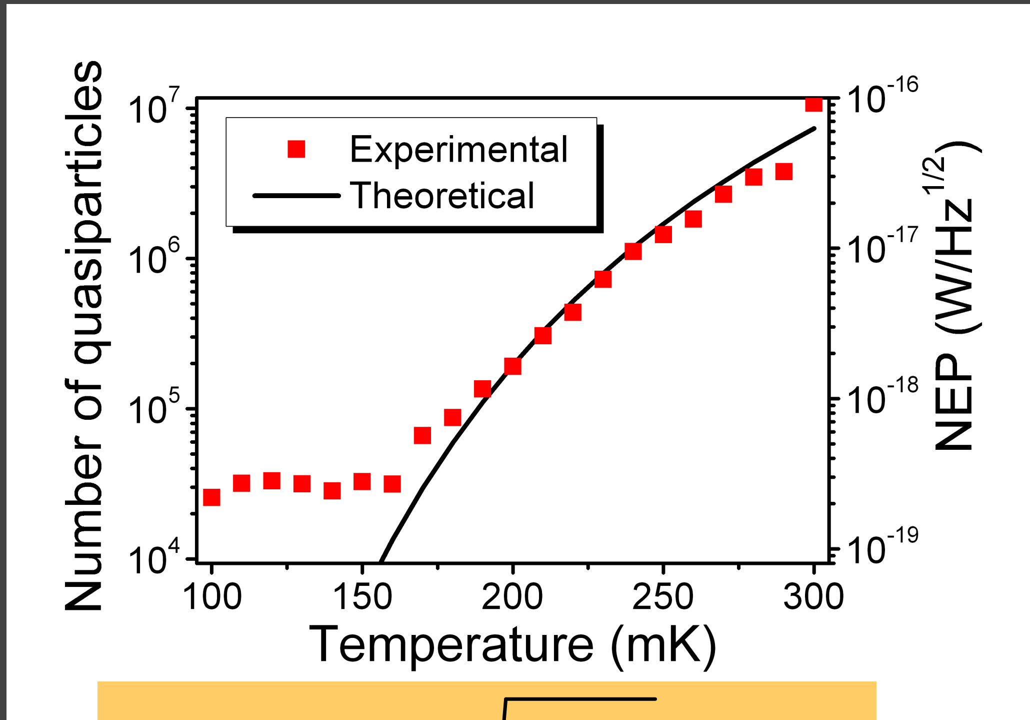
Lifetime limited by excess quasiparticles

Fundamental sensitivity for KIDs



$$NEP_A(\omega) = \sqrt{S_A}\left(\frac{\eta\tau}{\Delta}\frac{dA}{dN_{qp}}\right)^{-1}\sqrt{1-\omega^2\tau^2}$$

Fundamental sensitivity for KIDs



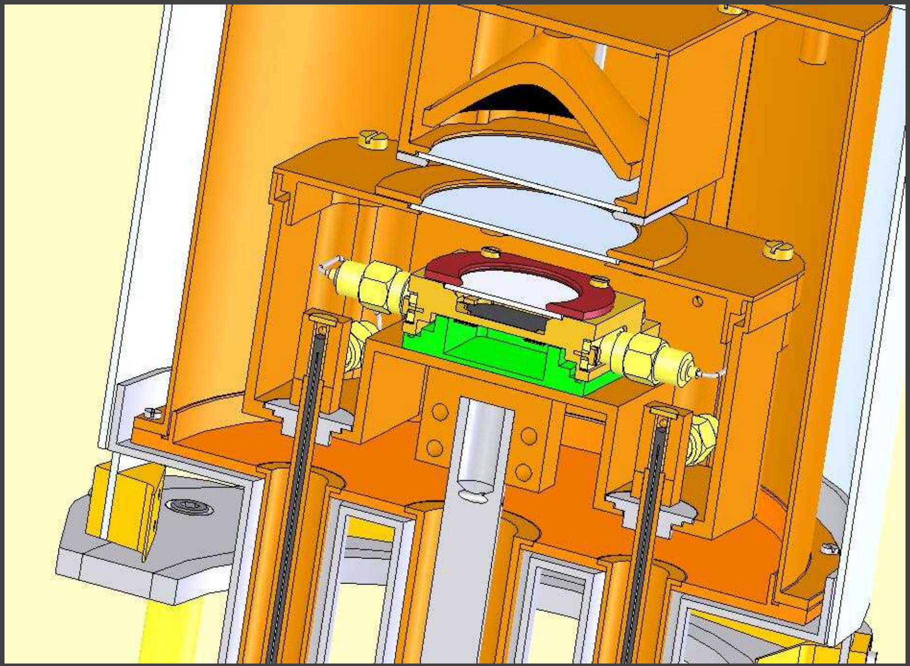
$$NEP_{g-r} \propto \sqrt{\frac{N_{qp}}{\tau_{qp}}} \approx N_{qp}$$

