Absorption of electromagnetic radiation and non-equilibrium superconductivity

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Photons ‘heat’ electrons and/or break pairs

- Superconducting tunnel-junctions (STJ’s)
- Normal metal absorber and a TES as thermometer
- Microwave kinetic inductance detectors

Observable S_{21}

$$NEP^2(\omega) = S_x \cdot \left[\frac{\eta\tau}{\Delta} \cdot \frac{\delta x}{\delta N_{qp}}\right]^{-2} (1+\omega^2\tau^2)(1+\omega^2\tau_{res}^2)$$

- ω is the frequency of the output spectrum
- x is Θ (for phase read-out) and R (for phase read-out)
- N_{qp} is the density of quasiparticles
- S_Θ is the phase noise
- S_R is the amplitude noise
- τ is the quasiparticle lifetime
- τ_{res} is the resonator ringtime $(Q/\pi F_0)$
- η is the efficiency of quasiparticle creation
- Δ is the superconducting gap

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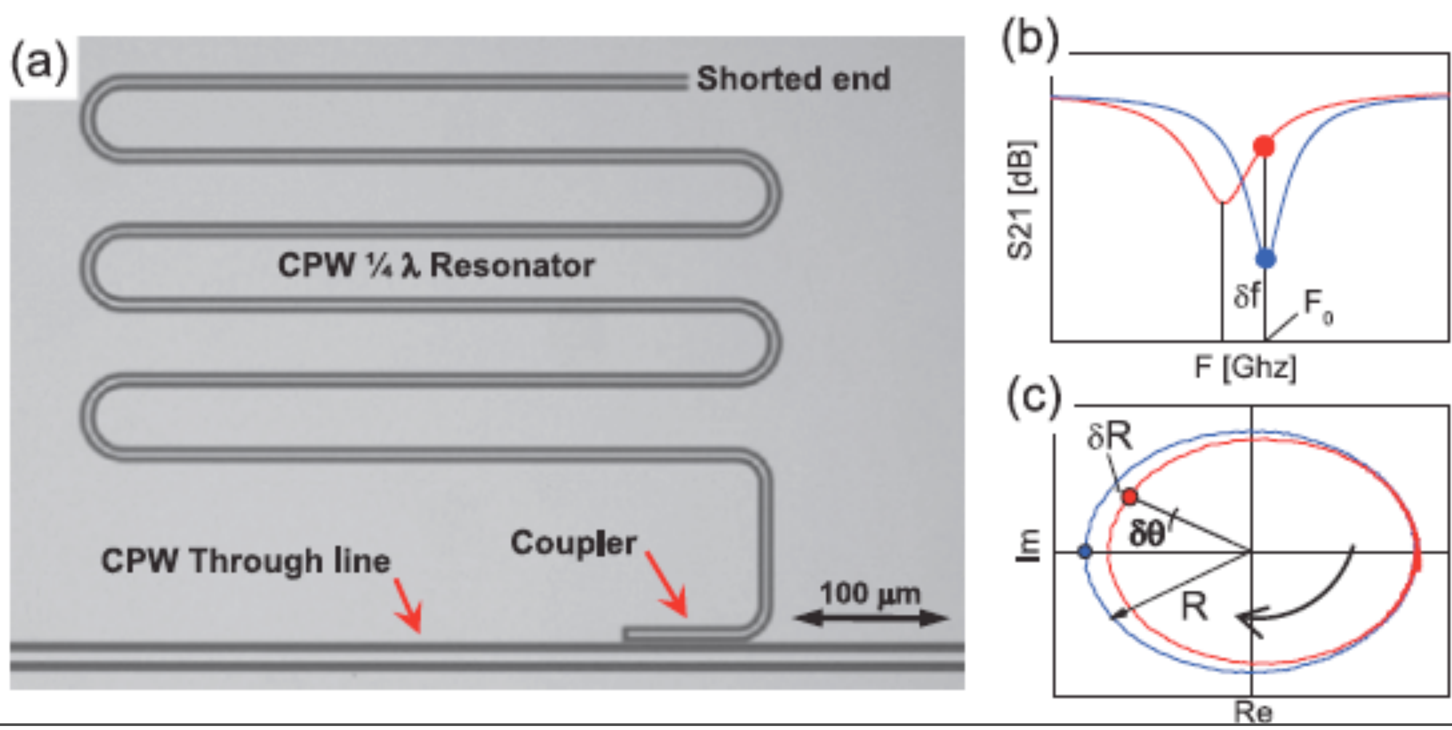

Aluminium

Titaniumnitride

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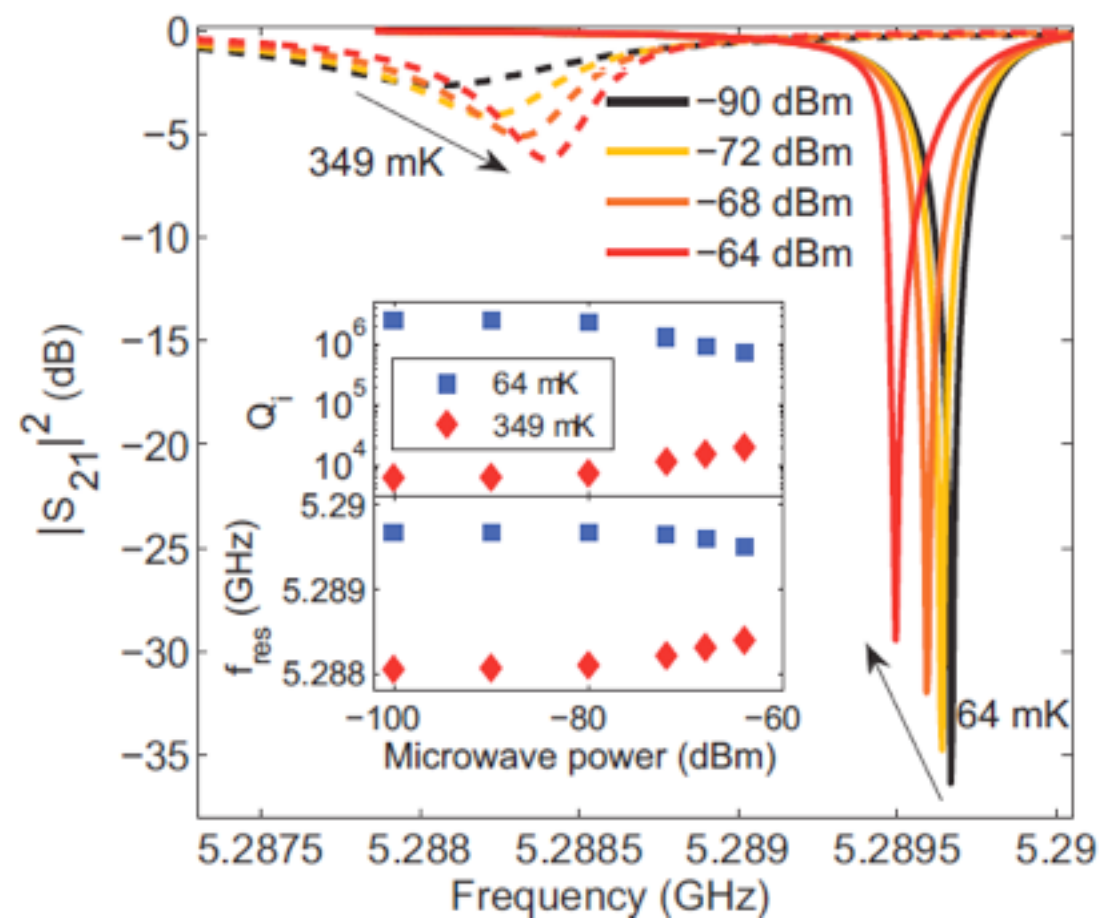
Two frequencies: GHz and THz

- Optical photons (to be detected): create quasi-particles (break pairs)
- Microwave signal (used for read-out): determine non-equilibrium superconducting state

Non-equilibrium superconductivity

- Excess quasi-particles (δN_{qp})
- f(E) electron-distribution
- n(Ω) phonon-distribution



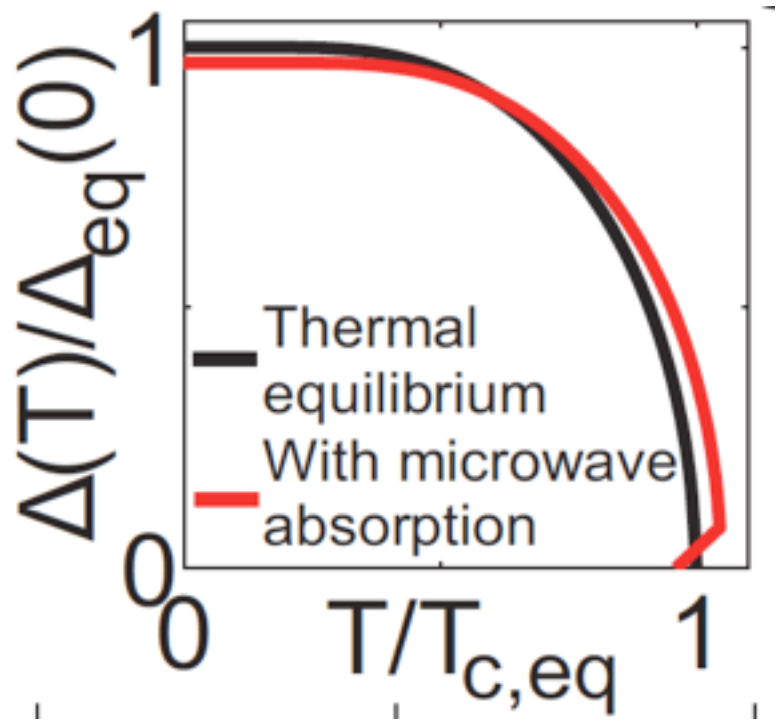
Counterintuitive results:

De Visser, Goldie, Diener, Withington, Baselmans, Klapwijk, arXiv 1306.4992 and LTD-15

Control parameter: f(E)

$$n_{\mathrm{qp}} = 4N_0 \int_{\Delta}^{\infty} dE \frac{E}{\sqrt{E^2 - \Delta^2}} f(E)$$

$$\frac{1}{N_0 V_{BCS}} = \int_{\Delta}^{\infty} \frac{1 - 2f(E)}{\sqrt{E^2 - \Delta^2}} dE$$



$$\frac{\Delta(T)}{\Delta(0)} \approx [1 - \frac{T}{T_c}]^{\frac{1}{2}}$$

Normally: $f(E) = \frac{1}{1 + e^{E/k_B T}}$

All BCS expressions in which the temperature appears is through f(E). No change in: V_{BCS}

