

# Introduction to superconductivity

Florence Levy-Bertrand

- General properties
  - Zero resistance
  - Perfect diamagnetism
  - Values:  $T_c, H_c, j_c, \lambda_L$
- Microscopic origin
  - Quantum state:  $\theta, \phi_0$
  - Cooper pairs:  $\xi_0$
  - electron-phonon interaction
  - superconducting gap  $\Delta$
- Type I and II
  - Ginzburg-Landau parameter  $\kappa$
  - critical fields  $H_c, H_{c1}, H_{c2}$
  - critical currents  $J_c, J_v$
  - role of disorder
- Specific properties
  - tunnel effect
  - Josephson effect
  - specific heat
  - thermal conduction
  - kinetic inductance
  - reflectivity / absorption

# General properties



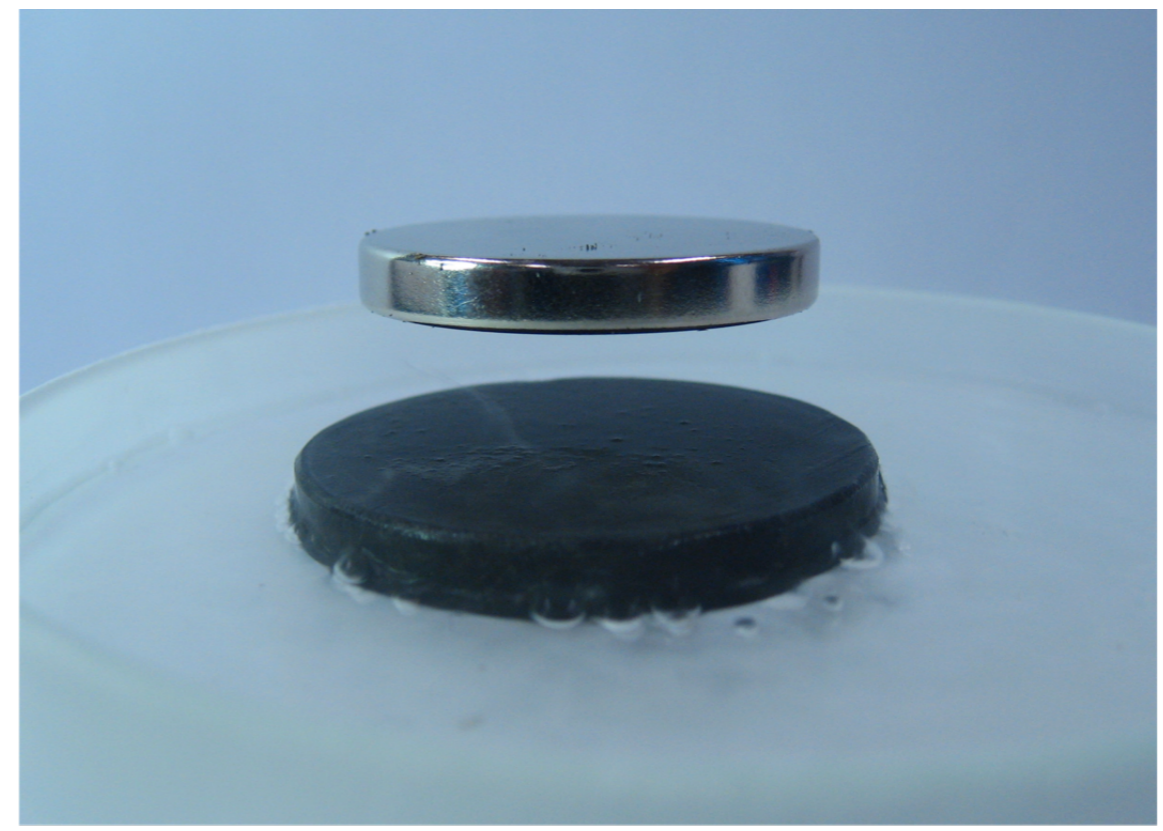
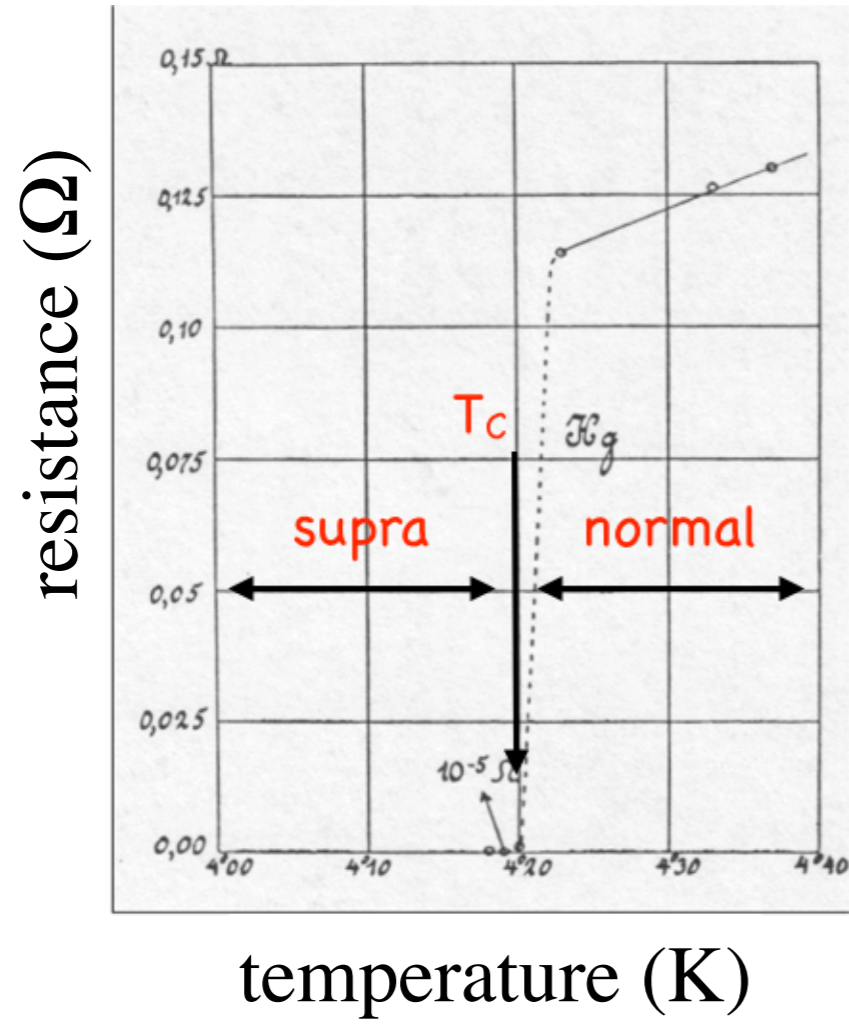
Superconductor = material for  $T < T_c$  such that  
 $T_c$  = critical temperature

$$R = 0$$

electrical resistance

$$B = 0$$

magnetic induction



+ current :  $j < j_c$ , magnetic field  $H < H_c$

# General properties



Superconductor = material for  $T < T_c$  such that  
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electrical resistance

$$B=0$$

magnetic induction

## Implication for detectors:

- low temperatures  $T \ll T_c$  are required
- $R=0$  allows high quality factor resonator (KID-detector)
- sharp transition to  $R=0$  allows TES (Transition Edge Sensor)
- effect of current: careful with readout power + potential tuning
- effect of magnetic field: careful with earth magnetic field + potential tuning

temperature (K)

+ current :  $j < j_c$ , magnetic field  $H < H_c$

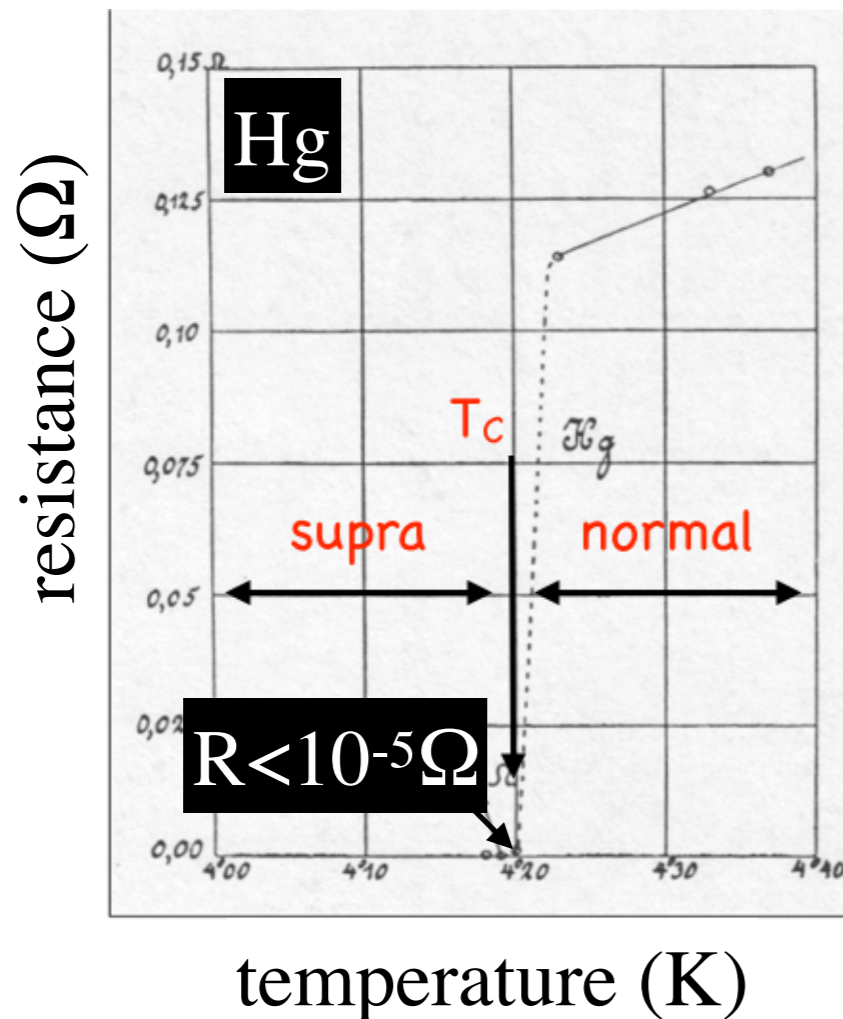
# General properties: $R=0$

Discovery in 1911 by Karmnerlingh Onnes

$T_c$  = critical temperature

$$R=0$$

electrical resistance



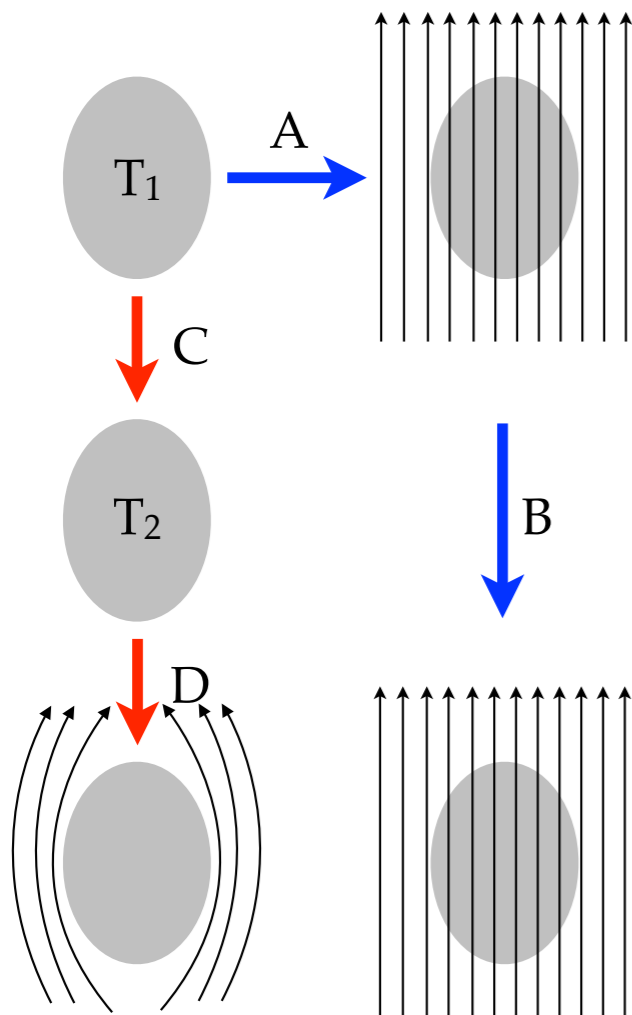
Historical framework:

- race to low temperatures:  
liquefaction of oxygen, hydrogen and helium
- electrical behavior of metal at  $T=0K$ ?  
 $R \rightarrow 0$  due to reduced thermal agitation?  
 $R \uparrow$  because of the location of the electrons?  
 $R \rightarrow R_0$  because of impurities?

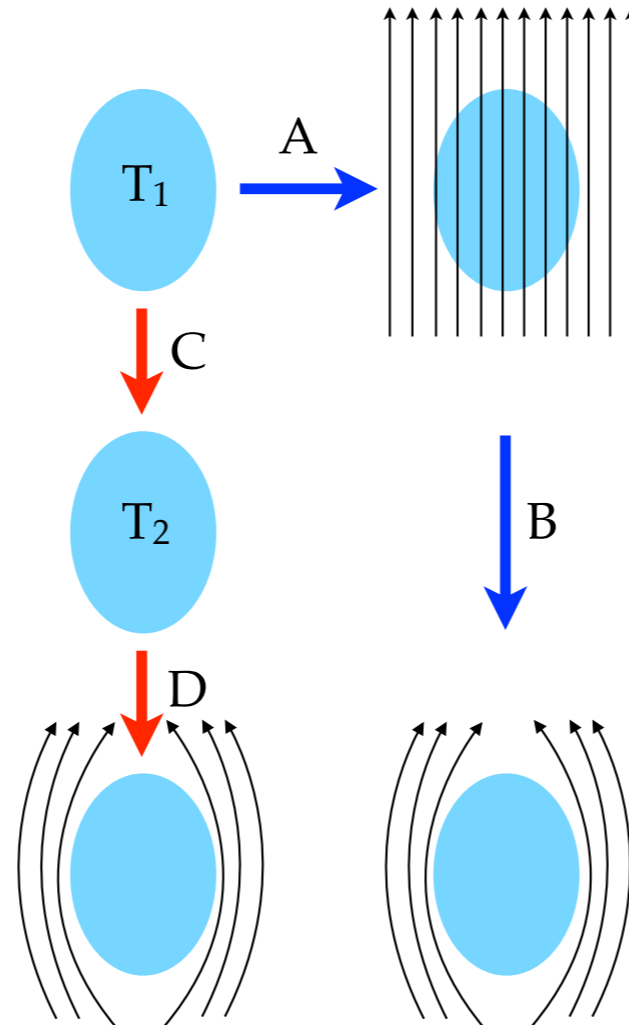
# General properties: $B=0$

Meissner-Ochsenfeld effect discovered in 1933

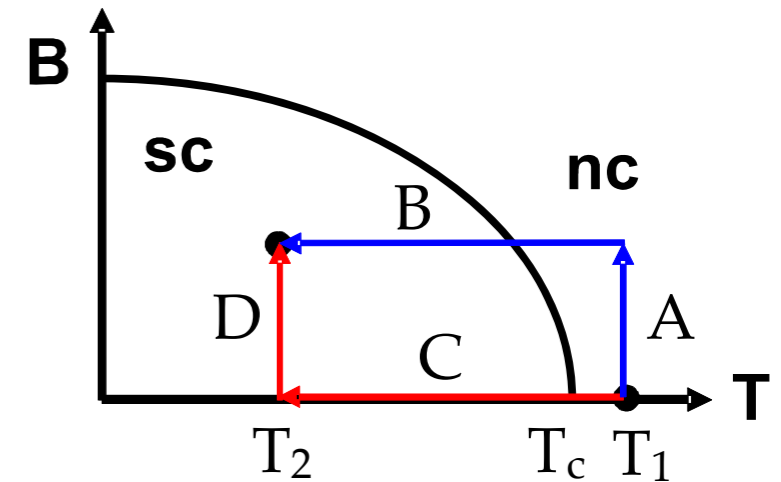
perfect conductor:  
 $\partial B / \partial t = 0$



superconductor:  
 $B = 0$



superconductor  
= thermodynamic state



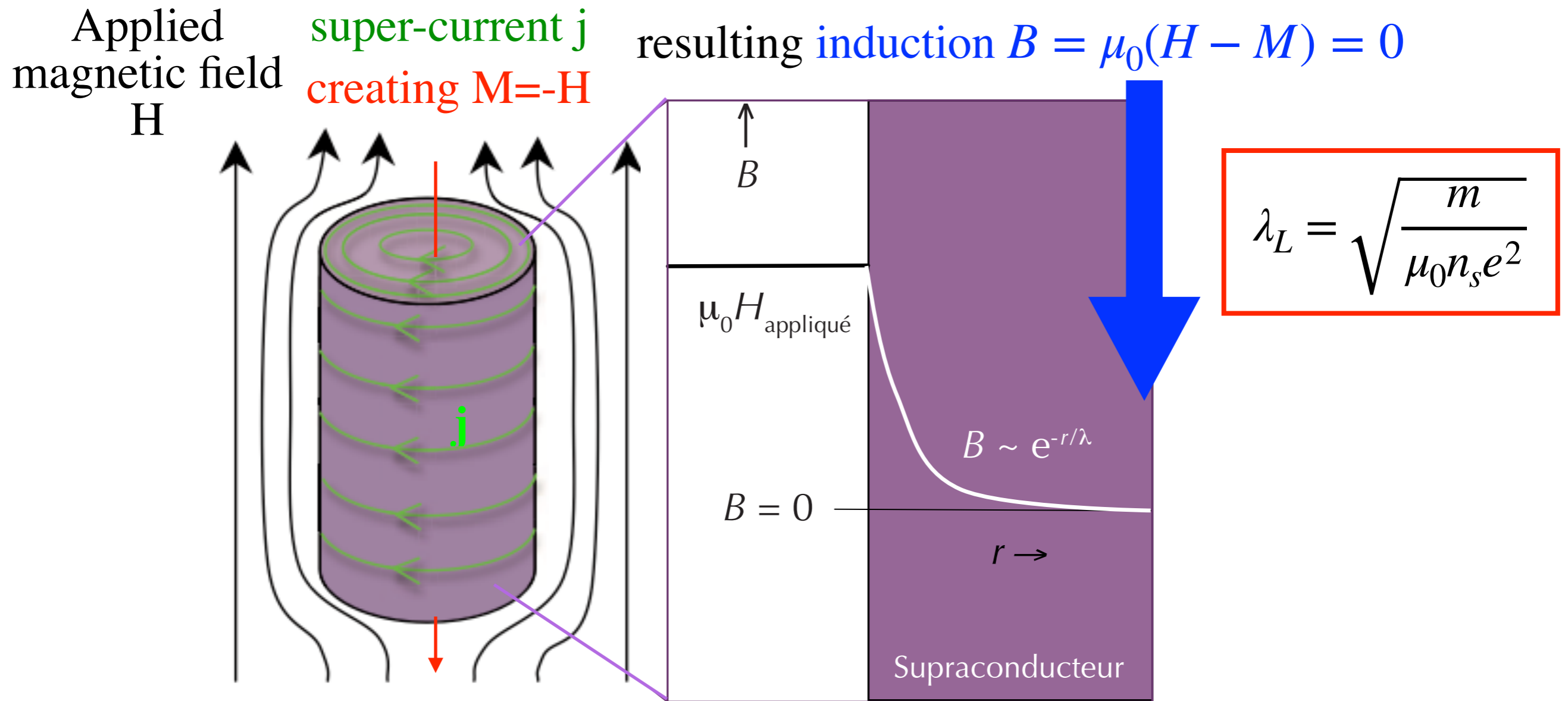
perfect diamagnetism

courtesy, H. Cercellier

# General properties: $\lambda_L$

Meissner-Ochsenfeld effect discovered in 1933

Screening super-current with spatial extension of London penetration depth  $\lambda_L$

