# Coherent excited states in superconductors due to a microwave field

## - *microscopic perspective on microwave nonlinearity* -

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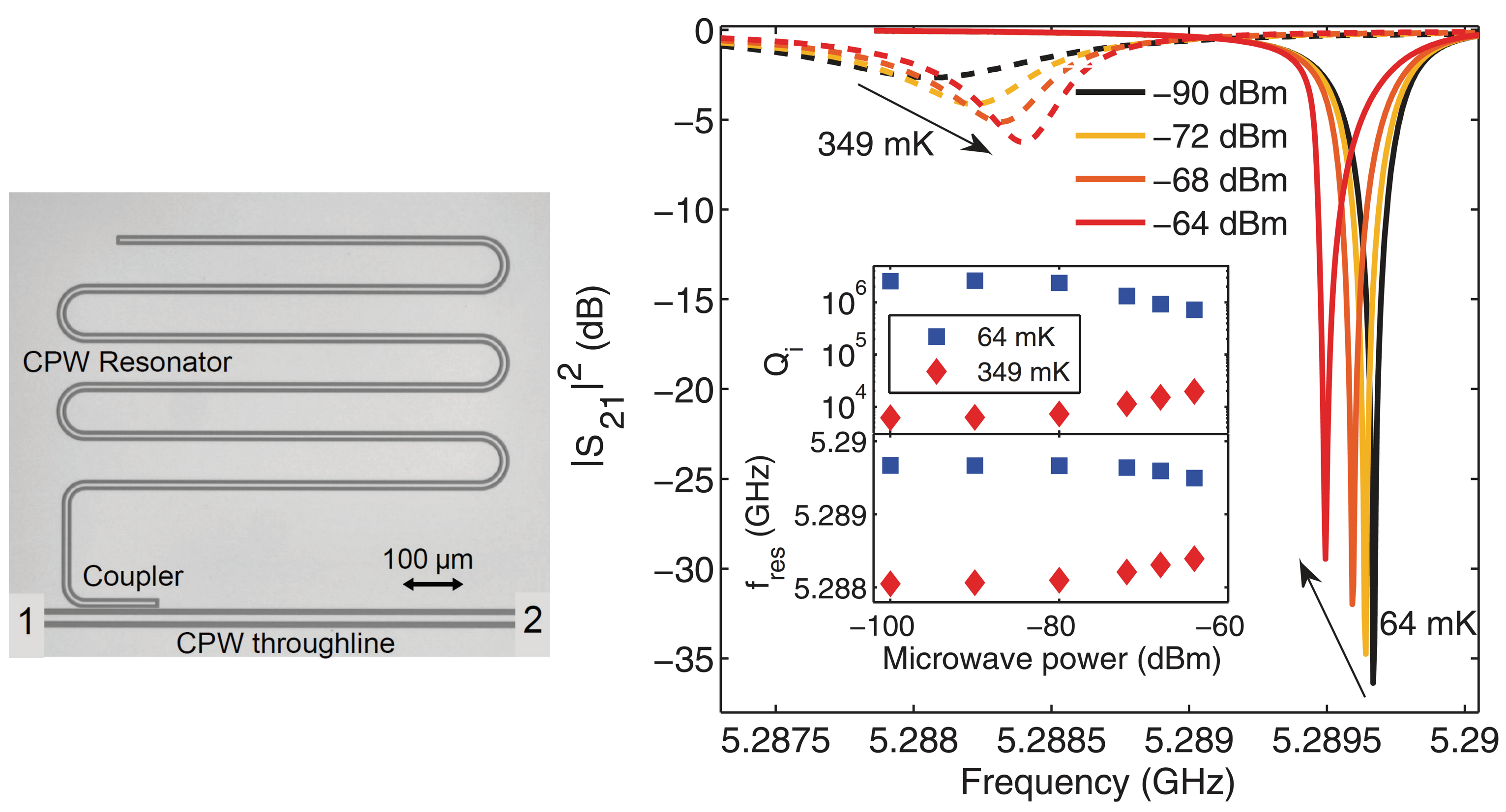
## Superconducting microwave resonators

In a superconductor at low temperature, electrons are paired in Cooper pairs, which leads to superconducting resonators with high quality factors and a long quasiparticle lifetime, desired for highly sensitive Kinetic Inductance Detectors. The electrodynamic response (quality factor, resonant frequency) in equilibrium is well described by Mattis-Bardeen theory. However, **the strong microwave field changes the electrodynamic response drastically.** Some observables can be explained as 'microwave heating' [1] or considering the full 'redistribution of quasiparticles' from microwave absorption [2].

