

Quand la physique quantique devient macroscopique

Le Prix Nobel 2025

Lauréats 2025:

John Clarke

Michel H. Devoret

John M. Martinis

"for the discovery of
**macroscopic quantum
mechanical tunnelling and
energy quantisation** in an
electric circuit"



John Clarke



Michel H. Devoret



John M. Martinis



Objectifs et étapes du séminaire

Objectifs:

- ▶ Décrypter l'effet tunnel et la quantification
- ▶ Découvrir un état quantique macroscopique
- ▶ Apprécier les travaux de John Clarke, Michel H. Devoret, John M. Martinis



Au menu du jour:

- ▶ Mécanique quantique (Schrödinger et Heisenberg)
- ▶ La quantification des états et l'effet tunnel
- ▶ La supraconductivité et les jonctions Josephson
- ▶ Découvertes majeures de 1985

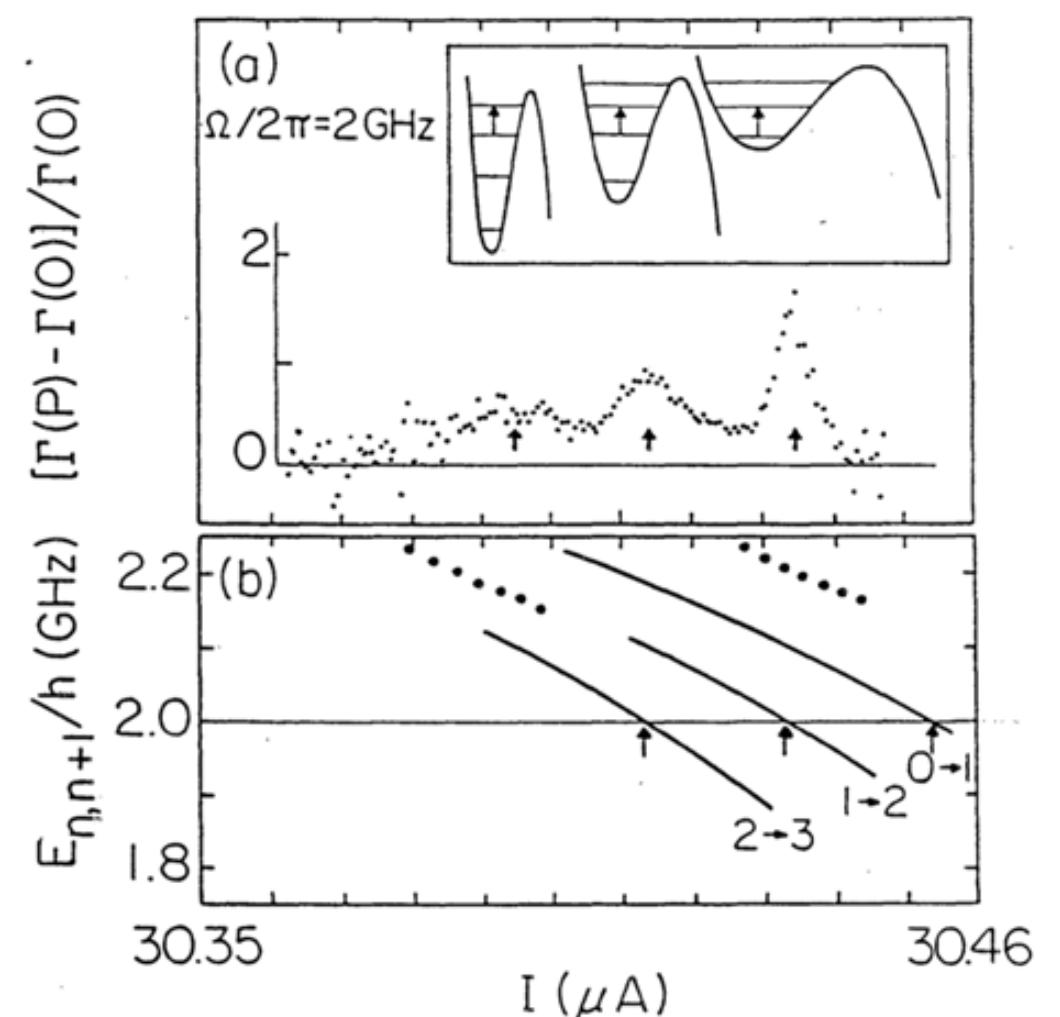
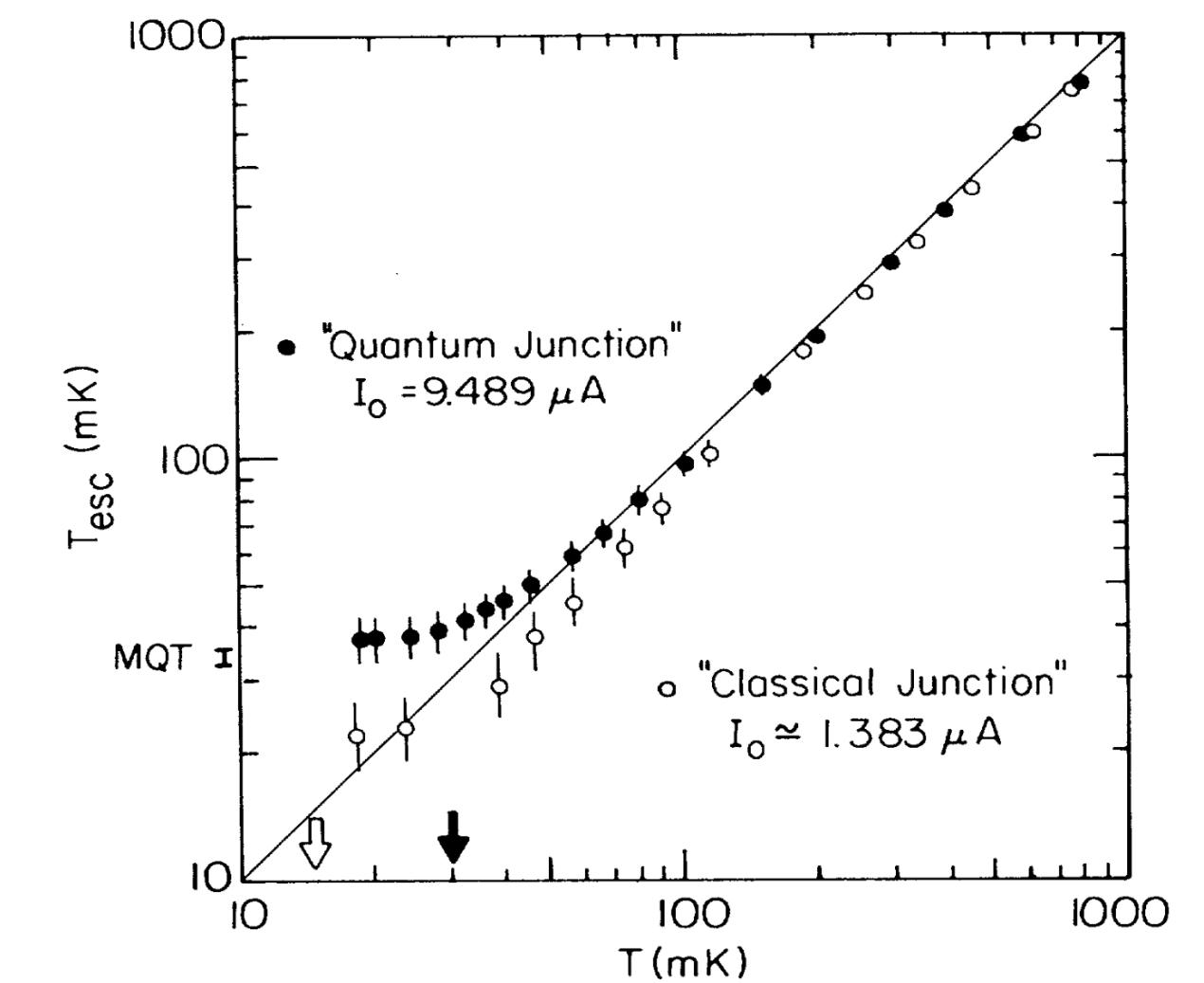
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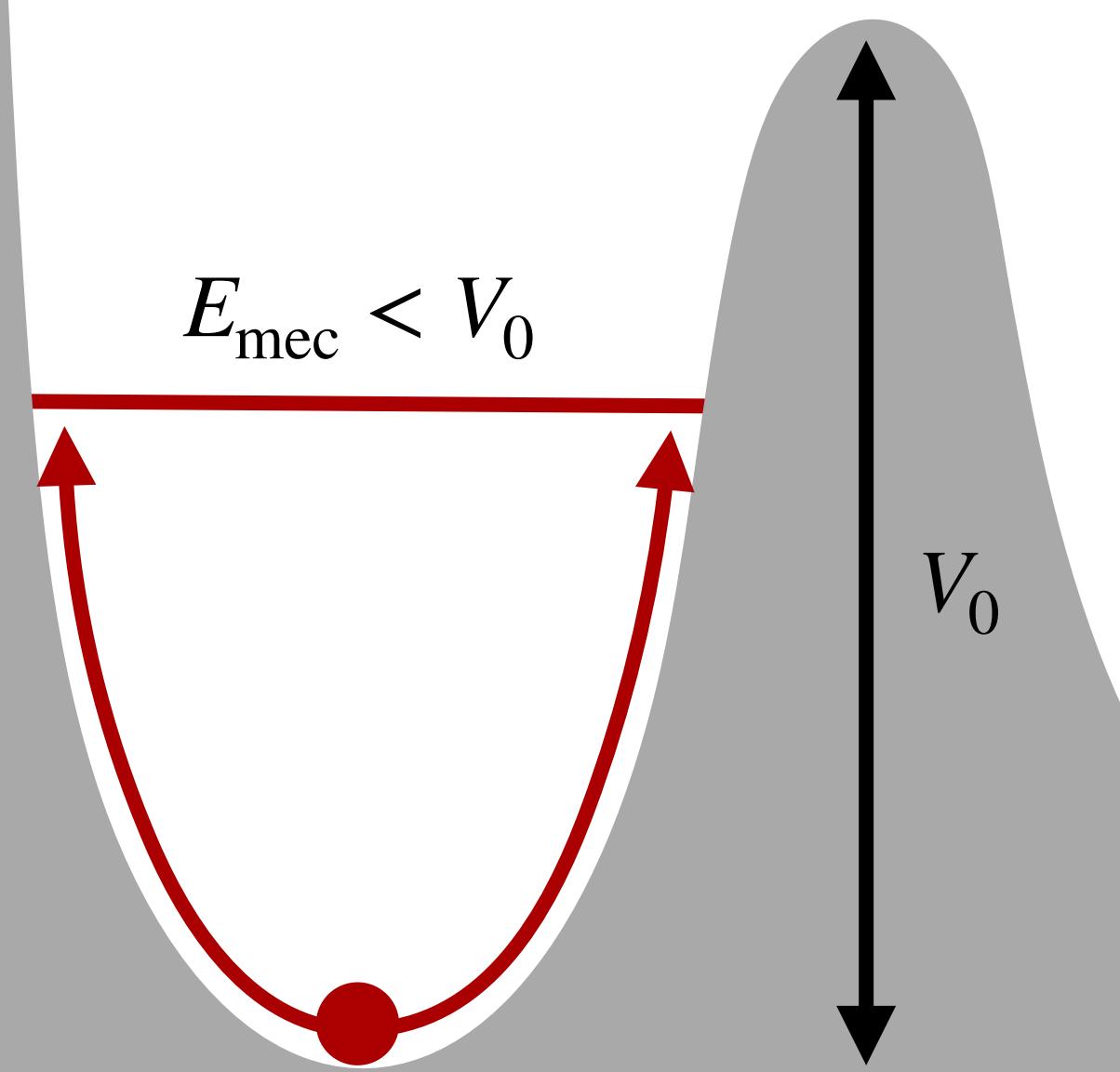
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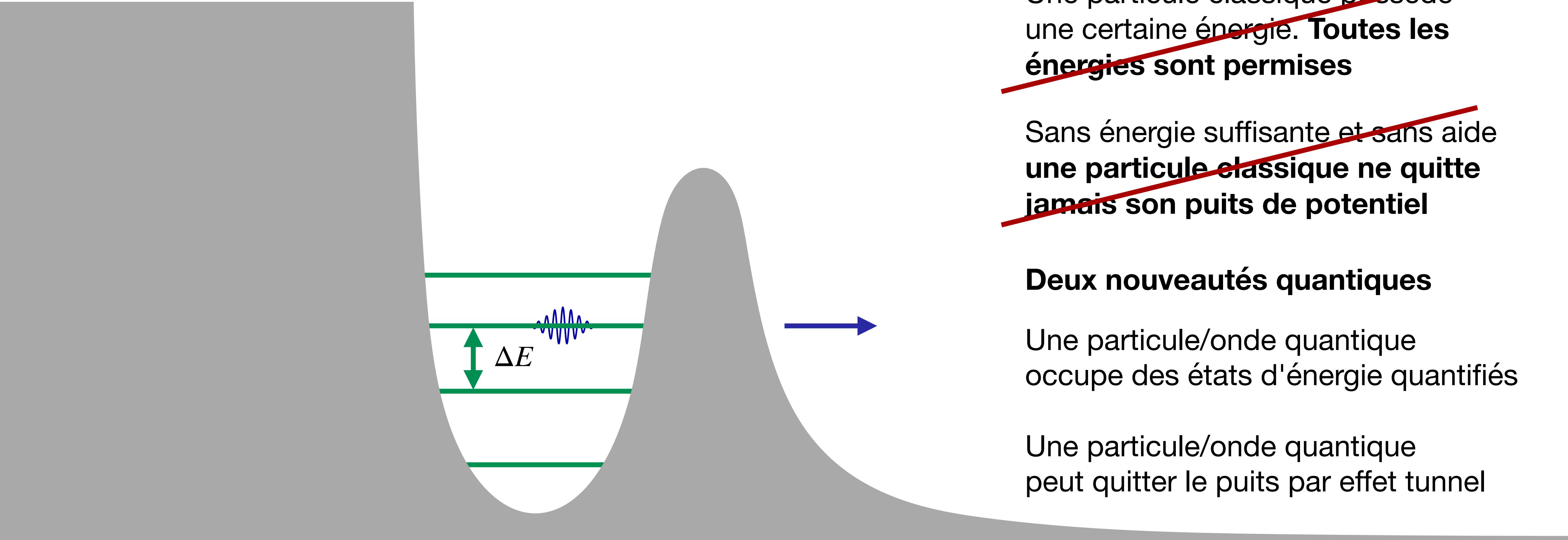


J. M. Martinis, M. H. Devoret, J. Clarke, PRL **55**, 1543 (1985),
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Une particule classique possède une certaine énergie. **Toutes les énergies sont permises**

Sans énergie suffisante et sans aide une particule classique ne quitte jamais son puits de potentiel





Werner Heisenberg (24 ans)

- ▶ À Göttingen, il travaille avec Max Born, Wolfgang Pauli, Paul Dirac, Enrico Fermi, et Robert Oppenheimer
- ▶ Été 1925, en retraite à Helgoland, il découvre une description matricielle de la mécanique quantique
- ▶ Peu de personnes le comprennent

$$\frac{d}{dt} A(t) = \frac{i}{\hbar} [H(t), A(t)]$$

Erwin Schrödinger (38 ans)

- ▶ En 'retraite' dans un chalet aux Grisons, il établit une équation d'onde pour décrire des particules
- ▶ Mathématiquement plus accessible

$$i\hbar \frac{d}{dt} \Psi(x, t) = \hat{H} \Psi(x, t)$$



L'équation de Schrödinger indépendante du temps

$$E \psi(x) = \hat{H}\psi(x)$$

$$\begin{aligned} \hat{H} &= \frac{-\hbar^2}{2m} \frac{d^2}{dx^2} + V(x) && \text{version quantique de l'énergie mécanique} \\ E_{\text{mec}} &= \frac{p^2}{2m} + E_{\text{pot}}(x) && p = mv \text{ devient } \hat{p} = -i\hbar\partial_x \end{aligned}$$

La fonction d'onde ψ (ou plutôt $|\psi(x)|^2$) donne la probabilité de trouver la particule/onde au point x

