Exploring THz electrodynamics of superconductors with Kinetic Inductance Detectors (KIDs)

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

with **gisKID collaborations (Néel, LPSC, IRAM, IPAG)**

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K. Le Calvez and B. Sacépé
A. Benoît, A. Bideaud, M. Calvo, U. Chowdhury, J. Goupy, and A. Monfardini

see poster « on-chip spectrometer with KIDs »

O. Bourrion, C. Hoarau, and A. Catalano

L. Grünhaupt, U. v. Luepke, N. Maleeva, F. Valenti, and I. M. Pop

A. Gomez

+NIKA2 & CONCERTO collaborations

Exploring THz electrodynamics of superconductors with Kinetic Inductance Detectors (KIDs)

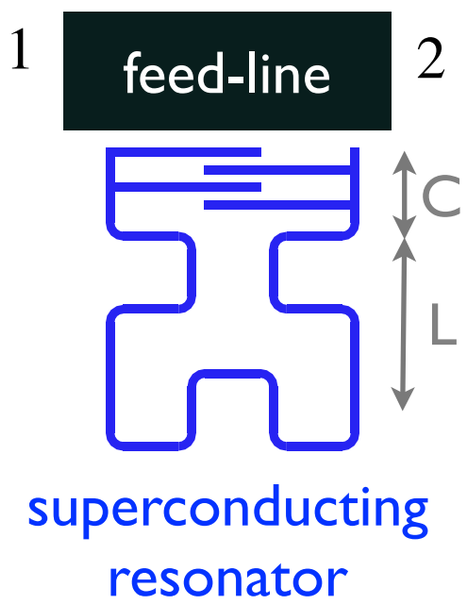
- Working principle of KID
- Astrophysics observations with KIDs
- THz electrodynamics of granular aluminum (grAl)
  - @100 mK, E=0-300 GHz, ΔE ~1GHz=4μeV
  - mode**S** below the superconducting gap!!!
- New detector using sub-gap modes: the SKID

Working principle of KID

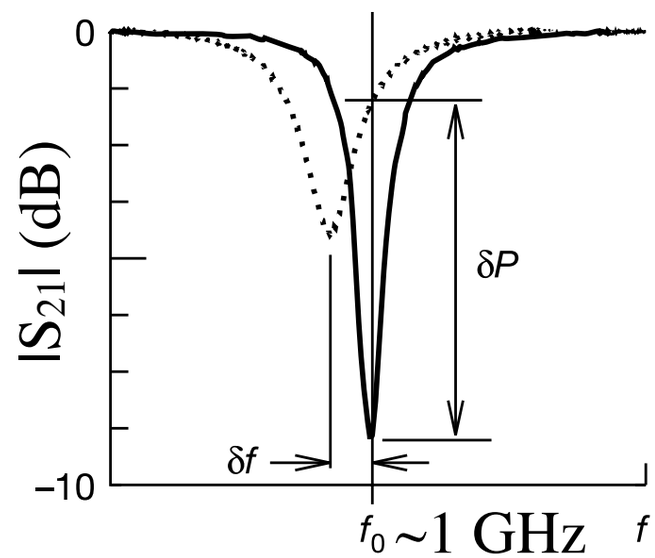
Day et al, Nature 425, 817 (2003)

Planar superconducting LC resonator on an insulating substrate

design



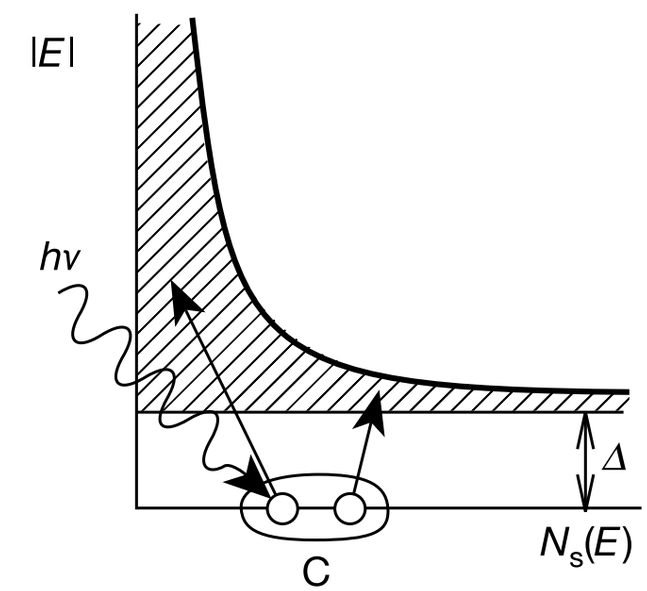
RF-electrical measurement



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

photon detection principle :

$h\nu > 2\Delta$



L ~ kinetic inductance of the superfluid

$L \sim 1/n_s$

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Day et al, Nature 425, 817 (2003)

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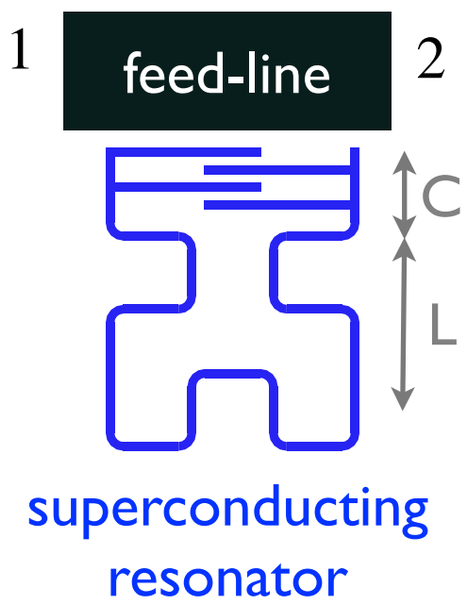

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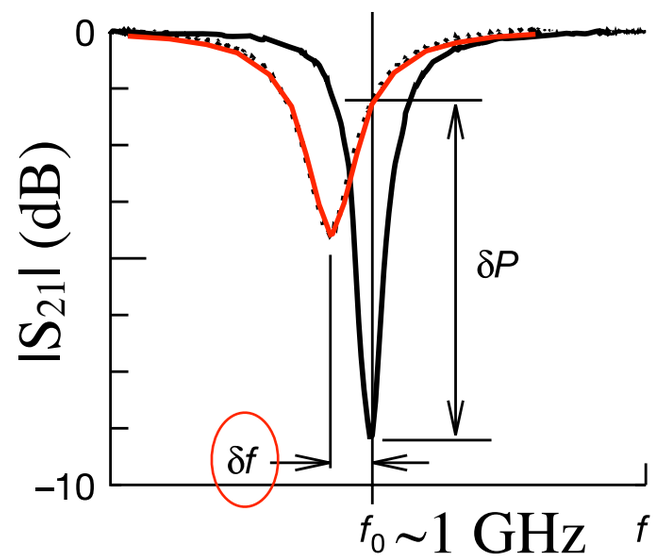

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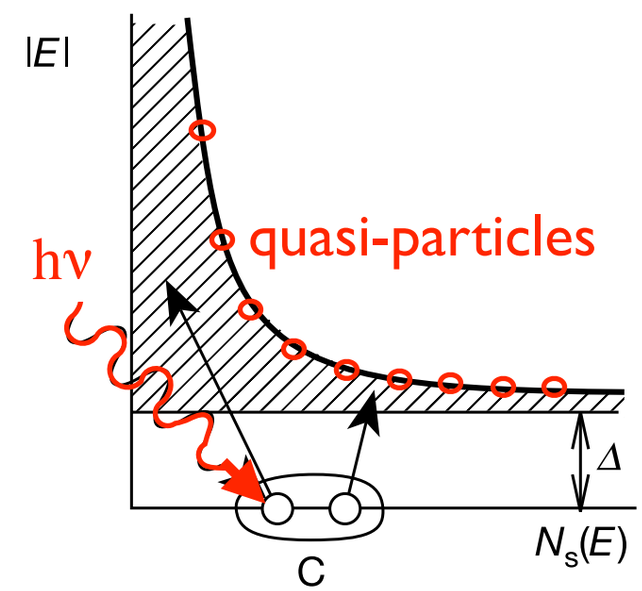


frequency shift: δf due to $n_s \downarrow$

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

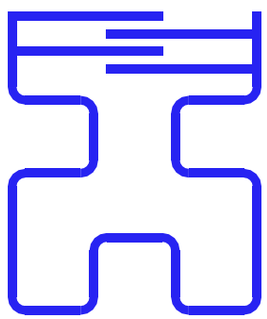
Working principle of KID

Day et al, Nature 425, 817 (2003)

Planar superconducting LC resonator on an insulating substrate

design

1 feed-line

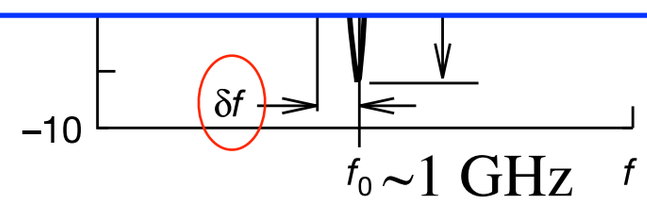


superconducting resonator

=

Kinetic Inductance Detector : KID

detection hν through $\delta f \propto \delta n_{qp} \propto P(h\nu)$

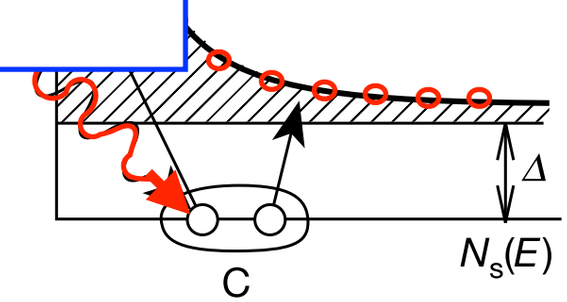


$\mathbf{f_o \sim (LC)^{-1/2}}$

etection principle :

