# Non-linear pulse response of a MKID

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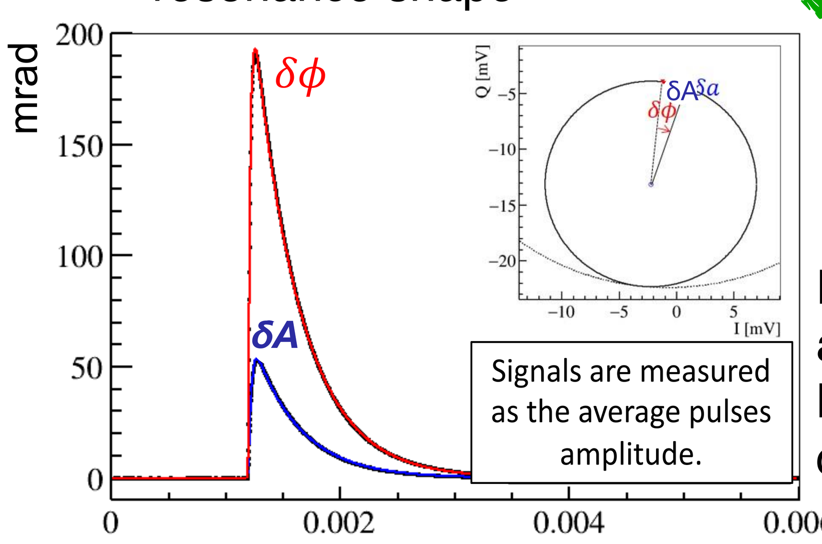
In most applications, the sensitivity of a Kinetic Inductance Detector (KID) is limited by the noise from the cryogenic amplifier. By increasing the readout power, this limit could be overcome at the cost of leading the resonator to the non-linear regime of response. In a view of using the KID as a single particle detector, the pulse response of this devices deserves an in-depth study. We, therefore, worked to build a pulse response model for a KID operated in the non-linear regime, taking into account not only the electrical effects due to the non-linear kinetic inductance but also the temperature variations caused by power absorption.

## Linear low-power response

Energy absorption changes the resonance shape




Pulses from a 400 nm LED via an optical fiber.

Dual signal: amplitude and phase modulation:

$$\delta S_{21} = \alpha \frac{Q^2}{Q_c} \frac{\delta n_{qp}}{2N(0)\Delta} (S_1(f_r,T) - jS_2(f_r,T))$$

$\delta A$ and $\delta\phi$ are uncorrelated

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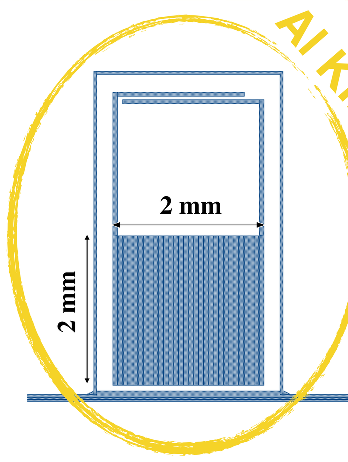
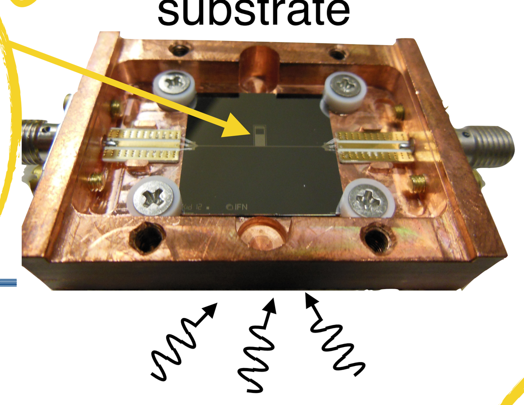



