Sub-gap modes observed with Kinetic Inductance Detectors (KIDs): source of extra-dissipation in disordered thin superconductors ?

Florence Levy-Bertrand, Néel Institute, Grenoble (France)

Outline:

- Working principe of Kinetic Inductance Detector (KID)
- Sub-gap modes in amorphous indium oxide
- Sub-gap modes in granular aluminum
- Sub-gap modes: source of extra-dissipation ?

RELATED TO « ANOMALOUS METAL » ???

TEMPERATURE & ENERGY SCALE ?

RELATED TO STRANGE TLS AND SATURATION OF LIFE TIME ?

Sub-gap modes observed with Kinetic Inductance Detectors (KIDs): source of extra-dissipation in disordered thin superconductors ?

Florence Levy-Bertrand, Néel Institute, Grenoble (France)

Collaborators:

Karlsruhe Institute of Technology

I. M. Pop
L. Grünhaupt
N. Maleeva
F. Valenti

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

A. Catalano
C. Hoarau
O. Bourrion

Néel institut

A. Monfardini
A. Benoît
M. Calvo
U. Chowdhury
J. Goupy
A. Bideaud
T. Klein
O. Dupré
T. Grenet
B. Sacépé
K. Le Calvez

CENTRO DE ASTROBIOLOGÍA
ASOCIADO AL NASA ASTROBIOLOGY INSTITUTE

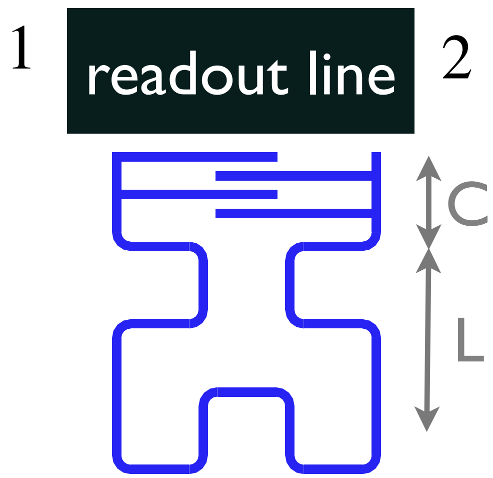
A. Gomez

Working principle of KID

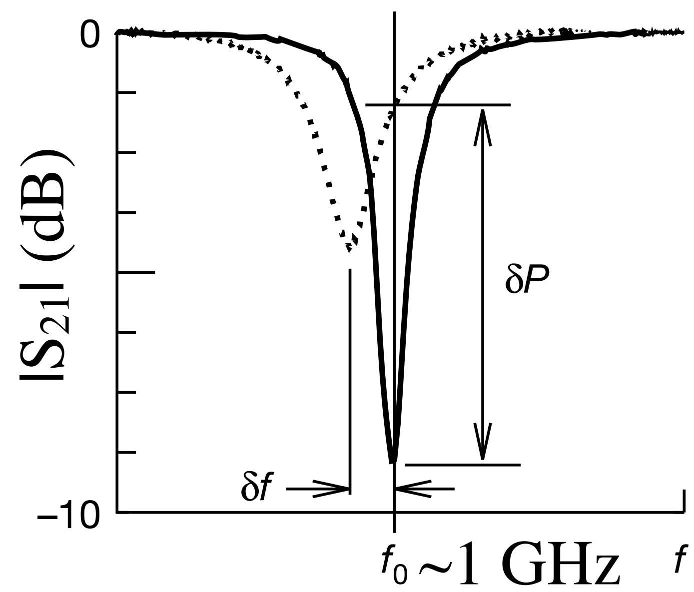
Day et al, Nature 425, 817 (2003)

Superconducting LC resonator:
design and electrical measurement

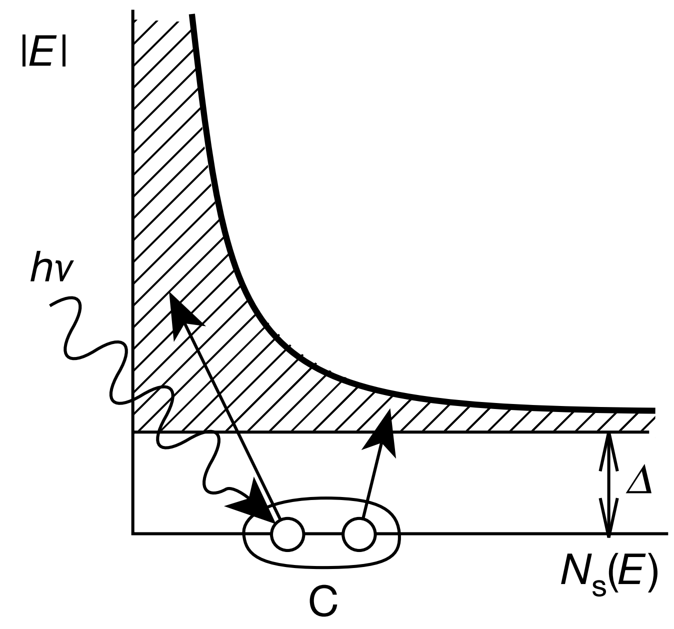
photon detection principle :
$h\nu > 2\Delta$



superconducting resonator



$f_0 \sim (LC)^{-1/2}$



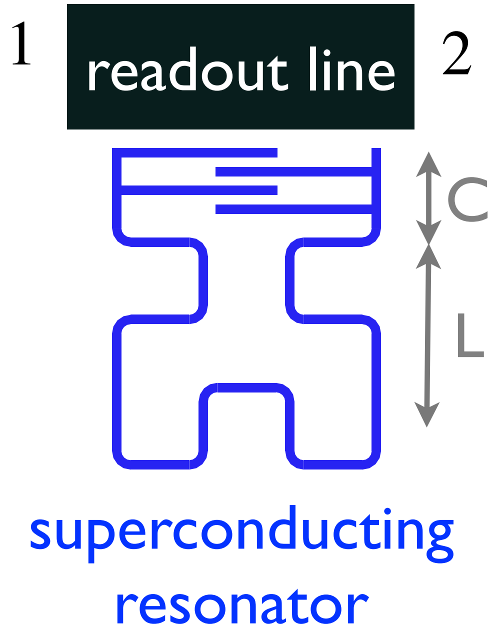
L ~ kinetic inductance of the superfluid
$L \sim 1/n_s$

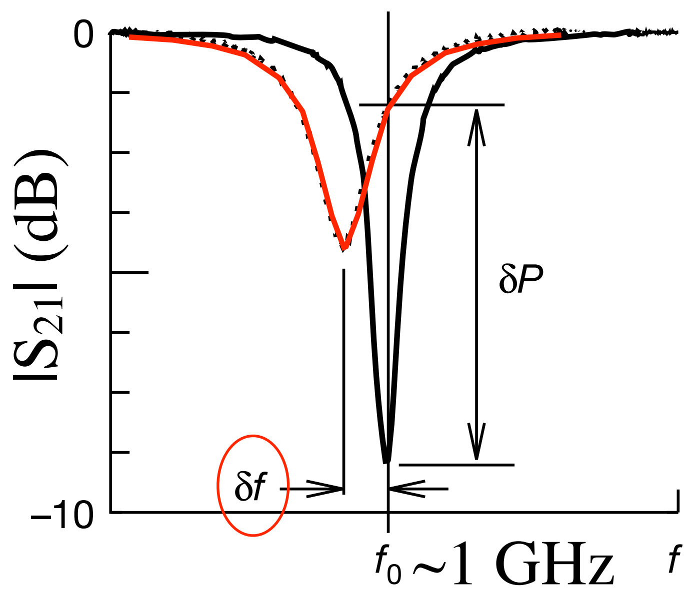
Working principle of KID

Day et al, Nature 425, 817 (2003)

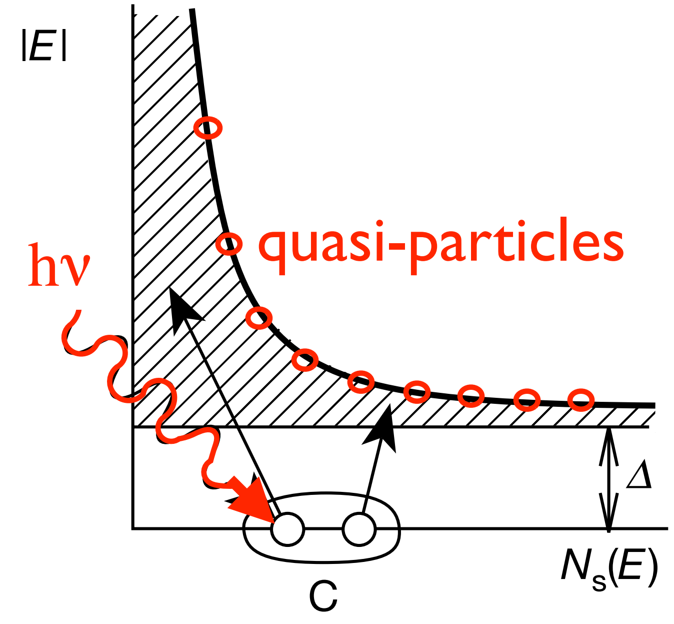
Superconducting LC resonator:
design and electrical measurement

photon detection principle :
$h\nu > 2\Delta$





$\mathbf{f_0 \sim (LC)^{-1/2}}$



frequency shift: δf due to $n_s\downarrow$

Q-factor$\downarrow$ due to dissipation$\uparrow$

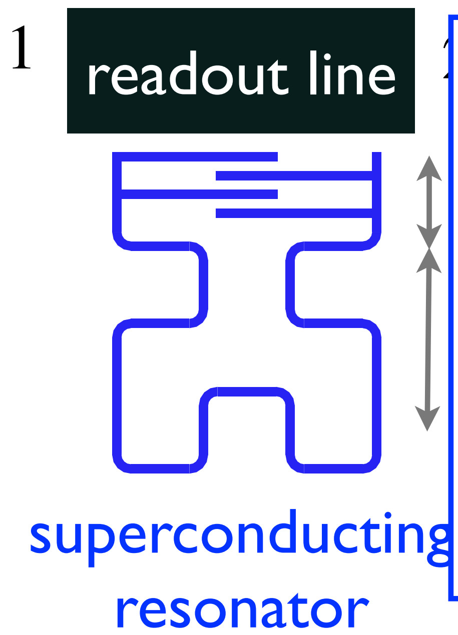
L ~ kinetic inductance of the superfluid
$L \sim 1/n_s$

Working principle of KID

Day et al, Nature 425, 817 (2003)

Superconducting LC resonator:
design and electrical measurement

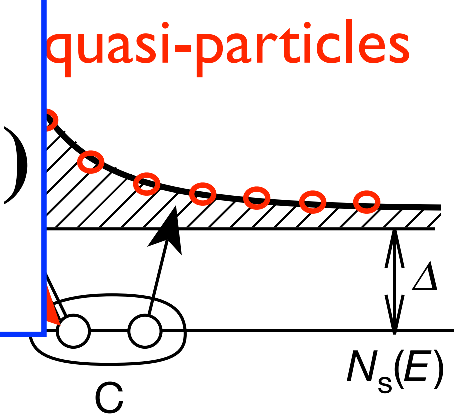
photon detection principle :
$h\nu > 2\Delta$



=

Kinetic Inductance Detector : KID

detection $h\nu$ through $\delta f \;\alpha\; \delta n_{qp} \;\alpha\; P(h\nu)$



$\boxed{f_0 \sim (LC)^{-1/2}}$

L ~ kinetic inductance of the superfluid
$L \sim 1/n_s$

frequency shift: δf due to $n_s\downarrow$

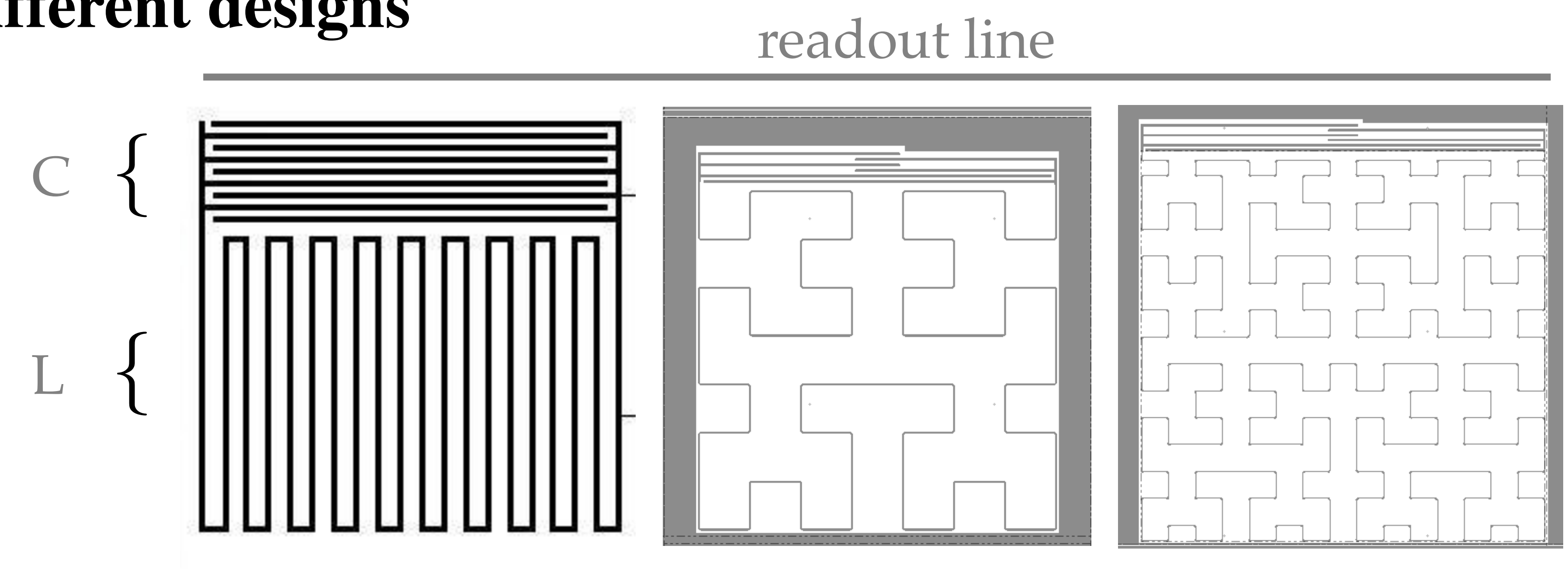
Q-factor$\downarrow$ due to dissipation$\uparrow$

