Introduction to superconductivity

Florence Levy-Bertrand

- General properties
  - Zero resistance
  - Perfect diamagnetism
  - Values: T_c , H_c , j_c , λ_L
- Microscopic origin
  - Quantum state: θ , ϕ_0
  - Cooper pairs: ξ_0
  - electron-phonon interaction
  - superconducting gap Δ
- Type I and II
  - Ginzburg-Landau parameter κ
  - 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

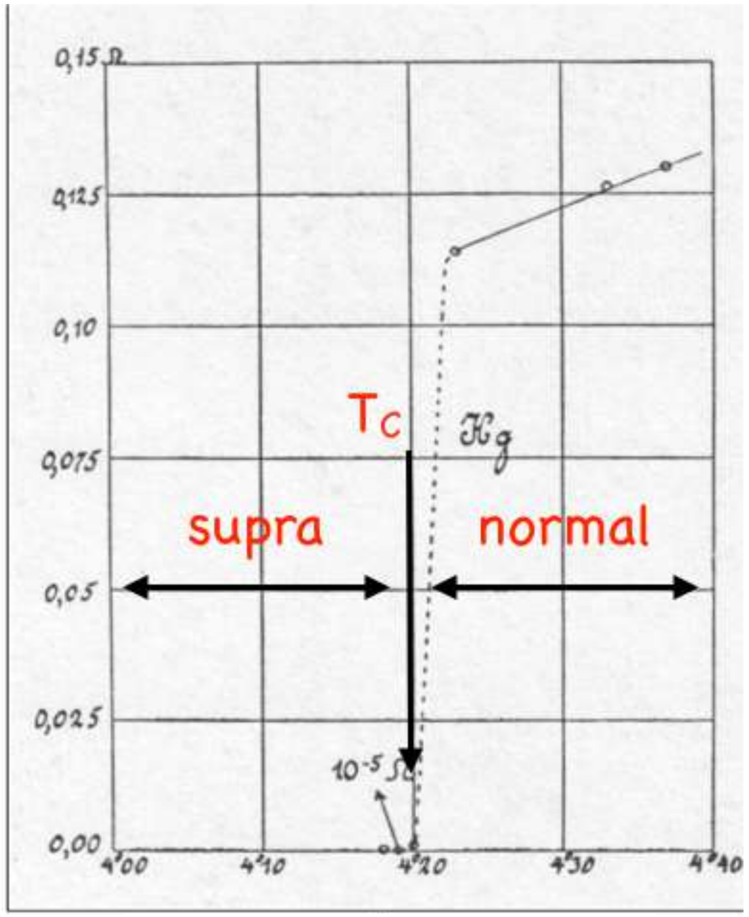
Superconductor = material for T<Tc such that

Tc = critical temperature

R= 0

electrical resistance

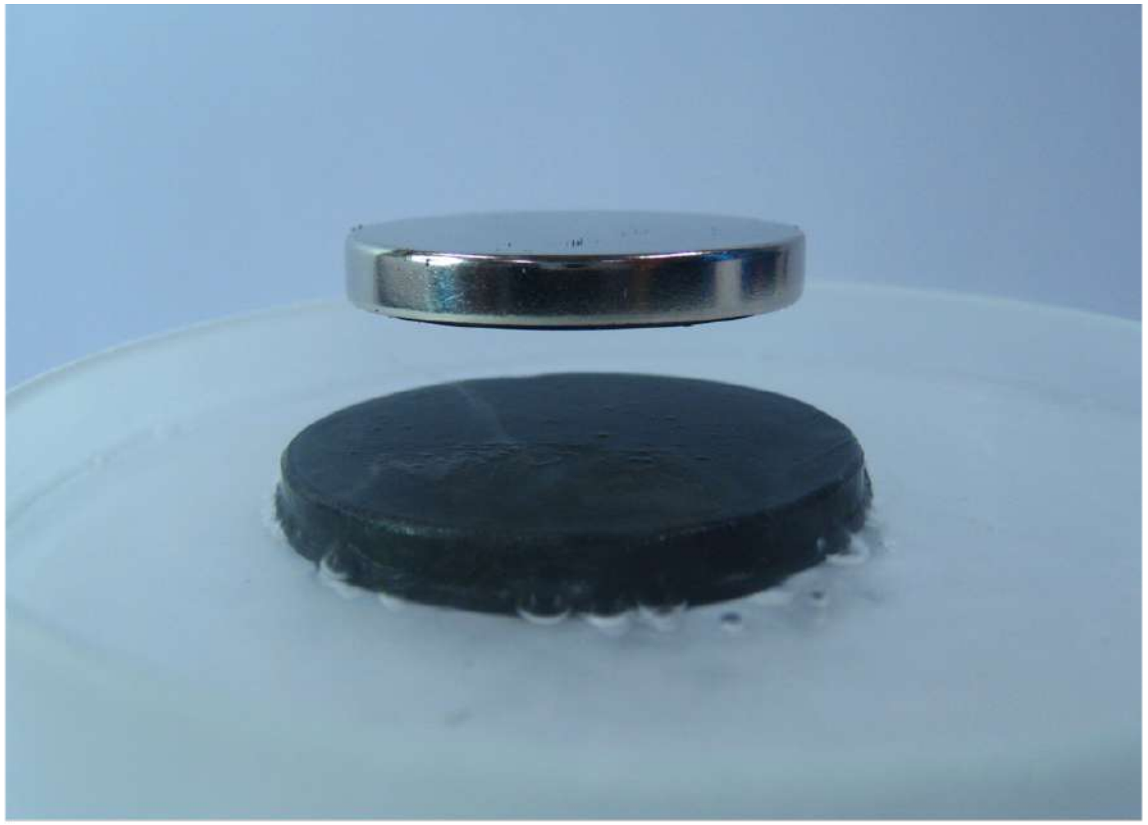
resistance (Ω)



temperature (K)

B=0

magnetic induction



+ current : j<jc, magnetic field H<Hc

General properties

Superconductor = material for $T<T_c$ such that

T_c = critical temperature

R= 0
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

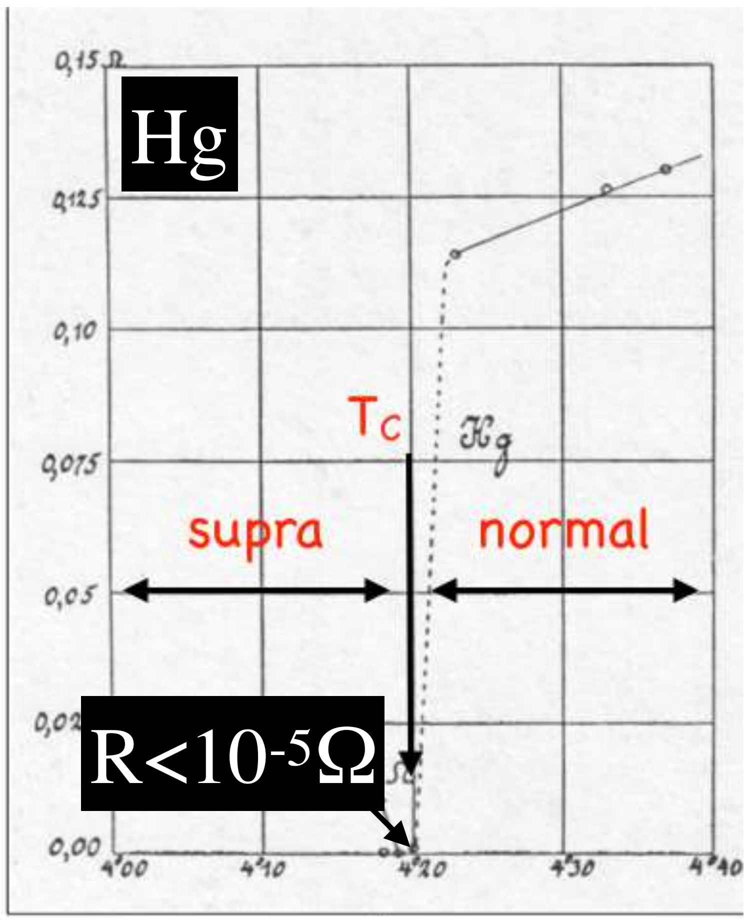
Discovery in 1911 by Karmerlingh Onnes

Tc = critical temperature

R= 0

electrical resistance

resistance (Ω)



temperature (K)

Historical framework:

- race to low temperatures:

liquefaction of oxygen, hydrogen and helium

- electrical behavior of metal at T=0K?

R->0 due to reduced thermal agitation?

R↑ because of the location of the electrons?

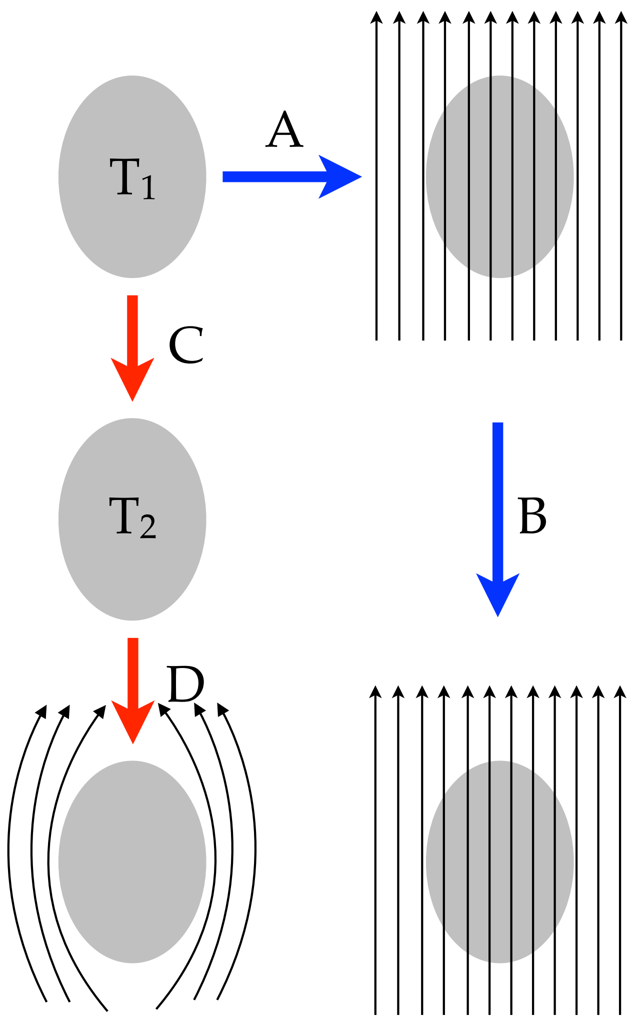
R->R_0 because of impurities?

General properties: B=0

Meissner-Ochsenfeld effect discovered in 1933

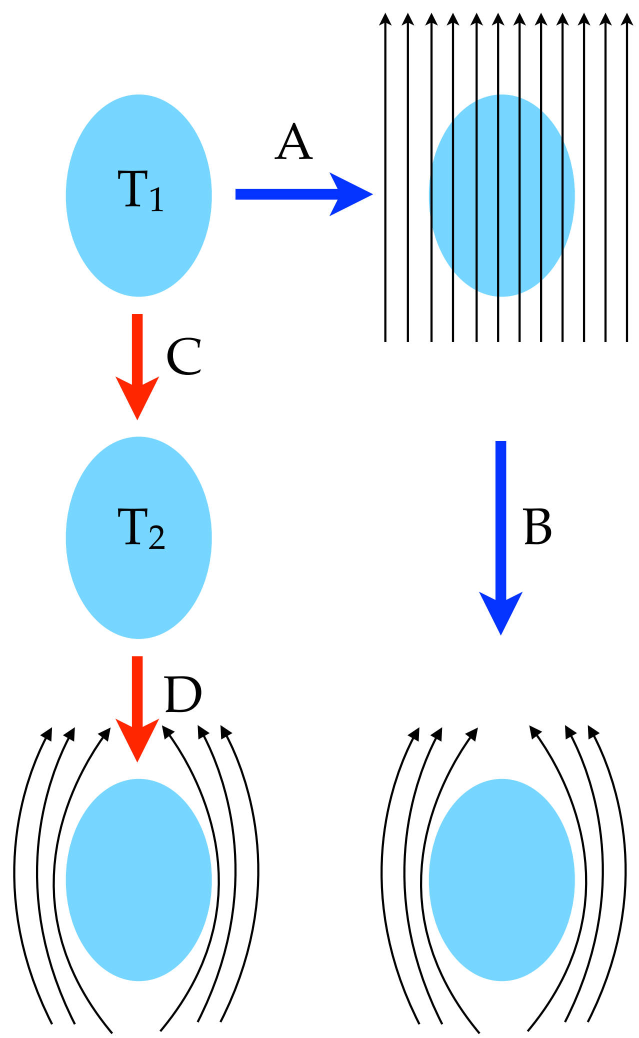
perfect conductor:

$\partial B / \partial t = 0$

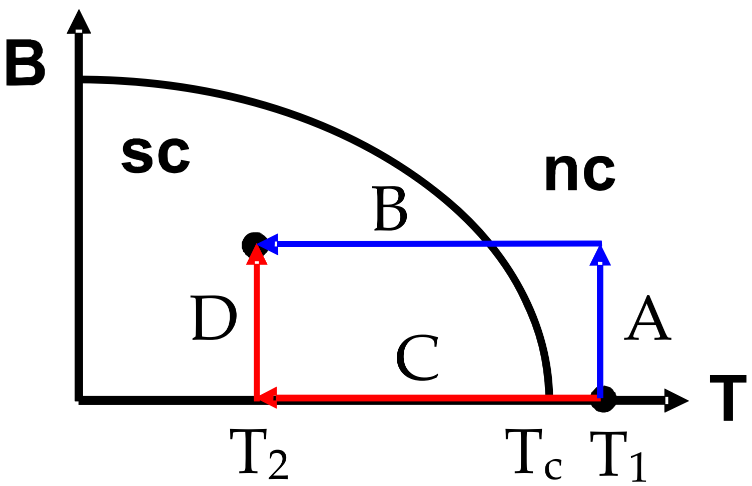


superconductor:

$B = 0$



superconductor = thermodynamic state



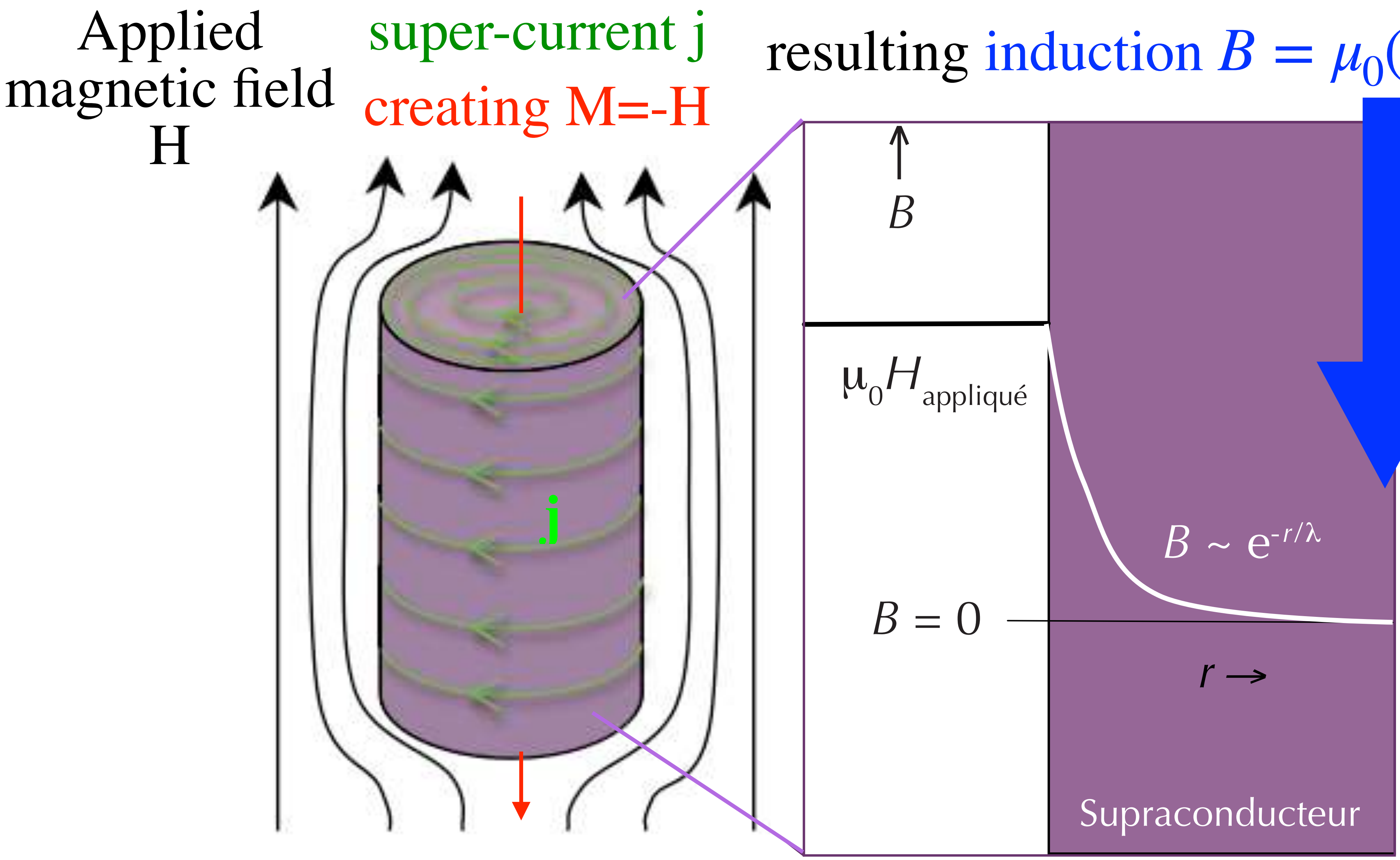
perfect diamagnetism

courtesy, H. Cercellier

General properties: λ_L

Meissner-Ochsenfeld effect discovered in 1933

Screening super-current with spatial extension of London penetration depth λ_L



resulting induction $B = \mu_0(H - M) = 0$

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

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

General properties: λ_L

Meissner-Ochsenfeld effect discovered in 1933

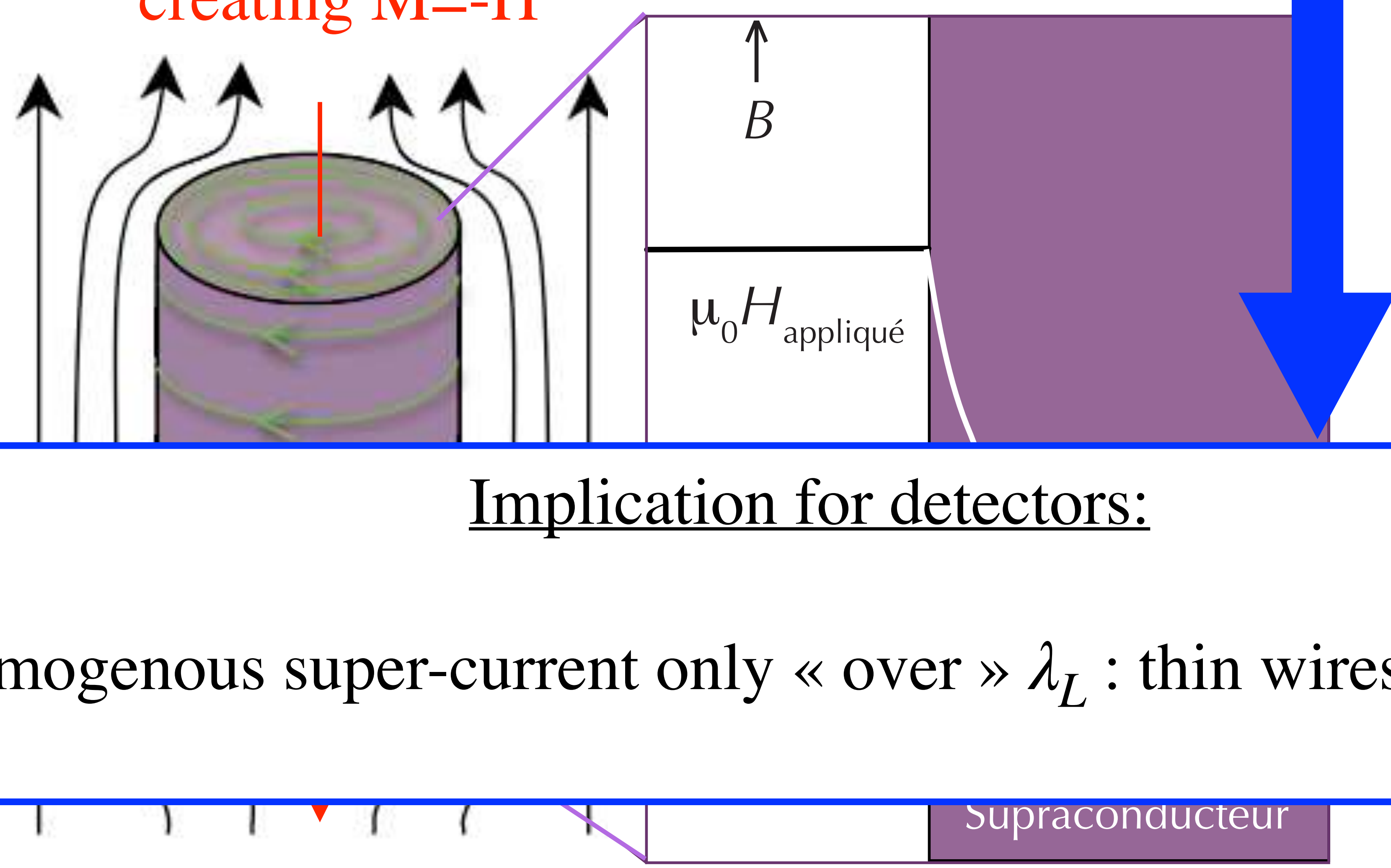
Screening super-current with spatial extension of London penetration depth λ_L

Applied magnetic field H

super-current j

creating M=-H

resulting induction $B = \mu_0(H - M) = 0$



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

Implication for detectors:

- homogenous super-current only « over » λ_L : thin wires are required

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)

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

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Microscopic origin: one wave function

Ginzburg-Landau theory 1951

macroscopic quantum state of many electrons (or holes)

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

θ phase

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

superfluid density $n_s(r)$ varies on ξ_0 coherence length

The coherence length ξ_0 is the rigidity of the SC order parameter, the length over which it can deviate from its equilibrium value.

Microscopic origin: one wave function

Ginzburg-Landau theory 1951

macroscopic quantum state of many electrons (or holes)

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

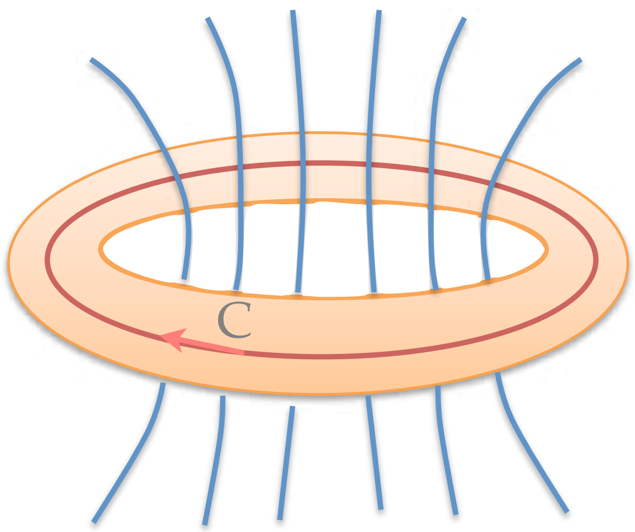
- phase θ -> magnetic flux quantification
  + supercurrents, Josephson effect…

- ξ_0 / λ_L -> two behaviors under H: type I / type II

θ phase

The coherence length ξ_0 is the rigidity of the SC order parameter, the length over which it can deviate from its equilibrium value.

Microscopic origin: ϕ_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 $\Delta\theta = 2n\pi$

$$\oint_C \hbar\nabla\theta.dl = 2n\pi\hbar = \oint_C -2e\mathbf{A}.dl = 2e\Phi$$

The total magnetic flux through a superconducting ring is quantized :

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

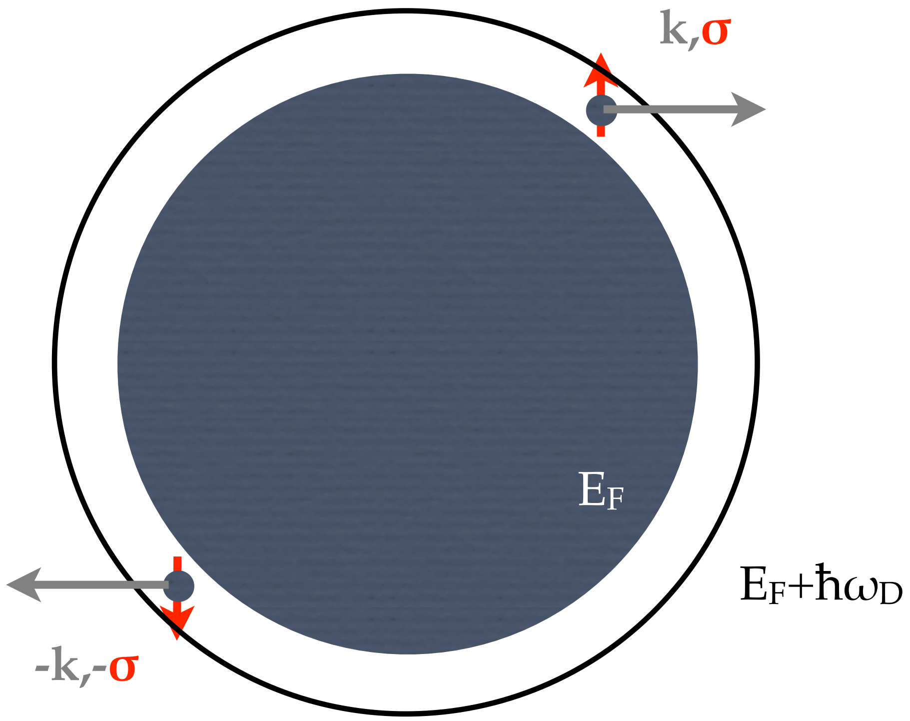
$$\Phi_0 = \frac{h}{2e} \approx 2.10^{-15} T.m^2$$

magnetic flux quantum

Microscopic origin: Cooper pair

Bardeen-Cooper-Schrieffer theory (BCS) 1957

Cooper instability: 2 electrons at E_F + attractive interaction



$$E_{Cooper\ pair} < 2E_e$$

« 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

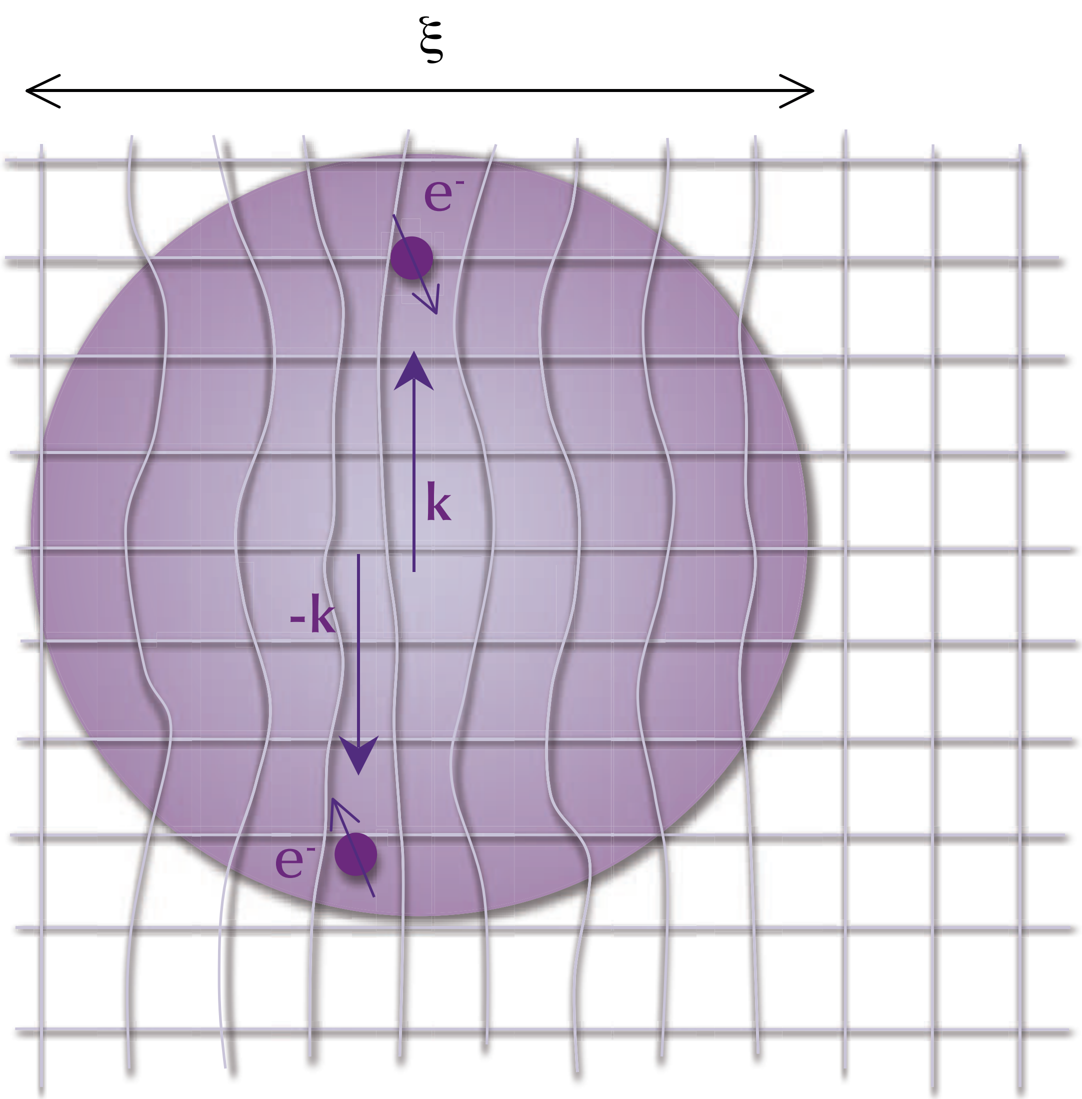
Attractive interaction between electrons via phonons

Coulomb repulsion « screened » by ions and V_F>>ions displacement speed.

Entire phonon spectrum up to Debye freq ω_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: ξ_{BCS}

Bardeen-Cooper-Schrieffer theory (BCS) 1957

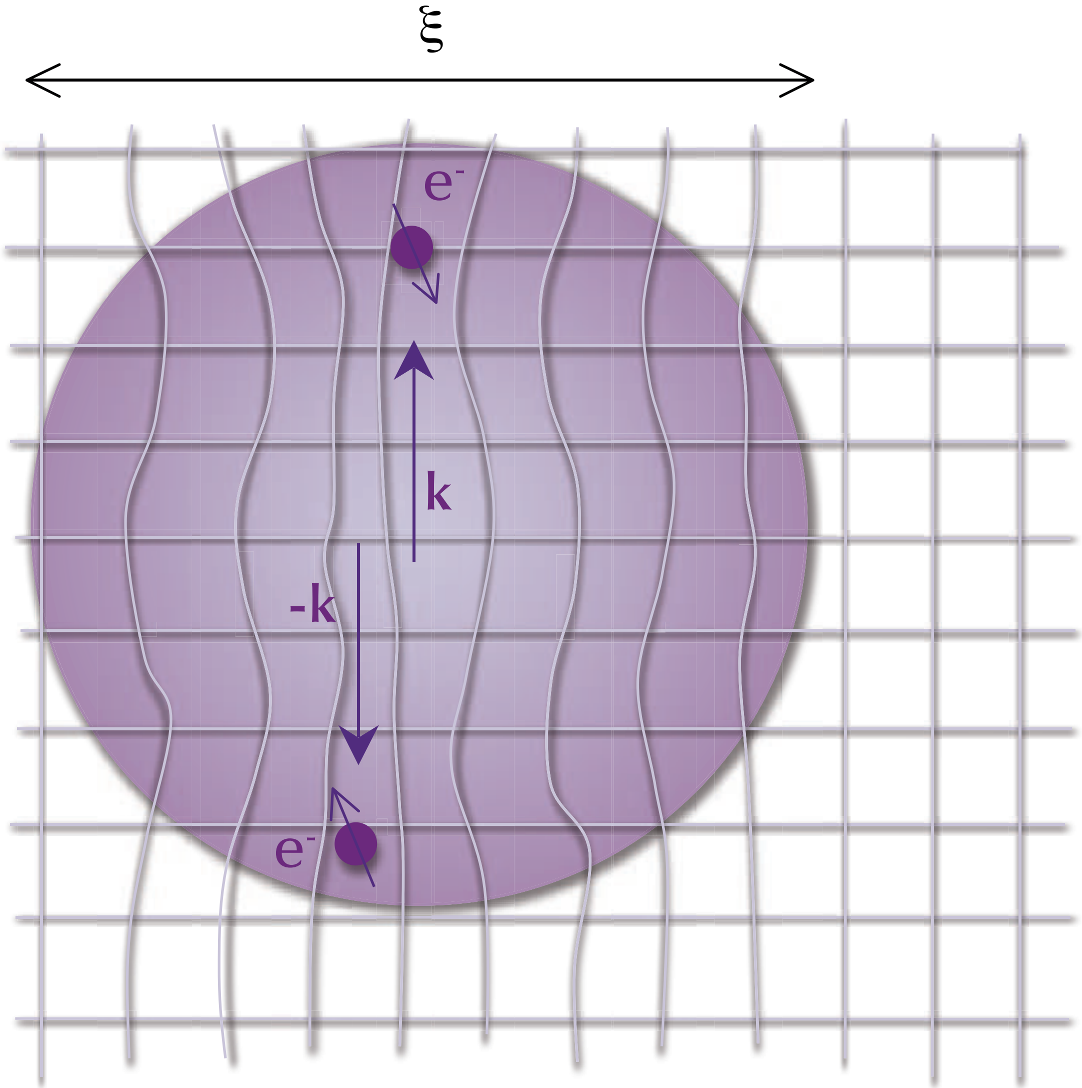
ξ average distance between two electrons of a Cooper pair

$$\delta t \delta E \sim \hbar$$
$$\delta E = k_B T_c$$

During the time dt the electron travels

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

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



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The coherence length ξ_0 is the rigidity of the SC order parameter, the length over which SC can be destroyed.