LC resonator

2x2 cm² silicon substrate



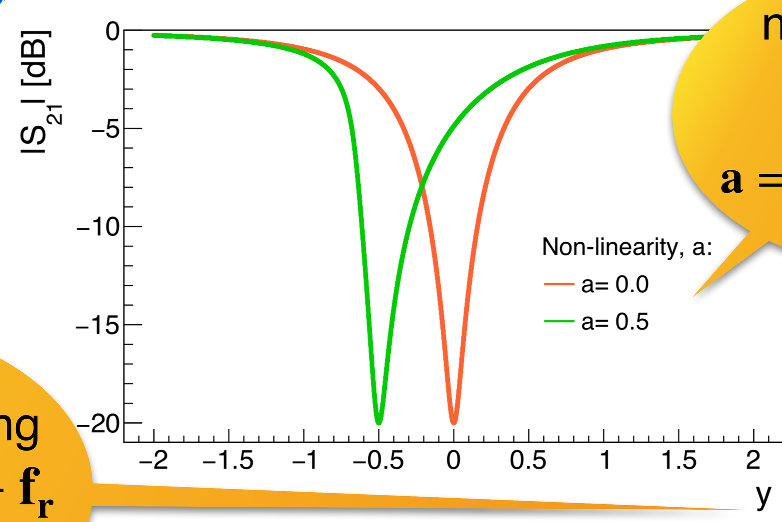
Photons absorbed by the silicon convert to athermal phonons that travel in the silicon until they are absorbed by the KID.

## Kinetic inductance non-linearity

Increase $P_{in}$

$L_k$ acquire a dependance on the current:

$$L_k(I) = L_k(0)\left[1 + \frac{I^2}{I_*^2} + \dots\right]$$




non-linearity parameter

$$a = \frac{2Q^3}{Q_c}\frac{P_{in}}{2\pi f_r E_*}$$

Fractional detuning

$$y = Q\frac{f - f_r}{f_r} = \frac{f - f_r}{\Delta f}$$

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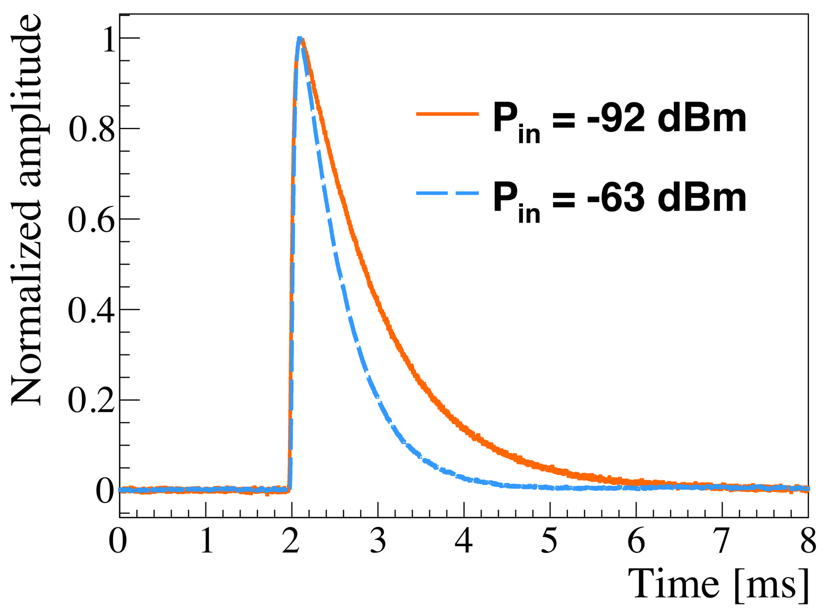
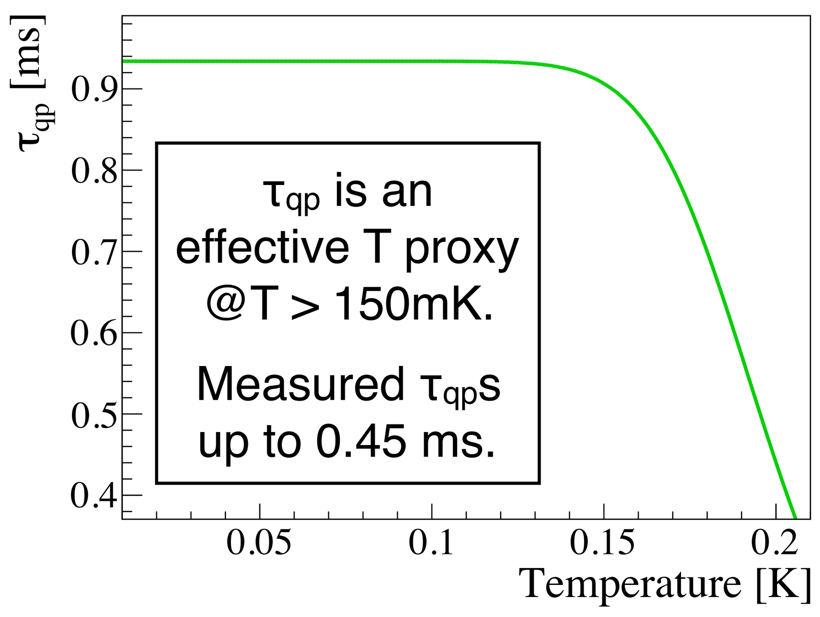
## Evidence of temperature variation…