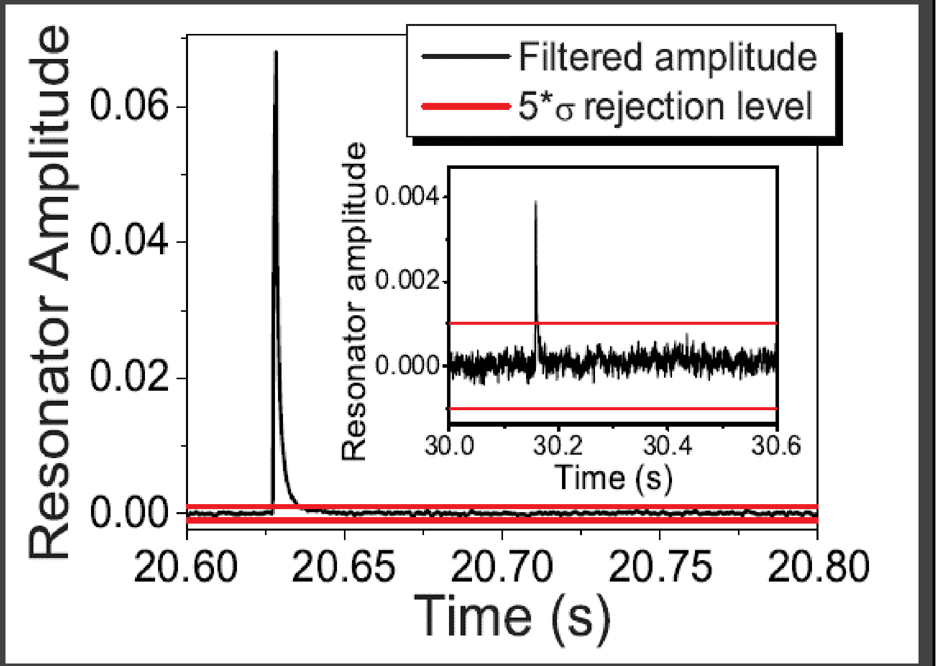
NEP_{g-r} behaves as theoretically expected

Low temperature NEP limited by excess quasiparticles

Sources of quasiparticles

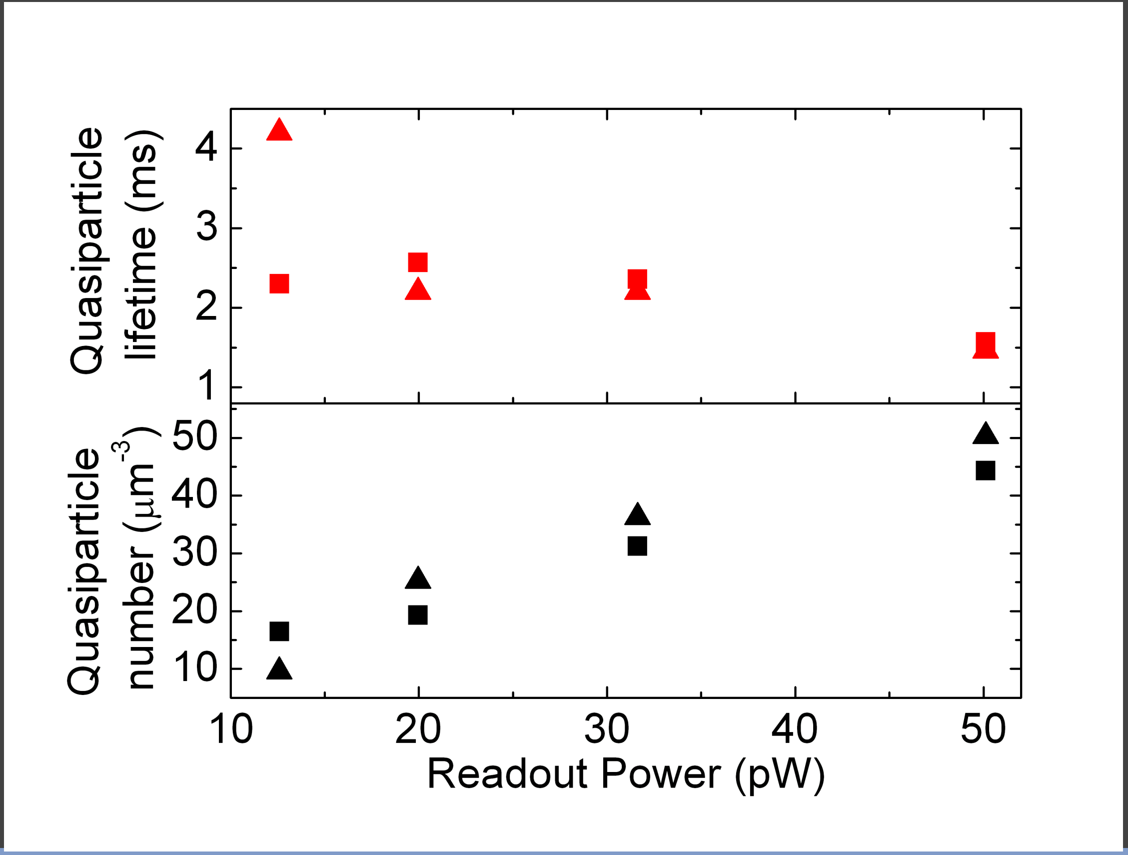
- Stray light creates quasiparticles -> Light-tight setup
  No photon noise observed
- (Cosmic ray) hits -> filter peaks out of noise analysis