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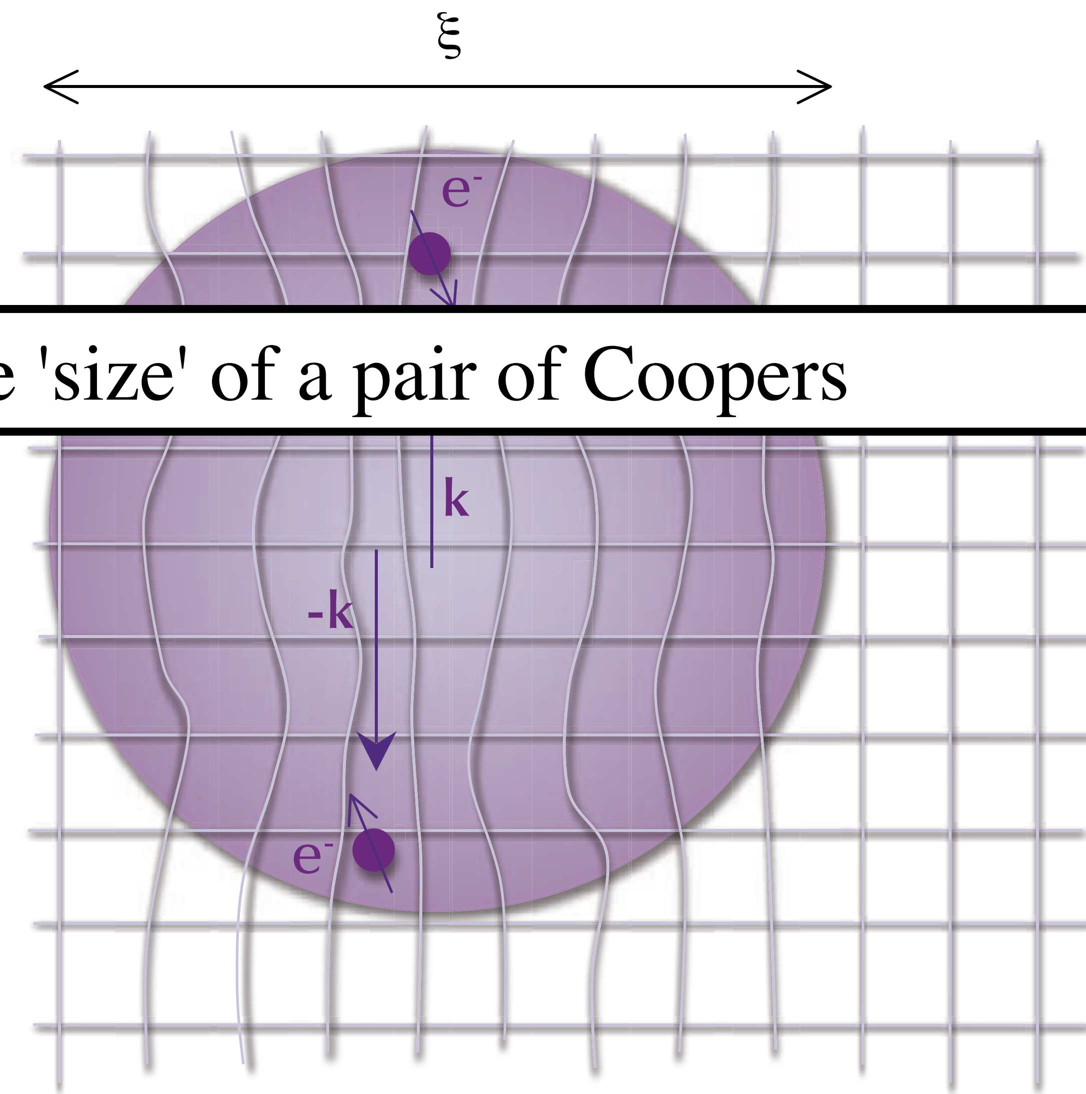

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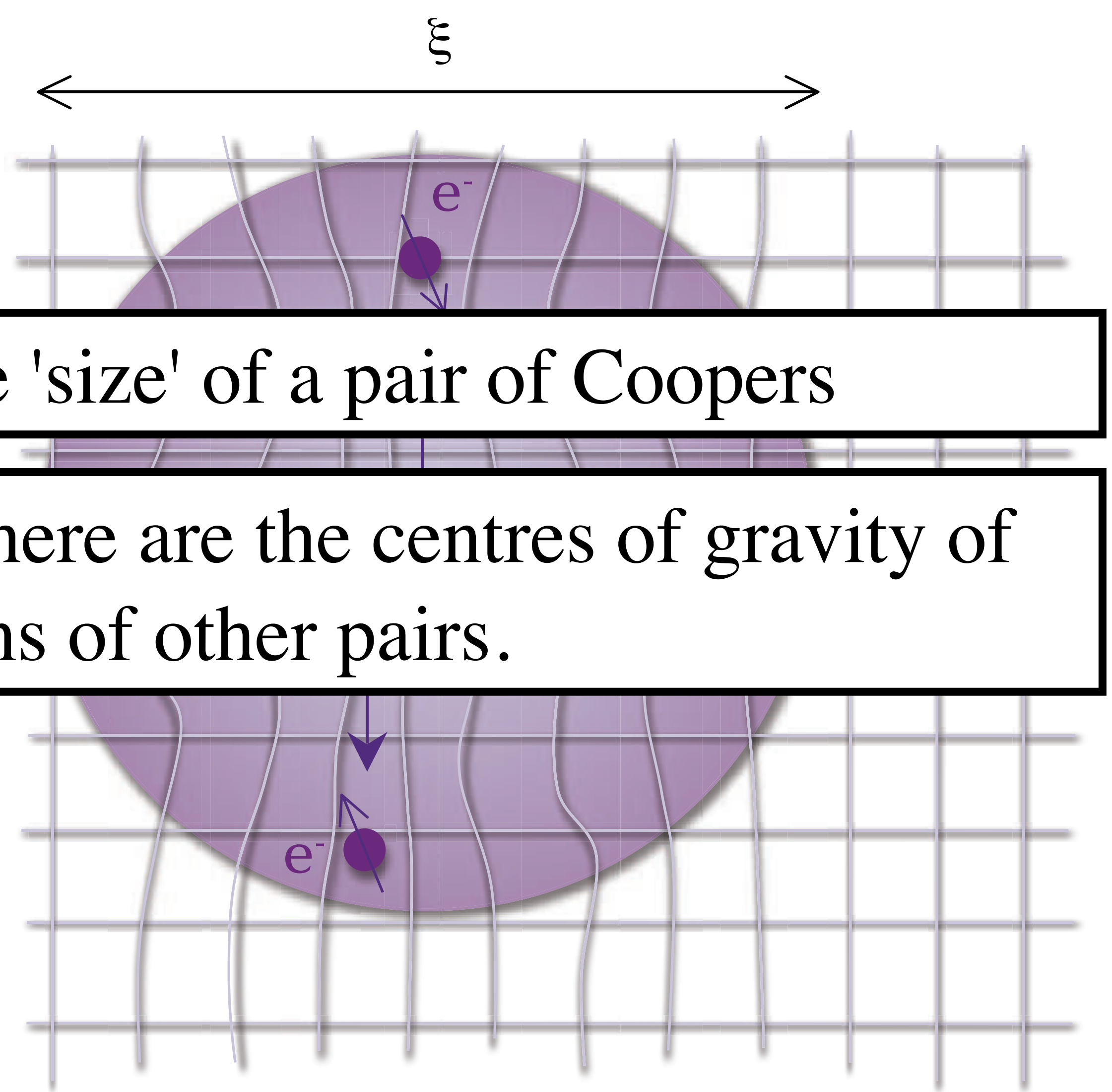

ξ is the 'size' of a pair of Coopers

In ξ³ there are the centres of gravity of millions of other pairs.

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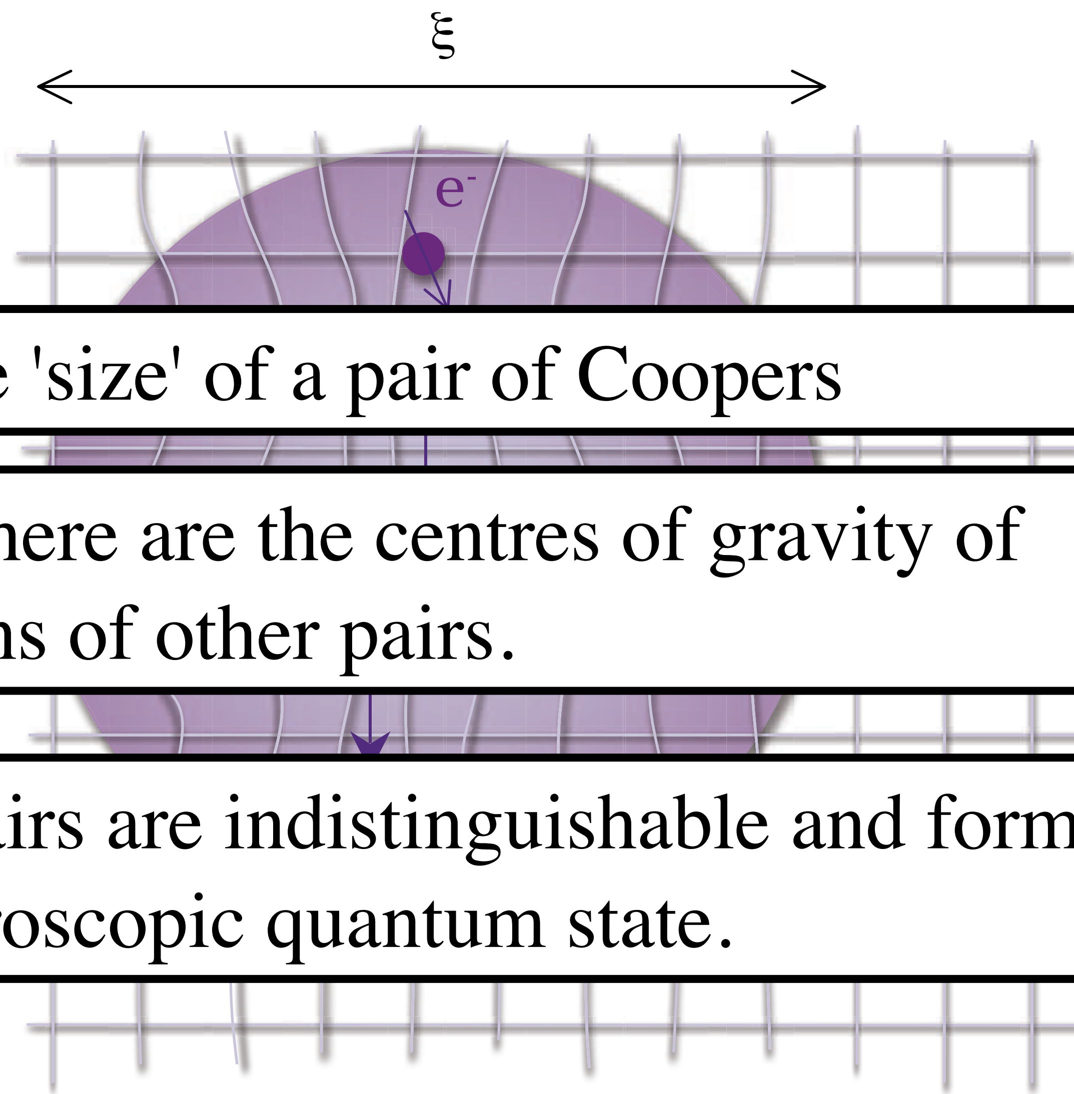


ξ is the 'size' of a pair of Coopers

In ξ^3 there are the centres of gravity of millions of other pairs.

The pairs are indistinguishable and form a macroscopic quantum state.

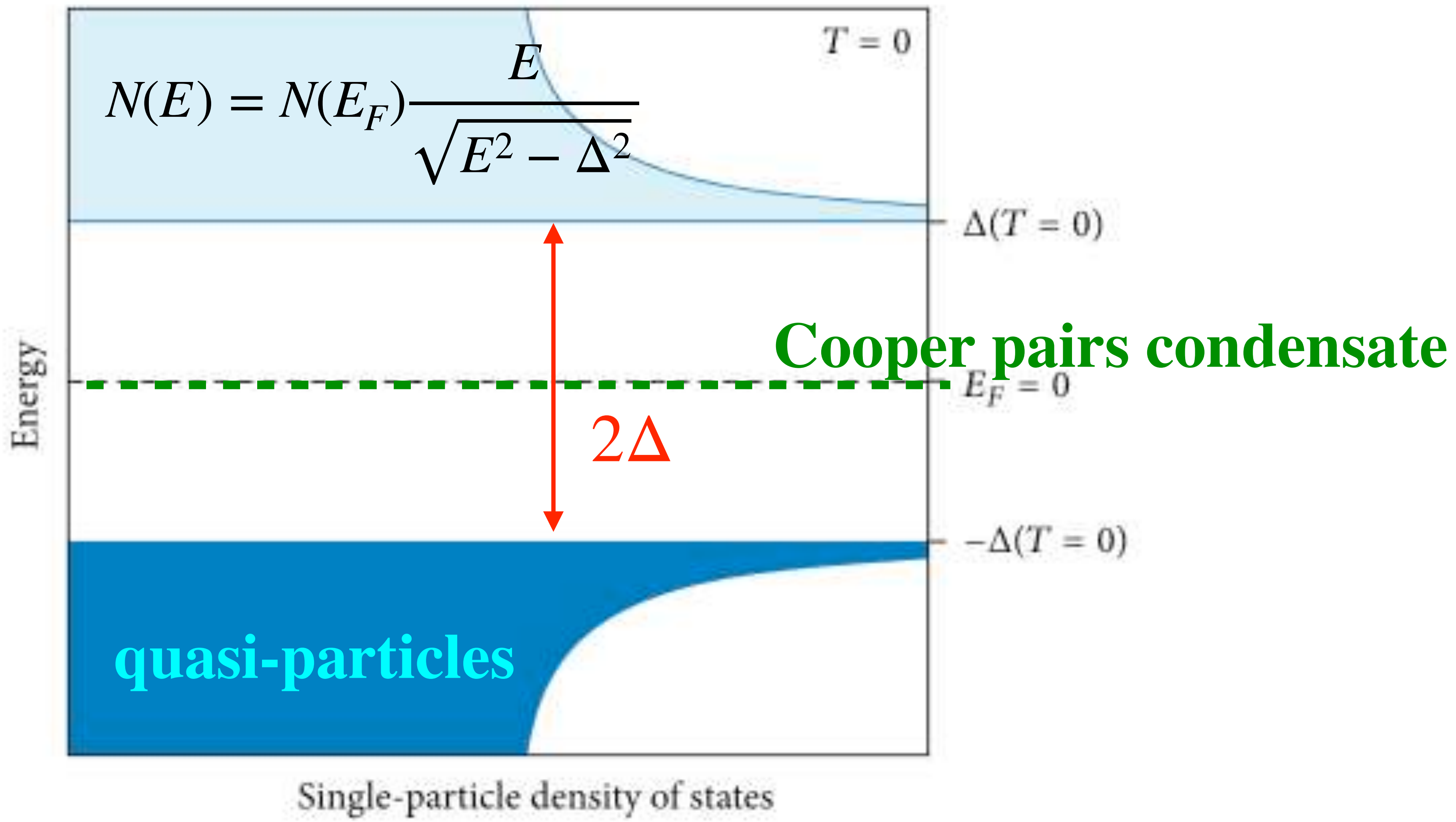
K. van der Beek, reflets de la physique n°27, 6 (2011)

The coherence length ξ_0 is the rigidity of the SC order parameter, the length over which SC can be destroyed.

Microscopic origin: gap Δ

Bardeen-Cooper-Schrieffer theory (BCS) 1957

A gap 2Δ opens in the single-particle density of states



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

The gap 2Δ 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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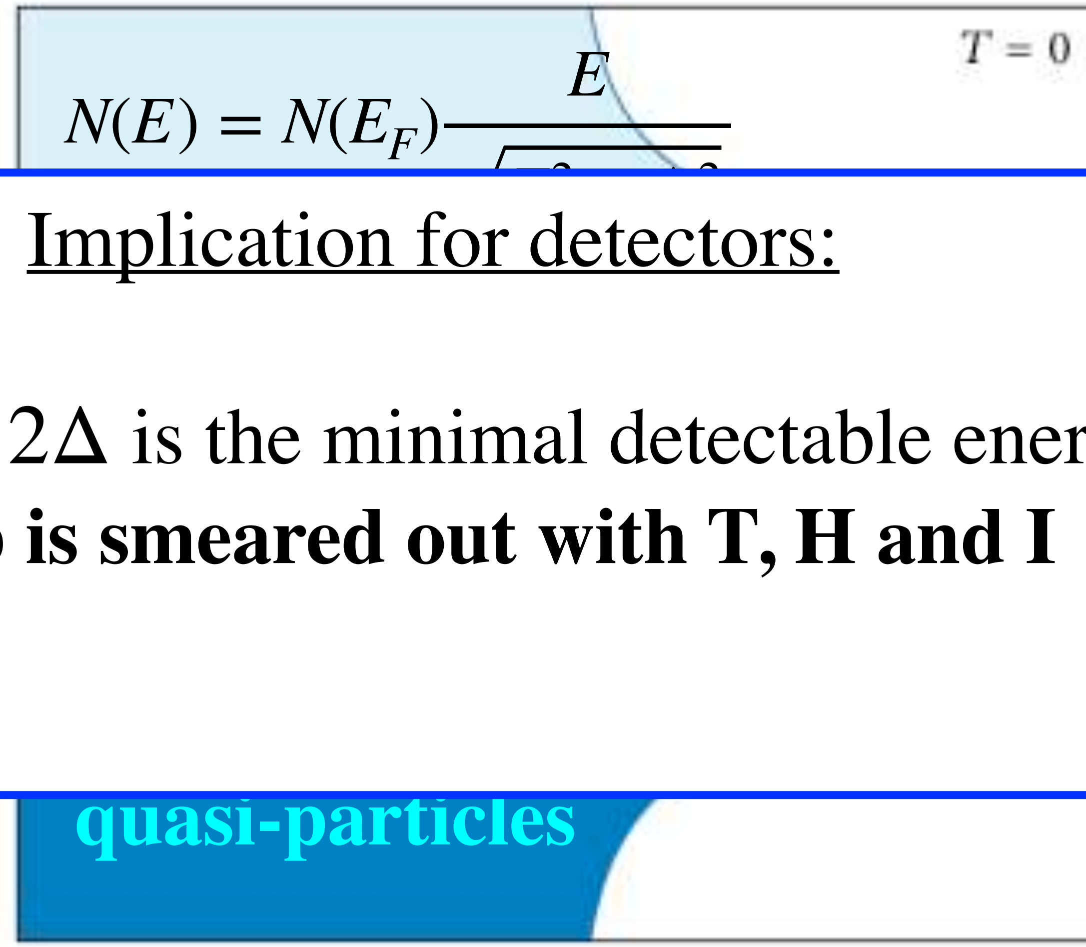