$h\nu > 2\Delta$

quasi-particles



L ~ kinetic inductance of the superfluid

$L \sim 1/n_s$

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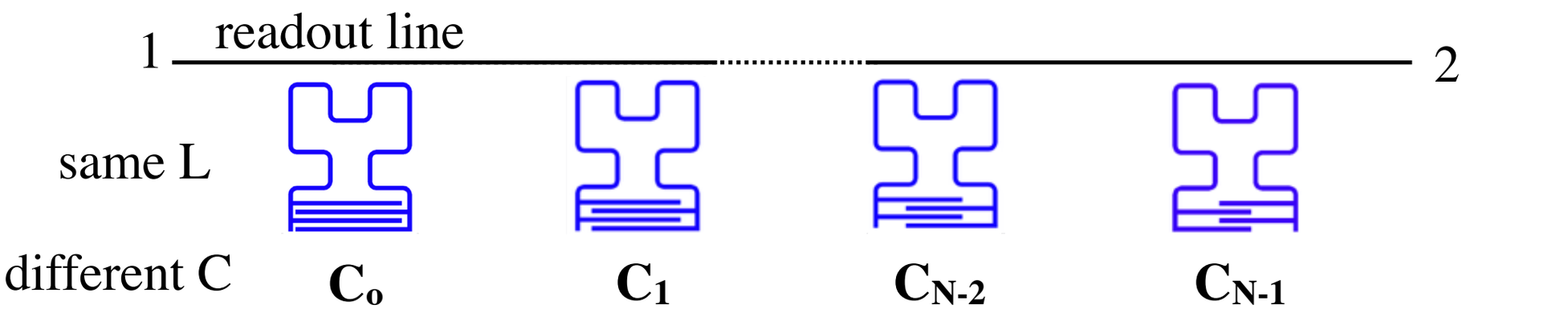
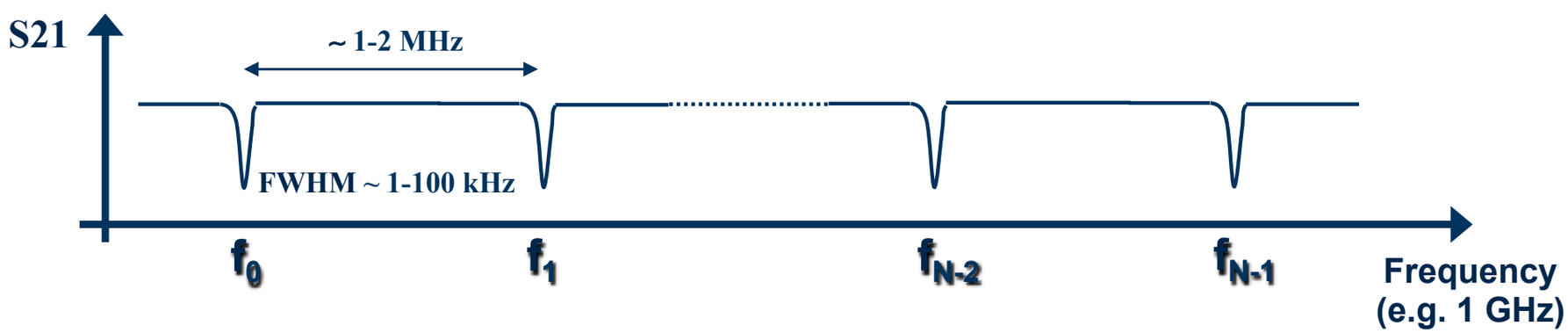
Working principle of KID

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

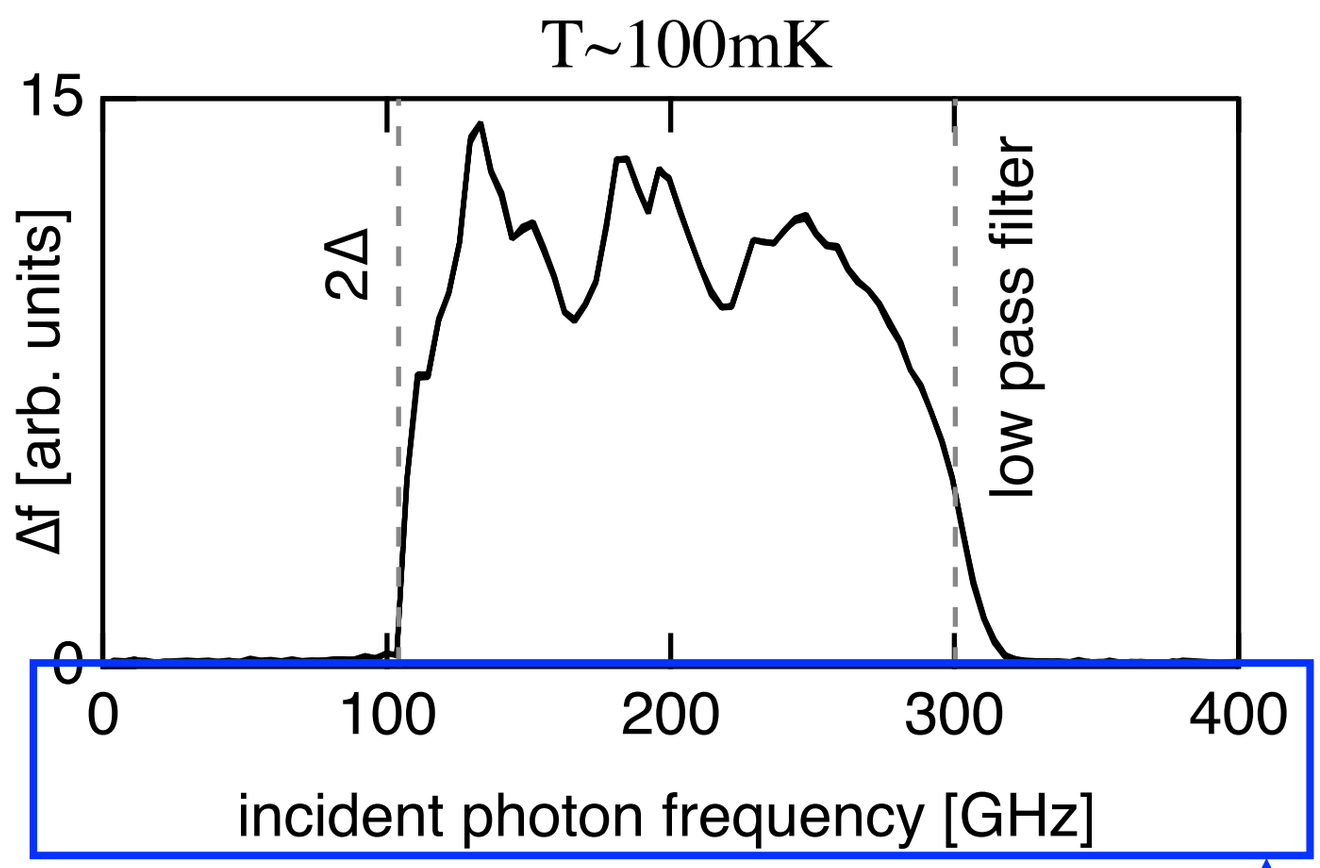


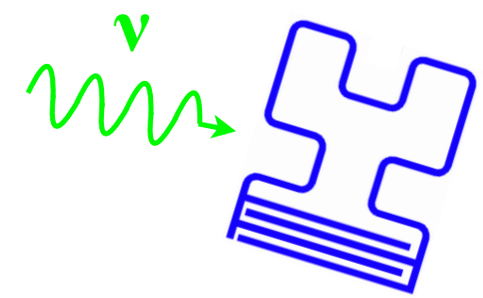


-> <u>one line to address hundreds of detectors</u>

Working principle of KID

Optical response of KID made of **20nm-thick Al**





KID
$h\nu > 2\Delta$

No sub-gap response.

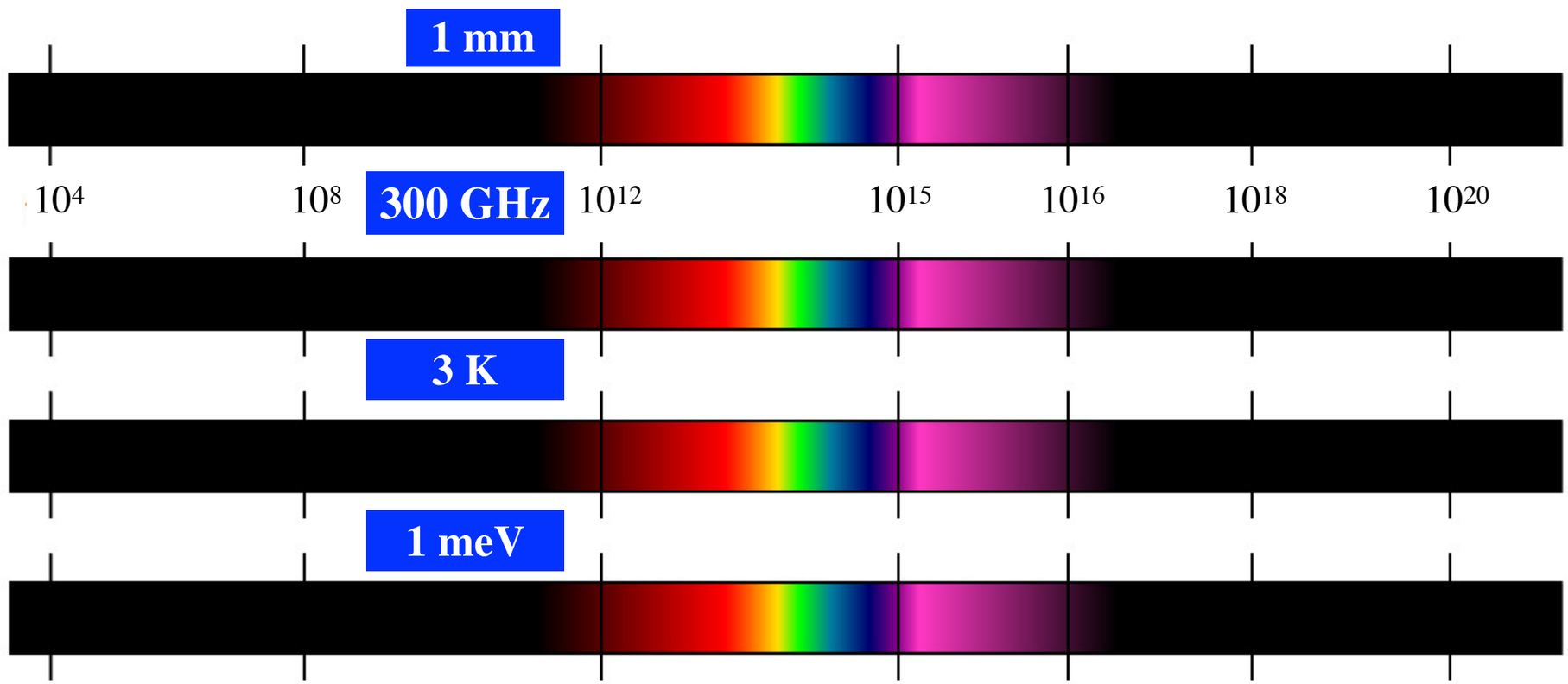
Incoming photons break Cooper pairs.

