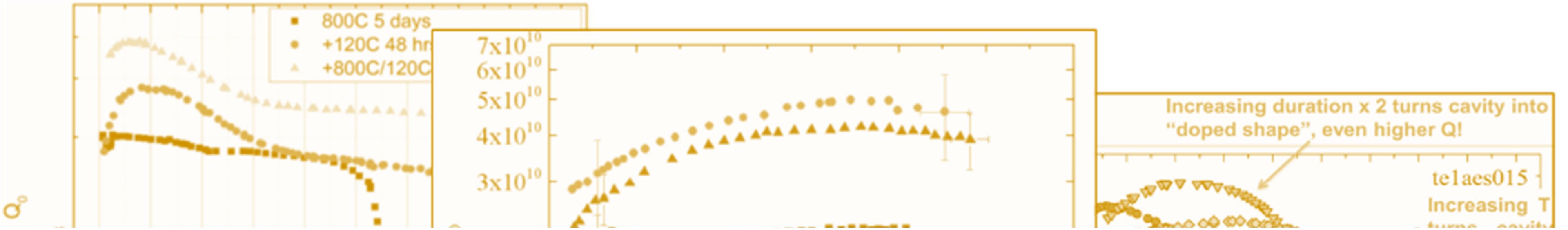
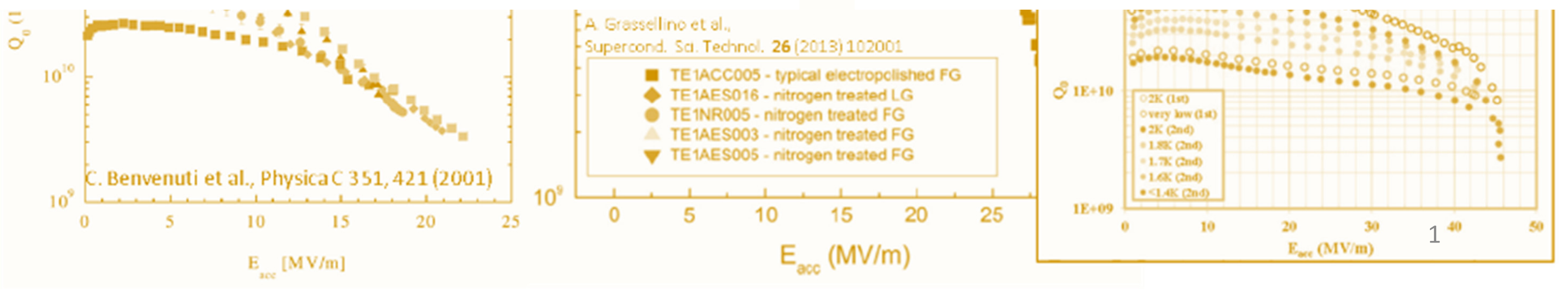


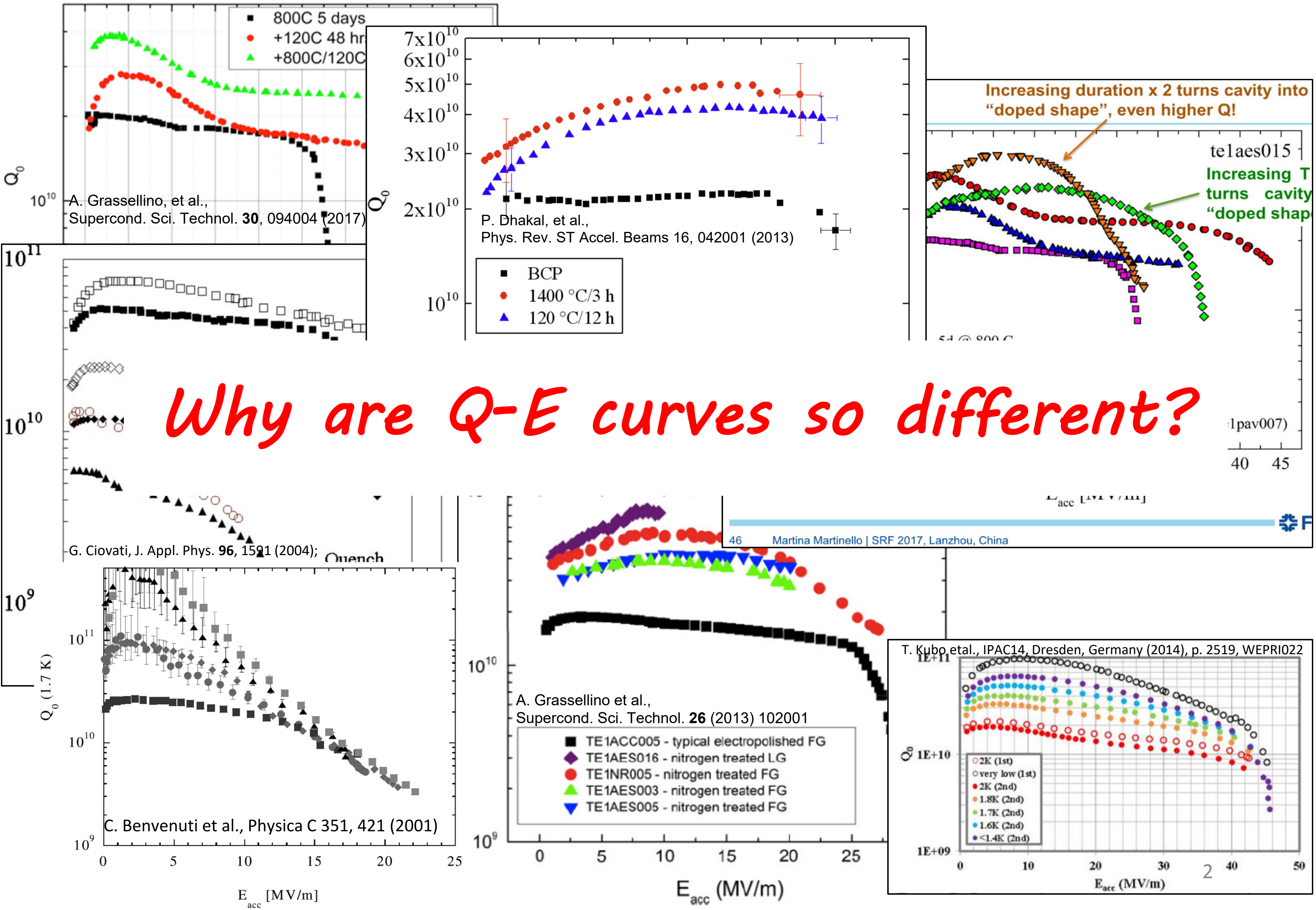
Field-dependent nonlinear surface resistance and its optimization by surface nano-structuring of SRF cavities

T. Kubo (KEK, ODU) and A. Gurevich (ODU)

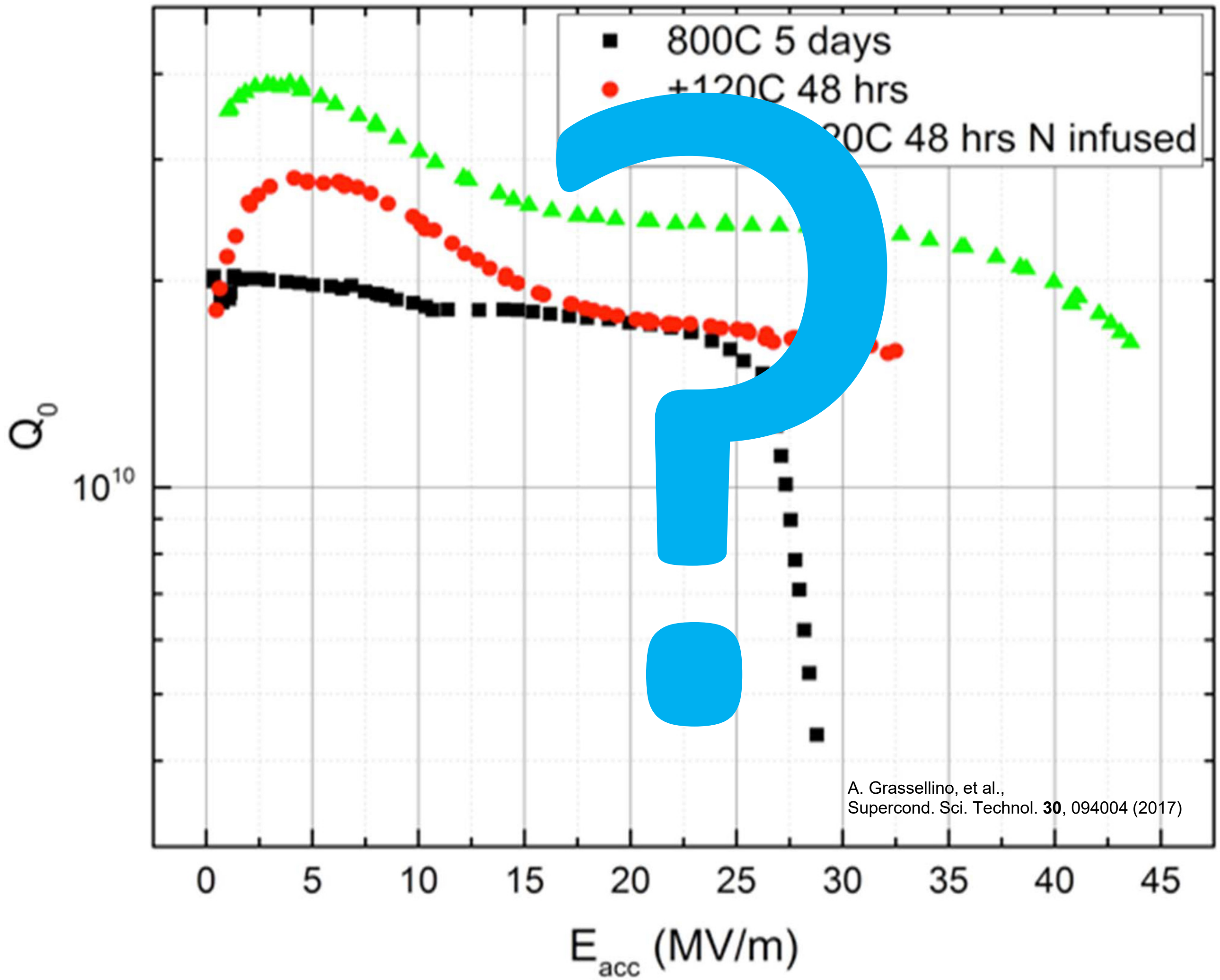
Supported by JSPS KAKENHI Grant No.17H04839, and No.17KK0100

Supported by NSF under Grant No.PHY-1416051



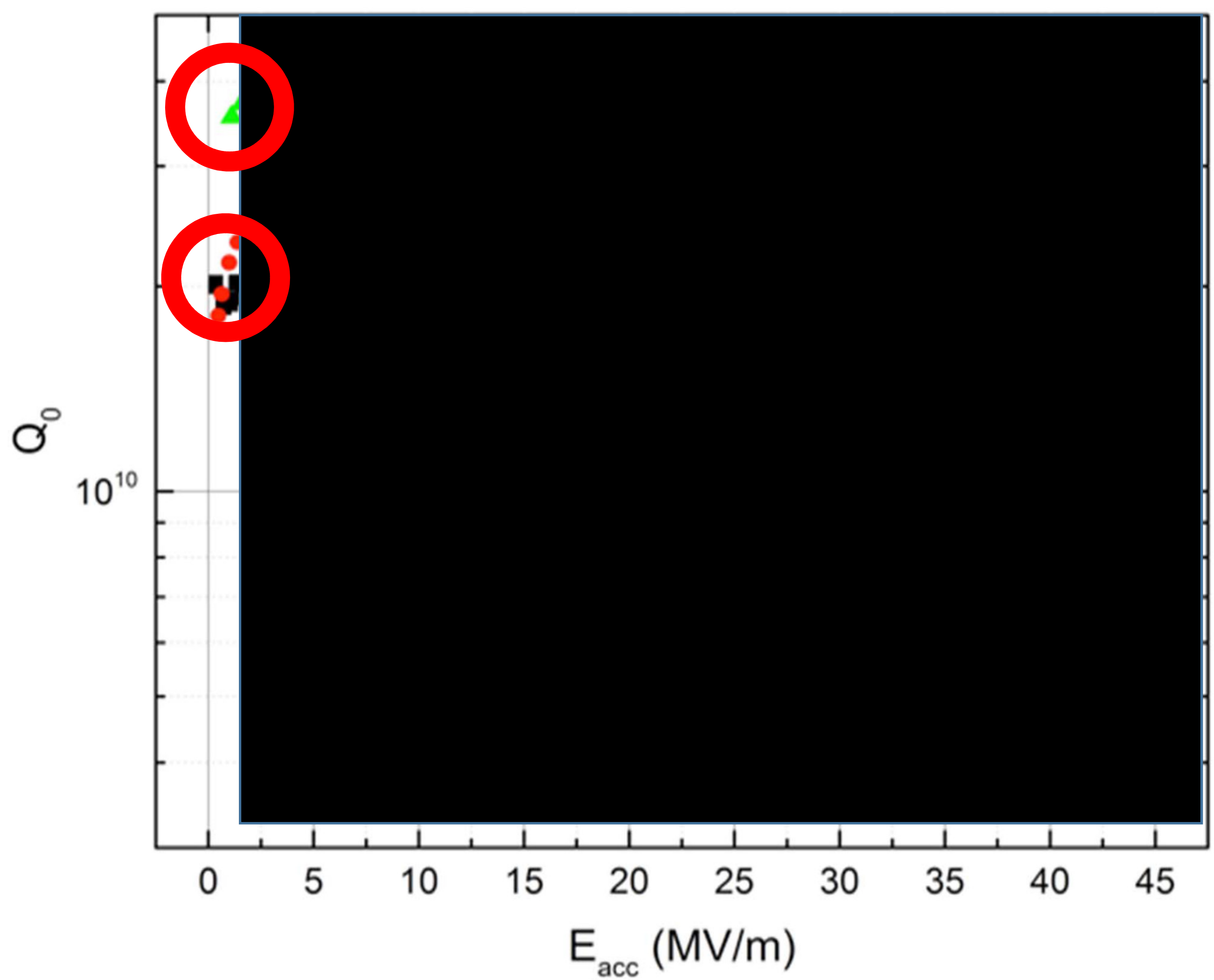

Why are Q-E curves so different?
800C 5 days
+120C 48 hr
+800C/120C
A. Grassellino, et al.,
Supercond. Sci. Technol. 30, 094004 (2017)
BCP
1400 °C/3 h
120 °C/12 h
P. Dhakal, et al.,
Phys. Rev. ST Accel. Beams 16, 042001 (2013)
Increasing duration x 2 turns cavity into "doped shape", even higher Q!
te1aes015
46 Martina Martinello | SRF 2017, Lanzhou, China
G. Ciovati, J. Appl. Phys. 96, 1591 (2004);
Quench
C. Benvenuti et al., Physica C 351, 421 (2001)
TE1ACC005 - typical electropolished FG
TE1AES016 - nitrogen treated LG
TE1NR005 - nitrogen treated FG
TE1AES003 - nitrogen treated FG
TE1AES005 - nitrogen treated FG
A. Grassellino et al.,
Supercond. Sci. Technol. 26 (2013) 102001
T. Kubo etal., IPAC14, Dresden, Germany (2014), p. 2519, WEPRI022
2K (1st)
very low (1st)
2K (2nd)
1.8K (2nd)
1.7K (2nd)
1.6K (2nd)
<1.4K (2nd)

Unfortunately, the Mattis-Bardeen's theory for the weak-field R_s tells you nothing about the shape of Q-E curve.



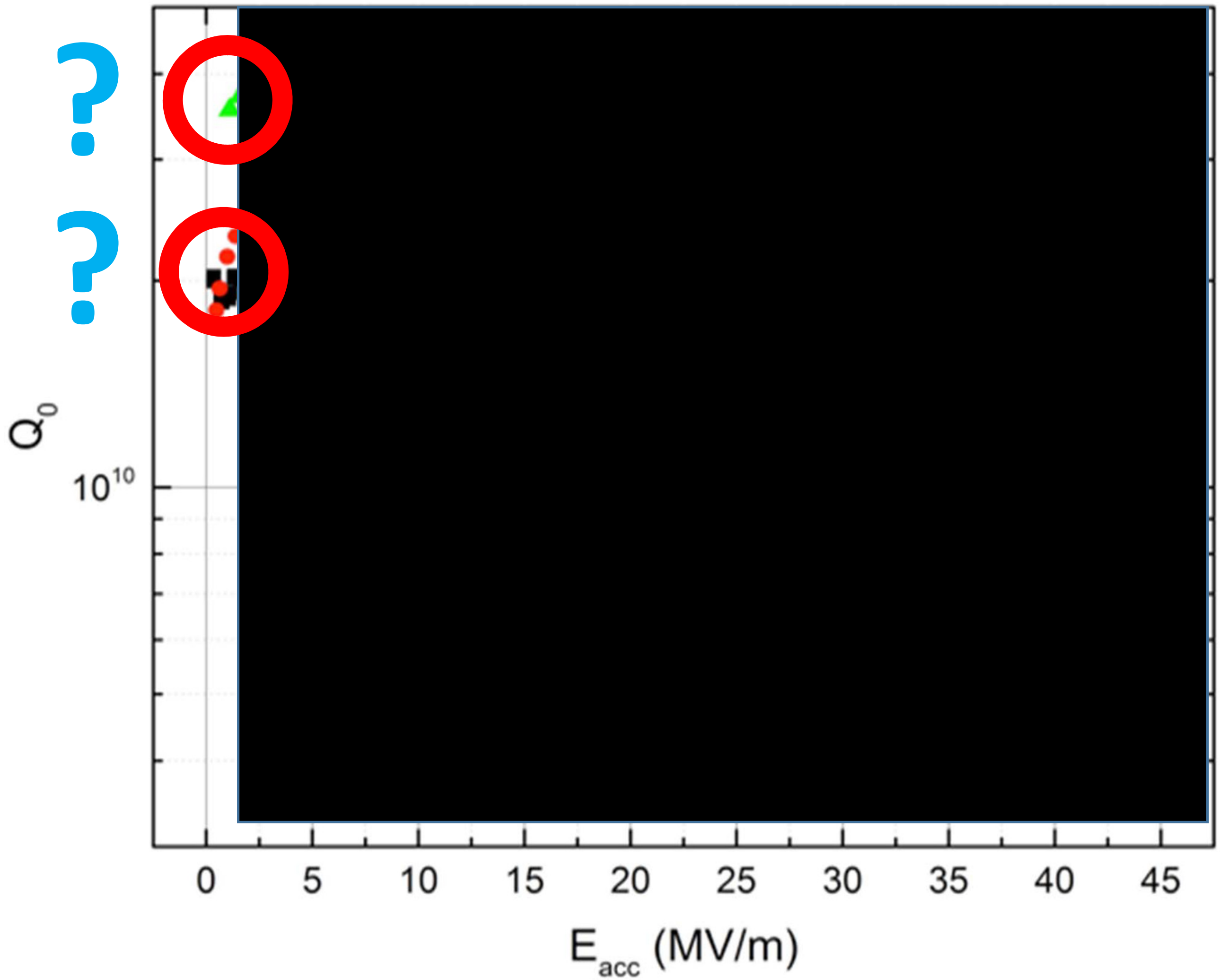
Unfortunately, the Mattis-Bardeen's theory for the weak-field R_s tells you nothing about the shape of Q-E curve.

- It is valid only at the weak-field limit: the left end of Q-E curve.



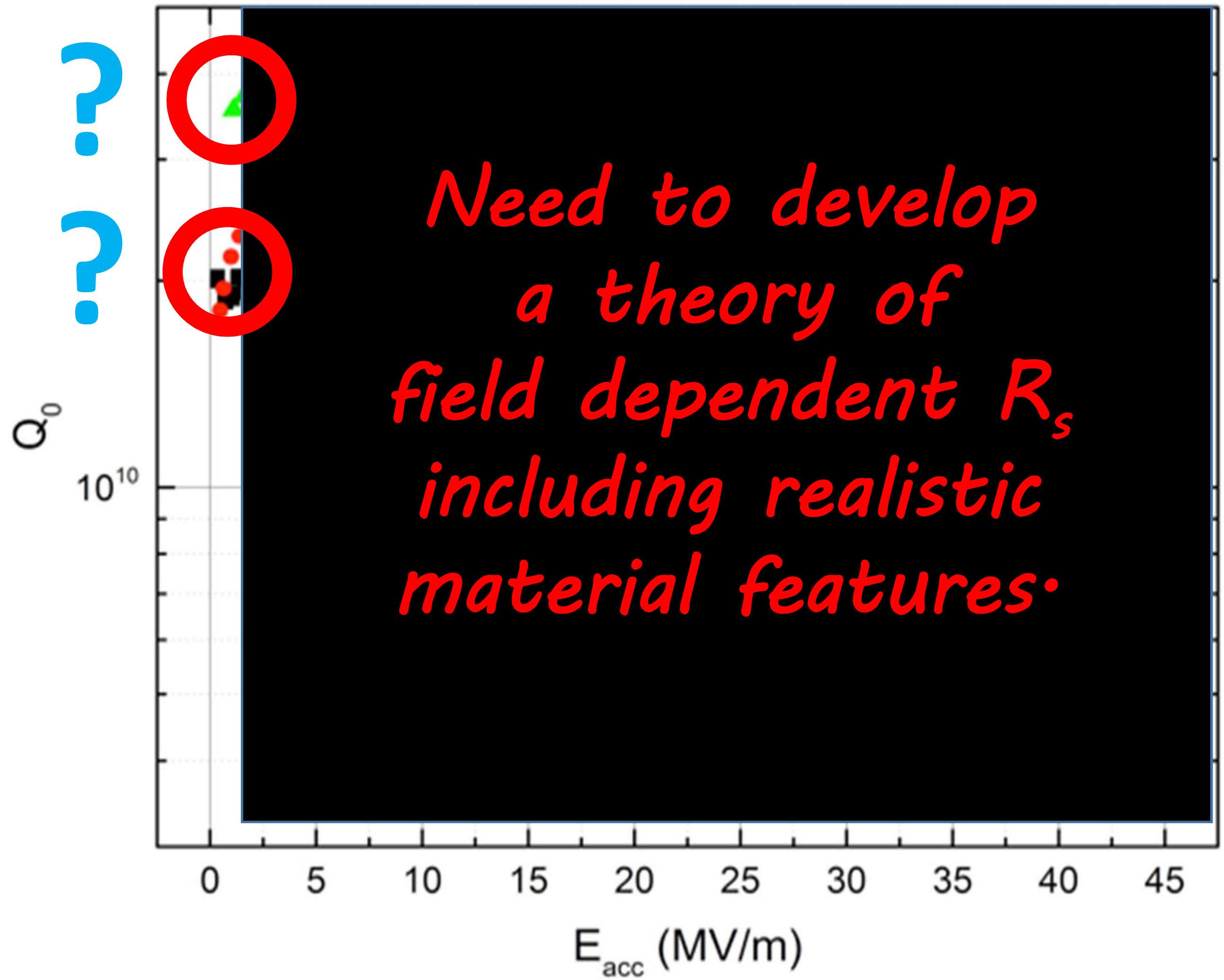
Unfortunately, the Mattis-Bardeen's theory for the weak-field R_s tells you nothing about the shape of Q-E curve.

- It is valid only at the weak-field limit: the left end of Q-E curve.
- Effects of material features other than mfp are not taken into account: thus may not be valid even at the weak-field limit.



Unfortunately, the Mattis-Bardeen's theory for the weak-field R_s tells you nothing about the shape of Q-E curve.

- It is valid only at the weak-field limit: the left end of Q-E curve.
- Effects of material features other than mfp are not taken into account: thus may not be valid even at the weak-field limit.



Part 1: Review

Effects of density of states (DOS) broadening

- A. Gurevich,
  Phys. Rev. Lett. **113**, 087001 (2014)

- A. Gurevich and T. Kubo,
  Phys. Rev. B **96**, 184515 (2017)

Review (1)

A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)

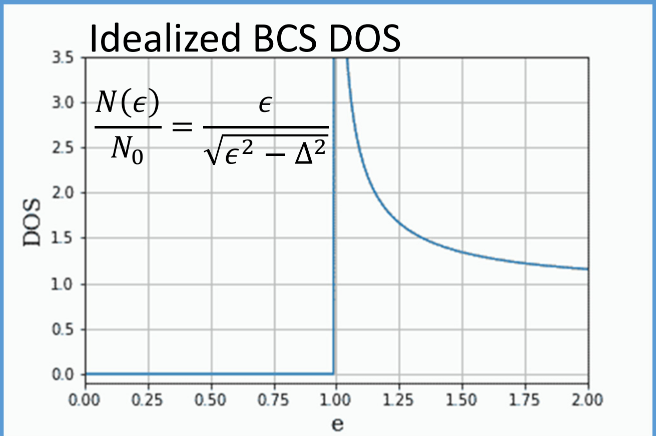
The surface resistance is given by

$$R_s = \frac{1}{2}\mu_0^2\omega^2\lambda^3\sigma_1$$

Here σ_1 is roughly (when $T \ll T_c$ and $\omega \ll T$)

$$\sigma_1 \sim \sigma_n \int_{\Delta}^{\infty} \underbrace{\boxed{N(\epsilon)}}_{\text{DOS}} N(\epsilon + \hbar\omega) e^{-\frac{\Delta}{kT}} d\epsilon$$

Weak-field limit



Mattis Bardeen's formula

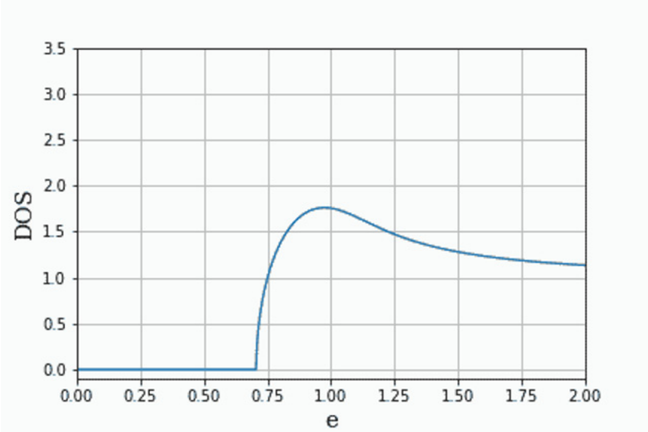
$$\sigma_1 = \sigma_n \frac{2\Delta}{kT} \ln\frac{CkT}{\hbar\omega} e^{-\frac{\Delta}{kT}}$$

comes from this DOS

J. Bardeen, Rev. Mod. Phys. 34, 667 (1962).
K. Maki, Prog. Theor. Phys. 29, 333 (1963)
P. Fulde, Phys. Rev. 137, A783 (1965).
A. Anthore, H. Pothier, D. Esteve, Phys. Rev. Lett. 90, 127001 (2003).

However, it is well known that the DOS is affected by the pair-breaking current.

DOS under a dc current



Review (1)

A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)

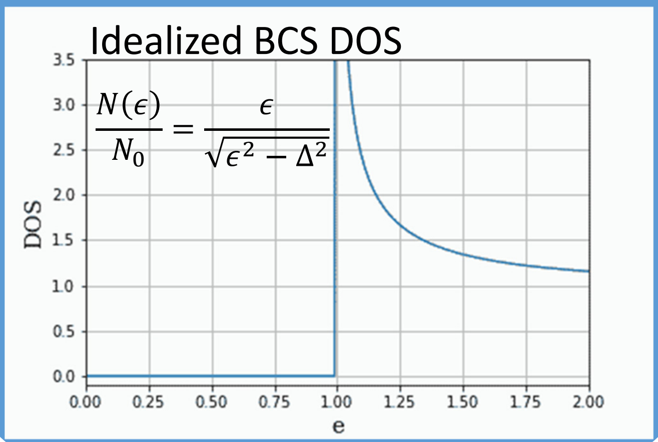
The surface resistance is given by

$$R_s = \frac{1}{2}\mu_0^2\omega^2\lambda^3\sigma_1$$

Here σ_1 is roughly (when $T \ll T_c$ and $\omega \ll T$)

$$\sigma_1 \sim \sigma_n \int_{\Delta}^{\infty} \underbrace{\boxed{N(\epsilon)}}_{\text{DOS}} N(\epsilon + \hbar\omega) e^{-\frac{\Delta}{kT}} d\epsilon$$

Weak-field limit



Mattis Bardeen's formula

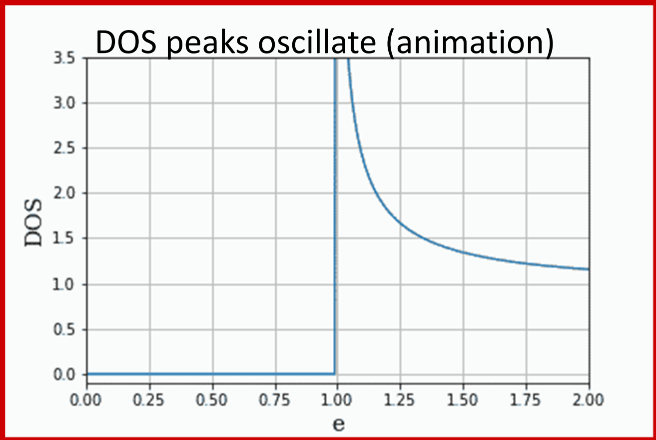
$$\sigma_1 = \sigma_n \frac{2\Delta}{kT} \ln\frac{CkT}{\hbar\omega} e^{-\frac{\Delta}{kT}}$$

comes from this DOS

J. Bardeen, Rev. Mod. Phys. 34, 667 (1962).
K. Maki, Prog. Theor. Phys. 29, 333 (1963)
P. Fulde, Phys. Rev. 137, A783 (1965).
A. Anthore, H. Pothier, D. Esteve, Phys. Rev. Lett. 90, 127001 (2003).

However, it is well known that the DOS is affected by the pair-breaking current.

Under a strong rf current



Review (1)

A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)

The surface resistance is given by

$$R_s = \frac{1}{2}\mu_0^2\omega^2\lambda^3\sigma_1$$

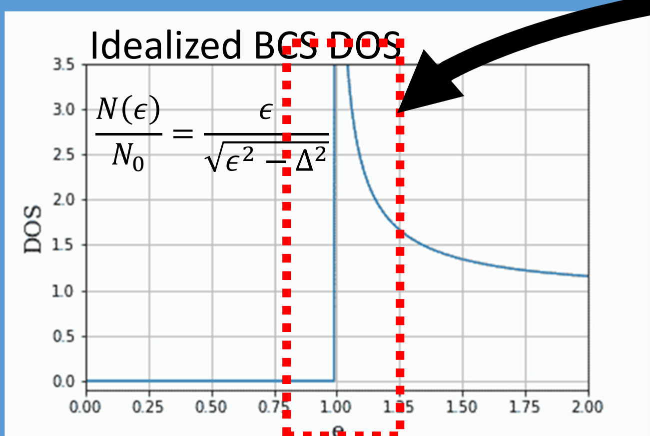
Here σ_1 is roughly (when $T \ll T_c$ and $\omega \ll T$)

$$\sigma_1 \sim \sigma_n \int_{\Delta}^{\infty} \underbrace{N(\epsilon)}_{\text{DOS}} N(\epsilon+\hbar\omega) e^{-\frac{\Delta}{kT}} d\epsilon$$

J. Bardeen, Rev. Mod. Phys. 34, 667 (1962).
K. Maki, Prog. Theor. Phys. 29, 333 (1963)
P. Fulde, Phys. Rev. 137, A783 (1965).
A. Anthore, H. Pothier, D. Esteve, Phys. Rev. Lett. 90, 127001 (2003).