Moving from the low- to the high-power regime: reduction in the pulses decay time.

decay time = $\tau_{qp}$

Quasiparticle lifetime decreasing trend with the temperature (BCS theory).

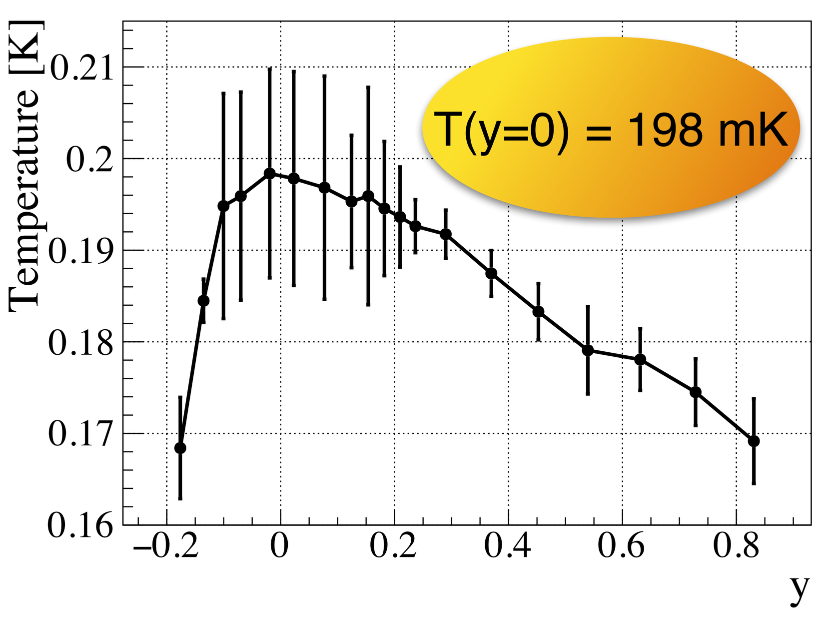



$\tau_{qp}$ is an effective T proxy @T > 150mK.

Measured $\tau_{qp}$s up to 0.45 ms.

