Electrodynamics of granular aluminum from superconductor to insulator: observation of collective superconducting modes

Florence Levy-Bertrand

work done with

A. Monfardini's group

MagSup team members

A. Gomez

I. Pop's group

B. Sacépé's group

Outline

- Introduction :
  collective superconducting modes

NEW

- Optical spectroscopy with superconducting resonator

- Study of granular aluminum versus ρ:

  - phase diagram SIT: Δ, T_c, J, E_c
  - various sub-gap optical absorptions for $h\nu<2\Delta$

Superconducting collective modes

Superconductivity: condensate of electrons with a *unique* phase

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

breaking the rotational U(1) symmetry.

	$|\Psi|$-fluctuation	θ-fluctuation
	"Higgs" mode	"Goldstone" mode
at q=0	$E=2\Delta$	$E=0$ or $\omega_{plasma}{}^{*} \gg \Delta$

Both modes optically inactive in conventional superconductor

BUT…

*with Coulomb interaction

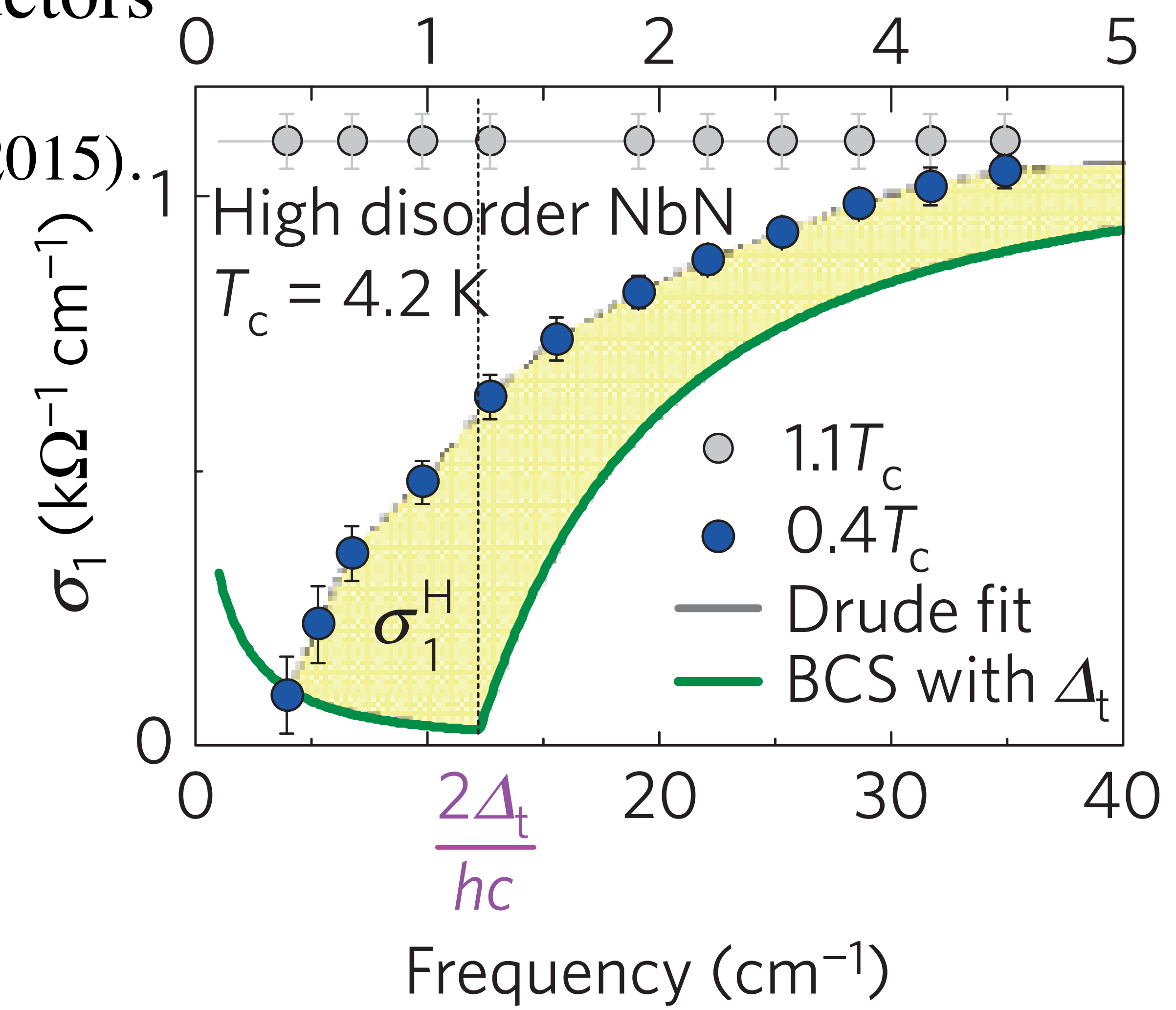
Below 2Δ: Higgs or Goldstone mode?

Excess of optical absorption below 2Δ interpreted as:

nature physics

The Higgs mode in disordered superconductors close to a quantum phase transition

D. Sherman and al, Nature Physics 11, 188–192 (2015).



PRB

Optical signatures of the superconducting Goldstone mode in granular aluminum: experiments and theory

U. S. Pracht and al, Phys. Rev. B 96, 094514 (2017).

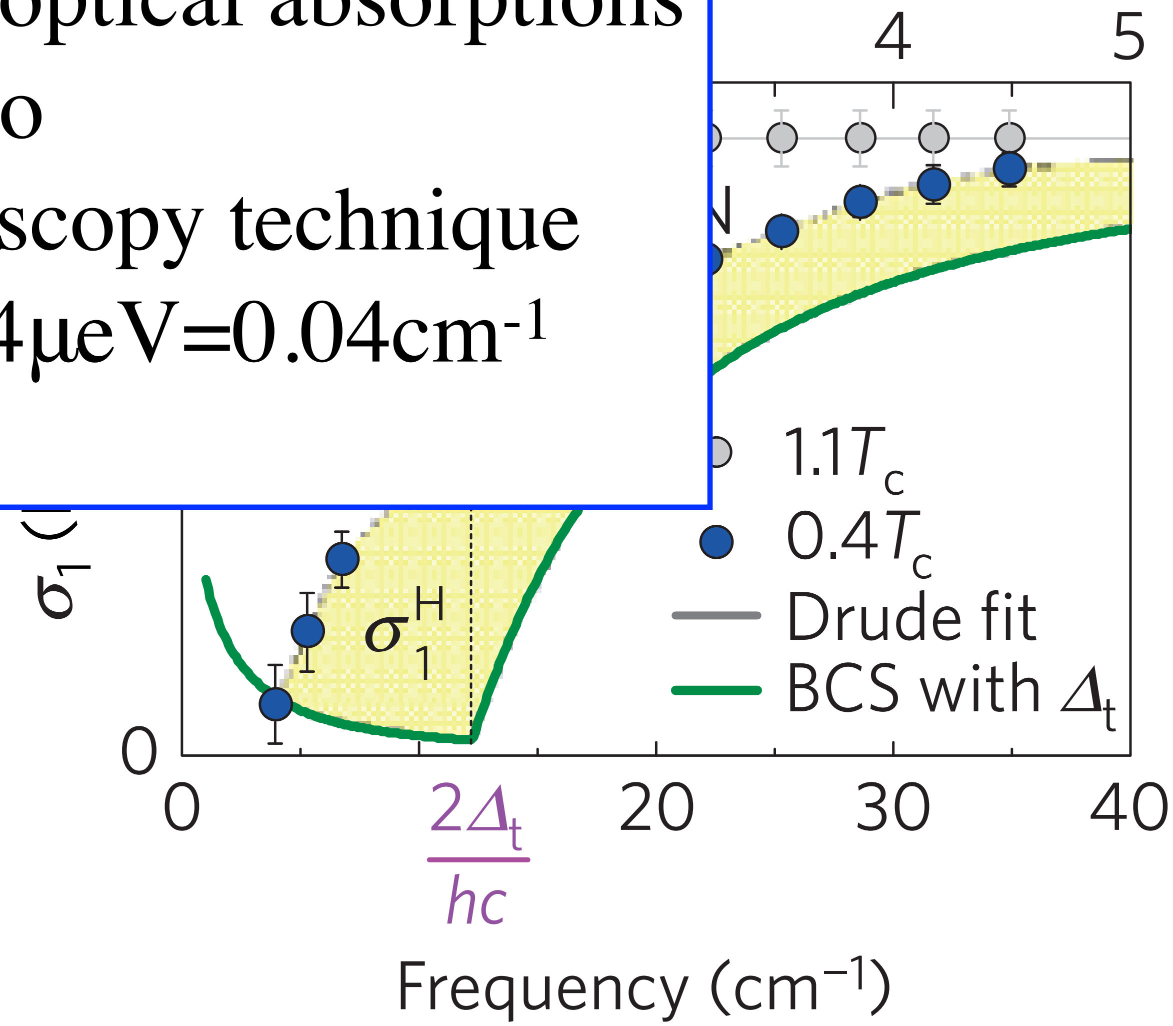
Below 2Δ: Higgs or Goldstone mode?