Working principle of KID

Superconducting LC resonator:

Superconducting thin film on insulating substrate (Si, MgO, Al_2O_3,…)

different designs

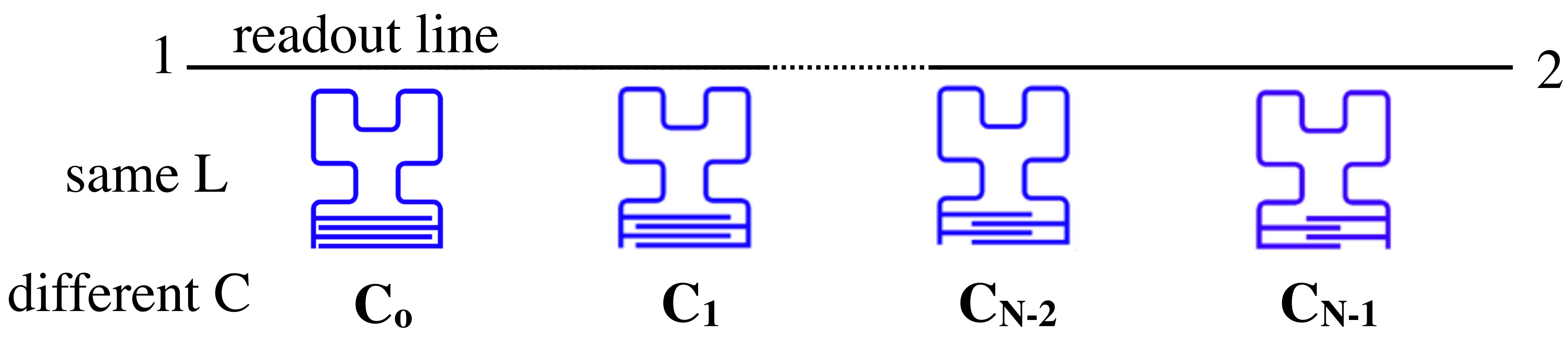


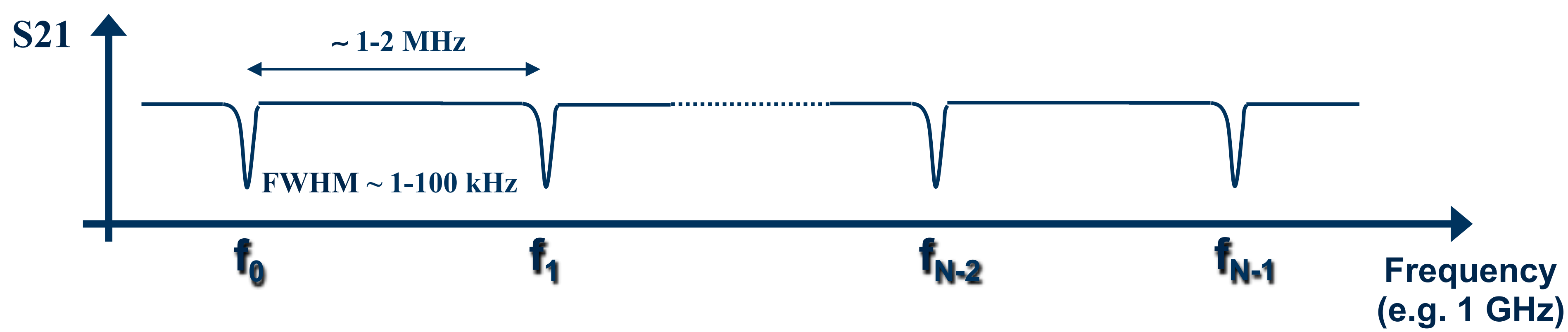
different superconducting materials: Al, Nb, NbN, …