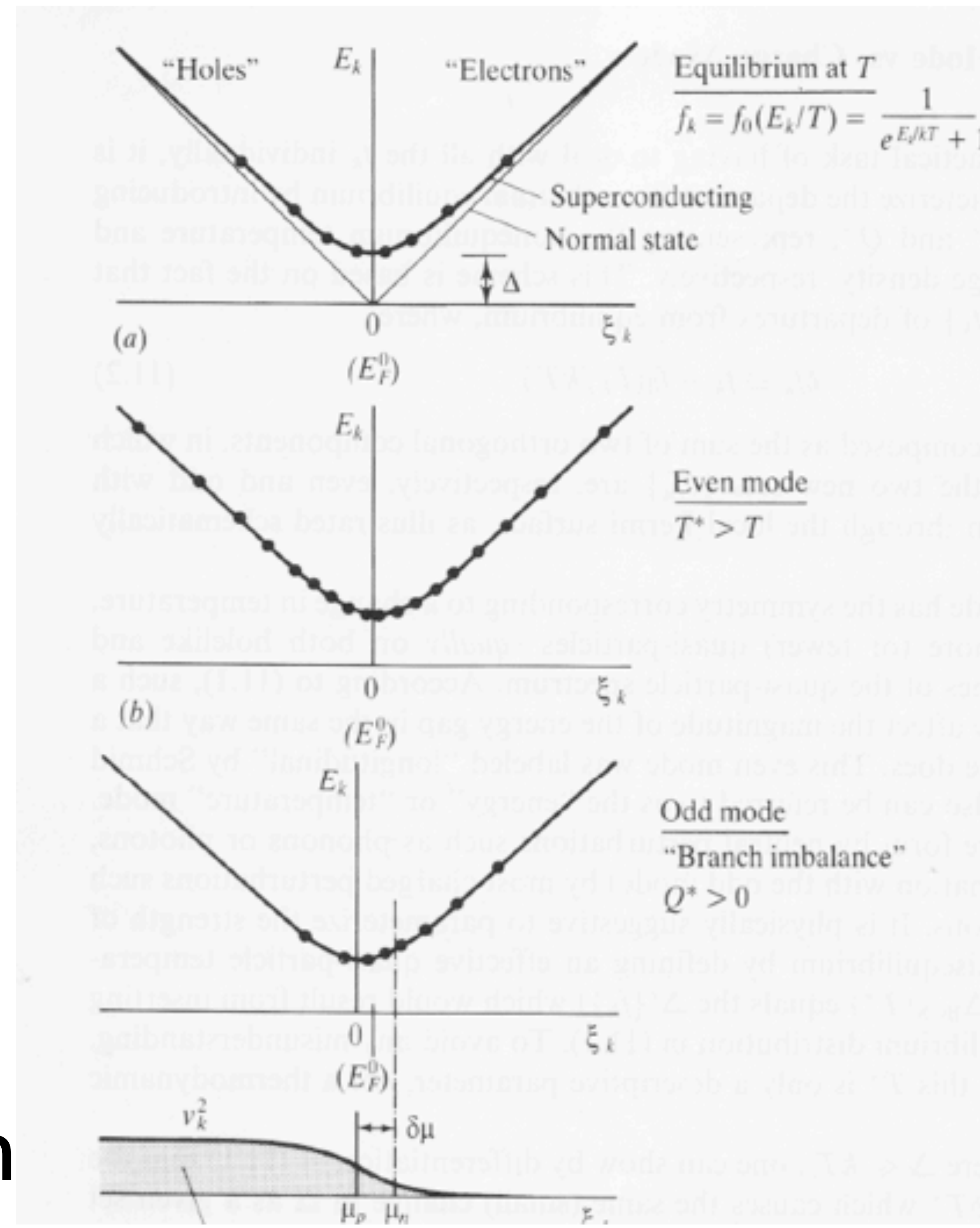
Even and odd f(E)

- Transversal and longitudinal nonequilibrium
- Charge and energy-mode nonequilibrium
- Asymmetric and symmetric nonequilibrium

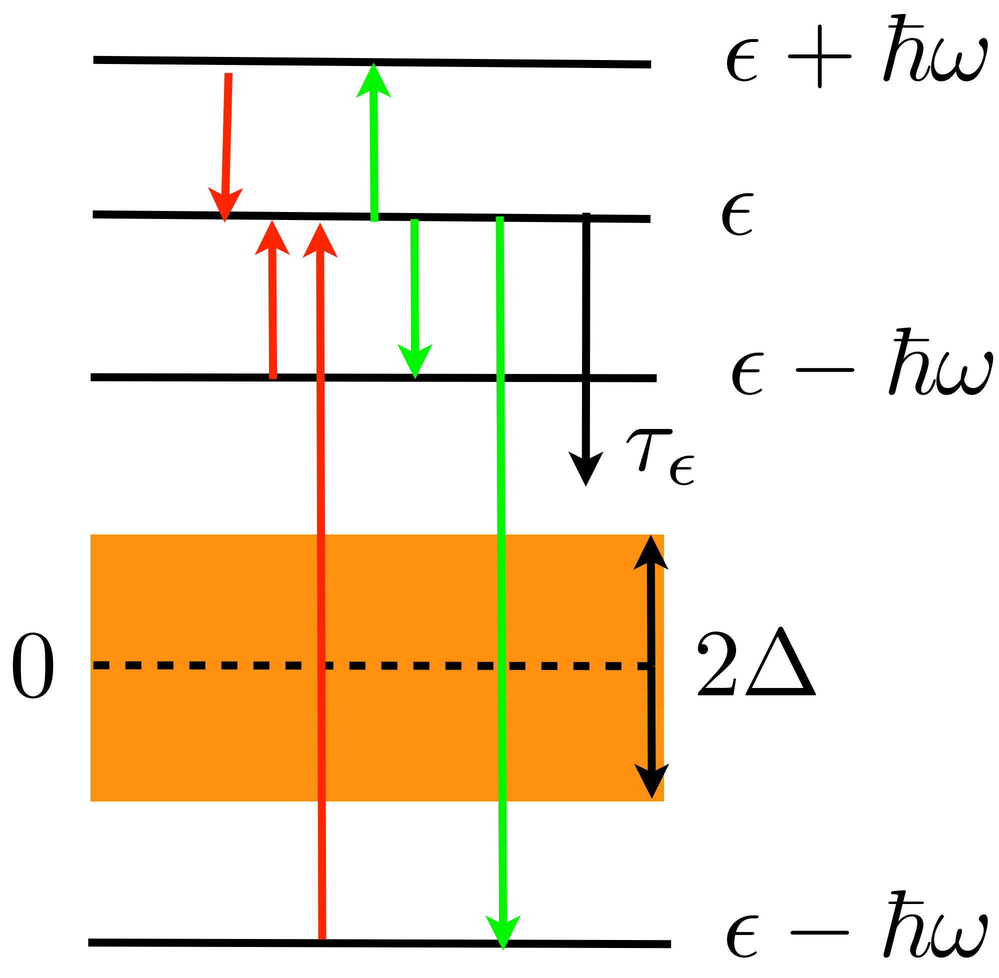
$$q_k = \frac{\xi_k}{E_k} = \frac{[E_k^2 - \Delta^2{}_k]^{1/2}}{E_k}$$