Ex as:

nature physics

The Higgs m
close t
D. Sherman an

present study (on grAl)
various resolved sub-gap optical absorptions
thanks to
a NEW optical spectroscopy technique
100mK, $\Delta E \sim 1GHz = 4\mu eV = 0.04cm^{-1}$



PRB

Optical signatures of the superconducting Goldstone mode
in granular aluminum: experiments and theory

U. S. Pracht and al, Phys. Rev. B 96, 094514 (2017).

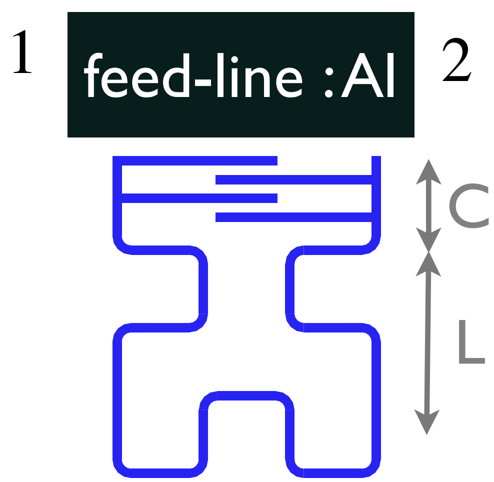
Optical spectroscopy with superconducting resonators

KIDs
hν > 2Δ

RLC resonator:
design and electrical measurement

photon detection principle :
hν > 2Δ

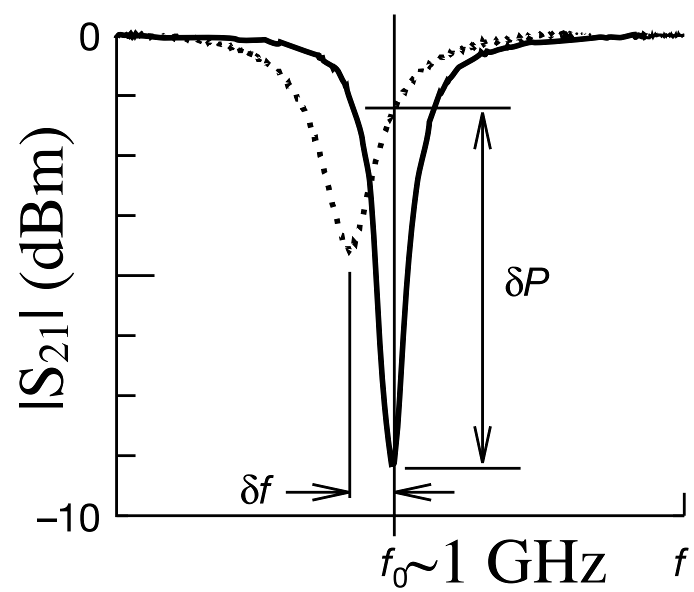
from Day et al, Nature 425, 817 (2003)



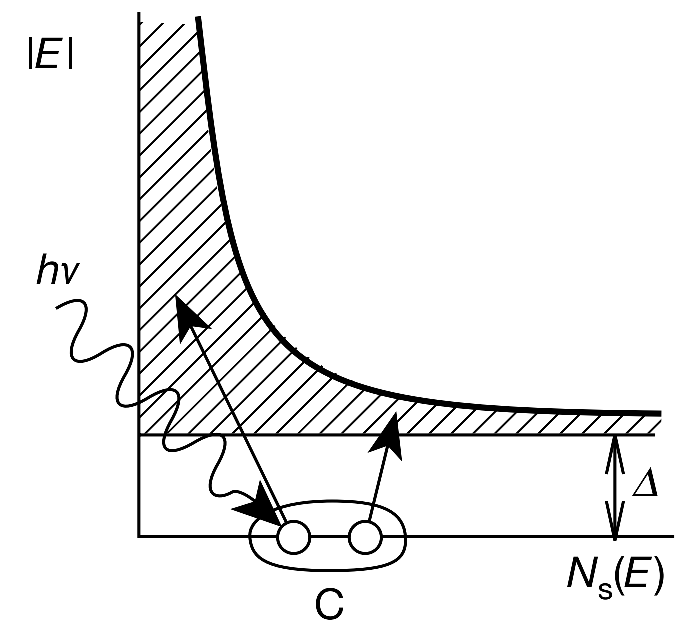
superconducting resonator

thin film ~tens of nm

substrate=Si, MgO, Al_2O_3,..



$f_o = (LC)^{-1/2}$



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

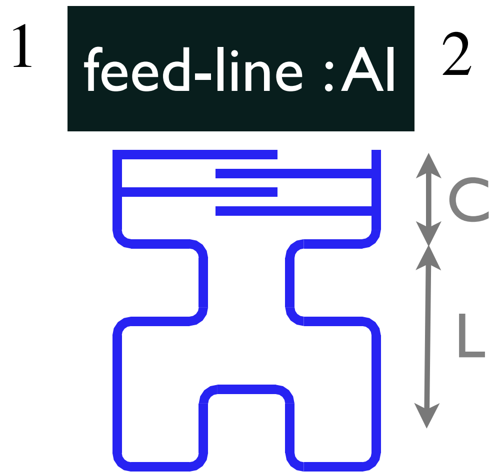
Optical spectroscopy with superconducting resonators

KIDs $h\nu > 2\Delta$

RLC resonator:
design and electrical measurement

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

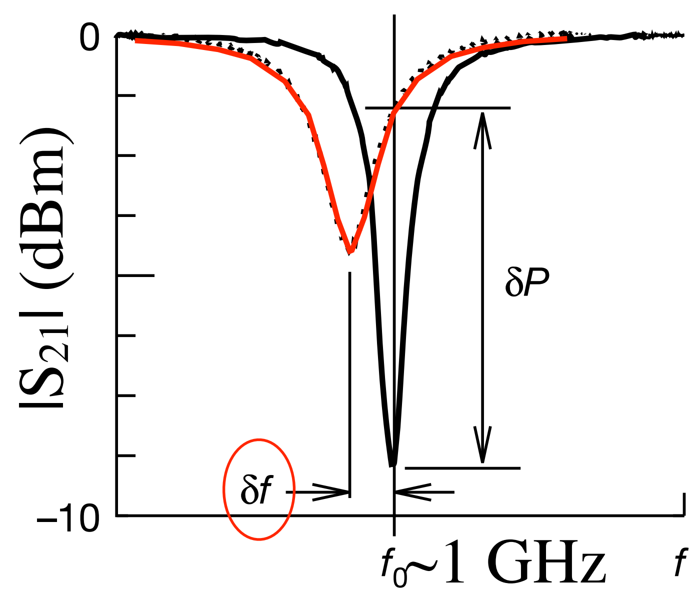
from Day et al, Nature 425, 817 (2003)



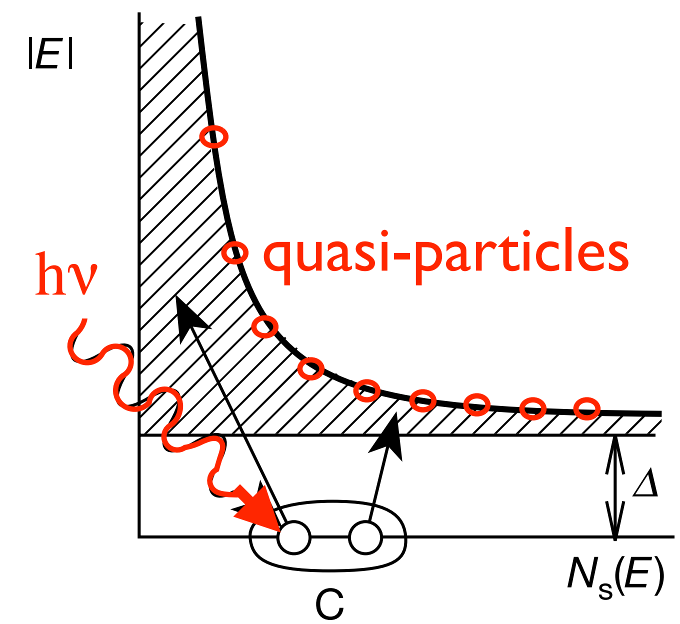
superconducting resonator

thin film ~tens of nm

substrate=Si, MgO, Al_2O_3,..



