Number Fluctuations of Sparse Quasiparticles in a Superconductor

Phys. Rev. Lett. **107**, 167004 (2011)

Diego Rainis

Journal Club 06.09.2011

Properties of a superconductor

Properties of a superconductor

- Electrons pairing up in Cooper pairs $c^\dagger_{\boldsymbol{k}\uparrow} c^\dagger_{-\boldsymbol{k}\downarrow}$

Properties of a superconductor

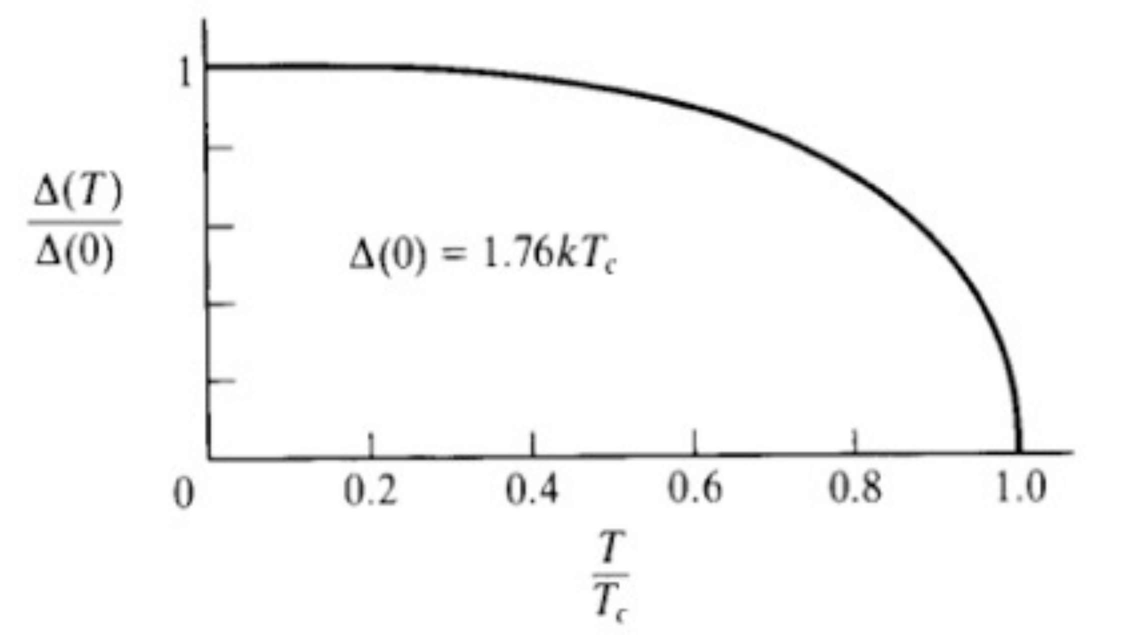
- Electrons pairing up in Cooper pairs $c^\dagger_{\boldsymbol{k}\uparrow} c^\dagger_{-\boldsymbol{k}\downarrow}$
- Presence of a energy gap in the spectrum Δ

Properties of a superconductor

- Electrons pairing up in Cooper pairs $c^\dagger_{\boldsymbol{k}\uparrow} c^\dagger_{-\boldsymbol{k}\downarrow}$
- Presence of a energy gap in the spectrum Δ
- Quasiparticle excitation spectrum $E_{\boldsymbol{k}} = \sqrt{\xi_{\boldsymbol{k}}^2 + \Delta^2}$

Properties of a superconductor

- Electrons pairing up in Cooper pairs $c^{\dagger}_{\boldsymbol{k}\uparrow}c^{\dagger}_{-\boldsymbol{k}\downarrow}$
- Presence of a energy gap in the spectrum Δ
- Quasiparticle excitation spectrum $E_{\boldsymbol{k}} = \sqrt{\xi^2_{\boldsymbol{k}} + \Delta^2}$

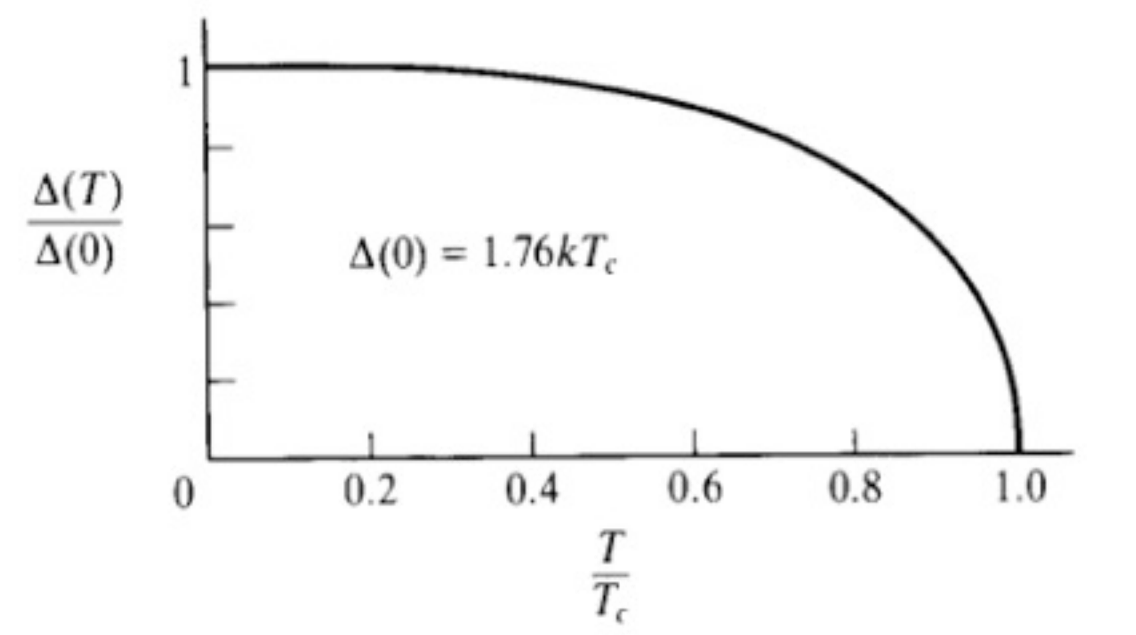


Properties of a superconductor

- Electrons pairing up in Cooper pairs $c^{\dagger}_{\boldsymbol{k}\uparrow}c^{\dagger}_{-\boldsymbol{k}\downarrow}$
- Presence of a energy gap in the spectrum Δ
- Quasiparticle excitation spectrum $E_{\boldsymbol{k}} = \sqrt{\xi^2_{\boldsymbol{k}} + \Delta^2}$

At $T \approx 0$

$$\frac{[\Delta(0) - \Delta(T)]}{\Delta(0)} \approx \mathrm{e}^{-\Delta(0)/kT}$$



Quasiparticle dynamics

Quasiparticle dynamics

Theory:

Quasiparticle dynamics

$$n_{qp} = 2\nu_0\sqrt{2\pi kT\Delta}\ \mathrm{e}^{-\Delta/kT}$$

Quasiparticle density

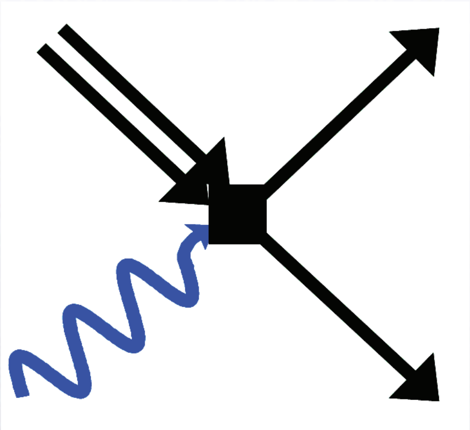
Theory:

Quasiparticle dynamics

$$n_{qp} = 2\nu_0 \sqrt{2\pi k T \Delta}\ \mathrm{e}^{-\Delta/kT}$$

Quasiparticle density

Theory:



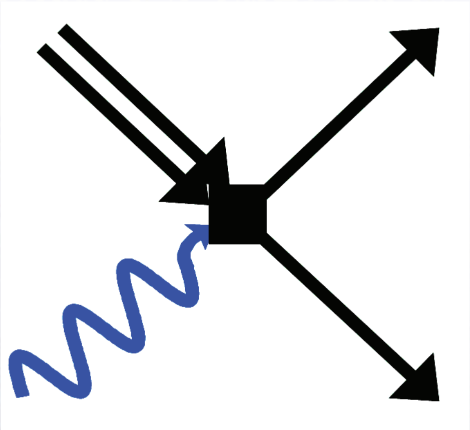
Quasiparticle dynamics

$$n_{qp} = 2\nu_0\sqrt{2\pi kT\Delta}\ \mathrm{e}^{-\Delta/kT}$$

Quasiparticle density

Theory:

Cooper pair



Quasiparticle dynamics

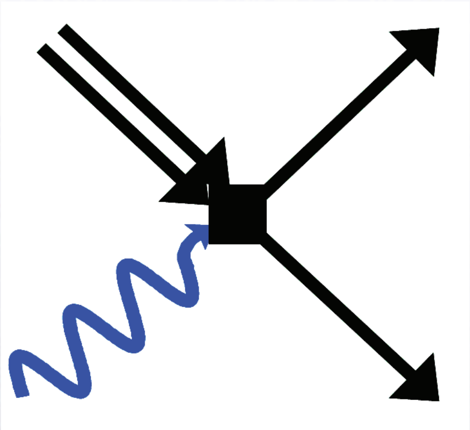
$$n_{qp} = 2\nu_0 \sqrt{2\pi k T \Delta}\ \mathrm{e}^{-\Delta/kT}$$

Quasiparticle density

Theory:

Cooper pair

Phonon



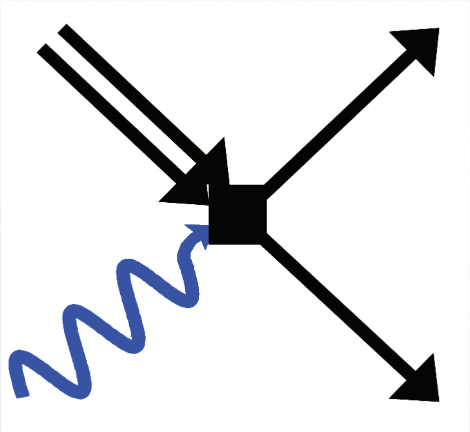
Quasiparticle dynamics

$$n_{qp} = 2\nu_0\sqrt{2\pi kT\Delta}\ \mathrm{e}^{-\Delta/kT}$$

Quasiparticle density

Theory:

Cooper pair



Quasiparticles

Phonon

Quasiparticle dynamics

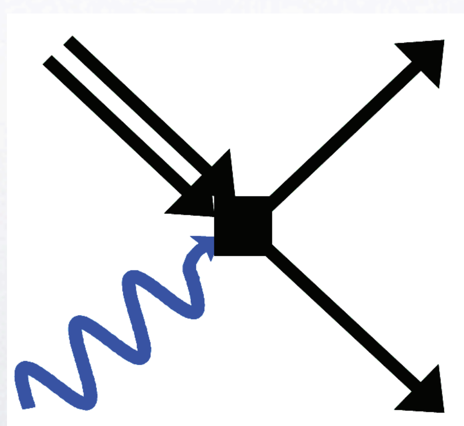
$$n_{qp} = 2\nu_0\sqrt{2\pi kT\Delta}\ \mathrm{e}^{-\Delta/kT}$$

Quasiparticle density

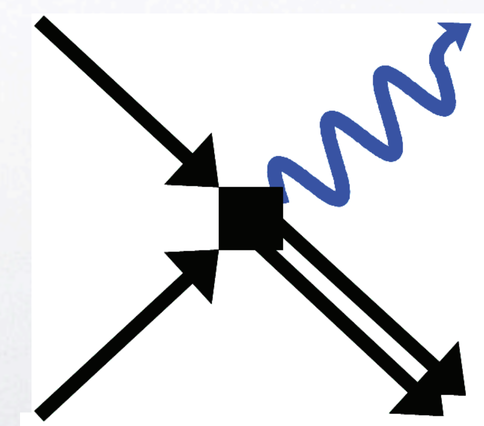
Theory:

Cooper pair

Phonon



Quasiparticles



Quasiparticle dynamics

Theory:

$$n_{qp} = 2\nu_0 \sqrt{2\pi k T \Delta}\; \mathrm{e}^{-\Delta/kT}$$

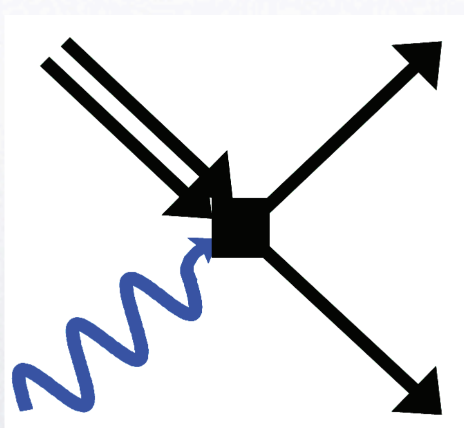
Quasiparticle density

$$\tau_r = \frac{\tau_0}{n_{qp}} \frac{\nu_0 (kT_c)^3}{2\Delta^2}$$

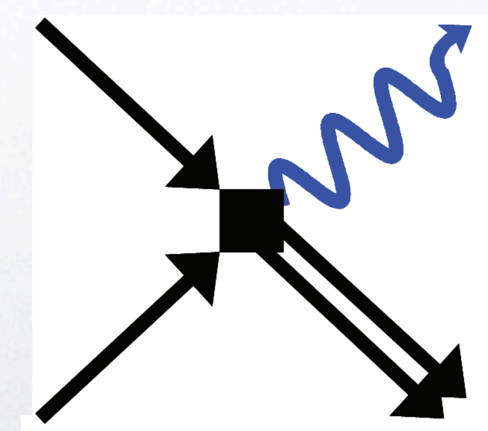
Recombination time

Cooper pair

Phonon



Quasiparticles



Quasiparticle dynamics

Theory:

$$n_{qp} = 2\nu_0\sqrt{2\pi kT\Delta}\ \mathrm{e}^{-\Delta/kT}$$

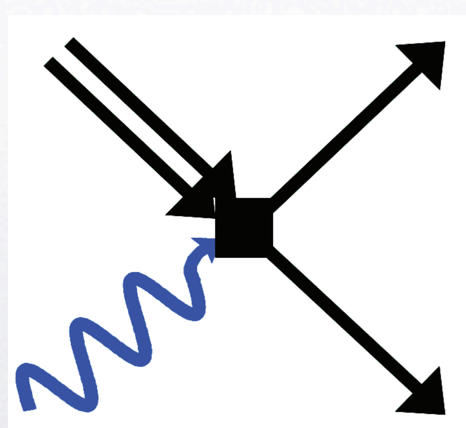
Quasiparticle density

$$\tau_r = \frac{\tau_0}{n_{qp}}\frac{\nu_0(kT_c)^3}{2\Delta^2}$$

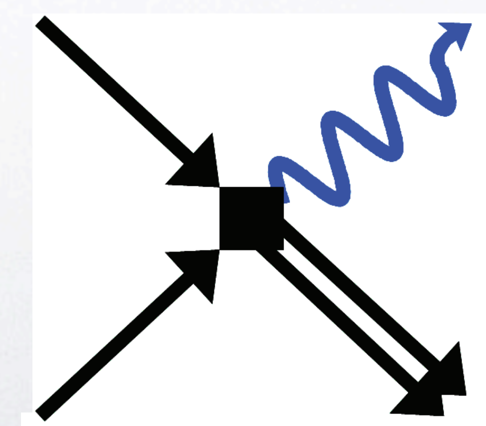
Recombination time
(τ_0 el-phonon interaction time)

Cooper pair

Phonon



Quasiparticles



Power Spectral density of qp fluctuations

Power Spectral density of qp fluctuations

Random qp fluctuations:

$$\sigma^2 =< \delta N_{qp}^2 >= N_{qp} = n_{qp}V$$

Power Spectral density of qp fluctuations

Random qp fluctuations:

$$\sigma^2 =< \delta N_{qp}^2 >= N_{qp} = n_{qp} V$$

Power spectral density:

$$S_N(\omega) = \frac{4 N_{qp} \tau_r}{1 + (\omega \tau_r)^2}$$

Power Spectral density of qp fluctuations

Random qp fluctuations:

$$\sigma^2 =< \delta N_{qp}^2 >= N_{qp} = n_{qp} V$$

Power spectral density:

$$S_N(\omega) = \frac{4 N_{qp} \tau_r}{1 + (\omega \tau_r)^2}$$

C.M. Wilson and D.E. Prober, PRB **69**, 094524 (2004)

Power Spectral density of qp fluctuations

Random qp fluctuations:

$$\sigma^2 =< \delta N_{qp}^2 >= N_{qp} = n_{qp} V$$

Power spectral density:

$$S_N(\omega) = \frac{4 N_{qp} \tau_r}{1 + (\omega \tau_r)^2}$$

Complex conductivity:

$$\sigma = \sigma_1 - i\sigma_2$$

C.M. Wilson and D.E. Prober, PRB **69**, 094524 (2004)

Power Spectral density of qp fluctuations

Random qp fluctuations:

$$\sigma^2 =< \delta N_{qp}^2 >= N_{qp} = n_{qp} V$$

Power spectral density:

$$S_N(\omega) = \frac{4 N_{qp} \tau_r}{1 + (\omega \tau_r)^2}$$

Complex conductivity:

$$\sigma = \sigma_1 - i\sigma_2$$

→ σ_1 resisitive, quasiparticles

C.M. Wilson and D.E. Prober, PRB **69**, 094524 (2004)

Power Spectral density of qp fluctuations

Random qp fluctuations:

$$\sigma^2 =< \delta N_{qp}^2 >= N_{qp} = n_{qp}V$$

Power spectral density:

$$S_N(\omega) = \frac{4N_{qp}\tau_r}{1 + (\omega\tau_r)^2}$$

Complex conductivity:

$$\sigma = \sigma_1 - i\sigma_2$$

→ σ_1 resisitive, quasiparticles

→ σ_2 inductive, condensate

C.M. Wilson and D.E. Prober, PRB **69**, 094524 (2004)

Power Spectral density of qp fluctuations

Random qp fluctuations:

$$\sigma^2 =< \delta N_{qp}^2 >= N_{qp} = n_{qp}V$$

Power spectral density:

$$S_N(\omega) = \frac{4N_{qp}\tau_r}{1+(\omega\tau_r)^2}$$

Complex conductivity:

$$\sigma = \sigma_1 - i\sigma_2$$

→ σ_1 resisitive, quasiparticles

→ σ_2 inductive, condensate

D.C. Mattis and J. Bardeen Phys. Rev. **111**, 412 (1958)