$$Q^* = \sum_k q_k \delta f_k$$

cf. NS current conversion



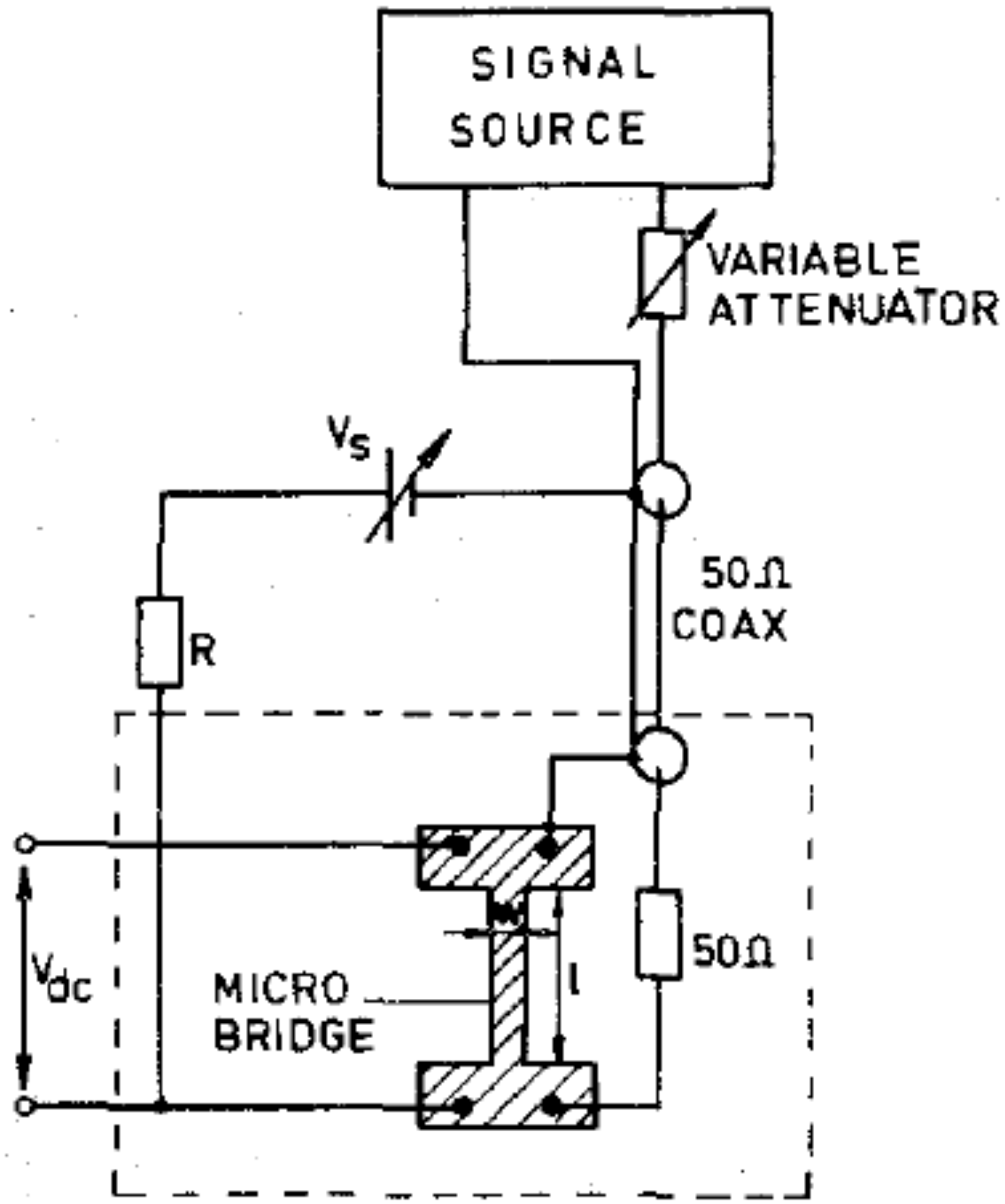
Microwave absorption + relaxation

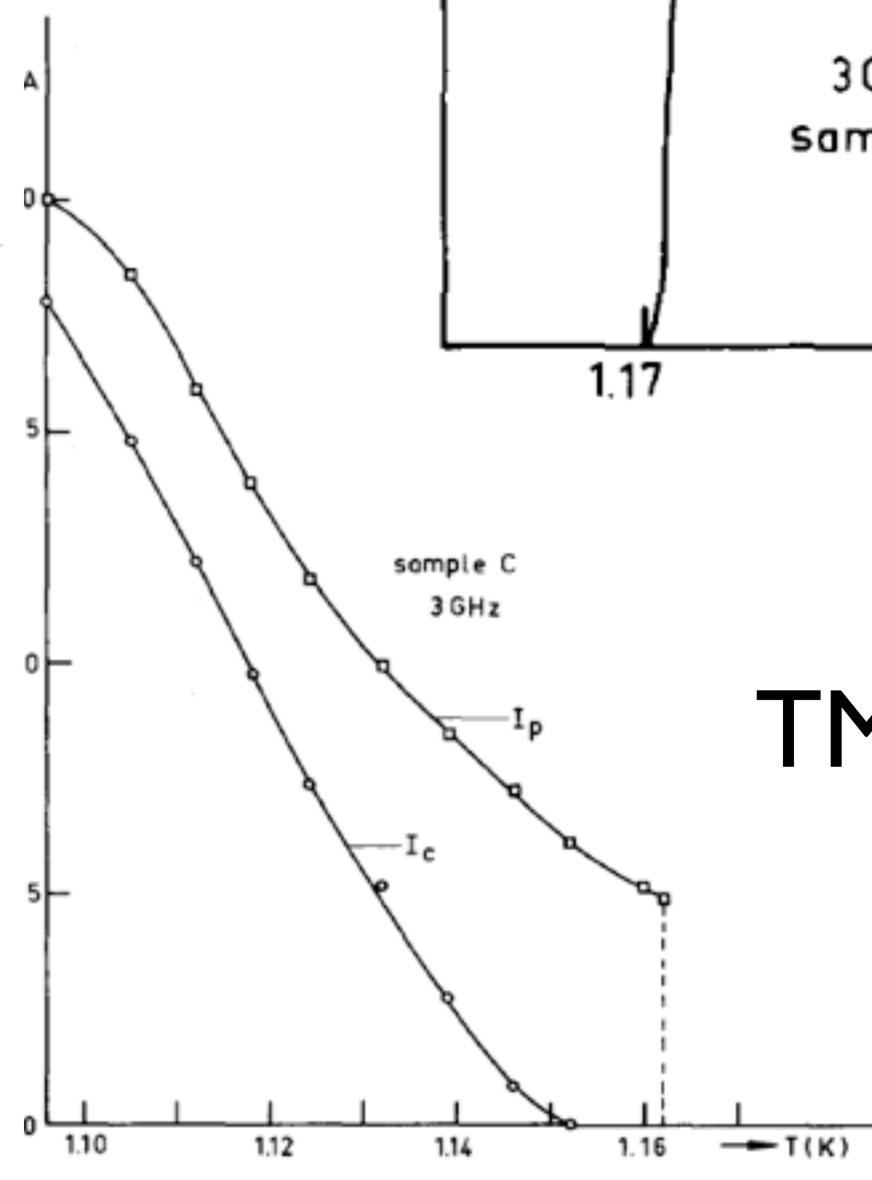


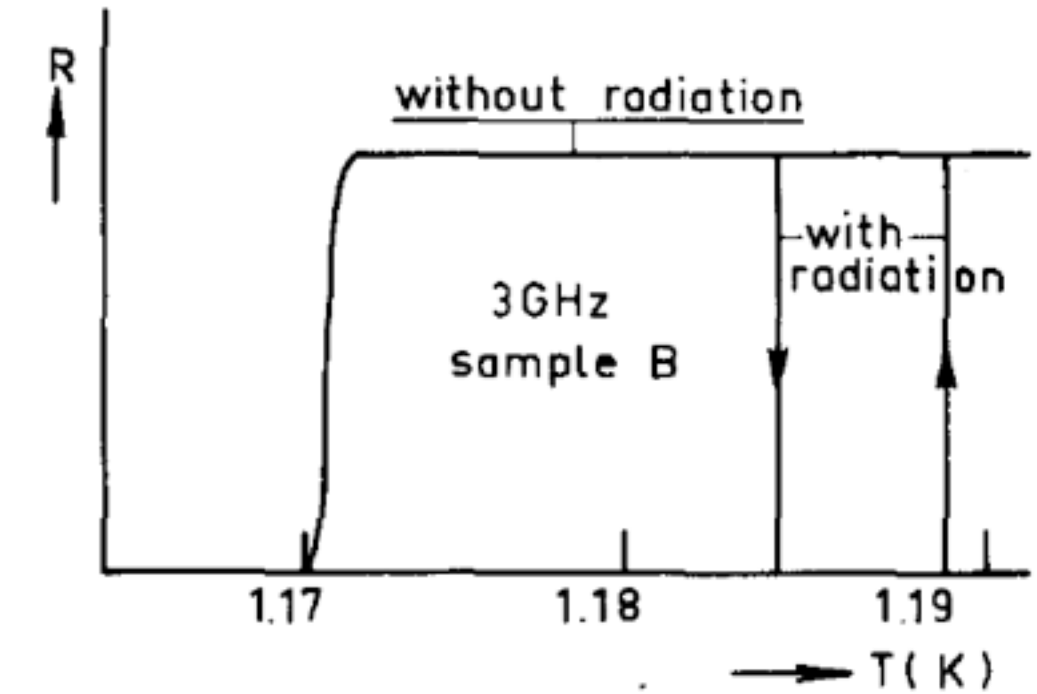
$$n_1(\varepsilon) = \frac{\alpha}{\gamma}\frac{\hbar\omega}{4kT_c}\left[\frac{\varepsilon(\varepsilon-\hbar\omega)+\Delta^2}{\varepsilon[(\varepsilon-\hbar\omega)^2-\Delta^2]^{1/2}}\theta(\varepsilon-\Delta-\hbar\omega) - \frac{\varepsilon(\varepsilon+\hbar\omega)+\Delta^2}{\varepsilon[(\varepsilon+\hbar\omega)^2-\Delta^2]^{1/2}}\theta(\varepsilon-\Delta) - \frac{\varepsilon(\varepsilon-\hbar\omega)+\Delta^2}{\varepsilon[(\varepsilon-\hbar\omega)^2-\Delta^2]^{1/2}}\theta(\varepsilon-\Delta)\theta(\hbar\omega-\Delta-\varepsilon)\right]$$

$$\gamma = \frac{\hbar}{\tau_\epsilon} \qquad \alpha = \frac{De^2}{\hbar c^2}A_\omega^2$$

Microwave-enhanced superconductivity





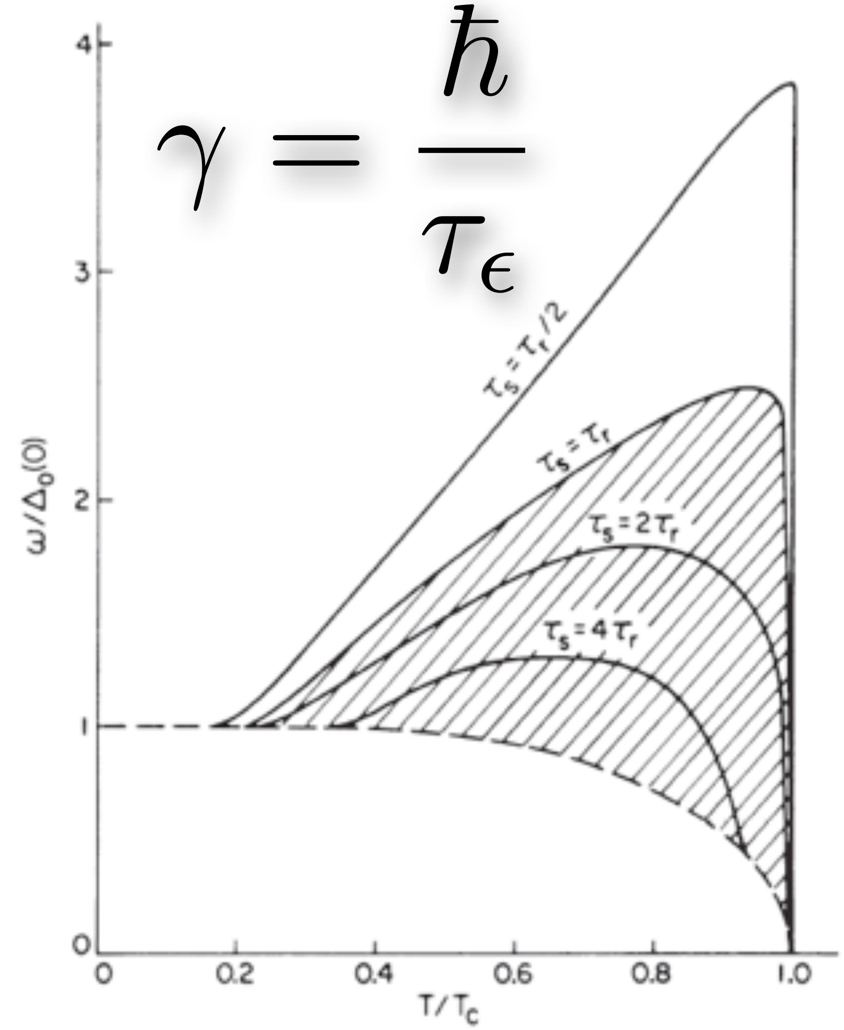


TMK et al, 1976

Energy-dependent relaxation processes

- Kaplan et al (1976)
- Chang-Scalapino (1978)
- Enhanced recombination rates at higher energies

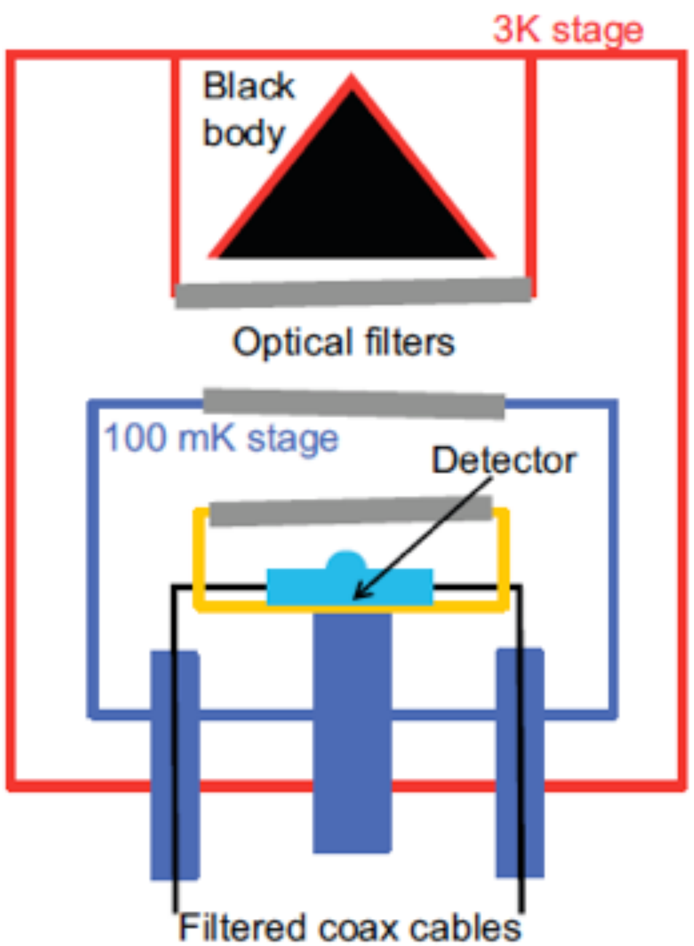
$$\gamma = \frac{\hbar}{\tau_\epsilon}$$