However, it is well known that the DOS is affected by the pair-breaking current.

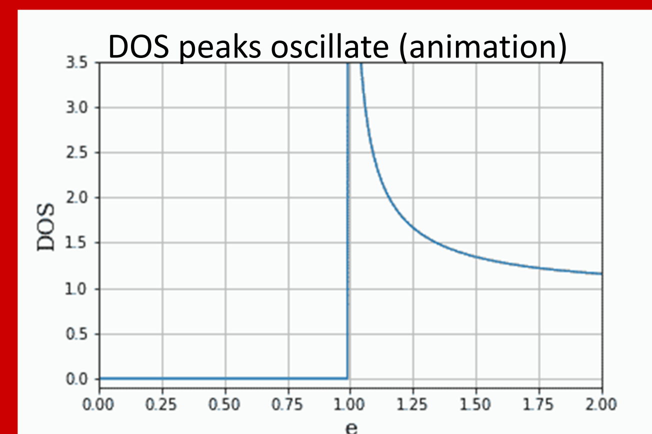
Weak-field limit



$$\sigma_1 = \sigma_n \frac{2\Delta}{kT} \boxed{\ln\frac{CkT}{\hbar\omega}} e^{-\frac{\Delta}{kT}}$$

This logarithmic factor in MB's formula comes from the sharp peak of the idealized BCS DOS

Under a strong rf current



Mattis Bardeen's formula

$$\sigma_1 = \sigma_n \frac{2\Delta}{kT} \ln\frac{CkT}{\hbar\omega} e^{-\frac{\Delta}{kT}}$$

comes from this DOS

Review (1)

A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)

The surface resistance is given by

$$R_s = \frac{1}{2}\mu_0^2\omega^2\lambda^3\sigma_1$$

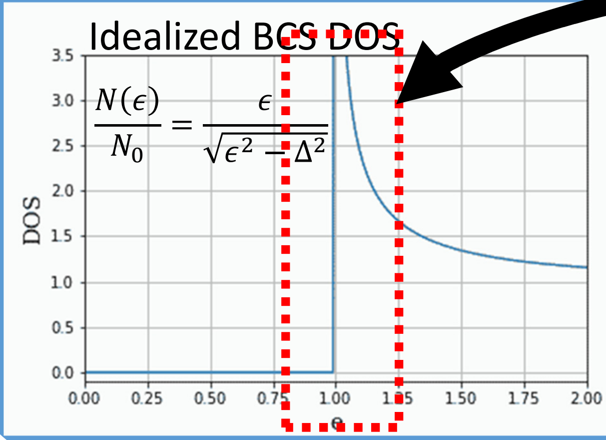
Here σ_1 is roughly (when $T \ll T_c$ and $\omega \ll T$)

$$\sigma_1 \sim \sigma_n \int_\Delta^\infty \underbrace{\boxed{N(\epsilon)}}_{\text{DOS}} N(\epsilon+\hbar\omega) e^{-\frac{\Delta}{kT}} d\epsilon$$

J. Bardeen, Rev. Mod. Phys. 34, 667 (1962).
K. Maki, Prog. Theor. Phys. 29, 333 (1963)
P. Fulde, Phys. Rev. 137, A783 (1965).
A. Anthore, H. Pothier, D. Esteve, Phys. Rev. Lett. 90, 127001 (2003).

However, it is well known that the DOS is affected by the pair-breaking current.

Weak-field limit

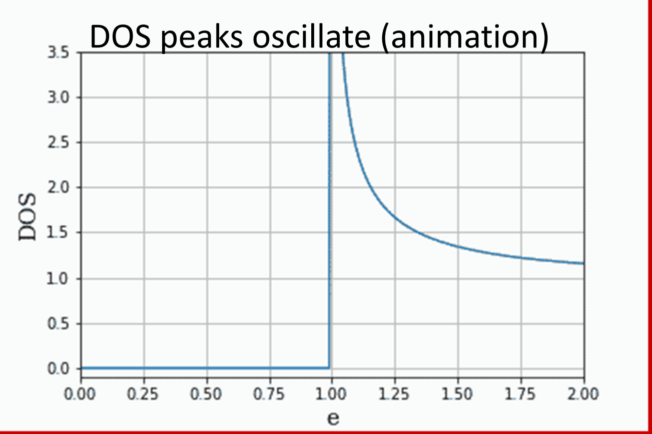


Under a strong rf current

$$\sigma_1 = \sigma_n \frac{2\Delta}{kT} \boxed{\ln\frac{CkT}{\hbar\omega}} e^{-\frac{\Delta}{kT}}$$

decreases

$$\ln\frac{CkT}{\text{peak width}}$$



Mattis Bardeen's formula

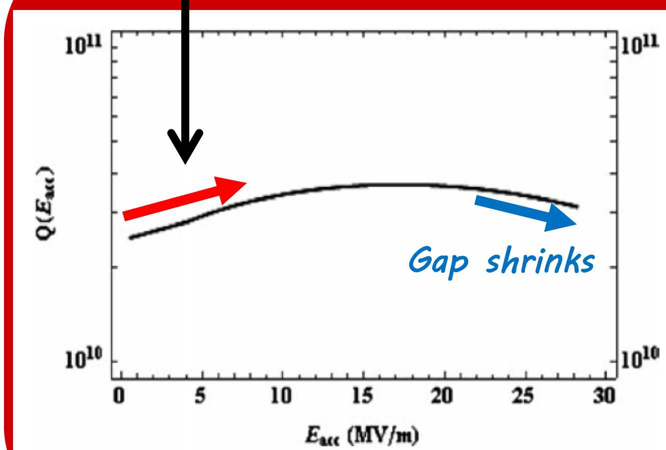
$$\sigma_1 = \sigma_n \frac{2\Delta}{kT} \ln\frac{CkT}{\hbar\omega} e^{-\frac{\Delta}{kT}}$$

comes from this DOS

Review (1)

A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)

Broadening of DOS peaks causes the Q rise

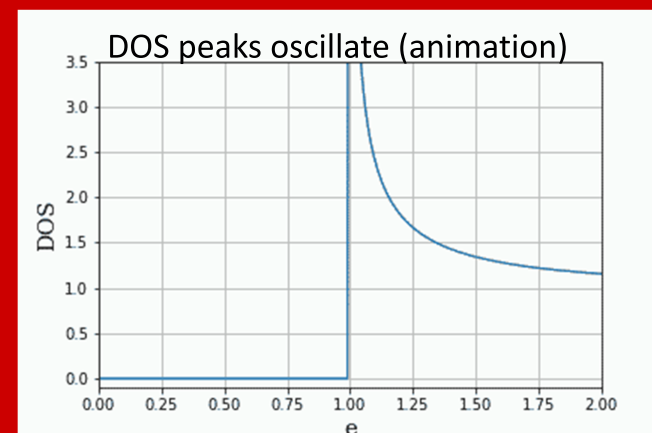


Under a strong rf current

$$\sigma_1 = \sigma_n \frac{2\Delta}{kT} \boxed{\ln \frac{CkT}{\hbar\omega}} e^{-\frac{\Delta}{kT}}$$

decreases

$$\ln \frac{CkT}{\text{peak width}}$$



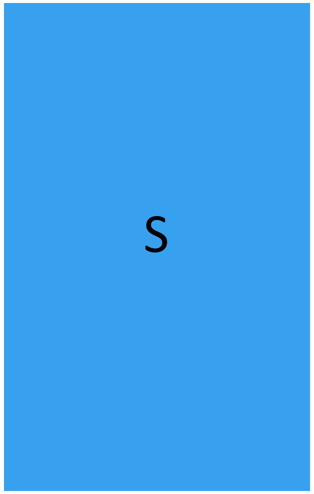
The extended Q-rise is not an exotic but the behavior which follows from the BCS model with the idealized DOS!

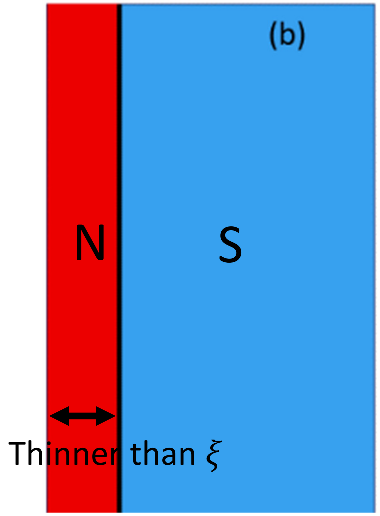
Review (2)

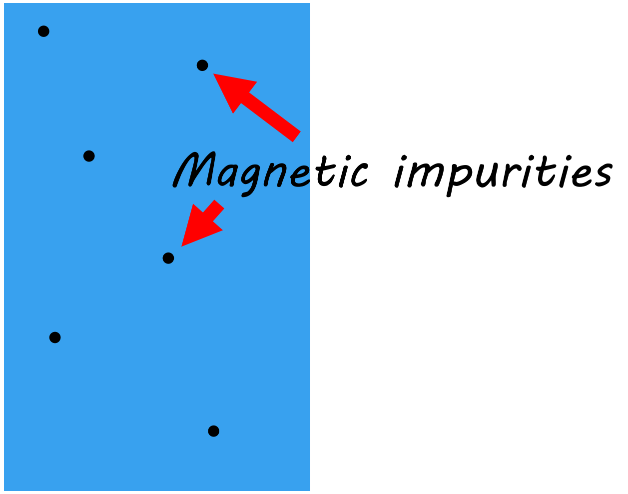
A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Other mechanisms which broaden DOS also affect R_s.
→ We Incorporated effects of pair-breaking mechanisms originating from **realistic material features** into R_s at the weak-field limit.

- Subgap states originating from a finite quasiparticle lifetime.
- Proximity coupled thin Normal layer on the surface
- Small density of magnetic impurities





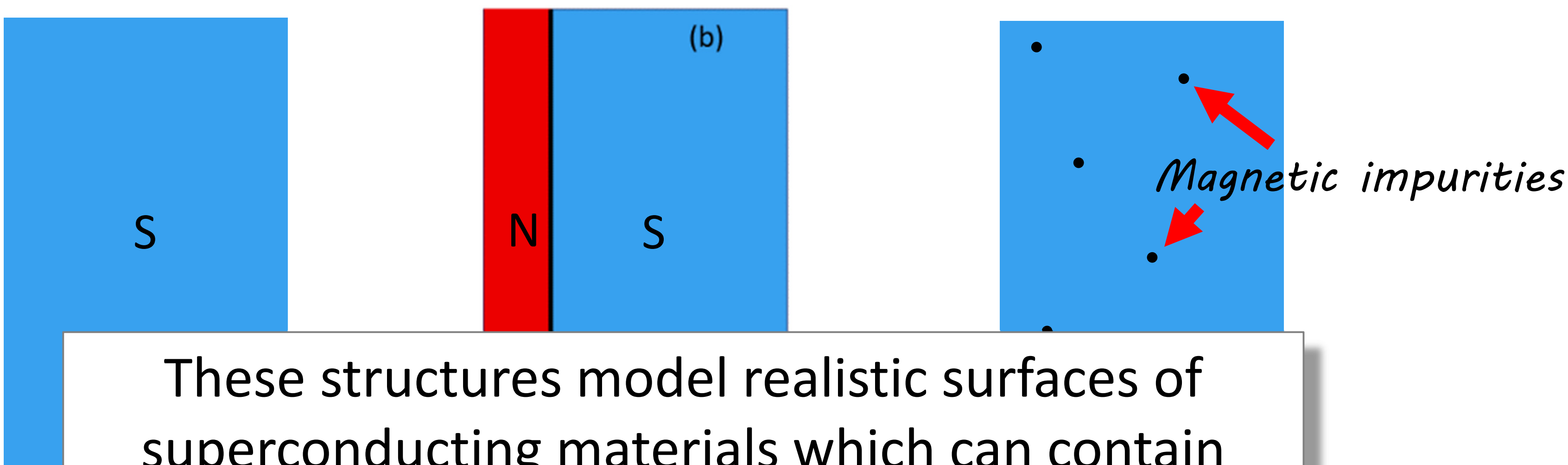


Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Other mechanisms which broaden DOS also affect R_s.
→ We Incorporated effects of pair-breaking mechanisms originating from **realistic material features** into R_s at the weak-field limit.

- Subgap states originating from a finite quasiparticle lifetime.
- Proximity coupled thin Normal layer on the surface
- Small density of magnetic impurities

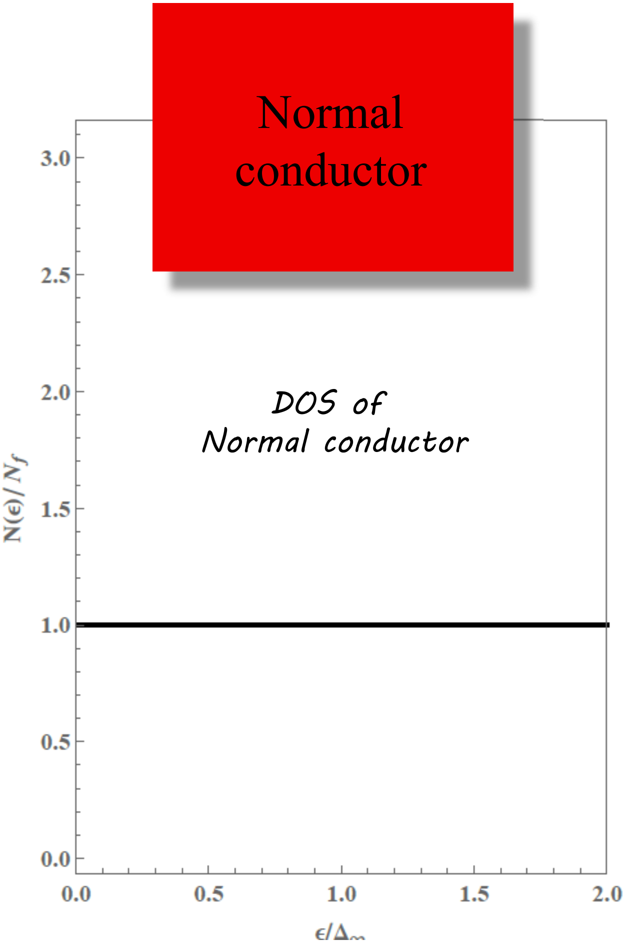


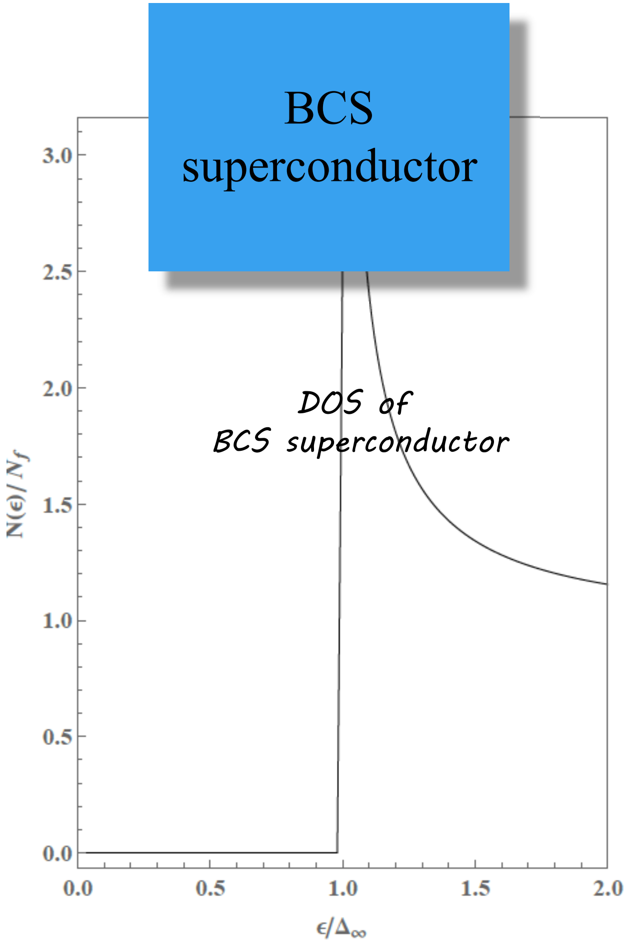
These structures model realistic surfaces of superconducting materials which can contain **oxide layers, hydrides, absorbed impurities or nonstoichiometric composition**.

Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example: Proximity-coupled thin N layer (metallic suboxides)

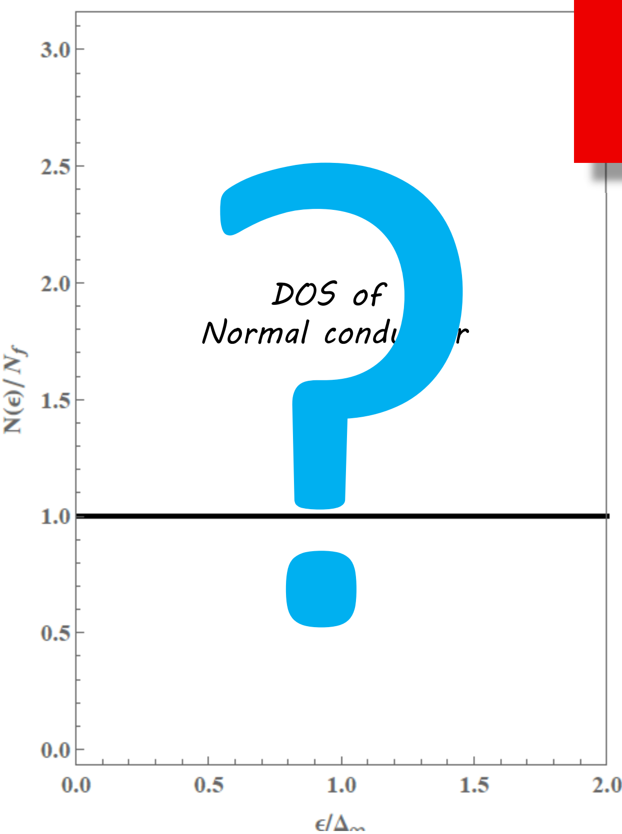


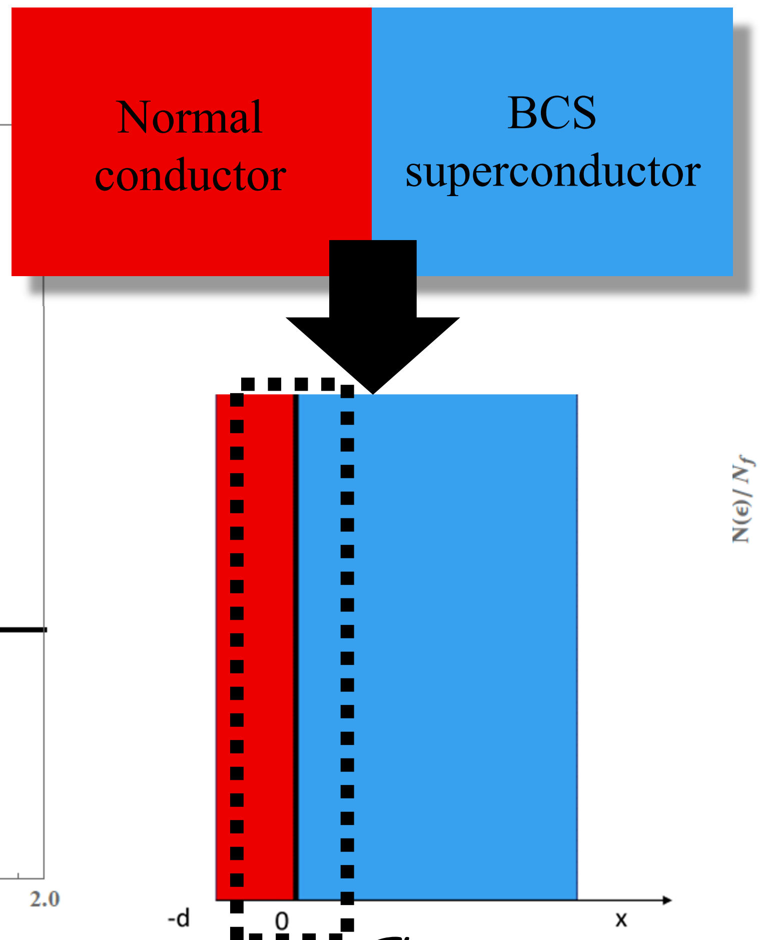


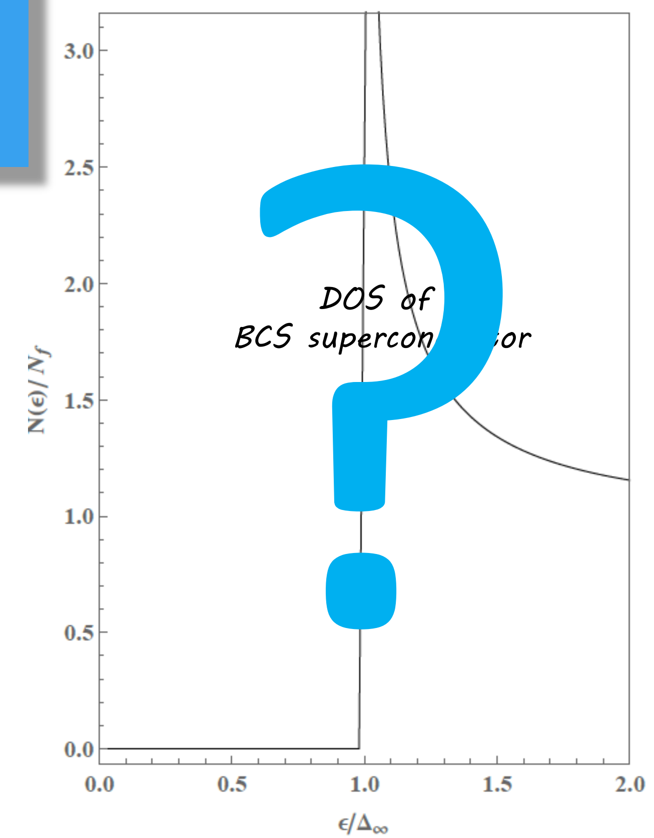
Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example: Proximity-coupled thin N layer (metallic suboxides)







The proximity effect changes DOS

Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example: Proximity-coupled thin N layer (metallic suboxides)

Parameters are sensitive to material processing!

d is an N layer thickness.
(e.g., thickness of suboxide on the Nb surface)

$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}} \qquad \boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$$

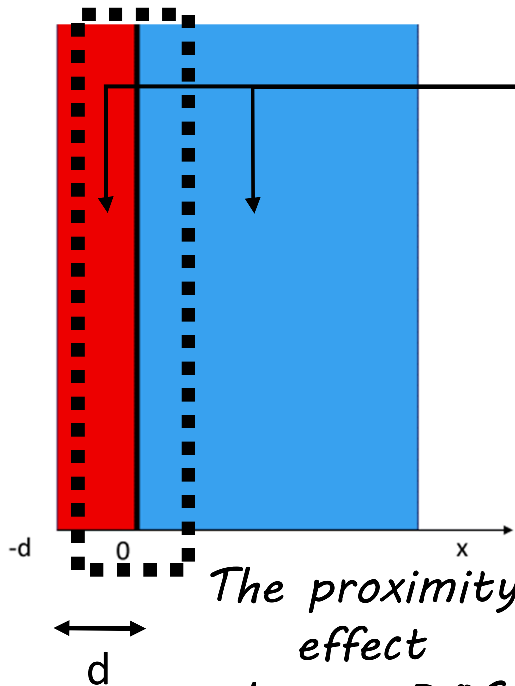
~thickness

~barrier between N&S

R_B is an interface resistance
Sensitive to heat treatment
(e.g., between Nb suboxide and Nb)

Ref: The lowest contact resistance of YBCO/Ag is $R_B \sim 10^{-13}\Omega \cdot m^2$
J. W. Ekin et al., Appl. Phys. Lett. **62**, 369 (1993)

We can calculate DOS by using the well-established method: Quasiclassical Green's function formalism of the BCS theory.



Conductance
σ_n N region
σ_s S region

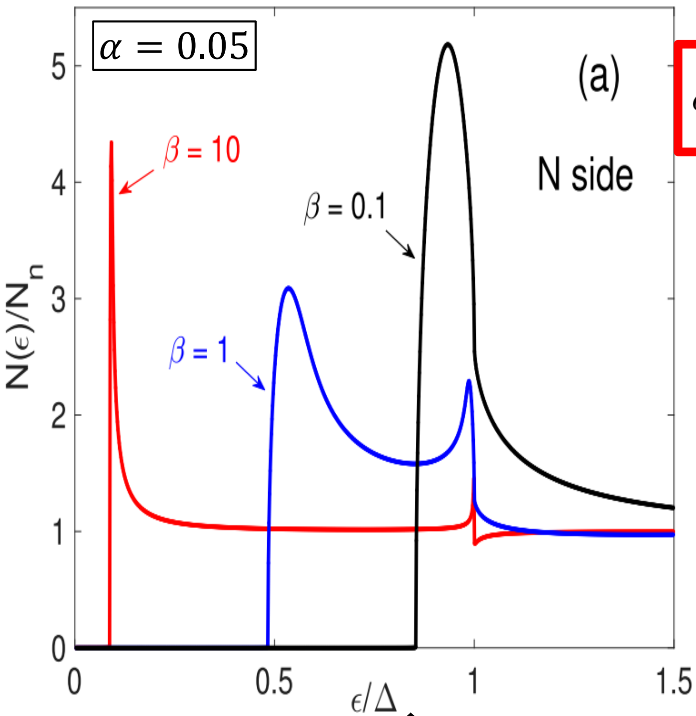
The proximity effect changes DOS

Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example: Proximity-coupled thin N layer (metallic suboxides)

N-side DOS

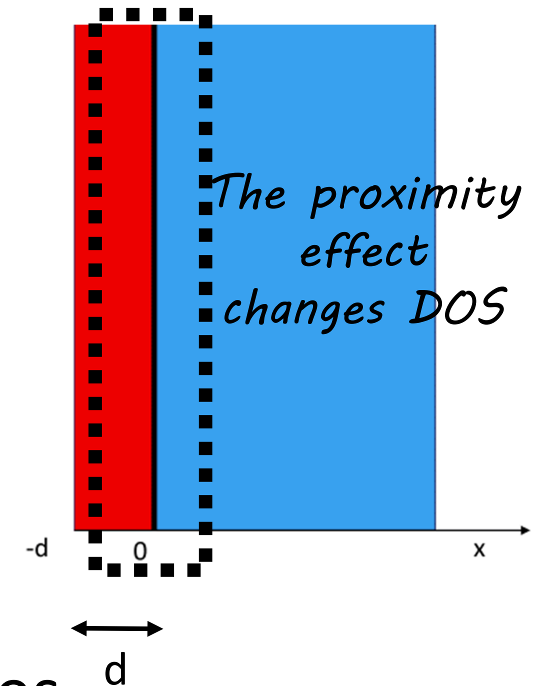


$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$

~thickness

$$\boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$$

~barrier between N&S



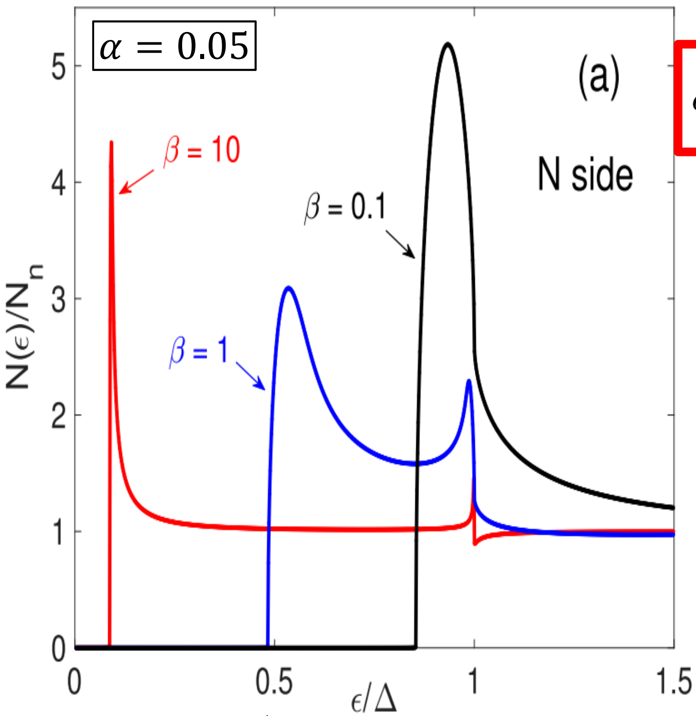
As β increases,
the <u>minigap</u> decreases

Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

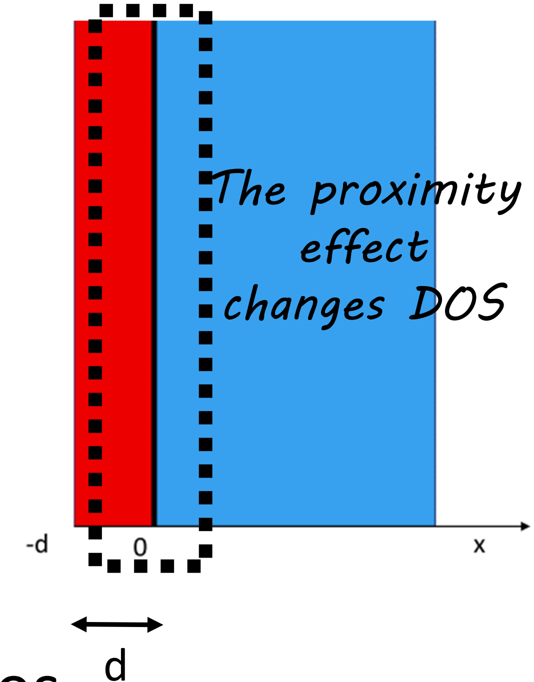
Example: Proximity-coupled thin N layer (metallic suboxides)

N-side DOS



$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$
~thickness

$$\boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$$
~barrier between N&S



The proximity effect changes DOS

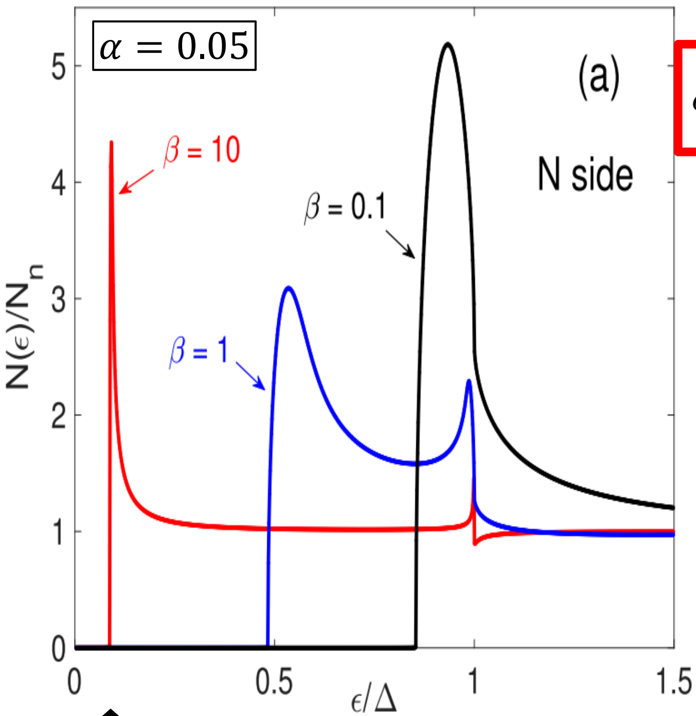
As β increases, the minigap decreases

Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

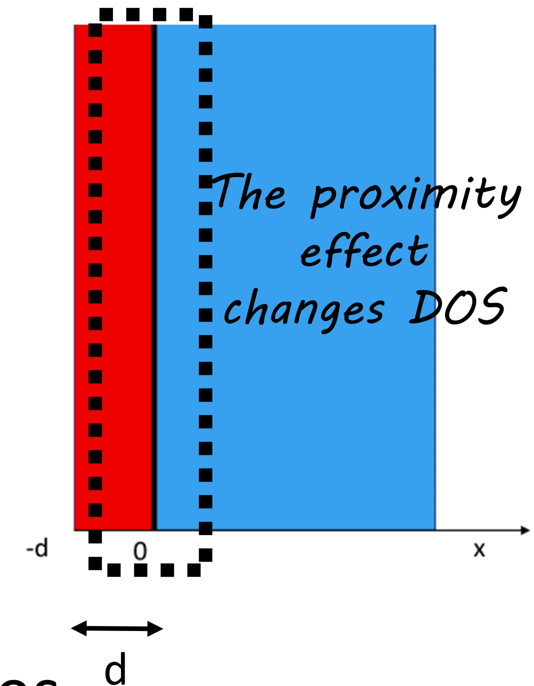
Example: Proximity-coupled thin N layer (metallic suboxides)