Single-particle density of states

<u>Implication for detectors:</u>

- the gap 2Δ is the minimal detectable energy
- **the gap is smeared out with T, H and I**

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

The gap 2Δ is the energy required to break ONE Cooper pair

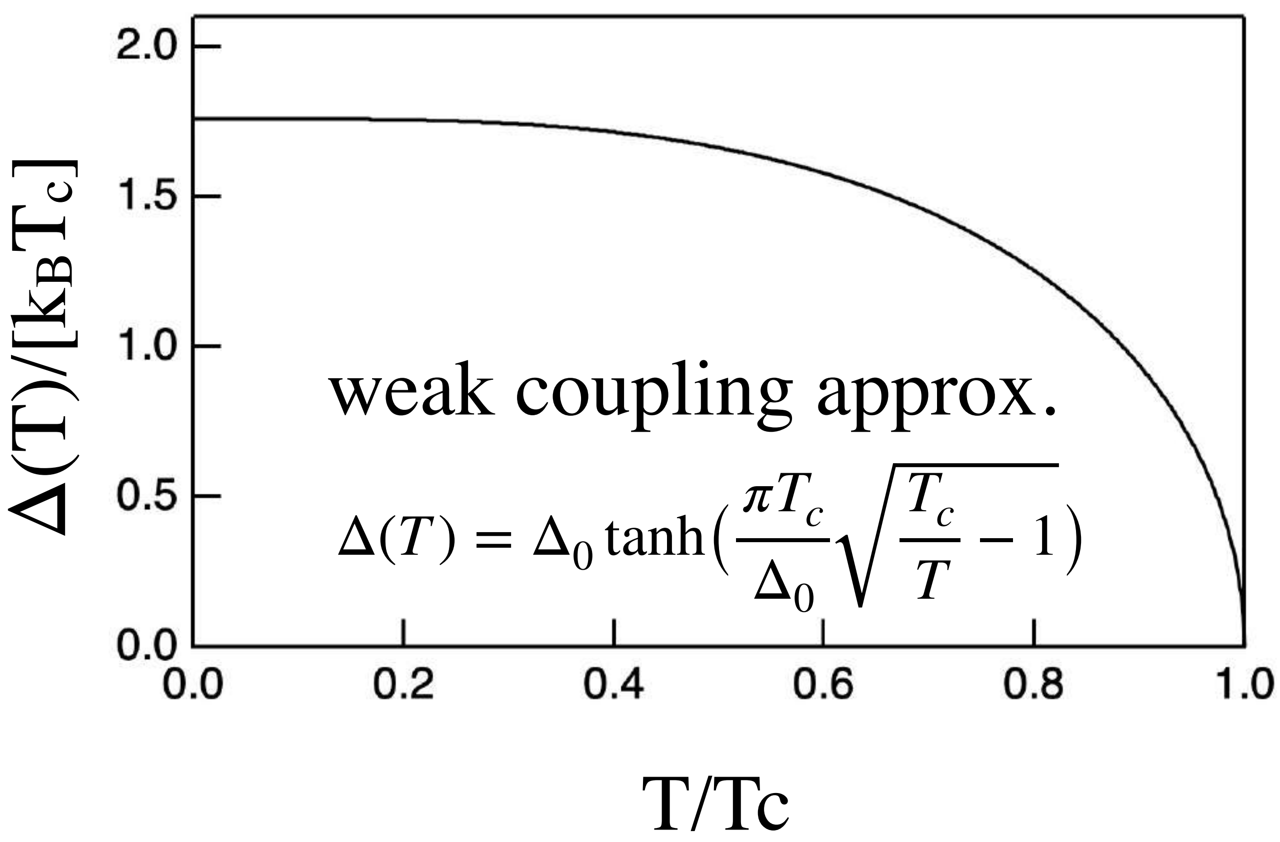
M. Dressel, *Electrodynamics of Metallic Superconductors*, Advances in Condensed Matter Physics **2013**, 1 (2013).

Microscopic origin: gap Δ and Tc

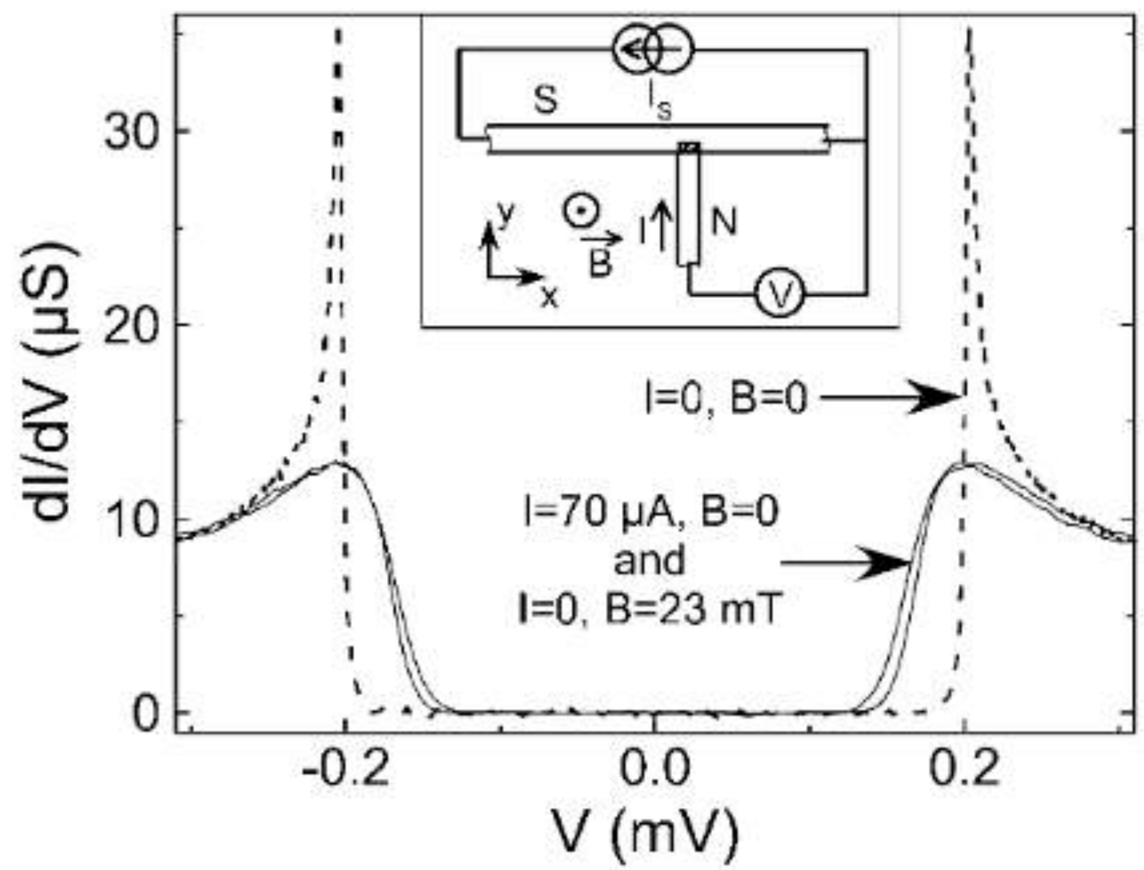
Bardeen-Cooper-Schrieffer theory (BCS) 1957

$$2\Delta(0) = 3.52 K_b T_c$$

T-variation of the gap



H, I - variation of the gap



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

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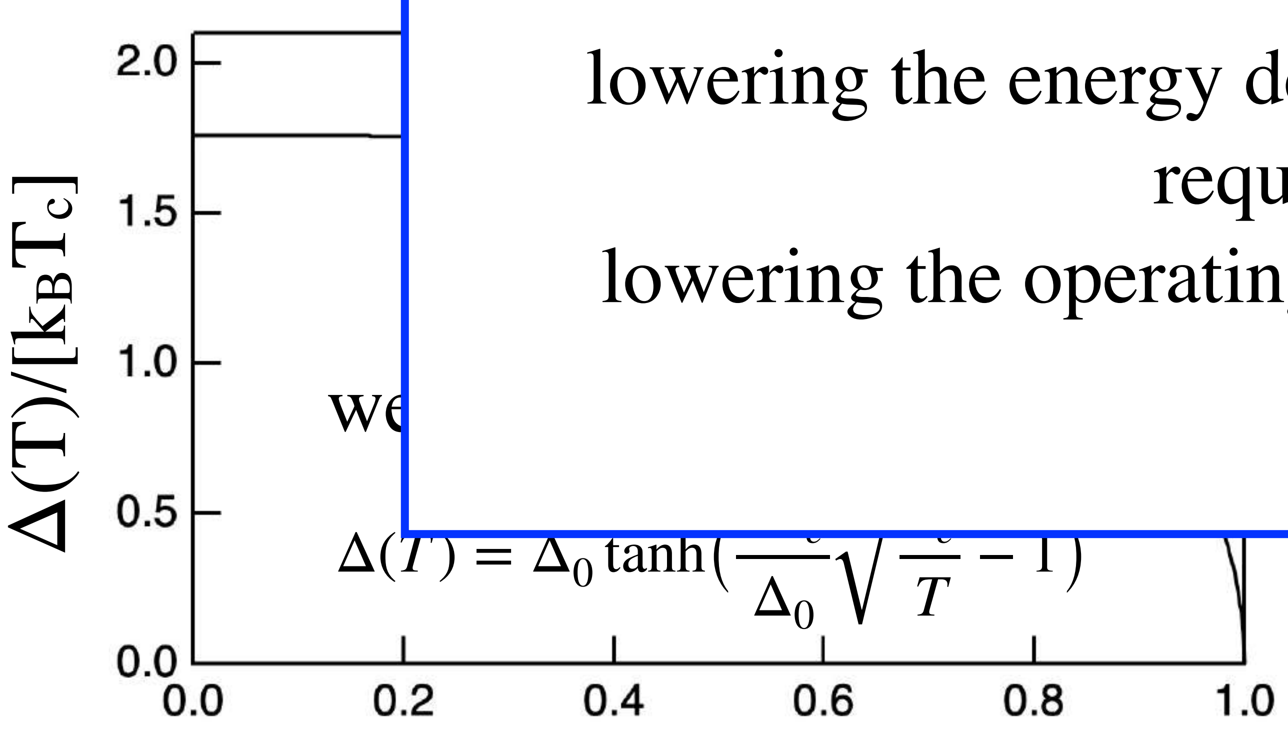
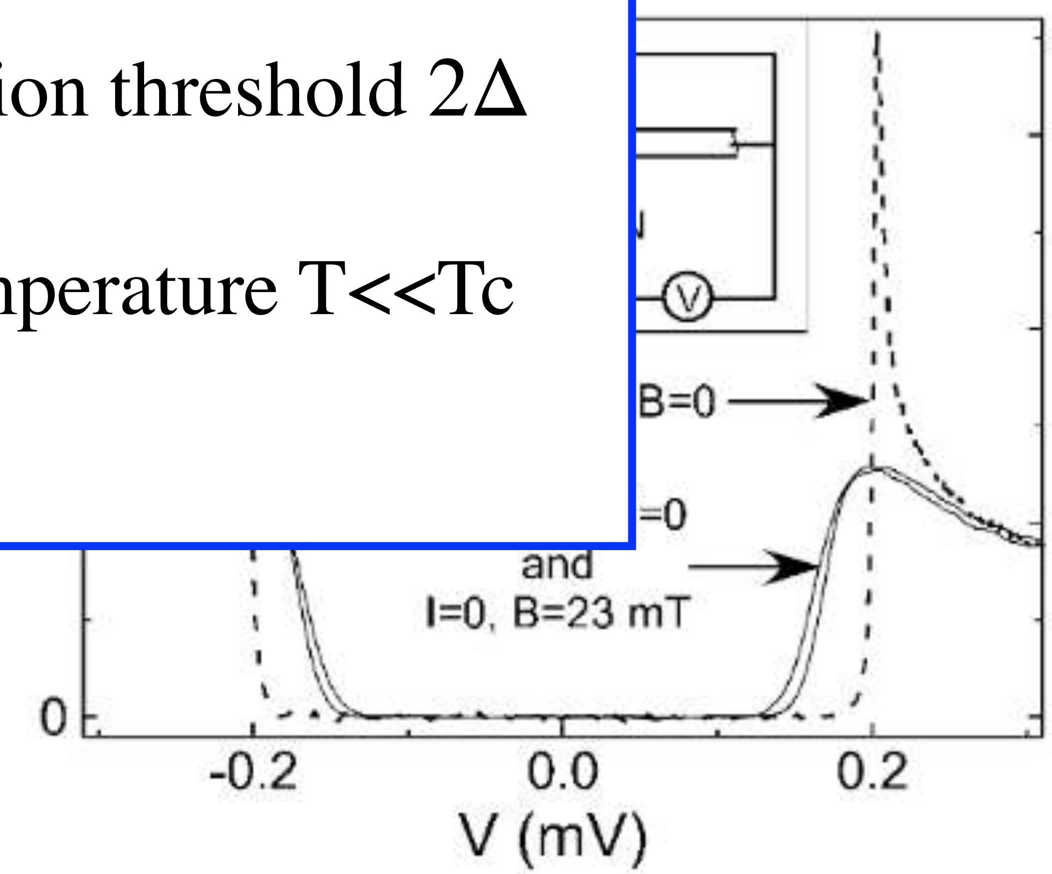
T-vari… …of the gap





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Implication for detectors:

lowering the energy detection threshold 2Δ
requires
lowering the operating temperature T<<Tc

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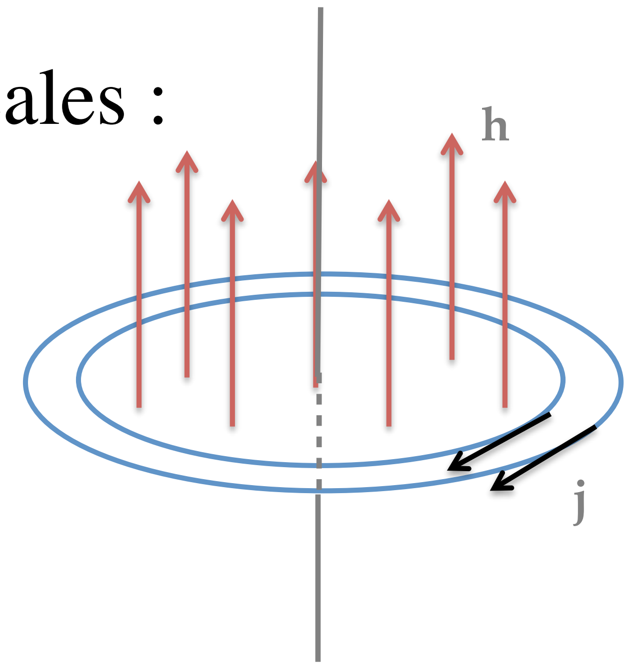
Types I et II: $\kappa = \lambda/\xi$

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

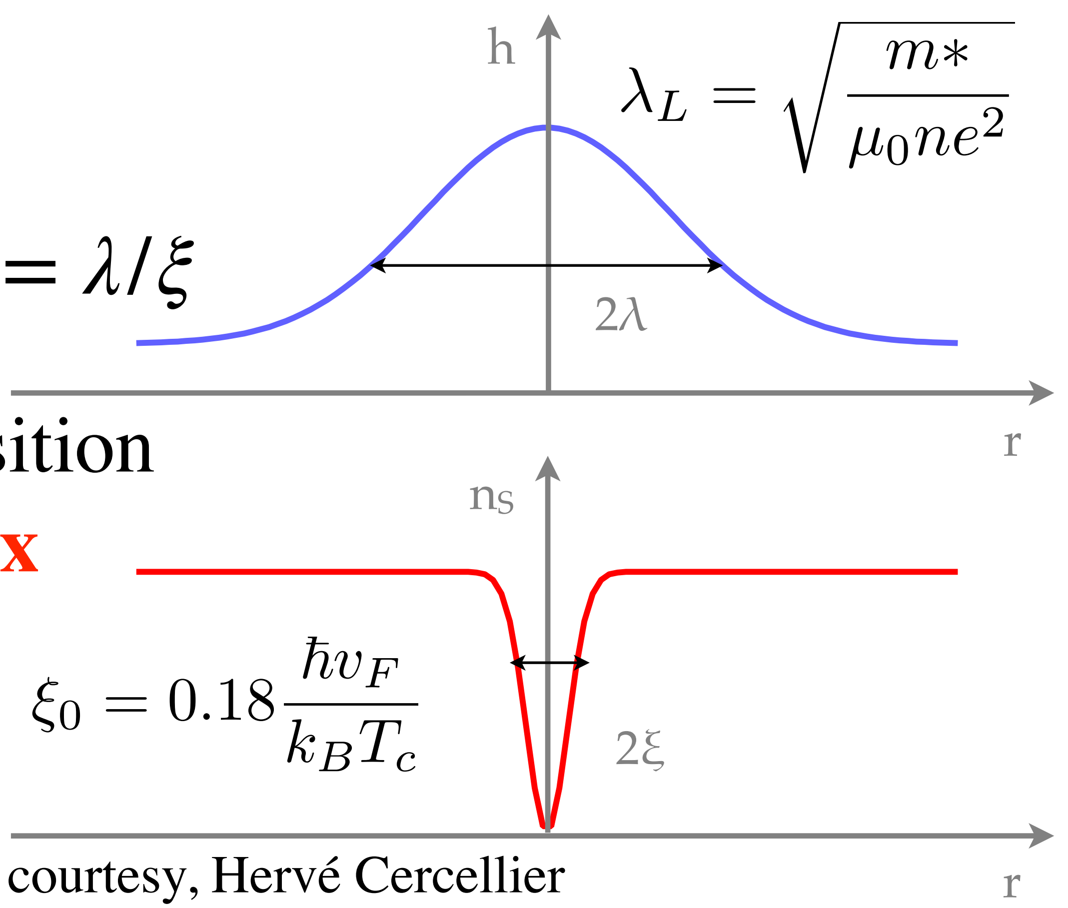
- the London penetration depth λ,
  the scale for current flow <=> magnetic field decay
- the coherence length ξ,
  the rigidity of the SC order parameter, the length over which it can deviate from its equilibrium value