$f_o = (LC)^{-1/2}$



frequency shift: δf due to n_s↓

Q-factor↓ due to dissipation↑

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

Optical spectroscopy with superconducting resonators

KIDs
$h\nu > 2\Delta$

=

Kinetic Inductance Detector : KID

detection <u>$h\nu > 2\Delta$</u> through δf

RL

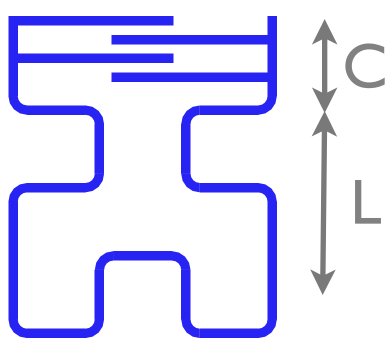
design and e

ion principle :

2Δ

03)

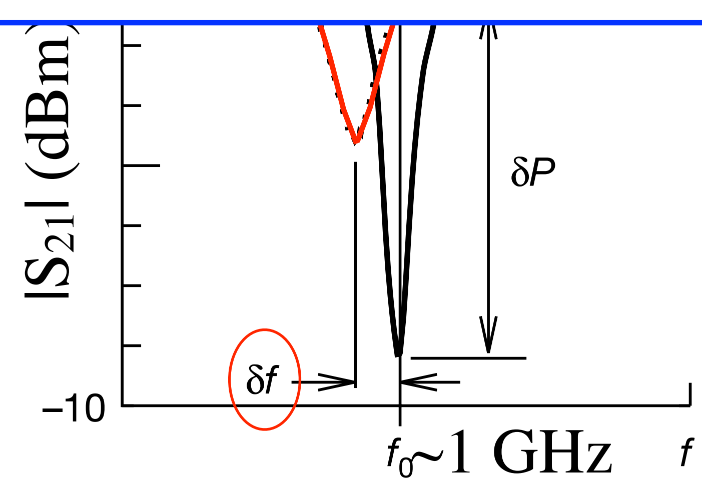
1 feed-line : Al 2



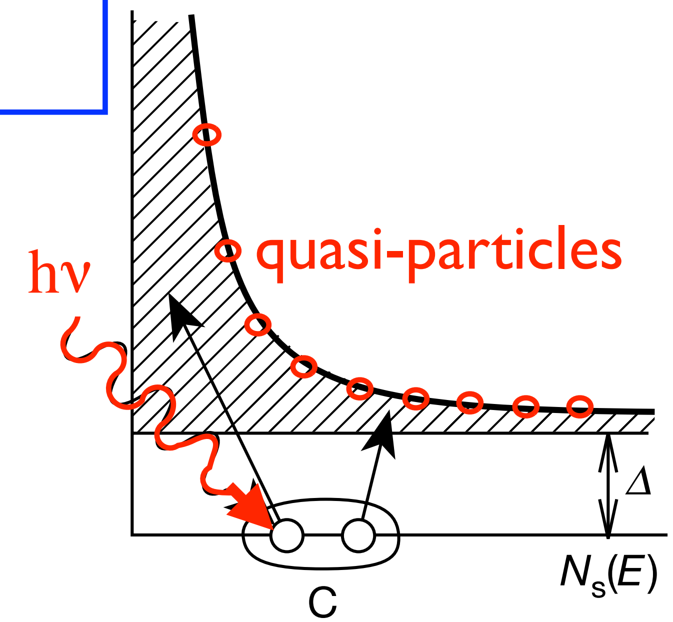
superconducting resonator

thin film ~tens of nm

substrate=Si, MgO, Al_2O_3,..



$f_o = (LC)^{-1/2}$



frequency shift: δf due to $n_s \downarrow$

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

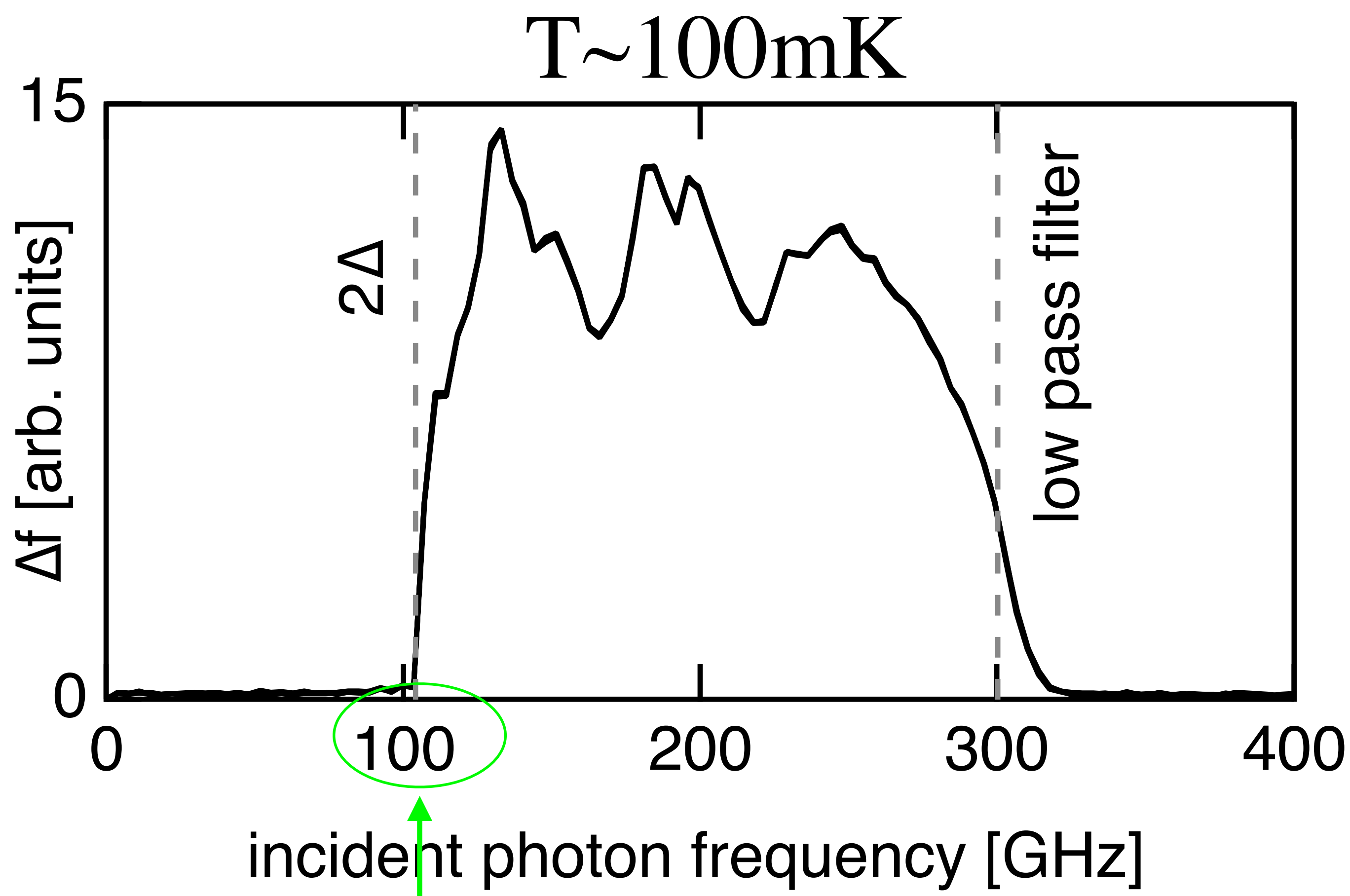
L ~ kinetic inductance of the superfluid