N-side DOS



$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$ ~thickness

$\boxed{\beta = \frac{4e^2}{\hbar}R_B N_n \Delta d,}$ ~barrier between N&S



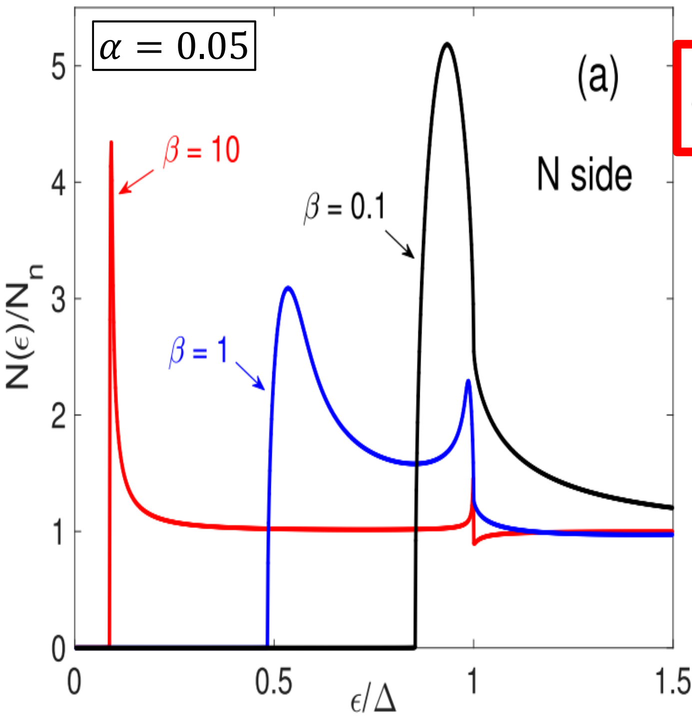
As β increases,
the <u>minigap</u> decreases

Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example: Proximity-coupled thin N layer (metallic suboxides)

N-side DOS

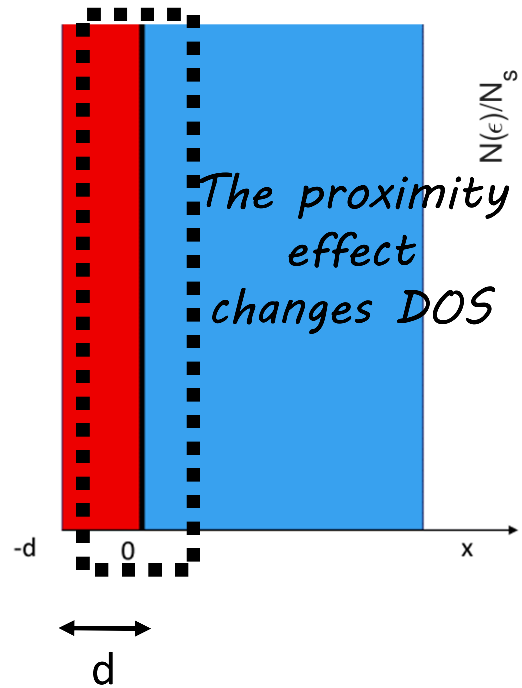


$$\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}$$

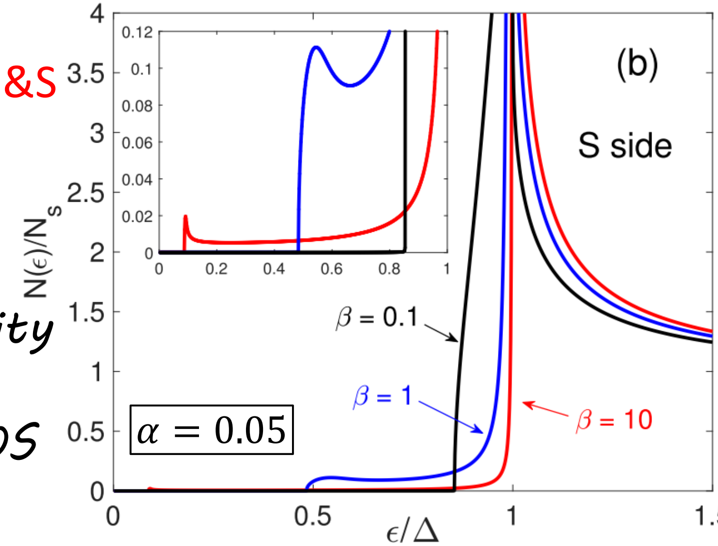
~thickness

$$\beta = \frac{4e^2}{\hbar}R_B N_n \Delta d,$$

~barrier between N&S



S-side DOS



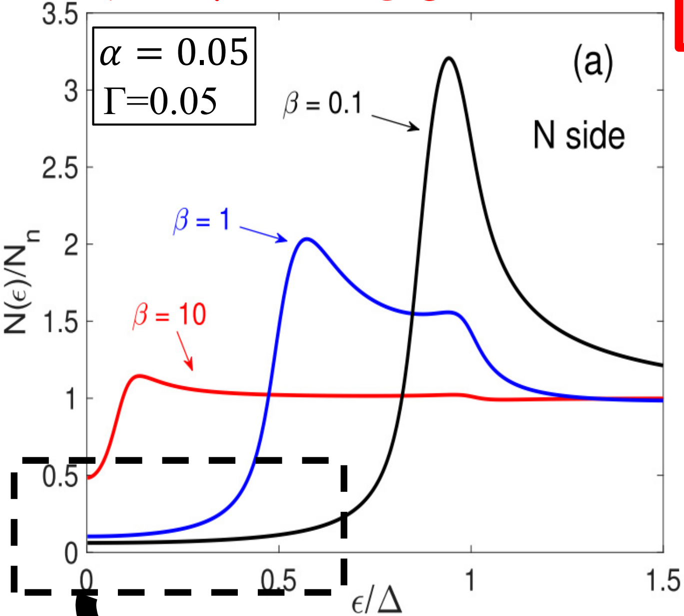
Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example: Proximity-coupled thin N layer (metallic suboxides)

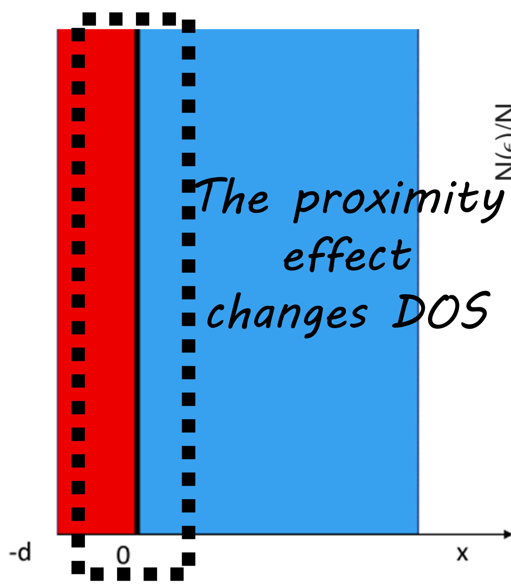
Taking a finite quasi particle lifetime into account ($\varepsilon \to \varepsilon + i\Gamma$), the cusps are smeared out.

N-side DOS

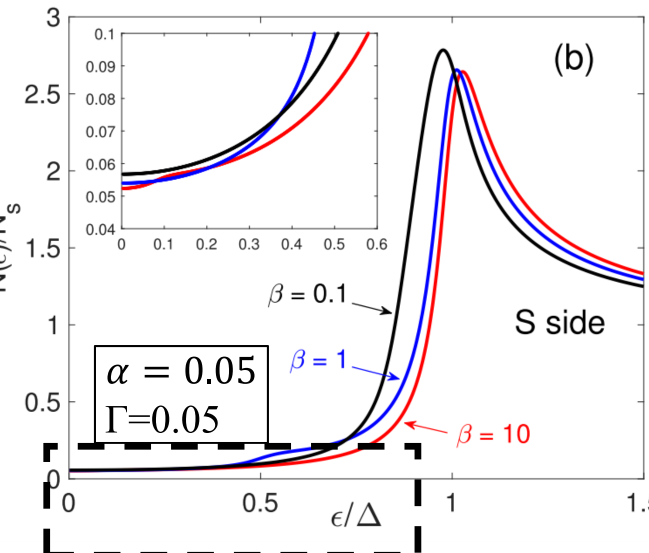


$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$
~thickness

$$\boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$$
~barrier between N&S



S-side DOS



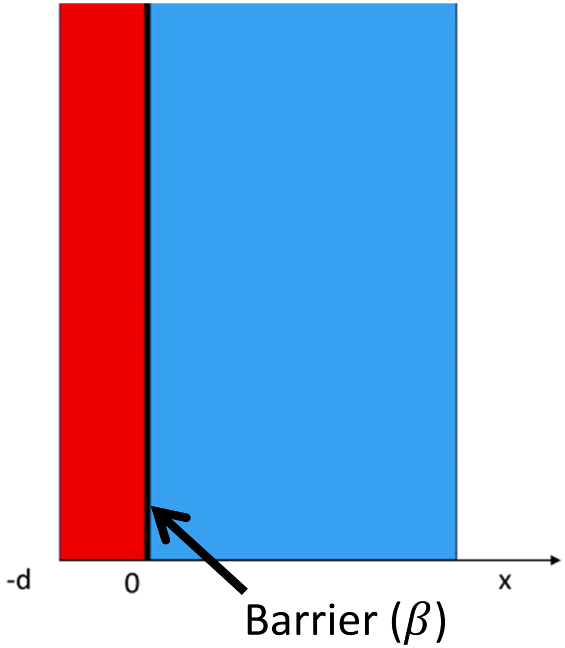
These subgap states contribute to <u>residual resistance</u> at T -> 0

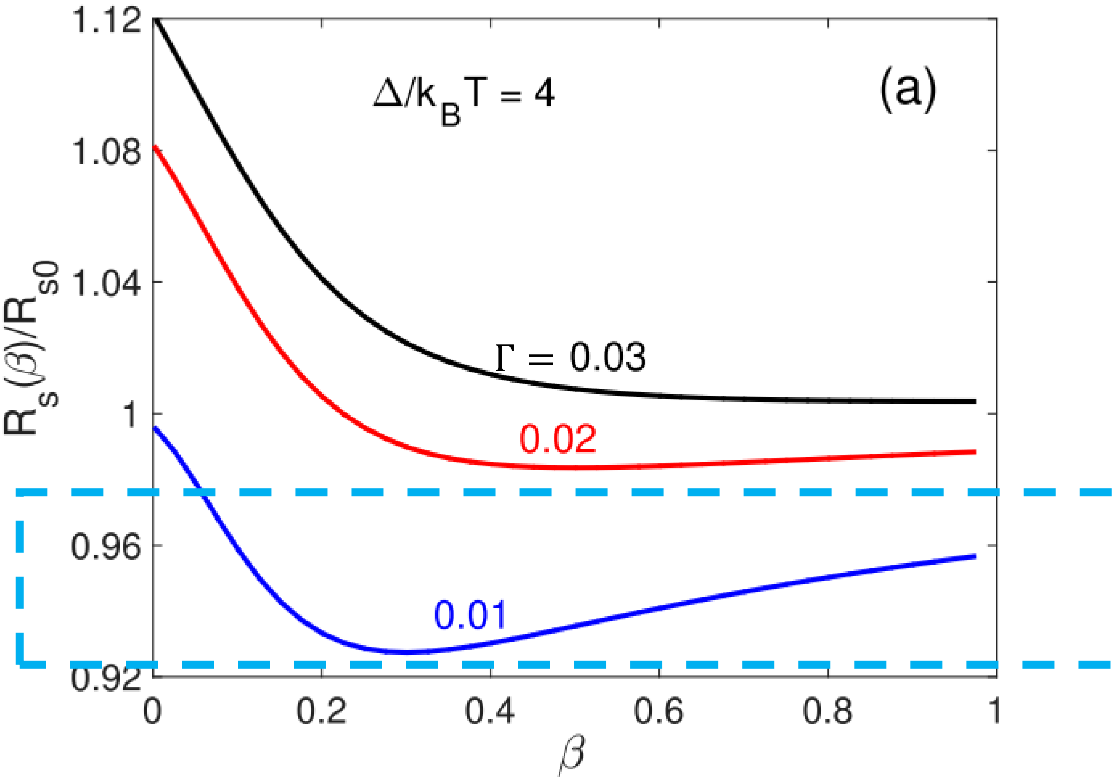
Review (2)

A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example: Proximity-coupled thin N layer (metallic suboxides)

- R_s depends on the N-layer parameters.
- R_s <u>can be optimized</u> by tuning them.
- R_s <u>can be smaller than R_s for the ideal surface</u> without N layer





$\boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$ (~ barrier between N&S) can be changed by <u>heat treatments</u>

Review (2)

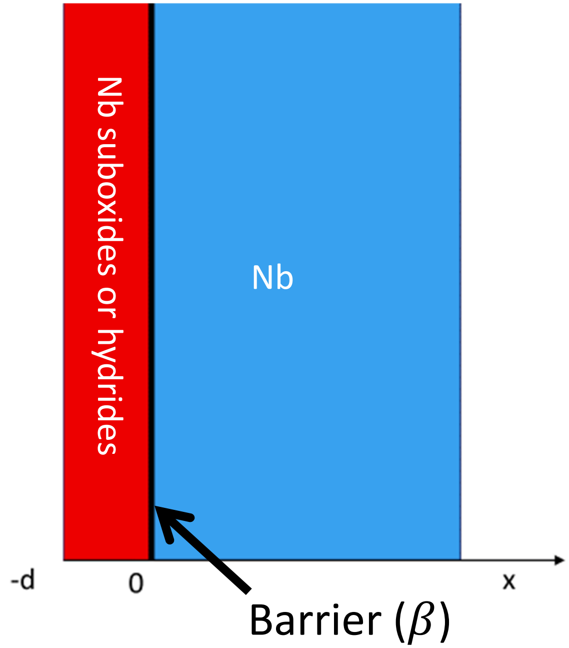
A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

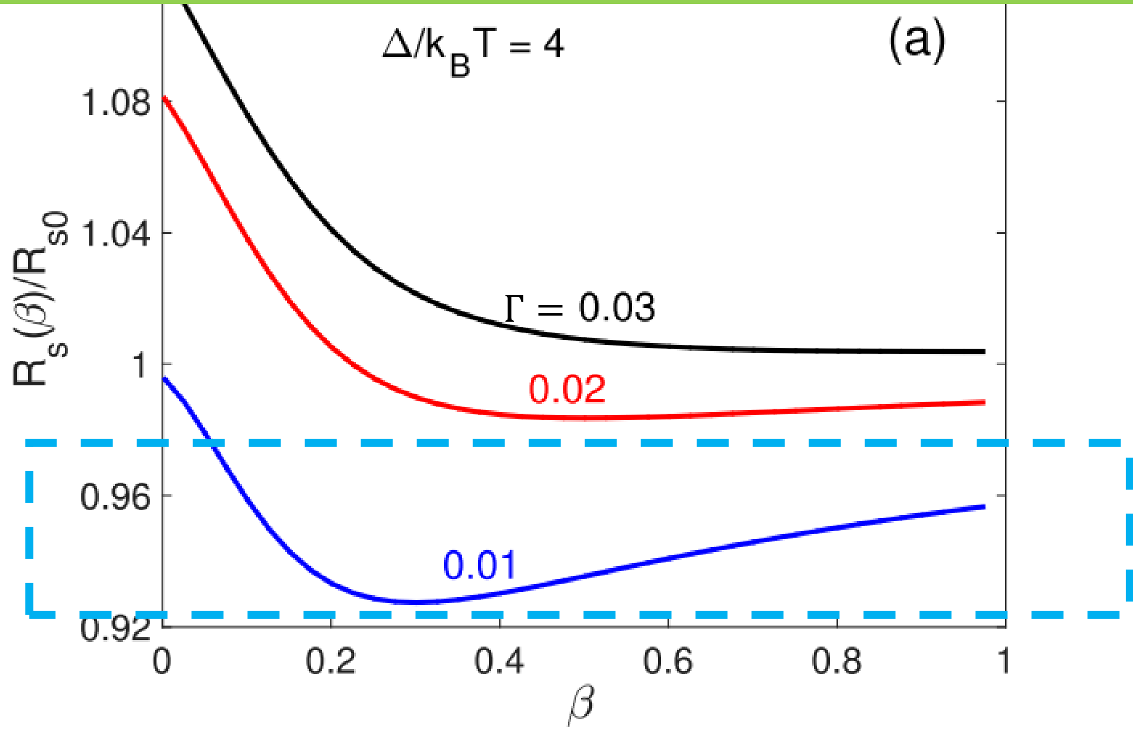
Taking Nb for example,

- $\alpha \propto$ thickness of Nb-suboxides or hydrides on the surface
- $\beta \propto$ the interface resistance between Nb suboxide and Nb

These can be easily affected by material processing recipes.

→ Link to the dependence of R_s on various recipes?





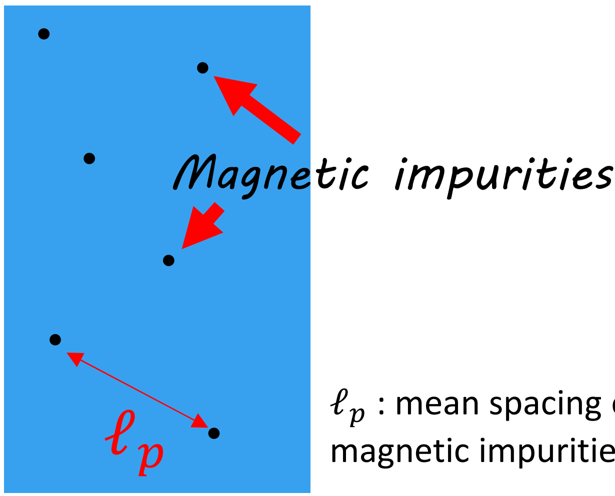
$\boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$ (~ barrier between N&S) can be changed by <u>heat treatments</u>

Changing the temperature of heat treatment, β can change and then R_s can change.

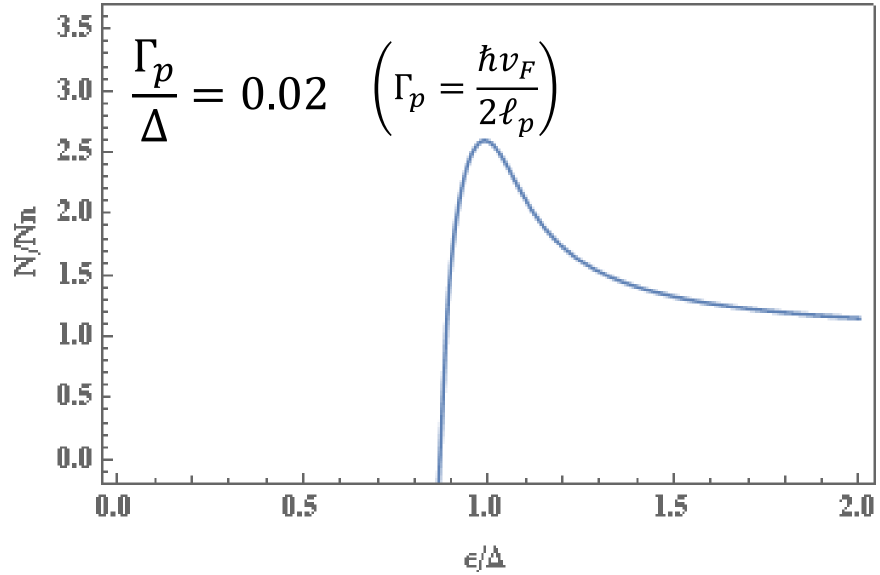
Review (2)

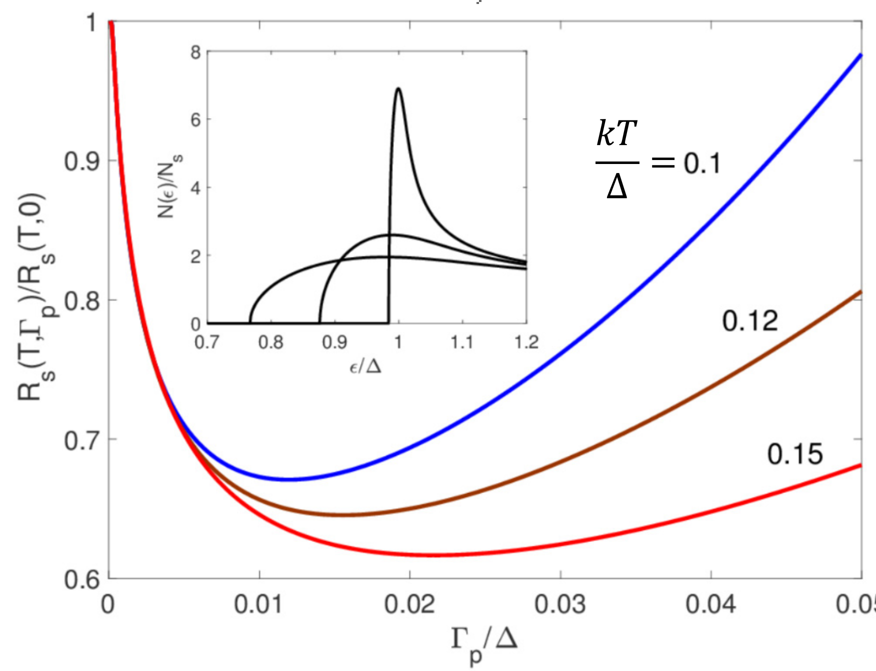
A. Gurevich and T. Kubo,
Phys. Rev. B **96**, 184515 (2017)

Example2: Magnetic impurities can also broaden DOS peaks



ℓ_p : mean spacing of magnetic impurities





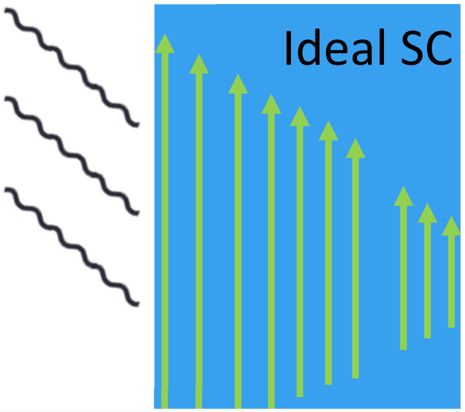
An appropriate density of magnetic impurities significantly reduce Rs!

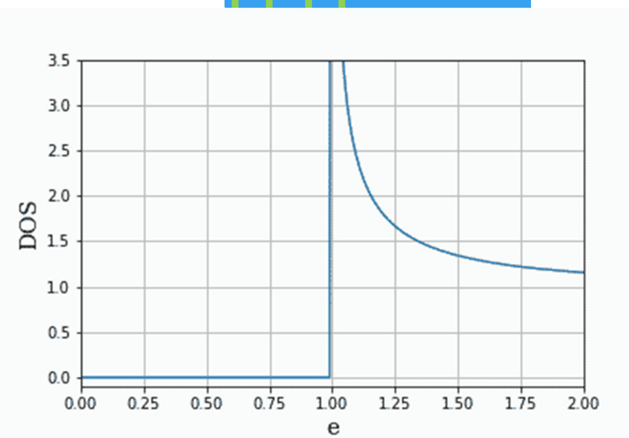
$\frac{\Gamma_p}{\Delta} \sim 0.01$ *corresponds to the mean spacing of magnetic impurities*

$\ell_p \sim \frac{\xi_0}{0.01} \sim$ *4μm*

Summary of the review part

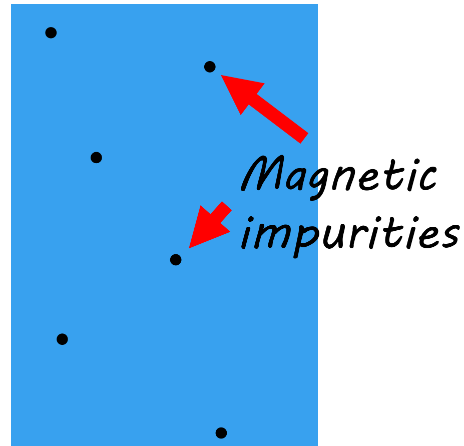
Pair-breaking current

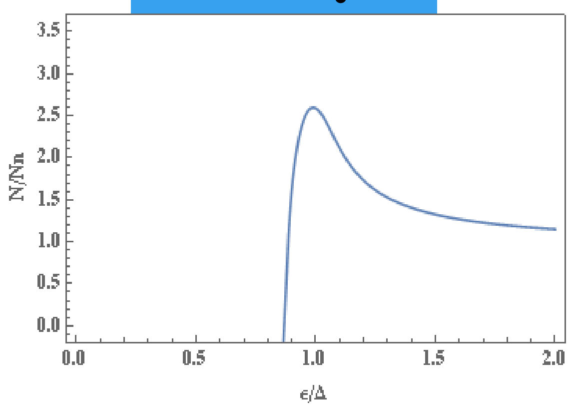




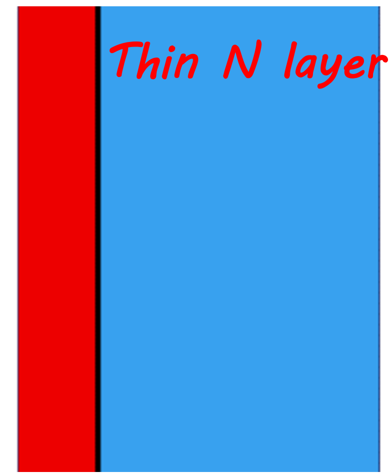
Current broadens DOS and affects R_s → field dependence

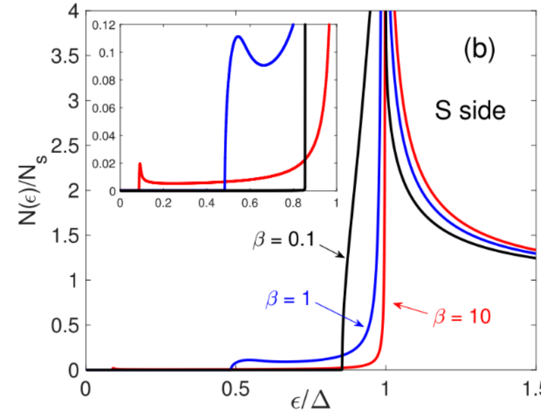
Pair-breaking mechanism originating from realistic material features





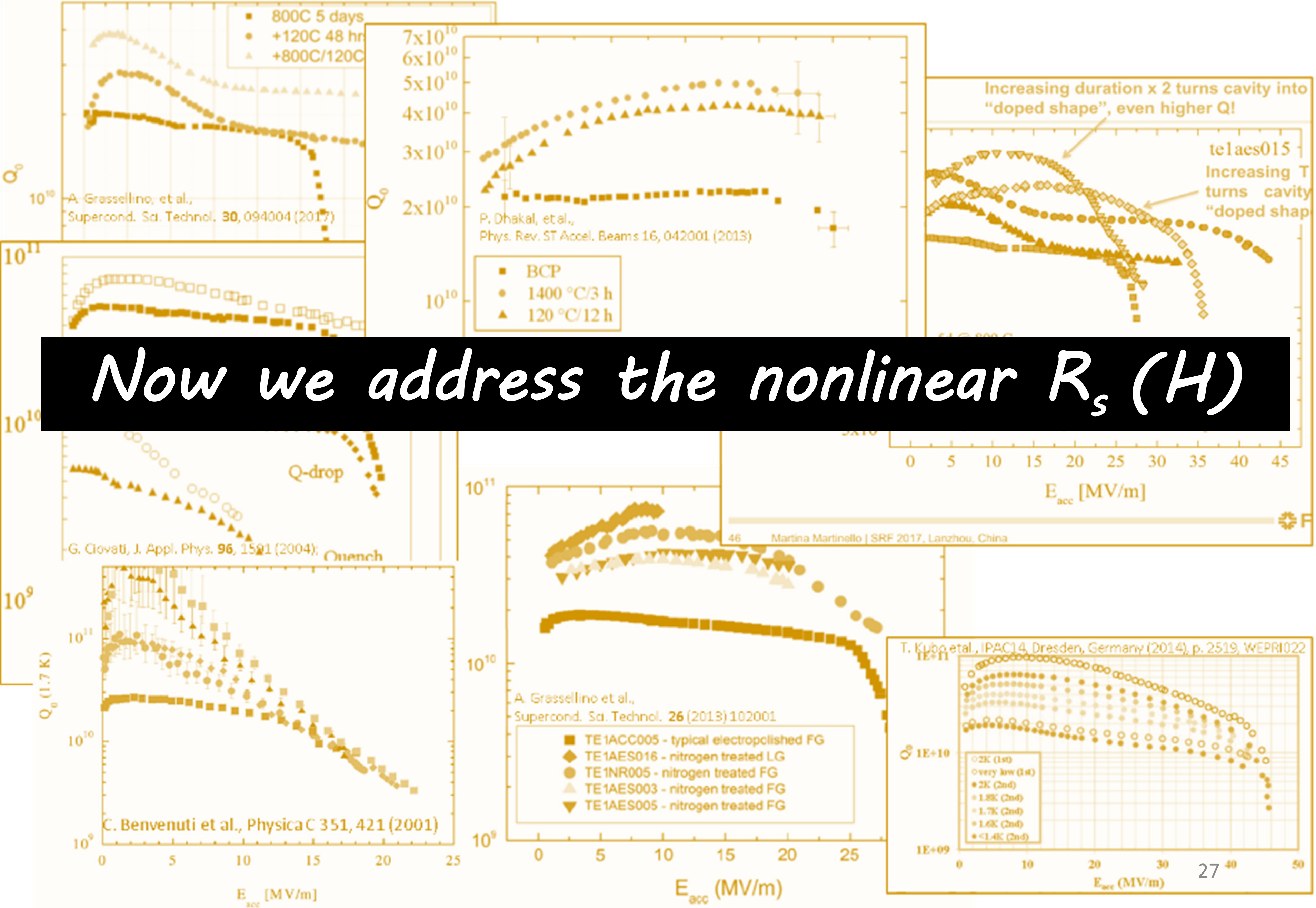
Magnetic impurities broaden DOS and affect R_s





Proximity effect broadens DOS and affects Rs. The N layer properties are sensitive to material processing.

