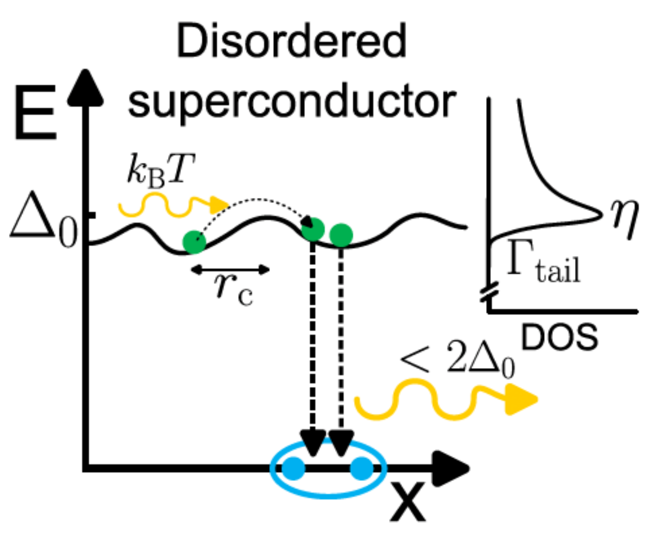
Quasiparticle recombination in disordered superconductors probed with microwave resonators

Pieter de Visser, Steven de Rooij

SRON SPACE RESEARCH ORGANISATION NETHERLANDS

TU Delft Delft University of Technology



BRINGING ABOUT BREAKTHROUGHS IN SPACE SCIENCE

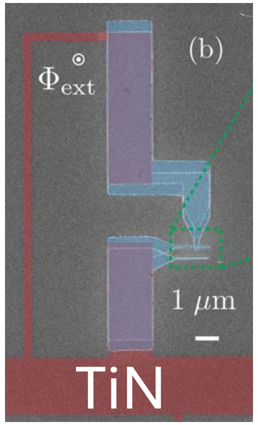
Content

- Resonators with disordered superconductors to detect single photons
- Equilibrium quasiparticle fluctuations
- Recombination as a multi-step process
- Non-equilibrium:
  - High-energy photons
  - Microwave readout photons
- Experimentally connecting quasiparticle dynamics to microwave losses and inductance
- Outlook

Quantum circuits

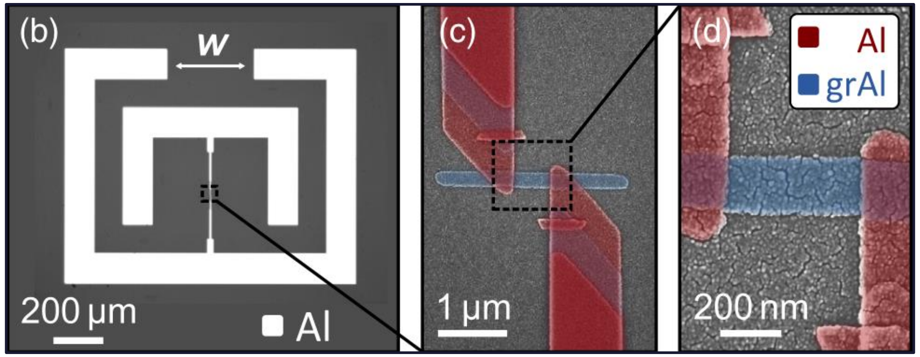
High L_k

Size reduction



J. T. Peltonen et al. *Sci Rep* **8**, 10033 (2018)

Non-linearity of L_k, replacing JJ



P. Winkel et al. *Phys. Rev. X* **10**, 031032 (2020)

$$L_k = \frac{\hbar R_n}{\pi \Delta}$$

Quantum circuits

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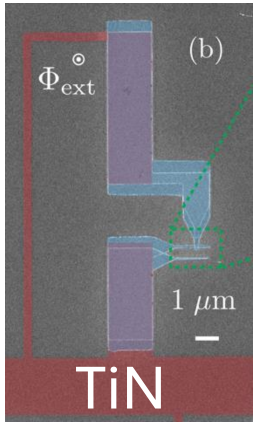

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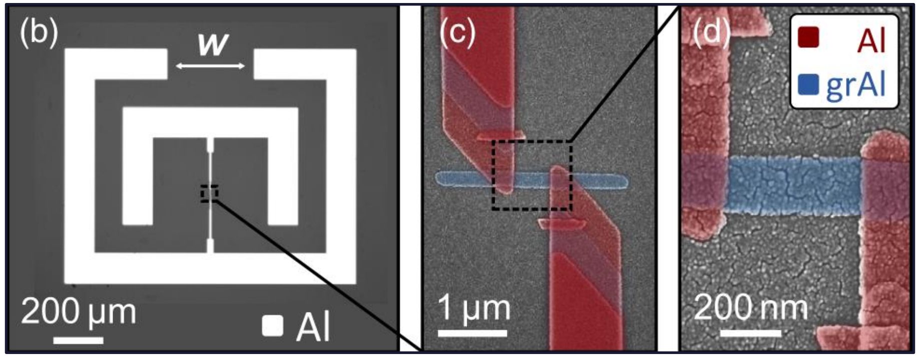

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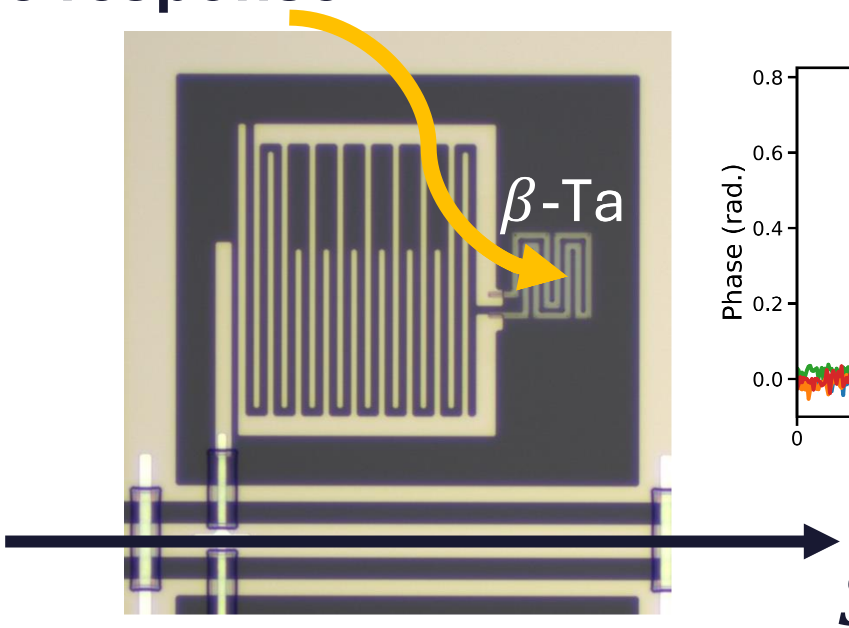
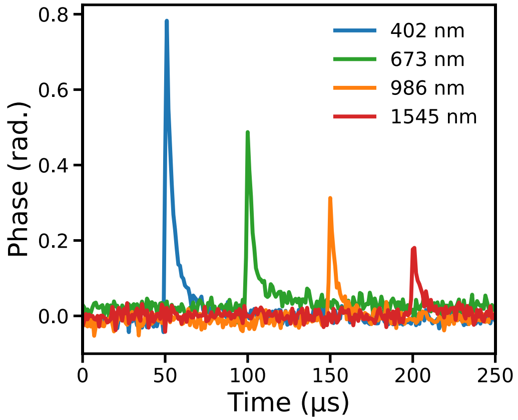
Radiation detectors: MKIDs

More response



S_{21}



Quantum circuits

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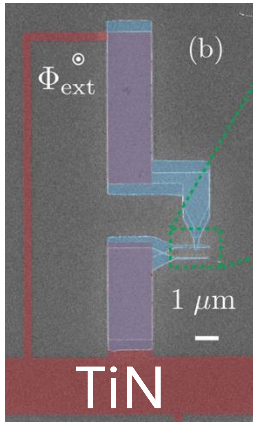

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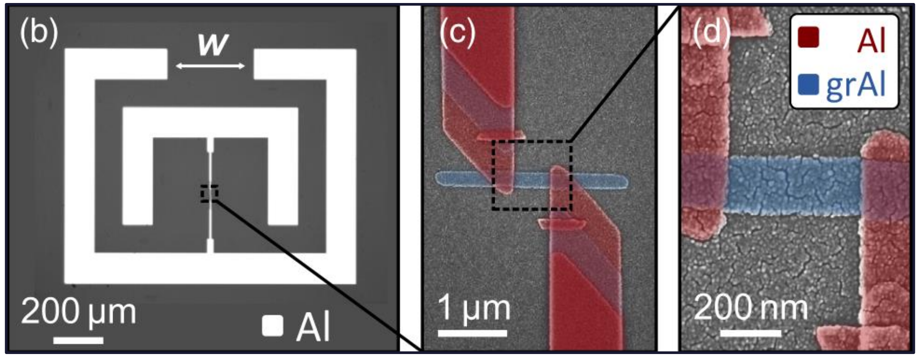

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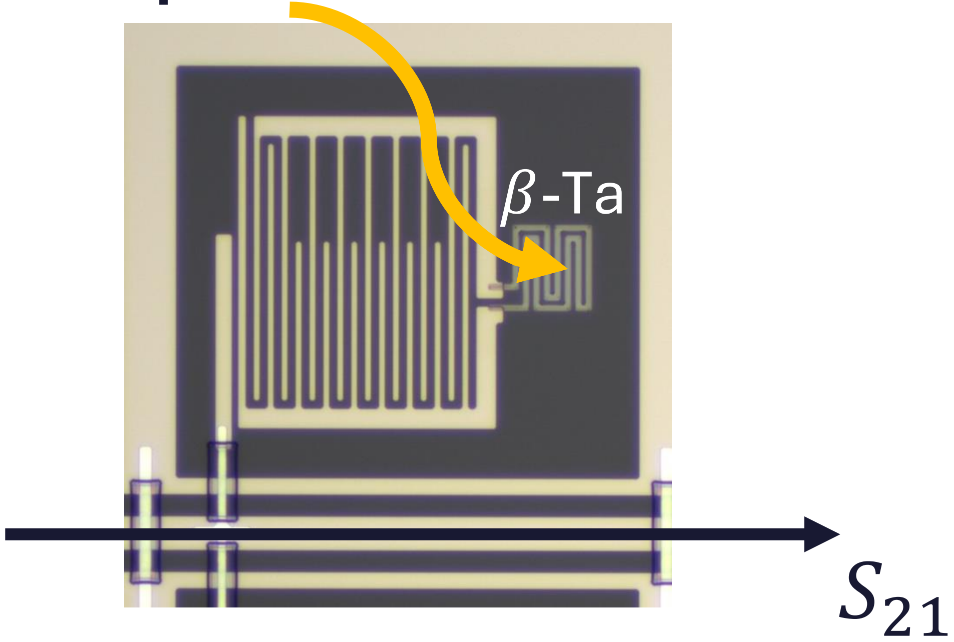
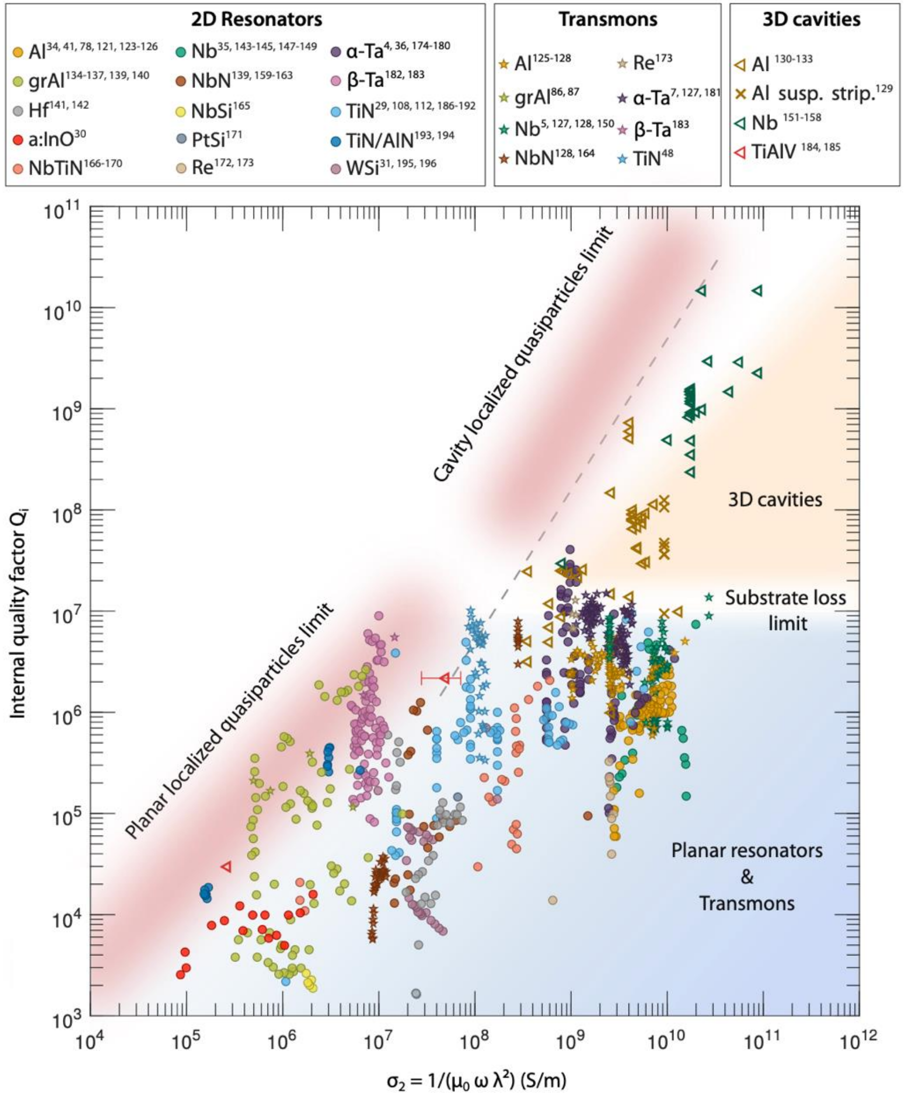


More absorption, e.g. TiN, PtSi, Hf, β-Ta

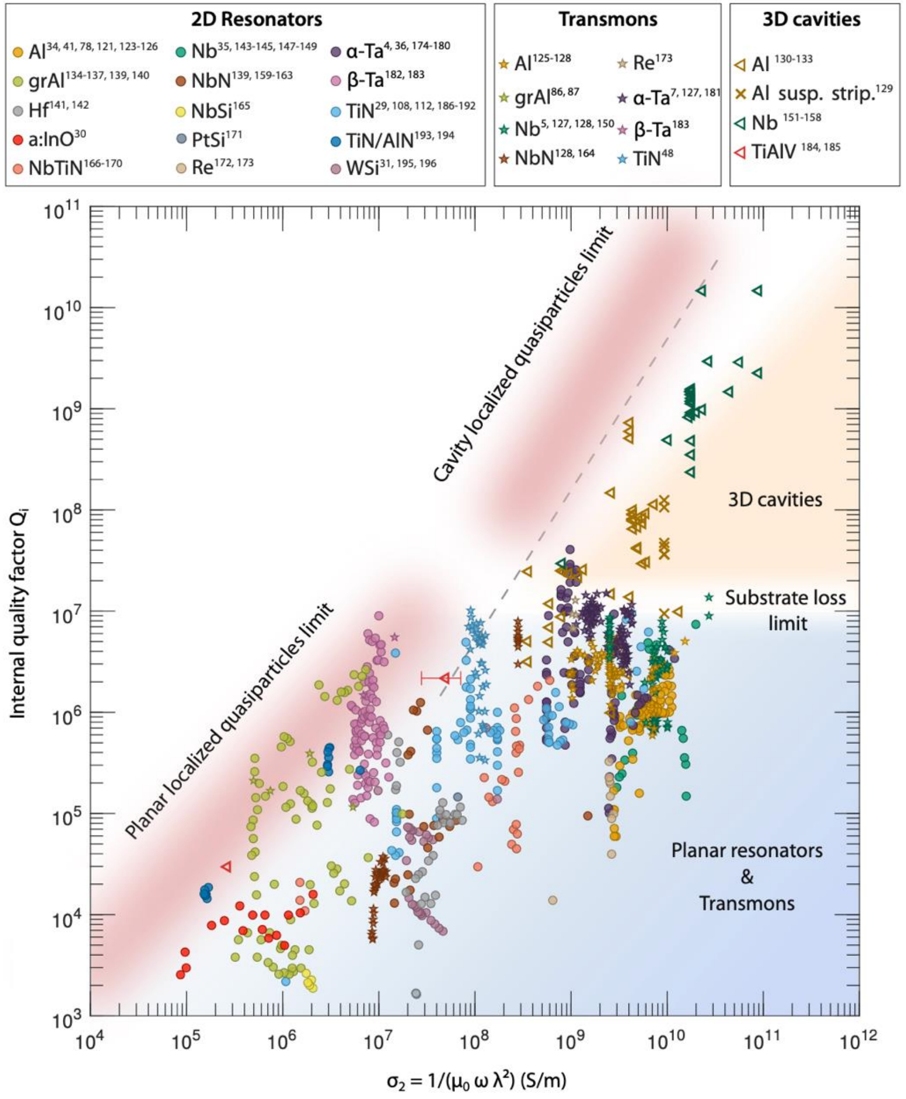
$$L_k = \frac{\hbar R_n}{\pi \Delta}$$

The downside..

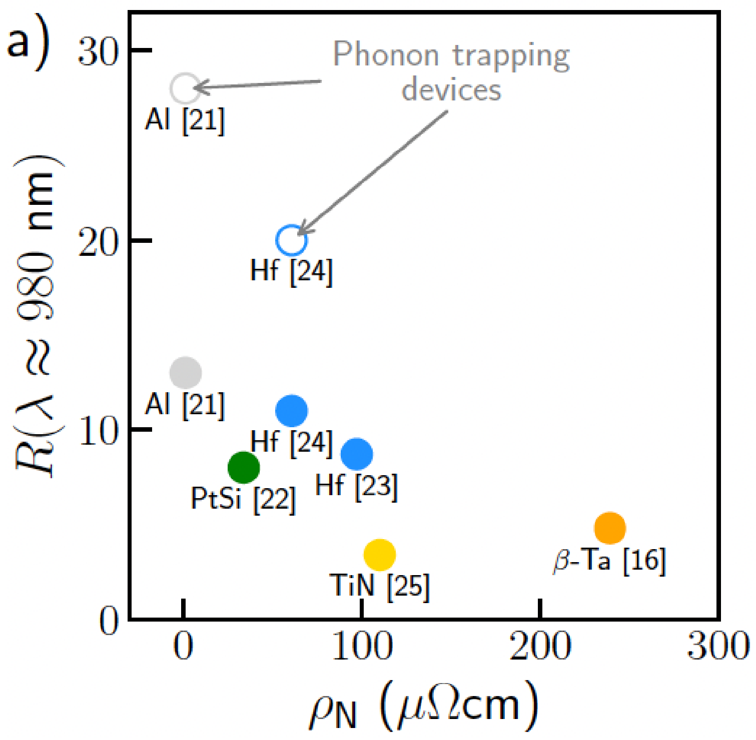


Charpentier et al. arXiv:2507.08953

The downside..