**The more fundamental question is: how does the superconducting state change in an AC/microwave field?**

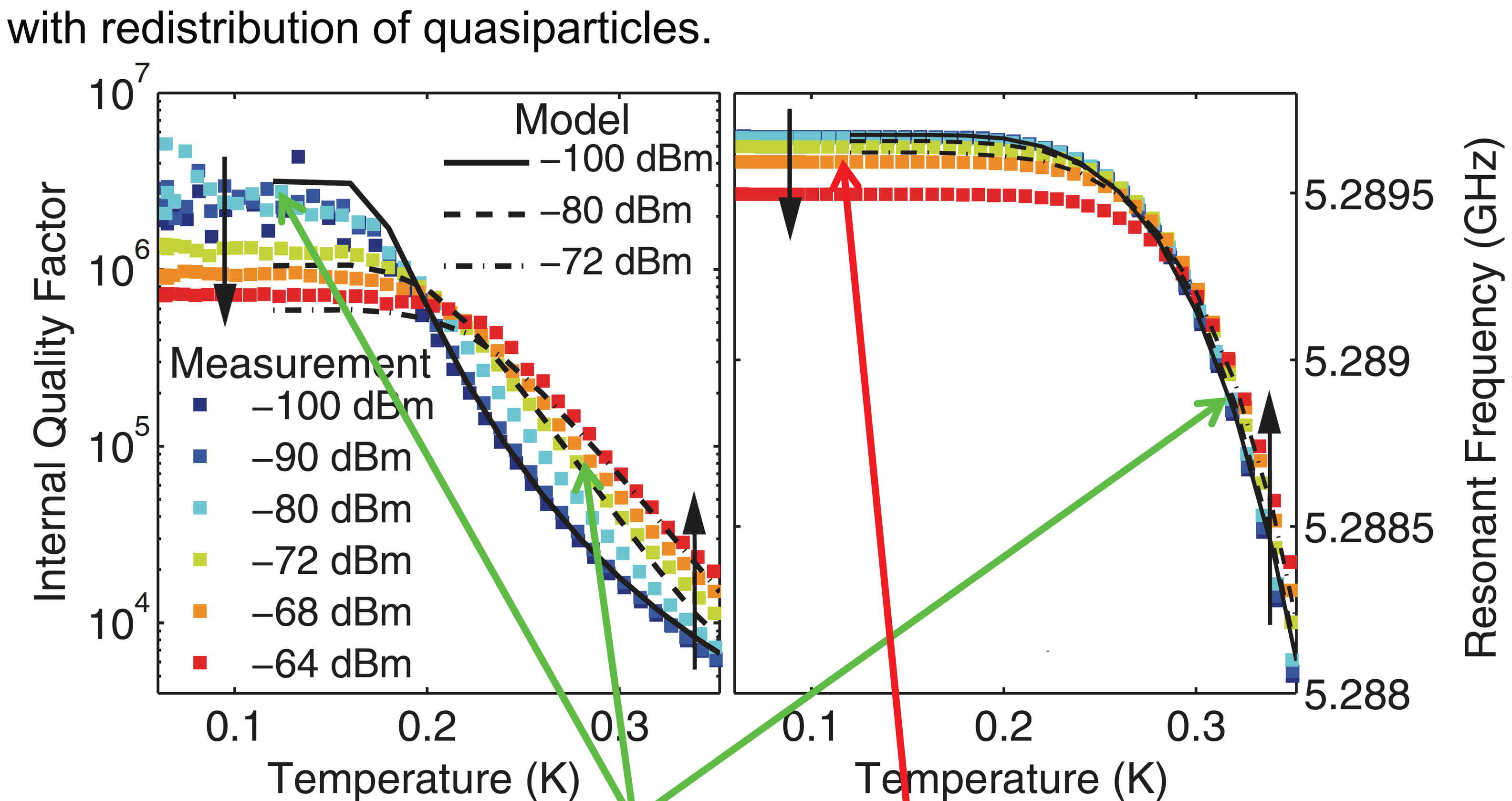



## Resonator observables

The microwave response of an aluminium resonator is measured as a function of microwave power and temperature. We extract the internal quality factor, $Q_i$ and resonant frequency $f_0$. Two regimes appear:

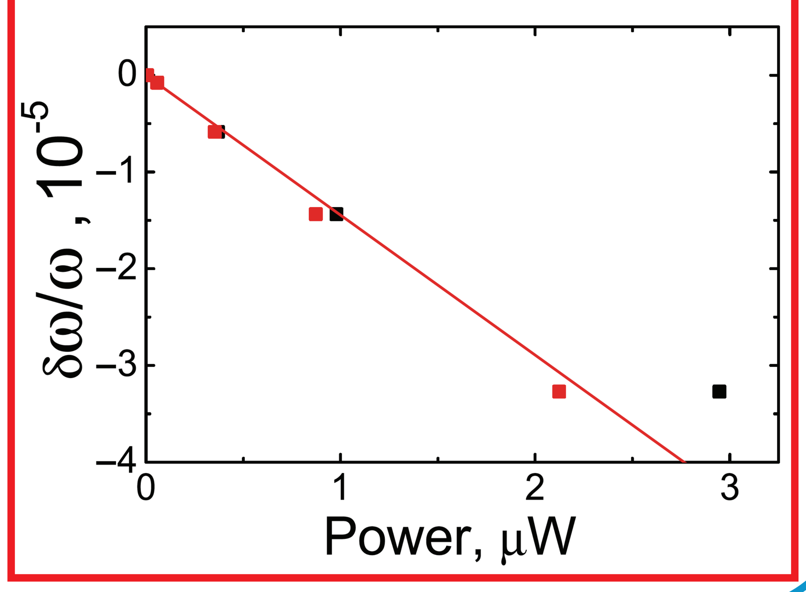
**Low temperature:** $Q_i$ and $f_0$ decrease for increasing power, analogous to heating, consistent with excess quasiparticles.

**Higher temperatures:** $Q_i$ and $f_0$ increase for increasing power, which cannot be described by a single effective temperature, but agrees very well with redistribution of quasiparticles.




These regimes agree with redistribution of quasiparticles due to microwave absorption. This also explains number of quasiparticles and recombination lifetime [2].

The low temperature frequency shift CANNOT be explained by redistribution-only. It scales as the P α I² nonlinearity that is well known for DC currents.