What is the origin of many different Q-E curves?

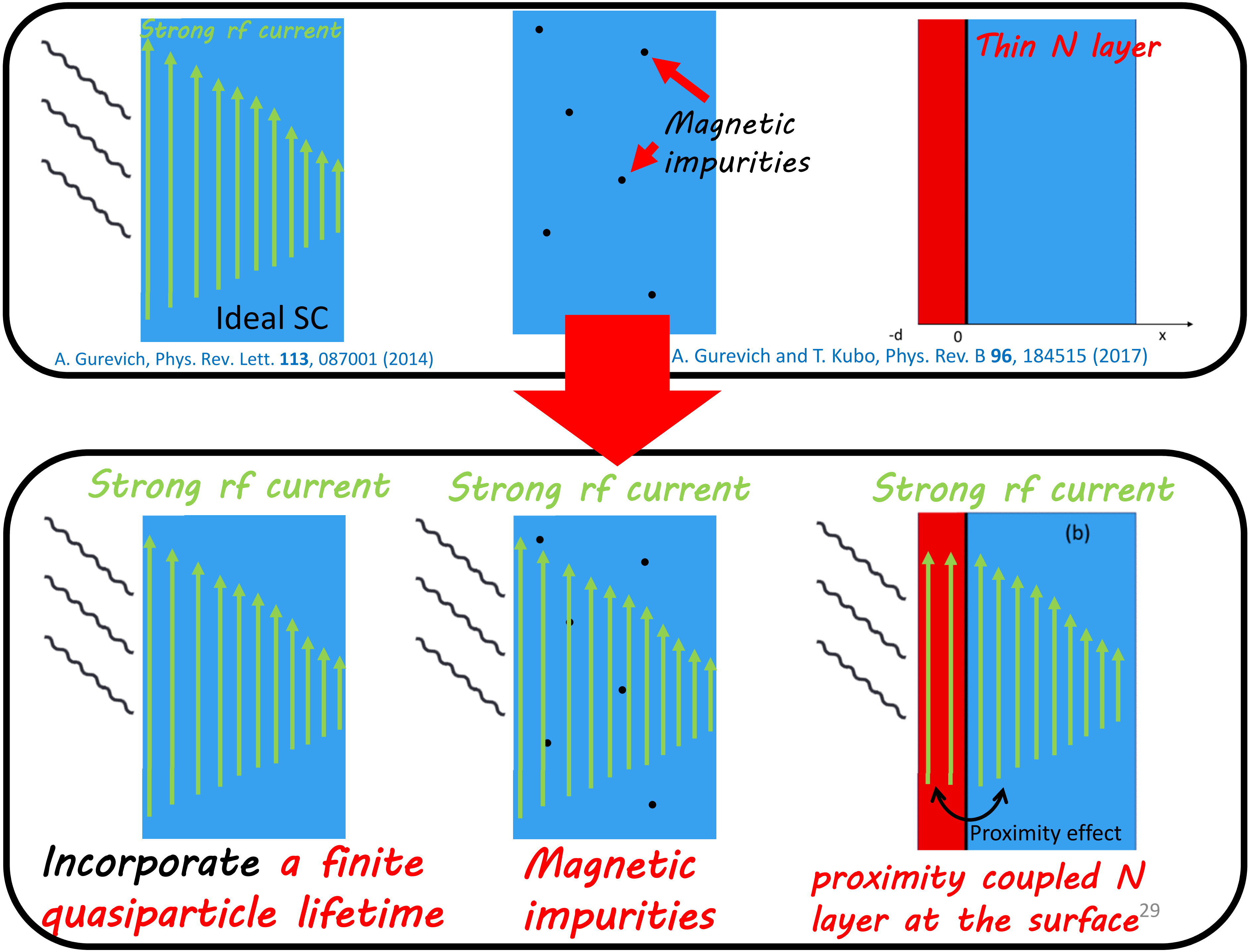


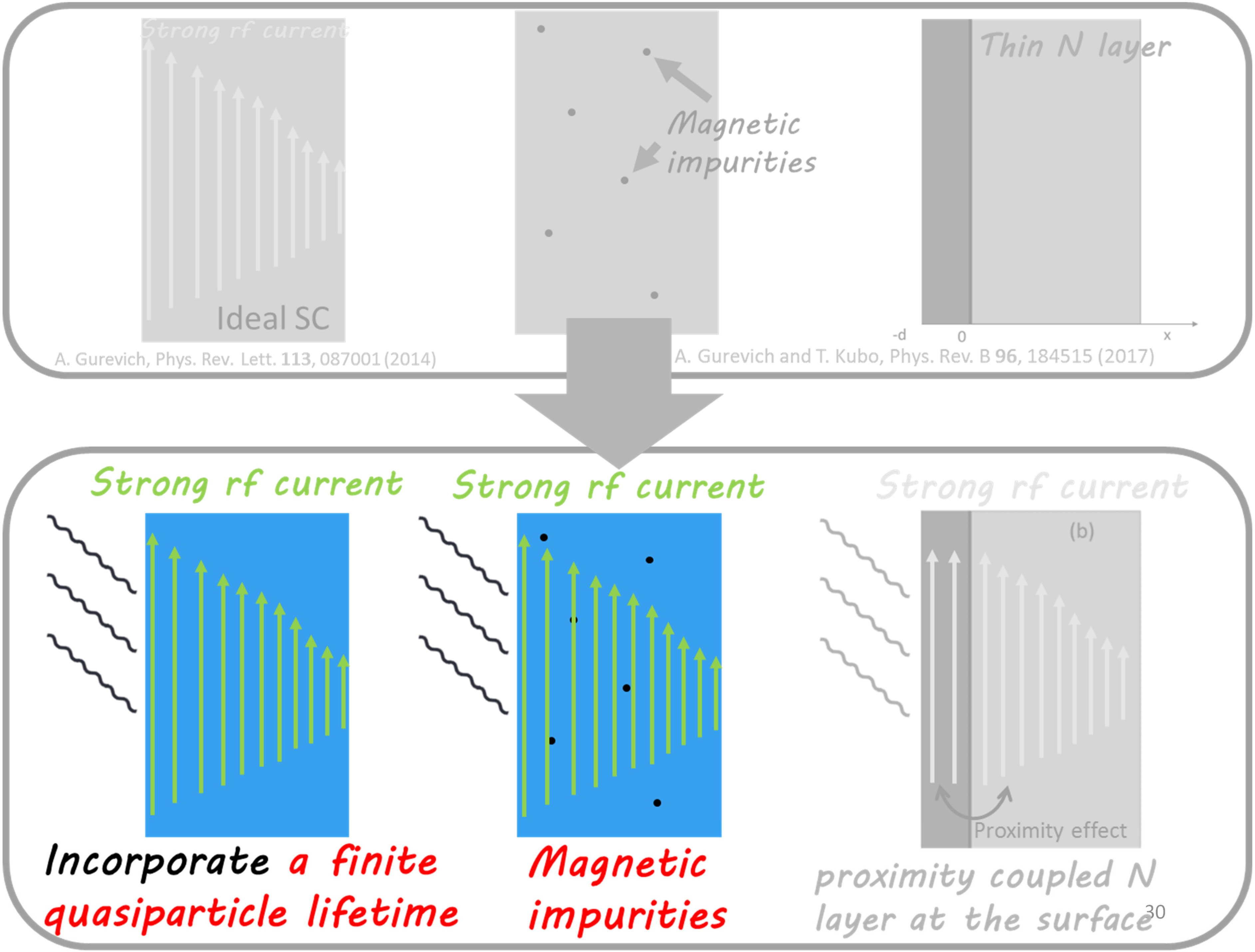
Now we address the nonlinear $R_s\,(H)$

Part 2

Effects of realistic material features on the field dependent $R_s(H)$

T. Kubo and A. Gurevich, to be published

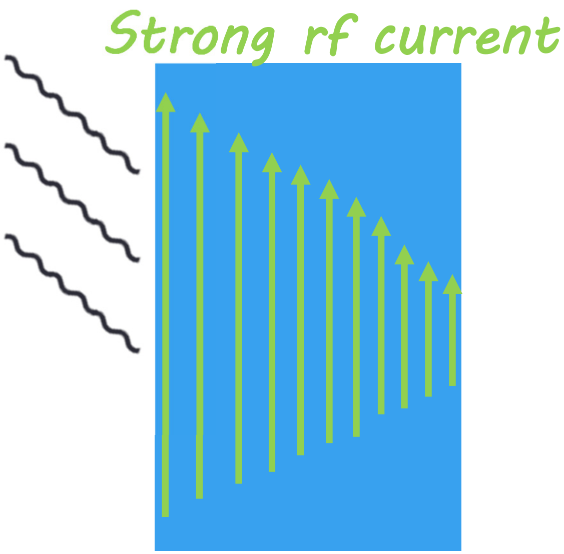

Strong rf current
Ideal SC
A. Gurevich, Phys. Rev. Lett. **113**, 087001 (2014)
Magnetic
impurities
Thin N layer
-d
0
x
A. Gurevich and T. Kubo, Phys. Rev. B **96**, 184515 (2017)
Strong rf current
Strong rf current
Strong rf current
(b)
Proximity effect
Incorporate a finite
quasiparticle lifetime
Magnetic
impurities
proximity coupled N
layer at the surface



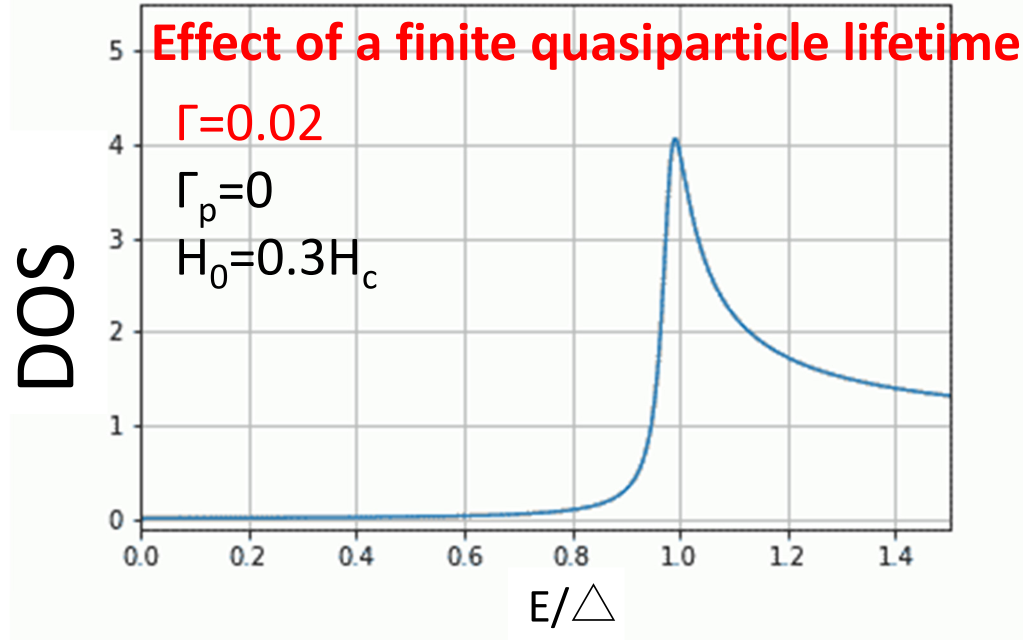
Strong rf current
Ideal SC
A. Gurevich, Phys. Rev. Lett. 113, 087001 (2014)
Magnetic impurities
Thin N layer
-d
0
x
A. Gurevich and T. Kubo, Phys. Rev. B 96, 184515 (2017)
Strong rf current
Strong rf current
Strong rf current
(b)
Proximity effect
Incorporate a finite quasiparticle lifetime
Magnetic impurities
proximity coupled N layer at the surface

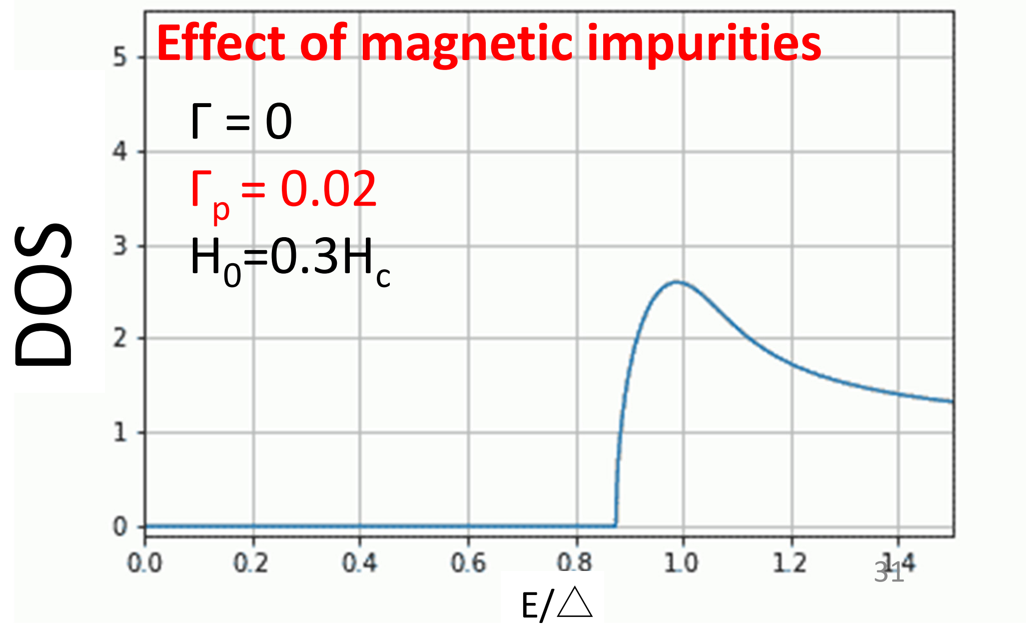
DOS under a strong rf field

Contain animations. See in Slide Show Mode.



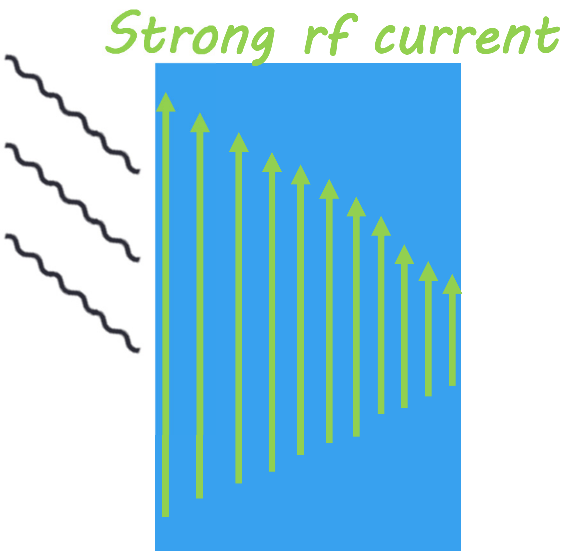
Dirty SC with nonmagnetic impurities;
Can incorporate a finite quasiparticle lifetime and can include magnetic impurities

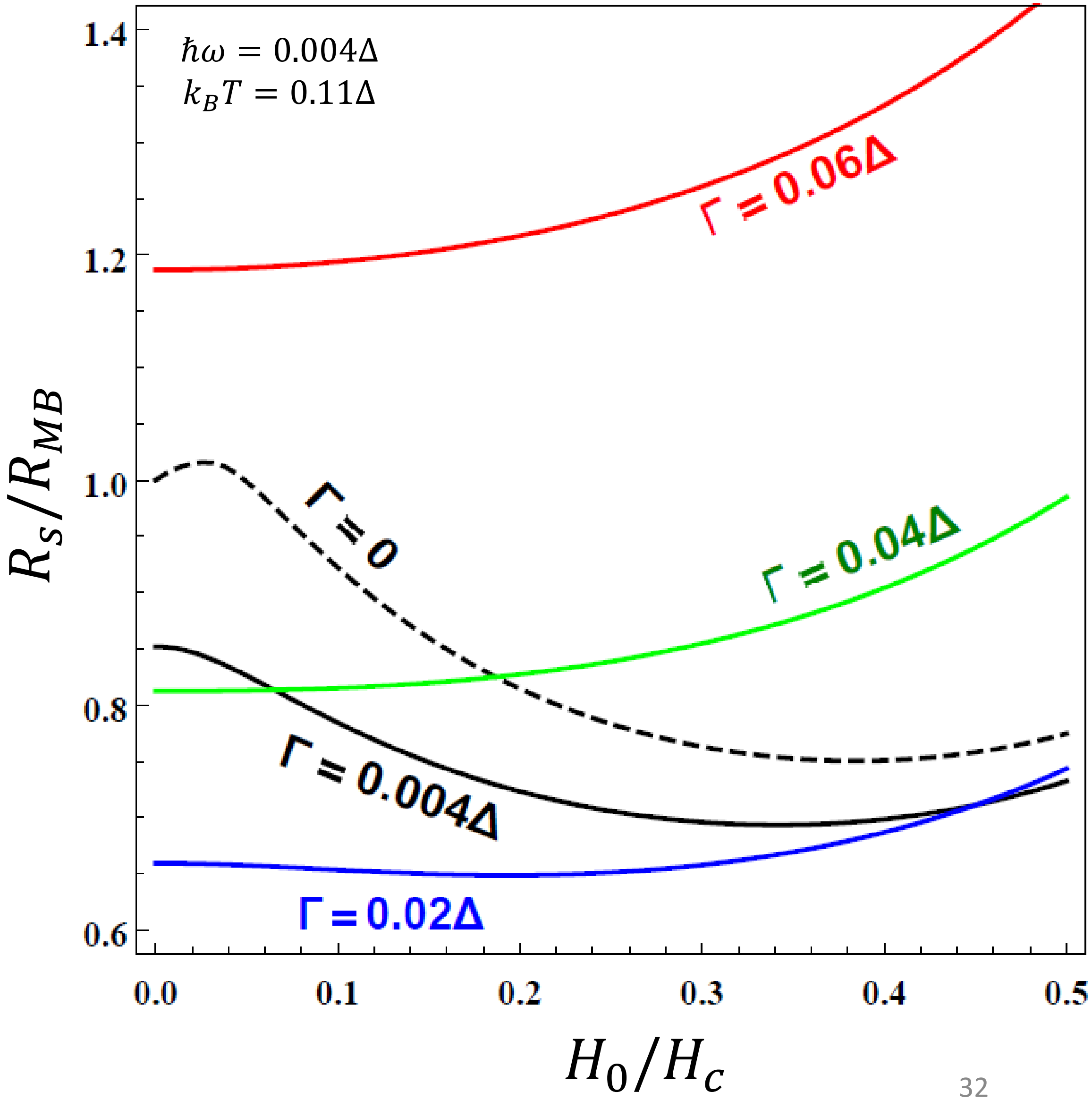




Field dependent Surface resistance $R_s(H_0)$

(1) Effect of a finite quasiparticle lifetime (Γ parameter)

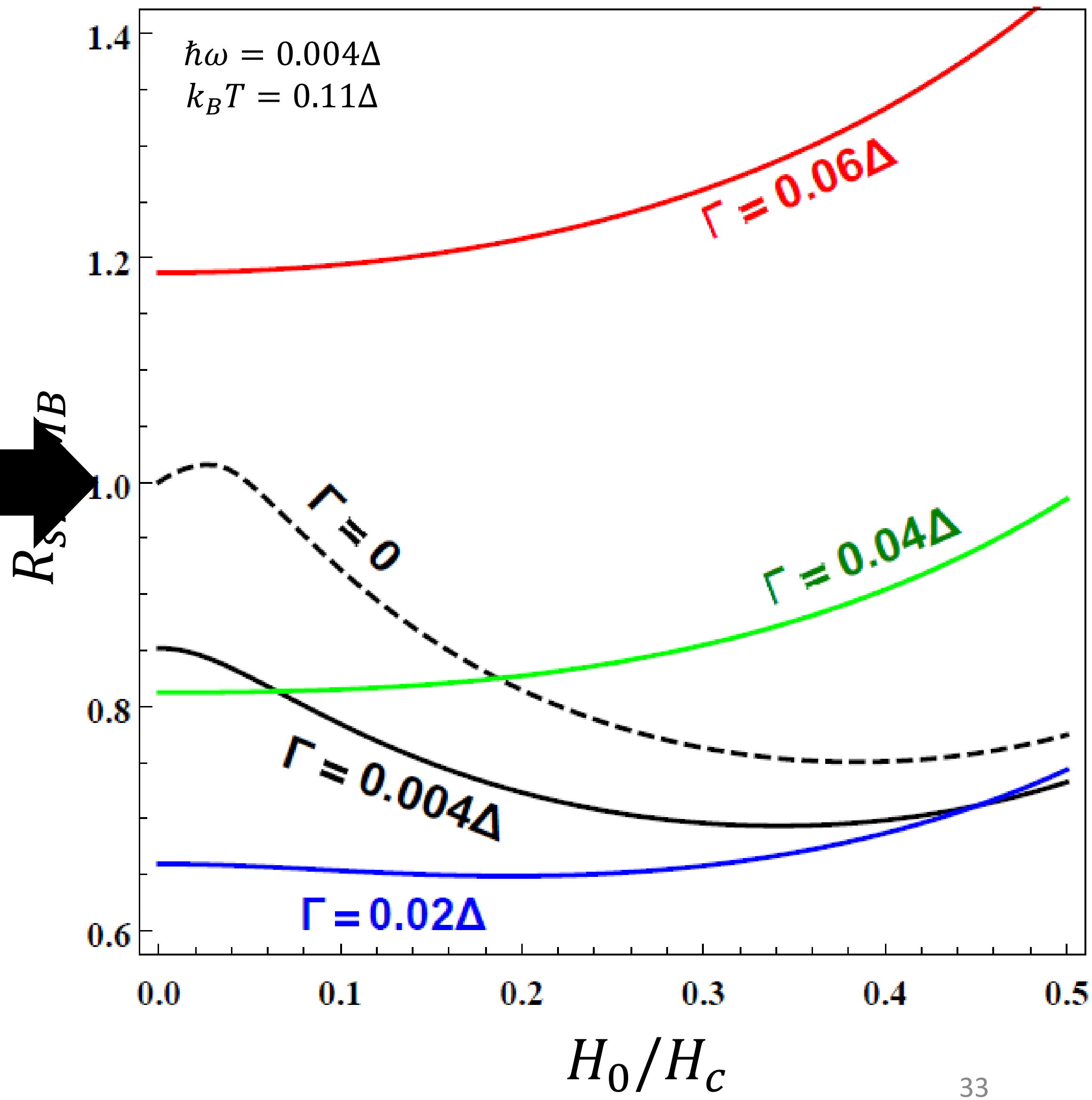




Field dependent Surface resistance $R_s(H_0)$

(1) Effect of a finite quasiparticle lifetime (Γ parameter)

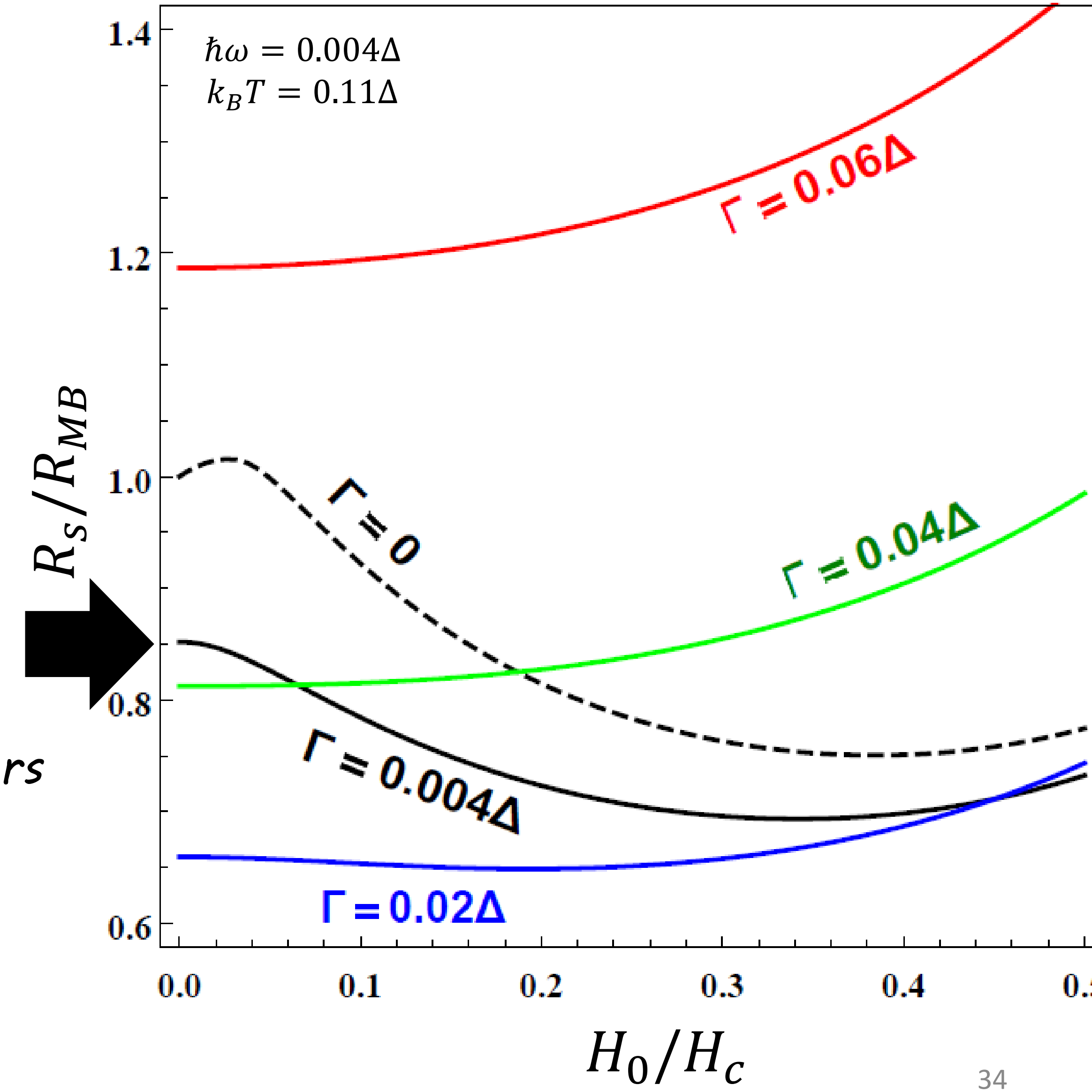
The Ideal BCS SC exhibits a <u>**deep R_s dip**</u>



Field dependent Surface resistance $R_s(H_0)$

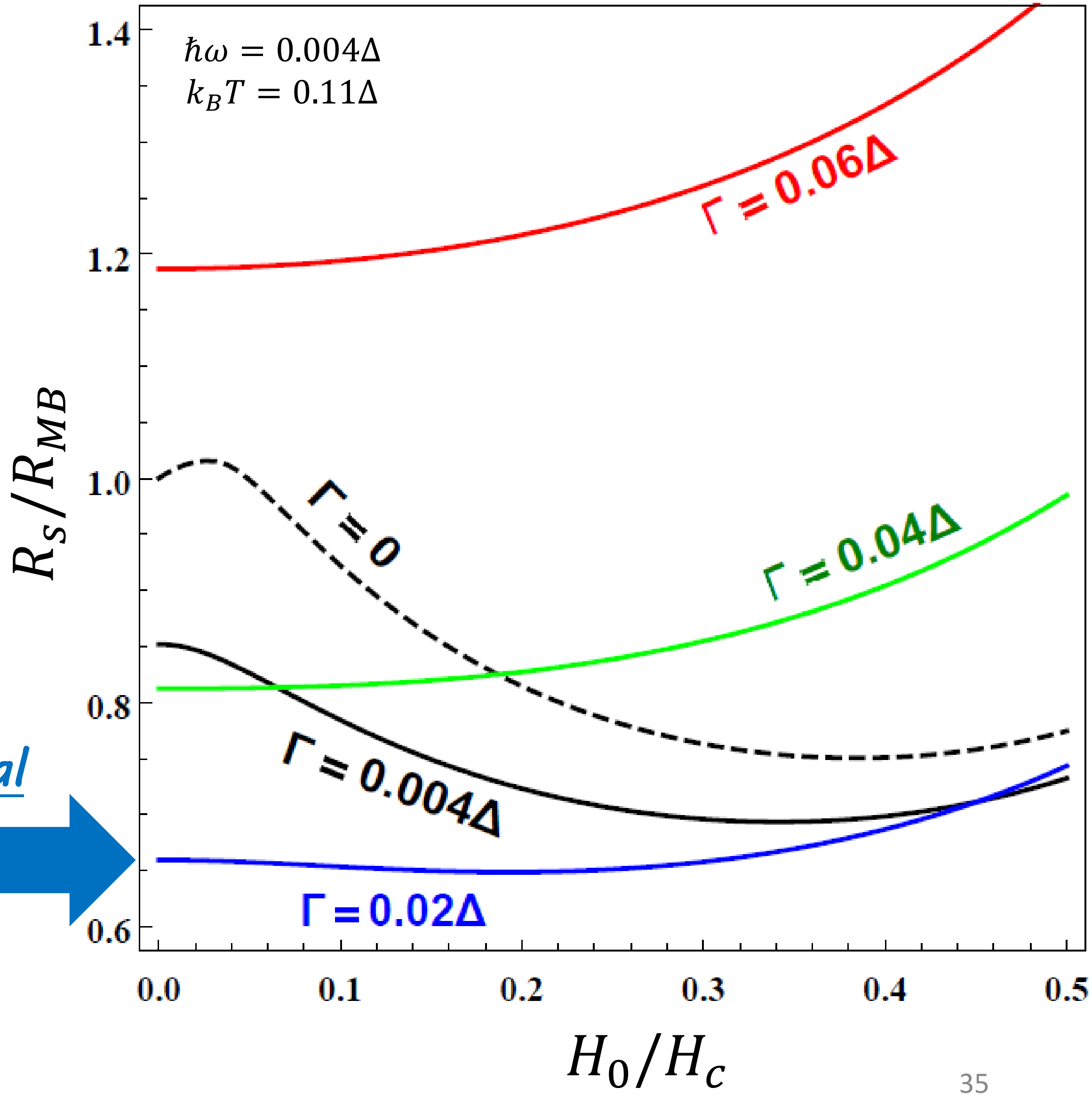
(1) Effect of a finite quasiparticle lifetime (Γ parameter)

The nearly Ideal BCS SC exhibits the <u>deep R_s dip</u>.
The first R_s rise disappears



Field dependent Surface resistance $R_s(H_0)$

(1) Effect of a finite quasiparticle lifetime (Γ parameter)

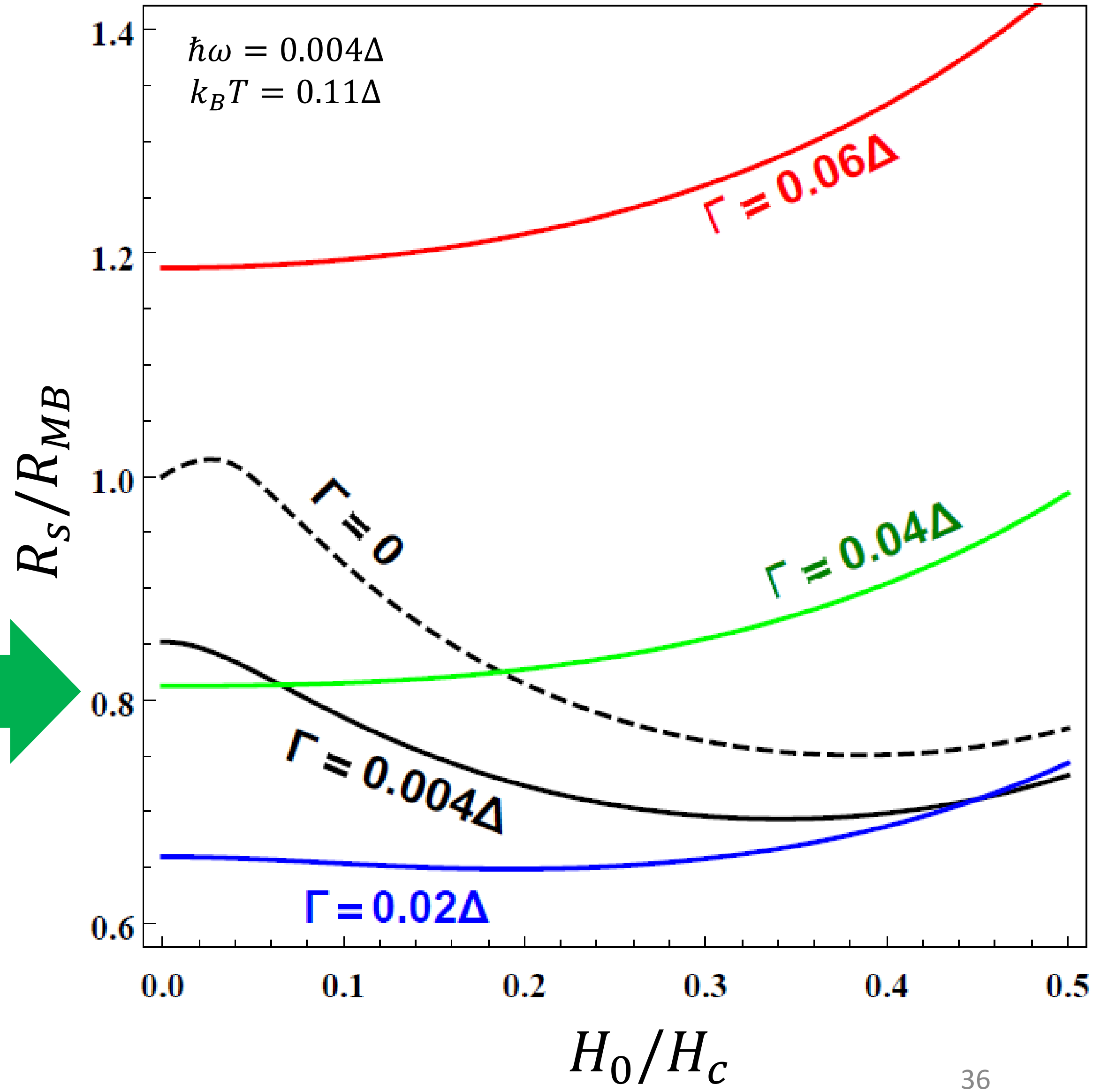


The R_s dip almost disappears, but the low-field R_s is better than ideal BCS SC due to the DOS broadening effect.