-> key point: planar lithography

Working principle of KID

Frequency multiplexing: $\boxed{f \sim (LC)^{-1/2}}$

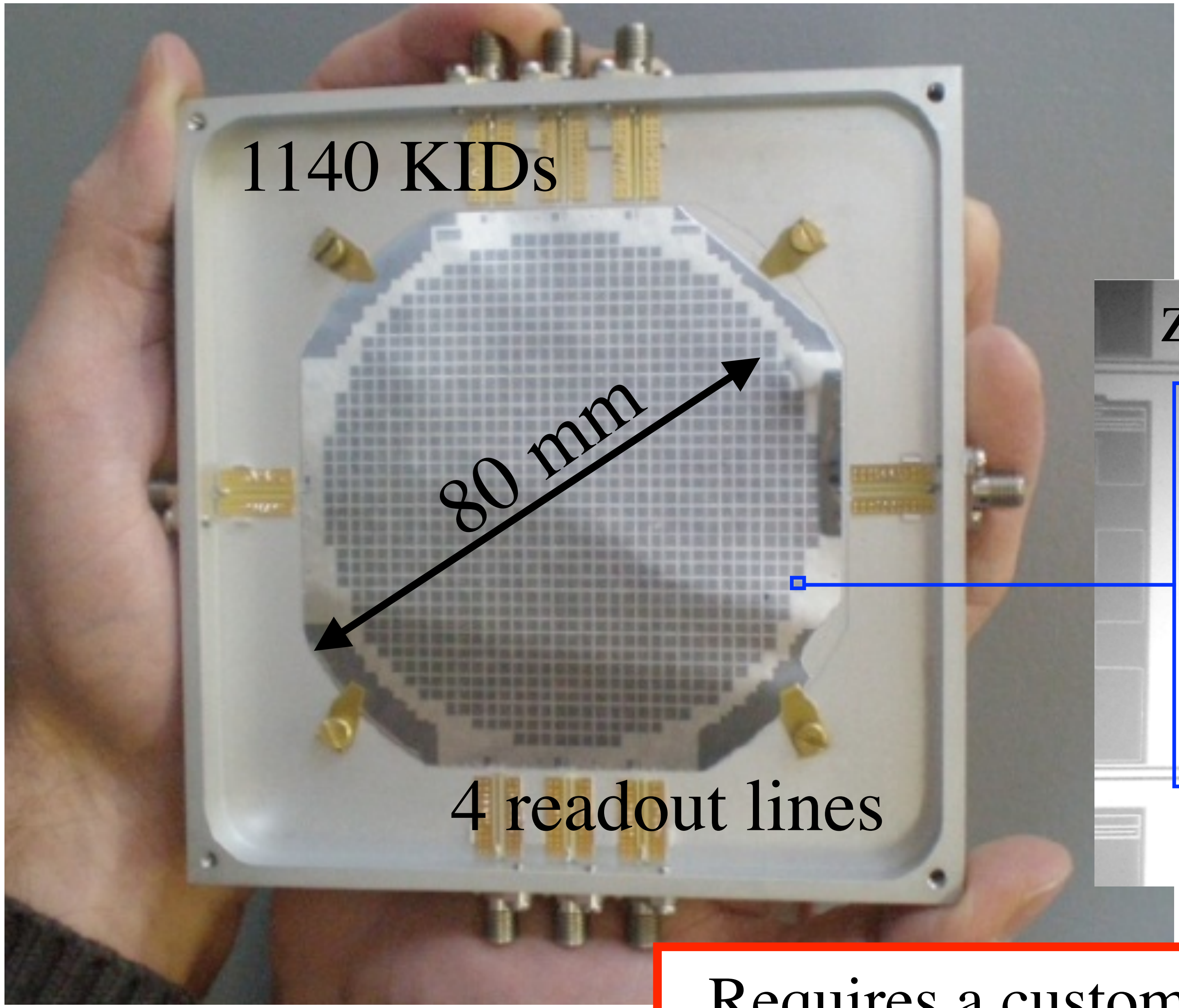


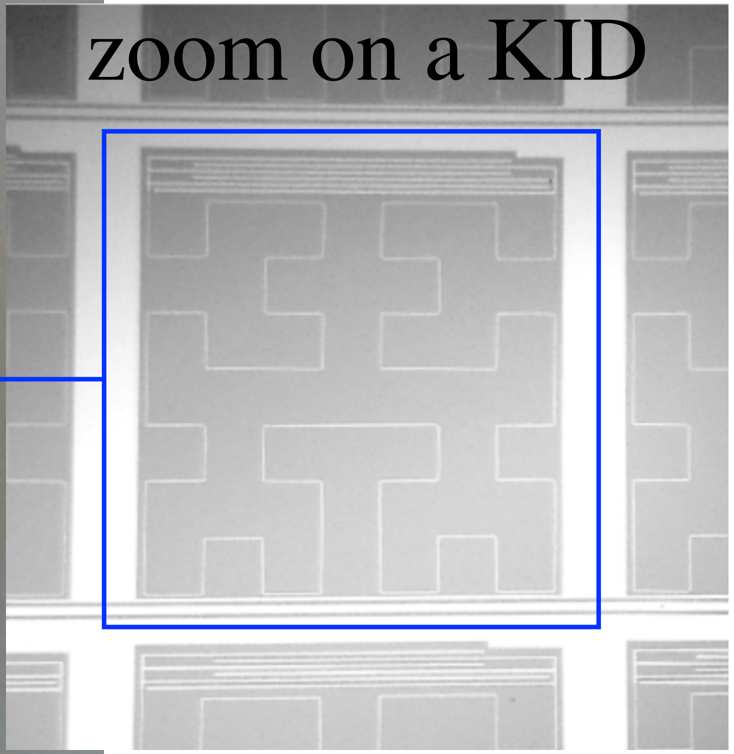


-> <u>one line to address hundreds of detectors</u>

Working principle of KID

Frequency multiplexing: $\boxed{\mathbf{f \sim (LC)^{-1/2}}}$



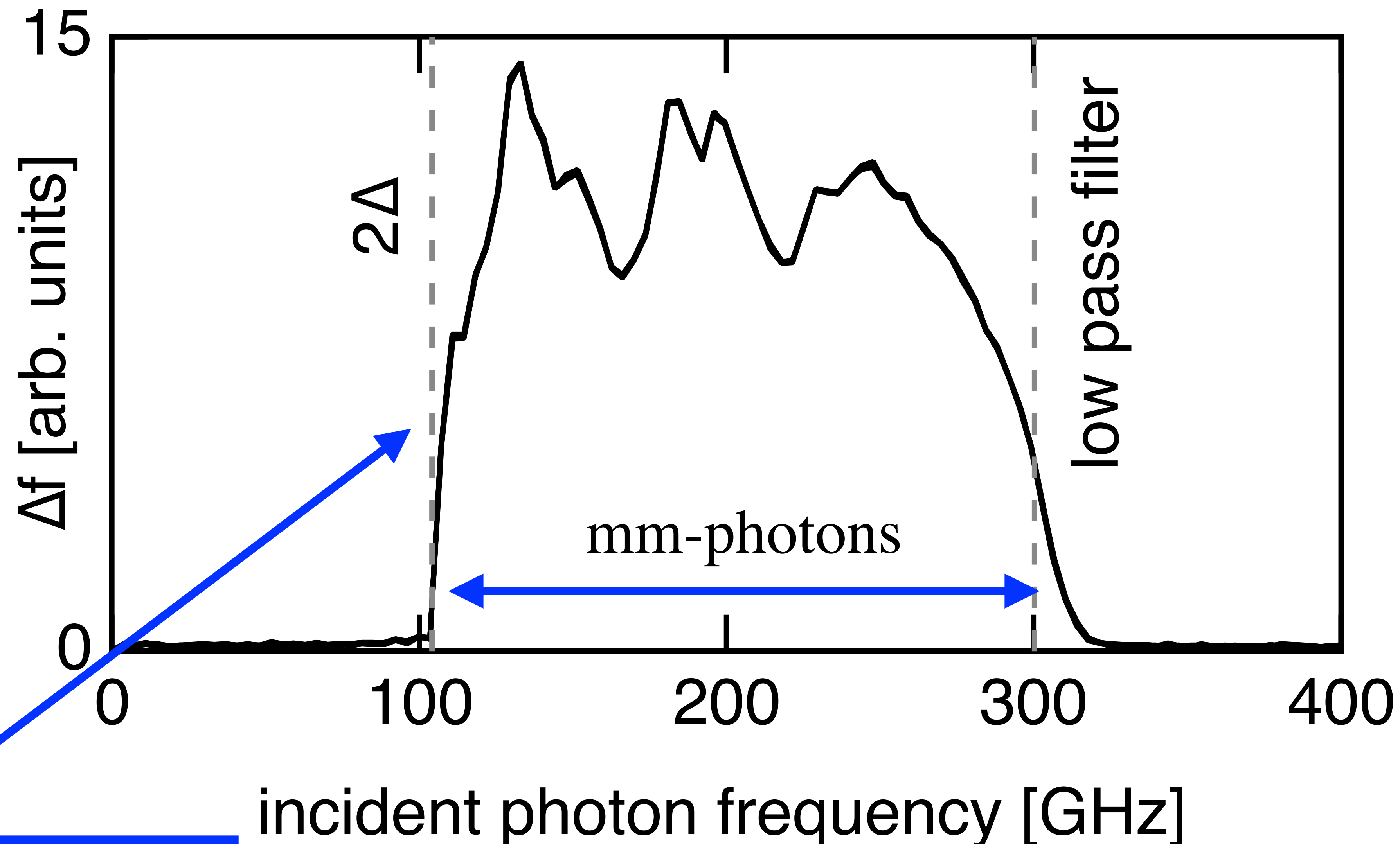


Requires a custom multiplexed RF-electronic

Working principle of KID

Optical response of KIDs made of 20nm-thick Al

@ T~100mK, T << T_c ~1.4 K



cutoff detection
$h\nu > 2\Delta = 3.52\ k_B T_c$

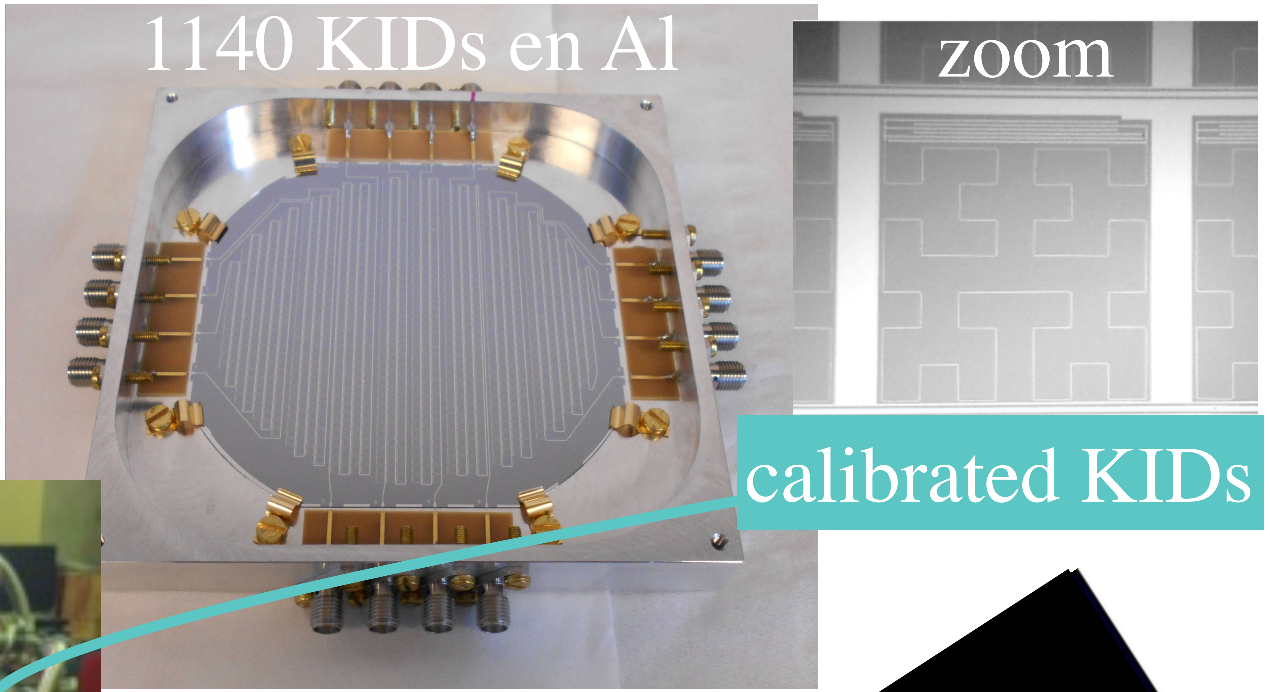
Requires a custom optical dilution refrigerator

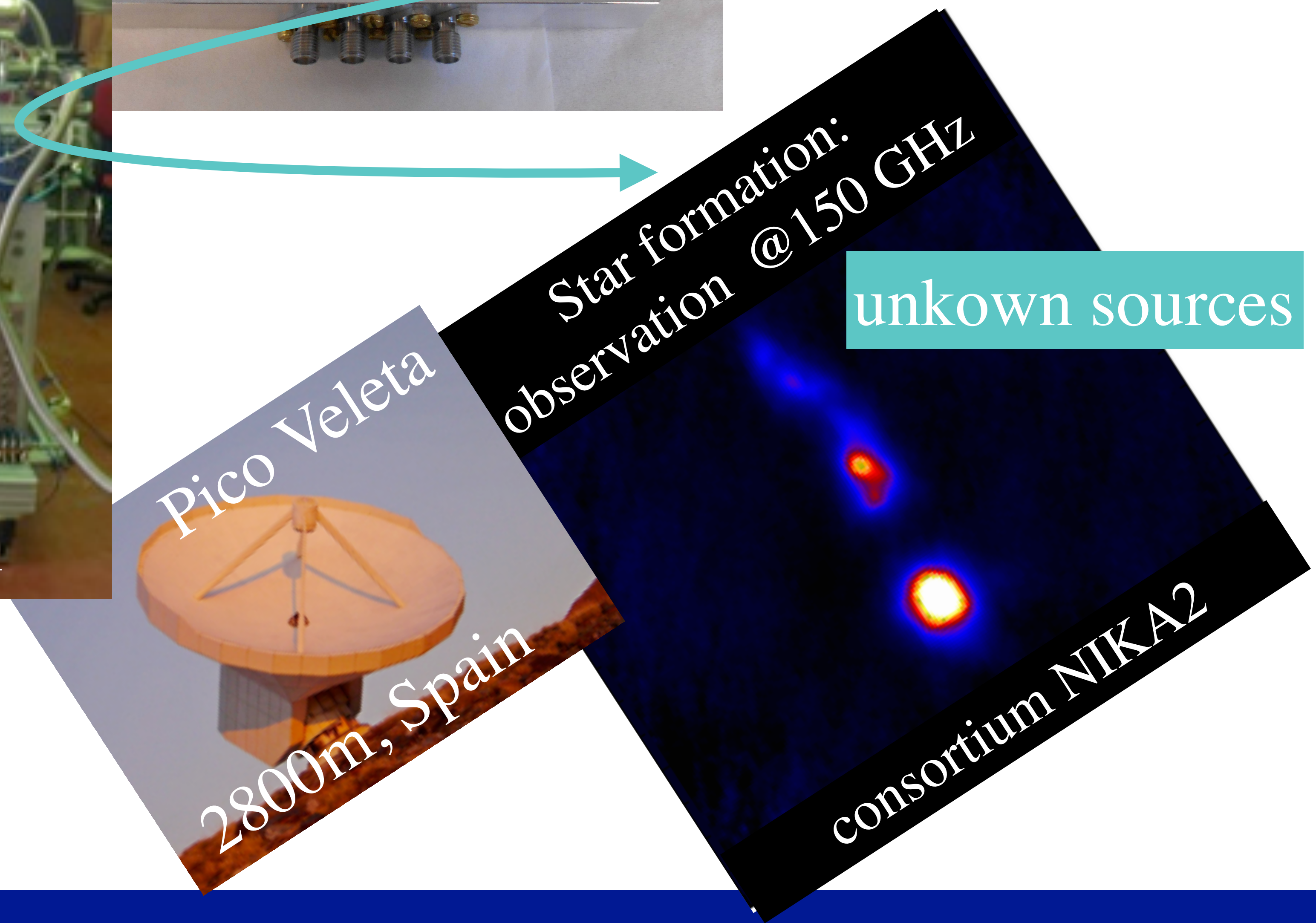
KID for astrophysics observations

NIKA2 mm-camera

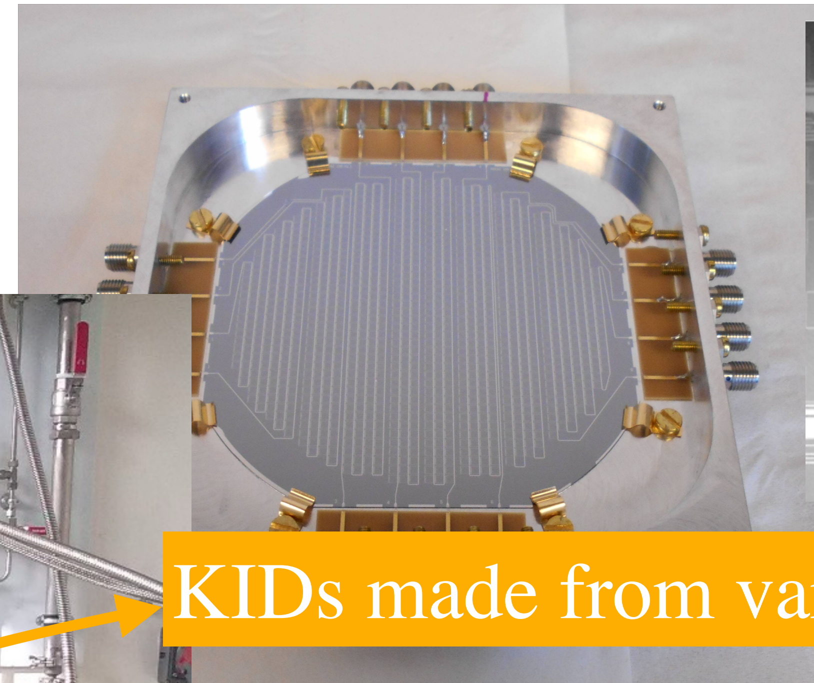
(2800m, Spain)

