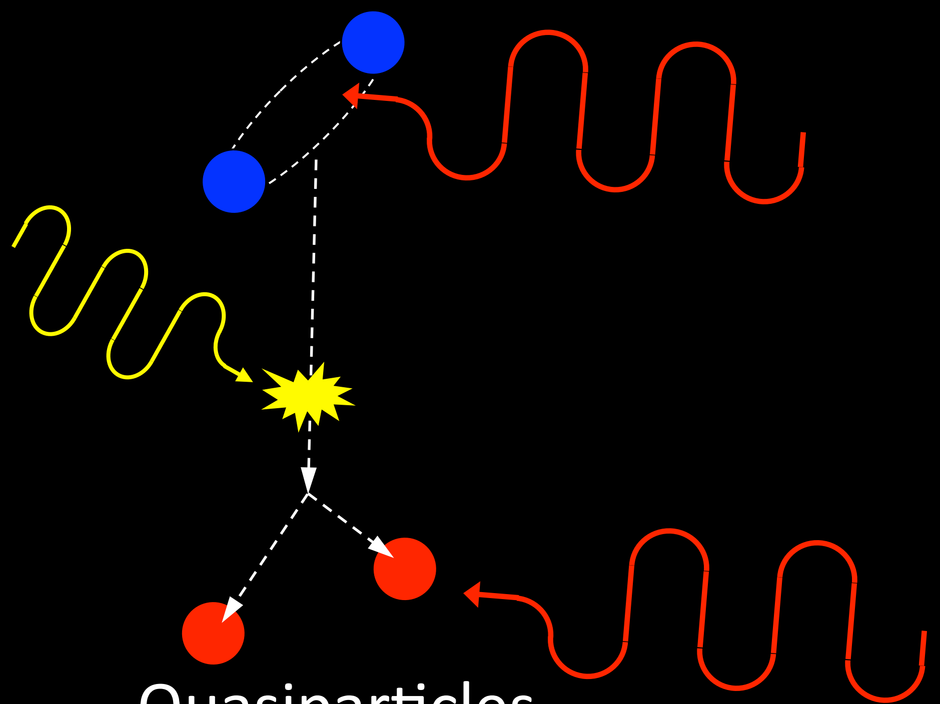
# Non-equilbribum superconductivity in aluminium microwave resonators

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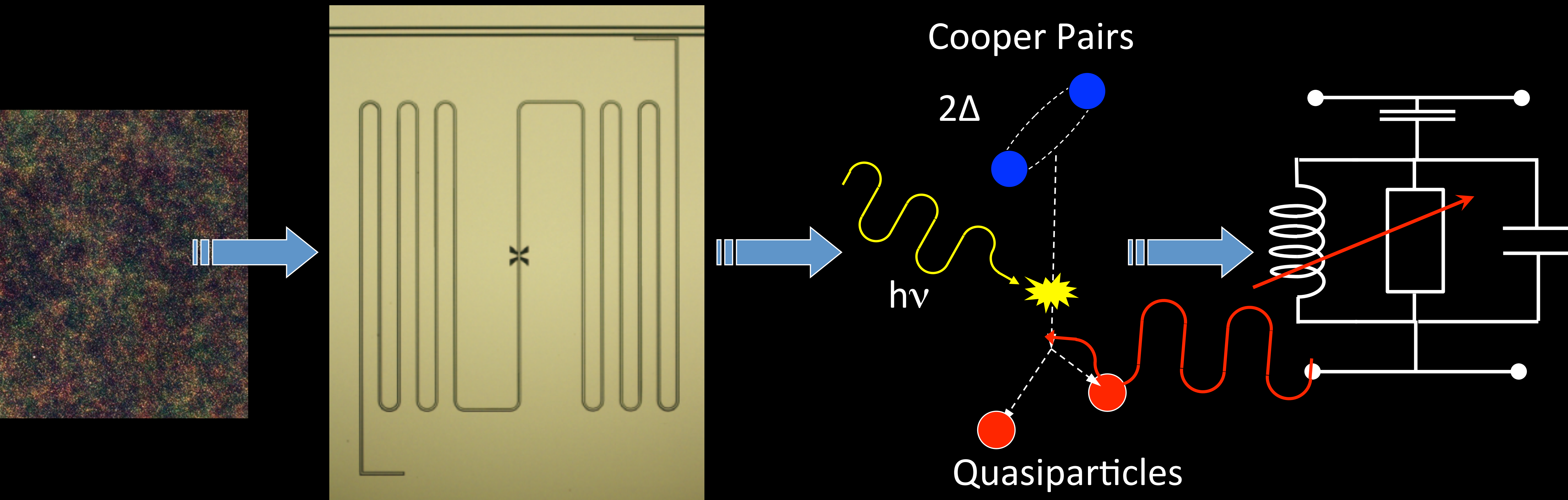
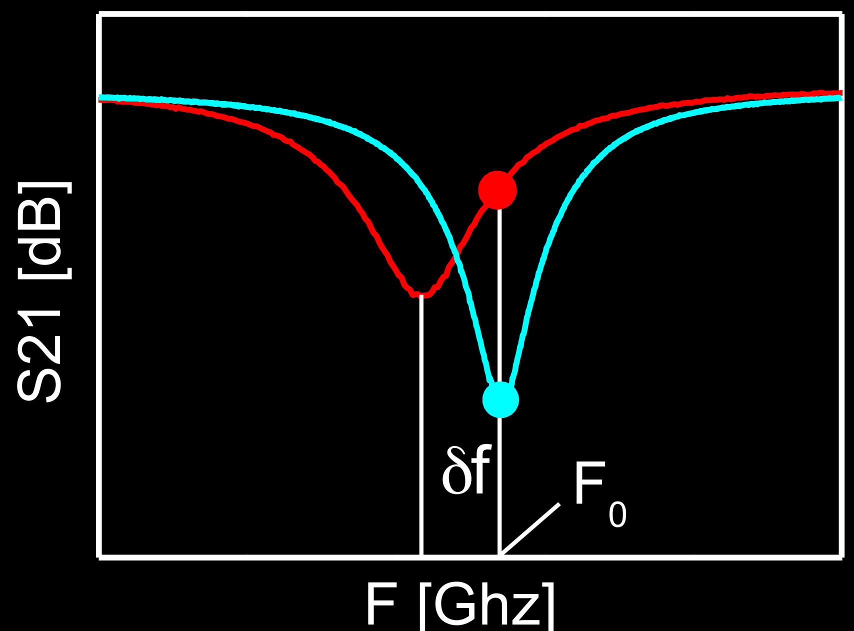
TUDelft

CosmoNanoscience

# From light to signal




Incoming photons break Cooper pairs

=> Higher resistance and inductance

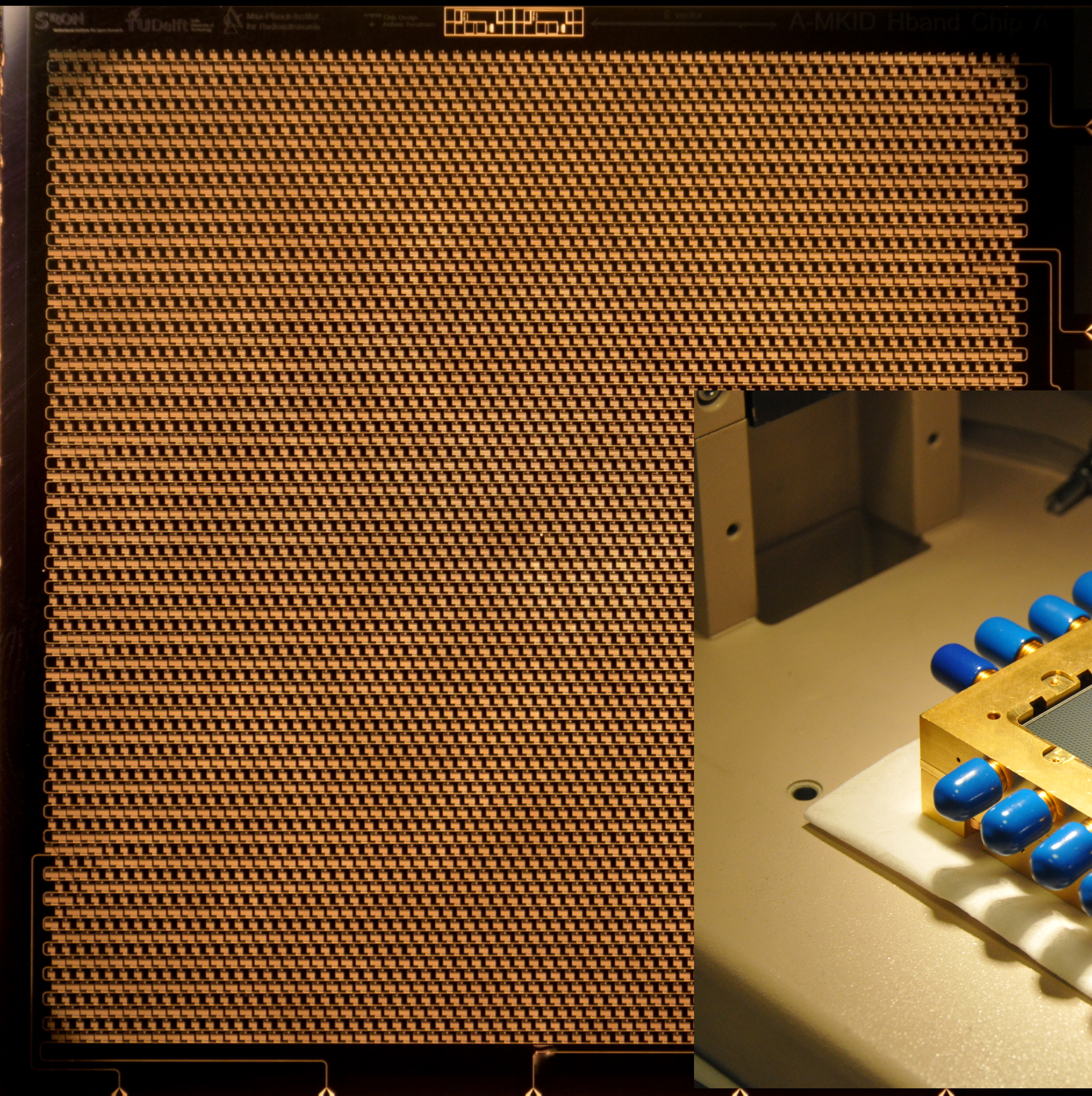
=> Resonance shifts and gets shallower

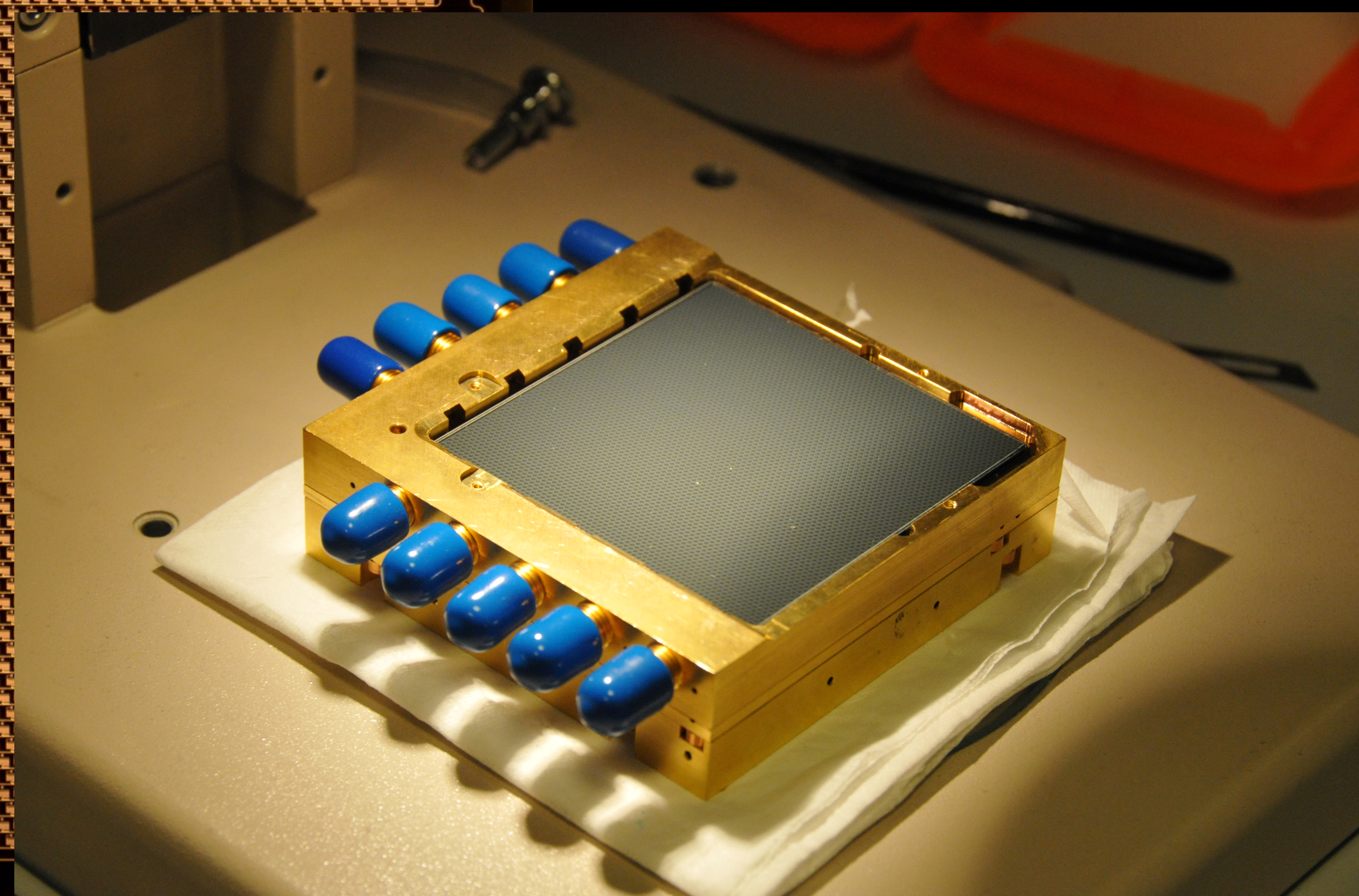
Microwave readout, energies far below the gap

Less background quasiparticles => more sensitive

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

# Thousands of  pixels, one pair of cables



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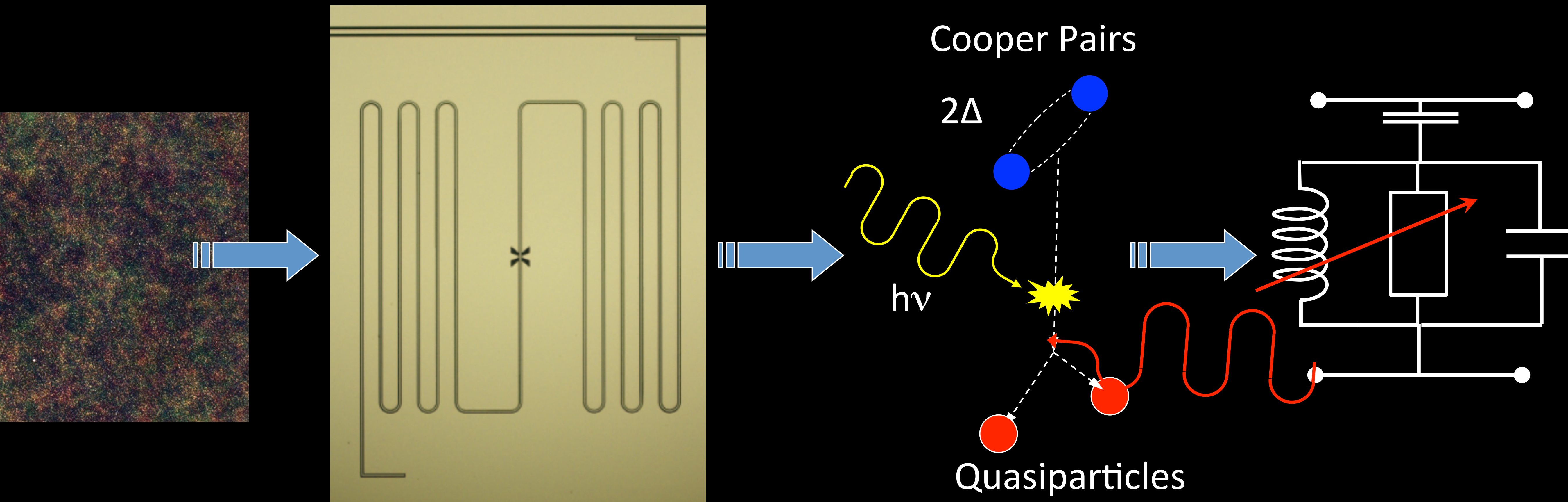
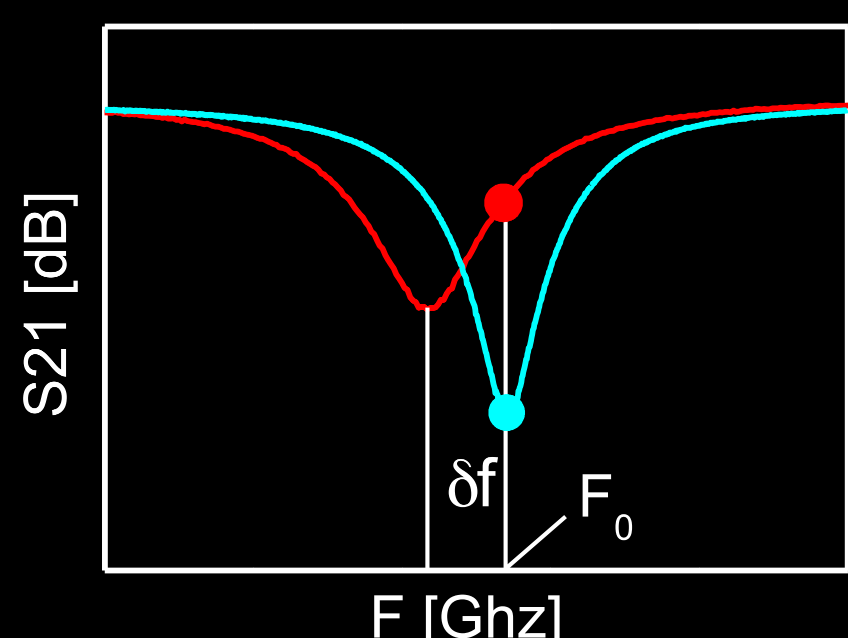


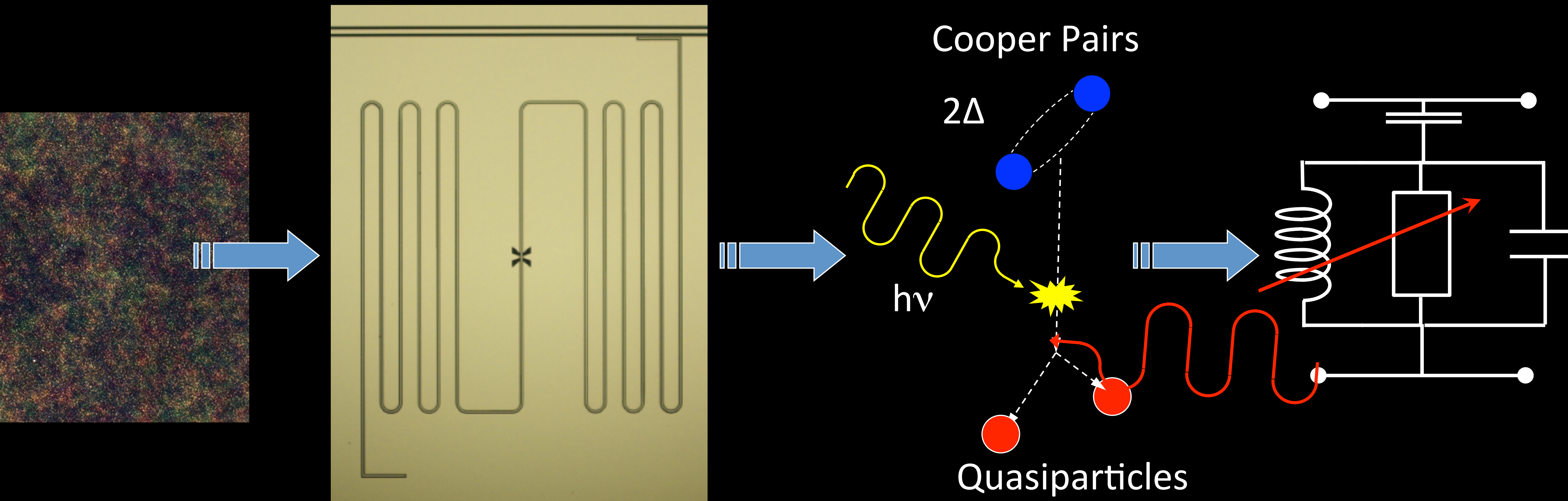

Simple picture: number of quasiparticles

$$\frac{dA}{dN_{qp}} = -\frac{\alpha_k \beta Q}{|\sigma| V} \frac{d\sigma_1}{dn_{qp}},$$
$$\frac{d\theta}{dN_{qp}} = -\frac{\alpha_k \beta Q}{|\sigma| V} \frac{d\sigma_2}{dn_{qp}}$$

$$\eta_{opt}\eta_{pb}P_{rad} = \frac{N_{qp}\Delta}{\tau_{qp}}$$

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

# From light to signal




Distribution function and density of states can change both, intrinsically non-equilibrium