Field dependent Surface resistance $R_s(H_0)$

(1) Effect of a finite quasiparticle lifetime (Γ parameter)

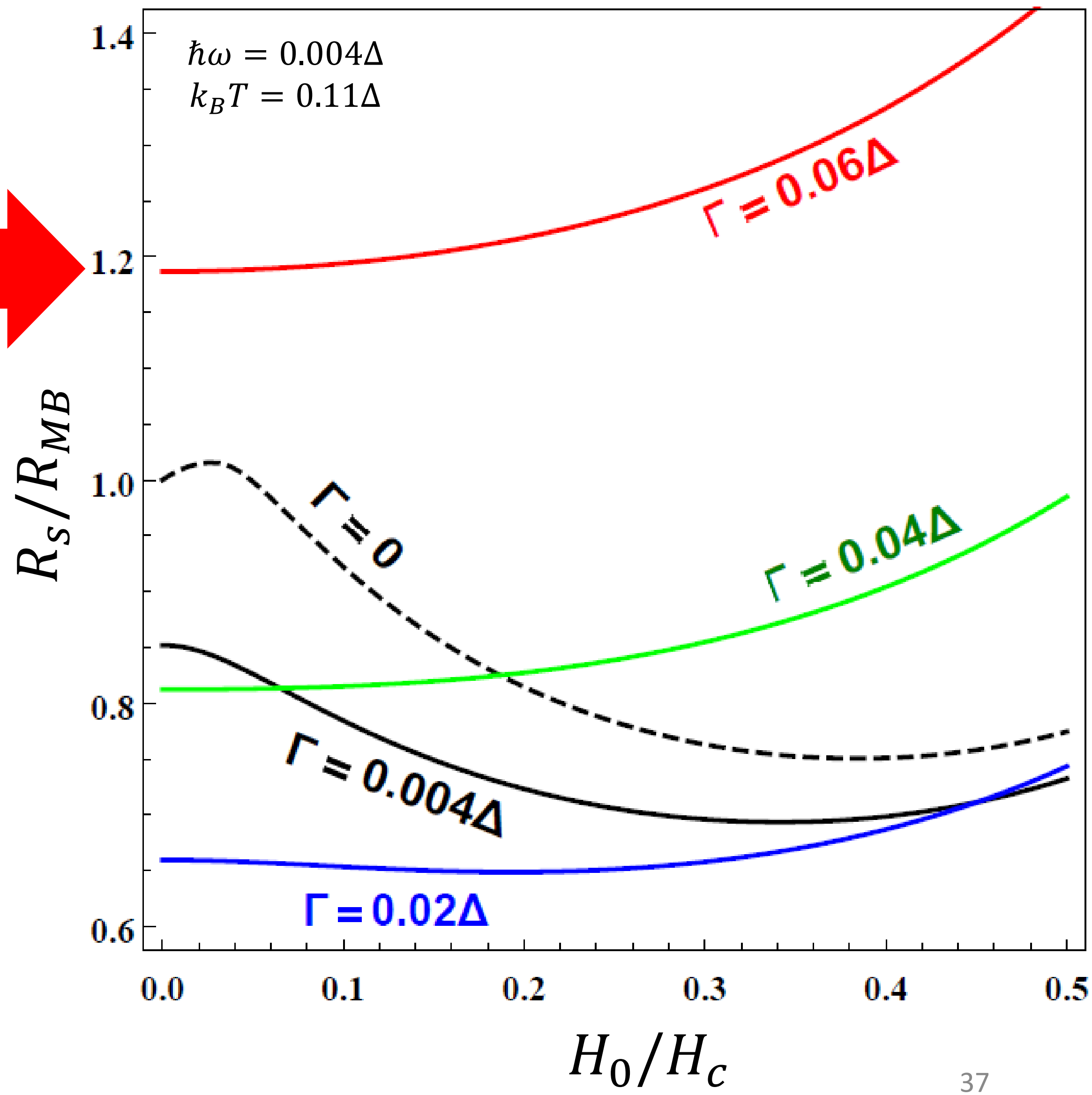
The R_s dip disappears, but the low-field R_s is better than ideal BCS SC due to the DOS broadening effect.



Field dependent Surface resistance $R_s(H_0)$

(1) Effect of a finite quasiparticle lifetime (Γ parameter)

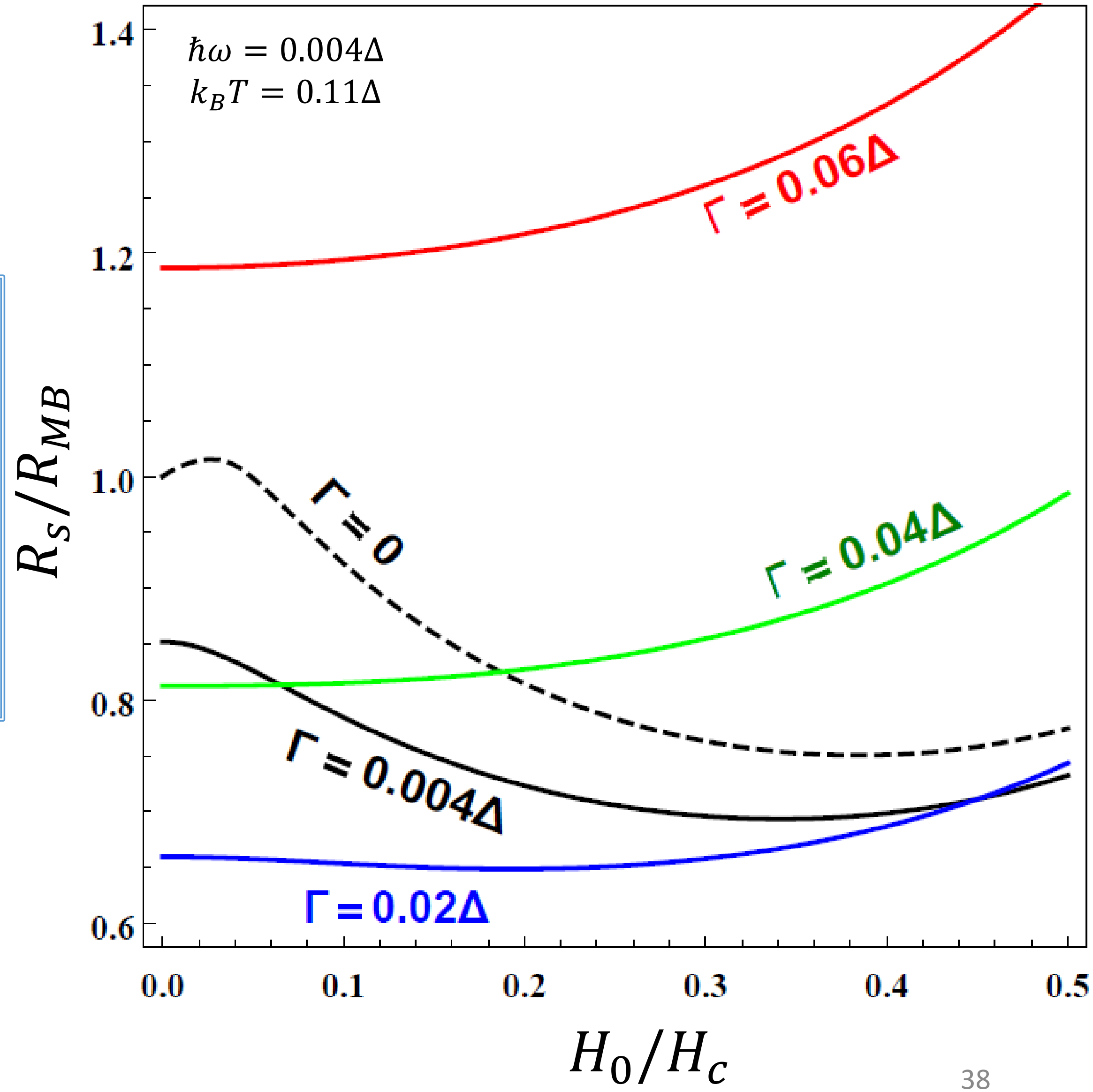
The R_s dip disappears.
R_s becomes larger.



Field dependent Surface resistance $R_s(H_0)$

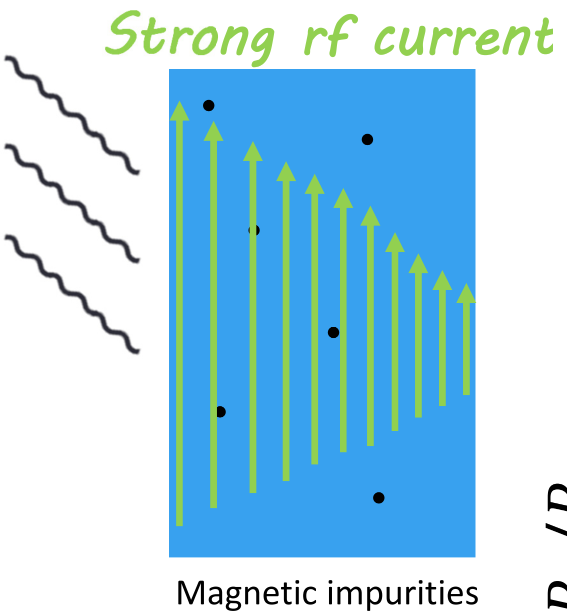
(1) Effect of a finite quasiparticle lifetime (Γ parameter)

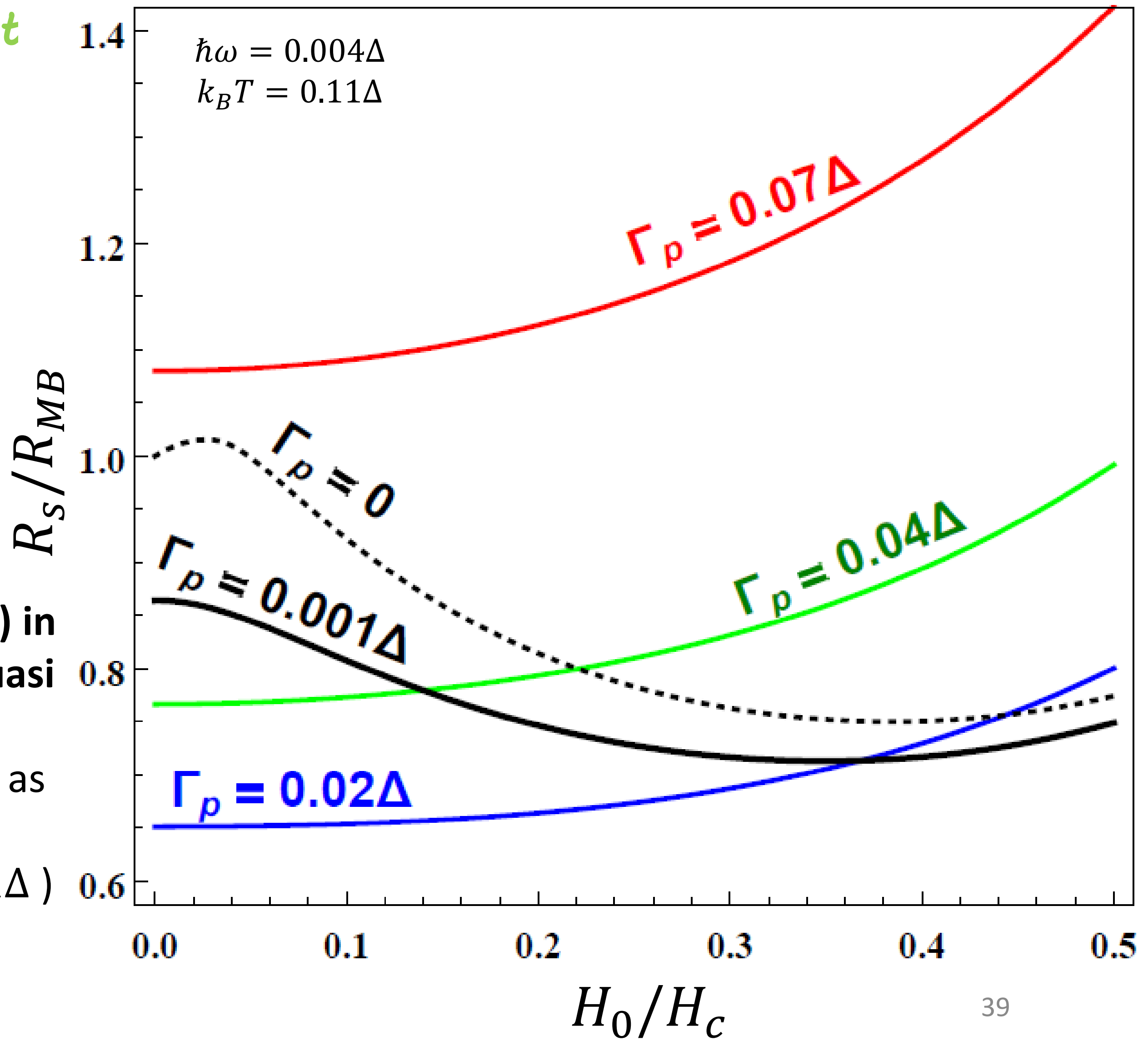
The broadening parameter (Γ) has a significant effect on the field dependent Rs.



Field dependent Surface resistance $R_s(H_0)$

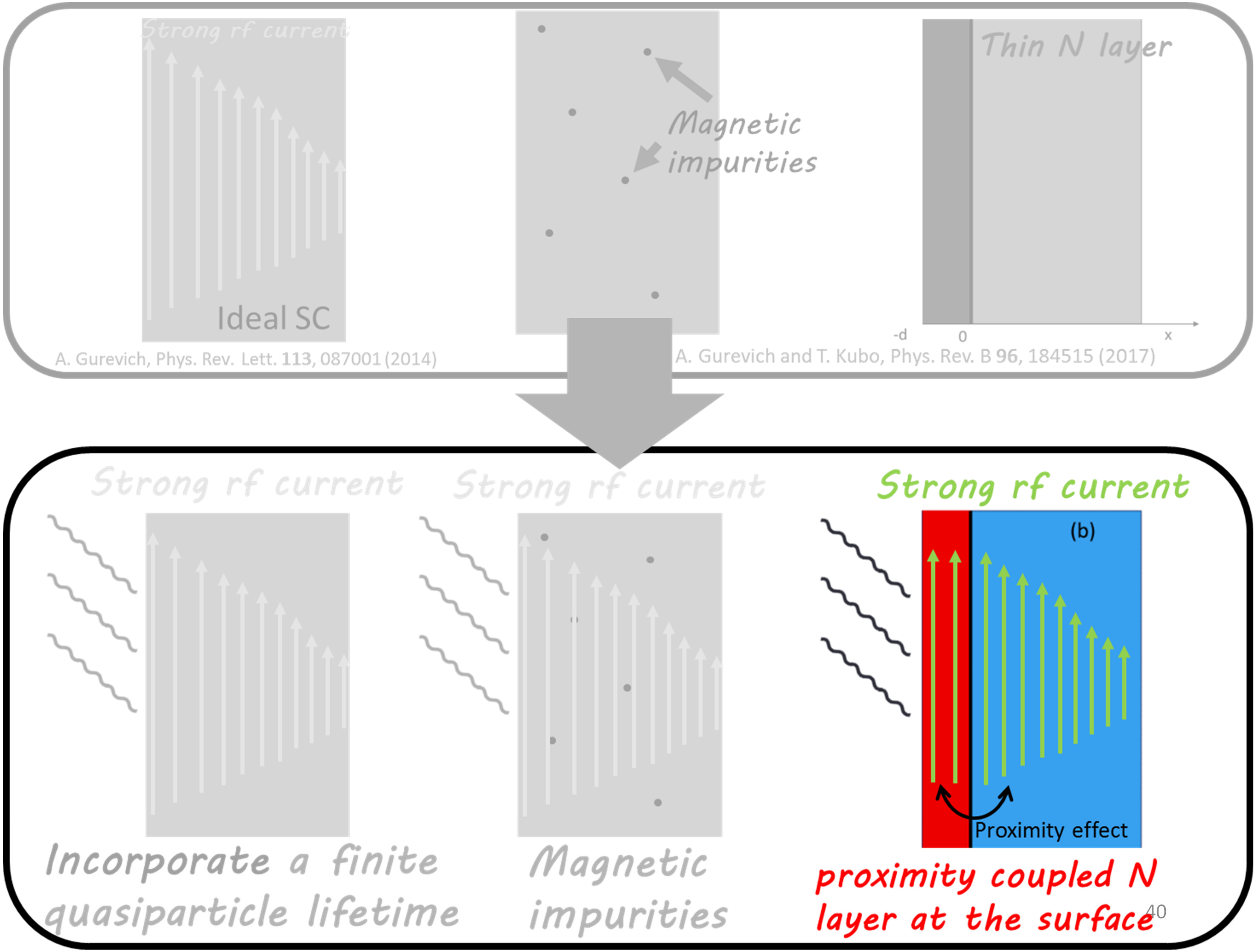
(2) Effect of magnetic impurities (Γ_p parameter)





Magnetic impurities affect $R_s(H_0)$ in the similar manner as a finite quasi particle lifetime Γ.

- The R_s dip becomes shallower as Γ_p increases.
- The low field R_s for ($\Gamma_p \sim 0.01\Delta$) is much smaller than the ideal BCS superconductor ($\Gamma_p = 0$).


Strong rf current
Ideal SC
A. Gurevich, Phys. Rev. Lett. 113, 087001 (2014)
Magnetic impurities
Thin N layer
-d
0
x
A. Gurevich and T. Kubo, Phys. Rev. B 96, 184515 (2017)
Strong rf current
Strong rf current
Strong rf current
(b)
Proximity effect
Incorporate a finite quasiparticle lifetime
Magnetic impurities
proximity coupled N layer at the surface

DOS under a strong rf field

Contain animations. See in Slide Show Mode.

d is an N layer thickness.

(e.g., thickness of suboxide on the Nb surface)

R_B is an interface resistance

Sensitive to heat treatment

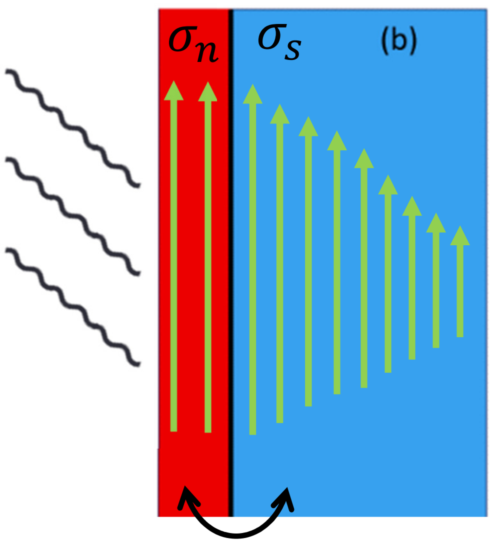
(e.g., between Nb suboxide and Nb)

$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$

~thickness

$$\boxed{\beta = \frac{4e^2}{\hbar}R_B N_n \Delta d,}$$

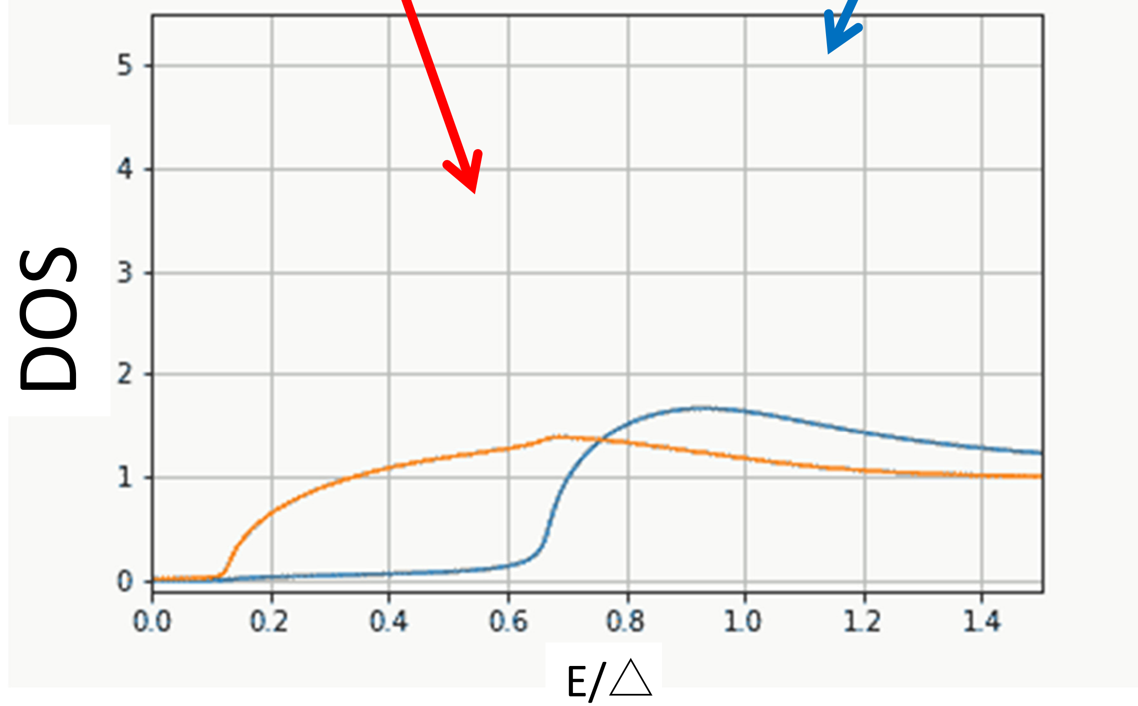
~barrier between N&S



Proximity effect

Proximity coupled N layer

S side



$$\alpha = 0.05\ ,\beta = 1\ ,\Gamma = 0.005$$

Field dependent Surface resistance $R_s(H_0)$

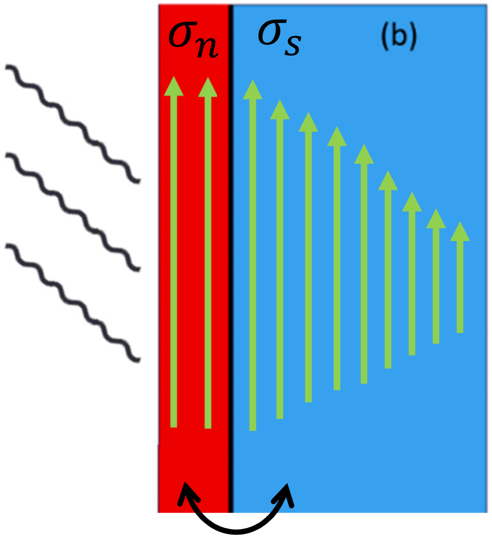
for different N-layer thickness

d is an N layer thickness.
(e.g., thickness of suboxide on the Nb surface)

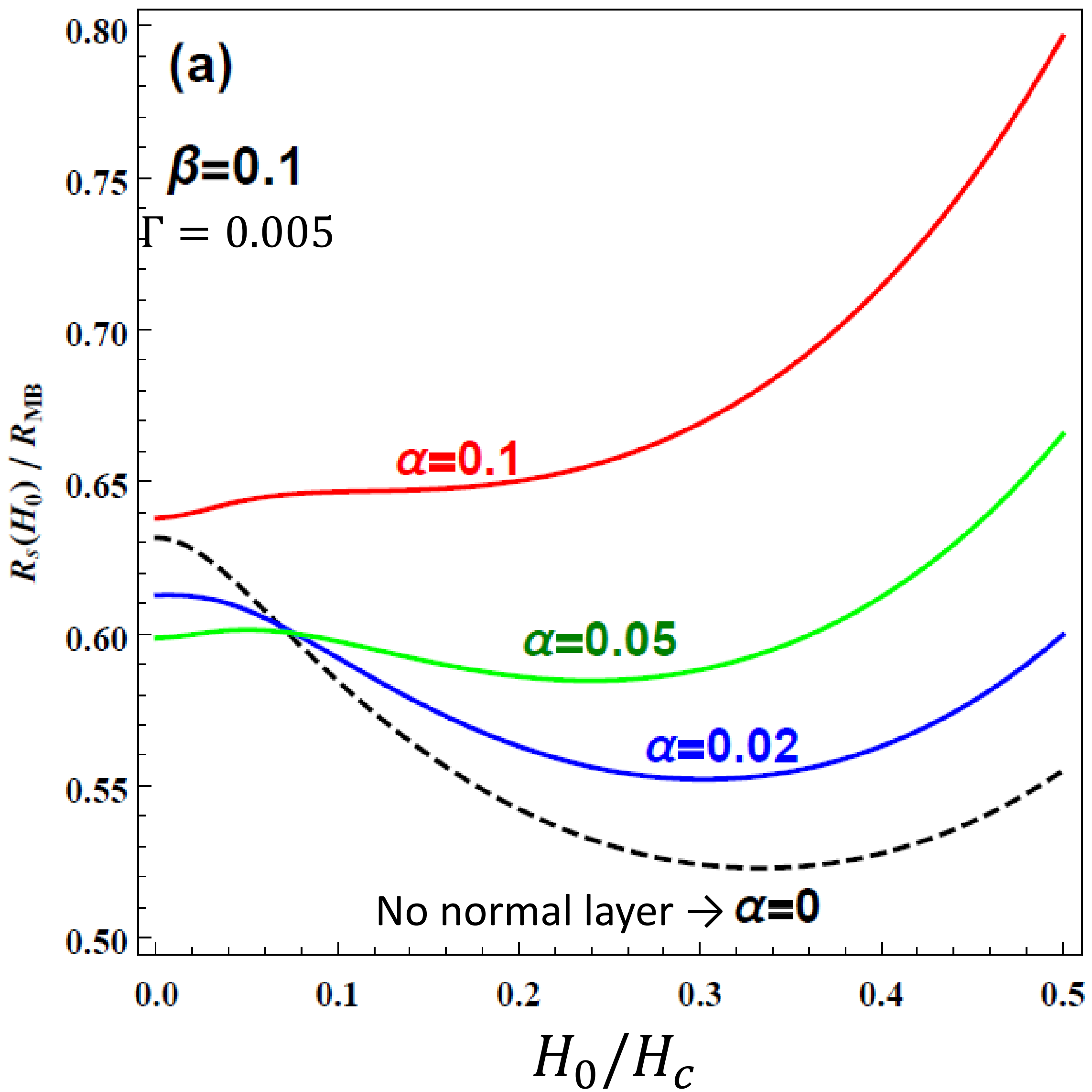
R_B is an interface resistance
Sensitive to heat treatment
(e.g., between Nb suboxide and Nb)

$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$
~thickness

$$\boxed{\beta = \frac{4e^2}{\hbar}R_B N_n \Delta d,}$$
~barrier between N&S



Proximity effect



As the N-layer thickness increases, the dip becomes shallower and finally disappears:

Continuously changes **from "N-doping-like"** to **"EP-like" shape.**

R_B is an interface resistance

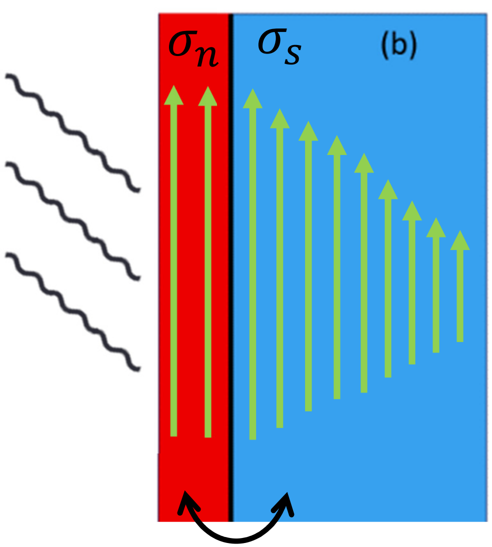
Sensitive to heat treatment
(e.g., between Nb suboxide and Nb)

