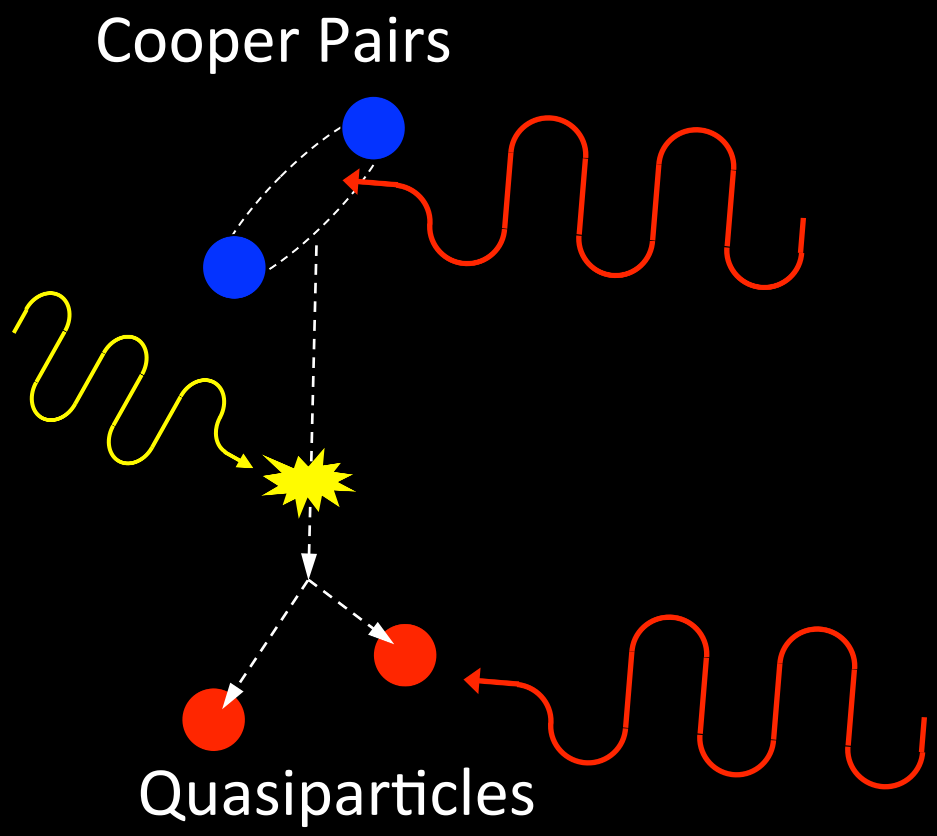
Quasiparticle dynamics in superconducting microwave resonators



Pieter de Visser

p.j.de.visser@sron.nl

SRON: Jochem Baselmans, Stephen Yates, Pascale Diener, Andrey Baryshev
Delft: Teun Klapwijk, Akira Endo, Nuria Llombart, Andrea Neto, Reinier Janssen
Cambridge: Tejas Guruswamy, David Goldie, Stafford Withington
Moscow: Sasha Semenov, Igor Devyatov

SRON Netherlands Institute for Space Research TUDelft THz Sensing Group CosmoNanoscience

Outline

- MKID basic principle
- Aluminium MKID well understood
  - Quasiparticle recombination dynamics and noise
  - Electrodynamic response
  - Pair-breaking radiation => redistribution of quasiparticles
  - Microwave absorption => redistribution of quasiparticles
- Comparison Al vs disordered superconductor (TiN)
- Visible/NIR KIDs at SRON

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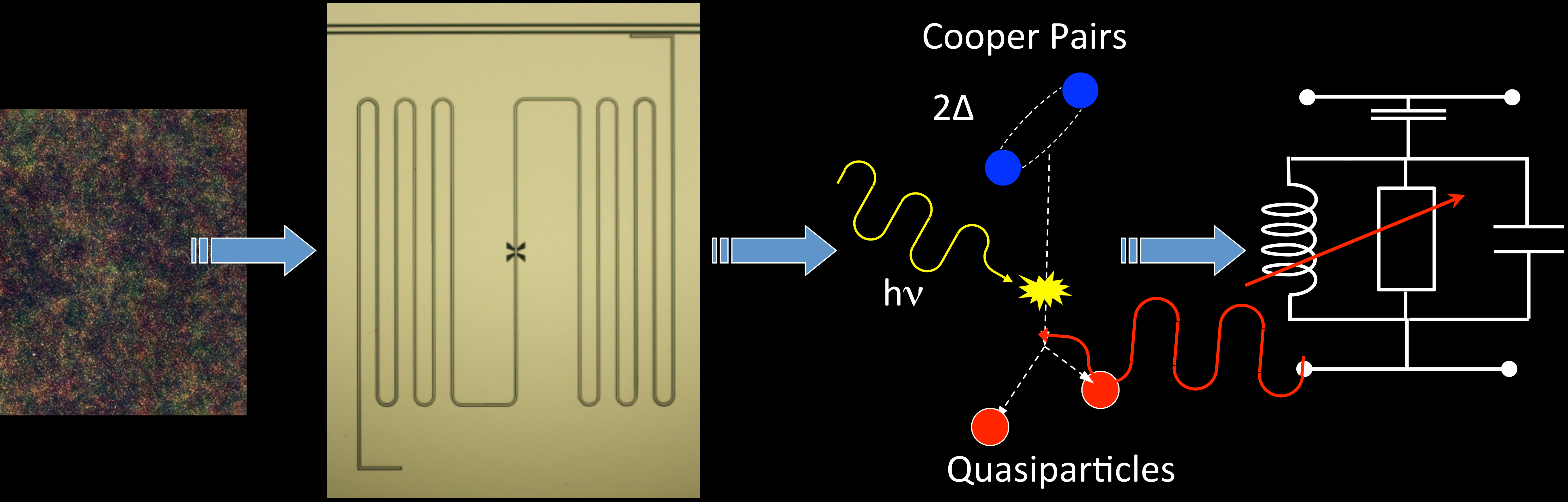
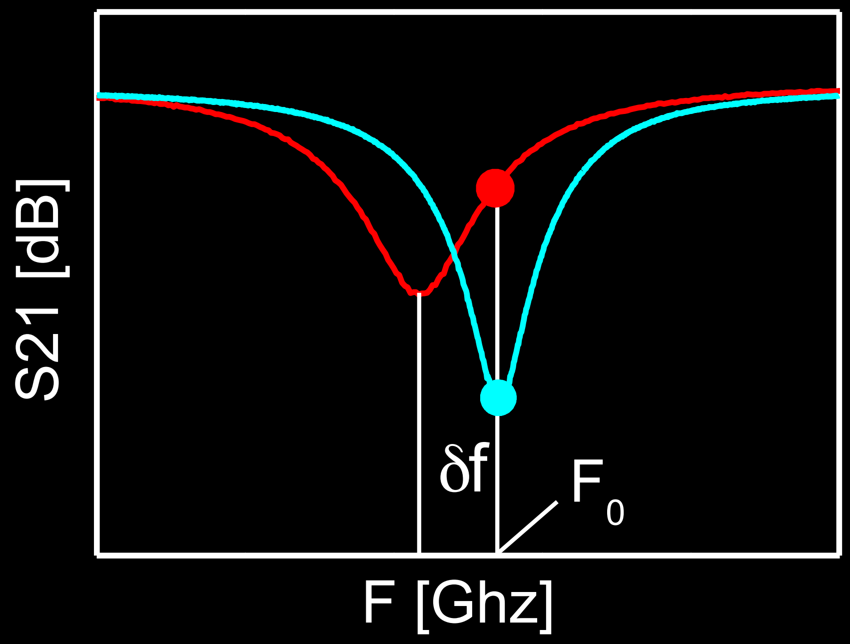
From light to signal





Simple picture: number of quasiparticles

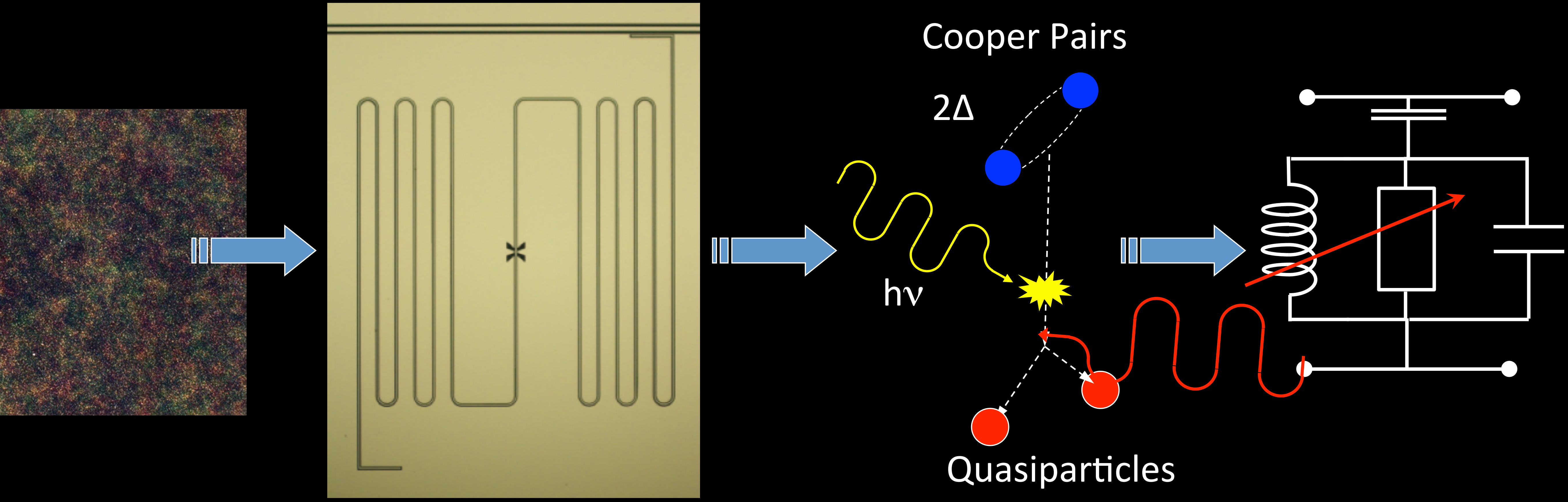
$$\frac{dA}{dN_{qp}} = -\frac{\alpha_k \beta Q}{|\sigma| V}\frac{d\sigma_1}{dn_{qp}},$$

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

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

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

From light to signal



Distribution function and density of states can change both, not always just Nqp

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

Microwave: Q_i, A

Pair breaking

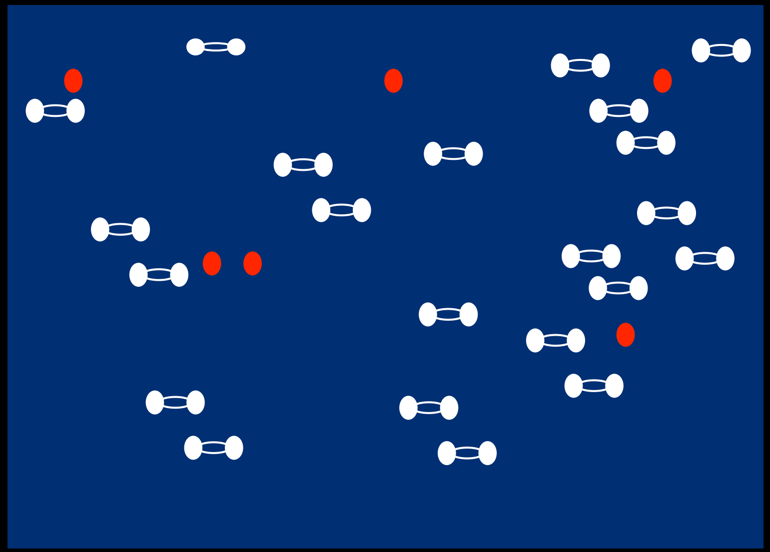
Microwave: f_{res}, θ

Temperature

Generation-recombination noise

Higher temperature:

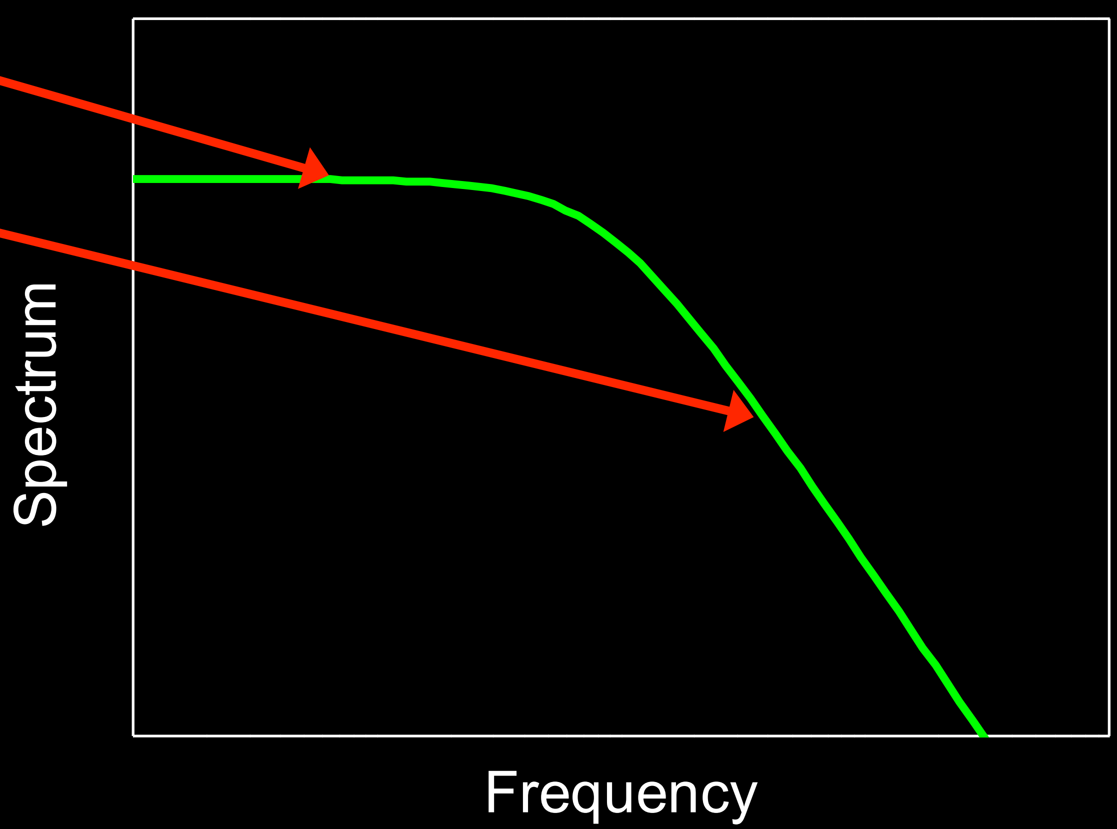
- More quasipartices
- Shorter recombination lifetime



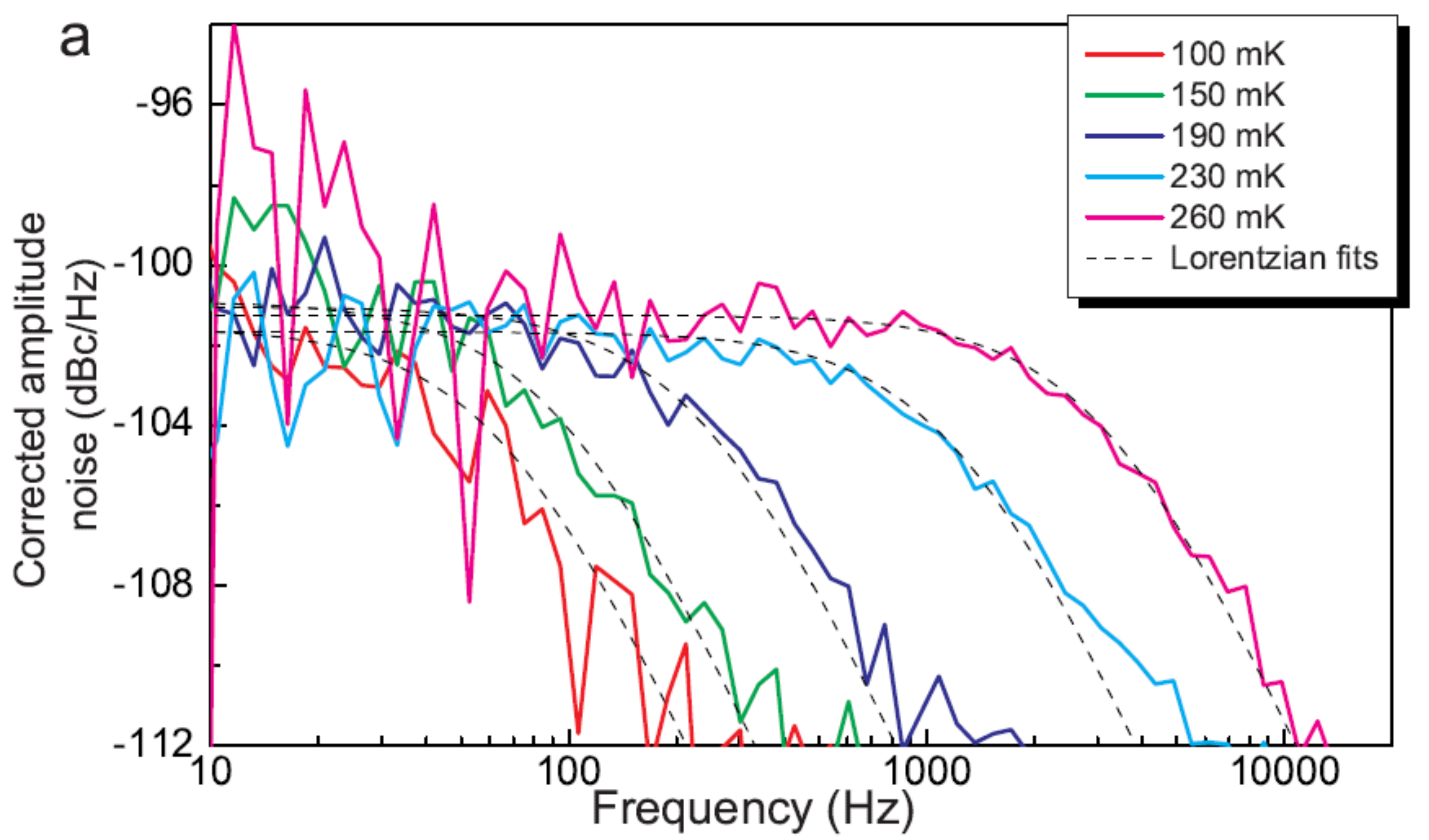
$$S_N = \frac{4 < N^2 > \tau}{1+\omega^2\tau^2} = \frac{4N\tau}{1+\omega^2\tau^2}$$

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

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



Measurement of quasiparticle fluctuations, all Al resonator

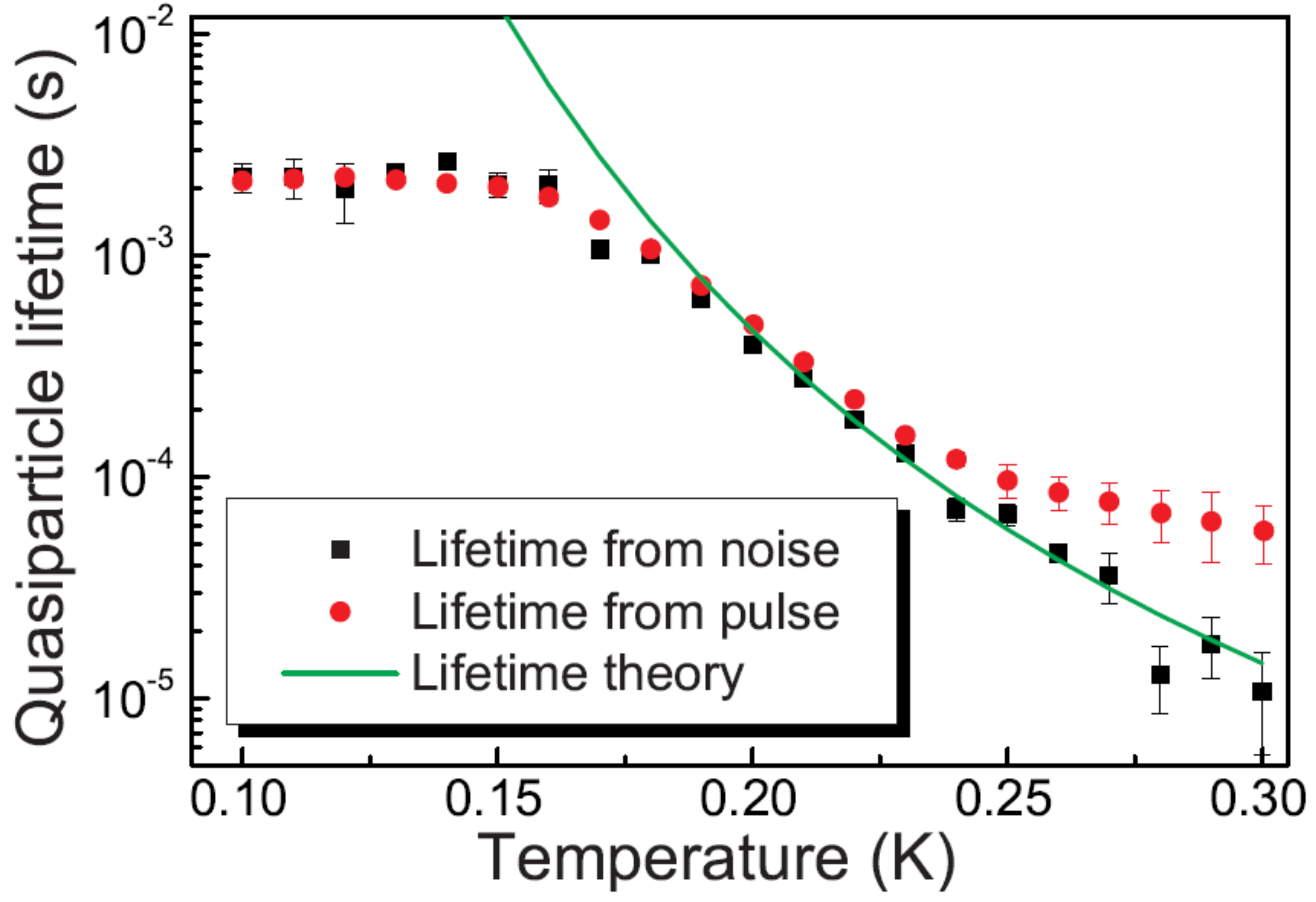


$$S_N = \frac{4N\tau}{1+\omega^2\tau^2}$$

✔

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

Measurement of quasiparticle fluctuations

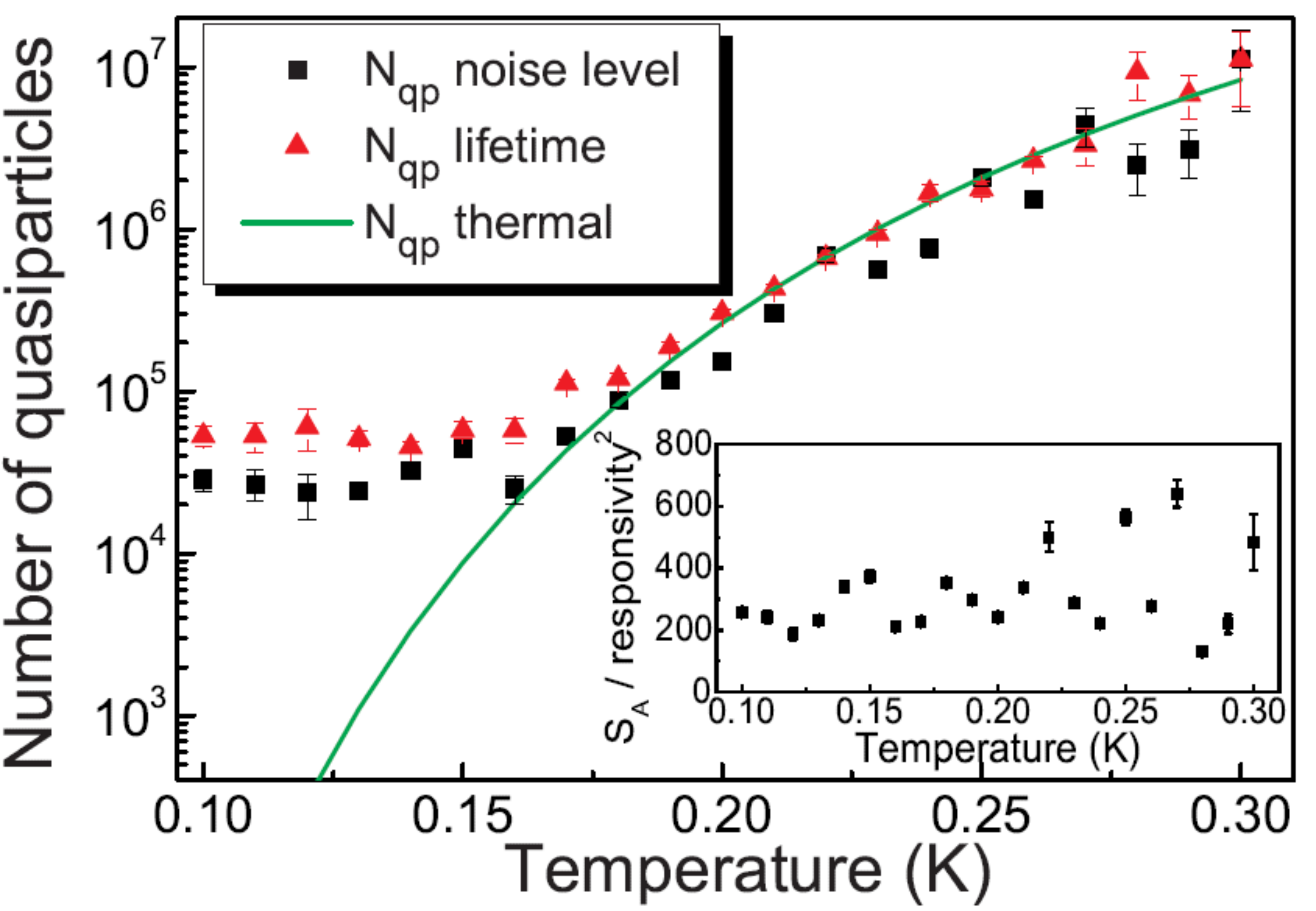


$$S_N = \frac{4N\tau}{1+\omega^2\tau^2}$$

✔

Consistent recombination lifetime from noise and pulse measurement

Measurement of quasiparticle fluctuations



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

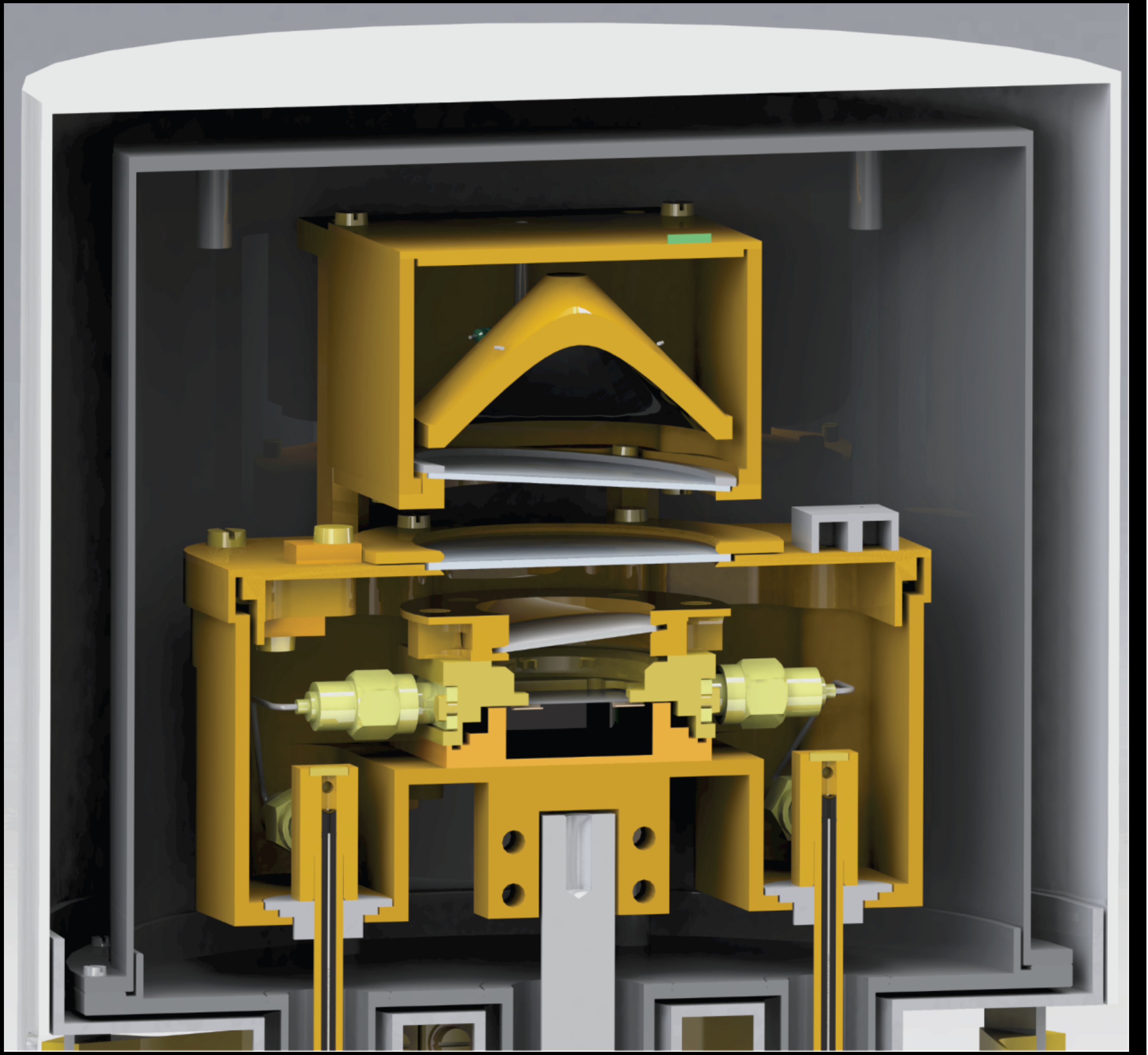
✓

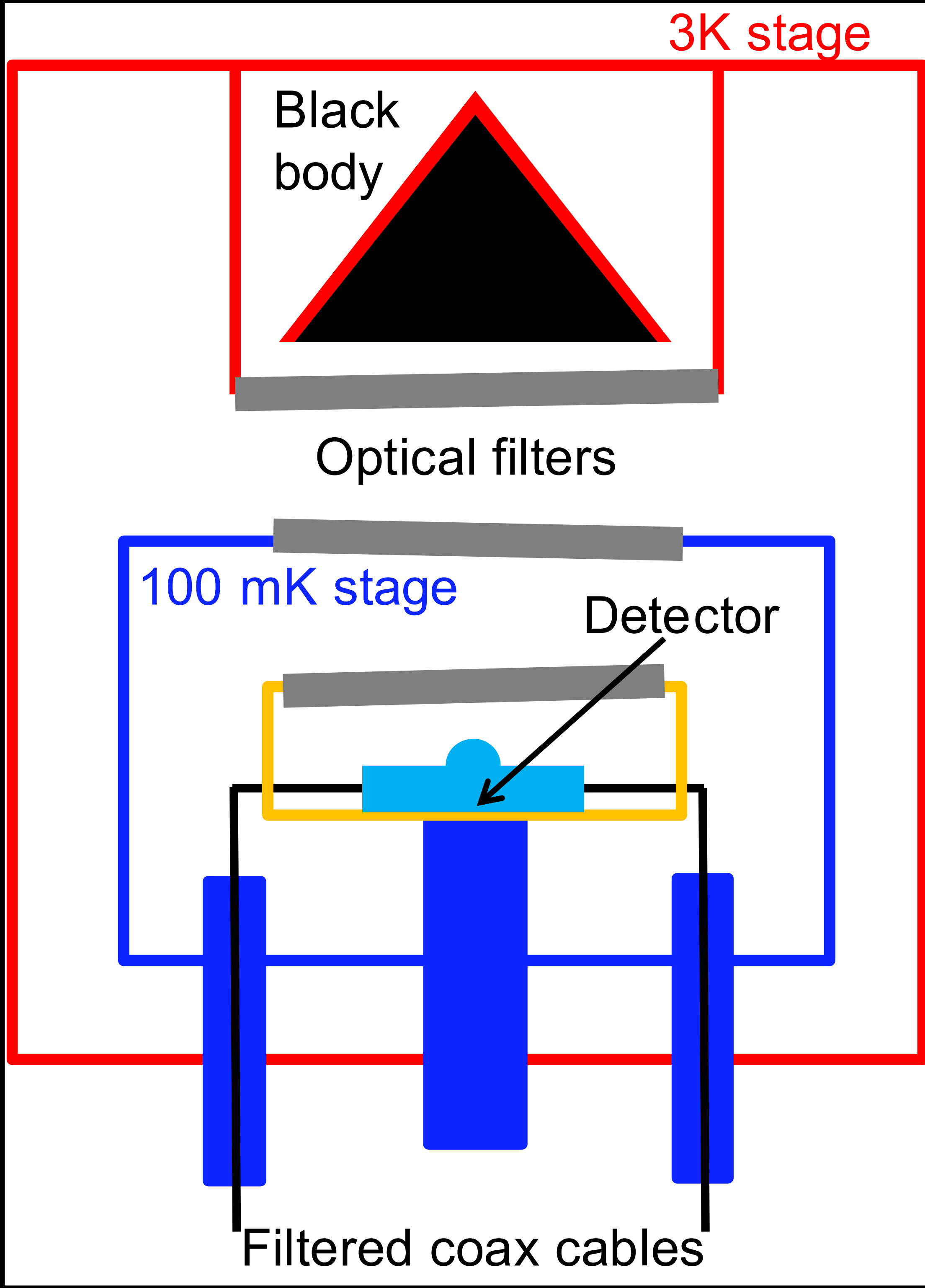
Measurement of the number of quasiparticles
Saturation of quasiparticle number at low temperature