E est l'énergie de la particule/onde



L'équation de Schrödinger indépendante du temps

$$\textcolor{green}{E} \psi(x) = \hat{H}\psi(x)$$

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La fonction d'onde ψ (ou plutôt $|\psi(x)|^2$) donne la probabilité de trouver la particule/onde au point x

$\textcolor{green}{E}$ est l'énergie de la particule/onde

Pour $V(x) = \text{const}$

$$\frac{-\hbar^2}{2m} \frac{d^2\psi}{dx^2} = [\textcolor{green}{E} - V]\psi(x)$$

les solutions fondamentales sont

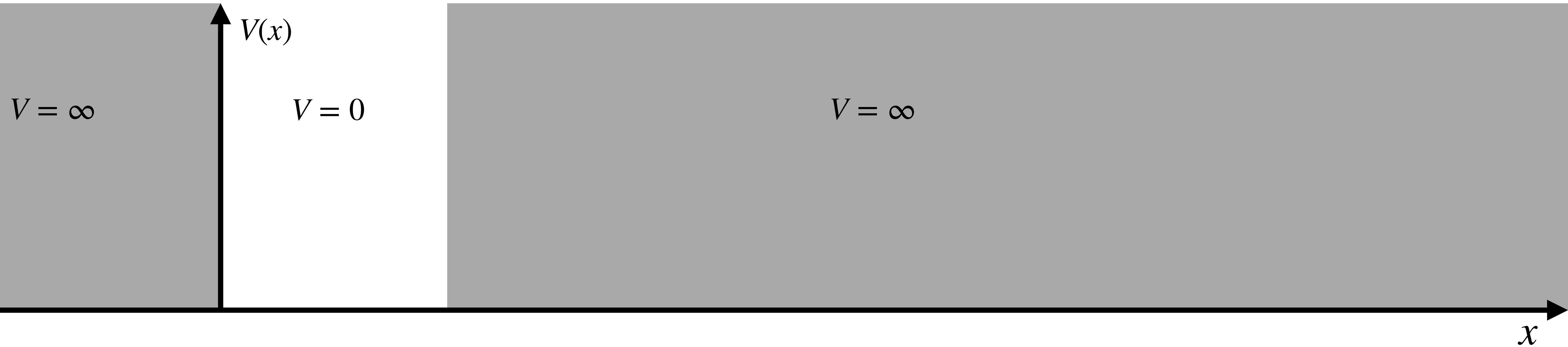
$$\psi_{\pm}(x) = \exp\left(\pm i\sqrt{2m(\textcolor{green}{E}-V)} x/\hbar\right) \Leftrightarrow \sin(\pm\sqrt{2m(\textcolor{green}{E}-V)} x/\hbar)$$



L'équation de Schrödinger: Particule dans une boîte

$$\frac{-\hbar^2}{2m} \frac{d^2\psi}{dx^2} = E\psi(x)$$

$$\psi_{\pm}(x) = \exp(\pm i\sqrt{2mE}x/\hbar) \Leftrightarrow \sin(\sqrt{2mE}x/\hbar)$$



$$\psi = 0$$

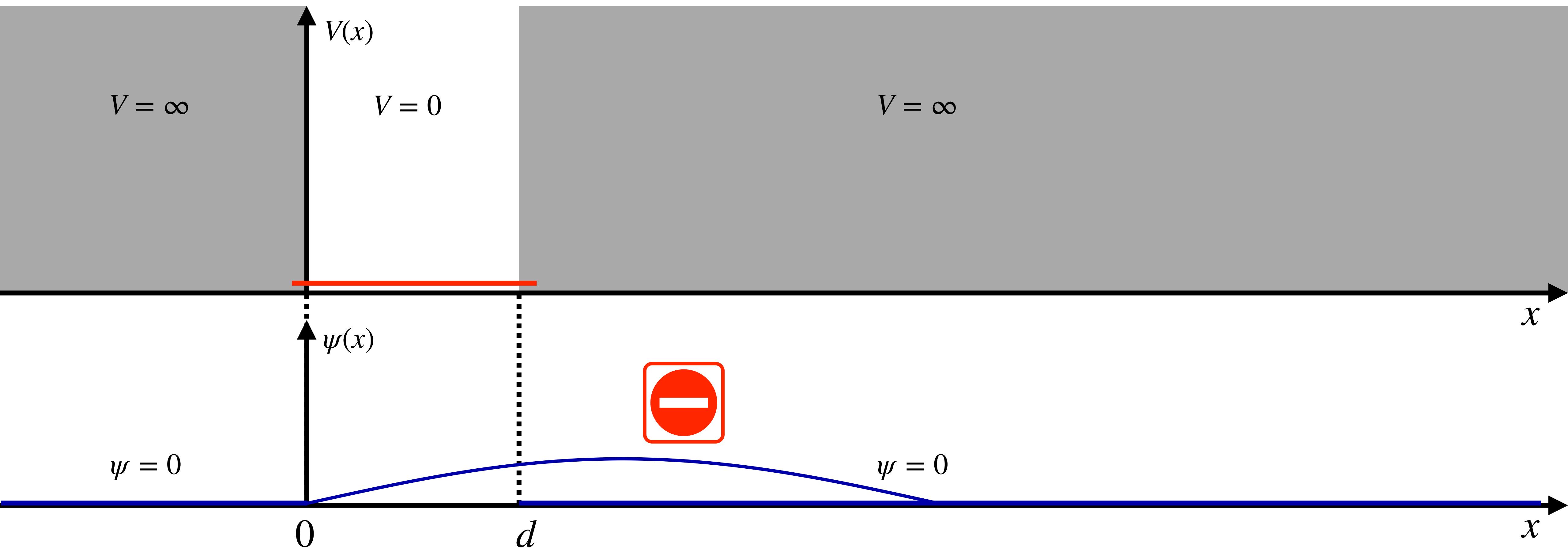
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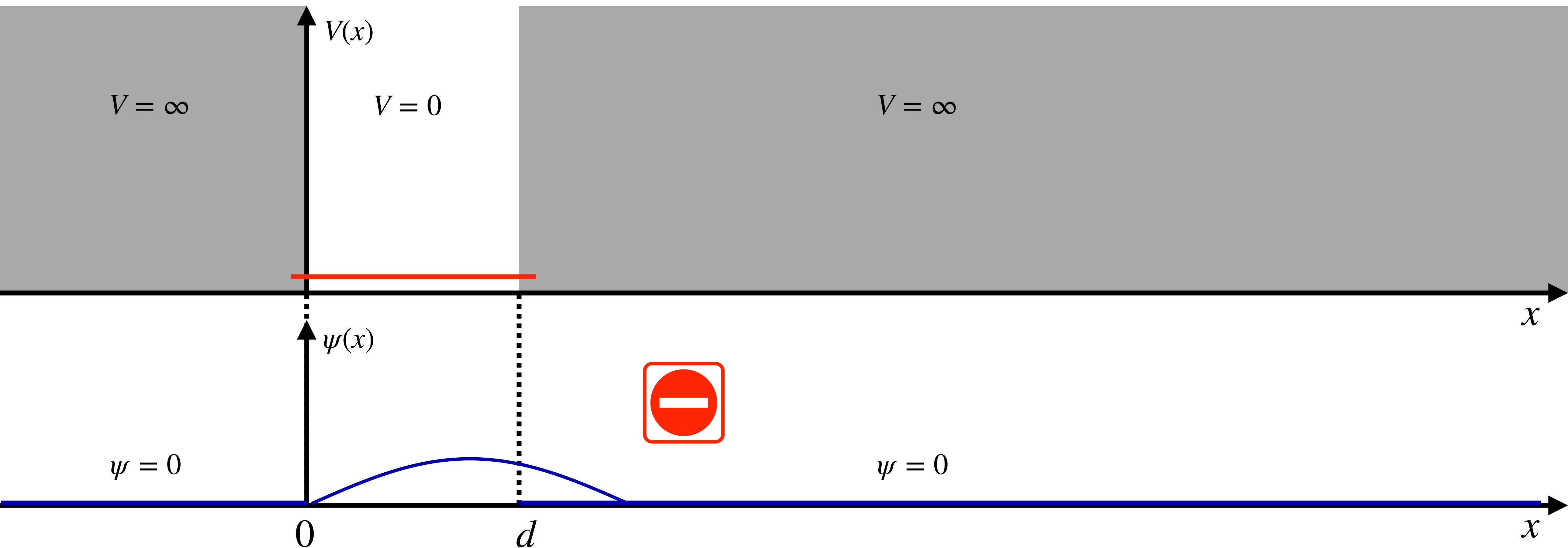
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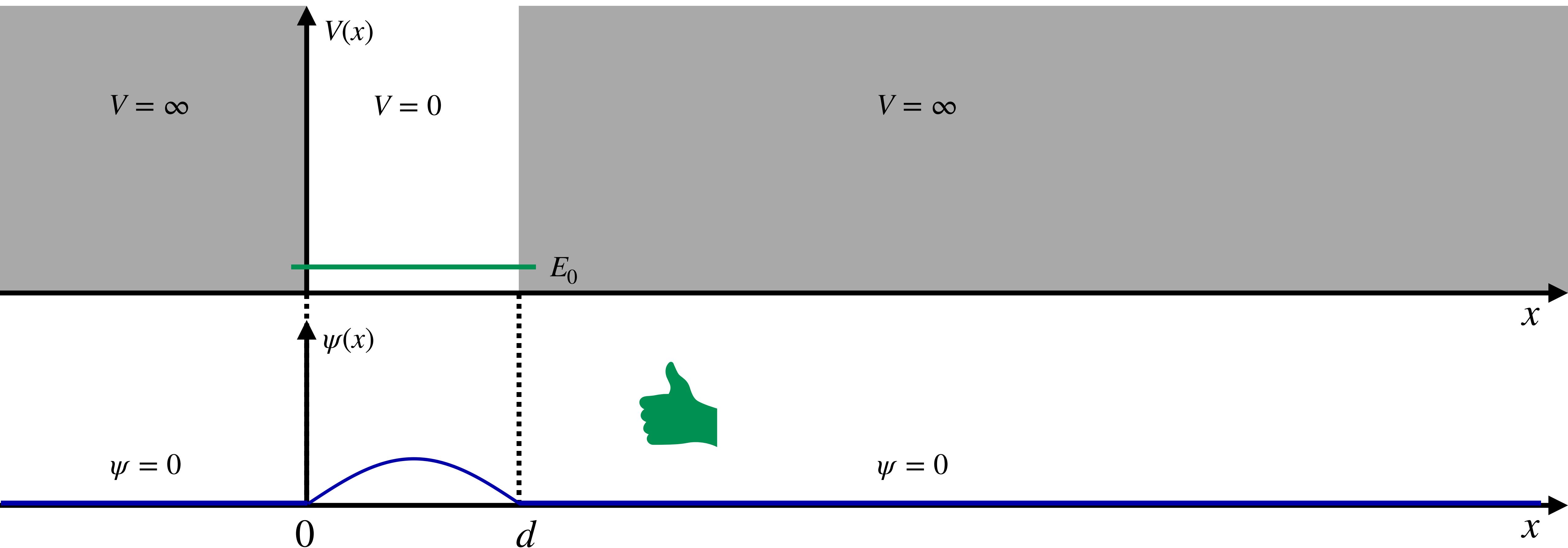
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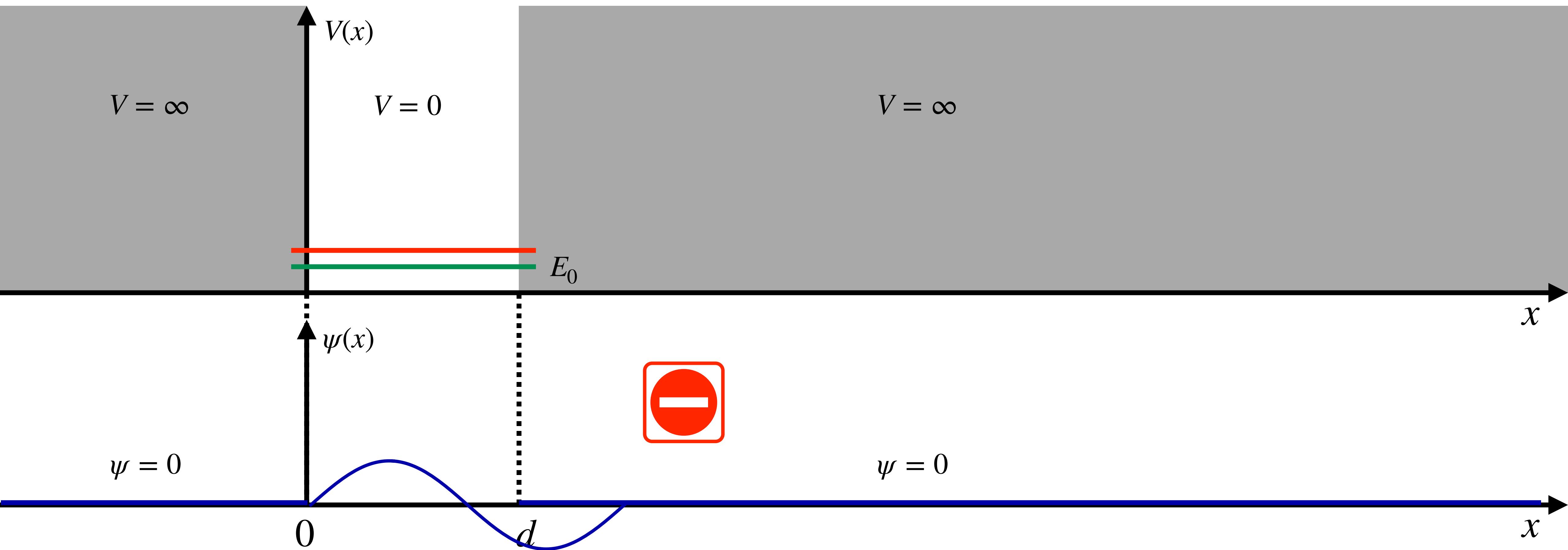
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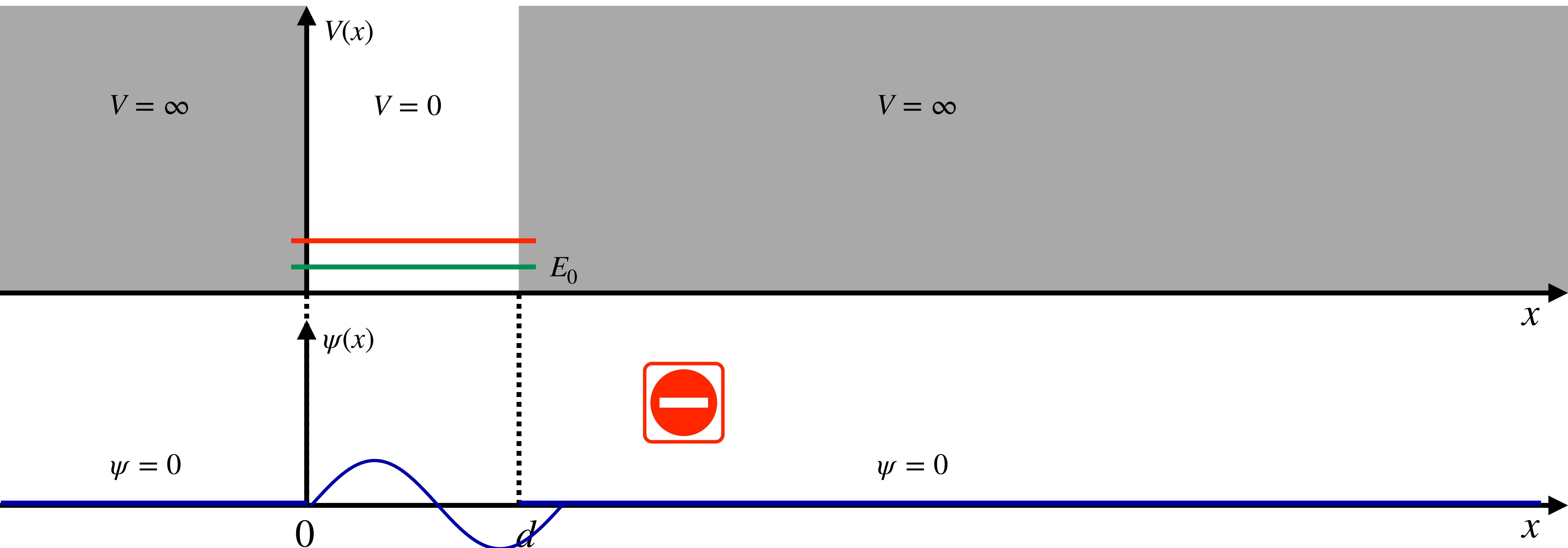
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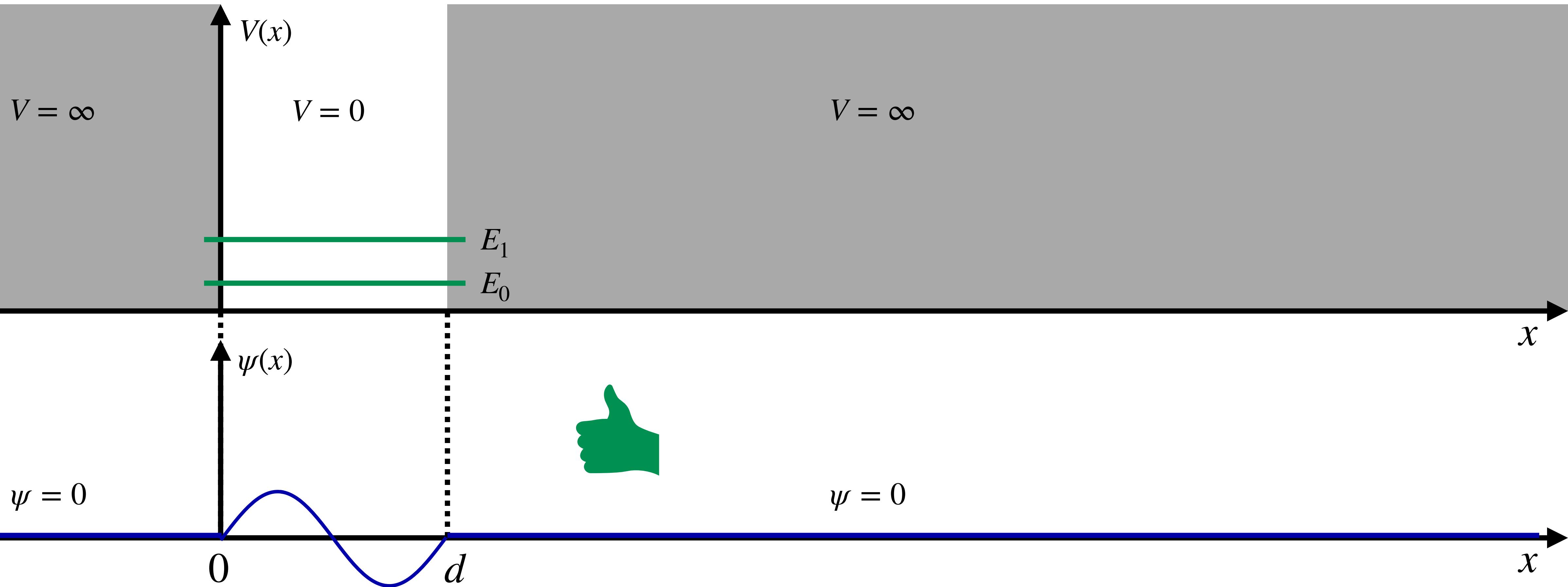
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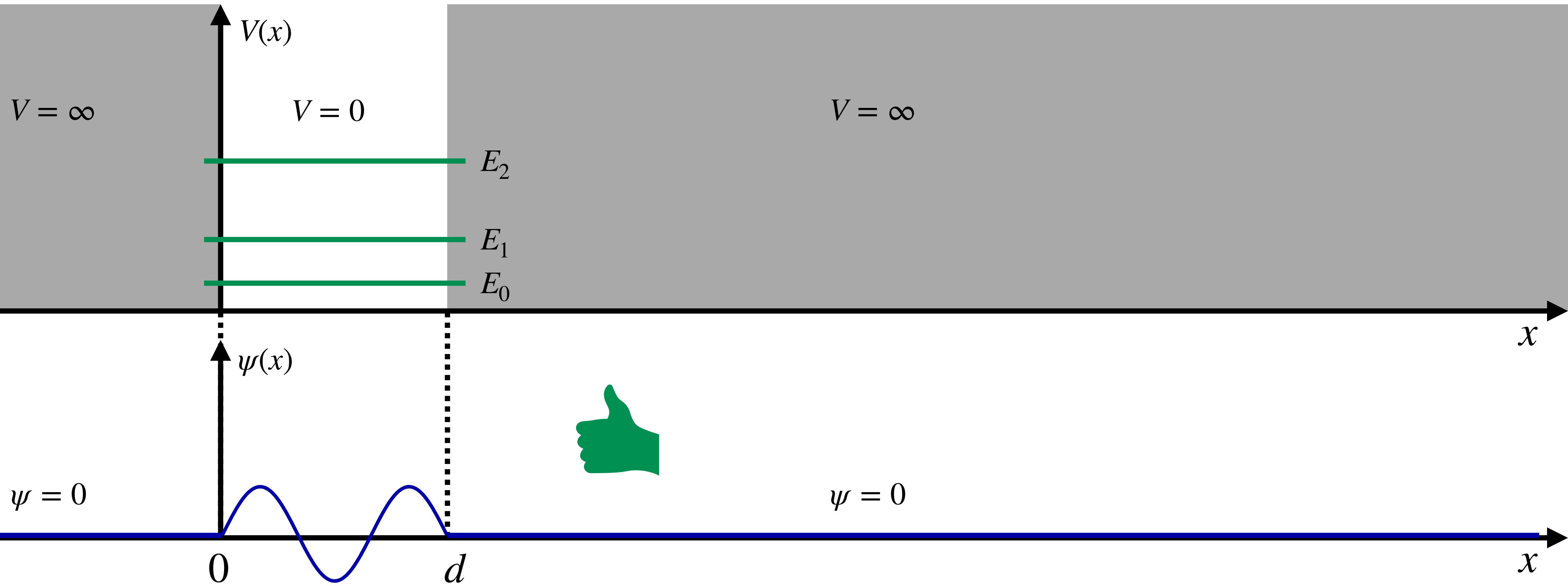
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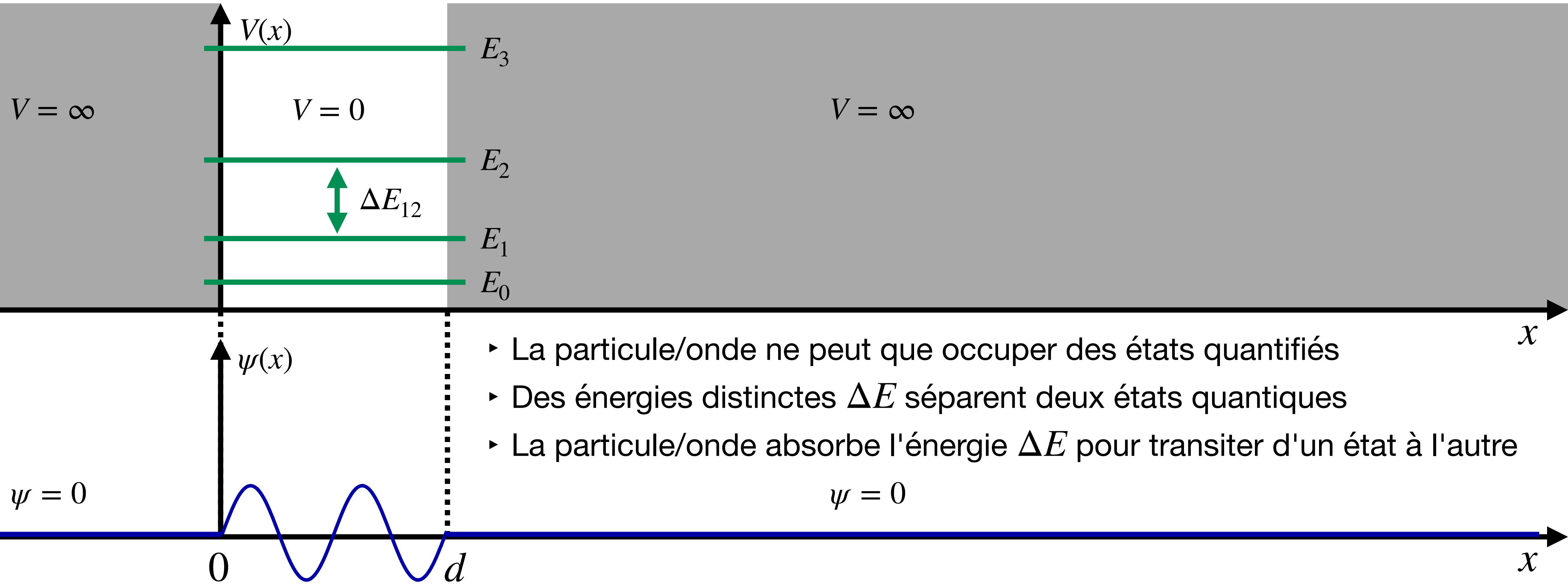
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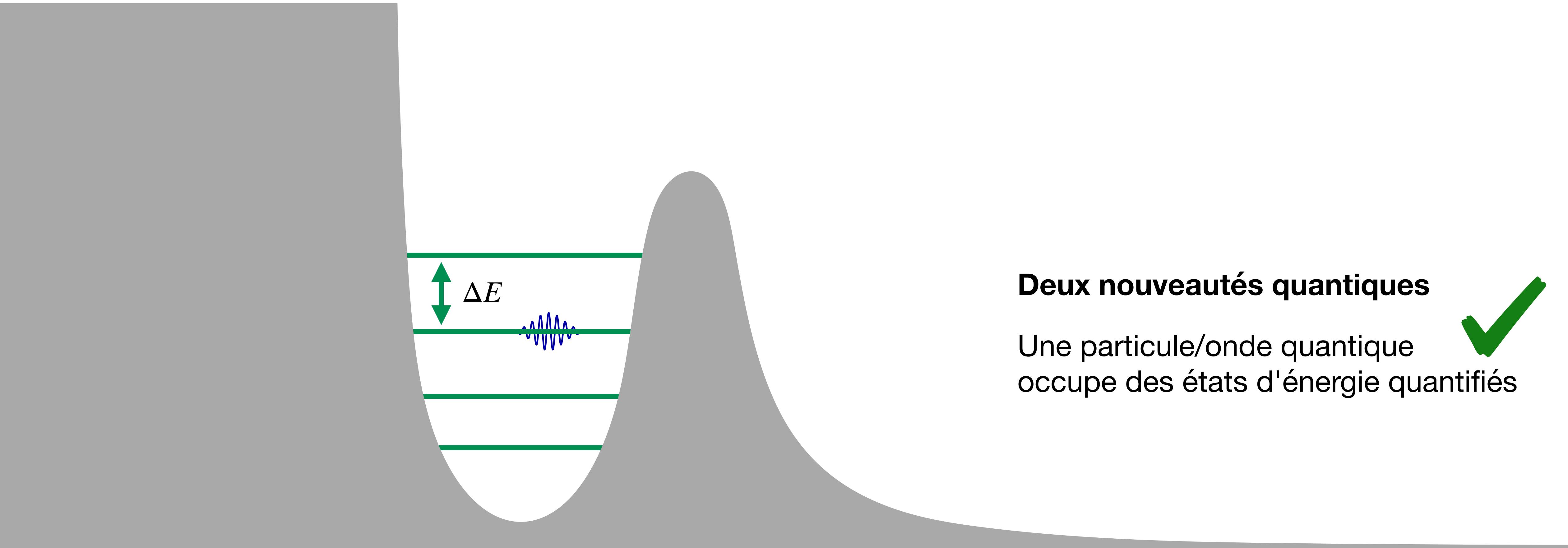
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L'équation de Schrödinger: Particule dans une boîte