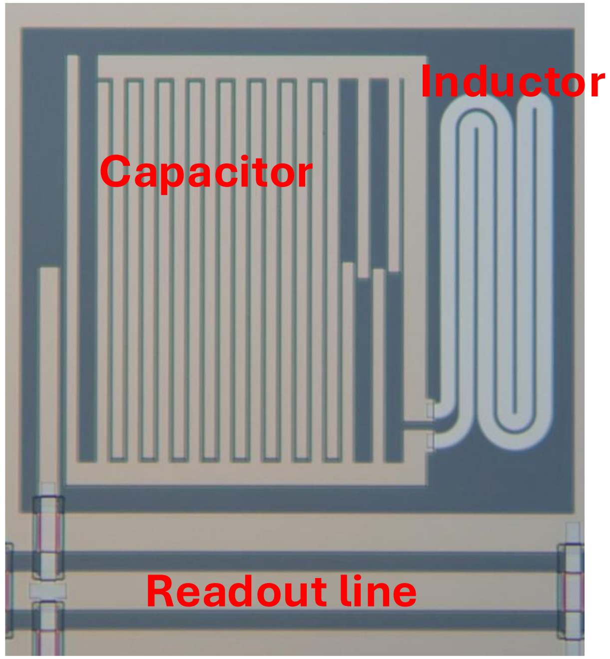
MKIDs



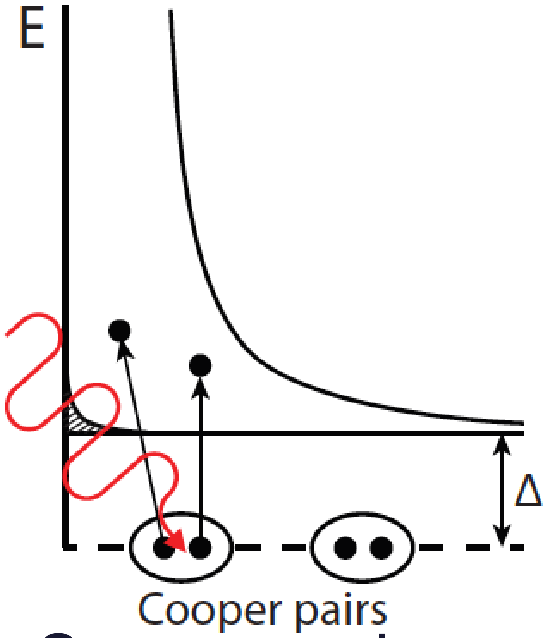
$$R = \lambda/\Delta\lambda$$

$$L_k = \frac{\hbar R_n}{\pi \Delta}$$

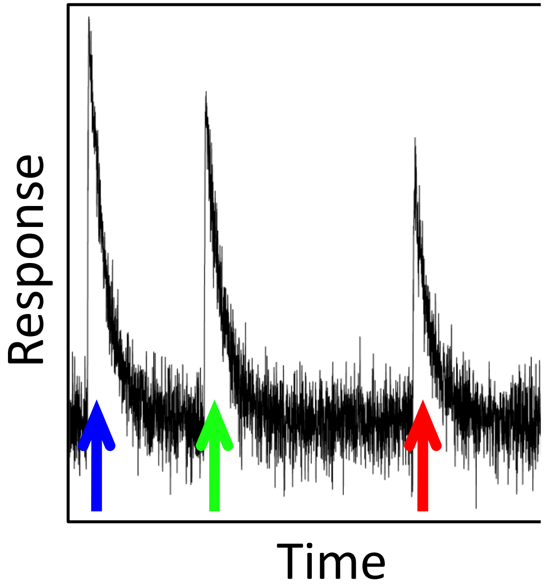
Microwave Kinetic Inductance Detectors



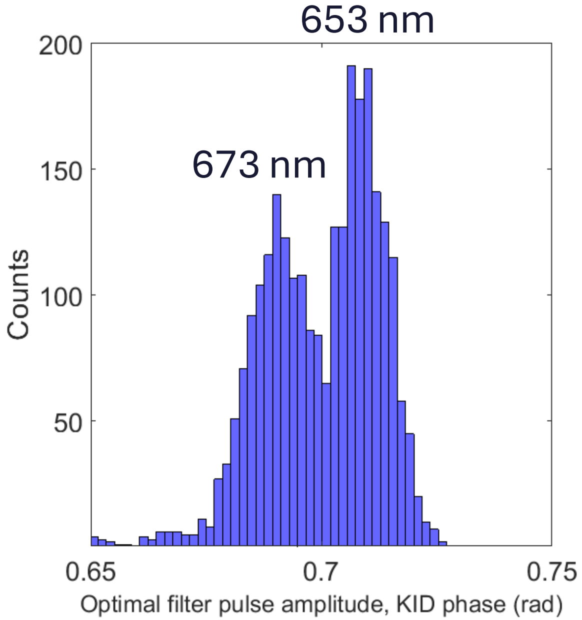
MKID detector



Superconductor

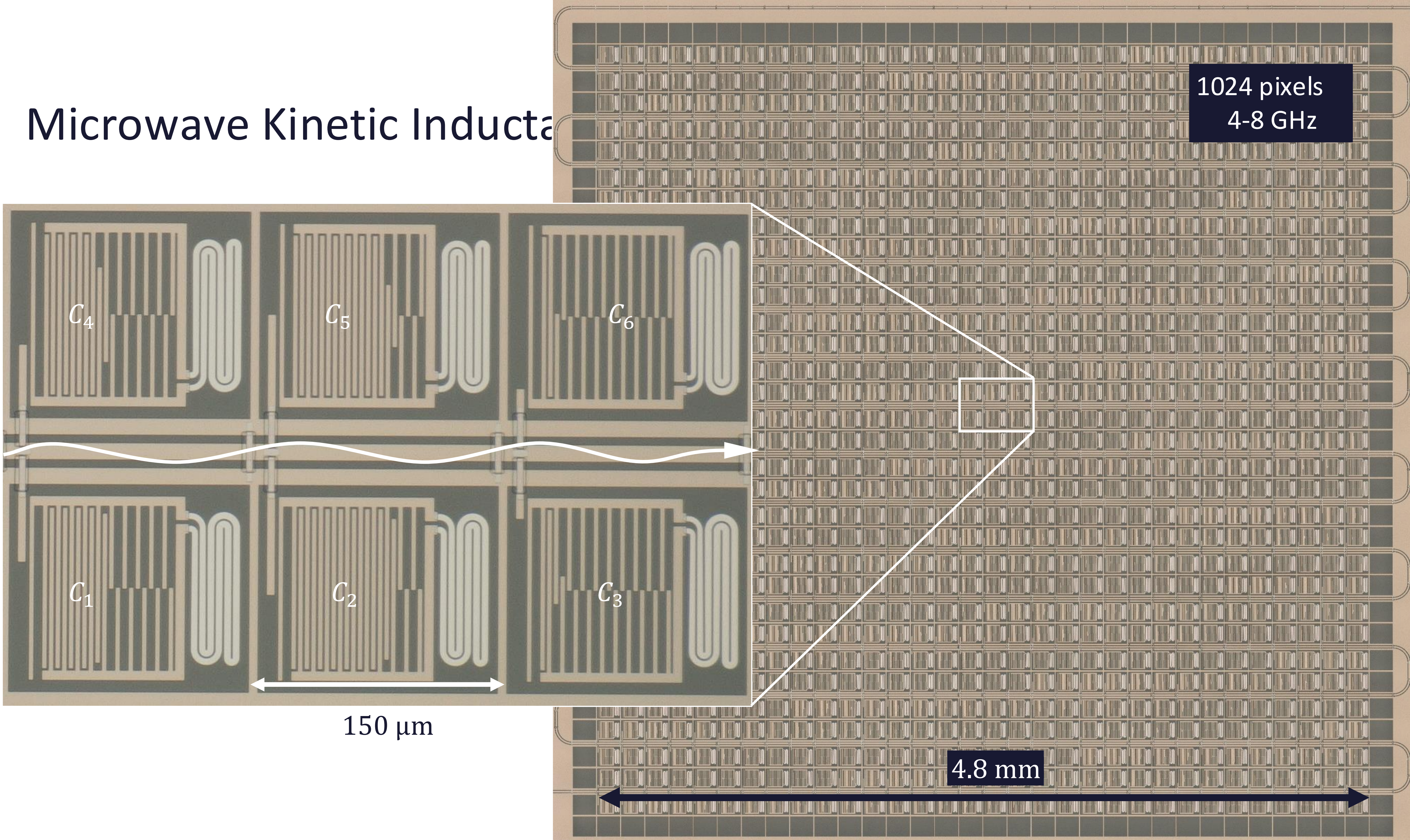


Pulse response



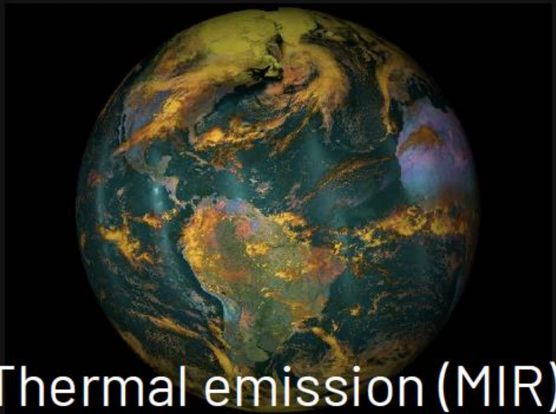
Intrinsic spectral resolution

Microwave Kinetic Inducta



Direct detection and characterisation of Earth-like exoplanets

Reflected light (UV - NIR)



Thermal emission (MIR)

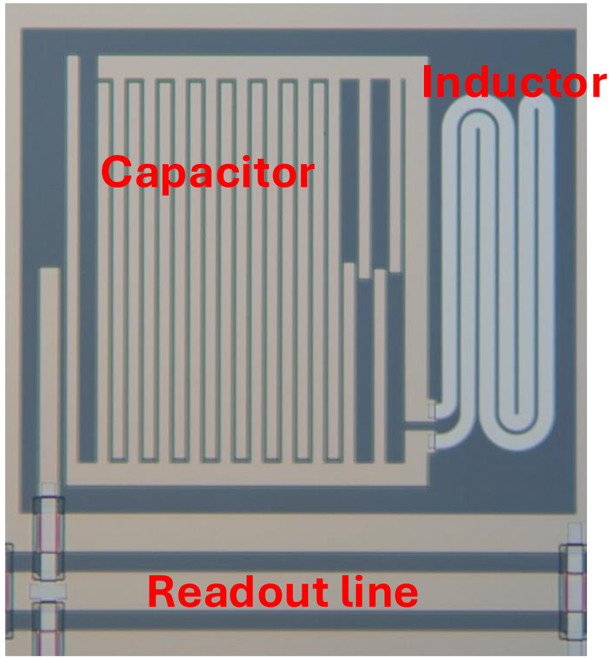
Solar-type stars

M stars

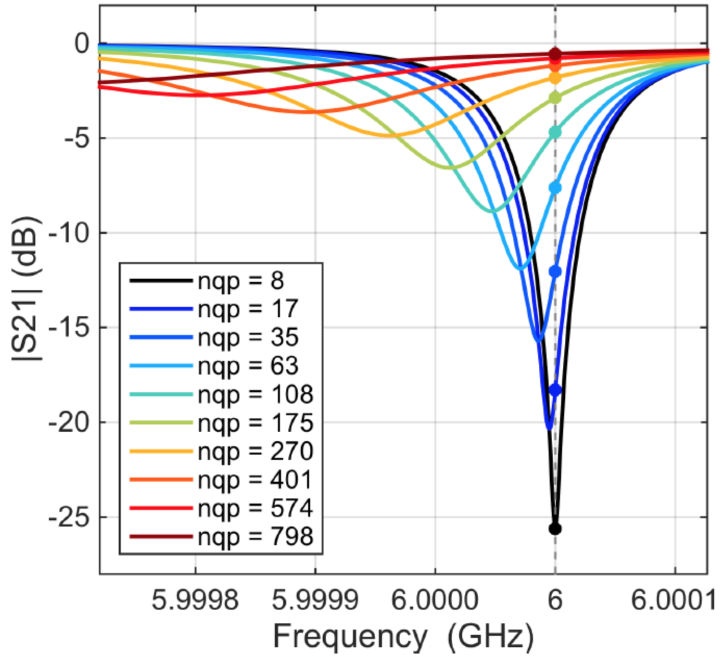
Image credit: NASA, LIFE Initiative, ESO, TMT, GMT

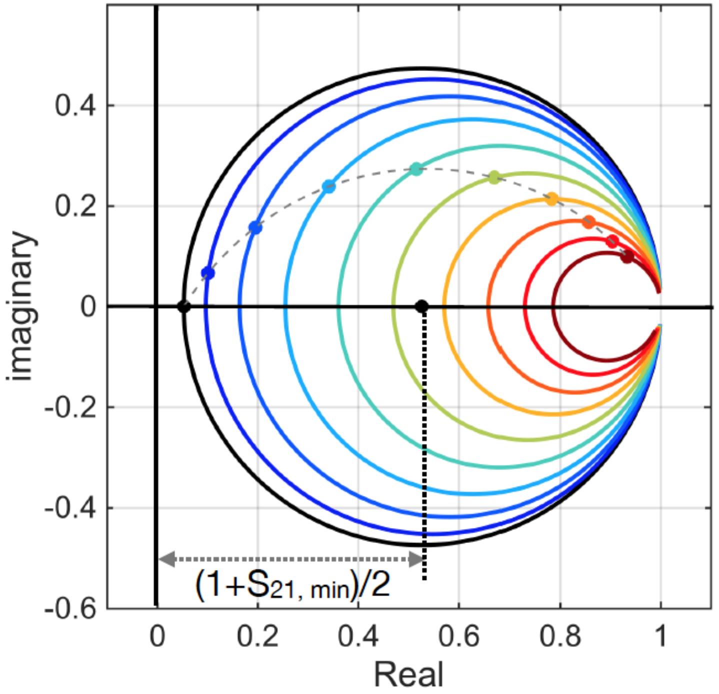
Quasiparticle Detector

Quasiparticle dynamics is key

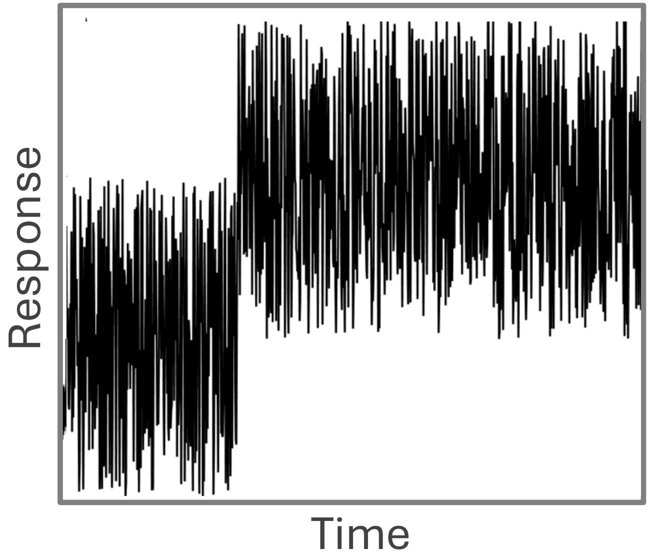


MKID detector

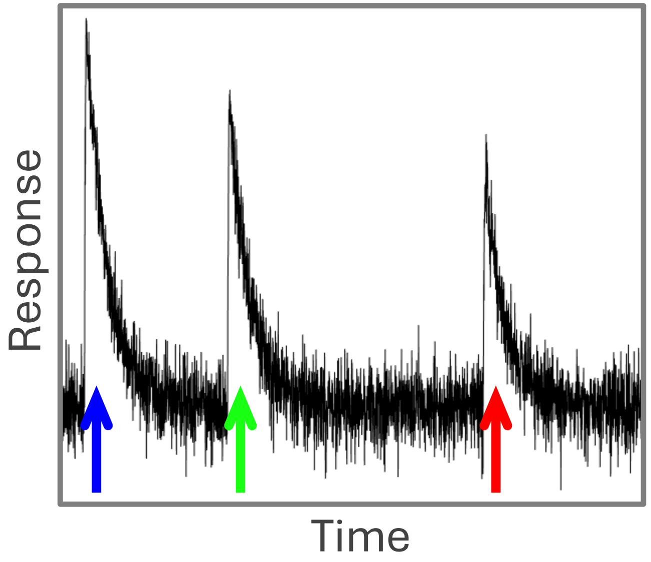


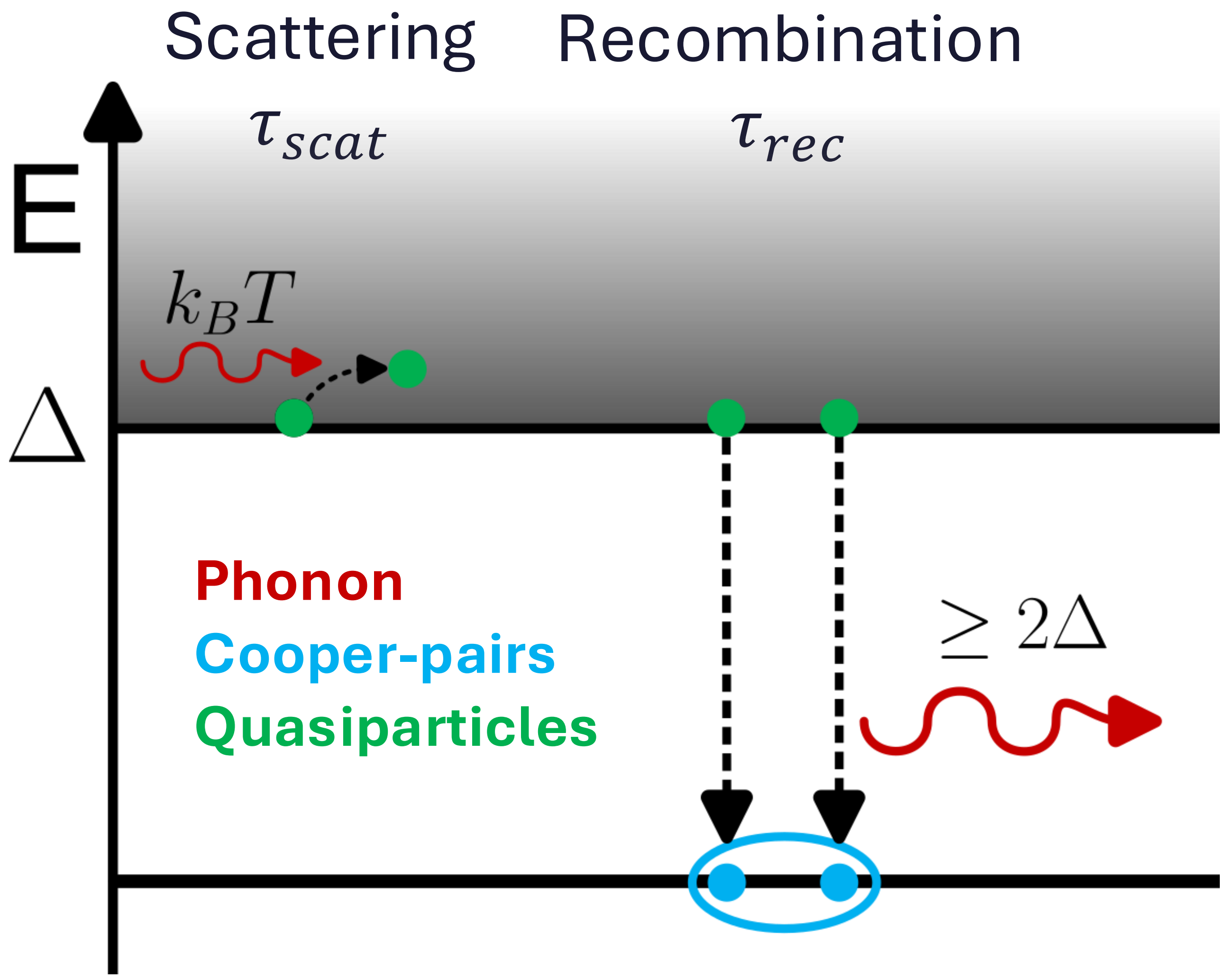


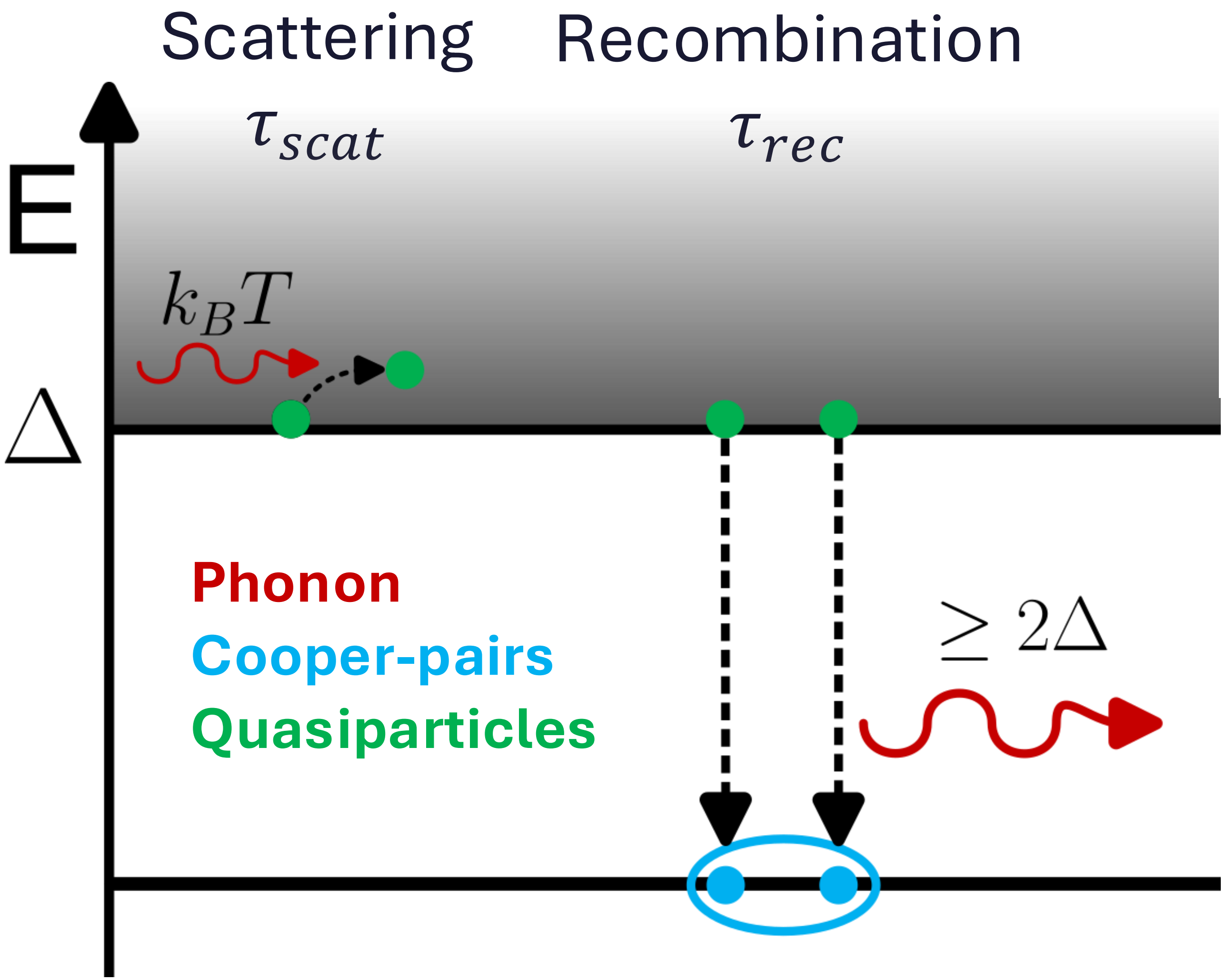
Equilibrium to steady-state response

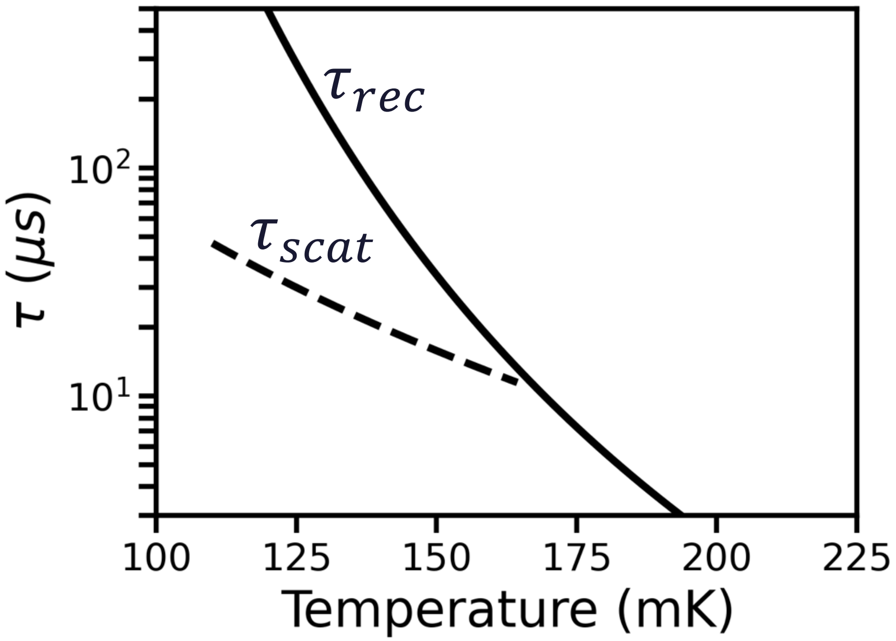


Pulse response – strong non-equilibrium




Scattering
Recombination
τ_{scat}
τ_{rec}
E
k_BT
Δ
Phonon
Cooper-pairs
Quasiparticles
$\geq 2\Delta$





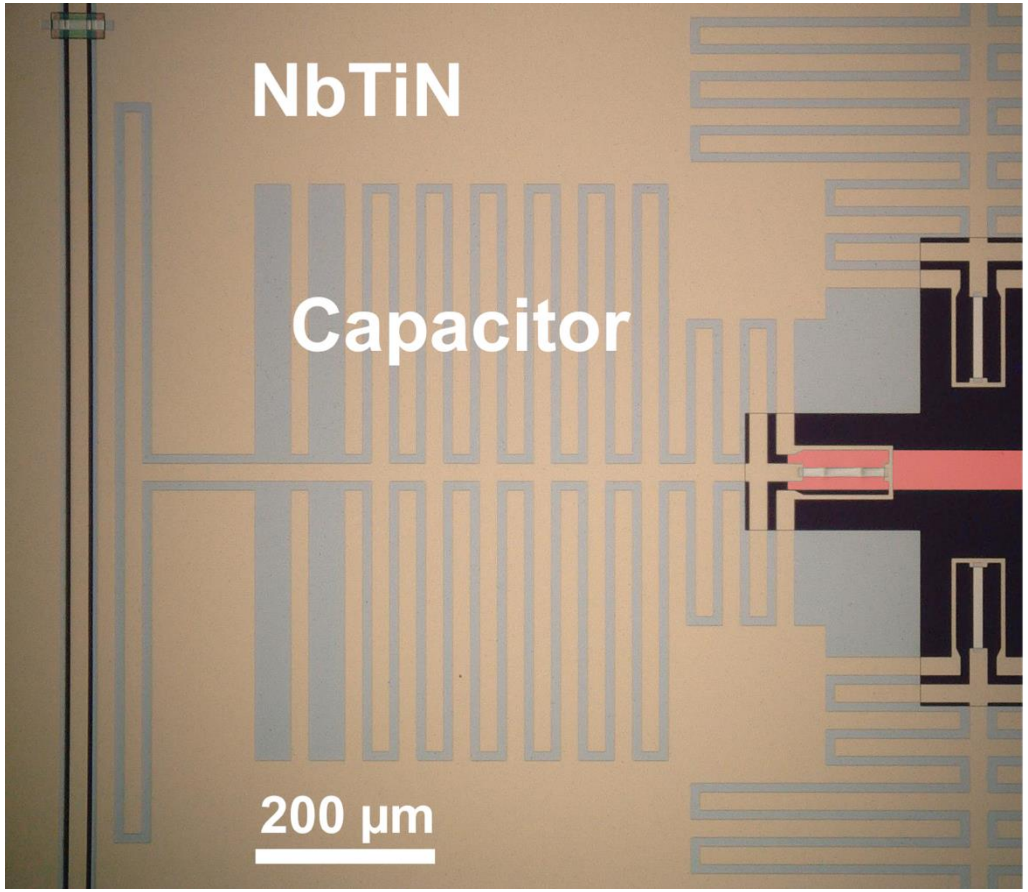
Disordered:

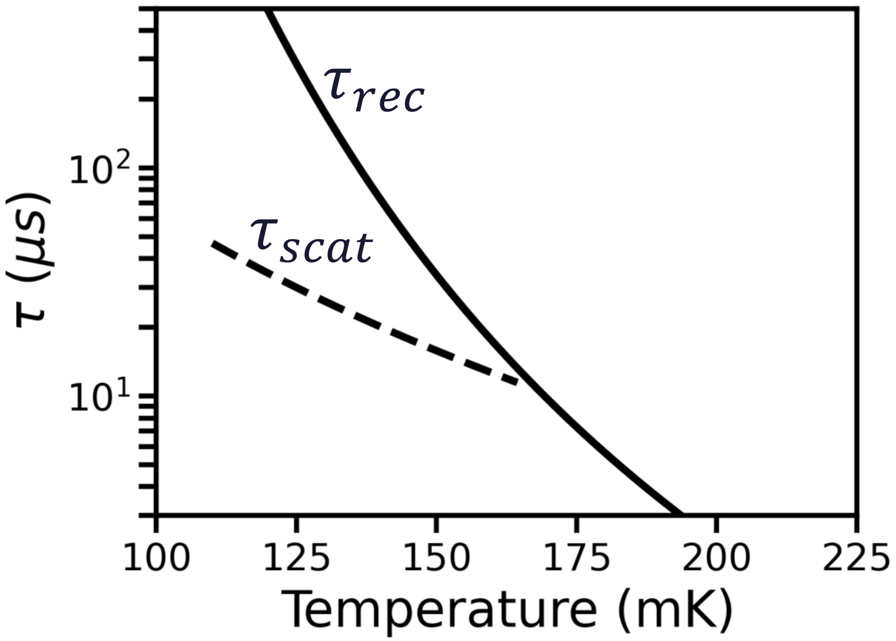
T. P. Devereaux et al. *Phys. Rev. B* **44**, 4587–4600 (1991)