Sources of quasiparticles

- The number of quasiparticles and lifetime are **microwave readout power dependent / limited**
- Means that we are sure other effects do not limit Nqp!
- Small range: one side bifurcation, other side amplifier noise



Resonator noise limited by intrinsic generation-recombination noise

Noise is a signal: powerful tool to count quasiparticles and determine their lifetime

Both saturate consistently at low temperature - due to the readout power

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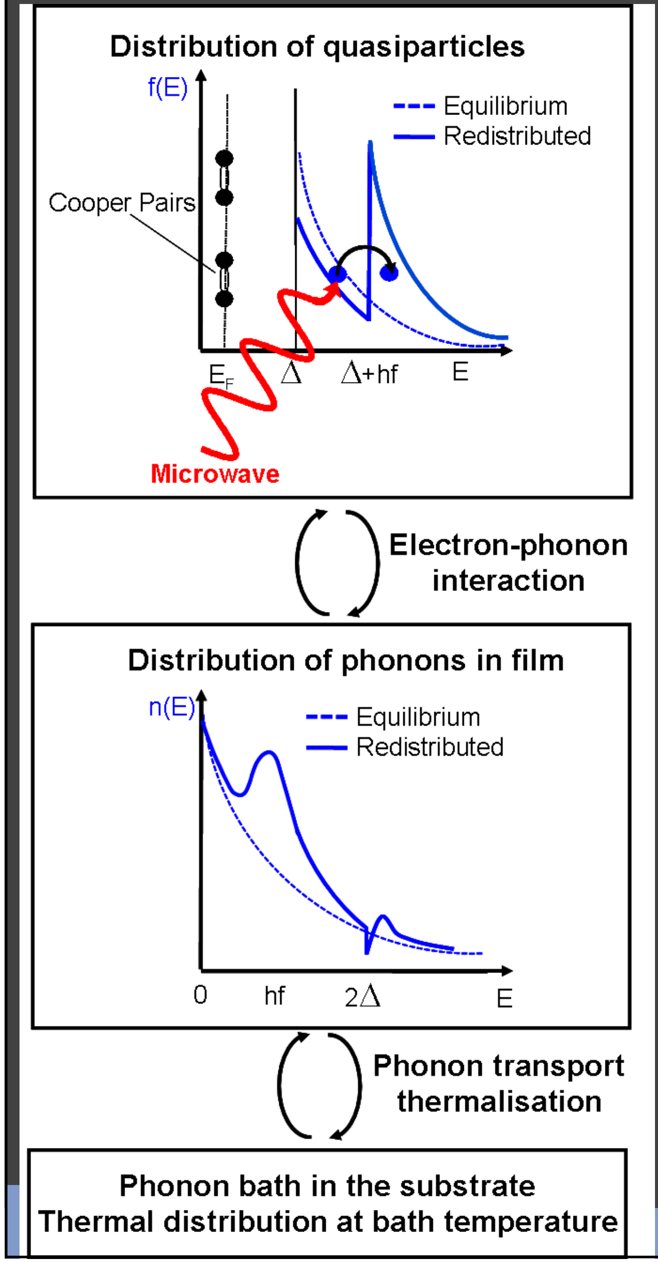
Phys. Rev. Lett. 106, 167004, 2011