L'équation de Schrödinger: L'effet tunnel

$$\frac{-\hbar^2}{2m} \frac{d^2\psi}{dx^2} = (E - V)\psi(x)$$

$$\psi_{\pm}(x) = \exp\left(\pm i\sqrt{2m(E-V)}x/\hbar\right)$$

$$V = 0$$

$$V = V_0$$

$$V = 0$$

$$E$$

x



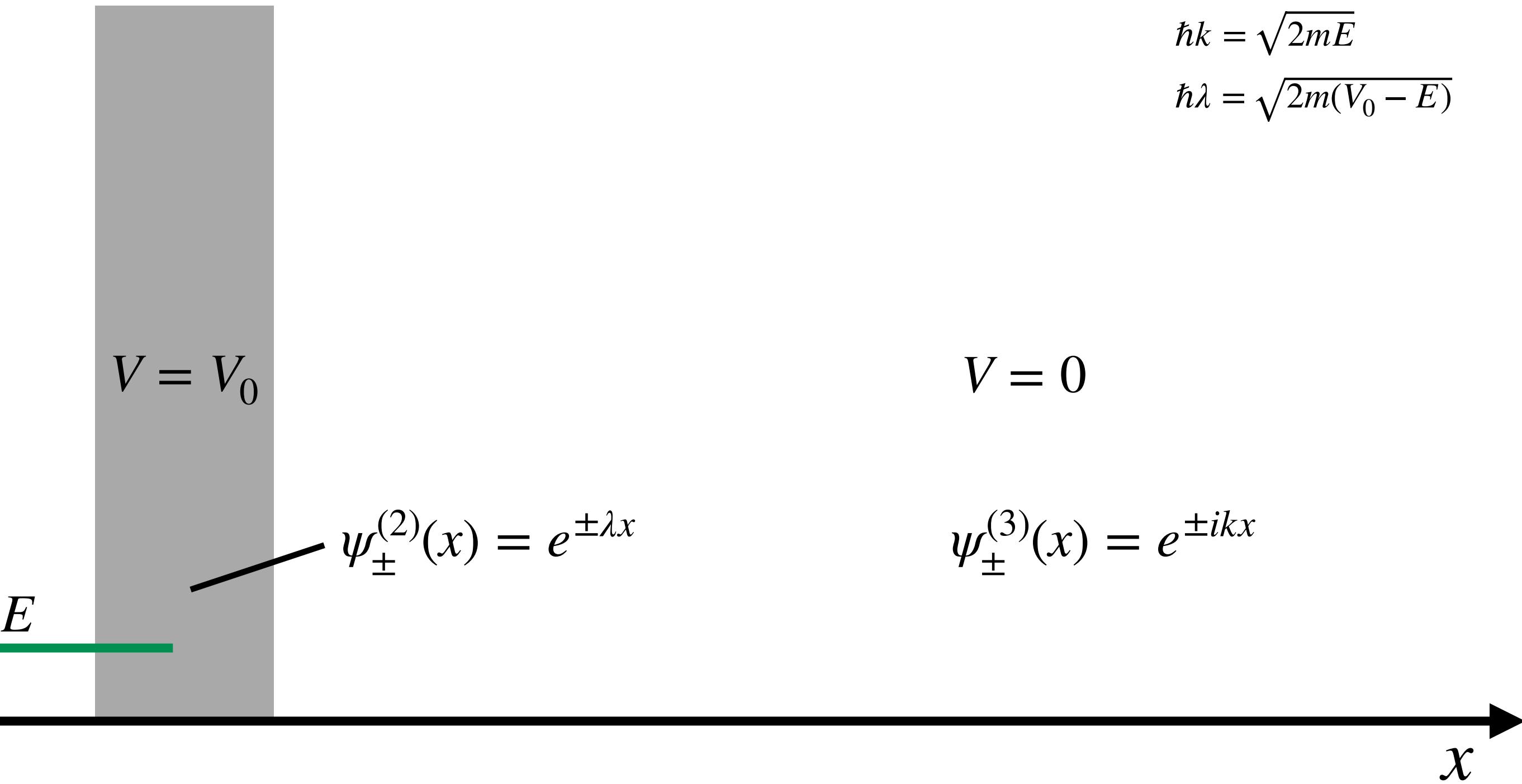
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$$V = 0$$