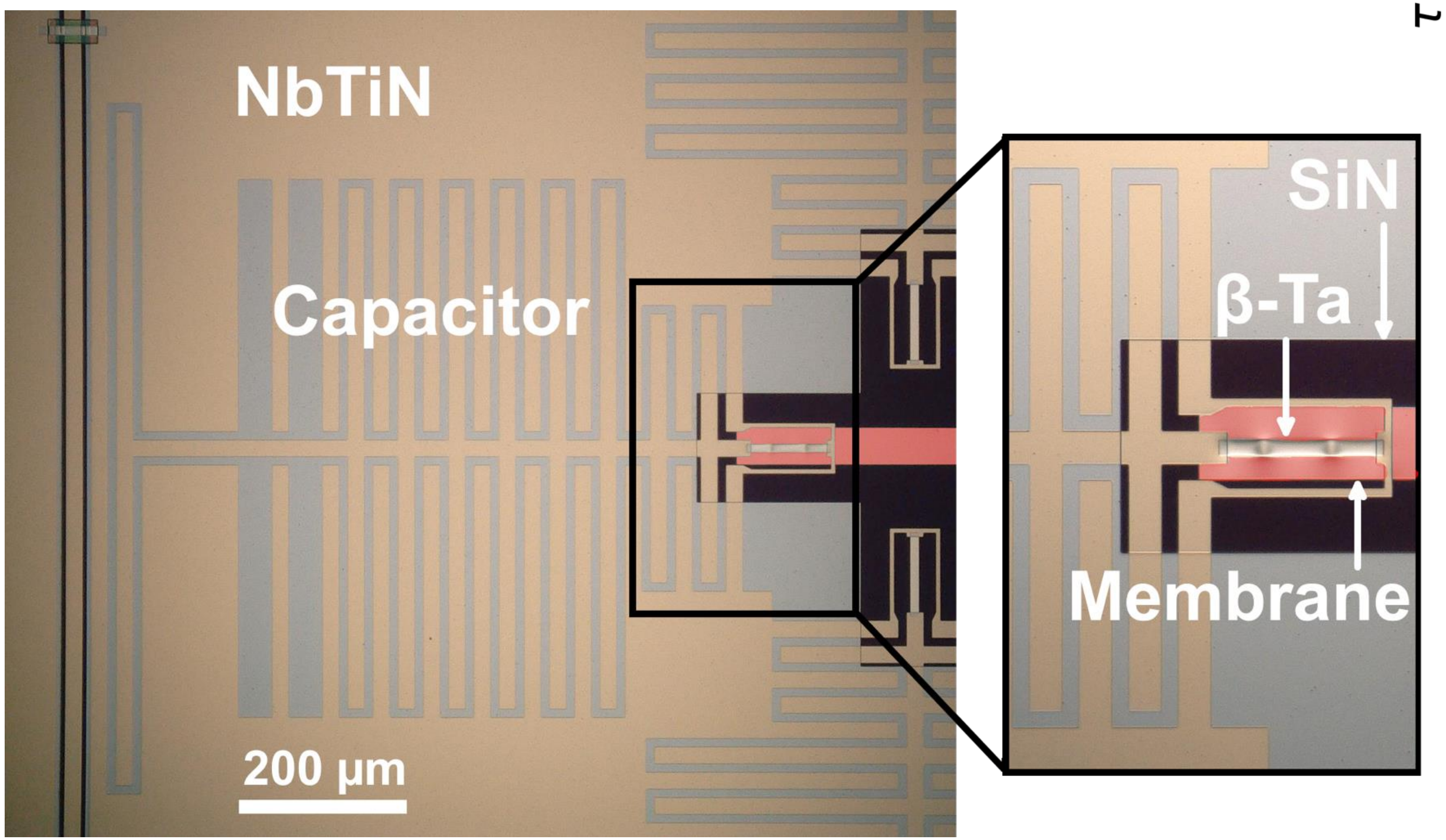
M. Y. Reizer et al. *Zh. Eksp. Teor. Fiz.* **90**, 1056 (1986)

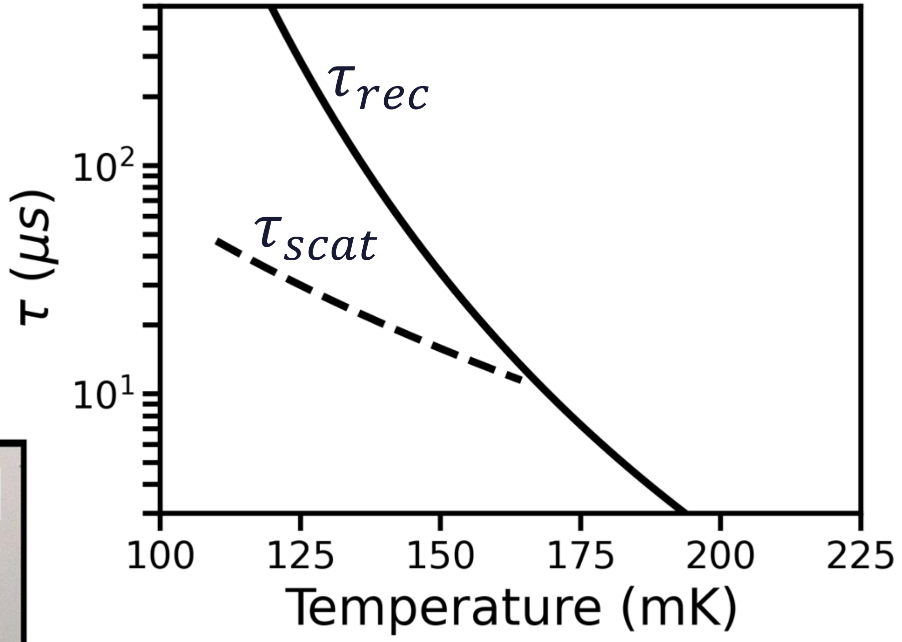
Clean:

S. B. Kaplan et al. *Phys. Rev. B* **14**, 4854–4873 (1976)

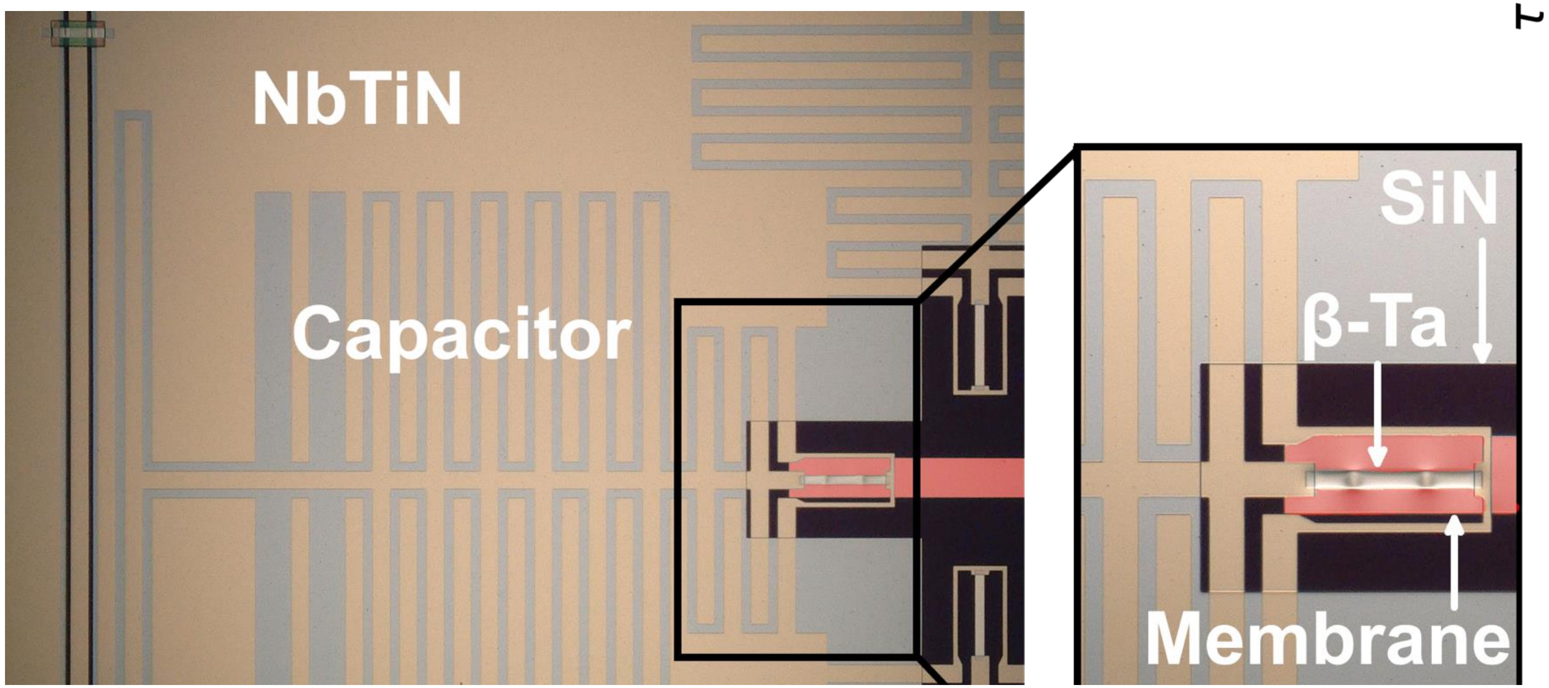

NbTiN
Capacitor
200 μm


τ_{rec}
τ_{scat}
τ (μs)
10^2
10^1
100
125
150
175
200
225
Temperature (mK)





β-Ta inductor, 81 pH/square



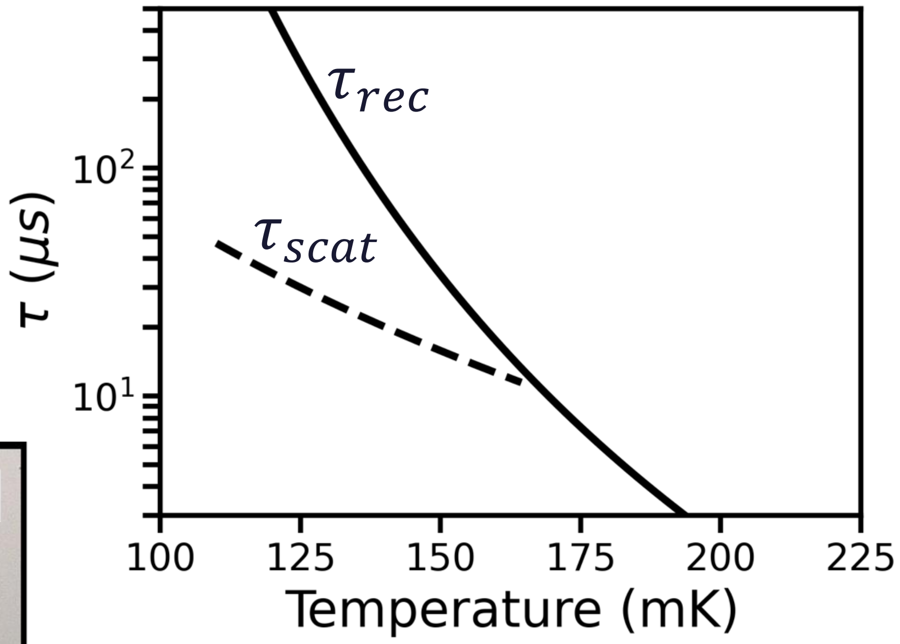
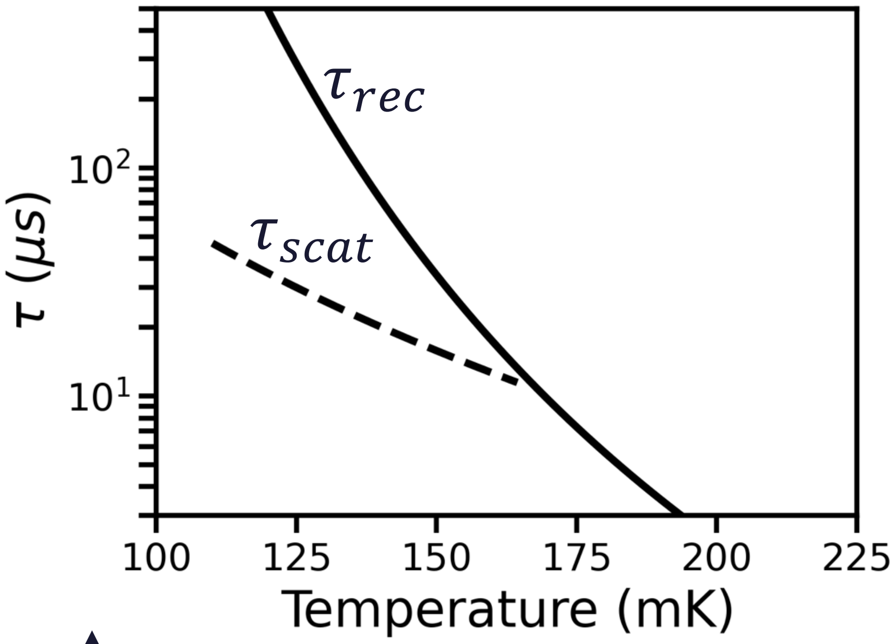


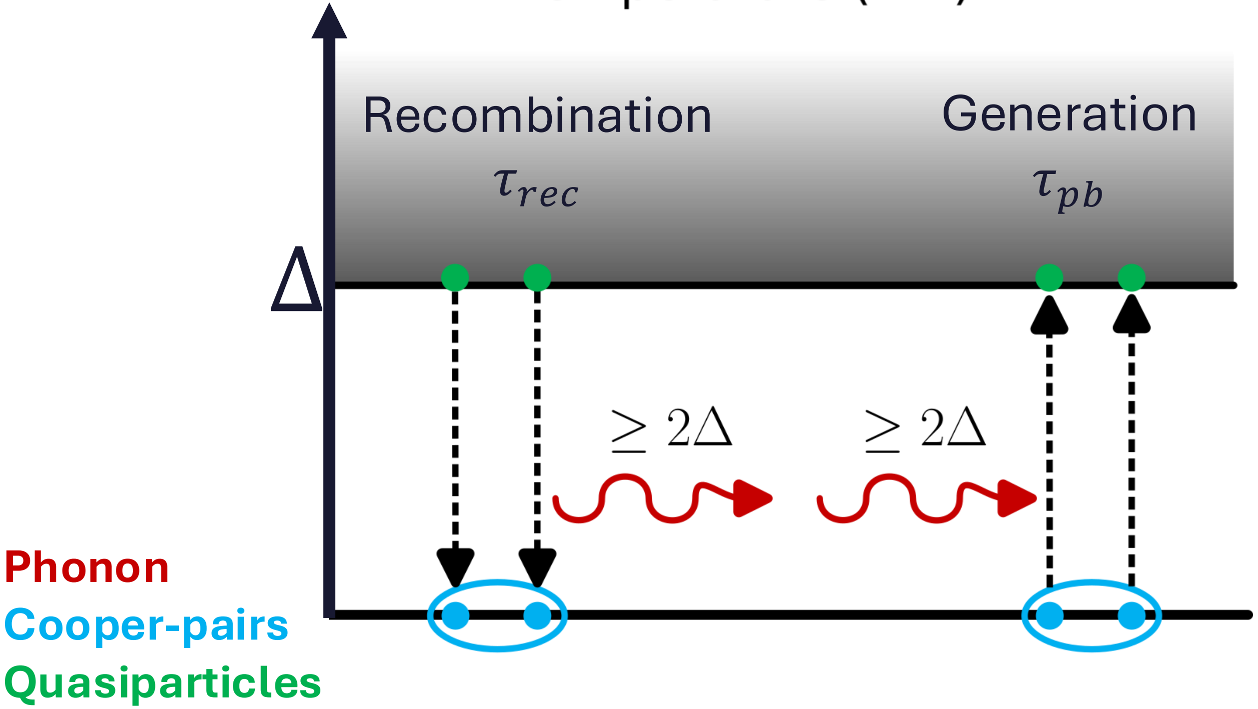
Table 1 | Geometry, electronic properties and phonon properties for β-Ta

Geometry			Measured electronic properties						Values from ref. 55			
d	W	L	T_c	$\rho_N(T=1\,K)$	D	n_e			$\hat{\rho}$	c_L	c_T	T_D
(nm)	(μm)	(μm)	(K)	(μΩcm)	(cm^2/s)	($μm^{-3}$)	RRR	$k_F l$	(g/cm^3)	(km/s)	(km/s)	(K)
40	10	90	0.87	206	0.74	9.3×10^{10}	1.03	4.2	16.6	4.34	1.73	221