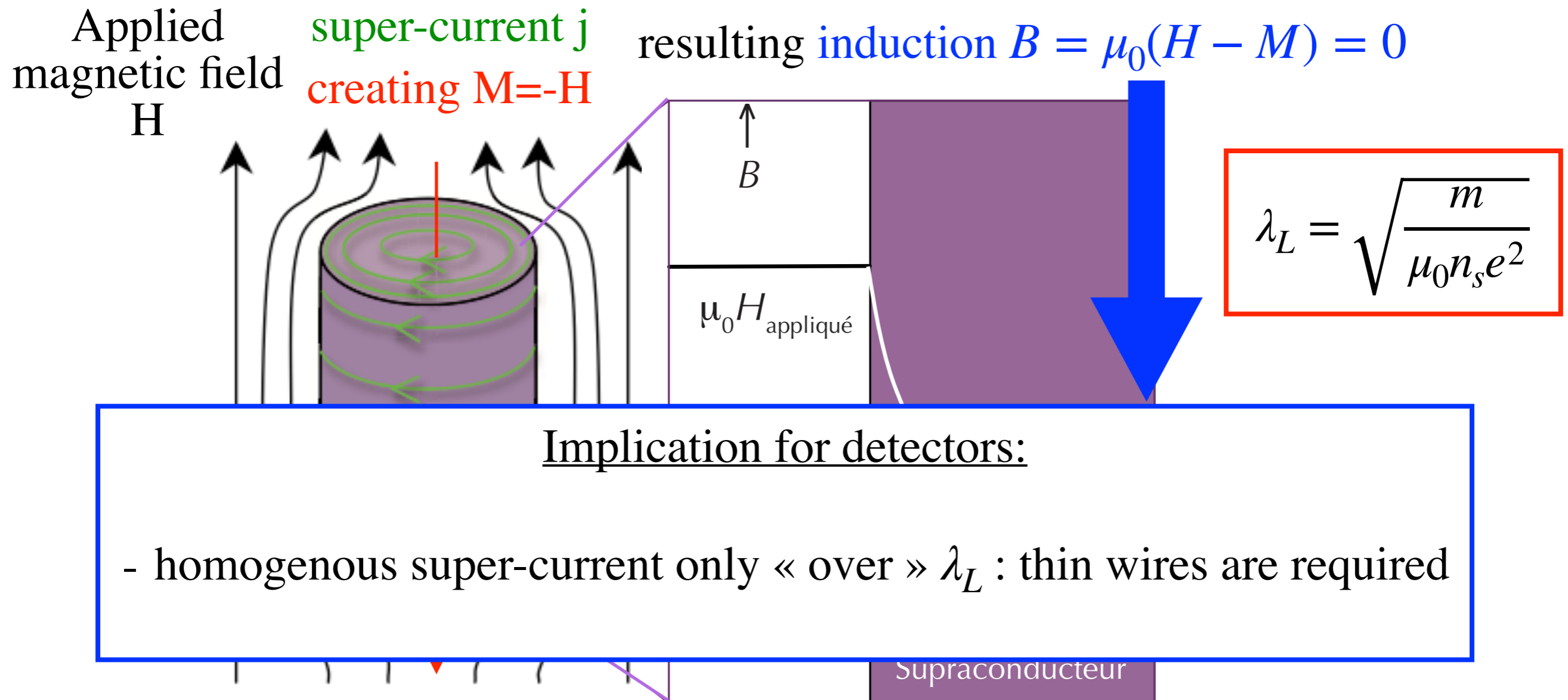


K. van der Beek, reflets de la physique n°27, 6 (2011)

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K. van der Beek, reflets de la physique n°27, 6 (2011)

# General properties: $H_c$ and $j_c$

$B=0$  as long as  $H < H_c$  magnetic critical field

$$E_{condensation} = \frac{1}{2} \mu_0 H_c^2$$

superconductivity as long as  $j < j_c$  critical current

**SILSBEE criteria (1916)**

$$j_c \sim \frac{H_c}{\lambda_L}$$



# Introduction to superconductivity

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# Microscopic origin: one wave function

Ginzburg-Landau theory 1951

**macroscopic quantum state** of many electrons (or holes)

$$\psi(r) = |\psi(r)| e^{i\theta(r)}$$

$\theta$  phase

$$|\psi(r)|^2 = n_s(r)$$

superfluid density  $n_s(r)$  varies on  $\xi_0$  coherence length

The coherence length  $\xi_0$  is the rigidity of the SC order parameter, the length over which it can deviate from its equilibrium value.

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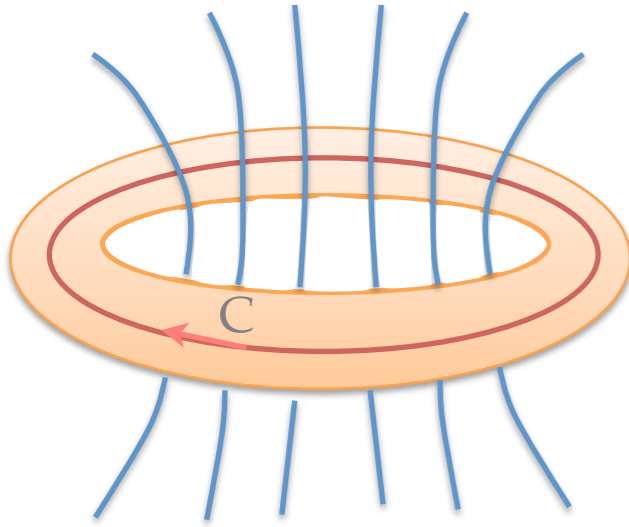
- phase  $\theta$   $\rightarrow$  magnetic flux quantification  
+ supercurrents, Josephson effect...

-  $\xi_0 / \lambda_L$   $\rightarrow$  two behaviors under H: type I / type II

$\theta$  phase

The coherence length  $\xi_0$  is the rigidity of the SC order parameter, the length over which it can deviate from its equilibrium value.

# Microscopic origin: $\phi_0$



courtesy, H. Cercellier

- Super currents  $\mathbf{j} = \frac{-2en}{m}(\hbar\nabla\theta + 2e\mathbf{A})$
- Meissner effect:  $\mathbf{j} = 0 \Leftrightarrow \hbar\nabla\theta = -2e\mathbf{A}$
- Phase shift on going once around the ring  $\Delta\theta = 2n\pi$

$$\oint_C \hbar\nabla\theta \cdot d\mathbf{l} = 2n\pi\hbar = \oint_C -2e\mathbf{A} \cdot d\mathbf{l} = 2e\Phi$$

The total magnetic flux through a superconducting ring is quantized :

$$\Phi = n \cdot \Phi_0 = \frac{nh}{2e}$$

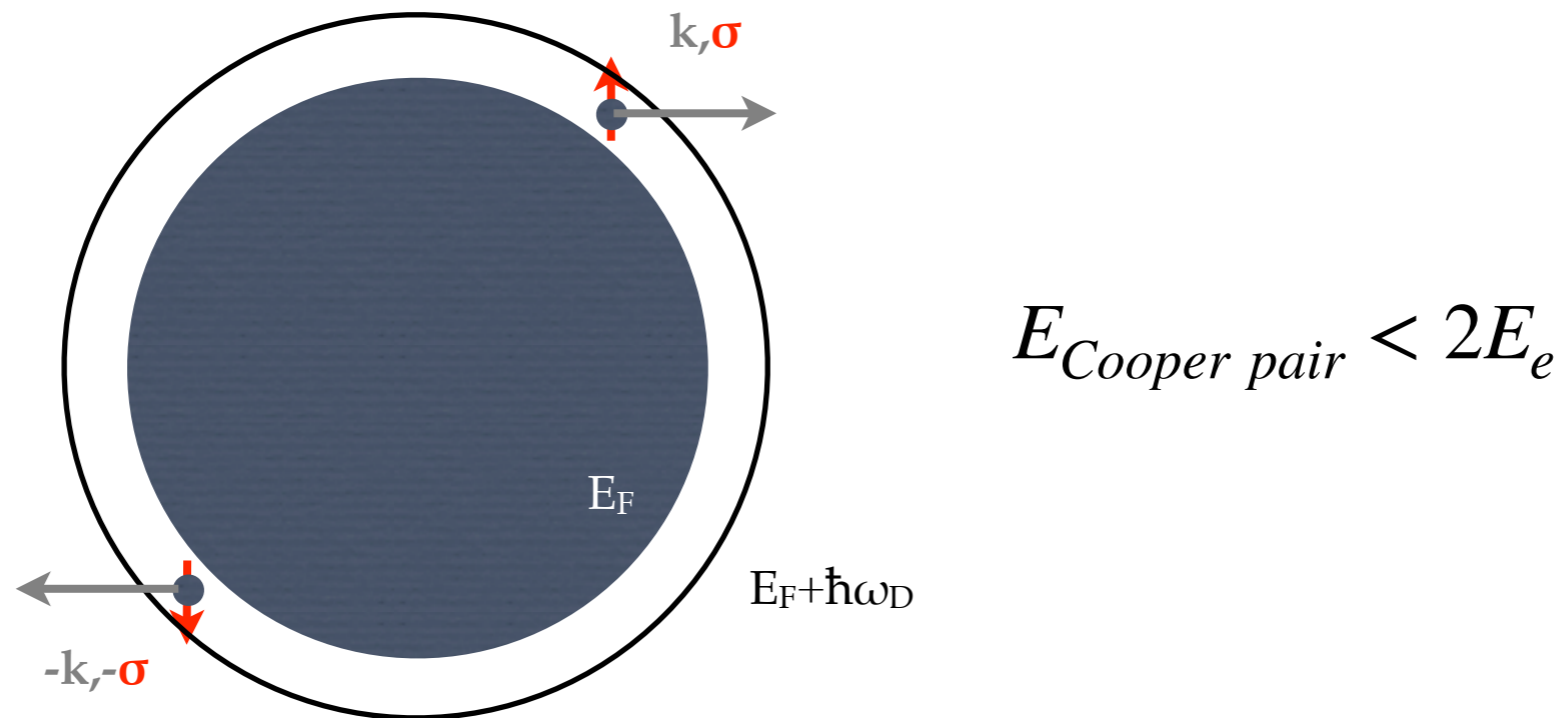
$$\Phi_0 = \frac{h}{2e} \approx 2.10^{-15} T \cdot m^2$$

magnetic flux quantum

# Microscopic origin: Cooper pair

Bardeen-Cooper-Schrieffer theory (BCS) 1957

Cooper instability: 2 electrons at  $E_F$  + attractive interaction



« Fermi sea » instable, formation of a new quantum state

1 electron = fermion (half integer spin), Pauli exclusion  
2 bonded electrons = boson (integer spin), Bose statistics

Cooper pairs Bose condensate

# Microscopic origin: interaction e-ph

Bardeen-Cooper-Schrieffer theory (BCS) 1957

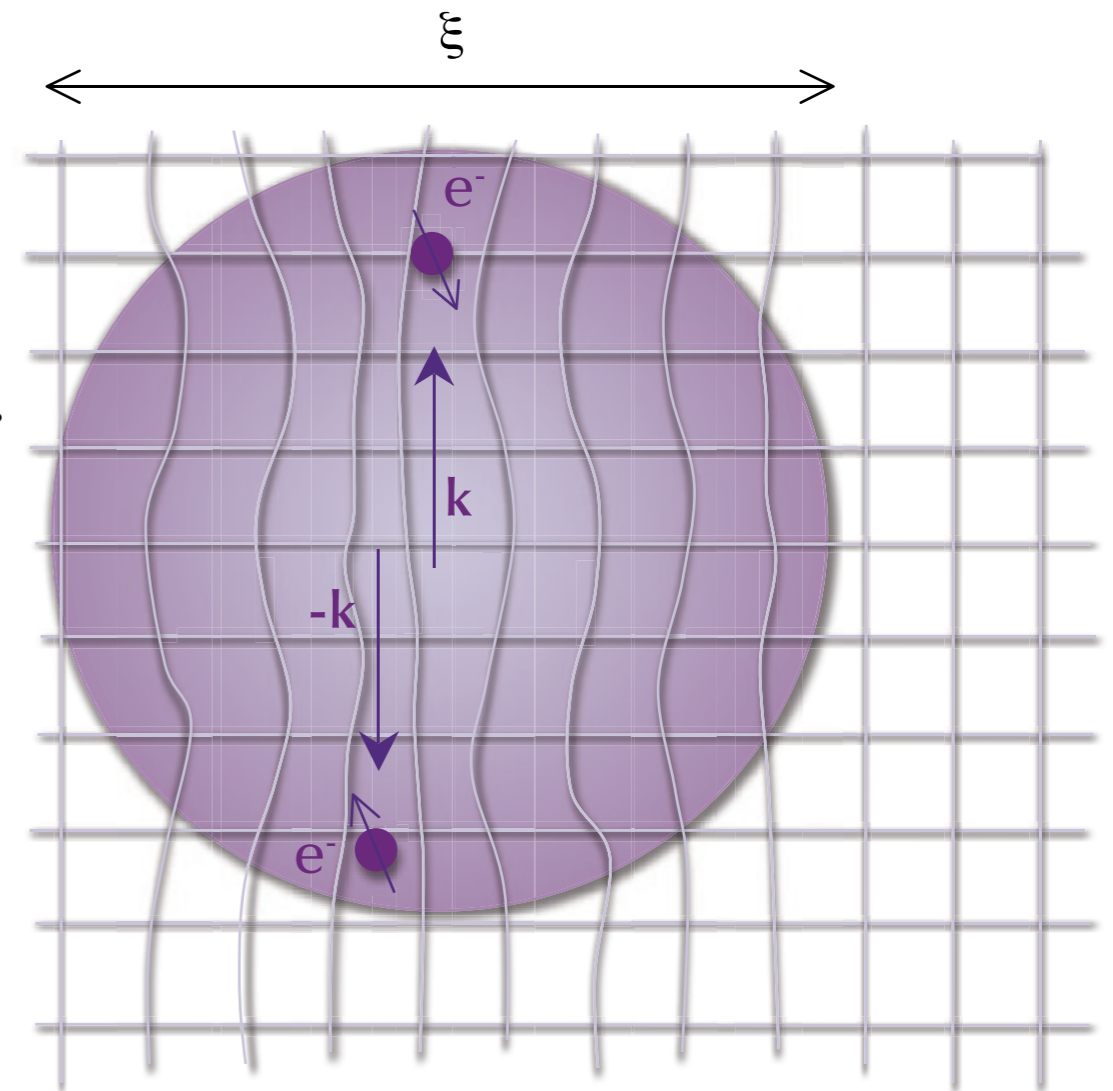
## Attractive interaction between electrons via phonons

Coulomb repulsion « screened » by ions and  $V_F \gg$  ions displacement speed.

Entire phonon spectrum up to Debye freq  $\omega_D$ .

Experimental evidence: isotopic effect

$$T_c^{iso} = \frac{Cte}{\sqrt{M^{iso}}}$$



K. van der Beek, reflets de la physique n°27, 6 (2011)

# Microscopic origin: $\xi_{BCS}$

Bardeen-Cooper-Schrieffer theory (BCS) 1957

$\xi$  average distance between two electrons of a Cooper pair

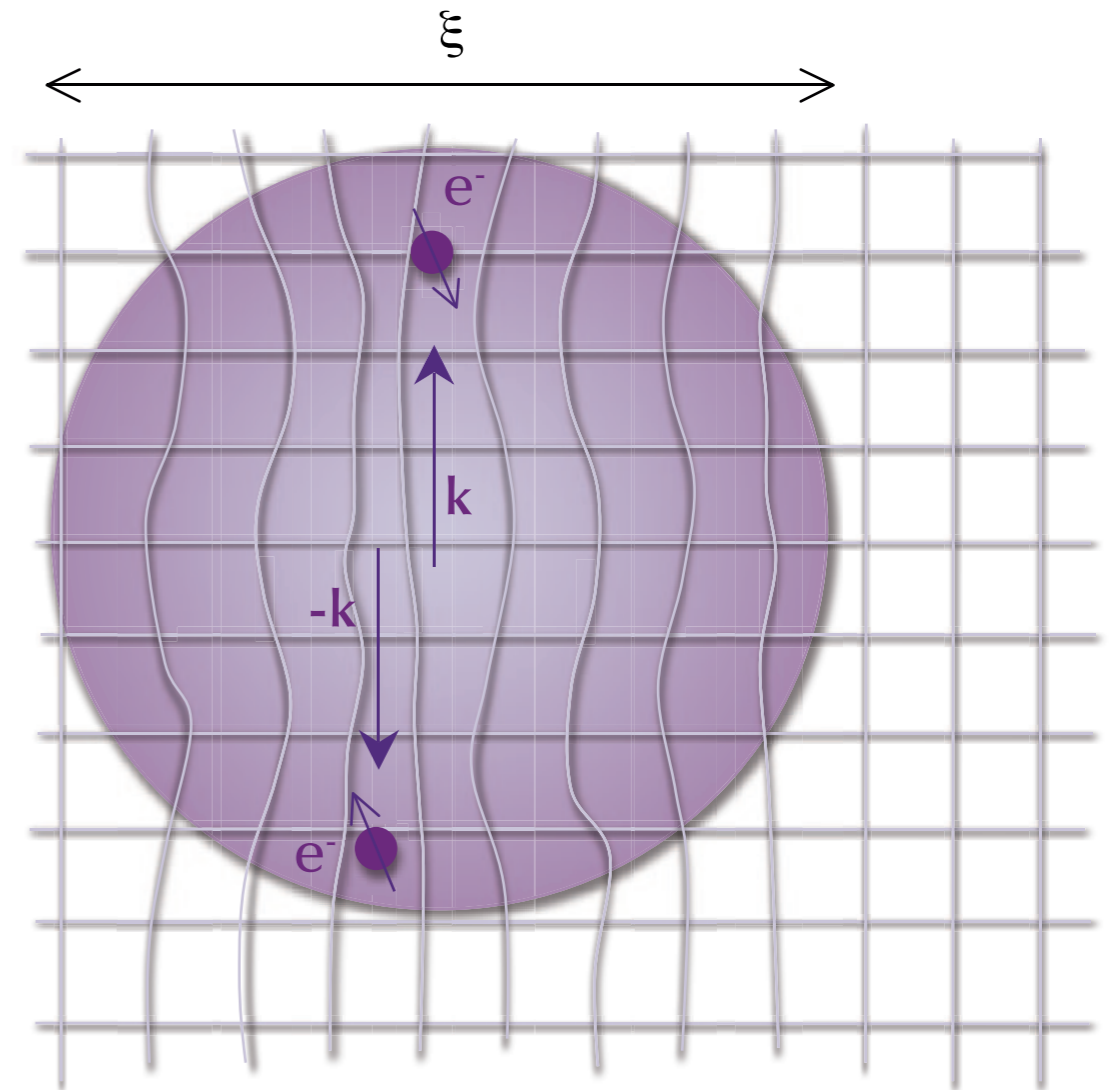
$$\delta t \delta E \sim \hbar$$

$$\delta E = k_B T_c$$

During the time  $dt$  the electron travels

$$\xi_{BCS} \sim v_F dt \sim \frac{\hbar v_F}{k_B T_c}$$

$$\xi_{BCS}(T) = \frac{\hbar v_F}{\pi \Delta(T)}$$



K. van der Beek, *reflets de la physique* n°27, 6 (2011)

The coherence length  $\xi_0$  is the rigidity of the SC order parameter, the length over which SC can be destroyed.