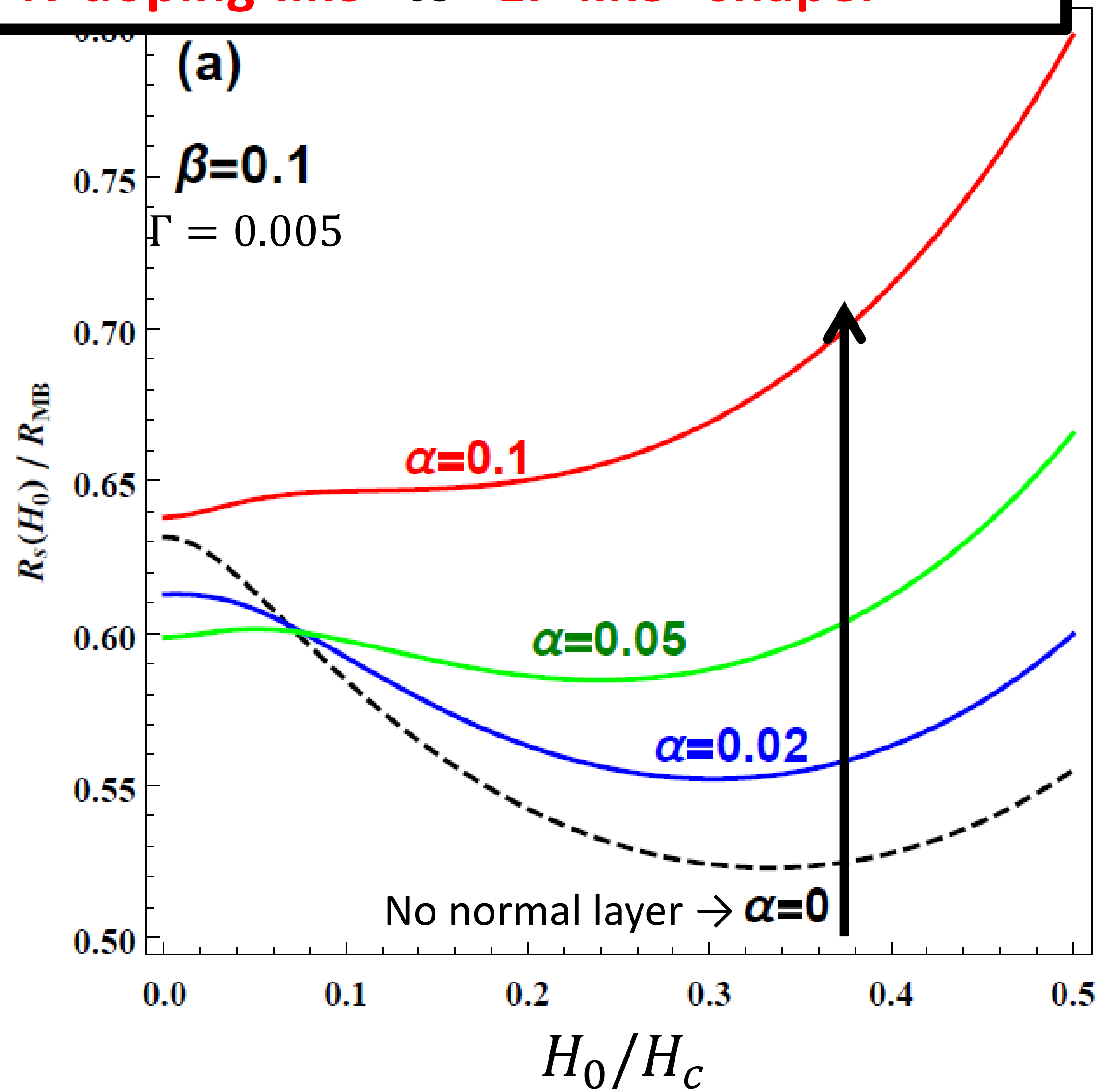
$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$

~thickness

$$\boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$$

~barrier between N&S





Field dependent Surface resistance $R_s(H_0)$ for different N-layer conductivity

***d* is an N layer thickness.**
(e.g., thickness of suboxide on the Nb surface)

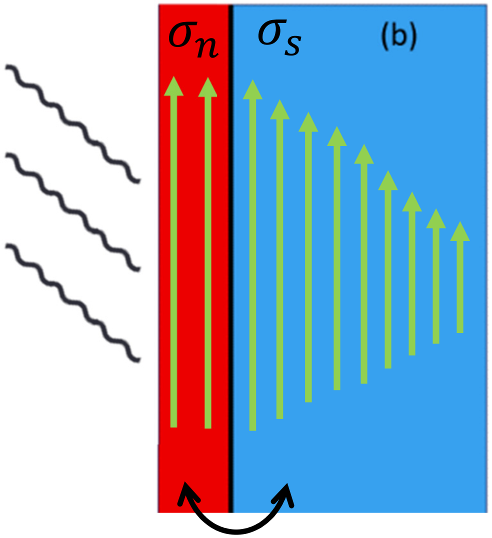
***R_B* is an interface resistance**
Sensitive to heat treatment
(e.g., between Nb suboxide and Nb)

$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$

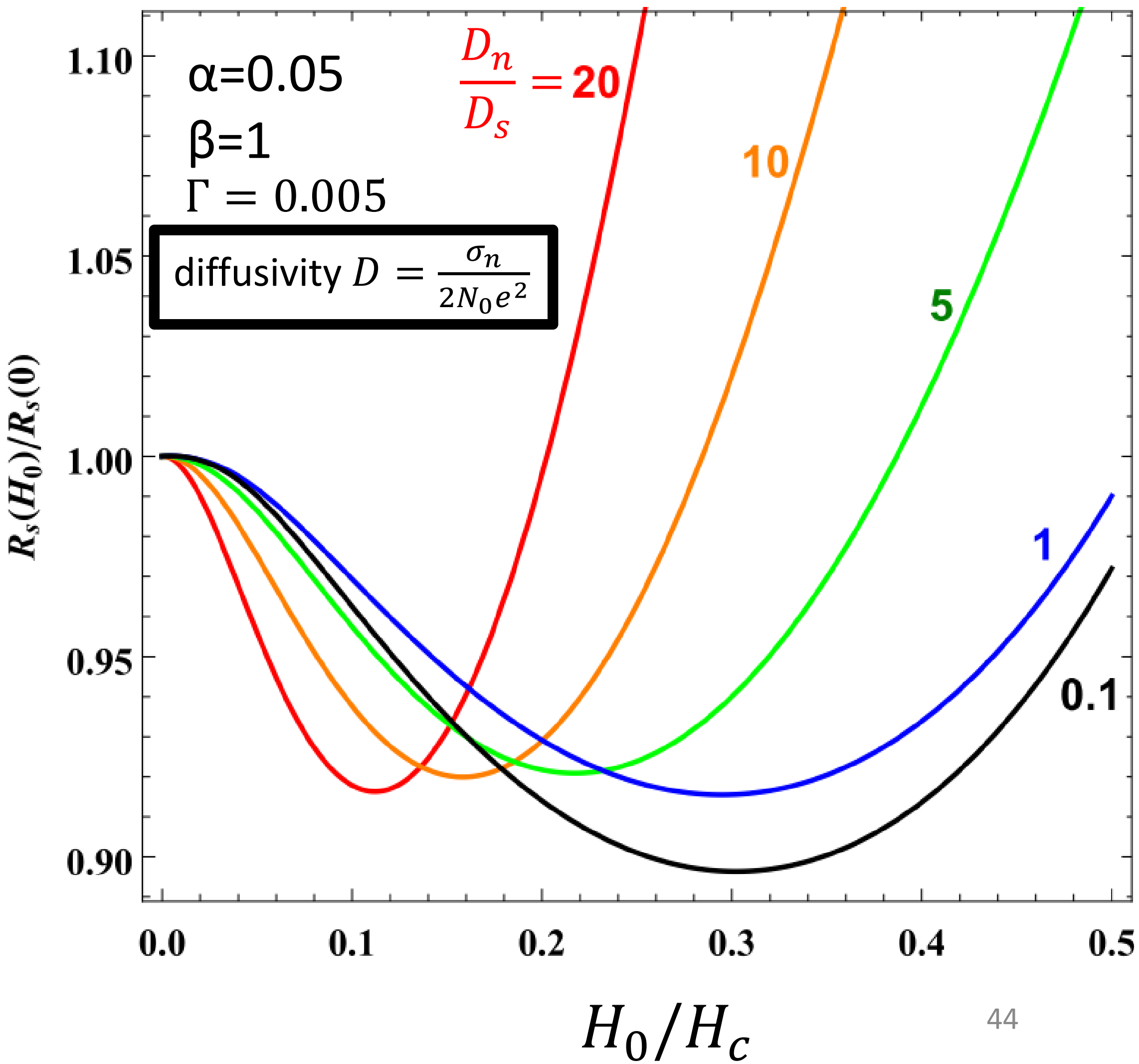
~thickness

$$\boxed{\beta = \frac{4e^2}{\hbar}R_B N_n \Delta d,}$$

~barrier between N&S



Proximity effect



The position of minimum shifts from medium fields to lower fields.

(e.g., thickness of suboxide on the Nb surface)

R_B is an interface resistance

Sensitive to heat treatment

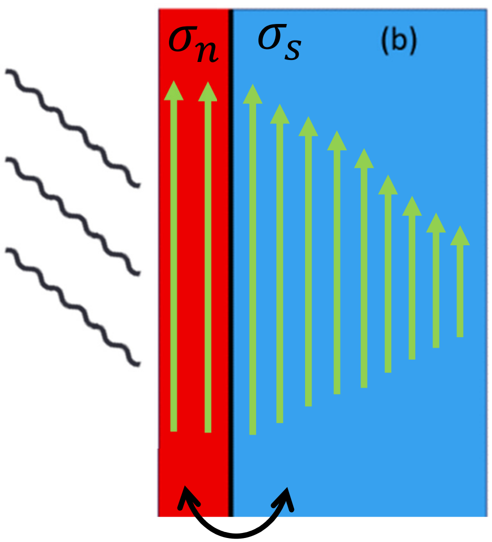
(e.g., between Nb suboxide and Nb)

$$\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}$$

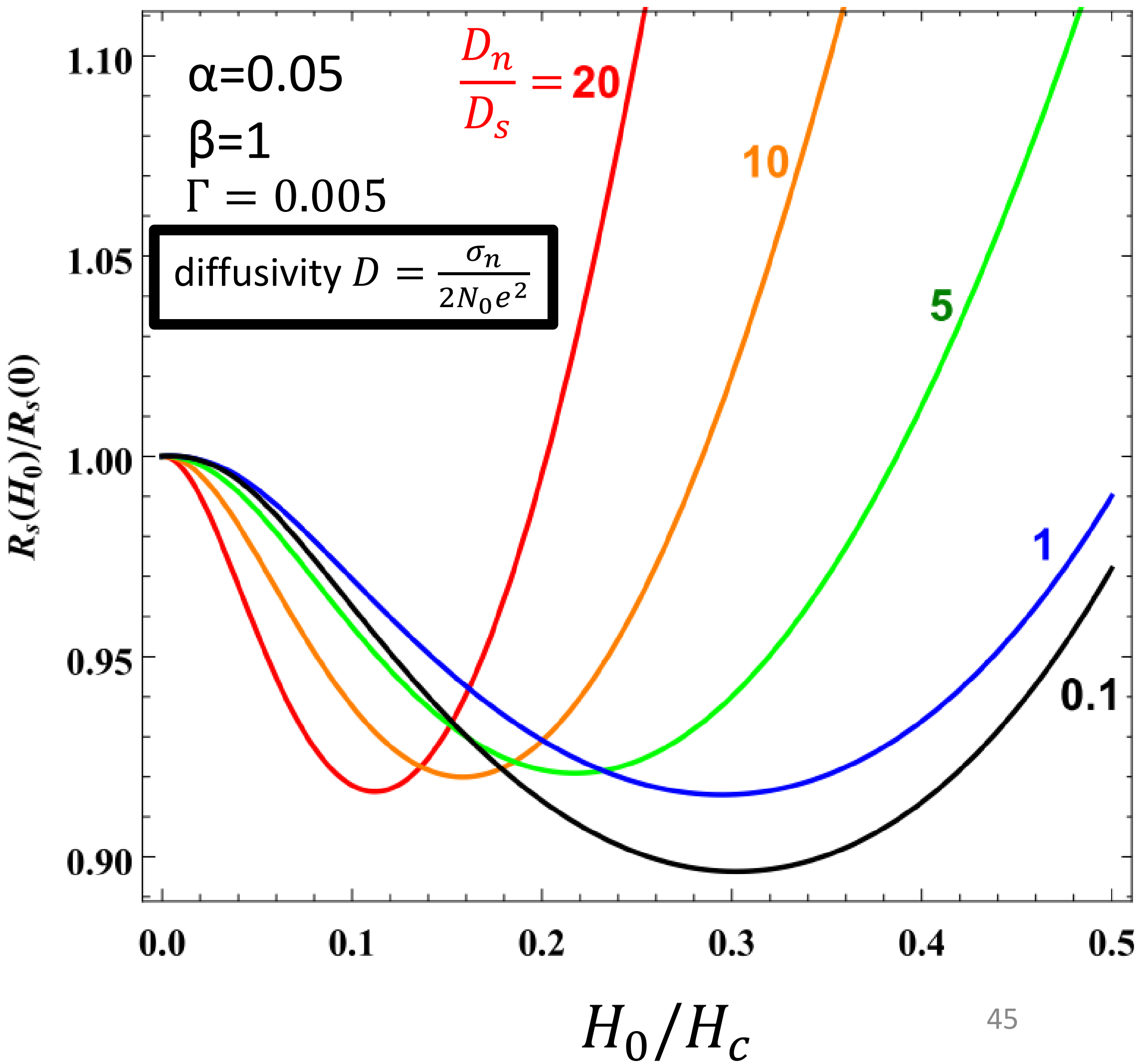
~thickness

$$\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,$$

~barrier between N&S



Proximity effect



Field dependent Surface resistance $R_s(H_0)$

for different temperatures

***d* is an N layer thickness**

Different types of temperature dependence appear.

***R_B* is an interface resistance**

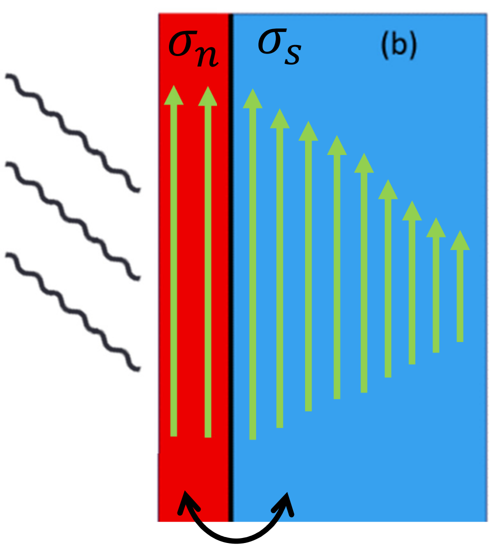
Sensitive to heat treatment
(e.g., between Nb suboxide and Nb)

$$\boxed{\alpha = \frac{N_n}{N_s}\frac{d}{\xi_S}}$$

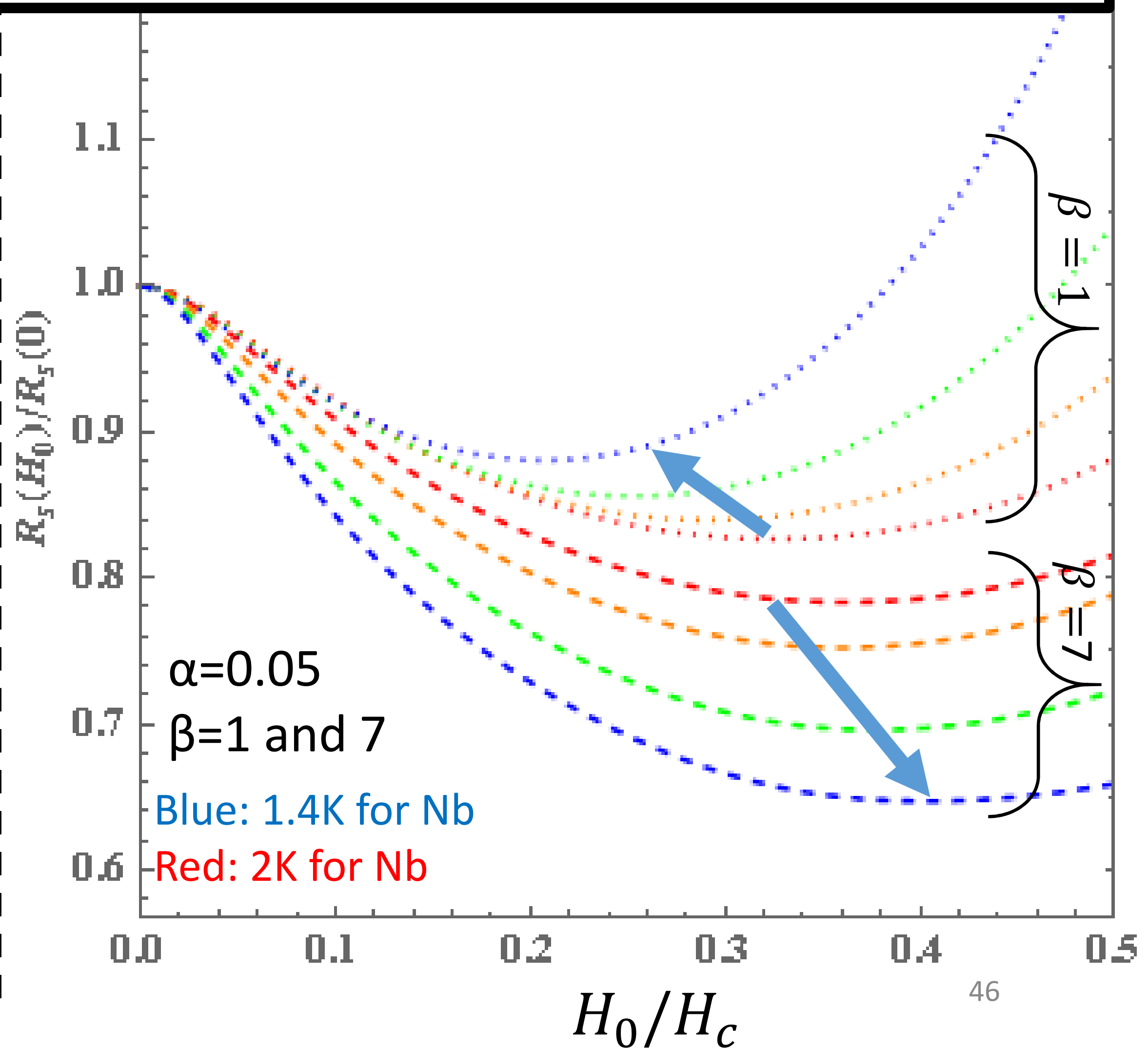
~thickness

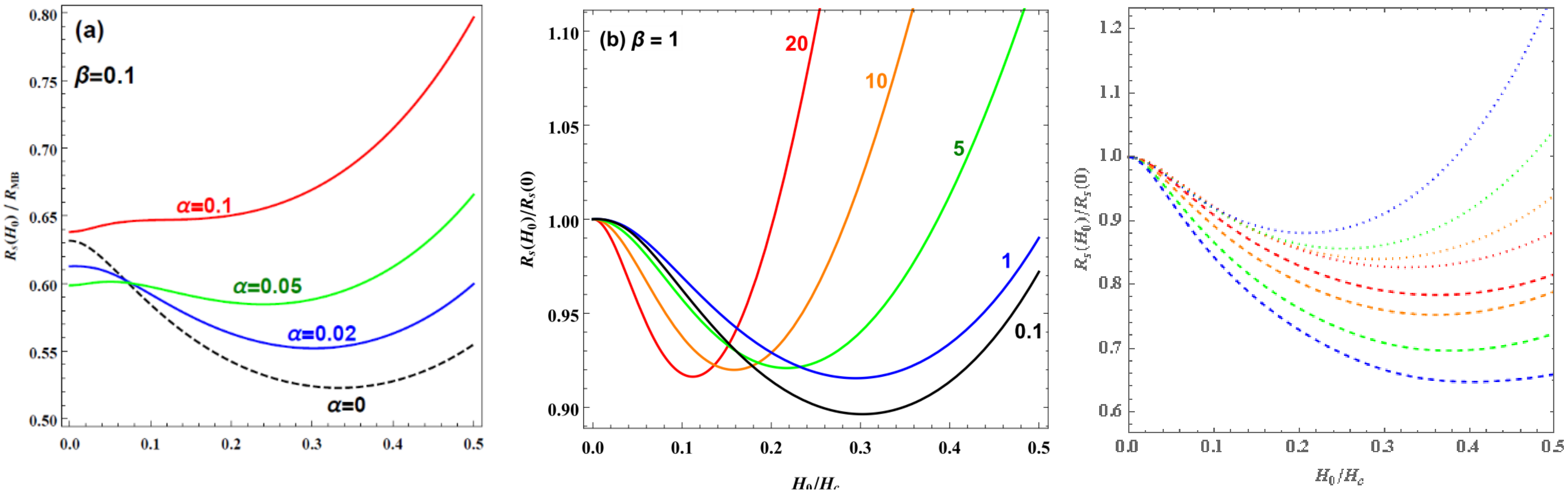
$$\boxed{\beta = \frac{4e^2}{\hbar} R_B N_n \Delta d,}$$

~barrier between N&S

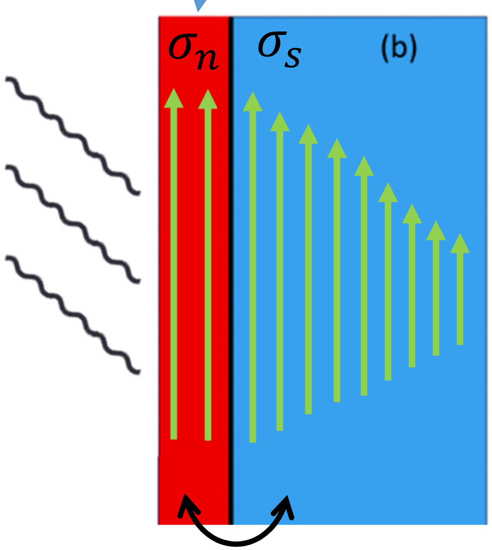


Proximity effect





e.g.) Nb suboxides or hydrides



Proximity effect

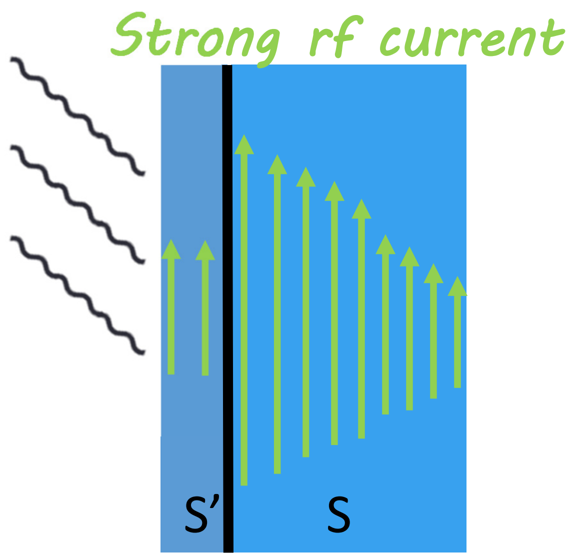
Many different shapes of $R_s(H)$ naturally result from the proximity coupled N-S model.

A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006).
T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014).
A. Gurevich, AIP Adv. 5, 017112 (2015).
T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017).

Field dependent surface resistance of

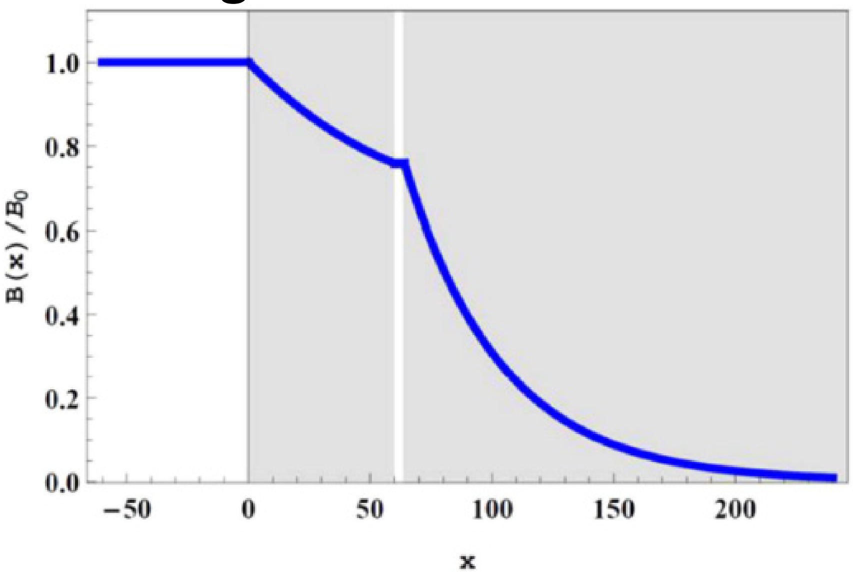
- Nb-Nb structure
- Nb_3Sn-Nb structure

T. Kubo and A. Gurevich, to be published

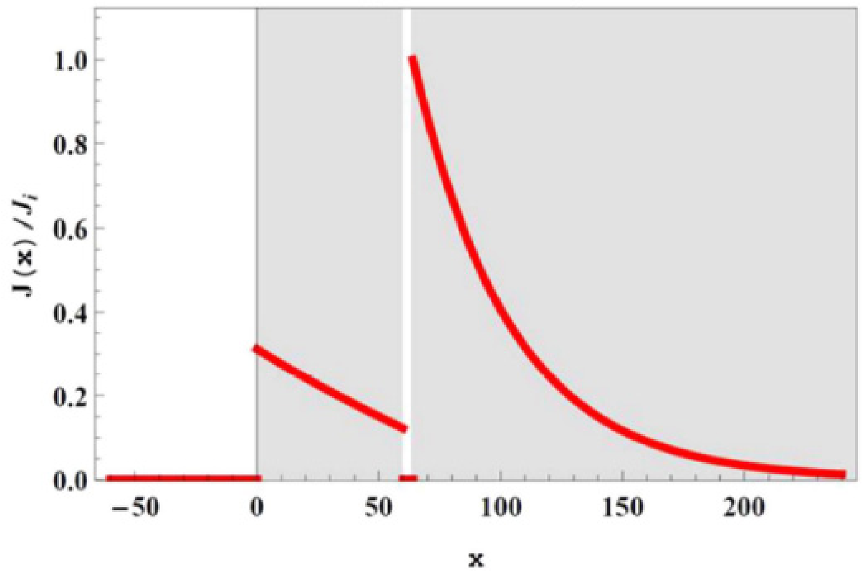


One of the most striking effects is the reduction of the current density at the top layer with $\lambda'(>\lambda)$

Magnetic field distribution



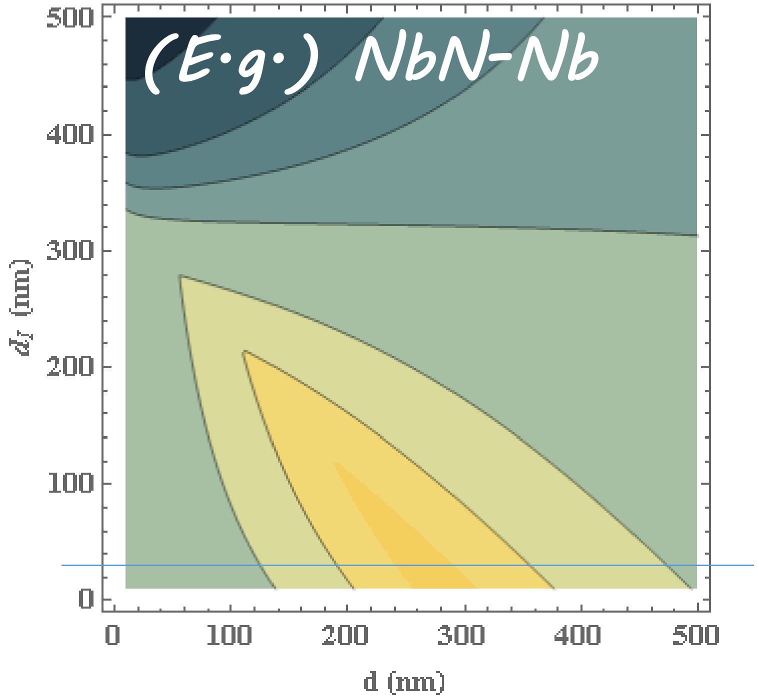
Current density distribution

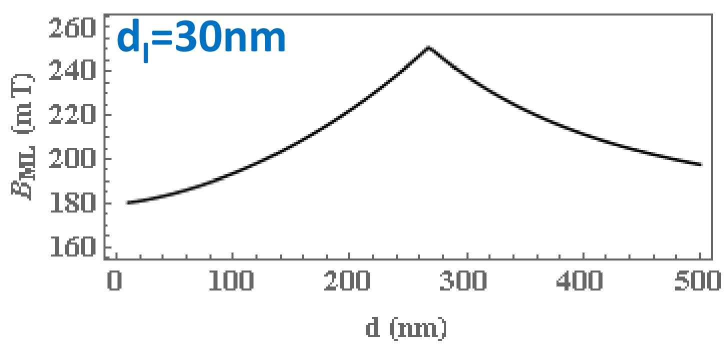


T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014).
A. Gurevich, AIP Adv. 5, 017112 (2015).
T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017).

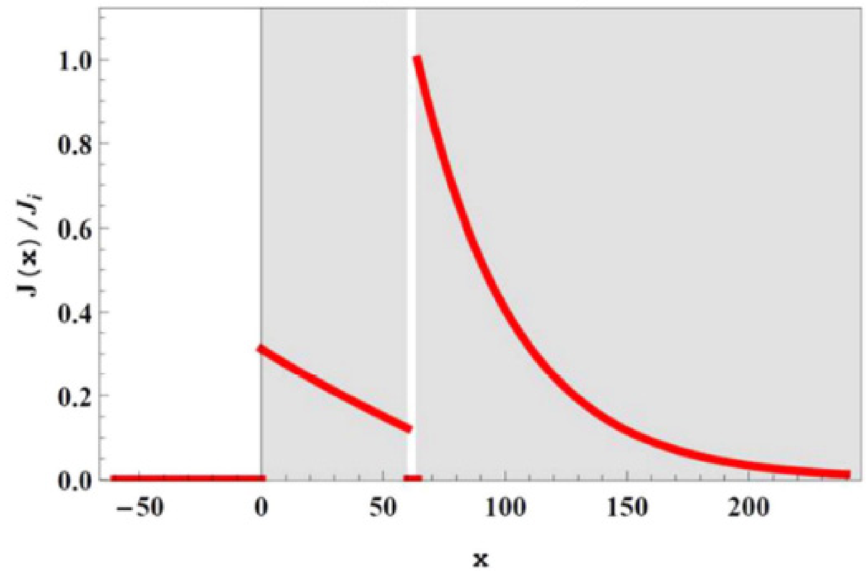
One of the most striking effects is the reduction of the current density at the top layer with $\lambda'(>\lambda)$

This enhances the field limit





Current density distribution



T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014).
A. Gurevich, AIP Adv. 5, 017112 (2015).
T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017).