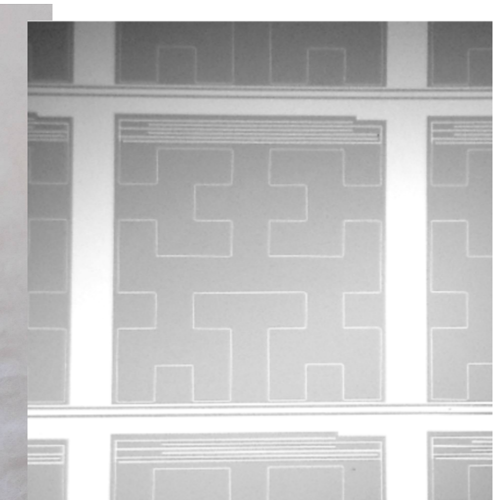
Installation in 2015



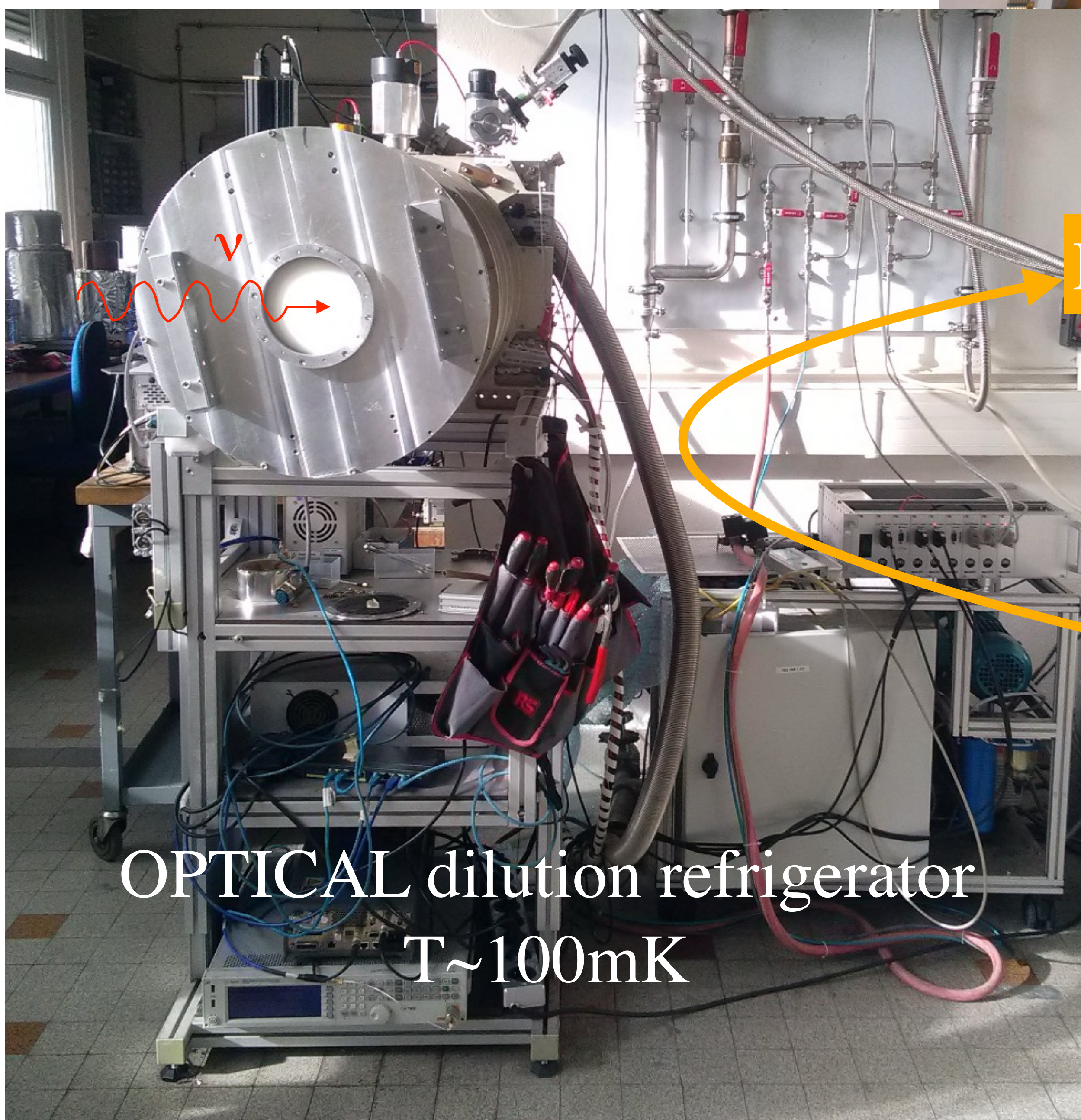


KID to access the electrodynamics of superconductors



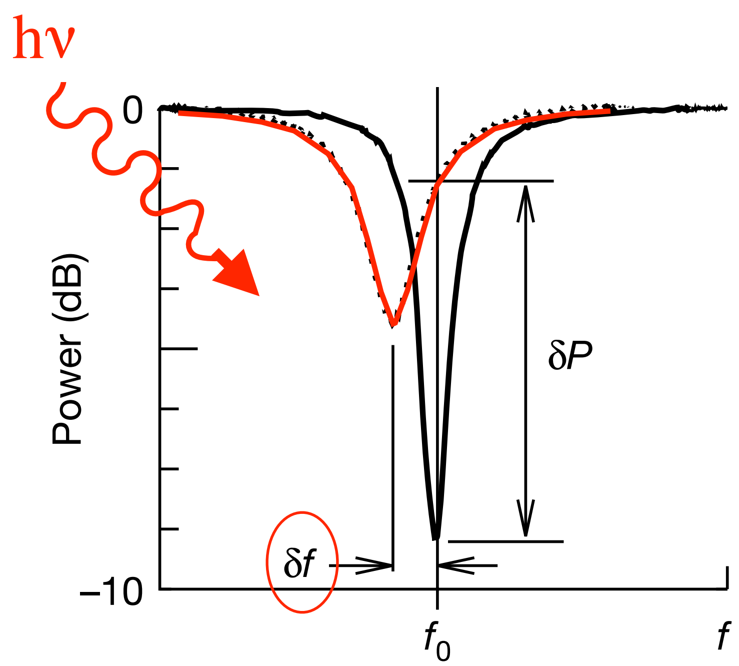


KIDs made from various superconductors



known sources

KID to access the electrodynamics of superconductors



$$f_0 = 1/(2\pi\sqrt{LC})$$

$$Q = 1/R\sqrt{L/C}$$

f_0 and Q are related to

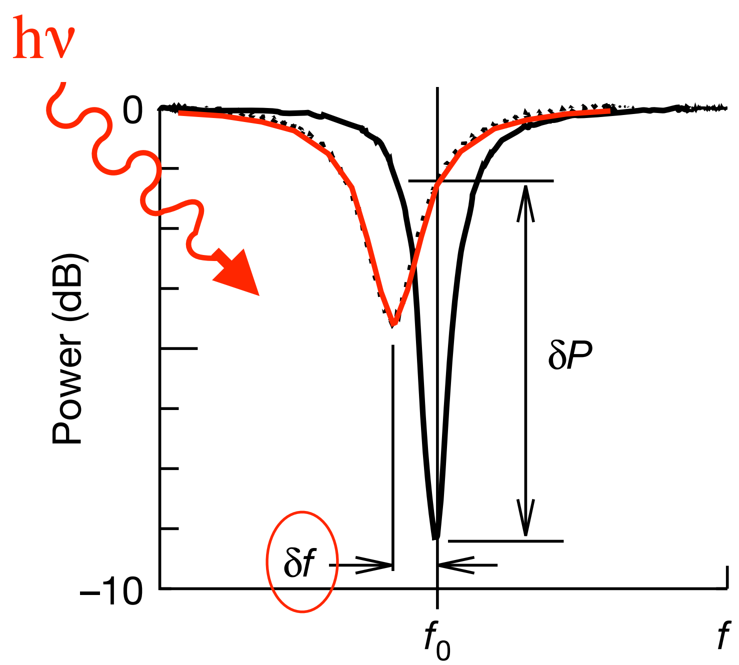
- the optical complex conductivity $\sigma(\omega) = \sigma_1 - i\sigma_2$
- the complex impedance $Z = R_{qp} + i\omega L_k$

for d<<λ
$Z = 1/(\sigma d)$

quasi-particles
dissipative response

SC- condensate
inductive response

KID to access the electrodynamics of superconductors



$$f_0 = 1/(2\pi\sqrt{LC})$$

$$Q = 1/R\sqrt{L/C}$$

$$\frac{\delta f_0}{f_0} \sim -\frac{\alpha}{2}\frac{\delta L_k}{L_k} \sim +\frac{\alpha}{2}\frac{\delta n_s}{n_s}$$

with $\alpha = L_k/(L_k + L_g)$

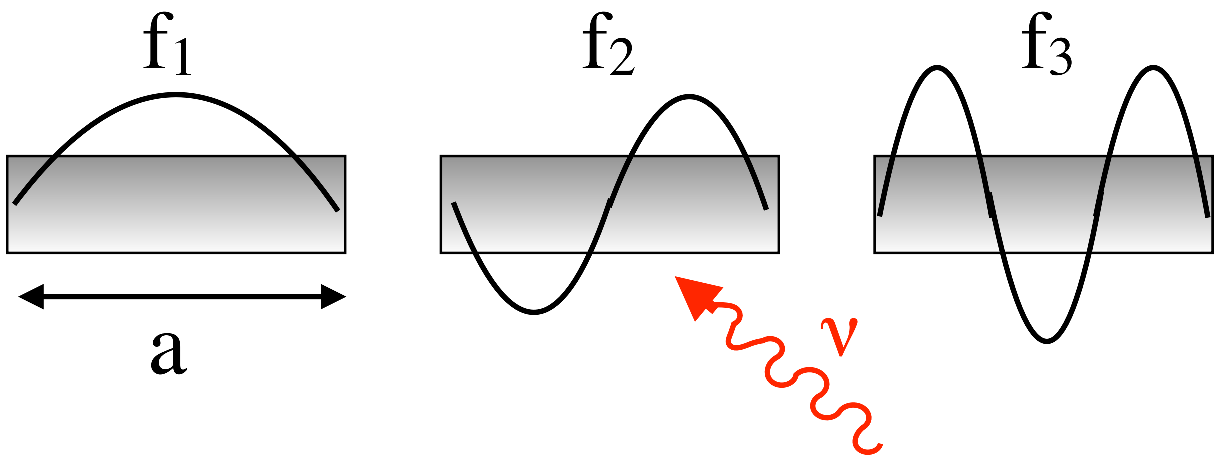
SC- condensate

$$\frac{\delta Q}{Q} \sim -\frac{\delta R_{qp}}{R_{qp}} + \frac{\alpha}{2}\frac{\delta L_k}{L_k}$$

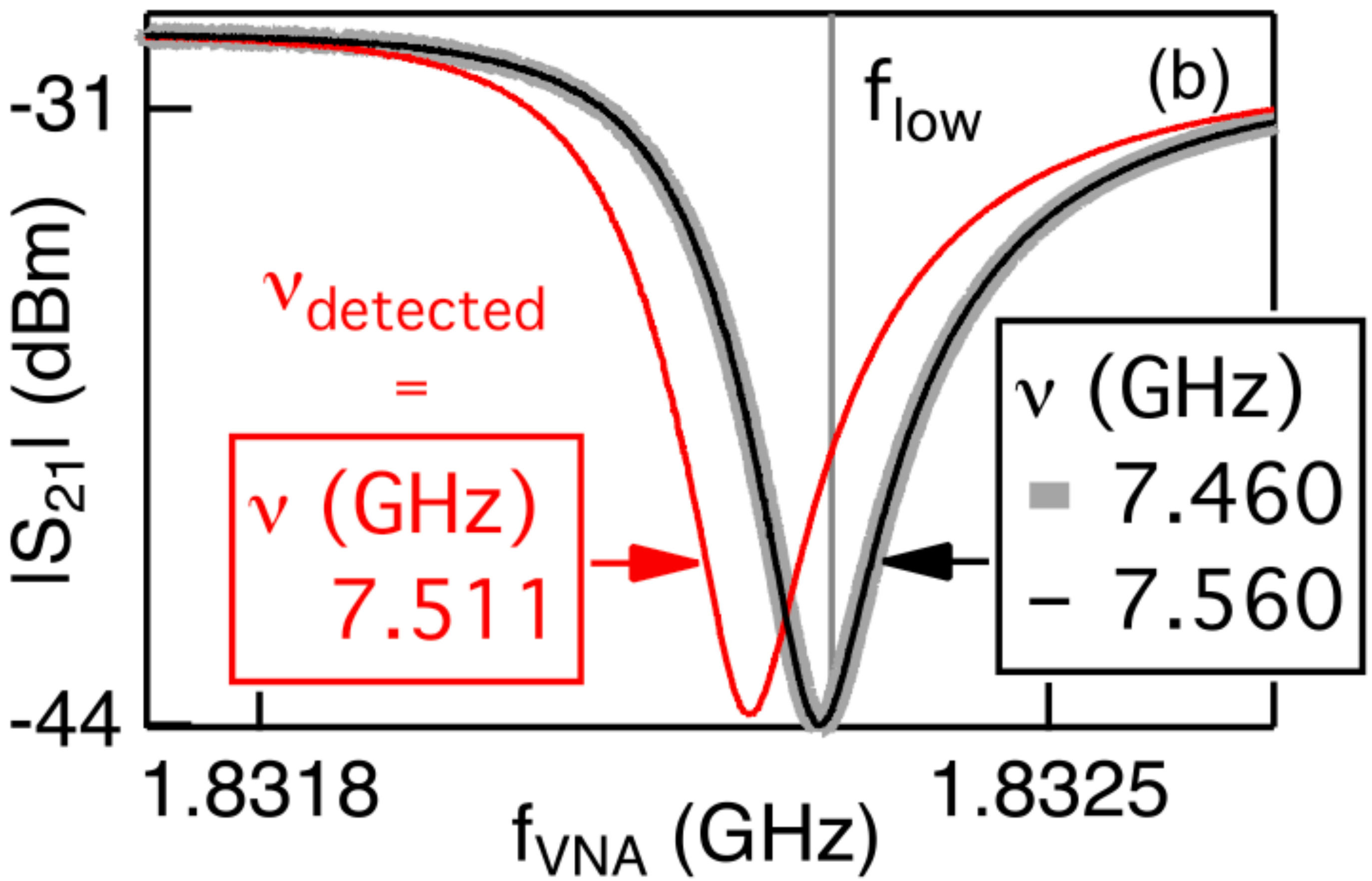
quasi-particles

Sub-gap modes in amorphous indium oxide

In superconducting resonator:
fondamental mode and harmonics f_n,
current oscillations of n_S.



ν-detected = third harmonic



In amorphous InO, $2\Delta \sim 200$ GHz

- STM: fully gap
- Optics: sub-gap state(s)

O. Dupré et al, SuST 30, 045007 (2017).

Sub-gap modes in amorphous indium oxide

Strong sub-gap modes in a:InO
because of large non-linearity:
$L_k(I) \sim L_k(0)[1 + I^2/I_*^2]$
because of low $I_* \sim I_c$