$$\psi_{\pm}^{(1)}(x) = e^{\pm ikx}$$



$$\hbar k = \sqrt{2mE}$$

$$\hbar\lambda = \sqrt{2m(V_0 - E)}$$



L'équation de Schrödinger: L'effet tunnel

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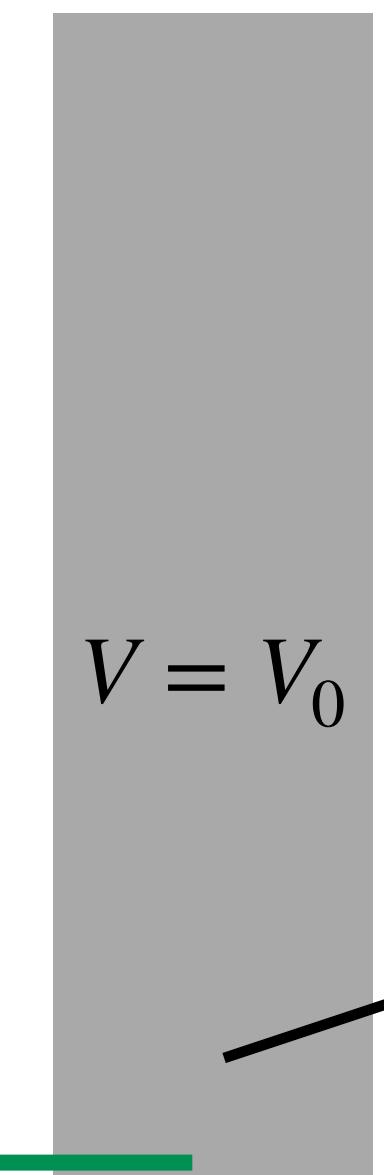
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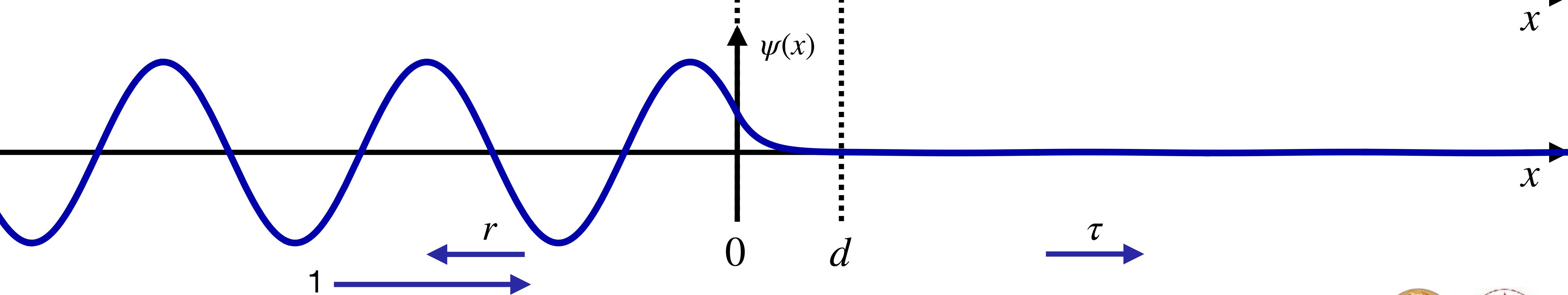
$$\hbar\lambda = \sqrt{2m(V_0 - E)}$$

$$V = 0$$

$$\psi_{\pm}^{(1)}(x) = e^{\pm ikx}$$



$$V = 0$$



$$\psi^{(1)}(x) = e^{ikx} + re^{-ikx}$$

$$\psi^{(3)}(x) = \tau e^{ikx}$$



L'équation de Schrödinger: L'effet tunnel

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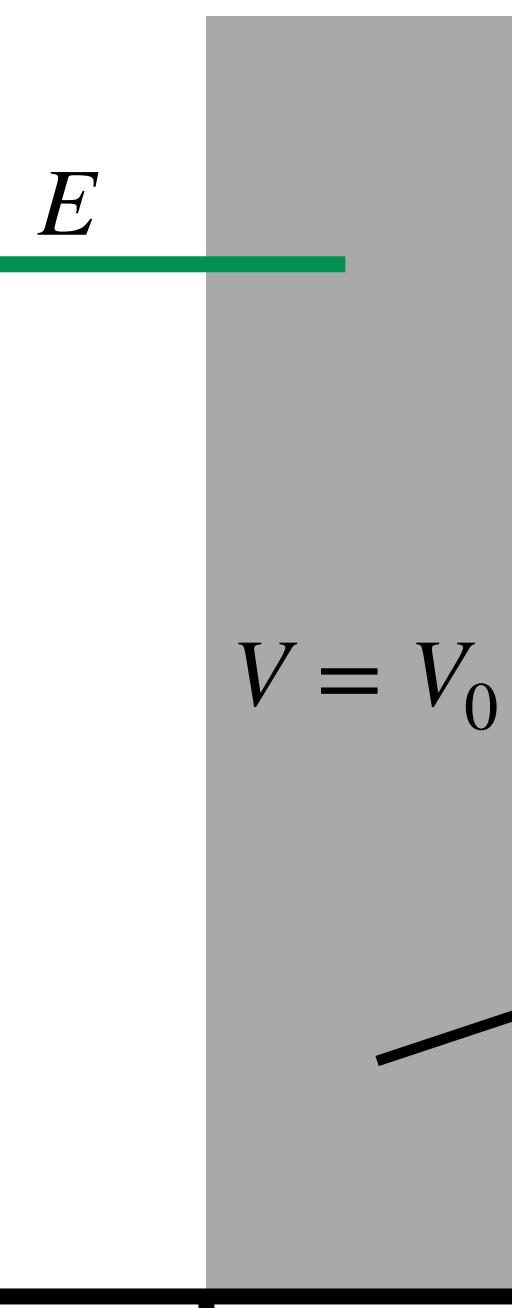
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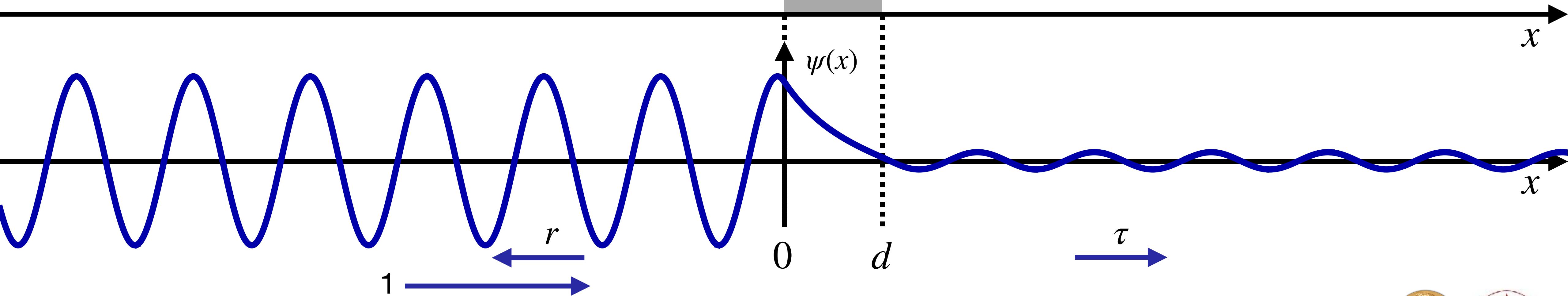
$$\psi_{\pm}^{(1)}(x) = e^{\pm ikx}$$



$$V = 0$$

$$\psi_{\pm}^{(2)}(x) = e^{\pm \lambda x}$$

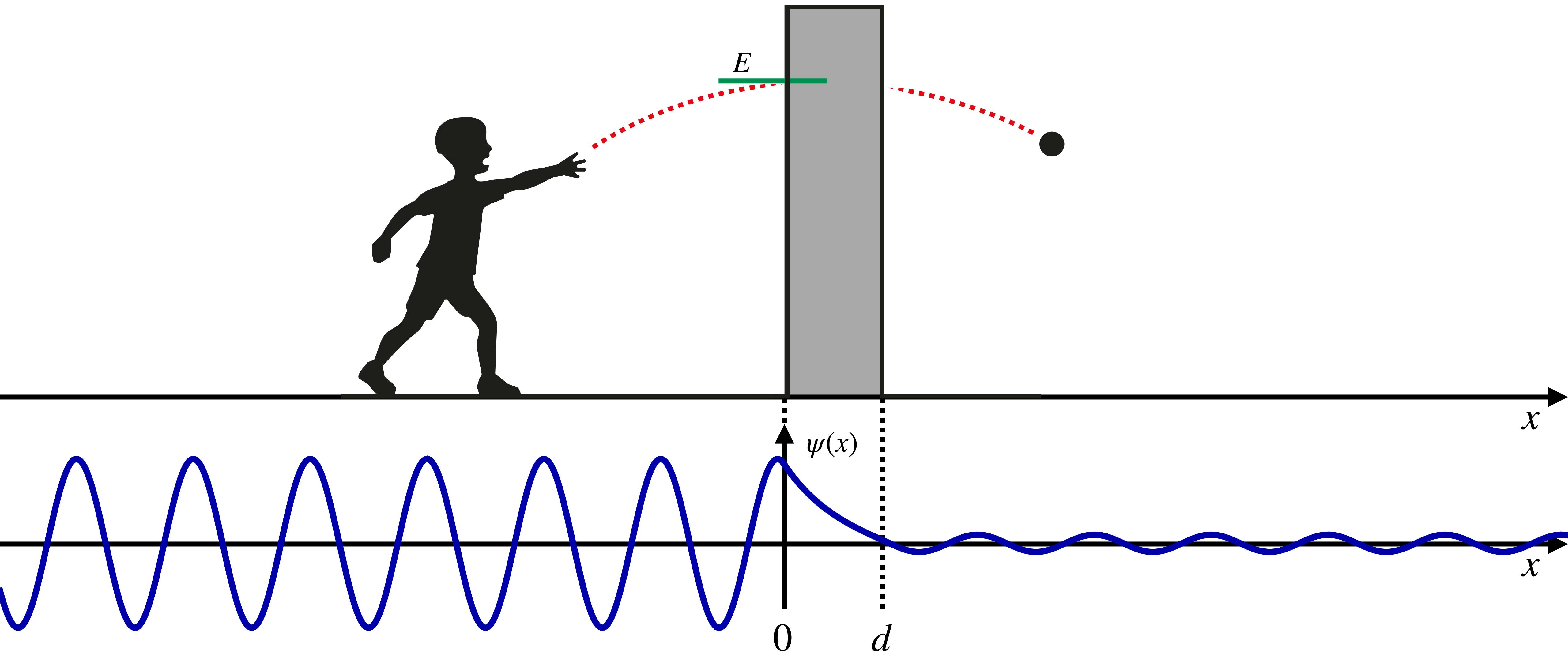
$$\psi_{\pm}^{(3)}(x) = e^{\pm ikx}$$

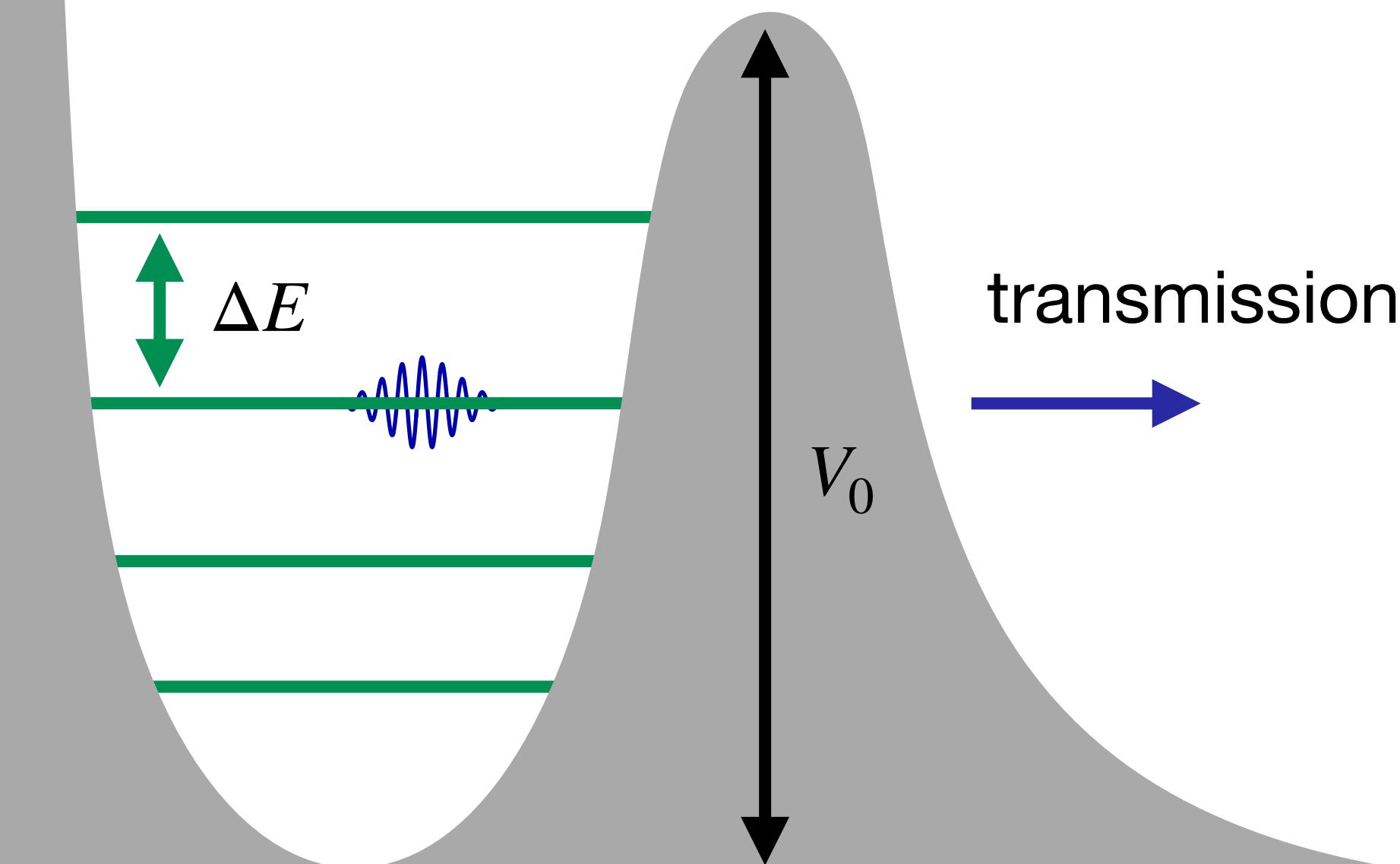


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L'équation de Schrödinger: L'effet tunnel