### Indirect temperature evaluation

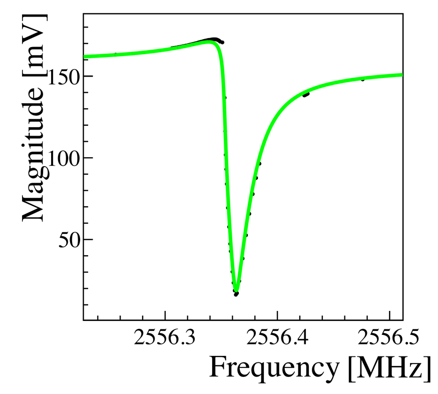


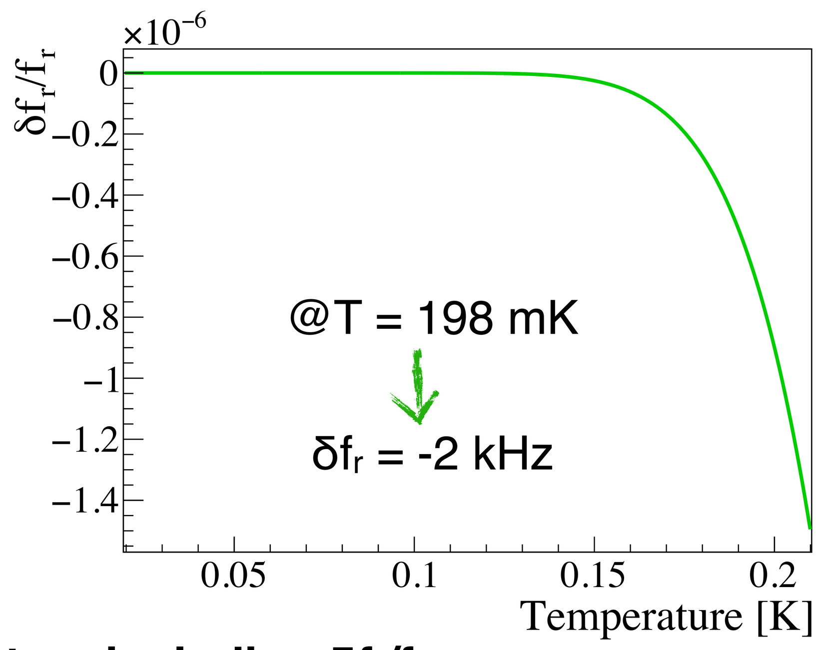

T(y=0) = 198 mK

- High input power.
- Pulses acquired at different frequencies (y) along the resonance.
- $\tau_{qp}$ measured fitting the pulses.
- Temperature evaluated from the $\tau_{qp}$(T) function.

## …and its effects

1. $f_r$ shift produced by thermally generated quasiparticle.




@T = 198 mK

$\delta f_r$ = -2 kHz

**Resonance parameters including $\delta f_r/f_r$:**

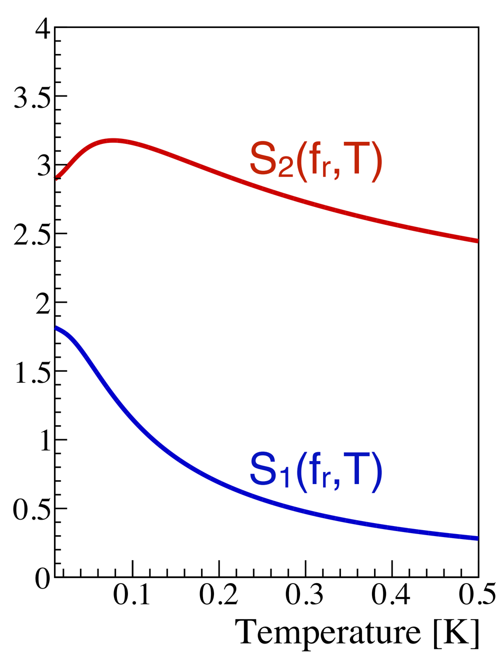
| $P_{in}$ [dBm] | a | $f_r$ [MHz] | Q | $Q_c$ | $Q_i$ |
|---|---|---|---|---|---|
| -63 | 0.46 | 2556.368 | 93k | 109k | 627k |