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

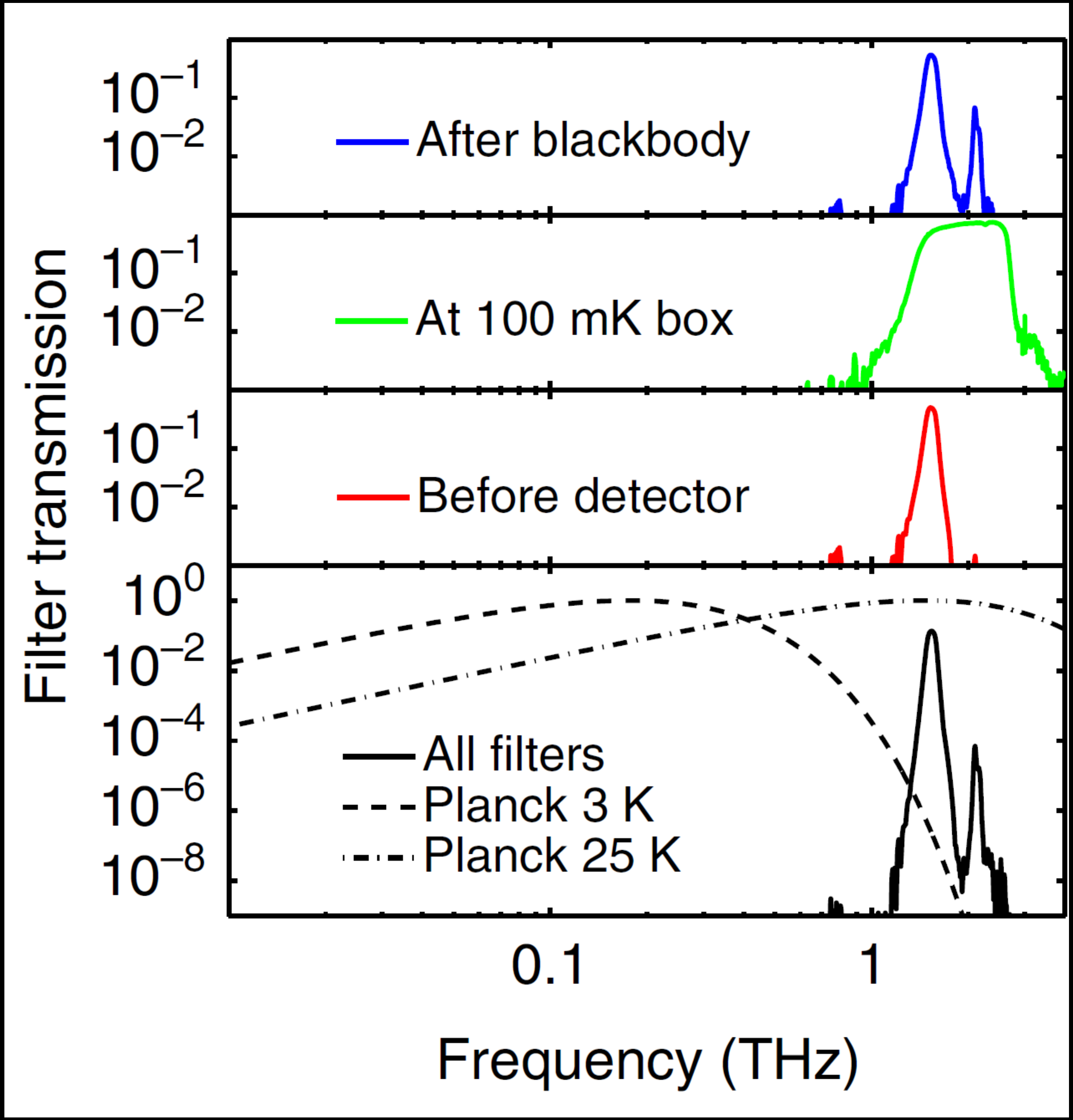
Pair breaking photons, 1.5 THz

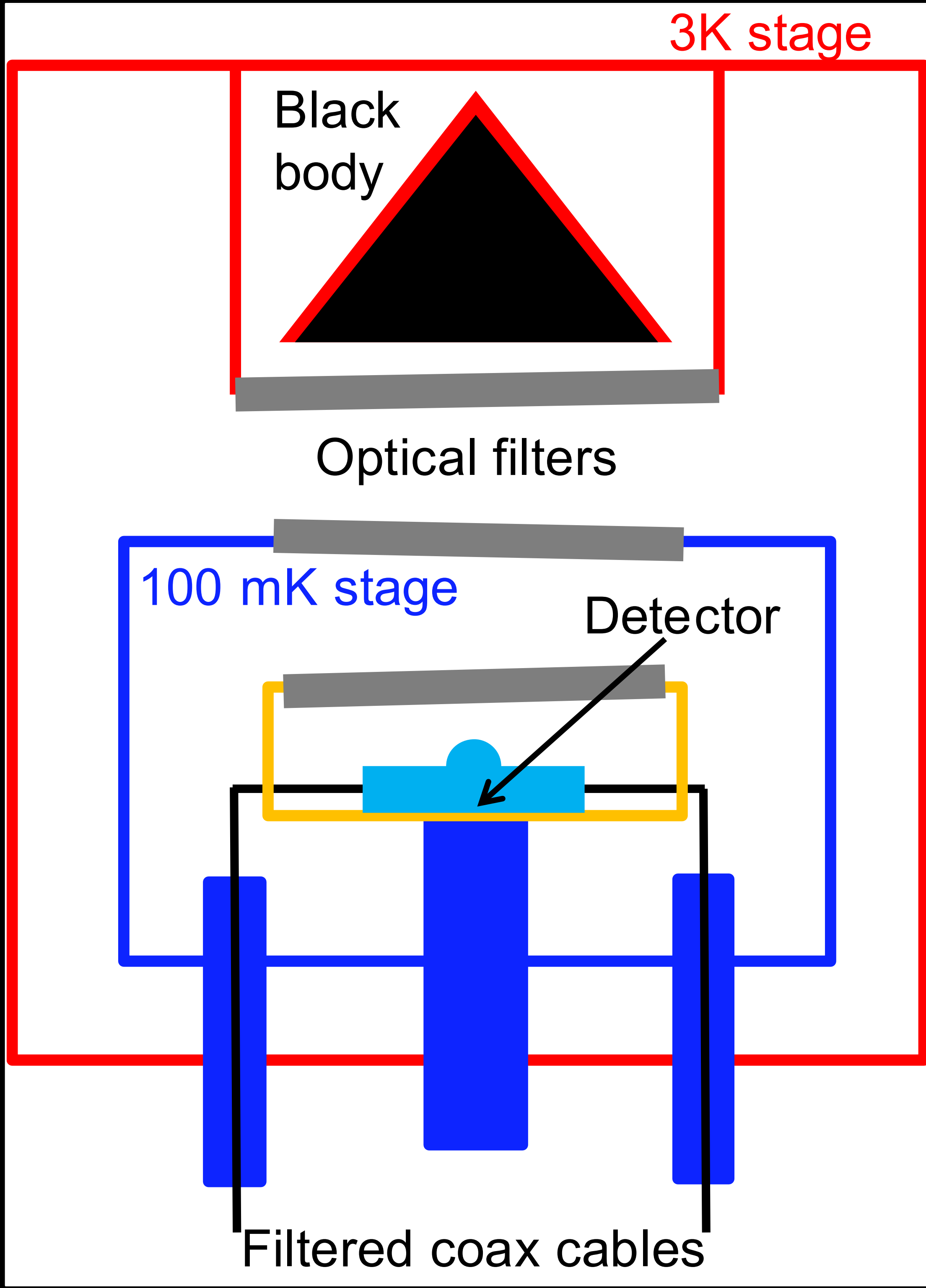
Low temperature, dark environment





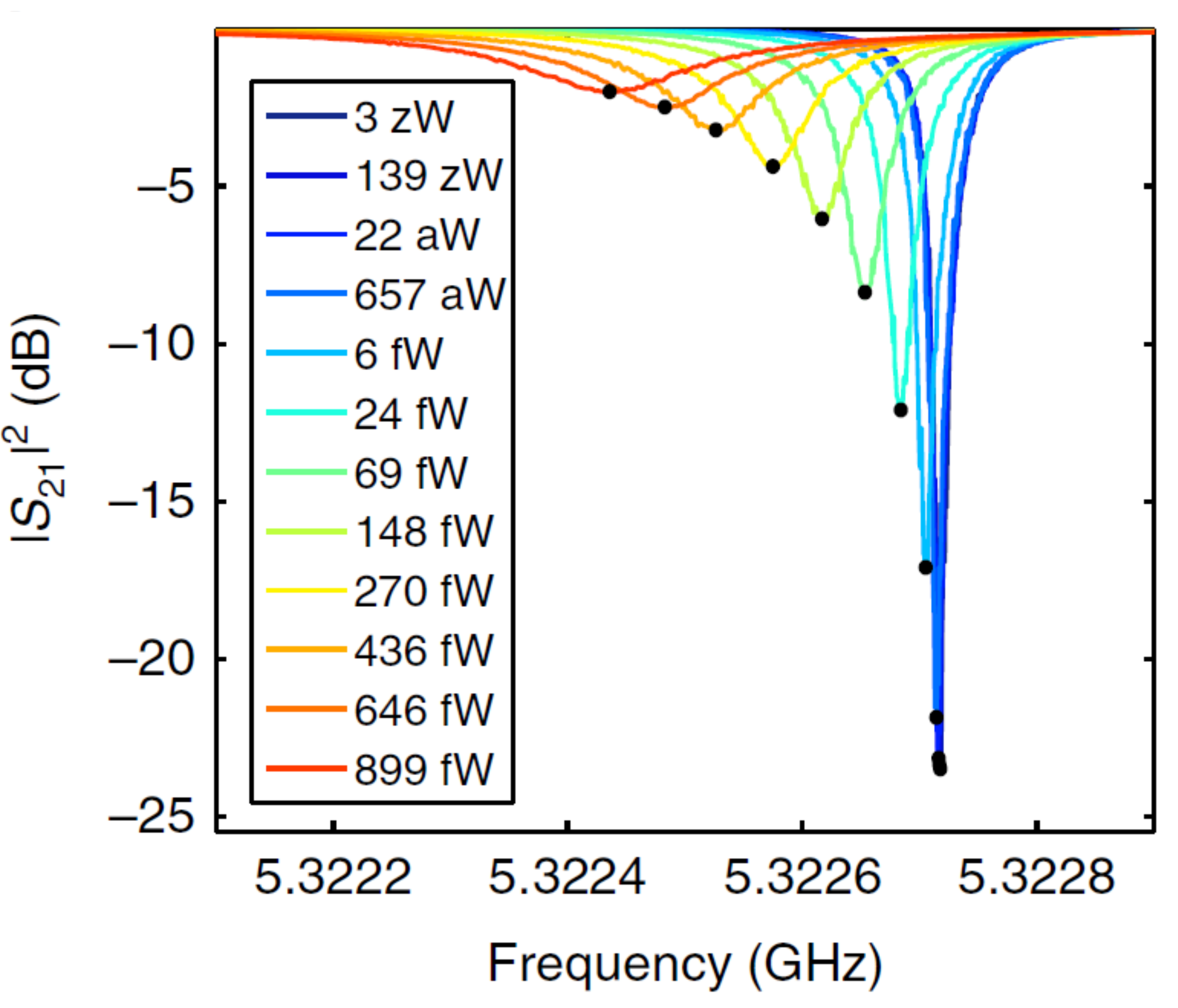
Well controlled excitation





Variation in power: 1 zW - 1 pW = $10^{-21} - 10^{-12}$ W

Signal vs pair-breaking power



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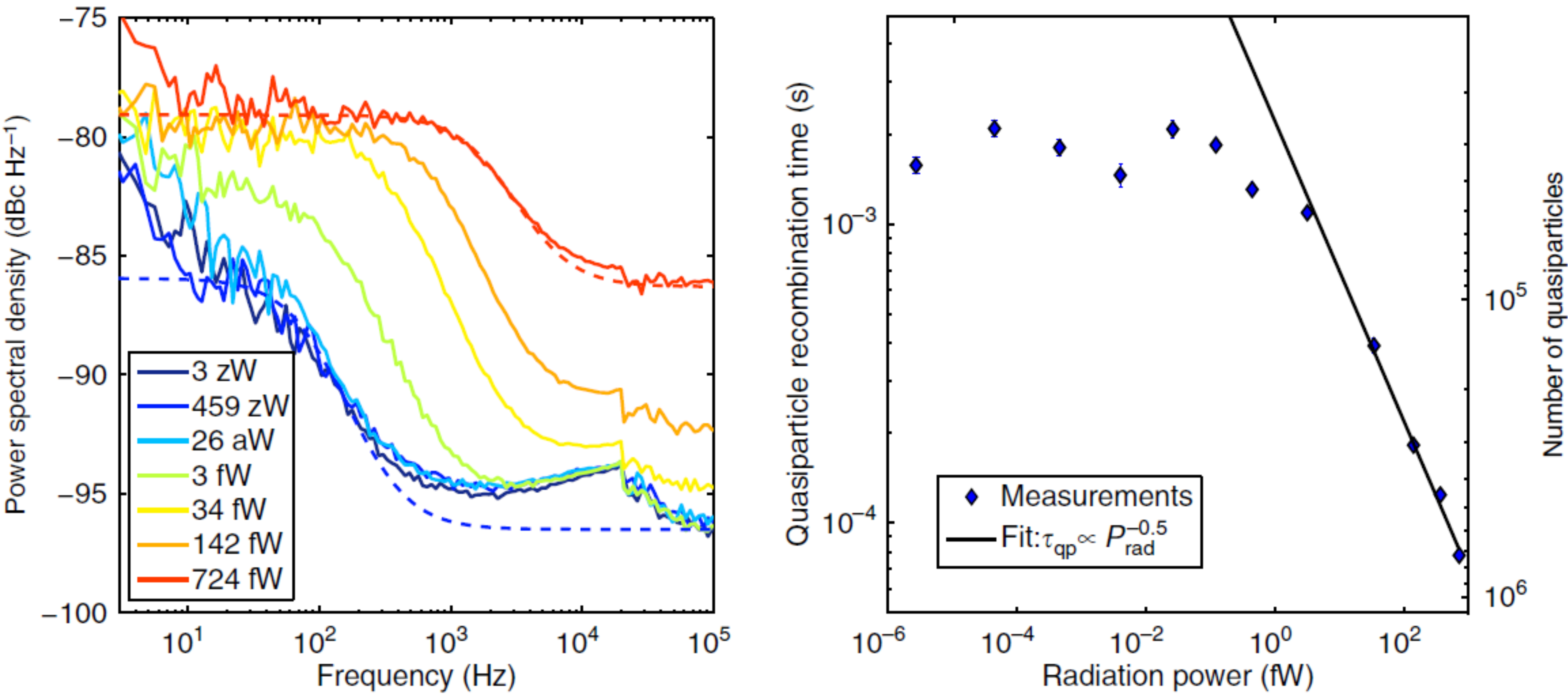
Photon noise

Fluctuations in the photon arrival rate
QP-lifetime from noise scales with sqrt(P) as expected



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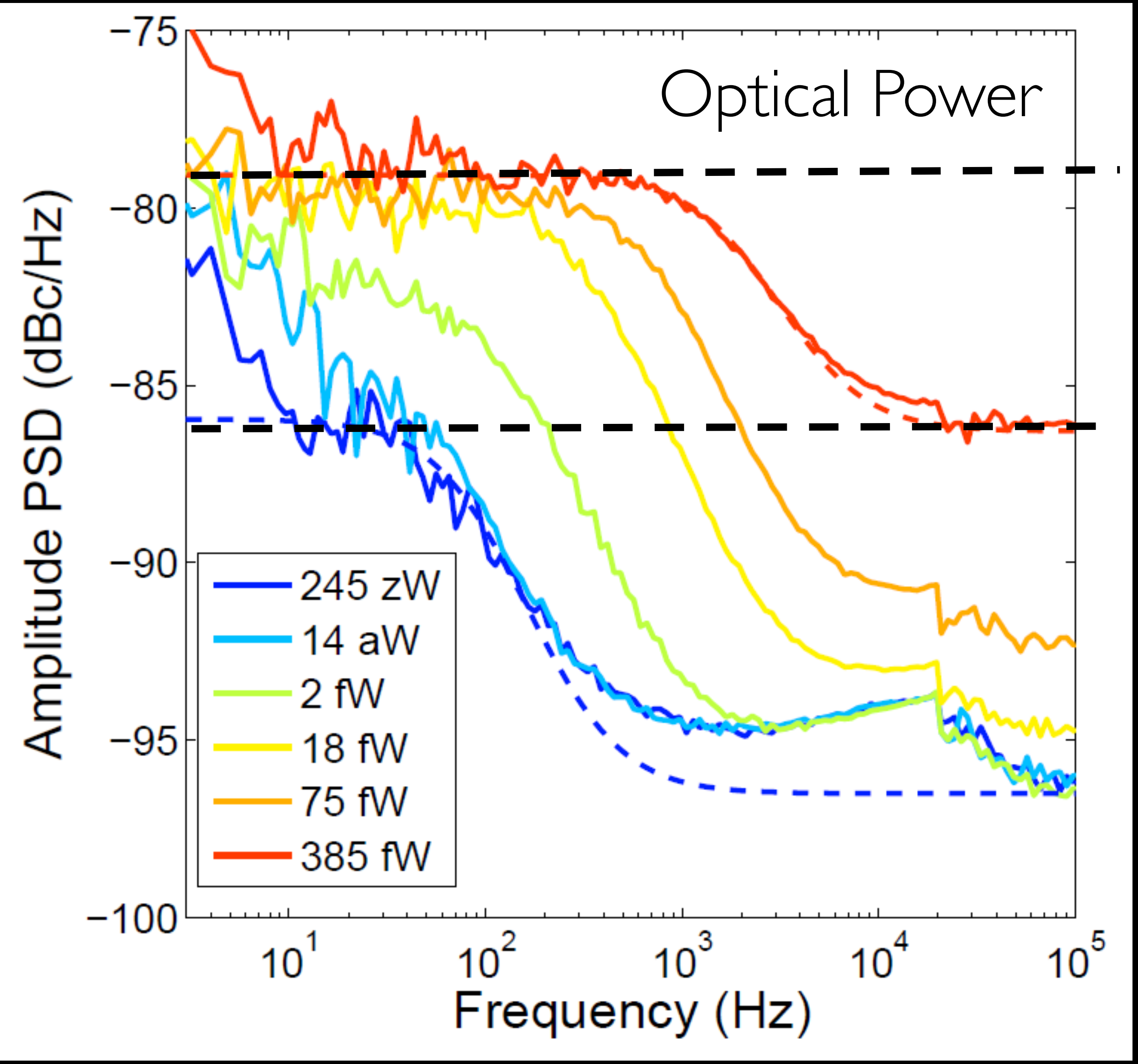
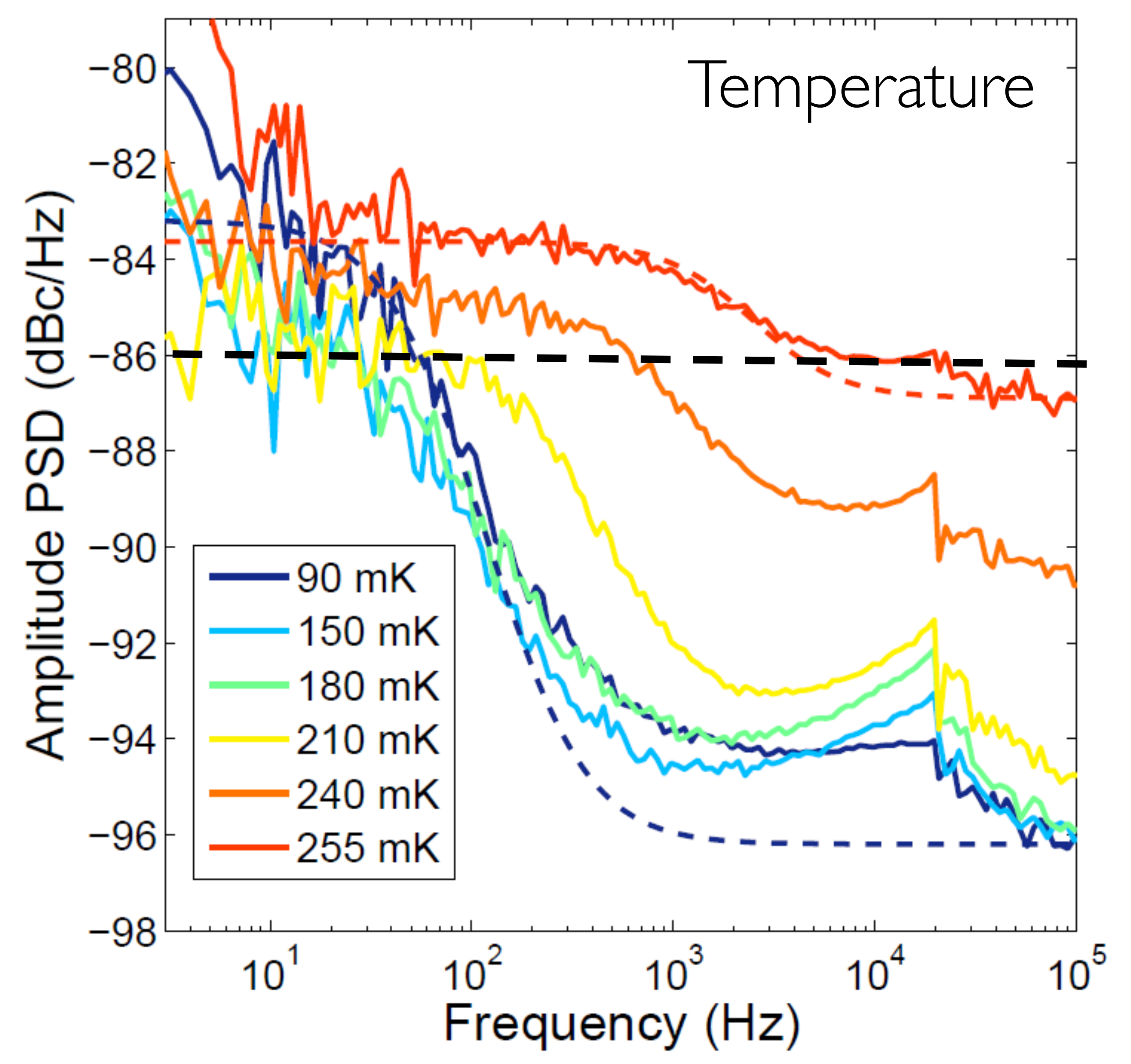
Noise levels





✔

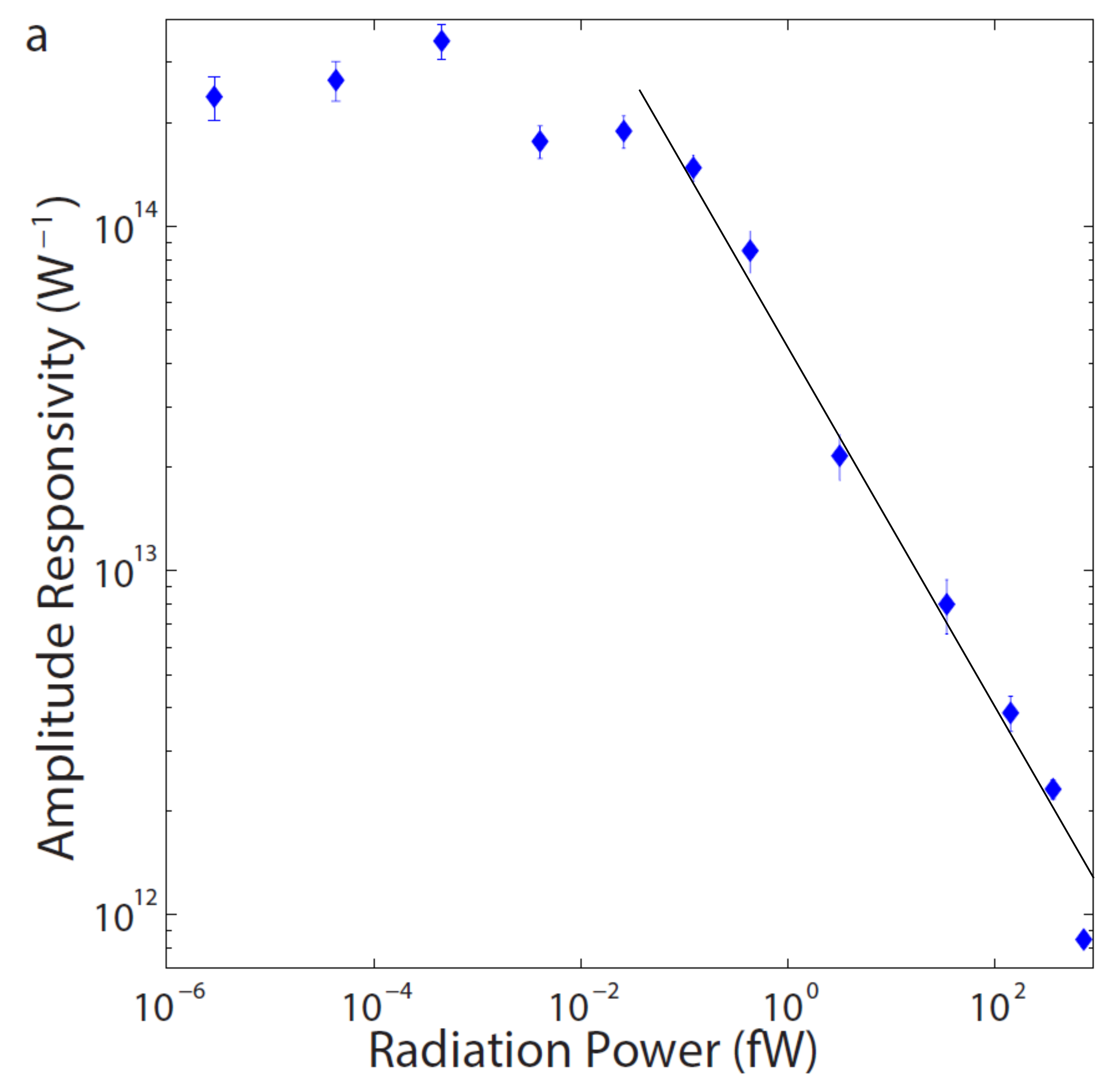
Optical responsivity

Responsivity = change in response upon a change in power

Scales with 1/sqrt(P), because Nqp changes, but also the lifetime with 1/Nqp

Thus, this is also a test of the relation

$\tau \; \alpha \; 1/n_{qp}$



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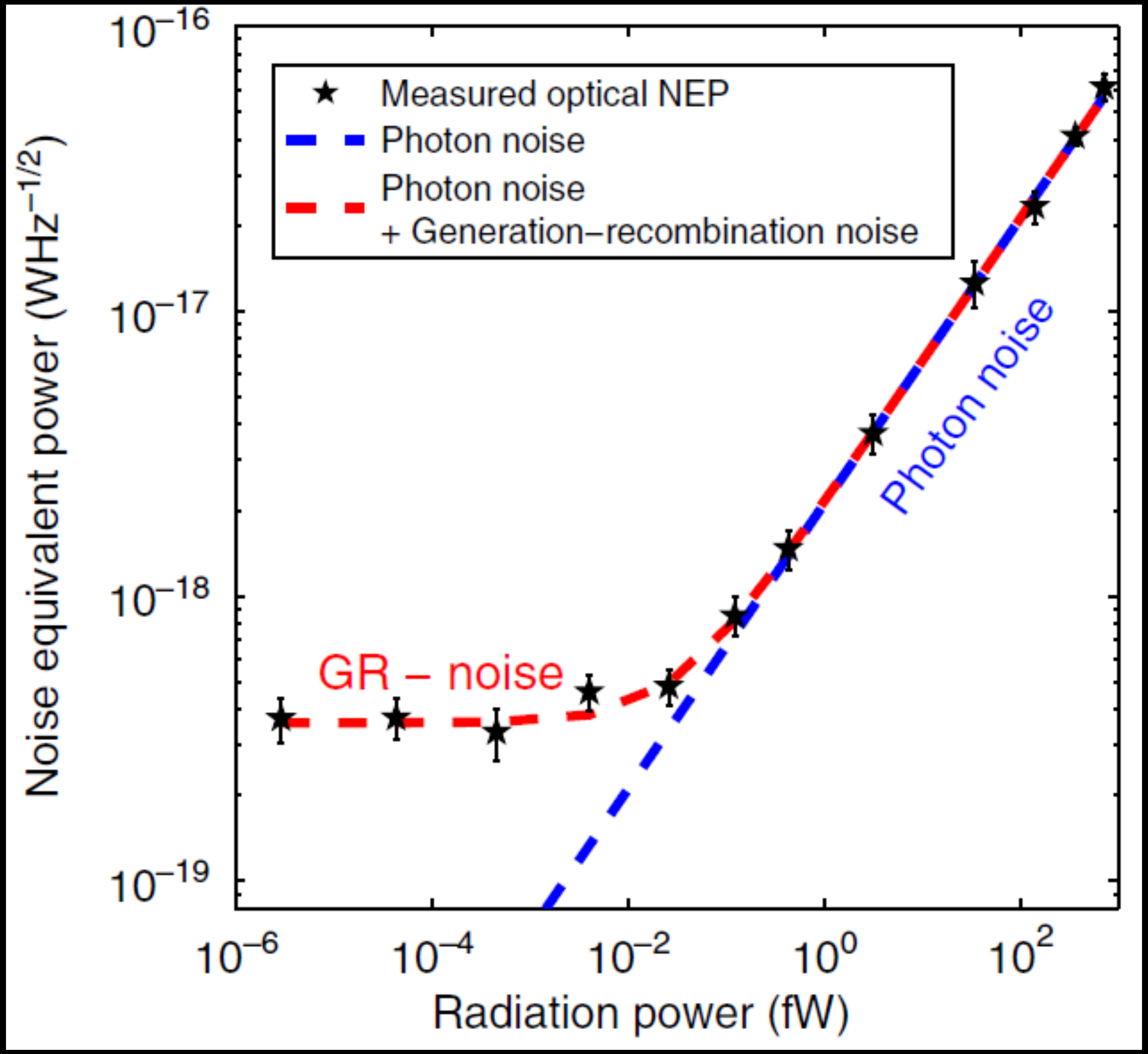
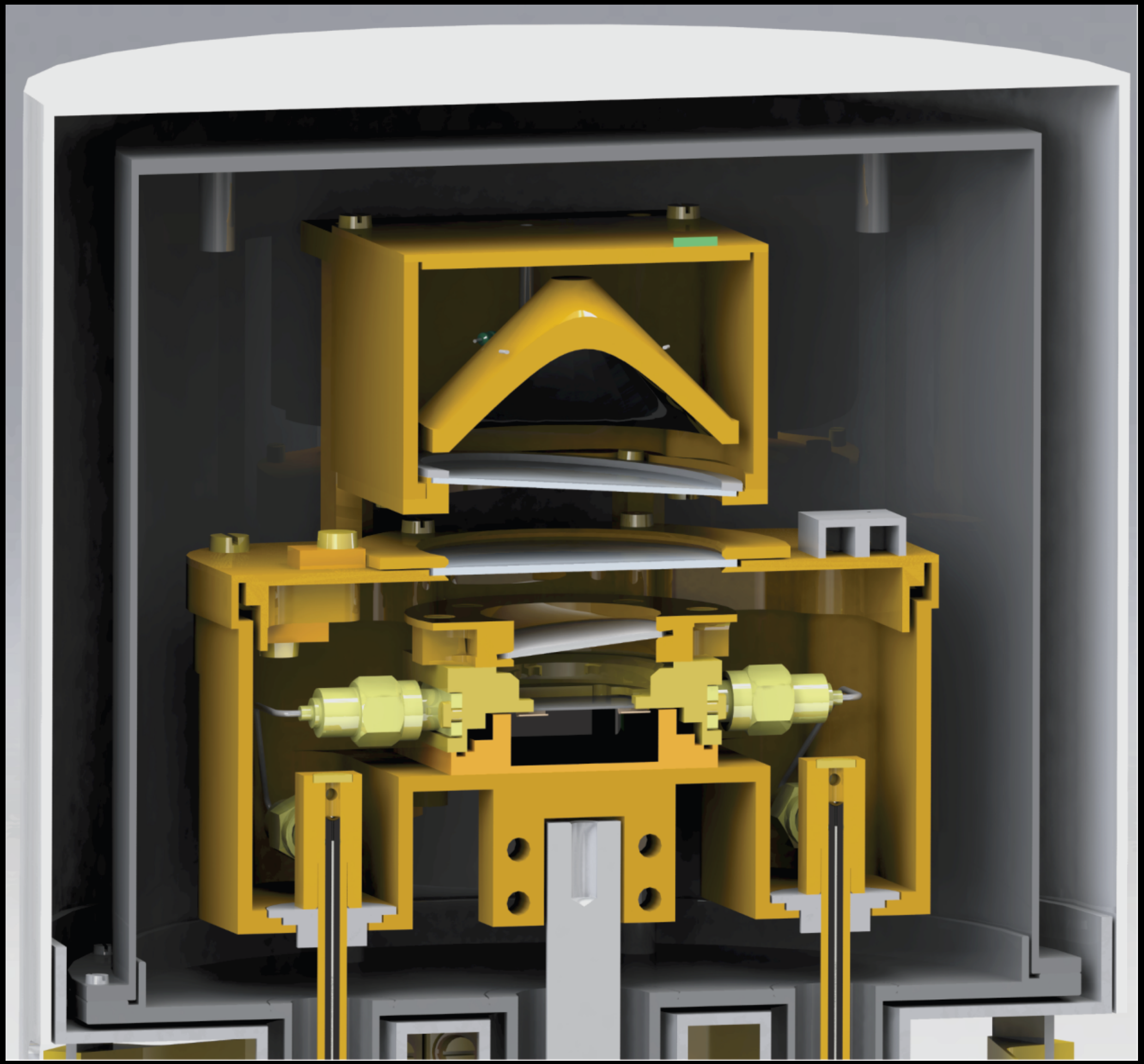
1.5 THz KID limited by fundamental (ie quasiparticle) noise processes



Nature Communications 5, 3130 (2014)

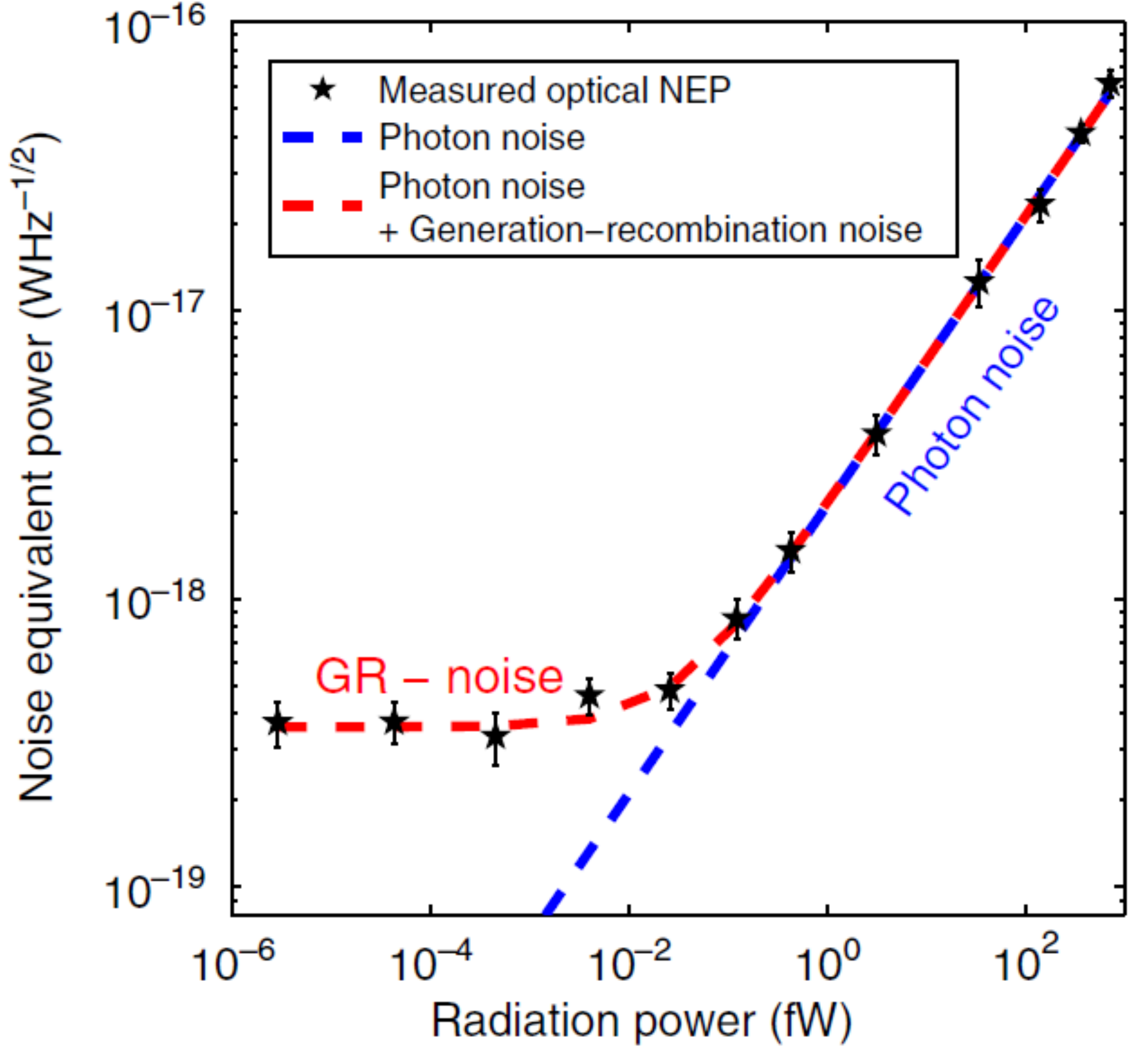


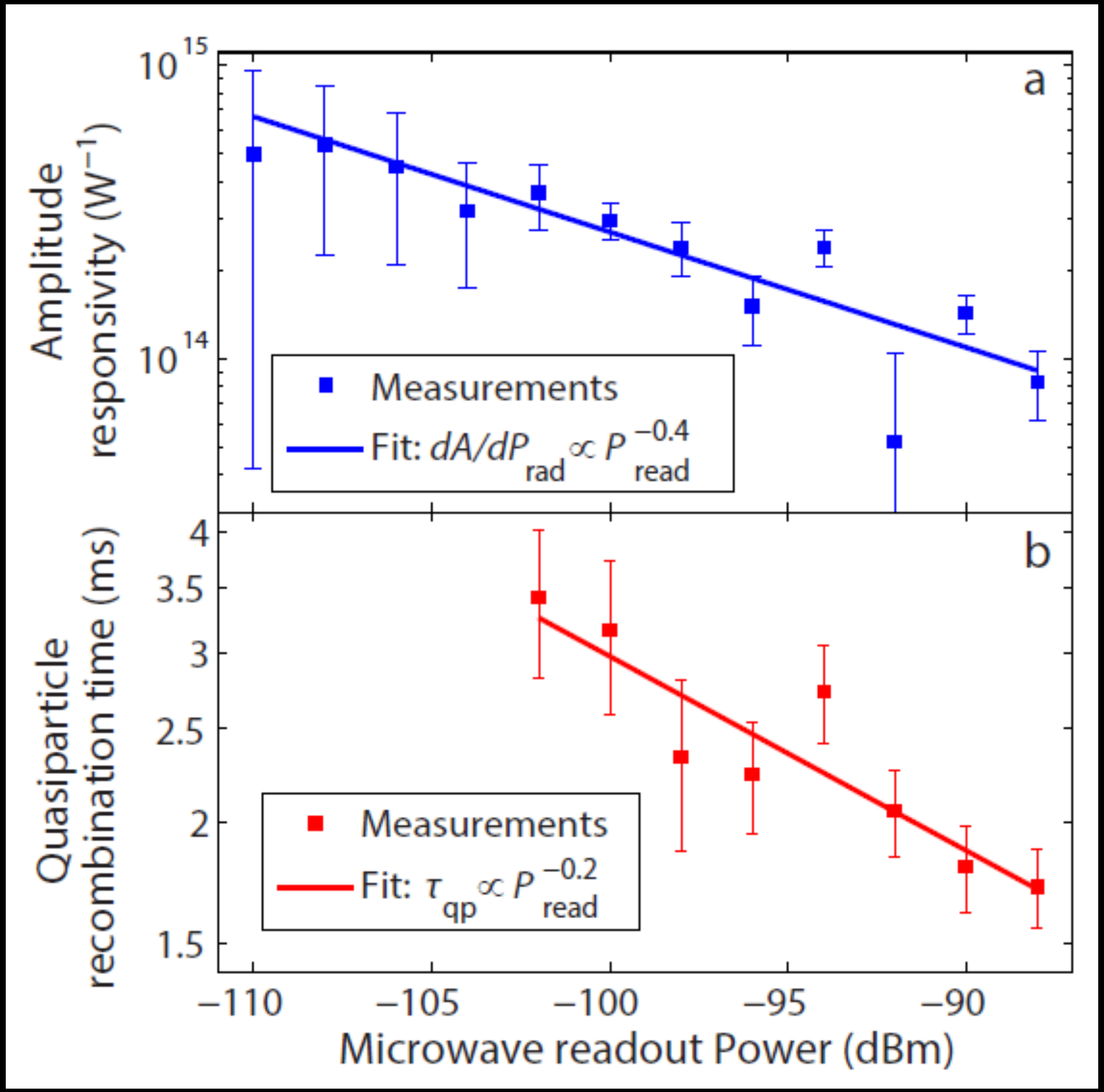
Not limited by stray-light

✓

Corresponds very well with dark NEP measured in similar resonator

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





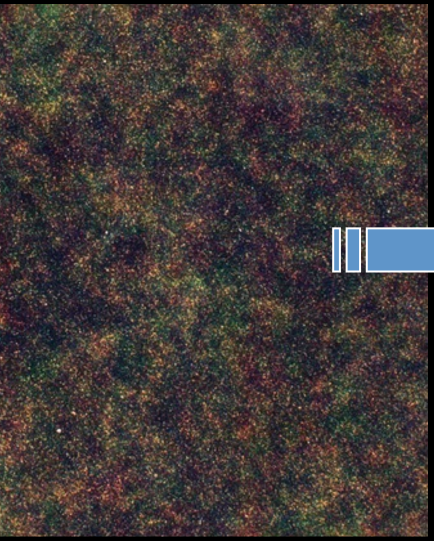
Detector sensitivity limited by excess QPs due to microwave readout