This opens the door to fundamentally limited KID - detectors

Microwave absorption changes the distribution function



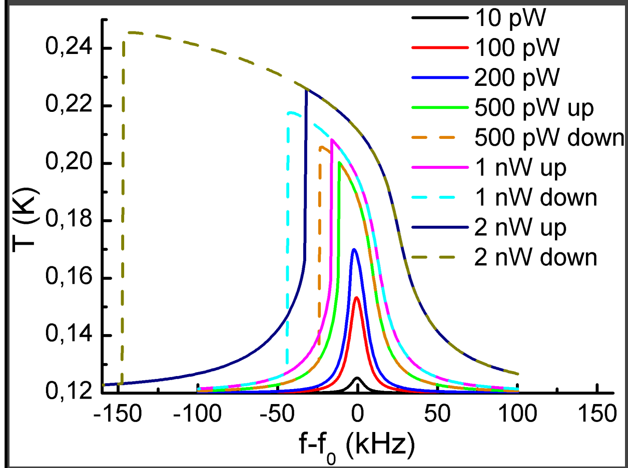
- Quasiparticle distribution function can change drastically
- Resulting distribution depends on ratios of scattering/recombination rates
- Number of quasiparticles and their lifetime energy dependent
- Microwave absorption can also result in effective cooling

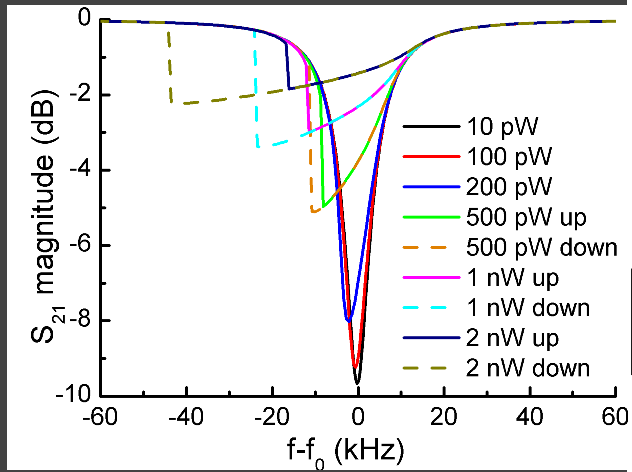
Full treatment will require solving kinetic equations

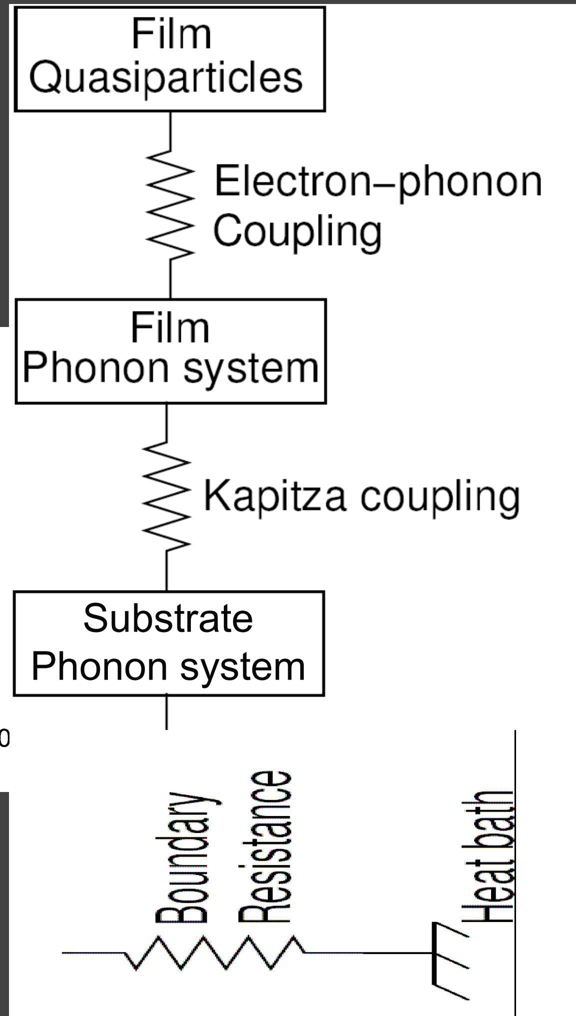
- B.I. Ivlev, S.G. Lisitsyn and G.M. Eliashberg, 'Nonequilibrium excitations in superconductors in high-frequency fields', J. Low Temp. Phys. 10, p449 (1973)
- J.-J. Chang and D.J. Scalapino, 'Kinetic-equation approach to nonequilibrium superconductivity', Phys. Rev. B 15, p2651 (1977)