Experimental setup

Experimental setup

- 40-nm thick Al superconducting film $T_c = 1.11$ K, $\Delta = 168\ \mu$eV

Experimental setup

- 40-nm thick Al superconducting film

$$T_c = 1.11 \text{ K}$$
$$\Delta = 168 \ \mu\text{eV}$$

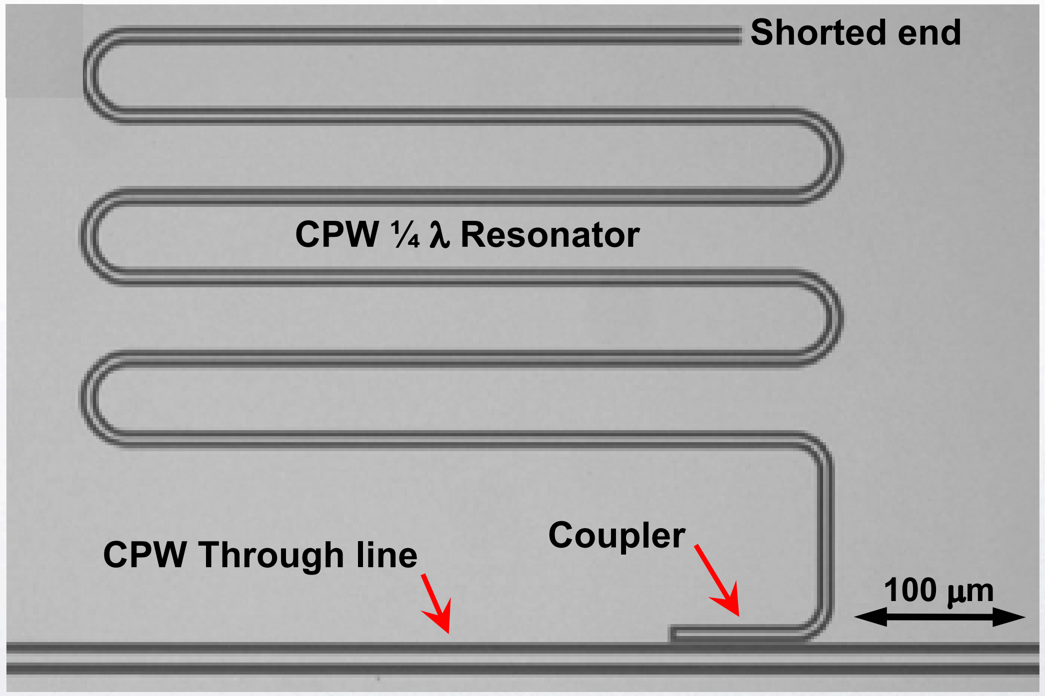
- patterned into microwave resonators

Experimental setup

- 40-nm thick Al superconducting film

$$T_c = 1.11 \text{ K}$$
$$\Delta = 168 \ \mu\text{eV}$$

- patterned into microwave resonators

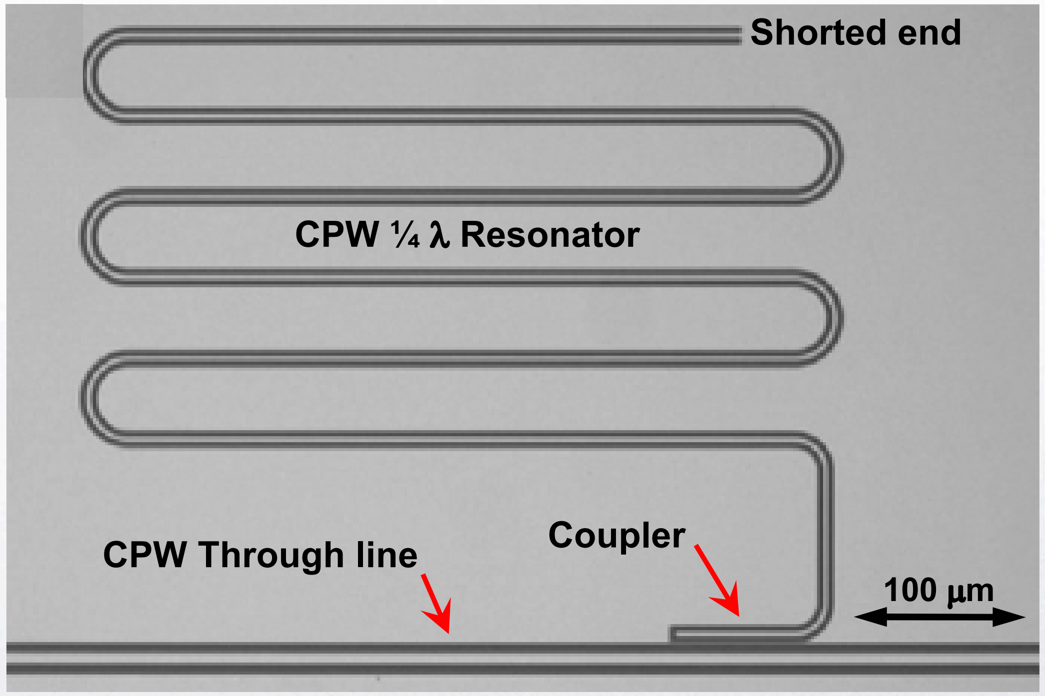


Experimental setup

- 40-nm thick Al superconducting film

$$T_c = 1.11 \text{ K}$$
$$\Delta = 168 \ \mu\text{eV}$$

- patterned into microwave resonators
- short light pulse on the sample



Experimental setup

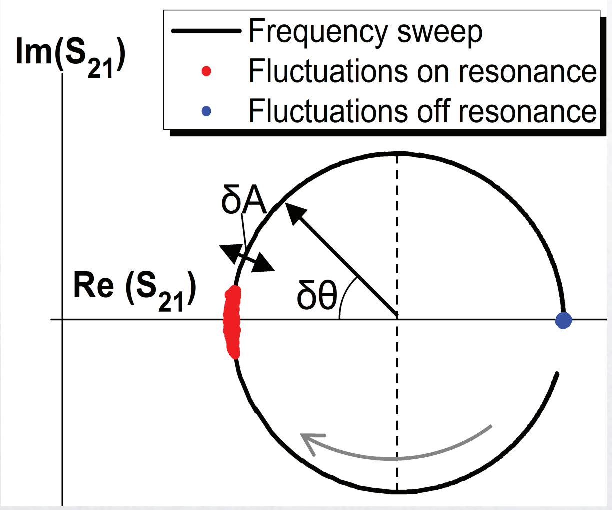
- 40-nm thick Al superconducting film

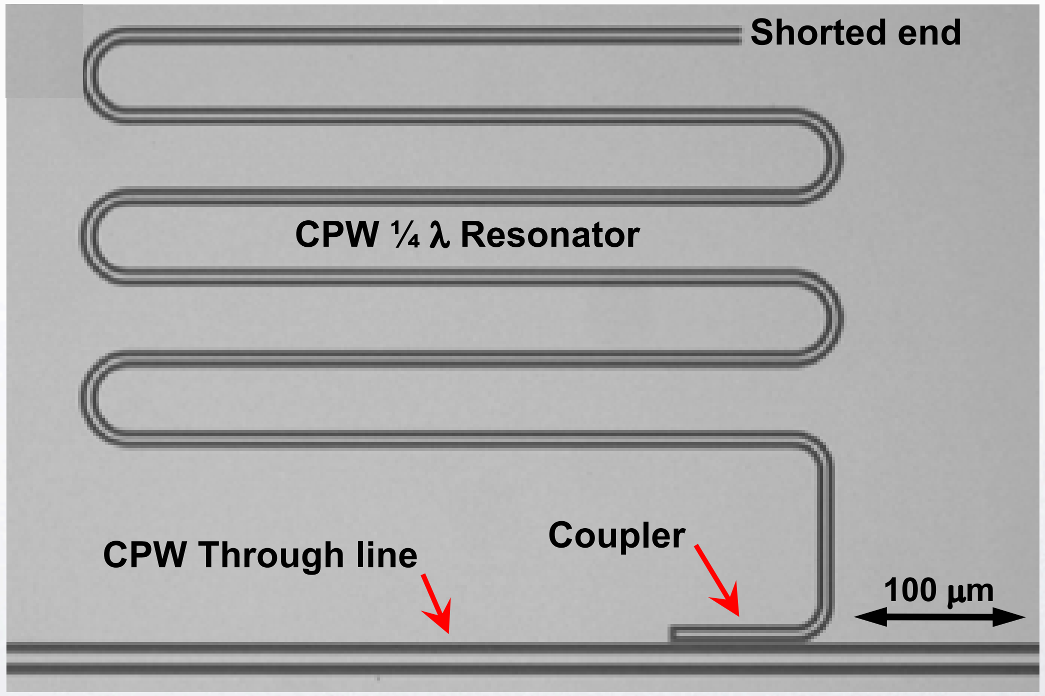
$$T_c = 1.11 \text{ K}$$
$$\Delta = 168 \ \mu\text{eV}$$

- patterned into microwave resonators
- short light pulse on the sample

↓

- Complex transmission measured





Readout

Readout

- Resonator amplitude responds mainly to changes in σ_1

Readout

- Resonator amplitude responds mainly to changes in σ_1
- Responsivity dA/dN_{qp} experimentally determined

Readout

- Resonator amplitude responds mainly to changes in σ_1
- Responsivity dA/dN_{qp} experimentally determined

Power spectral density of amplitude fluctuations:

Readout

- Resonator amplitude responds mainly to changes in σ_1
- Responsivity dA/dN_{qp} experimentally determined

Power spectral density of amplitude fluctuations:

$$S_A(\omega) = S_N(\omega)\frac{(dA/dN_{qp})^2}{1+(\omega\tau_{res})^2}$$

Readout

- Resonator amplitude responds mainly to changes in σ_1
- Responsivity dA/dN_{qp} experimentally determined

Power spectral density of amplitude fluctuations:

$$S_A(\omega) = S_N(\omega)\frac{(dA/dN_{qp})^2}{1+(\omega\tau_{res})^2}$$

(τ_{res} resonator characteristic time)

Readout

- Resonator amplitude responds mainly to changes in σ_1
- Responsivity dA/dN_{qp} experimentally determined

Power spectral density of amplitude fluctuations:

$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]} \frac{(dA/dN_{qp})^2}{[1+(\omega\tau_{res})^2]}$$

(τ_{res} resonator characteristic time)

Readout

- Resonator amplitude responds mainly to changes in σ_1
- Responsivity dA/dN_{qp} experimentally determined

Power spectral density of amplitude fluctuations:

$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]} \frac{(dA/dN_{qp})^2}{[1+(\omega\tau_{res})^2]}$$

(τ_{res} resonator characteristic time)

$\tau_r \gg \tau_{res} \approx 2\ \mu\mathrm{s}$

Readout

- Resonator amplitude responds mainly to changes in σ_1
- Responsivity dA/dN_{qp} experimentally determined

Power spectral density of amplitude fluctuations:

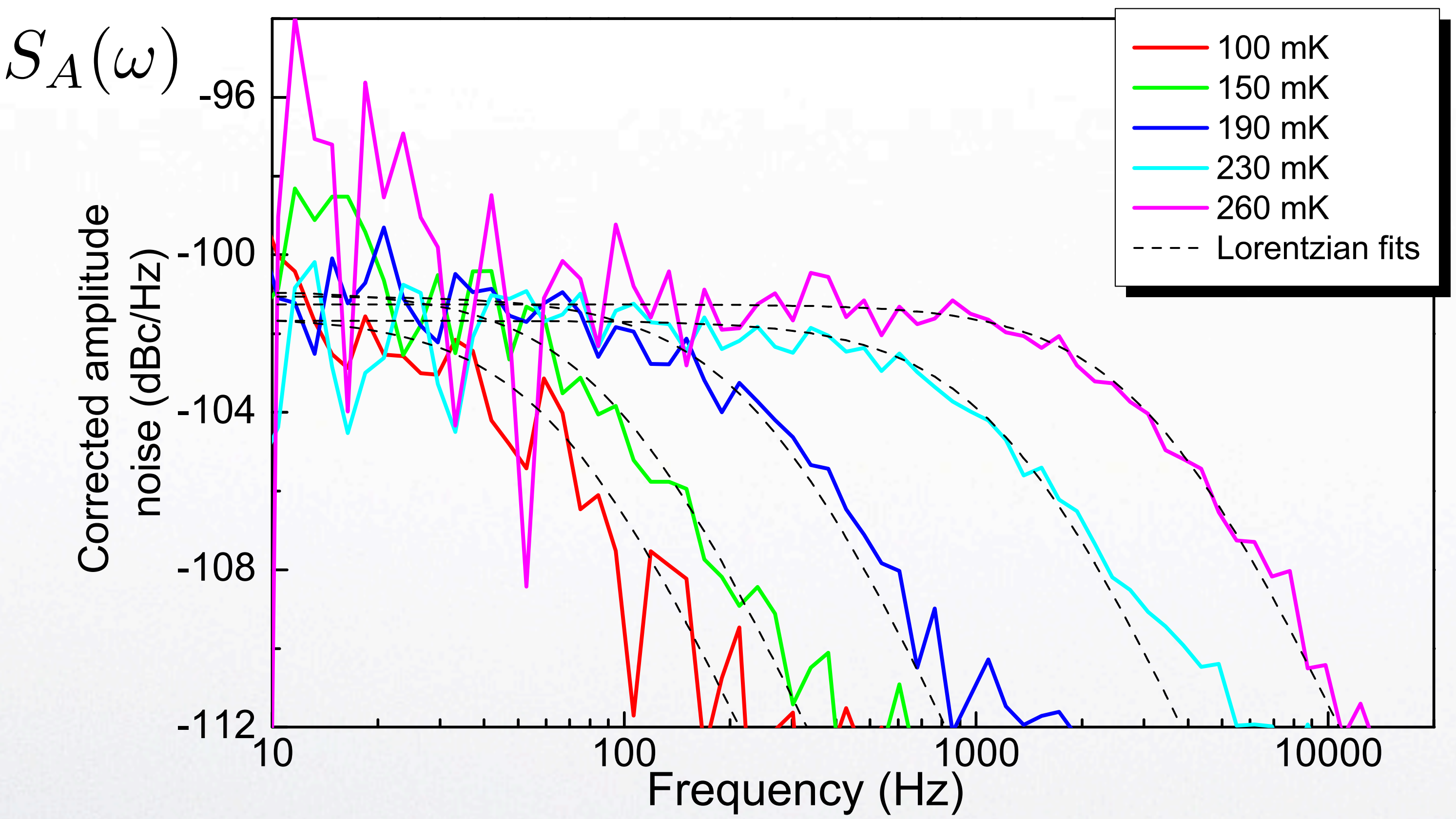
$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\frac{(dA/dN_{qp})^2}{[1+(\omega\tau_{res})^2]}$$

(τ_{res} resonator characteristic time)

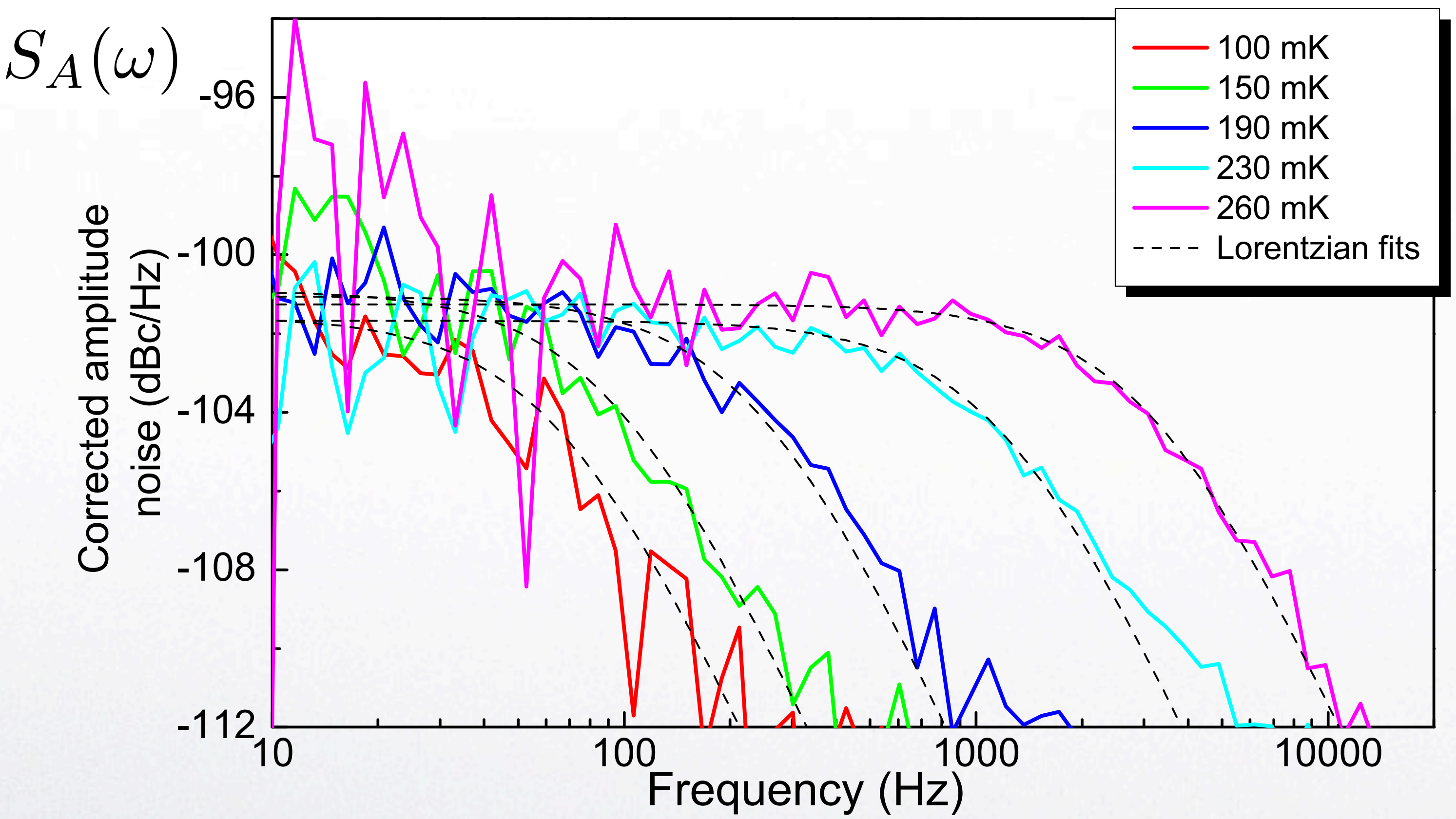
$\tau_r \gg \tau_{res} \approx 2\ \mu\mathrm{s}$ $\longrightarrow$ Roll-off in the noise spectrum determined solely by τ_r