One of the most striking effects is the reduction of the current density at the top layer with $\lambda'(>\lambda)$

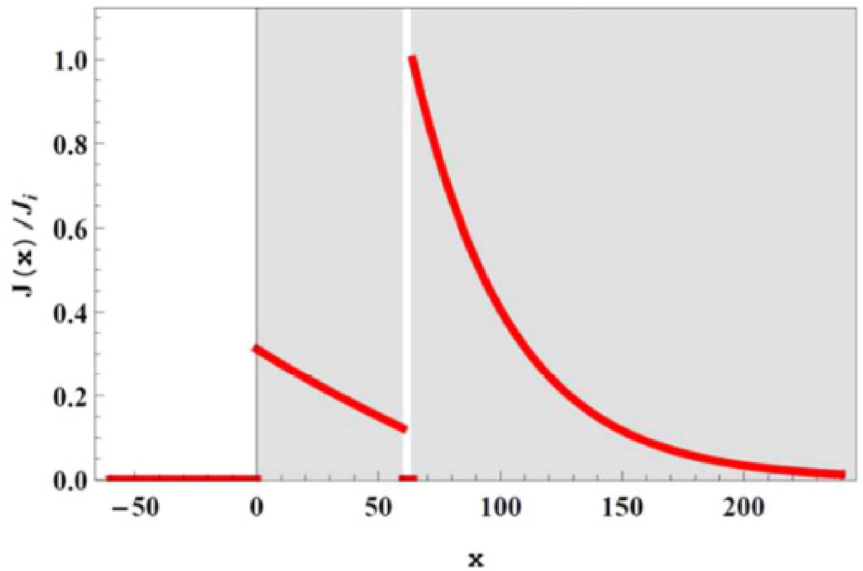
This enhances the field limit

and

should affects $R_s(H)$ too.

Let's see what happens to $R_s(H)$

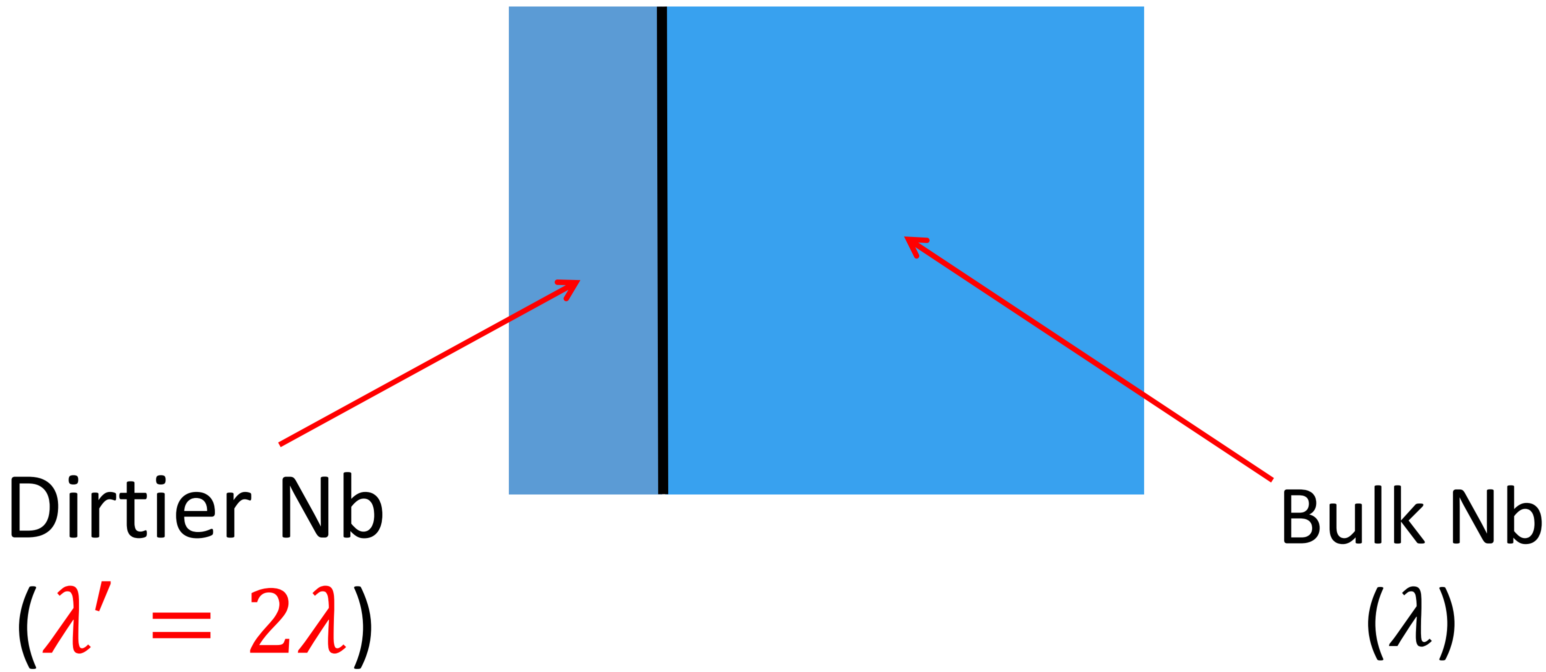
Current density distribution



T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014).
A. Gurevich, AIP Adv. 5, 017112 (2015).
T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017).

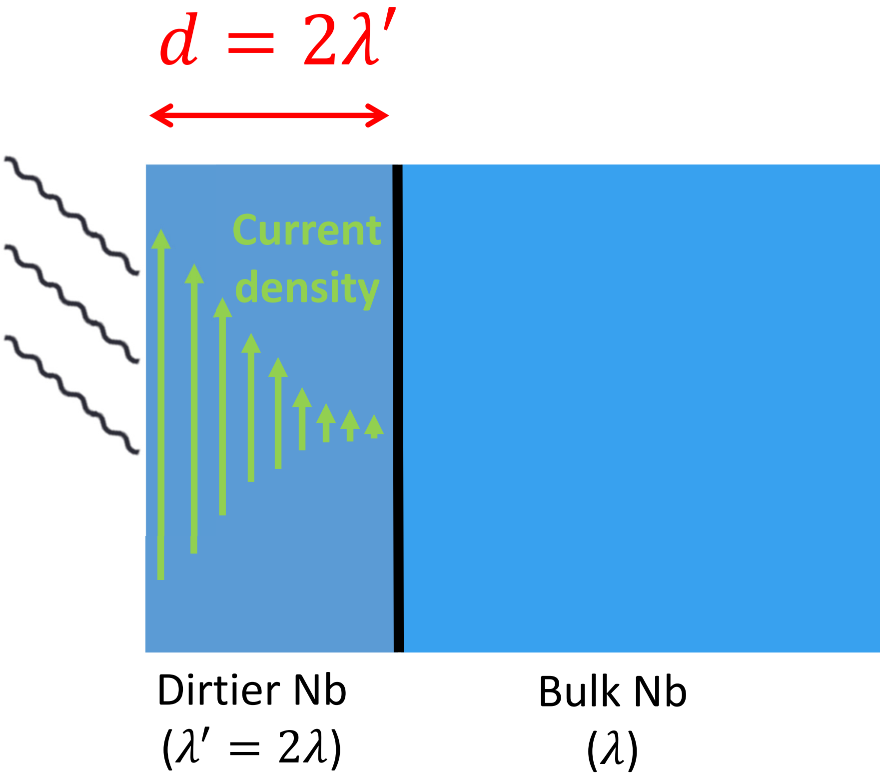
One of the most striking effects is the reduction of the current density at the top layer with $\lambda'(>\lambda)$

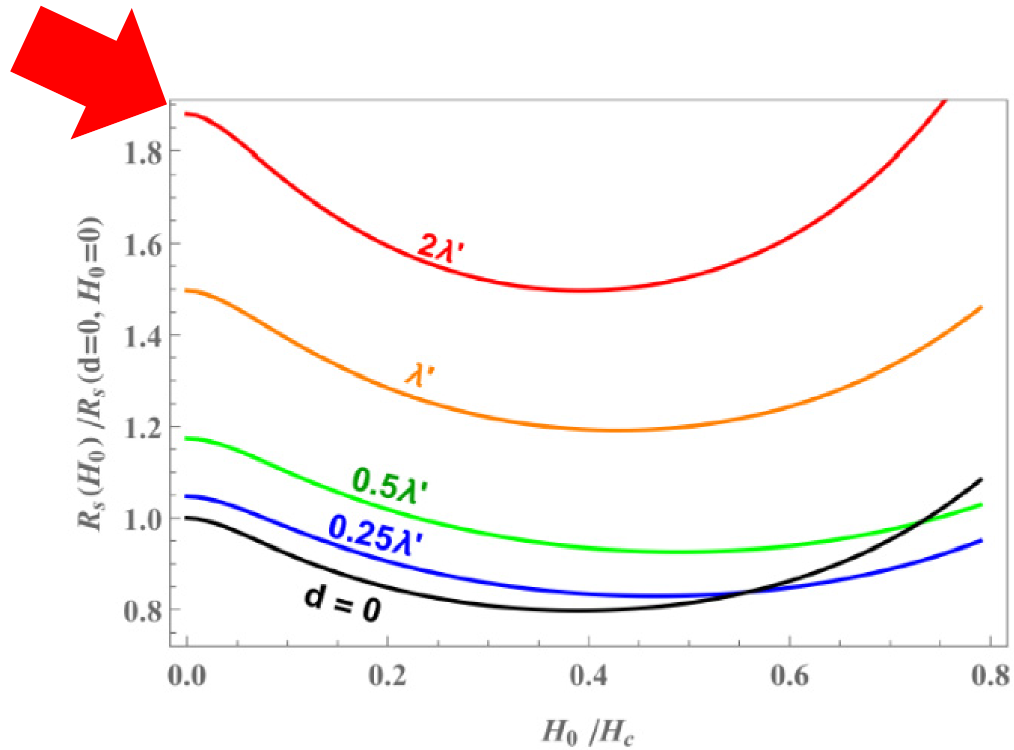
Example 1: Nb-Nb structure



One of the most striking effects is the reduction of the current density at the top layer with $\lambda'(>\lambda)$

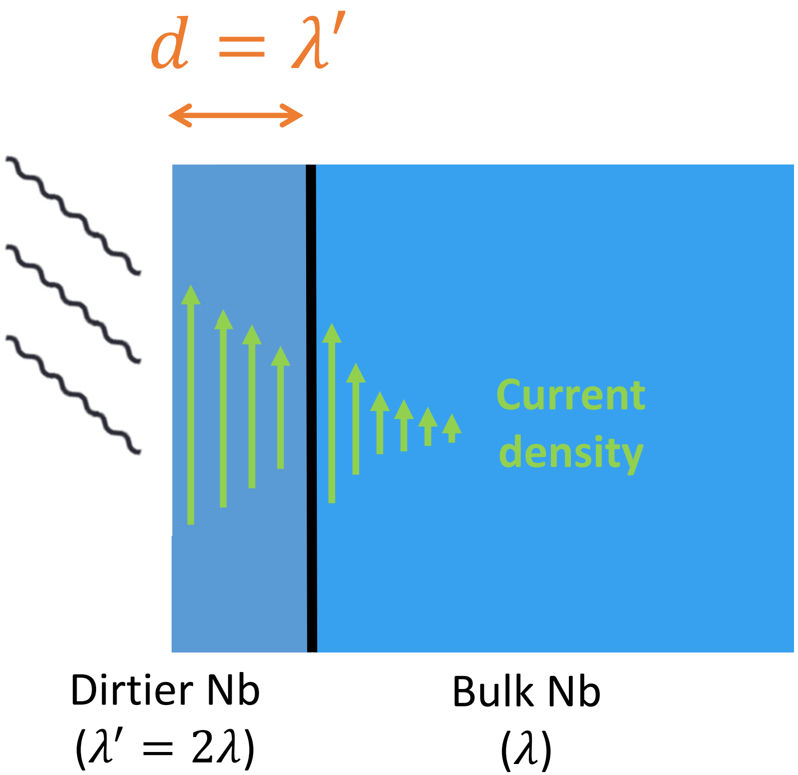
Example 1: Nb-Nb structure

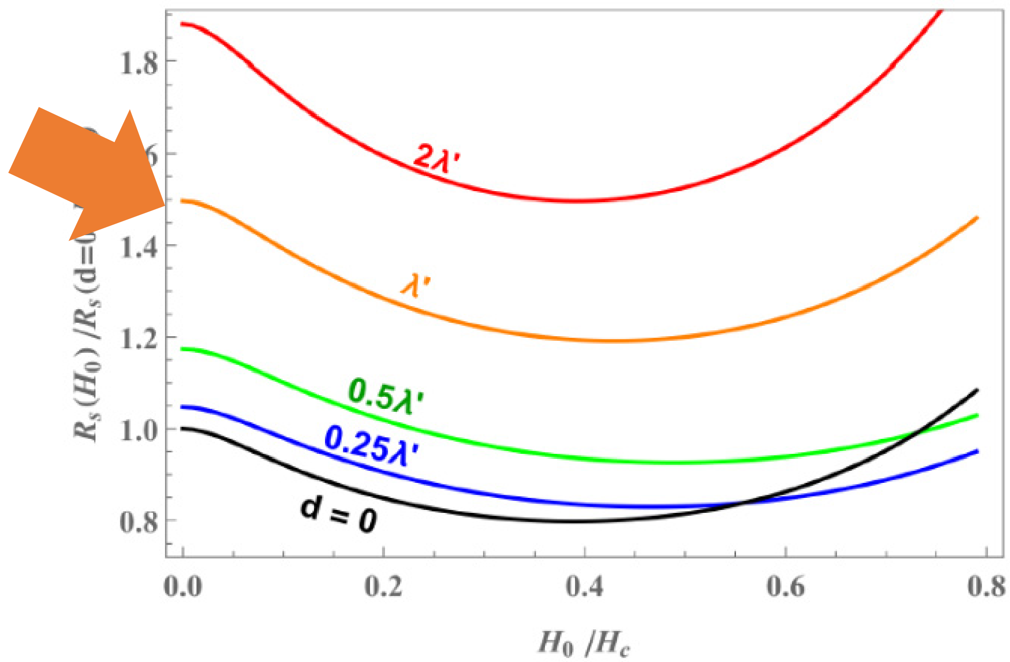




One of the most striking effects is **the reduction of the current density** at the top layer with $\lambda'(>\lambda)$

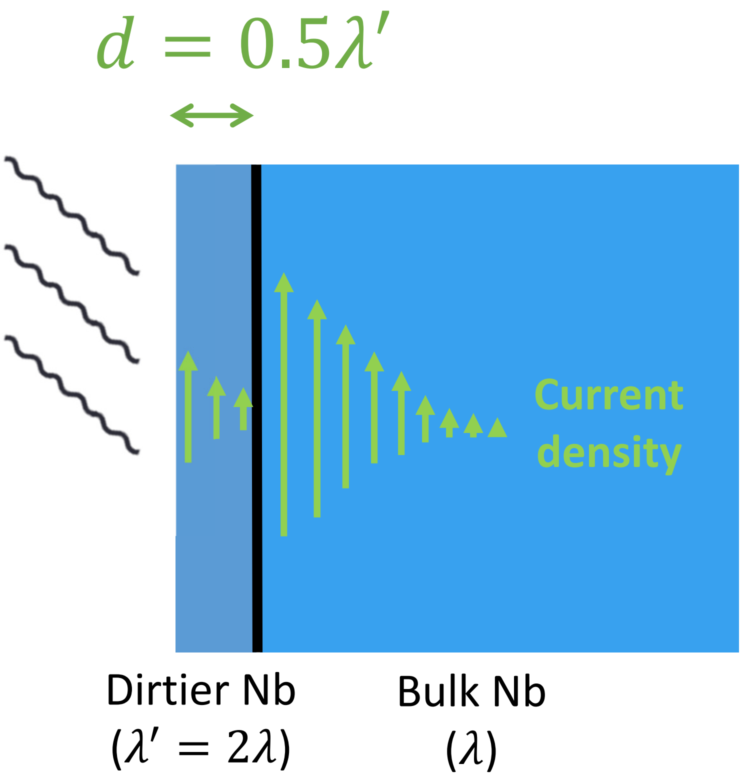
Example 1: Nb-Nb structure

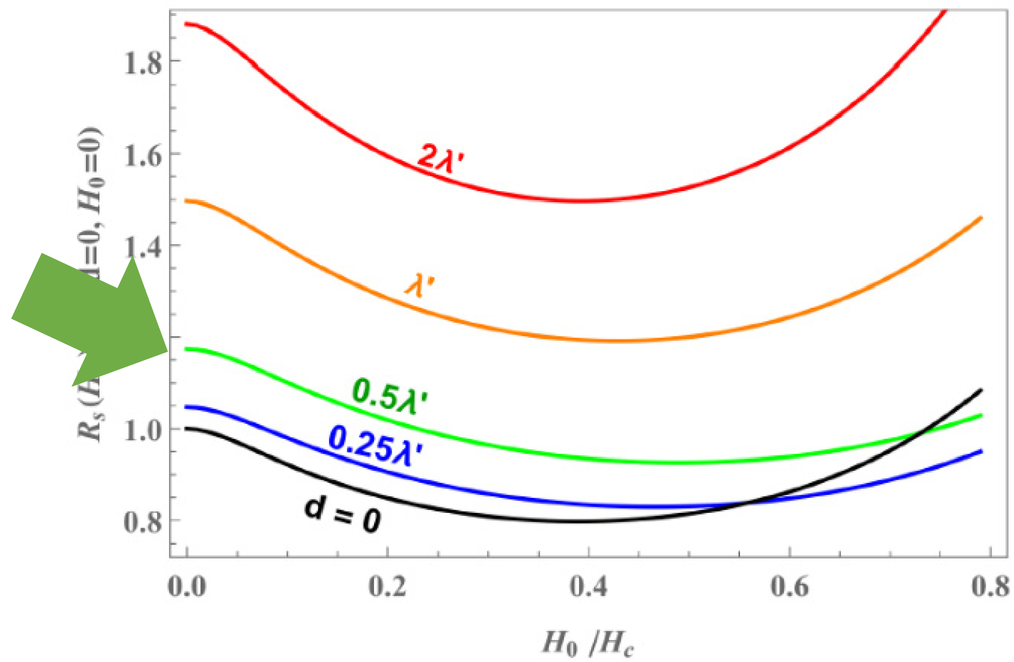




One of the most striking effects is the reduction of the current density at the top layer with $\lambda' (> \lambda)$

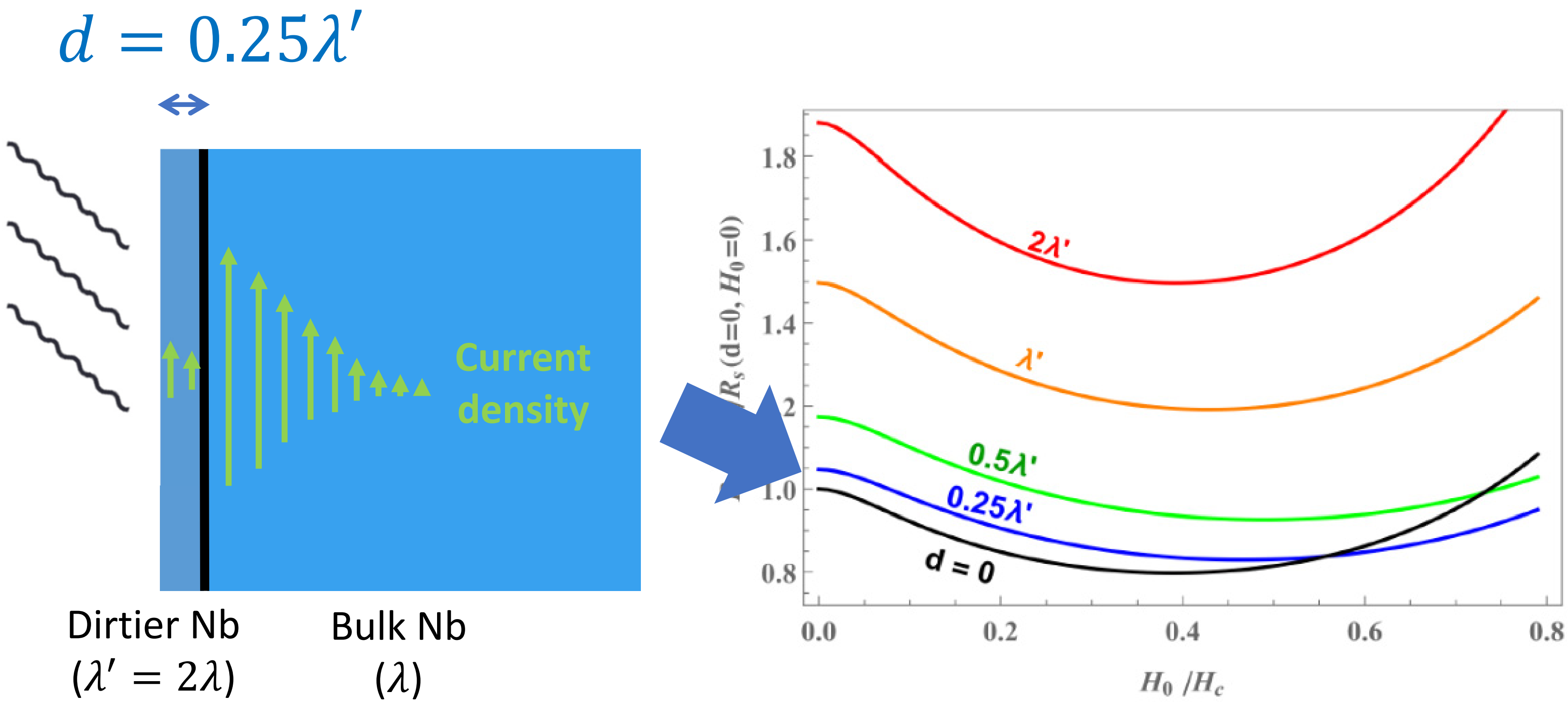
Example 1: Nb-Nb structure





One of the most striking effects is the reduction of the current density at the top layer with $\lambda'(>\lambda)$

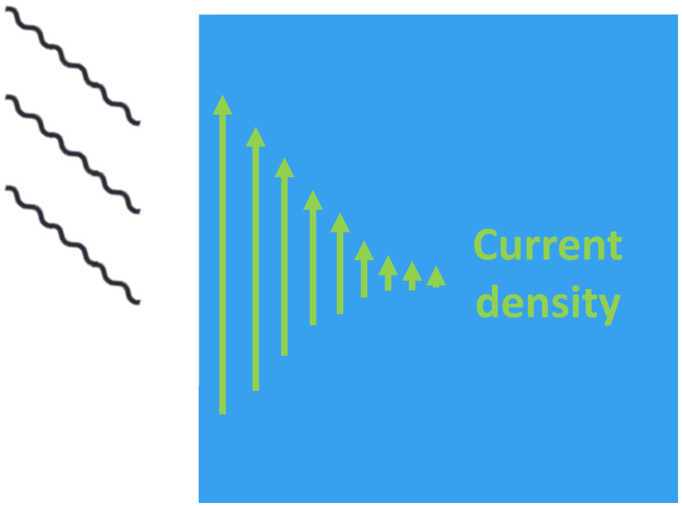
Example 1: Nb-Nb structure



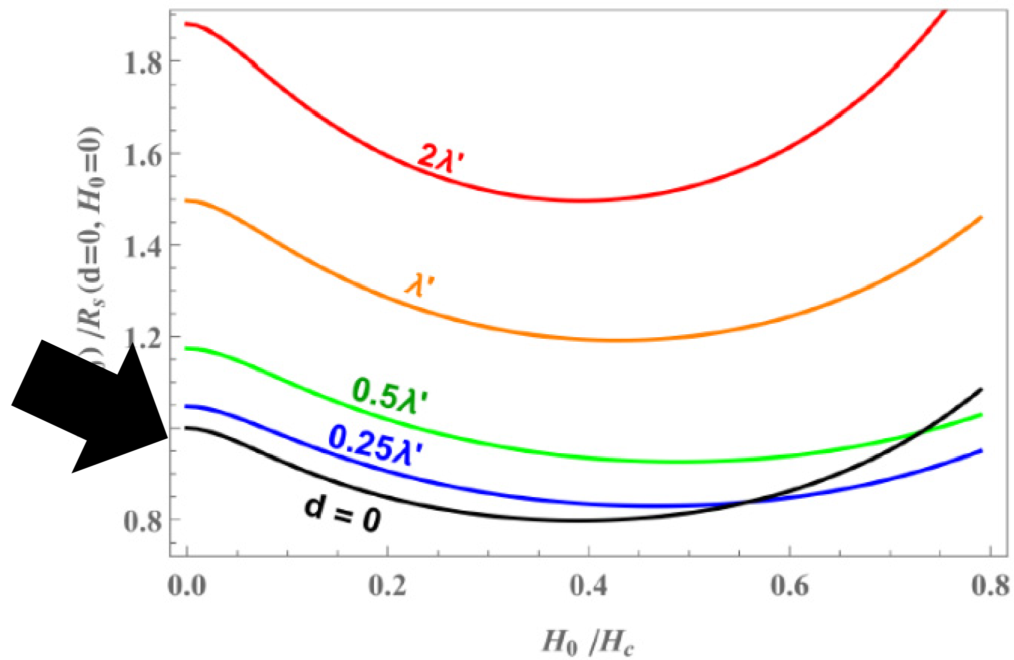
One of the most striking effects is the reduction of the current density at the top layer with $\lambda'(>\lambda)$

Example 1: Nb-Nb structure

$d = 0$



Bulk Nb
(λ)

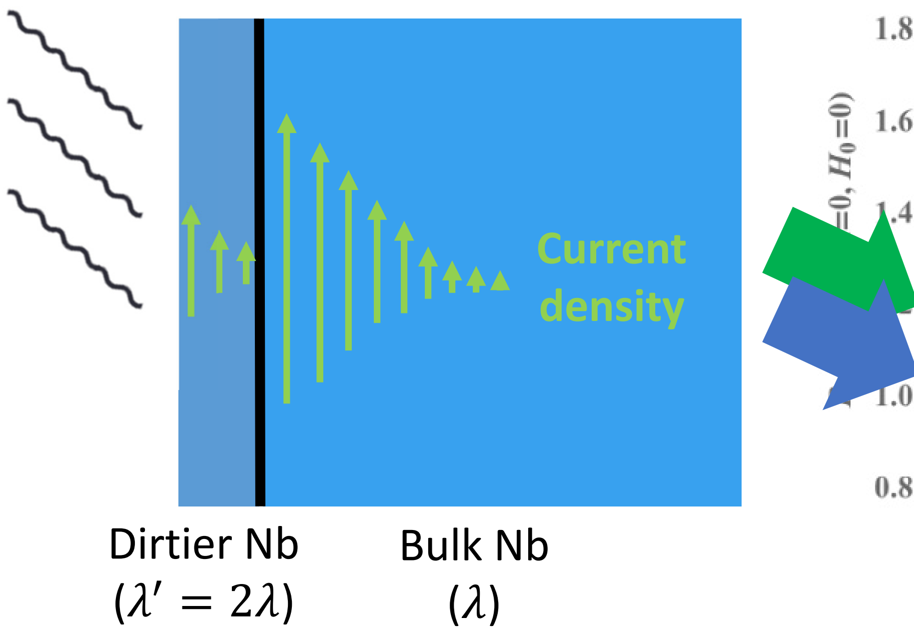


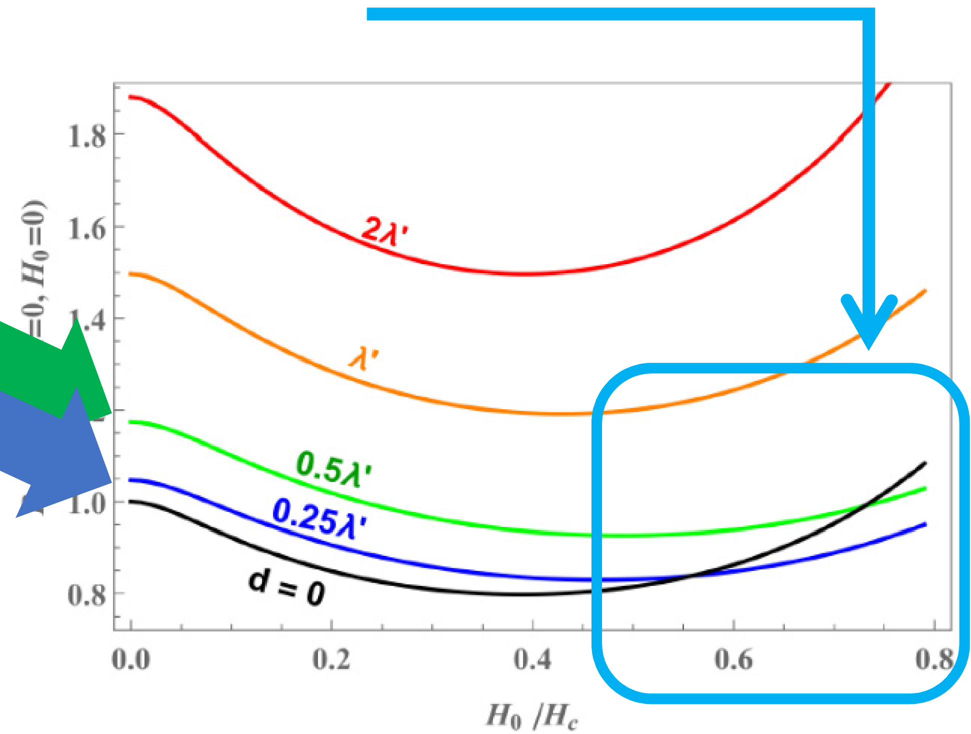
One of the most striking effects is ***the reduction of the current density*** *at the top layer with* $\lambda'(>\lambda)$

Example 1: Nb-Nb structure

A dirtier Nb layer with $d \lesssim \lambda'$ cures the Q slope:

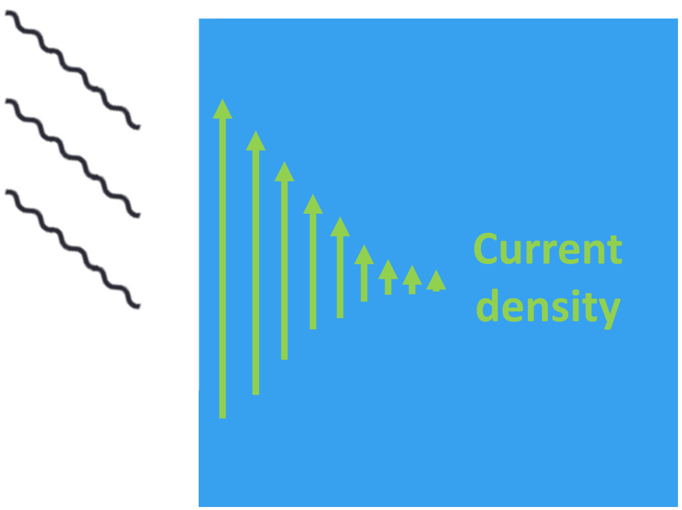
→ "<u>baking-like</u>" effect.