Electron-phonon coupling in metals

- $P_{e\text{-}ph} = V\Sigma(T_e^5 - T_{ph}^5)$
- $\Sigma = 0.2\ nW/K^5 /\mu m^3$
- We take $V\Sigma = 480\ nW/K^5$







See also: J. Appl. Phys. 108, 114504, 2010

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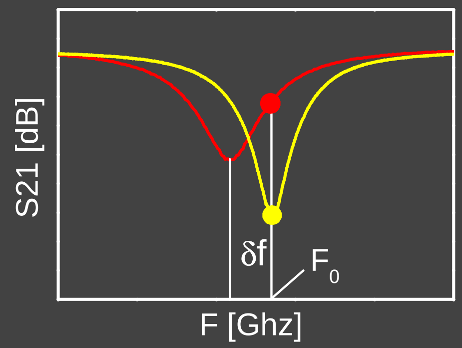
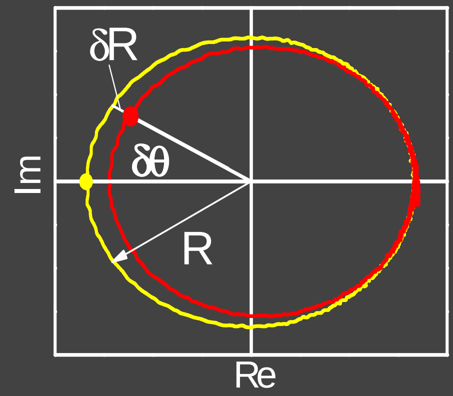
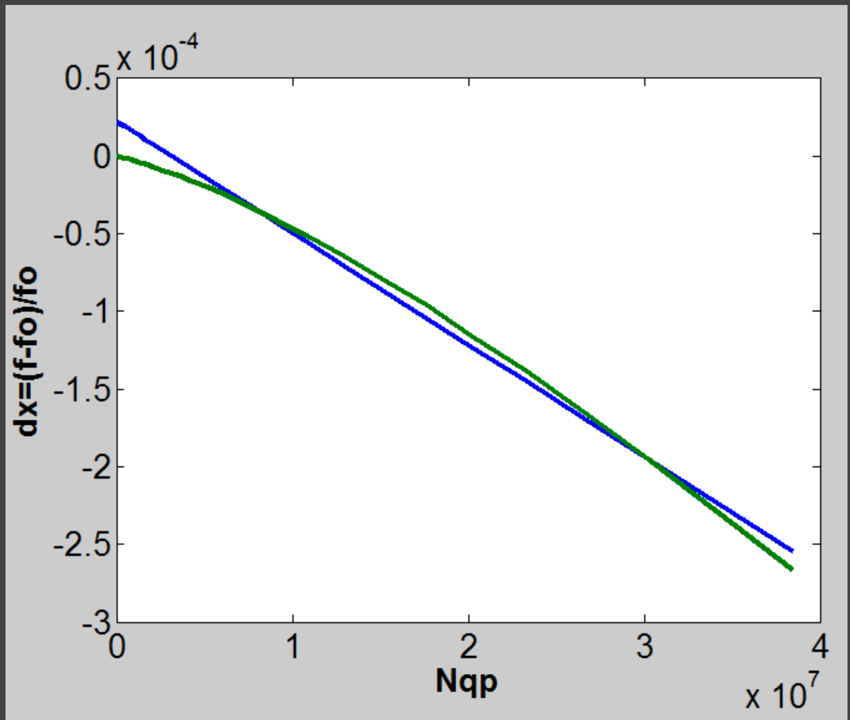
Determine the amplitude responsivity