Results

Results

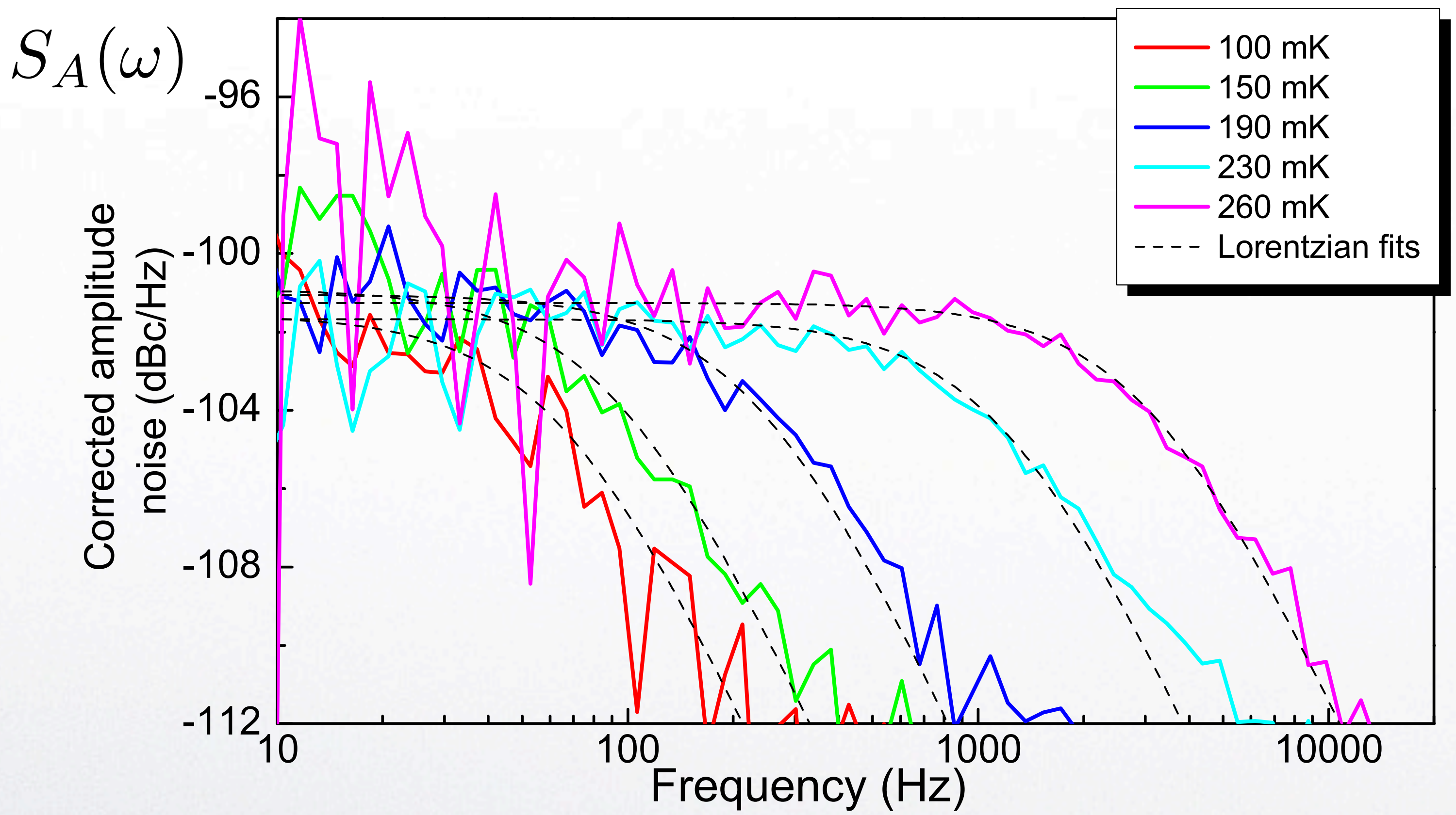

$S_A(\omega)$
-96
-100
-104
-108
-112
Corrected amplitude noise (dBc/Hz)
10
100
1000
10000
Frequency (Hz)
100 mK
150 mK
190 mK
230 mK
260 mK
Lorentzian fits

Results



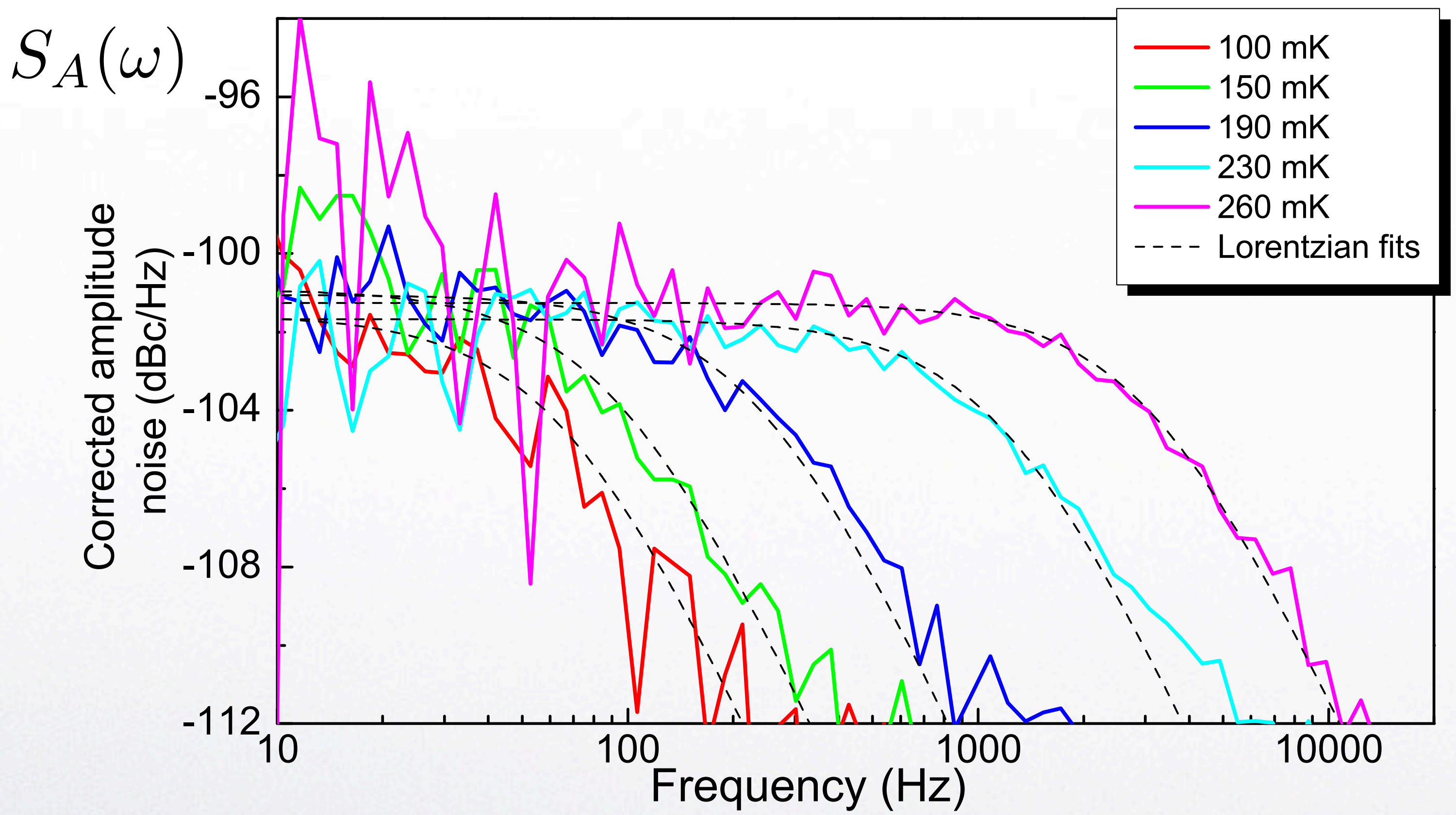
- constant at $\omega \approx 0$, same for all T

Results



- constant at $\omega \approx 0$, same for all T
- roll-off described by a single time scale

Results



- constant at $\omega \approx 0$, same for all T
- roll-off described by a single time scale

$\downarrow$

qp fluctuations

From

From

$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]} \frac{\left(dA/dN_{qp}\right)^2}{[1+(\omega\tau_{res})^2]} \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]} \left(\frac{dA}{dN_{qp}}\right)^2$$

From

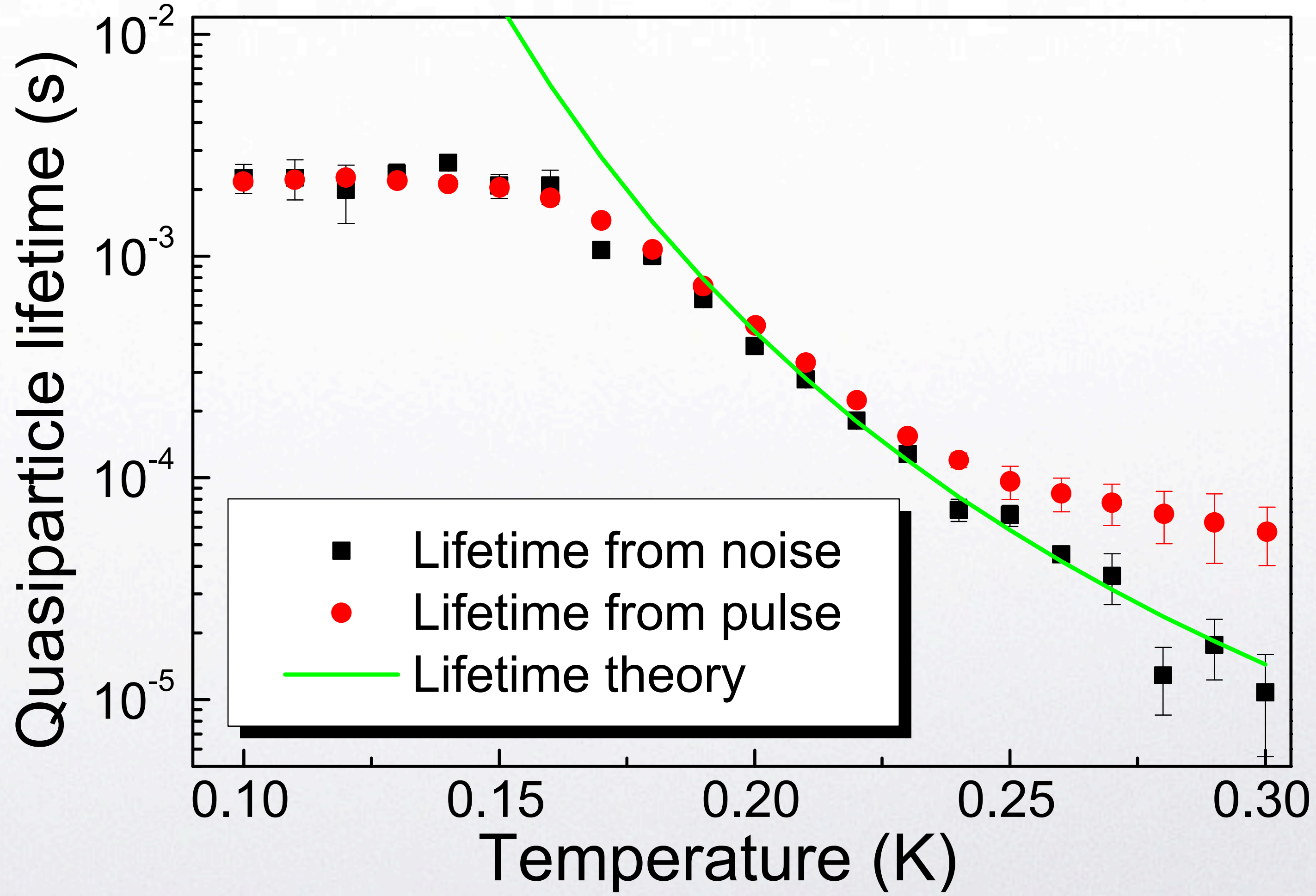
$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\frac{\left(dA/dN_{qp}\right)^2}{[1+(\omega\tau_{res})^2]} \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

τ_r is extracted

From

$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\frac{(dA/dN_{qp})^2}{[1+(\omega\tau_{res})^2]} \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