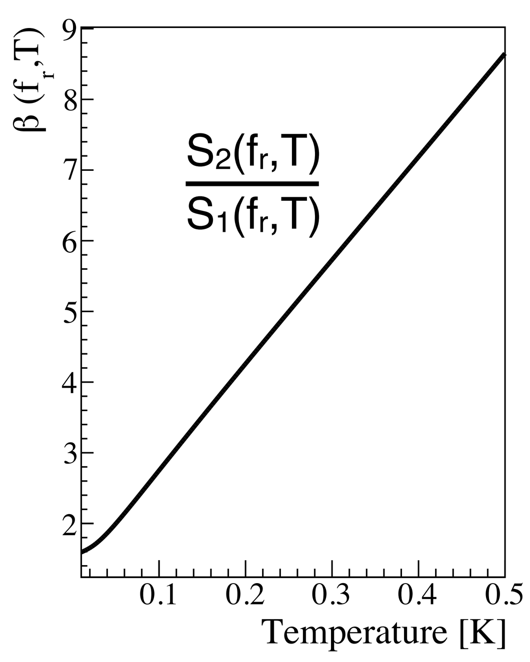
2. $\delta\phi$ and $\delta A$ depends on the temperature through $S_2(f_r,T)$ and $S_1(f_r,T)$.

In the low-power regime:

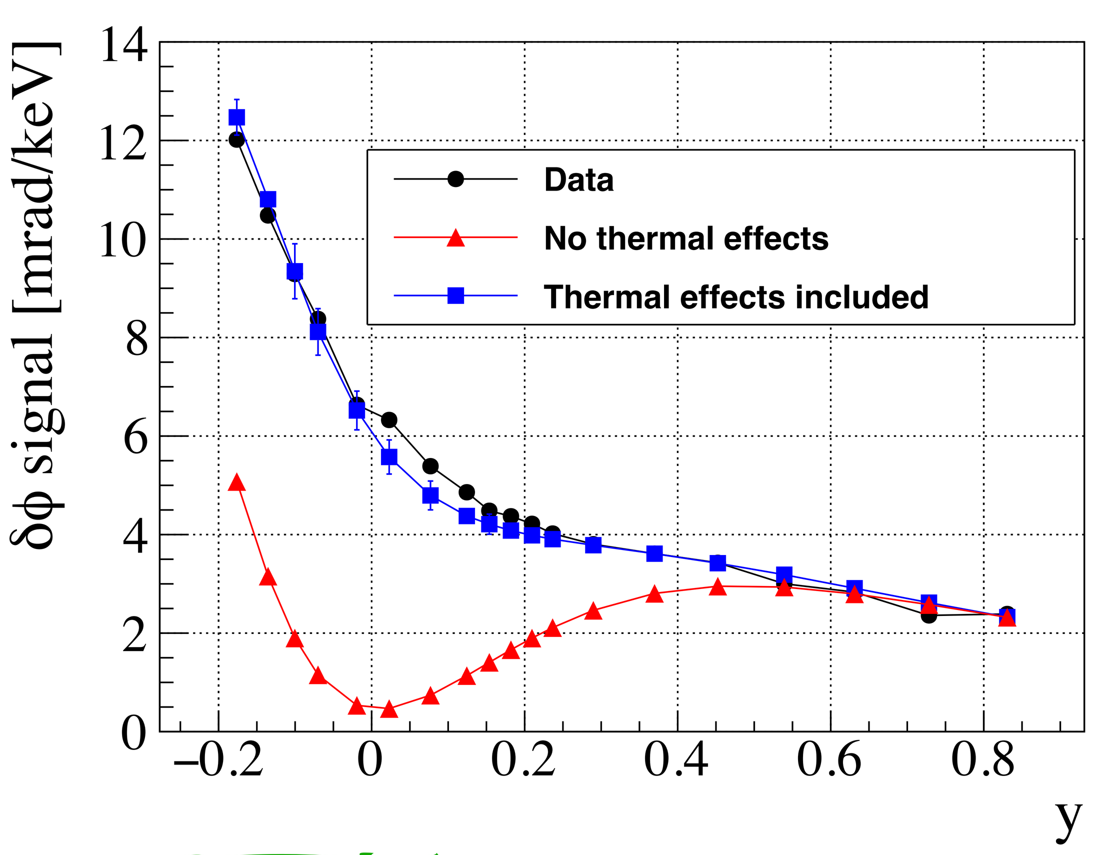
$$\frac{\delta\phi_0}{\delta A_0} = \frac{S_2(f_r,T_0)}{S_1(f_r,T_0)} = 1.93$$