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

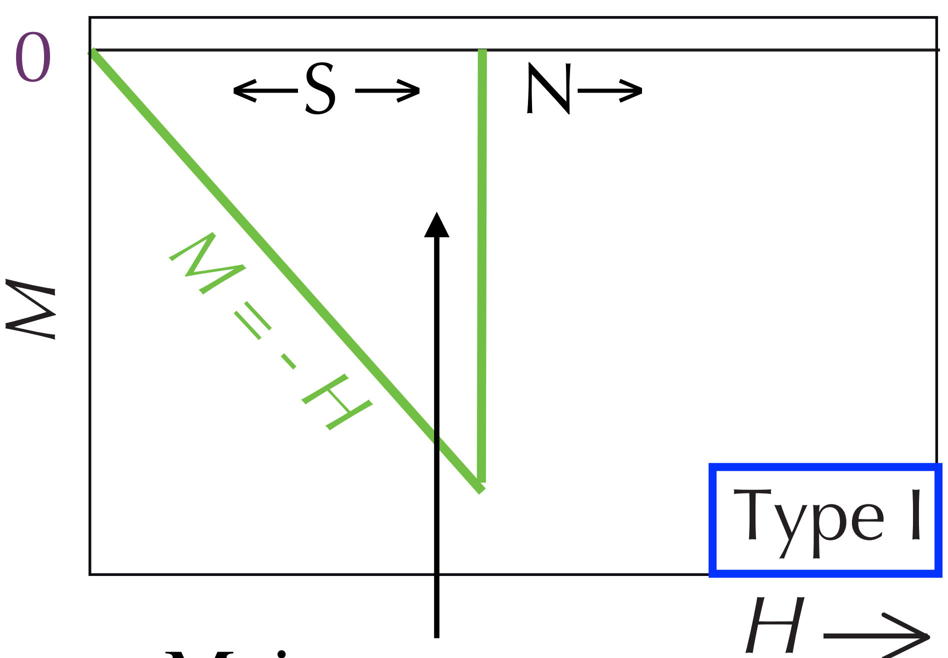
SC destroyed at H_c

«Perfect diamagnetism»
Meissner effect

Ex: Hg, Al, Pb, In

H_c

~10^{-1}-10^{-2} T



Meissner state

Type II

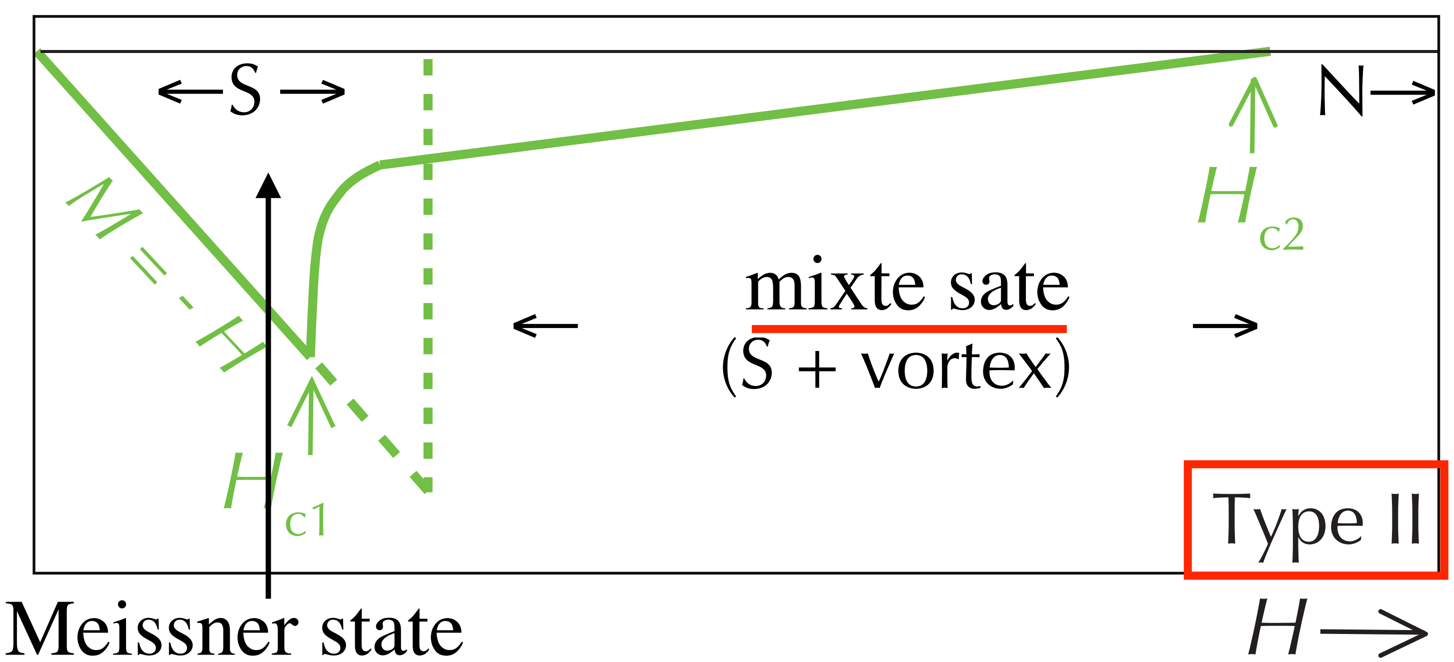
- H<Hc1: complete Meissner effect
- Hc1<H<Hc2 mixte state: SC + vortex
- Ex: Tin, Lead, Mercury

H_{c1}

~10-100 Gauss

H_{c2}

~1-100 T



Meissner state

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

leissner effect

«Perfect

Meissner effect

Ex: Hg, Al, Pb, In

- Hc1<H<Hc2 mixte state: SC + vortex
- Ex: Tin, Lead, Mercury

H_c

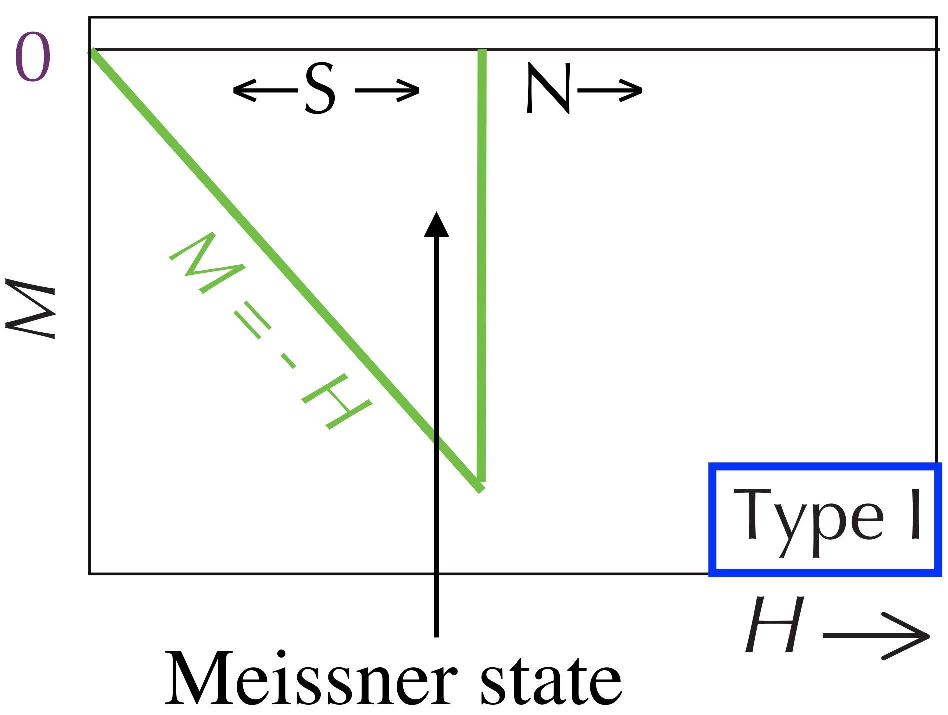
~10^{-1}-10^{-2} T

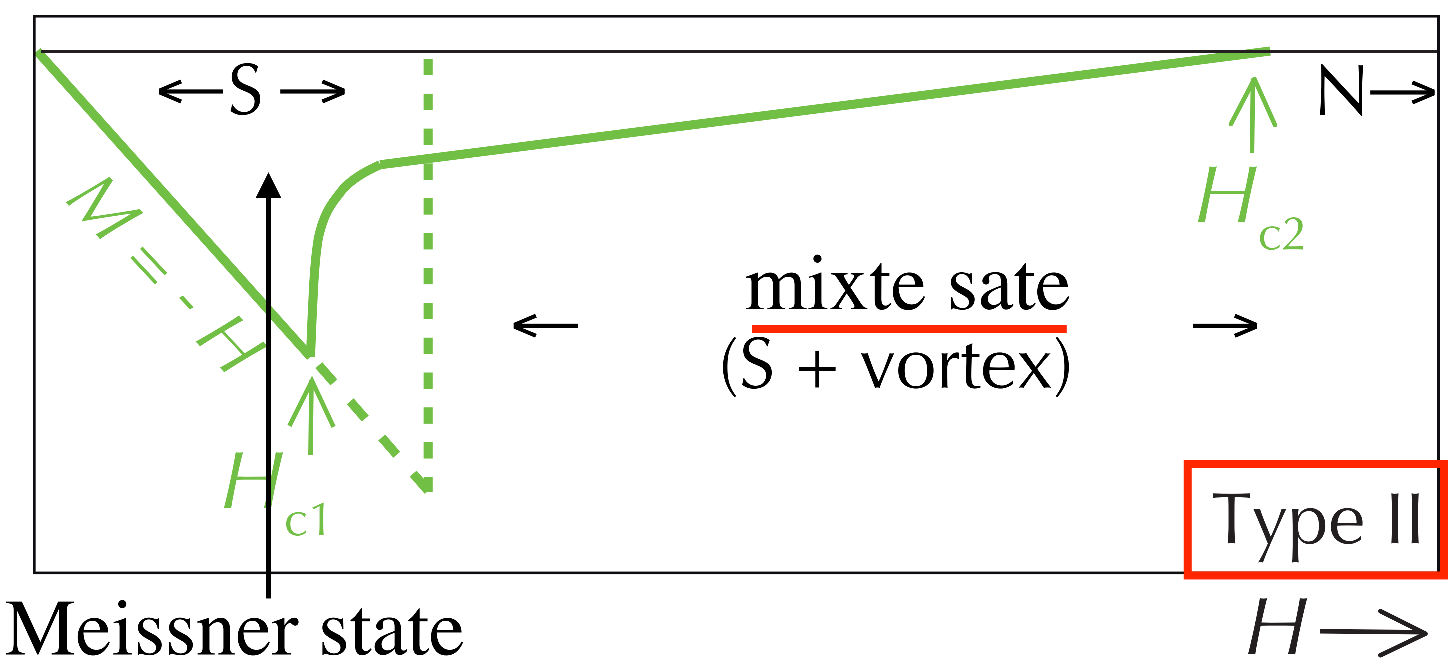
H_{c1}

~10-100 Gauss

H_{c2}

~1-100 T





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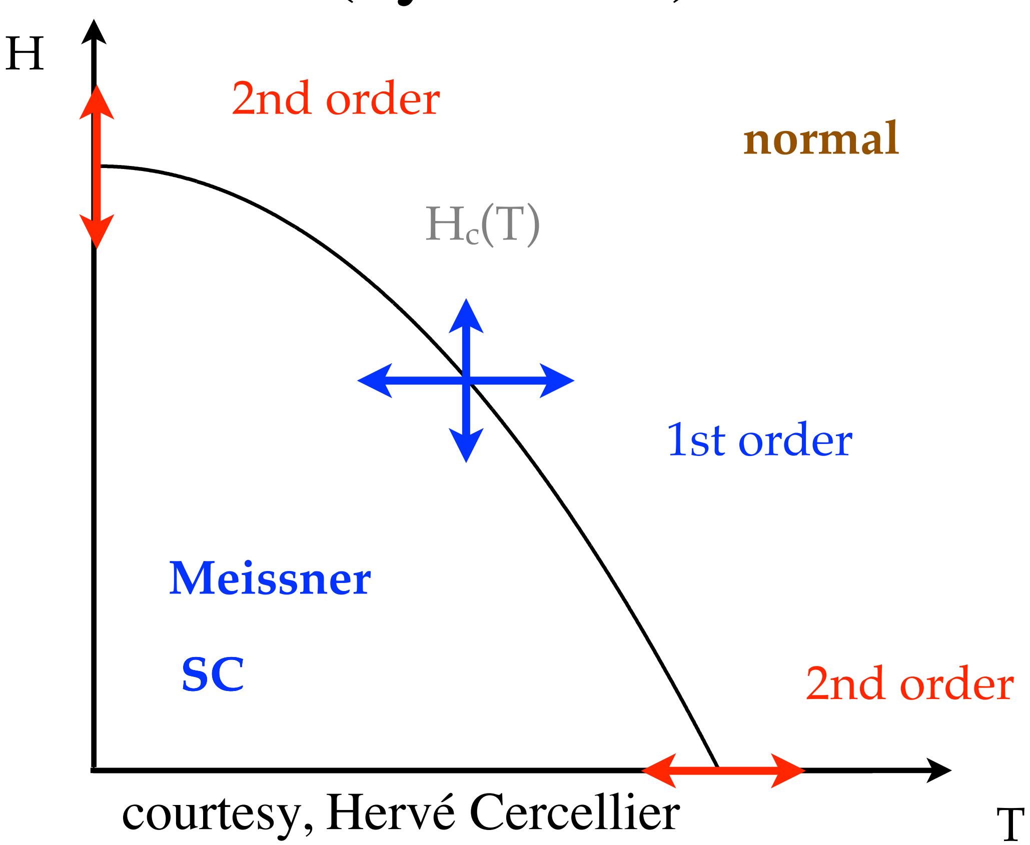
Type I

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

~10^{-1}-10^{-2} T

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



courtesy, Hervé Cercellier

Type II

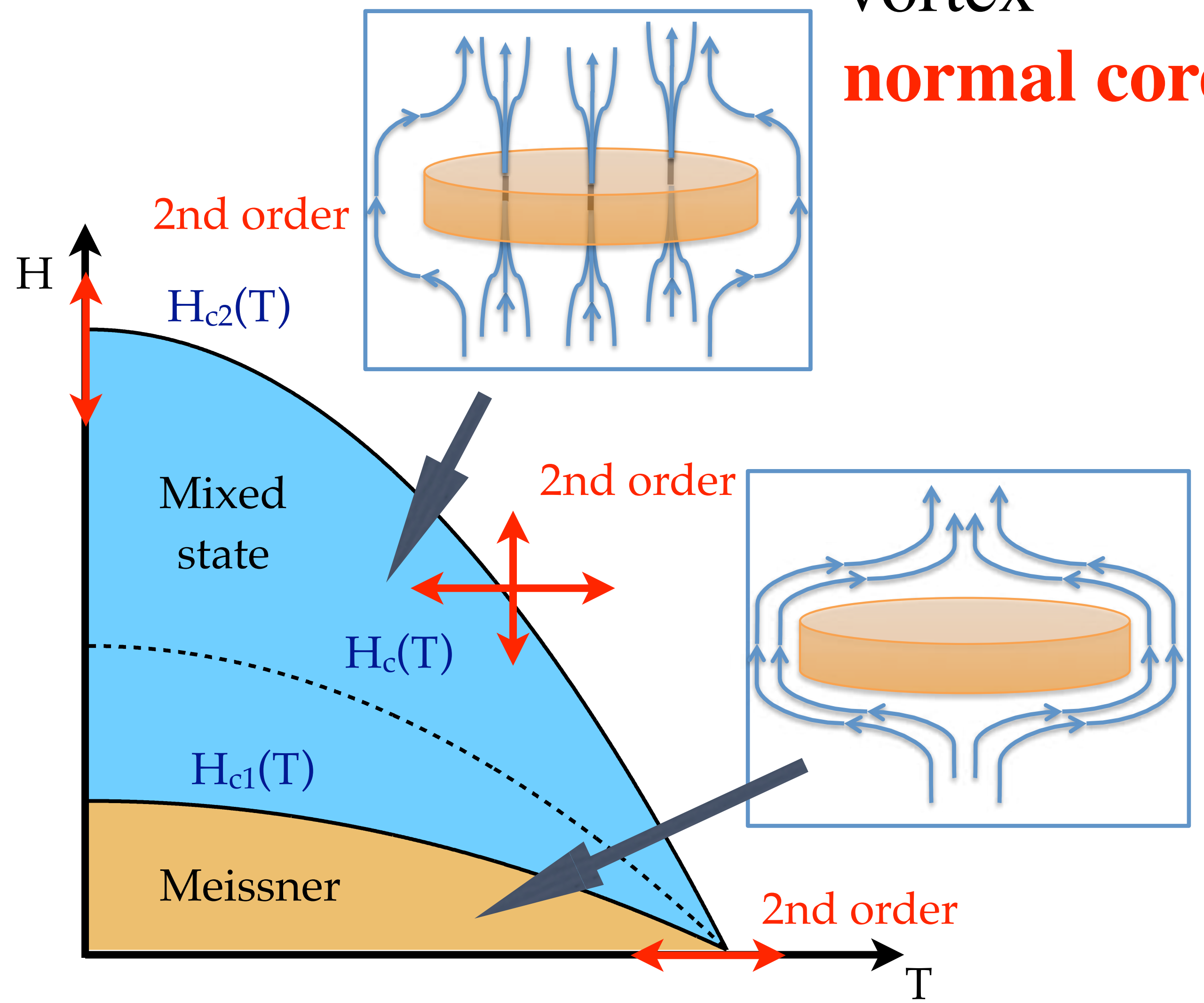
$$H_{c1} = \frac{\phi_0}{4\pi\mu_0\lambda^2} ln\left(\frac{\lambda}{\xi}\right)$$