$$\frac{\delta f_0}{f_0} \sim -\frac{\alpha}{2}\frac{\delta L_k}{L_k}$$

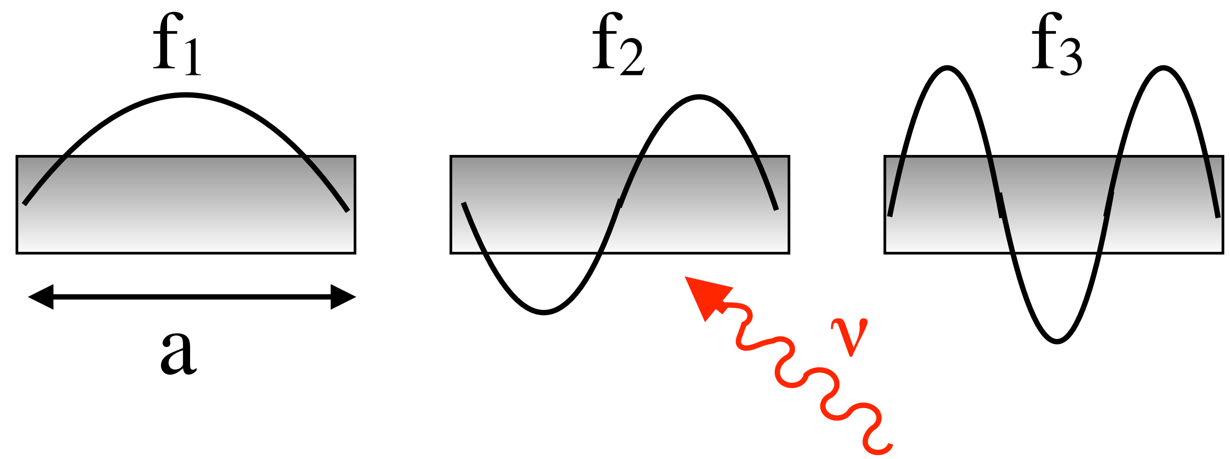
incident power

$$\frac{\delta n_s}{n_s} \sim \frac{I^2}{I_*^2}$$

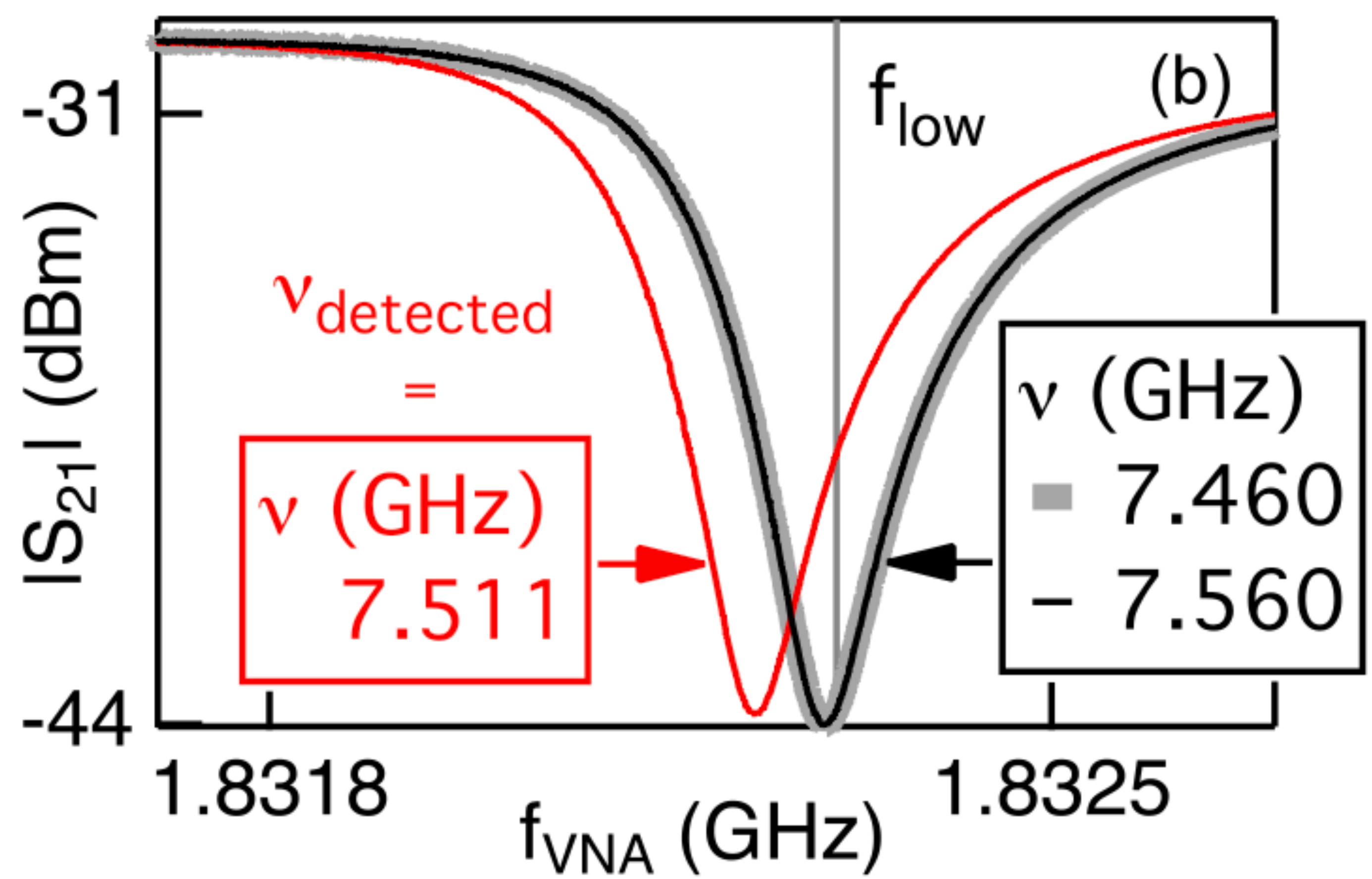
and $I_* \propto n_s$

$$\boxed{\delta n_s \propto I^2/I_*}$$

O. Dupré et al, SuST 30, 045007 (2017).



ν-detected = third harmonic



Sub-gap modes in amorphous indium oxide

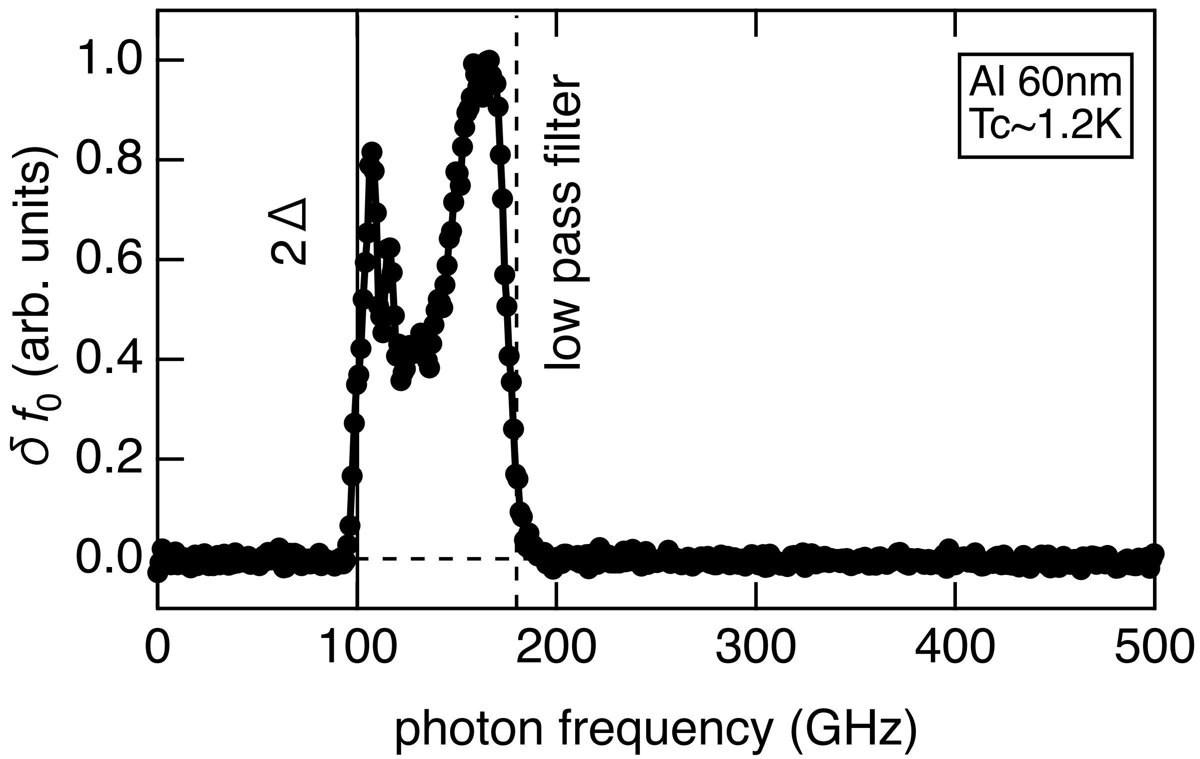
Strong sub-gap modes in a:InO
because of large non-linearity:
$L_k(I) \sim L_k(0)[1 + I^2/I_*^2]$
because of low $I_* \sim I_c$