$\nu_{min} = 2\Delta/h$

Al-KID is a sensitive detector in the THz-range

THz radiations (100 GHz- 10 THz)

	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma ray
Wavelength (m)	10^{3}	10^{-2}	10^{-5}	0.5×10^{-6}	10^{-8}	10^{-10}	10^{-12}
Frequency (Hz)	10^{4}	10^{8}	10^{12}	10^{15}	10^{16}	10^{18}	10^{20}
Temperature* (K)							
Energy (eV)							

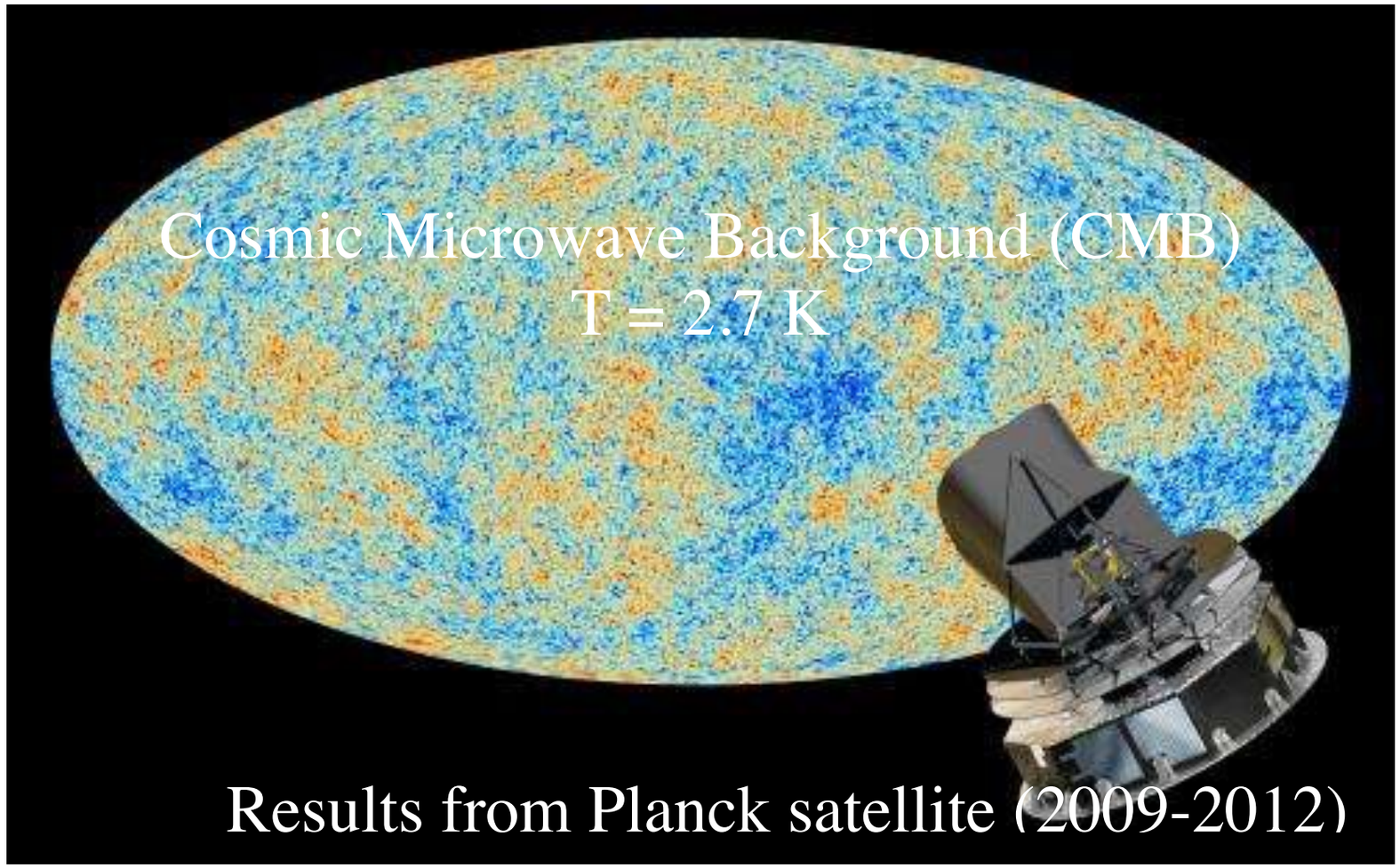


*the black body whose emission is maximum at the corresponding wavelength

Astrophysics observations with KID

Scientific motivations

Did inflation occur soon after the Big Bang ?

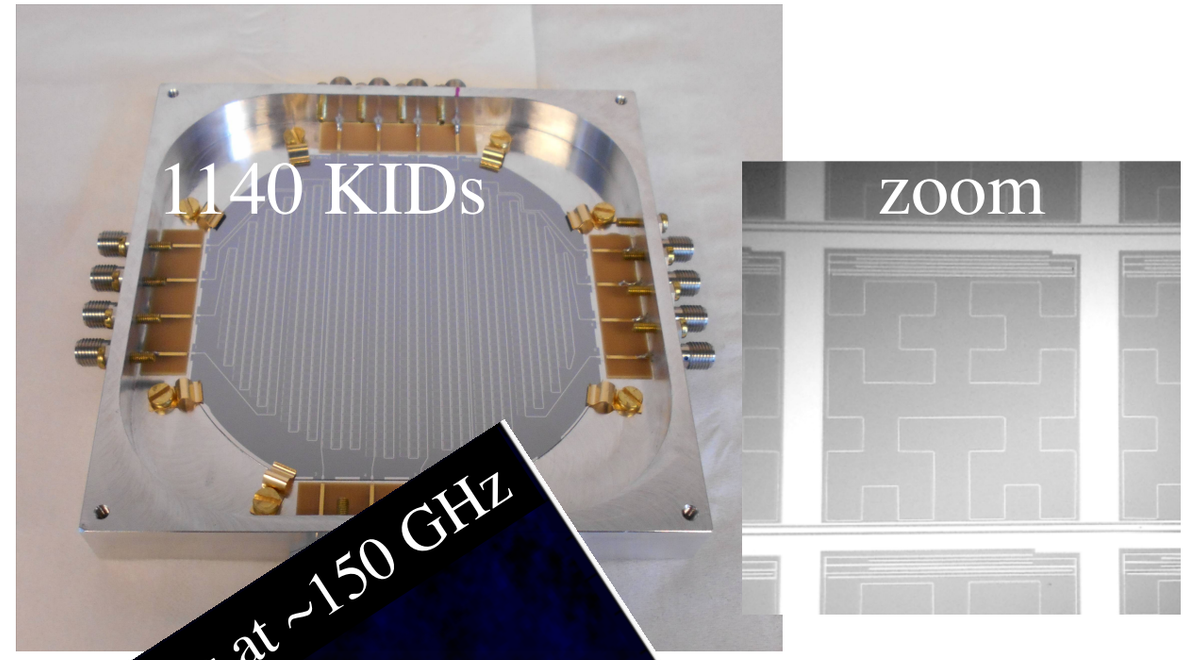


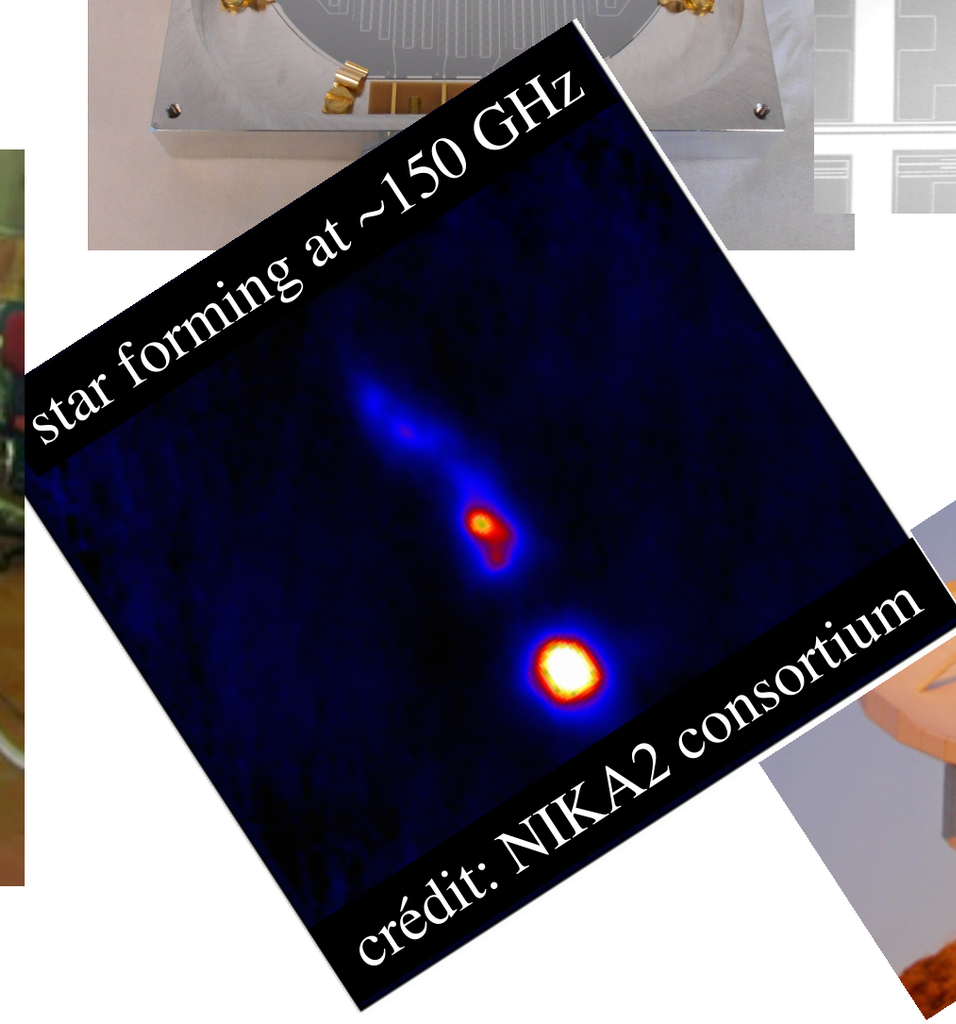
How the Universe structures formed ?