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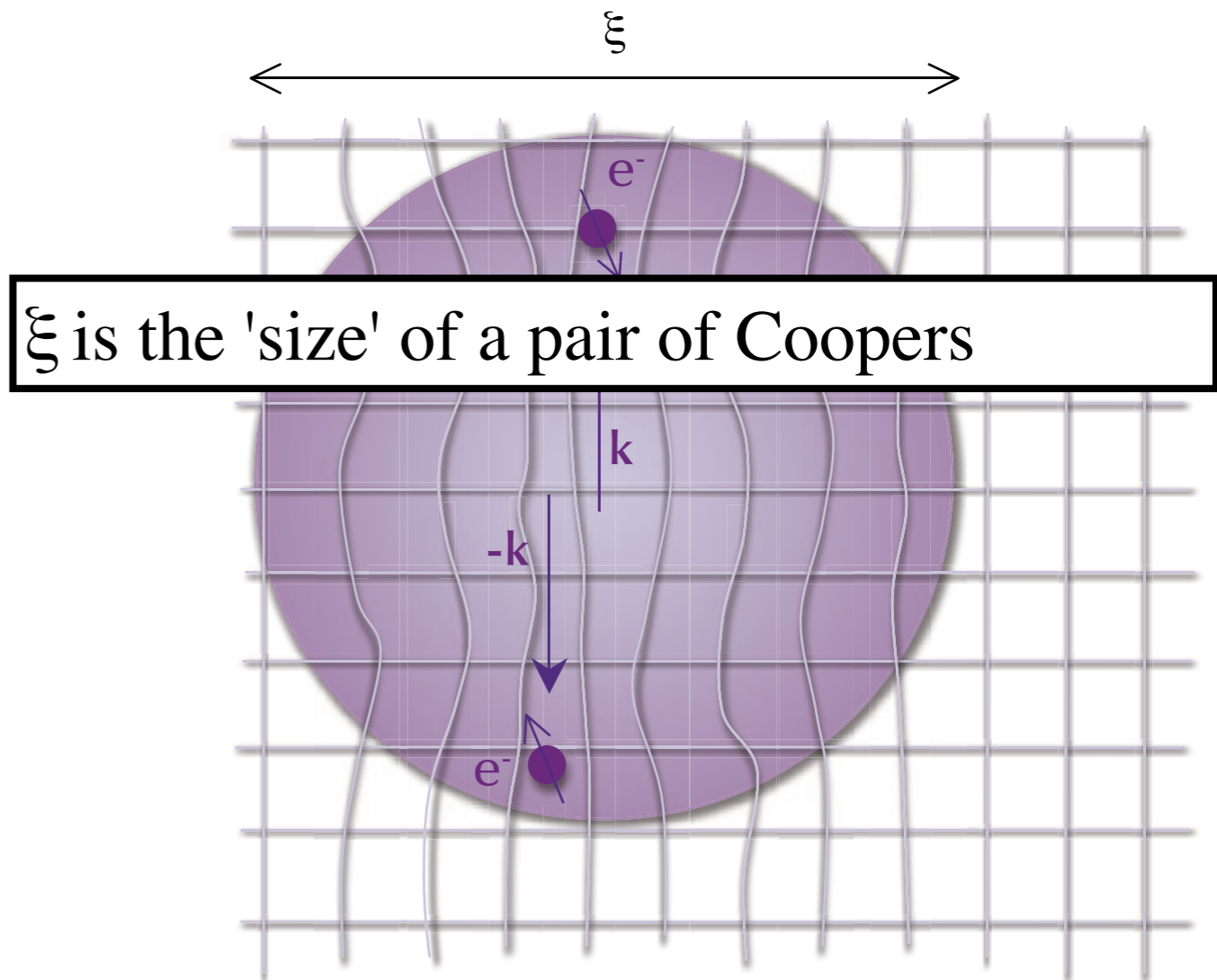
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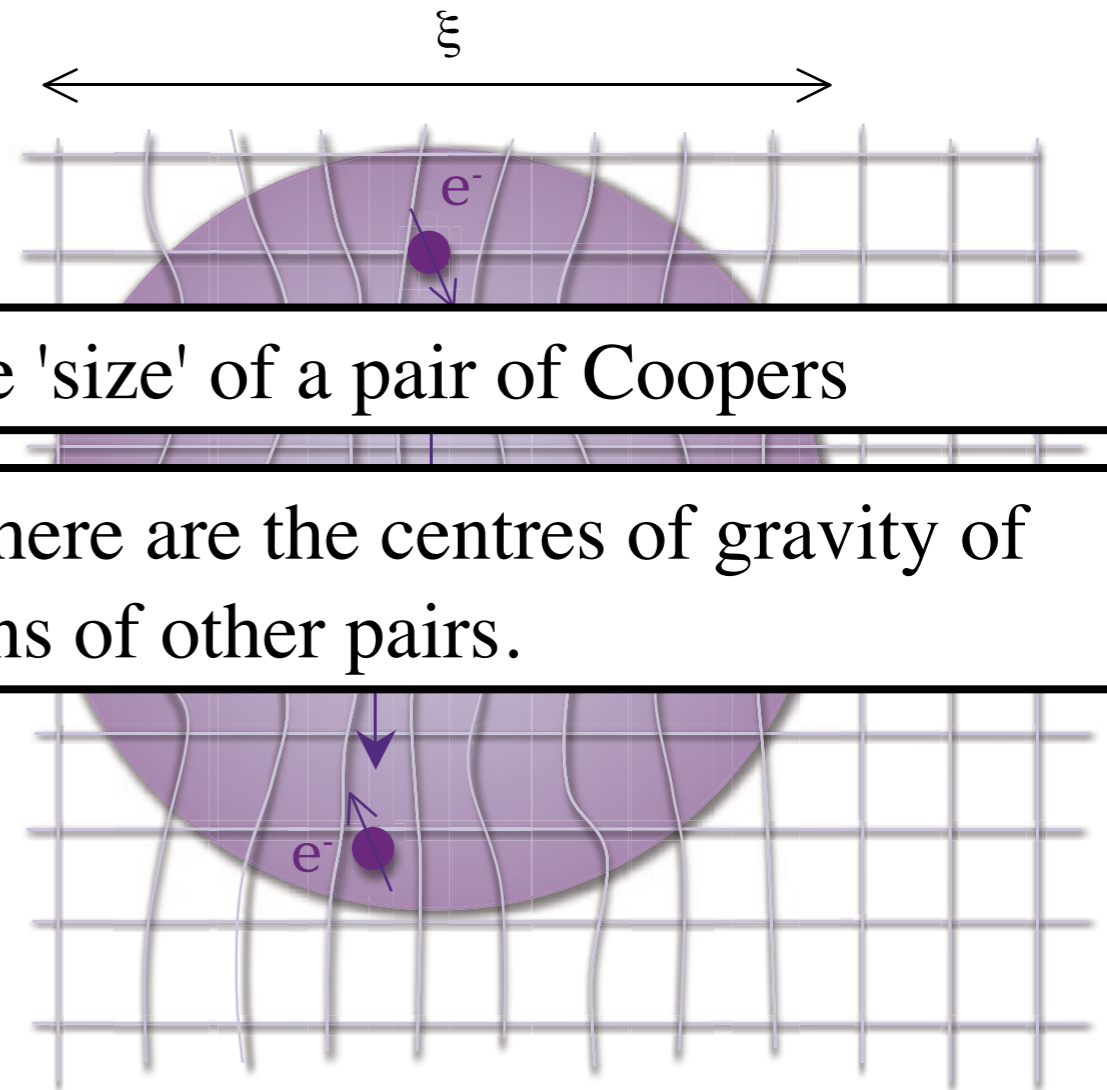
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$\xi$  is the 'size' of a pair of Coopers

In  $\xi^3$  there are the centres of gravity of millions of other pairs.

K. van der Beek, reflets de la physique n°27, 6 (2011)

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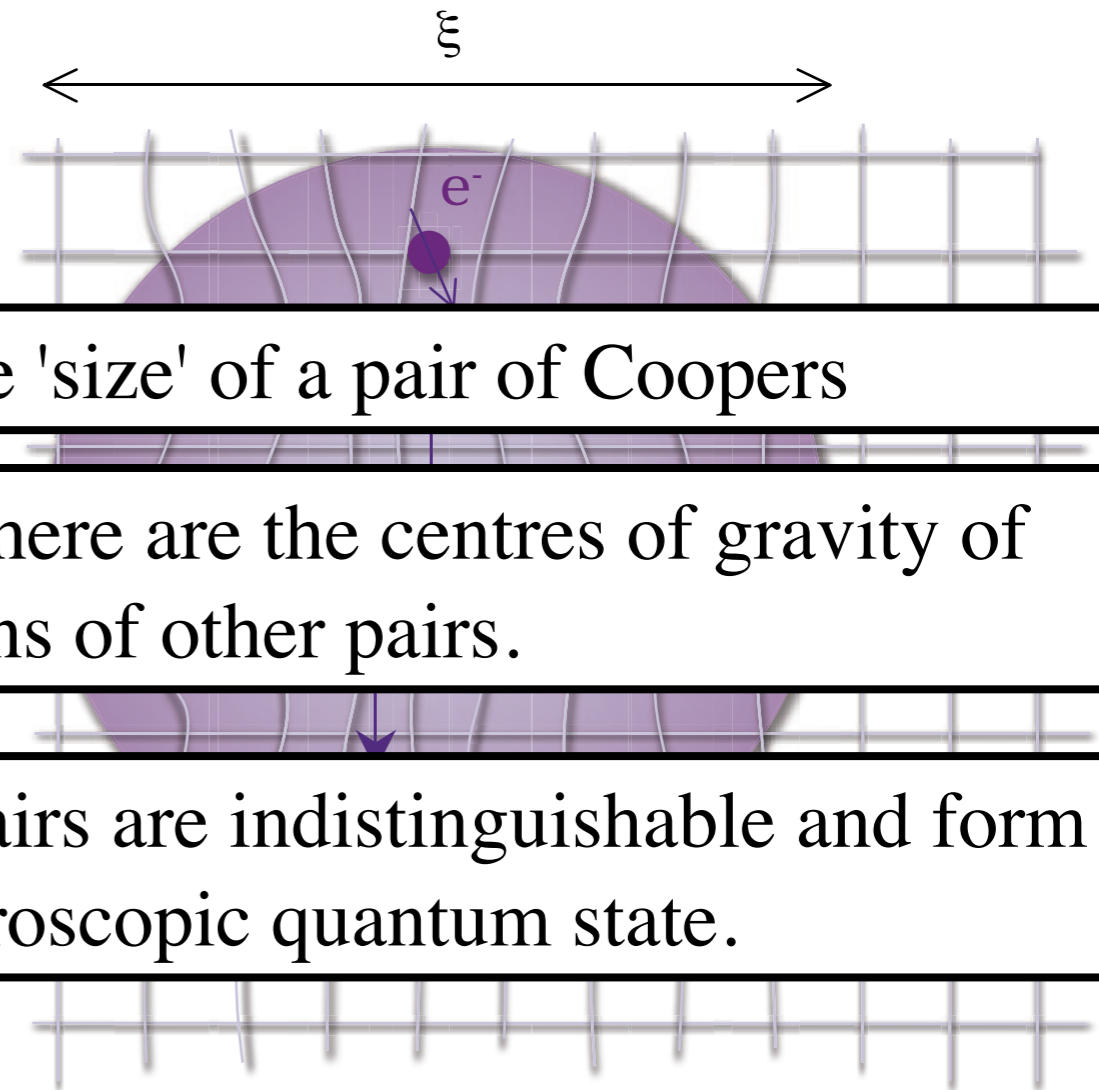
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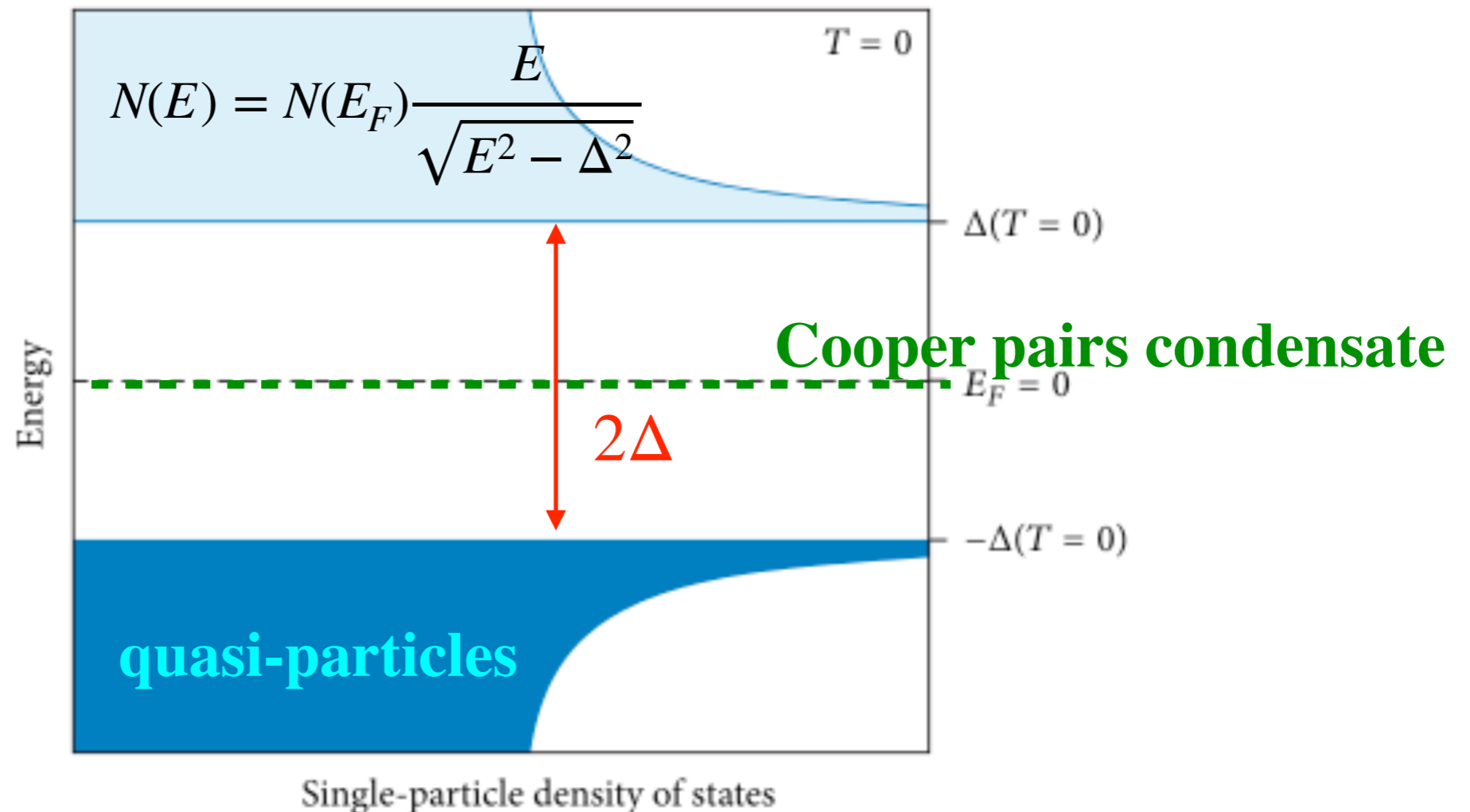
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# Microscopic origin: gap $\Delta$

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A gap  $2\Delta$  opens in the single-particle density of states