$L \sim 1/n_s$

Optical spectroscopy with superconducting resonators

KIDs
$h\nu > 2\Delta$

pure Al 20nm-thick



For bulk Al:
Tc = 1.2K, 2Δ = 85 GHz

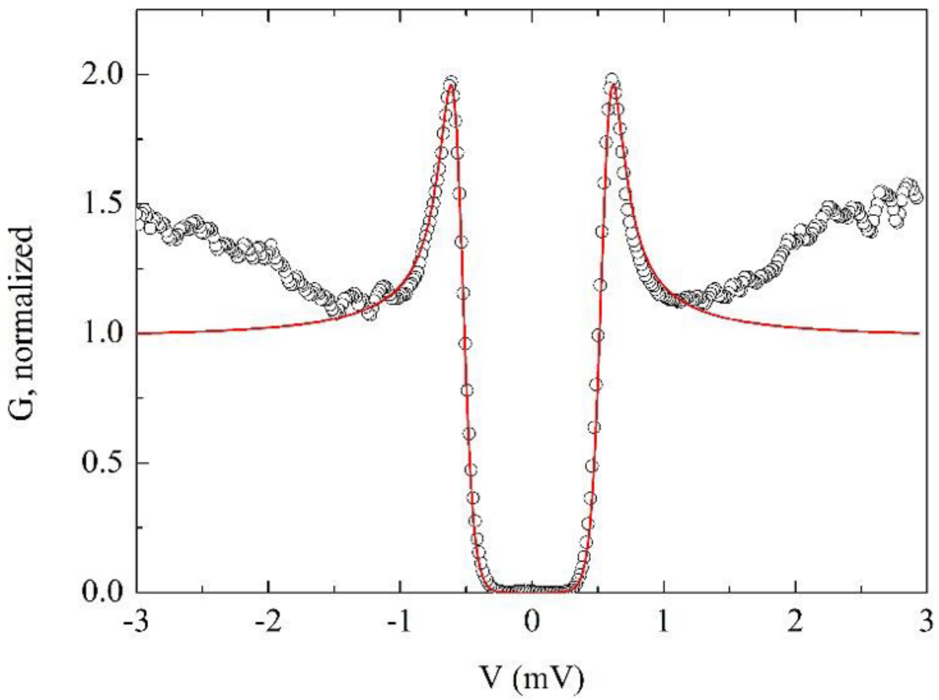
astrophysics detector

Optical spectroscopy with superconducting resonators

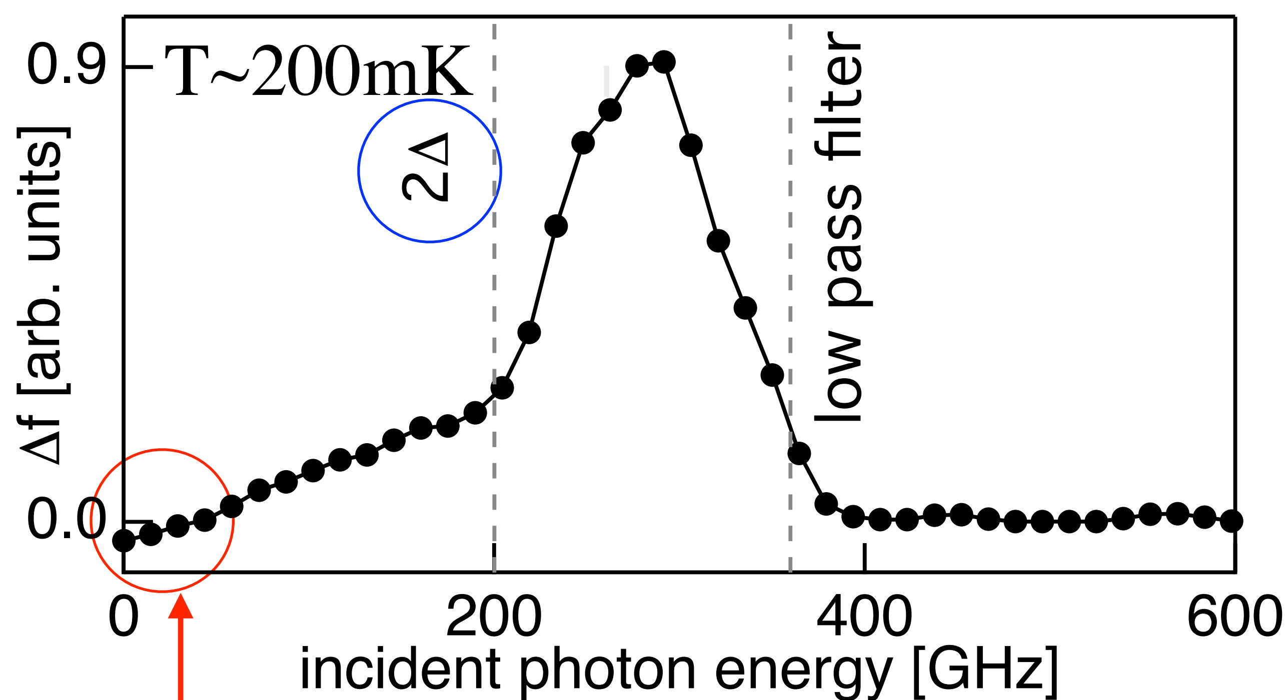
SKIDs
hν < 2Δ

present a:InO_x:
Tc ~ 2.8K, 2Δ ~ 260 GHz [1]

[1] Sacépé et al, PRB 91, 220508 (2015)



unpublished



detailed study

2Δ: STM and optical spectroscopy agreement

Optical spectroscopy with superconducting resonators

SKIDs
$h\nu < 2\Delta$

Tuna **sonators**

O 017).

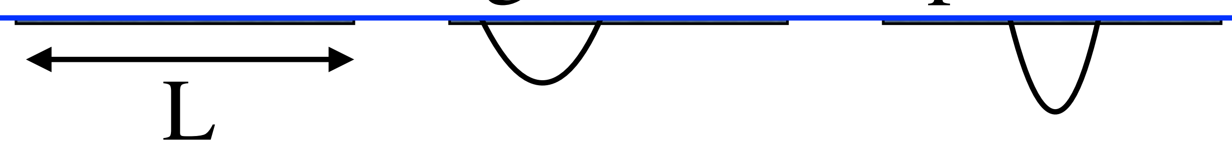
a:InOx

=

SKID : Sub-gap Kinetic Inductance Detector

detection through δf for a <u>specific</u> $h\nu < 2\Delta$

2π/L



- $h\nu$-selection = resonance mode (or any collective mode?)
- $h\nu$-absorbed -> superfluid current density J increases
  -> superfluid density n_s decreases
  -> kinetic inductance $L_k \sim 1/n_s$ increases
  -> resonance frequency shift

$$L(J) = L(0)[1 + J^2/J_*^2 + ..]^{1,2} \qquad J_* = 2/3^{3/2} J_c$$

[1] see any textbook on superconductivity (de Gennes, Tinkham)
[2] L. Swenson et al, J. Appl. Physics 113, 104501 (2013)

low Jc is *a priori* more adapted for **sub-gap detection**

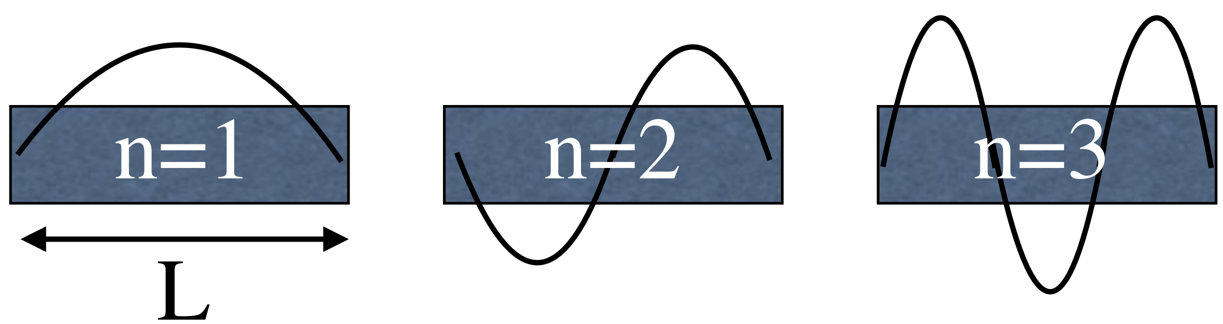
Optical spectroscopy with superconducting resonators

SKIDs

$h\nu < 2\Delta$

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

a:InOx



K=n.2π/L

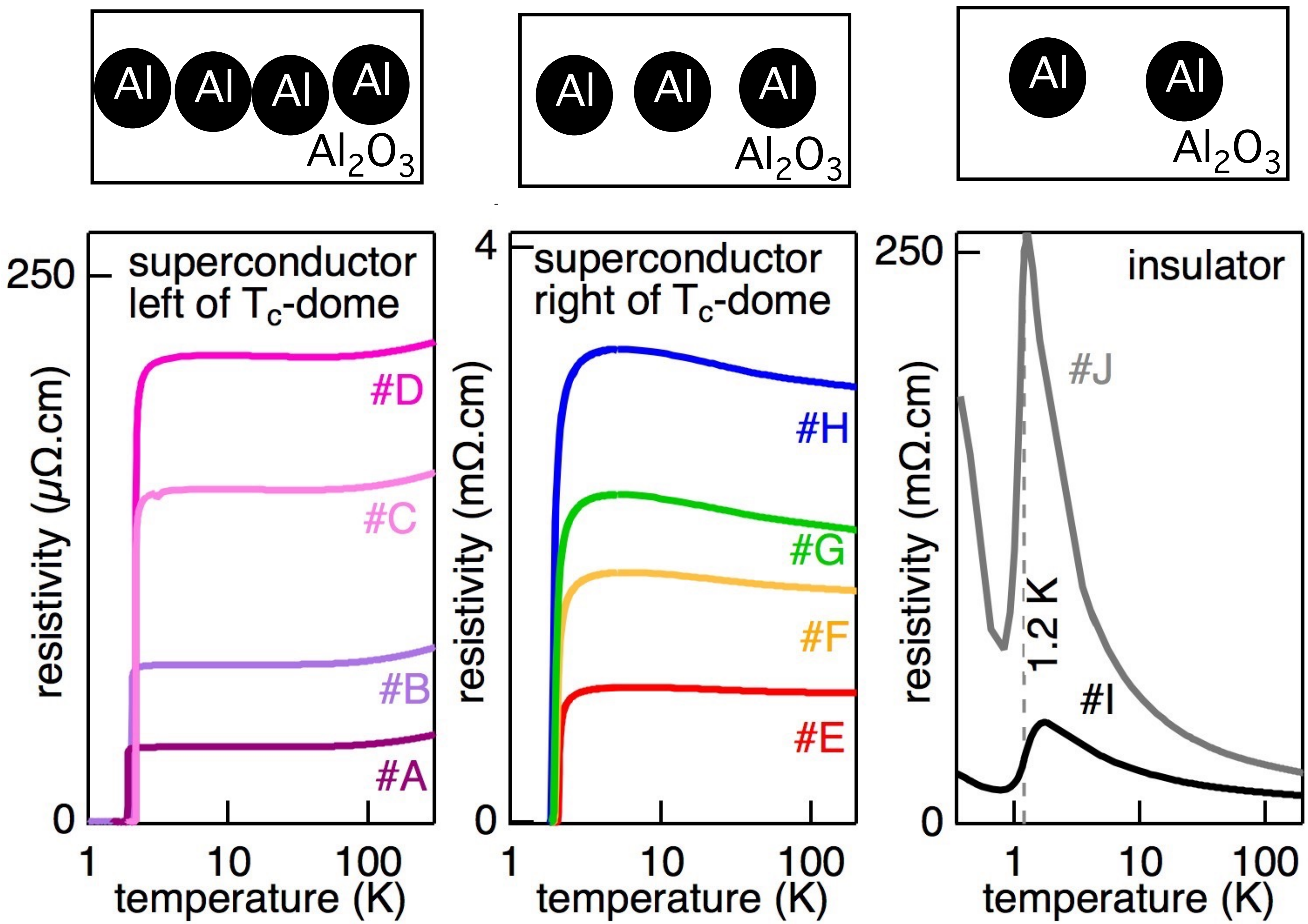
- hν-selection = resonance mode (or any collective mode?)
- hν-absorbed -> superfluid current density J increases
  -> superfluid density n_s decreases
  -> kinetic inductance $L_k \sim 1/n_s$ increases
  -> resonance frequency shift