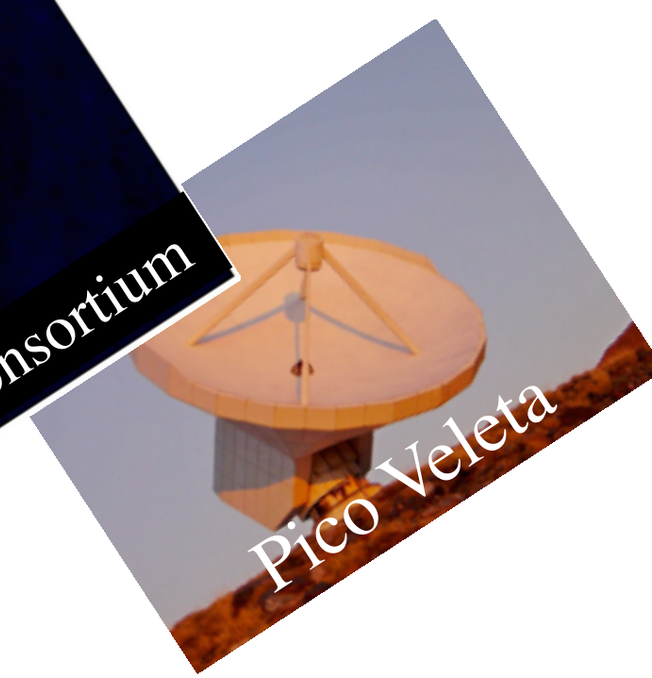
Astrophysics observations with KID

NIKA2: mm-camera
(2800m, Spain)

Installation in 2015

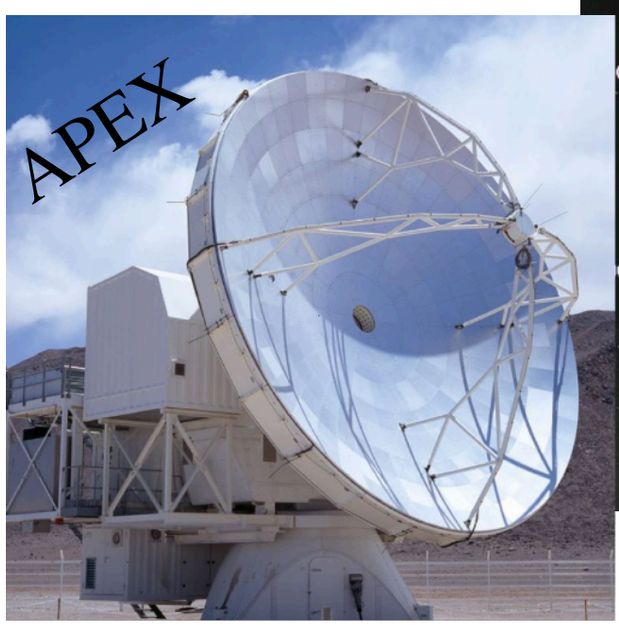


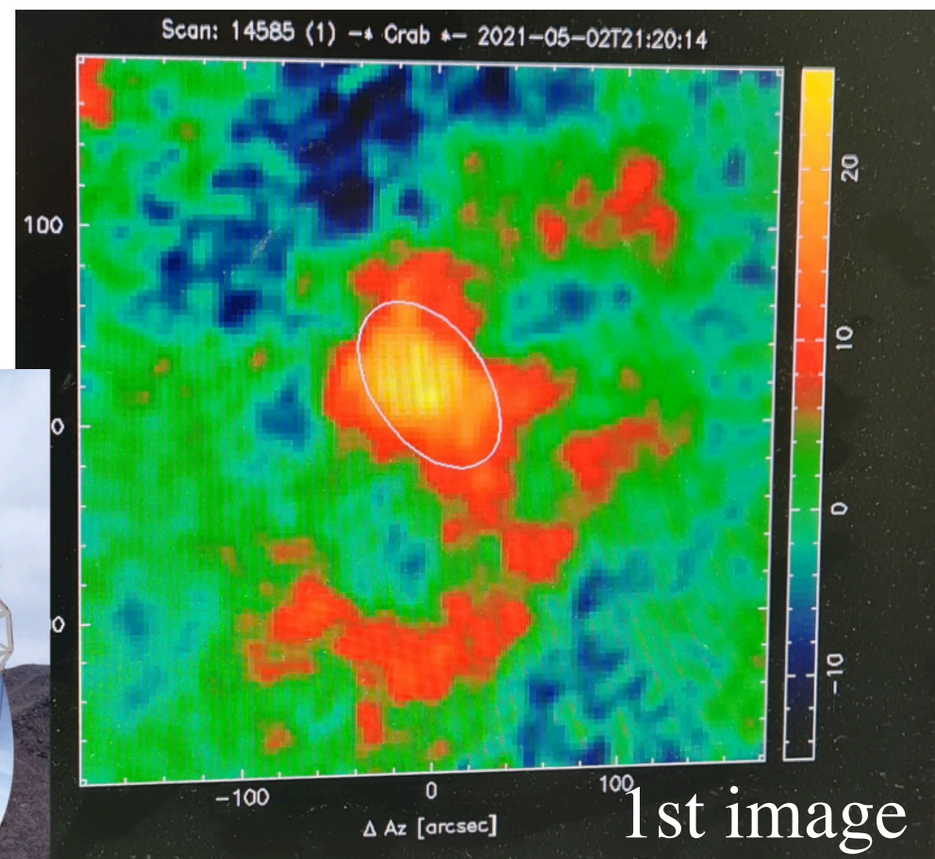




Astrophysics observations with KID

mm-camera
(5100m, Chili)