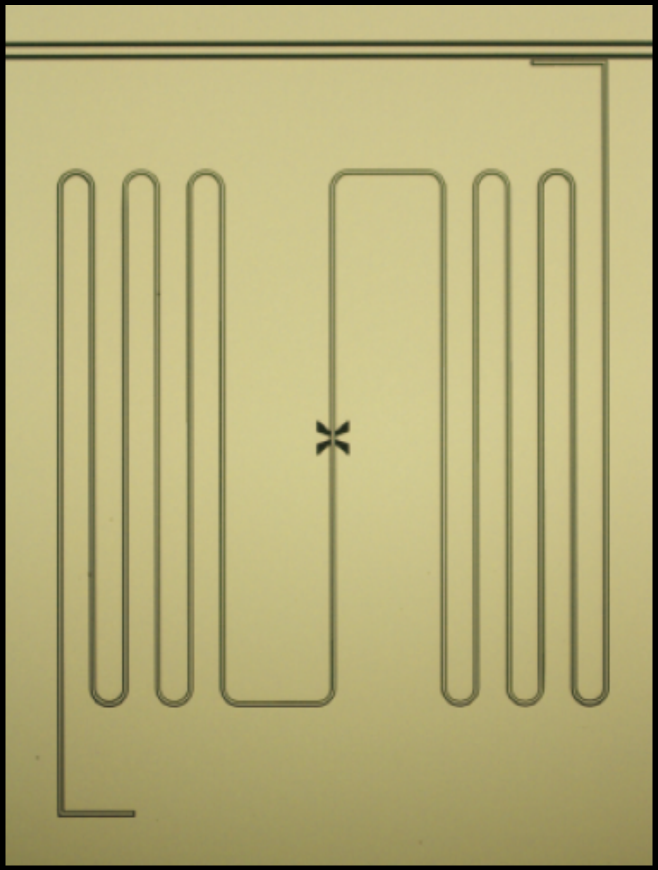
Nature Communications 5, 3130 (2014)

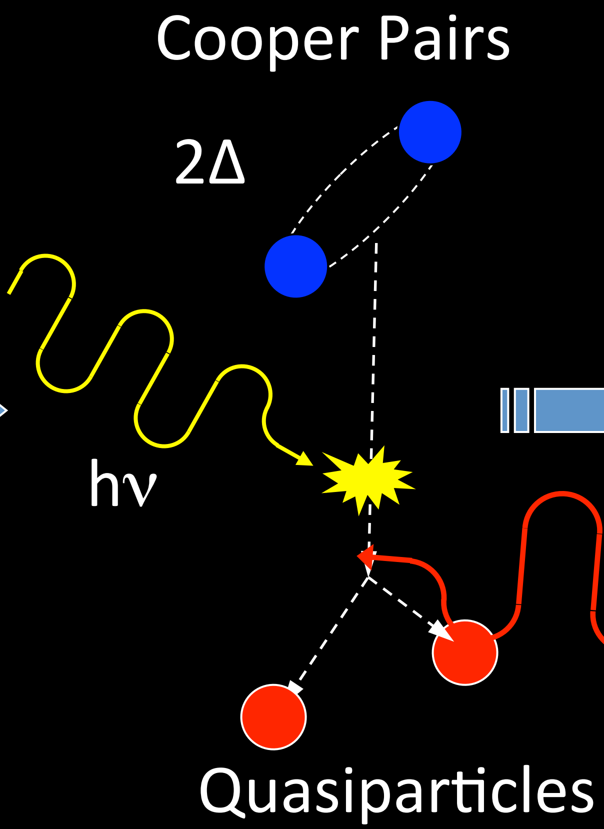
We can do the same now for 1000 pixel chips (Jochem Baselmans' talk)

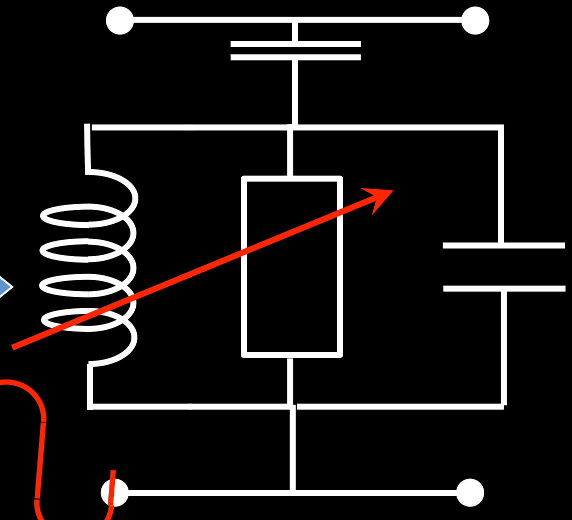
Pair-breaking photons vs energy

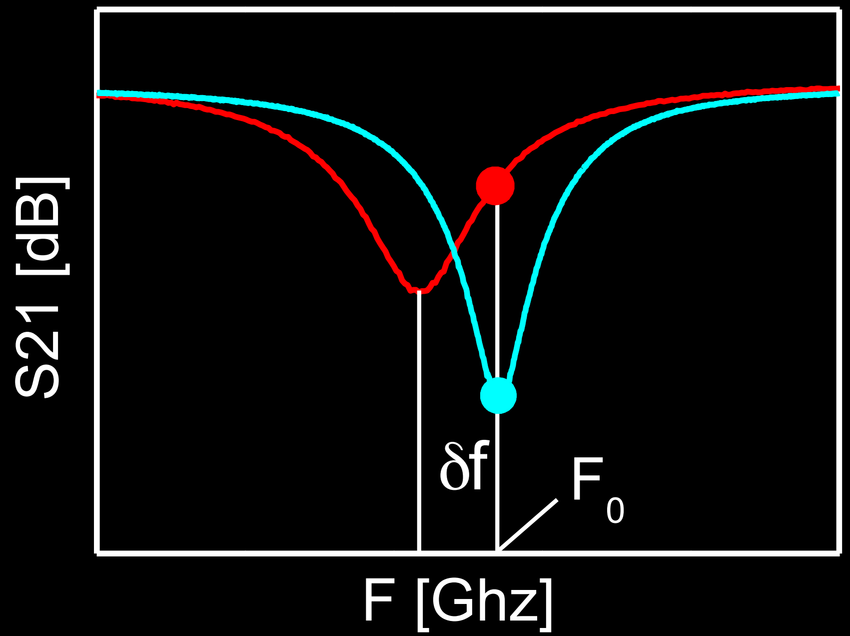
From light to signal











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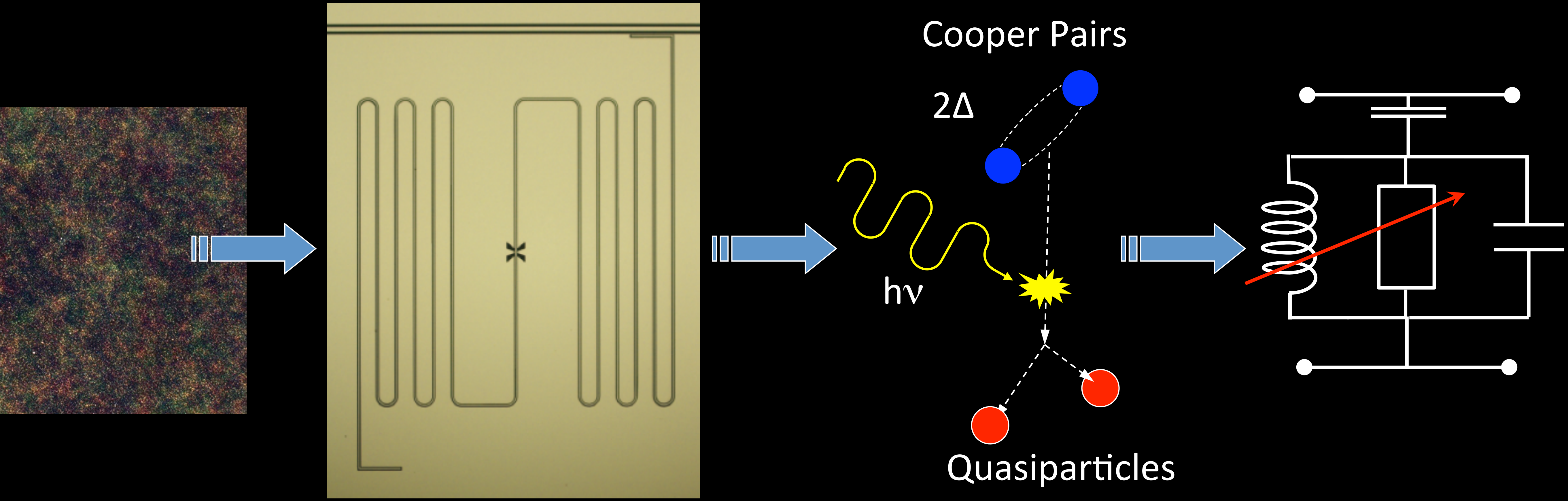
$$\eta_{opt} \boxed{\eta_{pb}} P_{rad} = \frac{N_{qp} \Delta}{\tau_{qp}}$$

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

From light to signal



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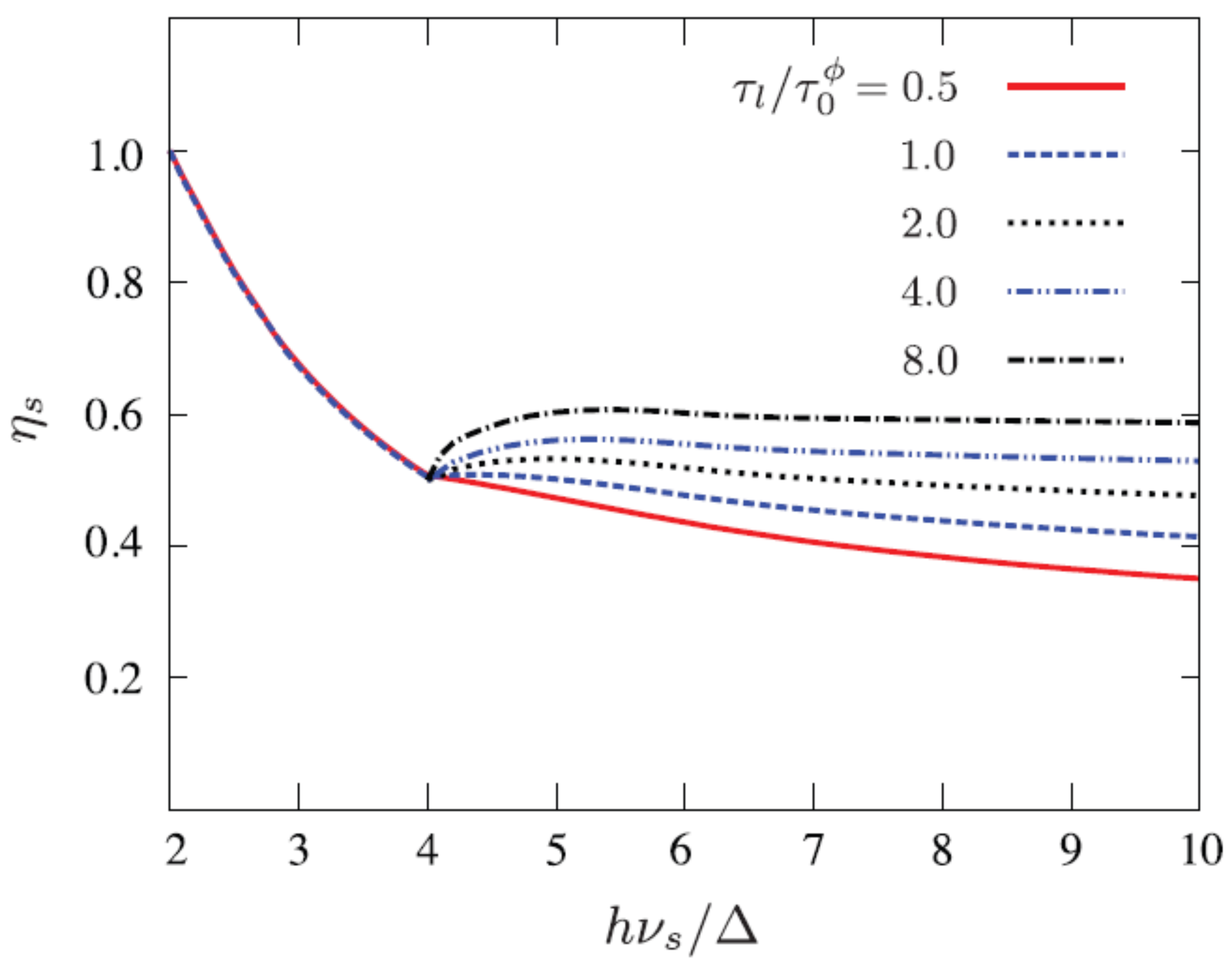
Microwave: Q_i, A

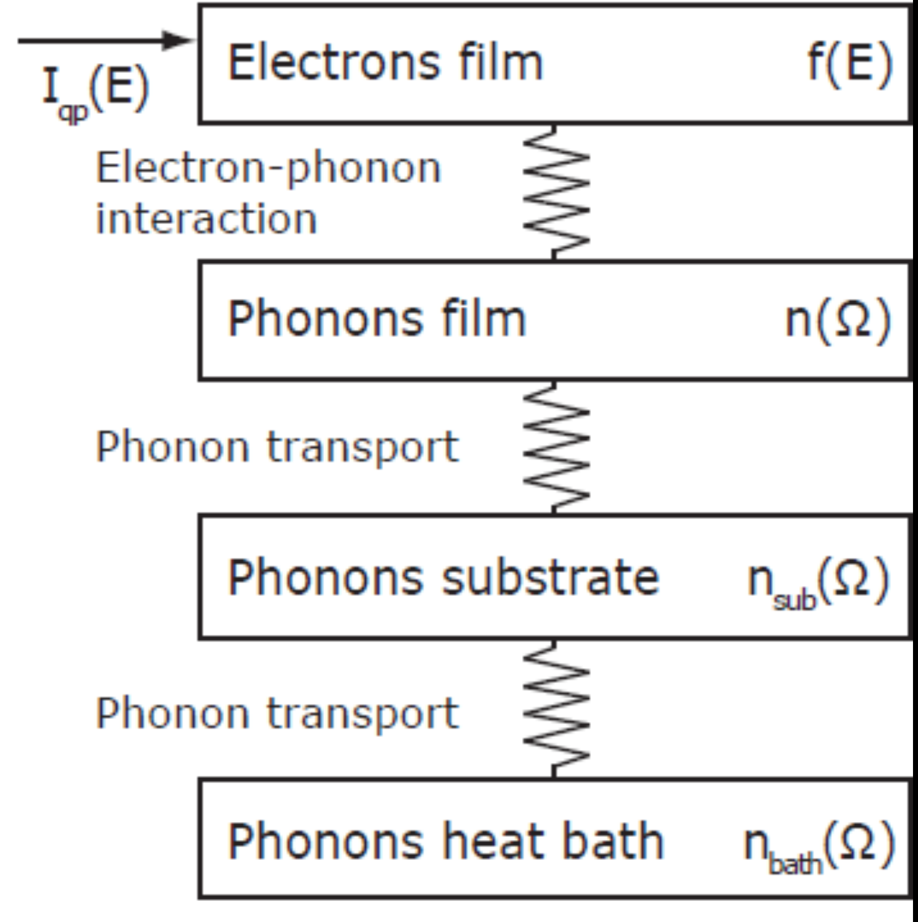
Pair breaking

Microwave: f_{res}, θ

‘Efficiency’ in converting photon energy to QPs close to the gap



Phonon trapping factor

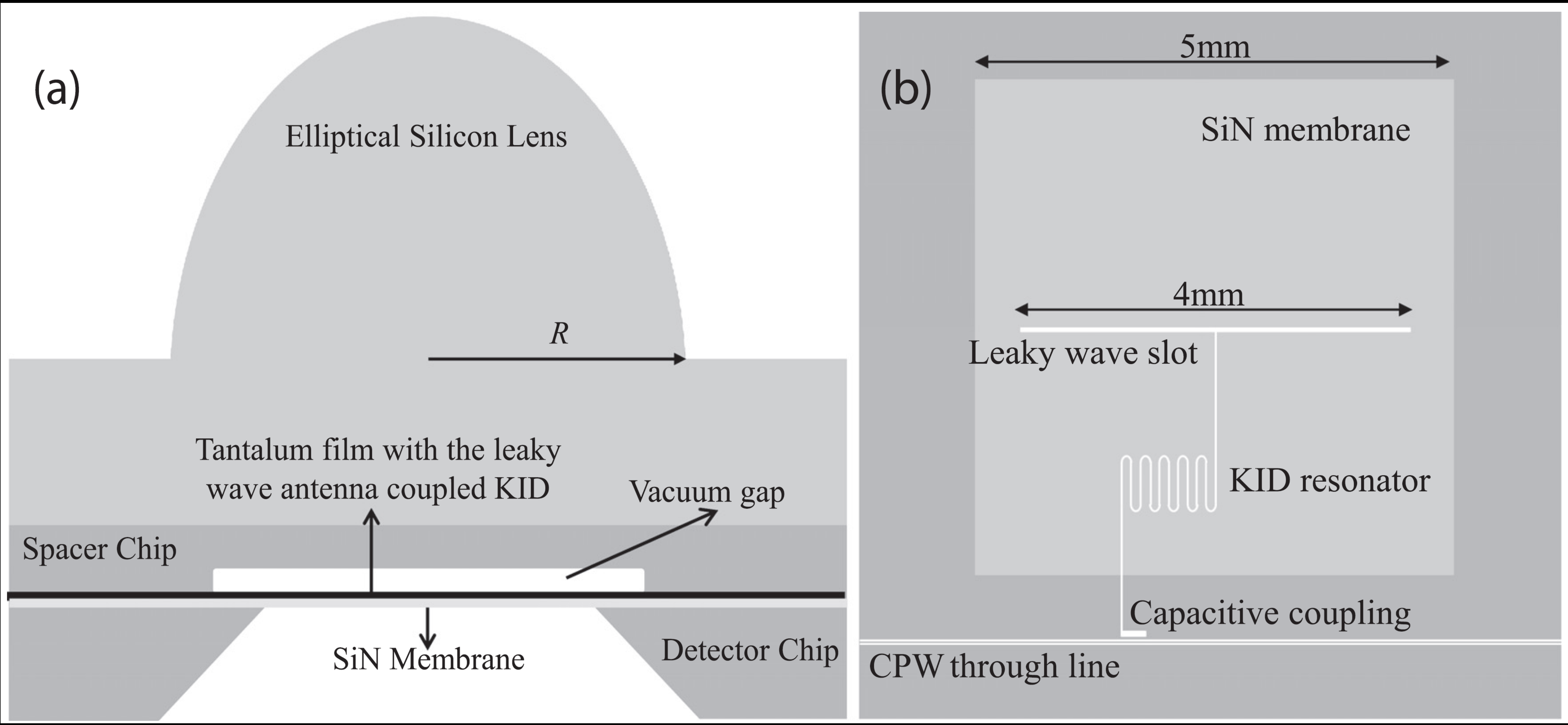


Kinetic equations, steady state, constant injected power but different energy
Guruswamy, Goldie, Withington, SuST 27, 055012 (2014)
Arises because observable is mainly sensitive to quasiparticles close to gap

Broadband antenna + lens

Tantalum KID, energy gap at 324 GHz

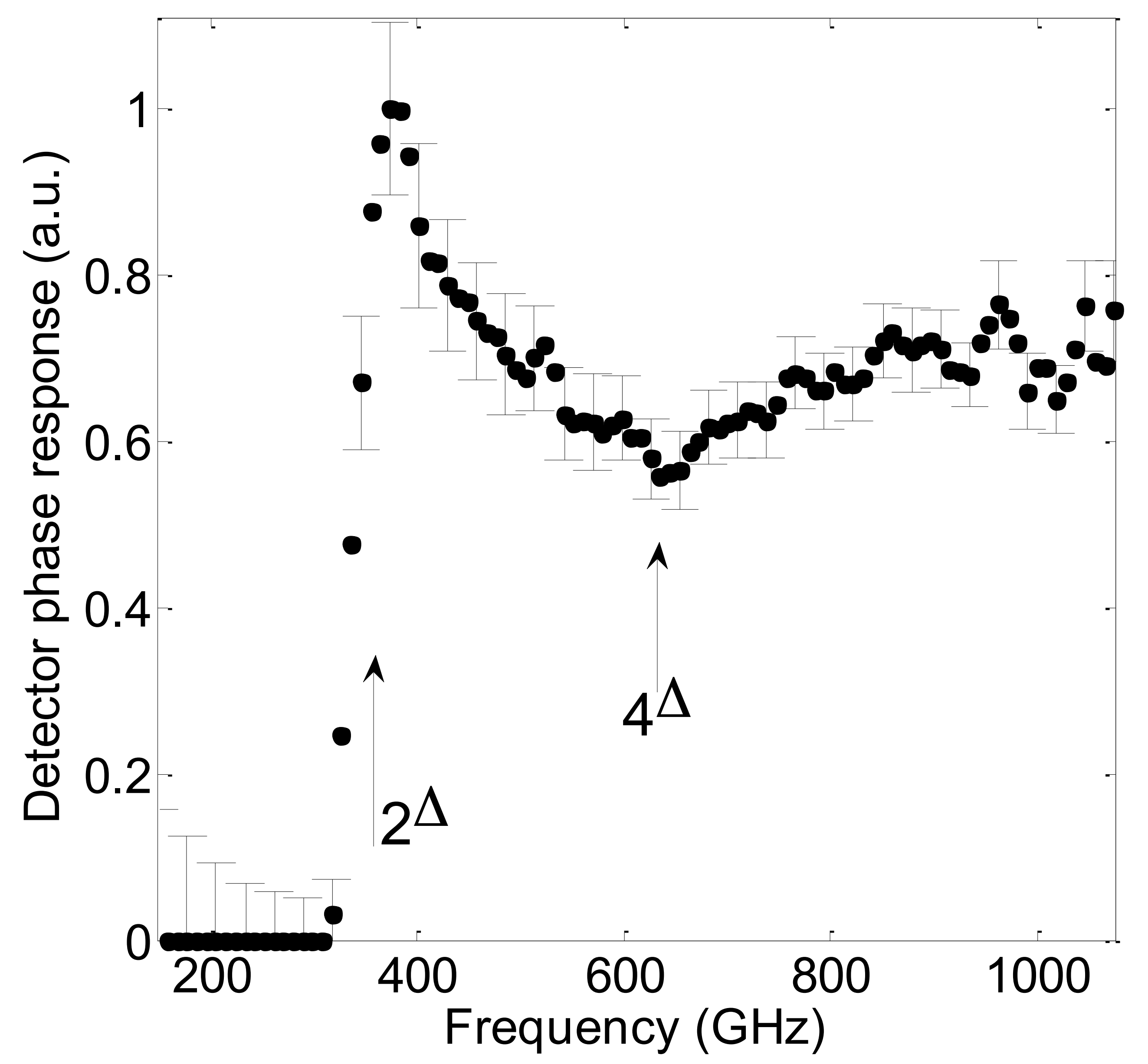
Absorber detector will not work, due to $Z_s(\omega)$, ~constant absorbed power needed!



Neto, IEEE Trans. Antennas and Prop. 58, 2238 (2010)

Neto et al. IEEE Trans. THz Sci. Tech. 4, 26 (2013)

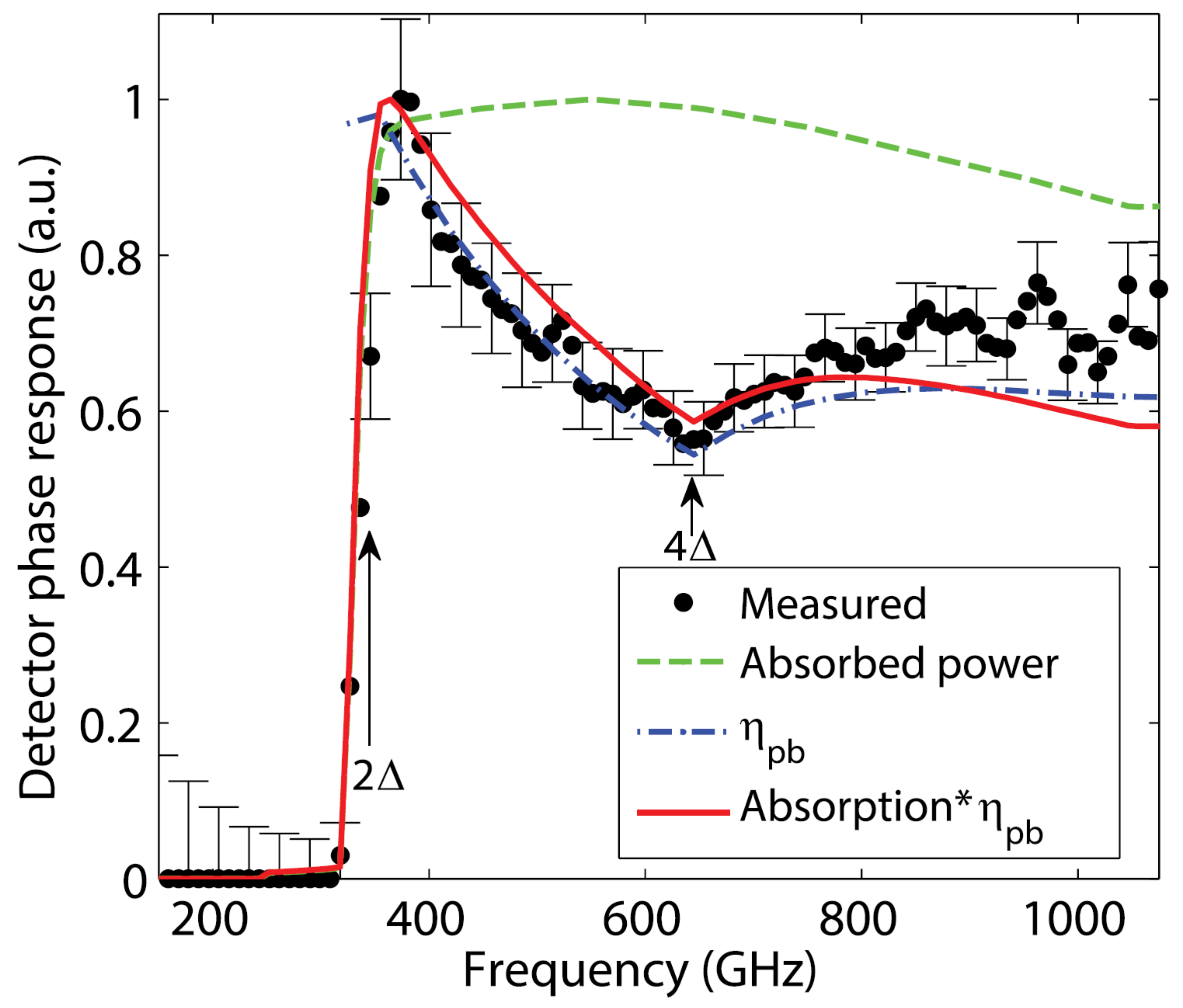
FTS response of Tantalum KID



Absorption measurement, KID is detector in FTS

- FTS dependence (calibrated)
- Antenna efficiency
- Absorption superconductor
- Response superconductor

We measured 'pair-breaking efficiency' due to f(E,F)



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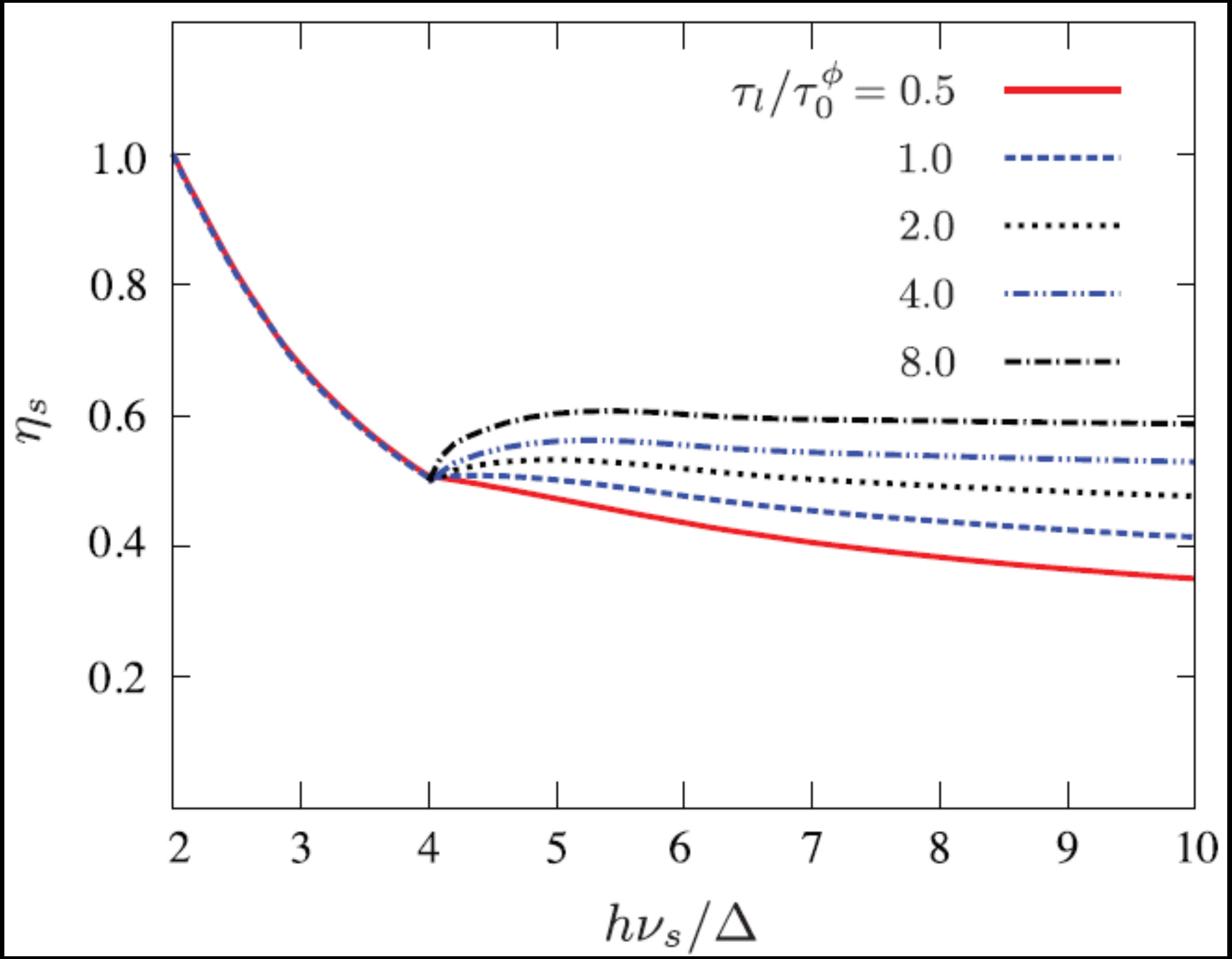
Appl. Phys. Lett. 106, 252602 (2015)

‘Efficiency’ in converting photon energy to QPs close to the gap



Why should we care?