~10-100 Gauss

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

~1-100 T

vortex
normal core



Type I

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

~10^{-1}-10^{-2} T

1st order transition:

coex

Type II

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

~10-100 Gauss

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

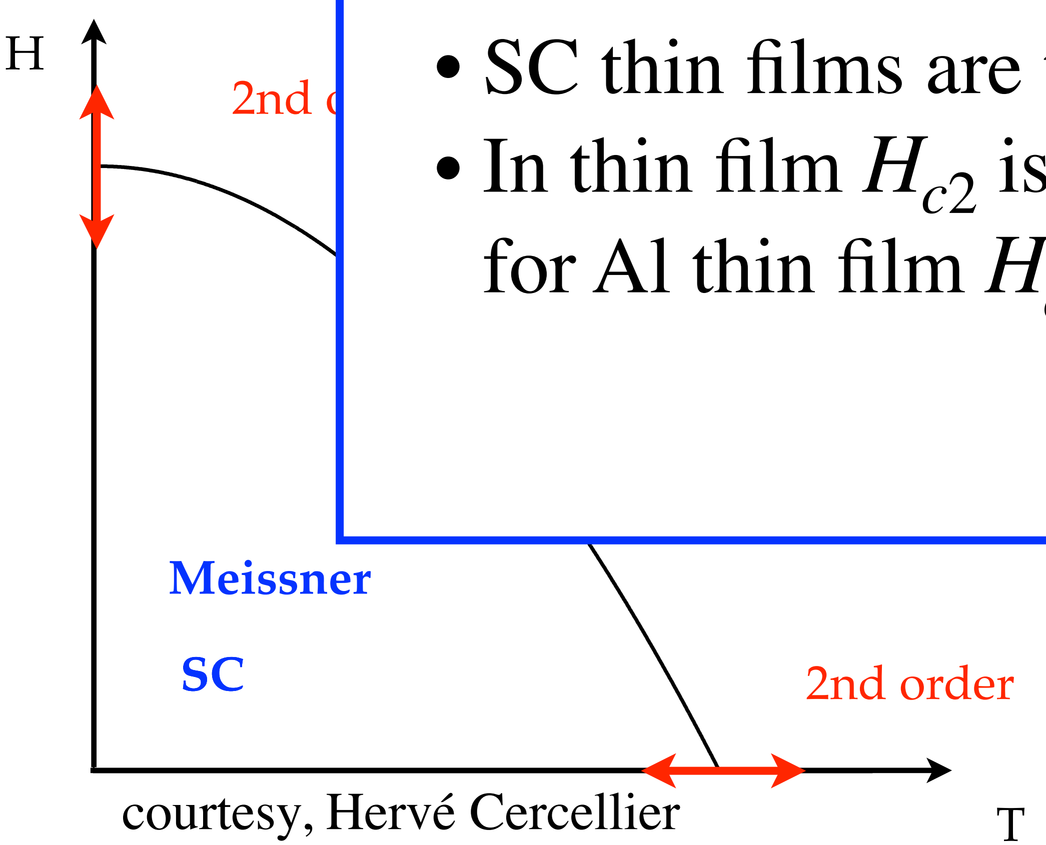
~1-100 T

vortex

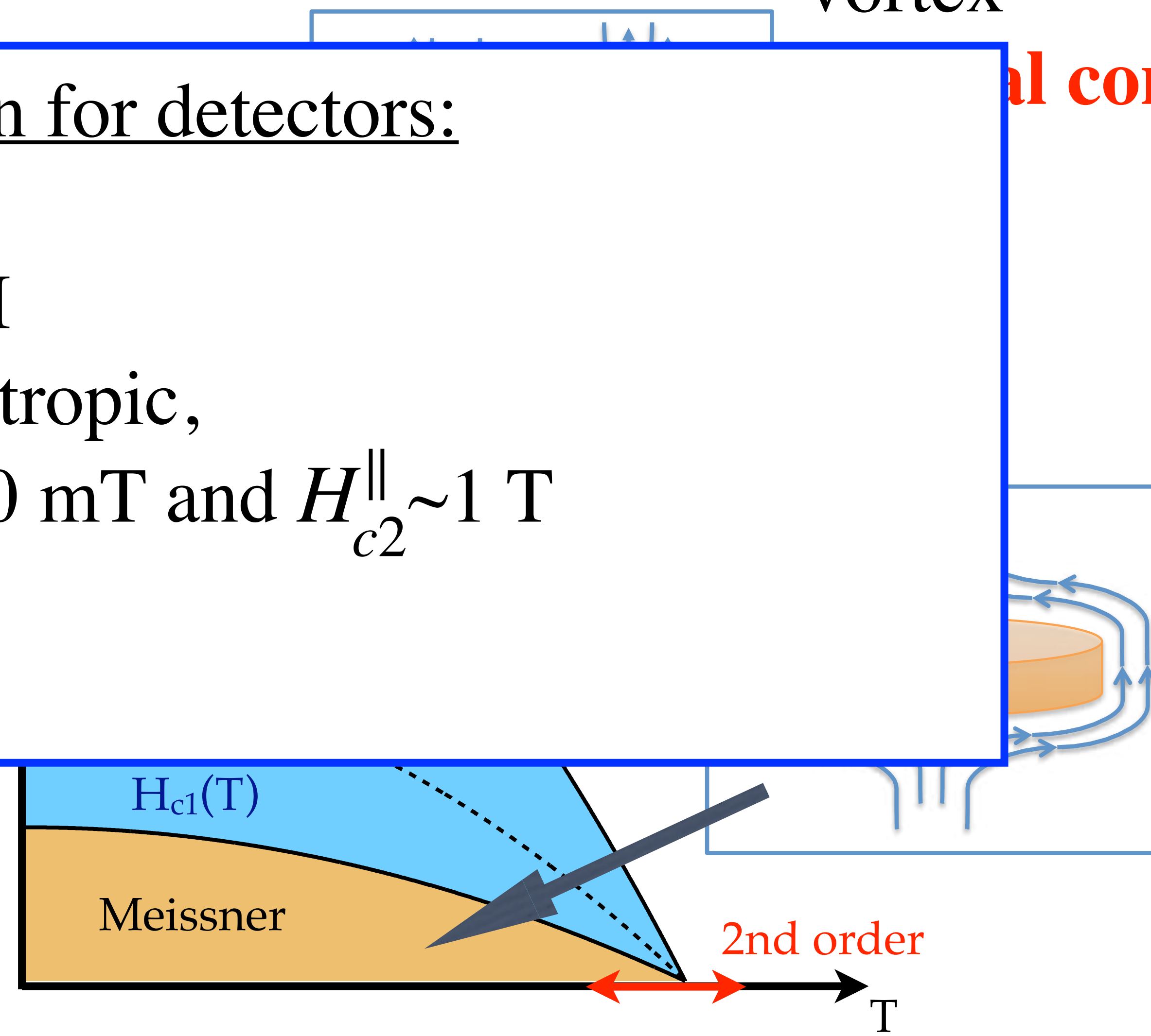
al core

Implication for detectors:

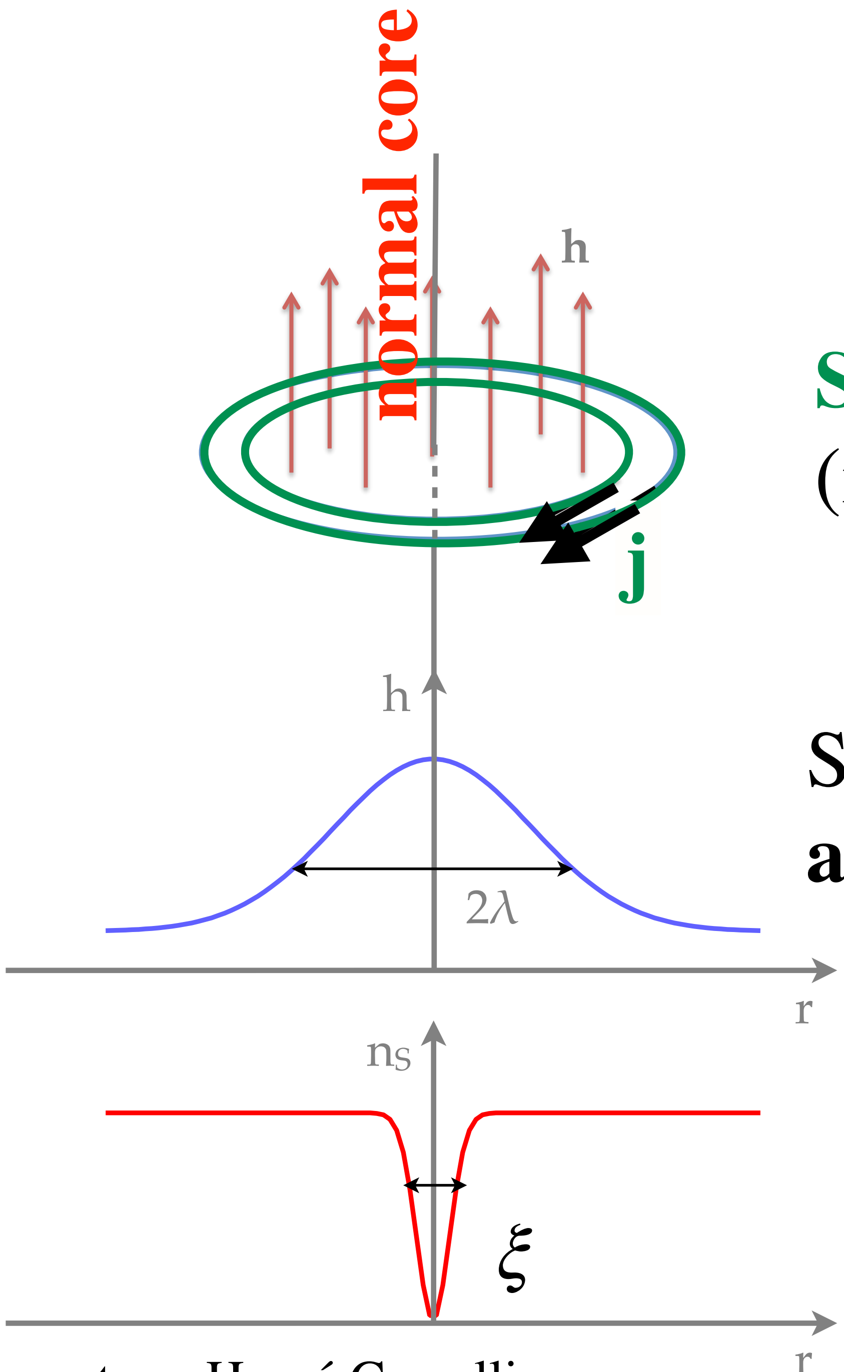
- SC thin films are type II
- In thin film H_{c2} is anisotropic, for Al thin film $H_{c2}^{\perp}$~100 mT and $H_{c2}^{\parallel}$~1 T



courtesy, Hervé Cercellier



Type II: vortex



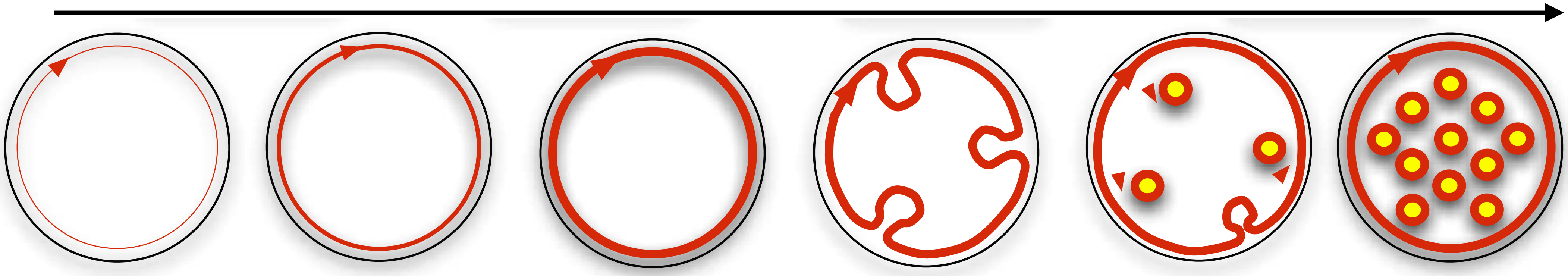
courtesy, Hervé Cercellier

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

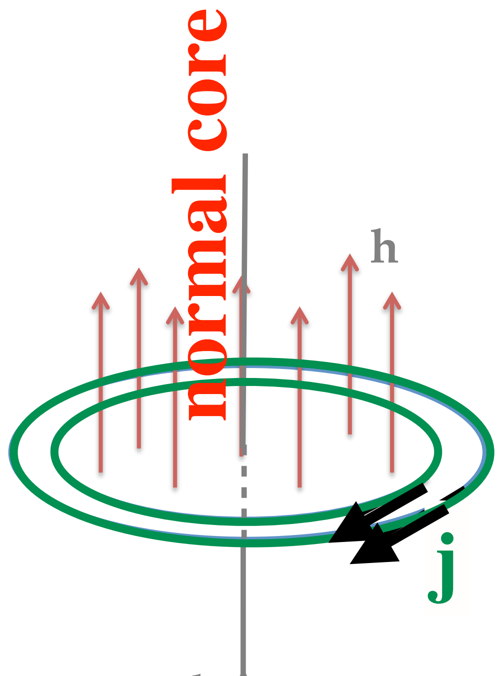
Supercurrent induces
a single magnetic flux quantum $\phi_0 = h/(2e)$

The size of the core is **the coherence length** ξ

Increasing H: creation of many vortex



Type II: vortex



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

$/(2e)$

th ξ

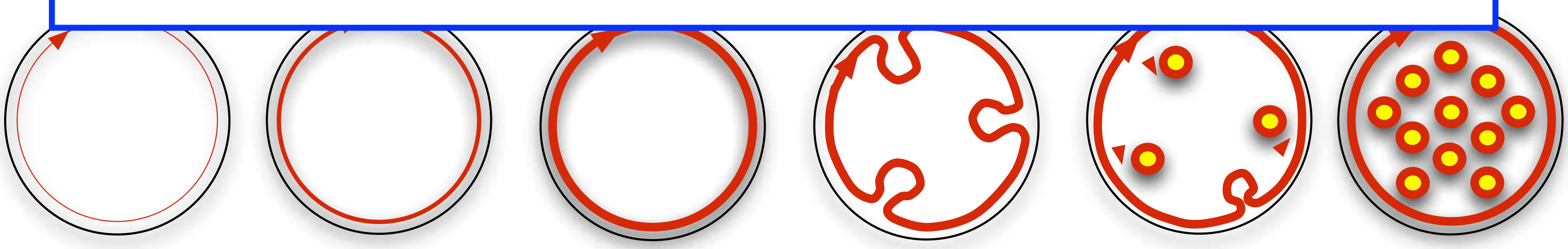
courtesy, He

ex

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)



Types I et II: j_c, j_v

Type I	Type II

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 ↓ while j ↑
For $j>j_c$ $n_s=0$

Type II

j_v vortex untrapping current

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

$L \geqslant \xi$ 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

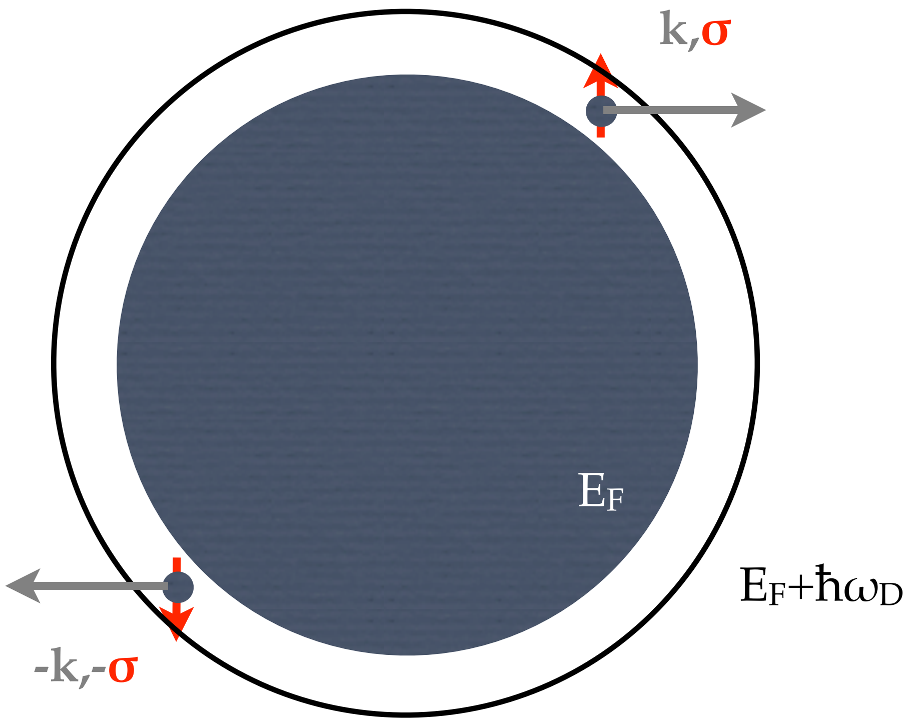
Normal state : $\sigma_n = \dfrac{ne^2\tau}{m}$ où $l = v_F\tau$

Superconductor state: $\sigma_s = 0$

But electrons undergo the same scattering

Anderson theorem (1959)