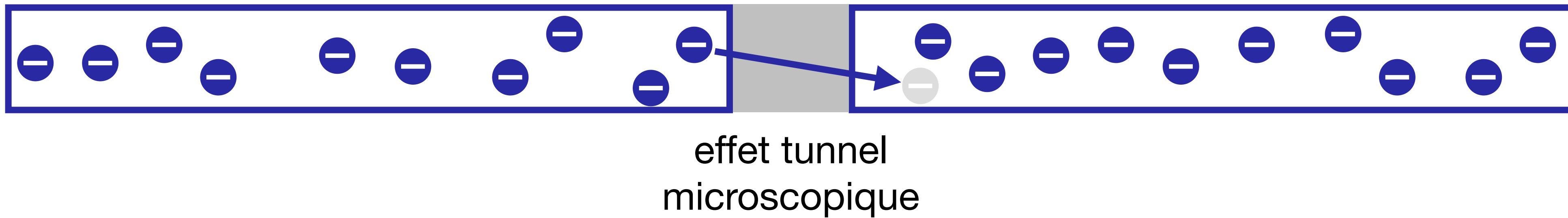
Deux nouveautés quantiques

Une particule/onde quantique occupe des états d'énergie quantifiés

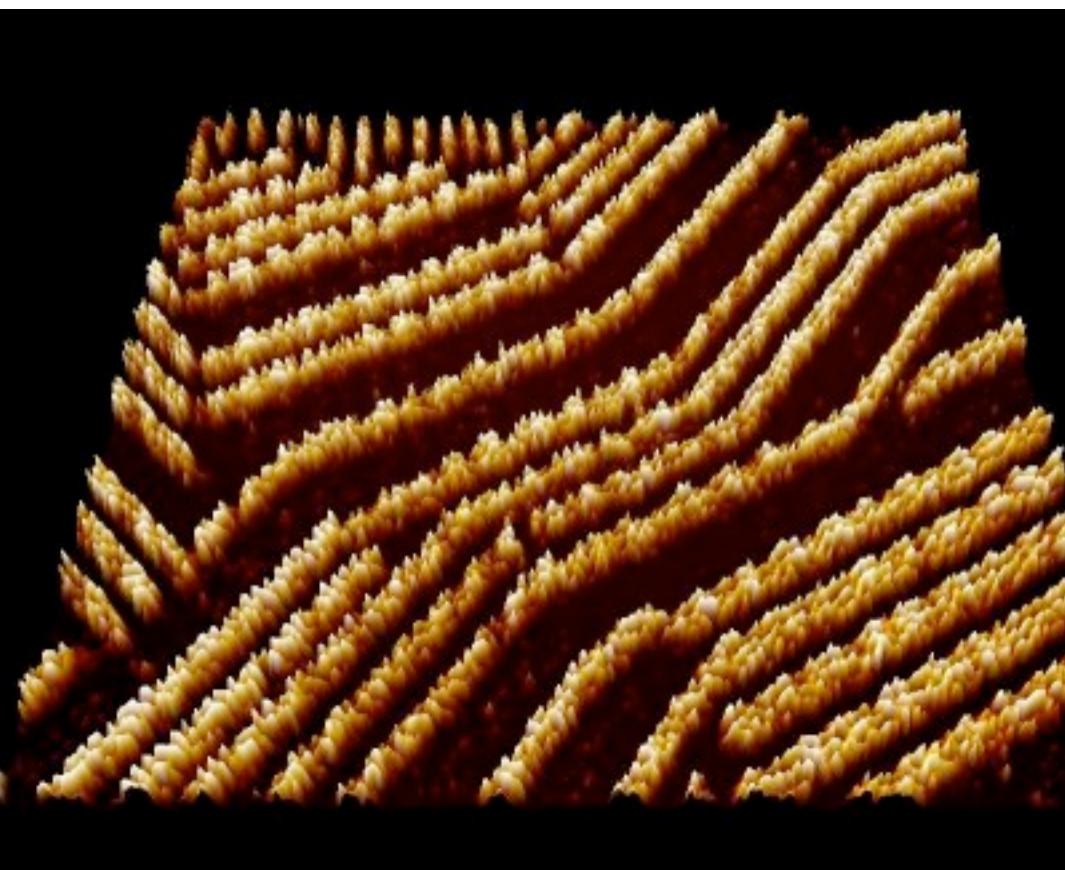
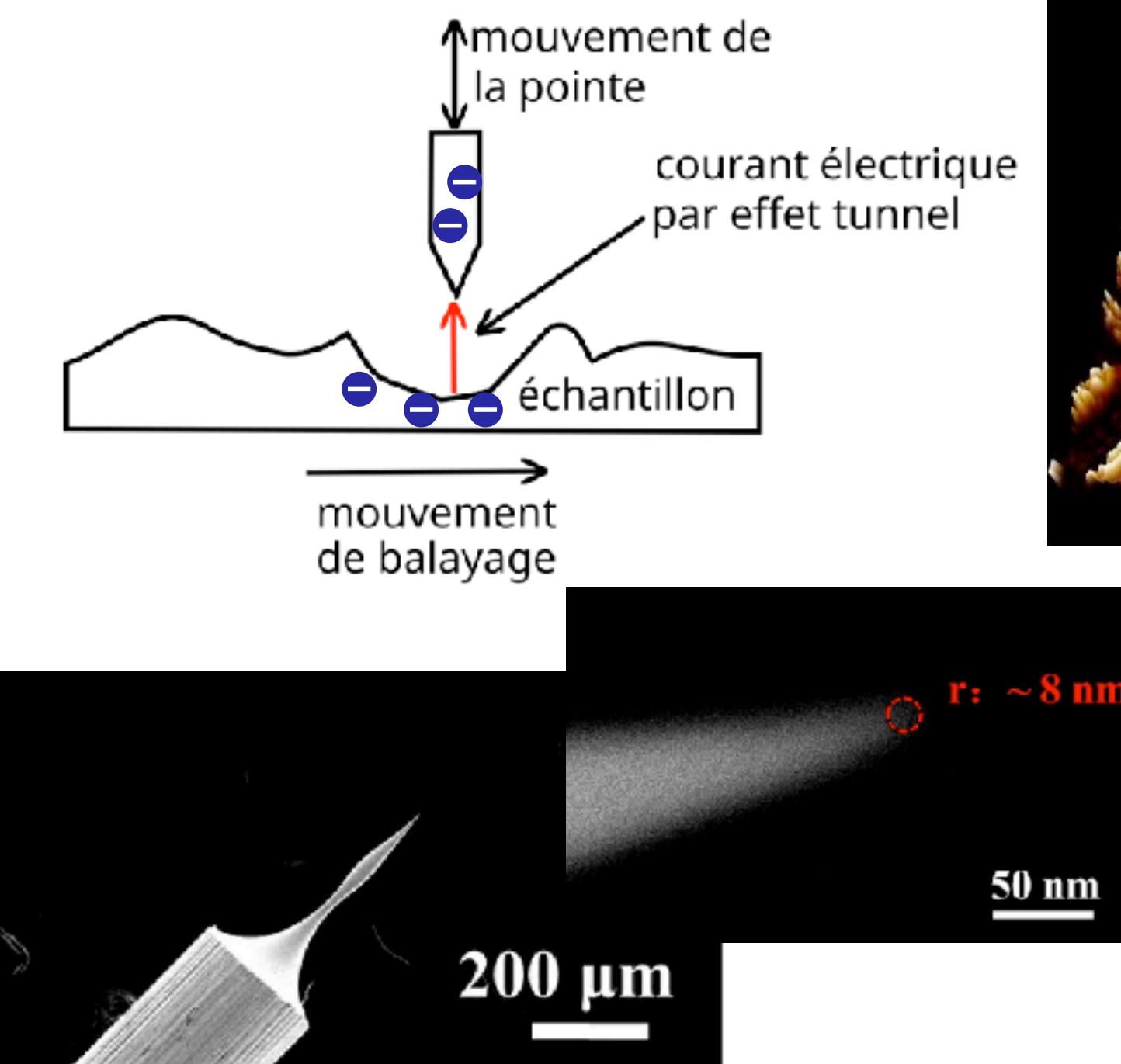
Une particule/onde quantique peut quitter le puits par effet tunnel



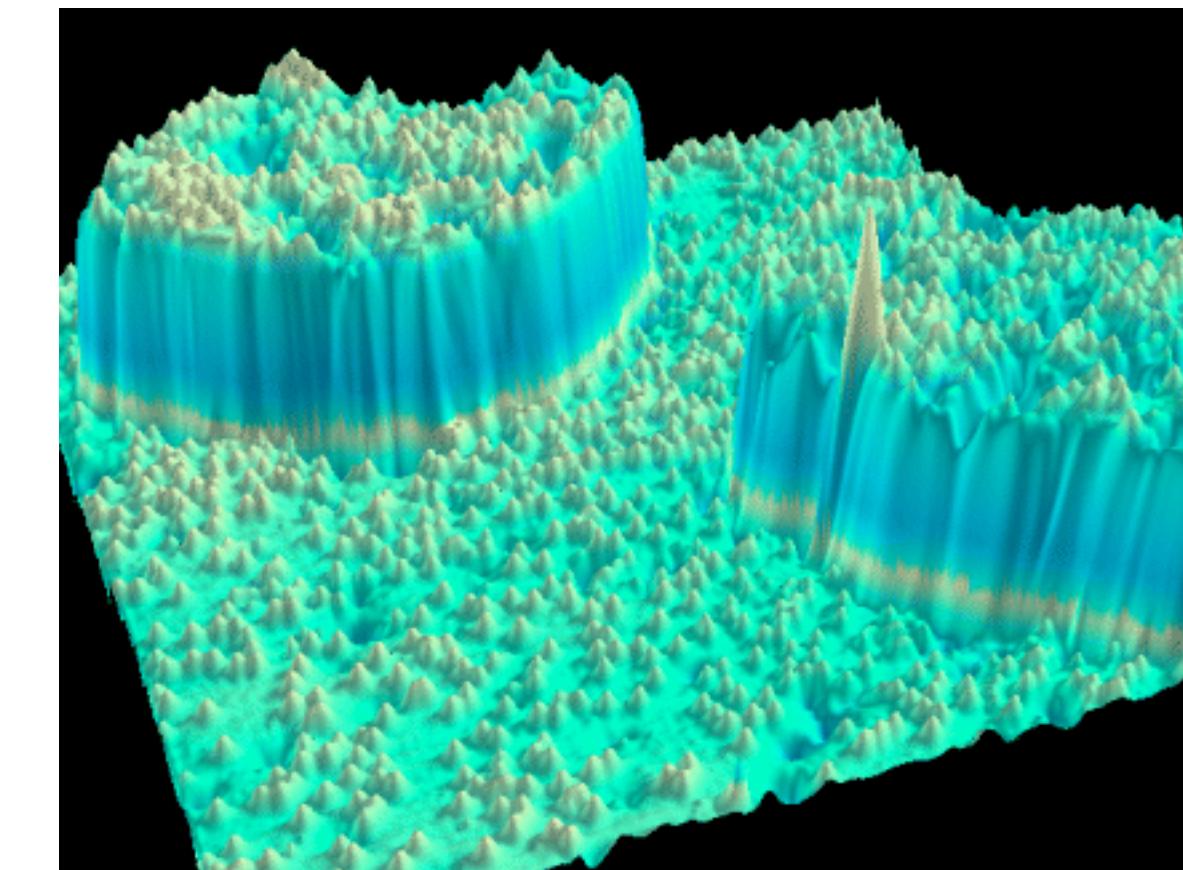
État microscopique:



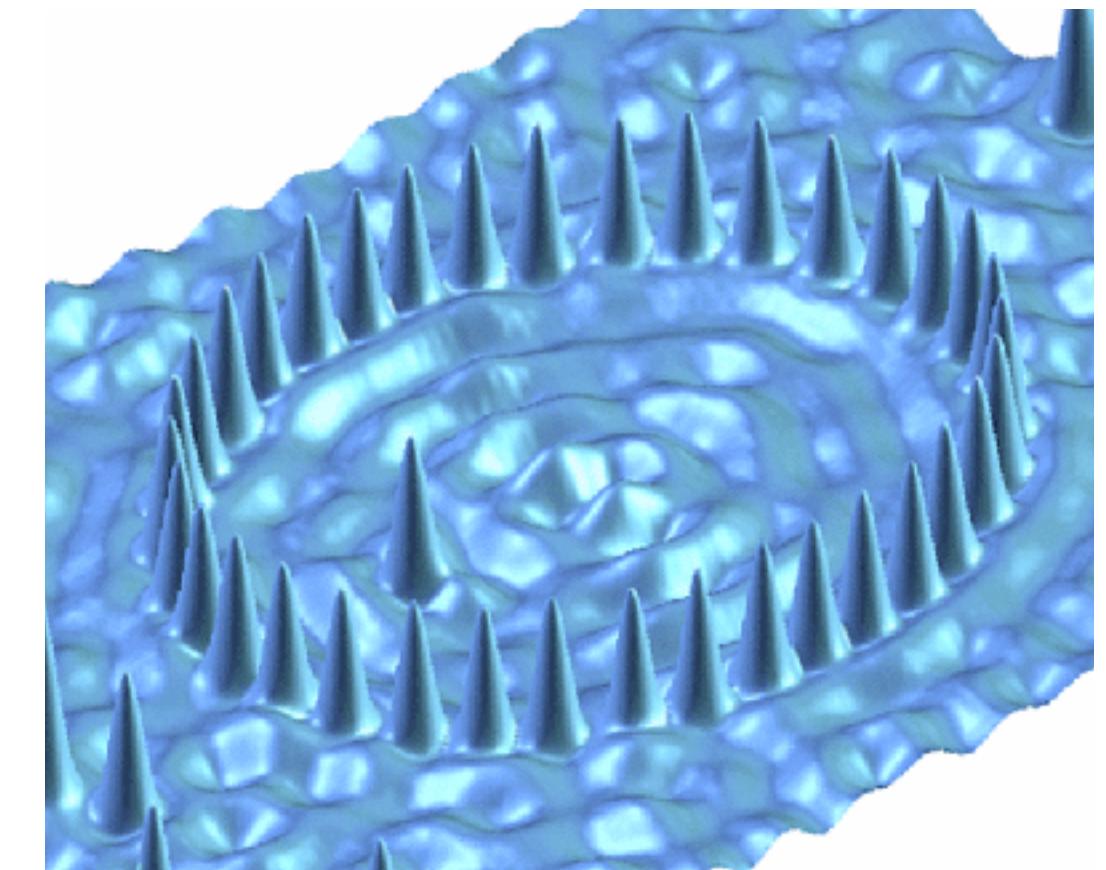
Microscope à effet tunnel



Auto-assemblage de
chaines moléculaires

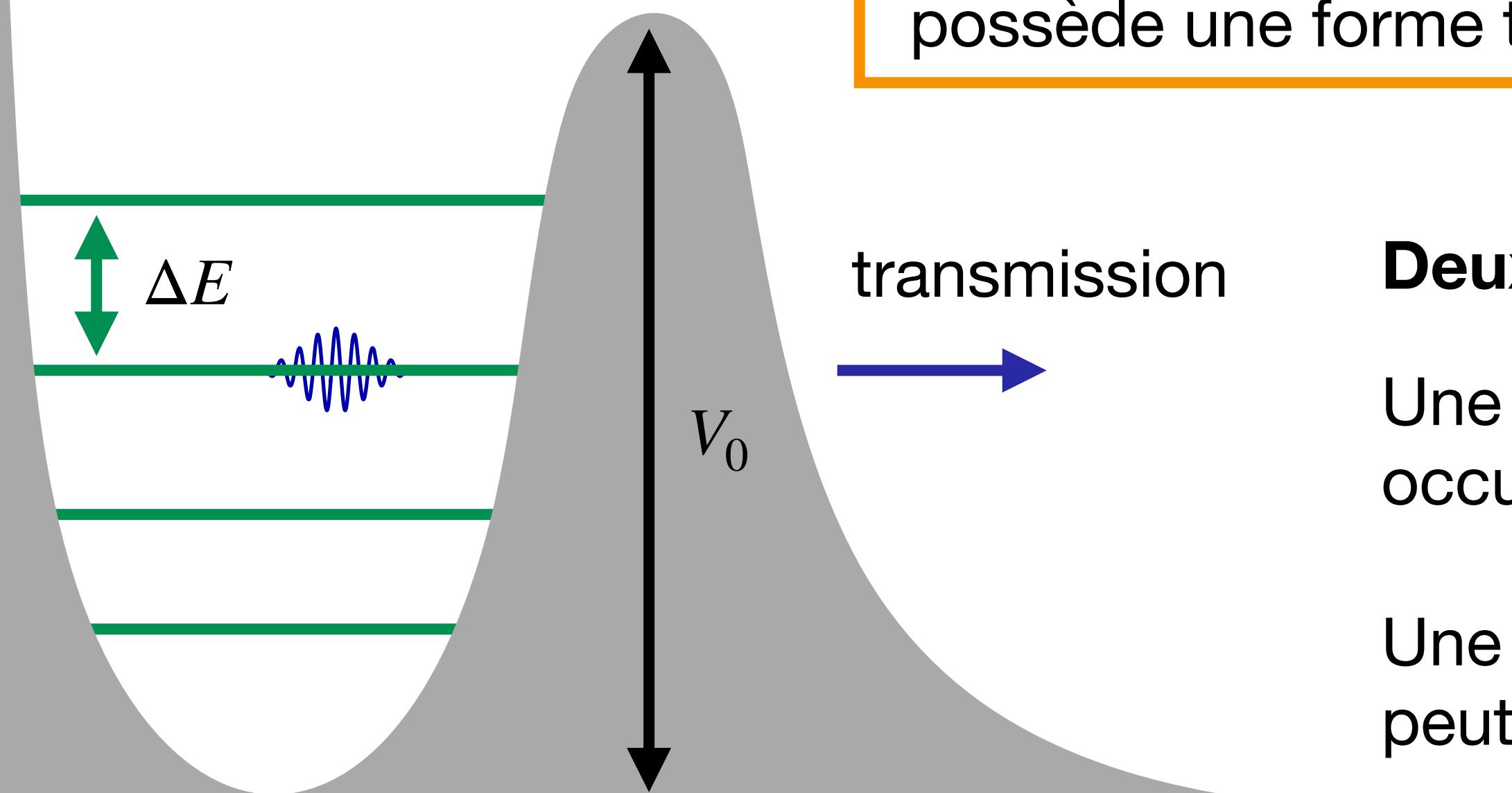


Atomes de Chrome (pointes)
sur un cristal de Fer



Ondes électroniques stationnaires
produites par des atomes de Cobalt
sur une surface de Cuivre