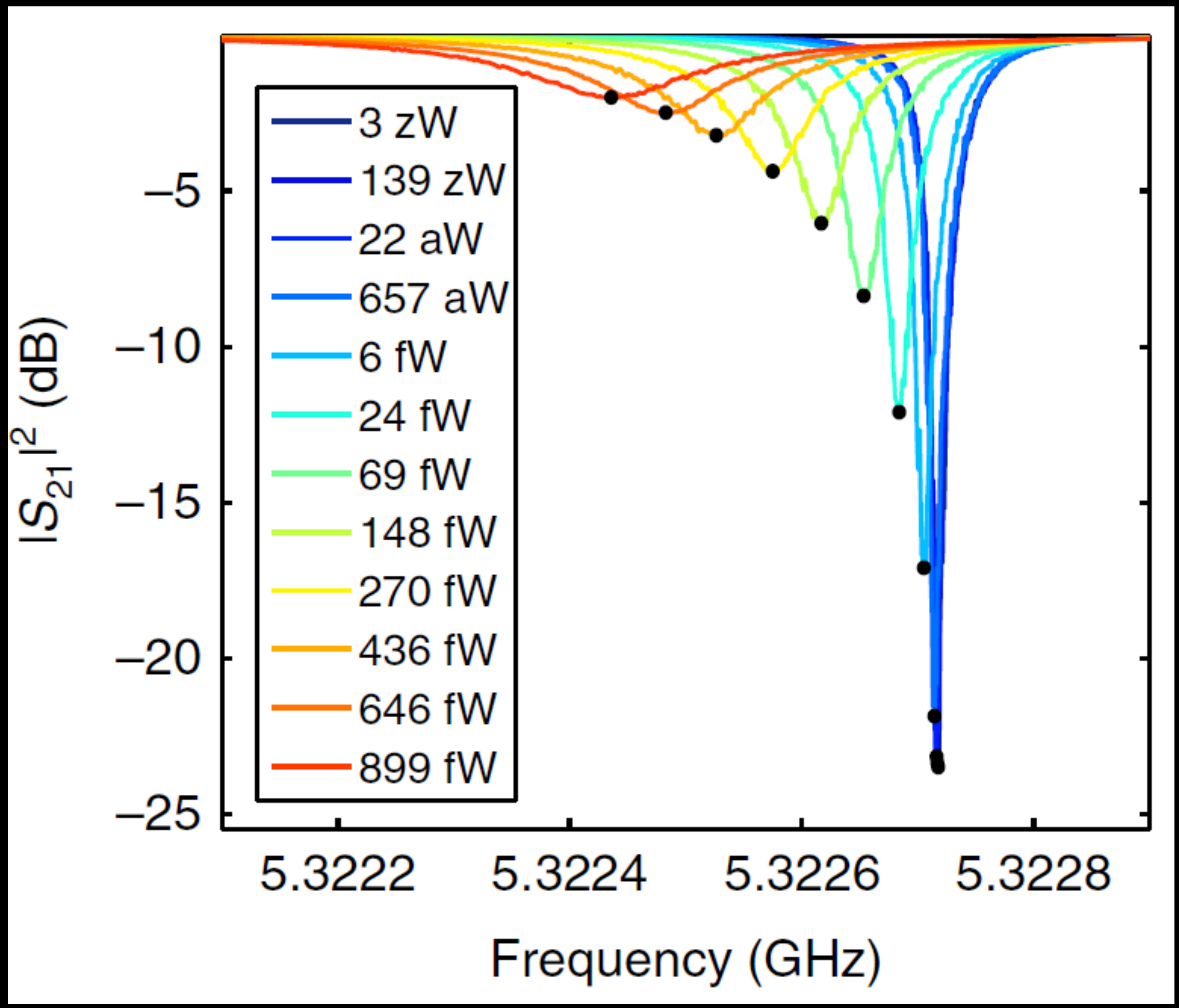
$$
\begin{aligned}
\frac{\sigma_1}{\sigma_N} &= \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}[f(E)-f(E+\hbar\omega)]g_1(E)dE \\
&+ \frac{1}{\hbar\omega}\int_{min(\Delta-\hbar\omega,-\Delta)}^{-\Delta}[1-2f(E+\hbar\omega)]g_1(E)dE \\
\frac{\sigma_2}{\sigma_N} &= \frac{1}{\hbar\omega}\int_{max(\Delta-\hbar\omega,-\Delta)}^{\Delta}[1-2f(E+\hbar\omega)]g_2(E)dE
\end{aligned}
$$

Microwave: $Q_i$, A

Pair breaking

Microwave: $f_{res}$, θ

# Signal vs pair-breaking power

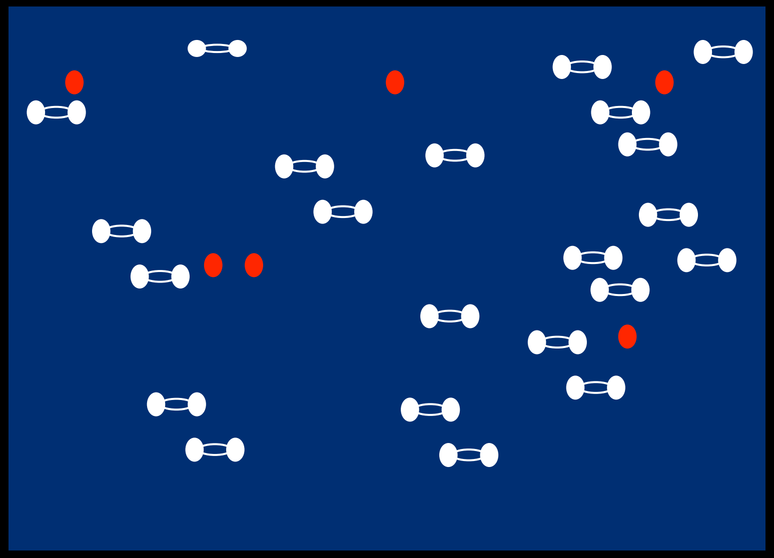


# Observables connected to superconductor

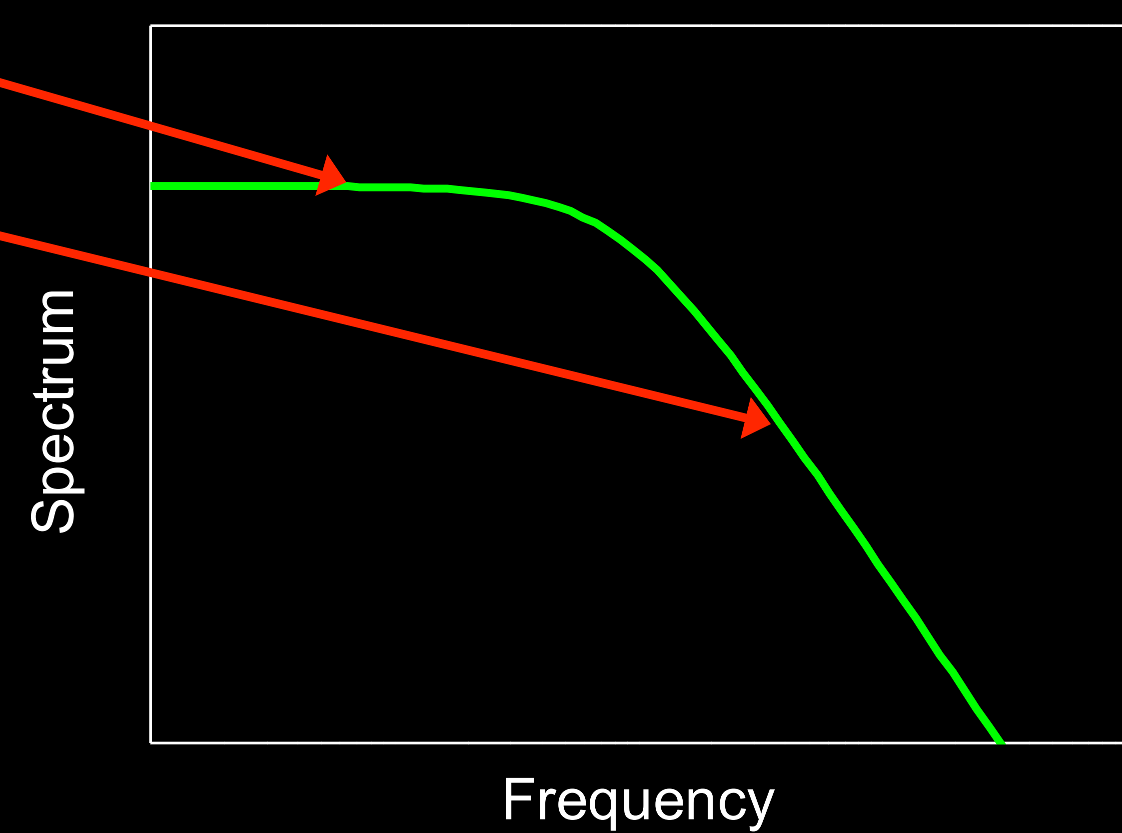
- Number of quasiparticles
- Quasiparticle recombination time
- Complex conductivity
  - Quality factor = losses, quasiparticles
  - Frequency/phase shift = kinetic inductance, condensate
  - Device responsivity
- Detector sensitivity (response/noise)

# Generation-recombination noise

Higher temperature:
- More quasipartices
- Shorter recombination lifetime



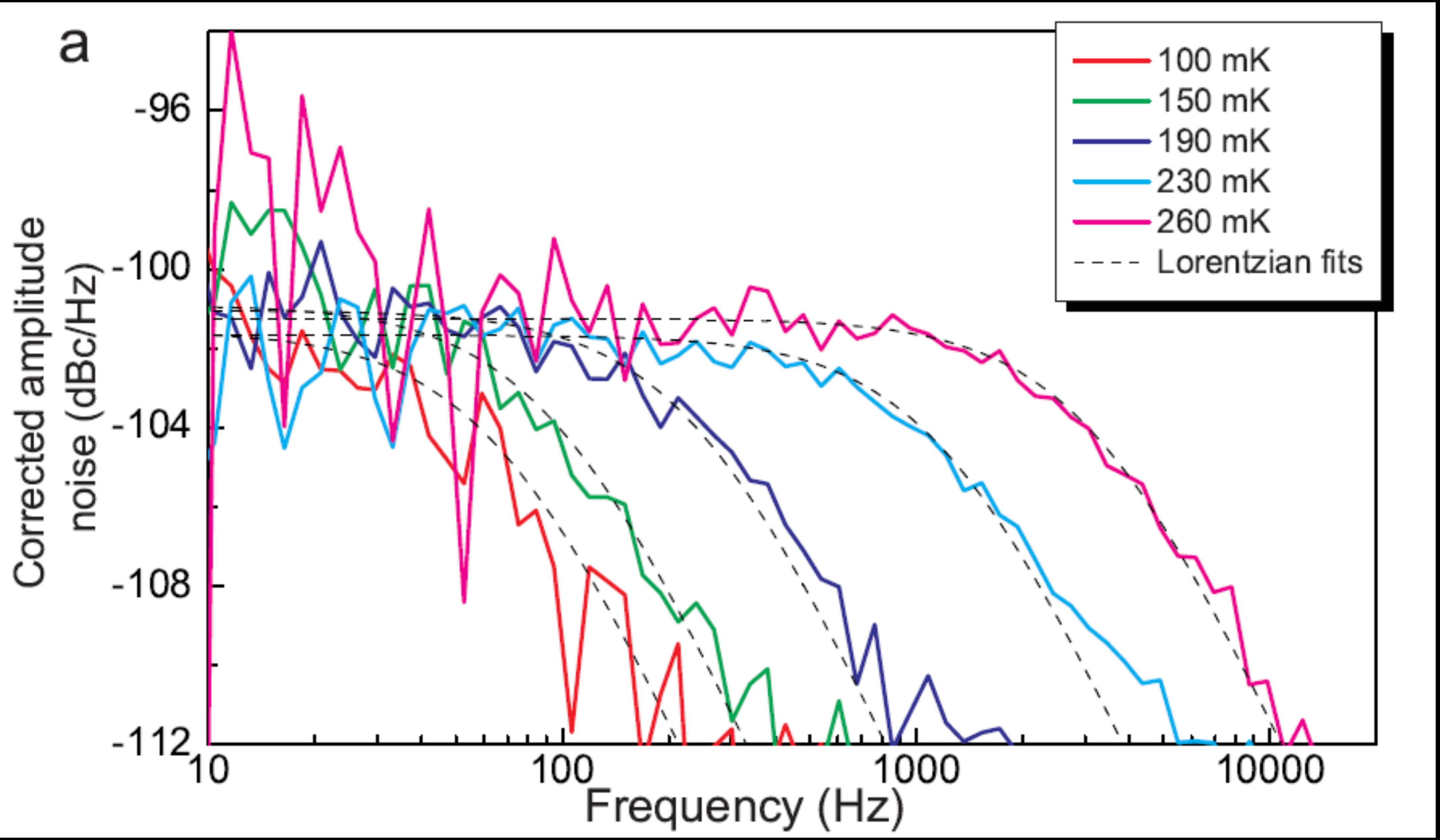
$$S_N = \frac{4 < N^2 > \tau}{1+\omega^2\tau^2} = \frac{4N\tau}{1+\omega^2\tau^2}$$




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

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

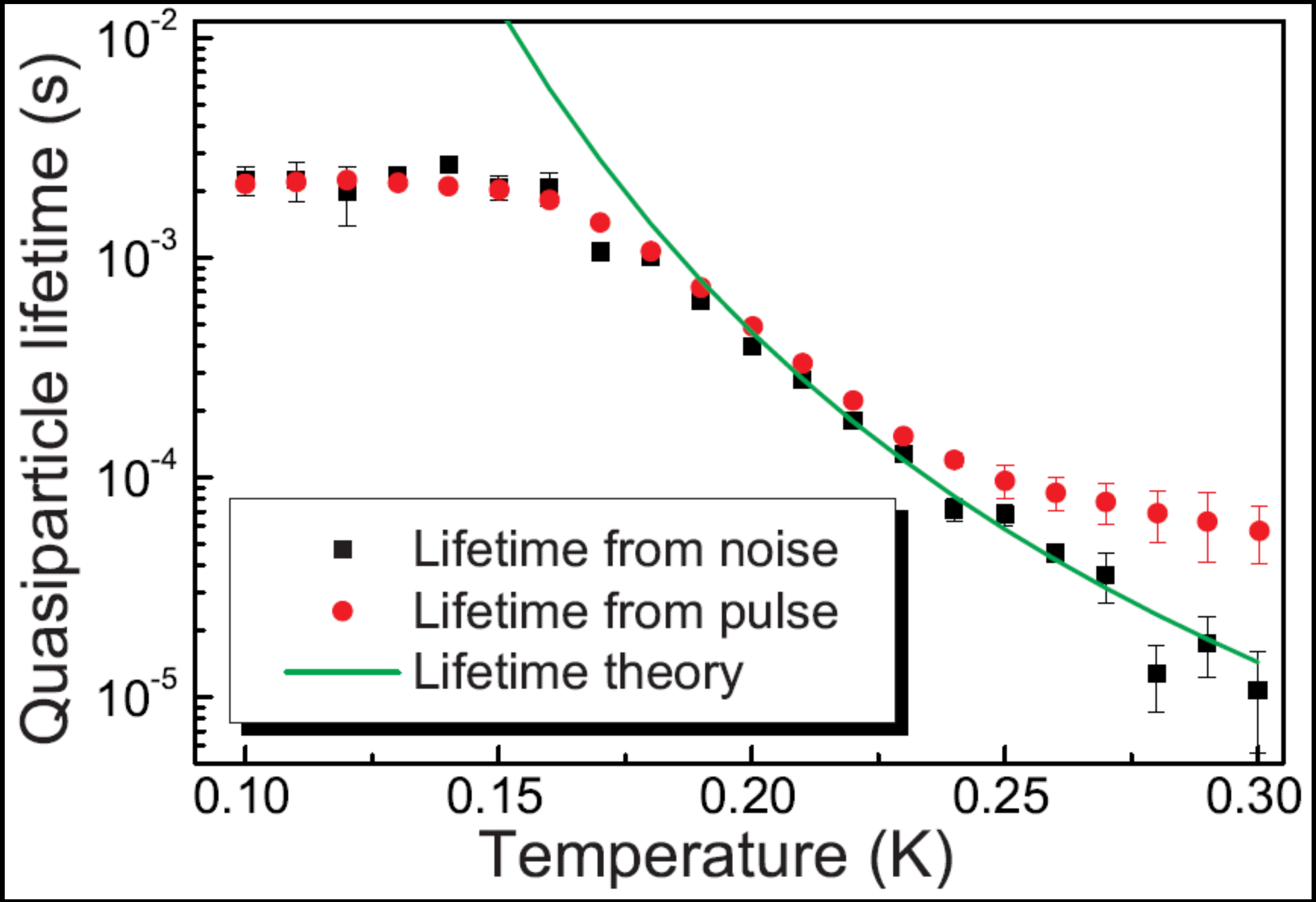
# Measurement of quasiparticle fluctuations, all Al resonator




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

Phys. Rev. Lett. 106, 167004 (2011)

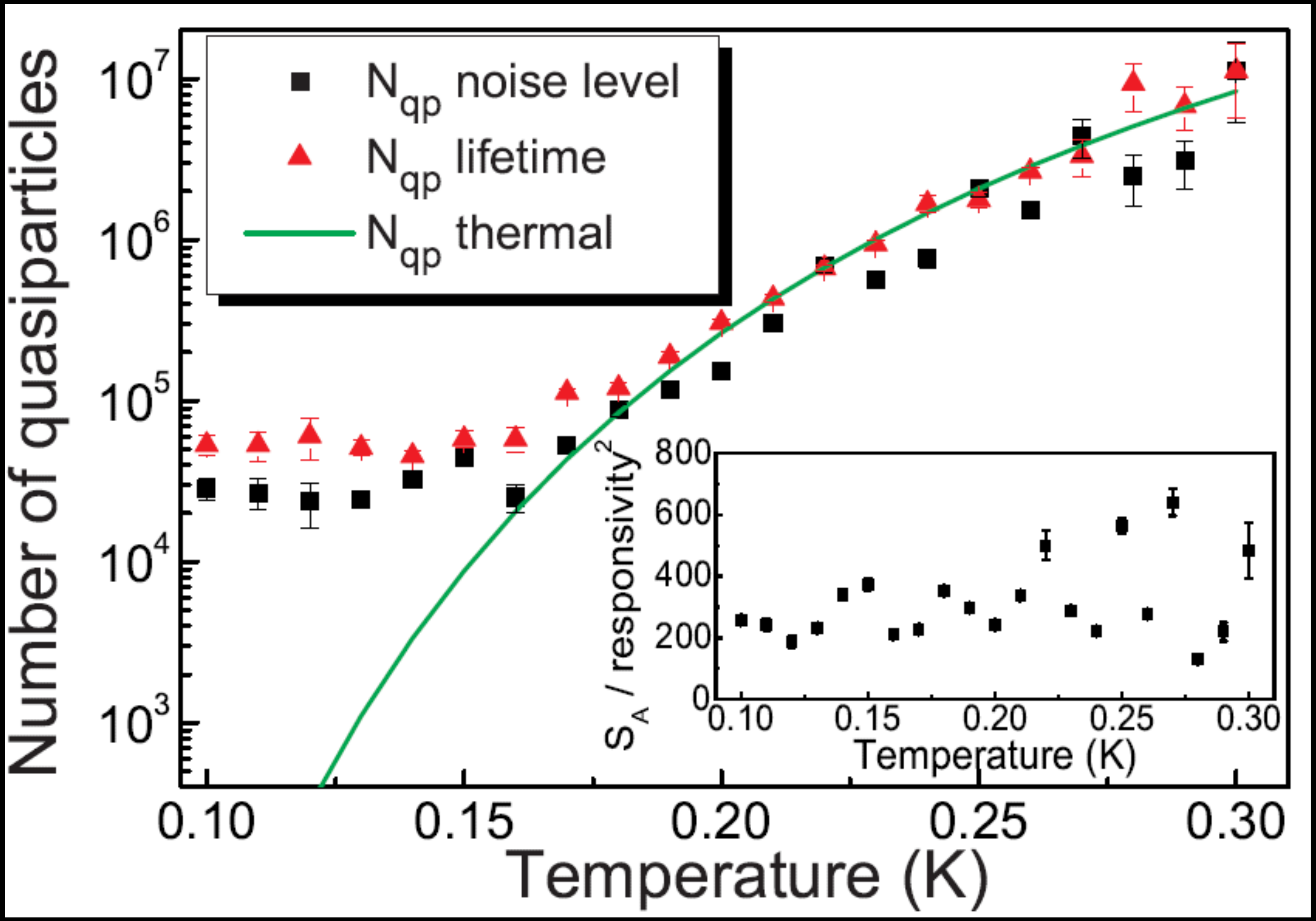
# Measurement of quasiparticle fluctuations