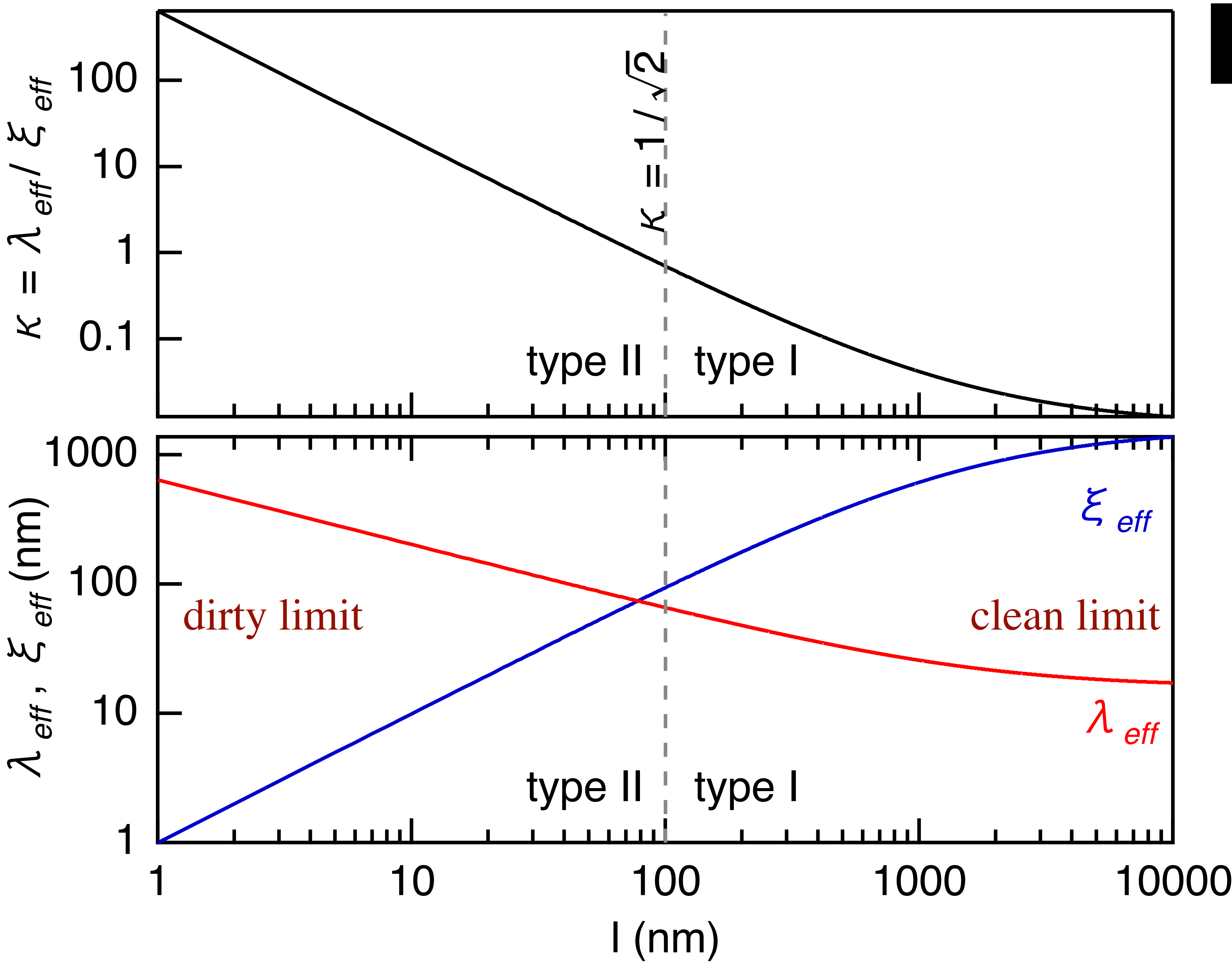
non magnetic impurities and $k_F l \gg 1$ no effect on T_c



Mean free path l: no effect on T_c nor on Δ

Disorder turns type I into type II

Mean free path l affects ξ et λ, disorder (small l) reduces ξ and increases λ.



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

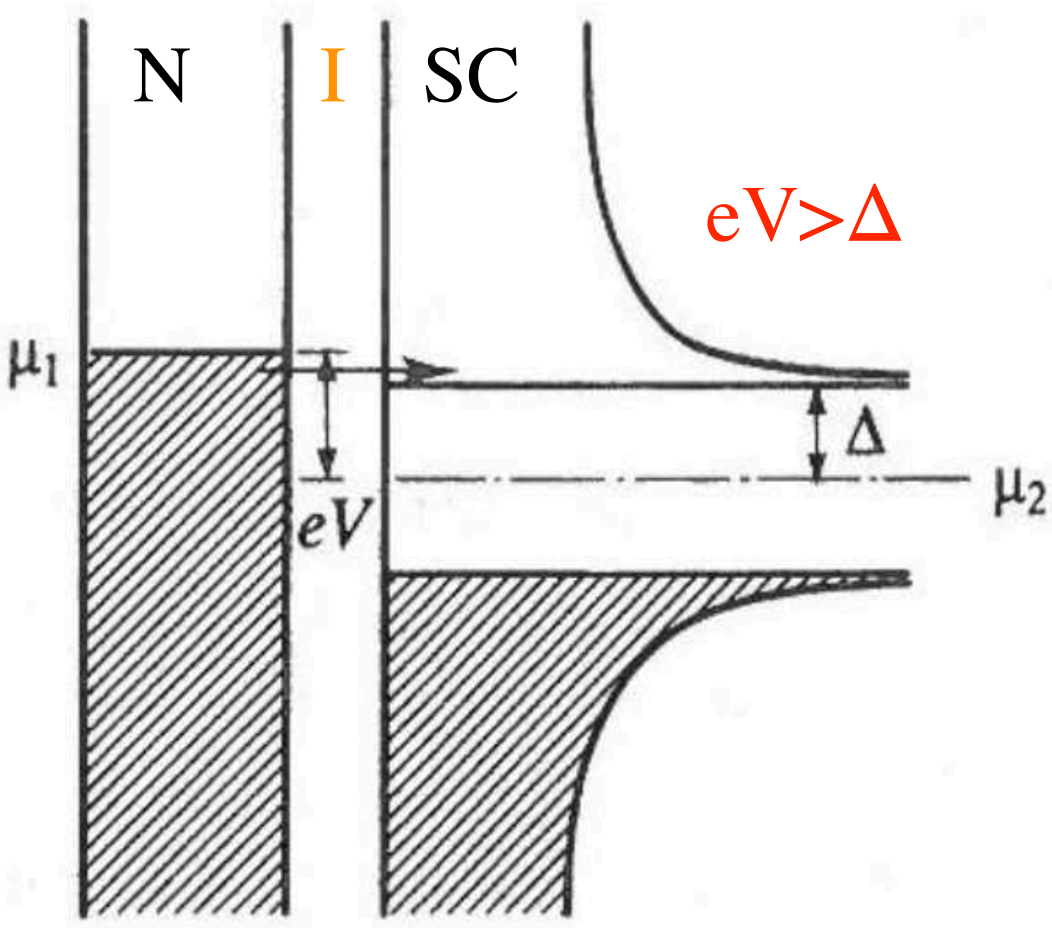
- General properties
  - Zero resistance
  - Perfect diamagnetism
  - Values: T_c , H_c , j_c , λ_L
- Microscopic origin
  - Quantum state: θ , ϕ_0
  - Cooper pairs: ξ_0
  - electron-phonon interaction
  - superconducting gap Δ
- Type I and II
  - Ginzburg-Landau parameter κ
  - critical fields H_c , 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

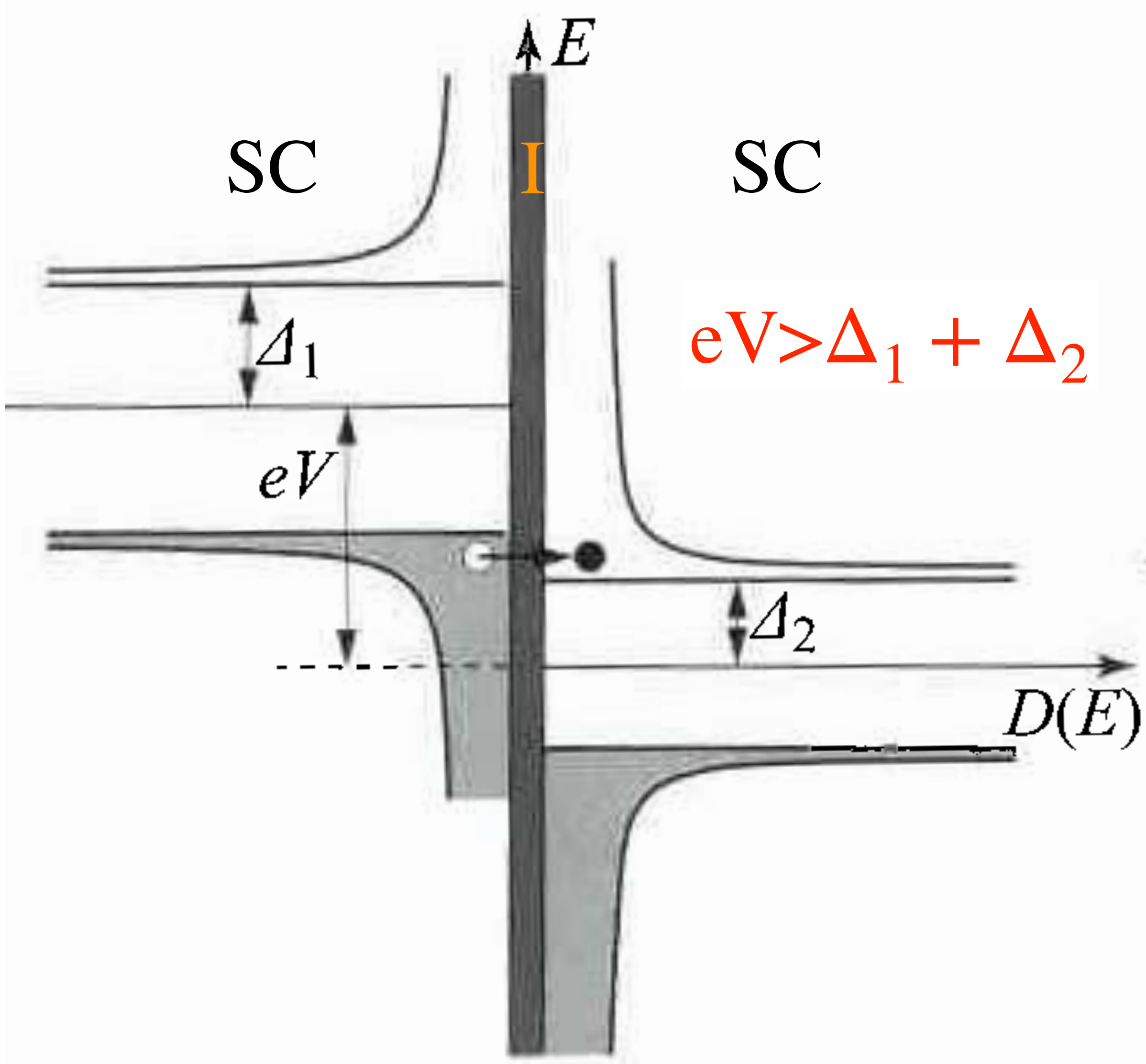
Tunnel effect

Single quasi-particles pass through a SIS or NIS junction

Thin insulating barrier (I)

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





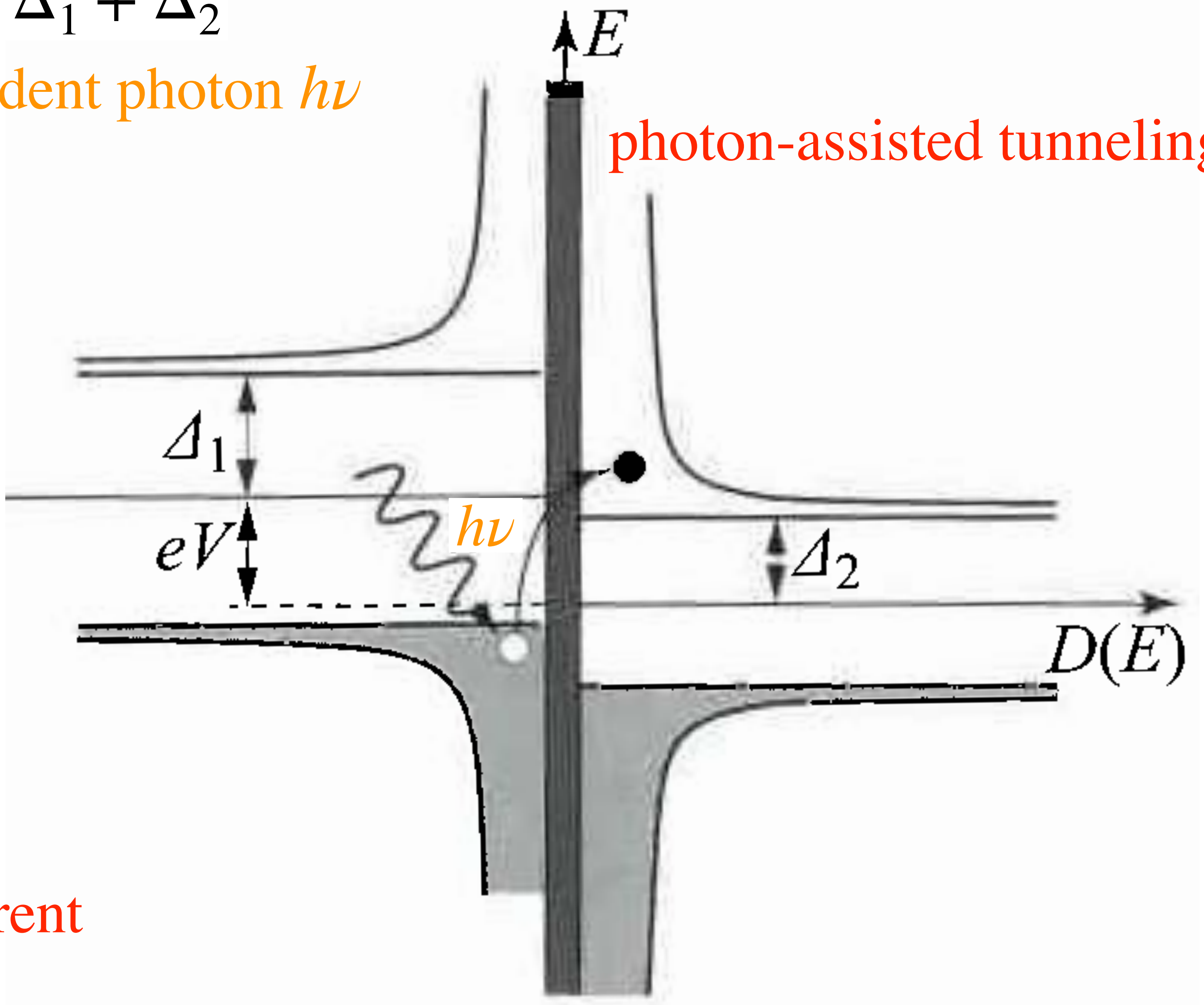
Tunnel effect

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

Thin insulating barrier (I)

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~1mA-10μA for 1meV and R=1-100Ω

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: $\dfrac{d(\varphi_1 - \varphi_2)}{dt} = \dfrac{2eV}{\hbar}$

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

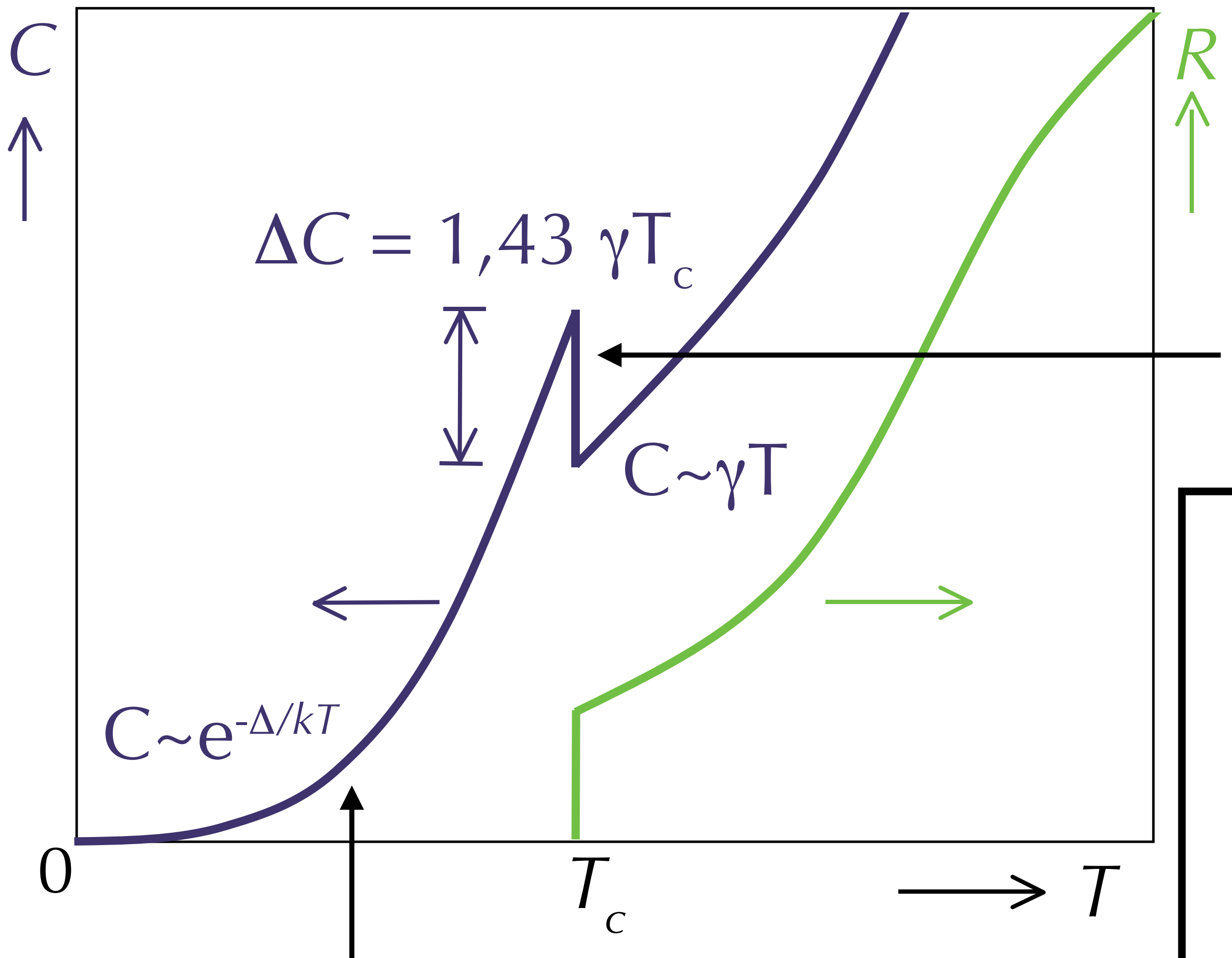
The frequency is $\boxed{\omega = \dfrac{2eV}{\hbar}}$ 483 GHz/mV

Application to *metrology* to determine accurately V.