- *Responsivity*, ie it is NOT an efficiency

- Recombination-noise vs photon noise ratio

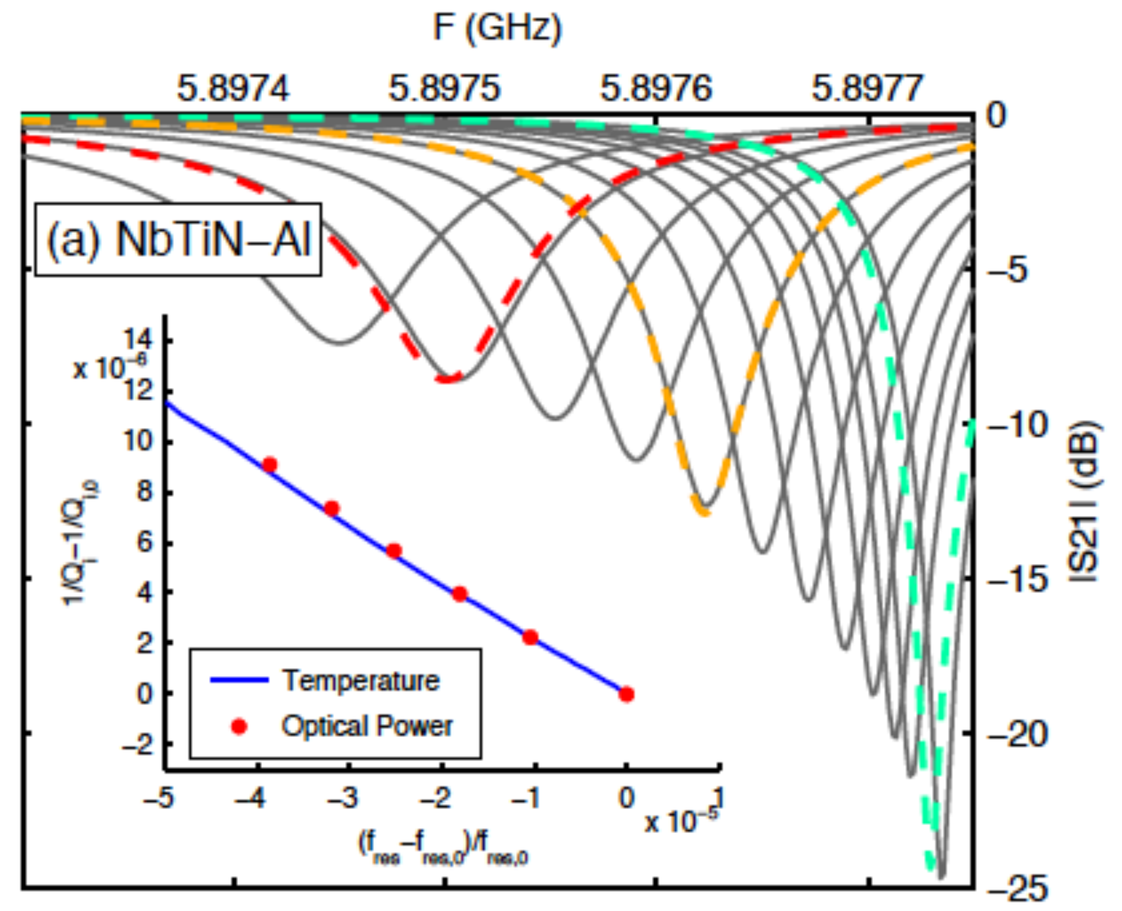
- Dark vs Optical NEP

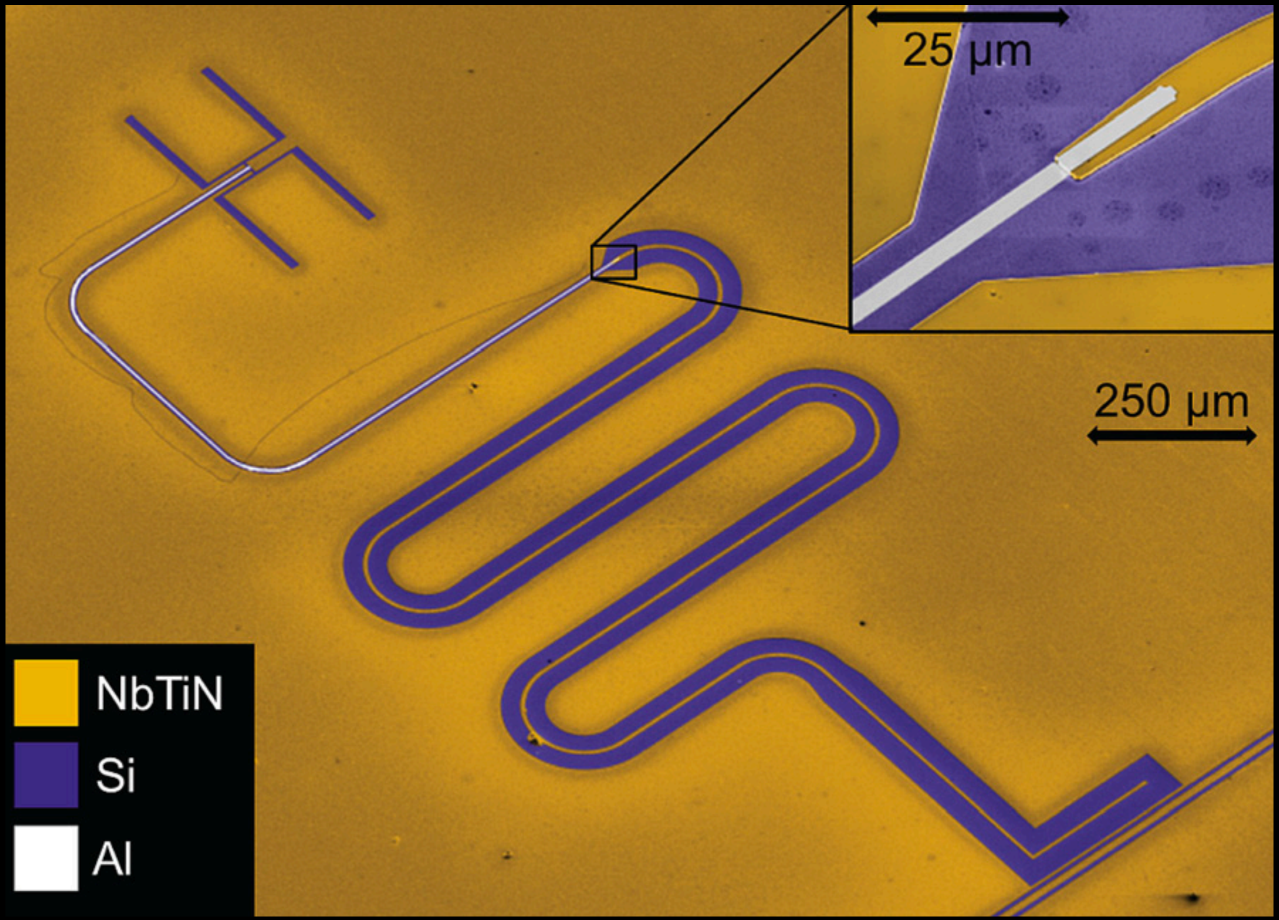
- It is the heart of the detector

Convention has long been to use eta = 0.6, but only valid for strong phonon trapping and E>>Δ (Kozorezov et al. PRB 77, 014501, 2008)

Both conditions are not fulfilled in many recent experiments.

Dark, thermal vs optical response





In well defined system with Al sensitive part, thermal and optical response agree, IF you take the correct 'pair-breaking efficiency'

Ie we know where the energy goes, recombination dynamics and electrodynamic response

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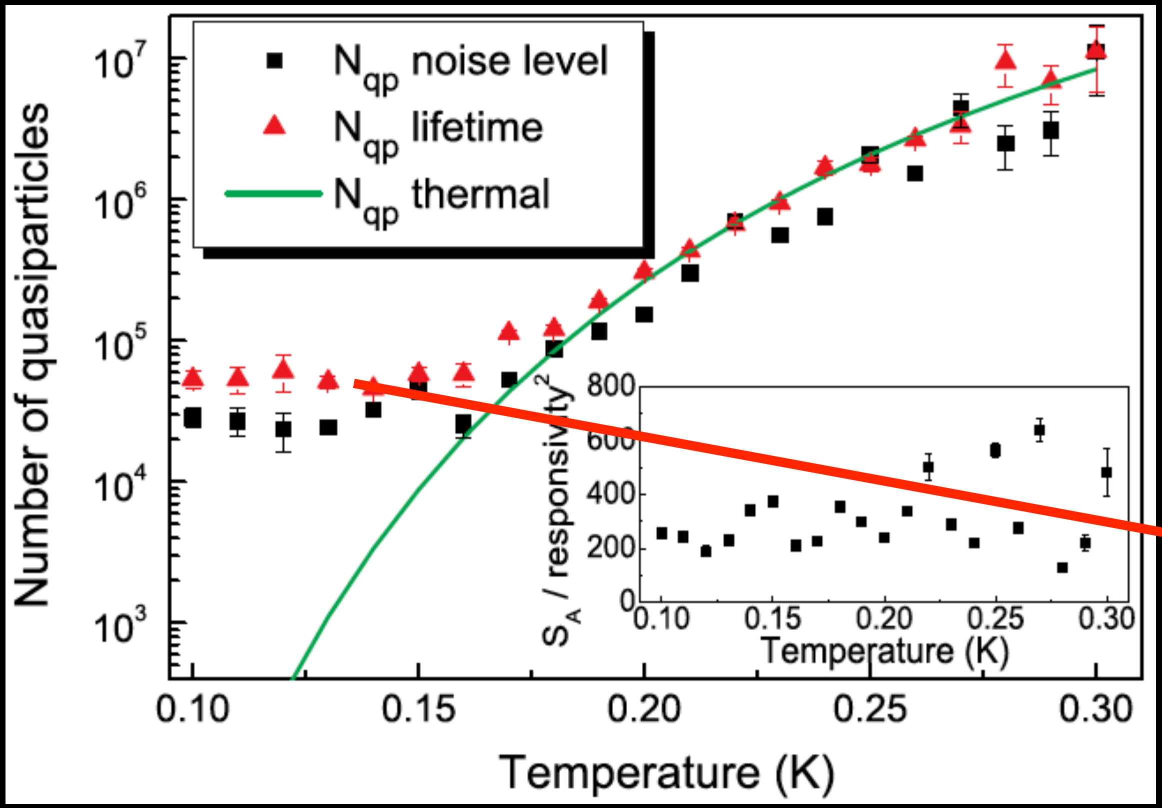
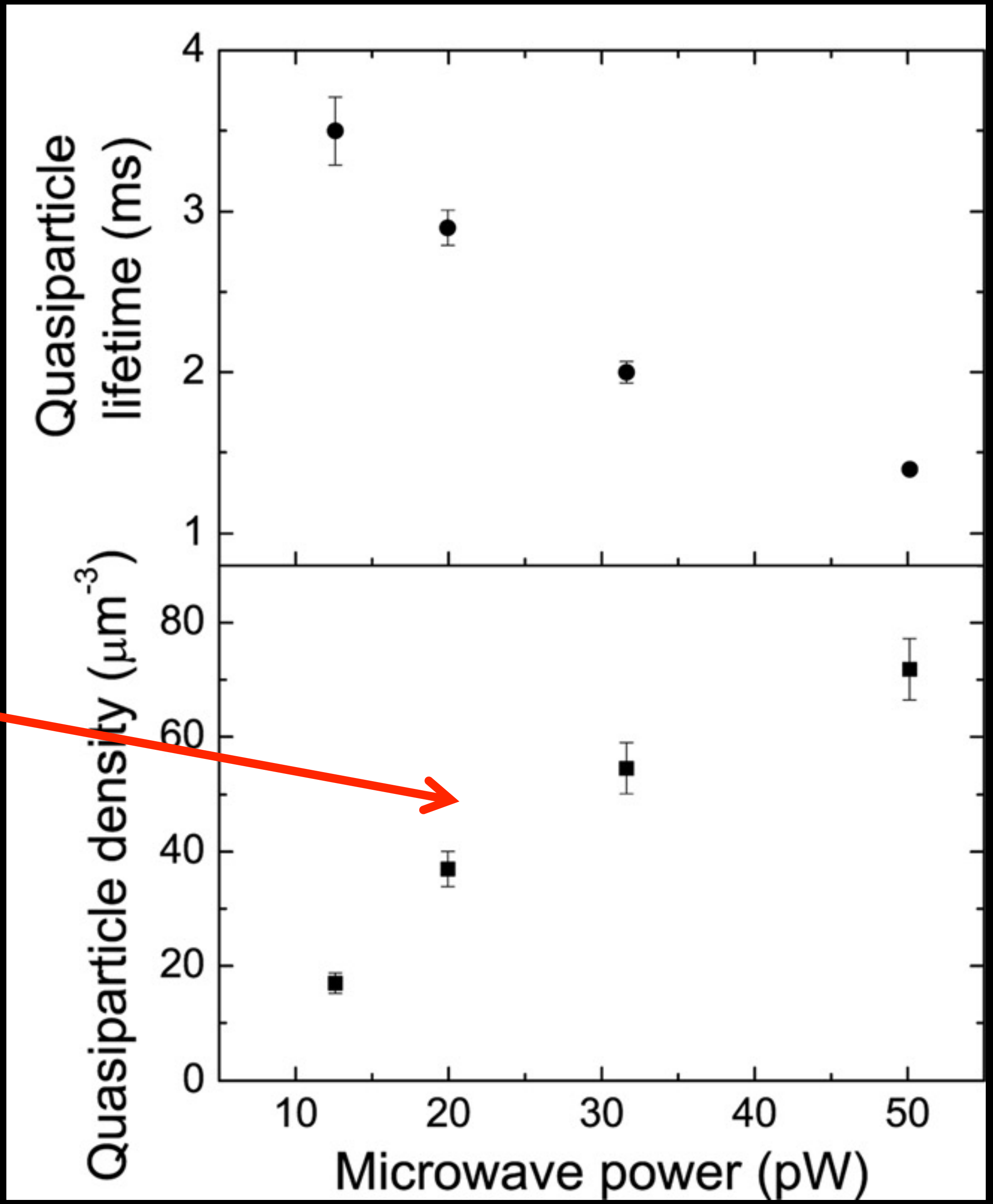
Janssen et al. APL105, 193504 (2014)

Microwave photons

Excess quasiparticles



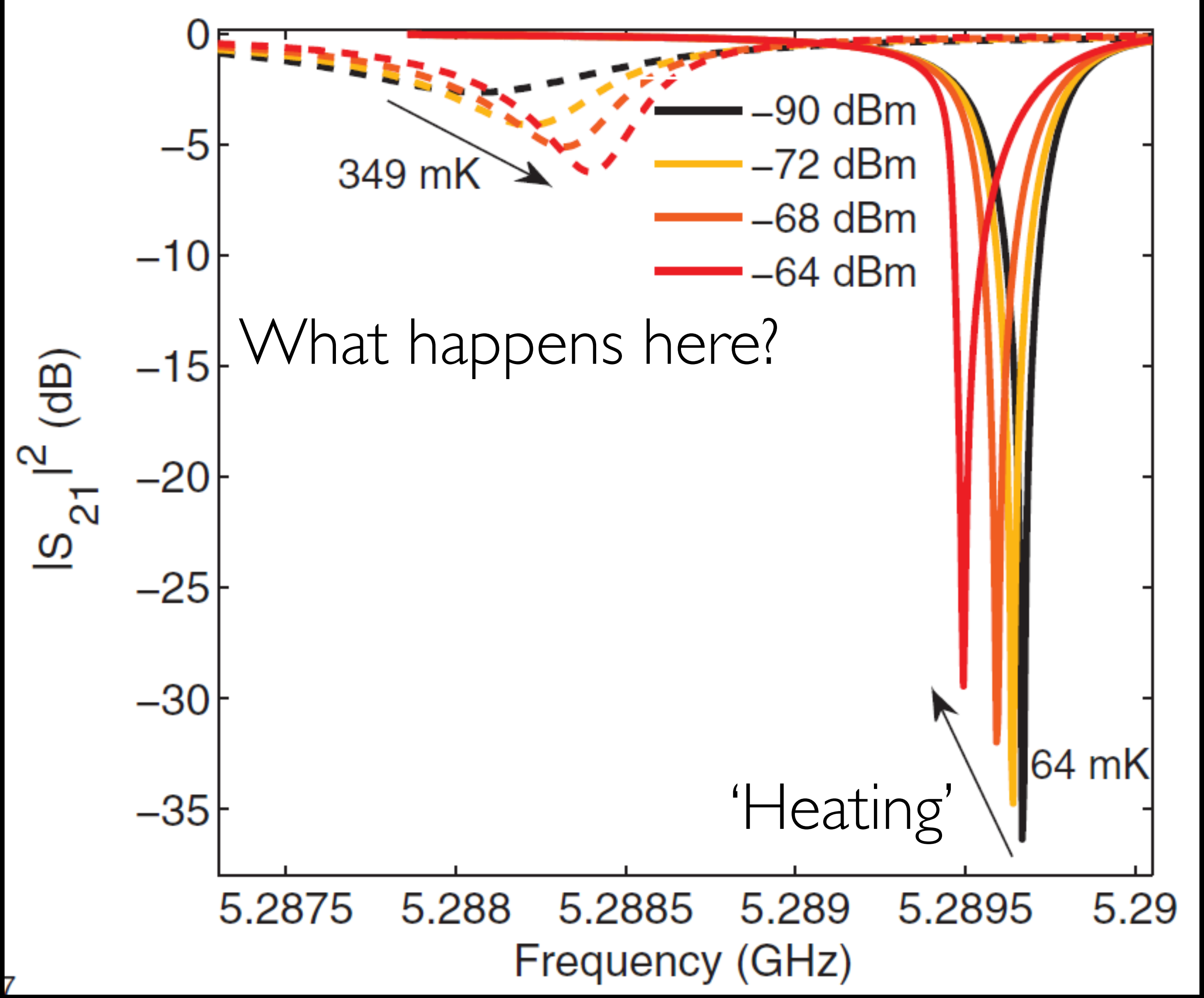
Phys. Rev. Lett. 106, 167004 (2011)



Microwave power dependent

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

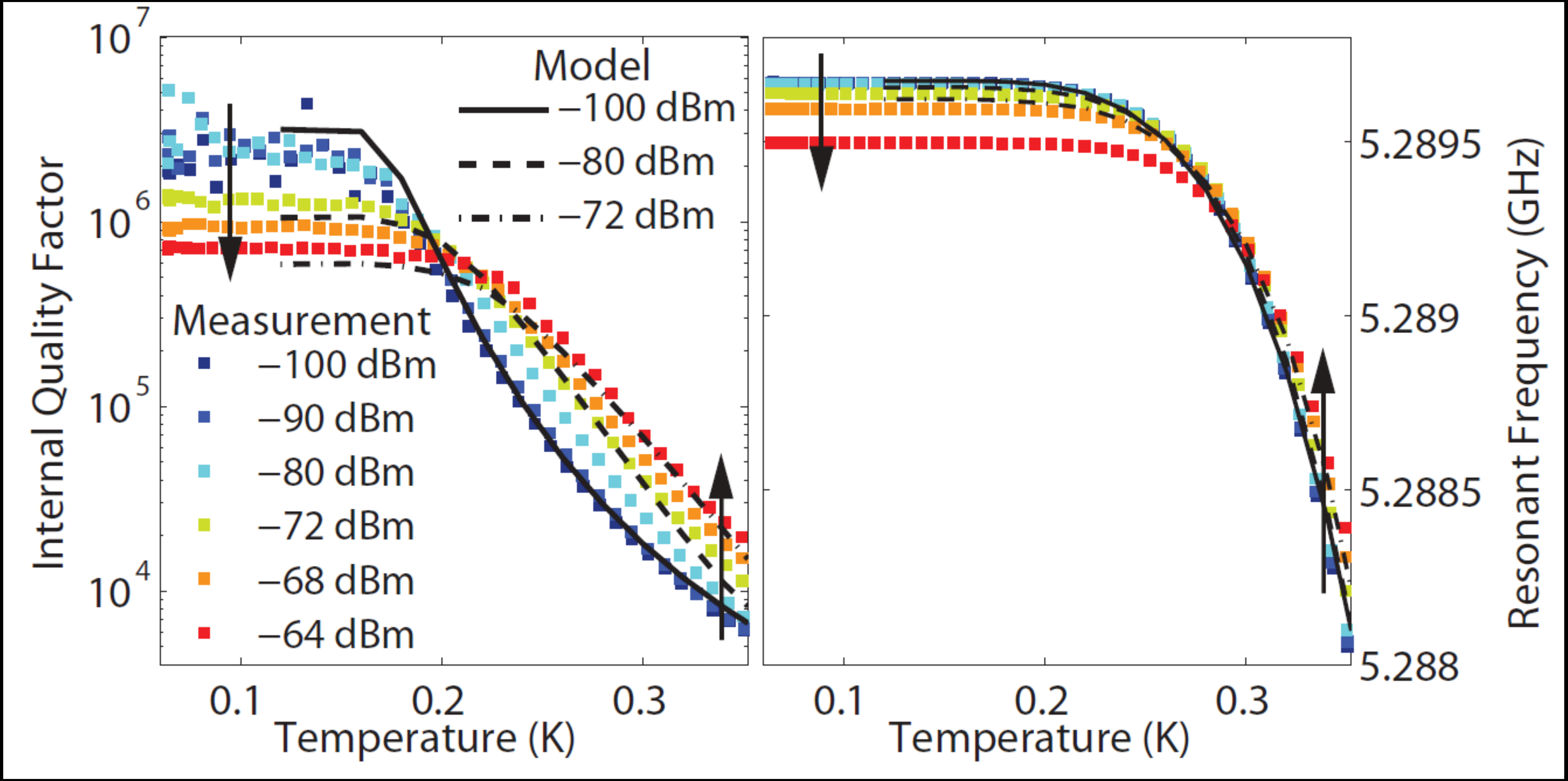
Non-linear resonator response curves



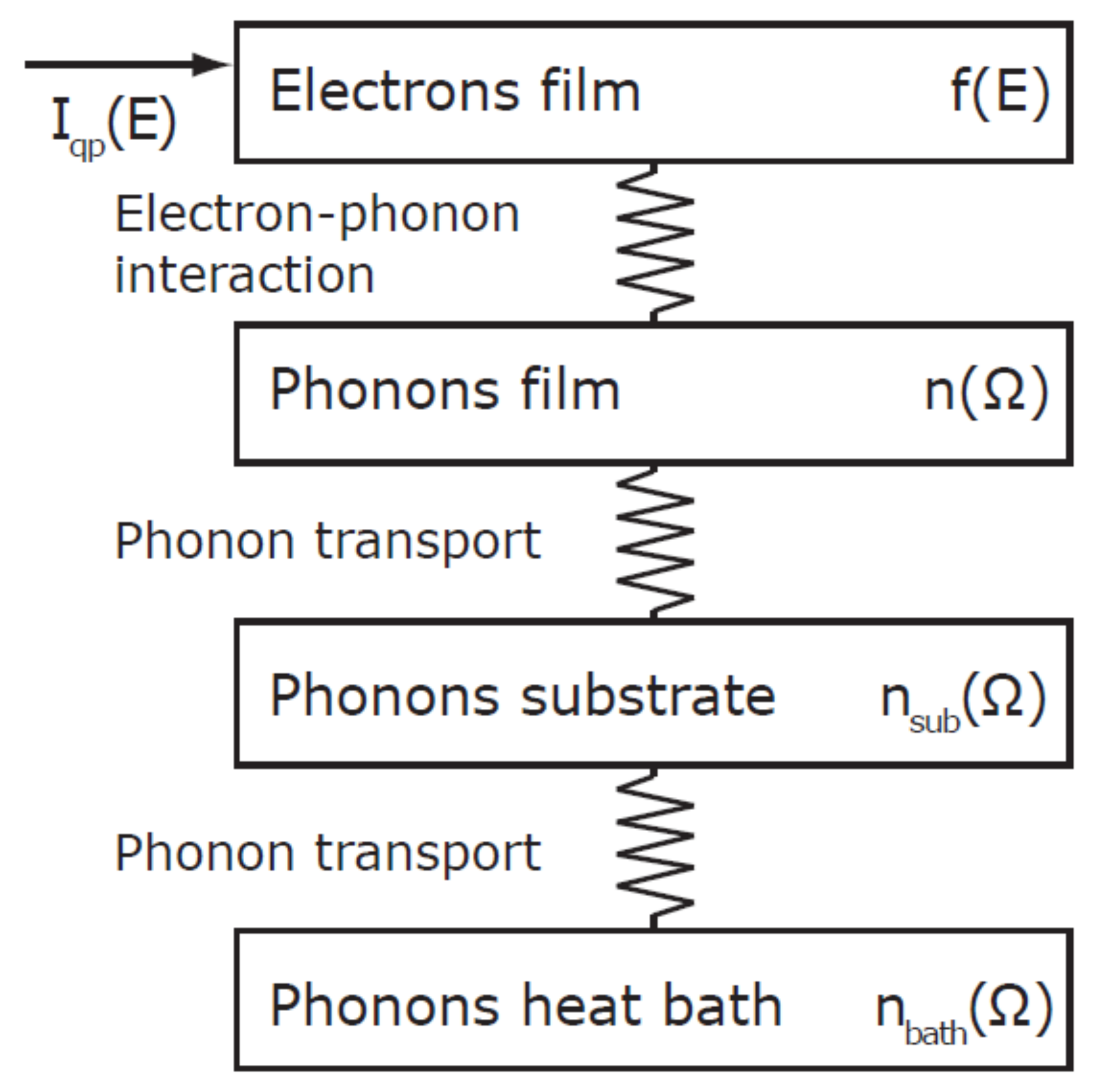
What happens here?

‘Heating’

Low T quasiparticle creation, but at higher T Q_i enhancement

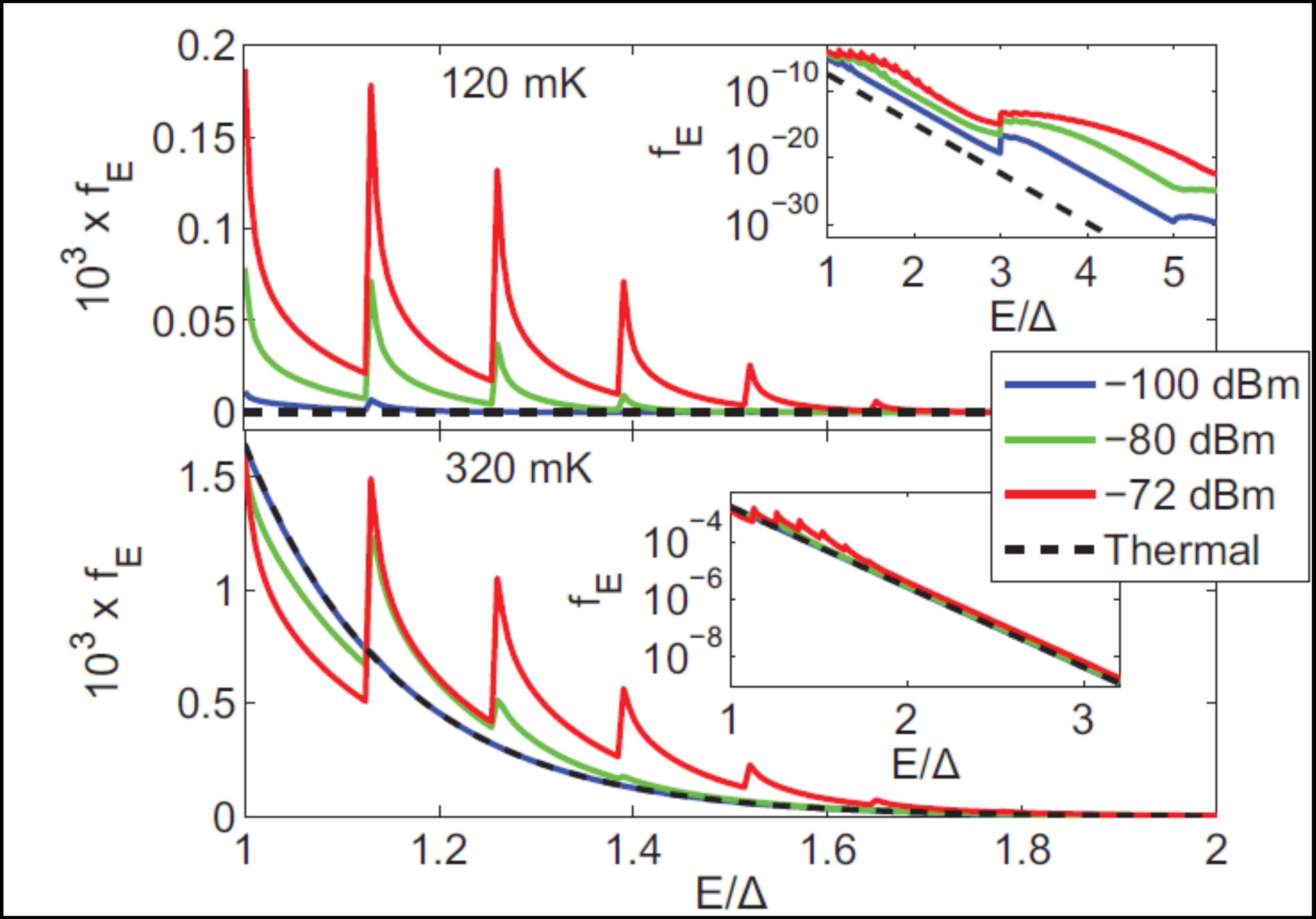


Non-equilibrium f(E)



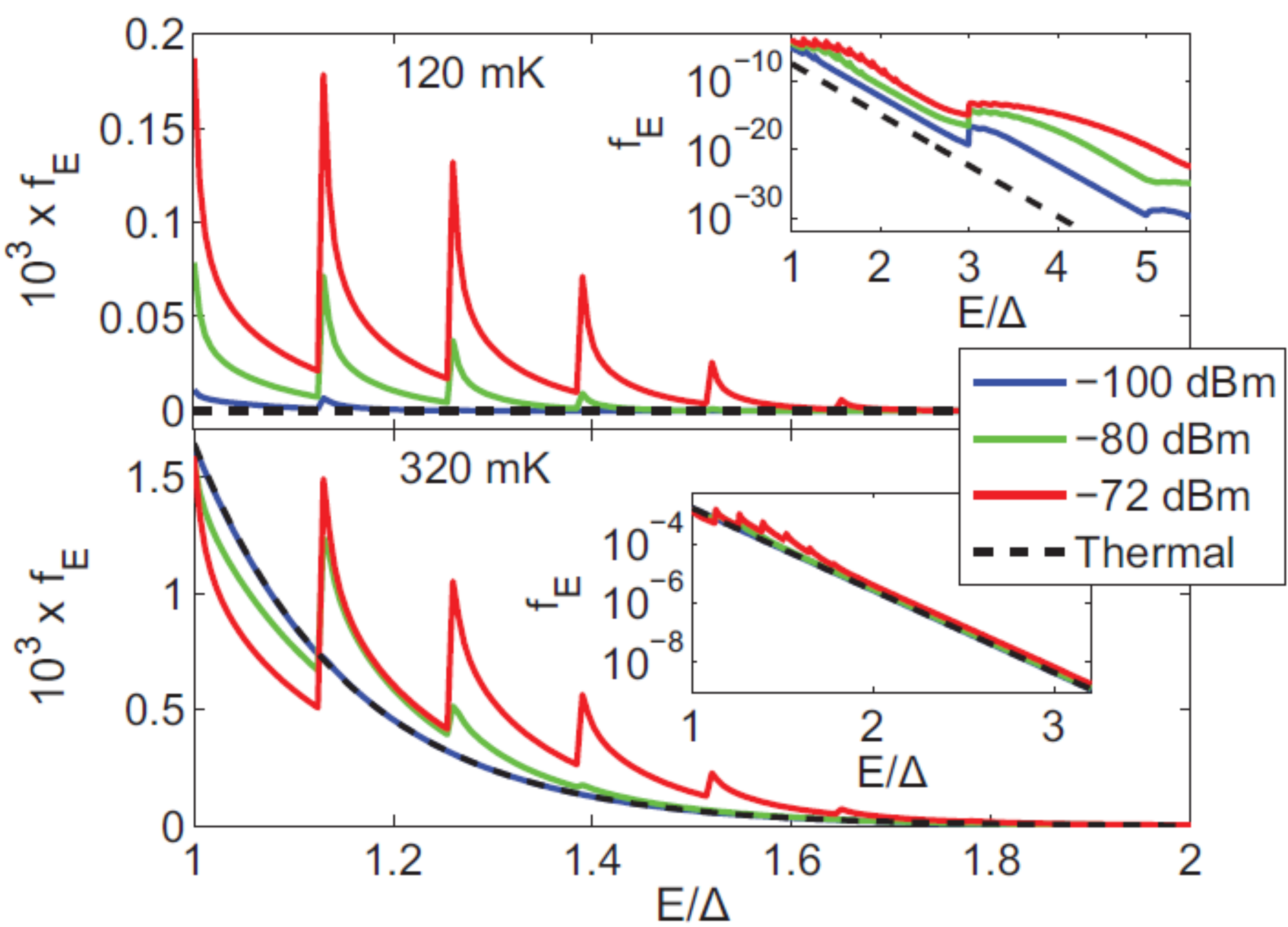
Ivlev, Lisitsyn, Eliashberg, JLPT 10, 449 (1973) - Microwave absorption, gap enhancement close to Tc
Chang and Scalapino, PRB 15, 2651 (1977) - kinetic equations
Goldie and Withington, SuST 26, 015004 (2013) – low temperature, resonators

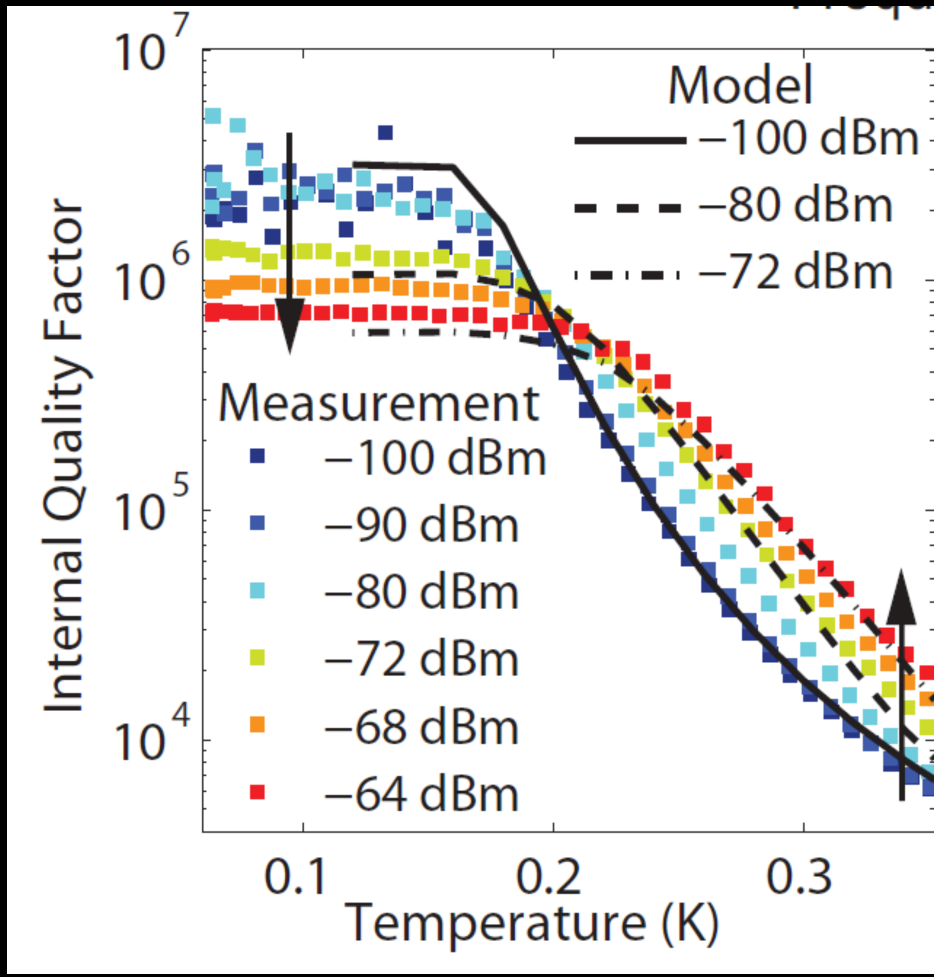
Non-equilibrium f(E) – steady state



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

Example f(E) -> σ_1, Q_i



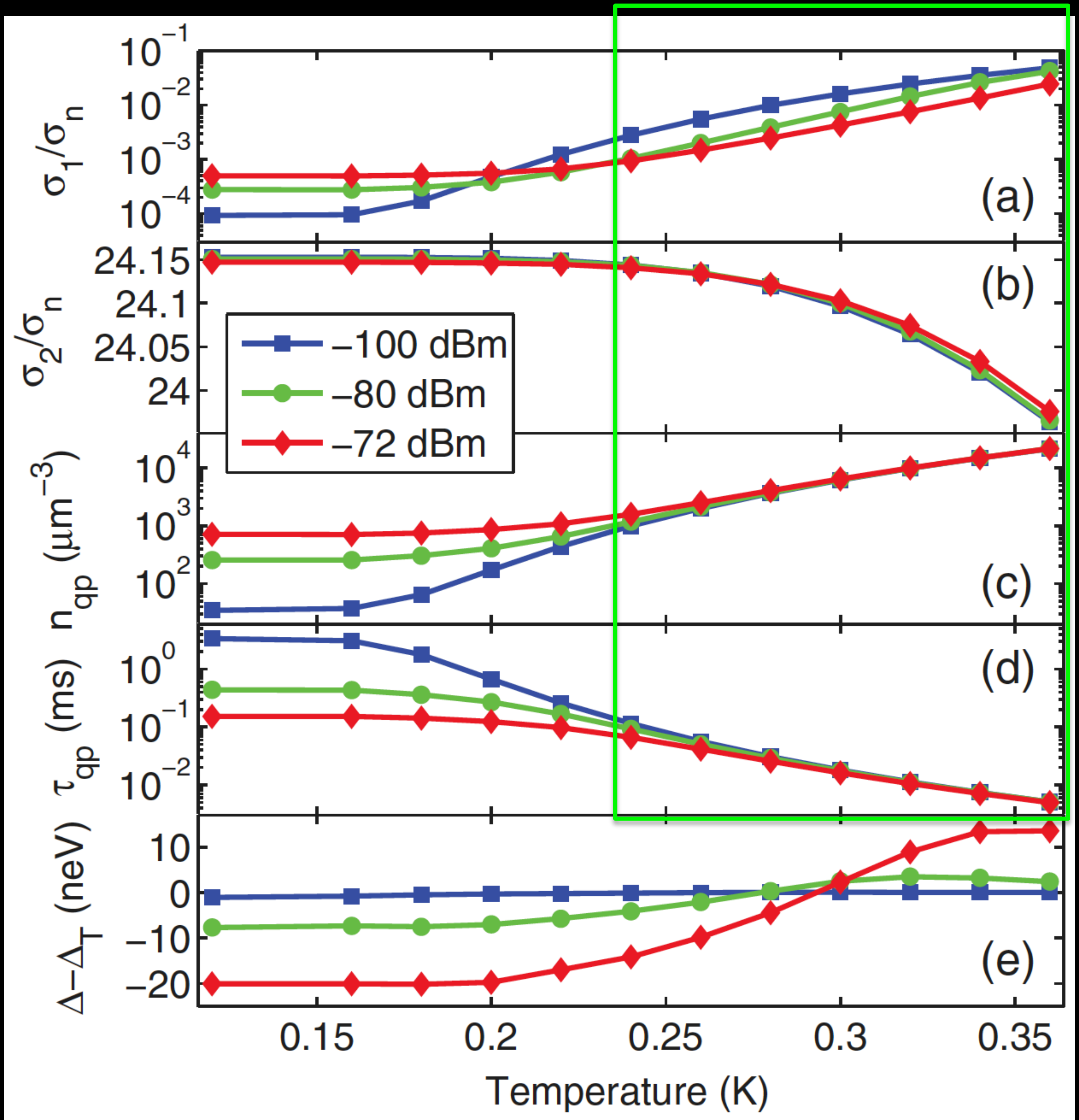


$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}[f(E) - f(E+\hbar\omega)]g_1(E)dE$$

✓

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

Other observables



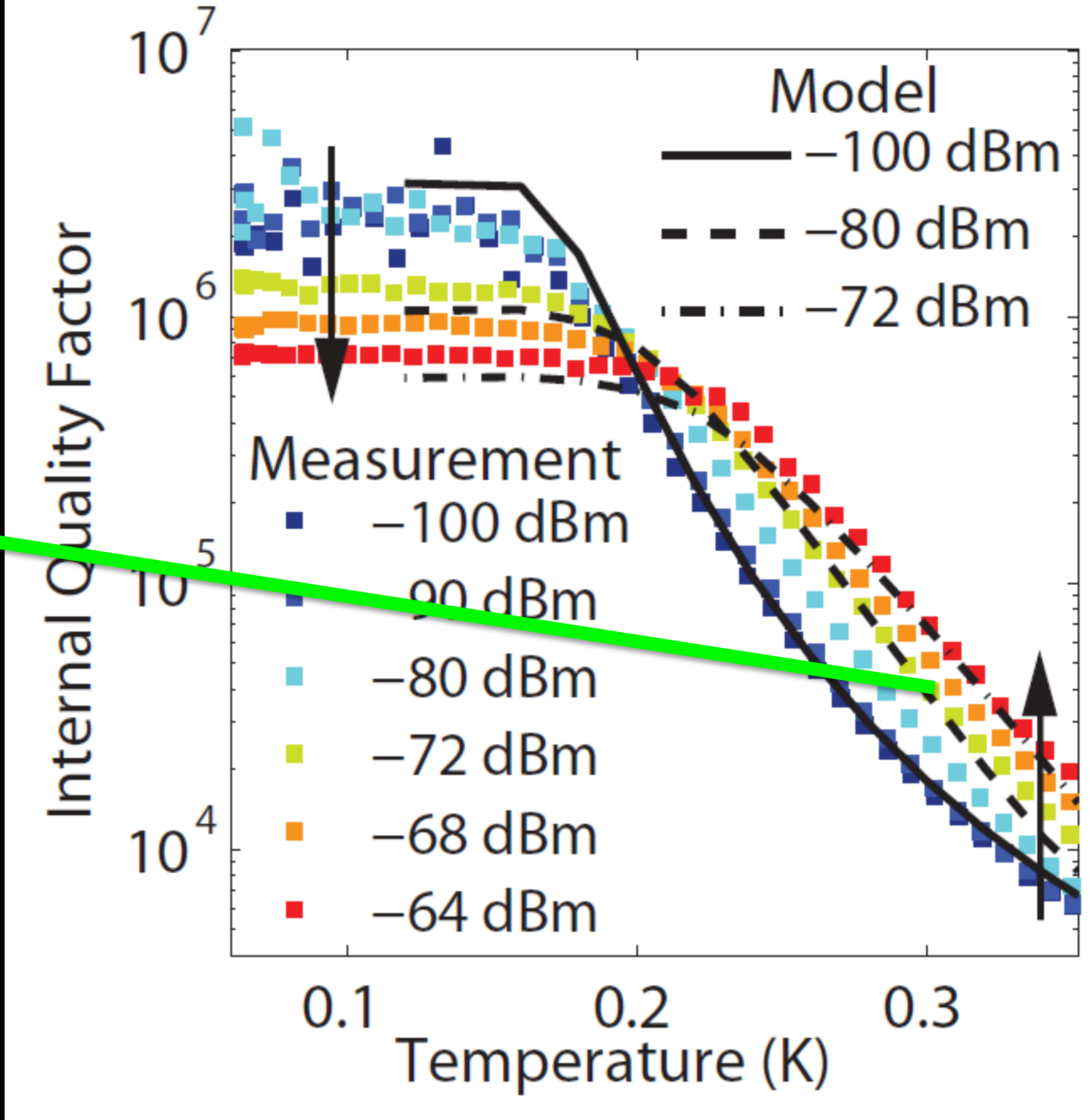
Consistent explanation of all MKID observables

Is this insight useful?