τ_r is extracted

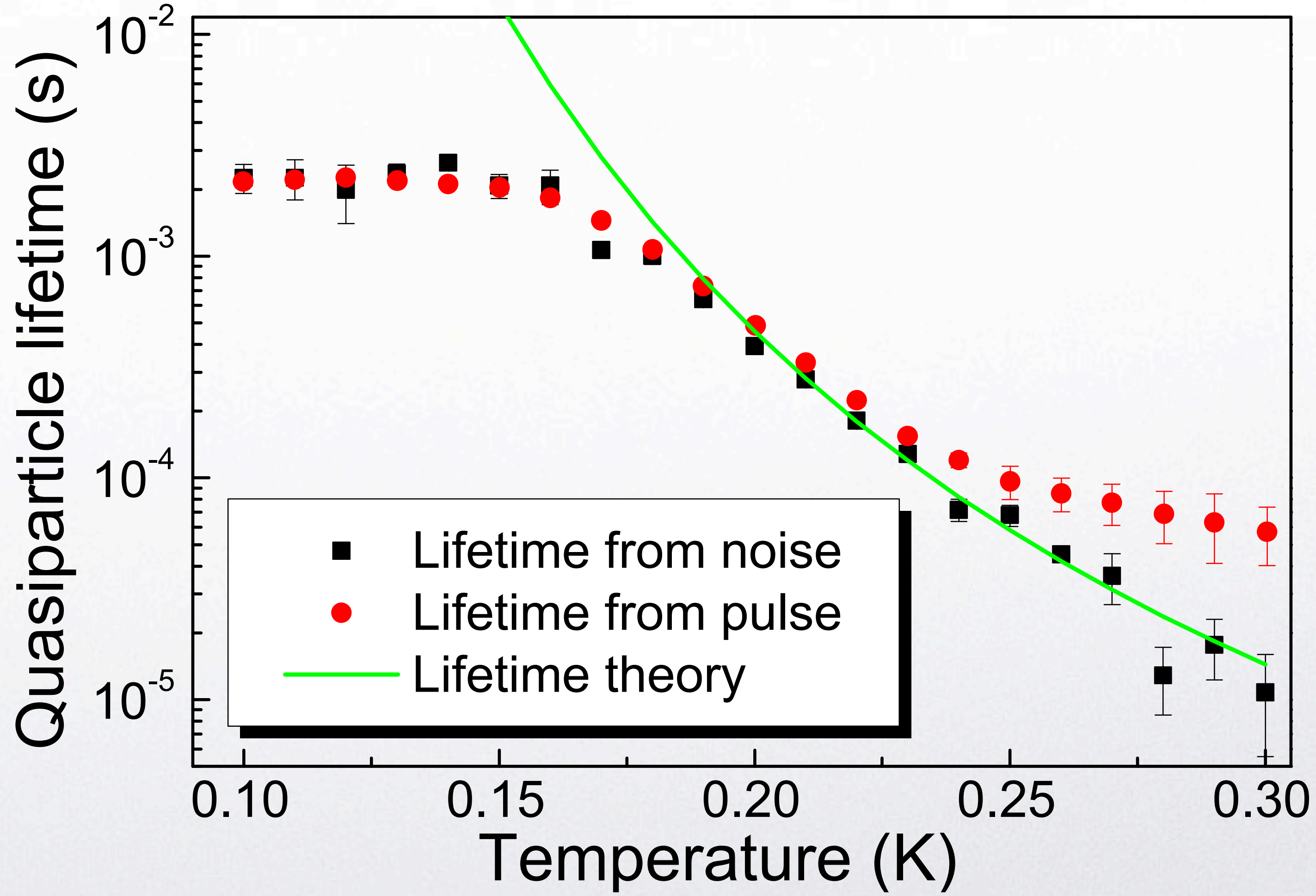


From

$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\frac{(dA/dN_{qp})^2}{[1+(\omega\tau_{res})^2]} \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

τ_r is extracted

- Expected exponential only from 180 mK

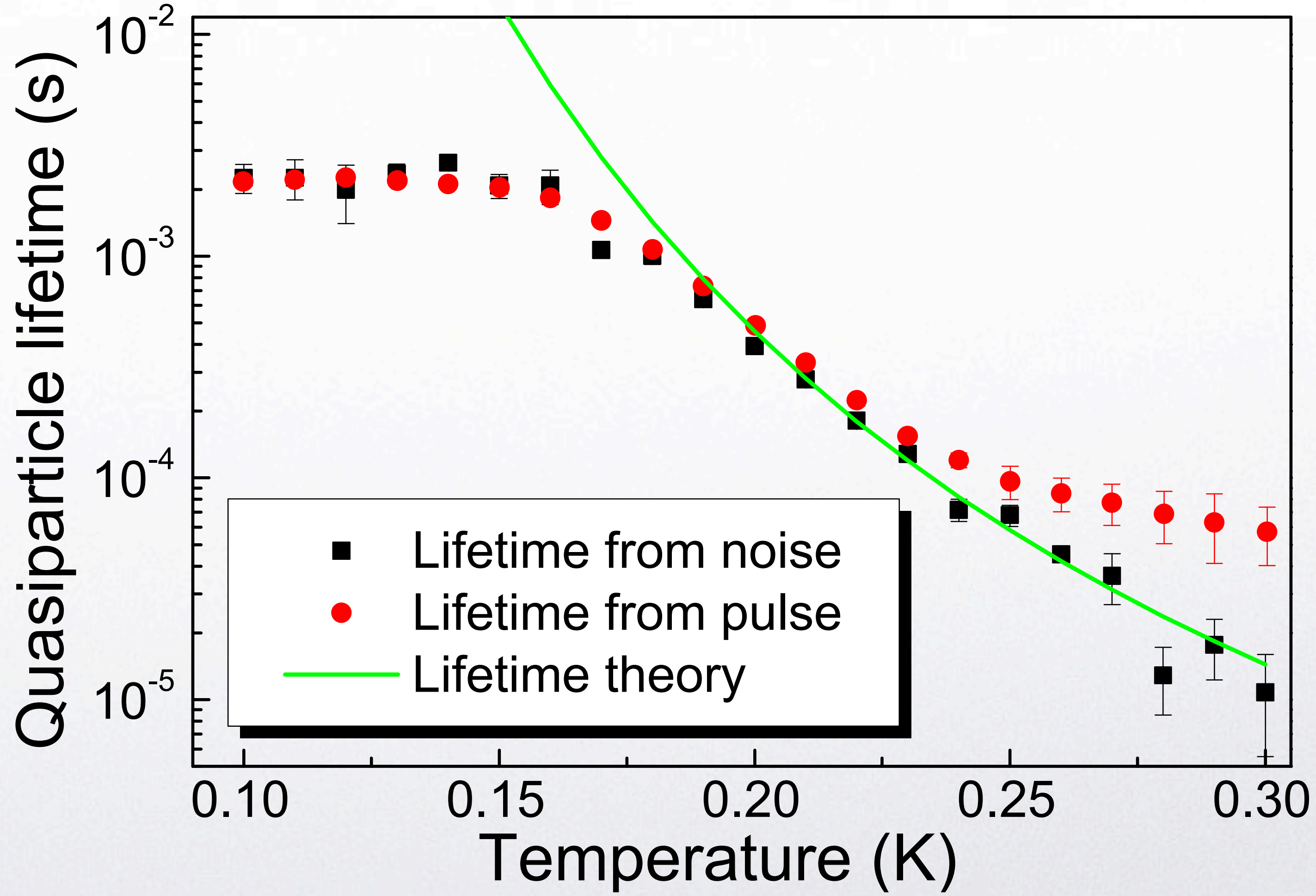


From

$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\frac{(dA/dN_{qp})^2}{[1+(\omega\tau_{res})^2]} \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