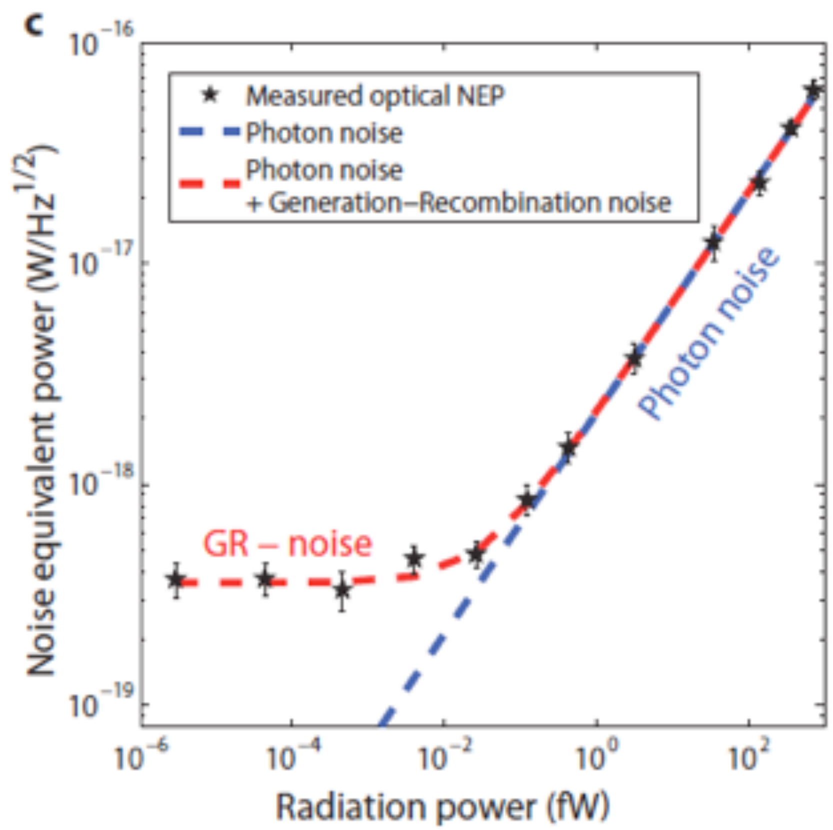


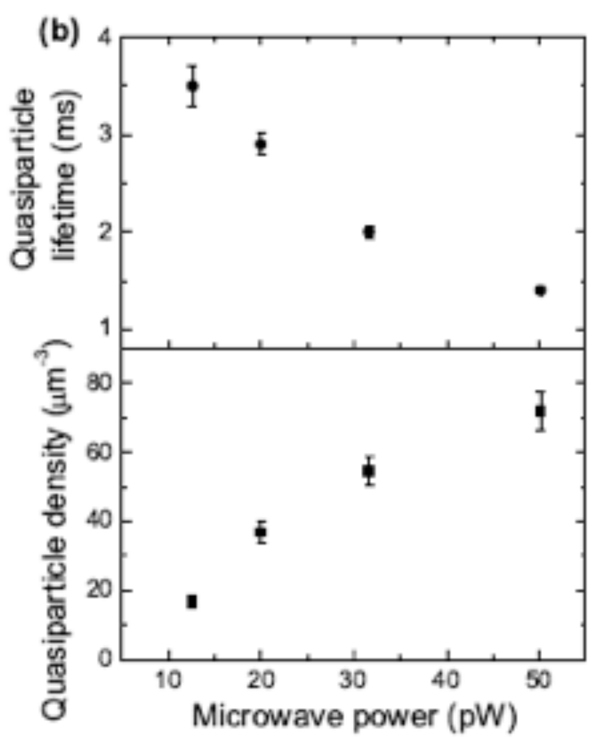
Aluminium

- Weak electron-phonon interaction
- Therefore high conductivity at room temperature
- Low T_c
- Slow energy-relaxation times; slow recombination times

NEP limited by background quasiparticle density



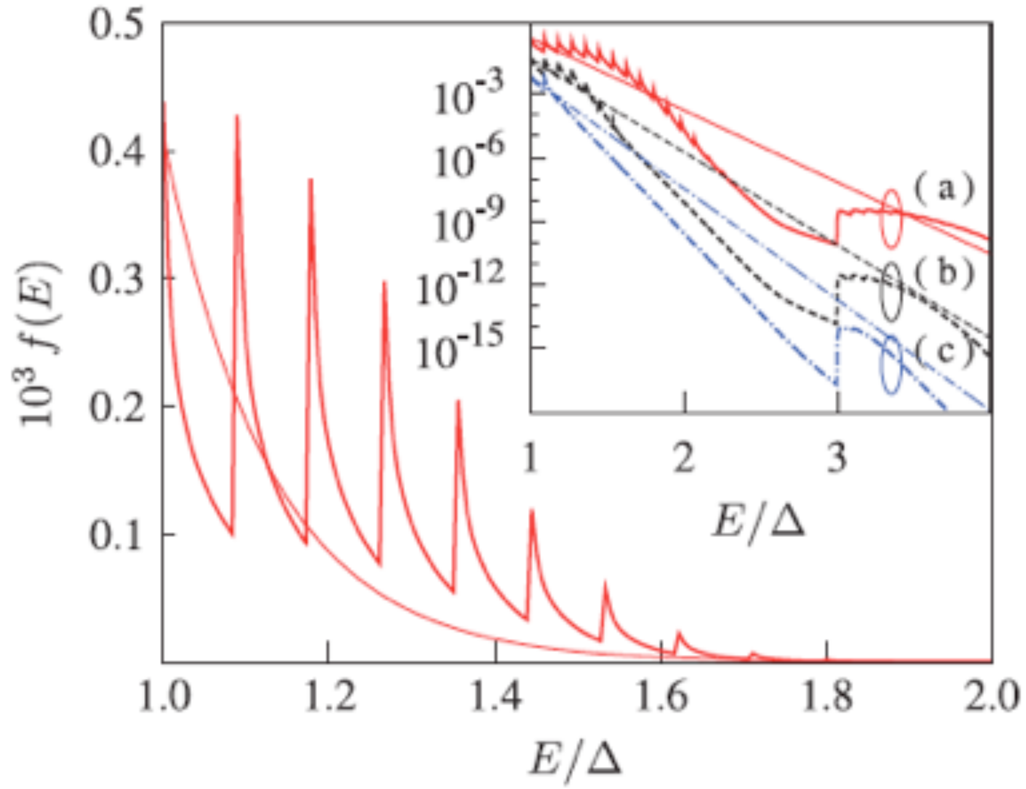


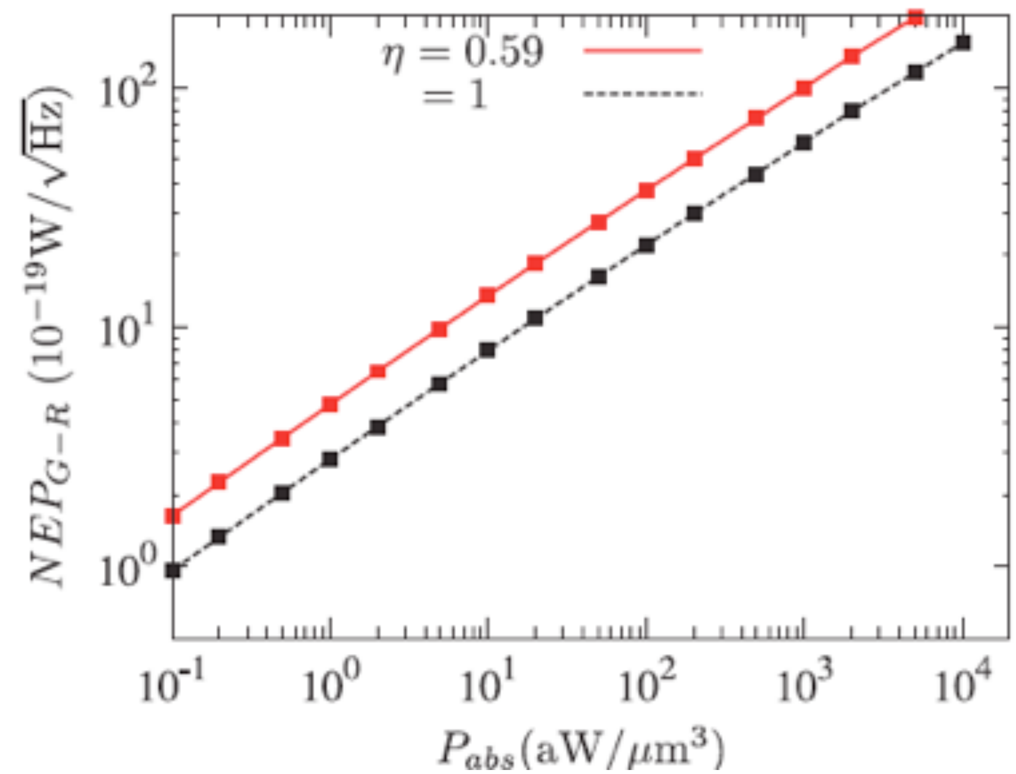


De Visser et al, APL **100**, 162601 (2012)

De Visser et al, arxiv 1306.4238

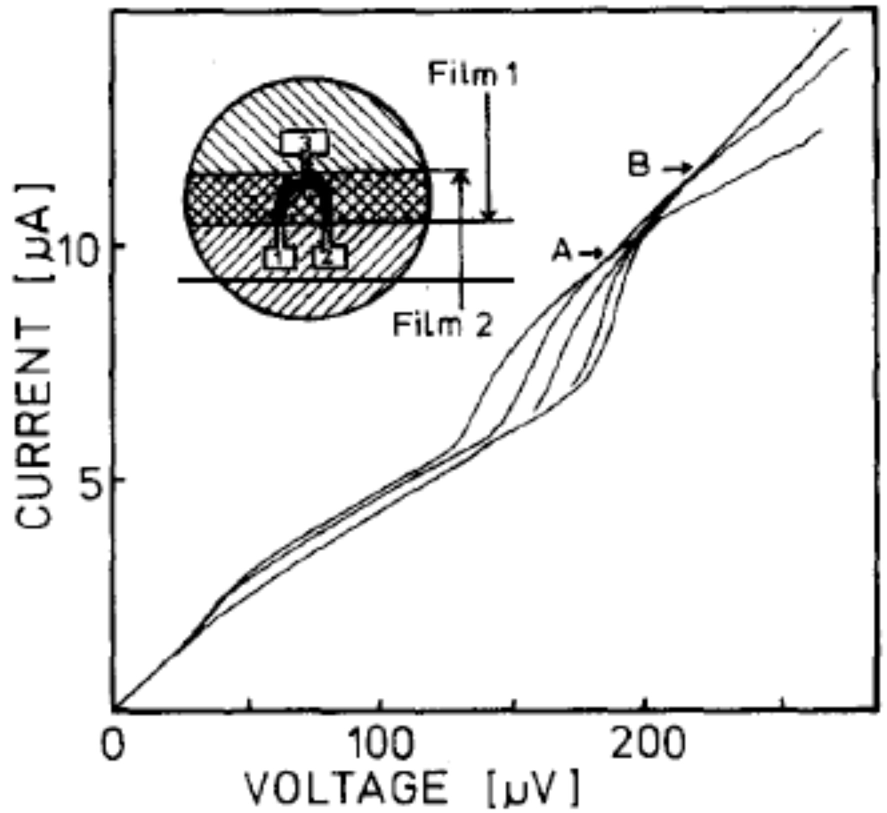
Full numerical analysis of Eliashberg and Chang-Scalapino

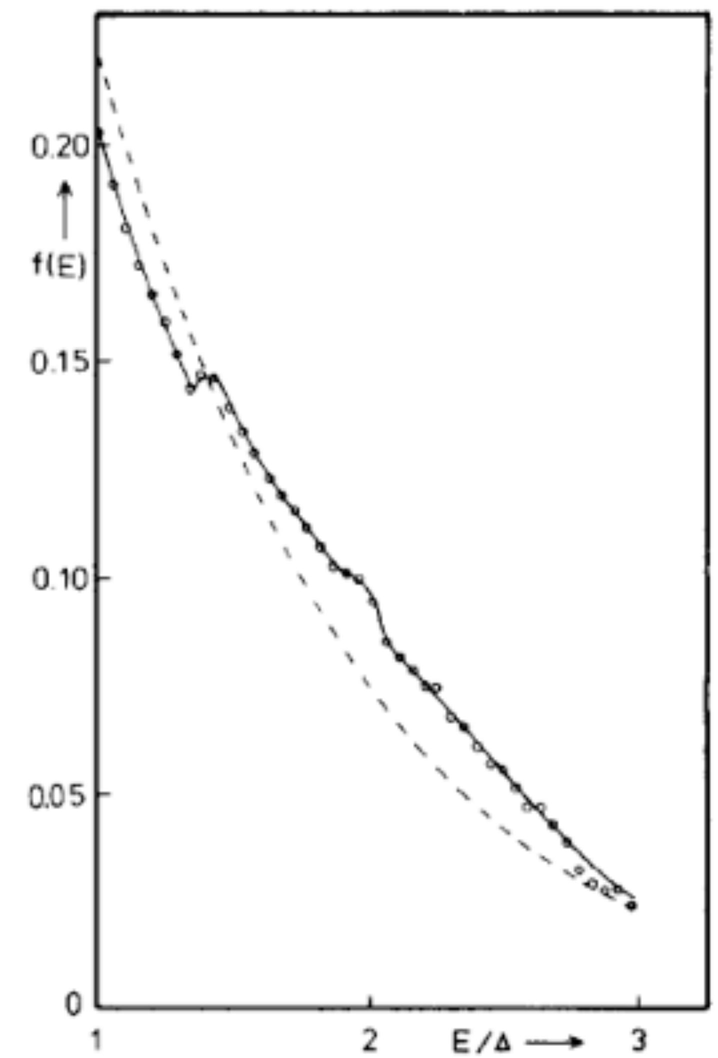




Goldie and Withington, SUST **26**, 015004(2013)