But: Trouver une "particule" macroscopique qui manifeste ces deux effets de la mécanique quantique

Attention:

La "particule" que nous allons discuter possède une forme très abstraite

Deux nouveautés quantiques

Une particule/onde quantique occupe des états d'énergie quantifiés

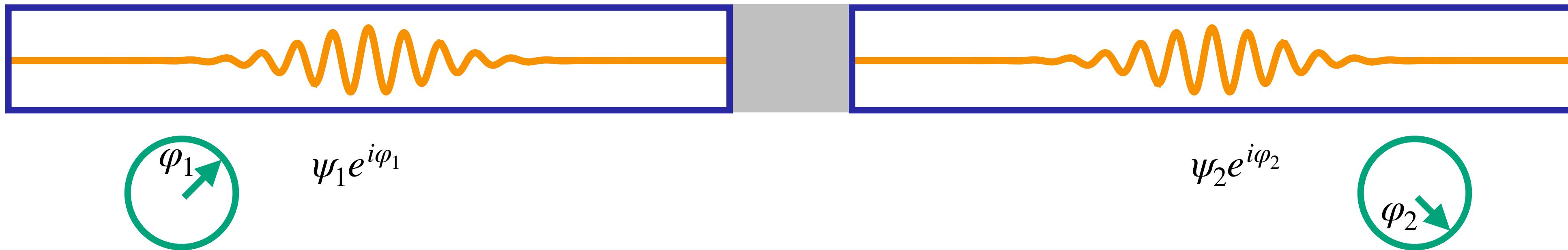
Une particule/onde quantique peut quitter le puits par effet tunnel



La "particule" doit se comporter comme telle

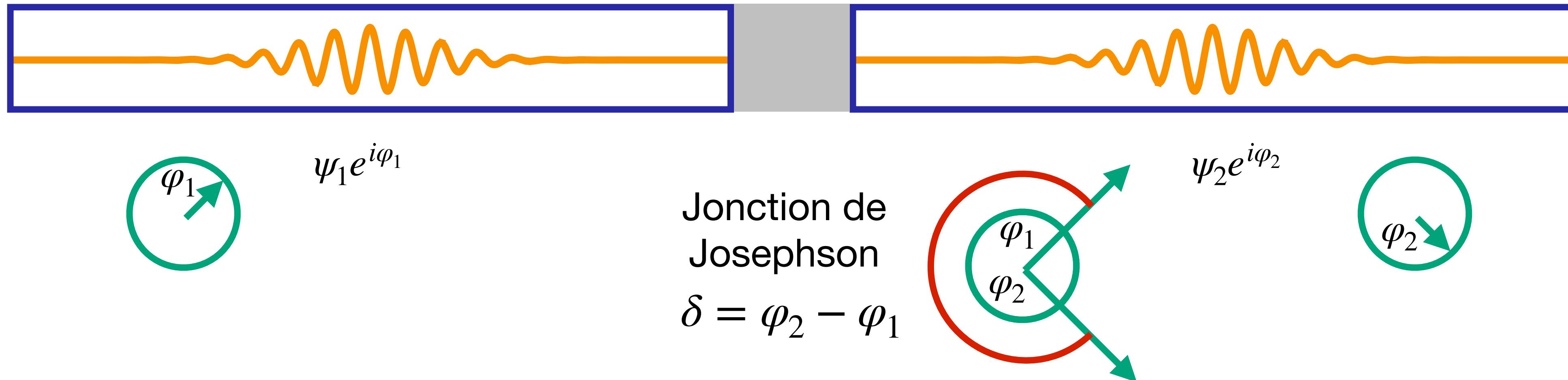
- une position de la particule
- une masse
- satisfaire la loi de Newton ($F = ma$)

État macroscopique:



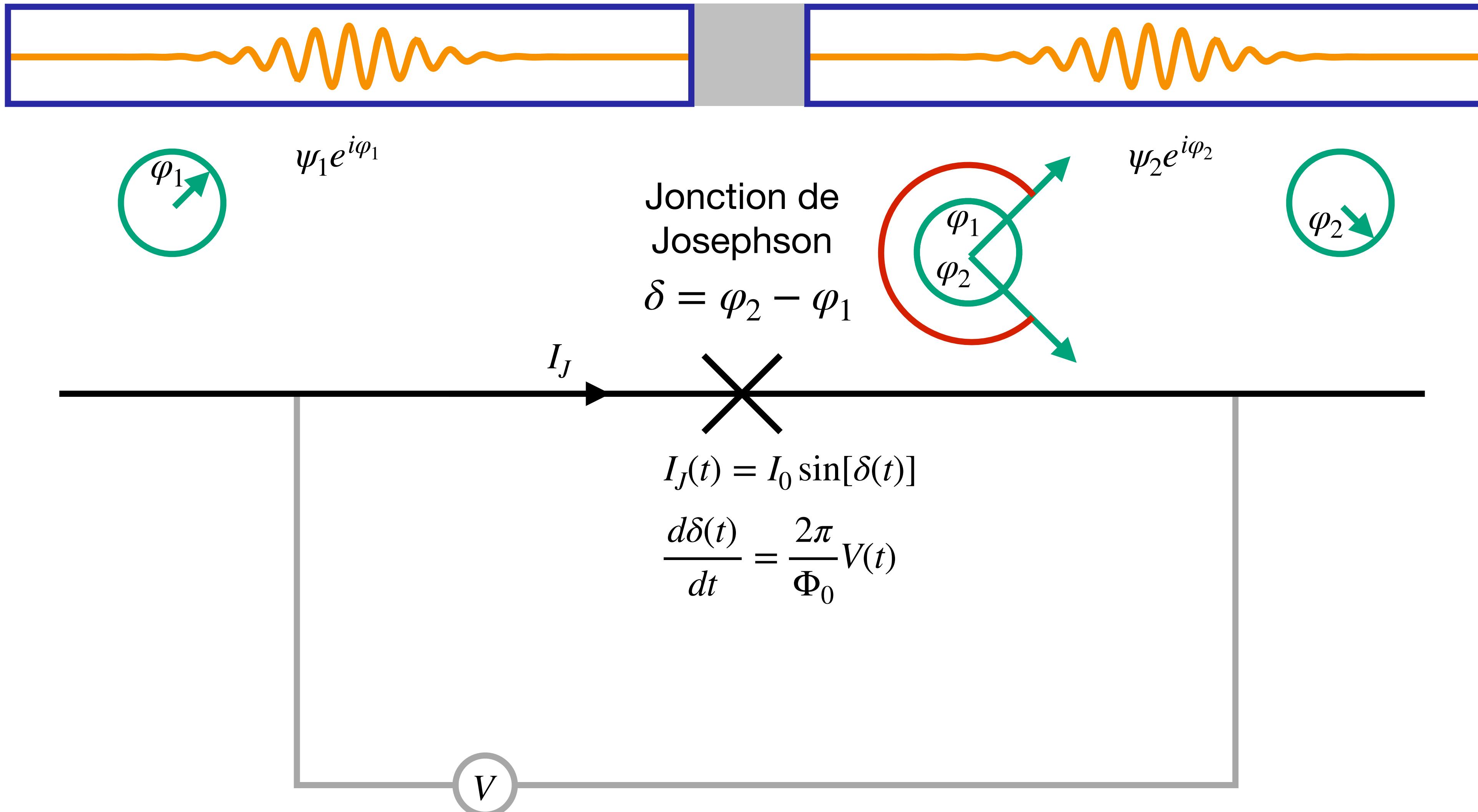
- ▶ Dans un supraconducteur, les électrons se mettent par paires (de Cooper).
- ▶ Le condensat des paires de Cooper se comporte comme une fonction d'onde complexe ψ
- ▶ Ici $|\psi|^2$ devient la densité de paires de Cooper, une quantité macroscopique
- ▶ En 1962 Brian Josephson étudie le comportement de ces jonctions dans un circuit électrique

L'effet Josephson ideal



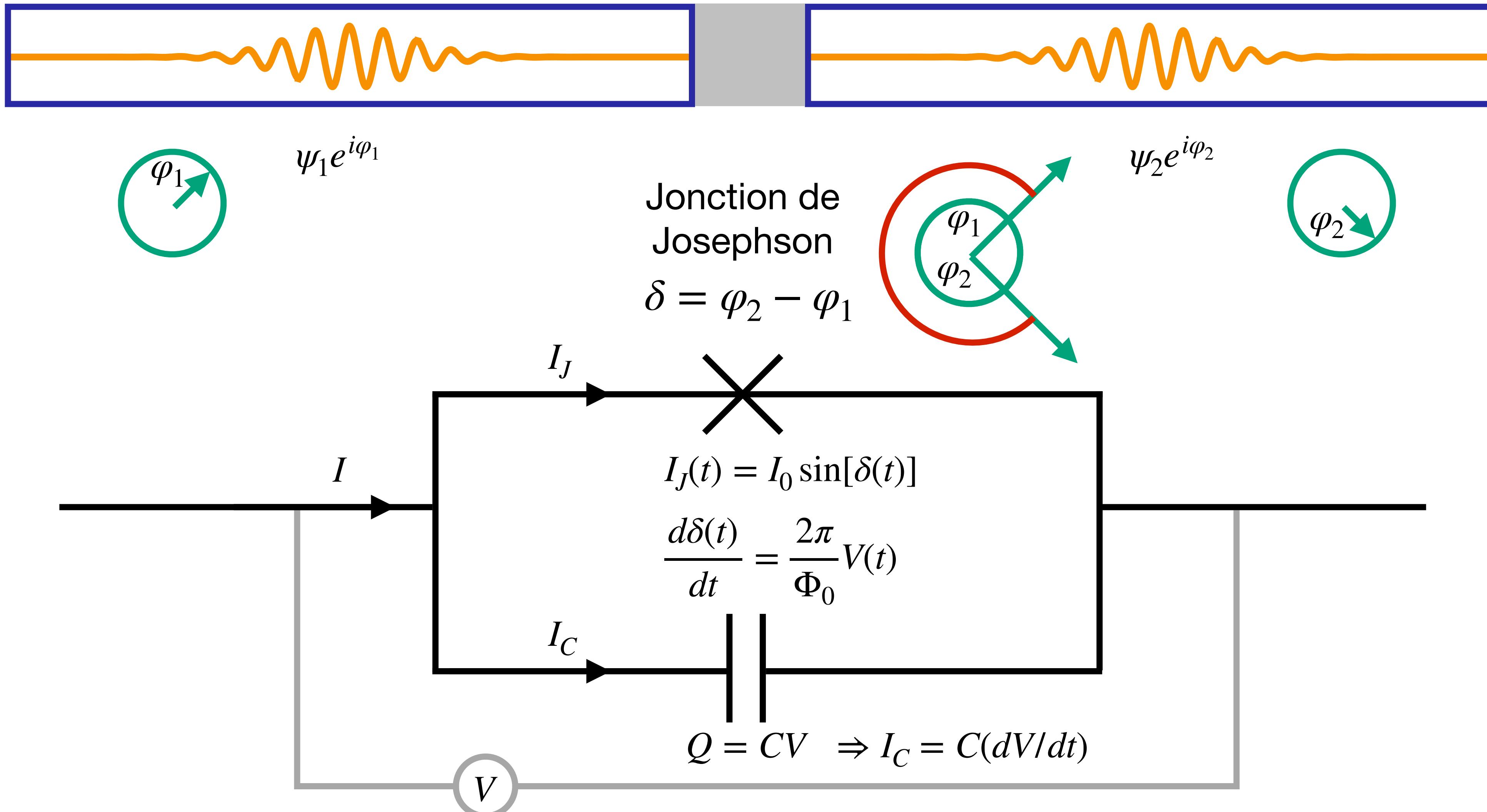
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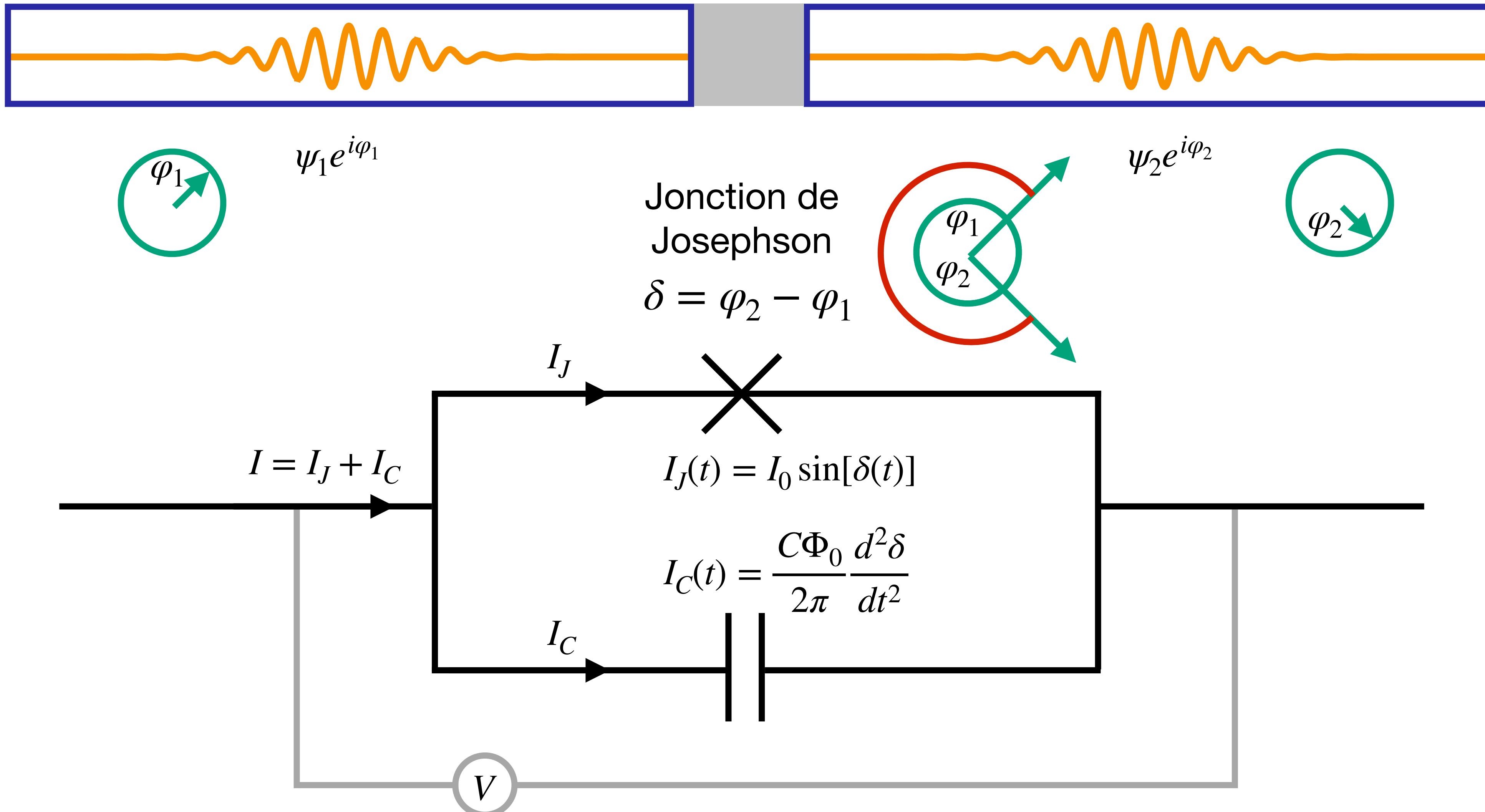