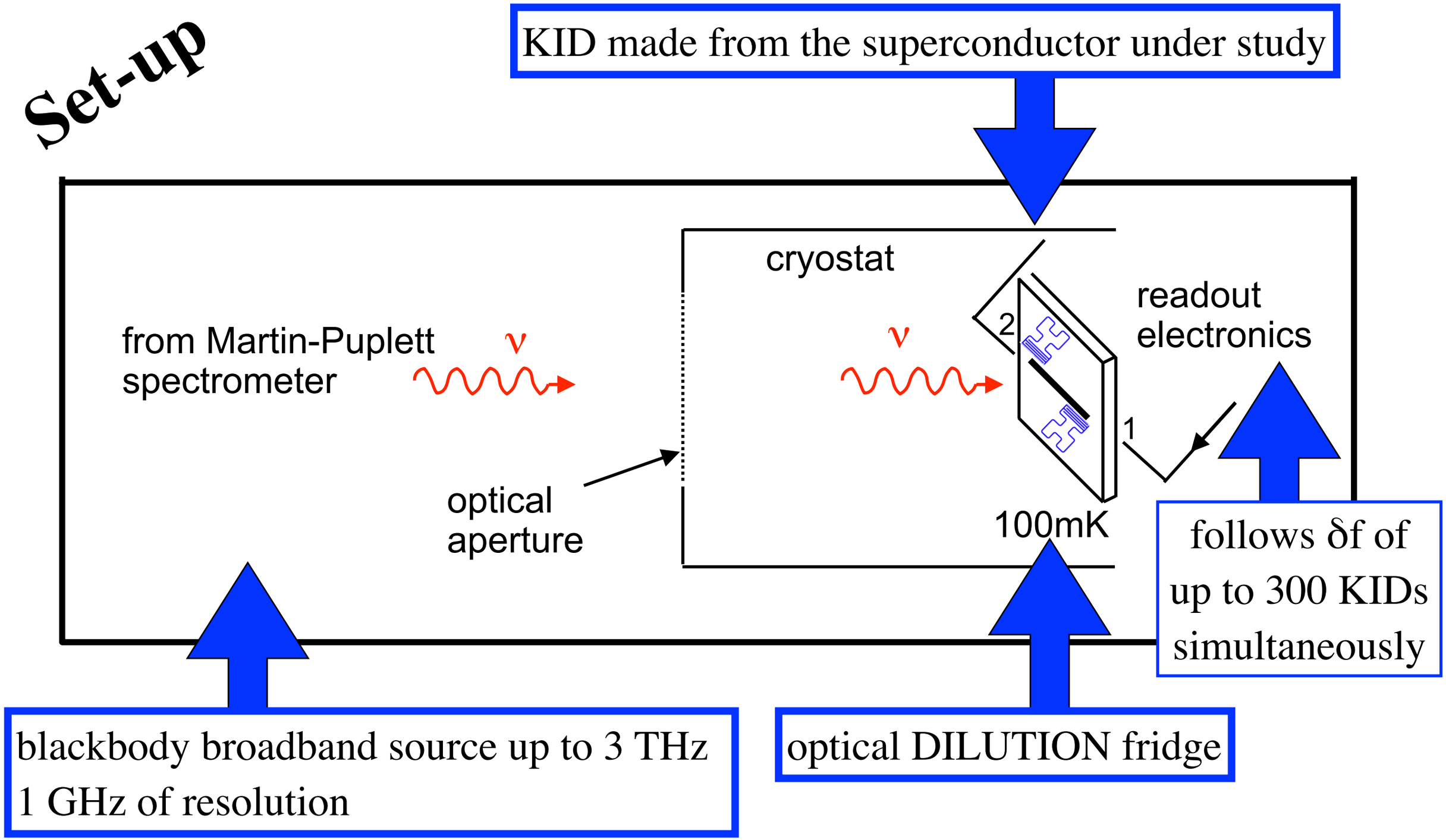




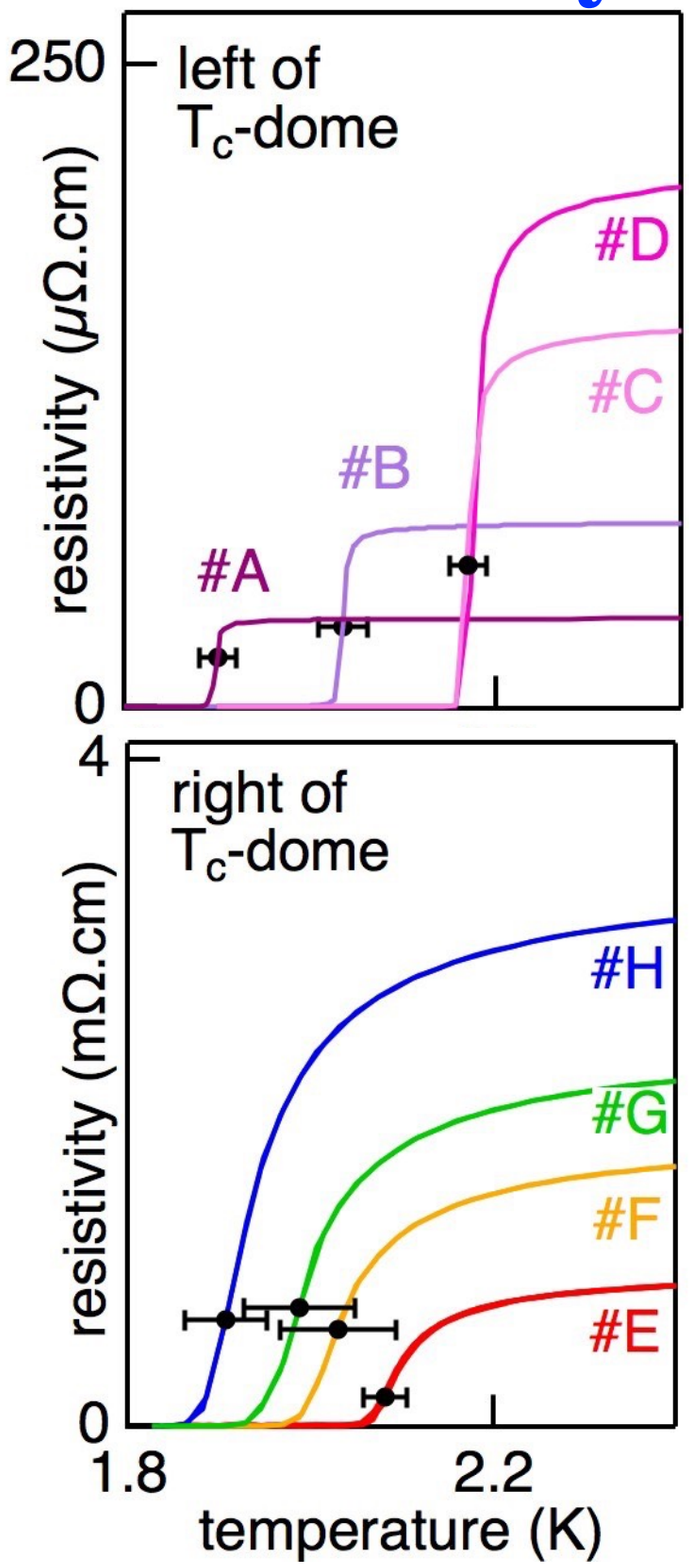
Installation in 2021 despite COVID!!

Electrodynamics of superconductors with KID

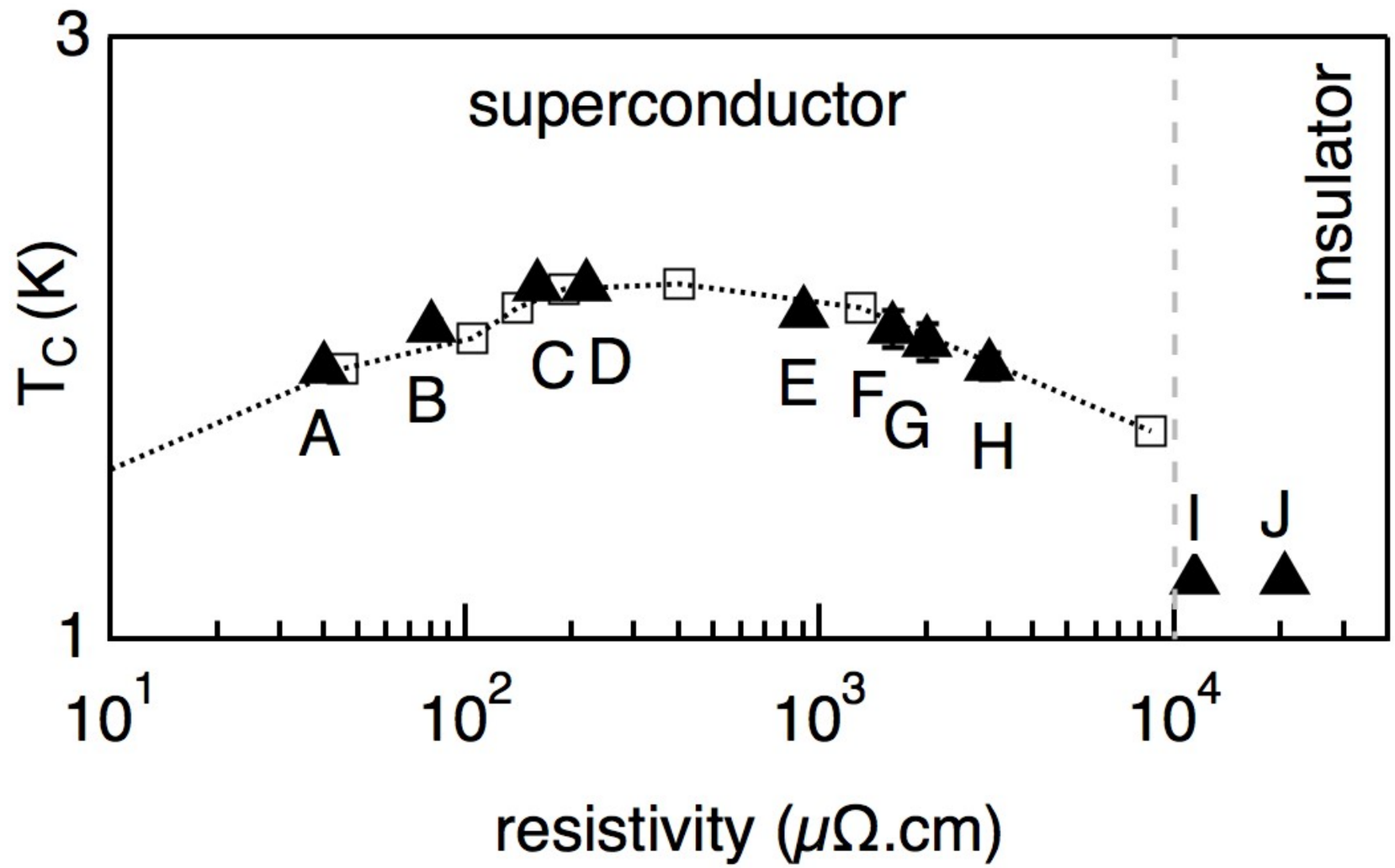
Set-up



THz electrodynamics of granular aluminum (grAl)



Tc-dome



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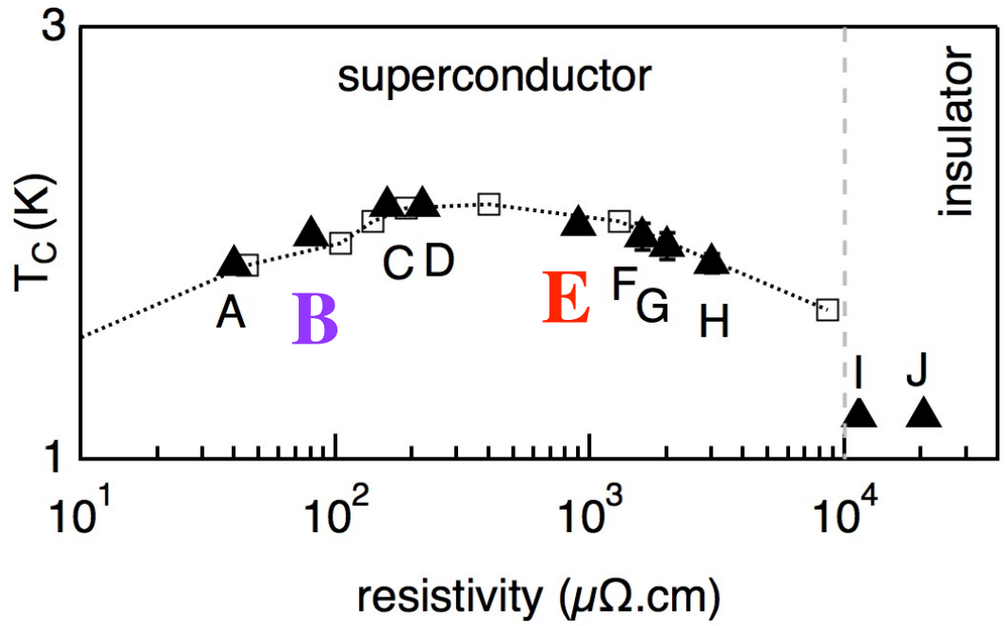
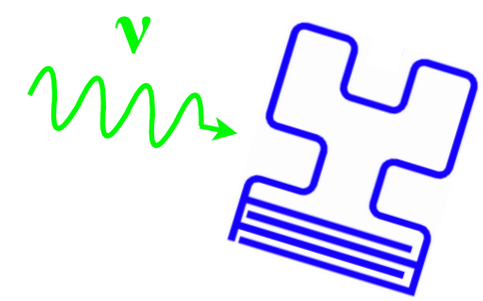
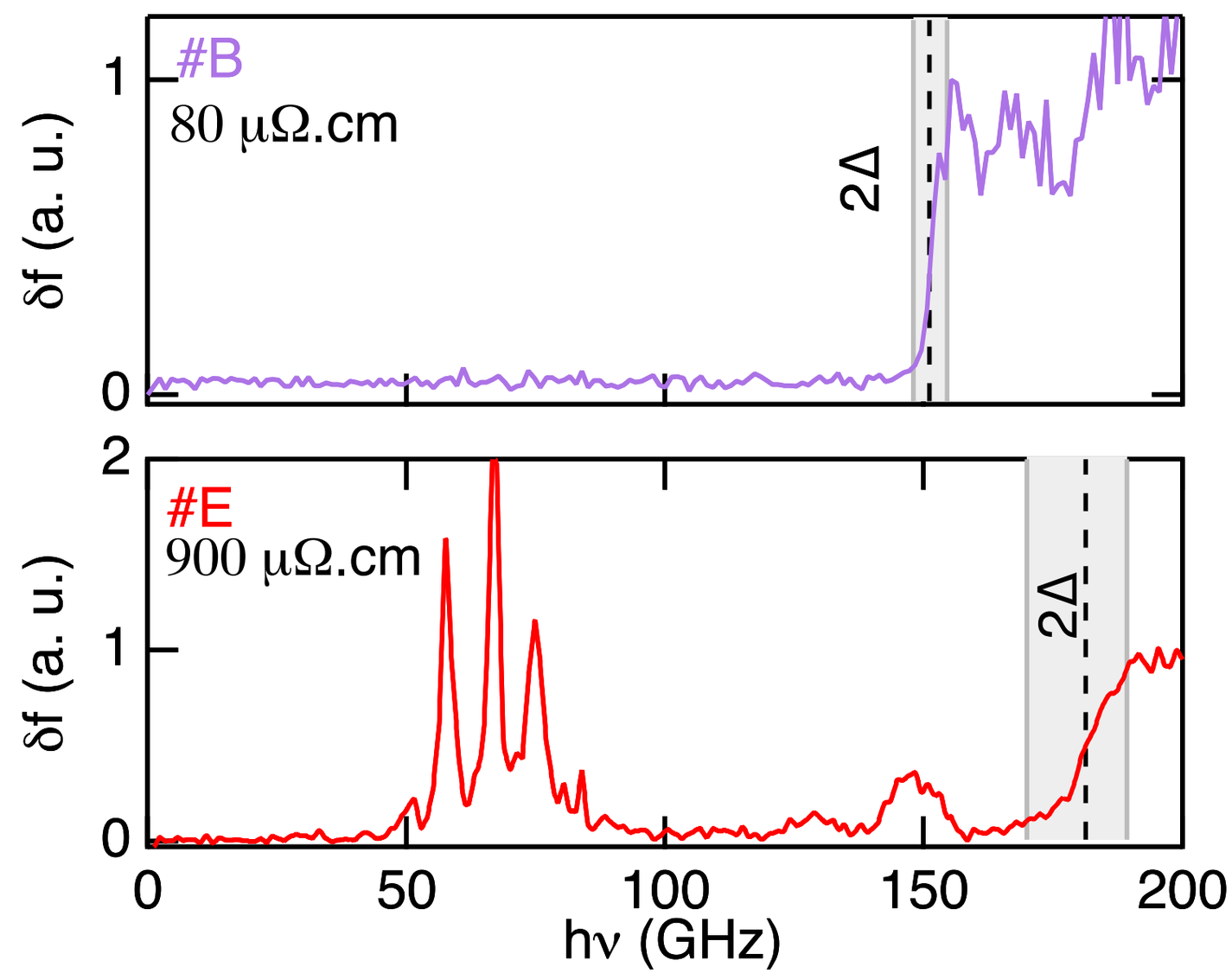