τ_r is extracted

- Expected exponential only from 180 mK
- Below 160 mK, $\tau_r \approx 2.2$ ms

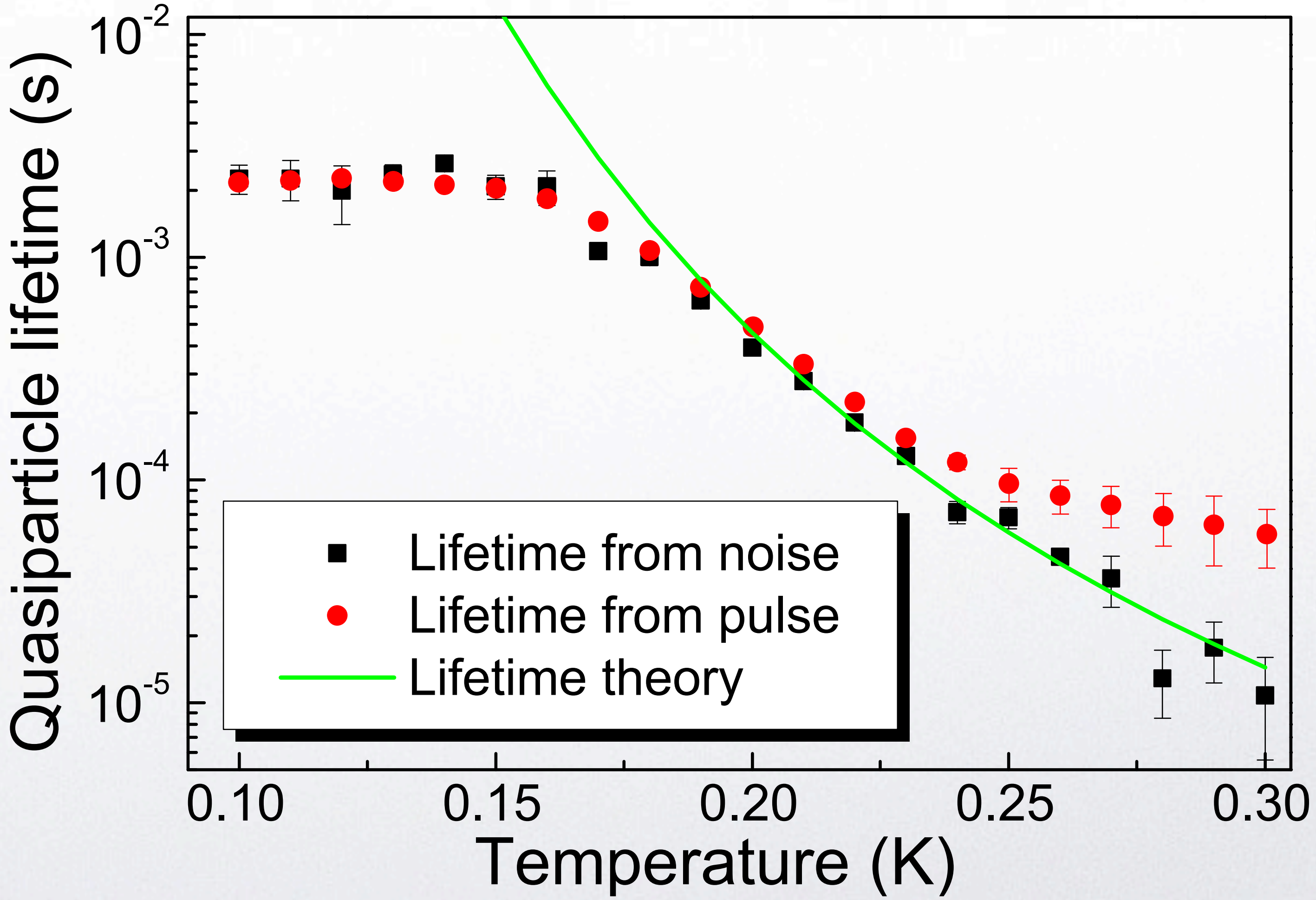


From

$$S_A(\omega) = \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\frac{(dA/dN_{qp})^2}{[1+(\omega\tau_{res})^2]} \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

τ_r is extracted

- Expected exponential only from 180 mK
- Below 160 mK, $\tau_r \approx 2.2$ ms
- $\tau_0 \approx 460$ ns is extracted with a fit



Using again

Using again

$$S_A(\omega) \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

Using again

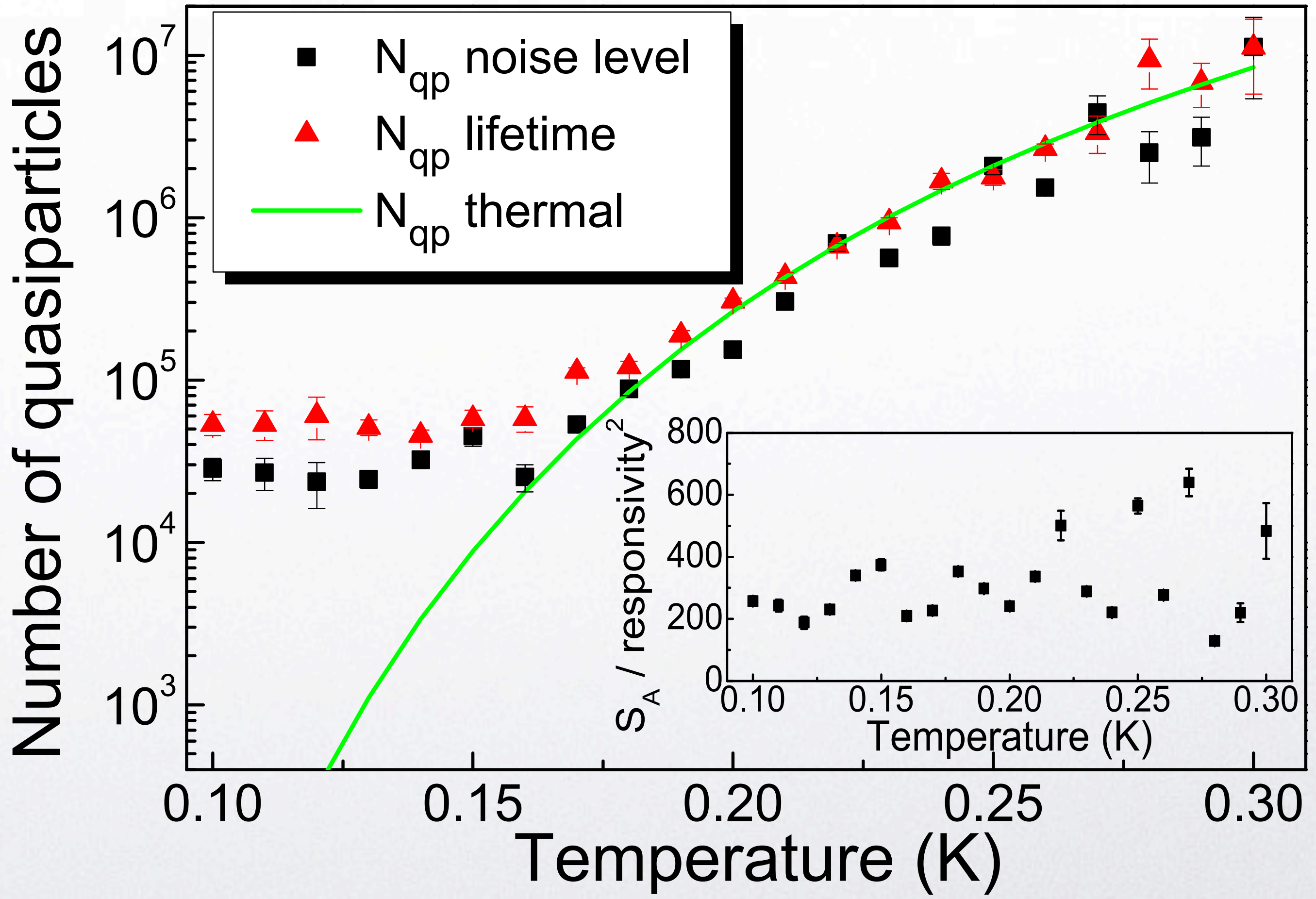
$$S_A(\omega) \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

one finds N_{qp}

Using again

$$S_A(\omega) \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

one finds N_{qp}

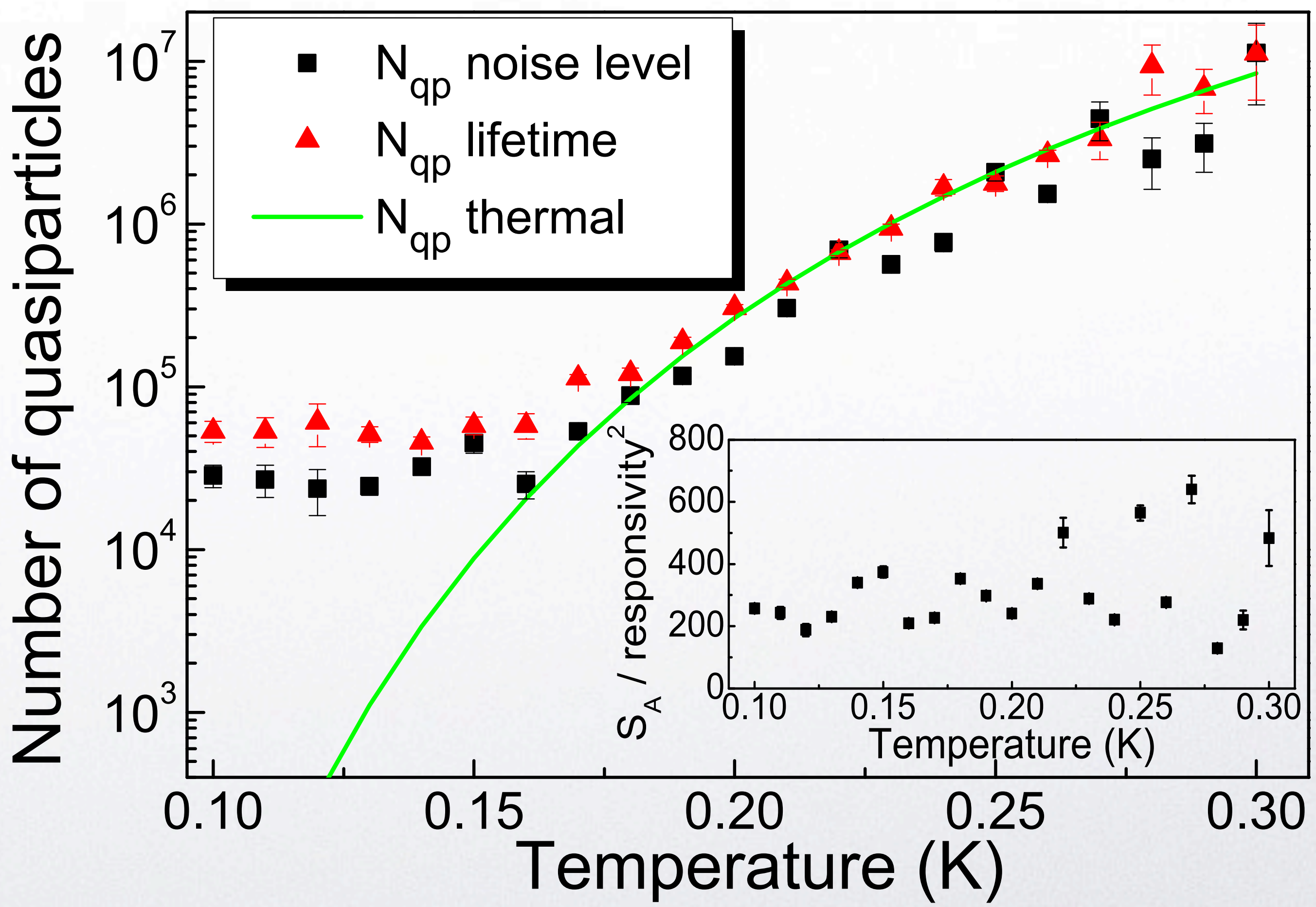


Using again

$$S_A(\omega) \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

one finds N_{qp}

As a cross-check:



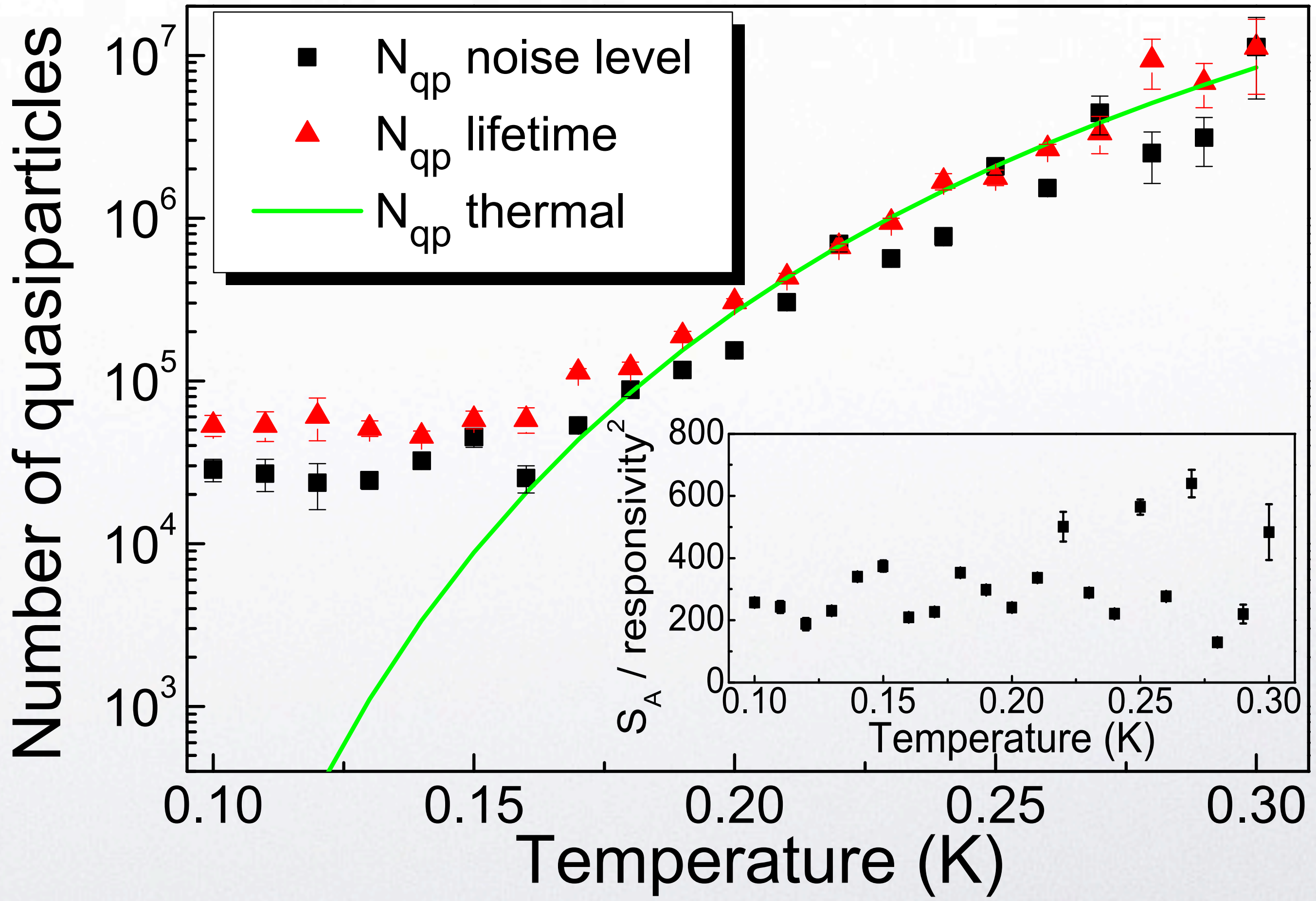
Using again

$$S_A(\omega) \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

one finds N_{qp}

As a cross-check:

$$\tau_r = \frac{\tau_0}{n_{qp}}\frac{\nu_0(kT_c)^3}{2\Delta^2}$$



Using again

$$S_A(\omega) \approx \frac{4N_{qp}\tau_r}{[1+(\omega\tau_r)^2]}\left(\frac{dA}{dN_{qp}}\right)^2$$

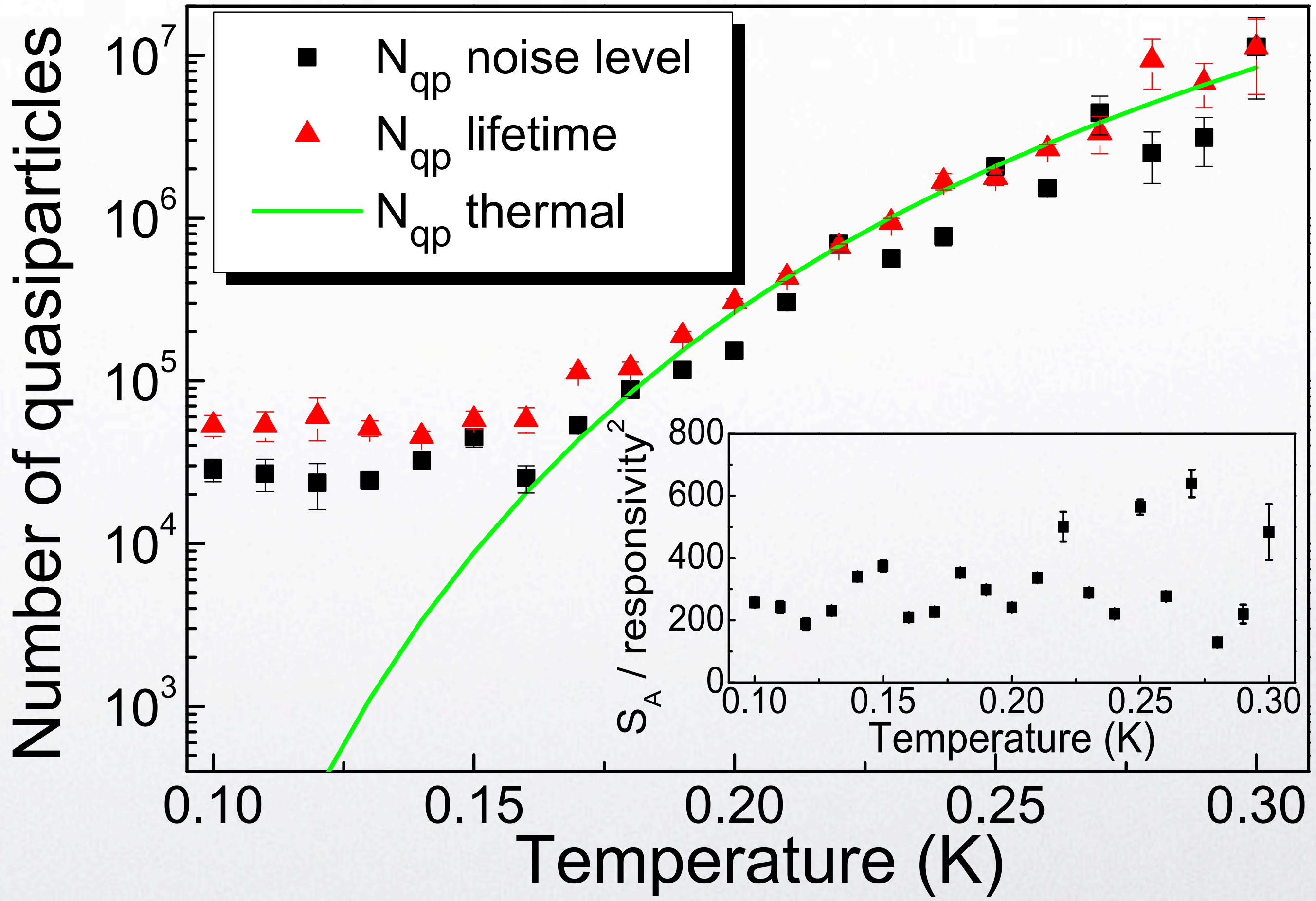
one finds N_{qp}

As a cross-check:

$$\tau_r = \frac{\tau_0}{n_{qp}} \frac{\nu_0(kT_c)^3}{2\Delta^2}$$

Agreement:

$n_{qp} \approx 25\text{–}55\ \mu\text{m}^{-3}$



⇨ Qp *lifetime* saturation is due to a qp *density* saturation

$\Rightarrow$ Qp *lifetime* saturation is due to a qp *density* saturation

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

⇨ Qp *lifetime* saturation is due to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

⇨ Qp *lifetime* saturation is due to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

- electromagnetic noise

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

Qp *lifetime* saturation is due
to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

- electromagnetic noise
- radiation

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

⇨ Qp *lifetime* saturation is due to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

- electromagnetic noise
- radiation
- cosmic rays

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

⇨ Qp *lifetime* saturation is due to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

- electromagnetic noise
- radiation
- cosmic rays
- local radioactivity

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

Qp *lifetime* saturation is due to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

- electromagnetic noise
- radiation
- cosmic rays
- local radioactivity
- slow heat release

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

⇨ Qp *lifetime* saturation is due to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

- electromagnetic noise
- radiation
- cosmic rays
- local radioactivity
- slow heat release
- stray light

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

⇨ Qp *lifetime* saturation is due to a qp *density* saturation

Possible explanations for these *non-thermal* quasiparticles:

- electromagnetic noise
- radiation
- cosmic rays
- local radioactivity
- slow heat release
- stray light

- Qp generation by the microwave signal

J.M. Martinis, M. Ansmann, and J. Aumentado, PRL **103**, 097002 (2009)

Summary

Summary

- Expected exponential suppression of qp

Summary

- Expected exponential suppression of qp
- Measure of qp fluctuations noise spectrum

Summary

- Expected exponential suppression of qp
- Measure of qp fluctuations noise spectrum
- Observed saturation of n_{qp} at low T

Summary

- Expected exponential suppression of qp
- Measure of qp fluctuations noise spectrum
- Observed saturation of n_{qp} at low T
- Observed saturation of τ_r at low T

Summary

- Expected exponential suppression of qp
- Measure of qp fluctuations noise spectrum
- Observed saturation of n_{qp} at low T
- Observed saturation of τ_r at low T
- Residual ("nonequilibrium") qp concluded

Thank you for your attention