« Application » to *Shapiro steps*.

Specific heat

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



$$\Delta T = \frac{Q}{C}$$ ← heat absorbed

excess of specific heat at T_c
important for Transition Edge Sensors

low specific heat
interesting for fast absorber

Time response of a detector varies as

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

adjustment of thermal conductivity K !!

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: $\tau = \dfrac{C}{K}$

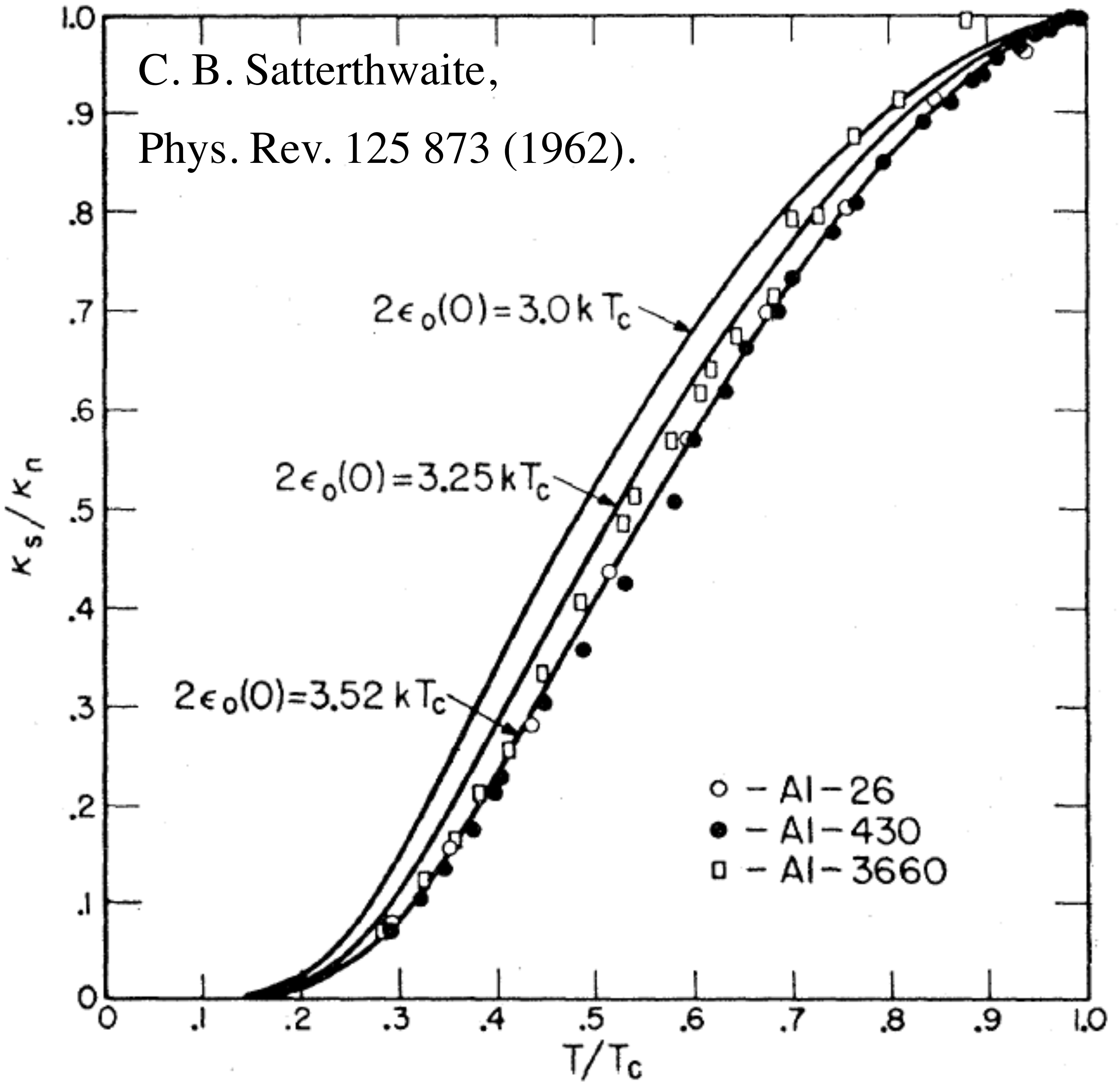


FIG. 3. Ratio of superconducting to normal thermal conductivity for aluminum.

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: $Z = 1/(\sigma d)$

$Z_s = R_s + i\omega L_s$

normal square resistance

Kinetic Inductance (thin film, low T, low ω) :

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

Kinetic Inductance

Thin film of thickness d, low T, low ω :

normal square resistance

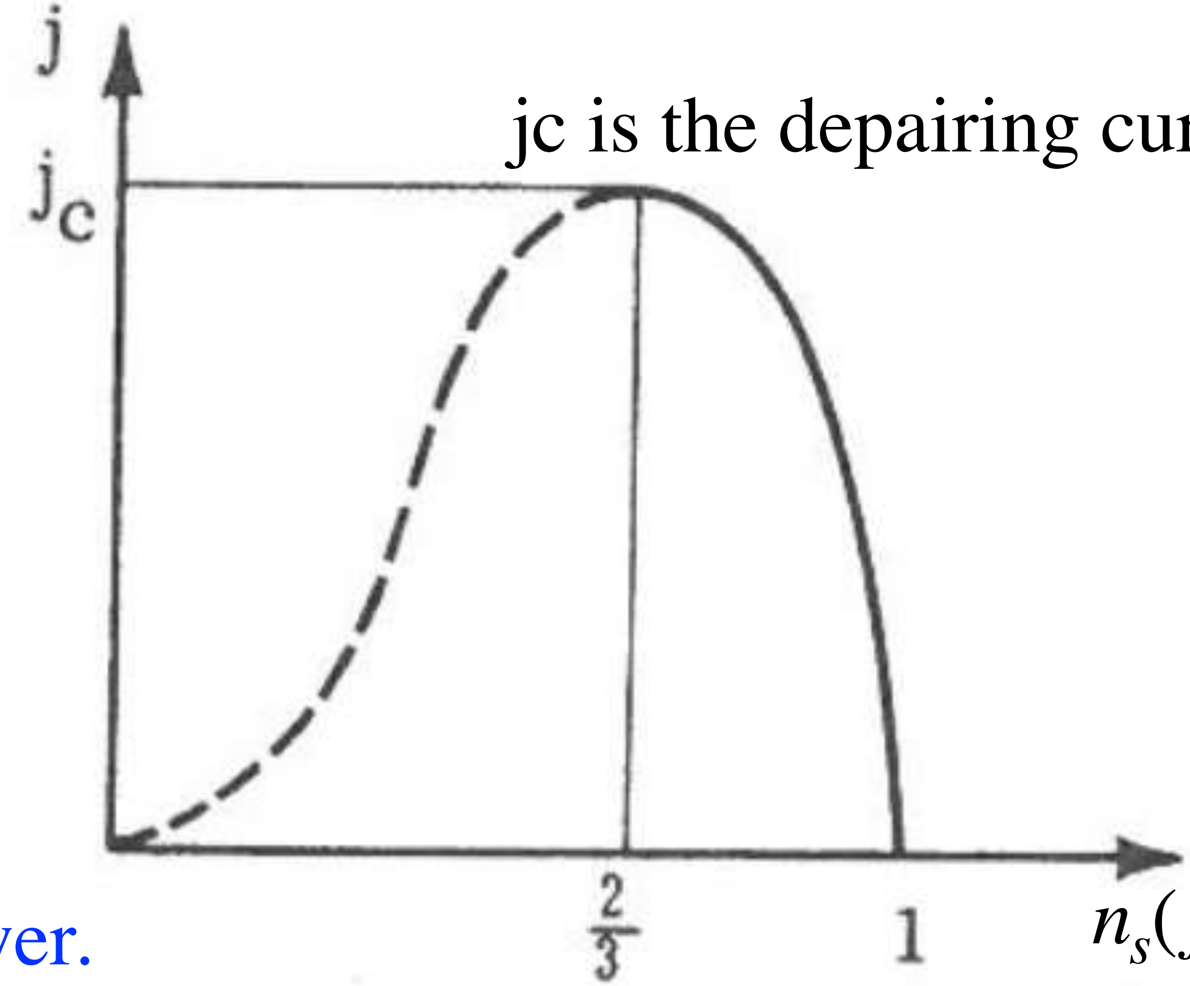
$$L_s = \frac{m}{n_s e^2 d} = \frac{\hbar R}{\pi \Delta}$$

Variation with current : $L_s(j) = L_s(0)(1 + j^2/j_*^2 + \dots)$ $\quad j_* = \frac{3\sqrt{3}}{2} j_c$

coming from variation of $n_s(j)$:

jc is the depairing current

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

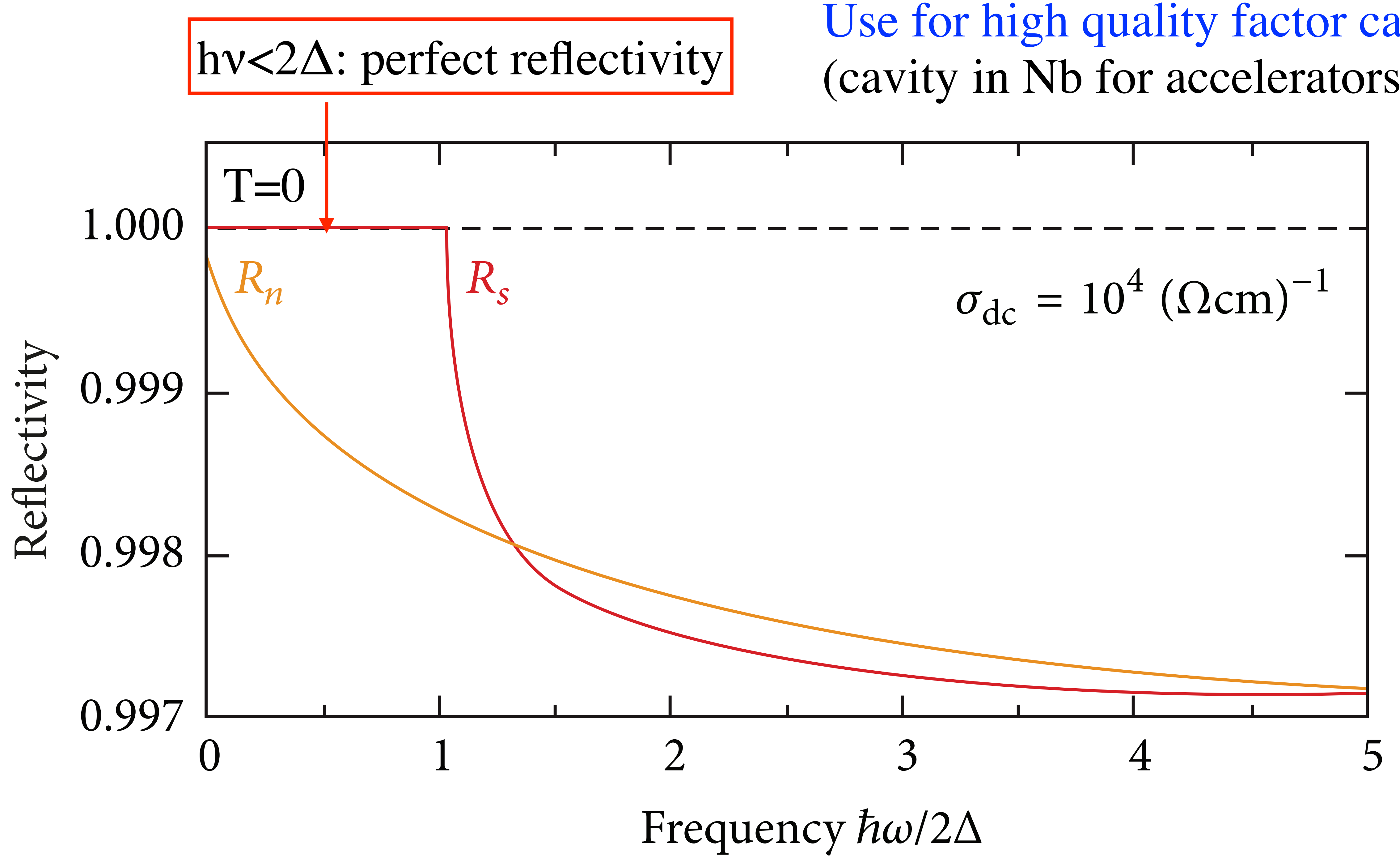


At play when setting the readout power.

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

Reflectivity

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

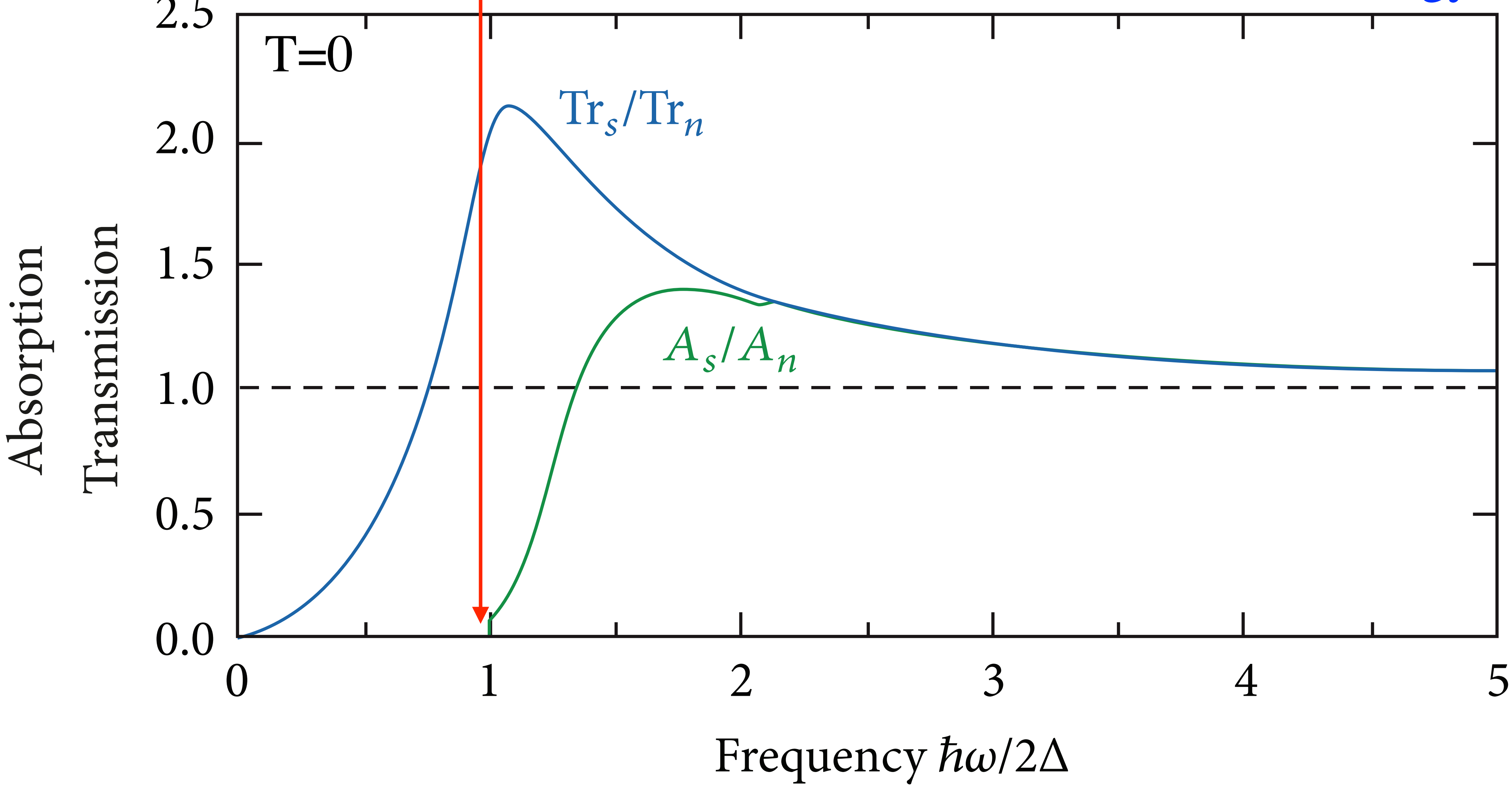


M. Dressel, Electrodynamics of Metallic Superconductors, Adv. in Cond. Mat. Physics (2013).

Absorption

2Δ: absorption threshold for photon

In KID: 2Δ minimum energy detected.



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Superconducting elements

T_c Superconducting

T_c under pressure

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

Ferro- or antiferromagnetic

courtesy, Hervé Cercellier

Some superconductors

	T_c (K)	$\lambda(0)$ (nm)	$\xi(0)$(nm)	κ
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_2B_2C	15	103	8.1	12.7
Nb_3Ge	23.2	90	3	30
K_3C_{60}	19.4	240	2.8	95
$YBa_2Cu_3O_{7-\delta}$	91	156	1.65	95

courtesy, Hervé Cercellier

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- «Cours de supraconductivité», T. Klein Institut Néel Grenoble
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Conclusion

Questions?

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THANKS

Questions?

Questions?

Questions?