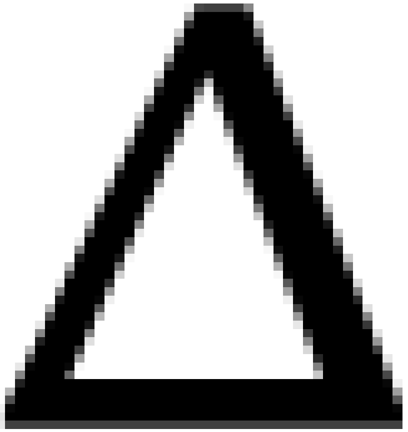
Generation - recombination

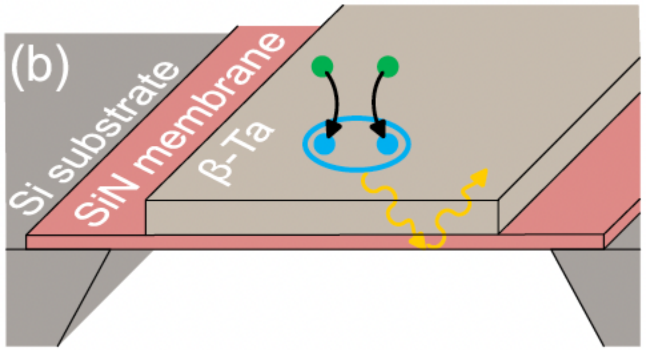
Δ

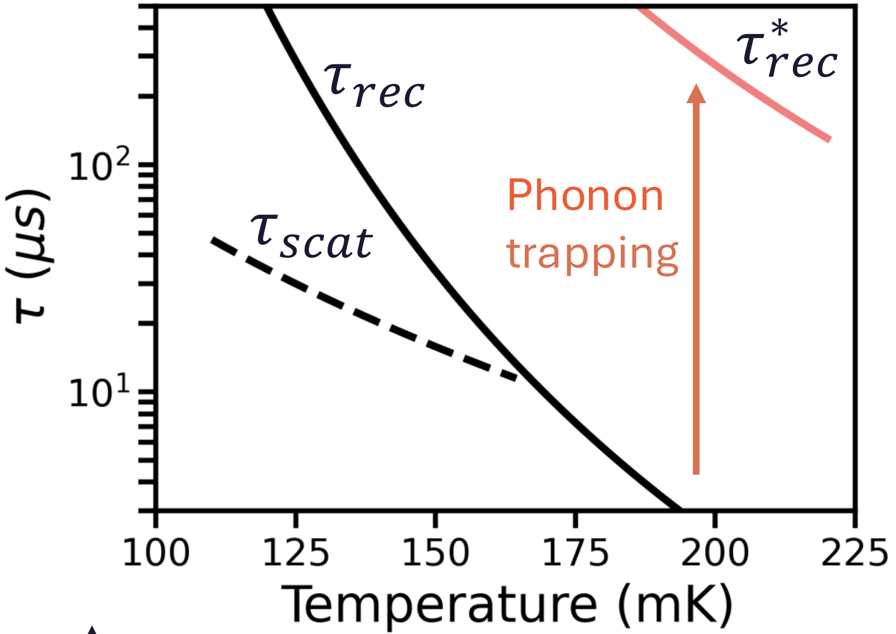


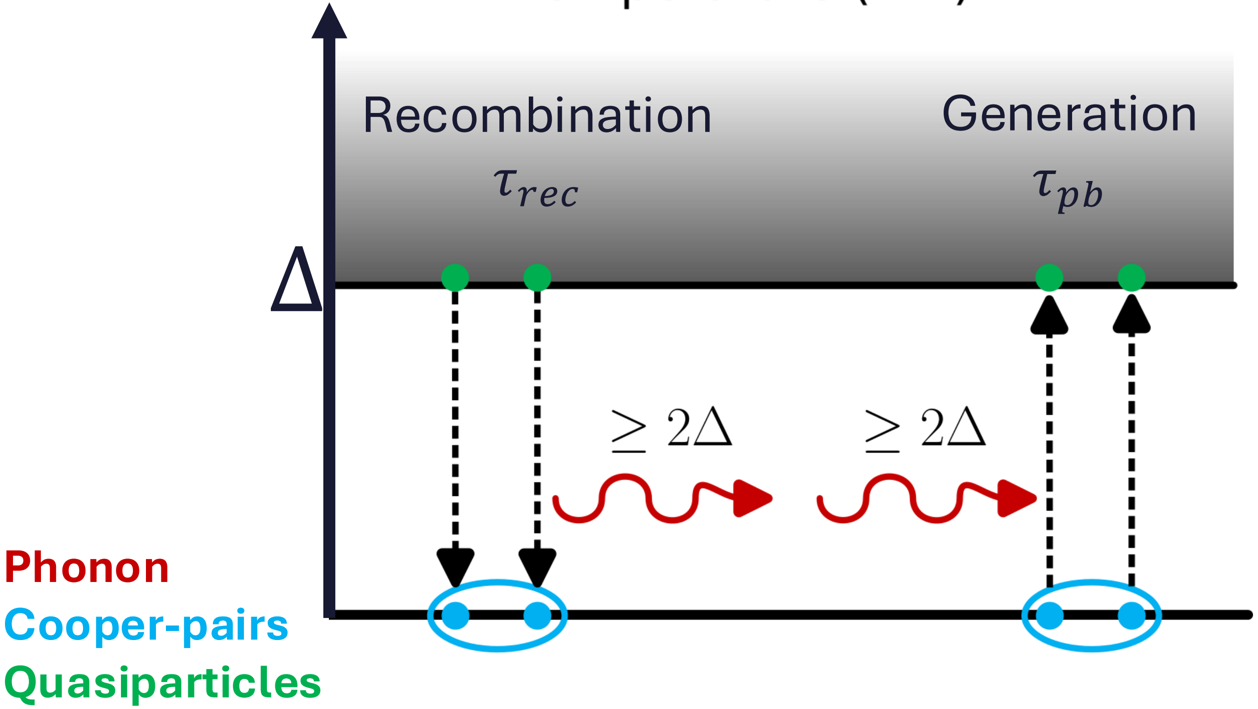


Phonon - recycling

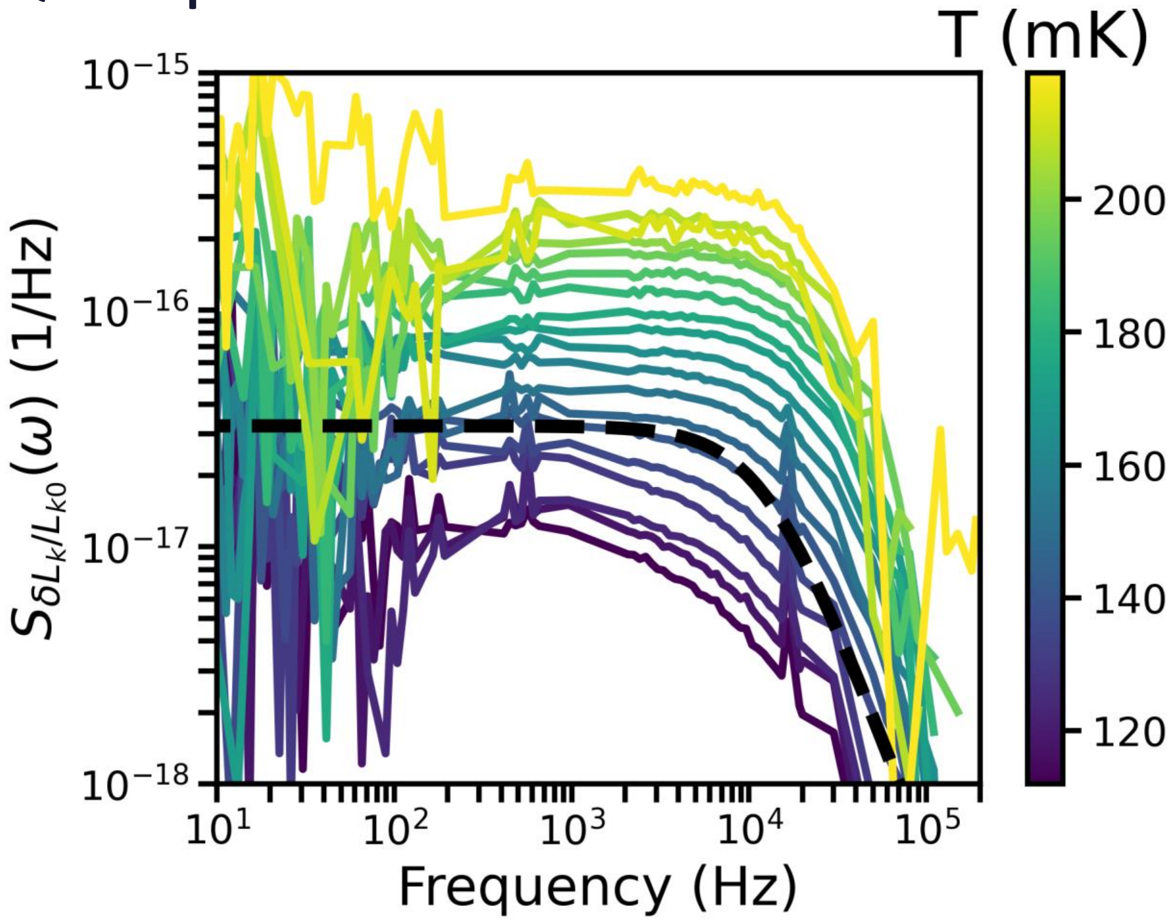








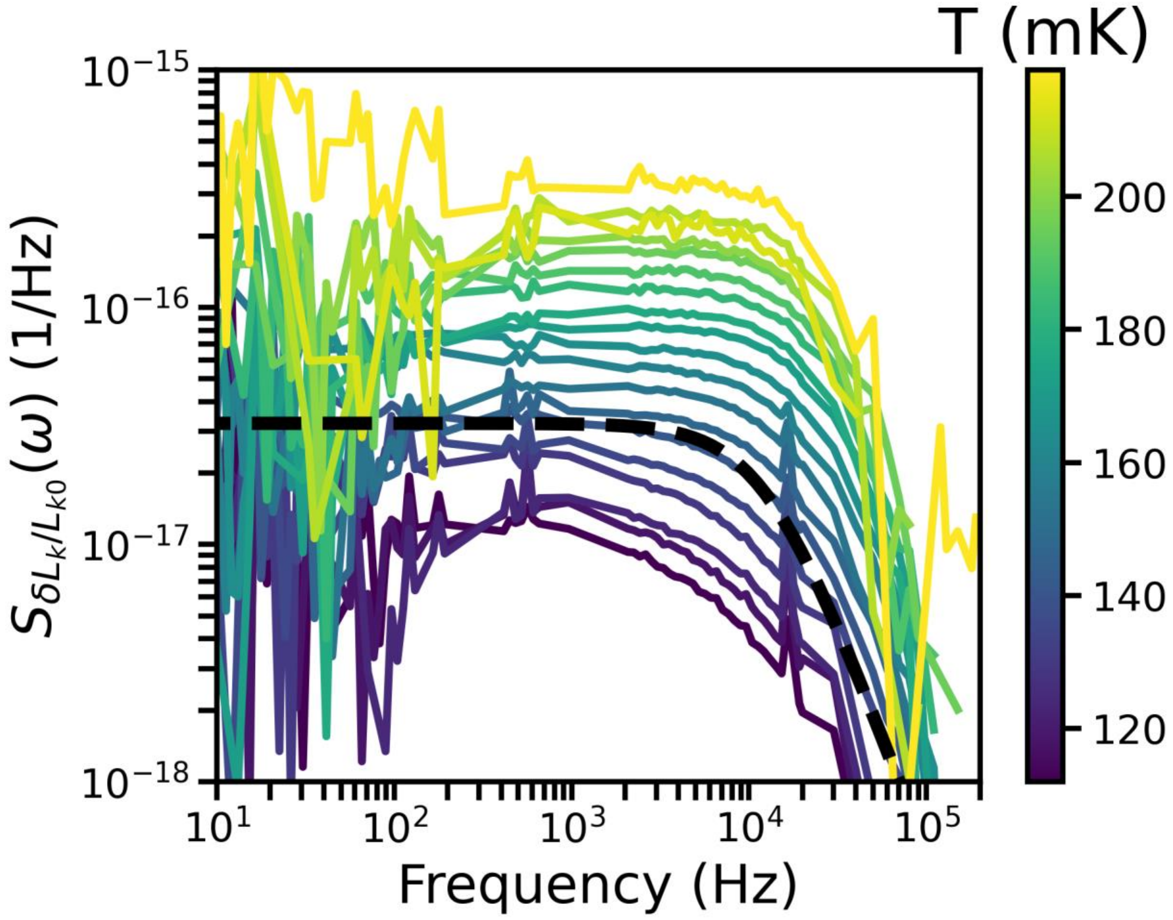
Quasiparticle fluctuations



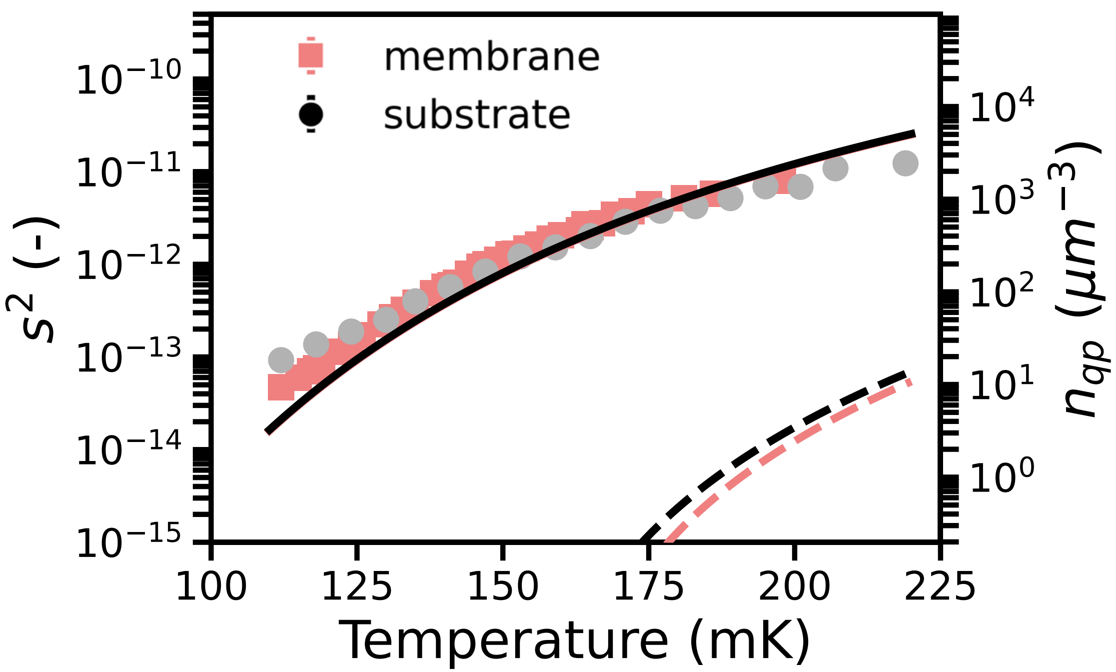
$$S_{\delta L_k/L_{k0}}(\omega) = \frac{4s^2\tau}{1 + (\omega\tau)^2}$$

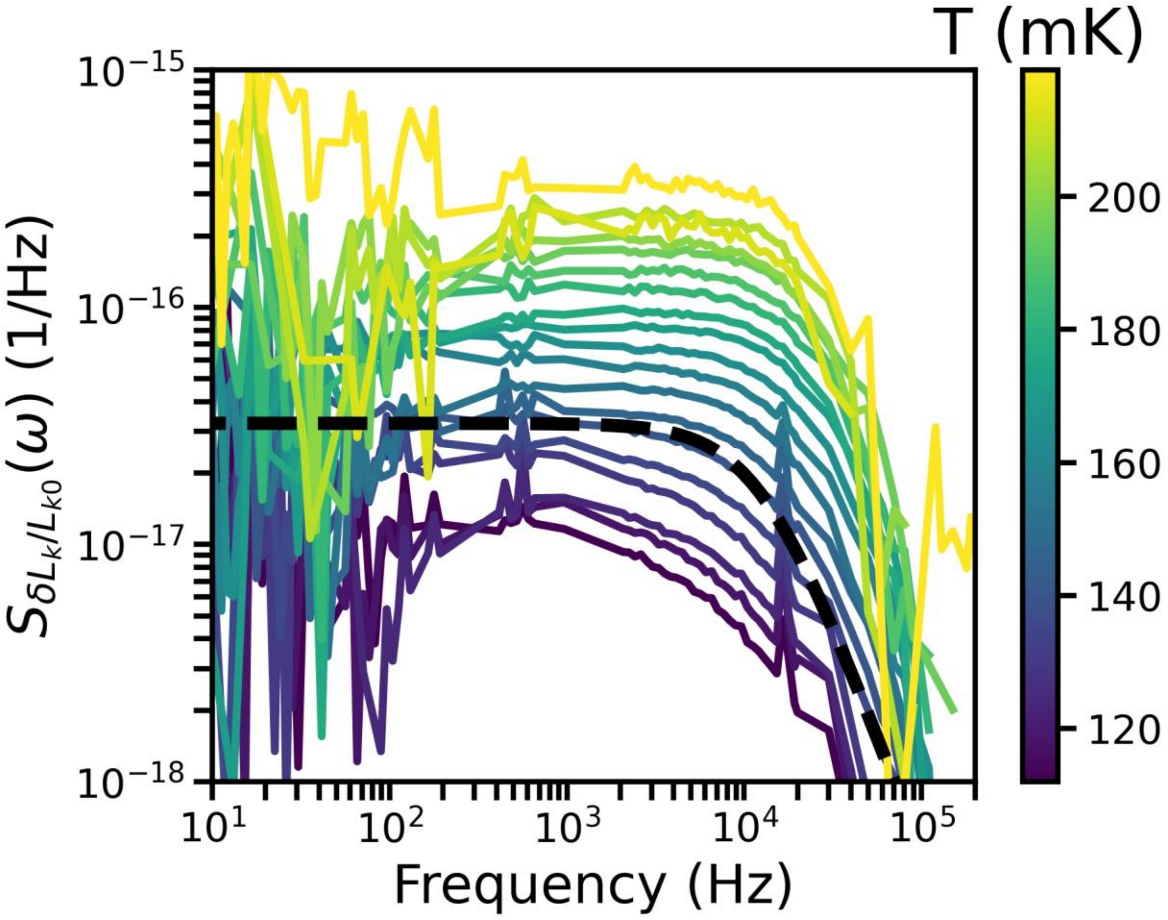
Quasiparticle fluctuations =>

Fluctuations in Kinetic Inductance (σ_2) and Dissipation (σ_1)

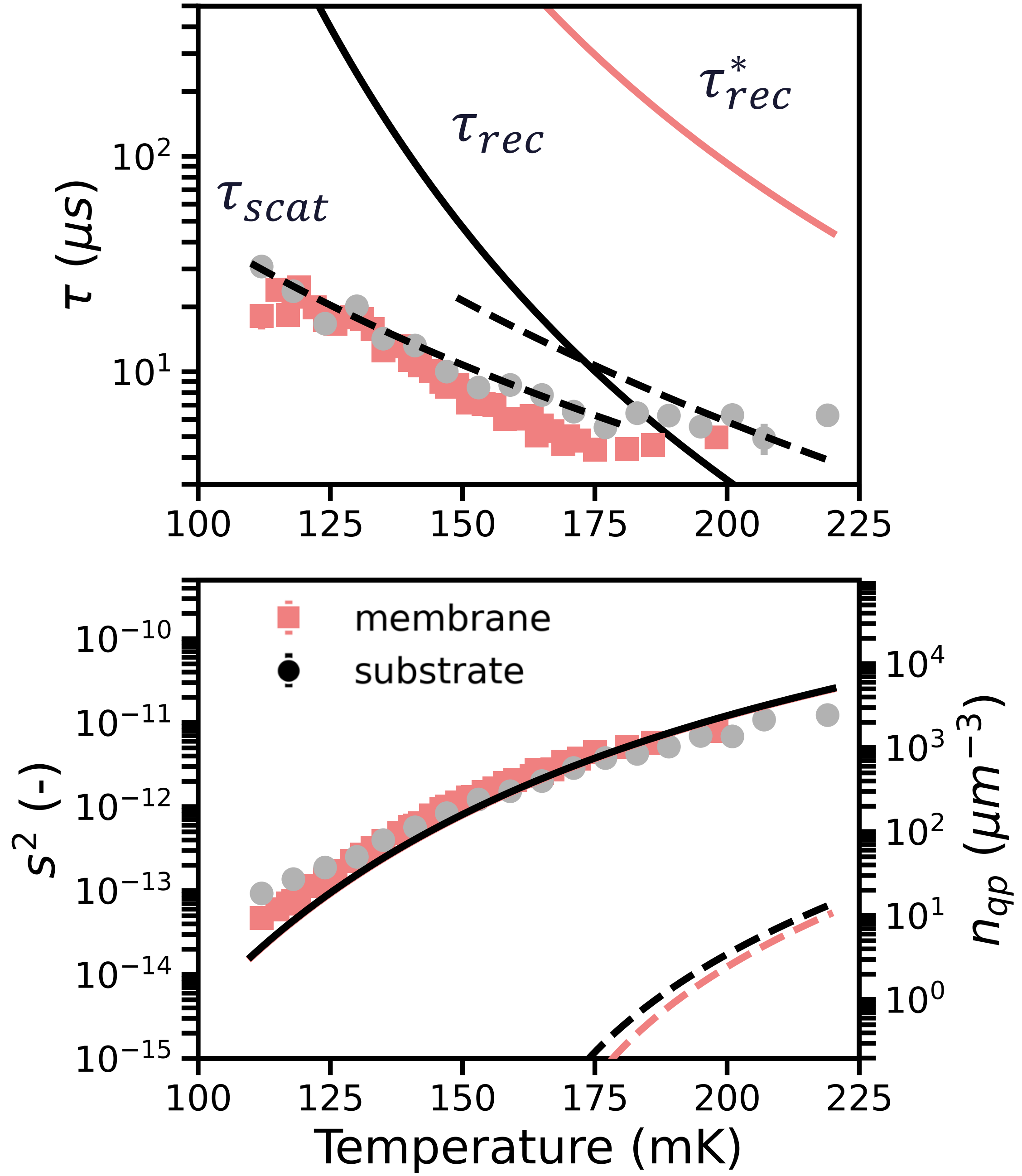


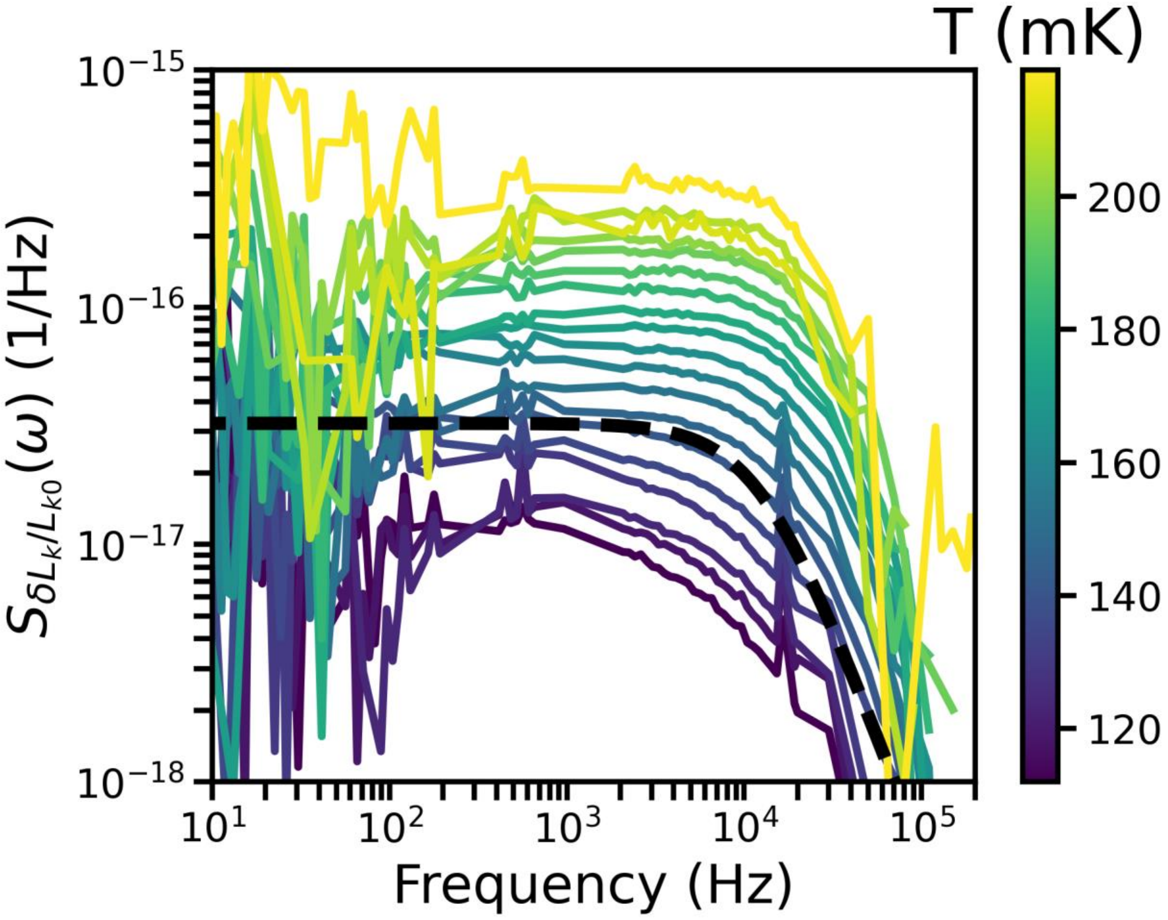
$$S_{\delta L_k/L_{k0}}(\omega) = \frac{4s^2\tau}{1+(\omega\tau)^2}$$





$$S_{\delta L_k/L_{k0}}(\omega) = \frac{4s^2\tau}{1+(\omega\tau)^2}$$





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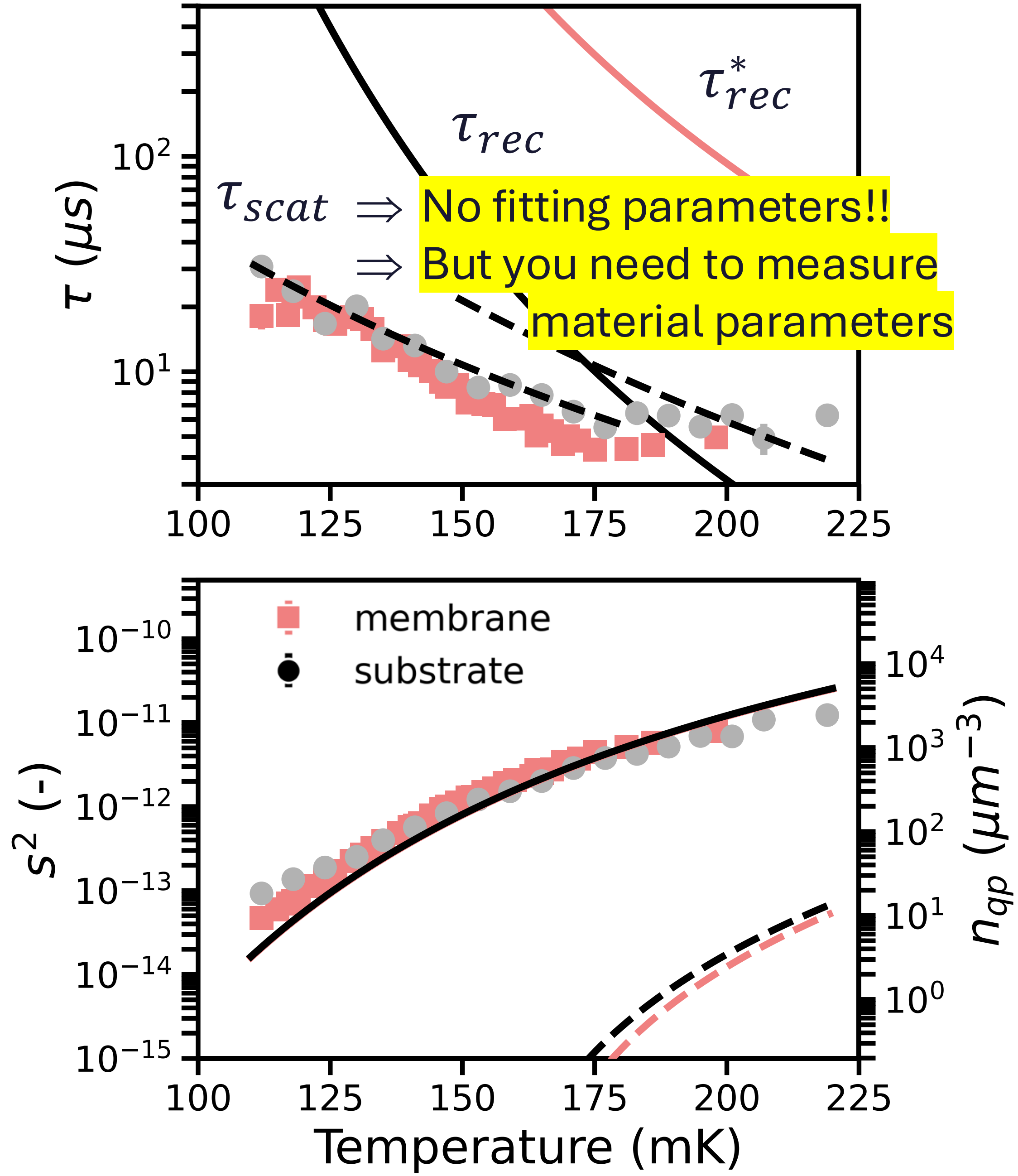