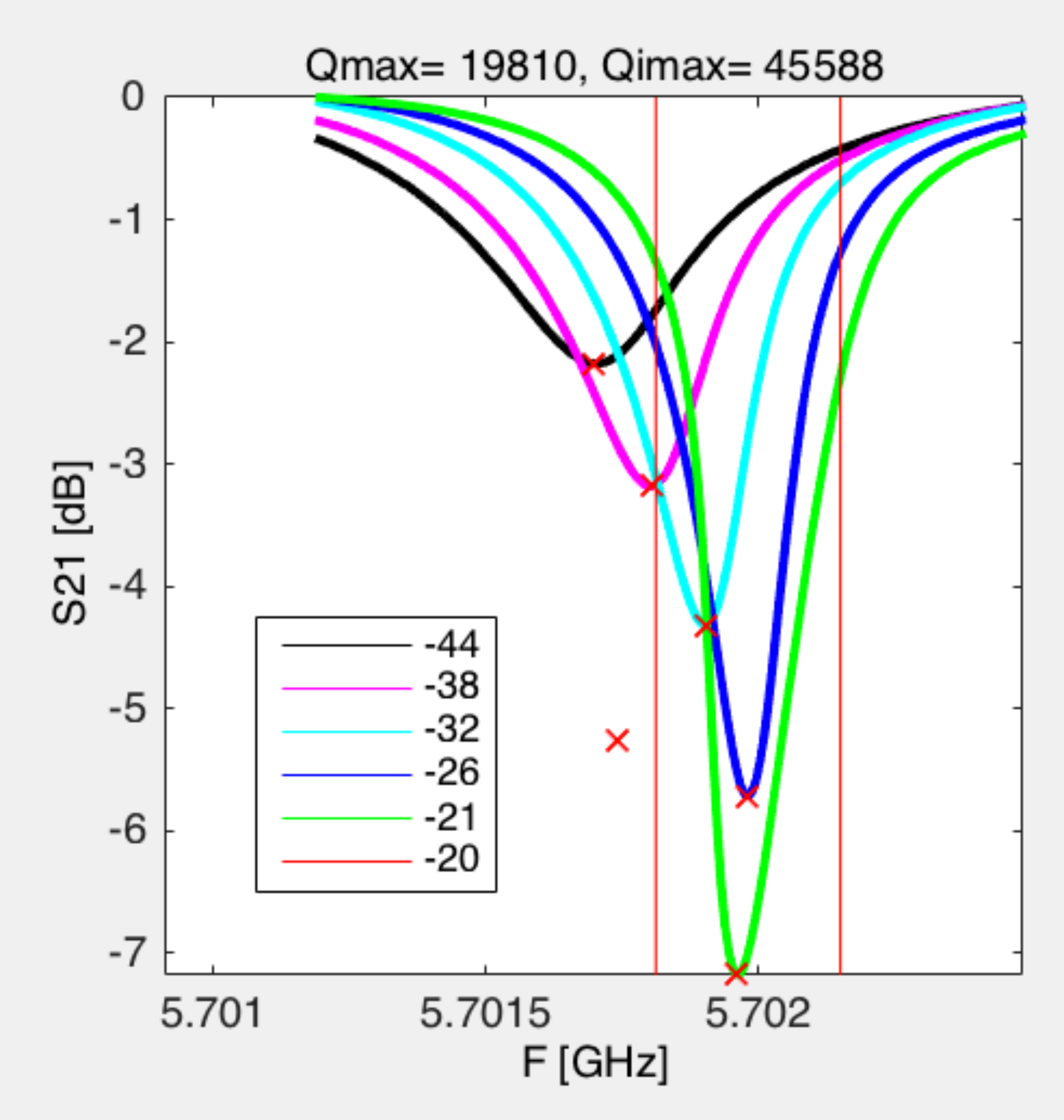
Under strong pair-breaking power Qi decreases rapidly, but microwave enhancement leads to >3x higher Qi

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

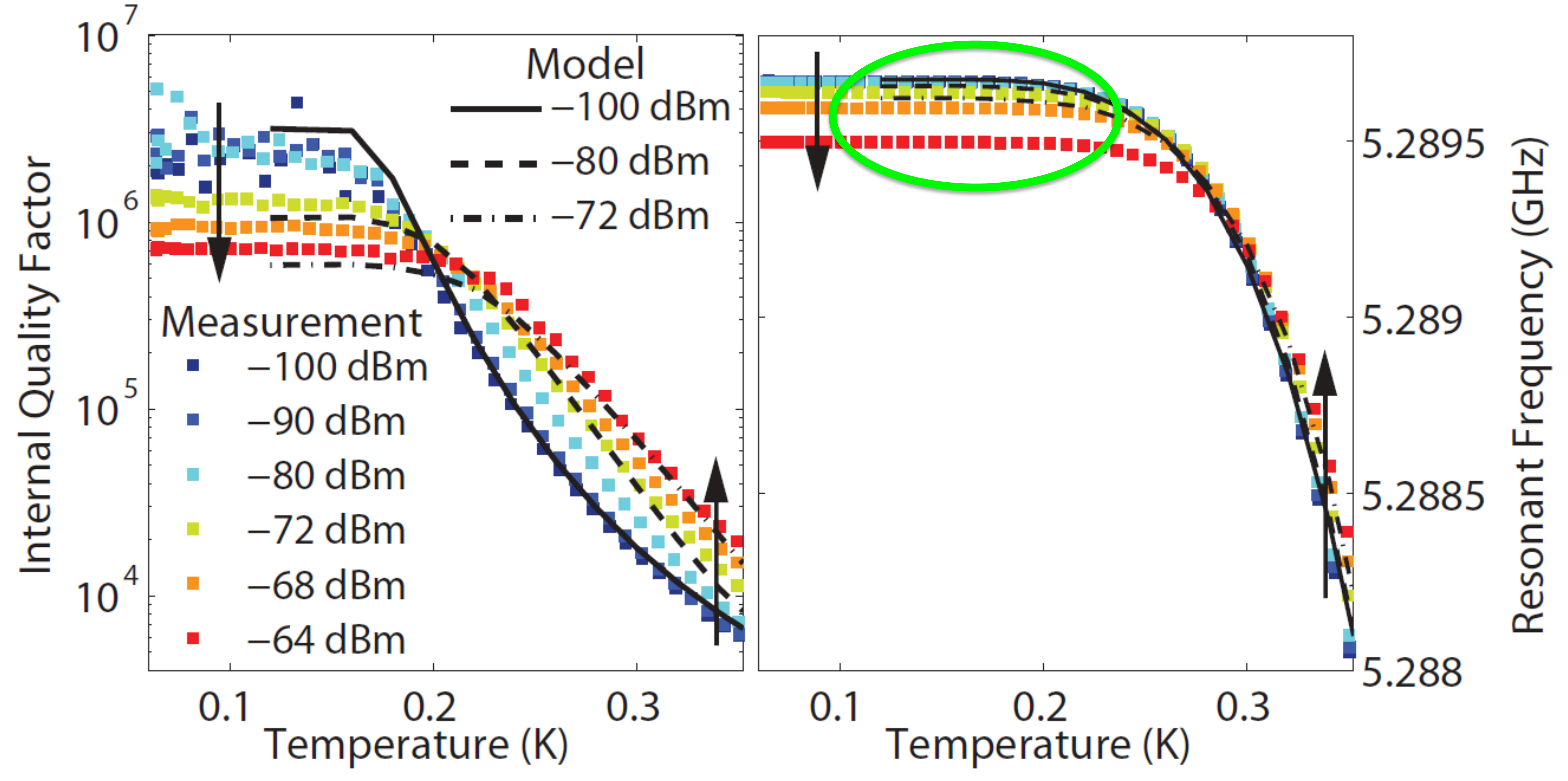
AND: you can use Al at much higher loading than thermal approximation suggests



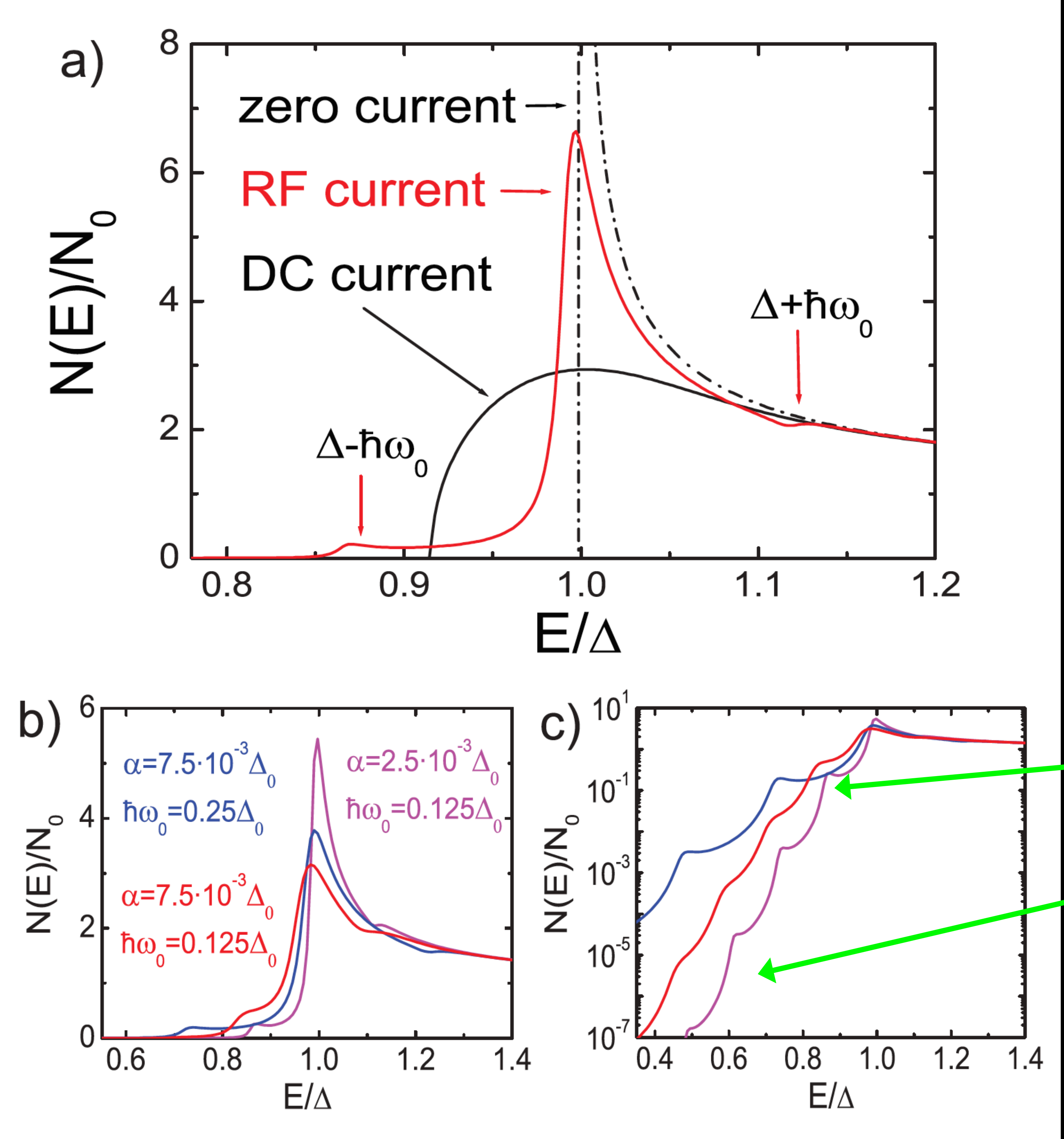
Under high loading, 850 GHz



Absorption does not explain everything



Microwave: ‘Coherent excited states’



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

2 differences compared to DC:

Steps at multiples of hf

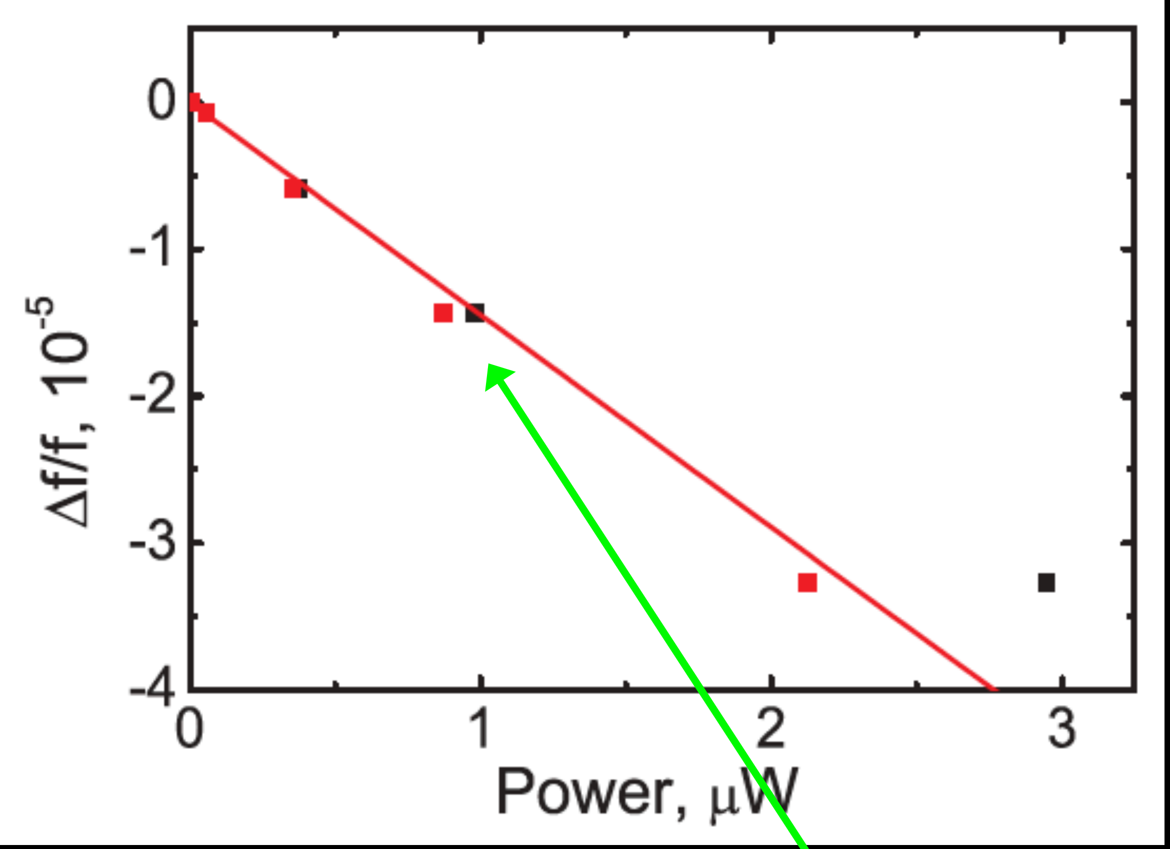
Exponential subgap tail

triggers absorption?

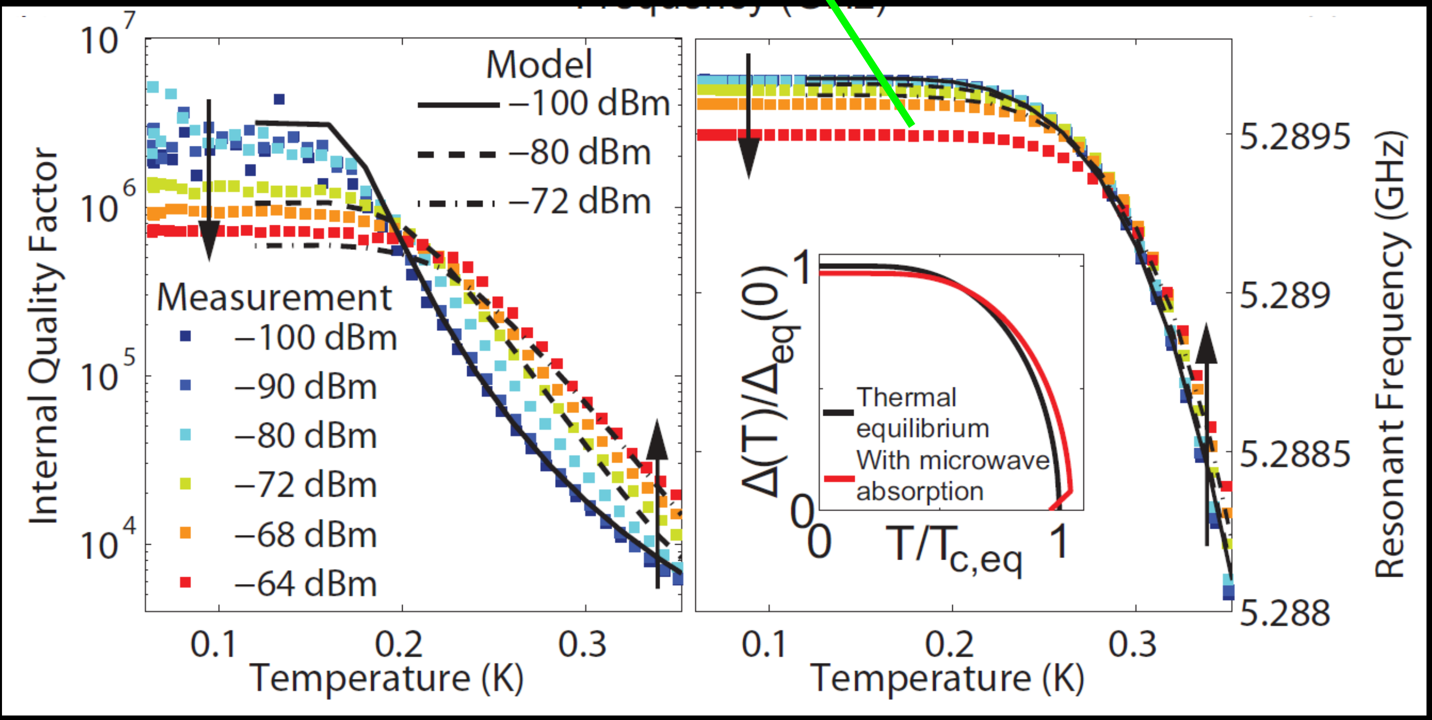
Much richer structure than DC

Semenov et al. PRL 117, 047002 (2016)

Effect on complex conductivity

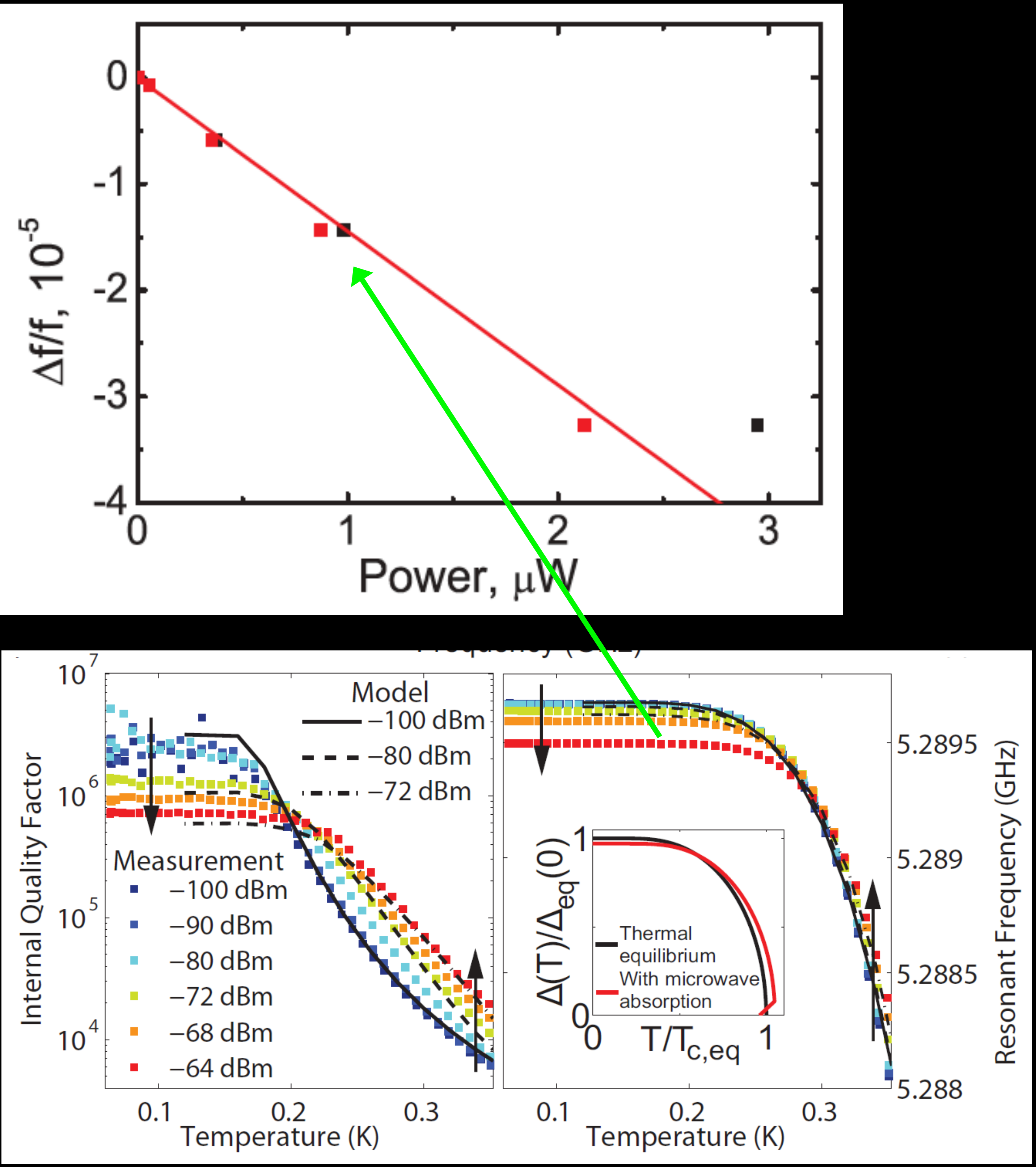


Nonlinear frequency-shift for Al resonator that is not due to f(E) effect, is quantitatively explained, no fitting parameters!



Semenov et al. PRL 117, 047002 (2016)

Effect on complex conductivity



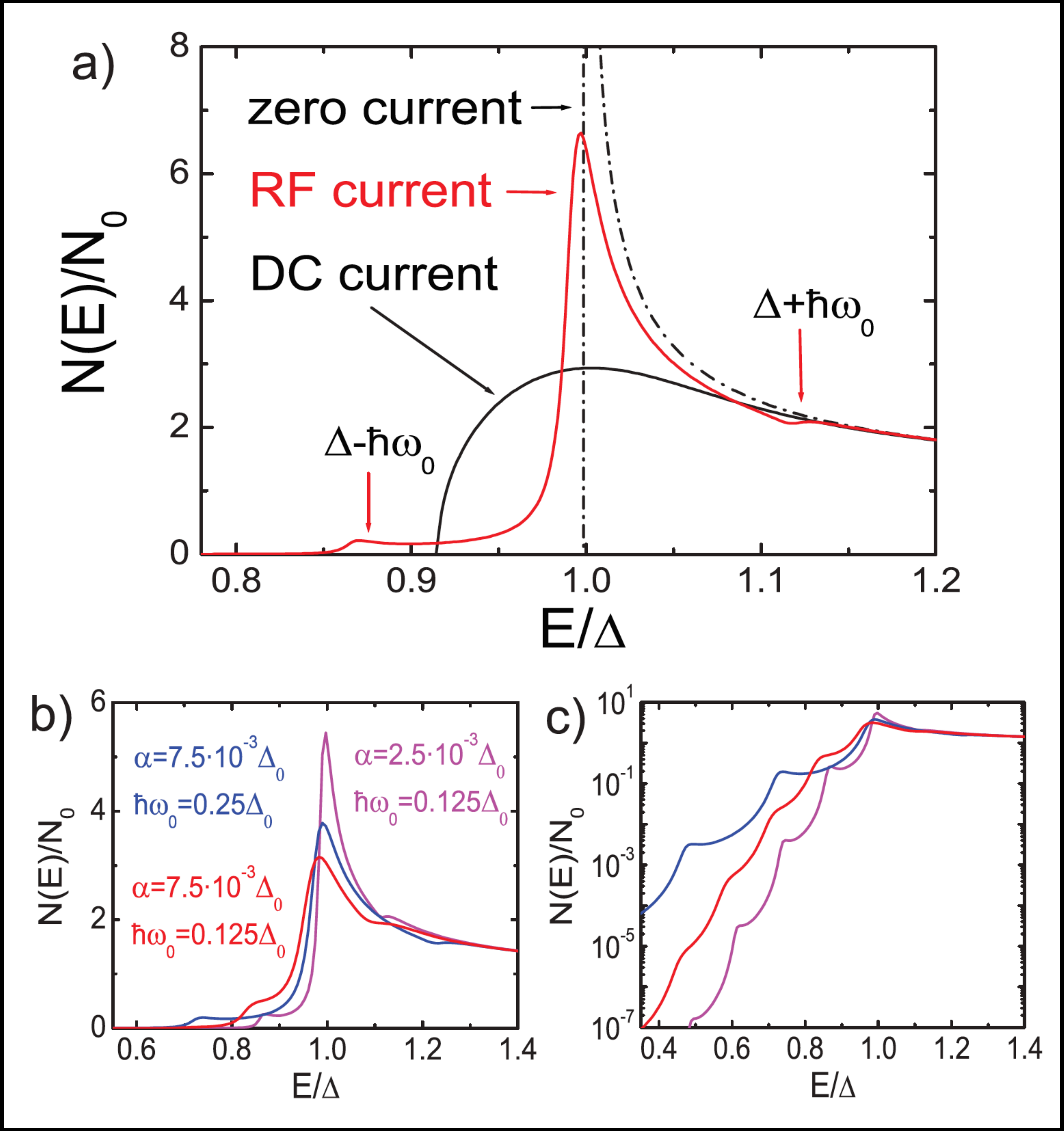
Thus dependent in which regime you are (field, temperature, relaxation), either f(E) or DOS change dominates in AC field

Semenov et al. PRL 117, 047002 (2016)

‘Lessons’ for paramps

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

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



Semenov et al. PRL 117, 047002 (2016)

Exponential tail due to nonlinearity can cause dissipation, and qp’s.

DC is not RF:

- DC nonlinearity comes without subgap tail
- If KID non-dissipative with high DC current, can still dissipate with high RF
- 3-wave should be easier than 4-wave

More work needed for higher Tc and high resistance materials.

Summary Aluminium MKIDs

Experiments under all relevant conditions very well understood

- Temperature
  - Complex conductivity Mattis-Bardeen
  - Generation-recombination noise, quasiparticle recombination dynamics + phonon dynamics
- Pair-breaking photons
  - Photon noise
  - Quasiparticle dynamics: recombination and responsivity
  - Pair-breaking efficiency: different f(E,hf) for different photon energies
- Microwave field
  - Absorption, excess quasiparticles, Qi enhancement: no Teff or Nqp approximations possible – redistribution f(E,hf)
  - Field strength effect – nonlinearity qualitatively different from DC

Still many combinations of these unexplored, but framework clear

Aluminium MKIDs – done?

Main challenge: NEP ~ 10^{-20}-10^{-21} W/$Hz^{1/2}$ for sub-mm / THz

- Very small volumes – design radiation coupling
- Single/few quasiparticle dynamics – photon counting
- Readout power effects in few qp / few photon regime

- Understand limits in qp – recombination time if you ‘screw up’ the fab => what is the physics of ‘screw up’ ?
- Variations of phonon trapping (membrane)
- Readout power effects vs microwave energy
- Responsivity dsigma/dNqp at high loading

Aluminium MKIDs – ~~done?~~

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High resistivity superconductors

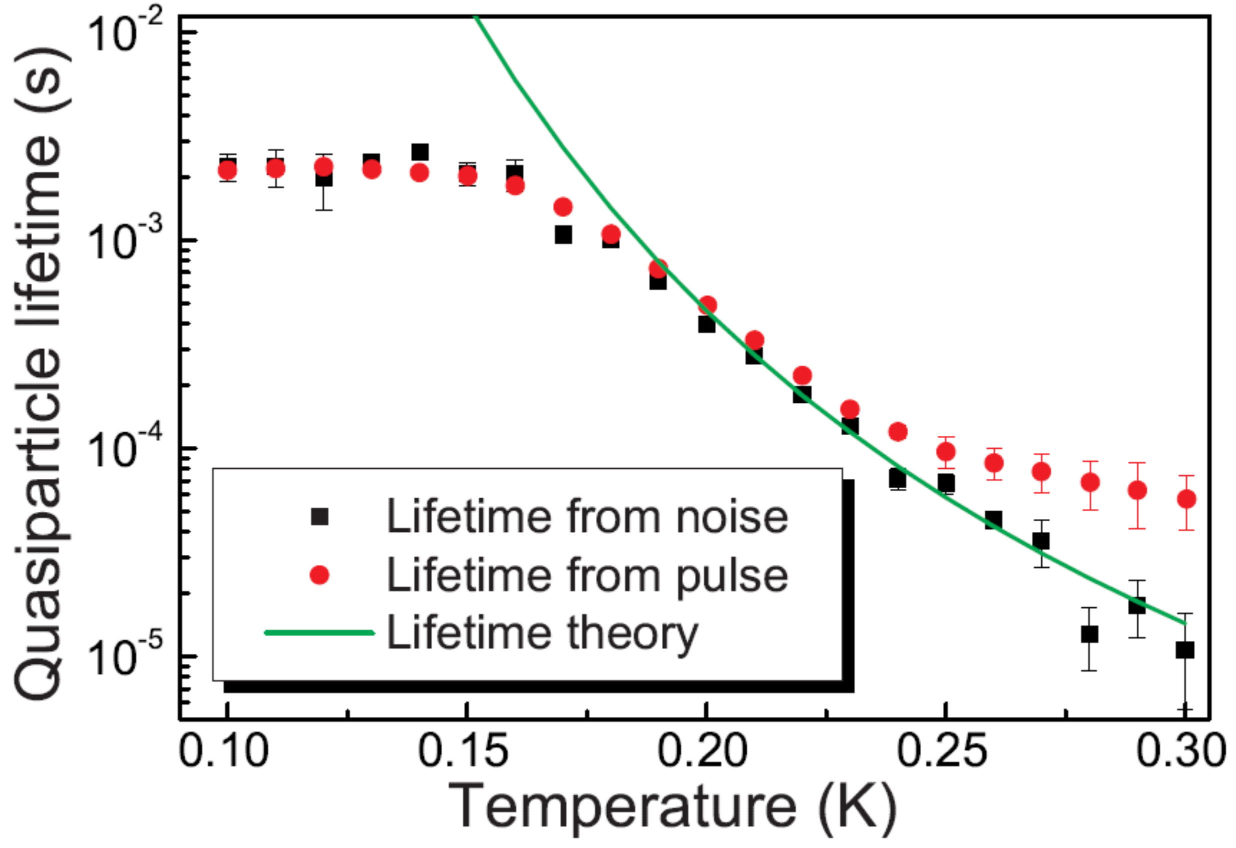
- Aluminium works wonderful but has limits/drawbacks:
  - Low resisitivity
  - Slow electron-phonon

- Solution: high resistivity superconductors (TiN, PtSi, InOx)
  - High kinetic inductance = higher MKID response
  - Lower volume = higher MKID response
  - Simply unavoidable for KIDs above few THz

- There is no high resistivity without disorder
  - Poorly understood response and poor sensitivity
  - Most data available for TiN => compare Al vs TiN

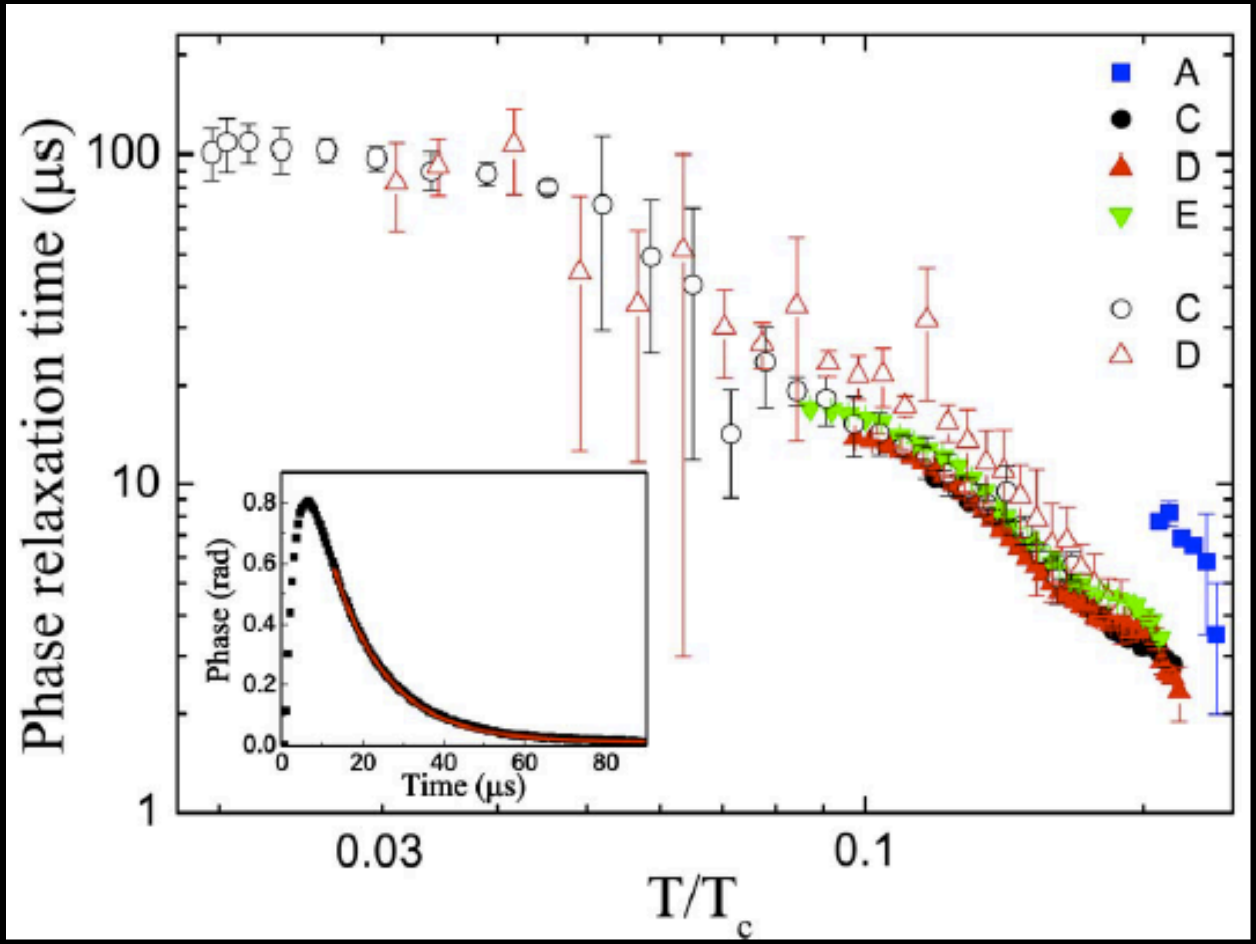
Recombination time vs temperature

Al



Aluminium lifetime follows Kaplan (1976) predictions for BCS. Saturation understood due to microwave power.