$$L(J) = L(0)[1 + J^2/J_*^2 + ..]^{1,2} \qquad J_* = 2/3^{3/2} J_c$$

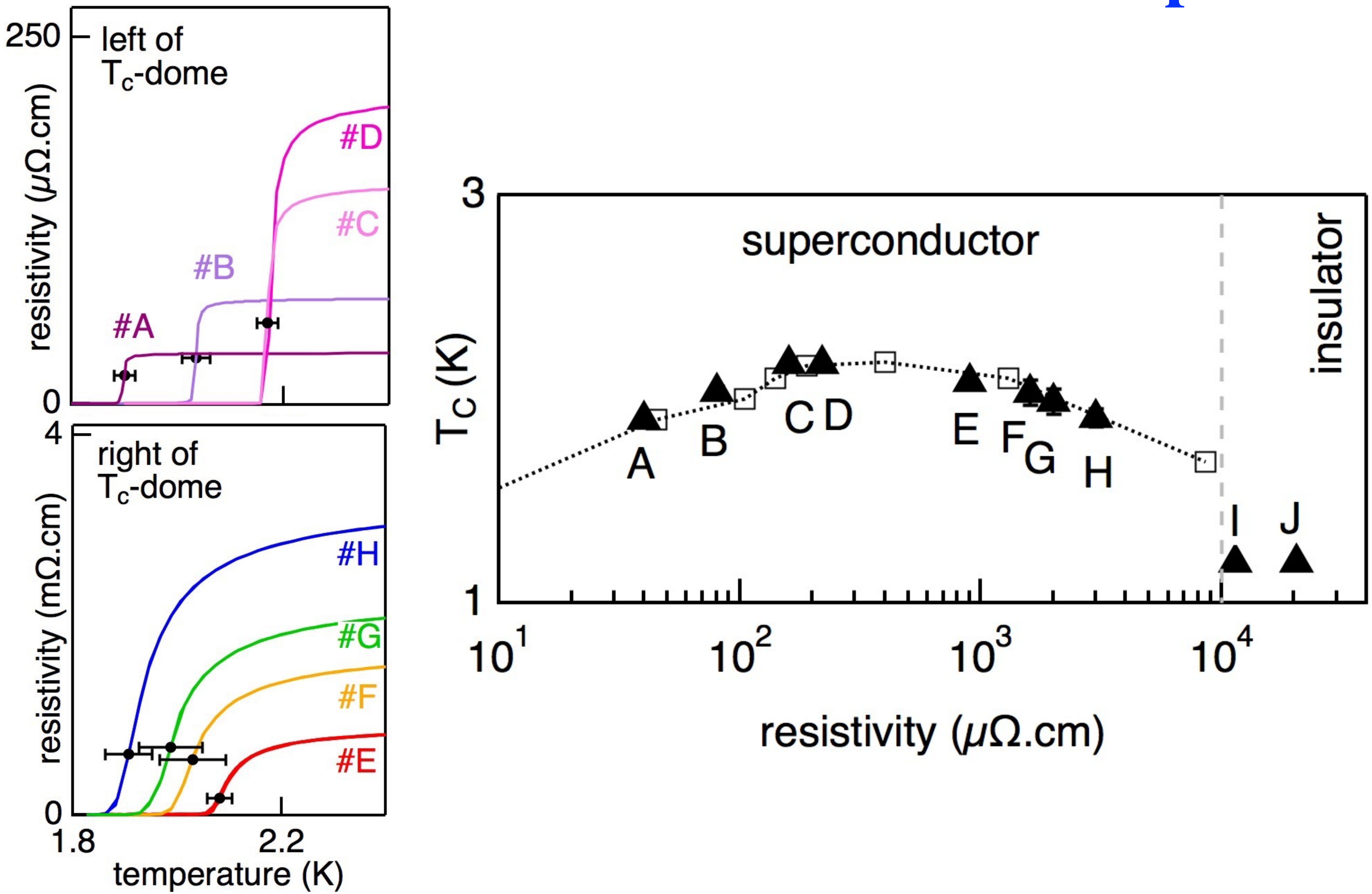
[1] see any textbook on superconductivity (de Gennes, Tinkham)
[2] L. Swenson et al, J. Appl. Physics 113, 104501 (2013)