The gap protects the SC-condensate from thermal/photon excitations

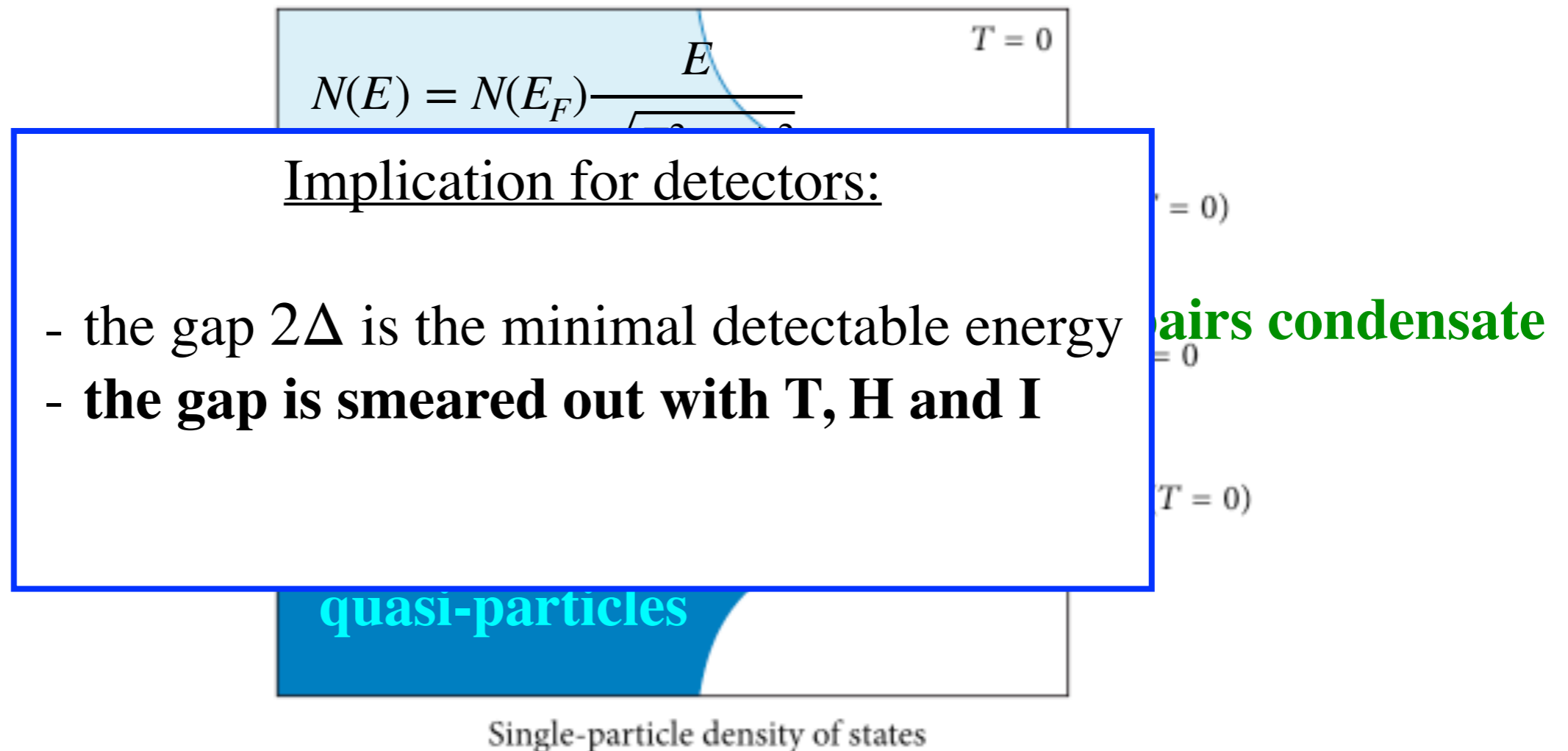
**The gap  $2\Delta$  is the energy required to break ONE Cooper pair**

M. Dressel, *Electrodynamics of Metallic Superconductors*, Advances in Condensed Matter Physics **2013**, 1 (2013).

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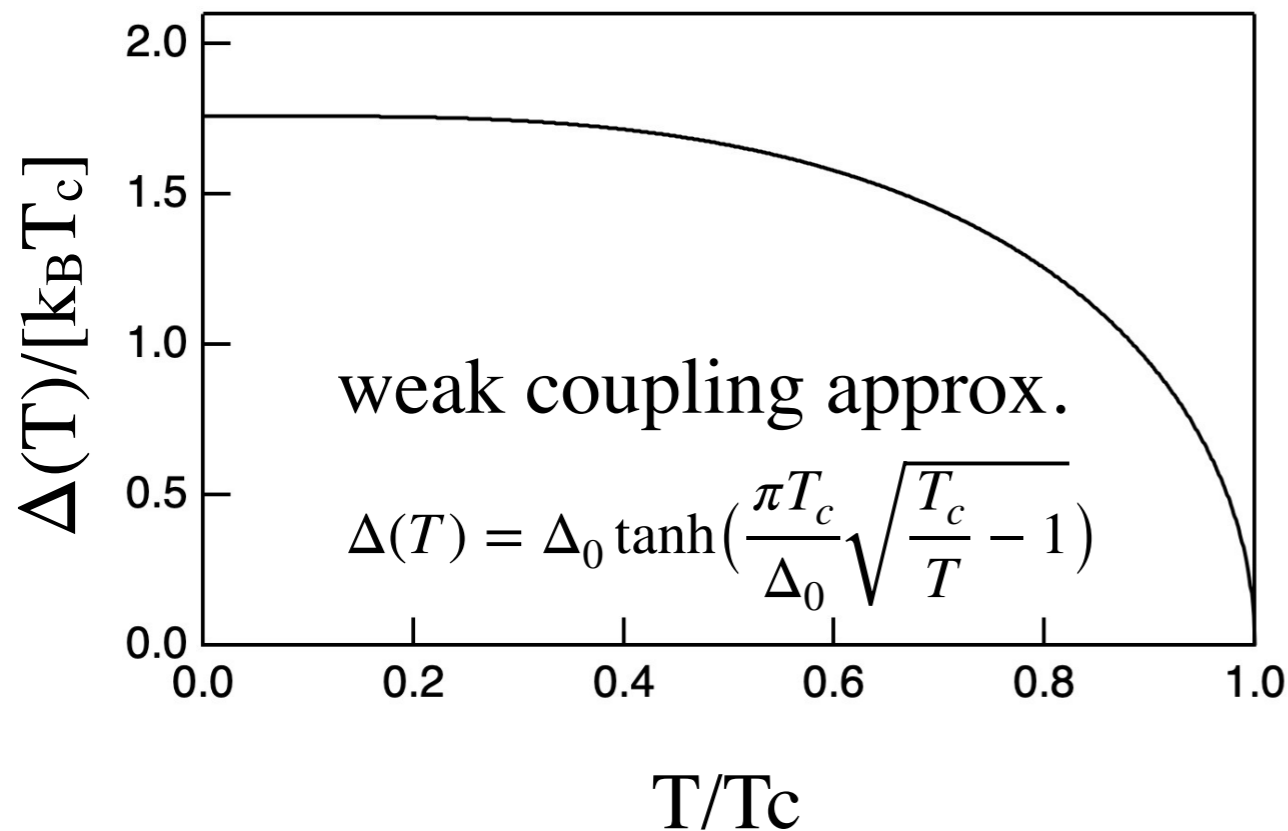
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# Microscopic origin: gap $\Delta$ and $T_c$

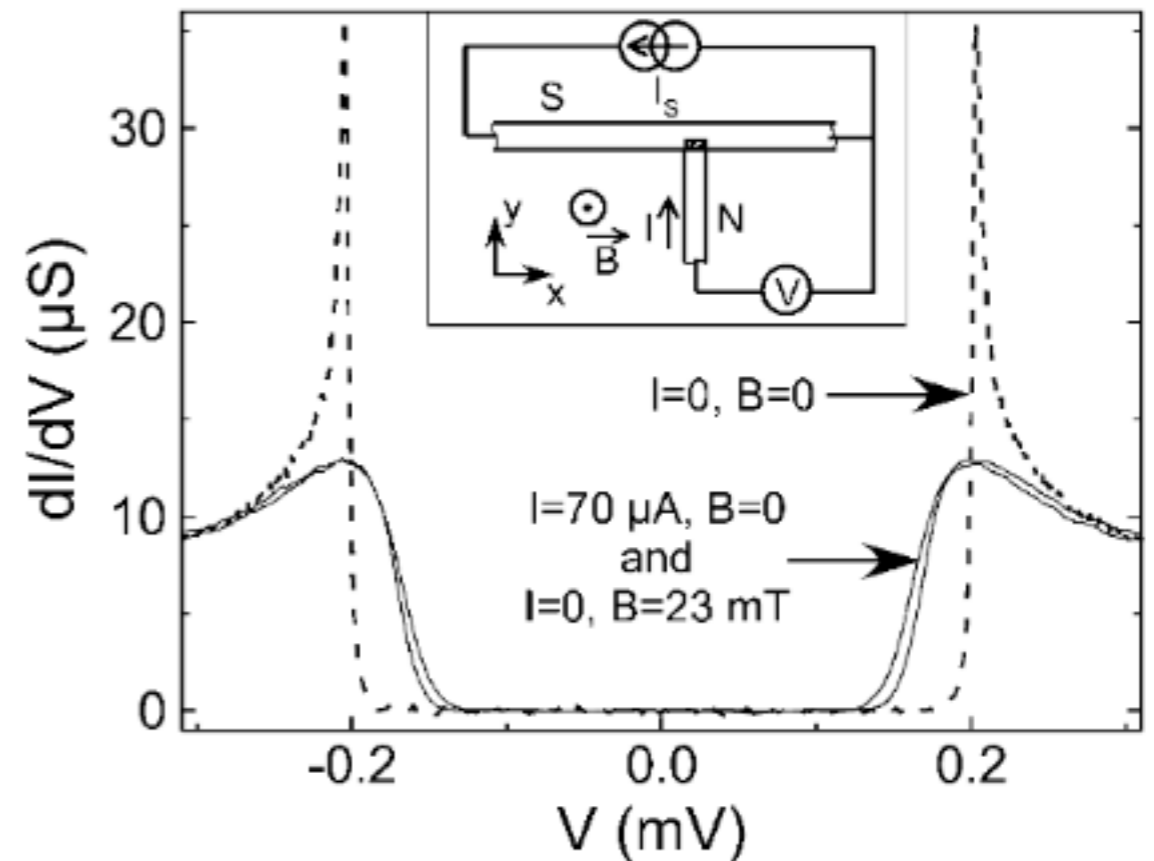
Bardeen-Cooper-Schrieffer theory (BCS) 1957

$$2\Delta(0) = 3.52K_bT_c$$

T-variation of the gap



H, I - variation of the gap



A. Anthore et al, PRL 90, 127001 (2003).

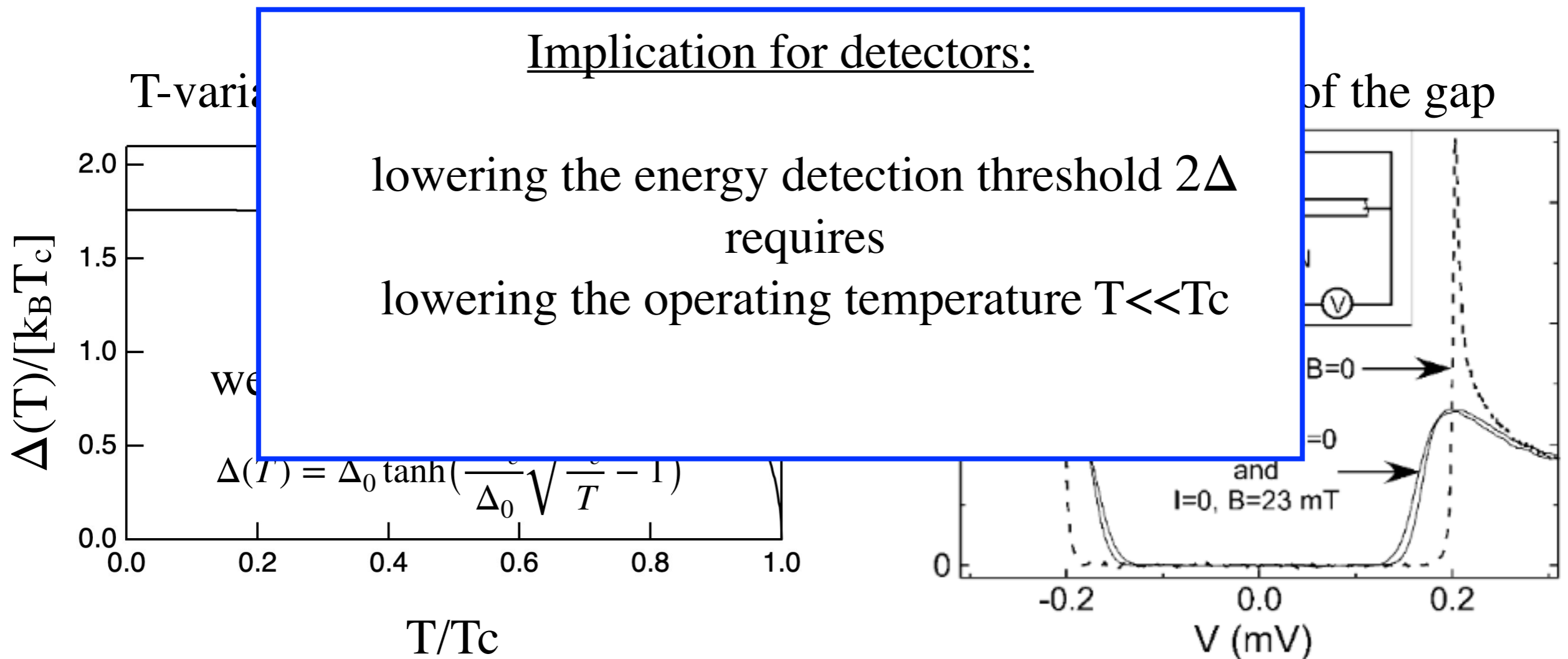
# Microscopic origin: gap $\Delta$ and $T_c$

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$$2\Delta(0) = 3.52k_bT_c$$

Implication for detectors:

lowering the energy detection threshold  $2\Delta$   
requires  
lowering the operating temperature  $T \ll T_c$



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# Introduction to superconductivity

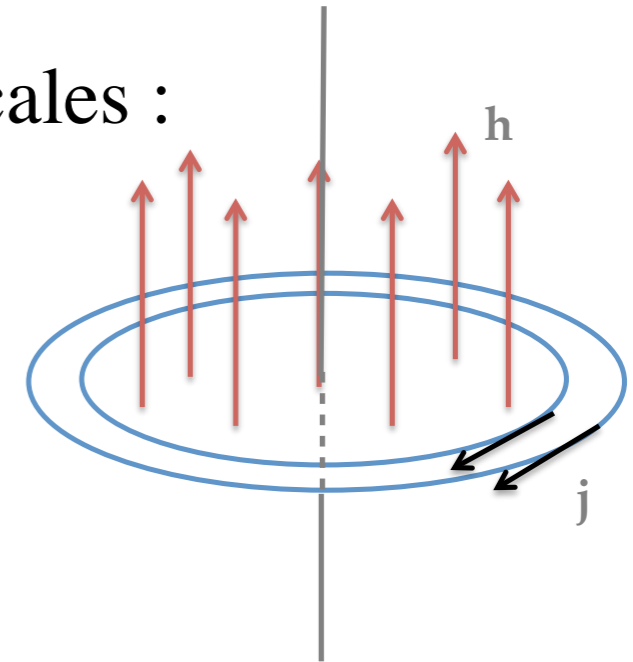
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# Types I et II: $\kappa = \lambda/\xi$

Type I and type II SC are characterized by two length scales :

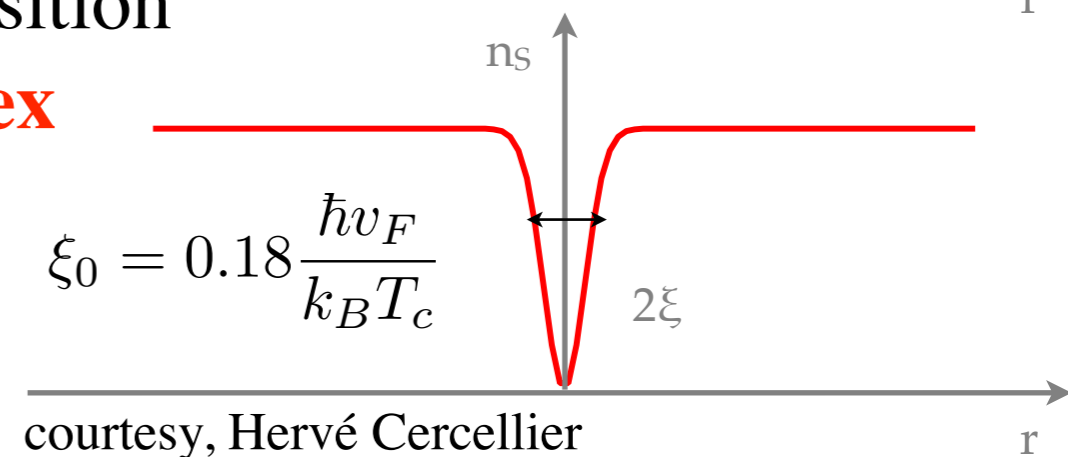
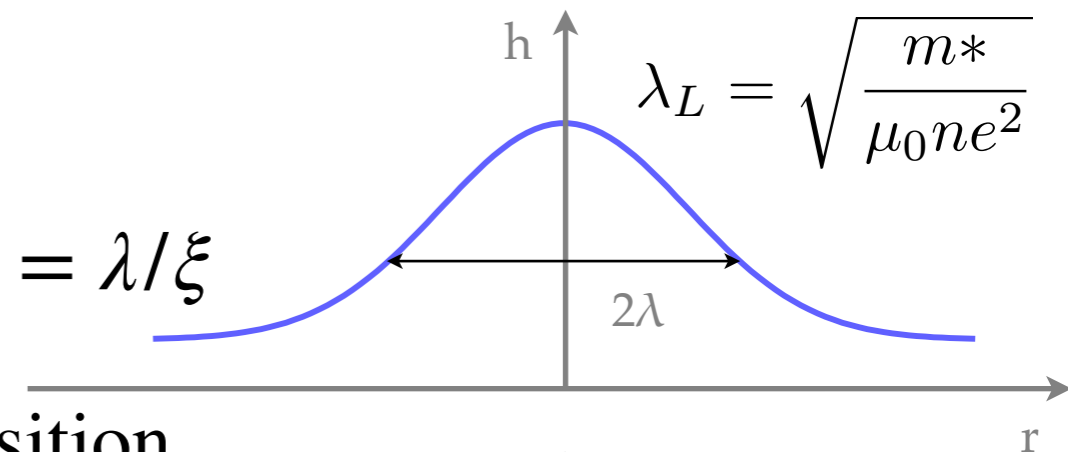
- the London penetration depth  $\lambda$ ,  
the scale for current flow  $\Leftrightarrow$  magnetic field decay
- the coherence length  $\xi$ ,  
the rigidity of the SC order parameter, the length over which it can deviate from its equilibrium value



**Two behavior under magnetic field H owing  $\kappa = \lambda/\xi$**

- **Type I**,  $\lambda < \xi$ , Meissner state to normal transition
- **Type II**,  $\xi < \lambda$ , penetration of field via **vortex**