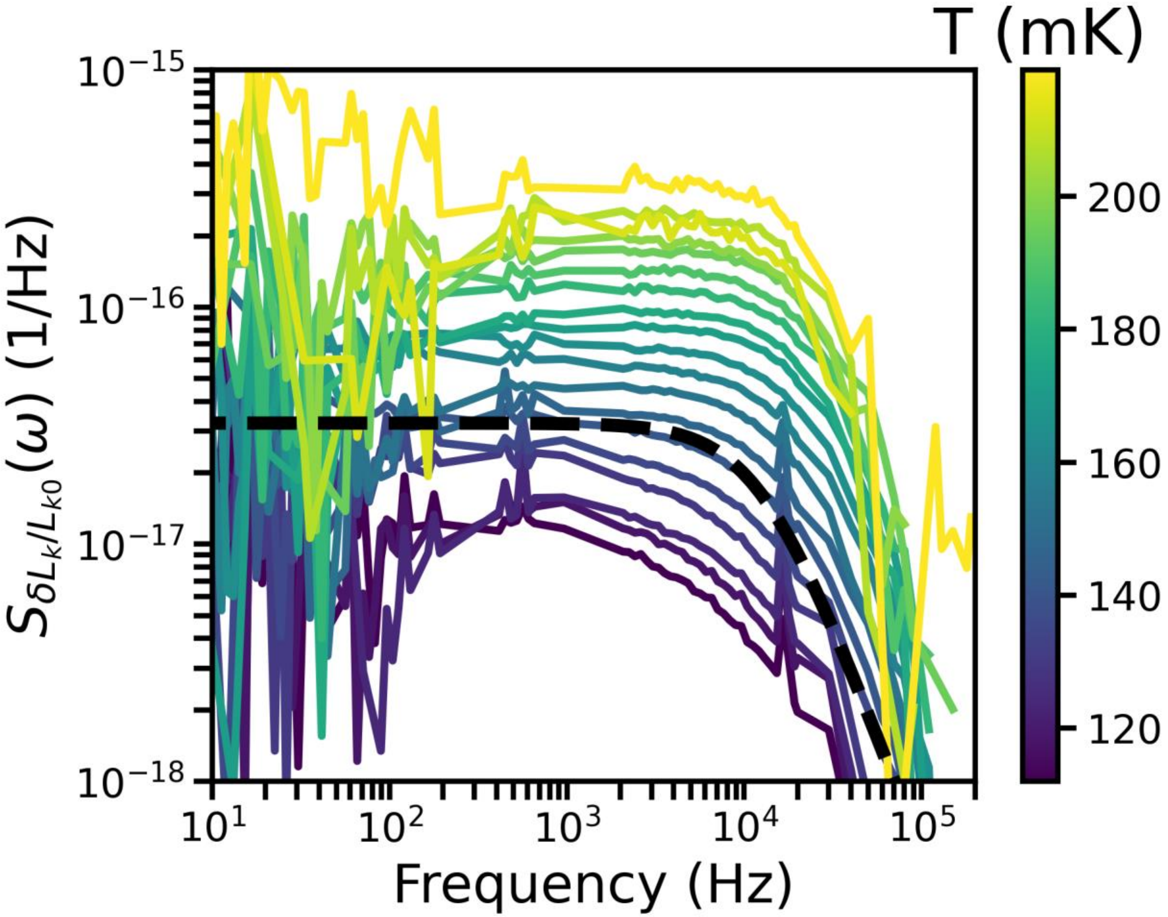

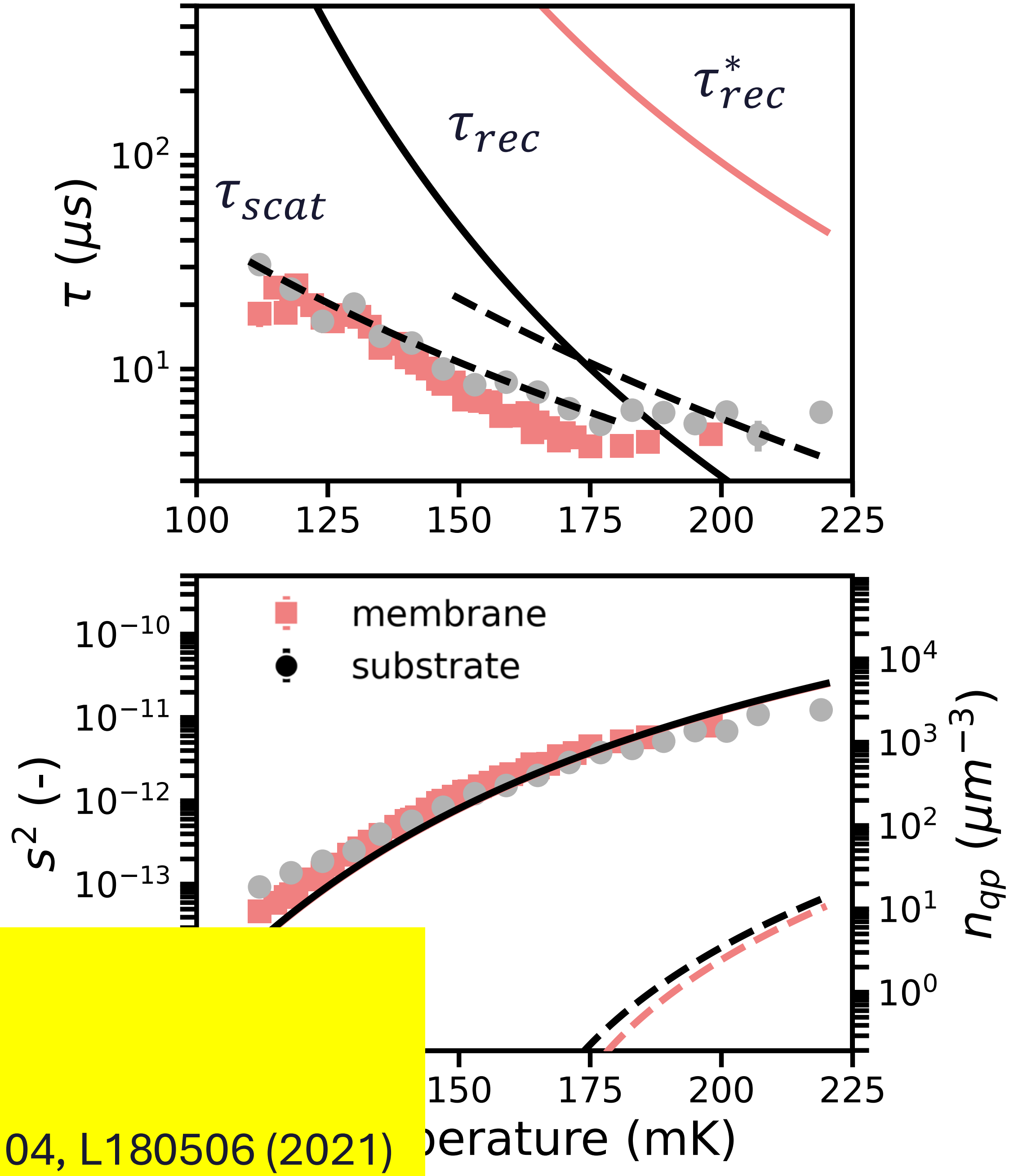

$$S_{\delta L_k/L_{k0}}(\omega) = \frac{}{1}$$

Note that $\tau_{qp} \not\propto \frac{1}{n_{qp}}$

See De Rooij et al. PRB104, L180506 (2021)

How should that work microscopically?

Observations to explain consistenly:

1. We measure recombination – from noise variance
2. Recombination takes place with scattering lifetime – from noise lifetime
3. Phonon-retrapping does not affect the process – membrane vs substrate

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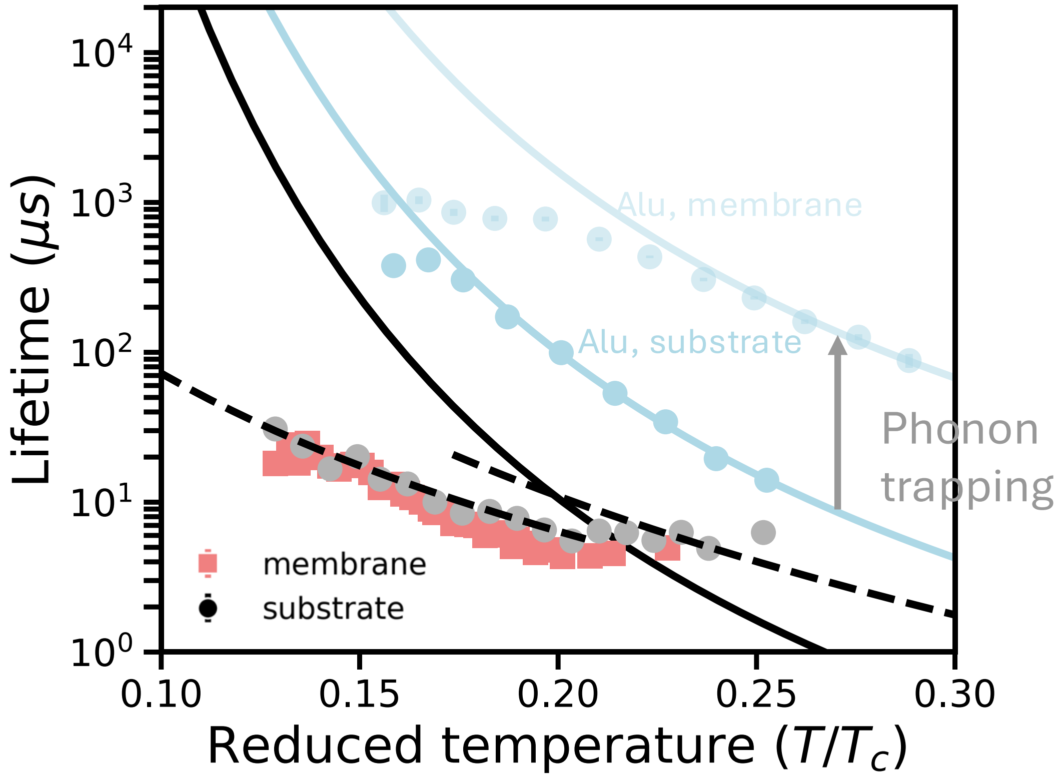
Observations to explain consistenly:

1. We measure recombination – from noise variance
2. Recombination takes place with scattering lifetime – from noise lifetime
3. Phonon-retrapping does not affect the process – membrane vs substrate

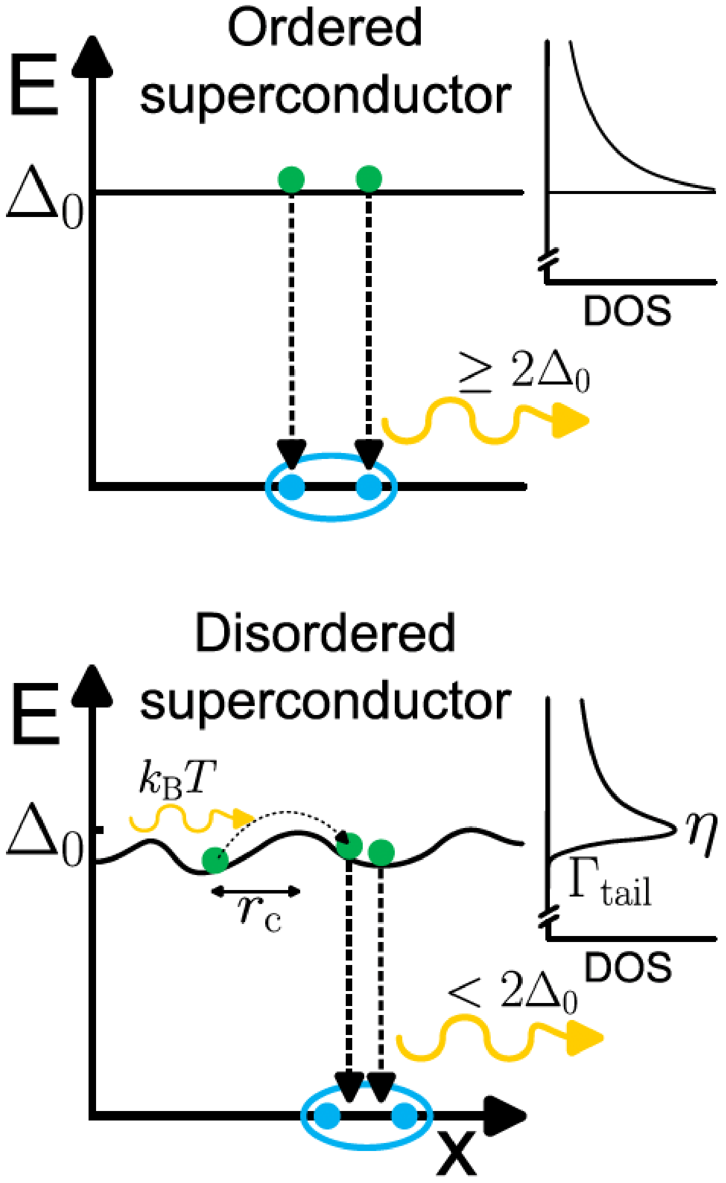
And from Alu + α-Ta experiments:

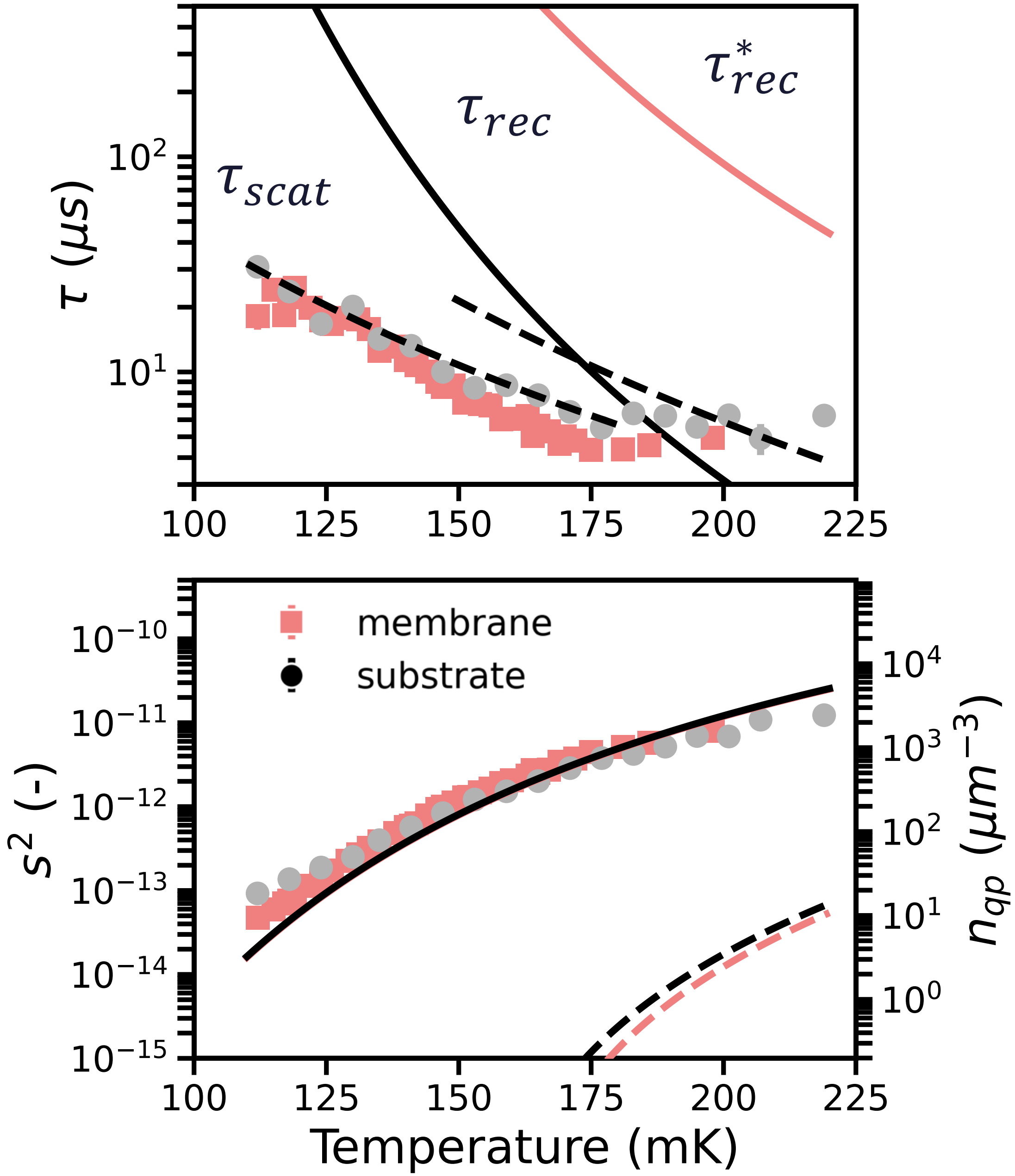
4. #2 and #3 are different for ordered superconductors

De Rooij et al, PRB 104 , L180506 (2021)
De Visser et al, PRL 106, 167004 (2011)

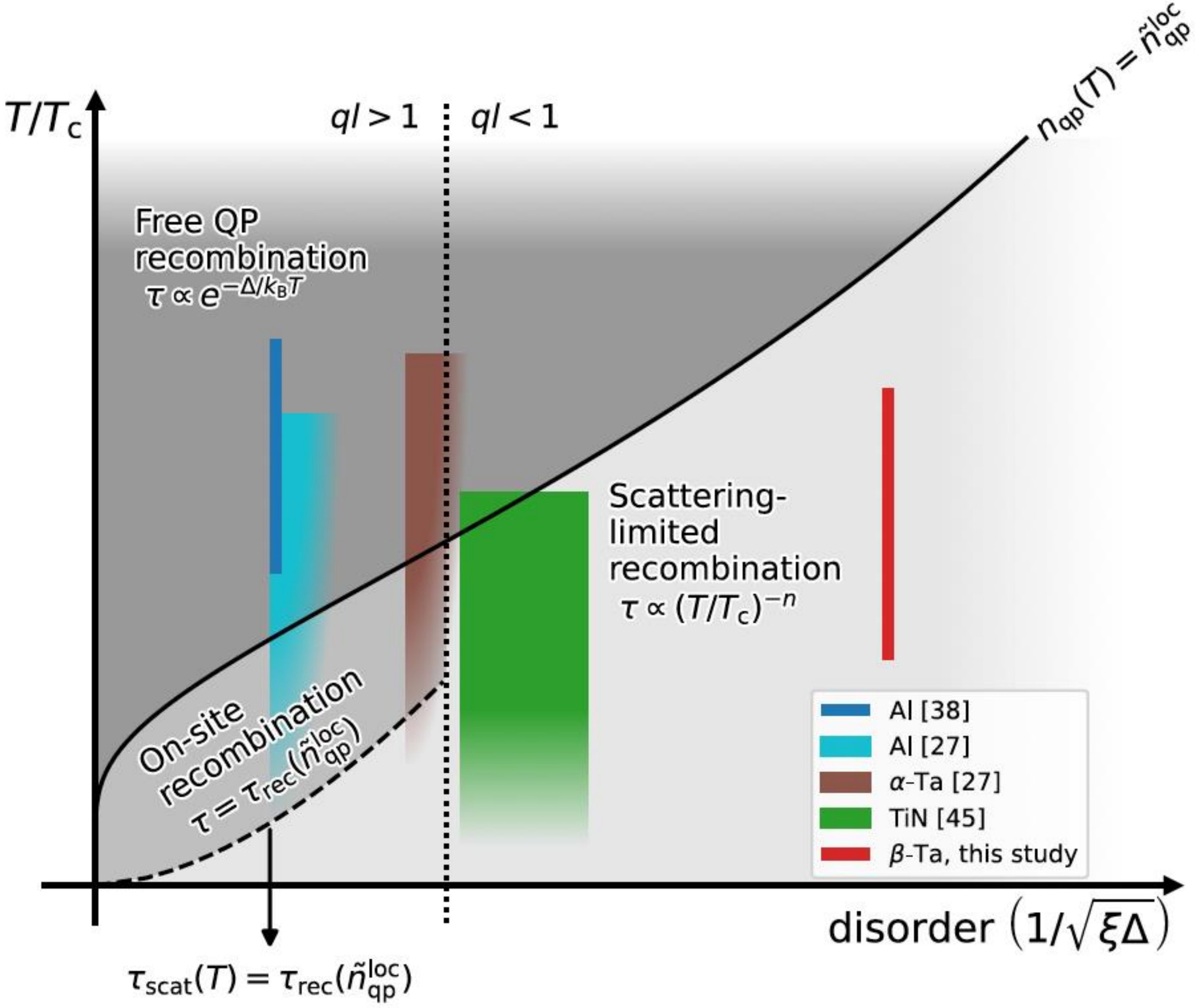


Recombination of localised quasiparticles = multi-step process





Nature Communications 16, 8465 (2025)

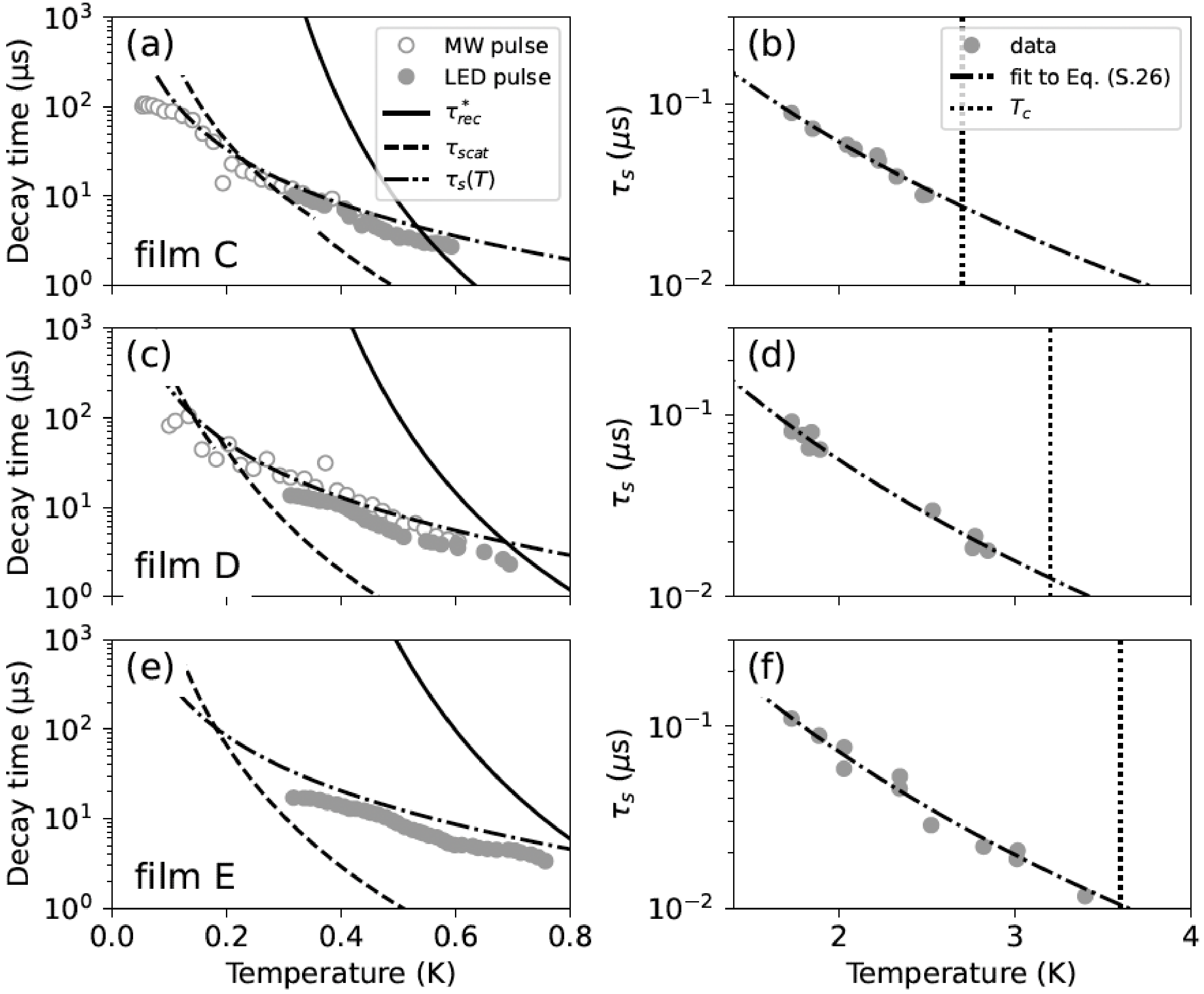


T/T_c
$ql > 1$
$ql < 1$
$n_{qp}(T) = \tilde{n}_{qp}^{loc}$
Free QP recombination
$\tau \propto e^{-\Delta/k_B T}$
Scattering-limited recombination
$\tau \propto (T/T_c)^{-n}$
On-site recombination
$\tau = \tau_{rec}(\tilde{n}_{qp}^{loc})$
Al [38]
Al [27]
α-Ta [27]
TiN [45]
β-Ta, this study
disorder $\left(1/\sqrt{\xi\Delta}\right)$
$\tau_{scat}(T) = \tau_{rec}(\tilde{n}_{qp}^{loc})$

Also TiN lifetime data vs disorder explained

Data: Coumou et al
IEEE TAS 23, 7500404 (2013)

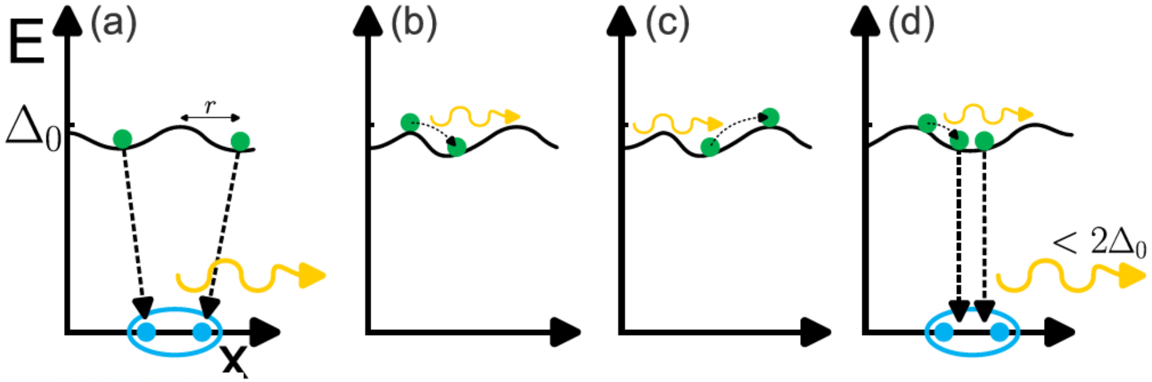
Data: Kardakova et al.
IEEE TAS 25, 1 (2015)