Direct measurements: horseshoe-shape tunnel-junctions





Wolter and Horstman,
Phys. Lett. **82A**, 43 (1981) and **86A**, 185 (1981)

Observables: complex impedance

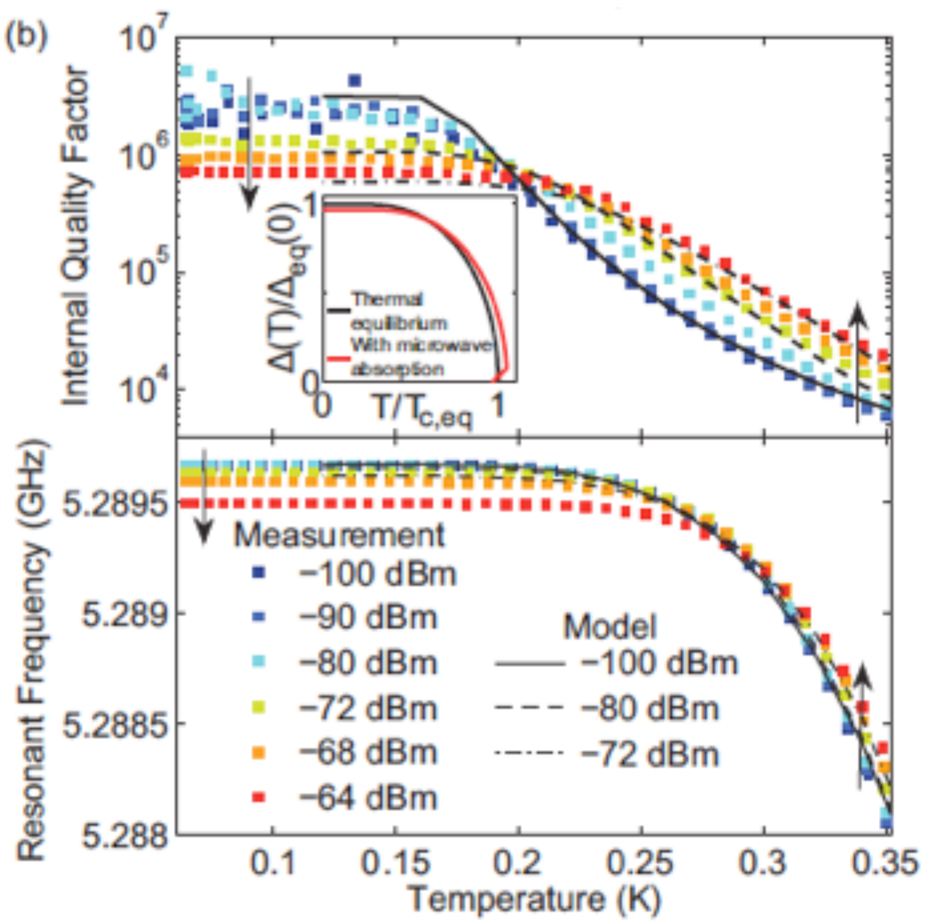
$$\vec{J}(\vec{r}) = \sigma(\omega)\vec{E}(\vec{r}) \qquad \sigma(\omega) = \sigma_1(\omega) - i\sigma_2(\omega)$$

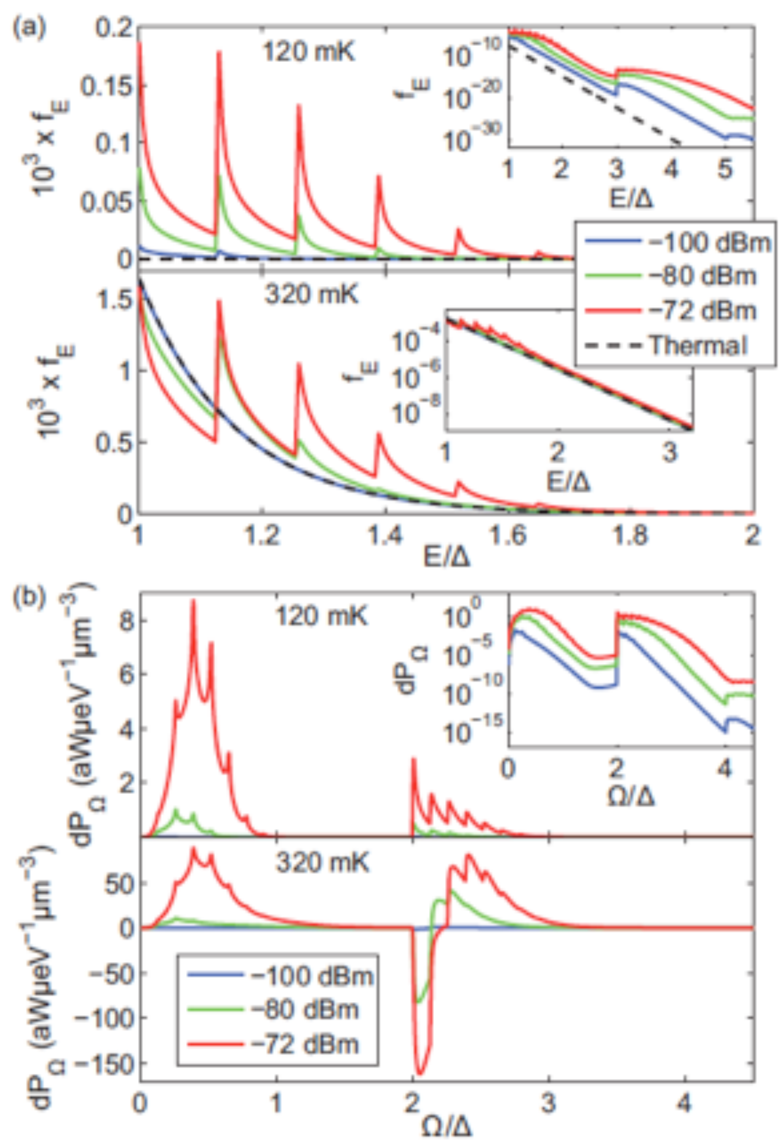
$$\frac{\sigma_1(\omega)}{\sigma_n} = \frac{2}{\hbar\omega}\int_\Delta^\infty dE\,\frac{E^2+\Delta^2+\hbar\omega E}{\sqrt{E^2-\Delta^2}\sqrt{(E+\hbar\omega)^2-\Delta^2}}\left[f(E)-f(E+\hbar\omega)\right]$$

$$\frac{\sigma_2(\omega)}{\sigma_n} = \frac{1}{\hbar\omega}\int_\Delta^{\Delta+\hbar\omega} dE\,\frac{E^2+\Delta^2-\hbar\omega E}{\sqrt{E^2-\Delta^2}\sqrt{\Delta^2-(E-\hbar\omega)^2}}\left[1-2f(E)\right]$$