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

Consistent recombination lifetime from noise and pulse measurement

# Measurement of quasiparticle fluctuations



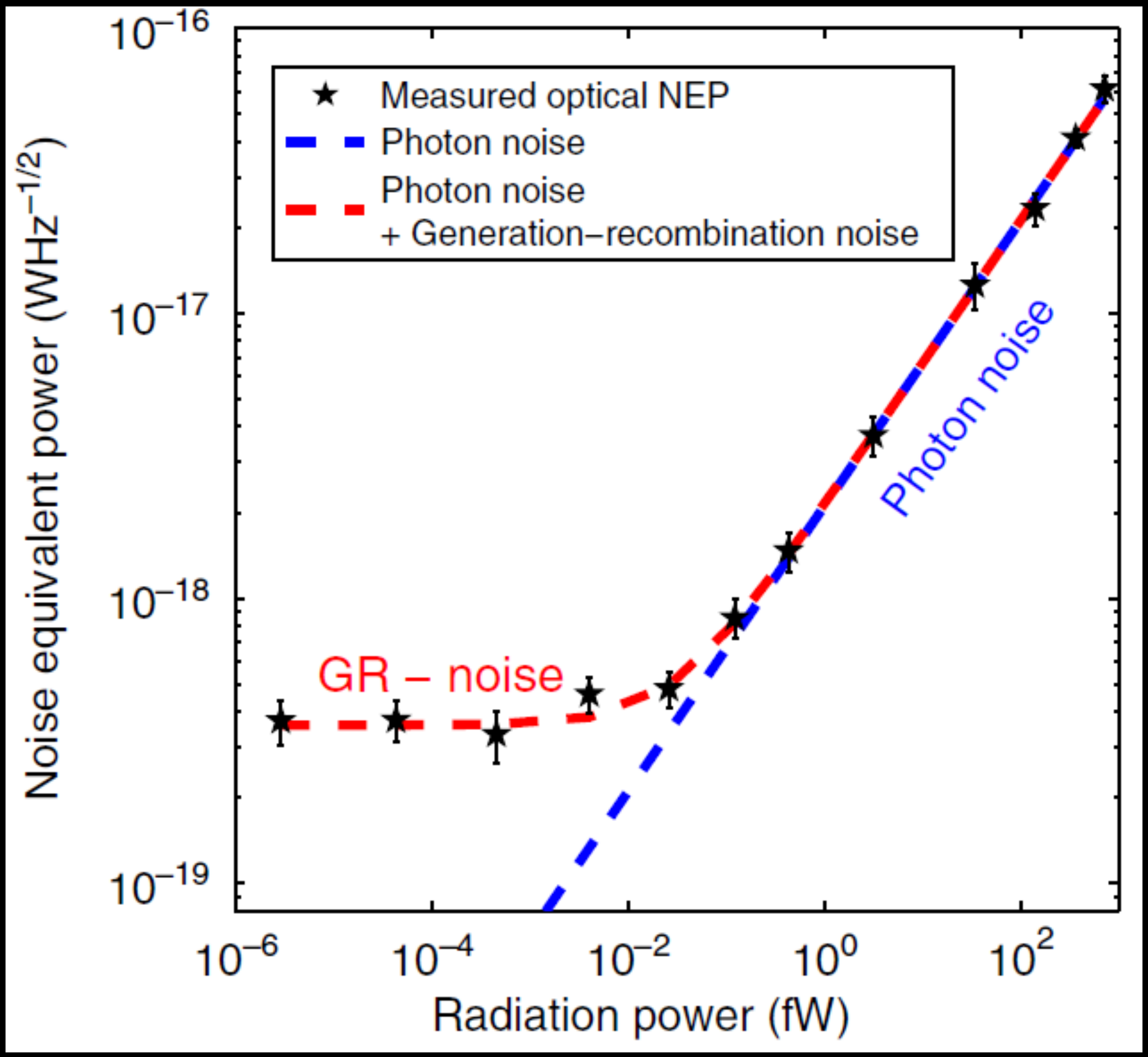

$$S_N = \frac{4N\tau}{1+\omega^2\tau^2}$$

Measurement of the number of quasiparticles
Saturation of quasiparticle number at low temperature

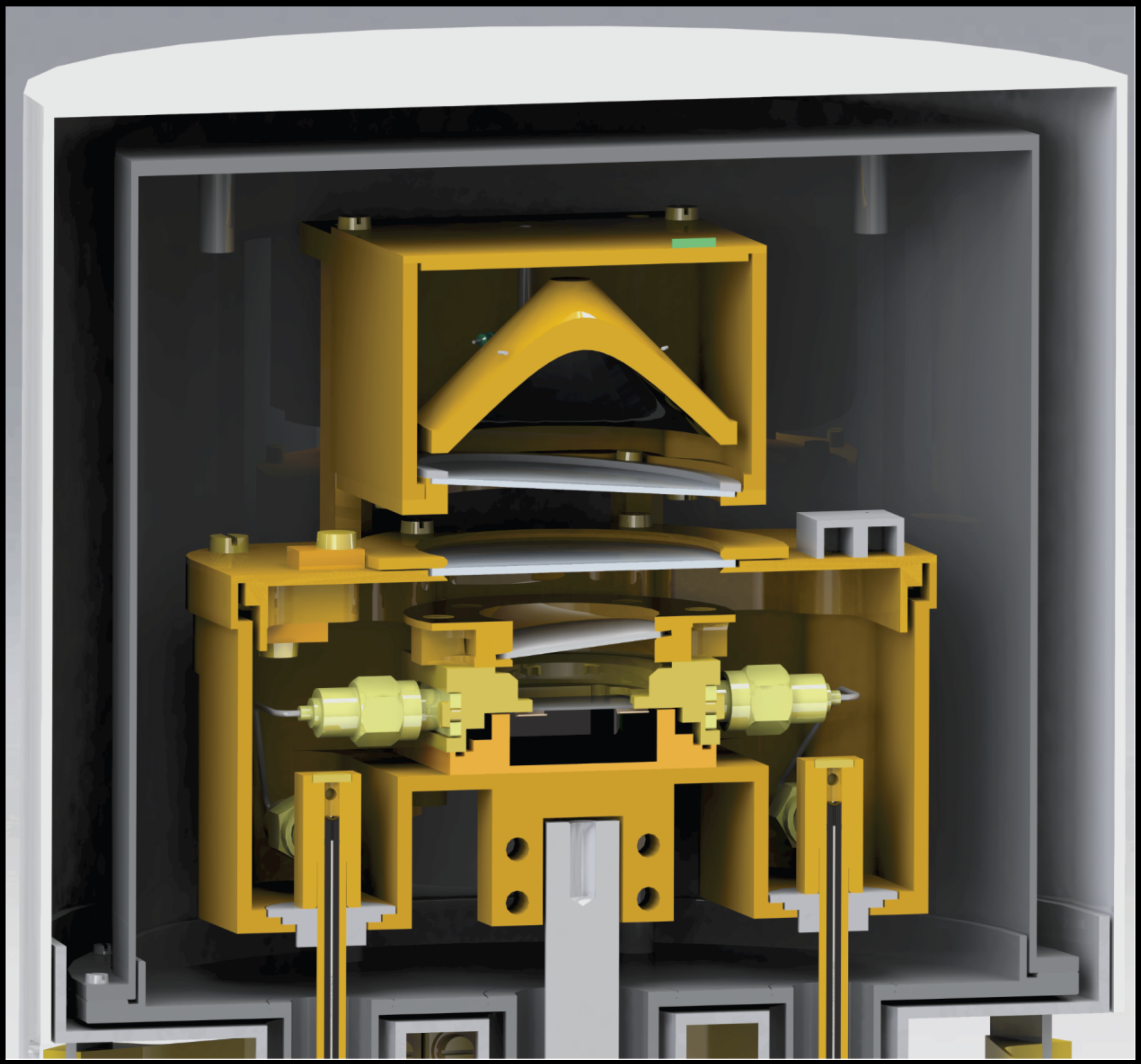
Phys. Rev. Lett. 106, 167004 (2011)

# Pair breaking photons, 1.5 THz

# 1.5 THz KID limited by fundamental (ie quasiparticle) noise processes

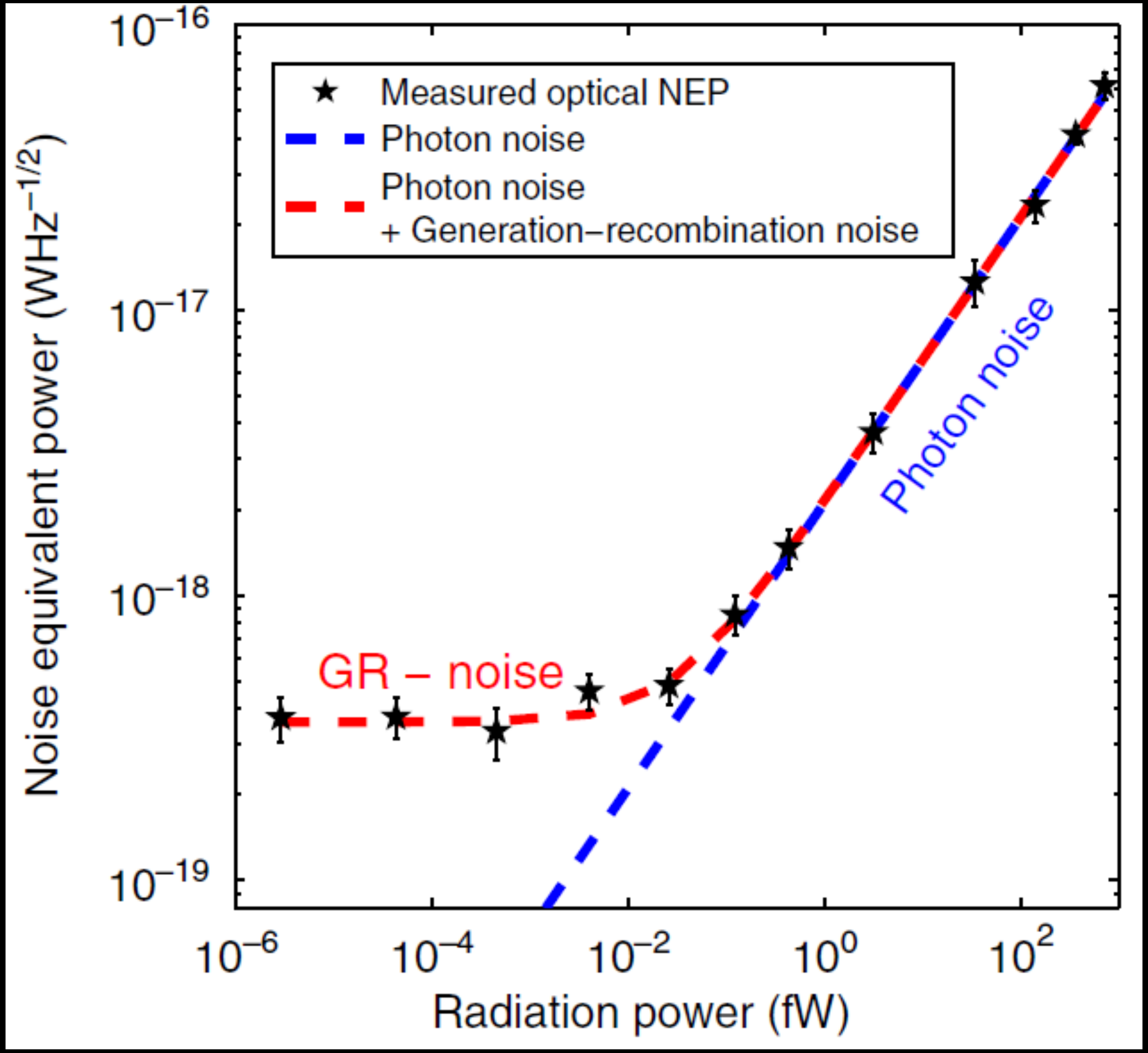


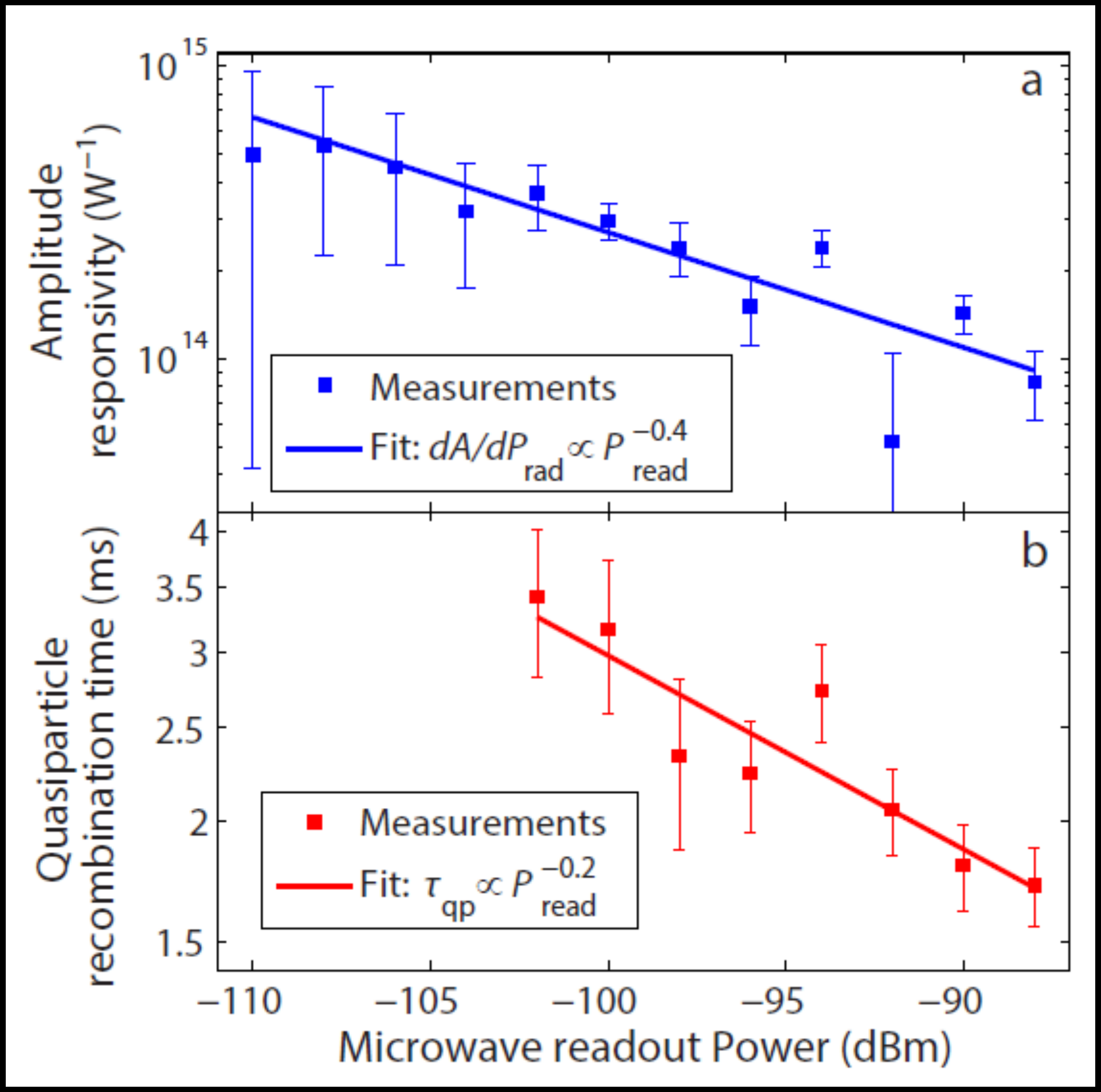

Nature Communications 5, 3130 (2014)