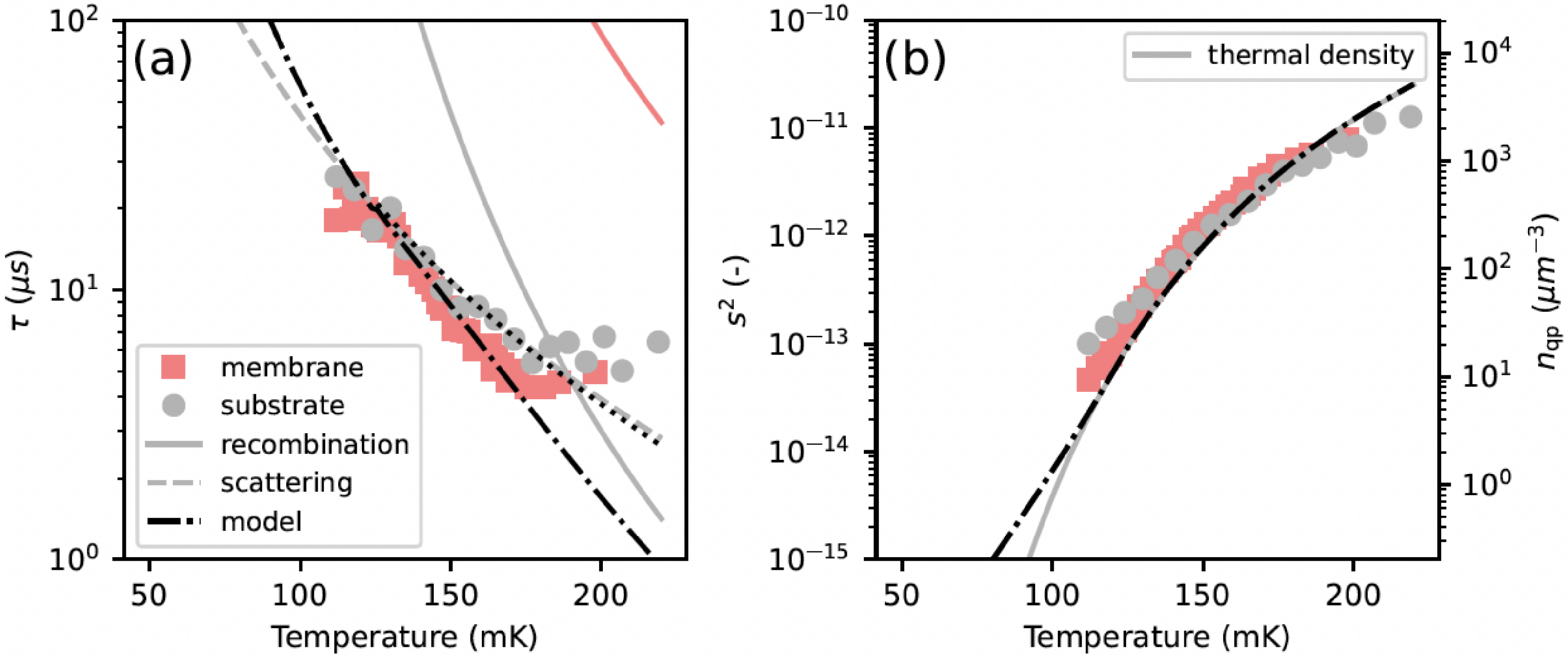


Interpretation – rate equations

$$\frac{dn_\mathrm{m}}{dt} = -\Gamma_\mathrm{l} n_m + \Gamma_\mathrm{d} n_l - 2R_\mathrm{os}\left(n_\mathrm{m} n_\mathrm{l} - n_\mathrm{m}^0 n_\mathrm{l}^0\right)$$

$$\frac{dn_\mathrm{l}}{dt} = -2R_\mathrm{l} n_\mathrm{l}^2 + 2\Gamma_\mathrm{pb} + \Gamma_\mathrm{l} n_m - \Gamma_\mathrm{d} n_l.$$

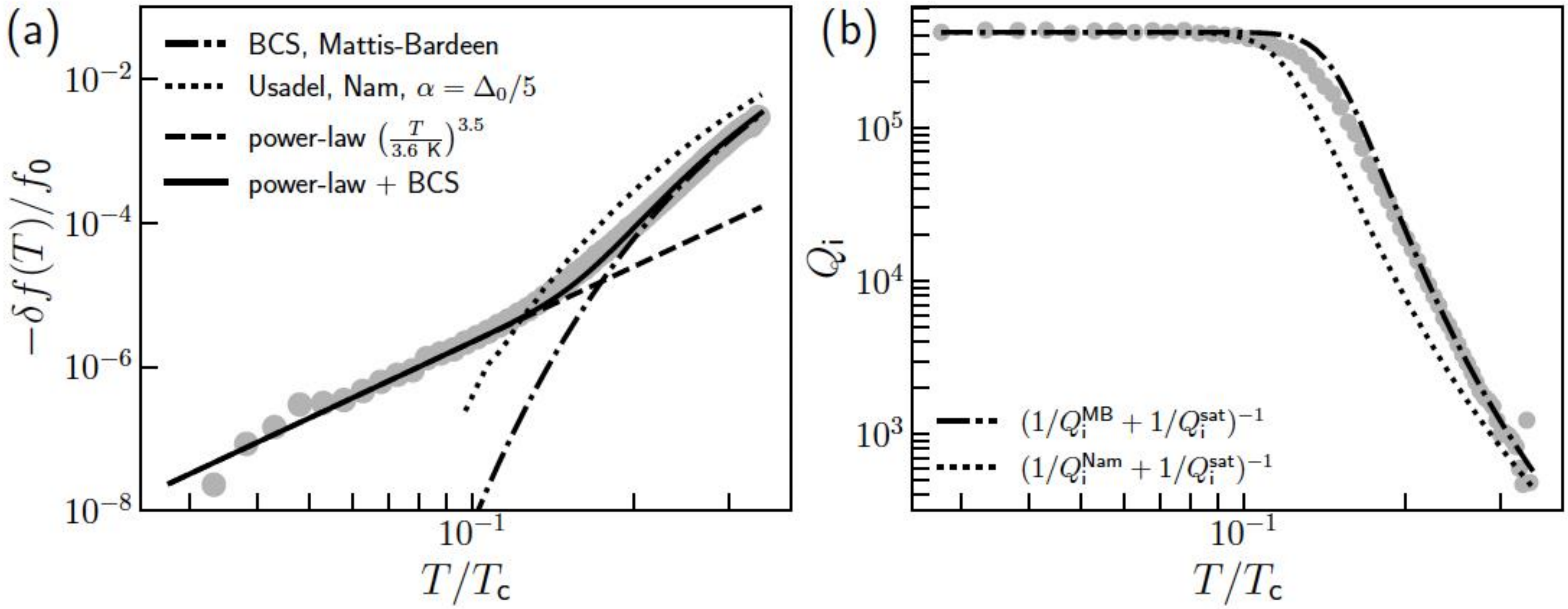




Mind the generation term!

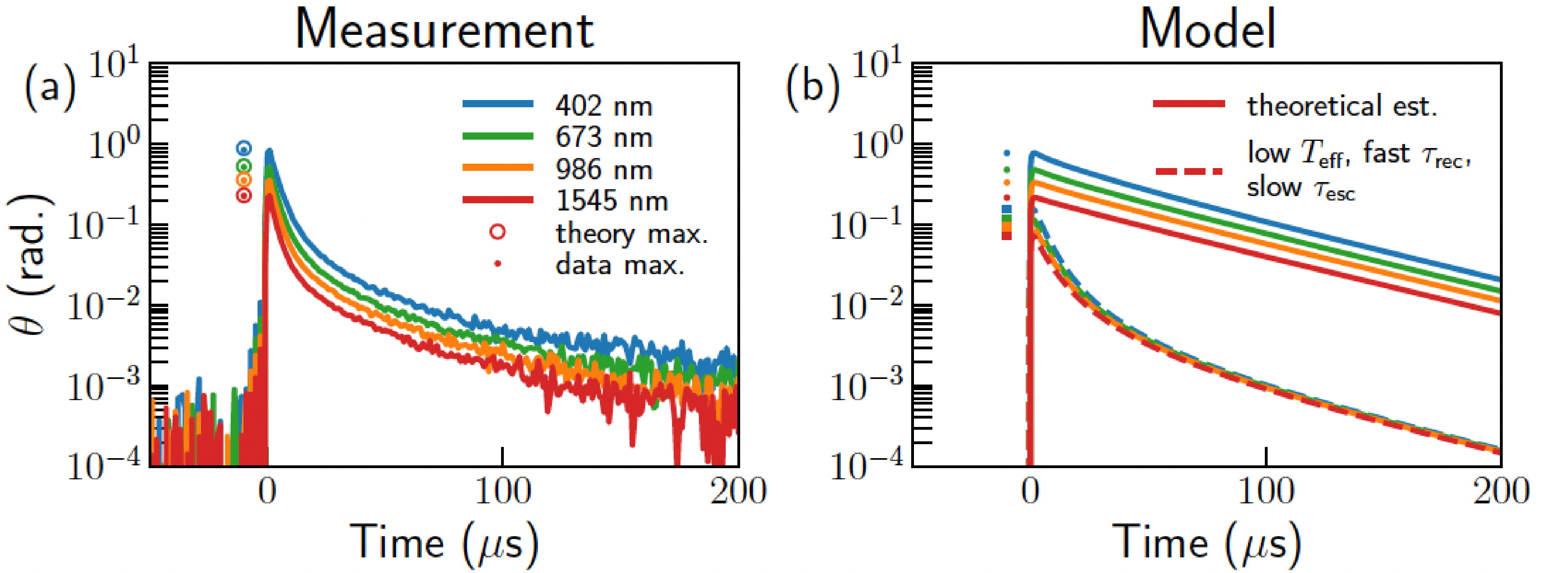
(which is irrelevant for non-equilibrium/pulse models)

Connection to conductivity deviations

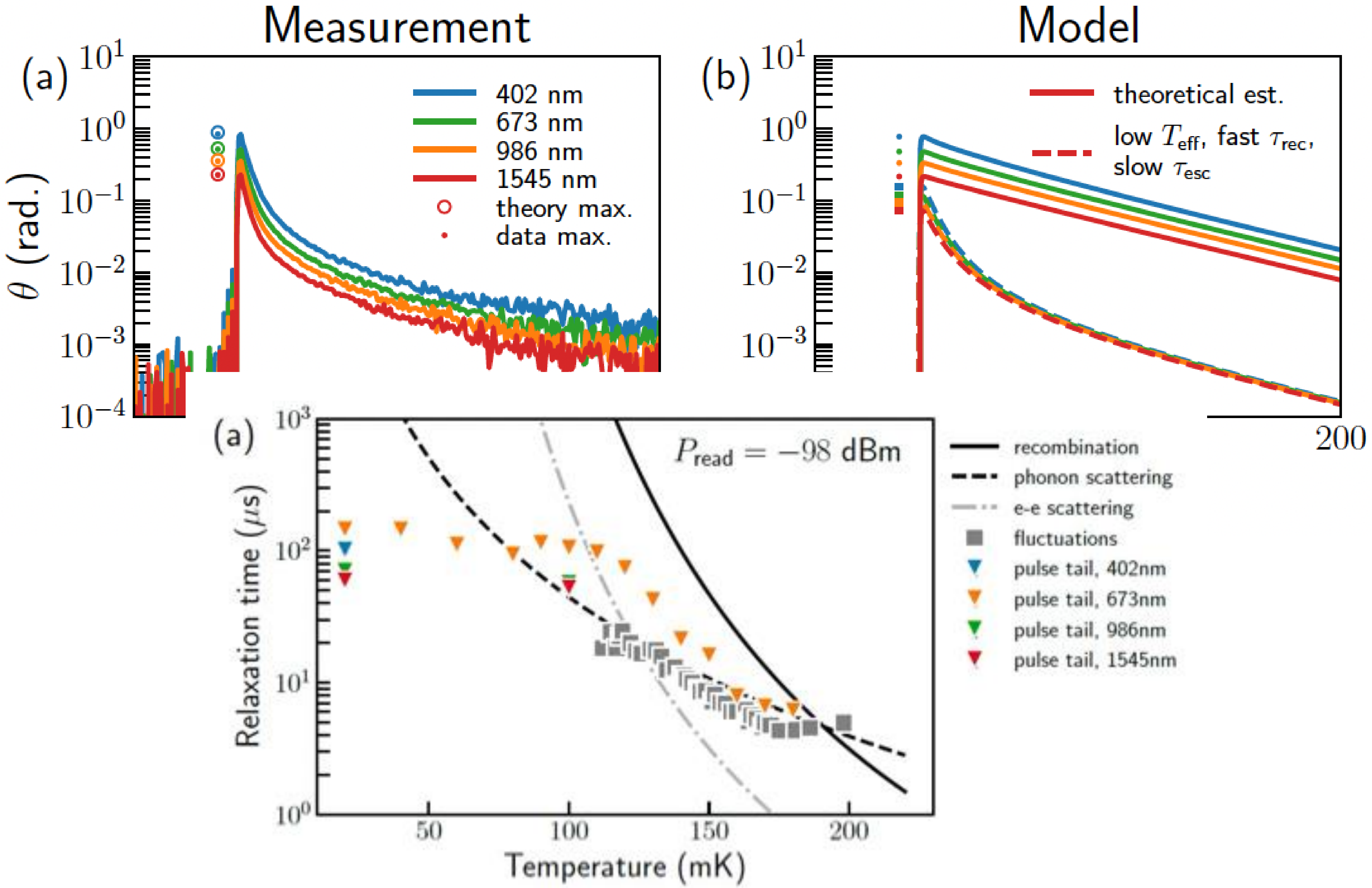


Khvalyuk et al. PRB 109, 144501 (2024), power laws exponent ~1.6, here 3.5

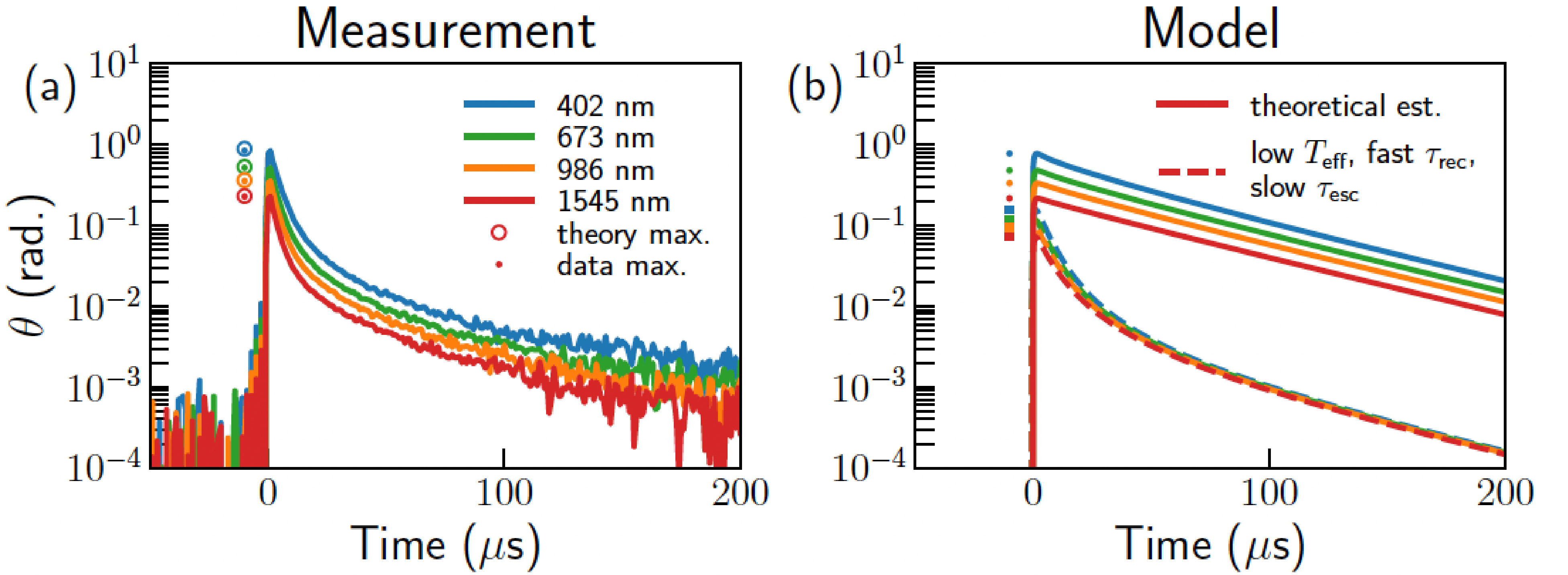
Photon pulse measurements



Photon pulse measurements

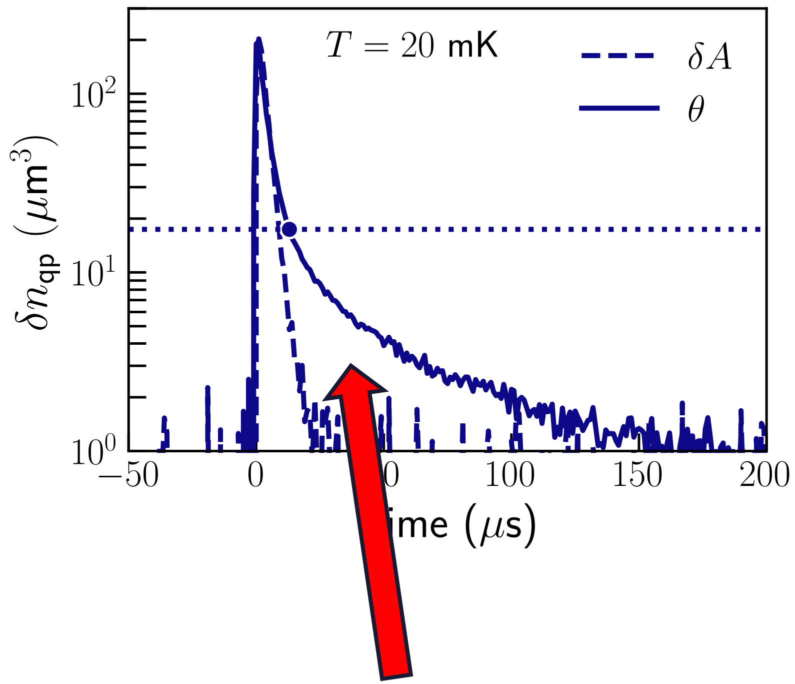


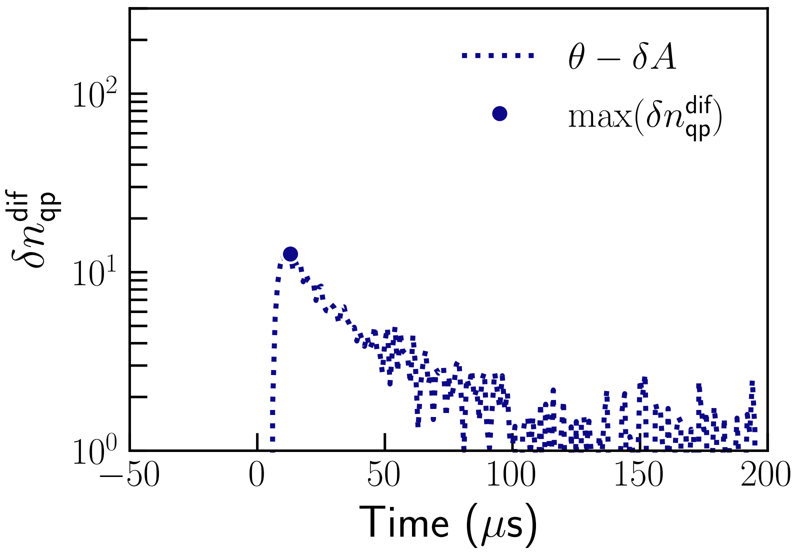
Non-equilibrium - single photon pulse measurements



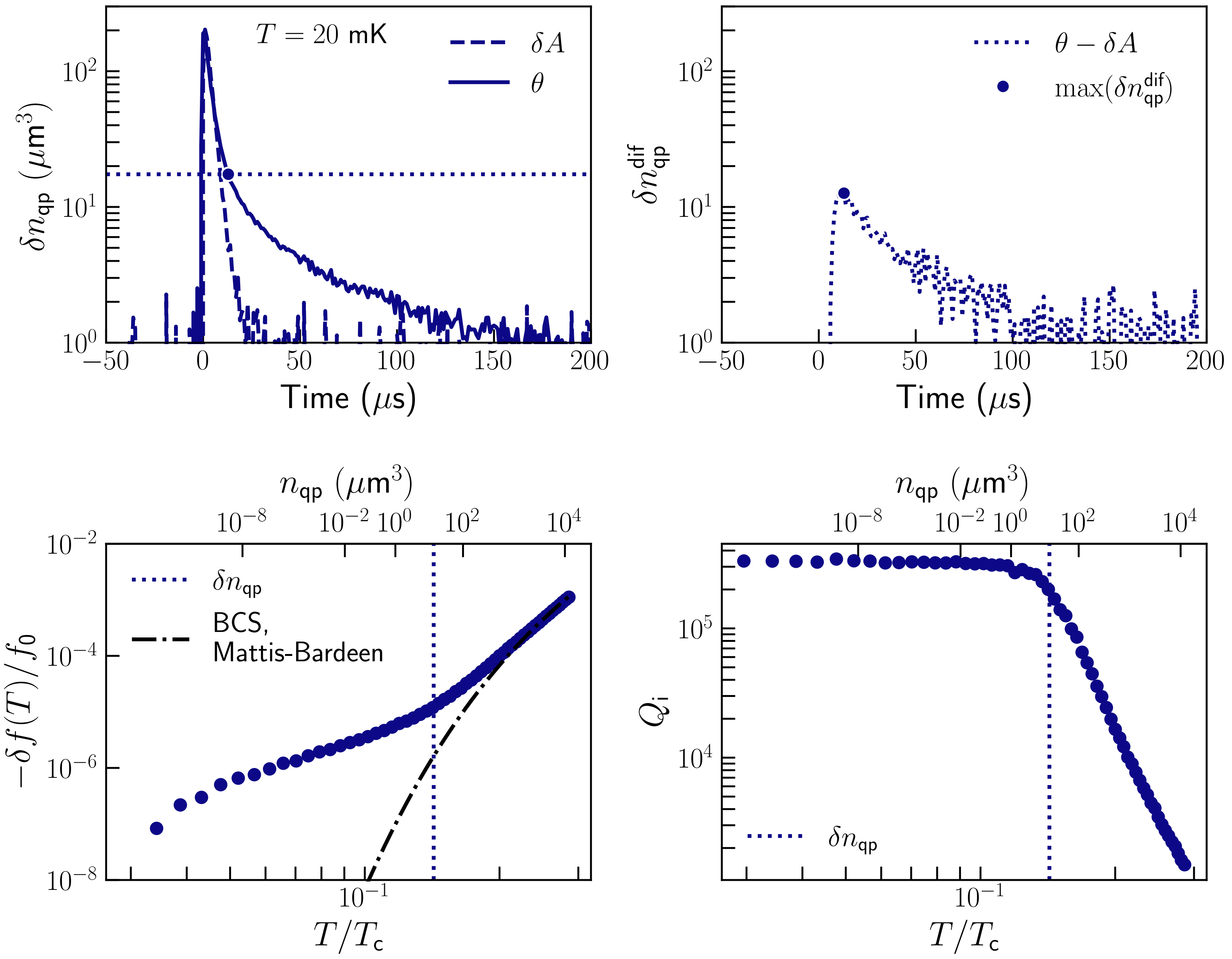
- The pulse height is exactly what we expect Nqp = ηE_ph/Δ
- The pulses scale entirely with photon energy !???
- Theoretical rate equations don't capture this:
  - In many nqp regime (dnqp<<nqp): pulses scale with wavelength, but should not show 2 distinct timescales
  - Or, in low nqp regime (dnqp>>nqp): crossover between 1/t and exponential decay expected, where tails are on top