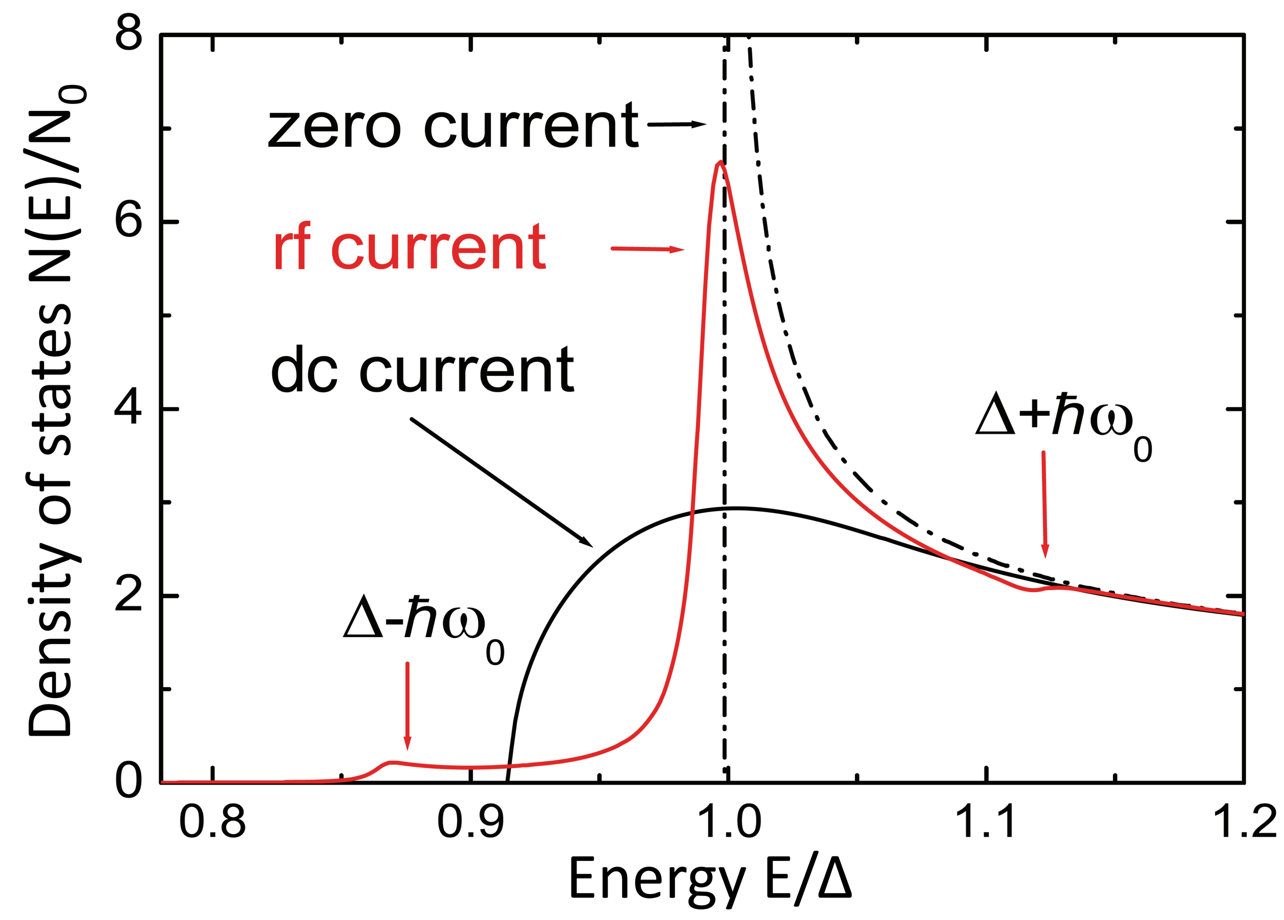



**This current-induced non-linearity in a superconductor was never addressed theoretically for a microwave field !**

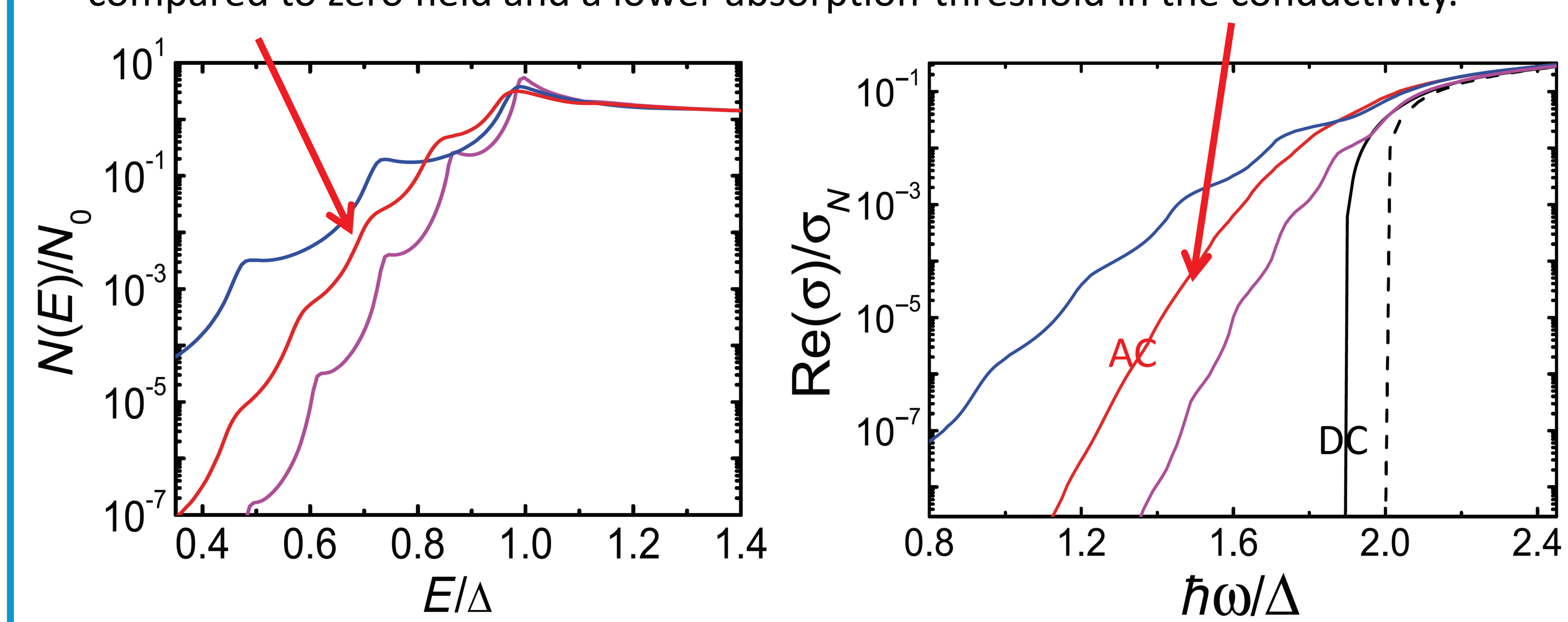
## Novel theory: superconducting state gets 'microwave dressed'

The quasiparticles in a Cooper pair together have zero momentum $\mathbf{k_1} + \mathbf{k_2} = 0$. In a DC field they gain a net momentum $\mathbf{k_1} + \mathbf{k_2} = \mathbf{q}$, where **q** depends on the field strength. This leads to a rounding of the density of states and a reduction of the gap energy, ie 'depairing'.

In a *microwave* field the net pair-momentum is $\mathbf{k_1} + \mathbf{k_2} = |\mathbf{q}|\cos(\omega_0 t)$. When the microwave energy is large enough compared to field strength (the quantum regime, relevant for GHz MKIDs) this leads to pronounced steps in the density of states at multiples of the microwave energy.




On top of this step-structure, the DOS acquires an exponential tail towards low energies, thus a pronounced sub-gap structure compared to equilibrium. Therefore there will be more excess quasiparticles at low temperature compared to zero field and a lower absorption-threshold in the conductivity.




**Theory describes resonator nonlinearity without fitting parameters**

As shown on the bottom-left of the poster (red line), this theory puts a rigorous basis under the well-known I² nonlinearity of resonators at low temperature, and even predicts the slope correctly based on material parameters (no fitting parameters)!!

**Exponential tail 'ignites' the creation of excess quasiparticles**

We have measured previously that microwave absorption causes excess quasiparticles at low temperature [2]. But microwave absorption itself requires quasiparticles to be present. The here discovered exponential DOS-tail could solve this chicken-egg problem.

**Future exploration of dressed states**

Do tunnelling measurements or harmonic generation experiments to study the full beauty of the microwave-driven density-of-states.

An experiment with a strong microwave drive, where the absorption of high frequency radiation is studied, could resolve the exponential step-like tail of the DOS.

**Theory wish:** an overarching theory covering both field-induced depairing (density of states) and quasiparticle redistribution due to absorption.

**References:**
1. J. Appl. Phys. 108, 114504 (2010)
2. Phys. Rev. Lett. 112, 047004 (2014)
3. Phys. Rev. Lett. 117, 047002 (2016) – **This work**

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