Not limited by stray-light

# Influence of microwave dissipation on pair-breaking response (1.5 THz)

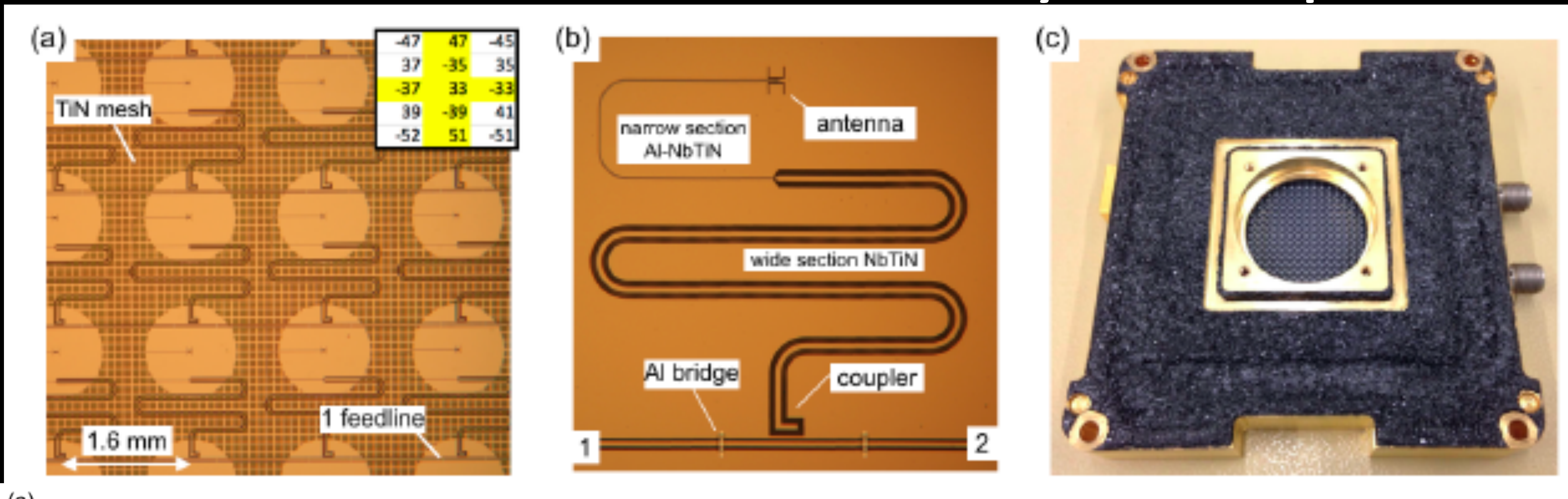


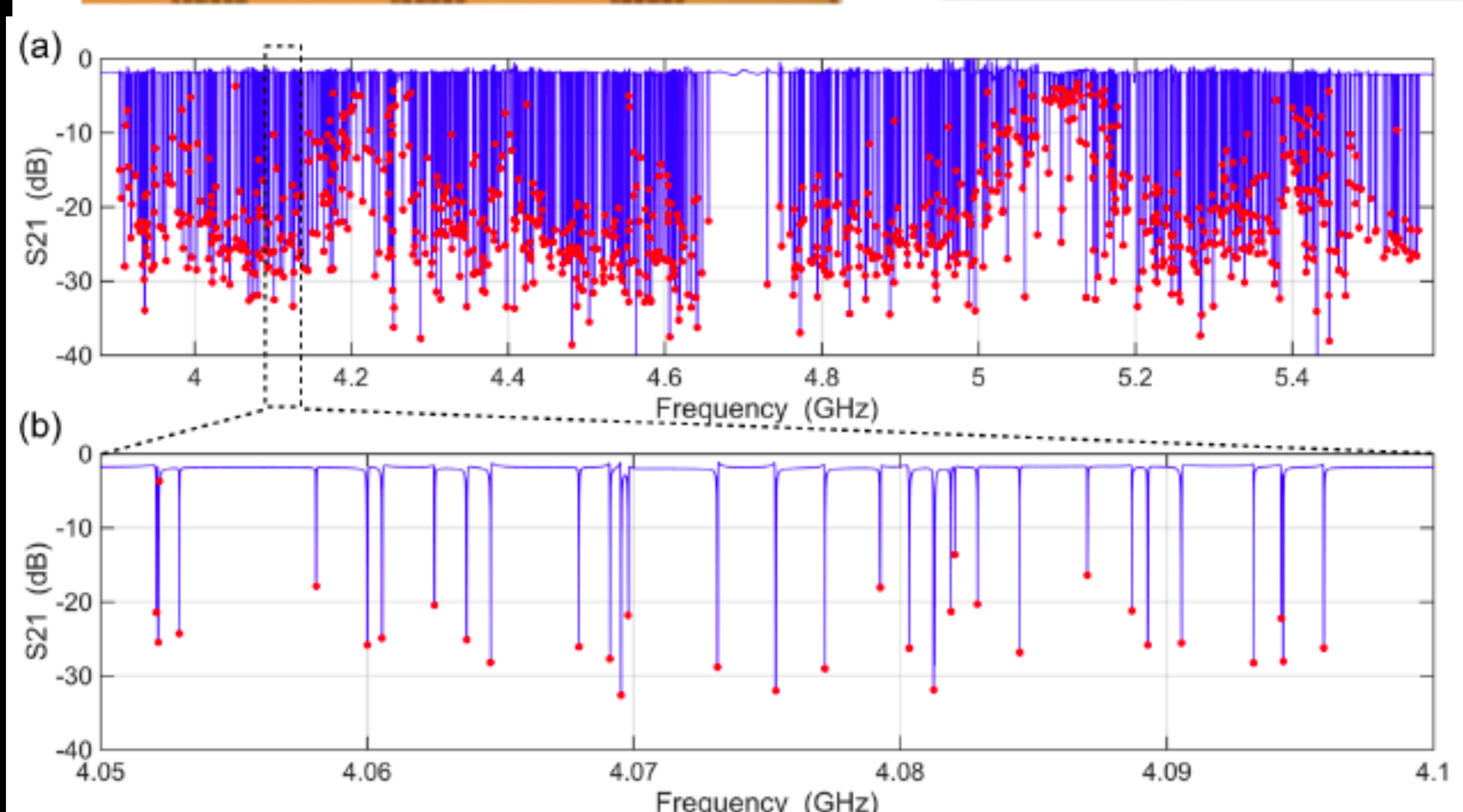



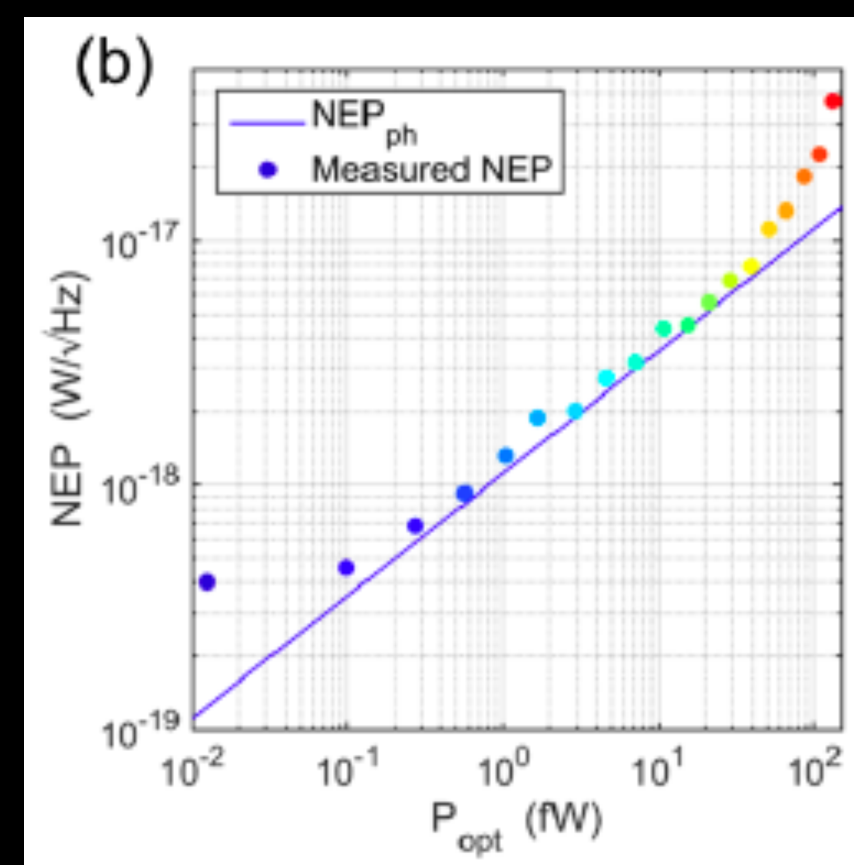

Detector sensitivity limited by excess QPs due to microwave readout

Nature Communications 5, 3130 (2014)

# Now also same sensitivity 1000 pixels



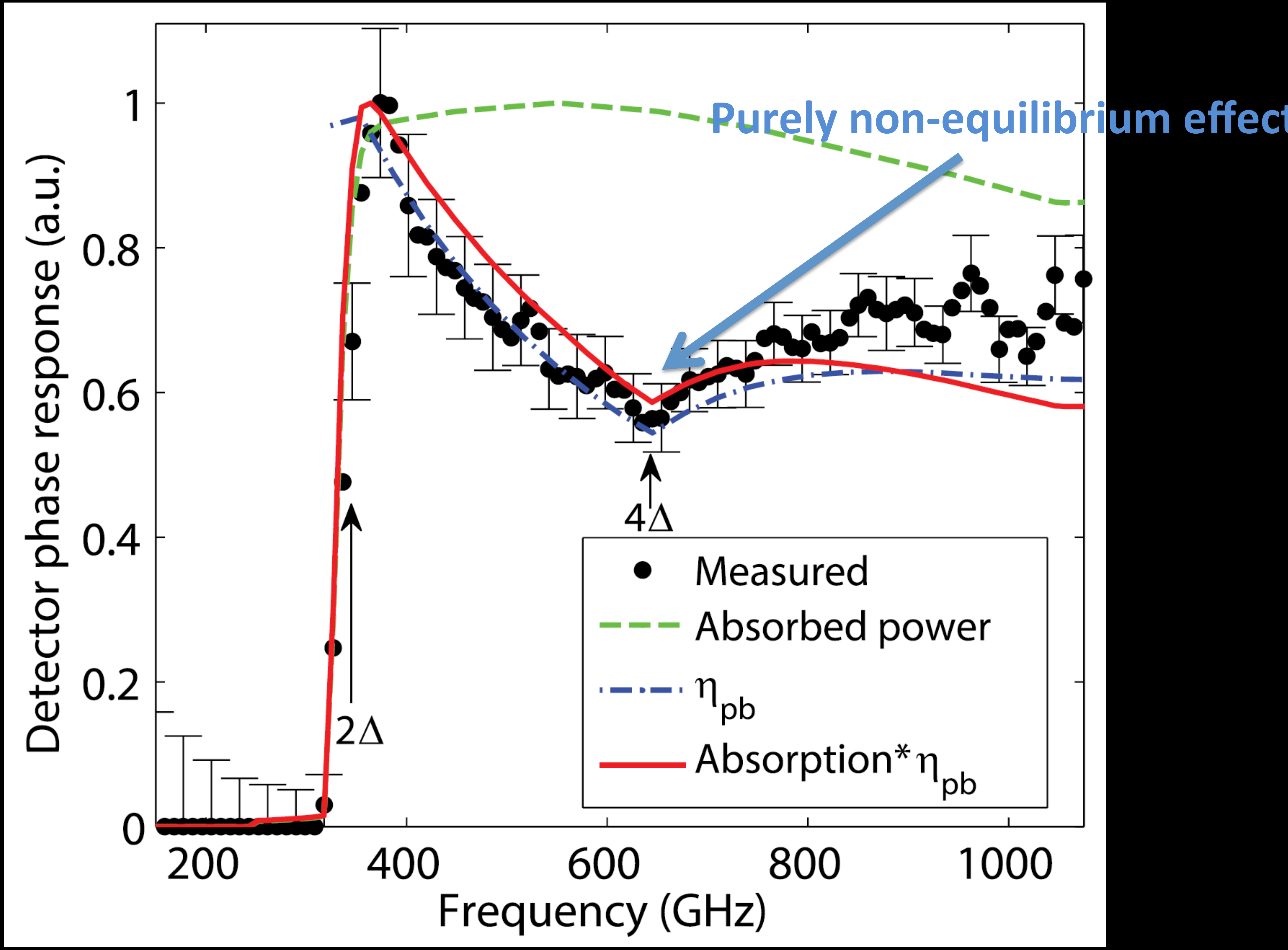




Baselmans et al. A&A (2017)

# Pair-breaking photons vs energy

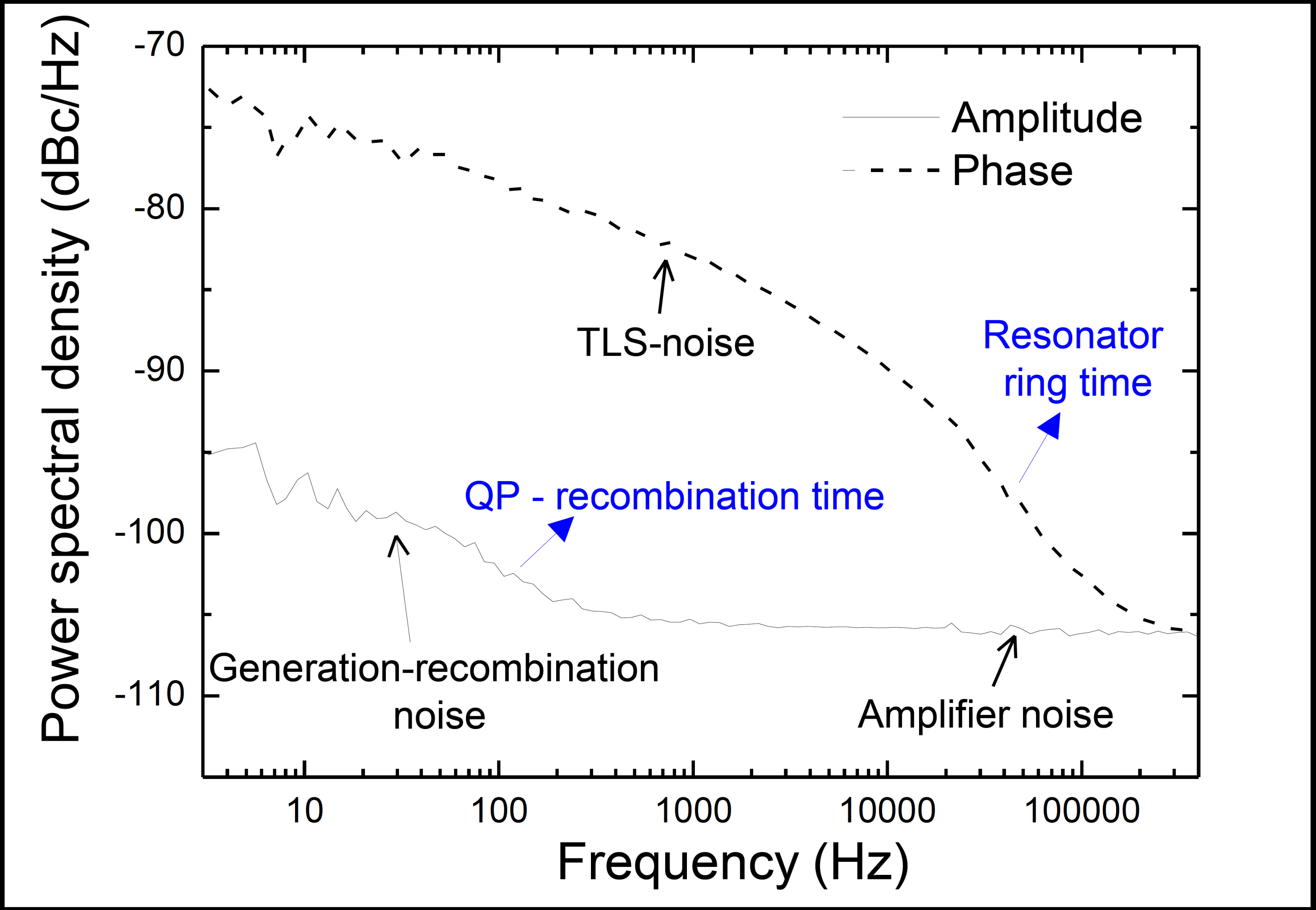
# Wide bandwidth FTS measurement



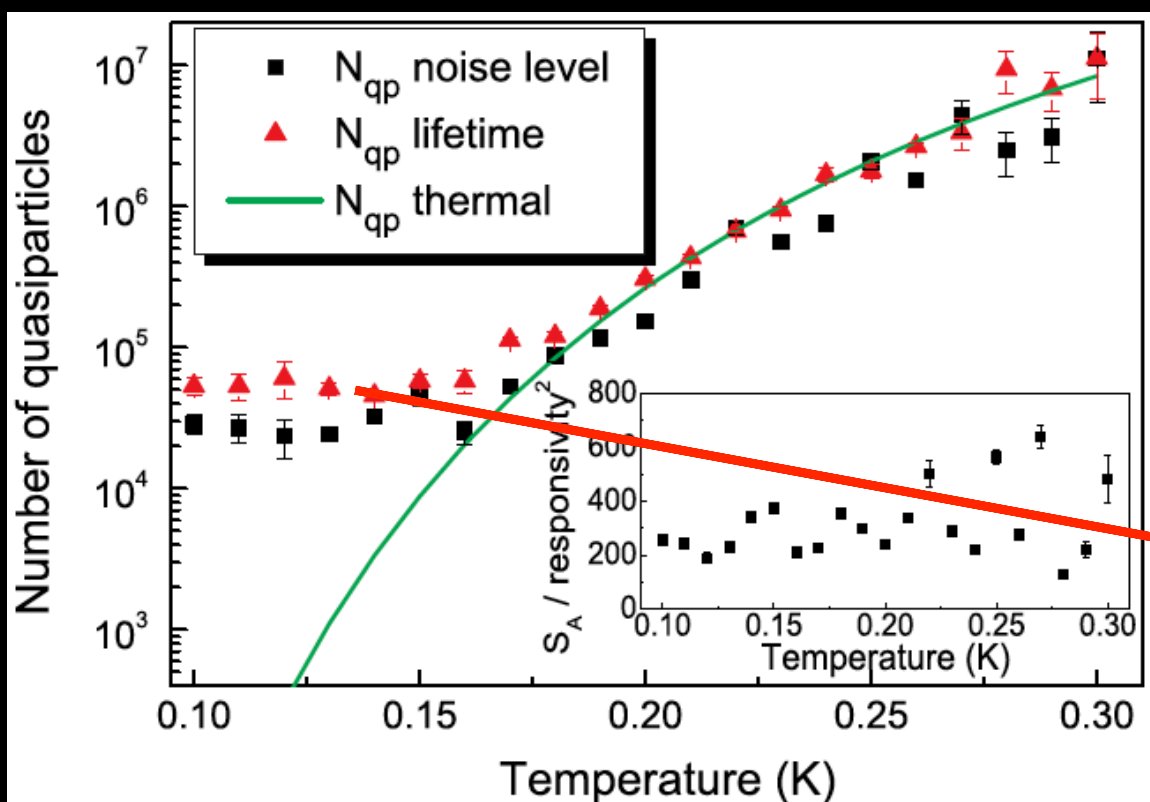

Appl. Phys. Lett. 106, 252602 (2015)

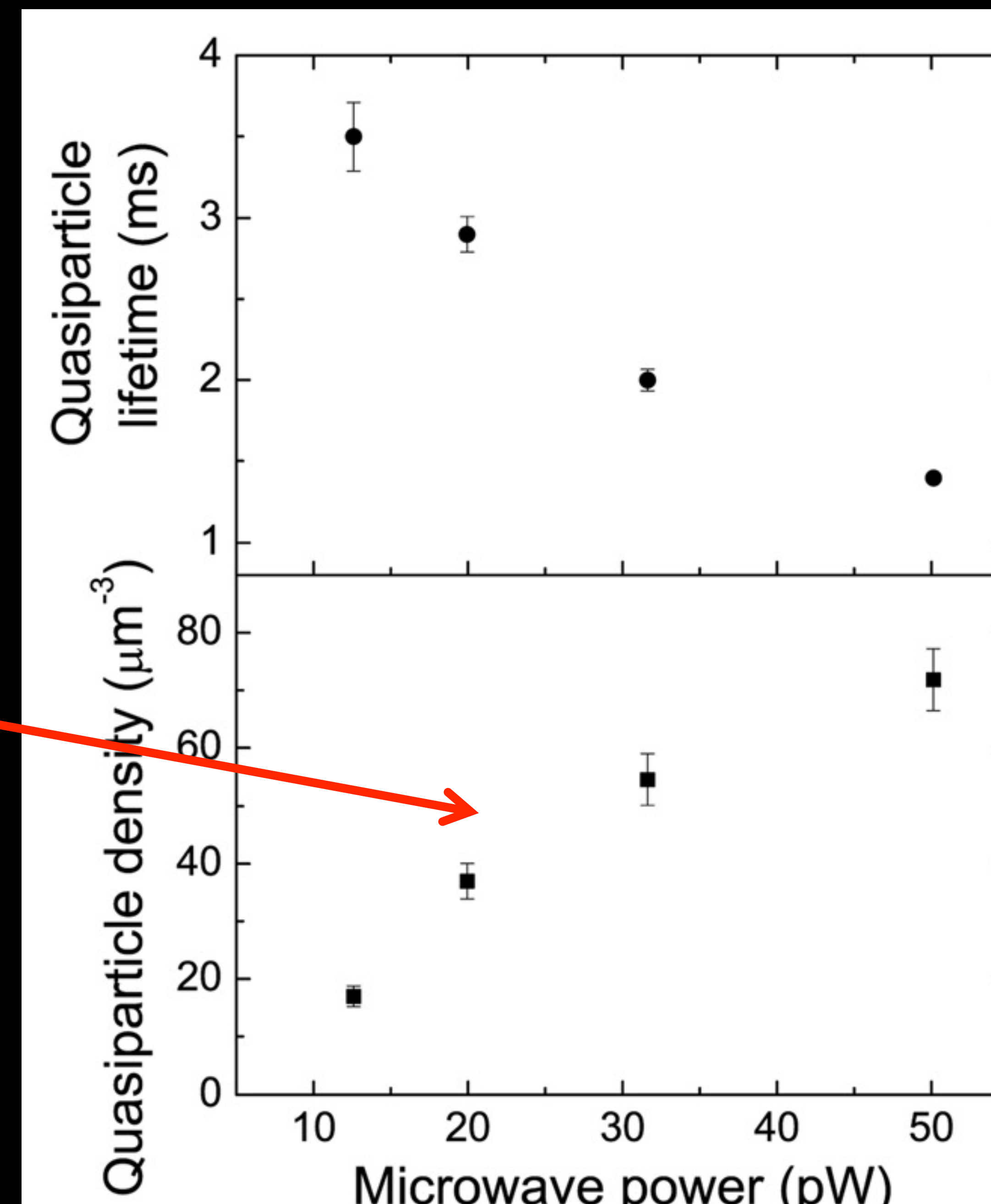
# Microwave field/photons

- We need a high microwave field to suppress noise
  - Amplifier/system noise
  - Two level system noise