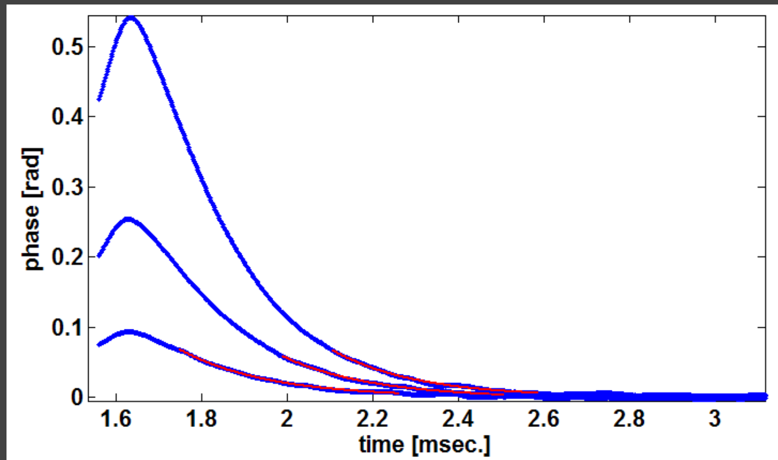
$$\frac{d\theta}{dN_{qp}} = -4Q_l \frac{d\left(\frac{\delta f}{f_0}\right)}{dN_{qp}}$$







$$\frac{dR}{dN_{qp}} = \frac{dR}{d\theta}\frac{d\theta}{dN_{qp}}$$



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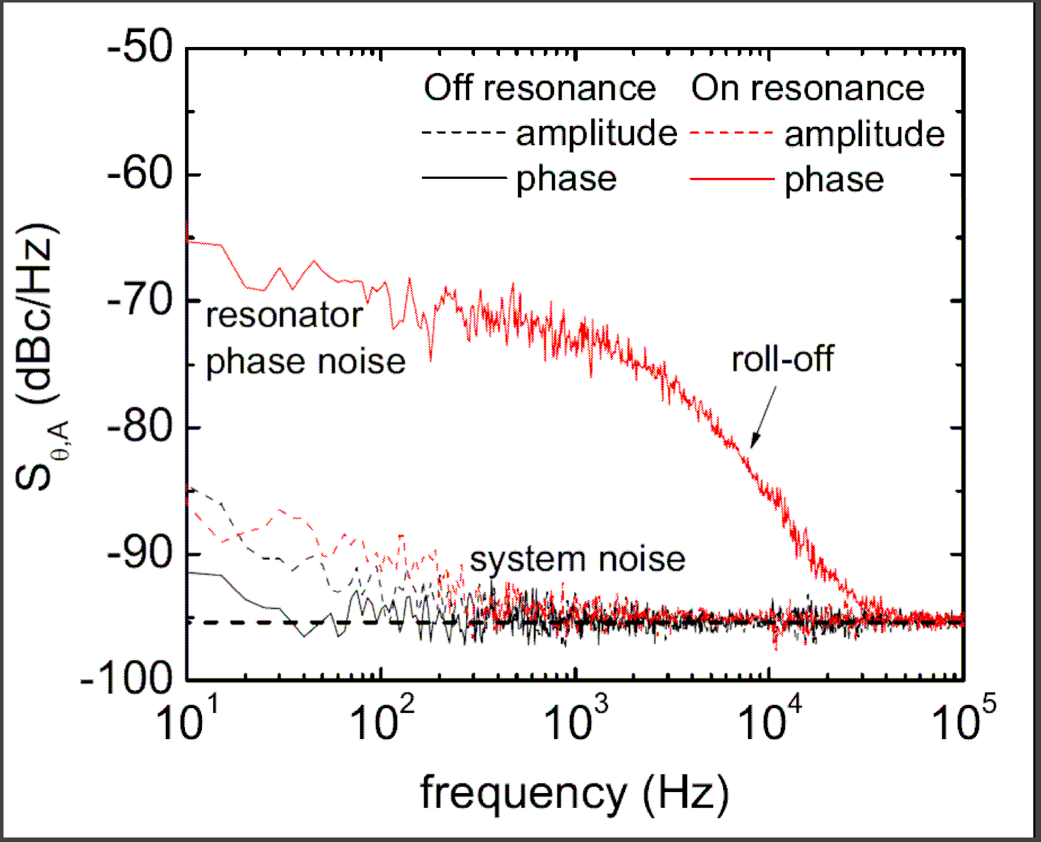
Amplitude vs phase noise

- Phase noise is dominated by two level system noise in the dielectric (Rami's thesis)
- Amplitude noise dominated only by amplifier



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