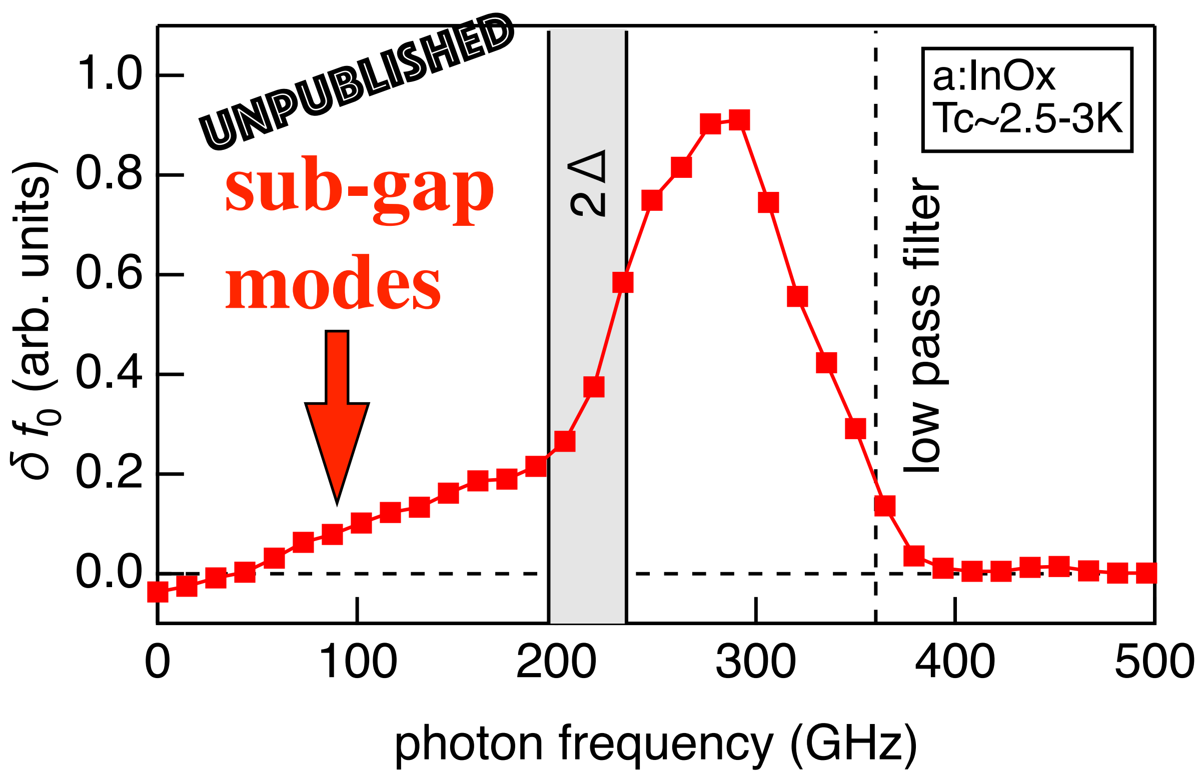
$$J*(Al) \sim 1.10^{12} A/m^2$$

$$\boxed{\delta n_s \propto I^2/I_*}$$

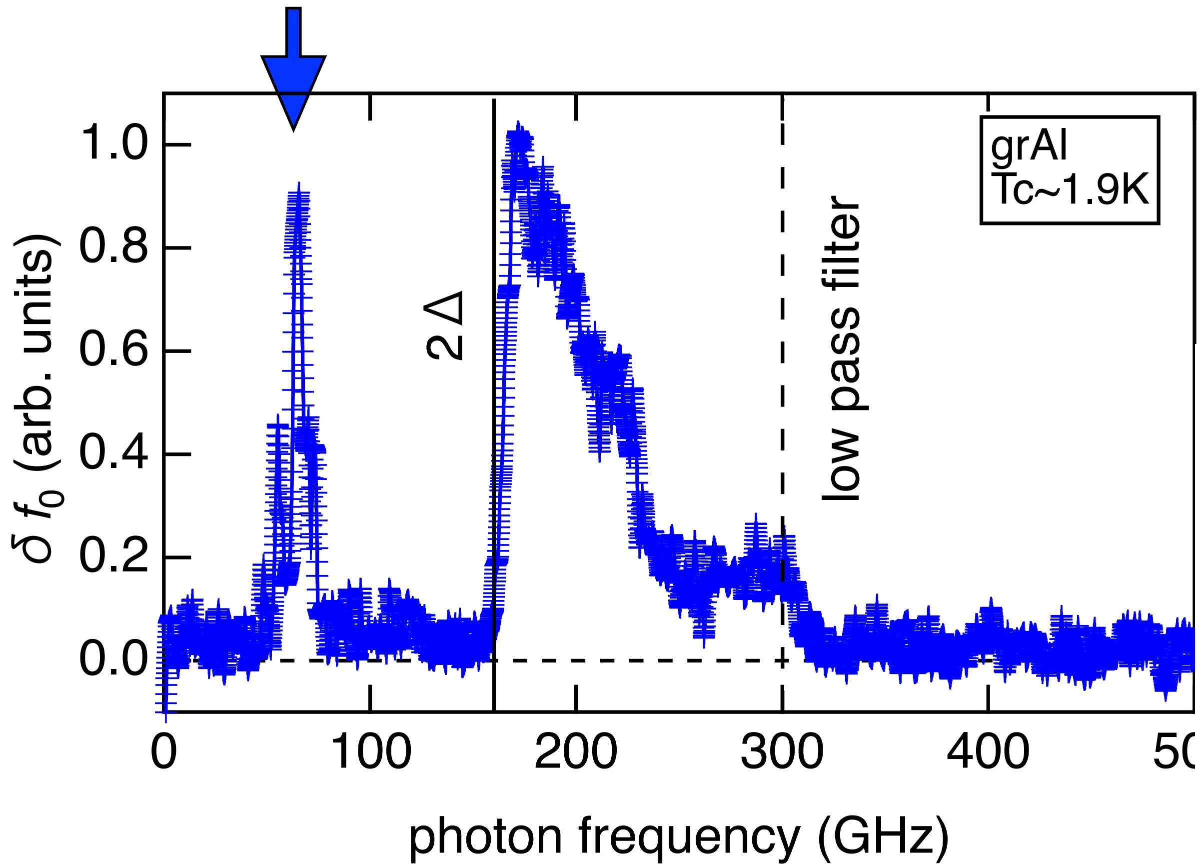
$$10^3 \times n_{qp}$$

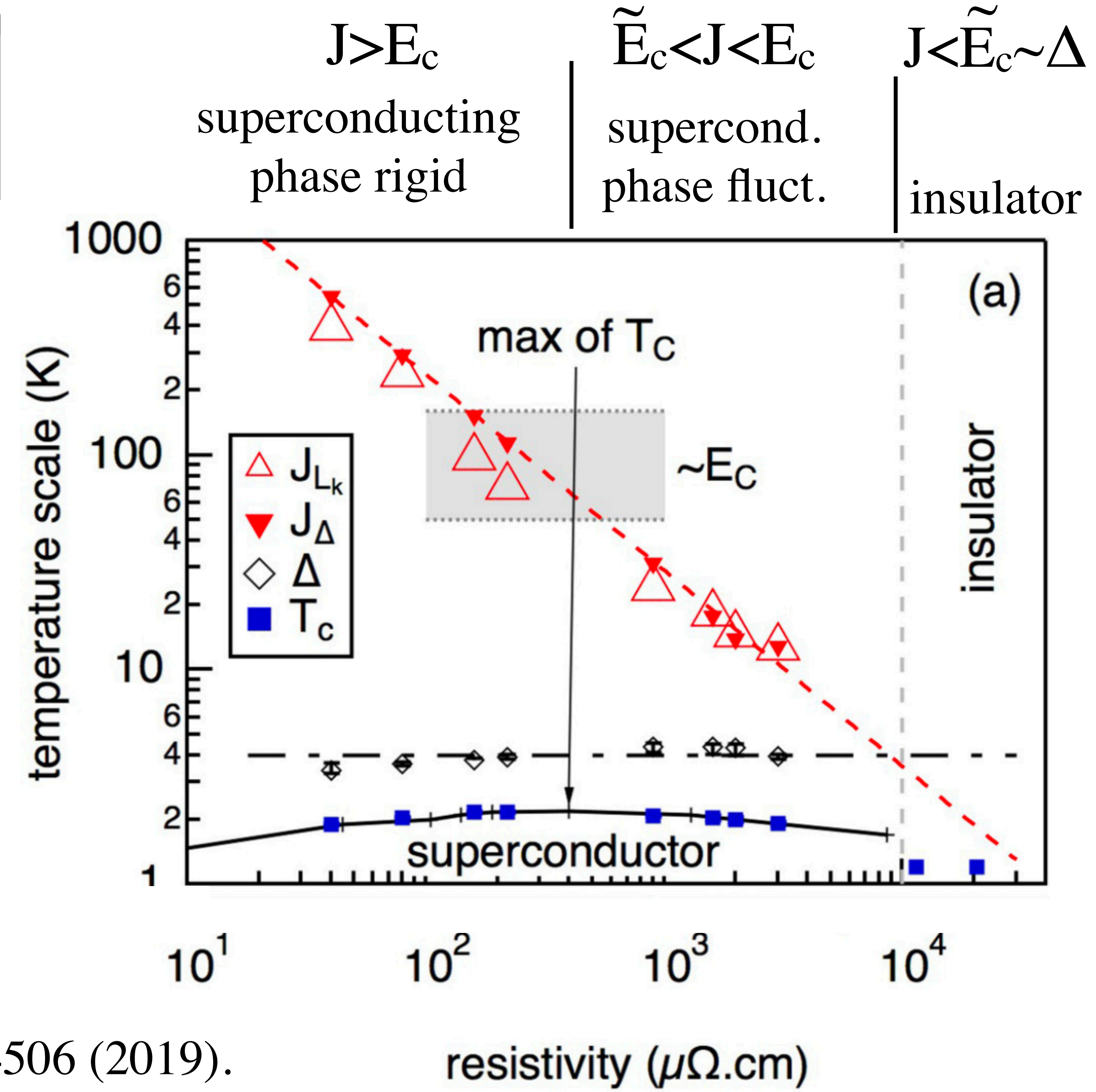
$$J*(a:In0) \sim 4.10^9 A/m^2$$





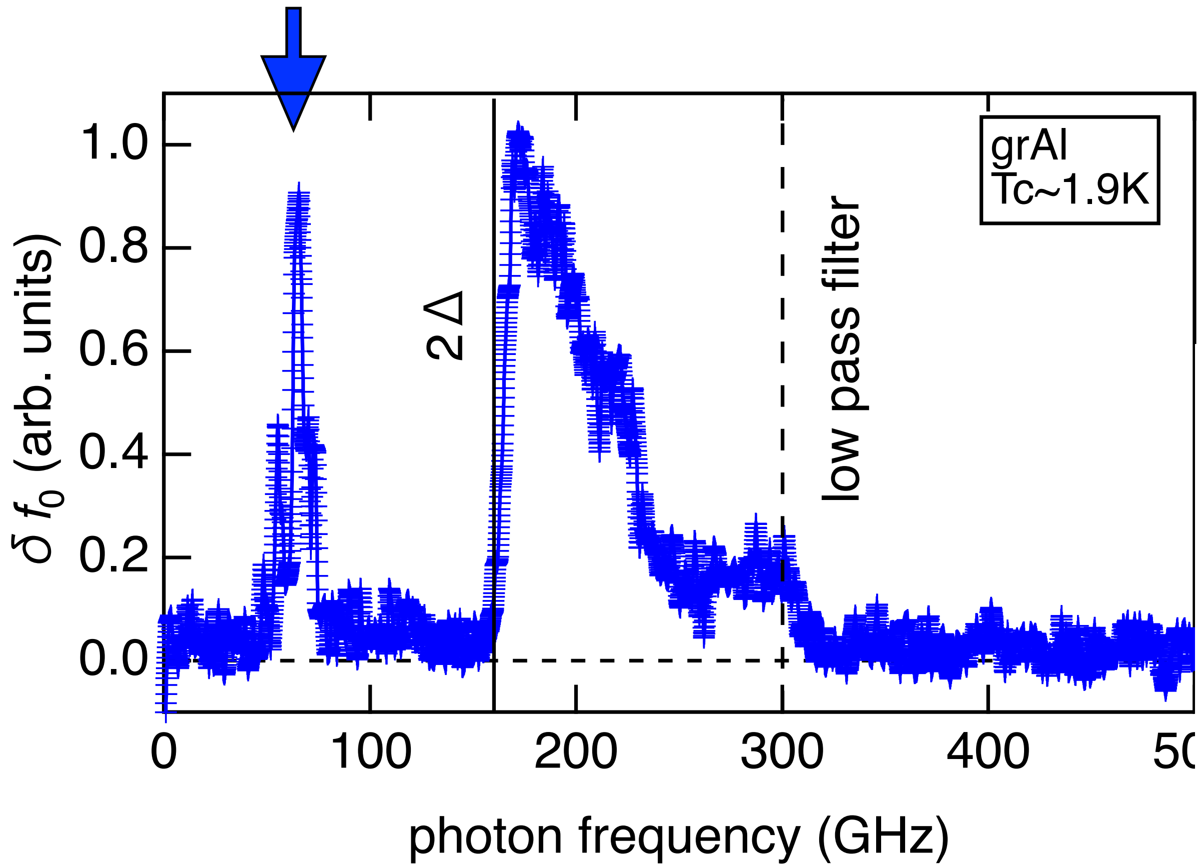
Sub-gap modes in granular aluminum



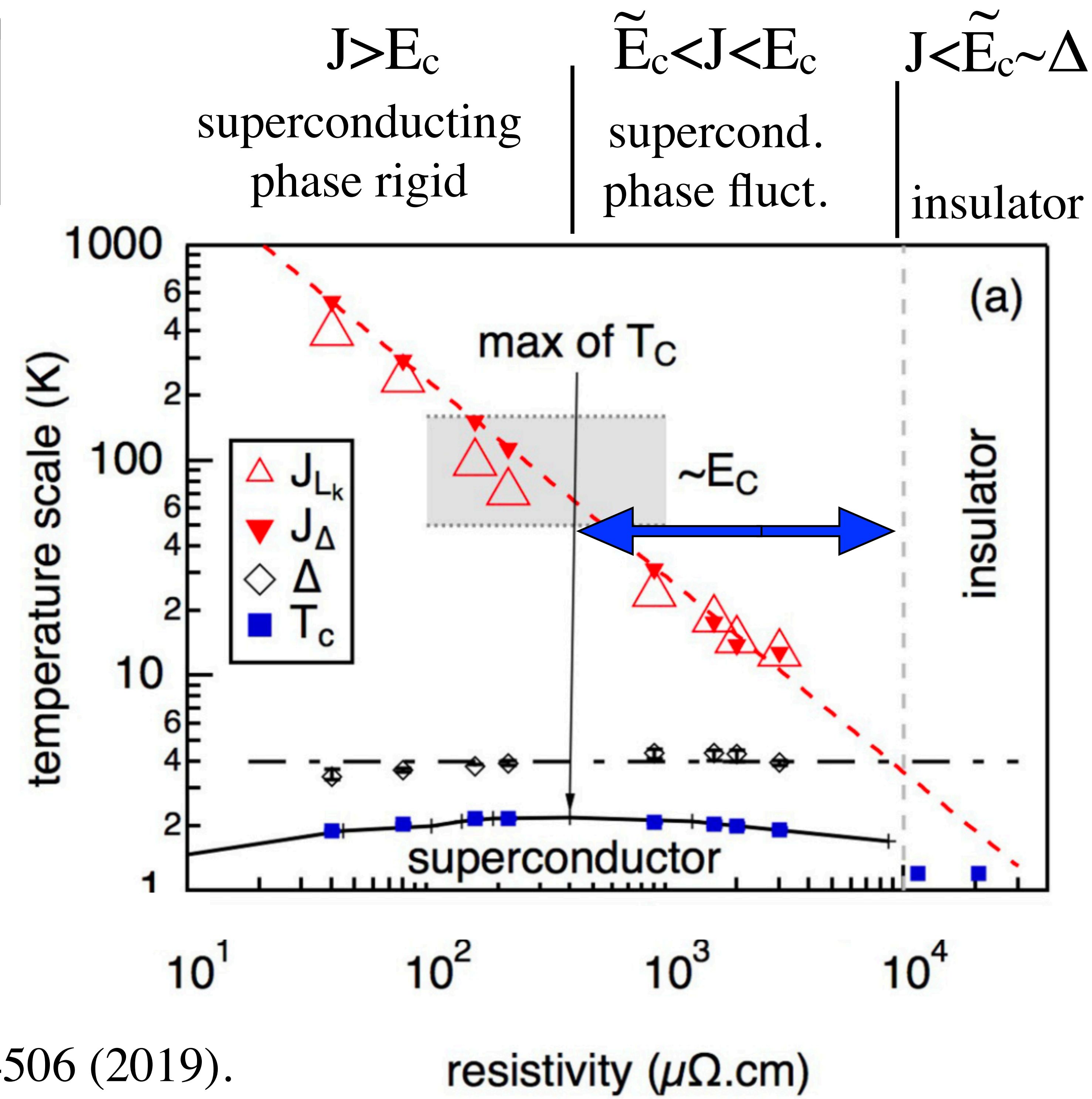


F. Levy-Bertrand et al, Phys. Rev. B 99, 094506 (2019).

Sub-gap modes in granular aluminum



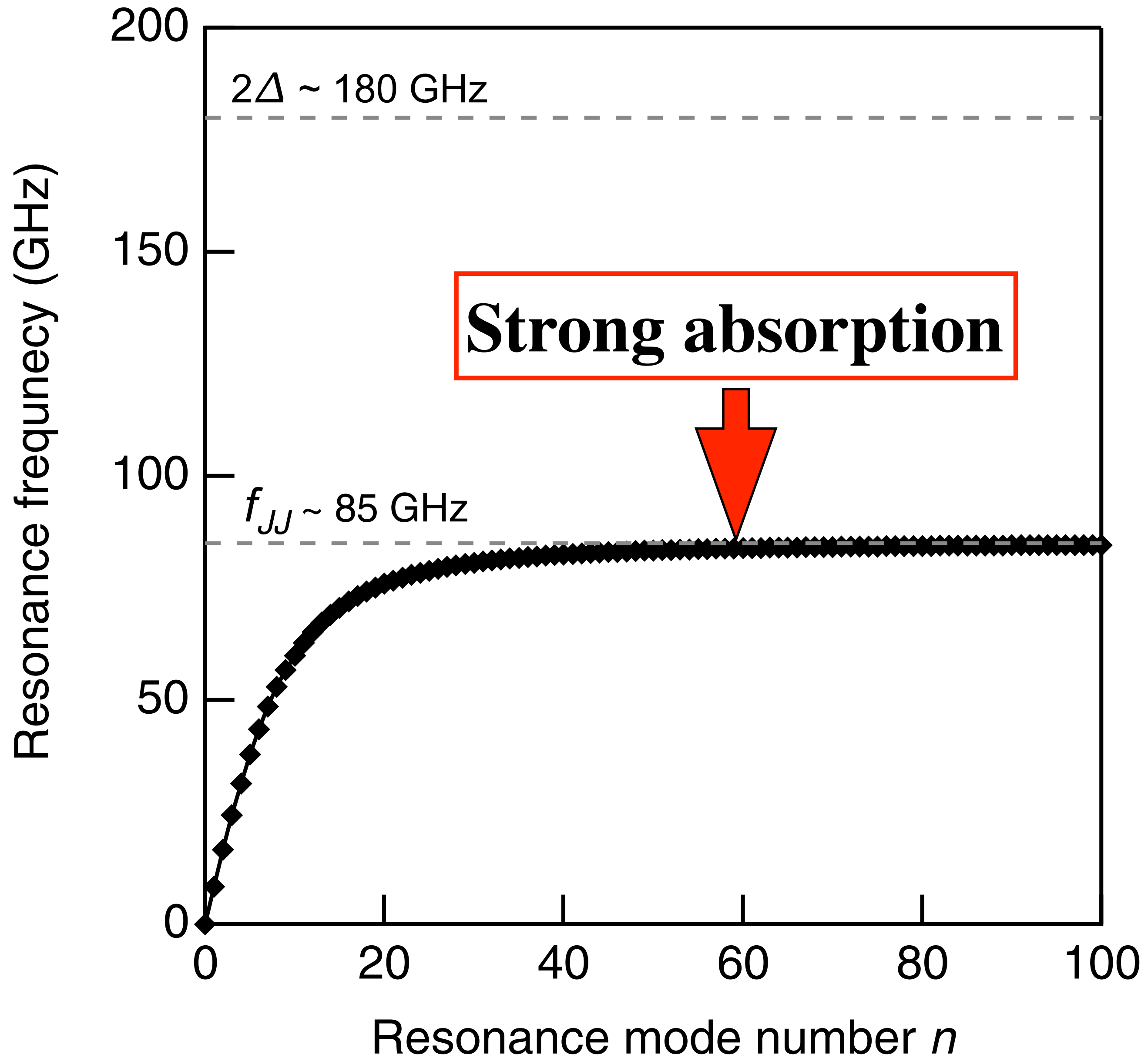
Sub-gap modes when $J<E_c$

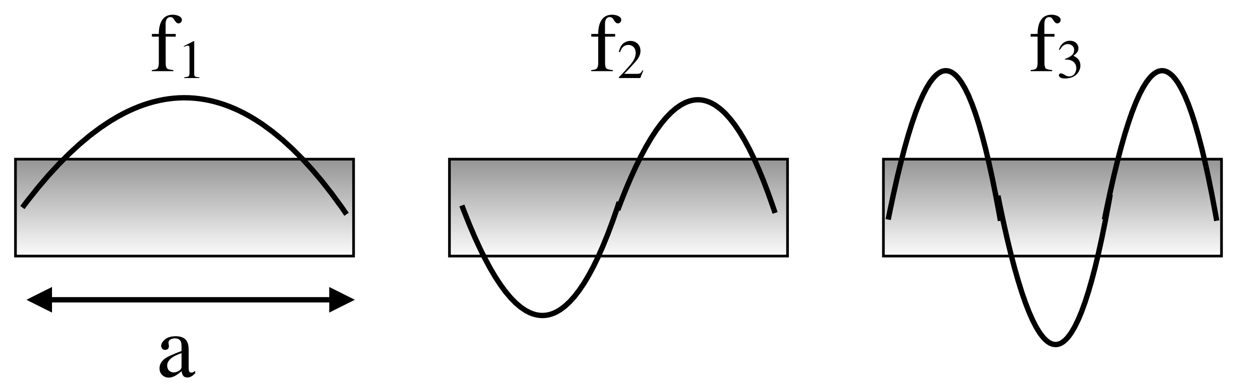


F. Levy-Bertrand et al, Phys. Rev. B 99, 094506 (2019).

Sub-gap modes in granular aluminum

Dispersion of the resonances:





array of JJ (like in grAl), saturation at the **JJ plasma frequency**

$$f_{\mathrm{JJ}} = \frac{1}{2\pi}\sqrt{\frac{2eI_c}{\hbar C_J}}$$

the density of sub-gap modes diverges, a **strong photon absorption** is expected.

N. Maleeva and al, Nature Communications 9, 3889 (2018).