$$\Delta = \Delta(f(E))$$

Microwave-impedance analysis for Al

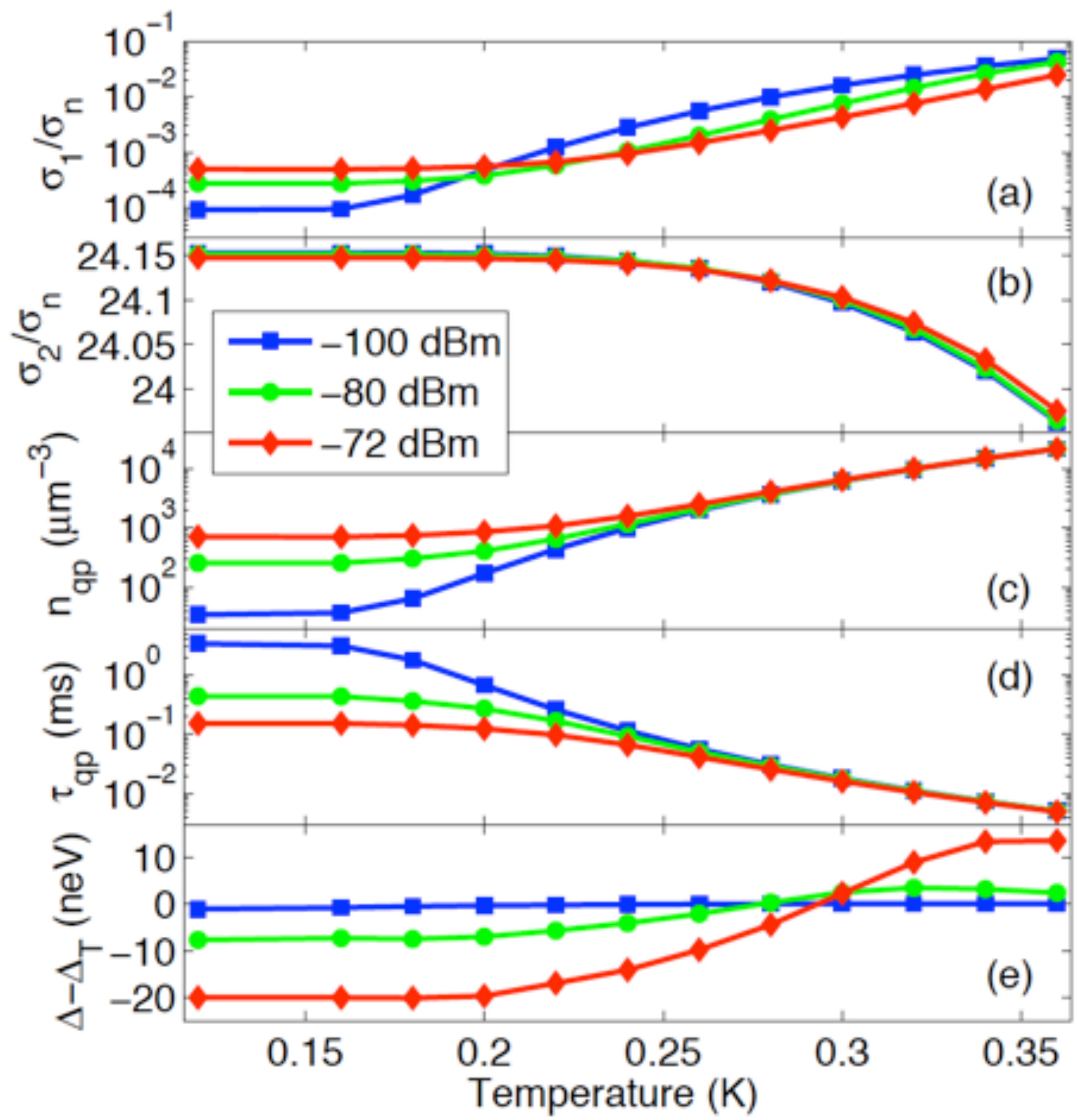


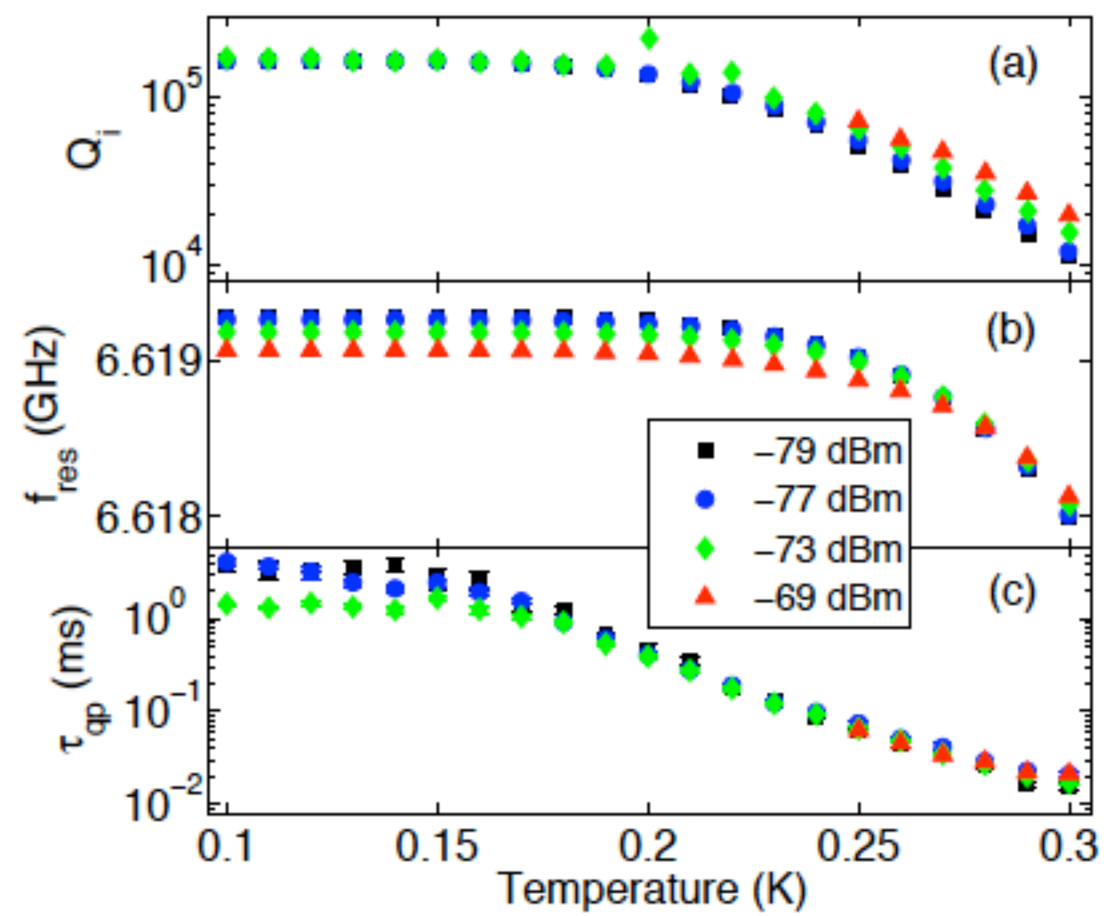


Counterintuitive results:

De Visser, Goldie, Diener, Withington, Baselmans, Klapwijk, arXiv 1306.4992 and LTD-15

Response of different observables





De Visser et al, arXiv 1306.4992 and LTD-15

Any implication for TiN?

$$\vec{J}(\vec{r}) = \sigma(\omega)\vec{E}(\vec{r}) \qquad \sigma(\omega) = \sigma_1(\omega) - i\sigma_2(\omega)$$

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

$$\frac{\sigma_2(\omega)}{\sigma_n} = \frac{1}{\hbar\omega}\int_{\Delta}^{\Delta+\hbar\omega} dE \frac{E^2 + \Delta^2 - \hbar\omega E}{\sqrt{E^2 - \Delta^2}\sqrt{\Delta^2 - (E-\hbar\omega)^2}}[1 - 2f(E)]$$

$$\Delta = \Delta(\vec{r})$$

Singularities: rounded density-of-states

Temperature dependence of f_0

Driessen et al, PRL **109,** 107003 (2012)

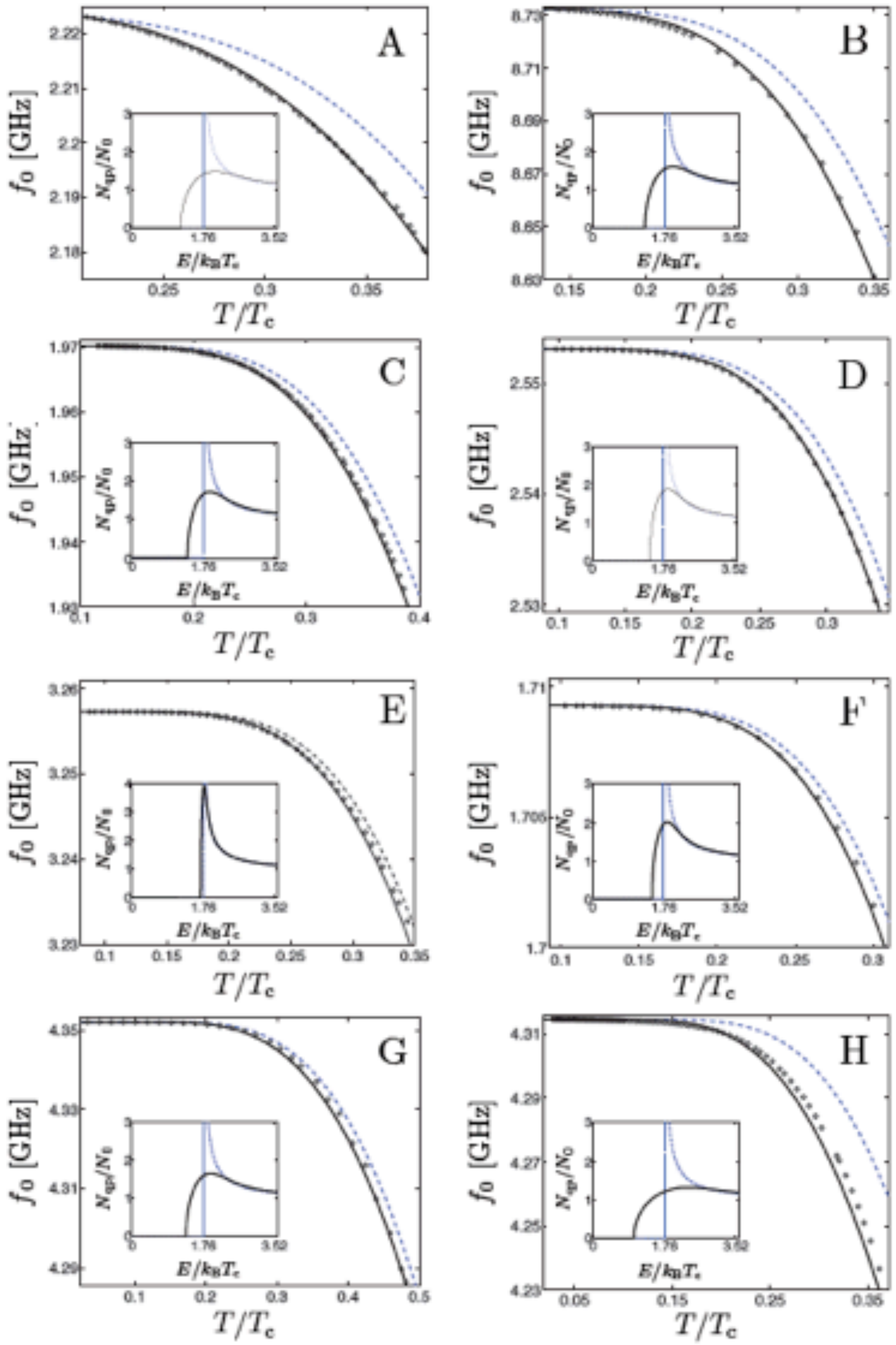
TABLE I. Parameters of the films studied in this experiment.

Film ID	Sub-strate	d [nm]	b [nm]	ρ [$\mu\Omega$cm]	$k_F l$	l [Å]	τ [fs]	T_c [K]	α [$k_B T'_c$]
				TiN ALD-deposited films					
A	SiO_2	6	25	380	3.3	3.4		1.5	0.22
B	SiO_2	11	27	356	3.5	3.5	1.2	2.2	0.17
C	SiO_2	22	32	253	4.6	4.4		2.7	0.13
D	SiO_2	45	37	187	6.1	5.7	1.2	3.2	0.10
E	SiO_2	89	42	120	8.6	7.3	1.7	3.6	0.01
F	H-Si	55	44	212	6.0	6.4	1.4	3.3	0.08
				NbTiN sputter-deposited films					
G	Sapphire	300	85	150	8.2	6.3		14.8	0.15
H	H-Si	50	30	506	2.4	2.4		11.9	0.34

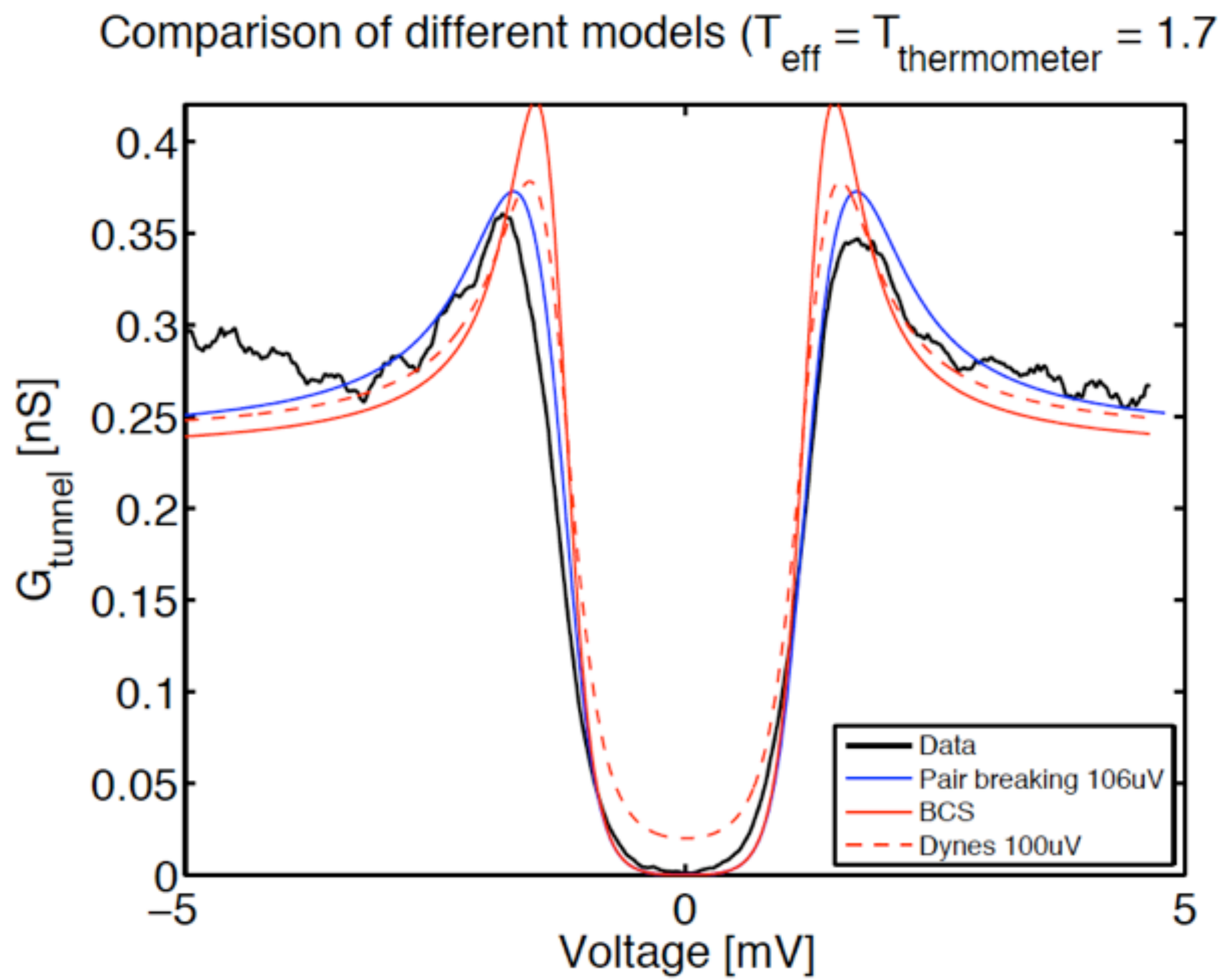
$$iE\sin\theta + \Delta\cos\theta - \alpha\sin\theta\cos\theta = 0.$$