$$\frac{\delta f}{f} \sim \frac{\delta n_s}{n_s} \sim \left(\frac{I}{I^*}\right)^2$$



T ~ 100mK



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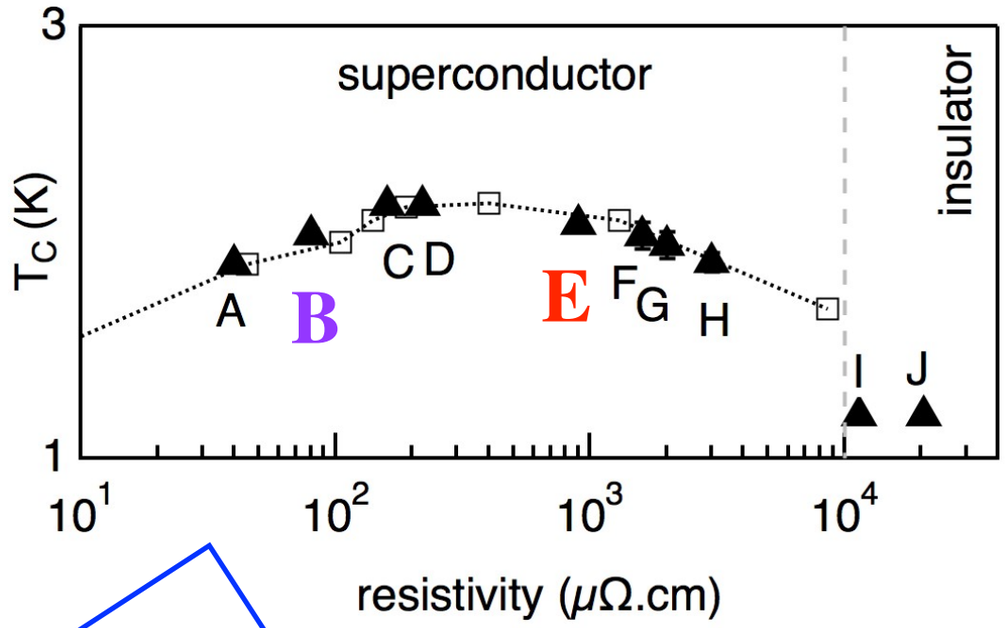

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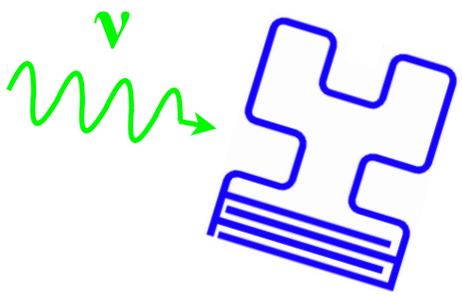

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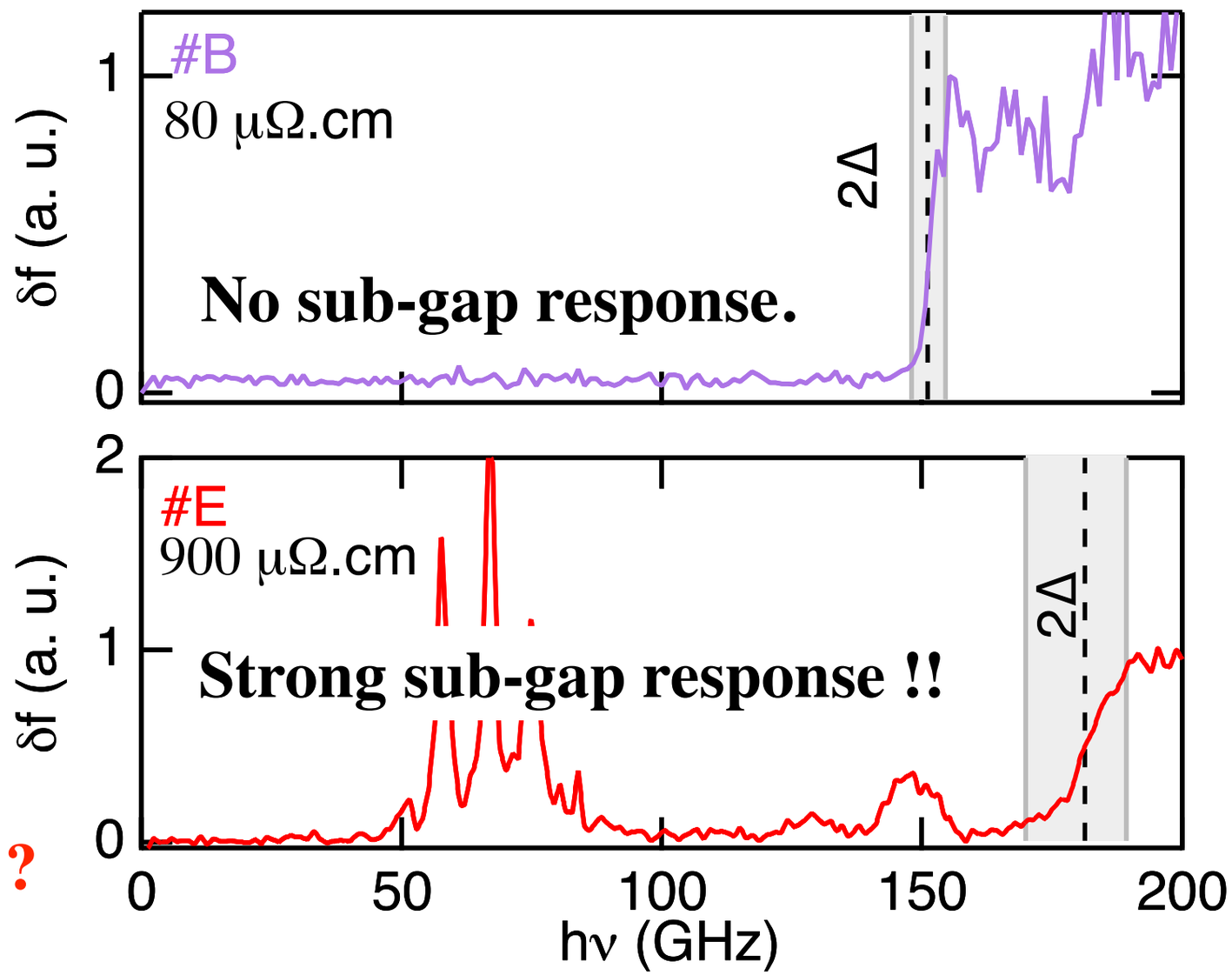

KID
hν > 2Δ

Incoming photons break Cooper pairs.

SKID

"S" for Sub-gap

Incoming photons reduce the superfluid density (textbook),

BUT **origin of the sub-gap modes ?**

THz electrodynamics of granular aluminum (grAl)

Origin of the sub-gap modes ?

Excess of optical absorption in superconductors below 2Δ interpreted as:

The **Higgs mode** in disordered superconductors close to a quantum phase transition, D. Sherman and al, Nature Physics 11, 188–192 (2015).

Optical signatures of the superconducting **Goldstone mode** in granular aluminum: experiments and theory, U. S. Pracht and al, Phys. Rev. B 96, 094514 (2017).