low Jc is *a priori* more adapted for **sub-gap detection**

Granular Aluminium: resistivity

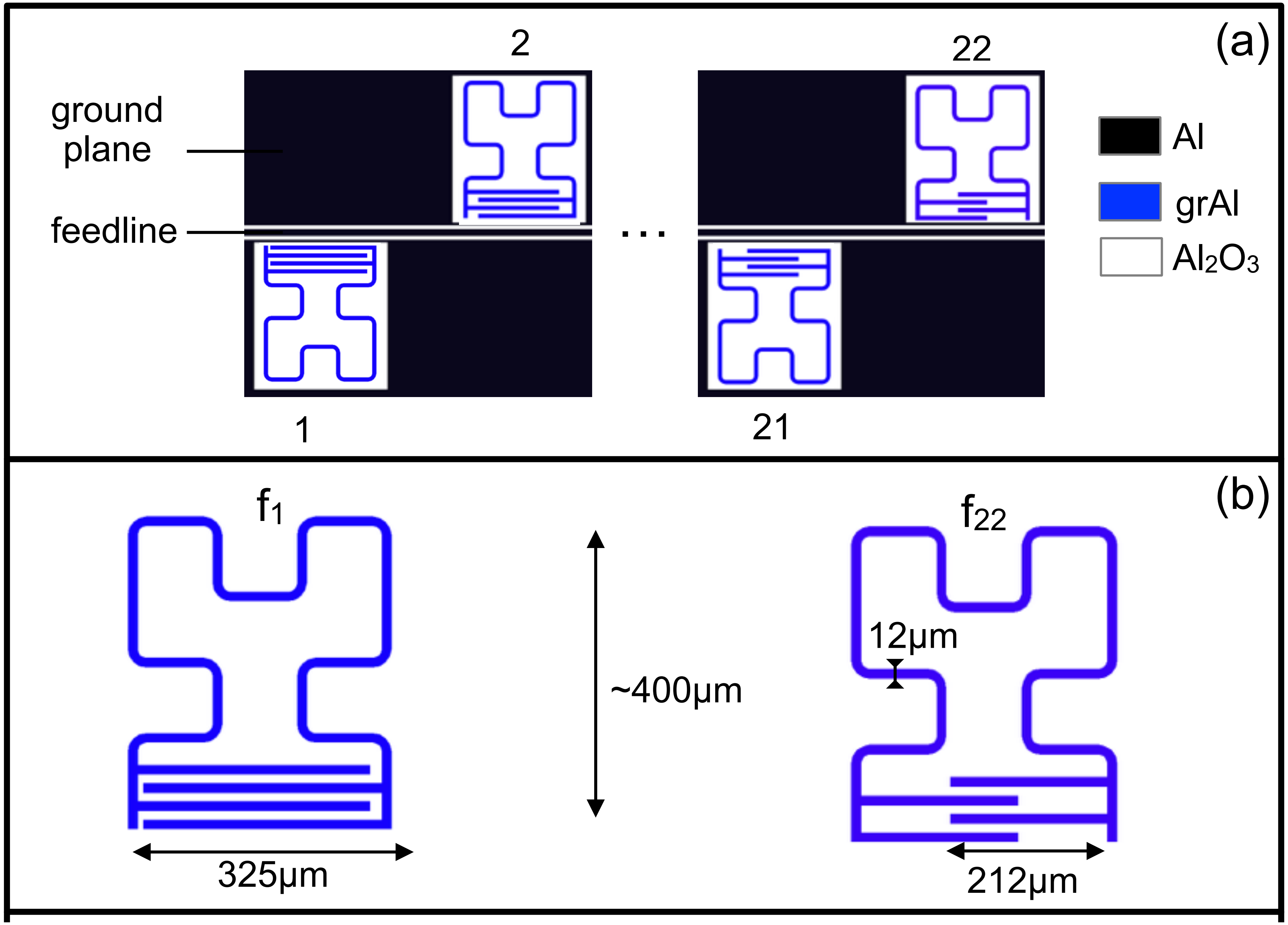


Granular Aluminium: Tc dome shape



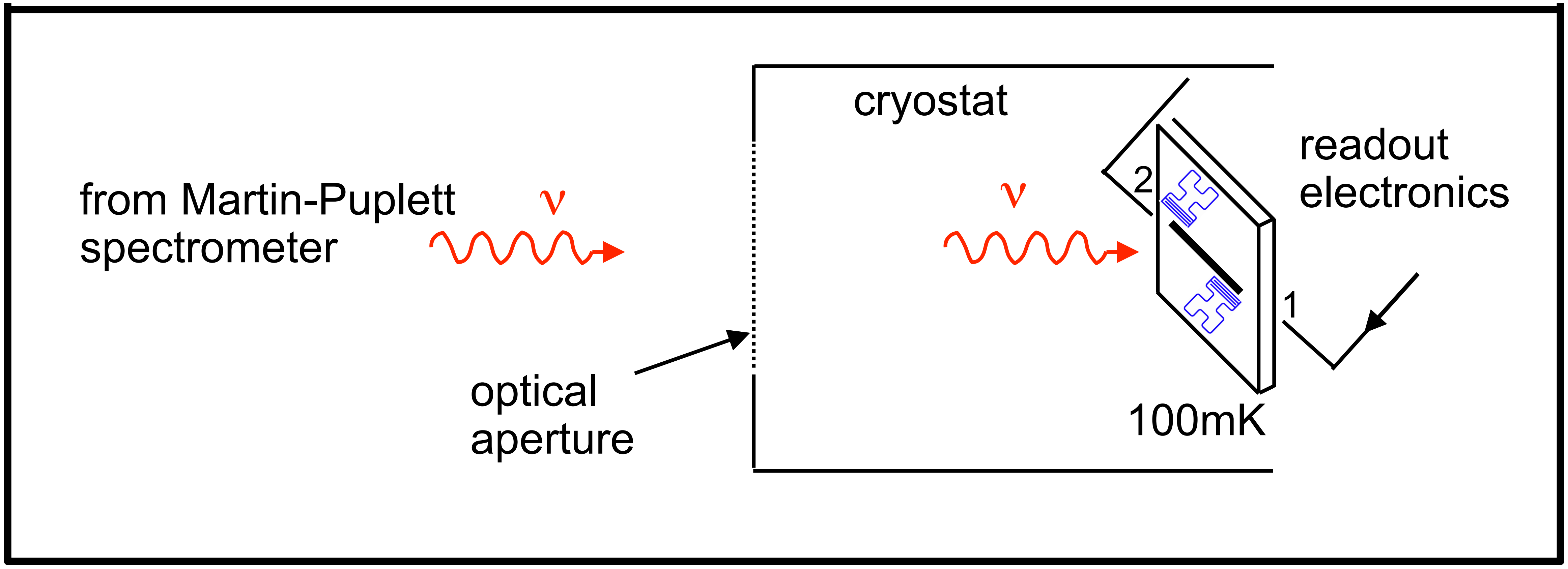
Granular Aluminium: optical spectroscopy with superconducting resonators