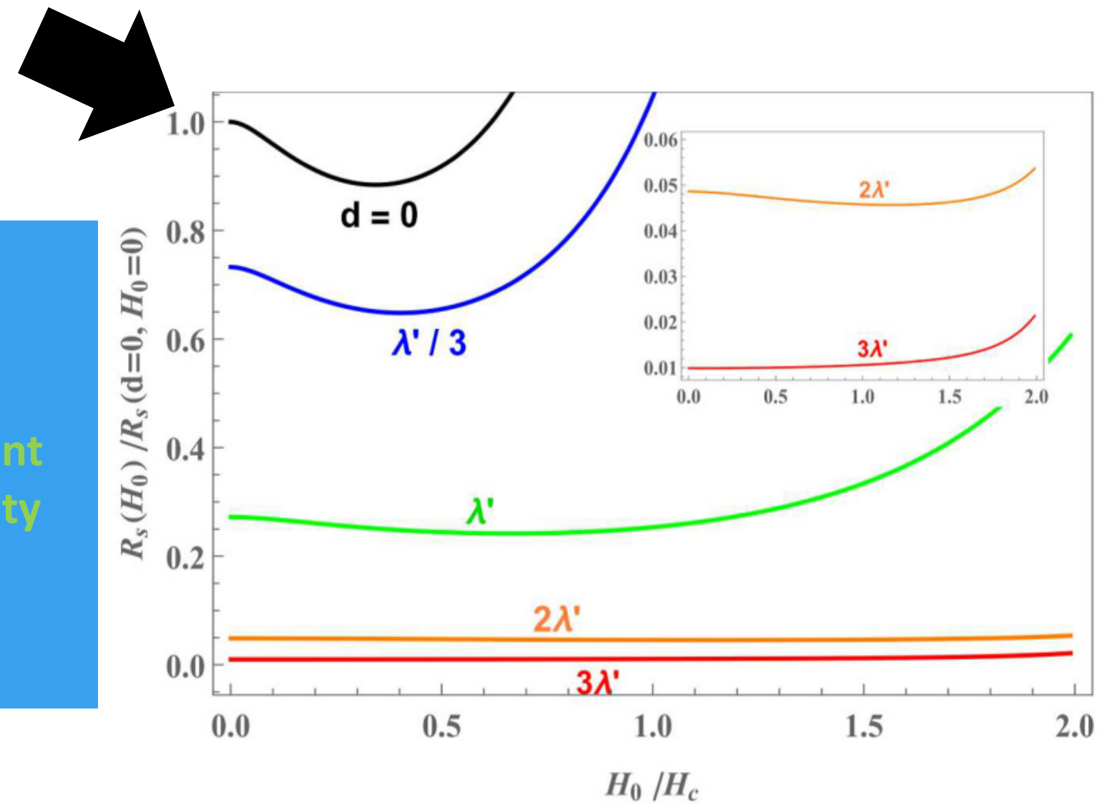


Example 2: Nb_3Sn-Nb structure

$d = 0$

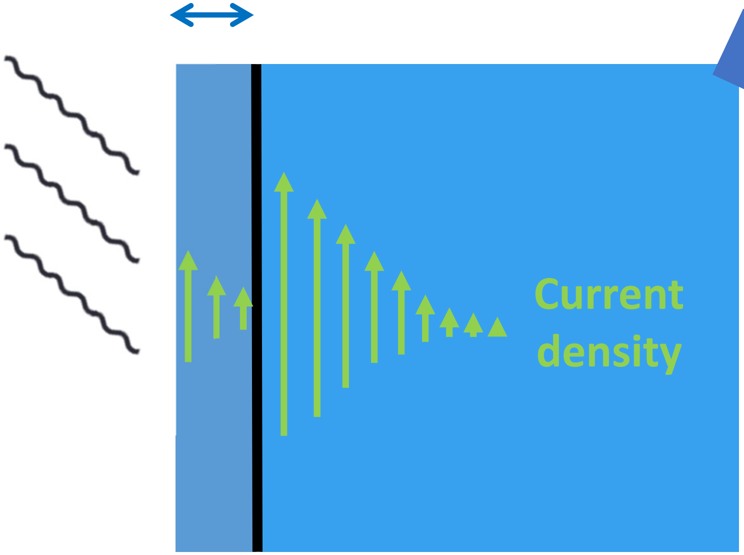


Bulk Nb
(λ)
$\Gamma = 0.01$



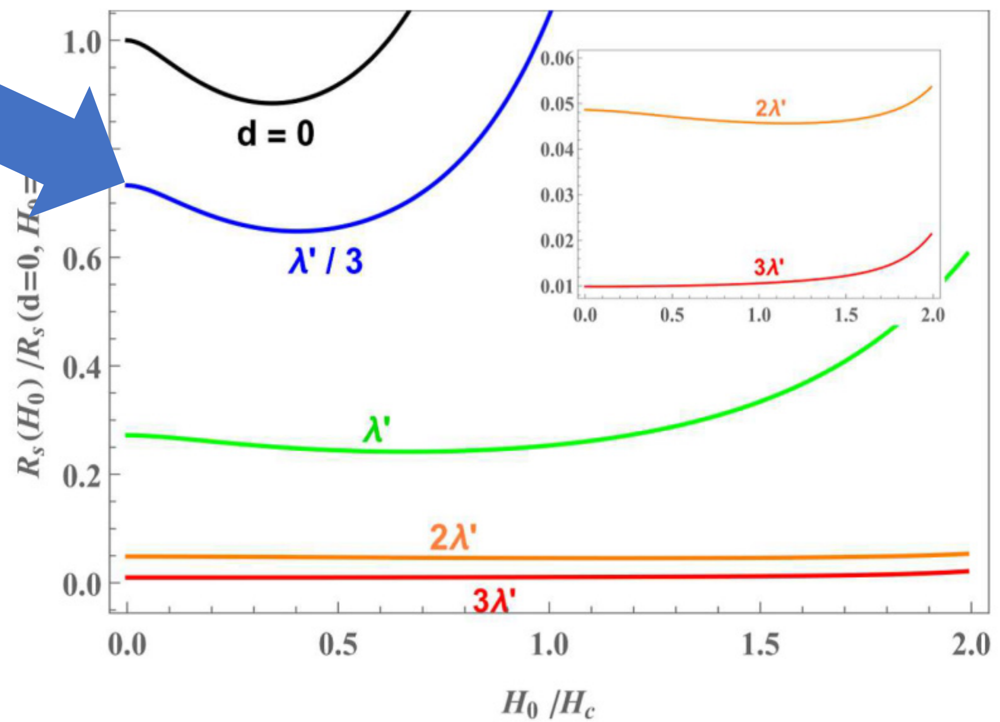
Example 2: Nb_3Sn-Nb structure

$d = 0.33\lambda'$

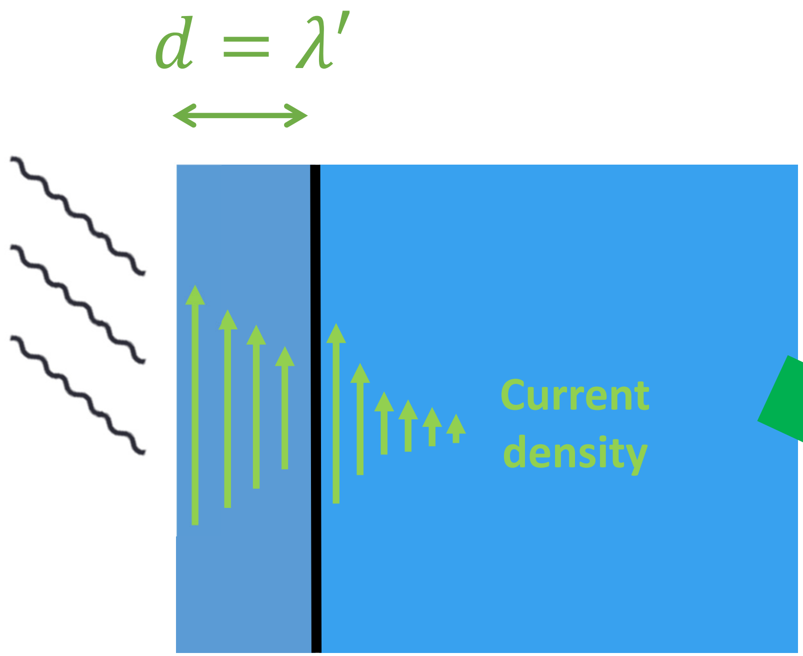


Nb_3Sn
$(\lambda' = 3\lambda)$
$\Gamma' = 0.05$

Bulk Nb
(λ)
$\Gamma = 0.01$

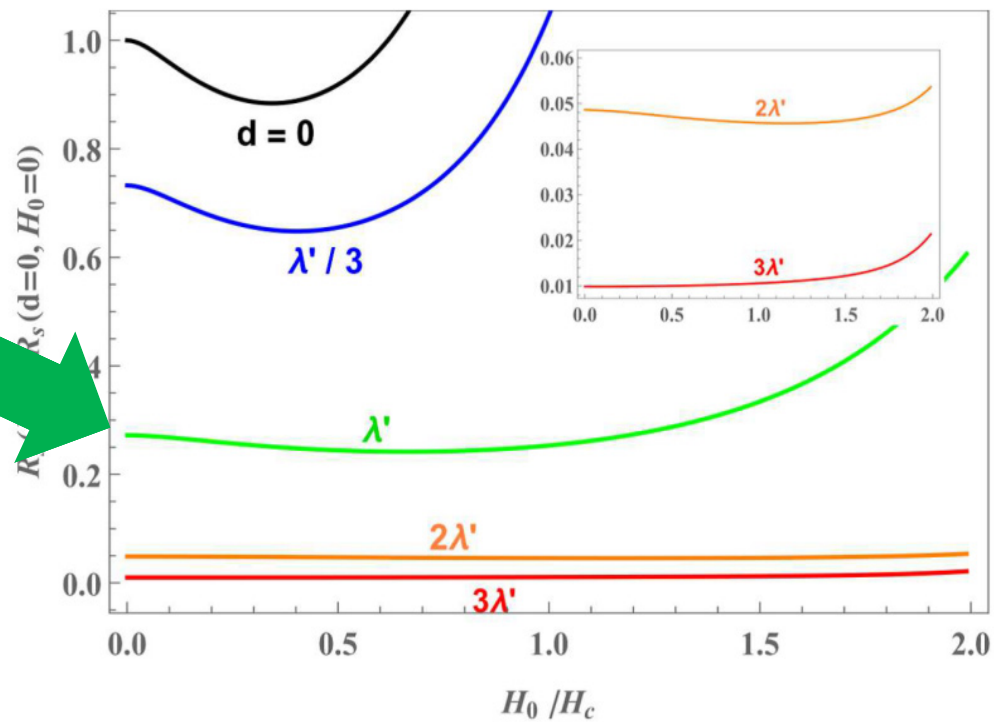


Example 2: Nb_3Sn-Nb structure

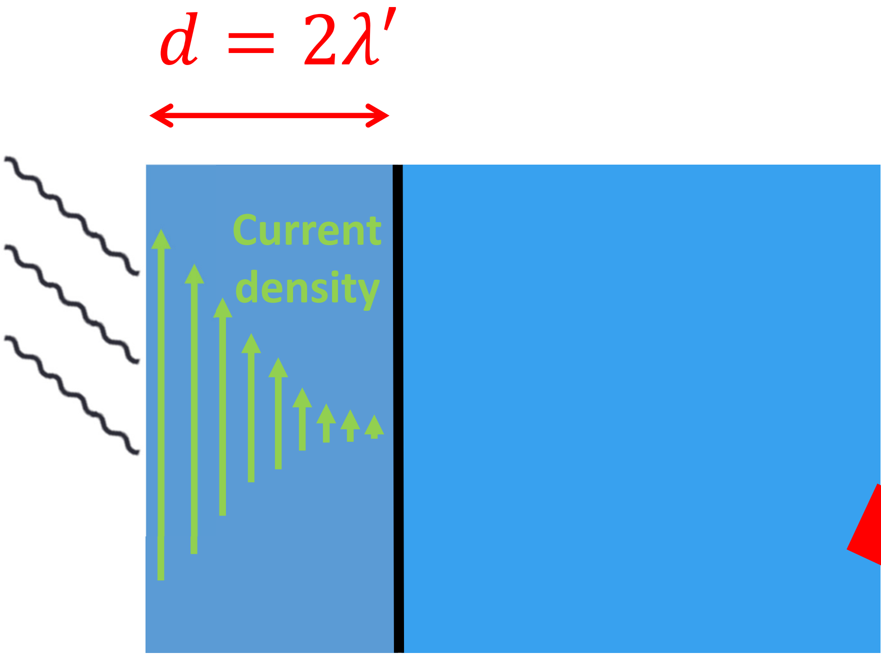


Nb_3Sn
$(\lambda' = 3\lambda)$
$\Gamma' = 0.05$

Bulk Nb
(λ)
$\Gamma = 0.01$

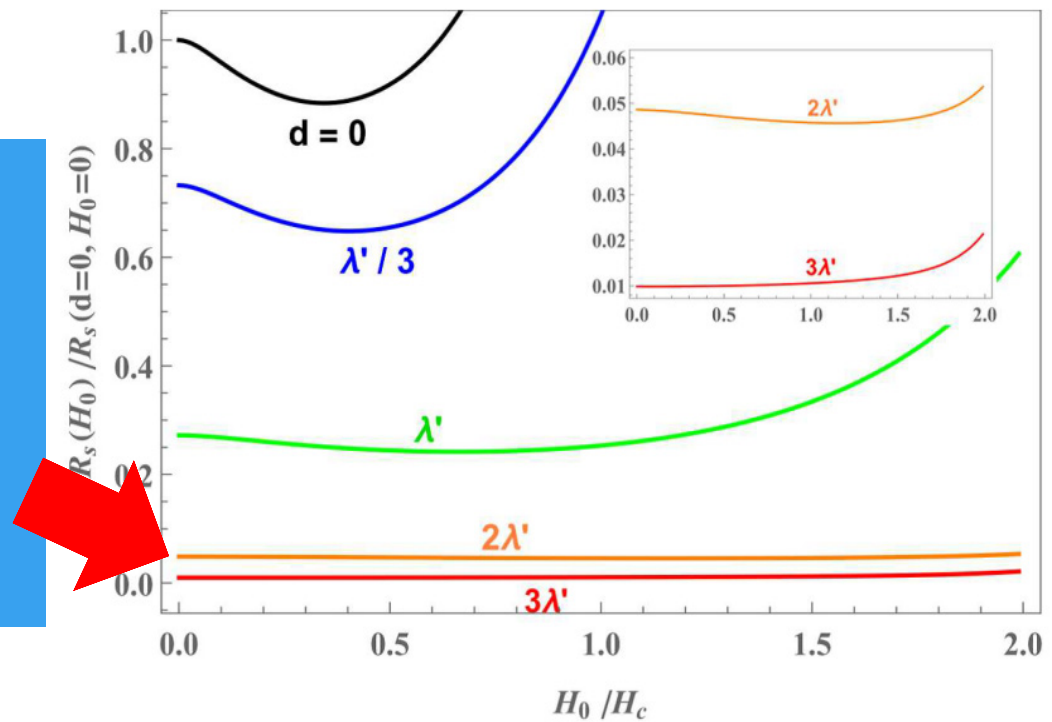


Example 2: Nb_3Sn-Nb structure

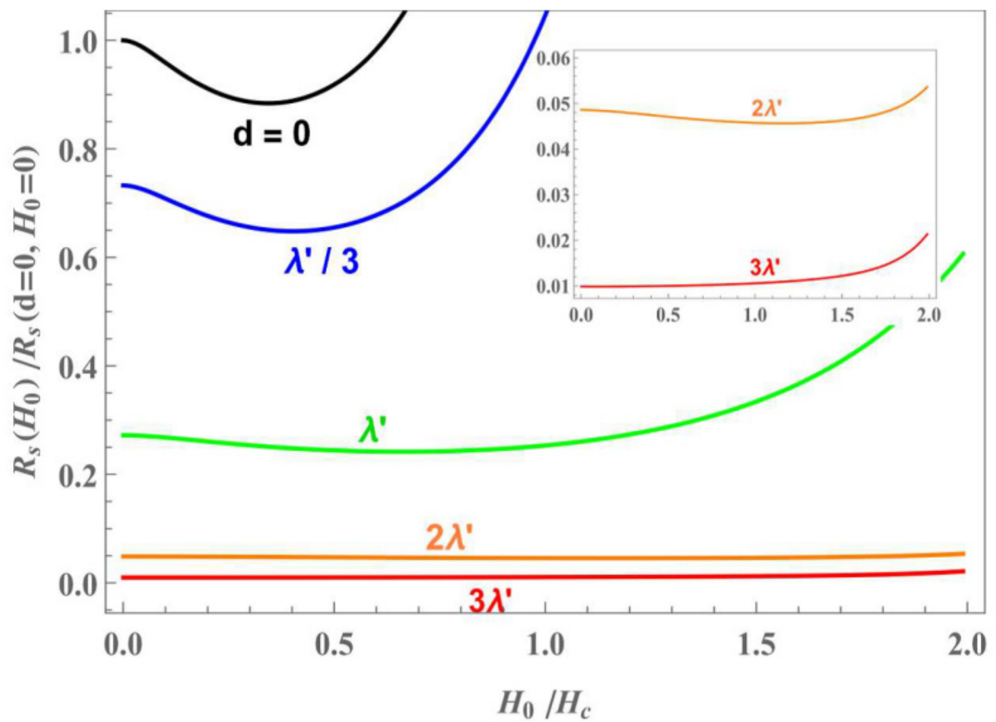


Nb_3Sn
$(\lambda' = 3\lambda)$
$\Gamma' = 0.05$

Bulk Nb
(λ)
$\Gamma = 0.01$



Example 2: Nb_3Sn-Nb structure



A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006).
T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014).
A. Gurevich, AIP Adv. 5, 017112 (2015).
T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017).

The optimum thicknesses for higher fields are given by $d \sim \lambda'$

Here, Q drops are not significant even at $H>H_c^{(Nb)}$

- We have developed a theory of **field dependent surface resistance** of a dirty superconductor in a strong RF field, **taking into account realistic materials features** based on the BCS theory.

- **Many different field dependencies $R_s(H_0)$ naturally result from realistic material features** such as a finite Γ, Γ_p or a thin N or S layer on the surface.

- The surface resistance **can be minimized** by engineering optimum impurity concentration or properties of the surface normal layer.

- To compare the theory with experiments and to utilize the theoretical consequences to improve cavity performances, **we need measurements of multiple parameters characterizing a particular material** (e.g., d and σ_n of the N layer, R_B, and Γ parameters) **as well as the way these parameters change after different materials treatments**.

Wait!
How about nonequilibrium effects on Rs(H)???

Part 3
Non-equilibrium effects under strong RF current

T. Kubo and A. Gurevich, to be published

The equation of motion for the Green's function in Keldysh-Nambu space for a dirty superconductor:

$$i\hbar D\check{\partial}\otimes[\check{G}\otimes(\check{\partial}\otimes\check{G})] = \left(\check{\tau}_z i\hbar\frac{\partial}{\partial t}+\check{\Delta}-\check{\Sigma}\right)\otimes\check{G}-\check{G}\otimes\left(\check{\tau}_z i\hbar\frac{\partial}{\partial t}+\check{\Delta}-\check{\Sigma}\right) \qquad \check{G}(\mathbf{R},t_1,t_2)=\begin{pmatrix}\hat{G}^R & \hat{G}^K\\ 0 & \hat{G}^A\end{pmatrix}$$

Consider the first order of slow variation and equilibrium phonons.

We can evaluate non-equilibrium effects under the strong RF current on the distribution function:

$$f(\epsilon)=\tanh\frac{\epsilon}{2k_BT}$$

Equilibrium (Fermi-Dirac)

$$f(\epsilon,t)=\tanh\frac{\epsilon}{2k_BT}+\delta f(\epsilon,t)$$

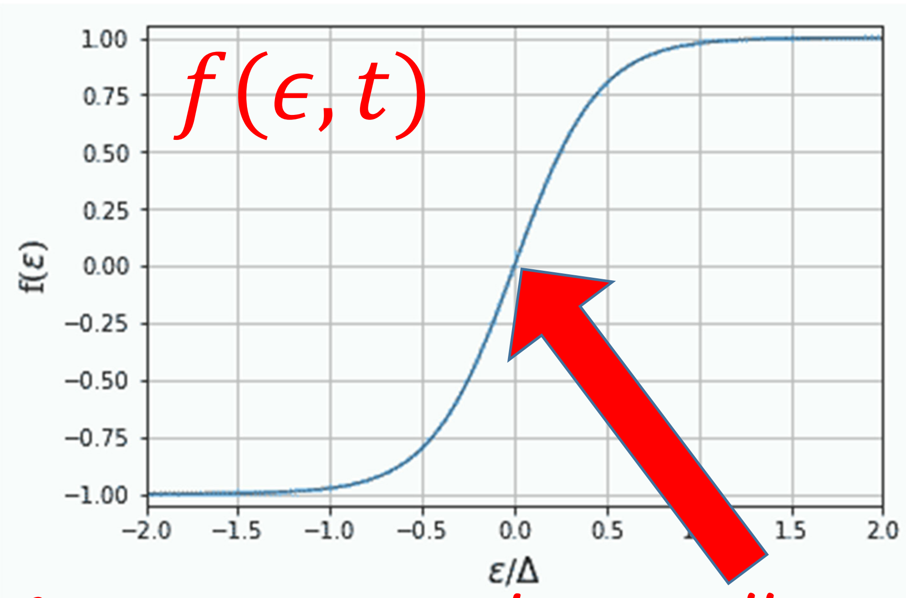
non-equilibrium effect

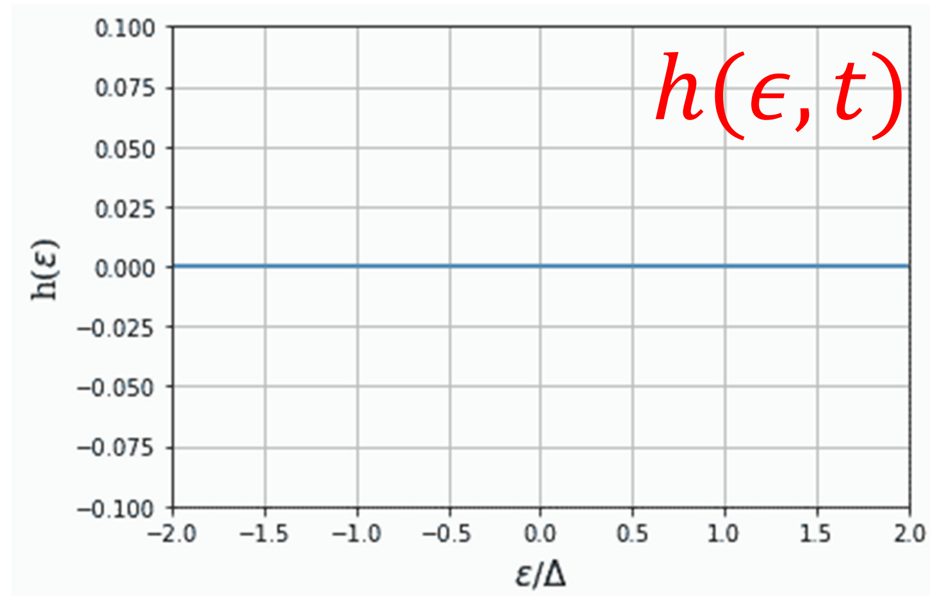
$$\boxed{\delta f(\epsilon,t)=\frac{h(\epsilon,t)}{\cosh^2\frac{\epsilon}{2k_BT}}}$$

- RF frequency ~ 1GHz
- T=4K
- Broadening parameter $\Gamma = 0.05$

Example (1)

Contain animations.
See in Slide Show Mode.





Can you see the oscillation?
Its effect is very small.

non-equilibrium effect

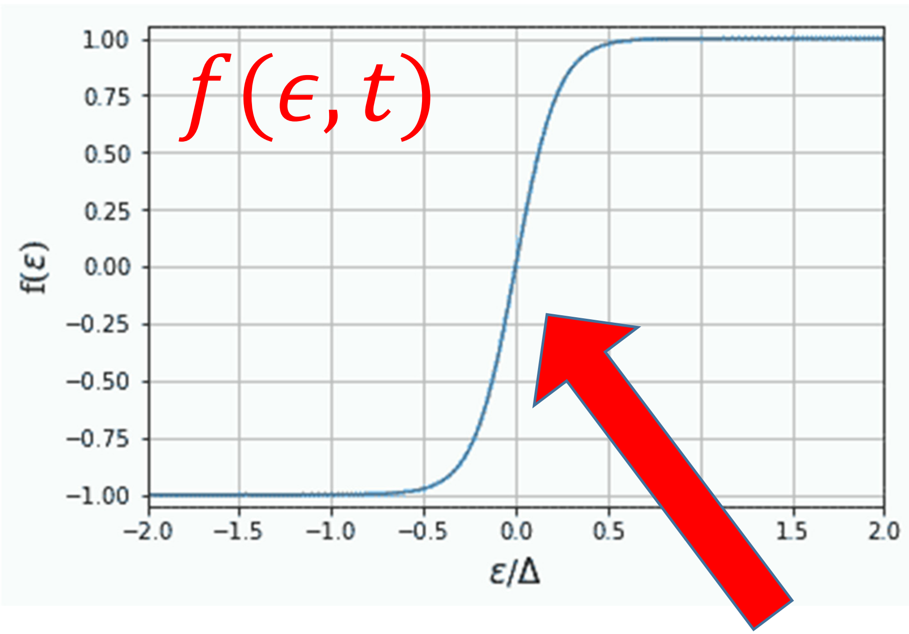
$$f(\epsilon,t) = \tanh\frac{\epsilon}{2k_BT} + \delta f(\epsilon,t)$$

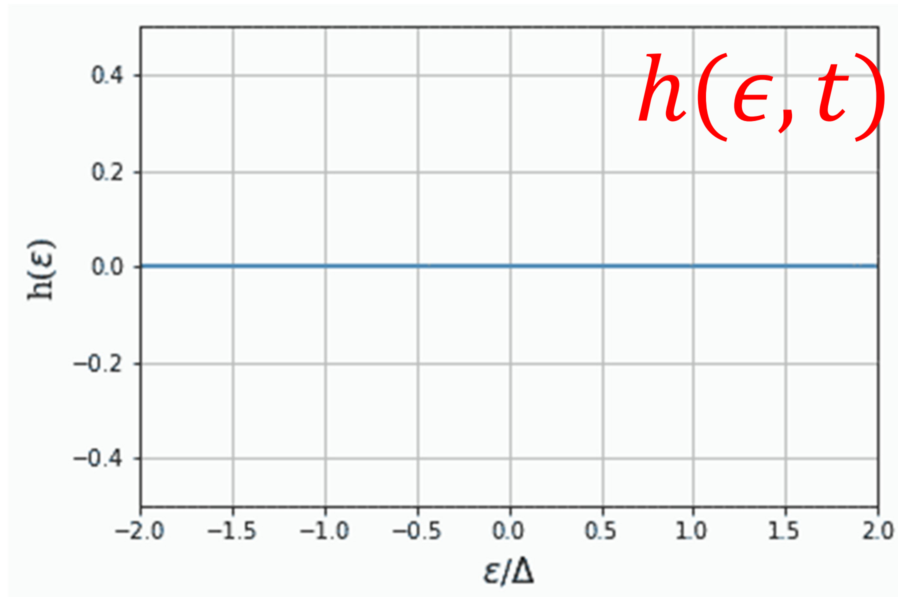
$$\boxed{\delta f(\epsilon,t) = \frac{h(\epsilon,t)}{\cosh^2\frac{\epsilon}{2k_BT}}}$$

Example (2)

Contain animations.
See in Slide Show Mode.

- RF frequency ~ 1GHz
- T=2K
- Broadening parameter $\Gamma = 0.1$

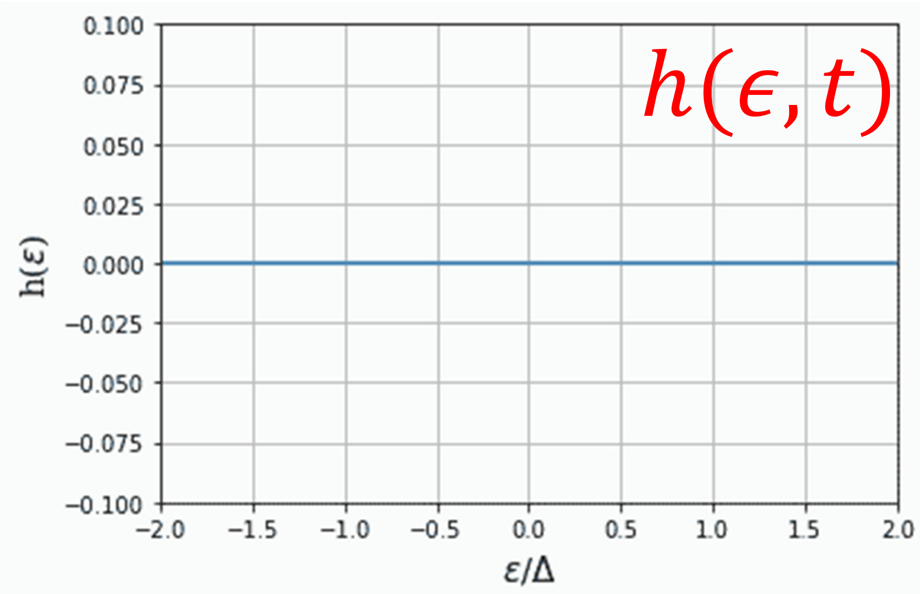


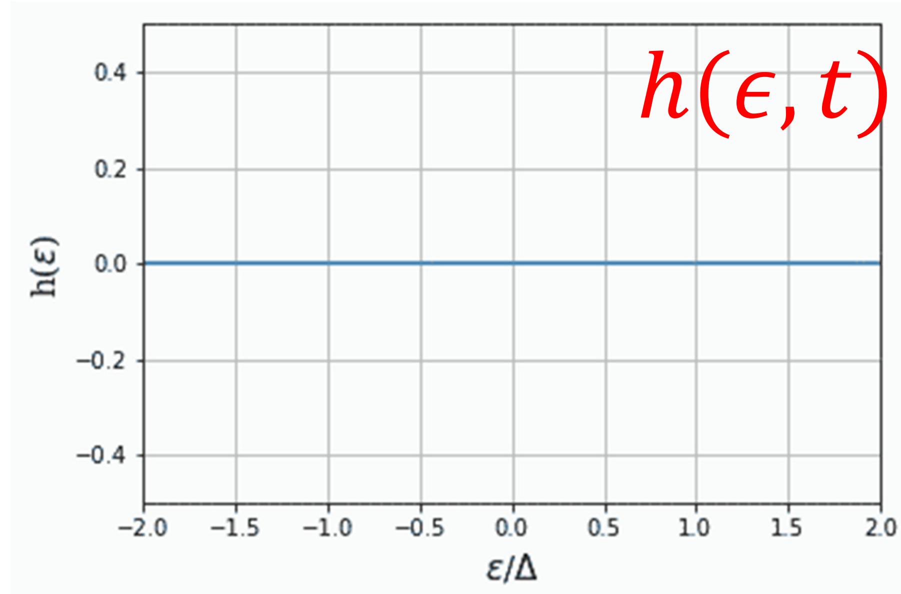


Oscillating $f(\epsilon,t)$

non-equilibrium effect

$$f(\epsilon,t) = \tanh\frac{\epsilon}{2k_BT} + \delta f(\epsilon,t) \qquad \boxed{\delta f(\epsilon,t) = \frac{h(\epsilon,t)}{\cosh^2\frac{\epsilon}{2k_BT}}}$$





- Nonequilibrium effects in $R_s(H)$ becomes significant at lower temperature, higher frequencies, and higher fields.
- We started to address this problem.

Look forward to next conferences

Vielen Dank für Ihre Aufmerksamkeit!

- We have developed a theory of **field dependent surface resistance** of a dirty superconductor in a strong RF field, **taking into account realistic materials features** based on the BCS theory.

- **Many different field dependencies $R_s(H_0)$ naturally result from realistic material features** such as a finite Γ, Γ_p or a thin N or S layer on the surface.

- The surface resistance **can be minimized** by engineering optimum impurity concentration or properties of the surface normal layer.

- To compare the theory with experiments and to utilize the theoretical consequences to improve cavity performances, **we need measurements of multiple parameters characterizing a particular material** (e.g., d and σ_n of the N layer, R_B, and Γ parameters) **as well as the way these parameters change after different materials treatments**.

- **Non-equilibrium effects** becomes significant at lower temperatures, higher frequencies and higher fields. **We have already started to address this problem**. Look forward to SRF2021!