# Excess quasiparticles



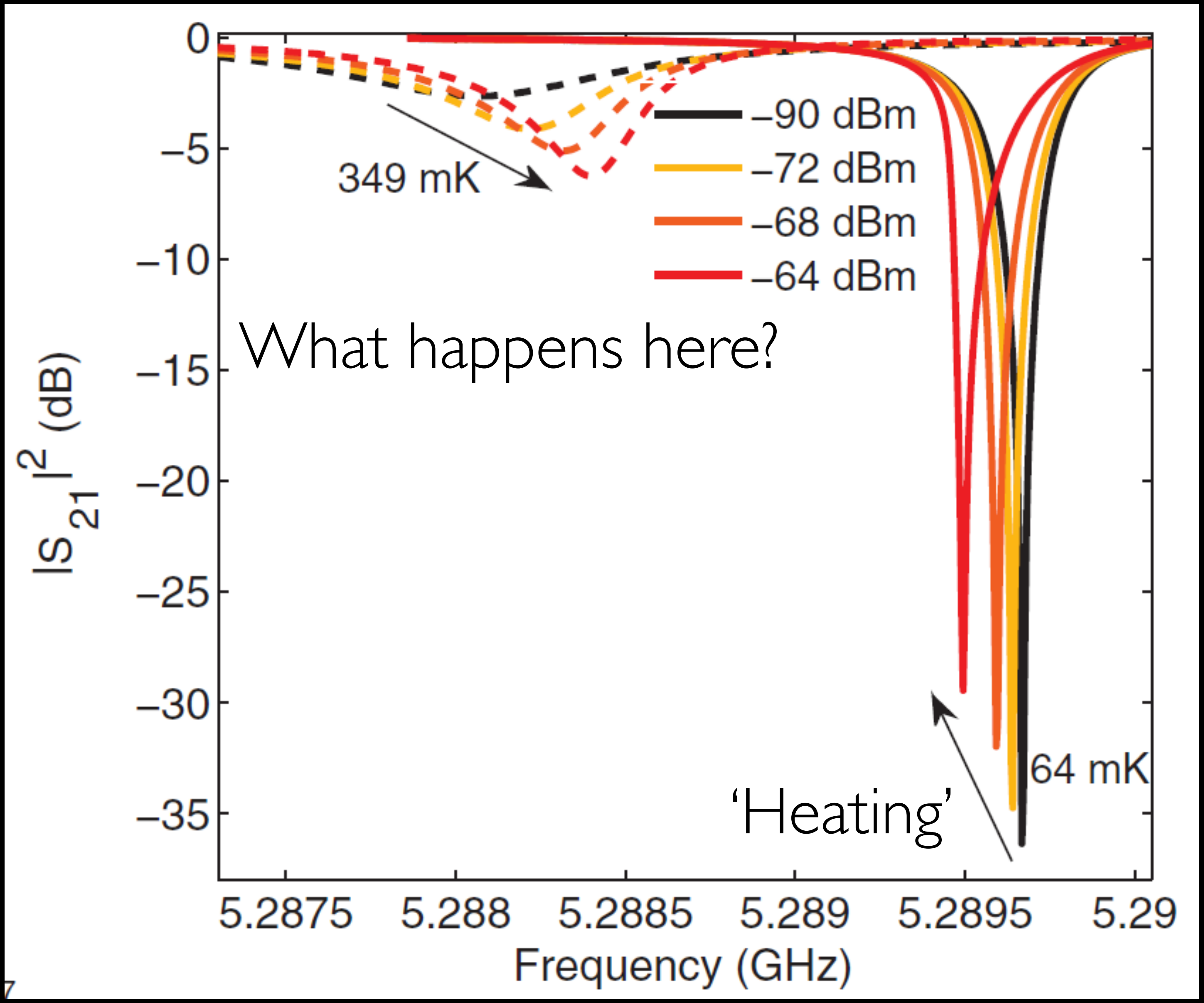




Microwave power dependent

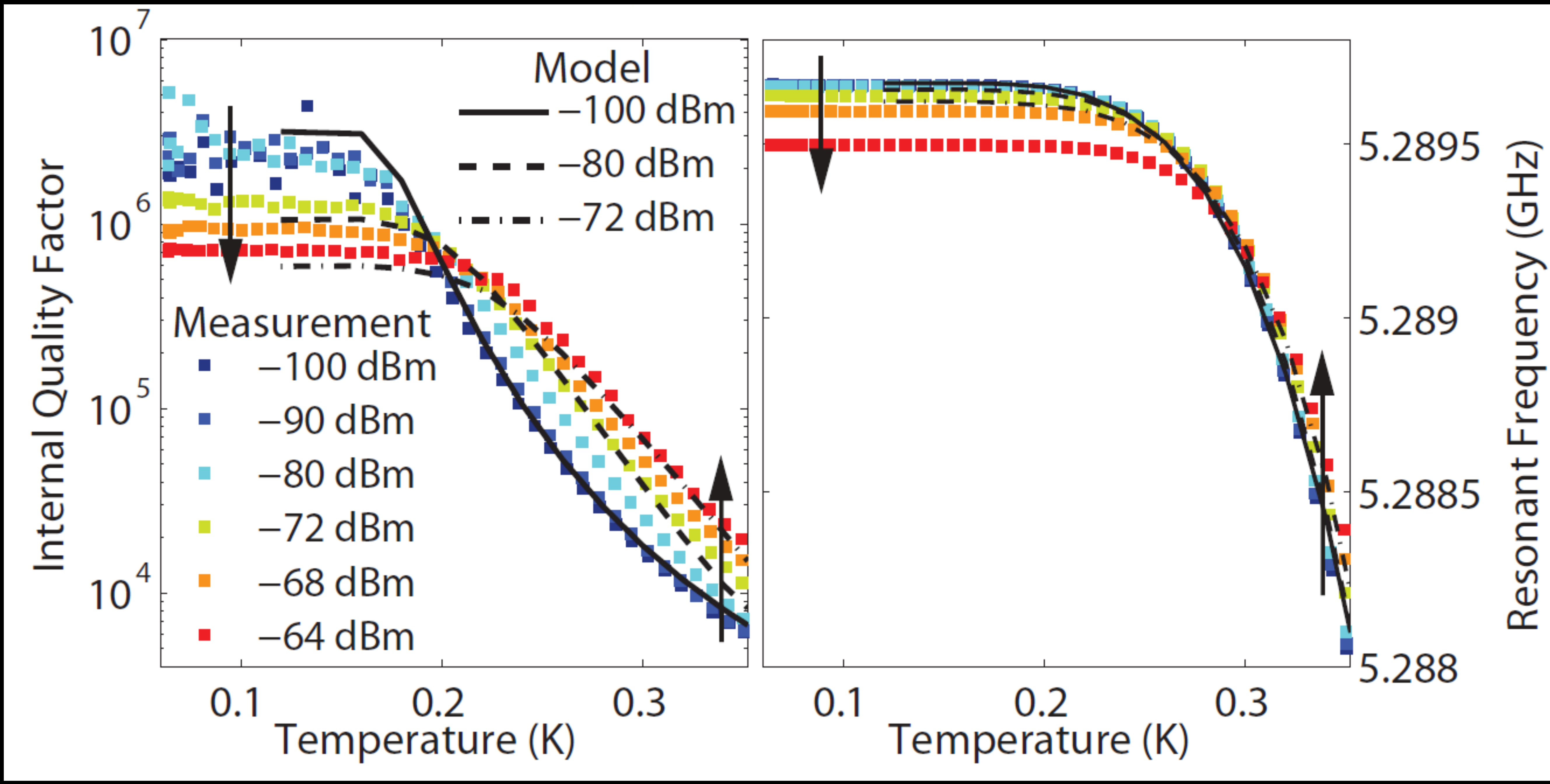
Phys. Rev. Lett. 106, 167004 (2011)

Appl. Phys. Lett. 100, 162601 (2012)

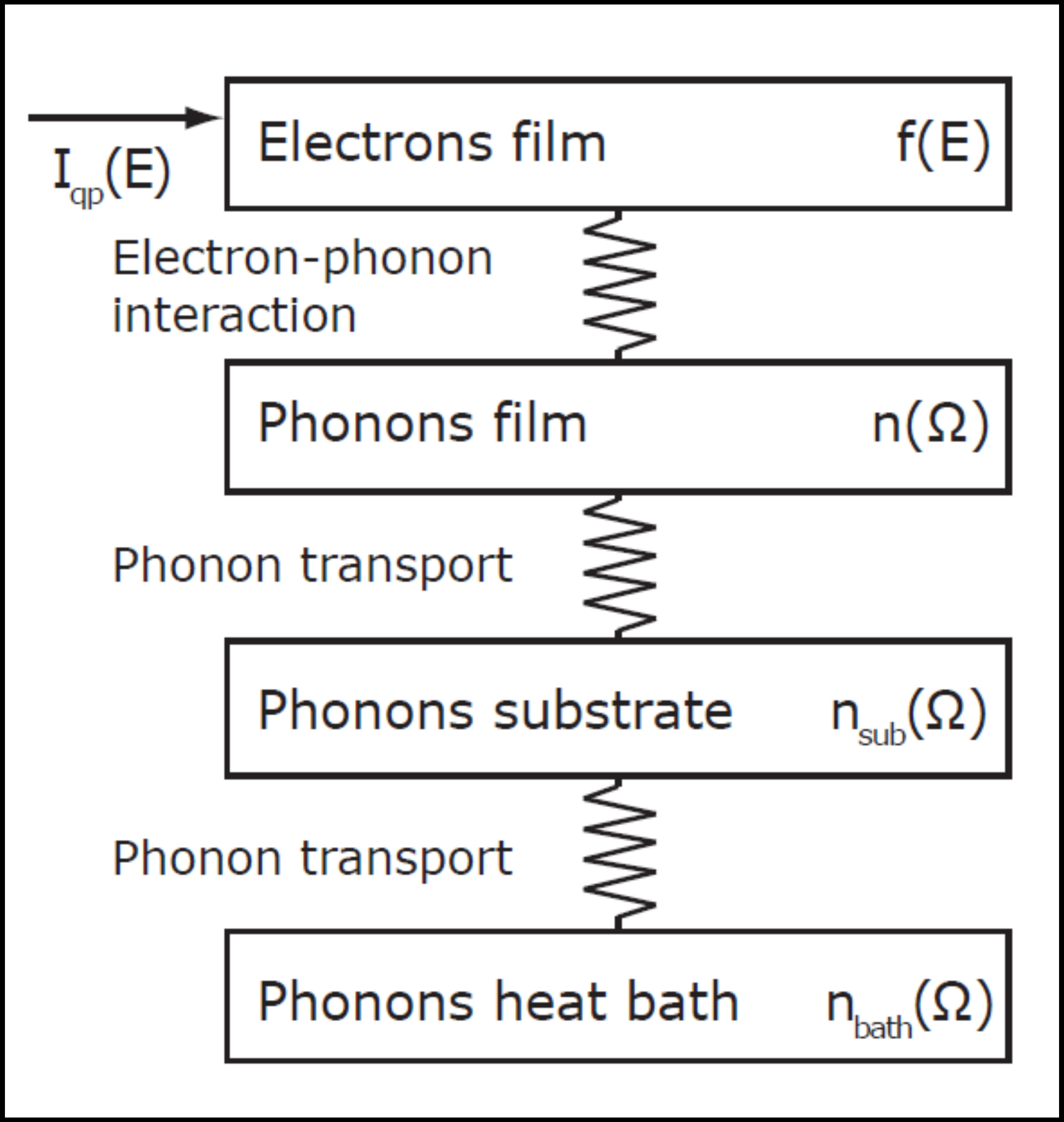
# Non-linear resonator response curves



# Low T quasiparticle creation, but at higher T $Q_i$ enhancement



# Non-equilibrium f(E)




Ivlev, Lisitsyn, Eliashberg, JLPT 10, 449 (1973) - Microwave absorption, gap enhancement close to Tc

Chang and Scalapino, PRB 15, 2651 (1977) - kinetic equations

Goldie and Withington, SuST 26, 015004 (2013) – low temperature, resonators

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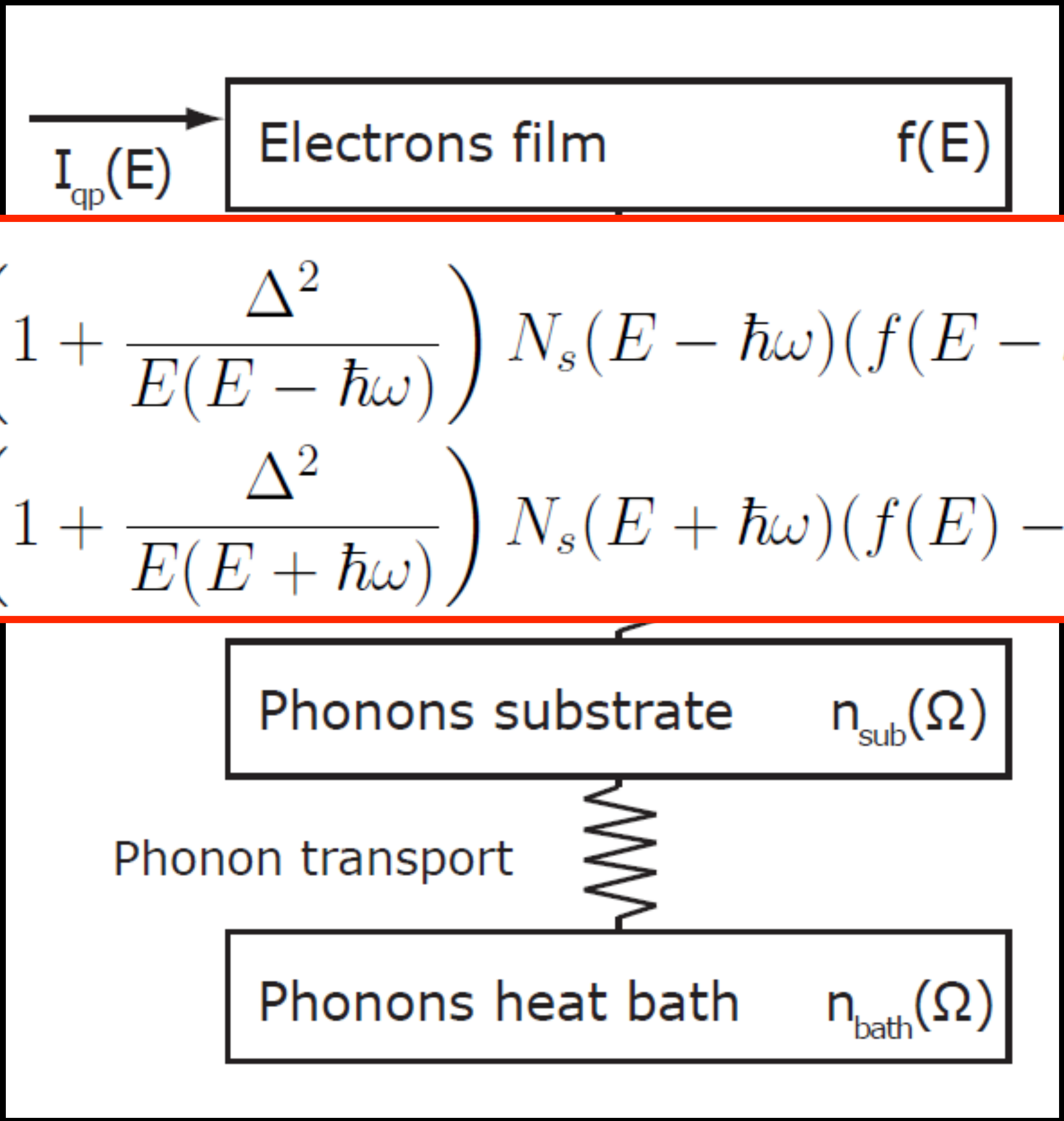


$$I_{qp}(E) = \frac{2\alpha_\omega}{\hbar}\Bigg[\left(1 + \frac{\Delta^2}{E(E-\hbar\omega)}\right) N_s(E-\hbar\omega)\big(f(E-\hbar\omega) - f(E)\big) - \left(1 + \frac{\Delta^2}{E(E+\hbar\omega)}\right) N_s(E+\hbar\omega)\big(f(E) - f(E+\hbar\omega)\big)$$

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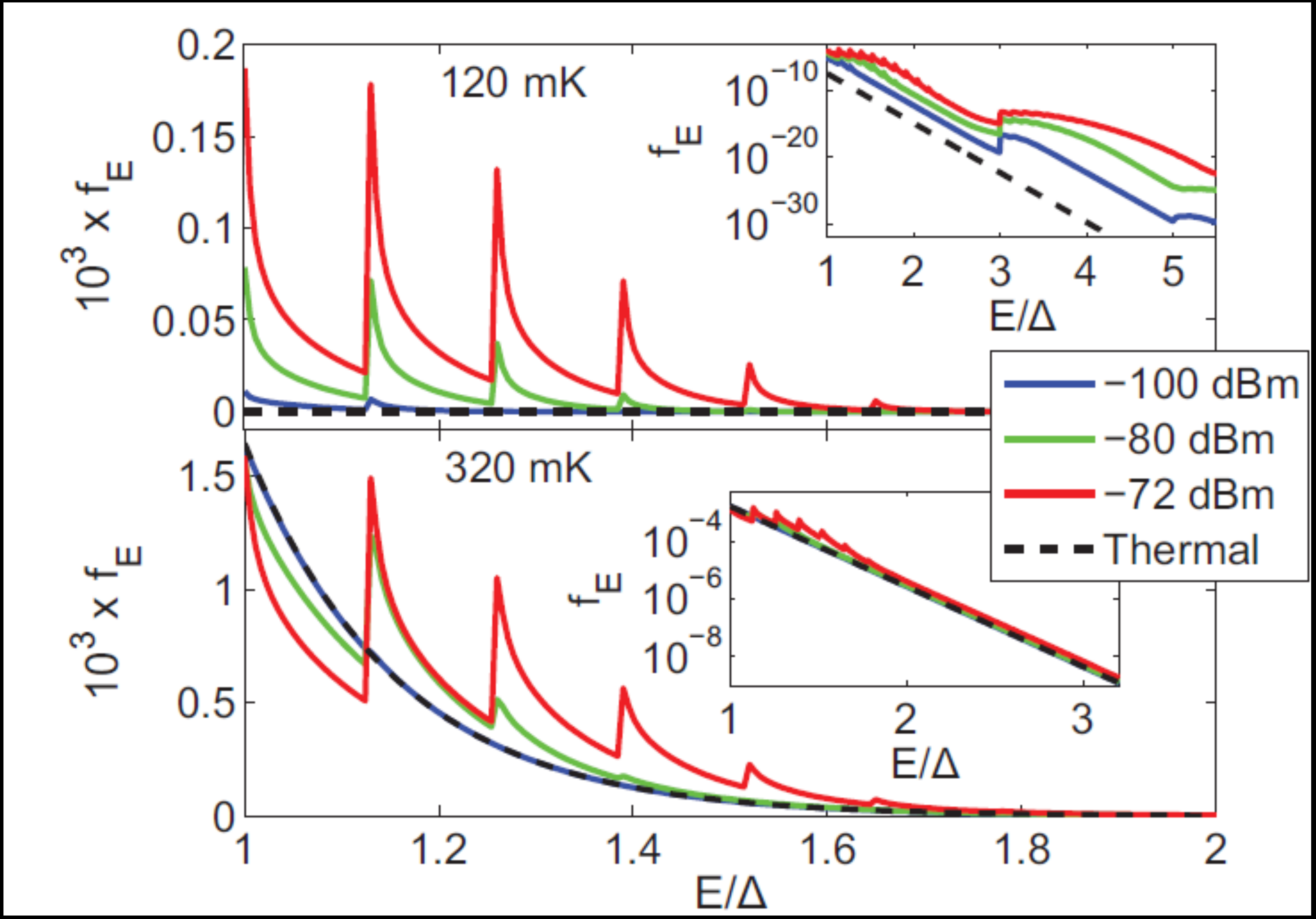
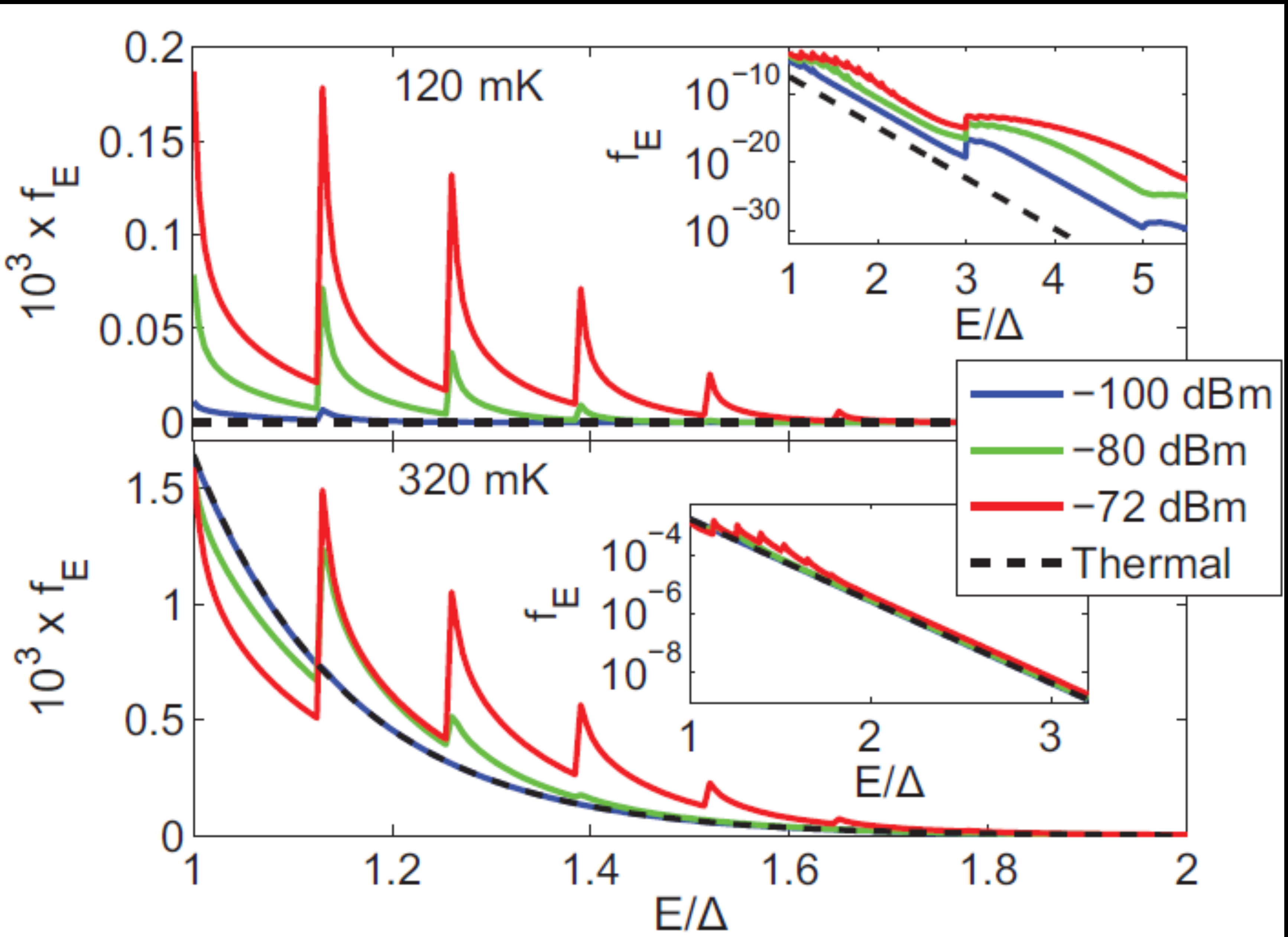
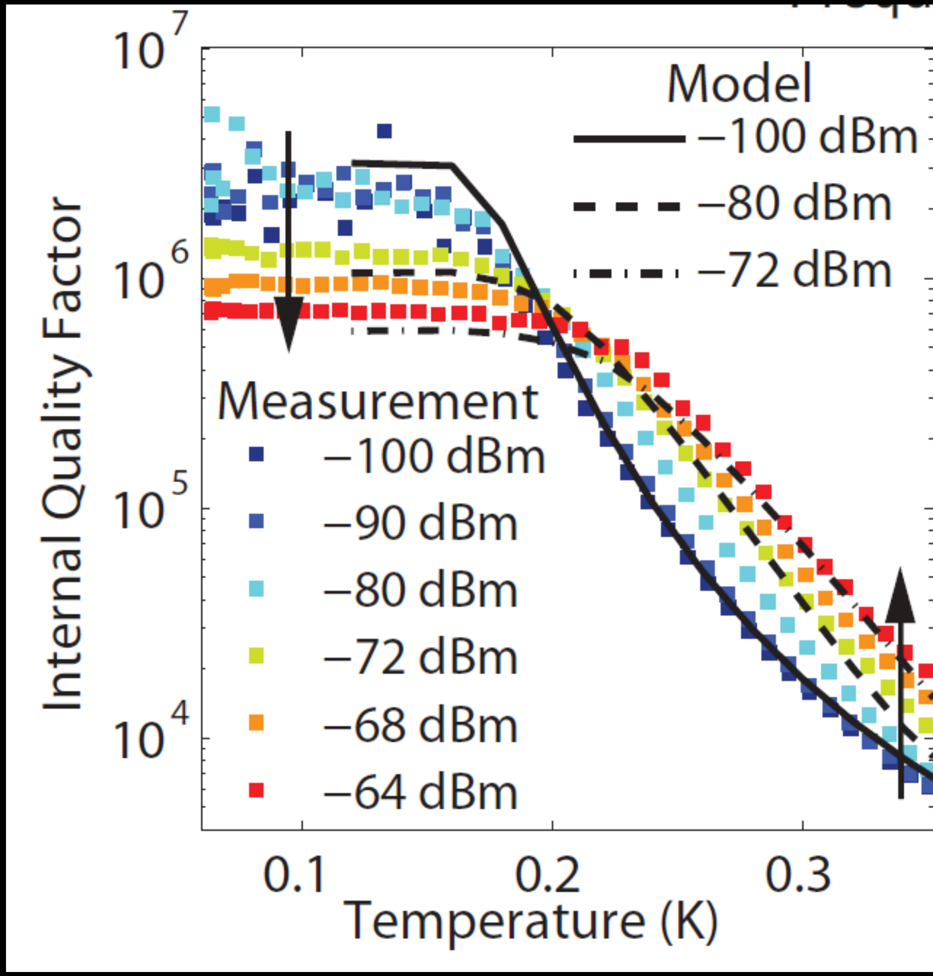
# Non-equilibrium f(E) – steady state