Stricto sensus limit at  $\kappa = 1/\sqrt{2}$



courtesy, Hervé Cercellier



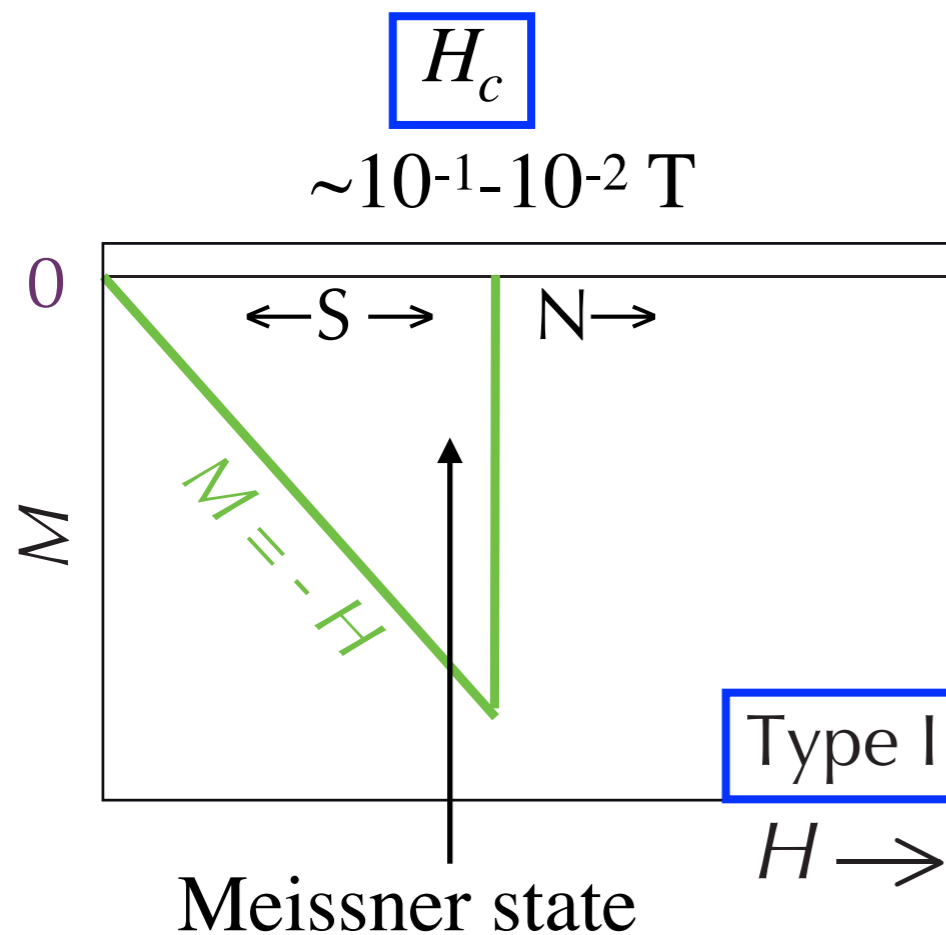
# Type I

SC destroyed at  $H_c$

«Perfect diamagnetism»

Meissner effect

Ex: Hg, Al, Pb, In

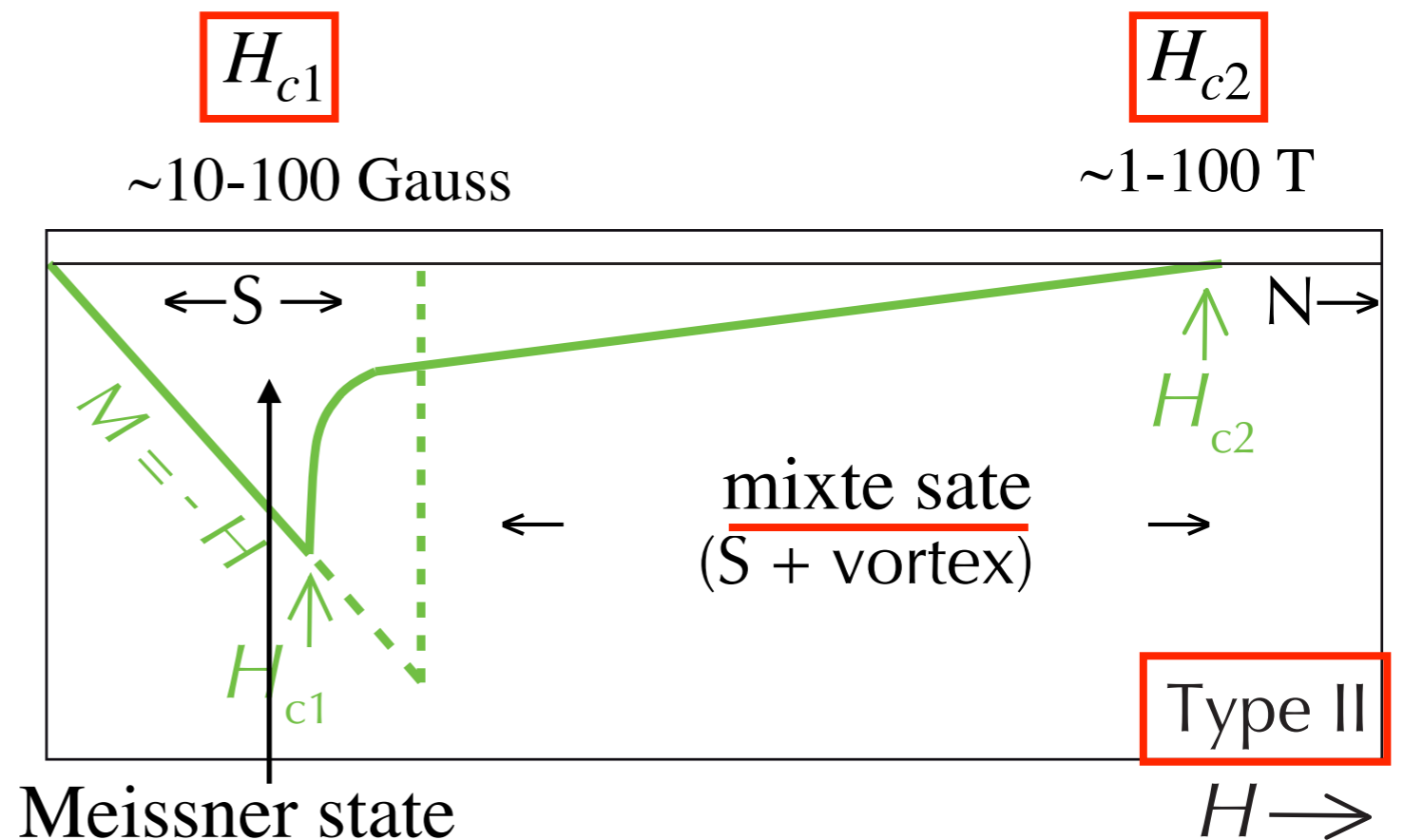


# Type II

- $H < H_{c1}$ : complete Meissner effect

- $H_{c1} < H < H_{c2}$  mixte state: SC + vortex

- Ex: Tin, Lead, Mercury



K. van der Beek, reflets de la physique n°27, 6 (2011)

# Type I



# Type II

SC

Disorder turns type I into type II  
 Ex: bulk Al is type I, thin Al is type II

Meissner effect

«Perfect diamagnetism»

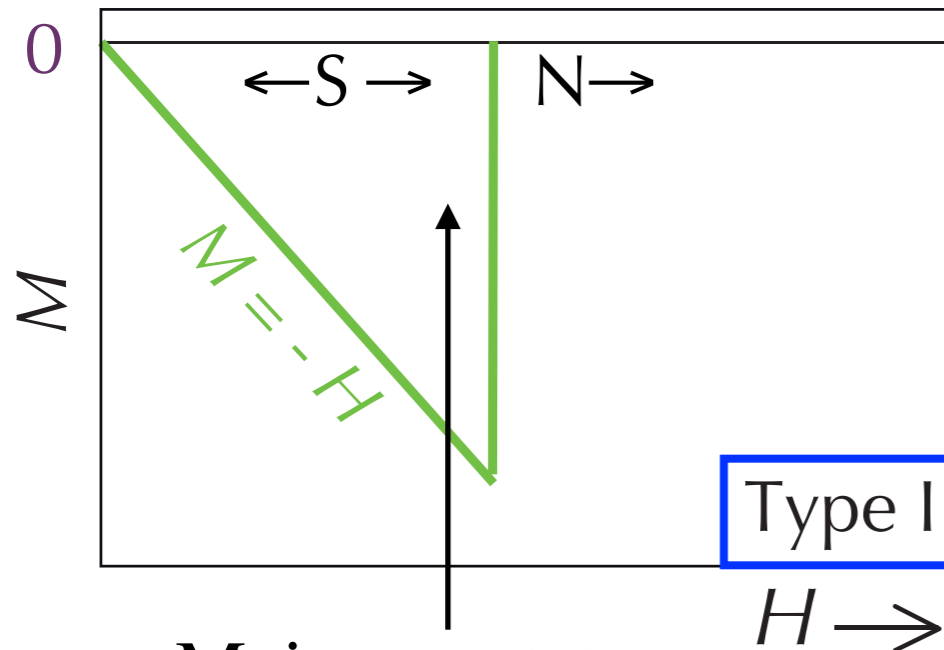
Meissner effect

Ex: Hg, Al, Pb, In

- $H_{c1} < H < H_{c2}$  mixte state: SC + vortex
- Ex: Tin, Lead, Mercury

$H_c$

$\sim 10^{-1} - 10^{-2}$  T



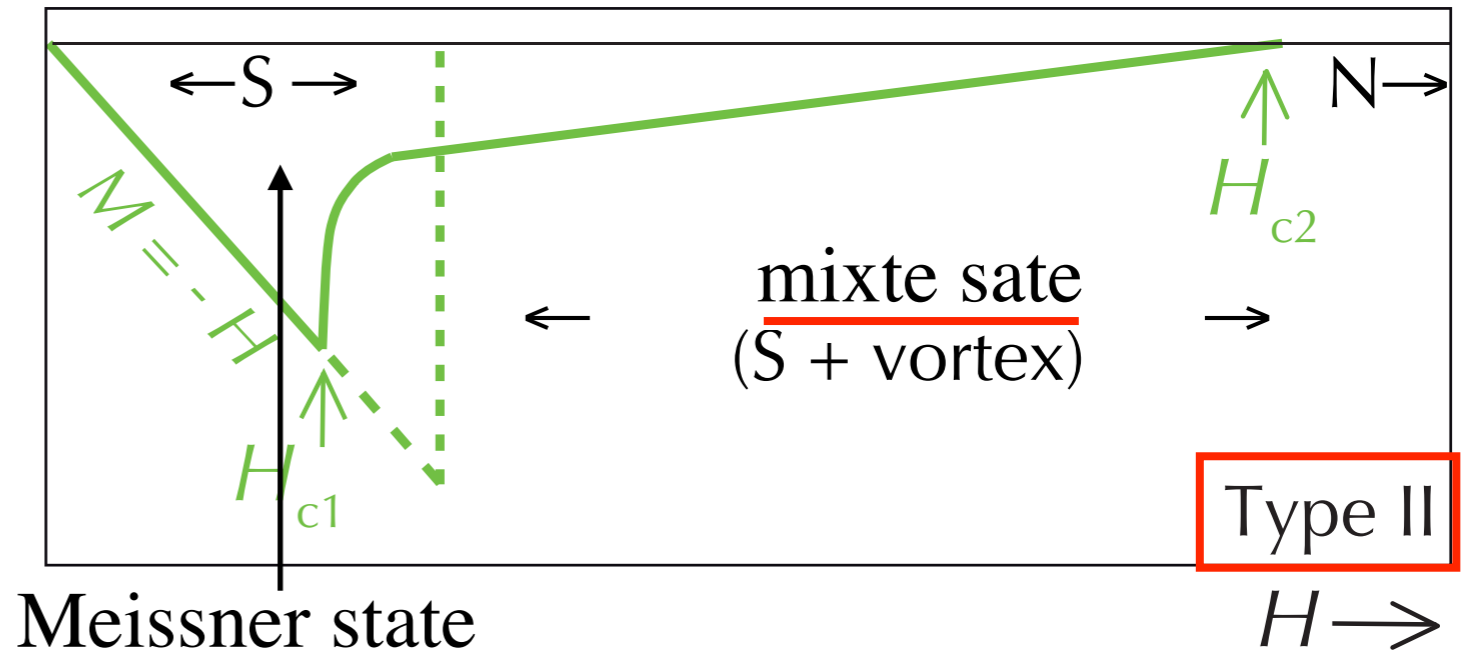
Meissner state

$H_{c1}$

$\sim 10 - 100$  Gauss

$H_{c2}$

$\sim 1 - 100$  T



Meissner state

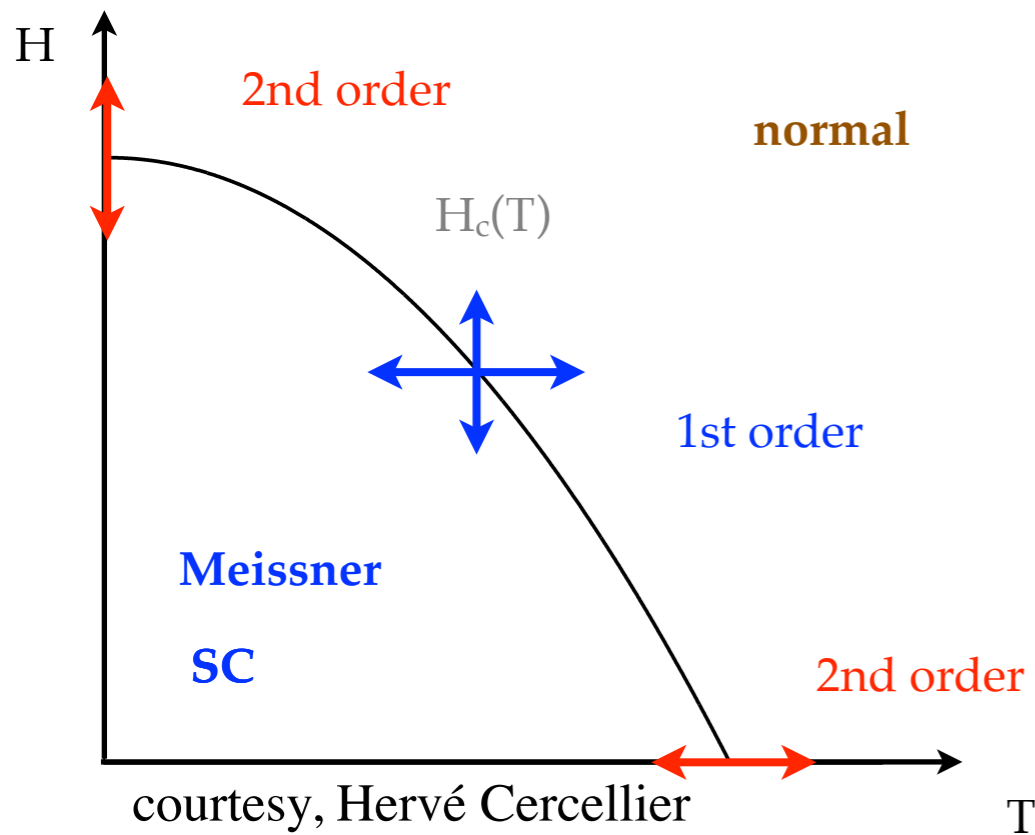
K. van der Beek, reflets de la physique n°27, 6 (2011)

# Type I

$$H_c = \frac{\phi_0}{2\pi\sqrt{2}\mu_0\lambda\xi}$$

$\sim 10^{-1}-10^{-2}$  T

1st order transition:  
coexistence of N+S  
(hysteresis)



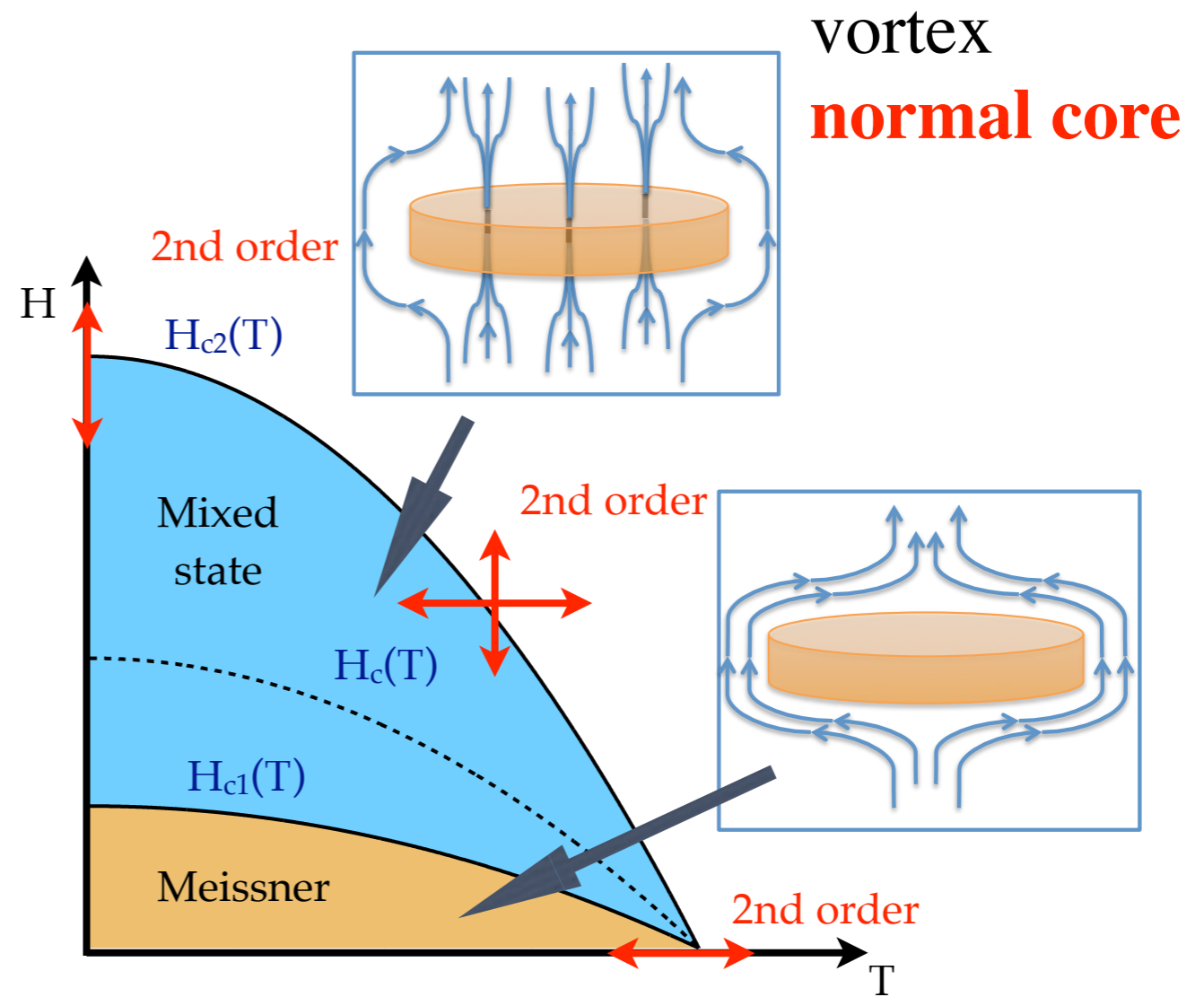
# Type II

$$H_{c1} = \frac{\phi_0}{4\pi\mu_0\lambda^2} \ln\left(\frac{\lambda}{\xi}\right)$$