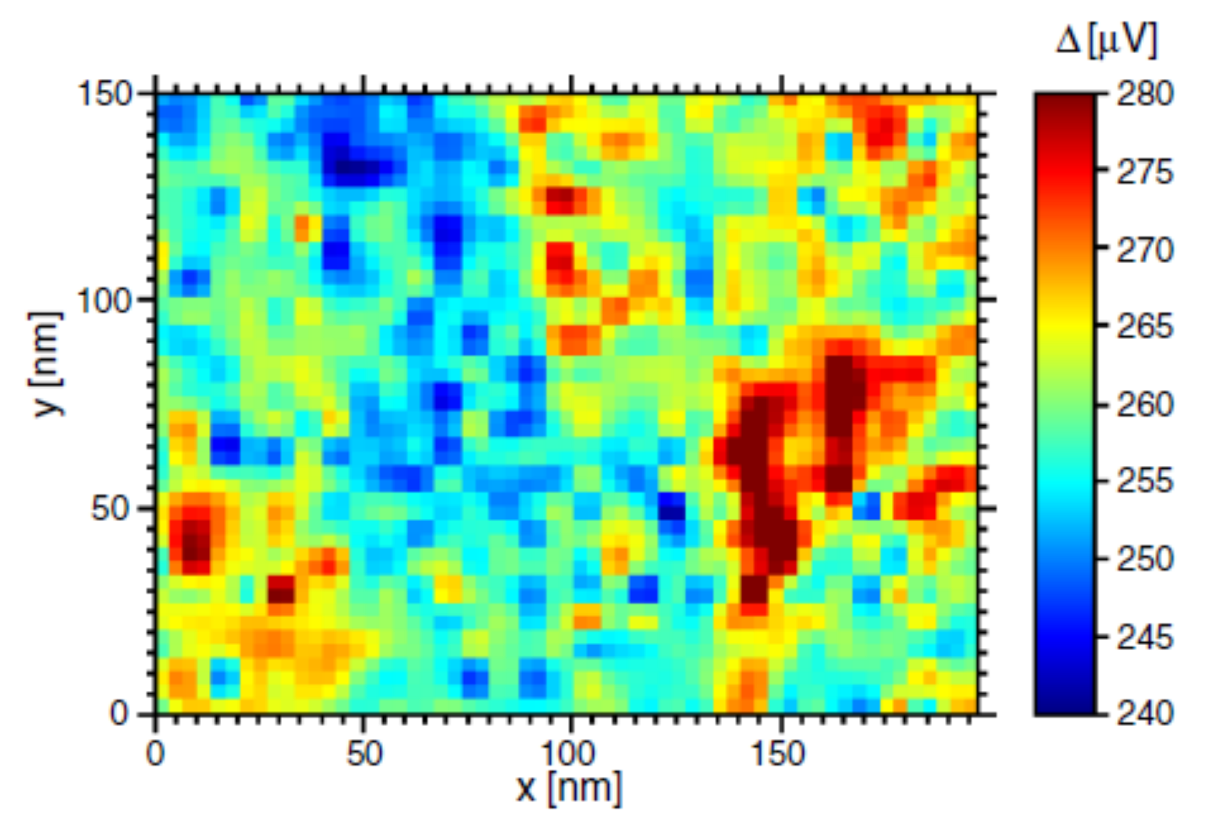
TiN



Power law? Saturation? Trapping?
Data for different disorder (and Tc) falls on top of each other

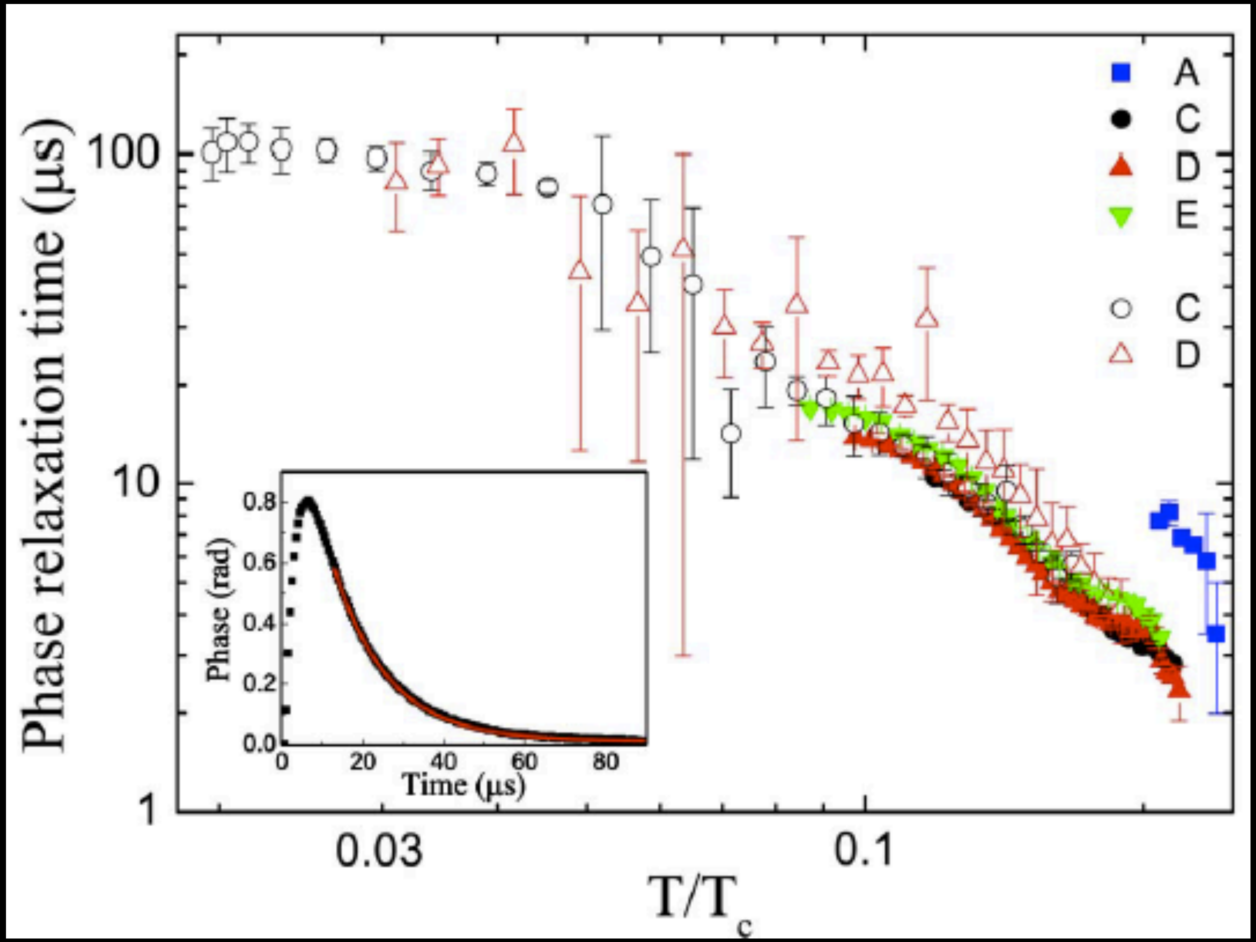
Coumou et al. IEEE Trans. Superc. 23, 7500404 (2013)

Recombination time vs temperature

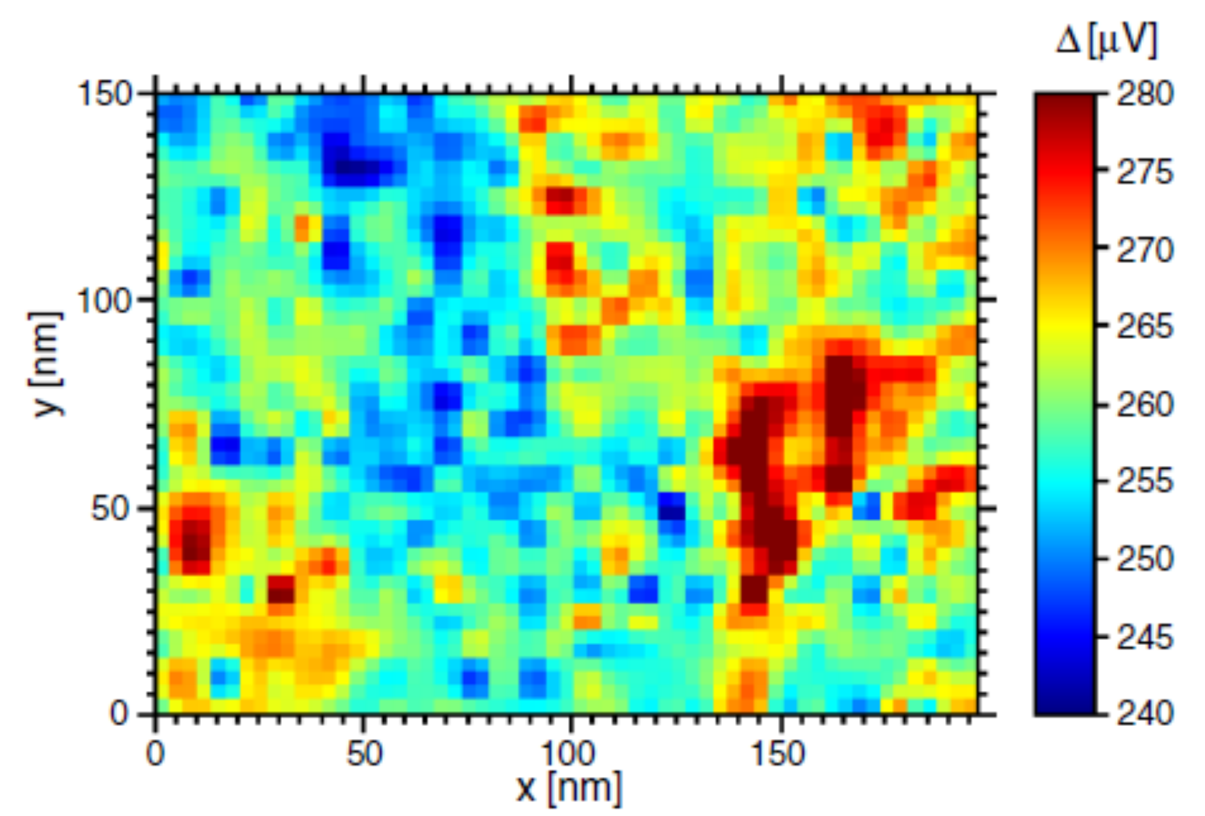


Trapping + diffusion

TiN



Recombination time vs temperature



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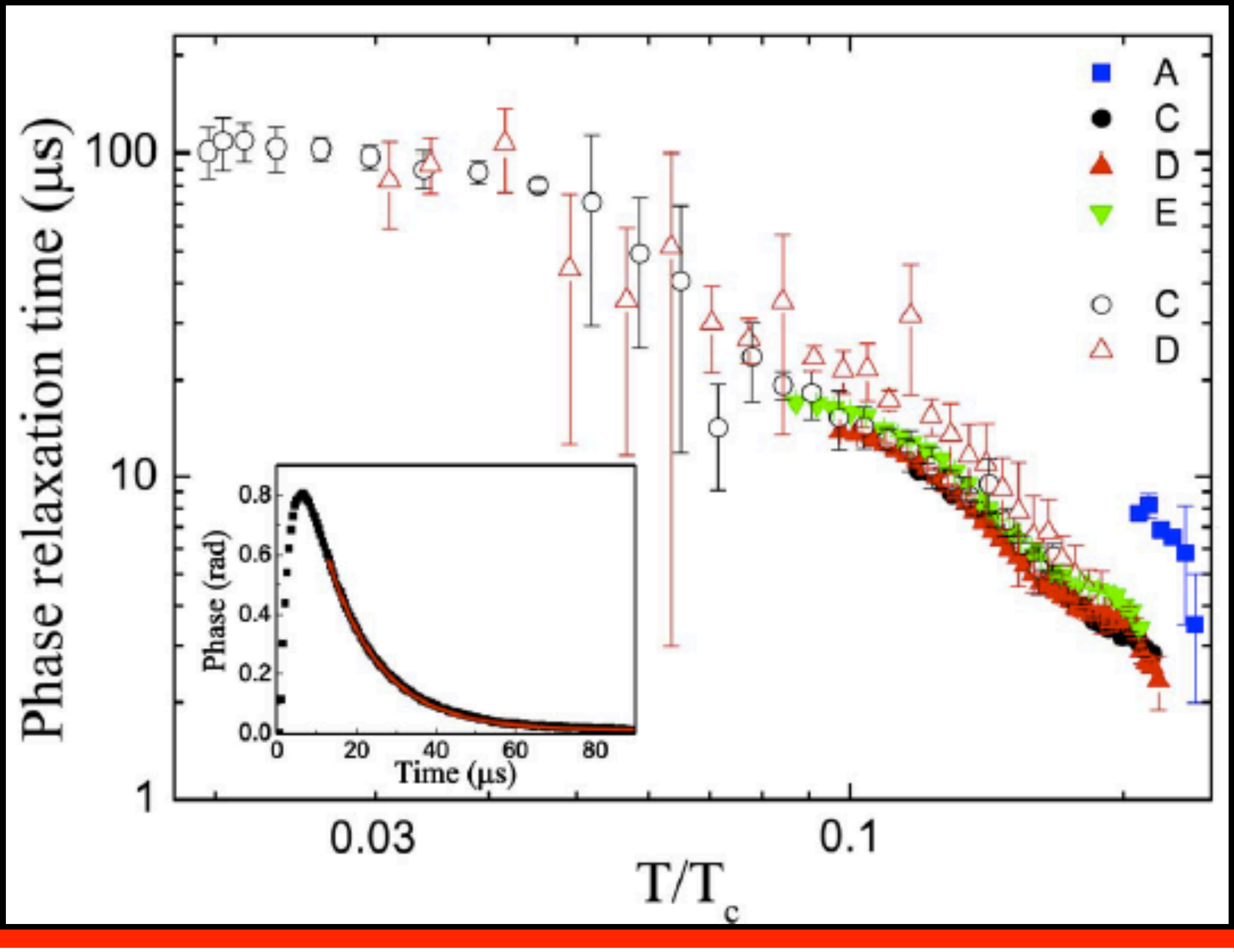
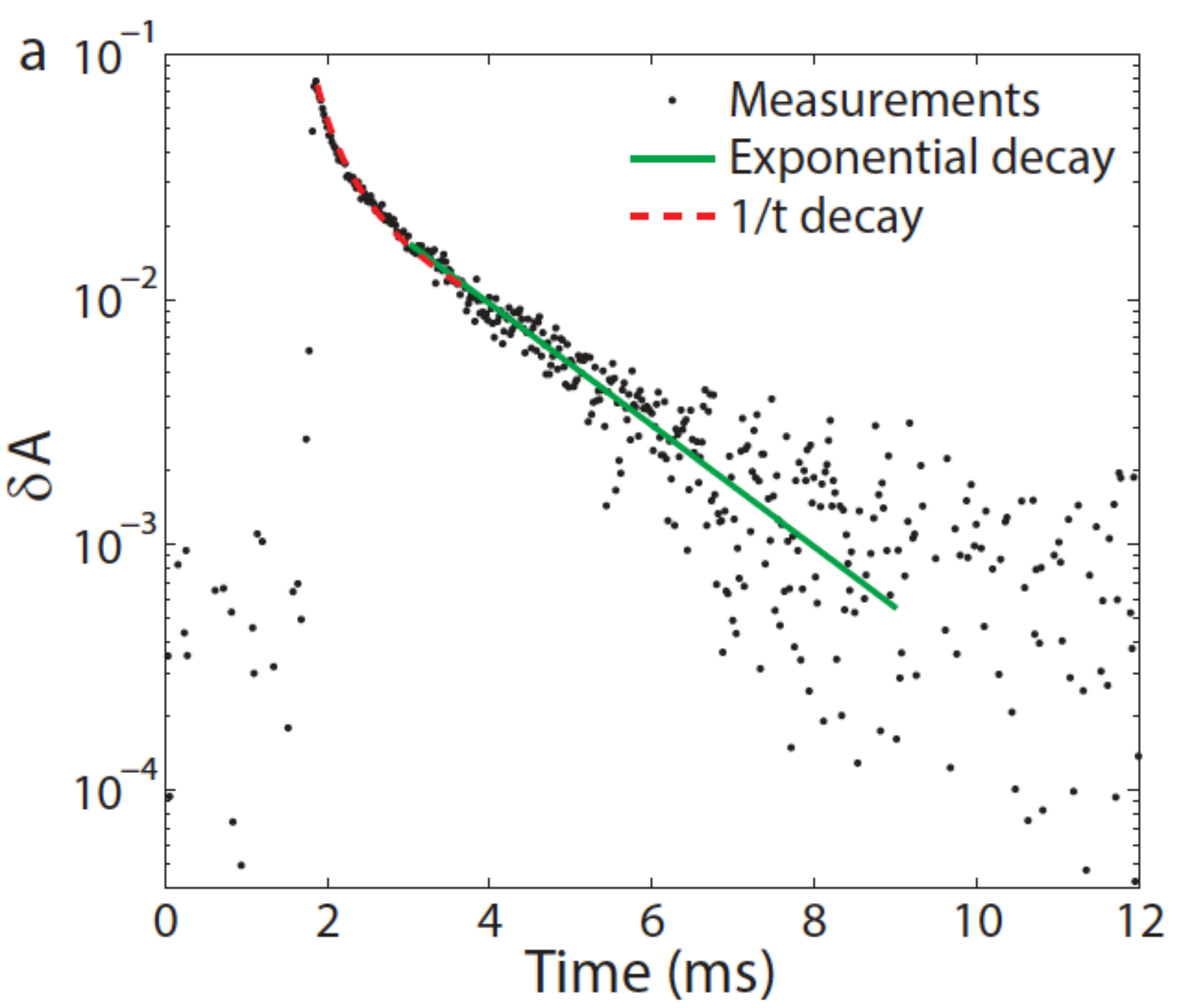


We need more statistics, more systematic data !!!

For each material and its variations document lifetime and responsivity vs temperature, power/energy

Benefit of trapping limited recombination



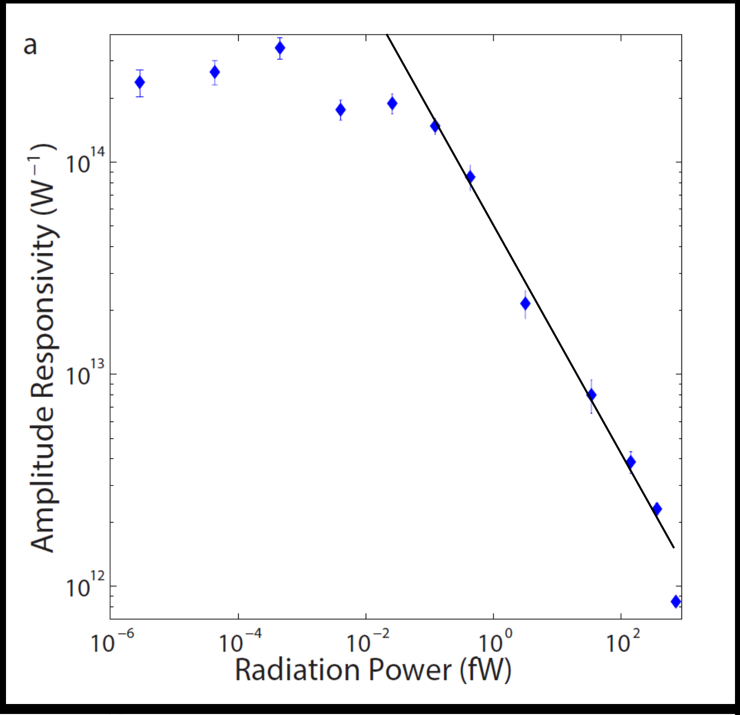
A high-response photon counting Al MKID will have 2 nonlinearities

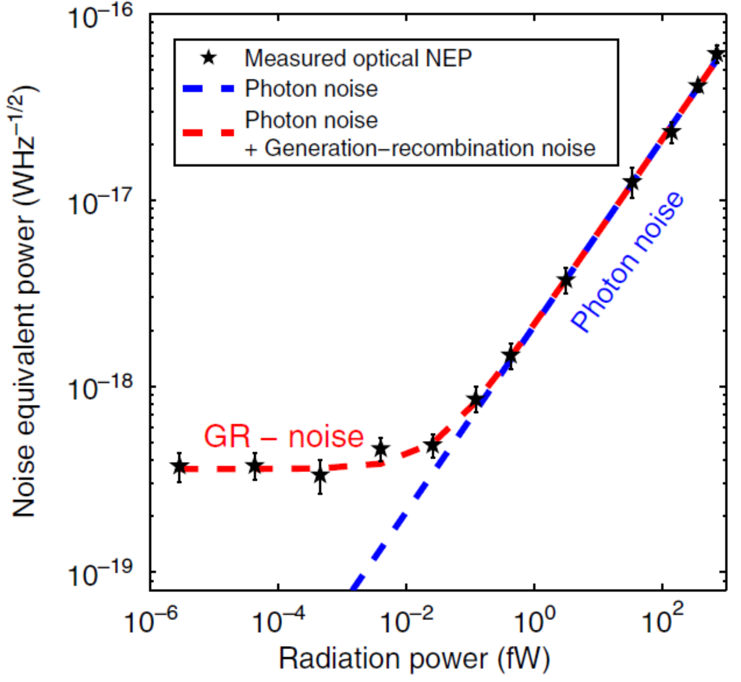
1. Initial Nqp^2 (i.e. 1/t) recombination before exponential tail
2. S21 nonlinearity

If trapping dominates the lifetime, the whole pulse is exponential => much easier to optimally filter (S21 remains).

Radiation: where does the power go?

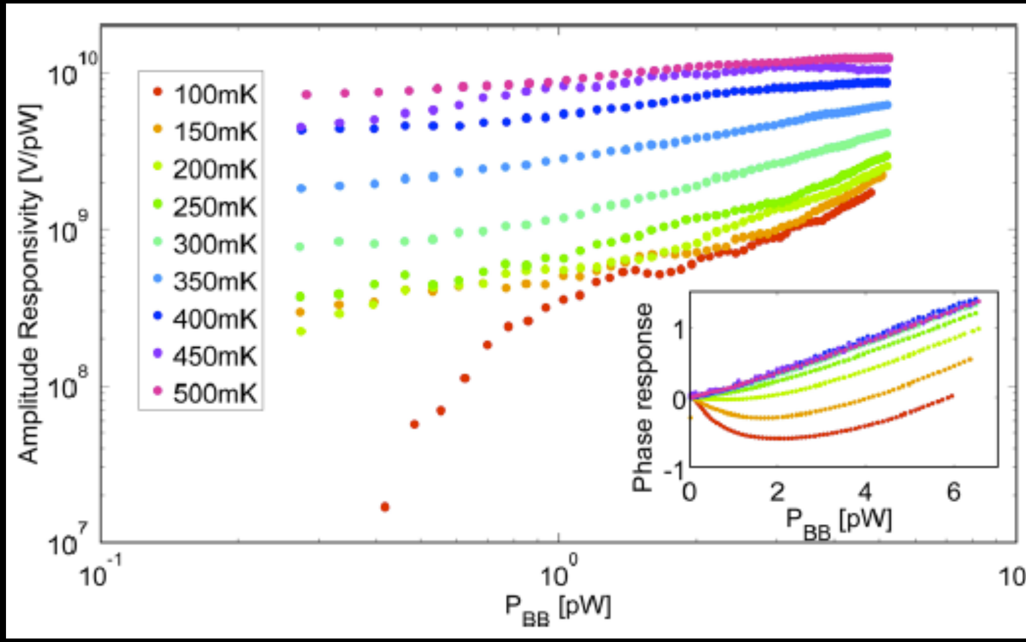
Al

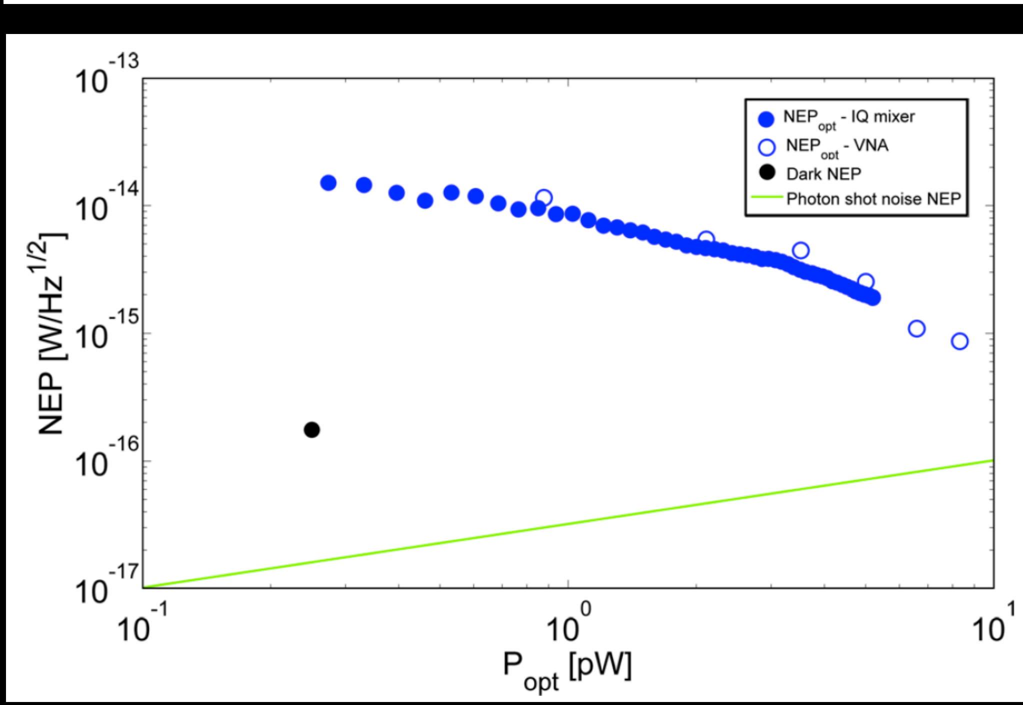




Exactly as predicted

TiN

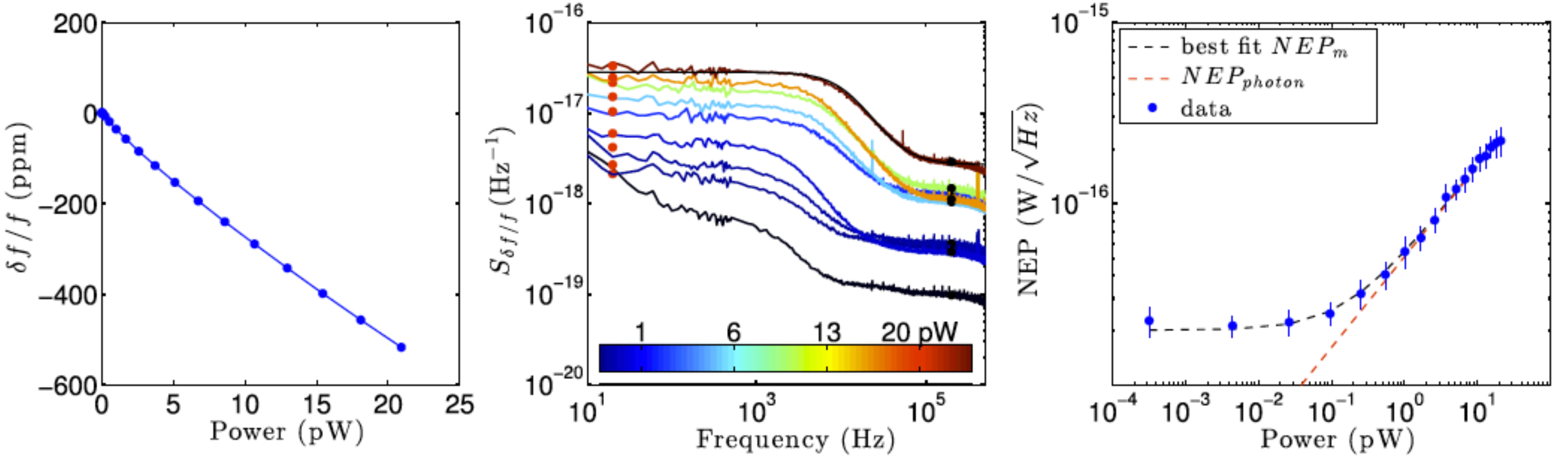




Exactly opposite to predicted
Bueno et al. APL 105, 192601 (2014)

Responsivity, photon noise limit

TiN



From Hubmayr et al. APL 105, 073505 (2015)

Panel (b) and (c): there is photon noise seen, with expected NEP vs P dependence

However the responsivity in (a) is linear in P, for Aluminium it is sqrt(P). Direct relation of σ_2 with nqp doesn't hold for TiN. Note that the qp-lifetime DOES scale with P (panel b roll-off).