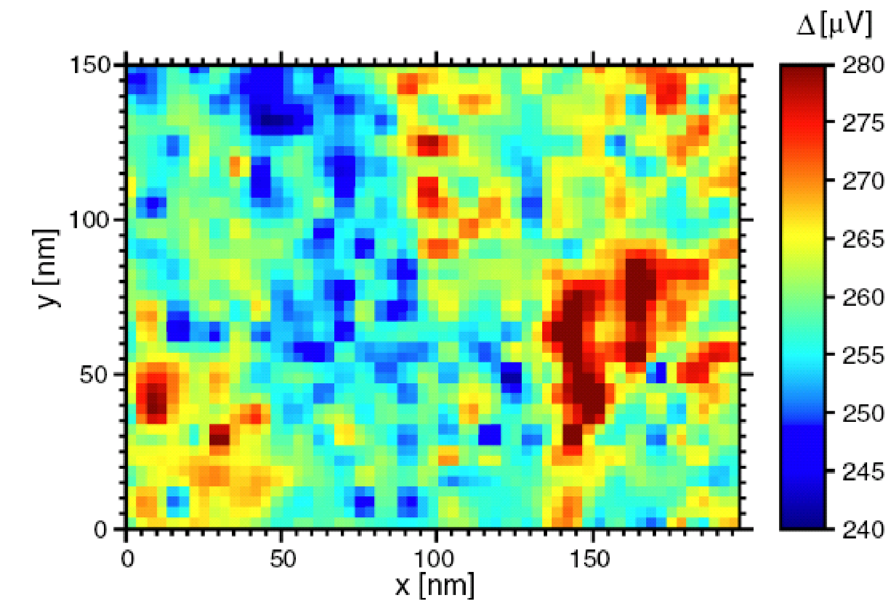
$$\hbar\omega\frac{\sigma_2}{\sigma_n} = \int_{-\hbar\omega}^{\infty} \mathrm{d}E\ g_2(E,E')\,[1-2f(E')] + \int_{0}^{\infty} \mathrm{d}E\ g_2(E',E)\,[1-2f(E)]$$

$$\Delta = N_0 V \int_0^{k_B\Theta_D} \mathrm{d}E\ \mathrm{Im}(\sin\theta)[1-2f(E)]$$



Local tunneling spectra much sharper





Driessen, unpubl. results

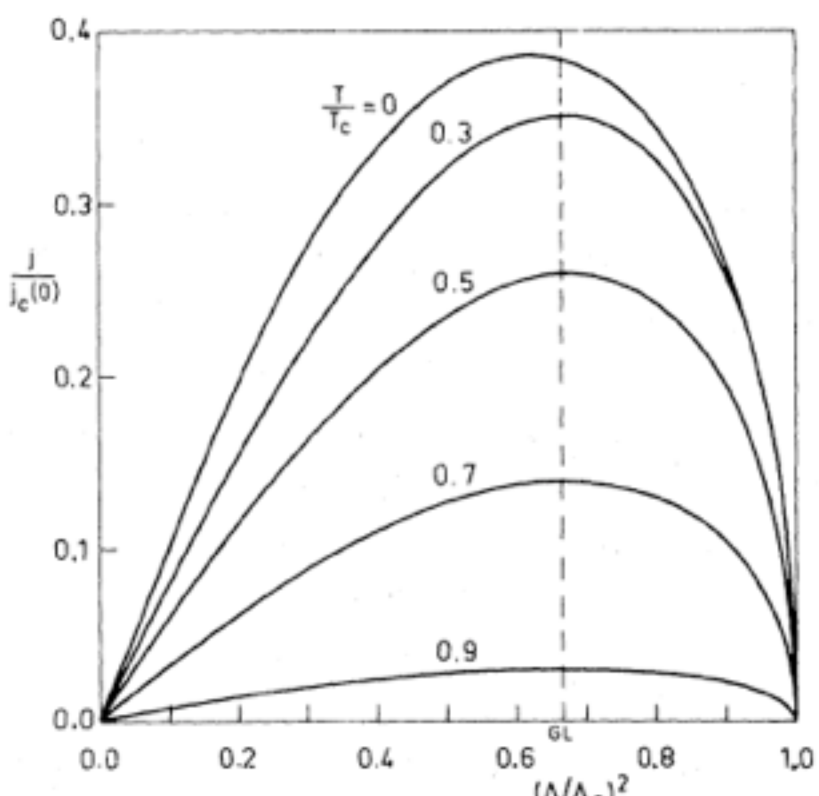
Current-carrying density-of-states

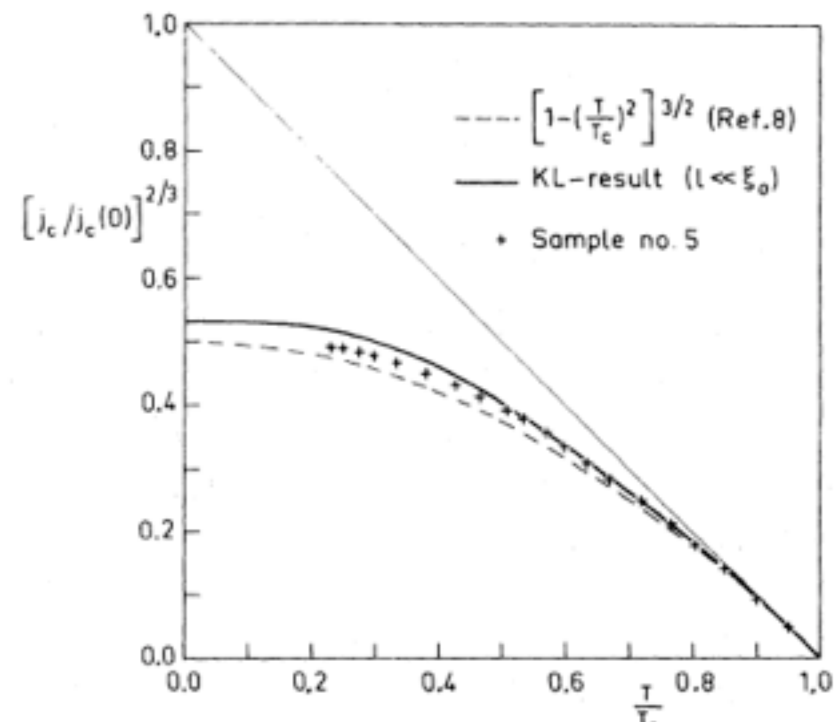
Anthore et al, PRL 2003

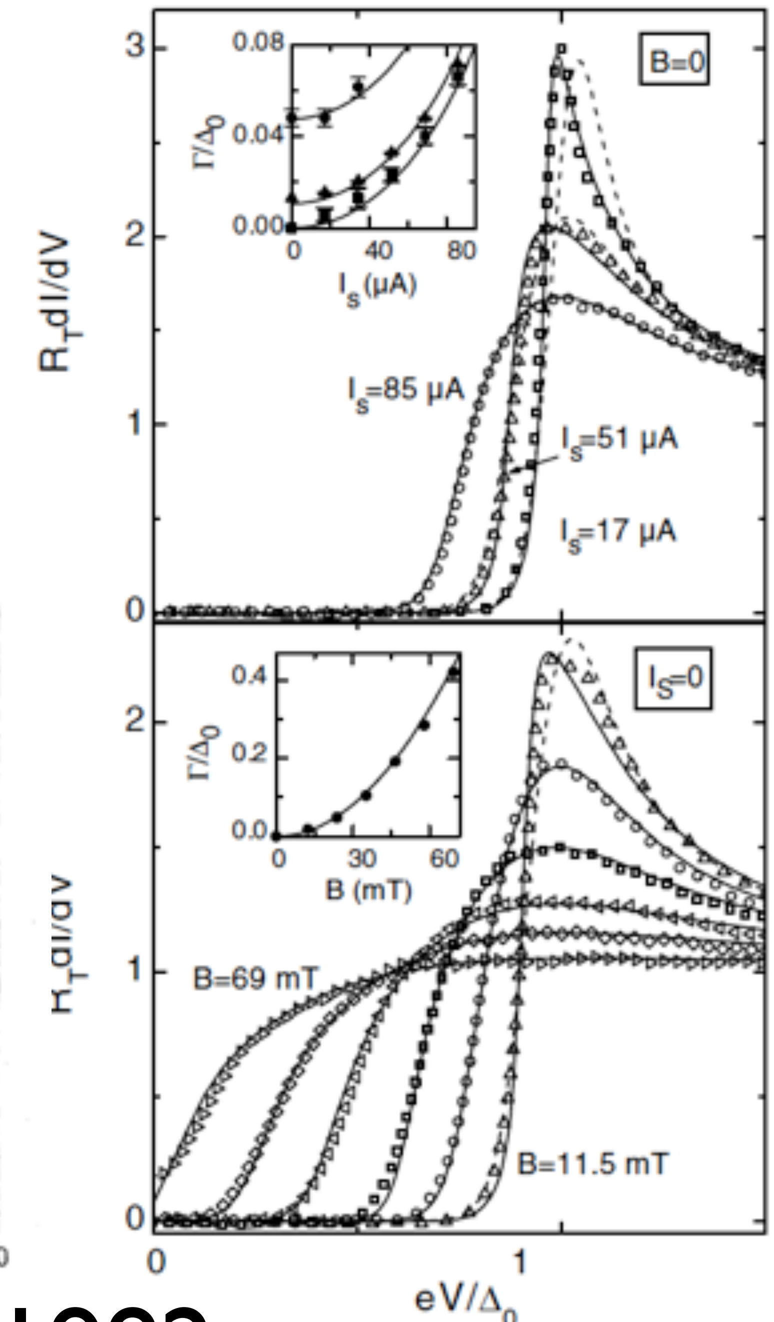
$$\frac{\hbar D}{2}\nabla^2\theta + \left[iE - \frac{\hbar}{2D}\vec{\mathbf{v}}_s^2 \cos\theta \right]\sin\theta + \Delta\cos\theta = 0$$

$$\vec{j}(\vec{r}) = \frac{\sigma}{eD}\int_0^\infty dE \tanh\left(\frac{\beta E}{2}\right)\mathrm{Im}(\sin^2\theta)\vec{\mathbf{v}}_s$$

$$\Delta(\vec{r}) = N(0)V_{\mathrm{eff}}\int_0^{\hbar\omega_D} dE \tanh\left(\frac{\beta E}{2}\right)\mathrm{Im}(\sin\theta)$$