$\sim 10-100$  Gauss

$$H_{c2} = \frac{\phi_0}{2\pi\mu_0\xi^2}$$

$\sim 1-100$  T



# Type I

$$H_c = \frac{\phi_0}{2\pi\sqrt{2}\mu_0\lambda\xi}$$

$\sim 10^{-1}-10^{-2}$  T

1st order transition:

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$\sim 10-100$  Gauss

$$H_{c2} = \frac{\phi_0}{2\pi\mu_0\xi^2}$$

$\sim 1-100$  T

vortex

coex

## Implication for detectors:

- SC thin films are type II
- In thin film  $H_{c2}$  is anisotropic, for Al thin film  $H_{c2}^\perp \sim 100$  mT and  $H_{c2}^\parallel \sim 1$  T

al core

H

2nd c

Meissner

SC

2nd order

$H_{c1}(T)$

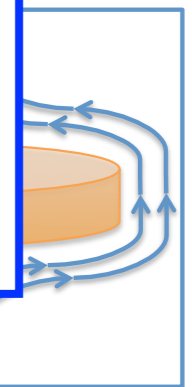
Meissner

2nd order

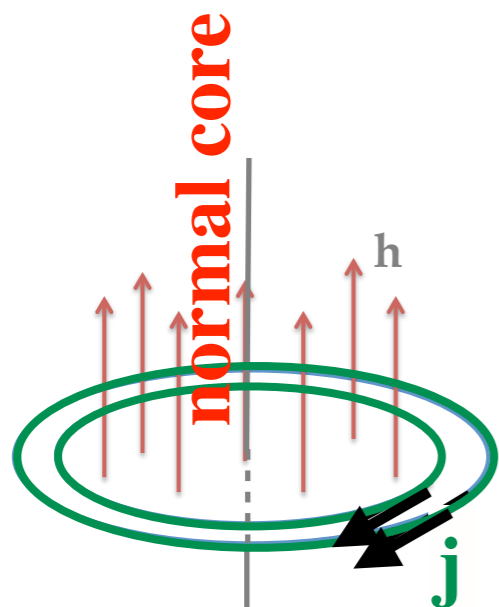
courtesy, Hervé Cercellier

T

T



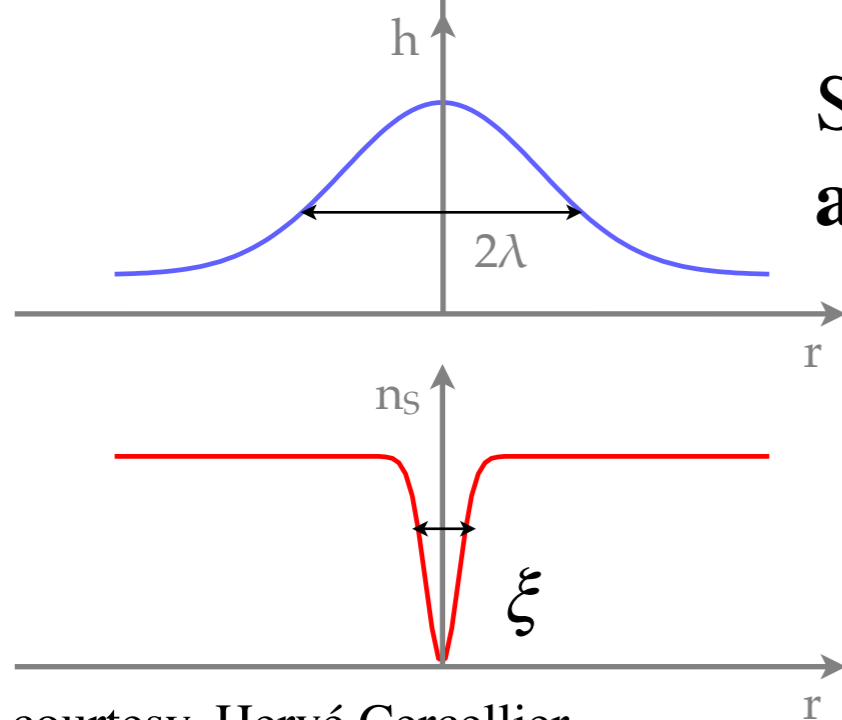
# Type II: vortex



**Supercurrent** circulates around the **normal** (i.e. non-superconducting) core of the vortex.

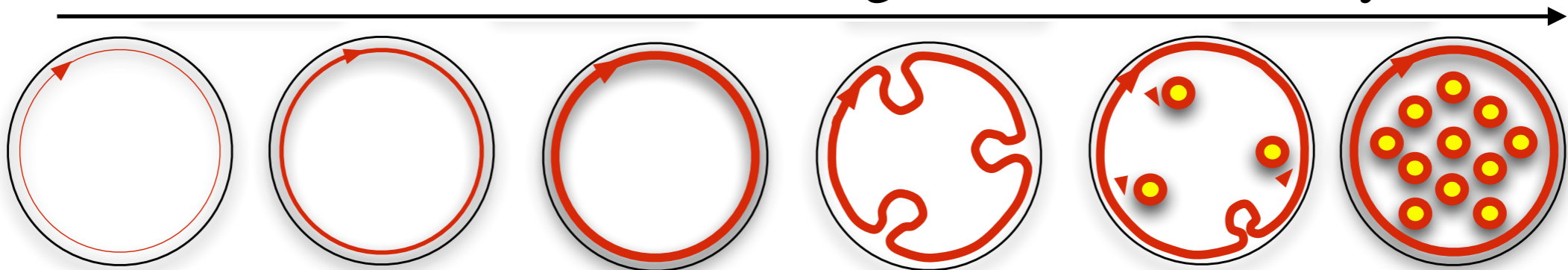
Supercurrent induces a single magnetic flux quantum  $\phi_0 = h/(2e)$

The size of the core is the coherence length  $\xi$

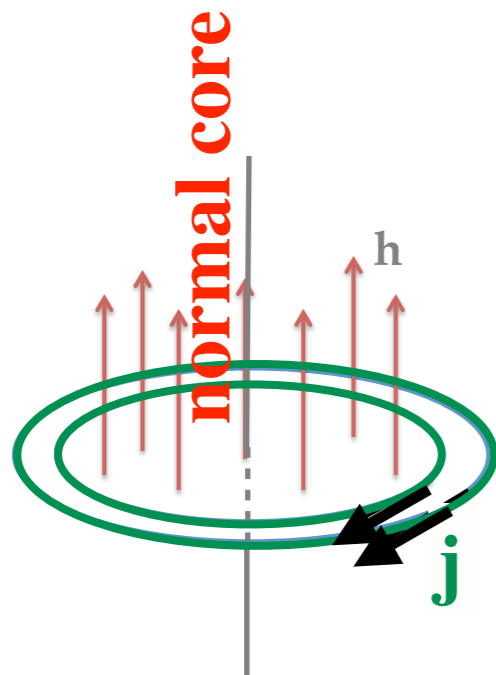


courtesy, Hervé Cercellier

Increasing H: creation of many vortex



# Type II: vortex



**Supercurrent** circulates around the **normal** (i.e. non-superconducting) core of the vortex.

## Implication for detectors:

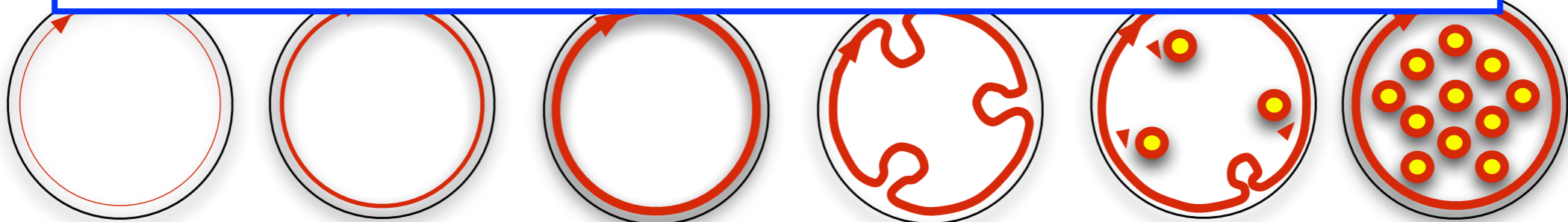
- The **movement of the vortex's** normal core **dissipates** effort to avoid vortex formation or to pin the vortex

Movement because of Lorentz force:  $F_L = \mathbf{J} \times \phi_0$   
(perpendicular to J and H)

$\lambda / (2e)$

$\lambda \xi$

$\xi$



courtesy, He

# Types I et II: $j_c, j_v$

Type I

$j_c$  depairing current

$$j_c \sim \frac{H_c}{\lambda_L}$$

$$H_c = \frac{\phi_0}{2\pi\sqrt{2}\mu_0\lambda\xi}$$

$$\lambda_L = \sqrt{\frac{m}{\mu_0 n_s e^2}}$$

For  $j < j_c$   $n_s \downarrow$  while  $j \uparrow$   
For  $j > j_c$   $n_s = 0$

Type II

$j_v$  vortex untrapping current

$$j_v \sim j_c \left(\frac{\xi}{L}\right)^2 < j_c$$

$L \geq \xi$  vortex trapping distance

Lorentz force on the vortex:  $F_L = \mathbf{J} \times \phi_0$

vortex in motion:  $R \neq 0$

The "dirtier" a type II is, i.e. for  $L$  small, the higher its critical current.

# Disorder influence

Normal state :  $\sigma_n = \frac{ne^2\tau}{m}$  où

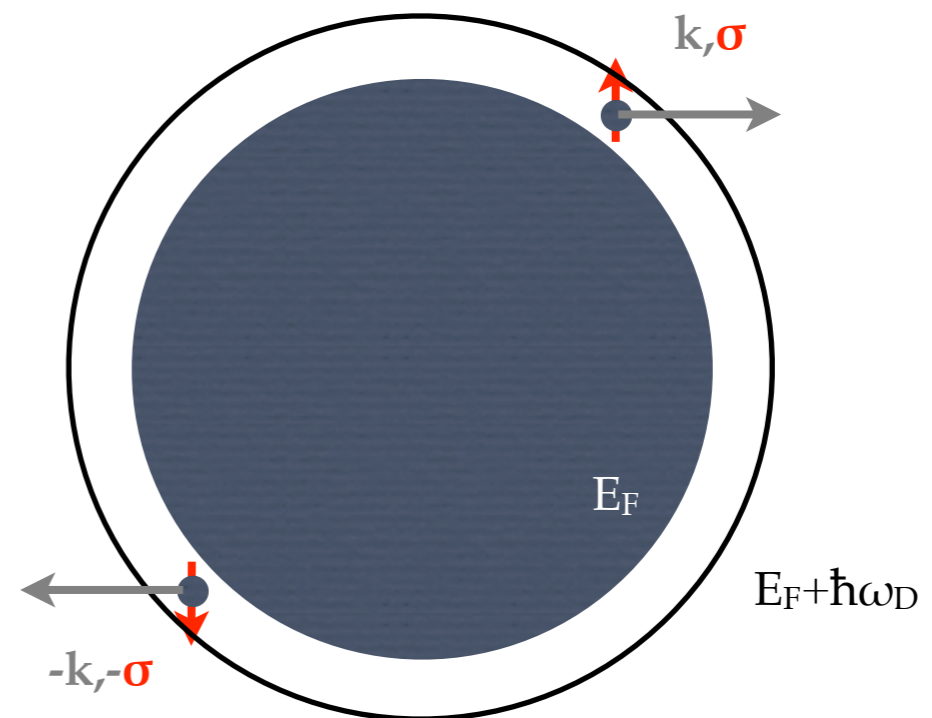
$$l = v_F\tau$$

Superconductor state:  $\sigma_s = 0$

But electrons undergo the same scattering

Anderson theorem (1959)

**non magnetic** impurities and  
 $k_F l \gg 1$  **no effect on  $T_c$**

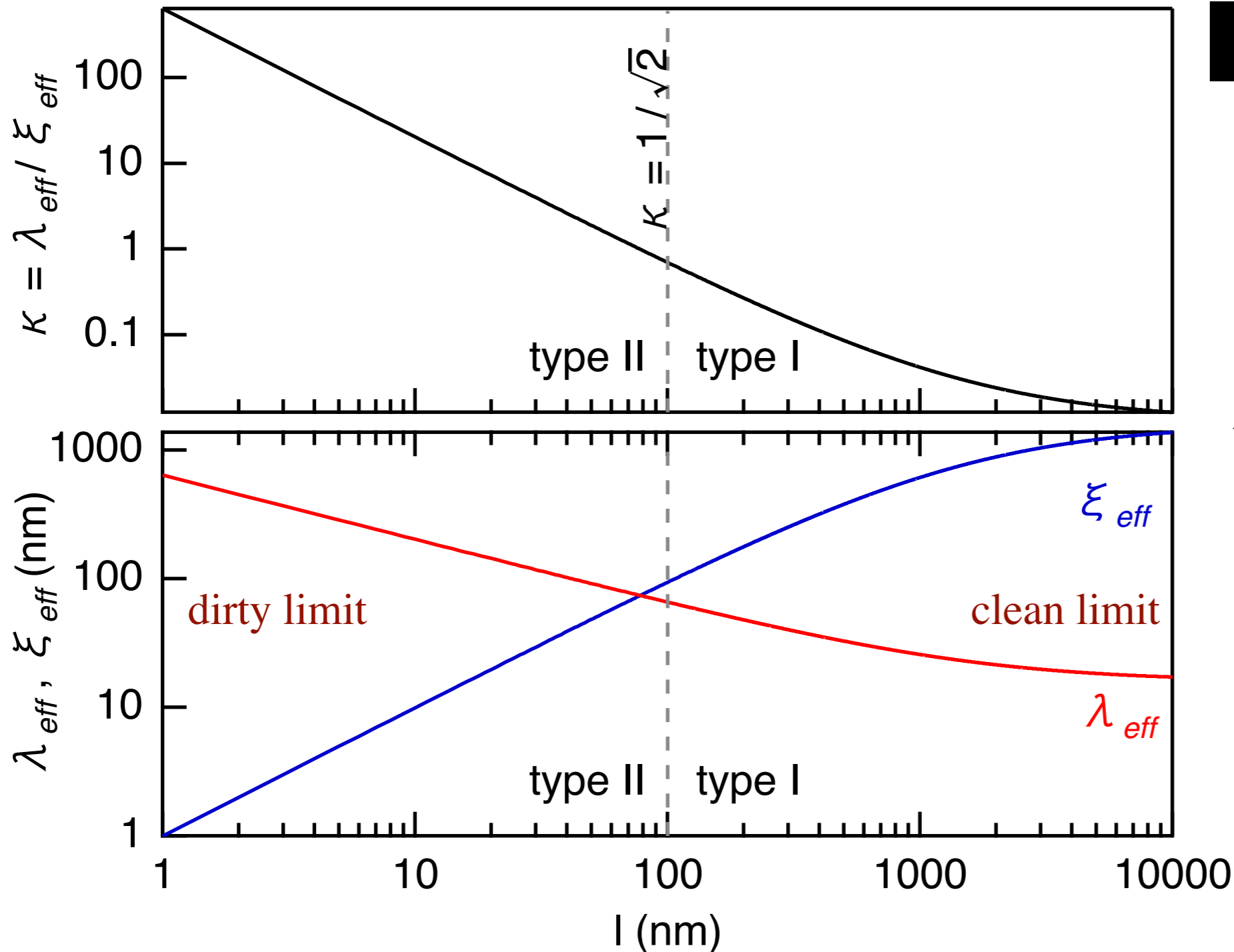


Mean free path  $l$ : **no effect on  $T_c$  nor on  $\Delta$**



# Disorder turns type I into type II

Mean free path  $l$  affects  $\xi$  et  $\lambda$ , **disorder (small  $l$ ) reduces  $\xi$  and increases  $\lambda$ .**