Connection to conductivity deviations

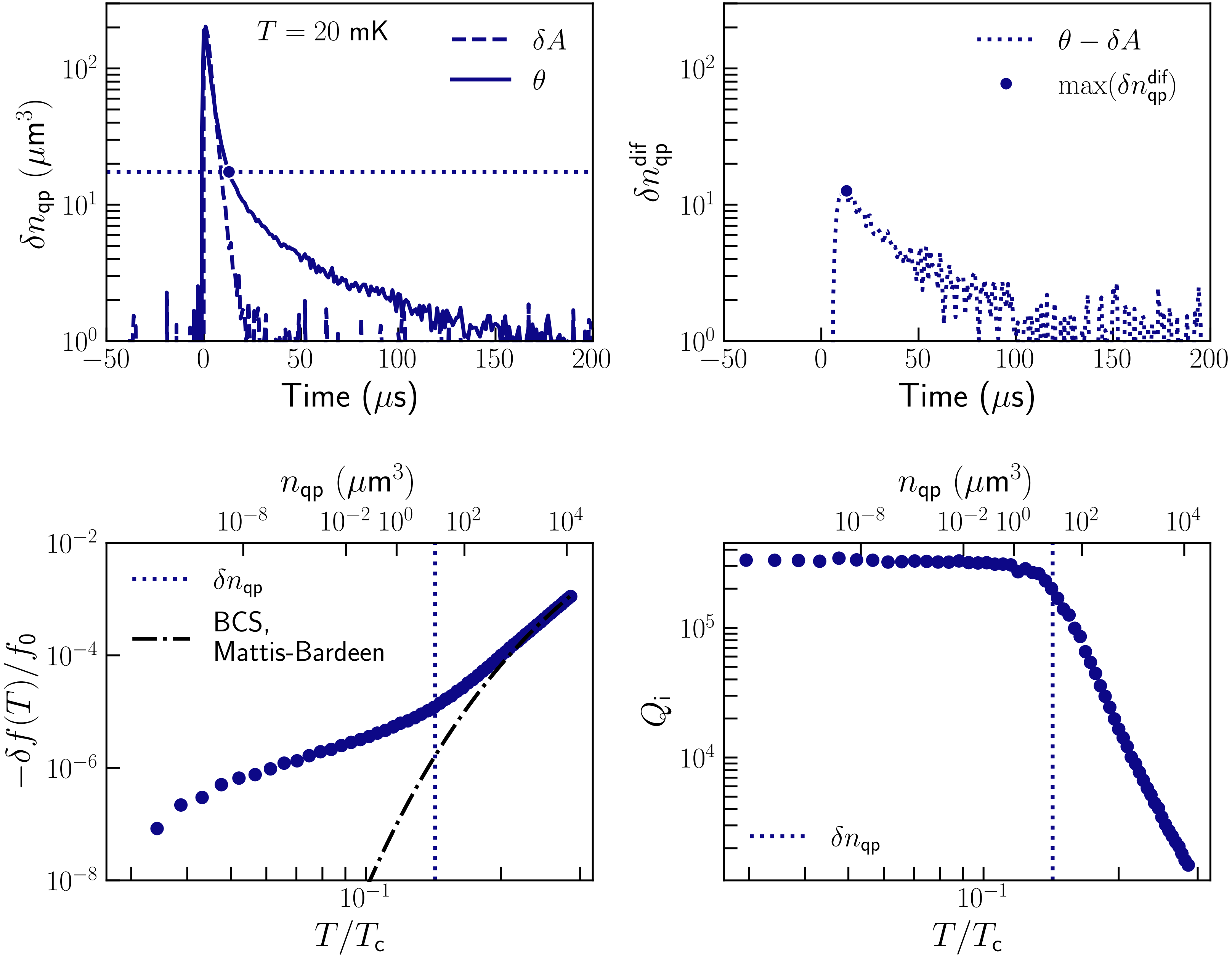


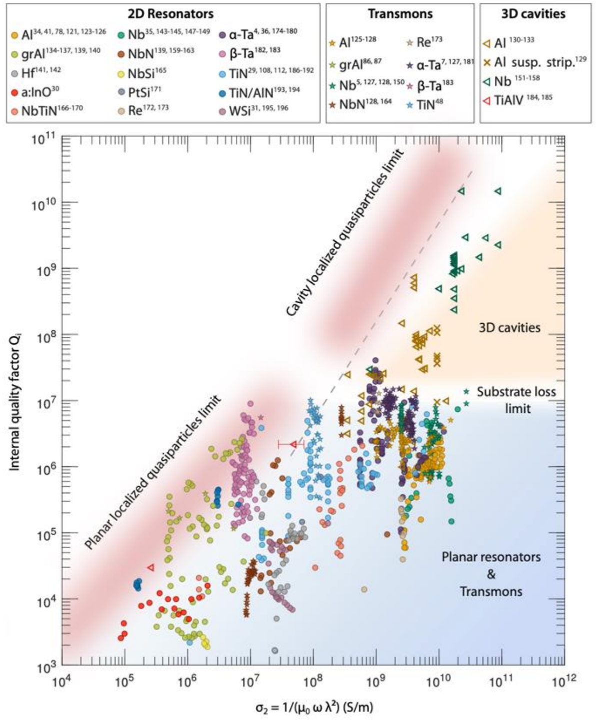


Connection to conductivity deviations

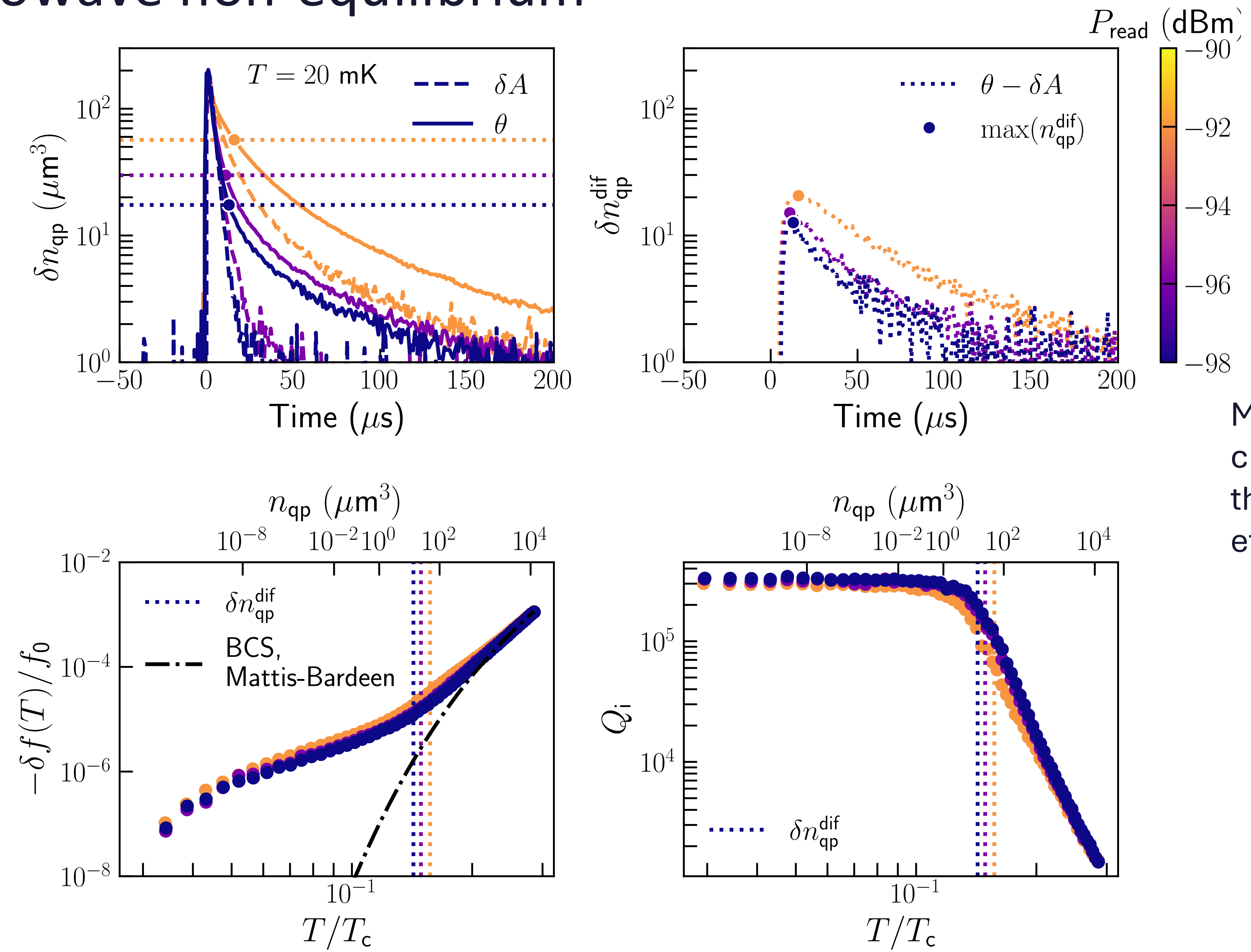


Connection to conductivity deviations





Microwave non-equilibrium



Microwave dissipation changes pulse shape, but the dominant conductivity effects persist

What is next?

- Explore quasiparticle dynamics systematically as function of disorder

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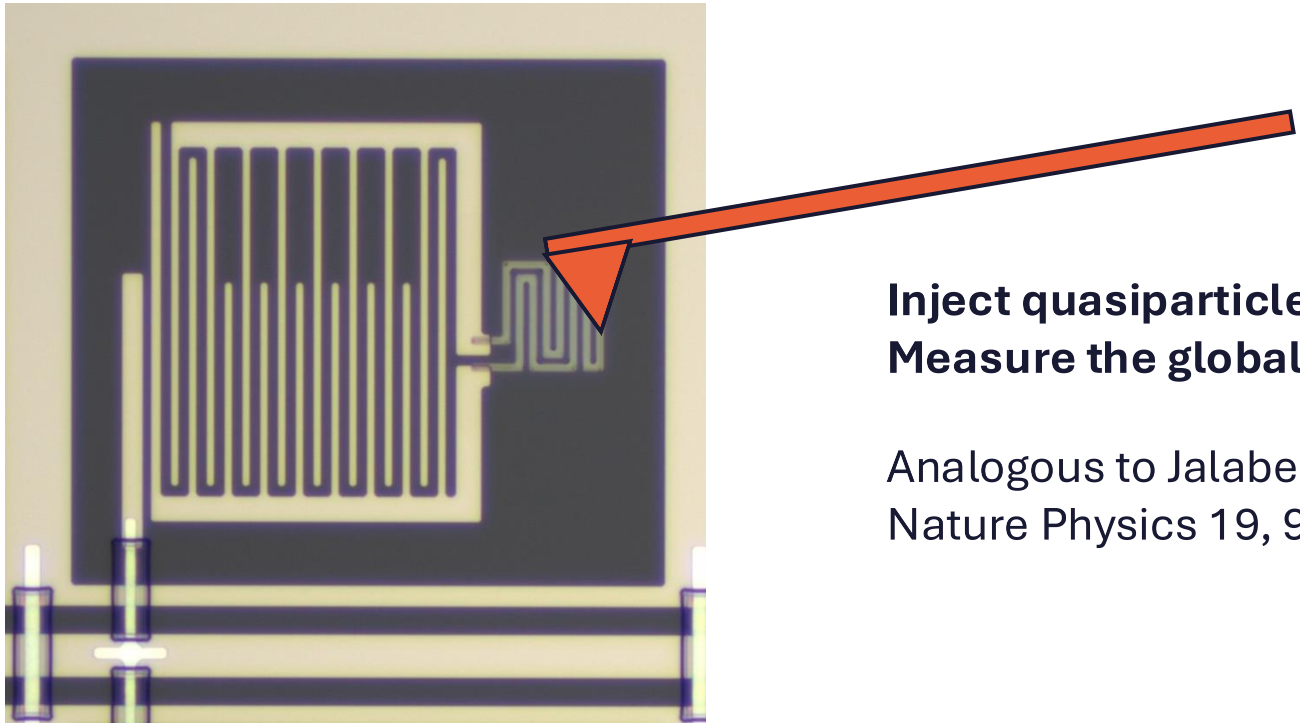

Inject quasiparticles locally
Measure the global microwave response **?**

Analogous to Jalabert et al for critical current
Nature Physics 19, 956–960 (2023)

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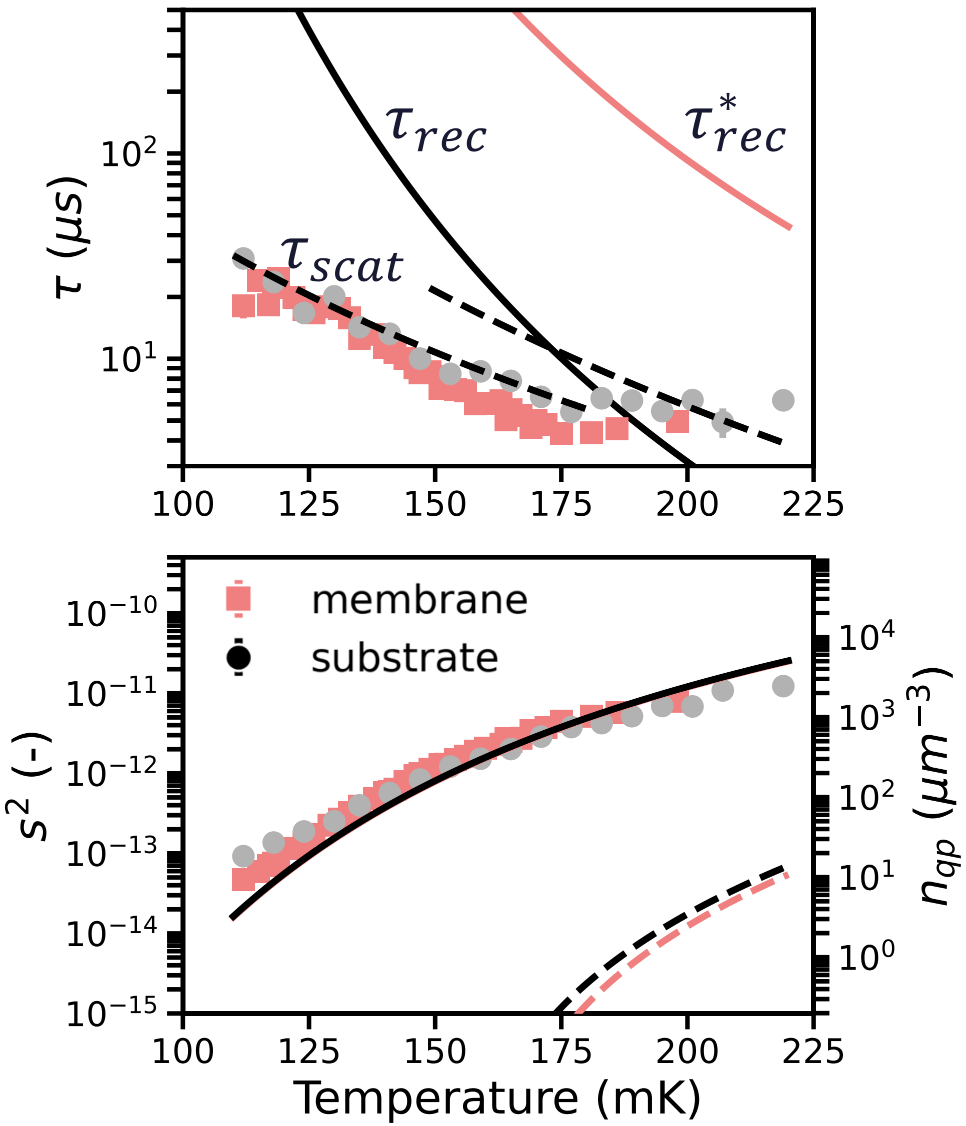
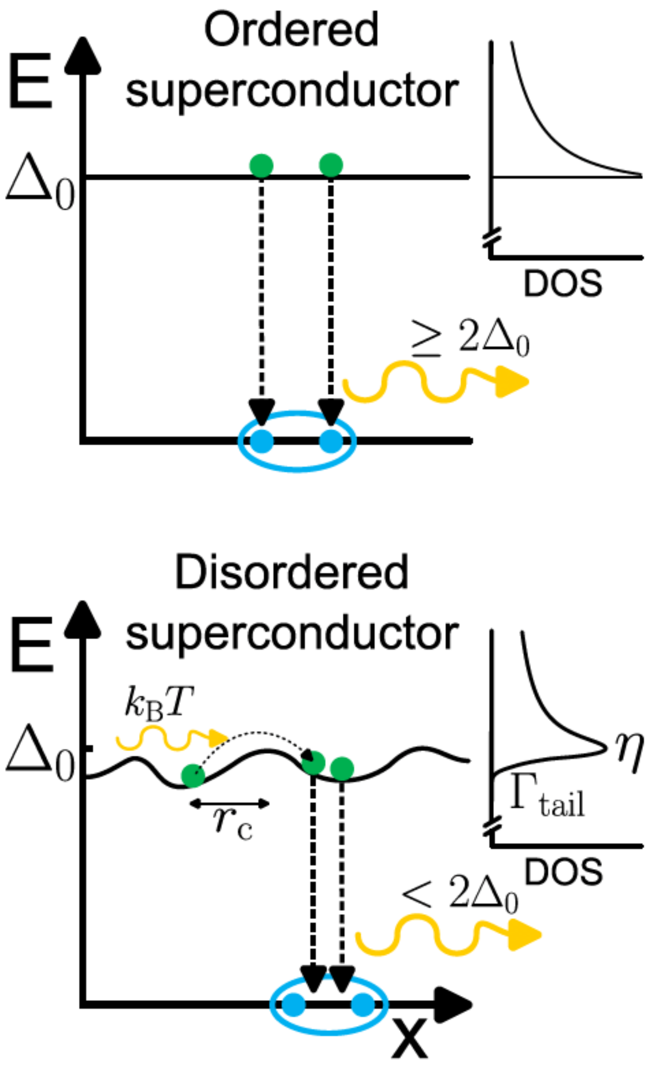
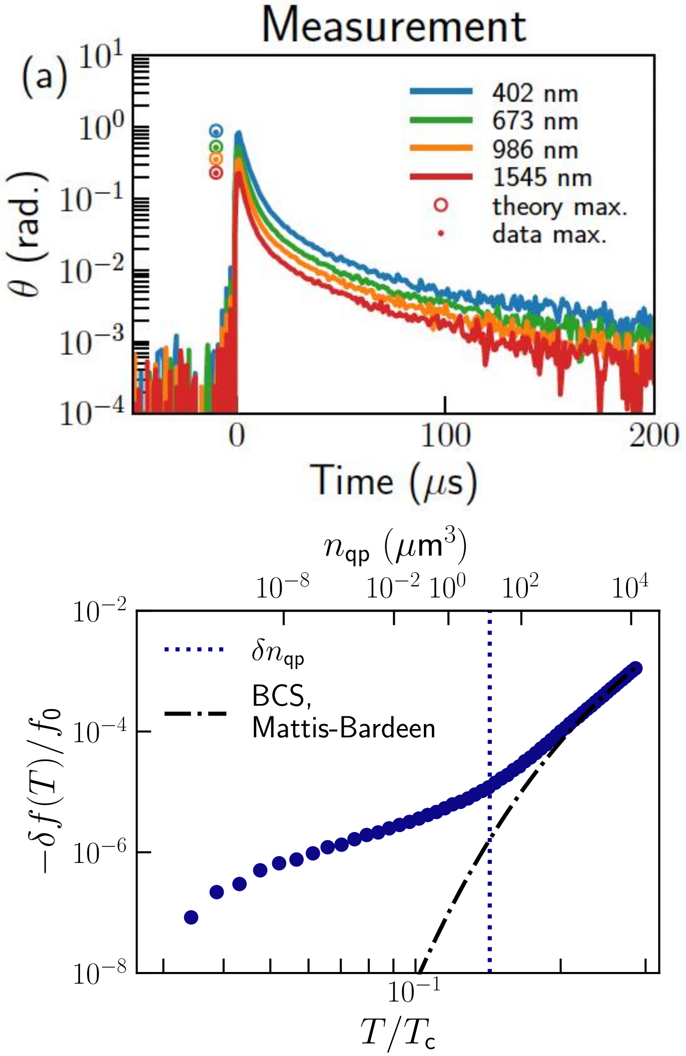
- Applied: what is the ‘ideal’ MKID material?

Summary





!?



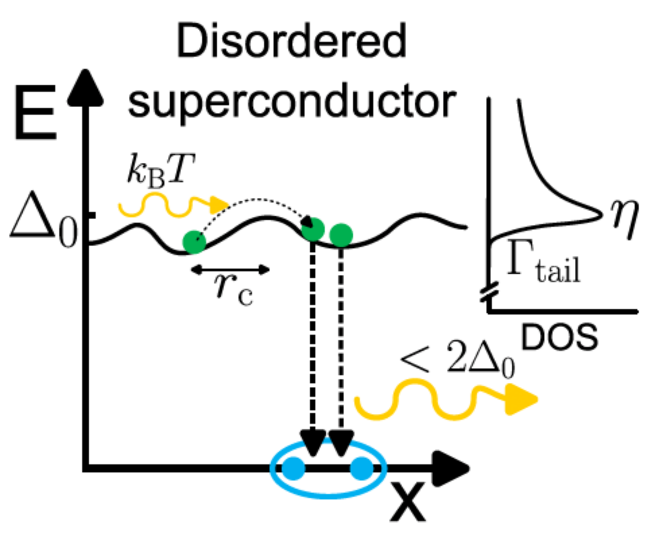
Nature Communications 16, 8465 (2025)
PhD thesis Steven de Rooij, Delft University of Technology, 2026

TU Delft SRON

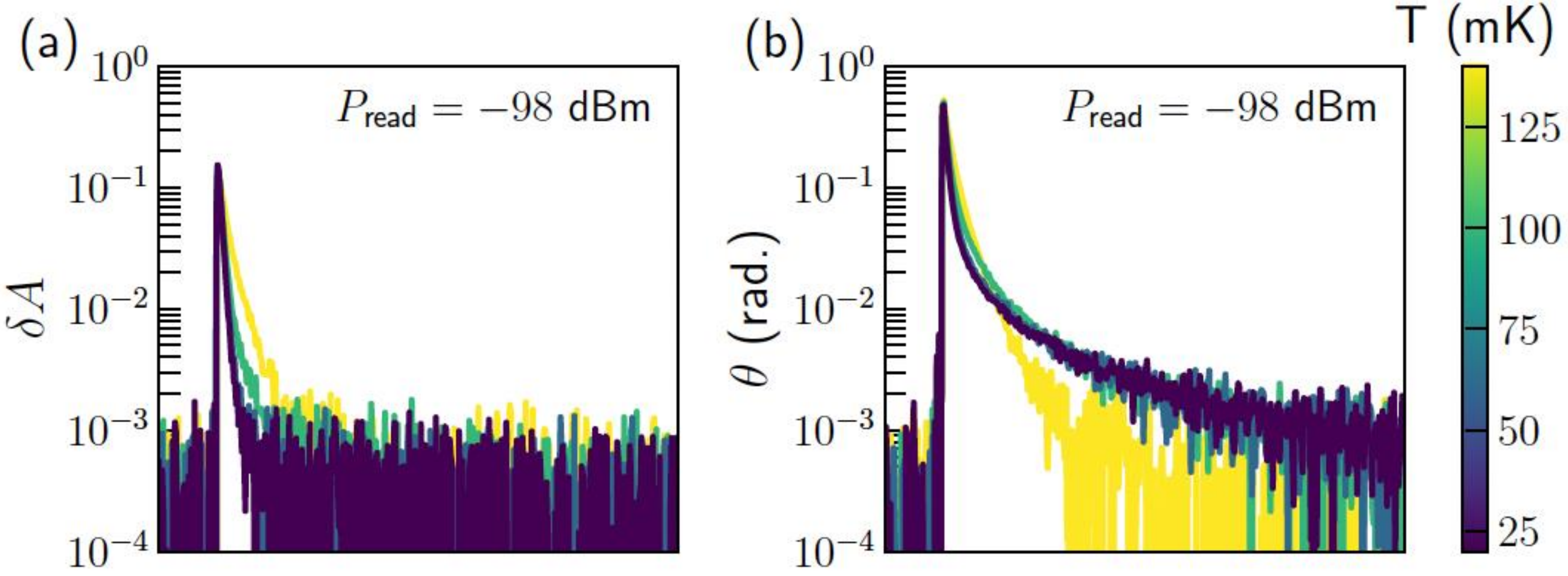
Are we alone?