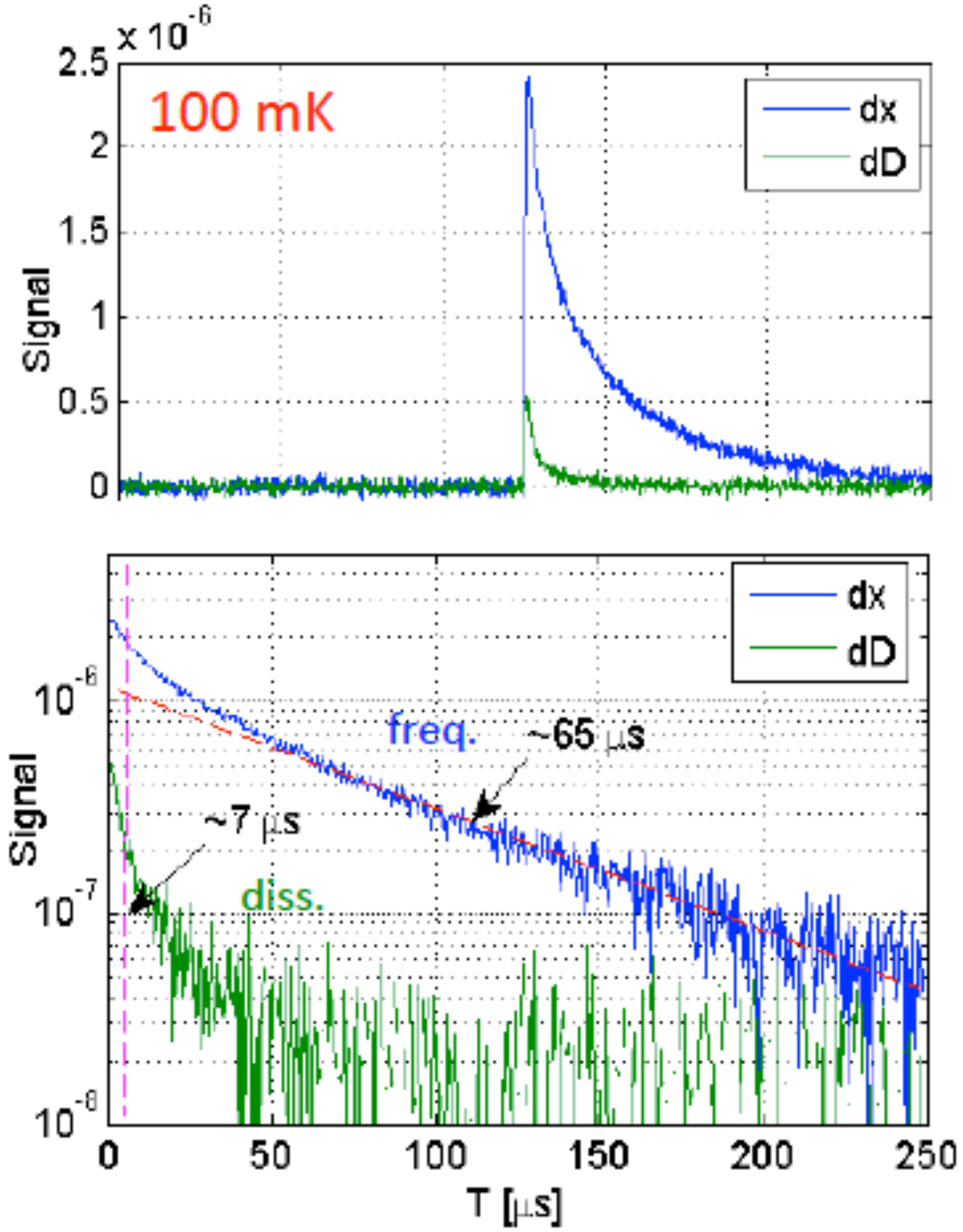


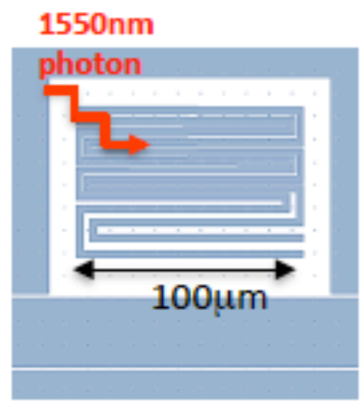




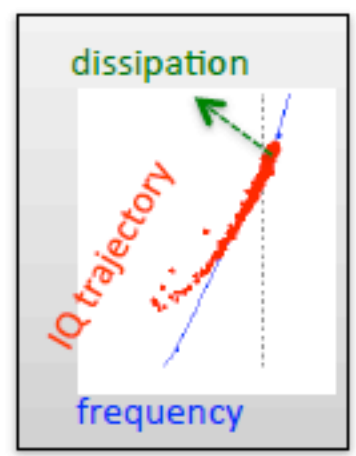
Romijn et al, PRB, 1982

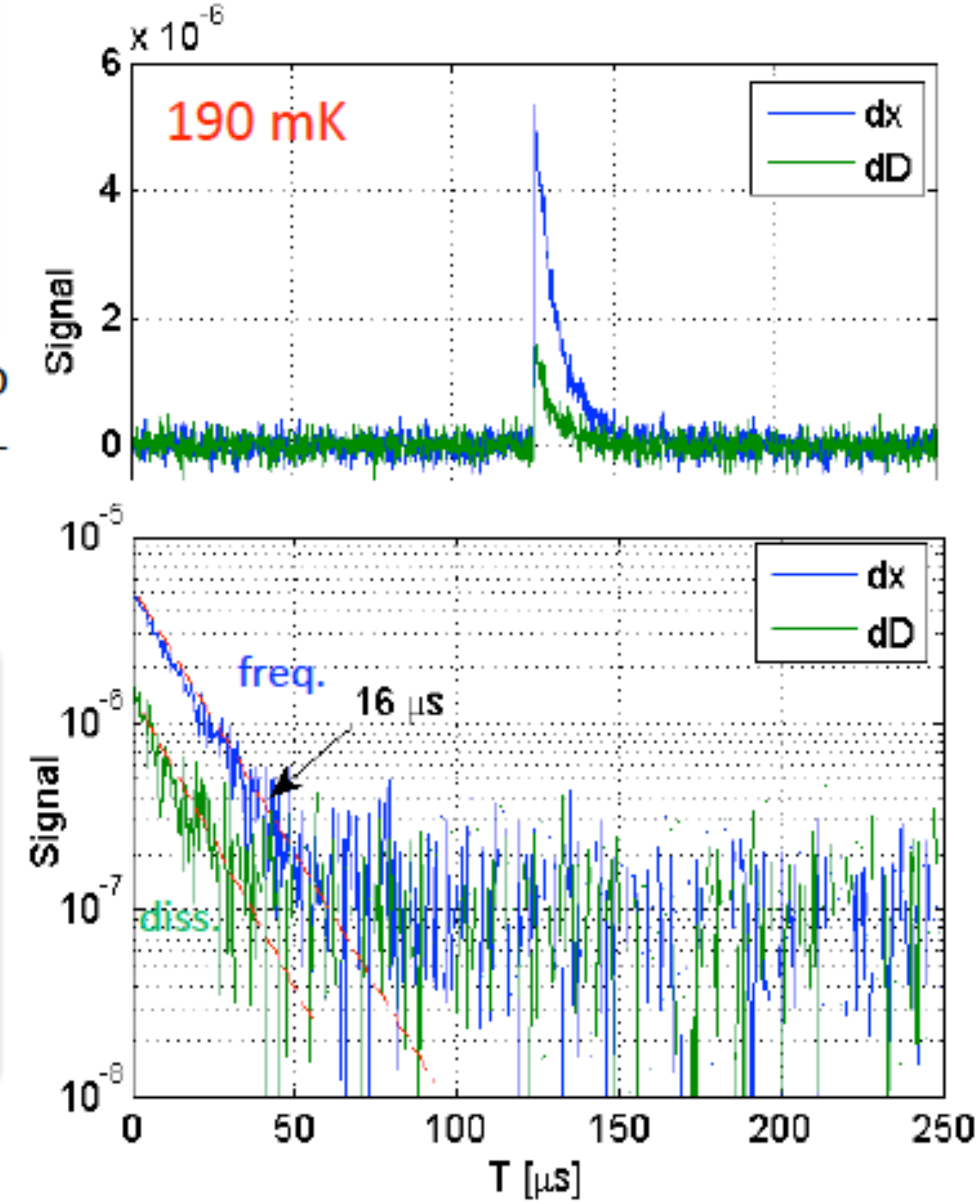
Anomalous Response to NIR Photon





20nm TiN OLEKID (UCSB design, JPL film, NIST fab) Tc~1 K





- At lower T, dissipation response shows shorter decay time than frequency response.
- At higher T, responses in the two quadratures show equal decay time.

J. Gao, et al, APL 101, 142602 (2012)

Non-equilibrium in an inhomogeneous system?

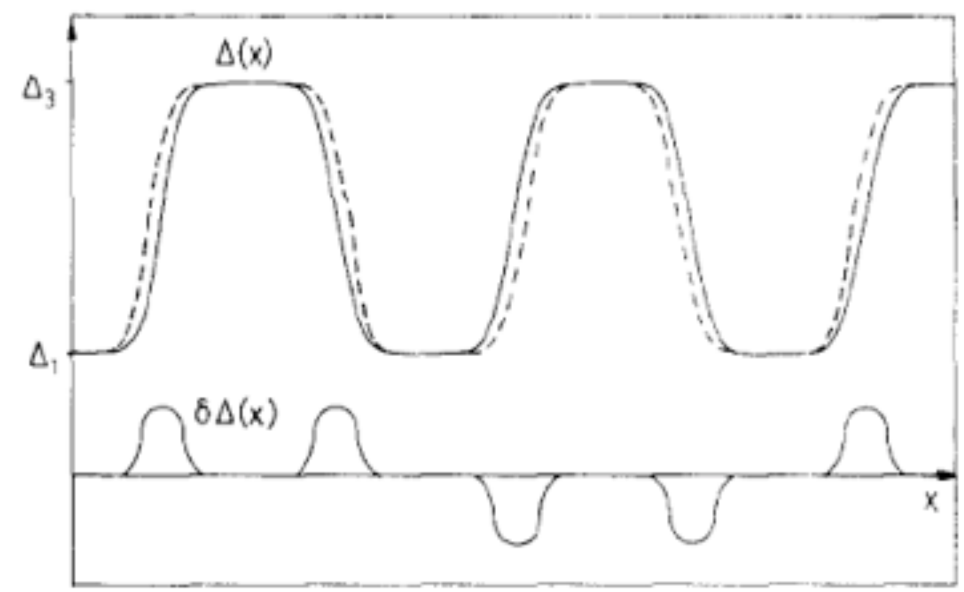


Fig. 3. A periodic structure of a conserved quantity with large wavelength may decay by coarsening [30].

G.Schön, Physica **109&110B**, 1677 (1982)

U.Eckern, A.Schmid, M.Schmutz, and G.Schön, J. Low Temp. Phys. **36**, 643 (1979)

Summary

- Detailed understanding based on f(E) is possible for Al
- Nonequilibrium analysis for Al very mature and usable.
- (The hybrids, which use NbTiN with Al equally successful)
- Robustness for TiN *vis à vis* such an analysis remains to be seen (See also Juan Bueno's poster).