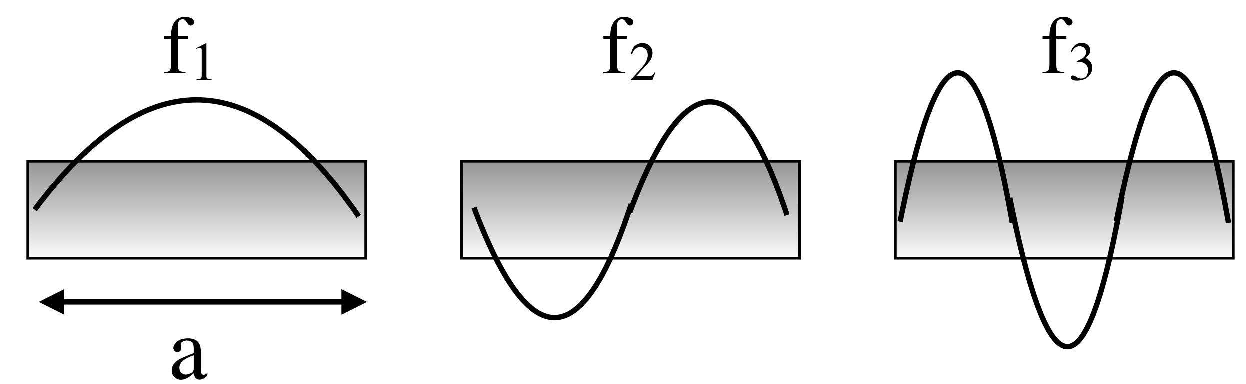
Sub-gap modes: source of extra-dissipation ?

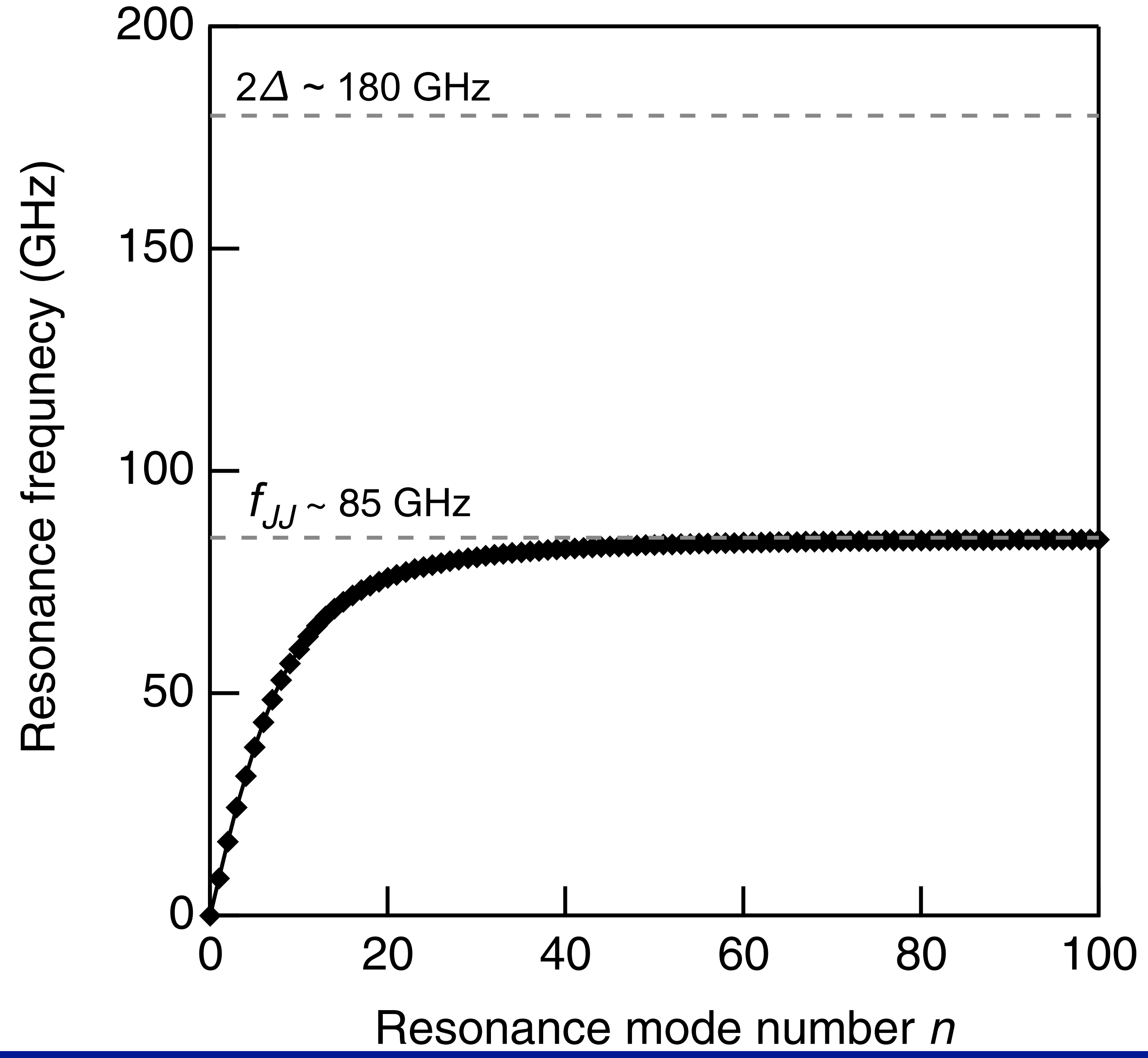
Harmonic sub-gap states f_n in any **thin superconductor**.

And $$\frac{\delta n_s}{n_s} \sim -\frac{I^2}{I_c^2}$$

Low critical current $I_c \propto n_s$ **results in extra-dissipation** for identical incident power

$$\delta n_s \propto P_{incident}/I_c$$





Sub-gap modes: source of extra-dissipation ?

Harmonic sub-gap states in thin superconductor

- Sub-gap quasi-particles (with long relaxation time)
- Enhanced dissipation for low critical current (=large L_k)

➡ Probable source of extra-dissipation scaling with L_k

$$L_K = \frac{m}{n_s e^2 d} = \frac{\hbar R_\square}{\pi \Delta}$$

RELATED TO « ANOMALOUS METAL » ???

Sub-gap modes: source of extra-dissipation ?

Probable extra-dissipation scaling with L_k

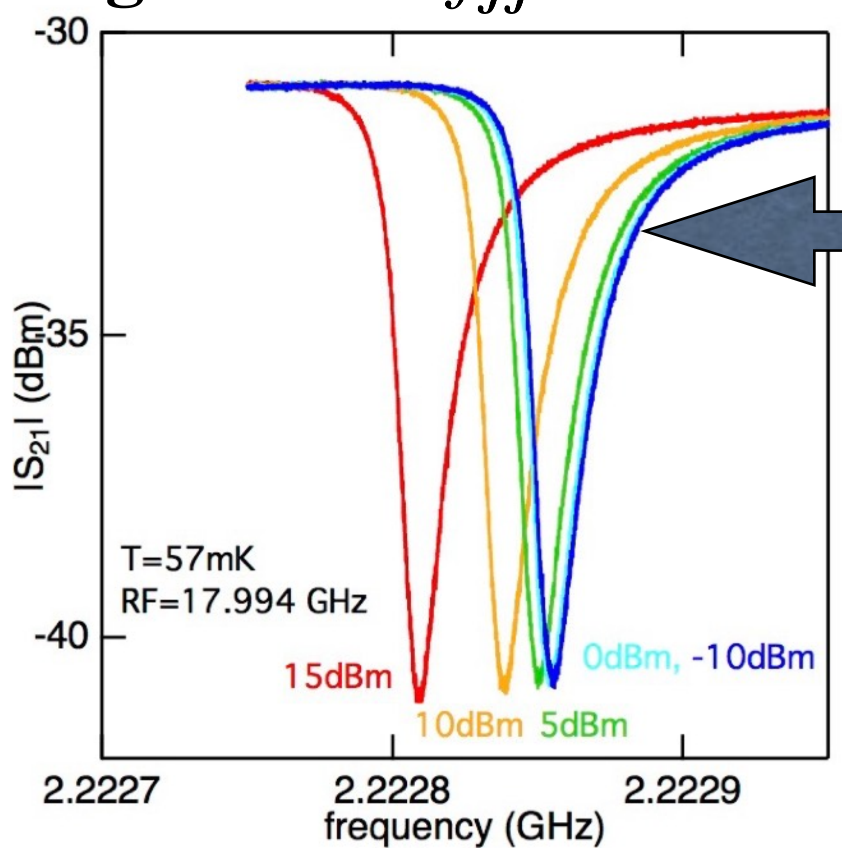
$$L_K = \frac{m}{n_s e^2 d} = \frac{\hbar R_\square}{\pi \Delta}$$

Relevant temperature and energy ?