$T_0$ = 45 mK




## Results and validation of the model



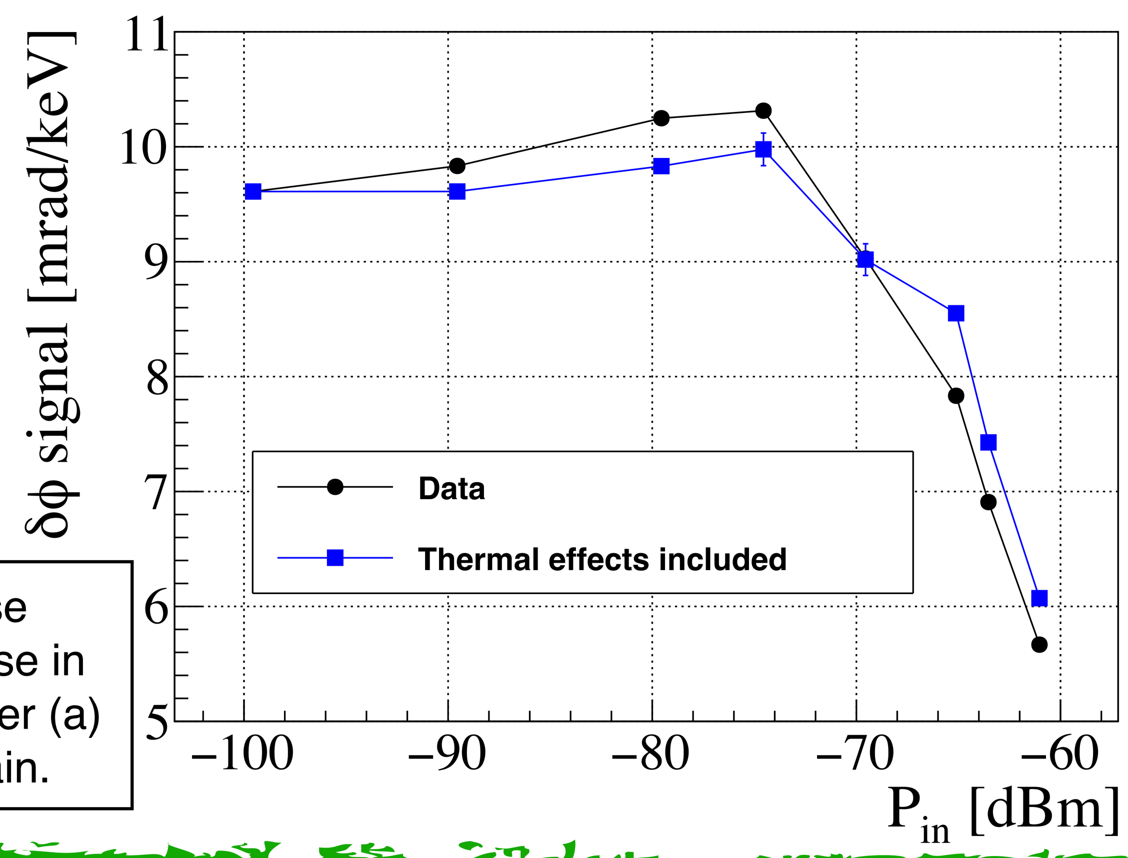

Pulse response in the frequency (y) domain.

Pulse response expression including thermal effects due to power absorption:

$$\delta\phi(y,a) = \frac{S_2(f_r,T)}{S_2(f_r,T_0)} \frac{\delta\phi_0}{1+4y^2} \frac{1 - \frac{4a}{(1+4y^2)^2}\frac{S_1(f_r,T)}{S_2(f_r,T)}}{1 + \frac{8ay}{(1+4y^2)^2}}$$

The model demonstrates to correctly reproduce the data within a maximum deviation of **10%**.

Pulse response in the power (a) domain.

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