Superconducting order parameter

$$|\Psi| e^{i\theta}$$

amplitude fluctuations

phase fluctuations

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Superconducting order parameter

$$|\Psi| e^{i\theta}$$

amplitude fluctuations **phase fluctuations**

KID-technique:
unprecedented energy resolution
unveiled two types of modes

previous publications	KID-technique
T_{base} = 1.6K	T_{base} < 100mK
hν = 60-700 GHz	hν = 0-400 GHz
Δν ~ 20 GHz	Δν = 1 GHz (4μeV)

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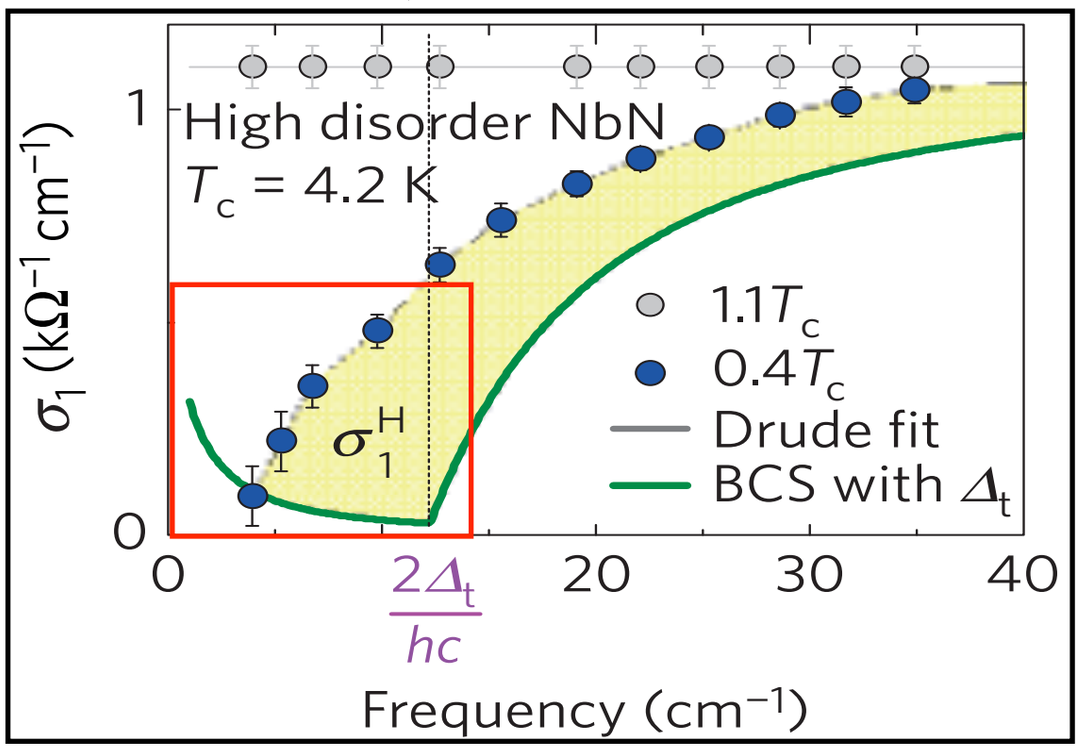
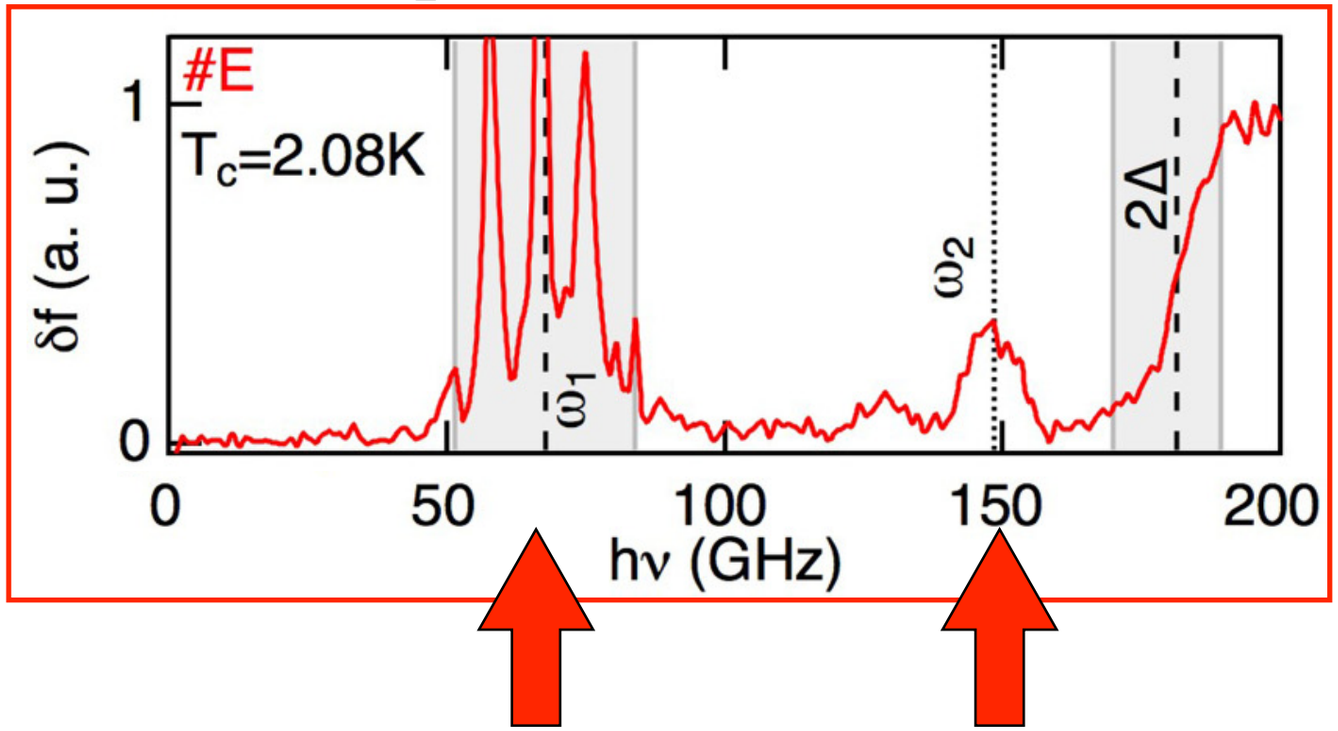


KID-technique: T=100mK~0.05T_c

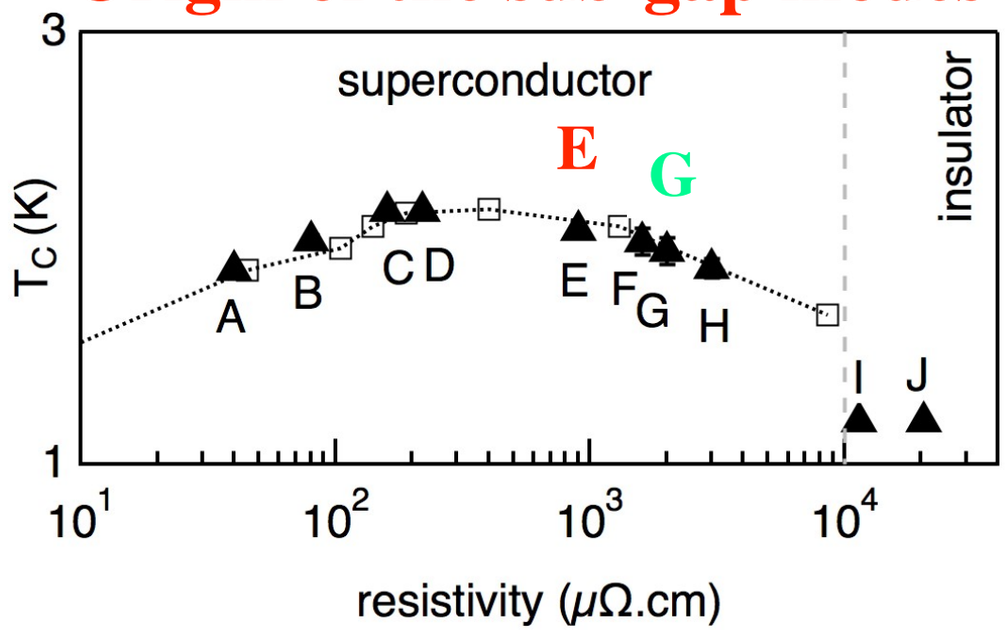


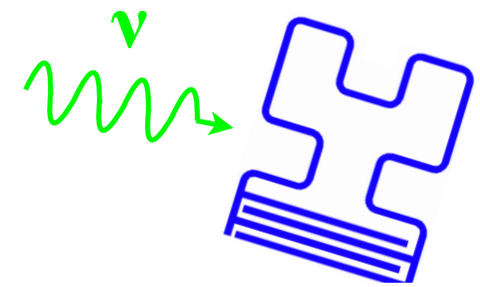
two sub-gap modes: ω_1, ω_2

different energy evolution with disorder

THz electrodynamics of granular aluminum (grAl)

Origin of the sub-gap modes ?