Goldie and Withington, SuST 26, 015004 (2013)
PdV et al. Phys. Rev. Lett. 112, 047004 (2014)

# Example f(E) -> $\sigma_{1,}$ $Q_i$

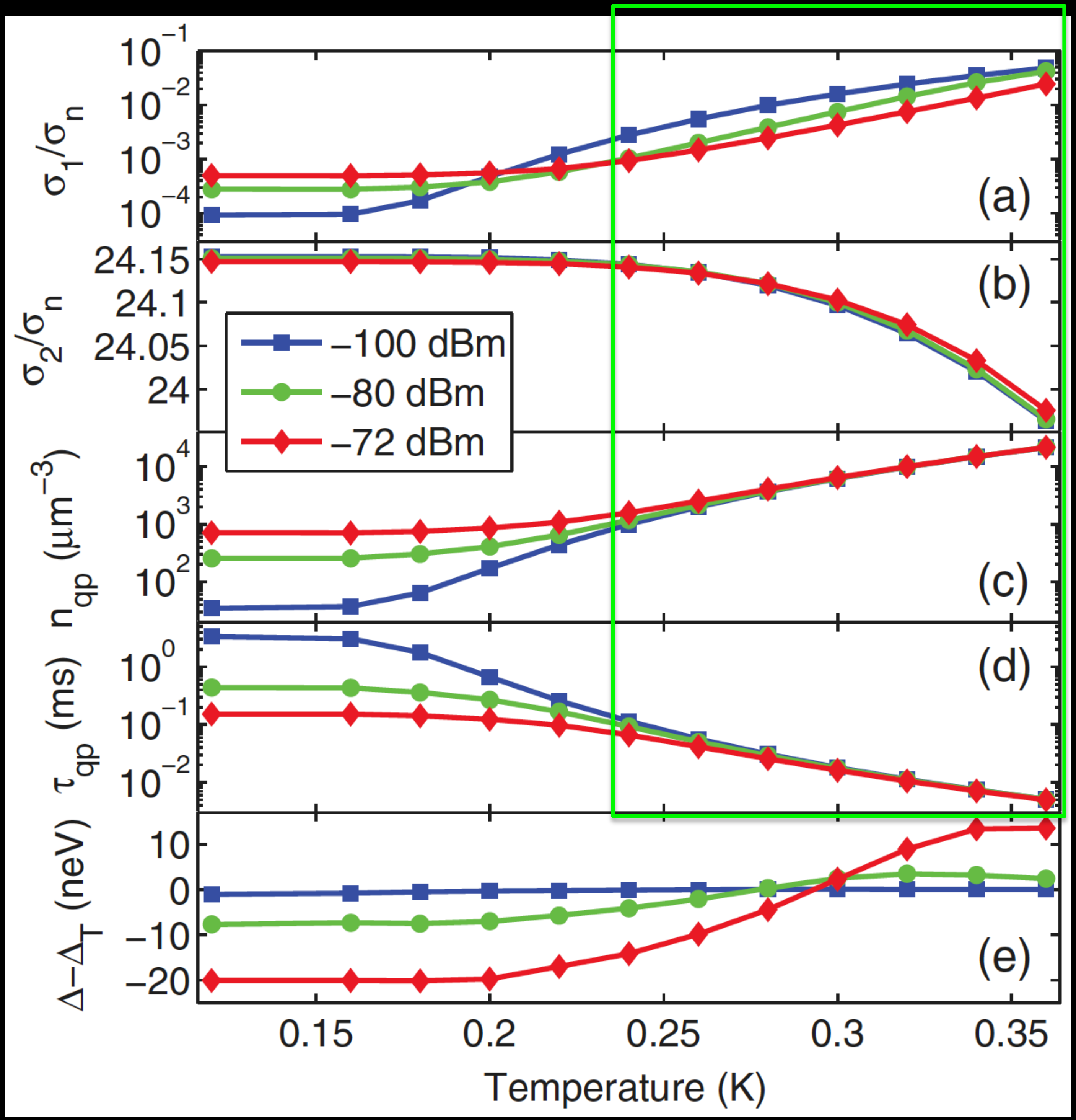



$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}[f(E) - f(E+\hbar\omega)]g_1(E)dE$$

Phys. Rev. Lett. 112, 047004 (2014)

# Other observables

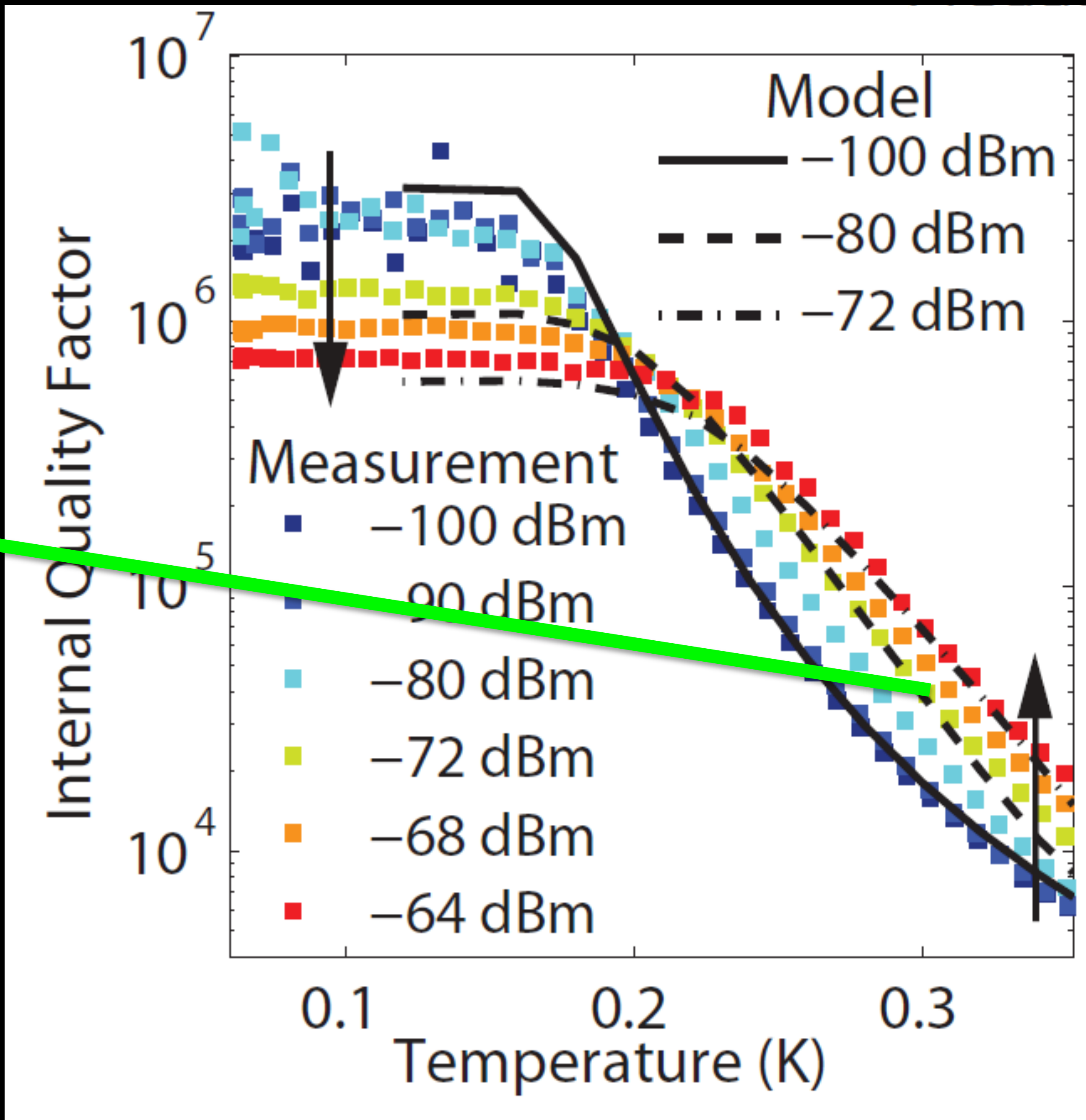



Nqp, lifetime: effective temperature possible, Qi, frequency not at all

# Is this insight useful?

Under strong pair-breaking power Qi decreases rapidly, but microwave enhancement leads to >3x higher Qi

If no Qi enhancement due to redistribution, Al MKIDs would not work at all at the telescope!



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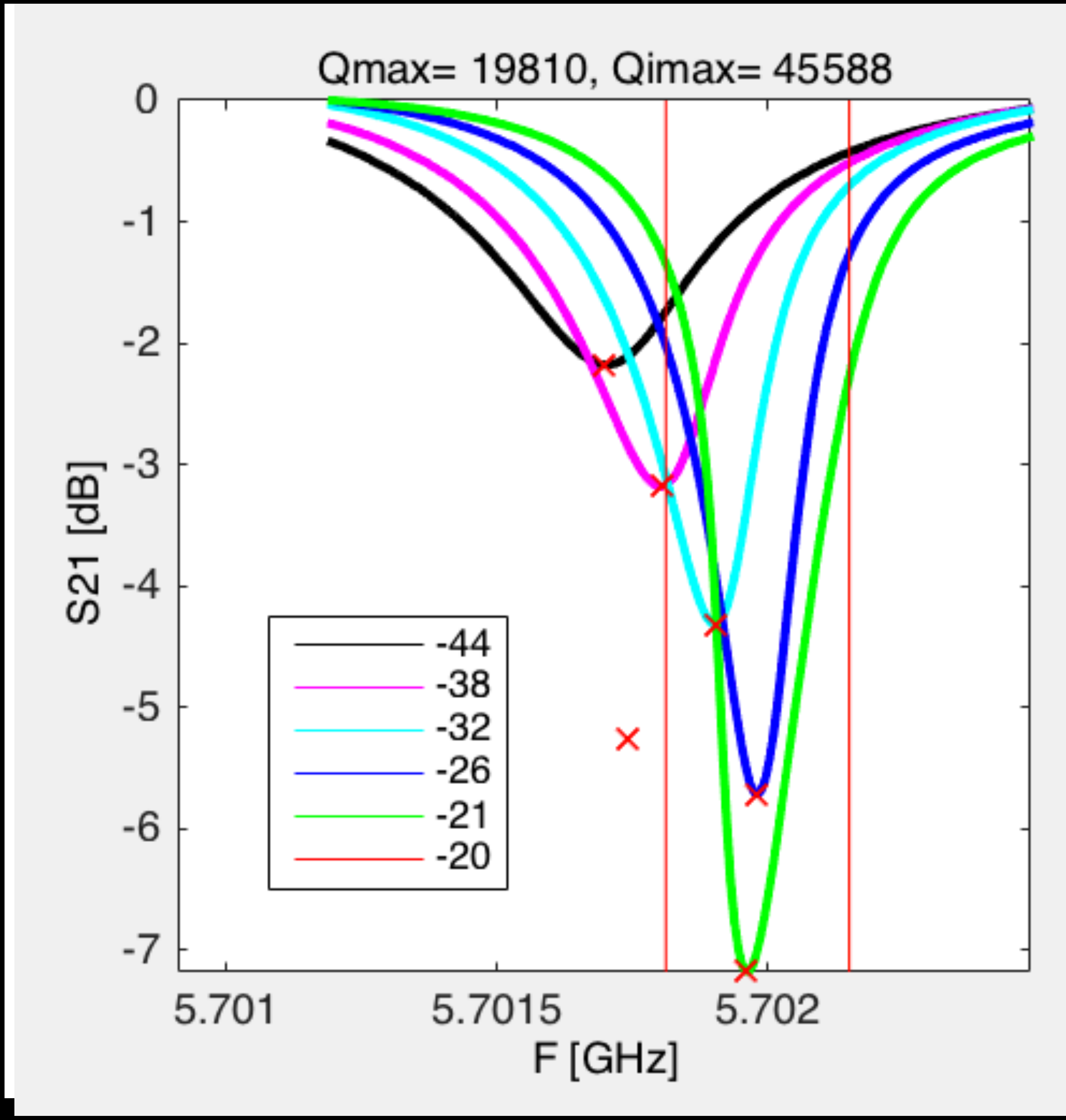
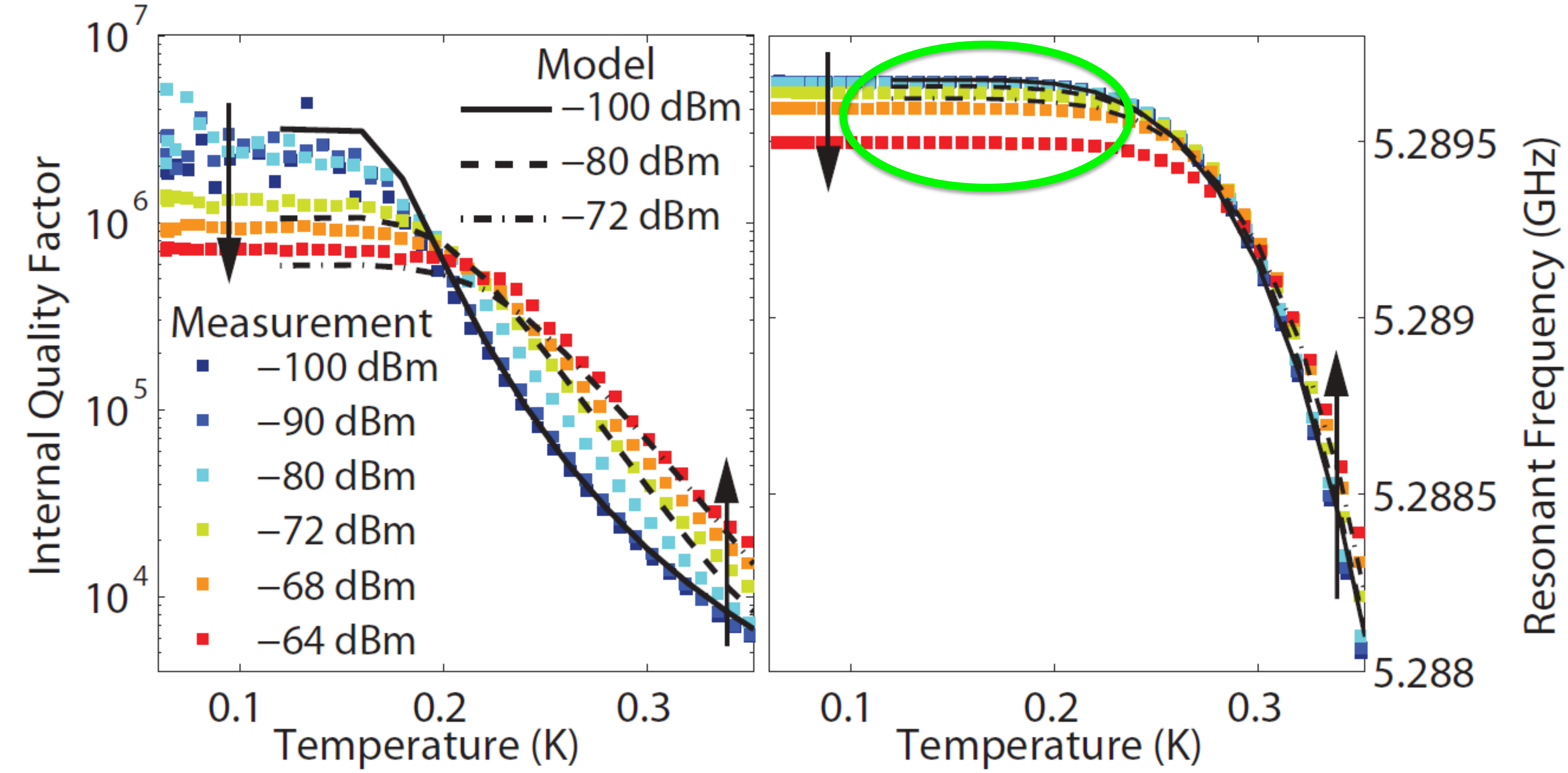
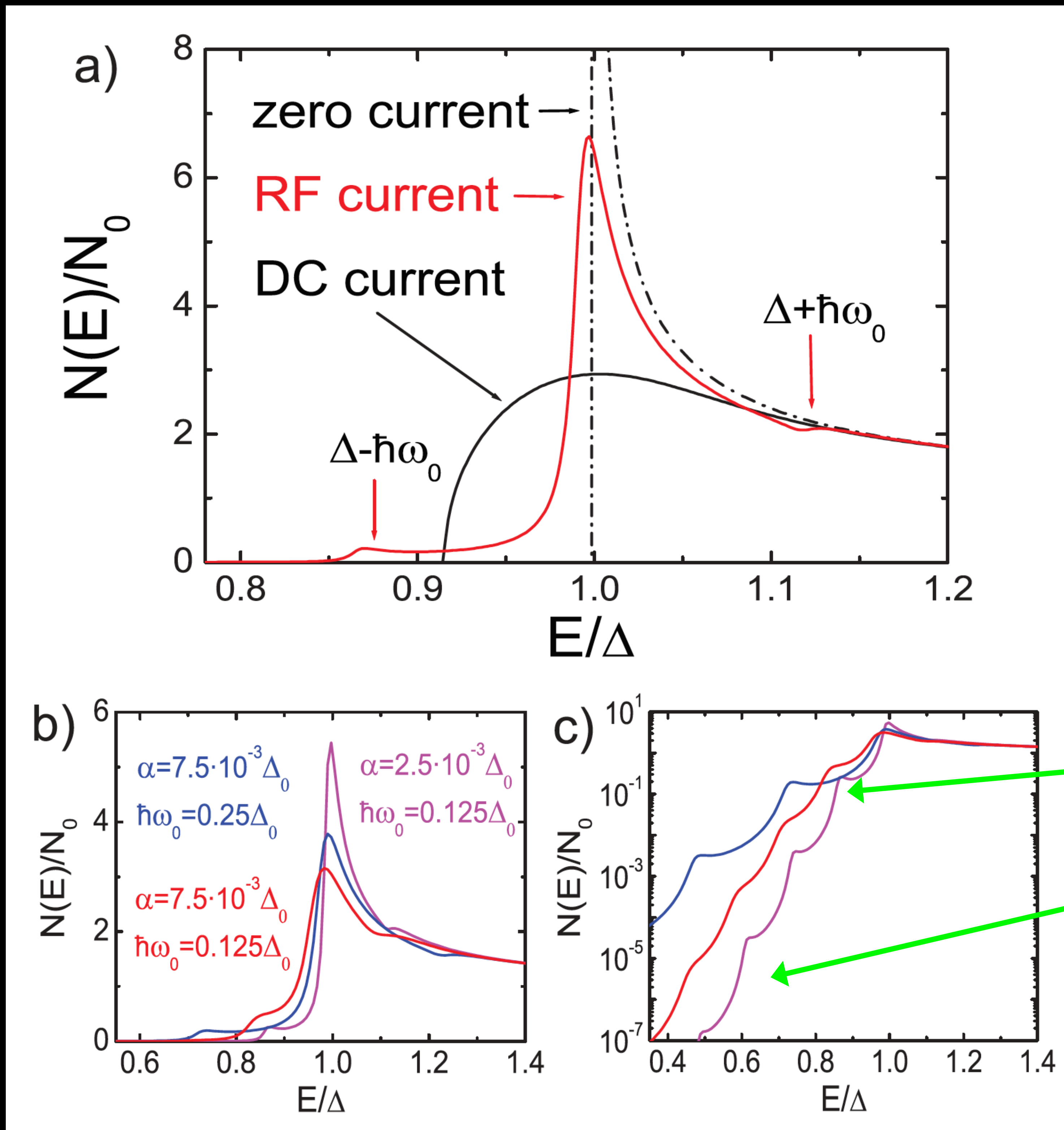


# Absorption, f(E) redistribution, does not explain everything




Quasiparticles only do not describe the condensate observable

# Microwave: 'Coherent excited states'




'Quantum regime'

$$\alpha \ll \hbar\omega_0 \ll 2\Delta,$$

$$\alpha = e^2 D E_0^2 / \hbar\omega_0^2$$

Superconducting ground state (density of states) changes drastically in field

2 differences compared to DC:

Steps at multiples of hf

Exponential subgap tail
triggers absorption?