Pippard model

$$\frac{1}{\xi_{eff}} = \frac{1}{\xi_0} + \frac{1}{l}$$

$$\lambda_{eff} = \lambda_L \sqrt{1 + \xi_0/l}$$

# Introduction to superconductivity

Florence Levy-Bertrand

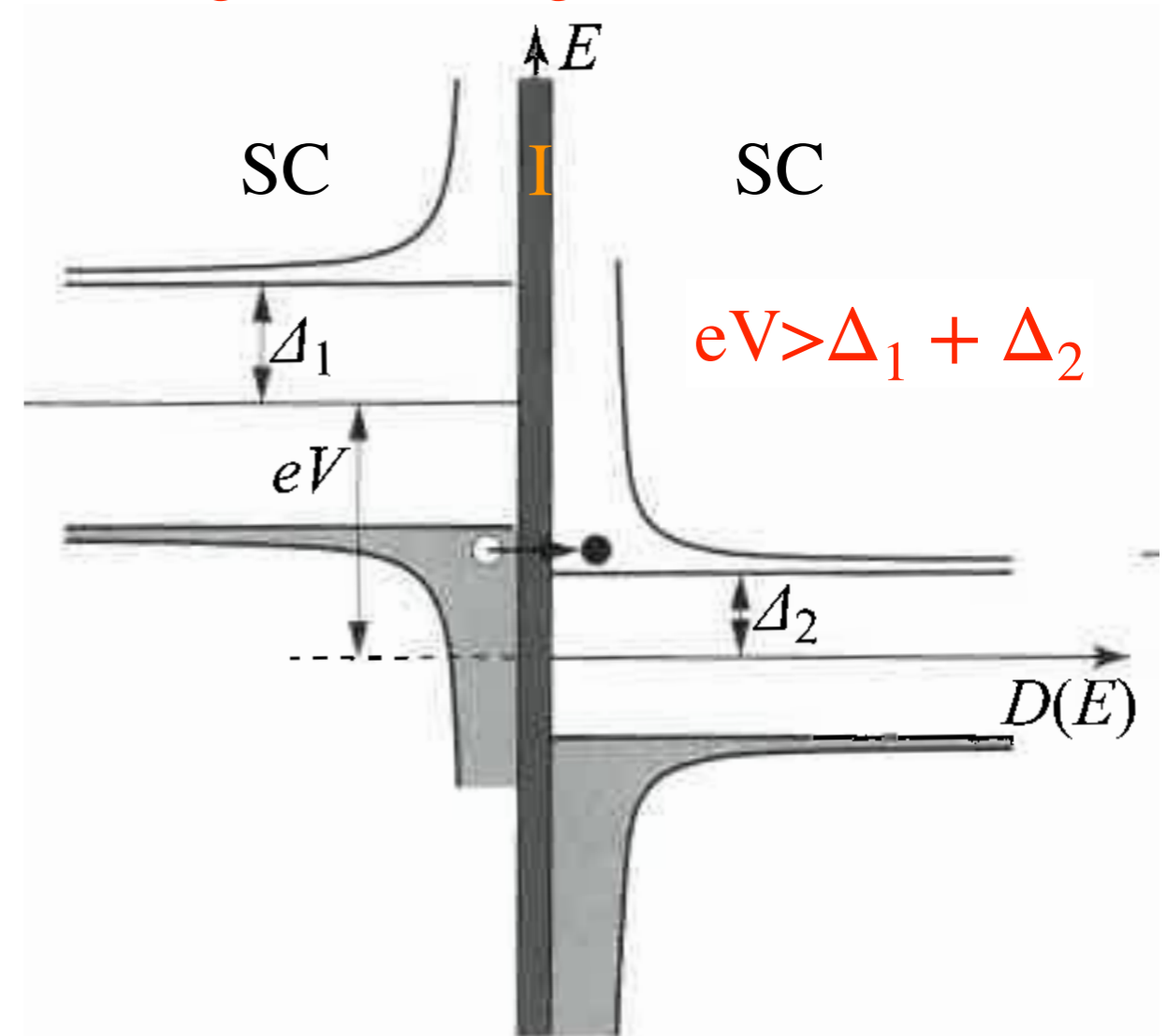
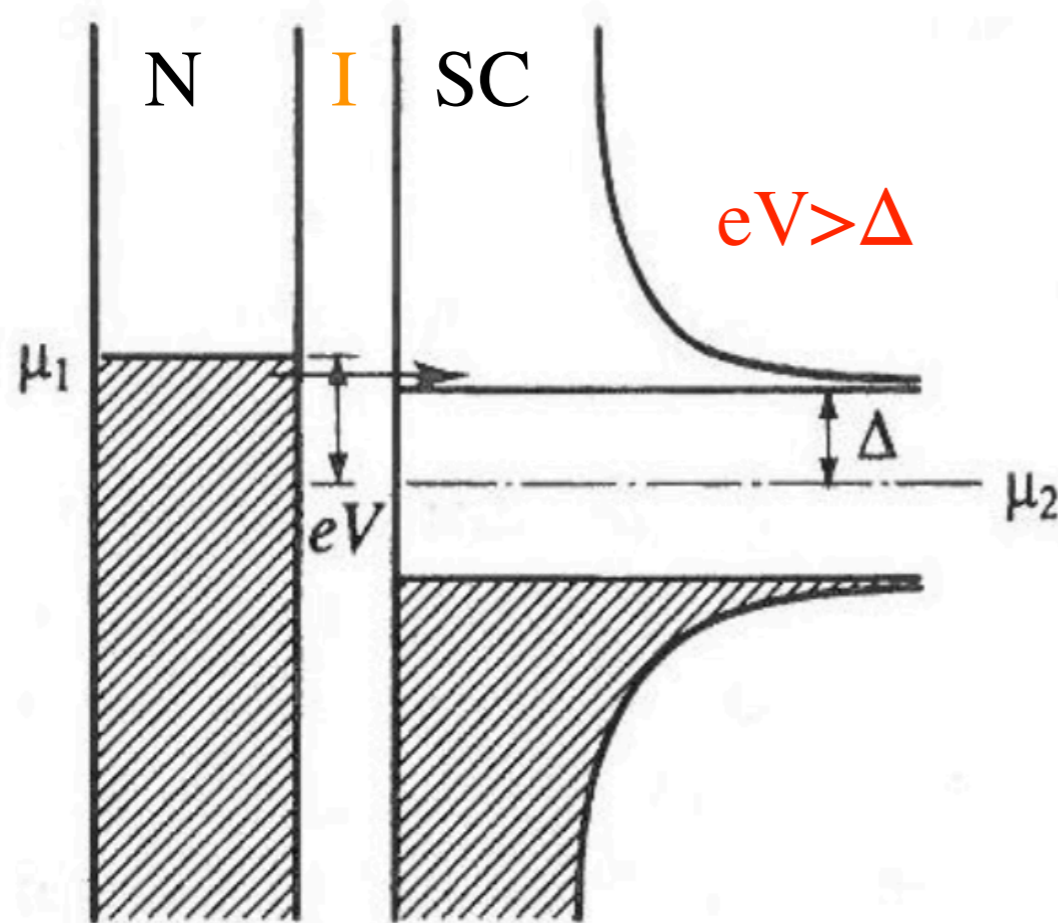
- General properties
  - Zero resistance
  - Perfect diamagnetism
  - Values:  $T_c, H_c, j_c, \lambda_L$
- Microscopic origin
  - Quantum state:  $\theta, \phi_0$
  - Cooper pairs:  $\xi_0$
  - electron-phonon interaction
  - superconducting gap  $\Delta$
- Type I and II
  - Ginzburg-Landau parameter  $\kappa$
  - critical fields  $H_c, H_{c1}, H_{c2}$
  - critical currents  $J_c, J_v$
  - role of disorder
- Specific properties
  - tunnel effect
  - Josephson effect
  - specific heat
  - thermal conduction
  - kinetic inductance
  - reflectivity / absorption

# Tunnel effect

Single quasi-particles pass through a SIS or NIS junction



Tunneling, i.e current when the voltage set is larger than:



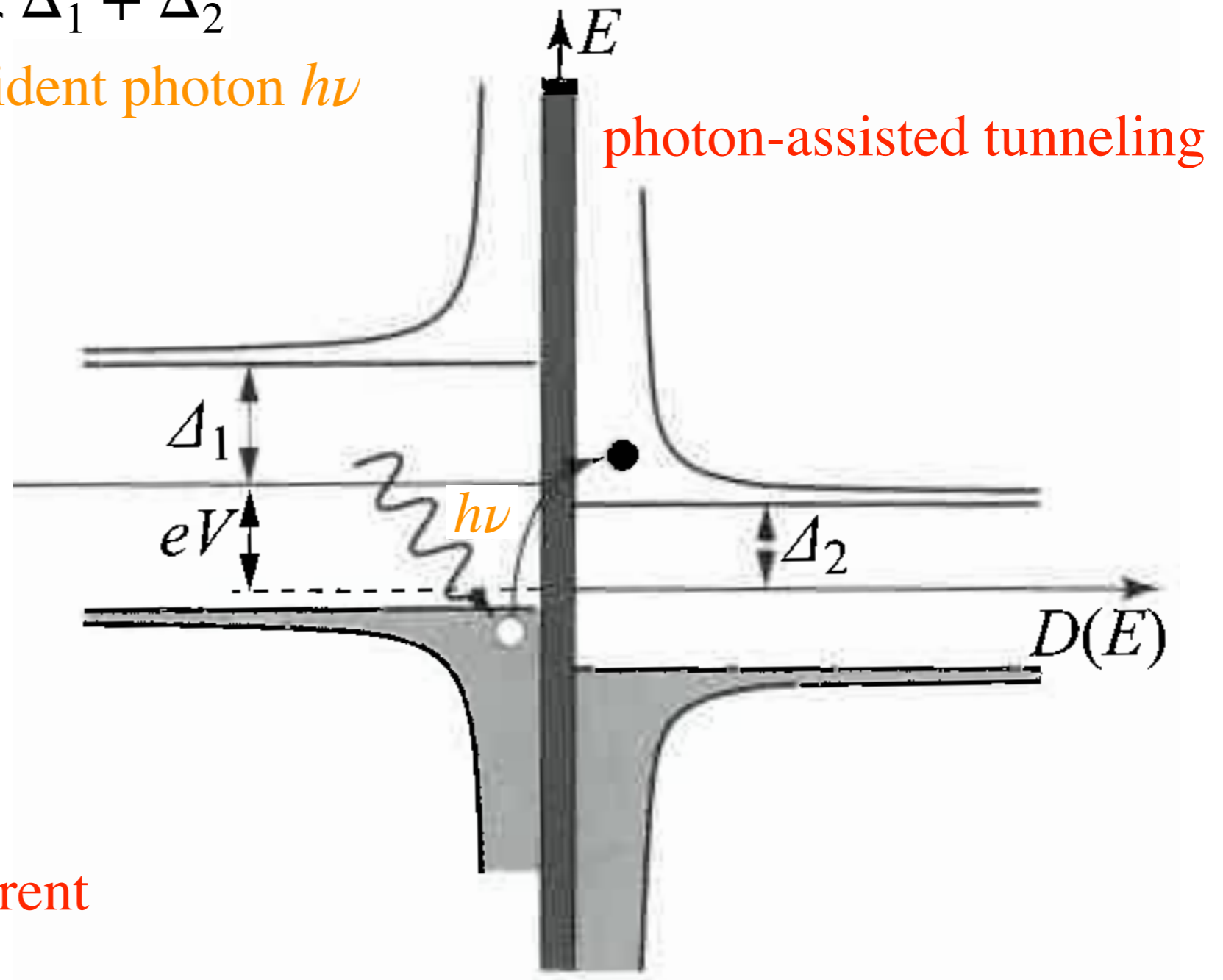
# Tunnel effect

Application to *Superconducting Tunnel Junction* STJ

In principle no current as  $eV < \Delta_1 + \Delta_2$

Tunneling current because **incident photon  $h\nu$**

So  $eV + h\nu > \Delta_1 + \Delta_2$



**Detection photon with the current**

Supraconducteurs en micro et nanotechnologie, P. Mangin et R. Kahn, edition edp sciences

# DC Josephson effect

Cooper pairs pass through a SIS junction



Superconductor:  $\psi(r) = |\psi(r)| e^{i\varphi(r)}$

More or less current owing the phase difference

Josephson current:  $J = J_c \sin(\varphi_1 - \varphi_2)$

$J_c$  depends on the junction resistance  $R$ , varies as  $1/R$

$J_c \sim 1\text{mA} - 10\mu\text{A}$  for  $1\text{meV}$  and  $R = 1 - 100\Omega$

Application to *SQUID*, magnetic field tunes the phase difference.

Detection of small field with the Josephson current.

# AC Josephson effect

Cooper pairs pass through a SIS junction



Superconductor:  $\psi(r) = |\psi(r)| e^{i\varphi(r)}$

Set **voltage** induces an **alternative phase difference**:  $\frac{d(\varphi_1 - \varphi_2)}{dt} = \frac{2eV}{\hbar}$

The phase difference creates an **alternative current**:  $J = J_c \sin(\varphi_1 - \varphi_2)$

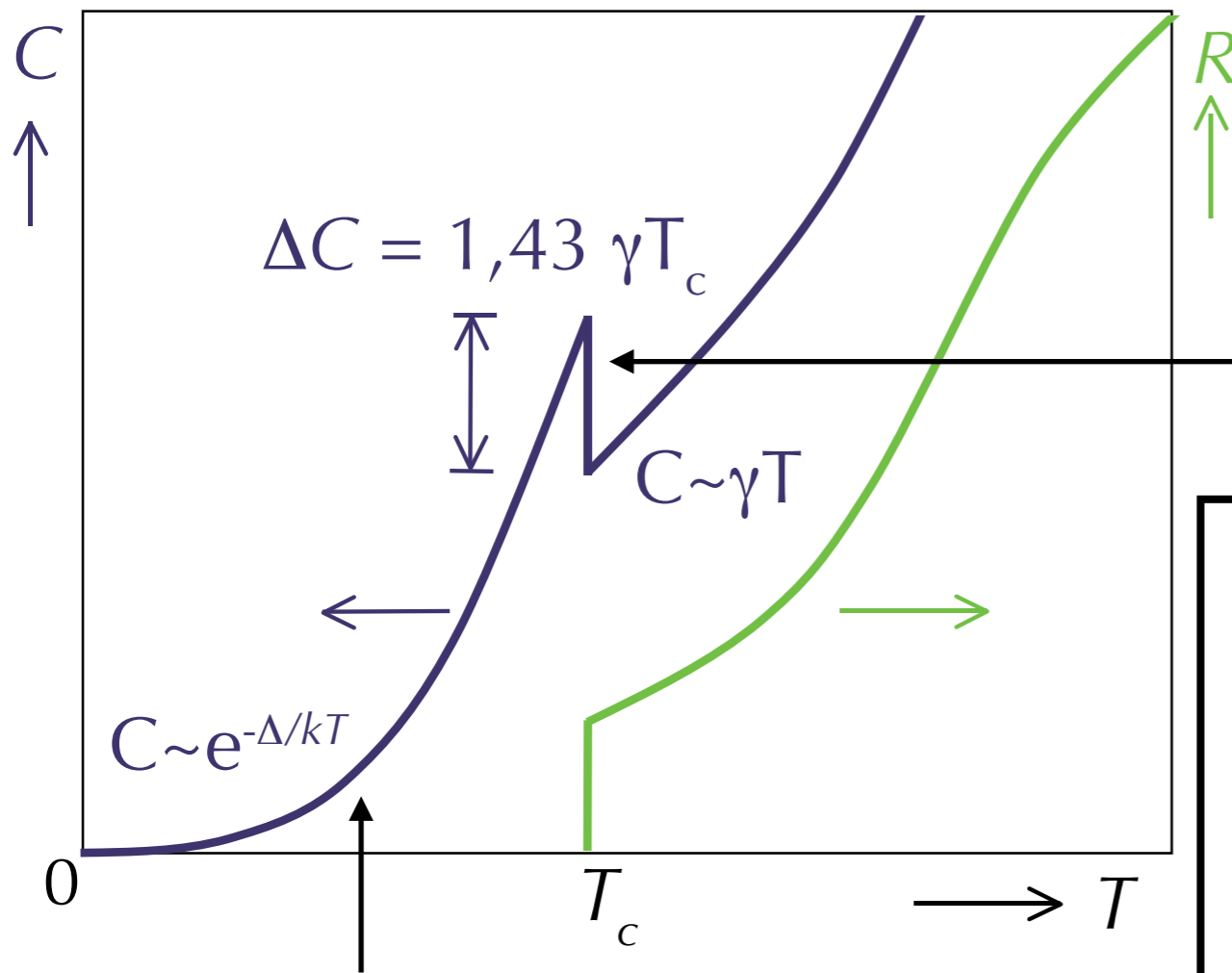
The frequency is  $\omega = \frac{2eV}{\hbar}$  483 GHz/mV

Application to *metrology* to determine accurately V.  
« Application » to *Shapiro steps*.

# Specific heat

$$\Delta T = \frac{Q}{C} \quad \leftarrow \text{heat absorbed}$$

K. van der Beek, *reflets de la physique* n°27, 6 (2011)



excess of specific heat at  $T_c$   
important for Transition Edge Sensors

Time response of a detector varies as

$$\tau = \frac{C}{K}$$

adjustment of **thermal conductivity  $K$  !!**

low specific heat

interesting for fast absorber

# Thermal conduction

- The superfluid carry no entropy
- Thermal conduction only due to few quasiparticles

The thermal conductivity of a superconductor  $K_S$  is **VERY LOW**

Application: thermal switch

Caution with time constant:  $\tau = \frac{C}{K}$

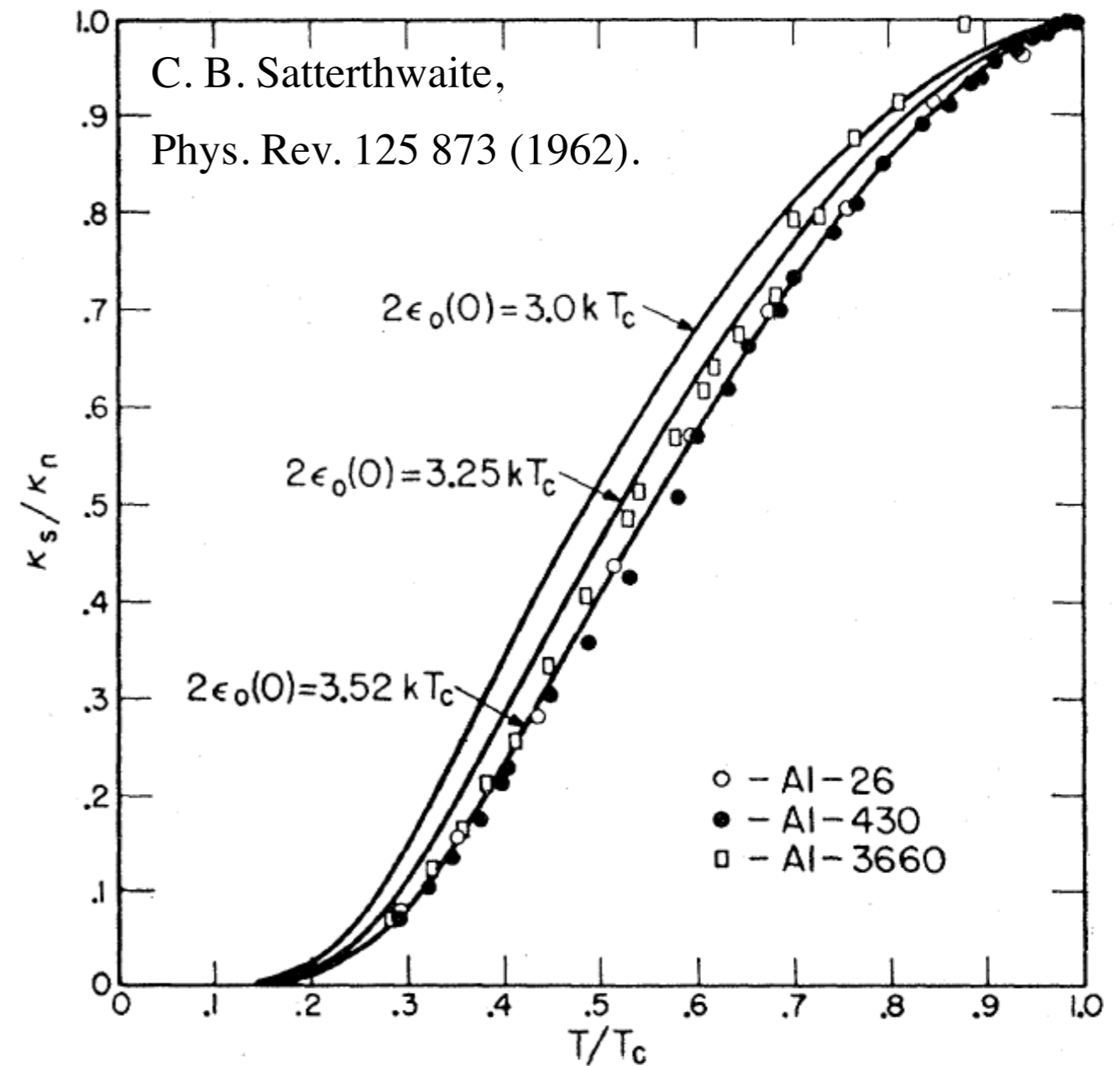


FIG. 3. Ratio of superconducting to normal thermal conductivity for aluminum.