SRON SPACE RESEARCH ORGANISATION NETHERLANDS

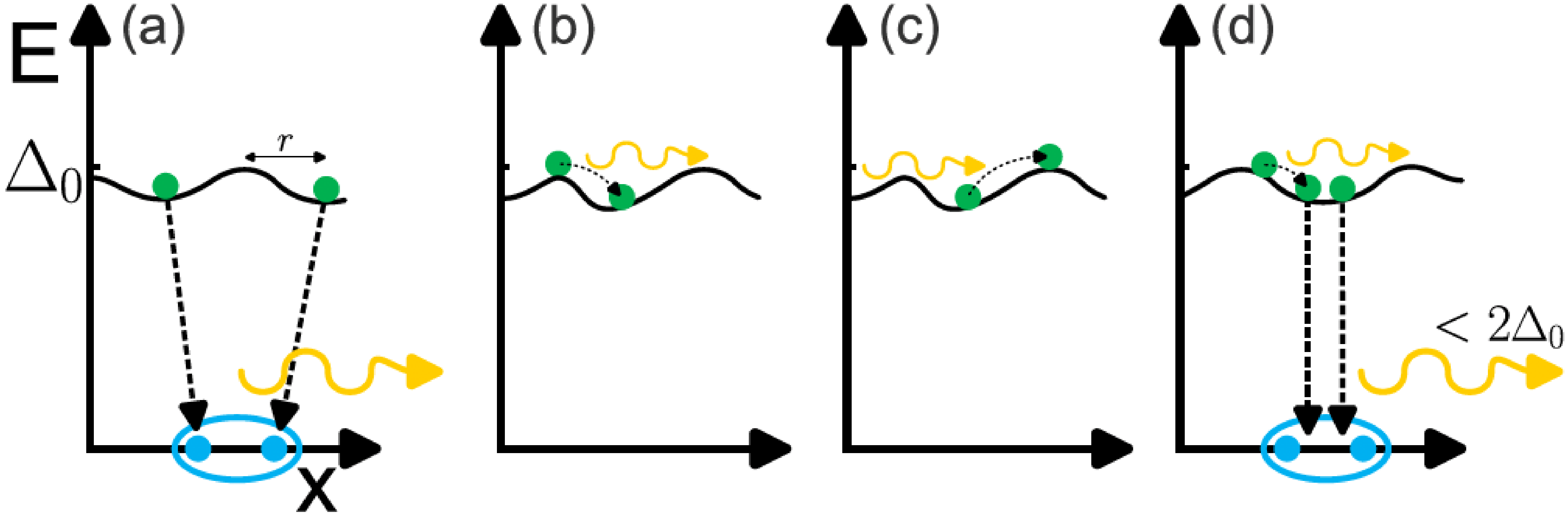
TU Delft Delft University of Technology



BRINGING ABOUT BREAKTHROUGHS IN SPACE SCIENCE



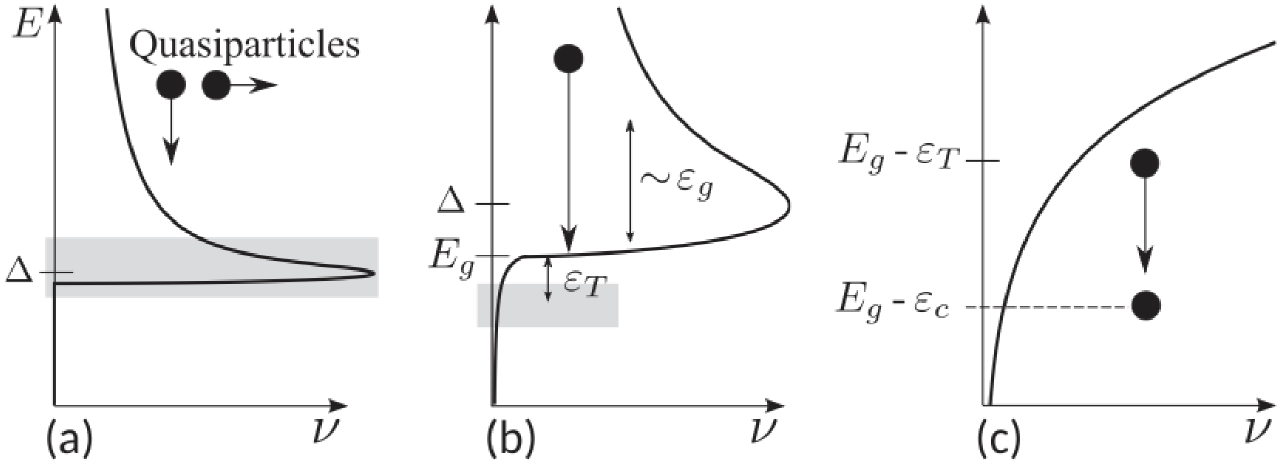
(a)
(b)
$P_{\text{read}} = -98$ dBm
$P_{\text{read}} = -98$ dBm
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
δA
θ (rad.)
T (mK)
125
100
75
50
25


E
(a)
(b)
(c)
(d)
Δ_0
r
x
$< 2\Delta_0$

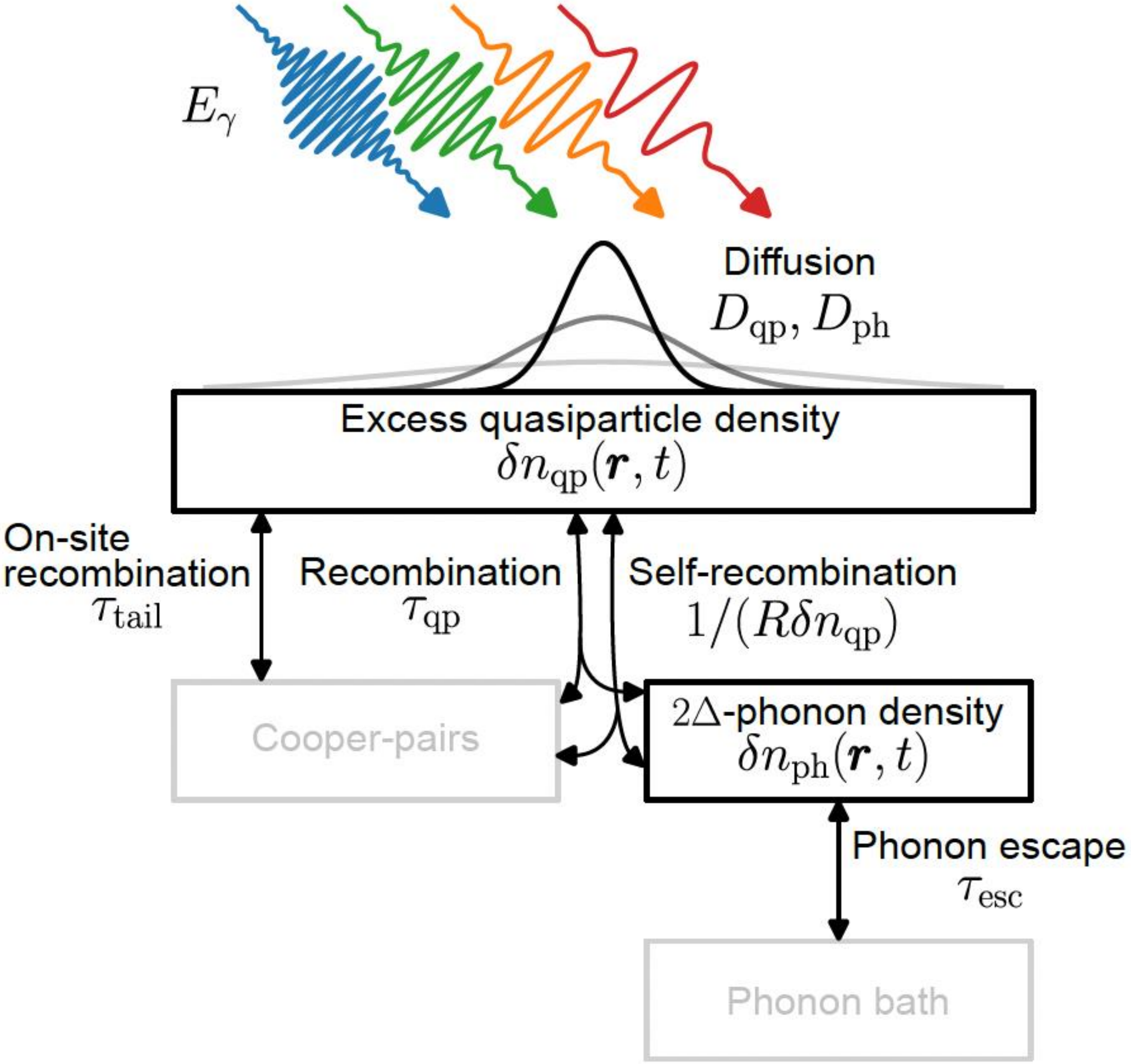
Interpretation – which states, which energies?

- Bespalov et al 2016
  - Excess qp's due to localised states – happens also for very mild disorder in Aluminium

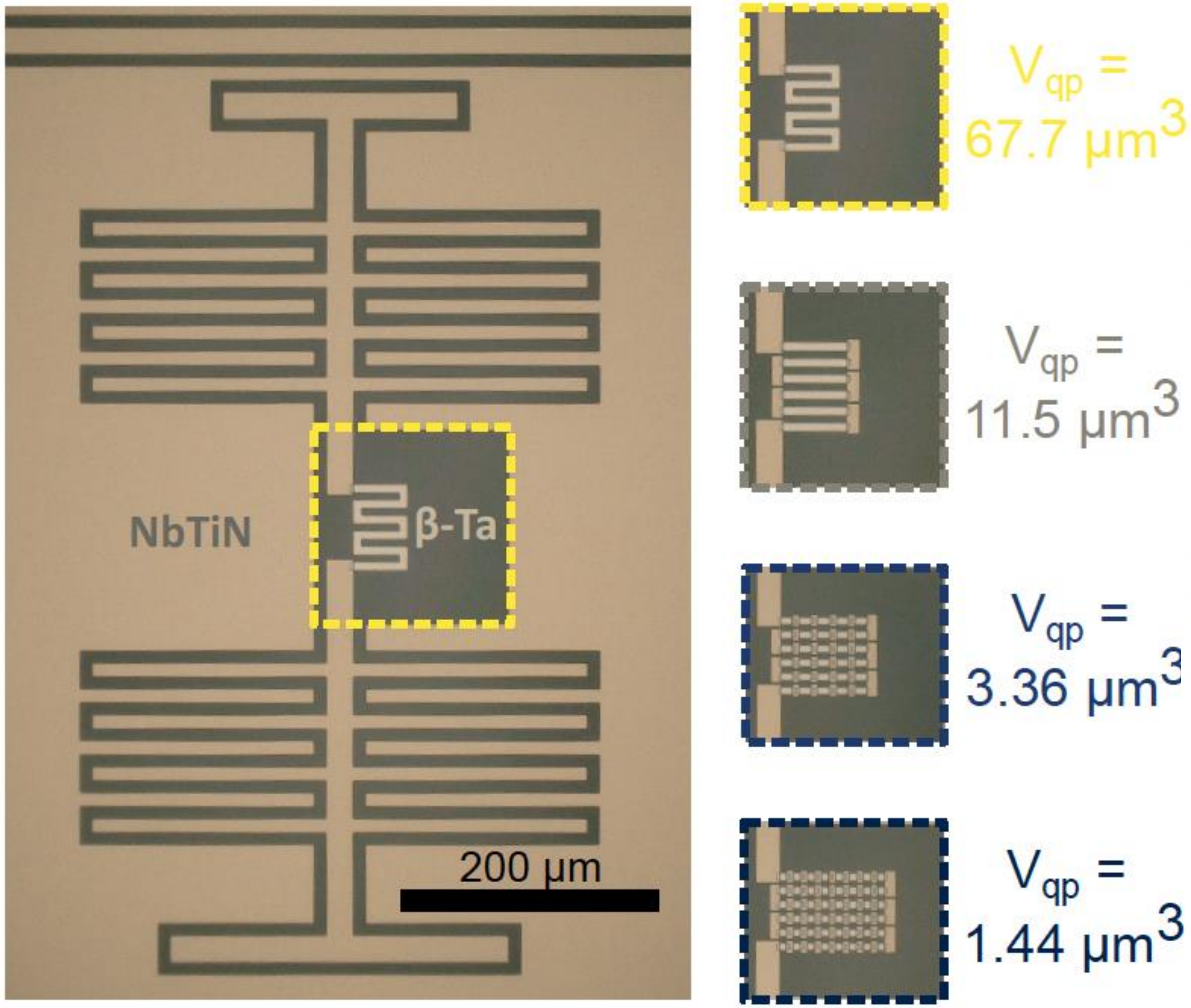
- Gurra et al 2026 & Fischer, Catelani 2026
  - Localised states are not deep enough

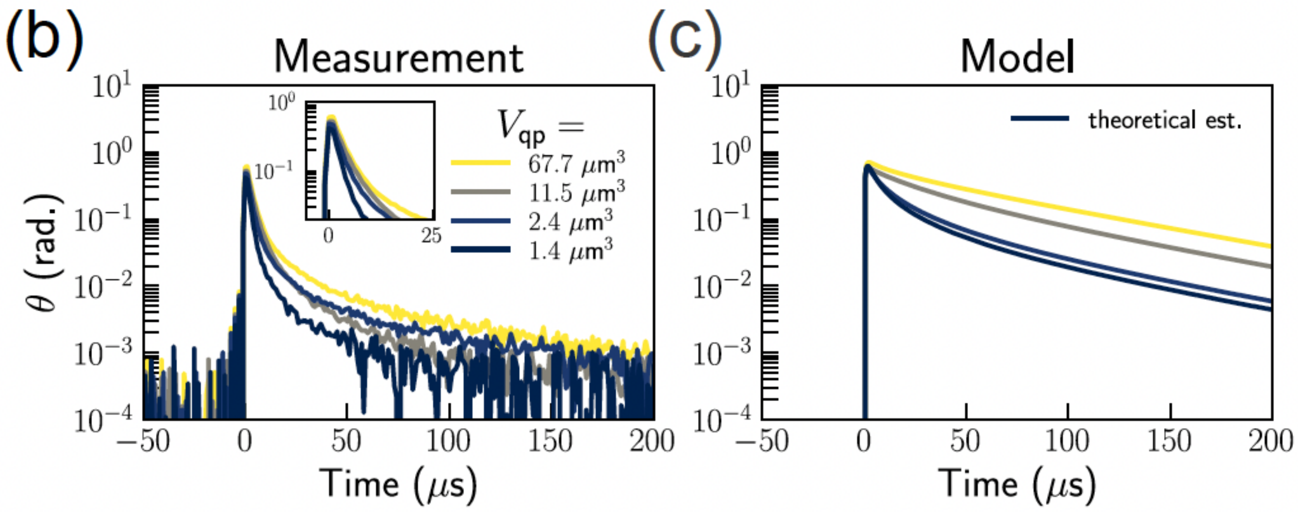


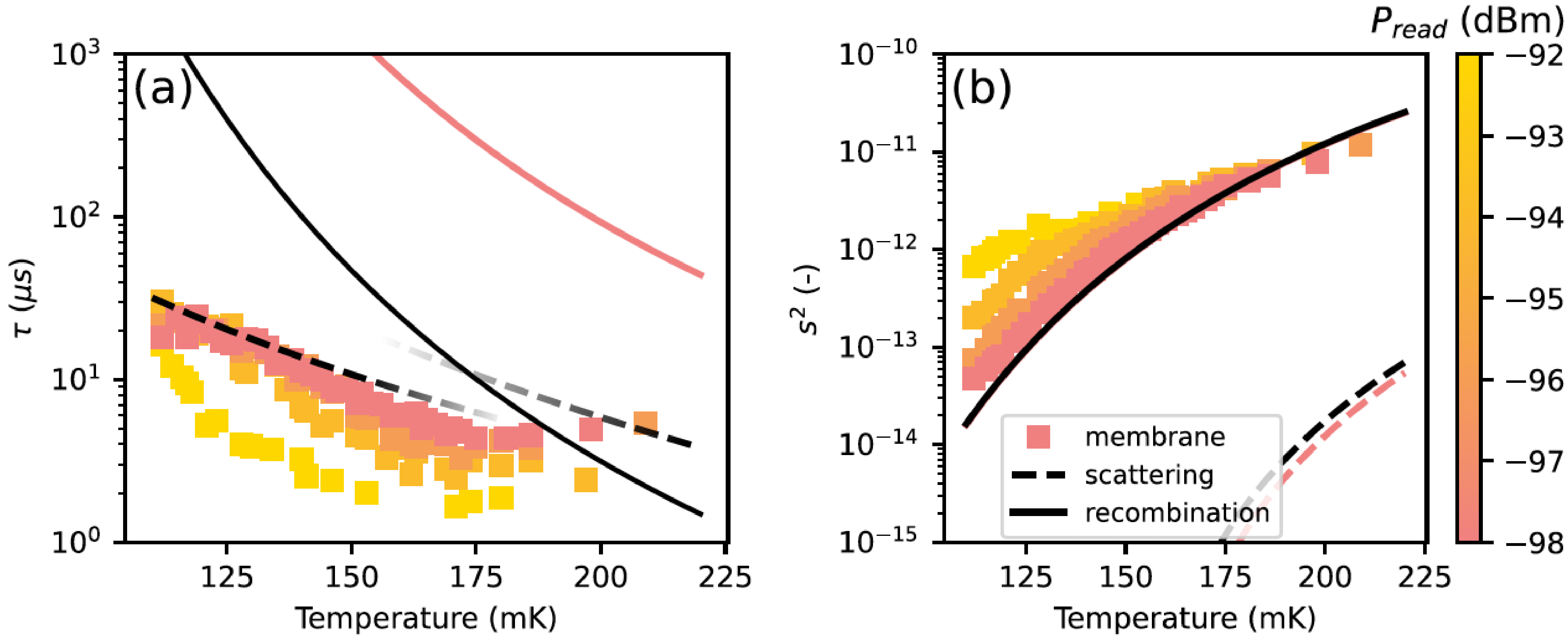
Diffusion effects



Diffusion effects






(a)
10^3
10^2
10^1
10^0
τ (μs)
125
150
175
200
225
Temperature (mK)
(b)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
s^2 (-)
membrane
scattering
recombination
Temperature (mK)
P_{read} (dBm)
−92
−93
−94
−95
−96
−97
−98

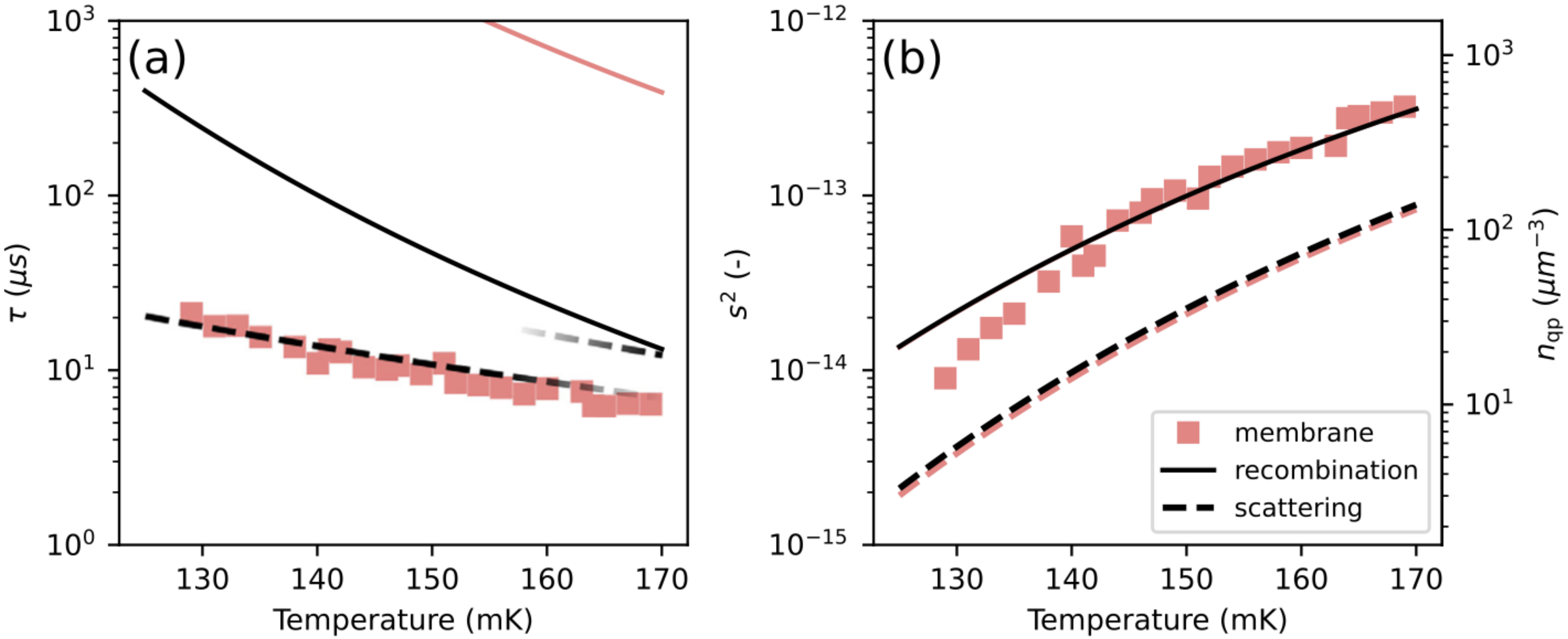
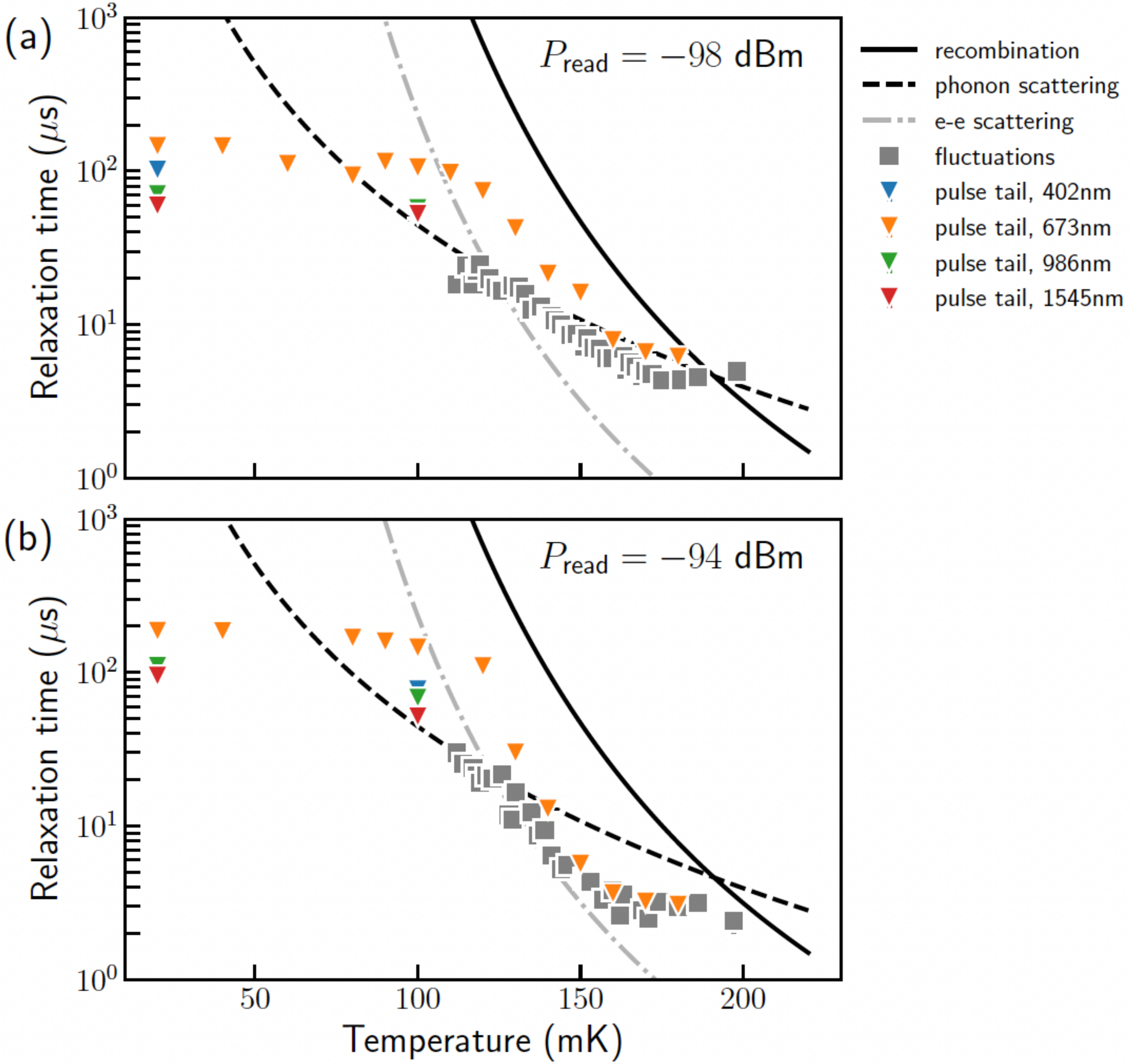


Fig. 5 | Fluctuation measurement of σ_1. Quasiparticle relaxation time (**a**) and the variance (**b**) are obtained the same way as in Fig. 2, but from the fluctuations of the dissipative part of the complex conductivity, $\delta\sigma_1$. Error bars indicating statistical fit errors are smaller than the data points. The quasiparticle signal in σ_1 is a few times lower than in σ_2[38], which results in a smaller usable temperature range. For the substrate resonator, we did not observe any Lorentzian signatures in the PSDs of σ_1.


(a)
$P_{read} = -98$ dBm
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Relaxation time (μs)
Temperature (mK)
10^0
10^1
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10^3
50
100
150
200
recombination
phonon scattering
e-e scattering
fluctuations
pulse tail, 402nm
pulse tail, 673nm
pulse tail, 986nm
pulse tail, 1545nm