Samples



Granular Aluminium: optical spectroscopy with superconducting resonators

Set-up



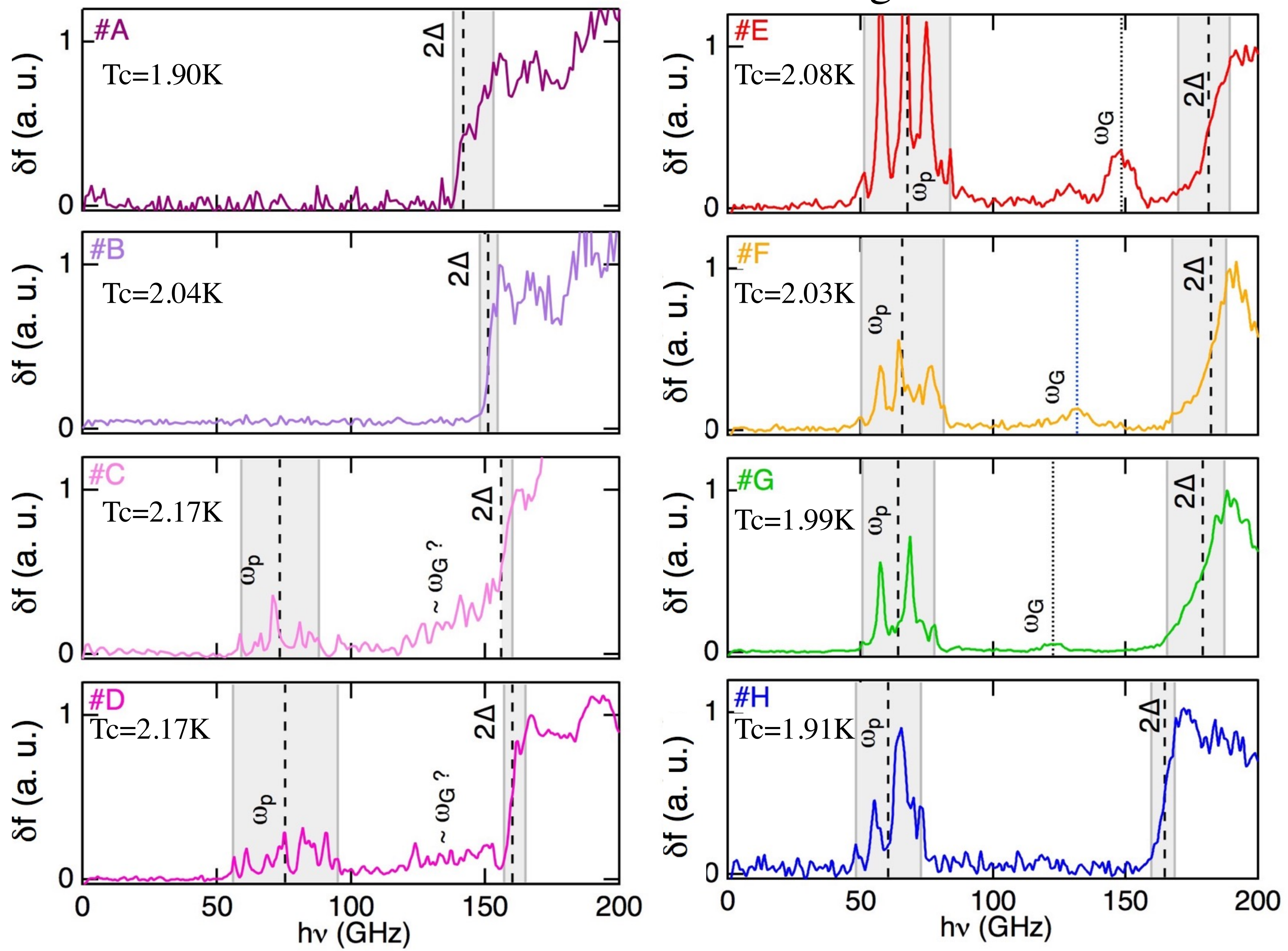
source = 300K black body

Fourier-Transform spectrometry

Granular Aluminium: optical spectroscopy

T_{mes}~100 mK

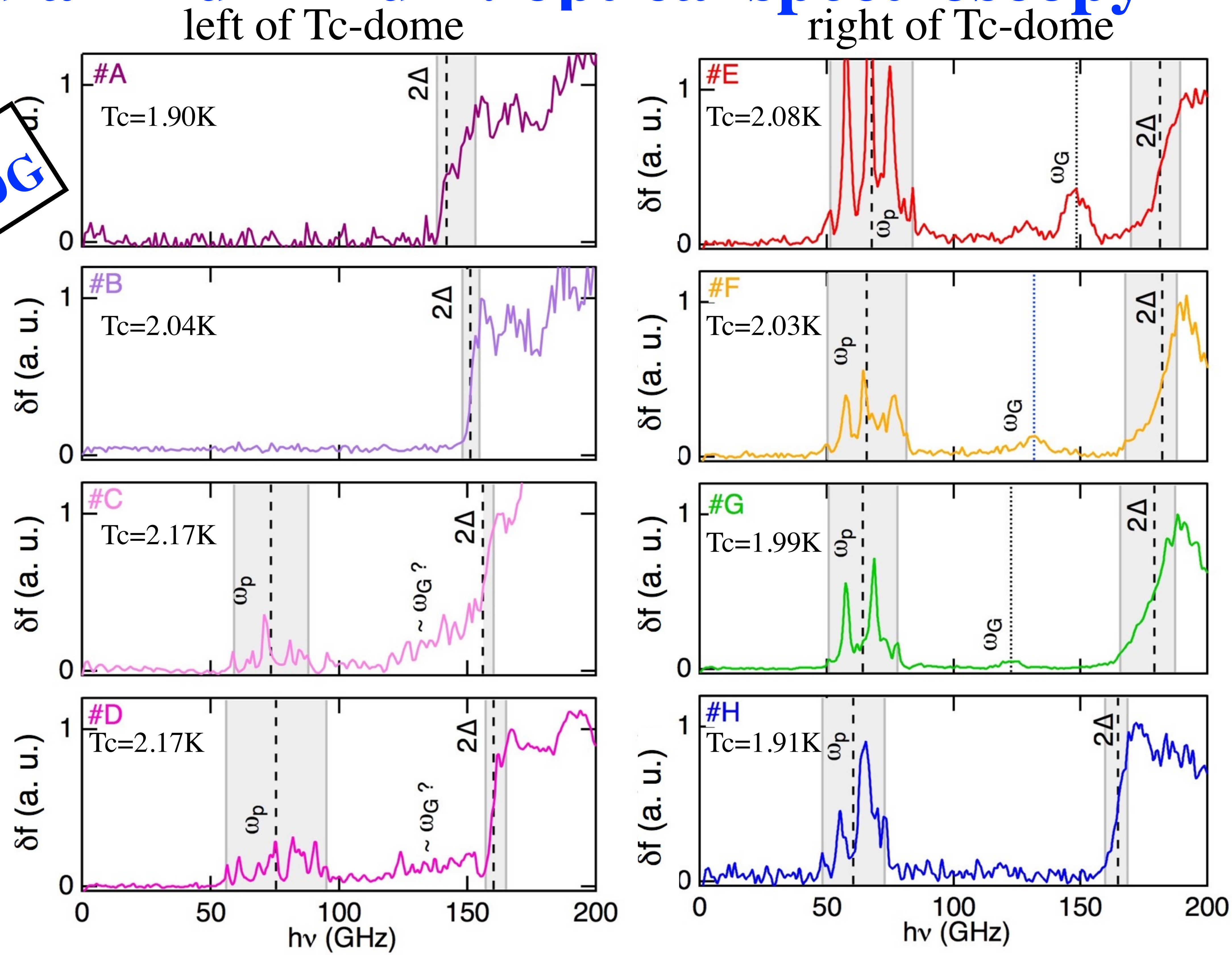
left of Tc-dome | right of Tc-dome



Granular Aluminium: optical spectroscopy

T_{mes}~100 mK

2Δ, ωp, ωG



Granular Aluminium: phase stiffness J

= Josephson energy

$$J = \frac{\hbar}{4e^2}\frac{\pi\Delta}{R_{sq}}$$ ⟶ J_Δ from measurements

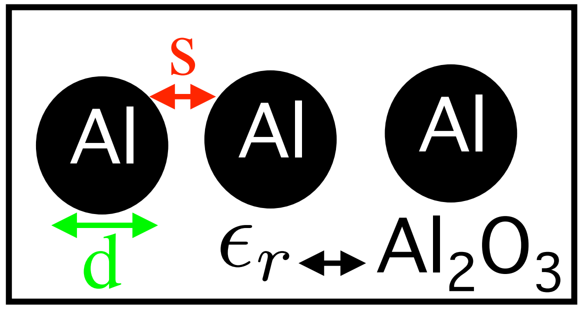
||

$$J = \frac{\hbar^2}{4e^2 L_s}$$ ⟶ J_{Ls} from kinetic inductance Ls

Ls obtained by RF-simulation
adjusting the actual
resonance frequencies $f=(LC)^{-1/2}$

Granular Aluminium: Coulomb E_c

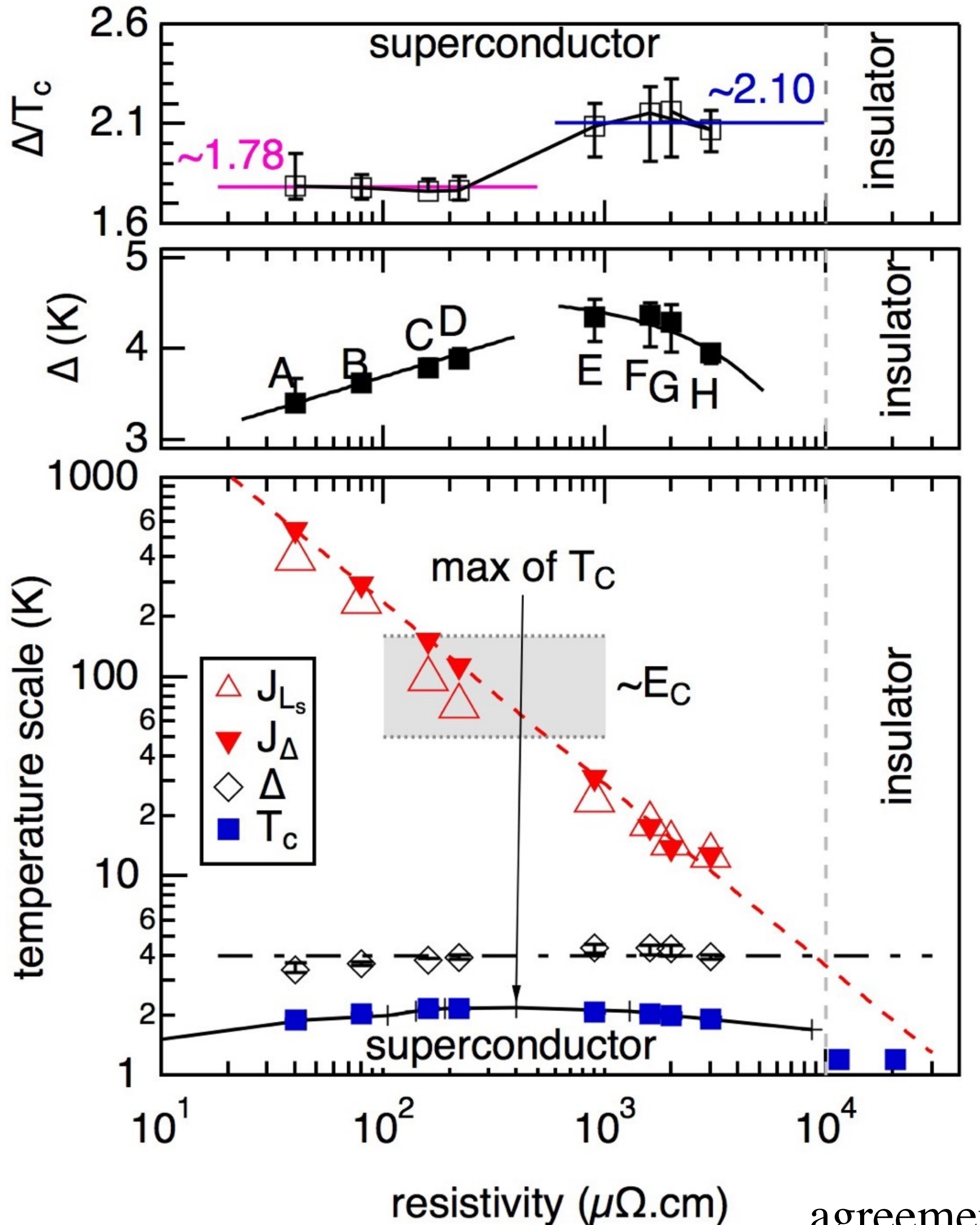
$$E_c = \frac{e^2}{4\pi\epsilon_0\epsilon_r d}\frac{s}{s+d/2}$$



d=3nm-6nm s=0.5nm $\epsilon_r = 8.5$

E_c ~ 100+/- 50 K

Granular Aluminium: phase diagram



interplay of J, E_c and Δ

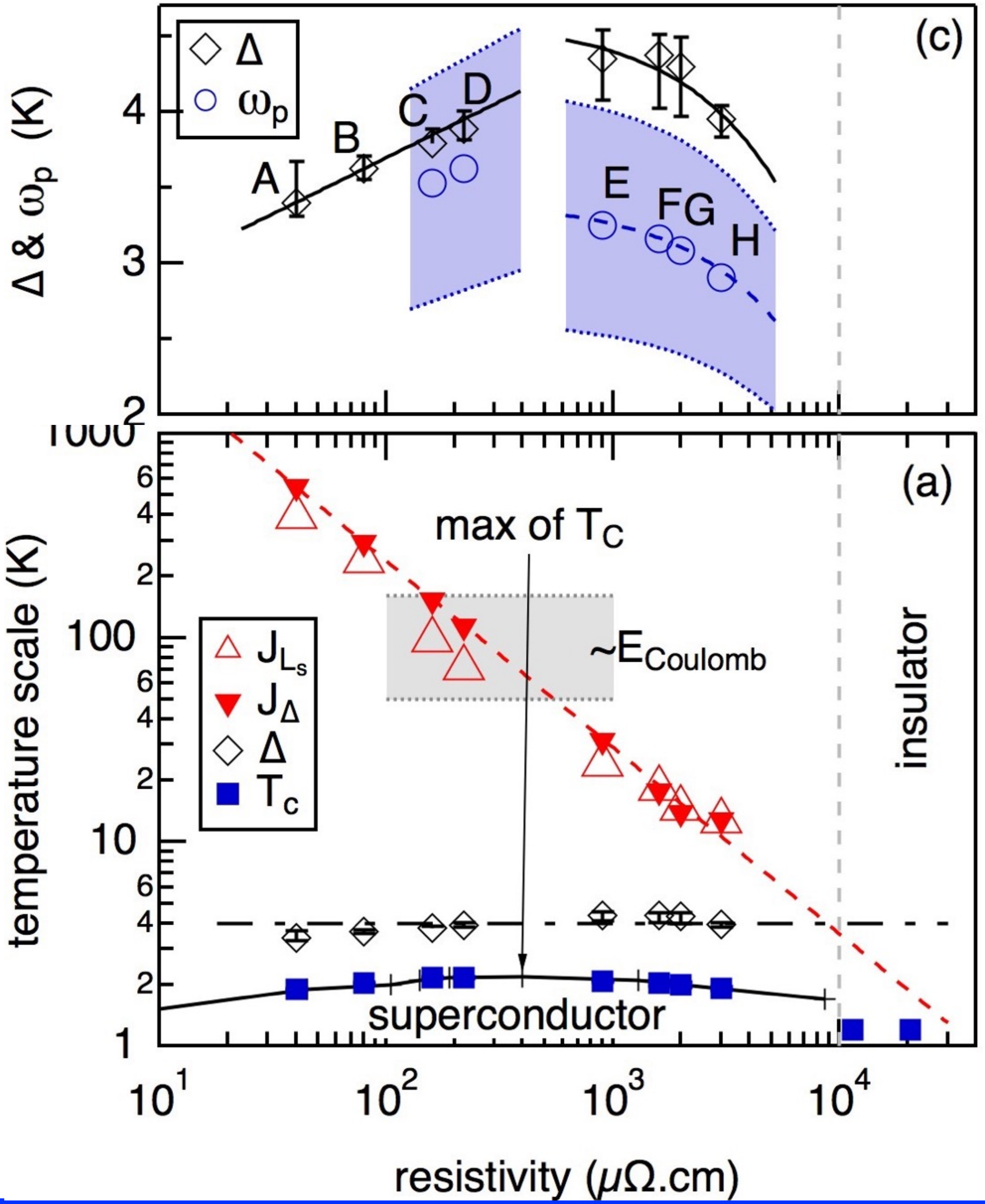
- $J > E_c$:
  "metal"
  $\Delta/T_c \sim 1.78$