Much richer structure than DC

Semenov et al. PRL 117, 047002 (2016)

# Naive understanding

Vector potential $A\cos(\omega t)$, pulls apart the pair in momentum space

- In equilibrium the two electrons have opposite momenta: $k_1+k_2=0$.
- In a DC-field this becomes $k_1+k_2=q$ => density of states broadening => nonlinear L
- For finite frequency: $k_1+k_2=q_0\cos(\omega t)$, now it depends on the frequency and field strength. Whether it is 'quantised' will depend on $q_0$ vs $\omega$.

NOTE: the momentum effect is also known as depairing or 'pair-breaking', but it is NOT the same as pair-breaking due to a photon/phonon with $E>2\Delta$

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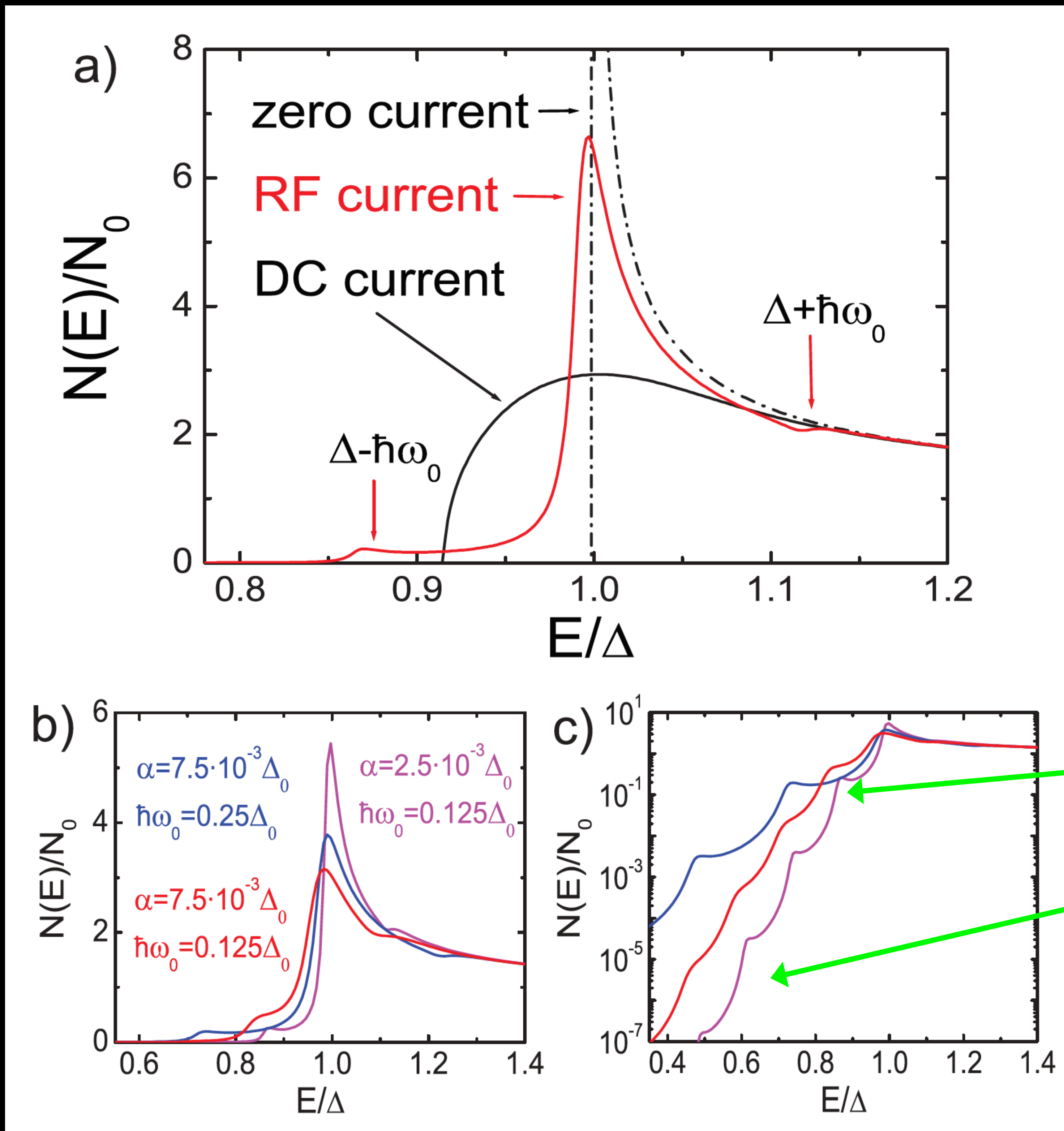


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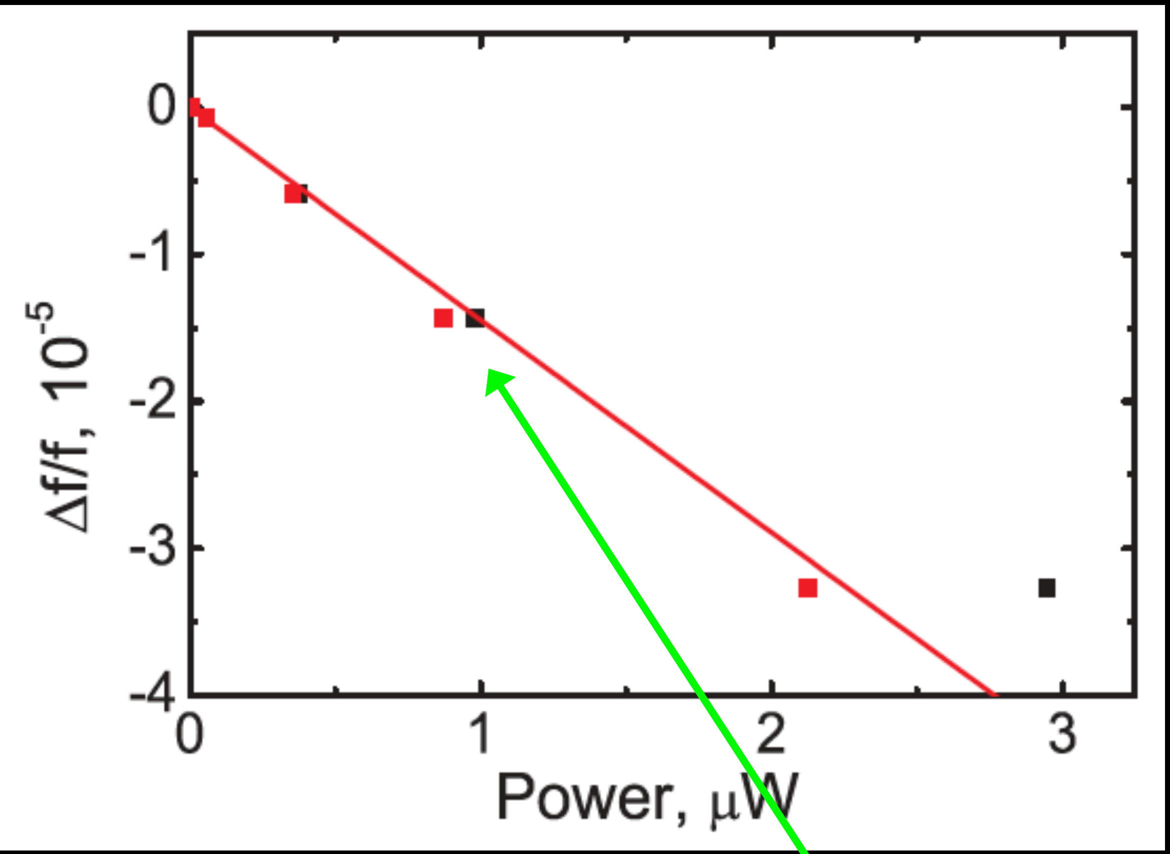
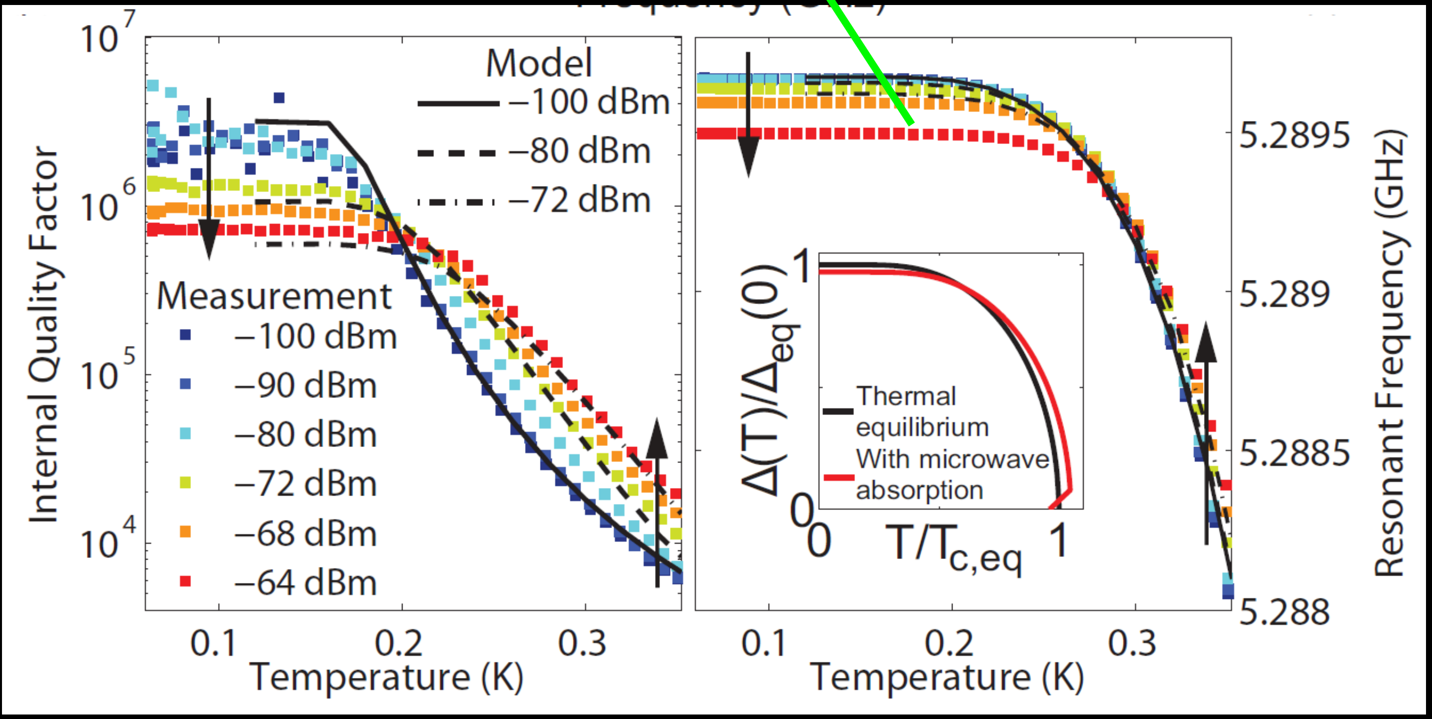
# Effect on complex conductivity




Nonlinear frequency-shift for Al resonator that is not due to f(E) effect, is quantitatively explained!

Scales with $I^2$, both for AC and DC, need for other type of experiments to fully explore the density of states structure.




Semenov et al. PRL 117, 047002 (2016)

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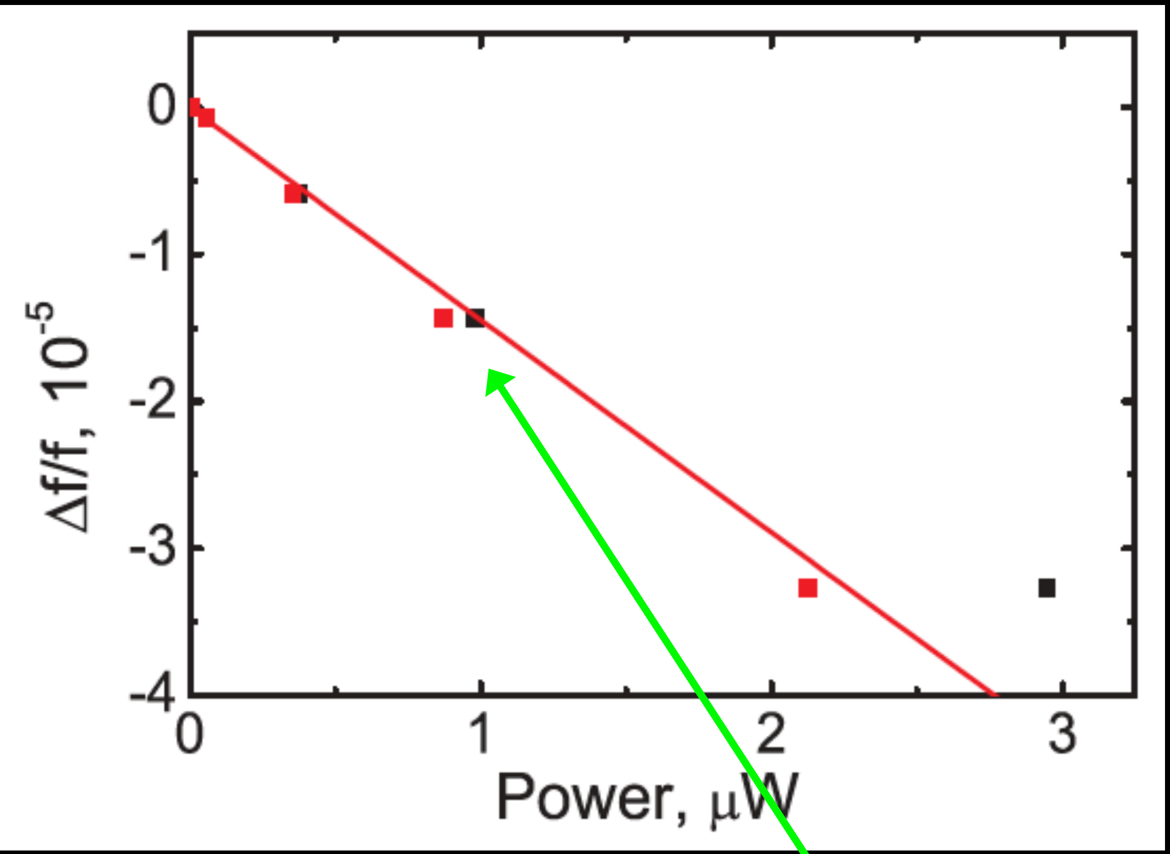


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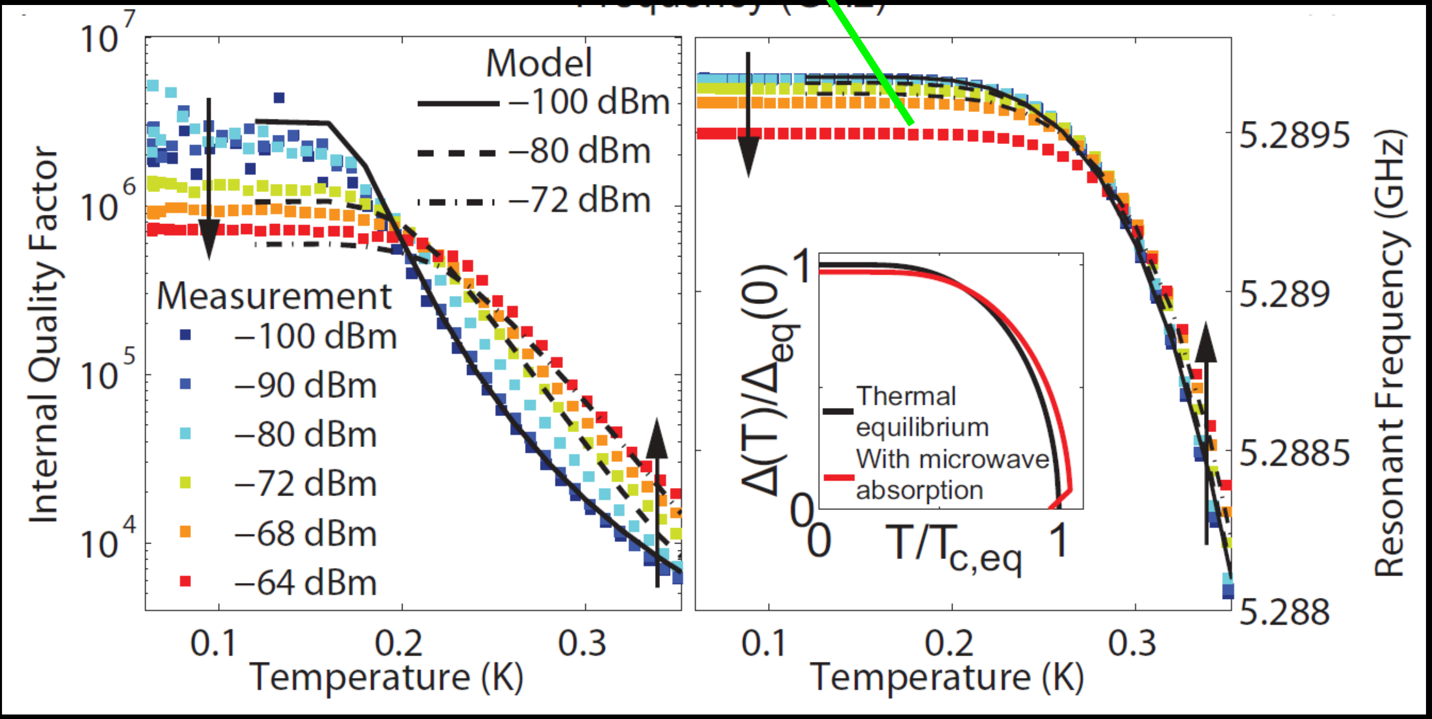
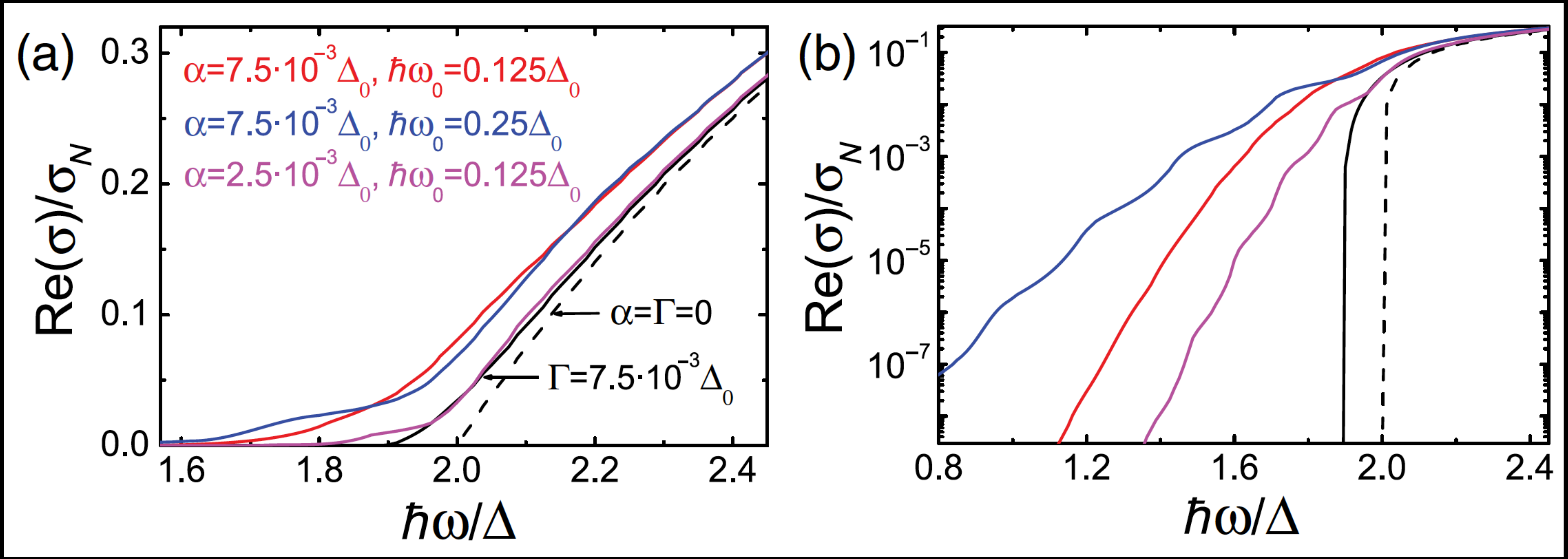