Responsivity similar to what Erik Shirokoff showed yesterday

Optical/NIR MKIDs at SRON

Photon counting MKIDs, with energy resolution

- Spectrum per pixel: exoplanet spectroscopy (HABEX)
- Photon counting with no read/dark noise + reasonable speed: wavefront sensing / fringe tracking, few photon imaging

Goal 1: Energy resolution, take it to R~100

- Signal/noise problem => go non-linear and/or slower
- Understand disordered superconductors
  - MKID very sensitive to superconductor: where the qp’s go and how they generate response
  - Can apply radiation from below gap up to optical photons
- Phonons

Goal 2: Quantum efficiency

- Make absorption efficiency compatible with microwave design

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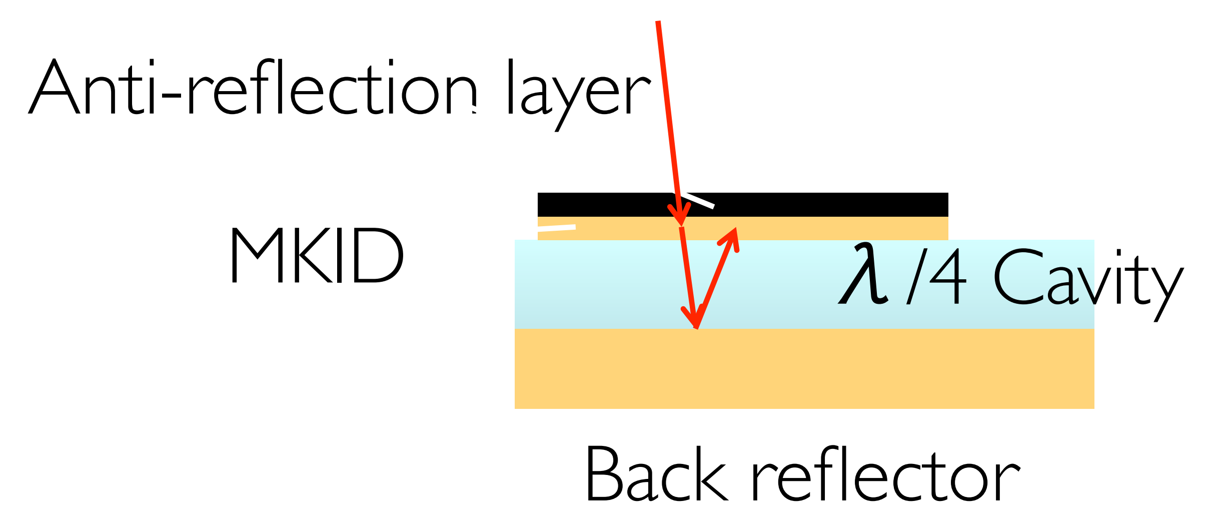
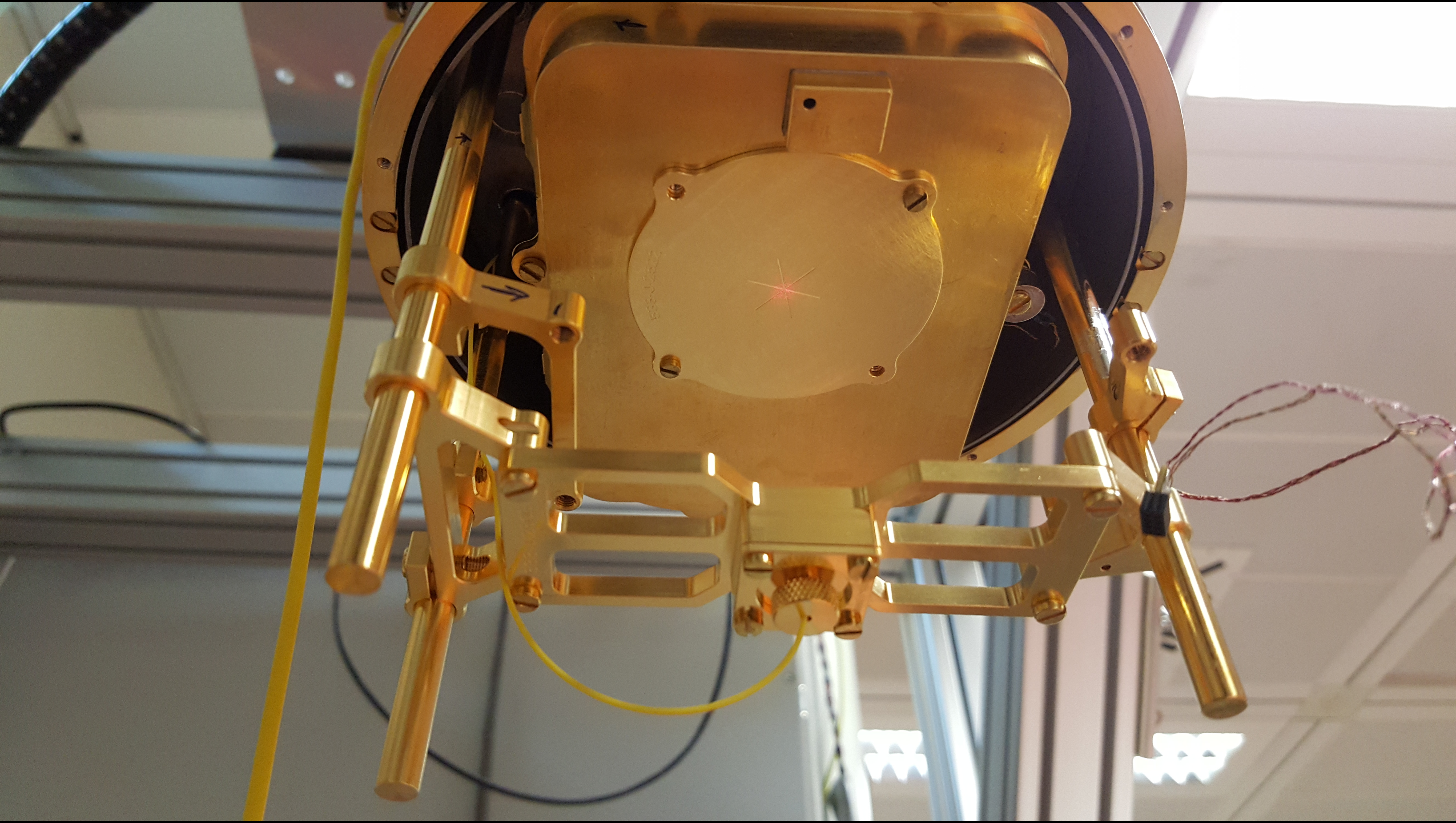


Optical/NIR MKIDs at SRON



400 , 670, 980, 1550 nm lasers, LEDs do not work for R=100 ambition ☺

Summary

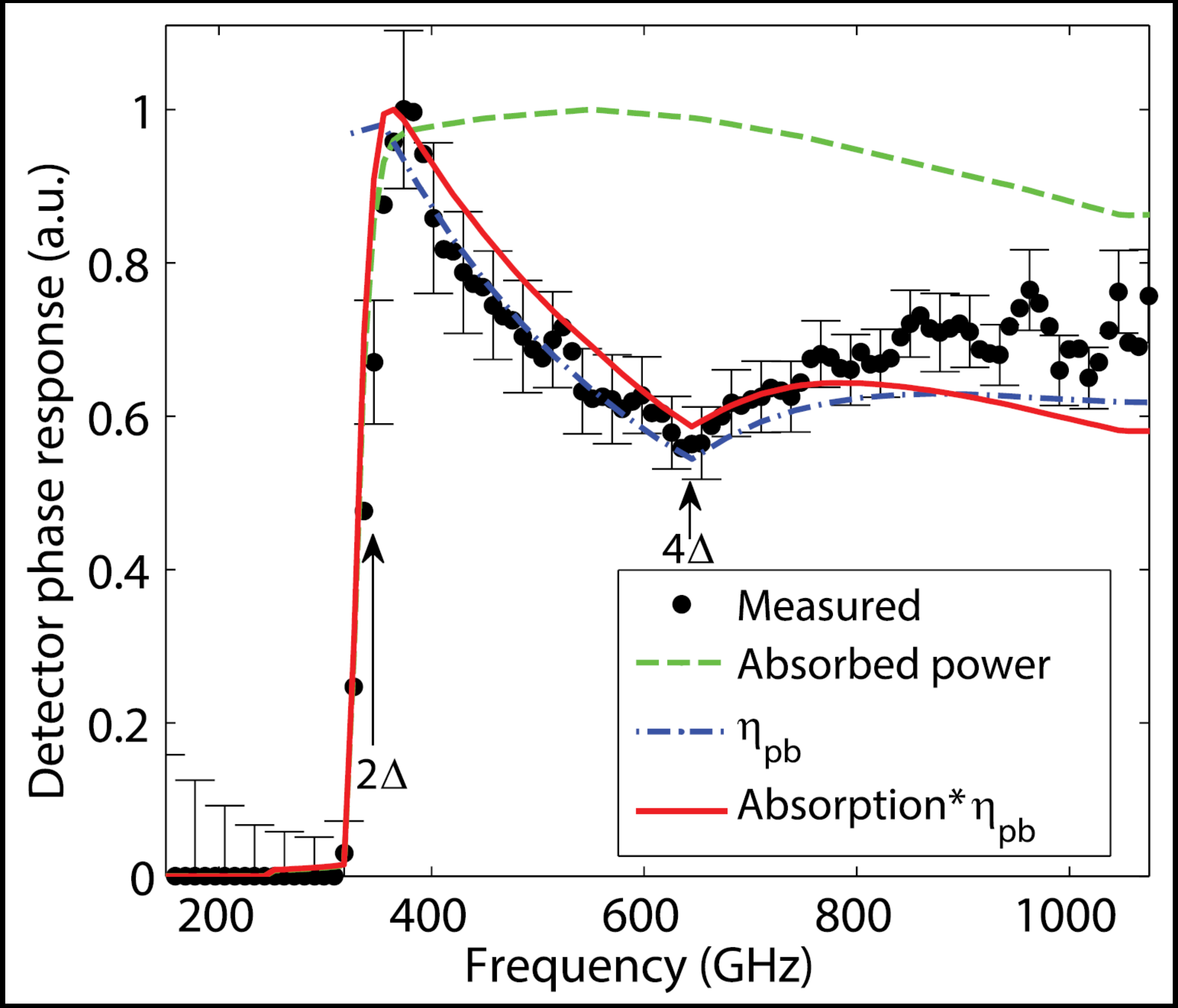
- Quasiparticle- and electrodynamics for Aluminium is well understood both in equilibrium and non-equilibrium
  - Main challenge: NEP 10^{-21} W/Hz$^{1/2}$
  - MKID is powerful ‘probe’ of (non)equilibrium superconductivity

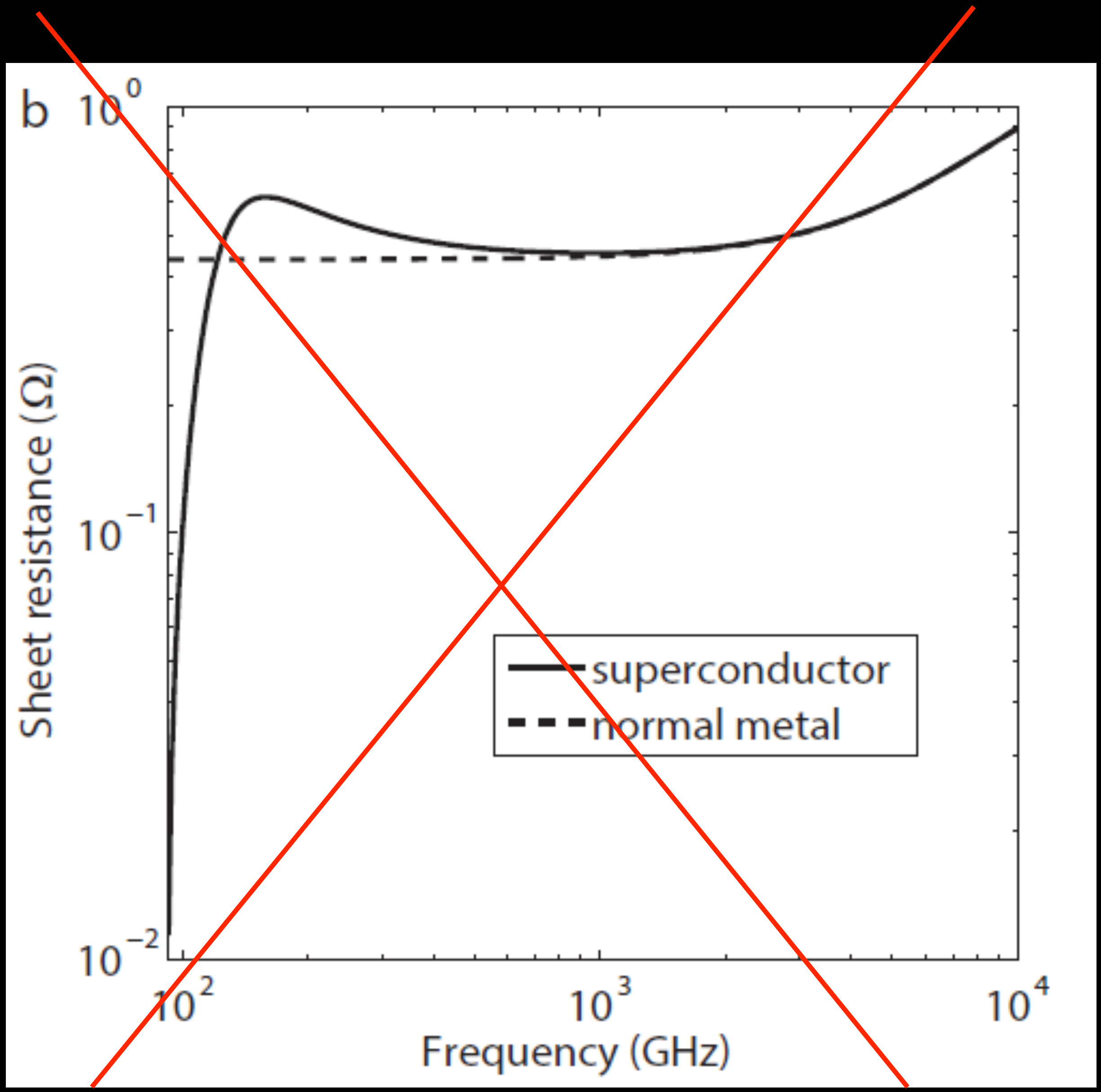
- For disordered superconductors (TiN), MKID measurements are difficult to interpret
  - More consistent experimental exploration of parameter space
  - Get theorists interested with more data
  - Even equilibrium physics not understood
  - ‘Non-equilibrium’ in ‘disordered superconductors’ = (difficult)^2
  - We need disordered superconductors!
  - But we have Al as a reference

- Visible/NIR MKIDs at SRON: focus on energy resolution, QE

Extra material / backup

Non-equilibrium FTS response

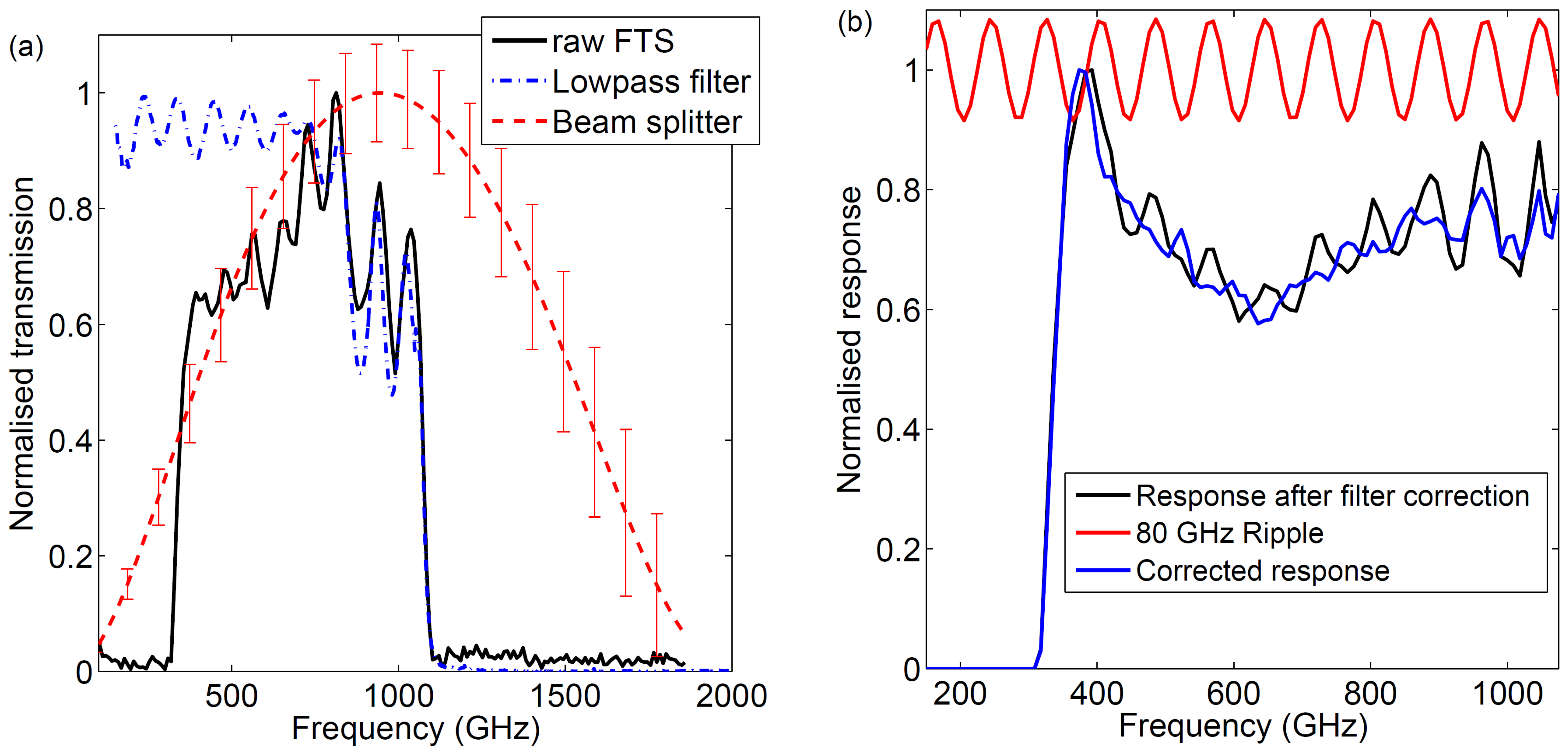




Not planar absorption but waveguide absorption, full absorption above 2Δ

Phonon losses, Cooper pairs have energy 2Δ => nonequilibrium f(E)

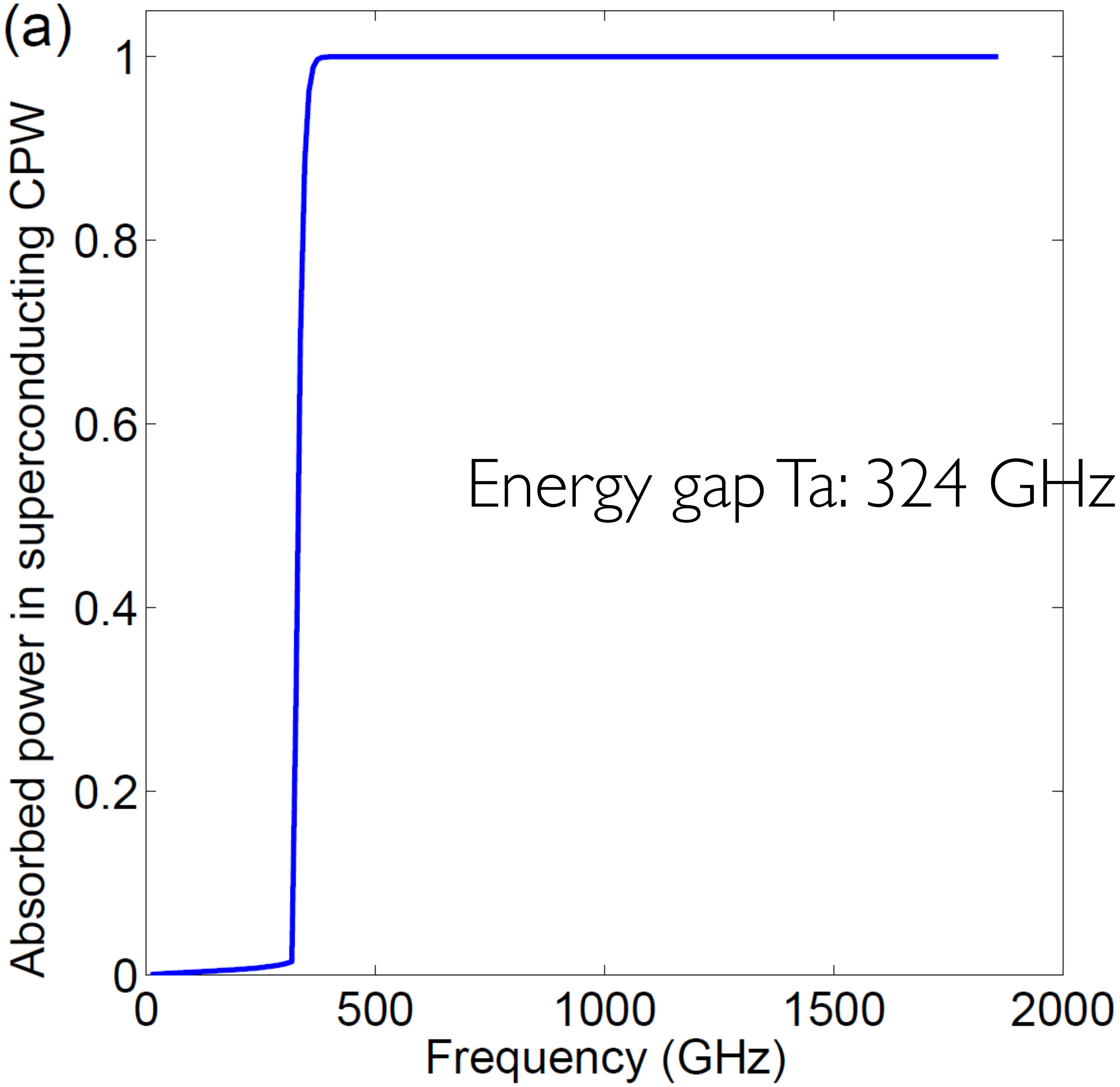
Corrections to raw FTS response



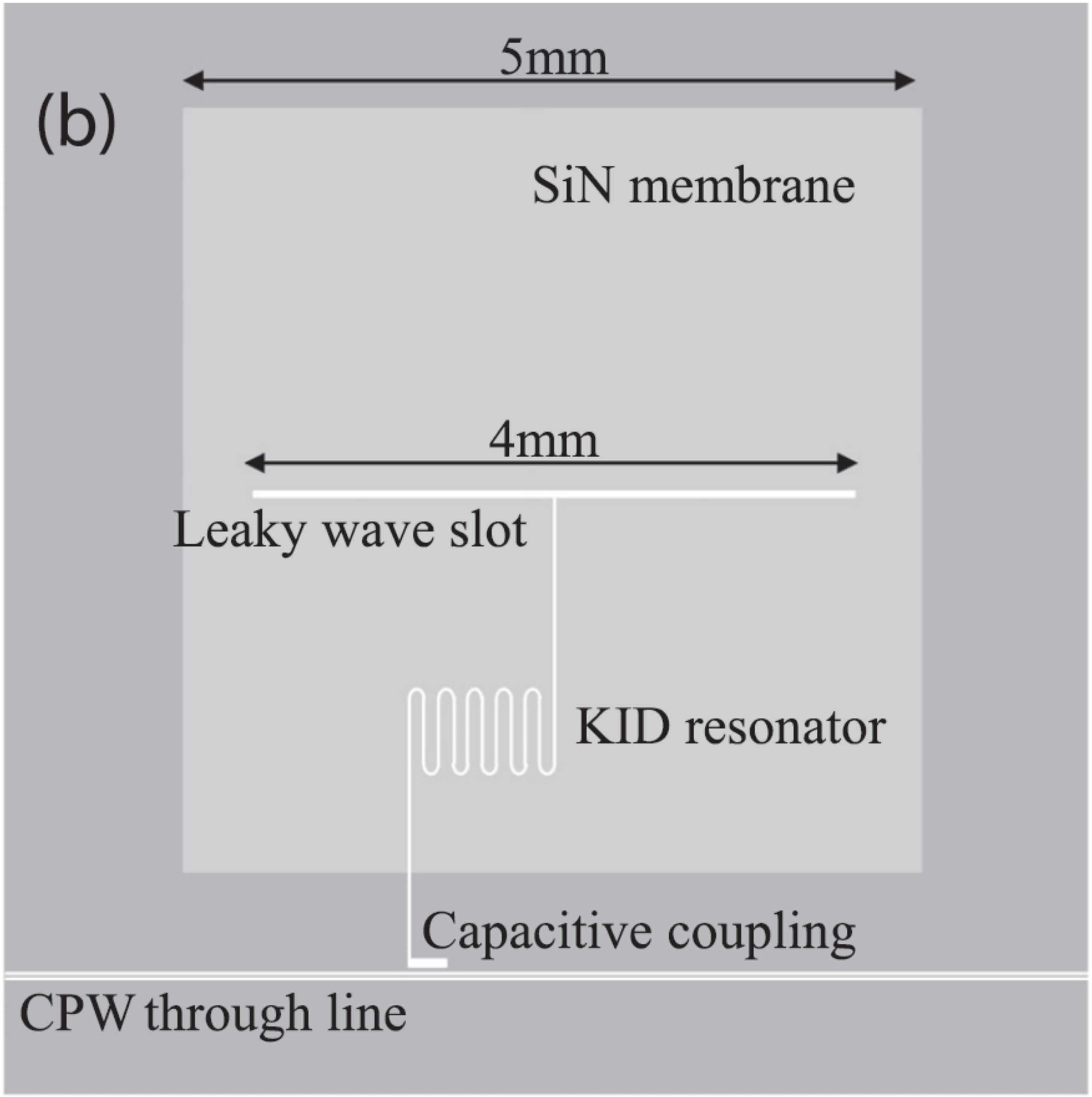
Absorption vs frequency

Pair-breaking in Superconducting CPW, travelling wave absorption

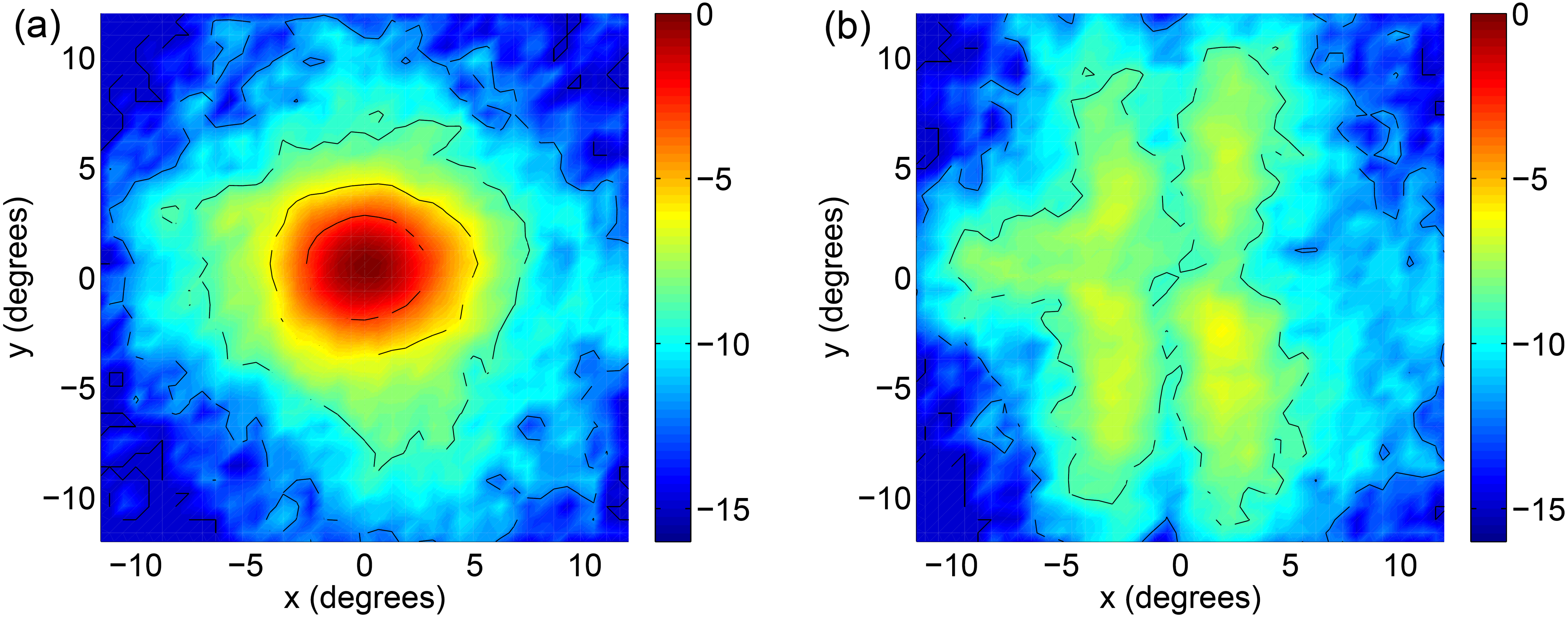
Crucial to remove f-dependence of R_{sheet}!



Energy gap Ta: 324 GHz



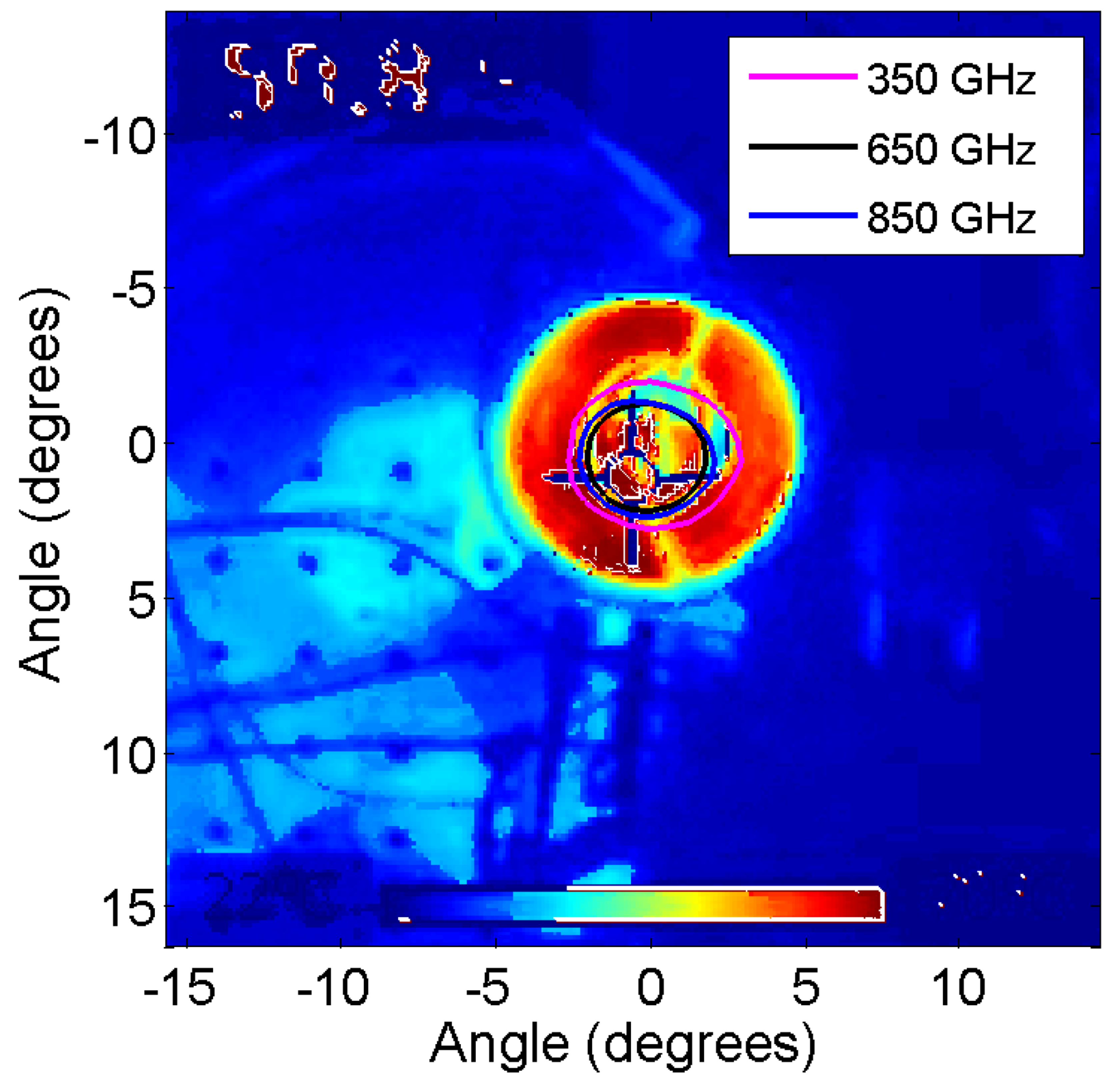
Measured beam patterns (350 GHz)