- $\Delta < J < E_c$:
  "non-metal"
  $\Delta/T_c \sim 2.10$
  sub-gap absorptions

- $J < \Delta$:
  insulator

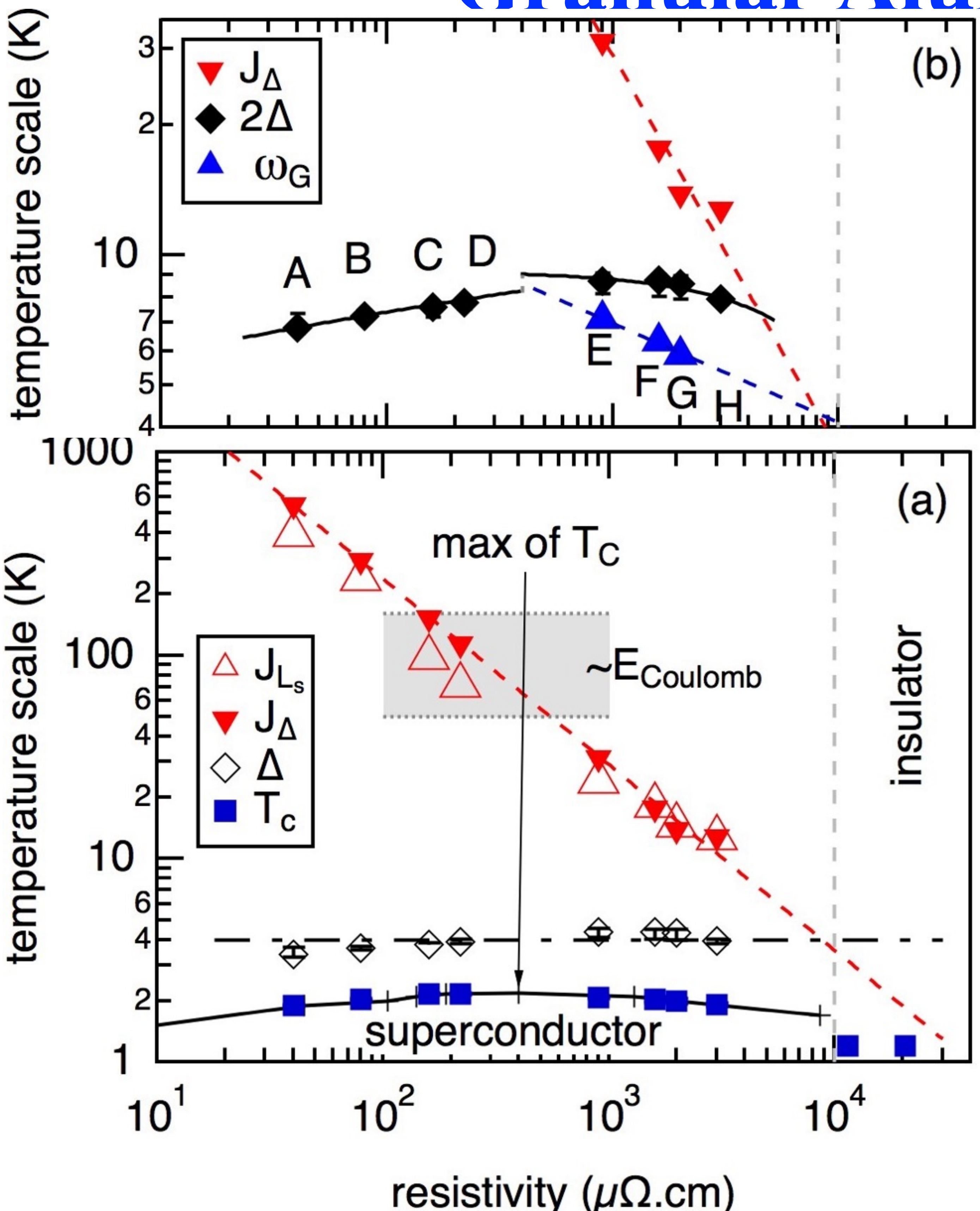
agreement with Pracht and al, PRB 93, 100503(R) 2016.

Granular Aluminium: ω_p



Scaling of ω_p with Δ

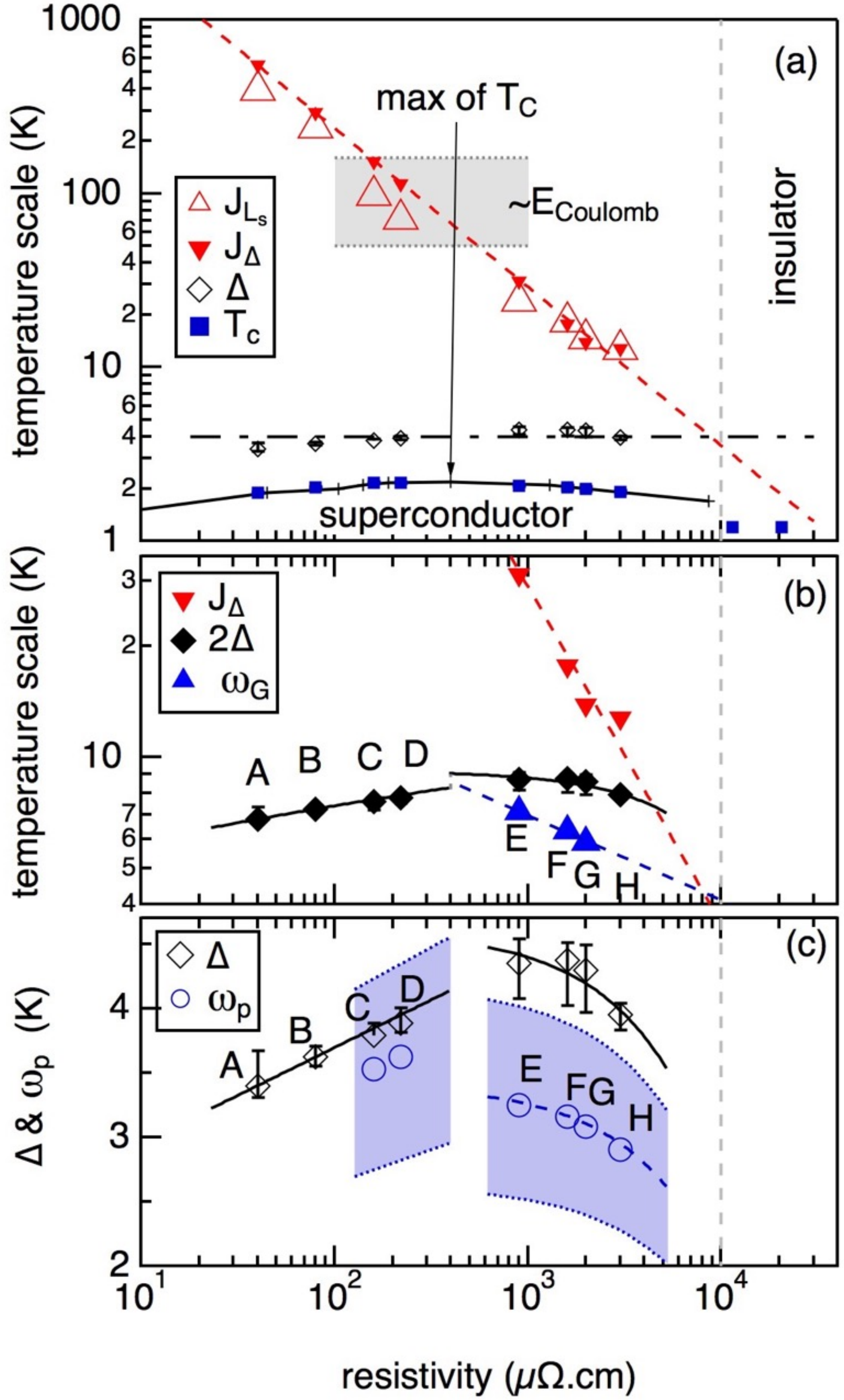
Granular Aluminium: ω_G



Scaling of ω_G with J (?)

Granular Aluminium

discussion



- sub-gap optical absorption in agreement with literature but now resolved features

- onset when $J \lesssim E_c$
suggest phase fluctuations

- literature explains 1 mode
observation of 2 (or more?) modes

- N. Maleeva and al, Nat. Com 9, 3889 (2018)
ω_p =saturation of 2D plasmon dispersion
quantitative agreement but for multipeaks

- ω_G ? …

Conclusion

- Sub-gap modes in (various) superconductors
- Origin(s) under debate
- Of interests for 3 communities:
  - astrophysics instrumentation (photon detection)
  - quantum engineering (high-L_K vs dissipation?)
  - fundamental studies

Conclusion

- Sub-gap modes in (various) superconductors
- Origin(s) under debate
- Of interests for 3 communities:
  - astrophysics instrumentation (photon detection)
  - quantum engineering (high-L_K vs dissipation?)
  - fundamental studies

THANK YOU