Thus dependent in which regime you are (field, temperature, relaxation), the f(E) or DOS change dominates in AC field

Semenov et al. PRL 117, 047002 (2016)

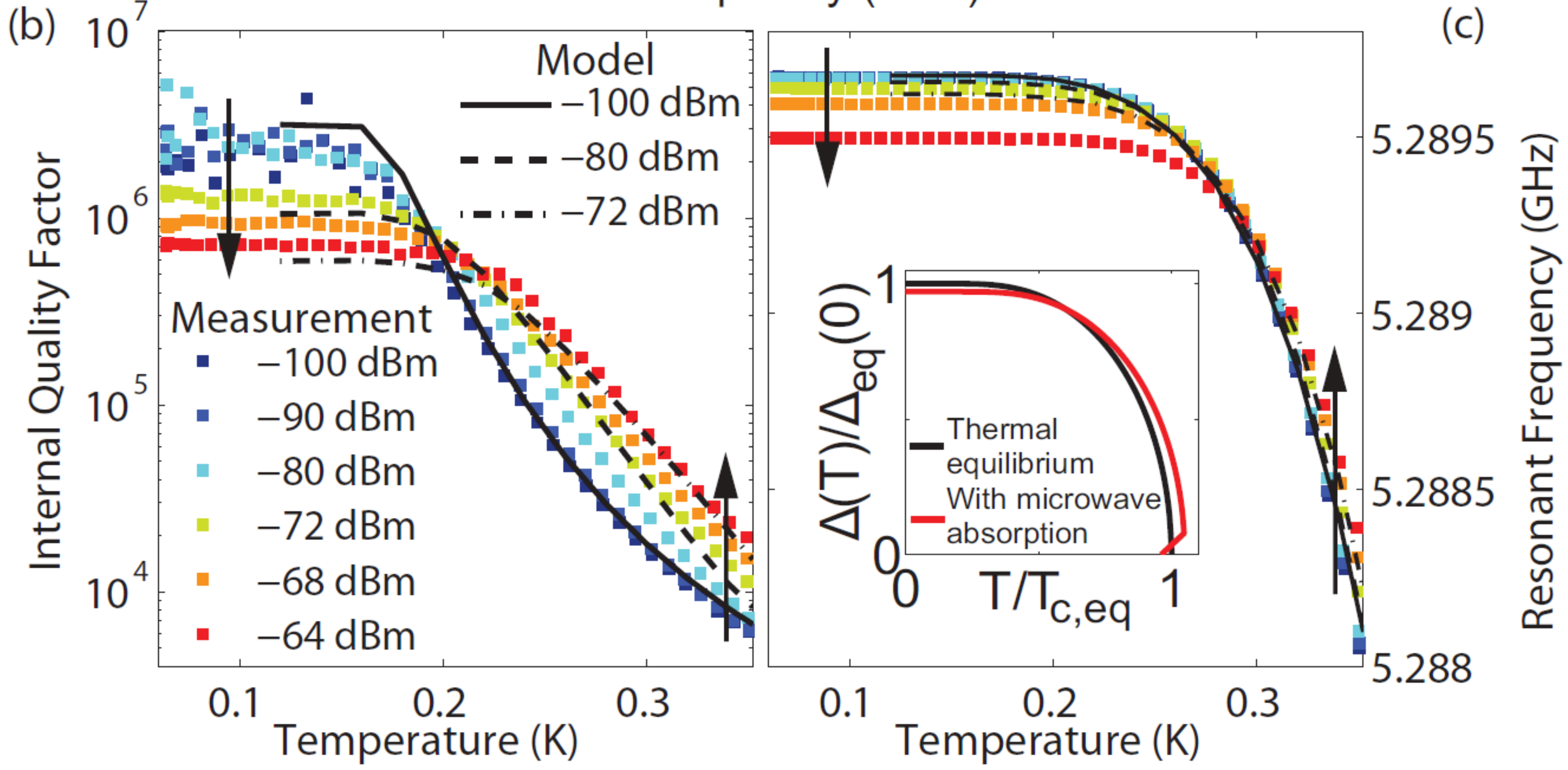
# Exponential tail influences absorption treshold around gap

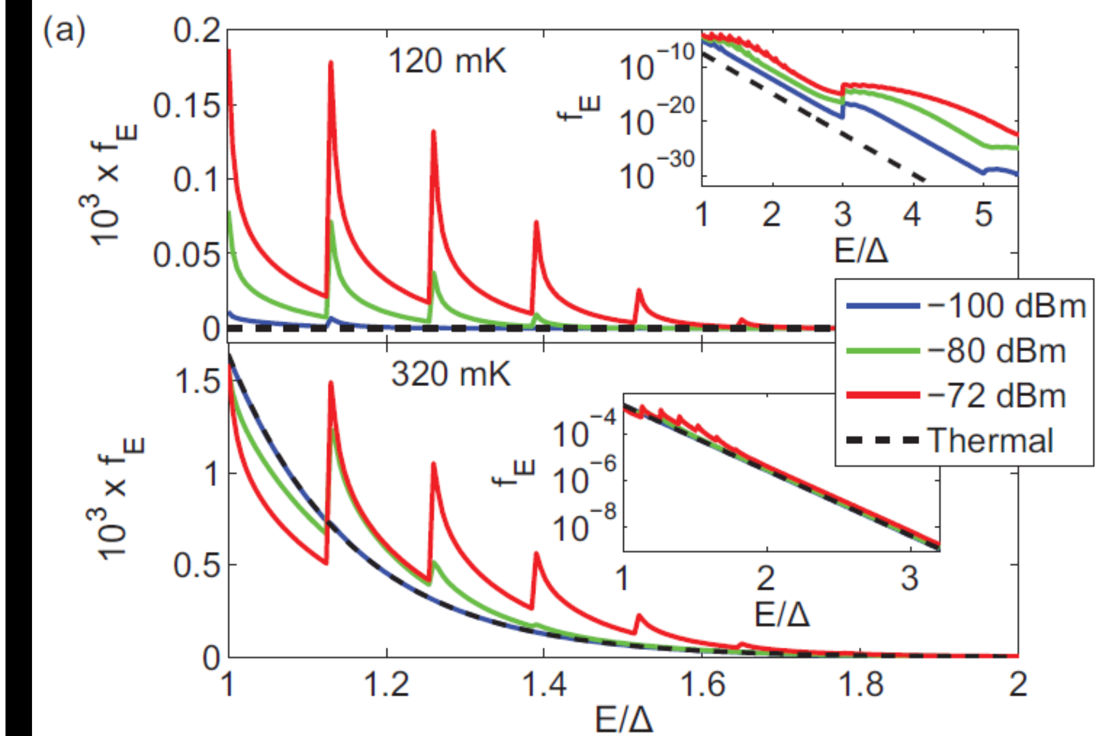


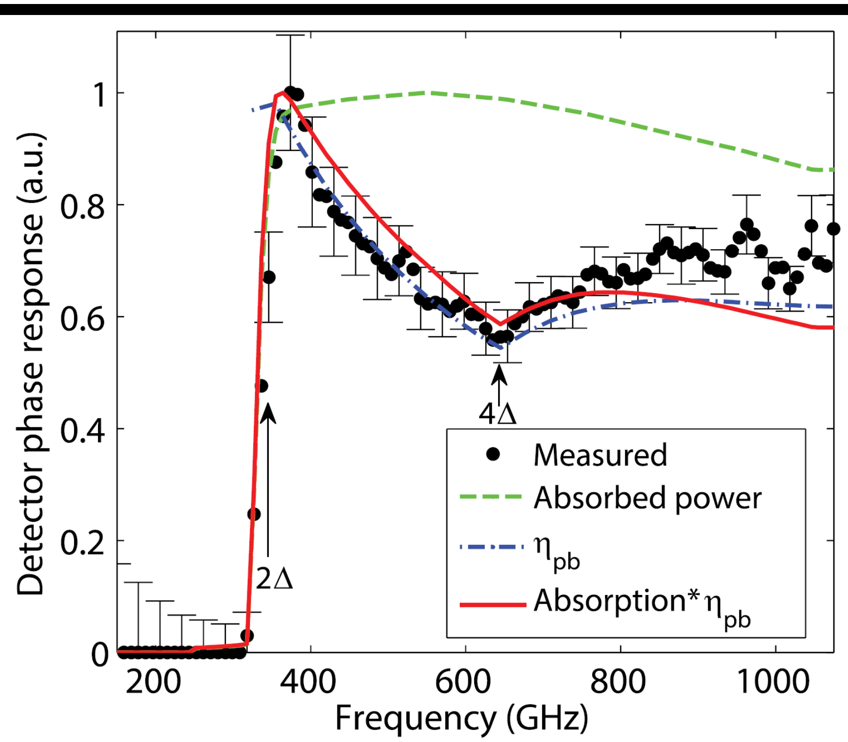
# Summary

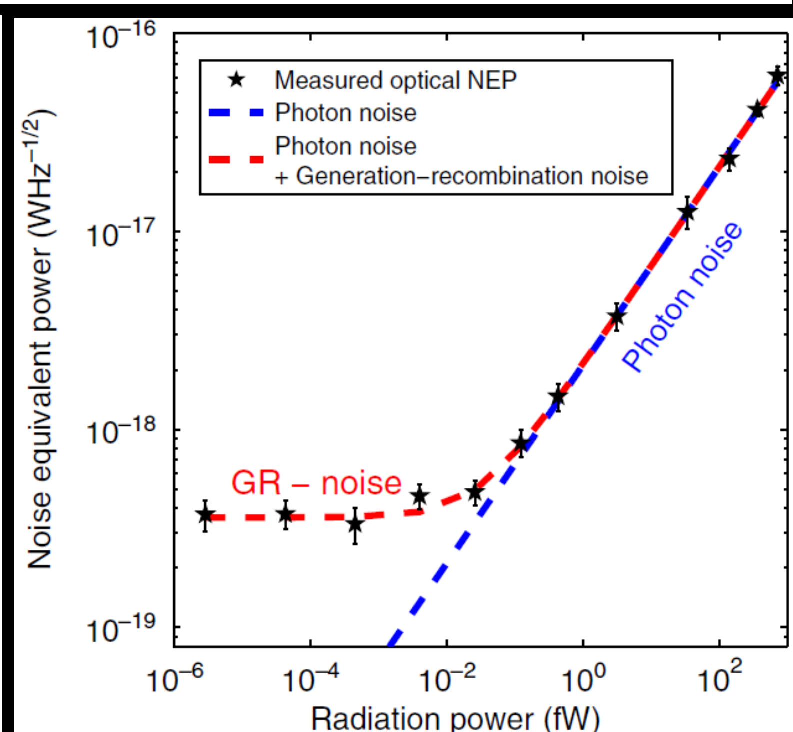
- Quasiparticle- and electrodynamics probed by microwave resonators: different observables access different aspects of non-equilibrium
- Excess quasiparticles present due to microwave absorption and slow relaxation in Al
- Non-equilibrium effect on the Density-of-states due to the current, Al at 5 GHz is in ‘quantum regime’.

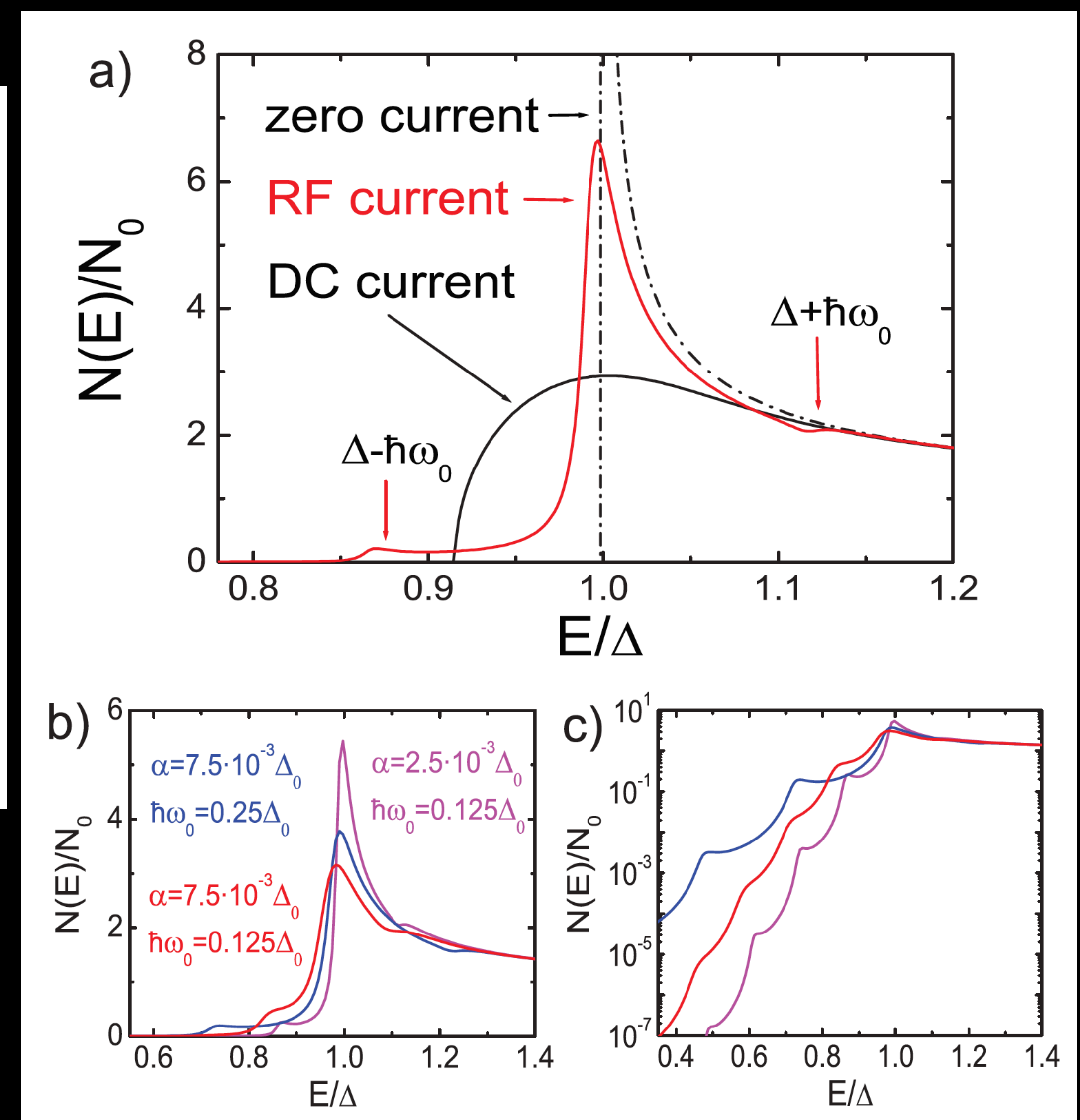
**KIDs exist by the virtue of non-equilibrium superconductivity**




Phys. Rev. Lett. 112, 047004 (2014)

Nature Comm. 5, 3130 (2014)

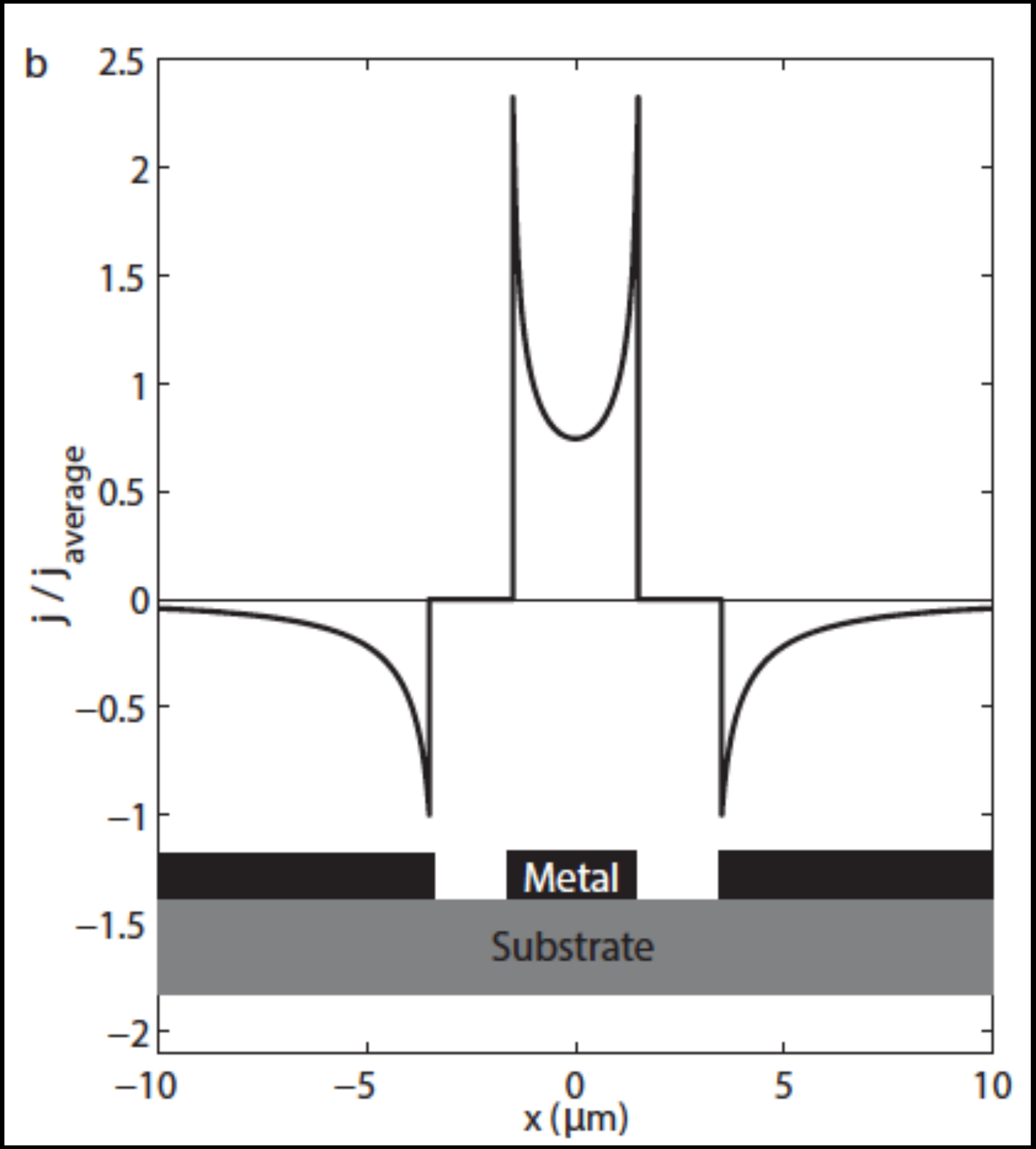
Appl. Phys. Lett. 106, 252602 (2015)

Phys. Rev. Lett. 117, 047002 (2016)

# Al properties

- Tc = 1.2K
- Microwave frequency = 5 GHz, Δ/hf~9
- Temperature: 100-300 mK, T/Tc~10 and hf/kT>1
- Qi ~ 2M
- At 100 mK, very slow relaxation (recombination >1ms, scattering ~100 us)
- D~100 $cm^2/s$
- Penetration depth ~100 nm

# Typical current distribution in Al CPW




Current distribution depends on penetration depth and film thickness (~120 nm and 40 nm in our case)