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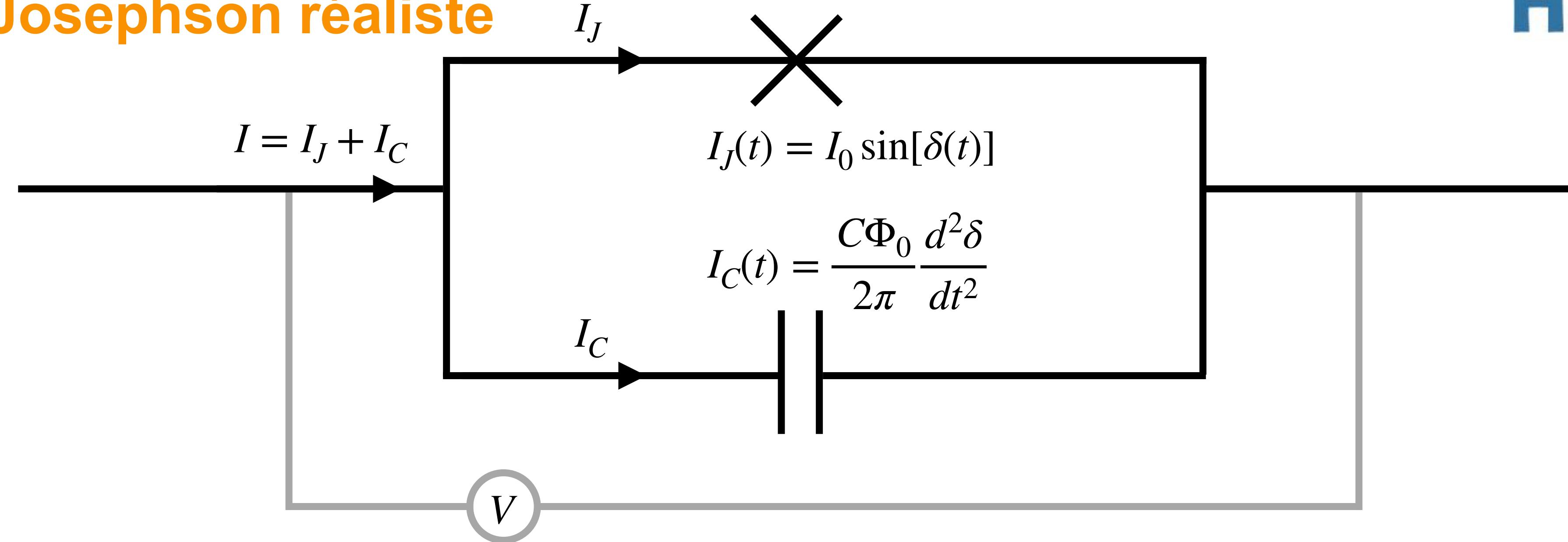
L'effet Josephson réaliste



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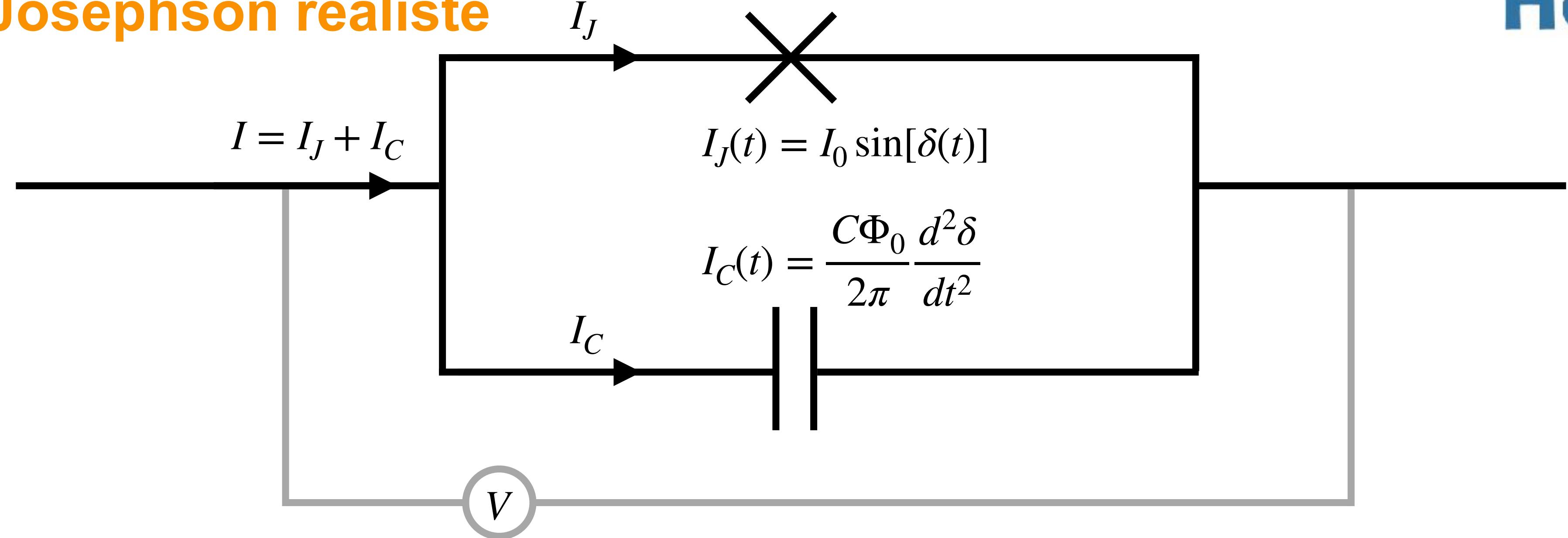


Equation pour $\delta(t)$

$$I = I_J + I_C$$



L'effet Josephson réaliste

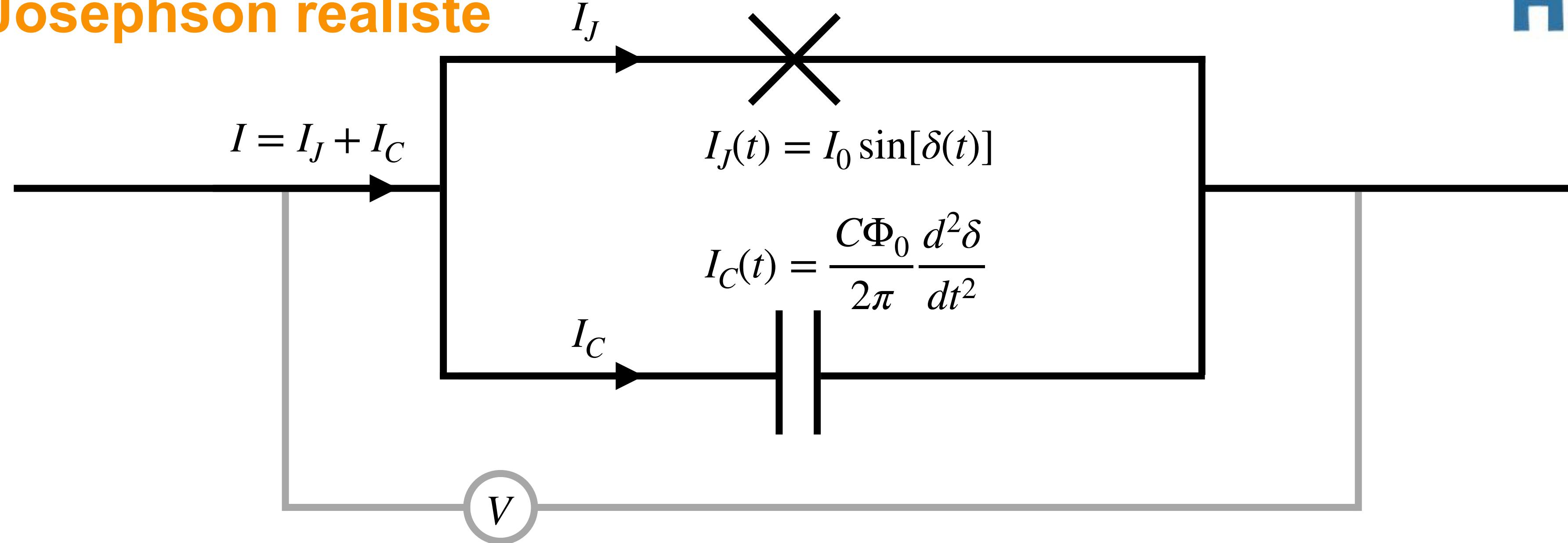


Equation pour $\delta(t)$

$$I = I_0 \sin(\delta) + \frac{C\Phi_0}{2\pi} \frac{d^2\delta}{dt^2}$$



L'effet Josephson réaliste



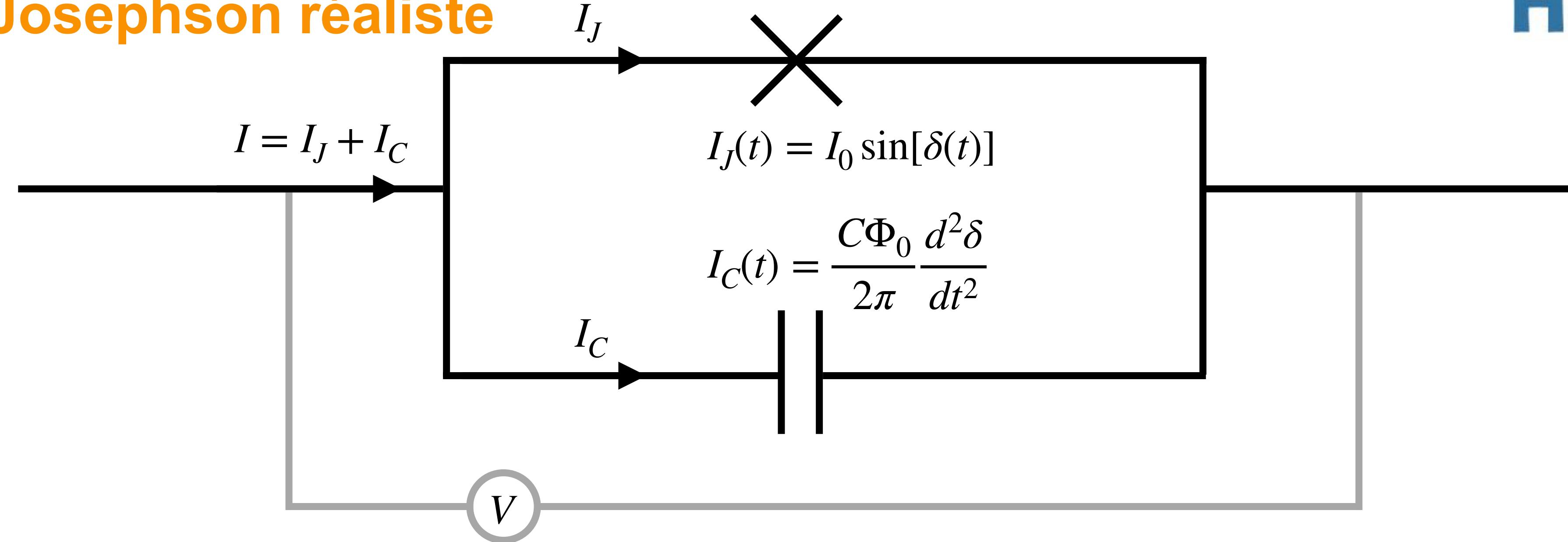
Equation pour $\delta(t)$

$$I = I_0 \sin(\delta) + \frac{C\Phi_0}{2\pi} \frac{d^2\delta}{dt^2}$$

$$\frac{I}{I_0} - \sin(\delta) = \frac{C\Phi_0}{2\pi I_0} \frac{d^2\delta}{dt^2}$$



L'effet Josephson réaliste



Equation pour $\delta(t)$

$$I = I_0 \sin(\delta) + \frac{C\Phi_0}{2\pi} \frac{d^2\delta}{dt^2}$$

$$\frac{I}{I_0} - \sin(\delta) = \frac{C\Phi_0}{2\pi I_0} \frac{d^2\delta}{dt^2}$$

$$F(x) = m \frac{d^2x}{dt^2}$$

Equation d'une particule

**Nous avons trouvé
notre "particule"**



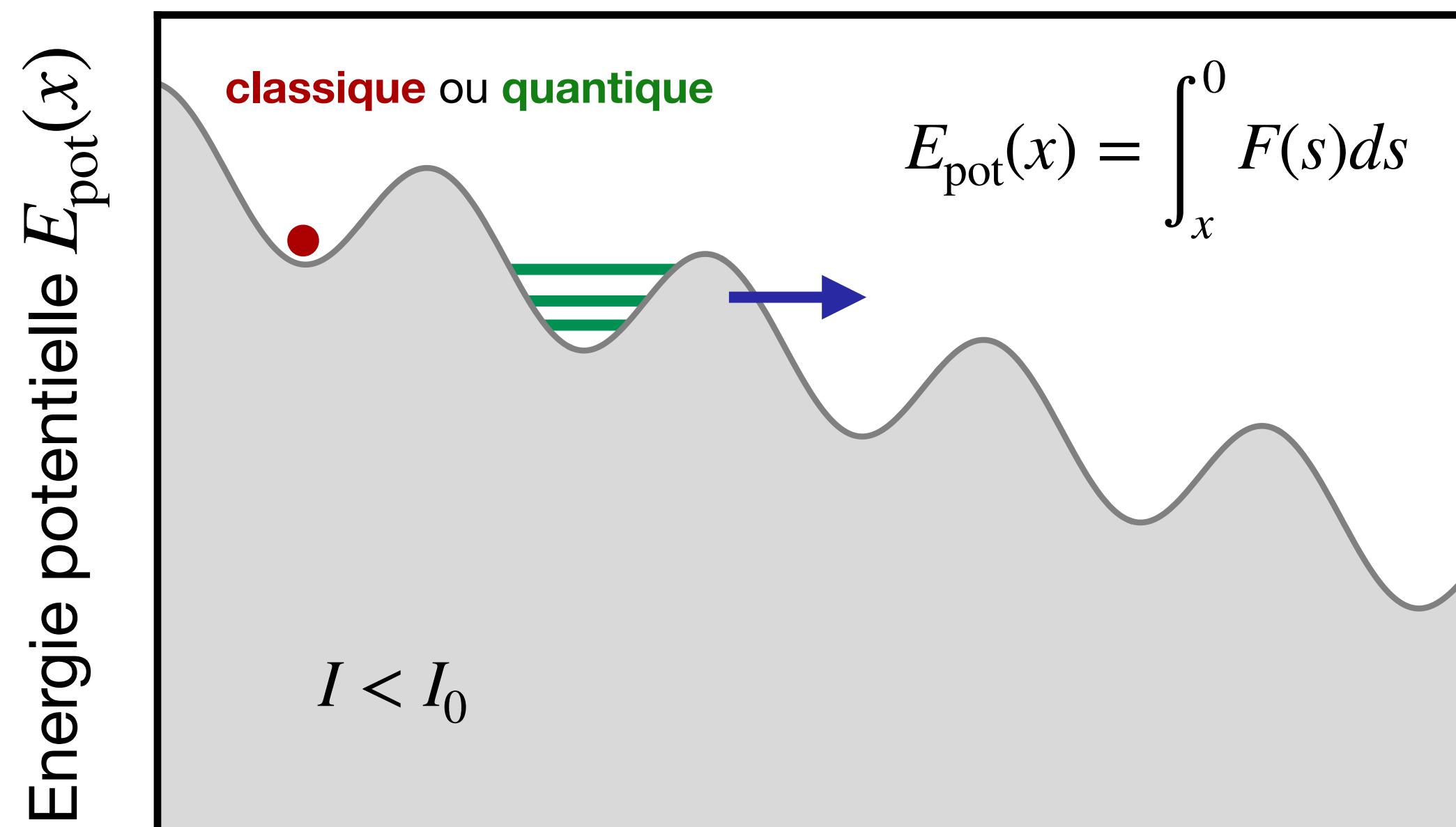
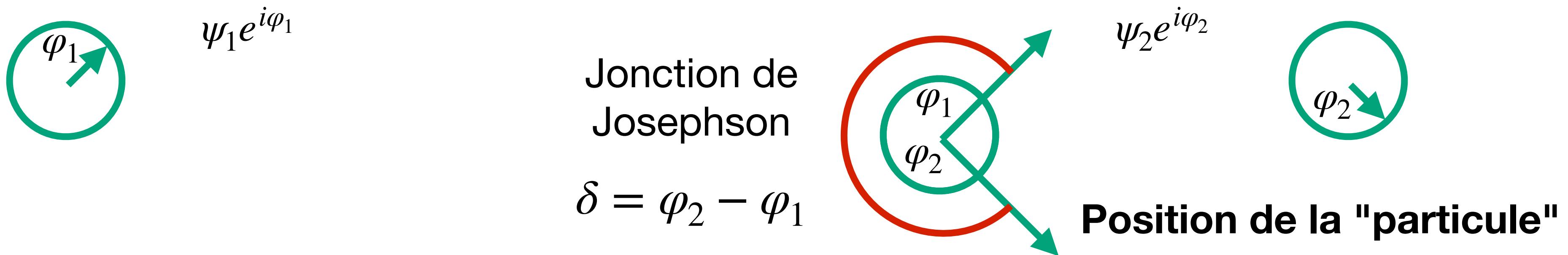
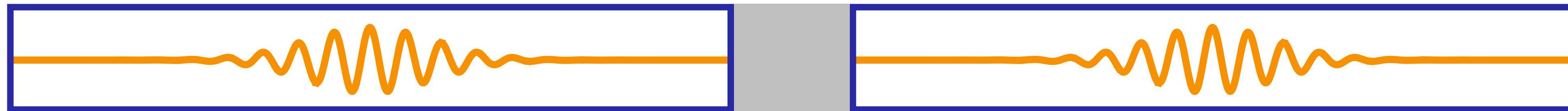
$$x = \delta$$