Guess: two level systems (TLS) approach with population: $\exp(-\beta\Delta_{TLS})$

-> because of observation of (strange) TLS behavior …

grAl: $\nu \ll f_{JJ}$ @various P

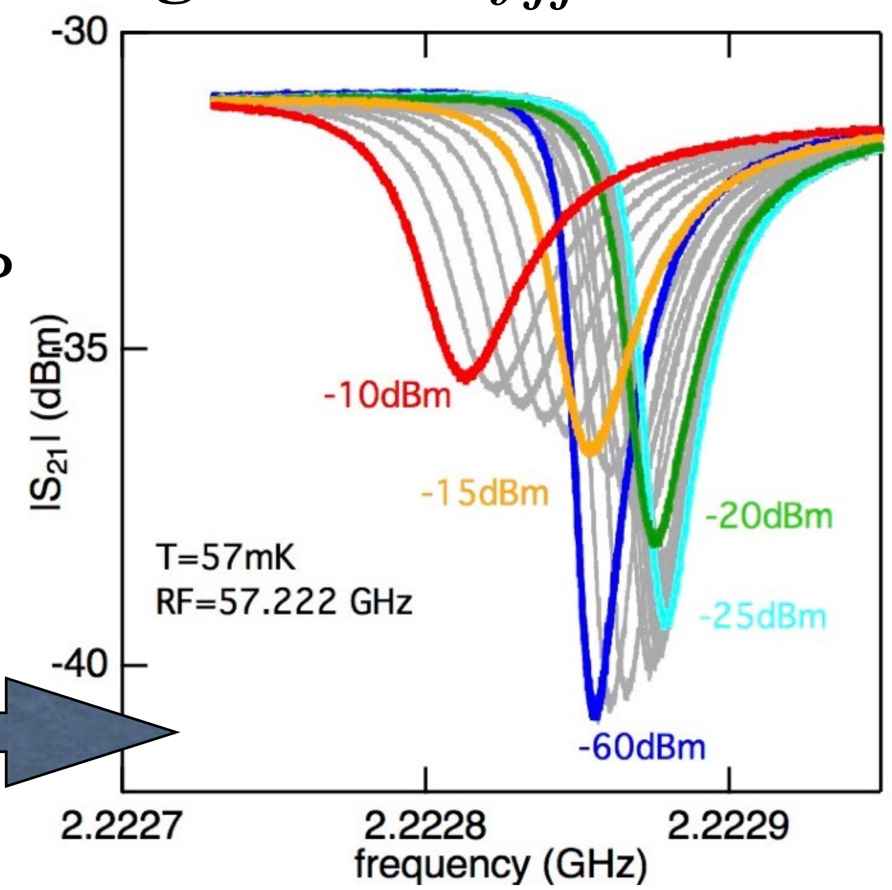


Normal behavior:
f_{JJ} and Q decrease with P

UNPUBLISHED

« TLS » behavior

grAl: $\nu \sim f_{JJ}$ @various P



Sub-gap modes: source of extra-dissipation ?

Probable extra-dissipation scaling with L_k

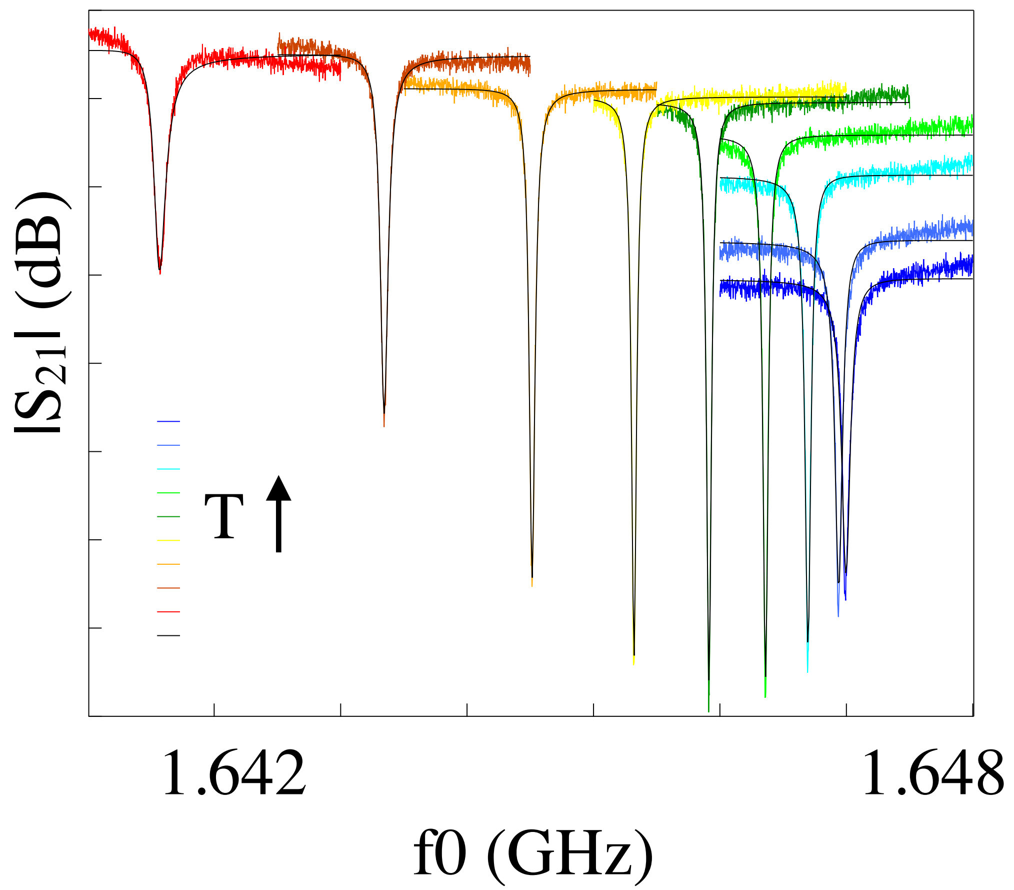
$$L_K = \frac{m}{n_s e^2 d} = \frac{\hbar R_\square}{\pi \Delta}$$

Relevant temperature and energy ?

Guess: two level systems (TLS) approach with population: $\exp(-\beta\Delta_{TLS})$

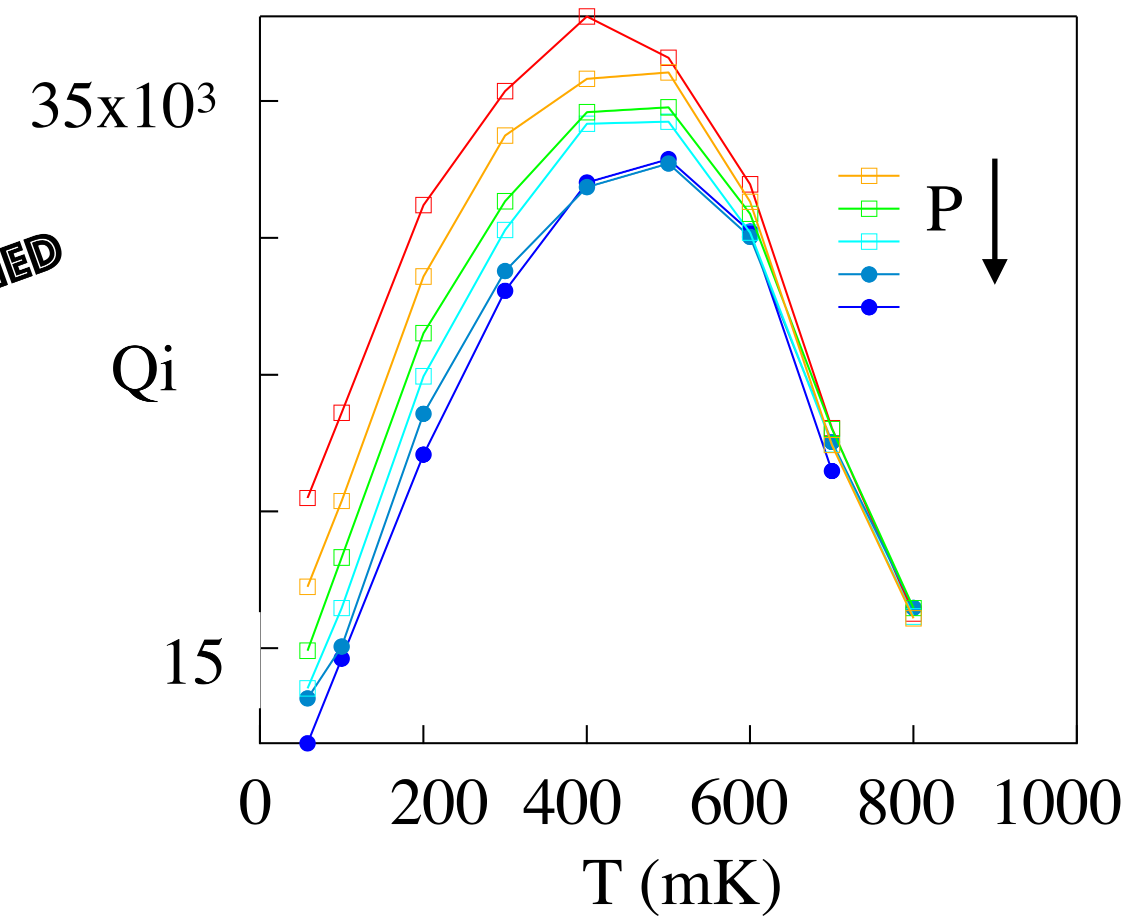
-> because of observation of (strange) TLS behavior …

a:InO: VNA@various T



UNPUBLISHED

a:InO: « TLS » behavior of Q



Sub-gap modes: source of extra-dissipation ?

Probable extra-dissipation scaling with L_k

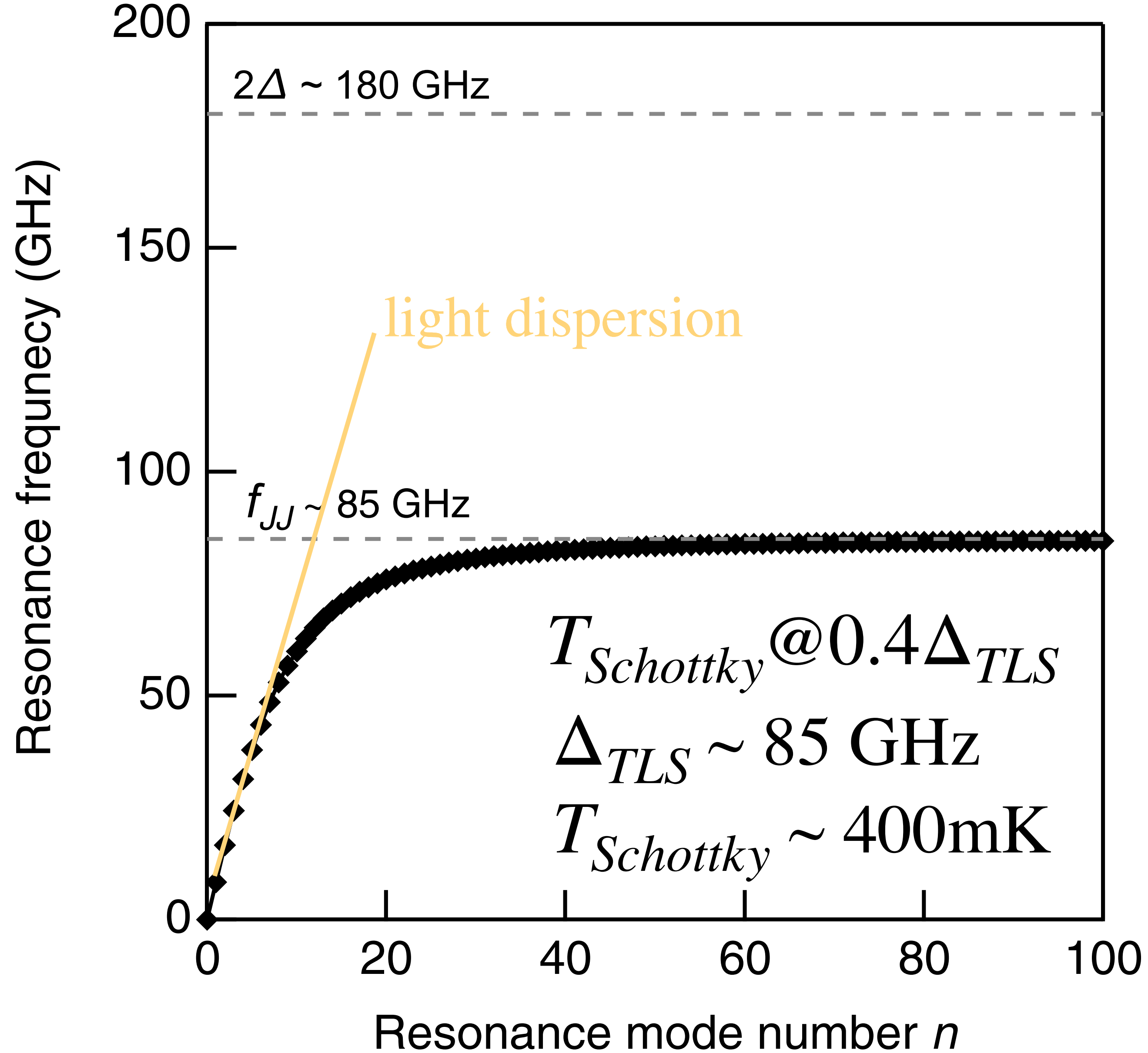
$$L_K = \frac{m}{n_s e^2 d} = \frac{\hbar R_\square}{\pi \Delta}$$

Relevant temperature and energy ?

Two level systems (TLS) approach with modes' dispersion ?

Does the deviation from light dispersion matter ?

- modes are more pack in energy
- extra-momenta needed



Sub-gap modes observed with Kinetic Inductance Detectors (KIDs): source of extra-dissipation in disordered thin superconductors ?

Strong sub-gap modes due to harmonic resonances observed in

- amorphous InO KIDs
- granular aluminum KIDs

Strong sub-gap modes due to harmonic resonances:

- Expected in any thin superconductor
- Originating out-of-equilibrium quasi-particles
- Enhanced for low I_c

➡ Probable source of extra-dissipation scaling with L_k

RELATED TO « ANOMALOUS METAL » ???

TEMPERATURE & ENERGY SCALE ?

RELATED TO STRANGE TLS AND SATURATION OF LIFE TIME ?