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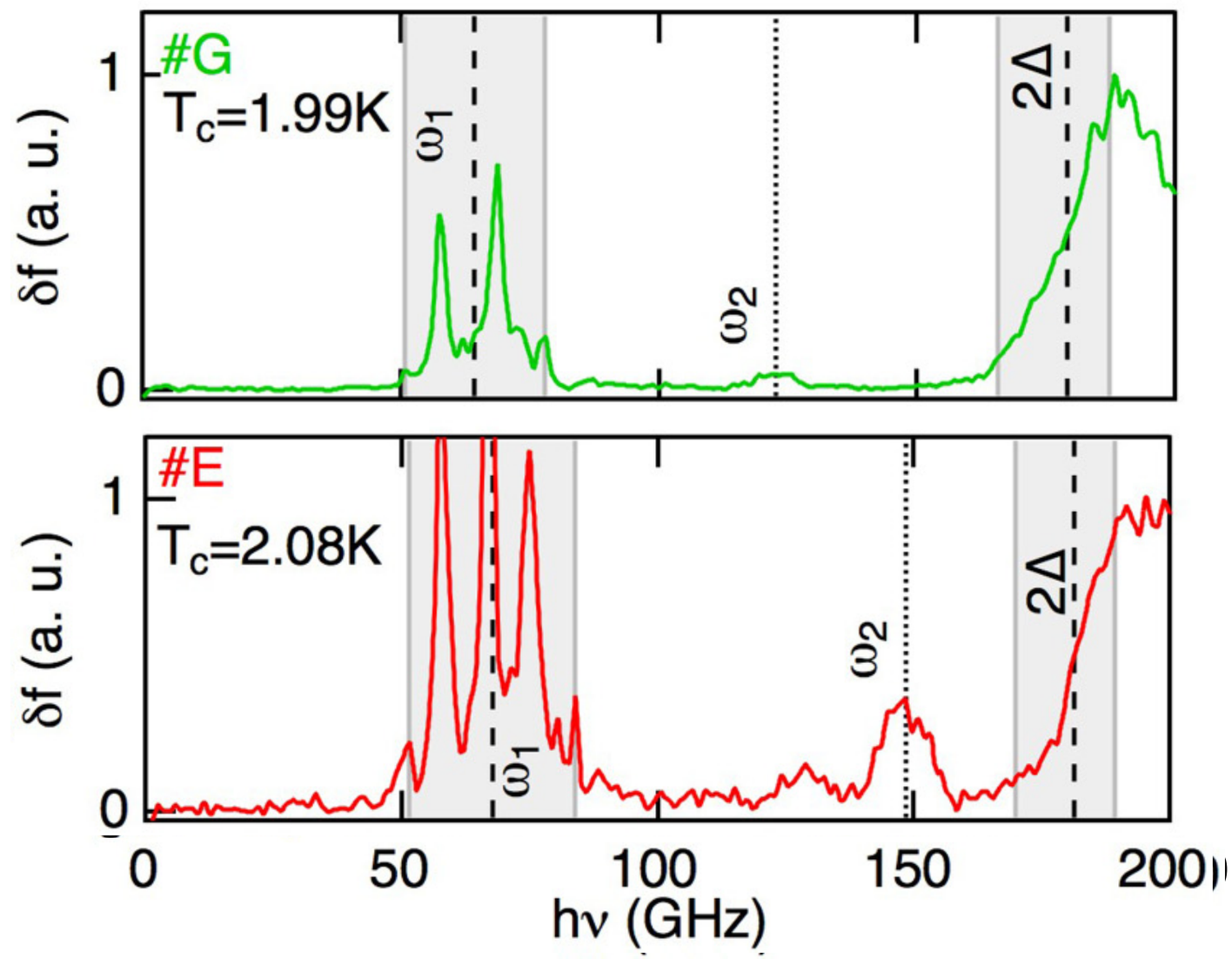

two sub-gap modes:

- ω_1 scales with Δ
- ω_2 scales with phase stiffness

probable two phases modes:

- ω_1 = JJ-plasma frequency?
- ω_2 = Carlson-Goldman mode?

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

THz electrodynamics of granular aluminum (grAl)

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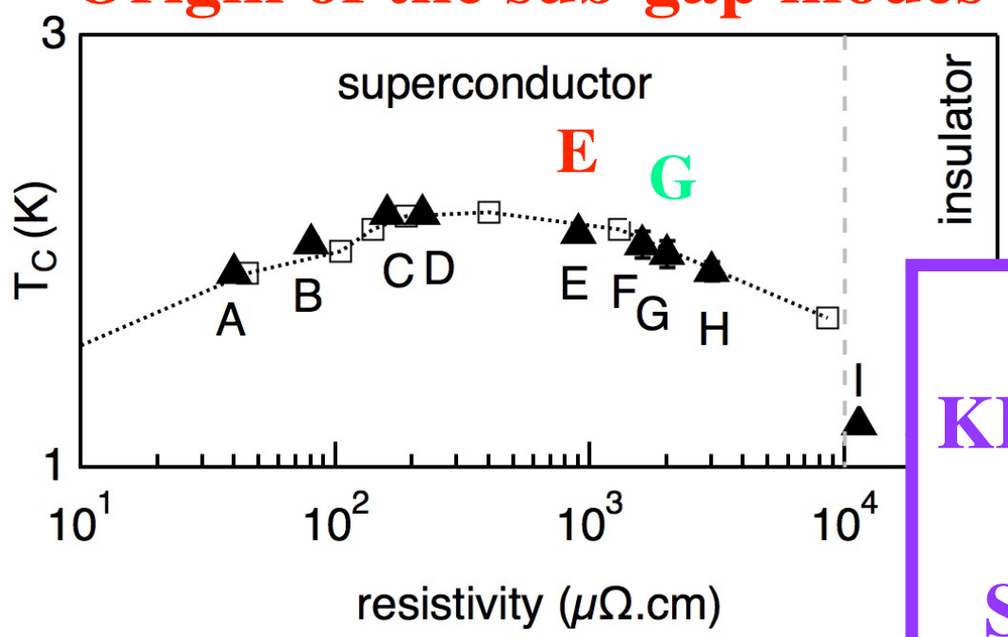

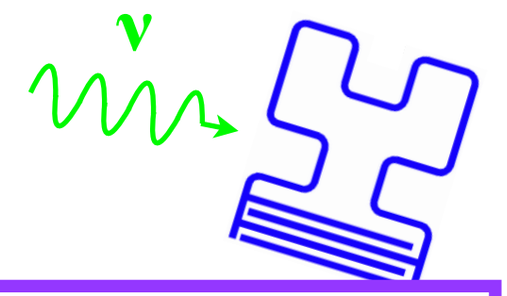

T ~ 100mK

BCS: $2\Delta = 3.52 k_B T_c$

KID: $\nu_{min} = 2\Delta/h$ **imposes operating** $T < T_c/10$

SKID: Sub-gap Kinetic Inductance Detector removes T **scaling with** ν_{min}

two sub-gap modes:

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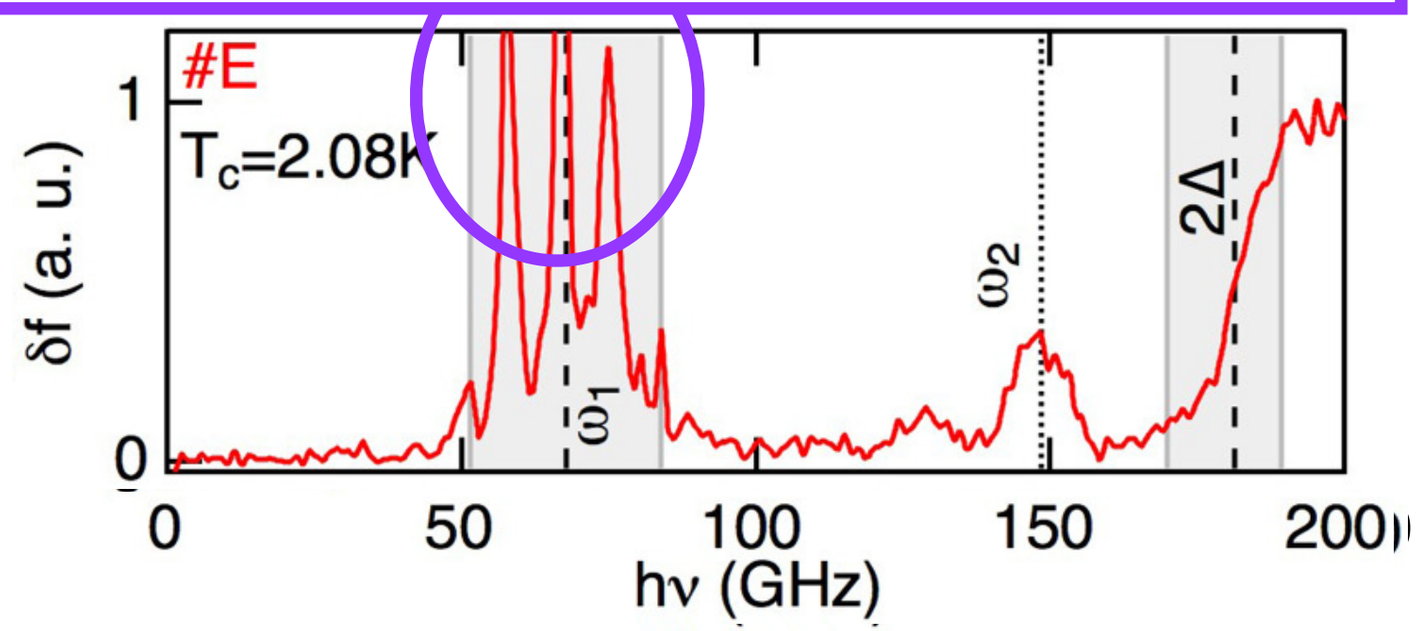
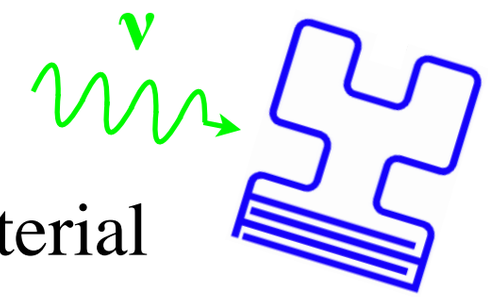


more in: F. Levy-Bertrand et al, Phys. Rev. B 99, 094506 (2019).

The SKID concept
Sub-gap Kinetic Inductance Detector

SKID removes the constraint T <-> $\nu_{min} = 2\Delta/h$

SKID is a KID made of a specific superconducting material



a:InOx

Tunable sub-gap radiation detection with superconducting resonators
O. Dupré et al, Supercond. Sci. Technol. 30, 045007 (2017).

ν = 7-9 GHz
NEP ~ 10^{-15} W/Hz$^{0.5}$

grAl

Subgap Kinetic Inductance Detector Sensitive to 85-GHz Radiation
F. Levy-Bertrand et al, Phys. Rev. Applied 15, 044002 (2021).

ν = 85 GHz
NEP ~ 10^{-16} W/Hz$^{0.5}$

Conclusion

- Kinetic Inductance Detector: versatile tool

- NEW technique to probe electrodynamic of superconductors
  100mK, ΔE ~1GHz=4μeV=0.04cm^{-1}
- THz electrodynamics of granular aluminum (grAl)
  two types of sub-gap modes, probable phase fluctuations
- NEW detector concept the SKID… useful ?

Related publications:

F. Levy-Bertrand et al, Phys. Rev. B 99, 094506 (2019). [PRB, ArXiv]
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THANK YOU

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