# Kinetic Inductance

Two fluids model (Drude-type):  $\sigma_{tot} = \sigma_{qp} + \sigma_s$

$$\sigma_{qp}(\omega) = \frac{n_n e^2}{m} \frac{1}{1 - i\omega\tau} \sim \frac{n_n e^2}{m} \frac{\tau}{1 + \omega^2 \tau^2}$$

**quasi-particles**  
dissipative response

$\tau \rightarrow \infty$

$$\sigma_s(\omega) = \frac{\pi n_s e^2}{m} \delta(\omega) - i \frac{n_s e^2}{\omega m}$$

**SC- condensate**  
dominates out-of-phase response

Impedance of a thin film of thickness  $d$ :  $Z = 1/(\sigma d)$  normal square resistance  
 $Z_s = R_s + i\omega L_s$

Kinetic Inductance (thin film, low T, low  $\omega$ ):

$$L_s = \frac{m}{n_s e^2 d} = \frac{\hbar R}{\pi \Delta}$$

# Kinetic Inductance

normal square  
↓  
resistance

Thin film of thickness  $d$ , low  $T$ , low  $\omega$  :

$$L_s = \frac{m}{n_s e^2 d} = \frac{\hbar R}{\pi \Delta}$$

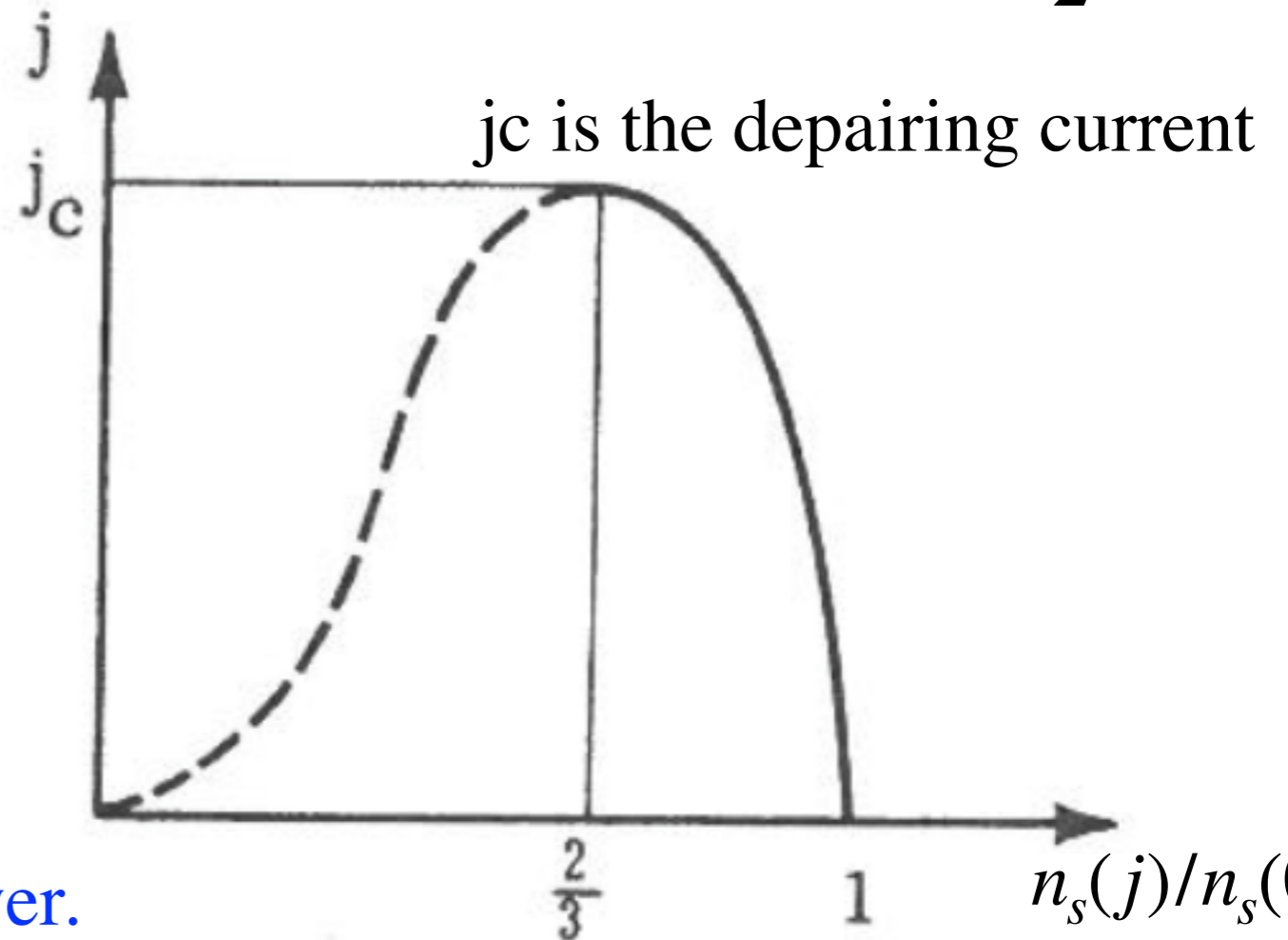
Variation with current :

$$L_s(j) = L_s(0) \left( 1 + j^2/j_*^2 + \dots \right)$$

$$j_* = \frac{3\sqrt{3}}{2} j_c$$

coming from variation of  $n_s(j)$  :

$$j_c = \frac{4en_s\hbar}{3\sqrt{3}m\xi}$$



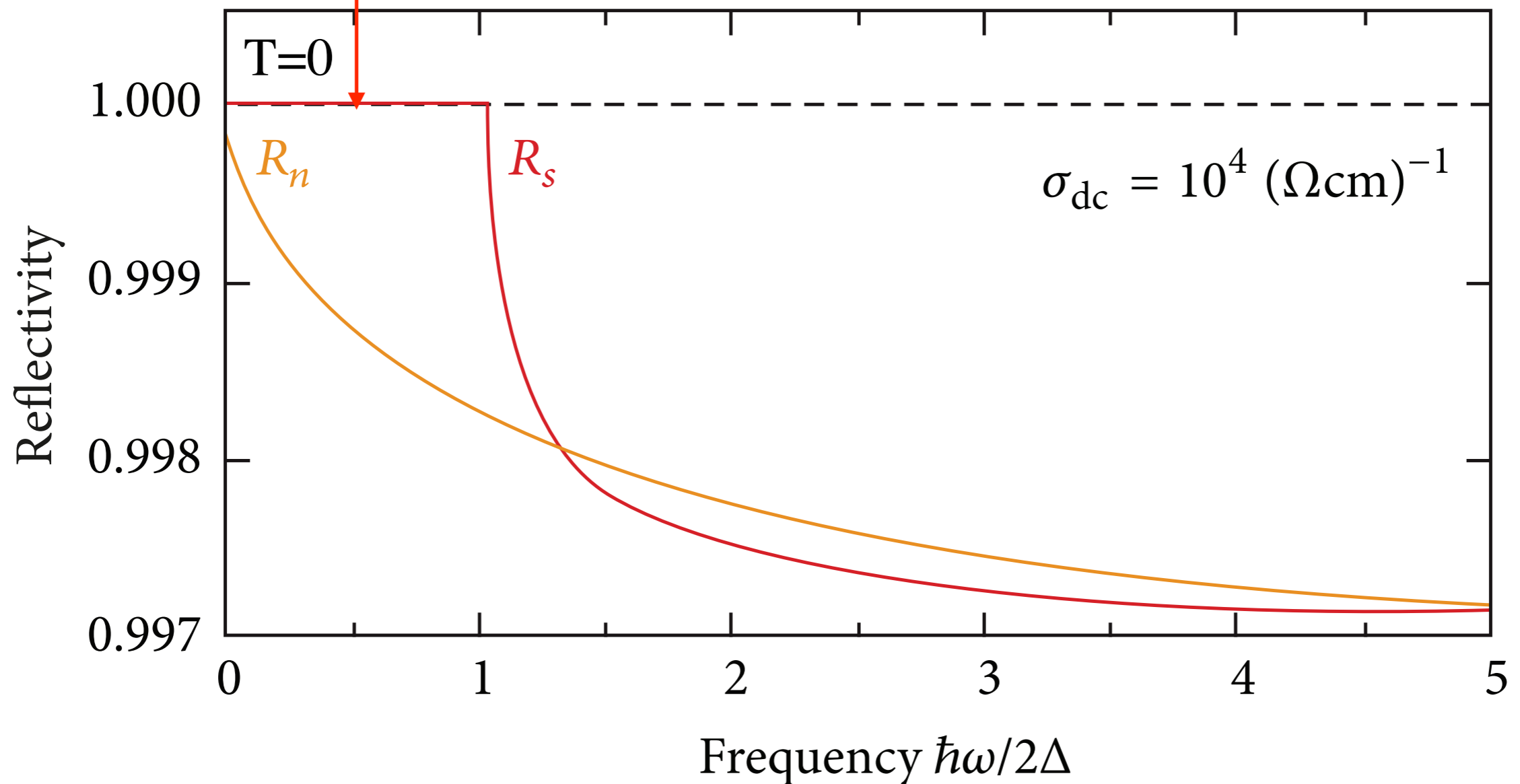
At play when setting the readout power.

De Gennes, *Superconductivity of Metals and Alloys*, chap 6.5

# Reflectivity

Use for high quality factor cavity  
(cavity in Nb for accelerators).

$h\nu < 2\Delta$ : perfect reflectivity

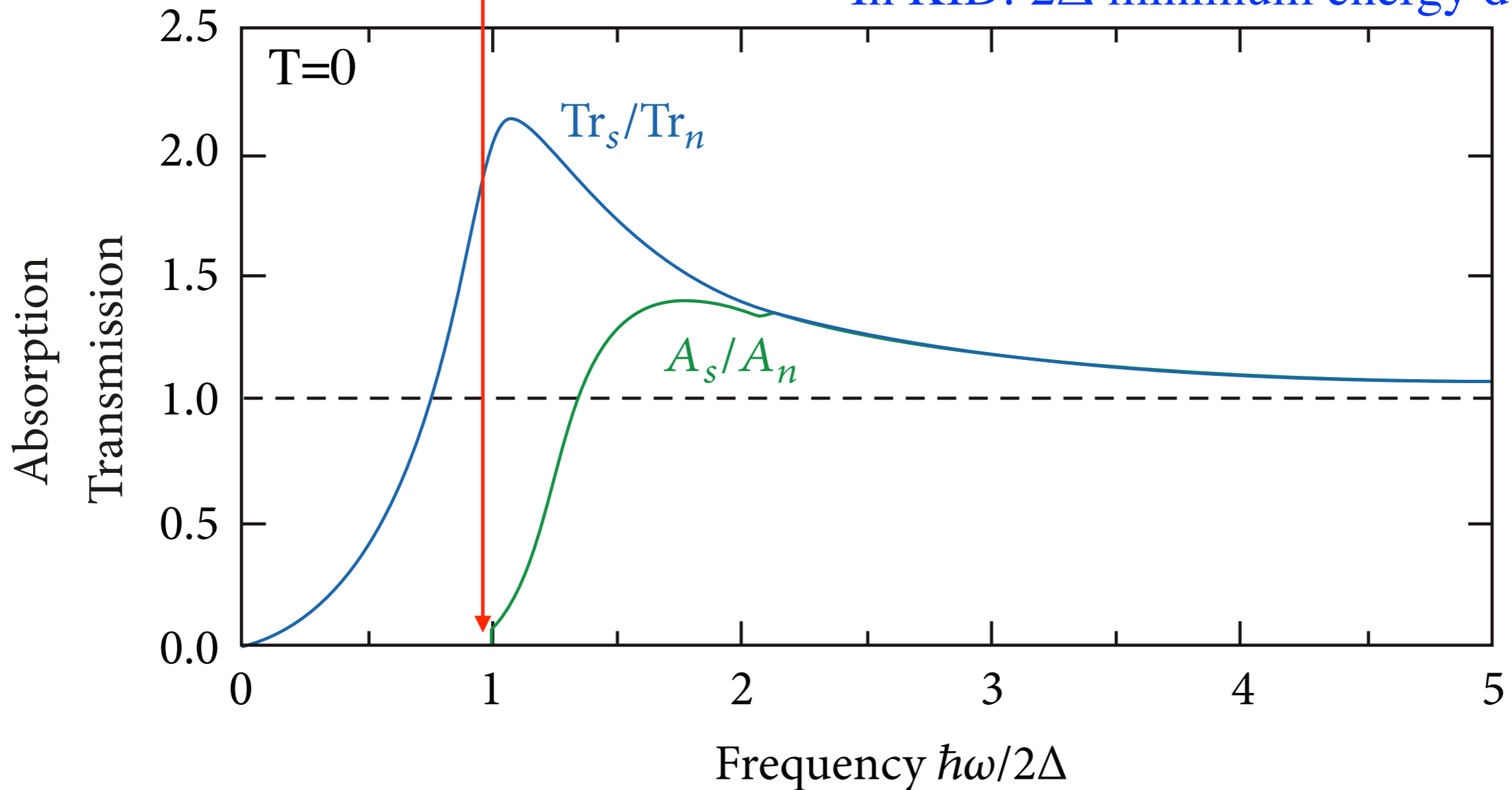


M. Dressel, Electrodynamics of Metallic Superconductors, Adv. in Cond. Mat. Physics (2013).

# Absorption

$2\Delta$ : absorption threshold for photon

In KID:  $2\Delta$  minimum energy detected.



M. Dressel, Electrodynamics of Metallic Superconductors, Adv. in Cond. Mat. Physics (2013).

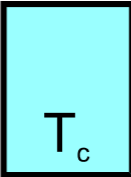
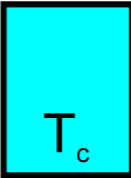
# Introduction to superconductivity


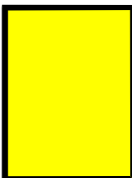
Florence Levy-Bertrand

- General properties
  - Zero resistance
  - Perfect diamagnetism
  - Values:  $T_c, H_c, j_c, \lambda_L$
- Microscopic origin
  - Quantum state:  $\theta, \phi_0$
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  - critical currents  $J_c, J_v$
  - role of disorder
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  - kinetic inductance
  - reflectivity / absorption

# Superconducting elements

H																	He	
<b>Li</b> 15	<b>Be</b> 0.03											<b>B</b> 11	<b>C</b>	<b>N</b>	<b>O</b> 0.6	<b>F</b>	<b>Ne</b>	
<b>Na</b>	<b>Mg</b>											<b>Al</b> 1.19	<b>Si</b> 6.7	<b>P</b> 6.1	<b>S</b> 16	<b>Cl</b>	<b>Ar</b>	
<b>K</b>	<b>Ca</b> 5	<b>Sc</b> 0.35	<b>Ti</b> 0.39	<b>V</b> 5.3	<b>Cr</b> 1-3	<b>Mn</b>	<b>Fe</b> 1.8	<b>Co</b>	<b>Ni</b>	<b>Cu</b>	<b>Zn</b> 0.9	<b>Ga</b> 1.1	<b>Ge</b> 5.4	<b>As</b> 0.5	<b>Se</b> 5.6	<b>Br</b> 1.3	<b>Kr</b>	
<b>Rb</b>	<b>Sr</b> 4	<b>Y</b> 2.7	<b>Zr</b> 0.55	<b>Nb</b> 9.2	<b>Mo</b> 0.92	<b>Tc</b> 7.8	<b>Ru</b> 0.5	<b>Rh</b> 325 $\mu$	<b>Pd</b>	<b>Ag</b>	<b>Cd</b> 0.55	<b>In</b> 3.4	<b>Sn</b> 3.7;5.3	<b>Sb</b> 3.6	<b>Te</b> 6.8	<b>I</b> 1.2	<b>Xe</b>	
<b>Cs</b> 1.5	<b>Ba</b> 5.1	<b>La</b> 5.9	<b>Hf</b> 0.13	<b>Ta</b> 4.4	<b>W</b> 0.01	<b>Re</b> 1.7	<b>Os</b> 0.65	<b>Ir</b> 0.14	<b>Pt</b>	<b>Au</b>	<b>Hg</b> 4.15	<b>Tl</b> 2.4	<b>Pb</b> 7.2	<b>Bi</b> 8.5	<b>Po</b>	<b>At</b>	<b>Rn</b>	
<b>Fr</b>	<b>Ra</b>	<b>Ac</b>																
			<b>Ce</b> 1.7	<b>Pr</b>	<b>Nd</b>	<b>Pm</b>	<b>Sm</b>	<b>Eu</b>	<b>Gd</b>	<b>Tb</b>	<b>Dy</b>	<b>Ho</b>	<b>Er</b>	<b>Tm</b>	<b>Yb</b>	<b>Lu</b> 0.7		
			<b>Th</b> 1.4	<b>Pa</b> 1.3	<b>U</b> 0.2	<b>Np</b> 0.07	<b>Pu</b>	<b>Am</b> 0.8	<b>Cm</b>	<b>Bk</b>	<b>Cf</b>	<b>Es</b>	<b>Fm</b>	<b>Md</b>	<b>No</b>	<b>Lw</b>		

 **Superconducting**  
 **under pressure**

  **Ferro- or antiferromagnetic**

courtesy, Hervé Cercellier

# Some superconductors

	$T_c$ (K)	$\lambda(0)$ (nm)	$\xi(0)$ (nm)	$\kappa$
Al	1.18	45	1550	0.03
Sn	3.72	42	180	0.23
Pb	7.2	39	87	0.48
Nb	9.25	52	39	1.3
YNi <sub>2</sub> B <sub>2</sub> C	15	103	8.1	12.7
Nb <sub>3</sub> Ge	23.2	90	3	30
K <sub>3</sub> C <sub>60</sub>	19.4	240	2.8	95
YBa <sub>2</sub> Cu <sub>3</sub> O <sub>7-<math>\delta</math></sub>	91	156	1.65	95

courtesy, Hervé Cercellier

# References

- K. van der Beek, « Supraconducteurs, la mécanique quantique à grande échelle », reflets de la physique n°27, 6 (2011).
- K. van der Beek et F. Lévy-Bertrand, « Les vortex dans les supraconducteurs, une matière molle au sein de la matière dure », reflets de la physique n°28, 4 (2012).
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# Conclusion

Questions? Questions? Questions?  
Questions? **THANKS** Questions?  
Questions? Questions?