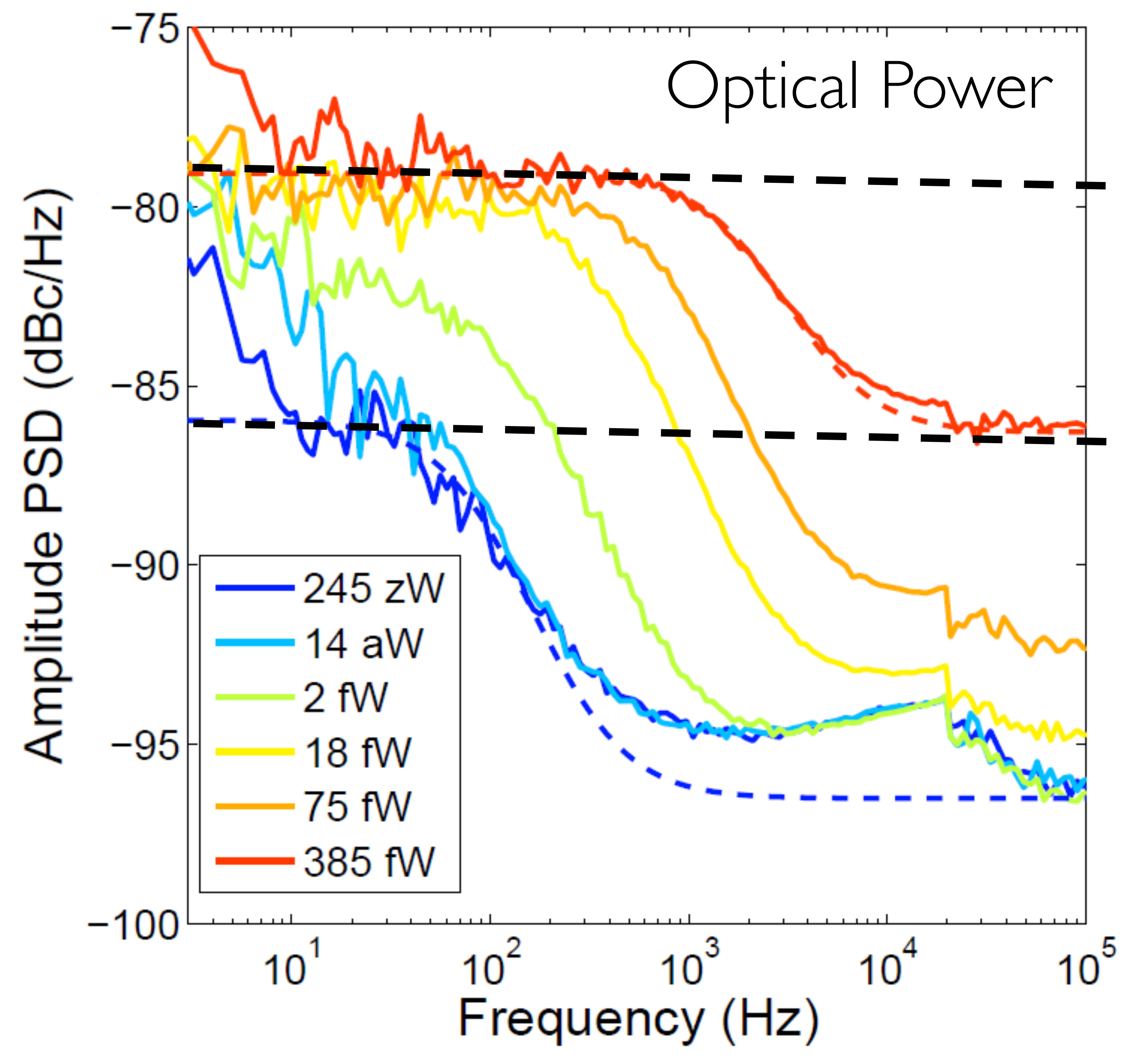
Co - pol

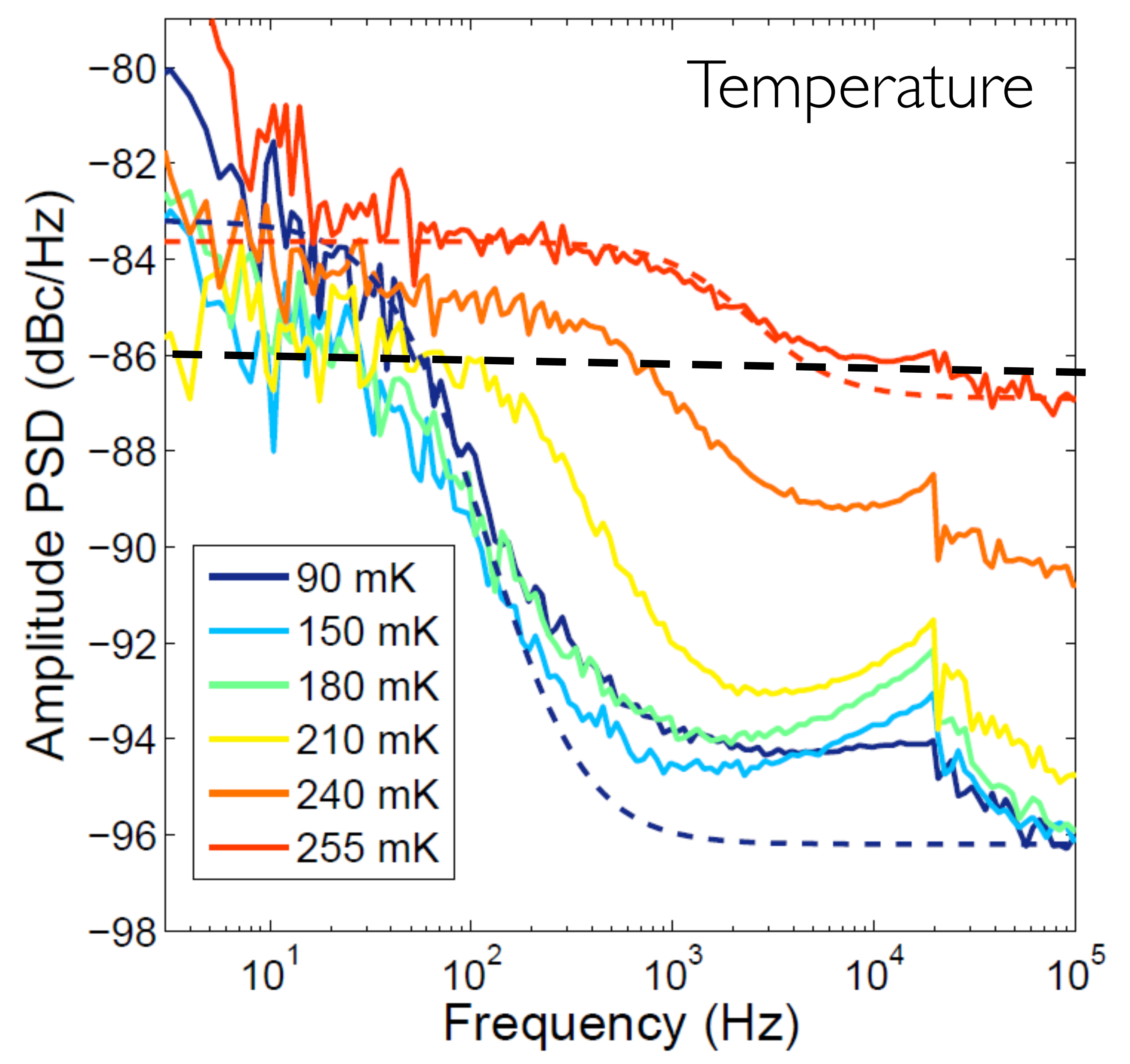
Cross - pol

Source vs beampattern contours

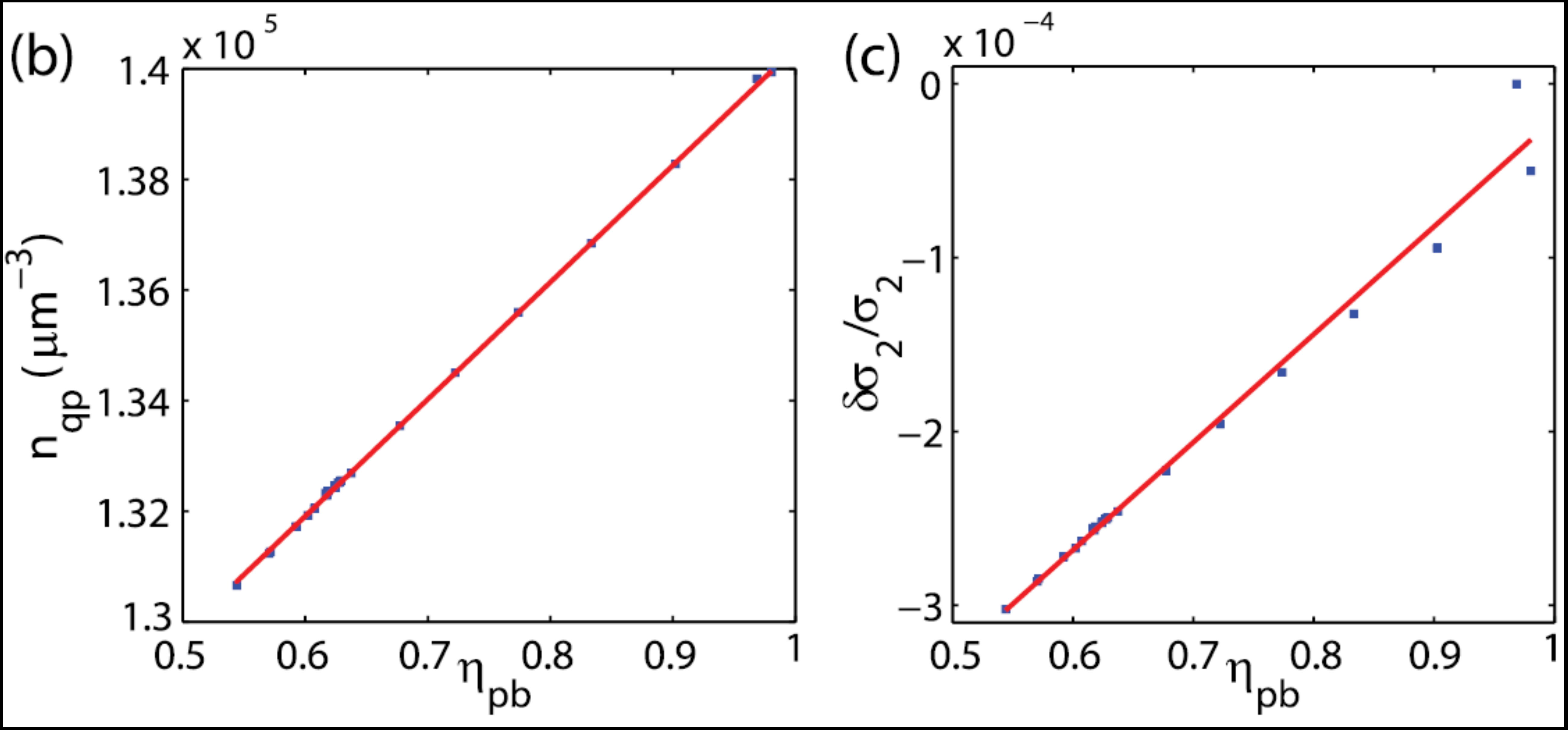


Noise levels

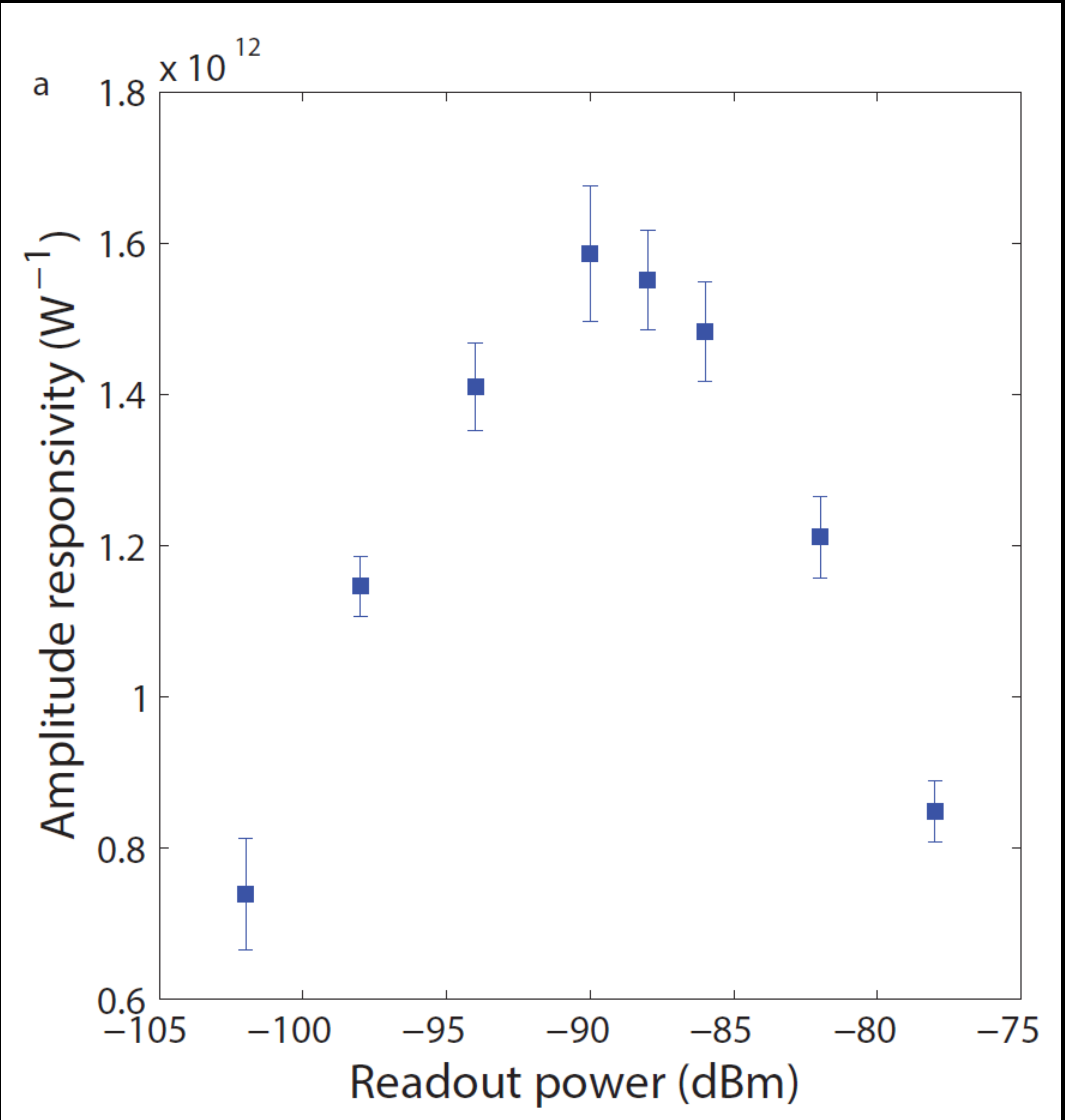


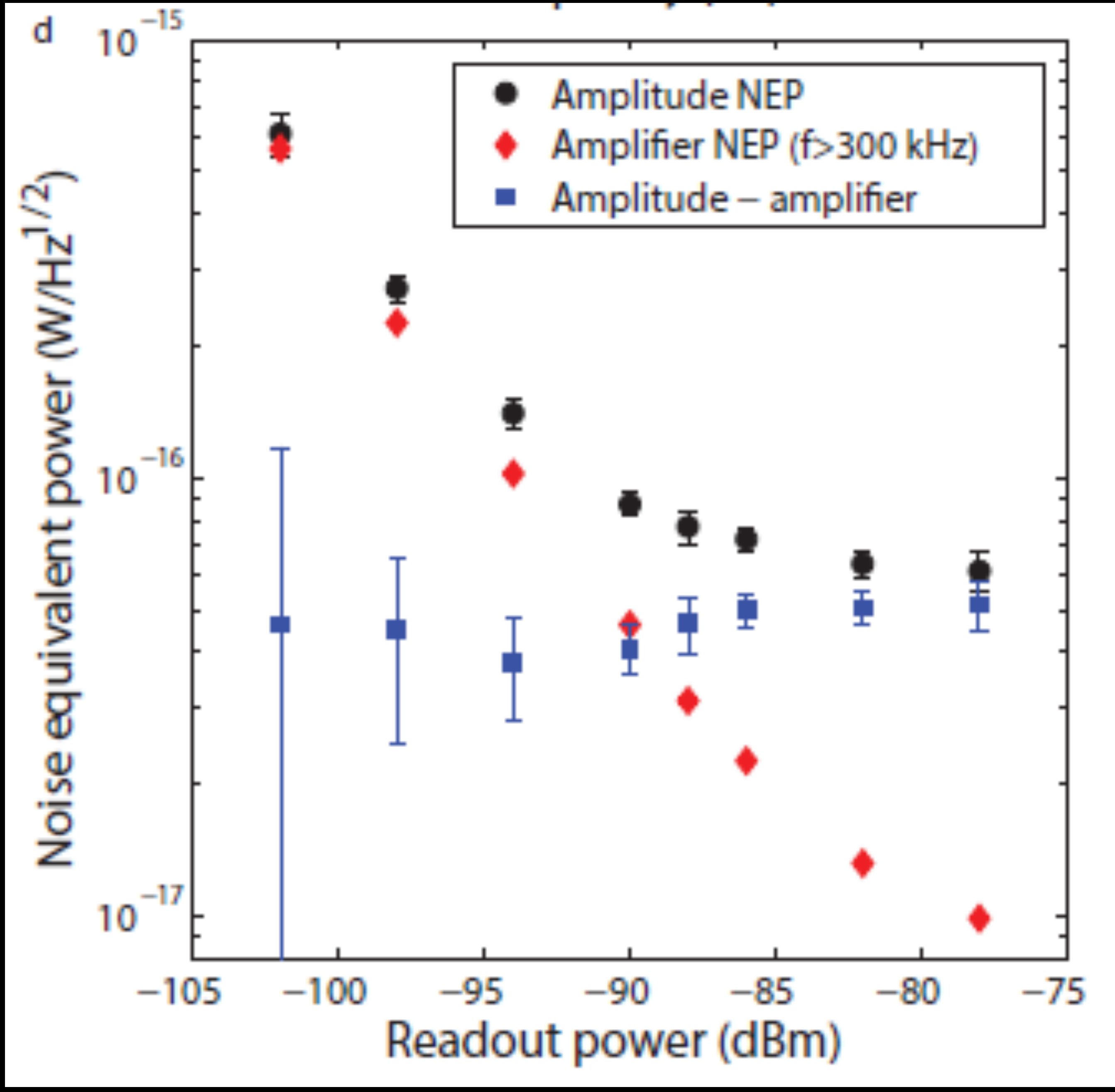


Connecting to observables

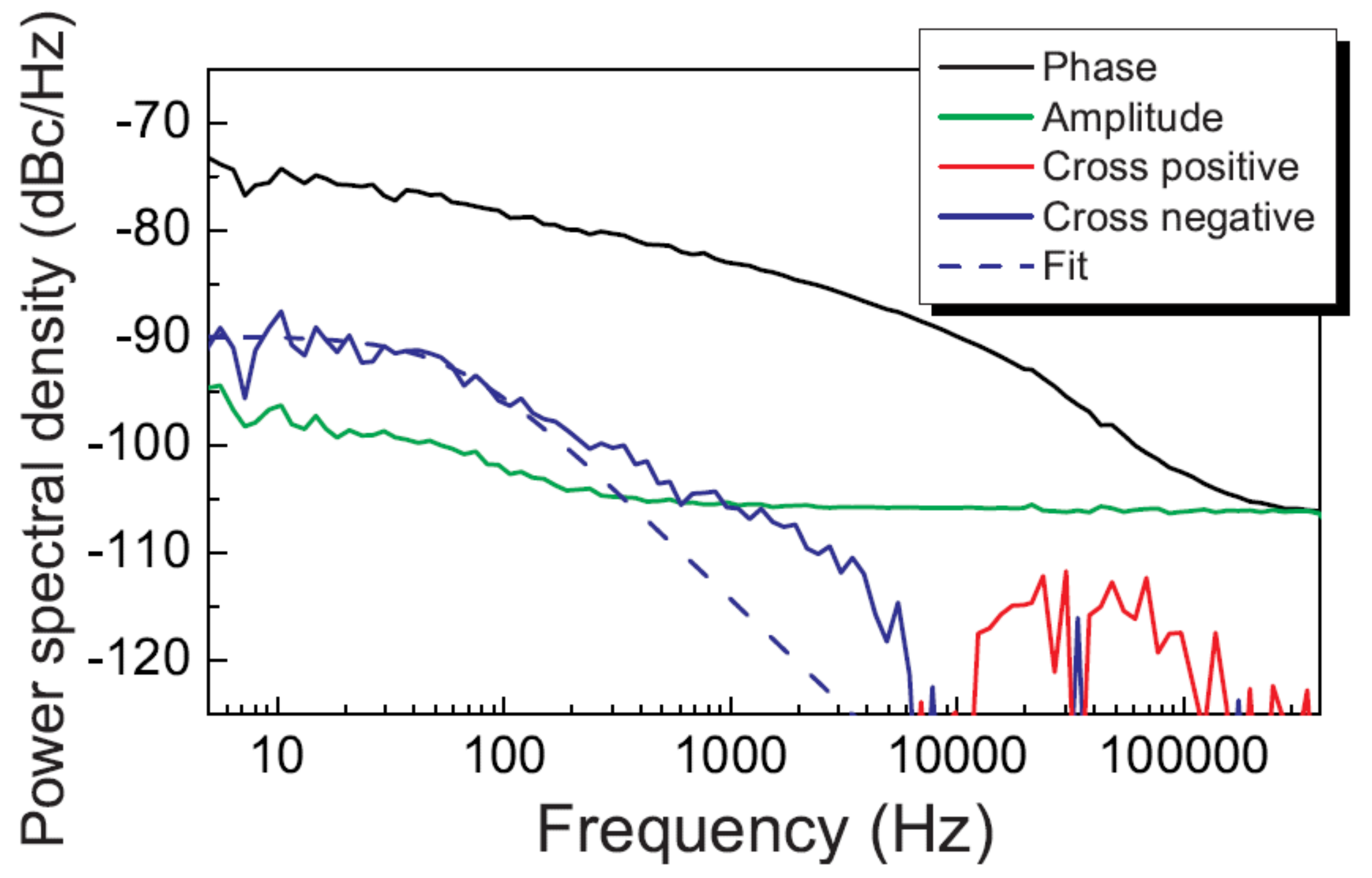


Pread dependence high loading





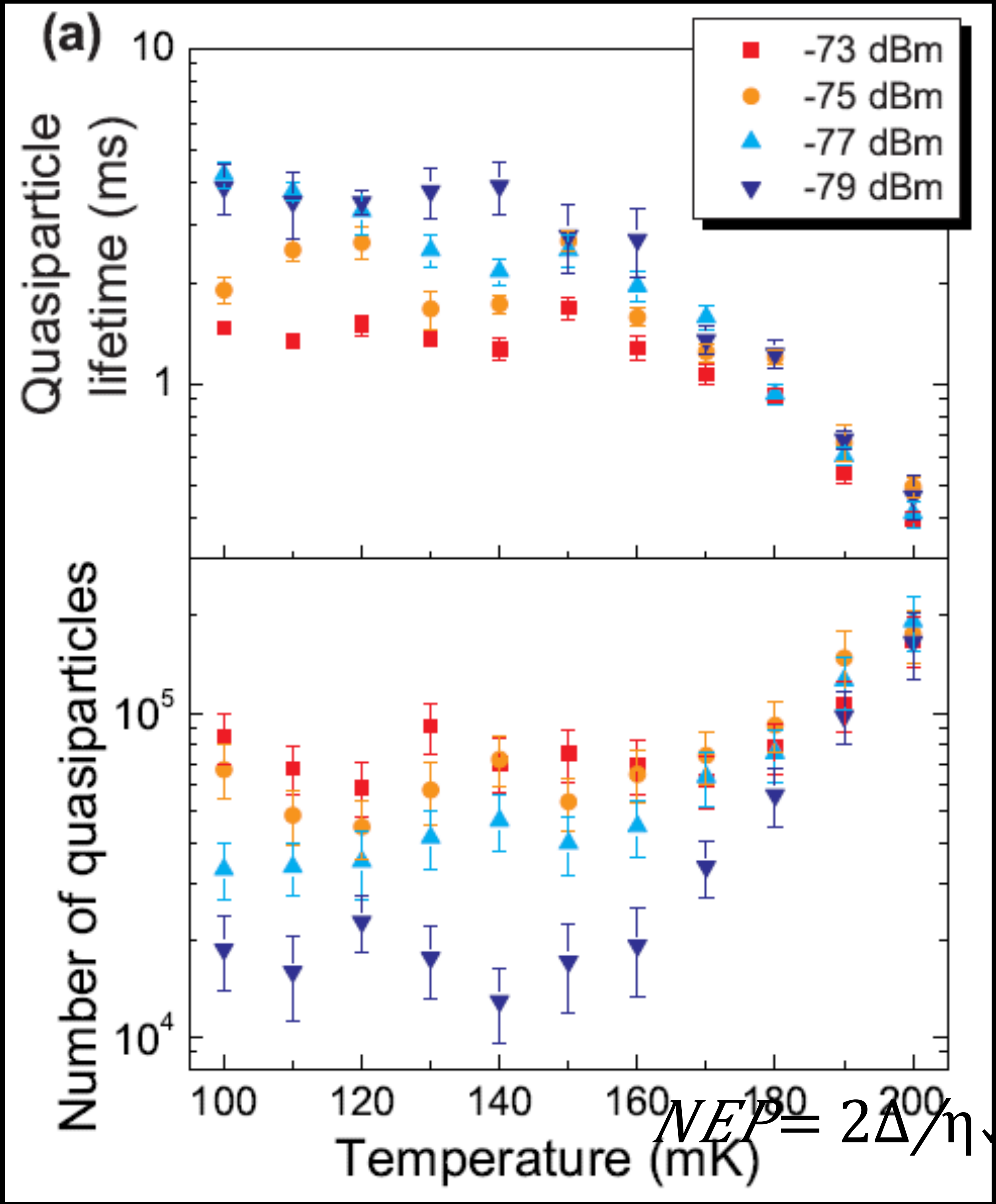
2 quadratures, correlated noise



Phase (inductance) and Amplitude (losses) are orthogonal quadratures
In microwave response => in correlation more sensitive to qp-fluctuations

Appl. Phys. Lett. 100, 162601 (2011)

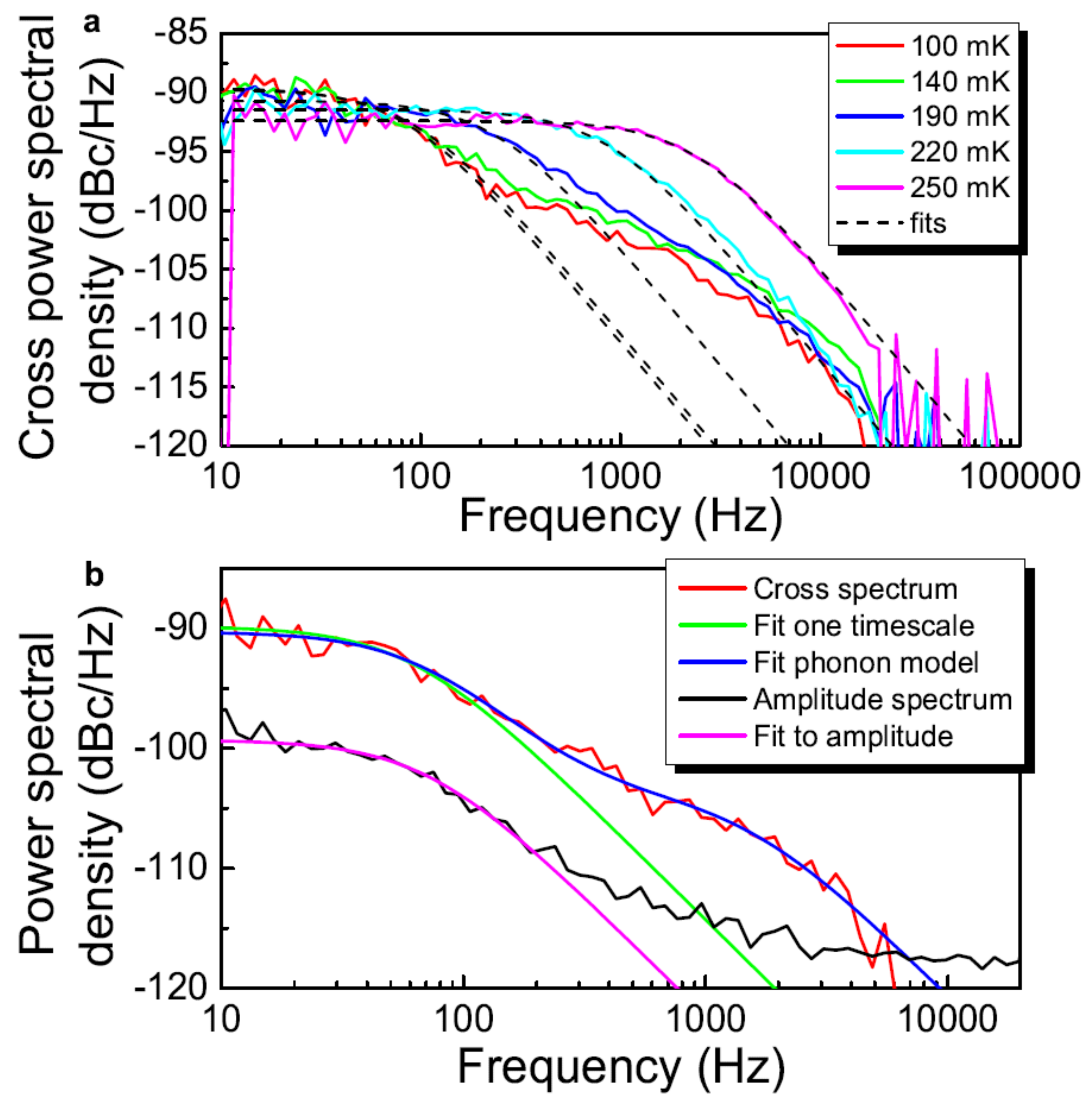
Saturation due to microwave readout signal



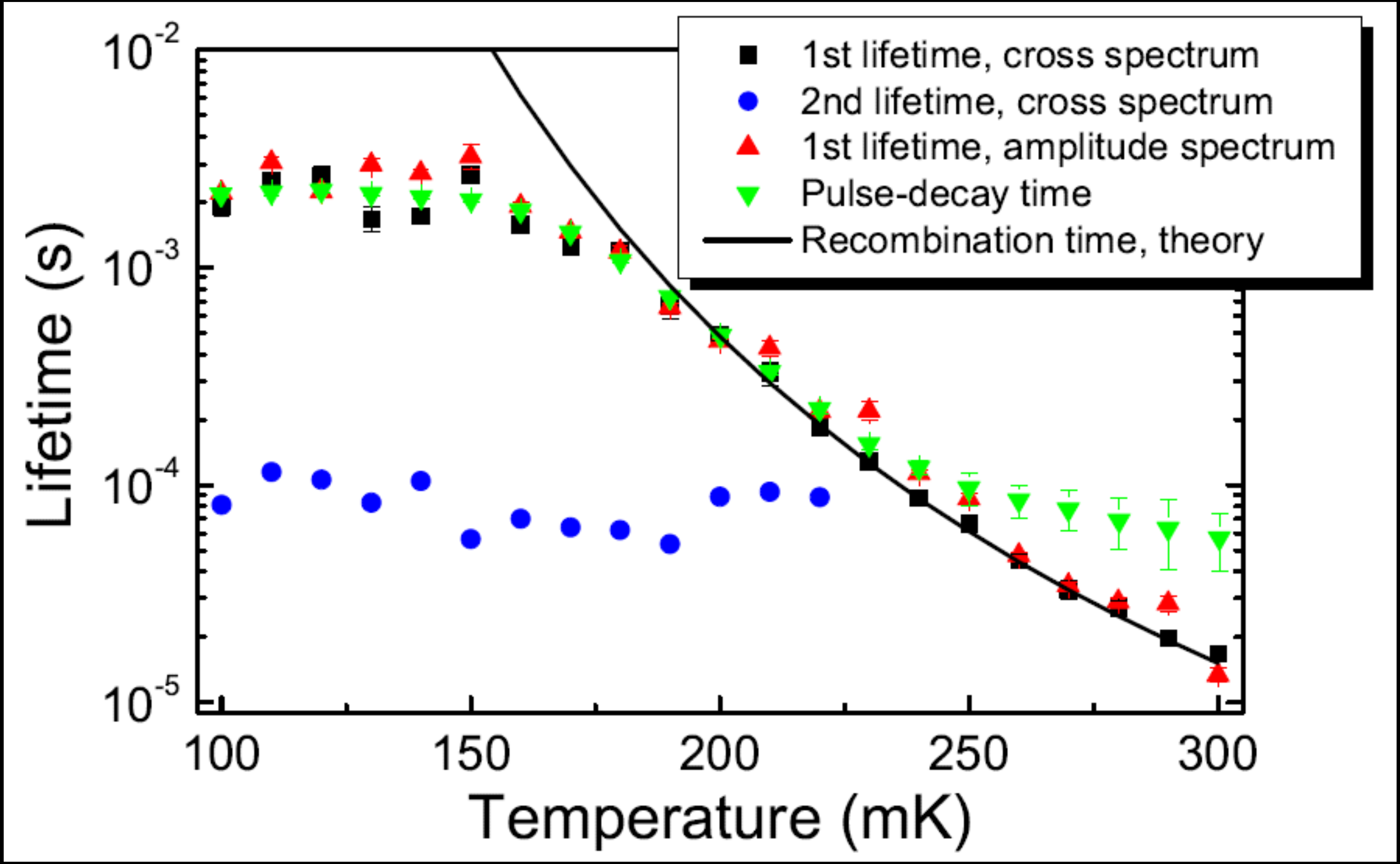
$NEP = 2\Delta/\eta$

Best dark NEP: 2×10^{-19} W/Hz$^{1/2}$

Phonon fluctuations

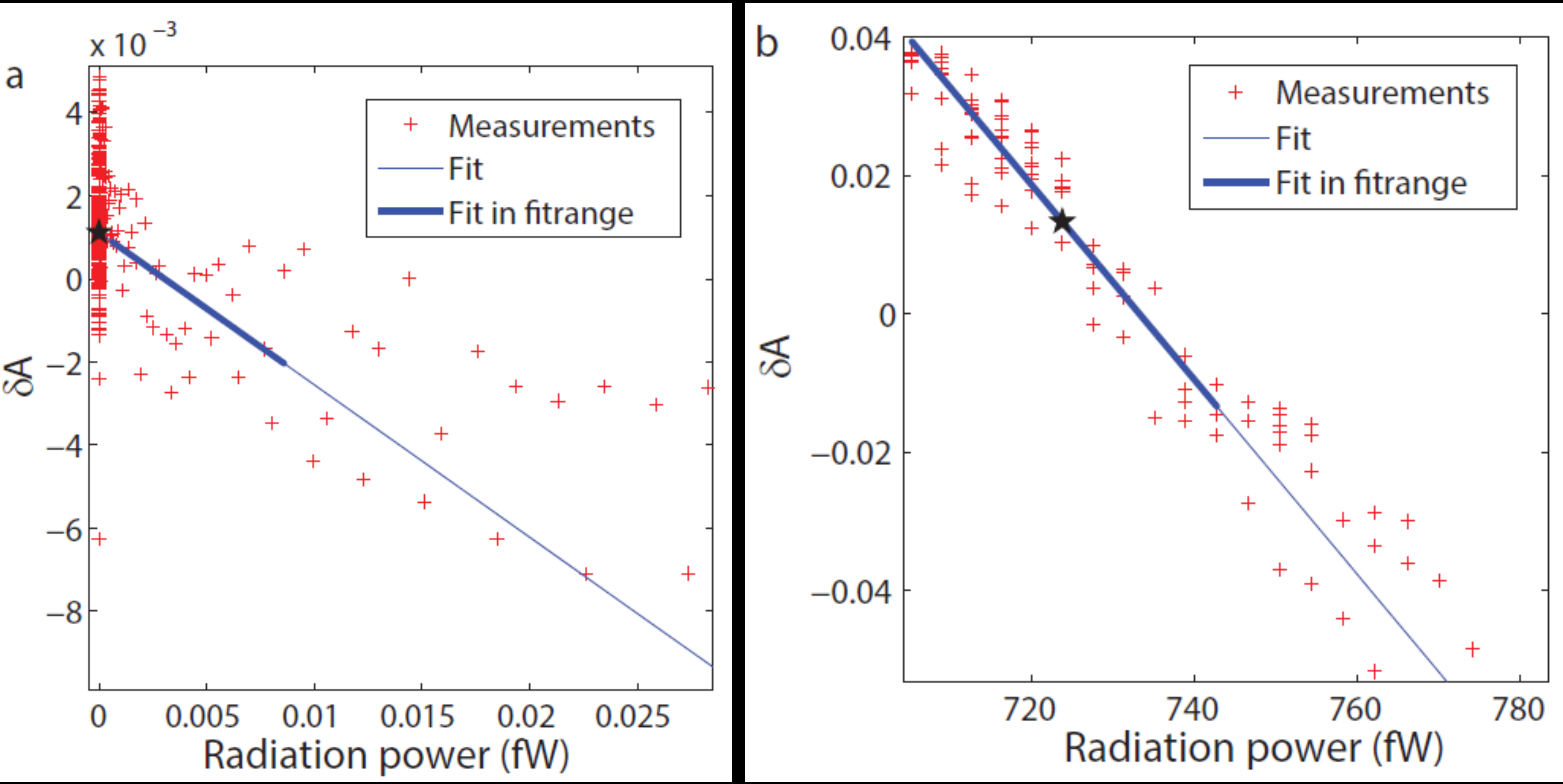


Phonon fluctuations



PdV, PhD thesis, TU Delft 2014, appendix B

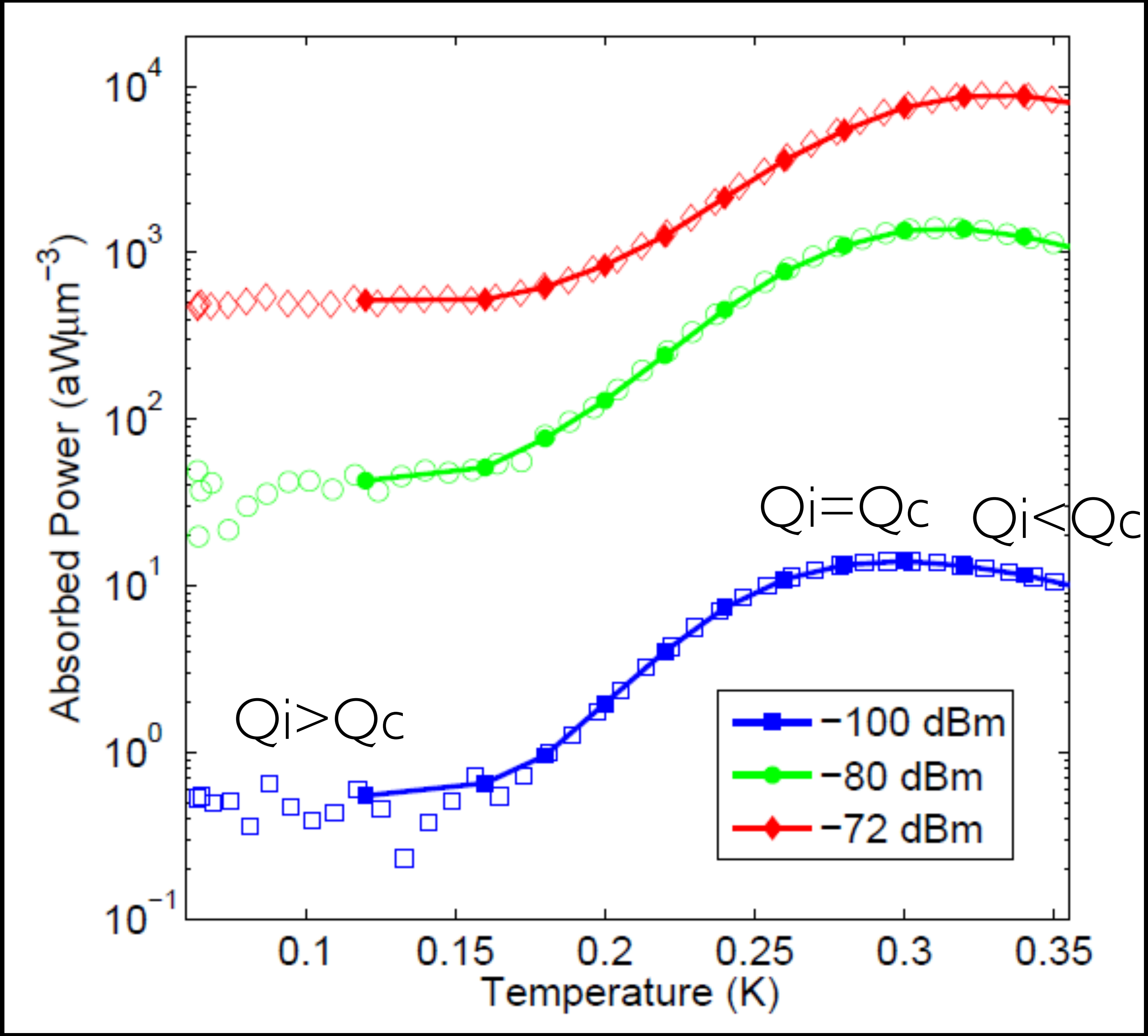
Optical responsivity fit



Lowest power

Highest power

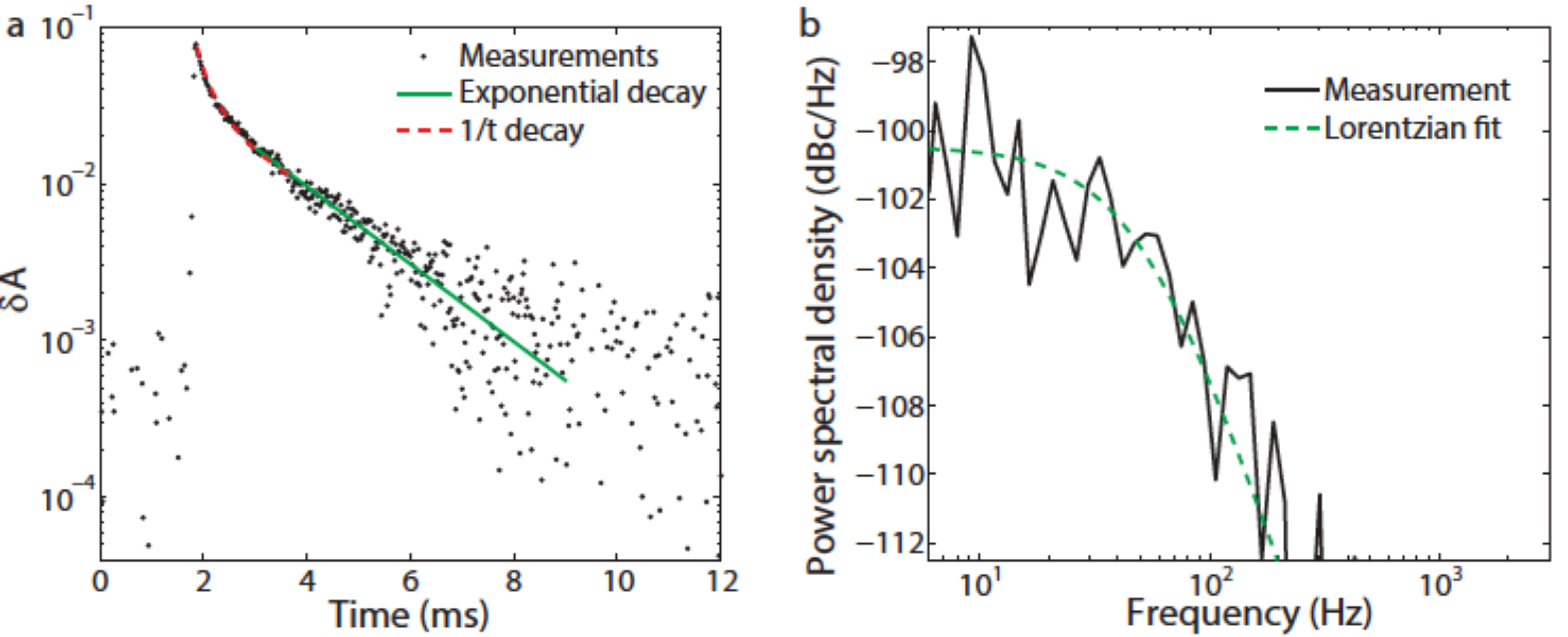
Absorbed microwave power, Qfactors



Maximum dissipation at critical coupling

Pulse, initial 1/t decay

- Nqp2 term dominates start of large pulse
- Equilibration with exponential



PdV, PhD thesis, TU Delft 2014, Ch2