$$m = \frac{C\Phi_0}{2\pi I_0}$$

$$F(x) = I/I_0 - \sin(x)$$



L'effet Josephson réaliste



Différence de phase $x = \delta = \varphi_2 - \varphi_1$



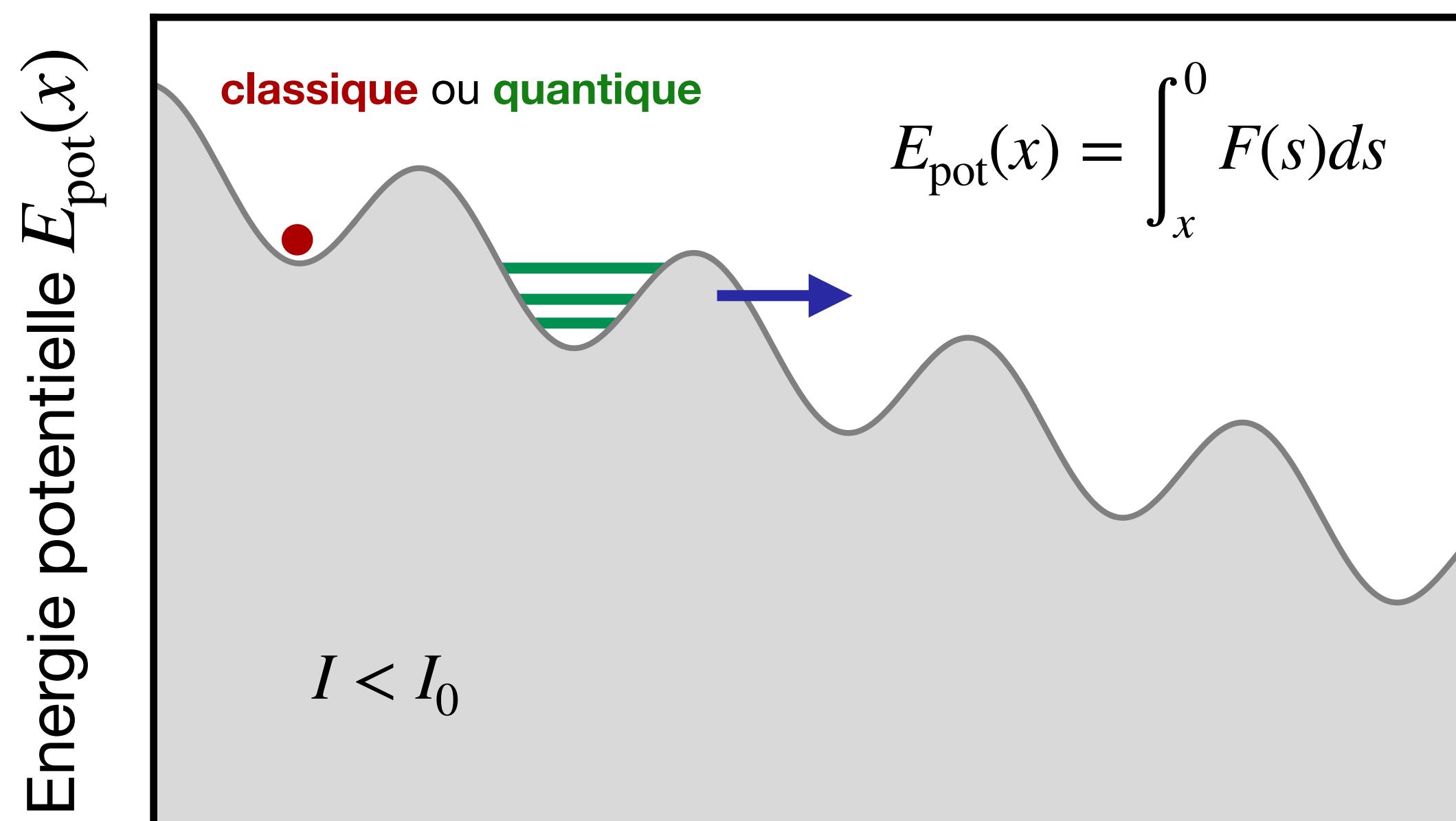
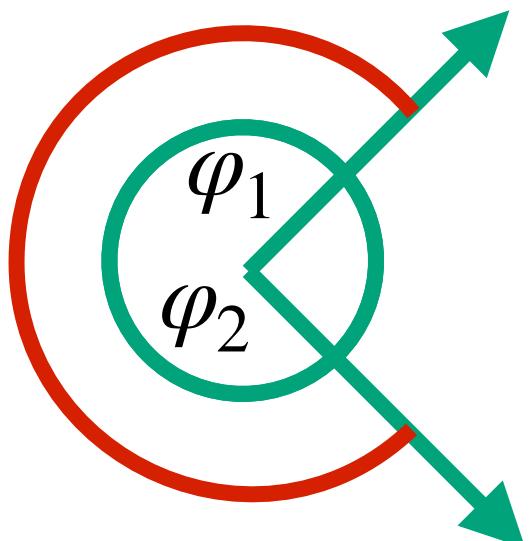
Défi expérimental relevé par Clarke, Devoret et Martinis

Réaliser/caractériser une jonction de Josephson

Démontrer la quantification des états d'énergie

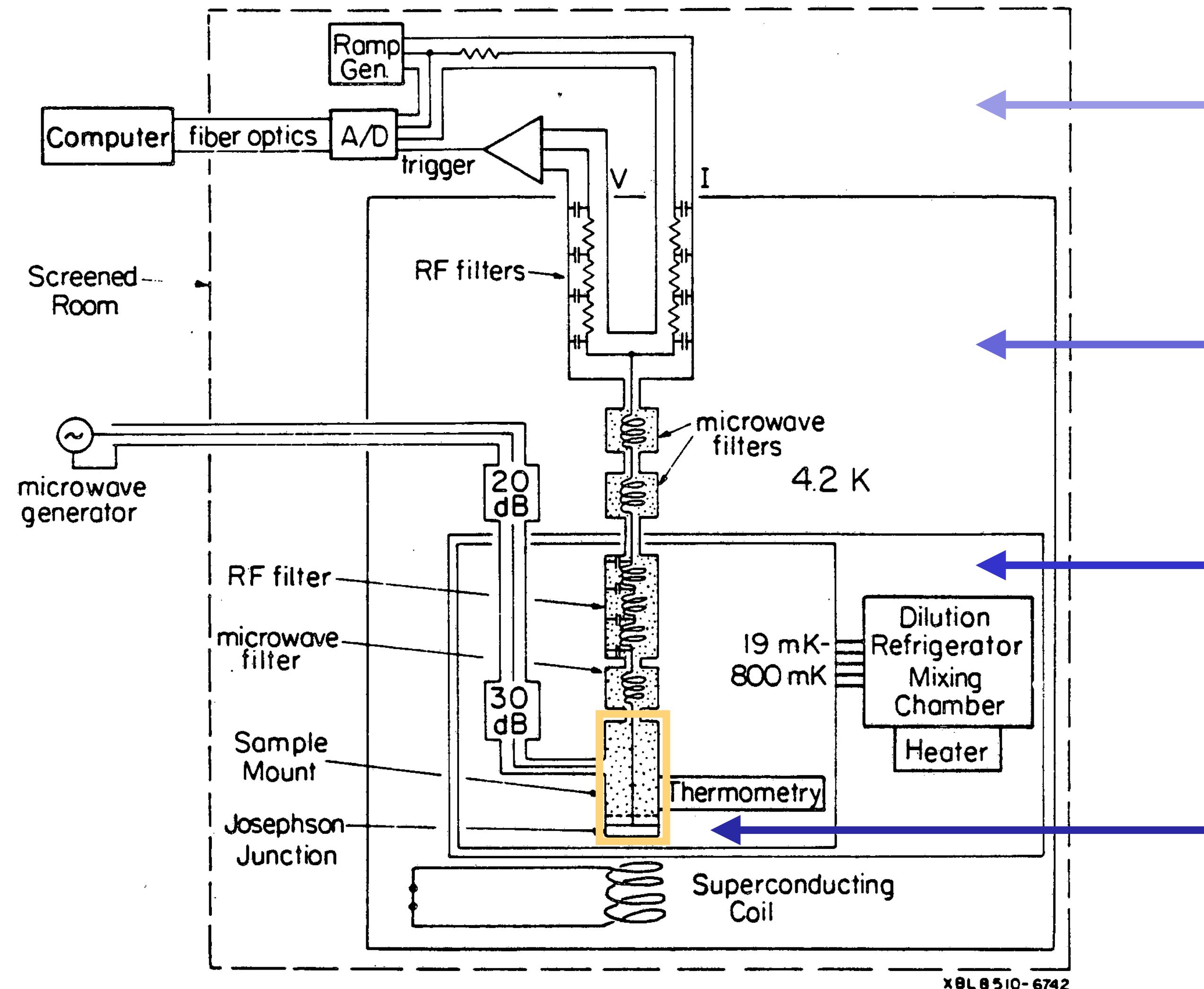
Démontrer la libération par l'effet tunnel

$$\delta = \varphi_2 - \varphi_1$$



$$\text{Différence de phase } x = \delta = \varphi_2 - \varphi_1$$

Expérience cryogénique



Froid (Azote liquide 77K = -196°C)

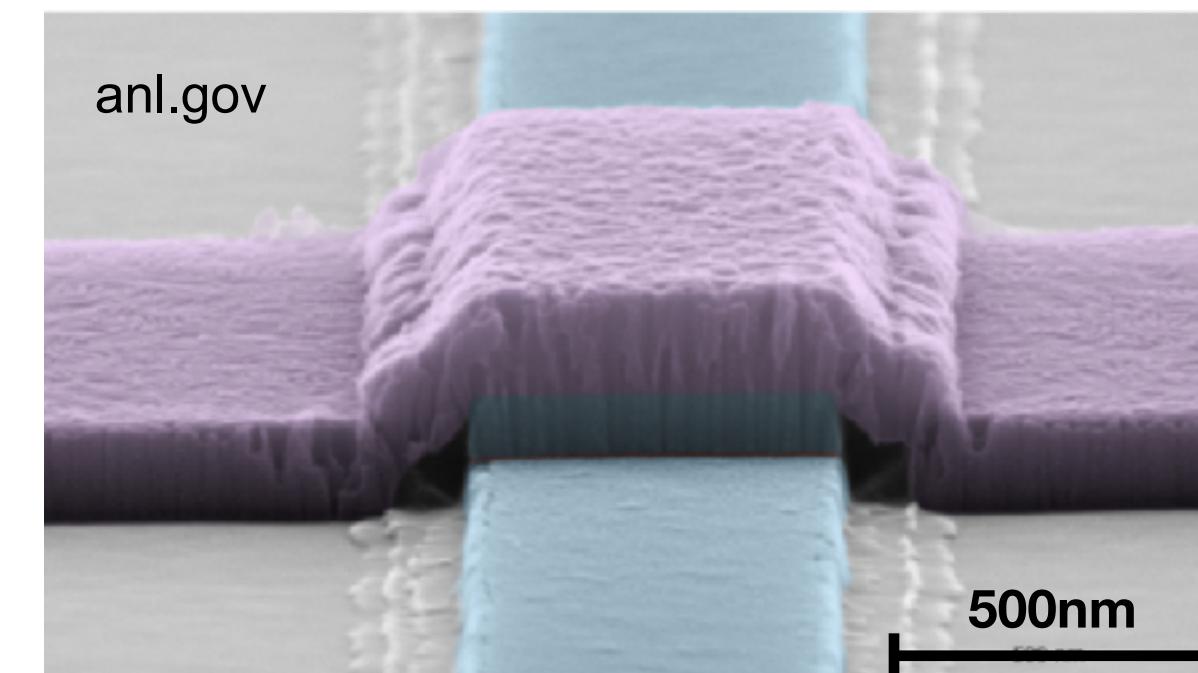
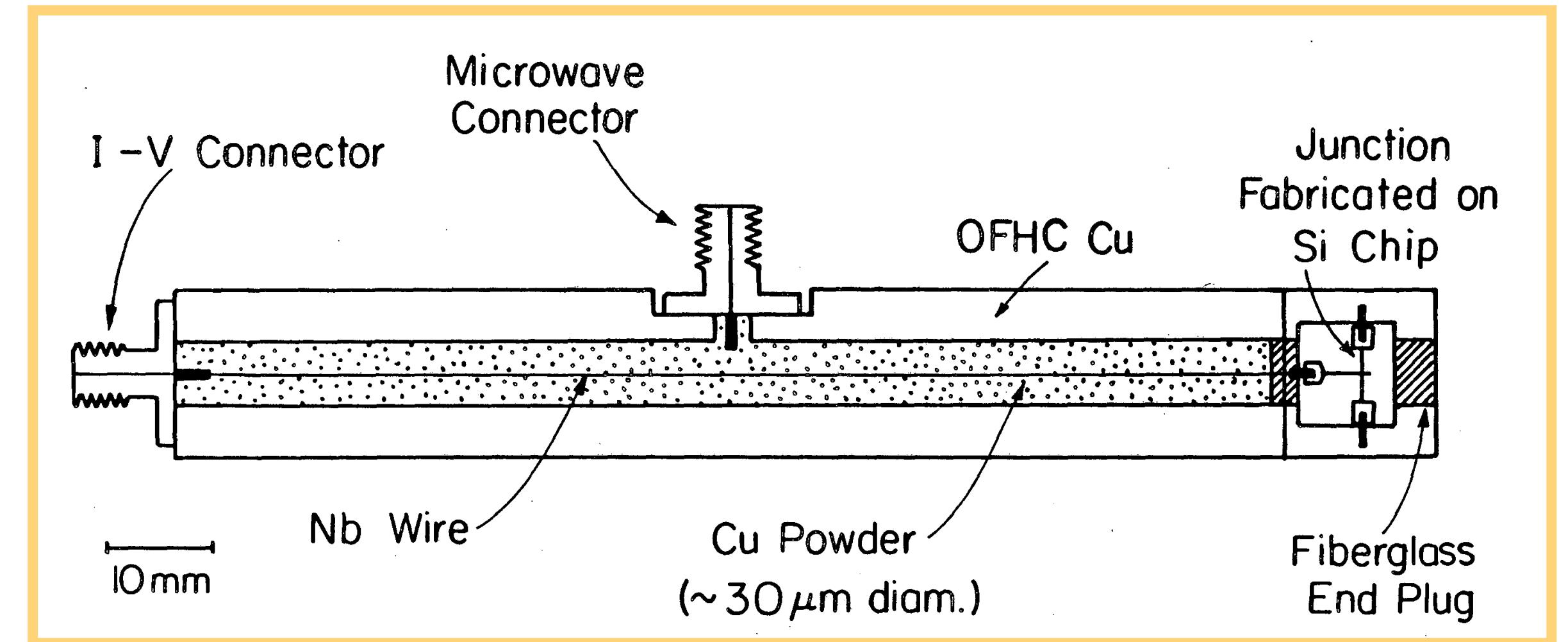
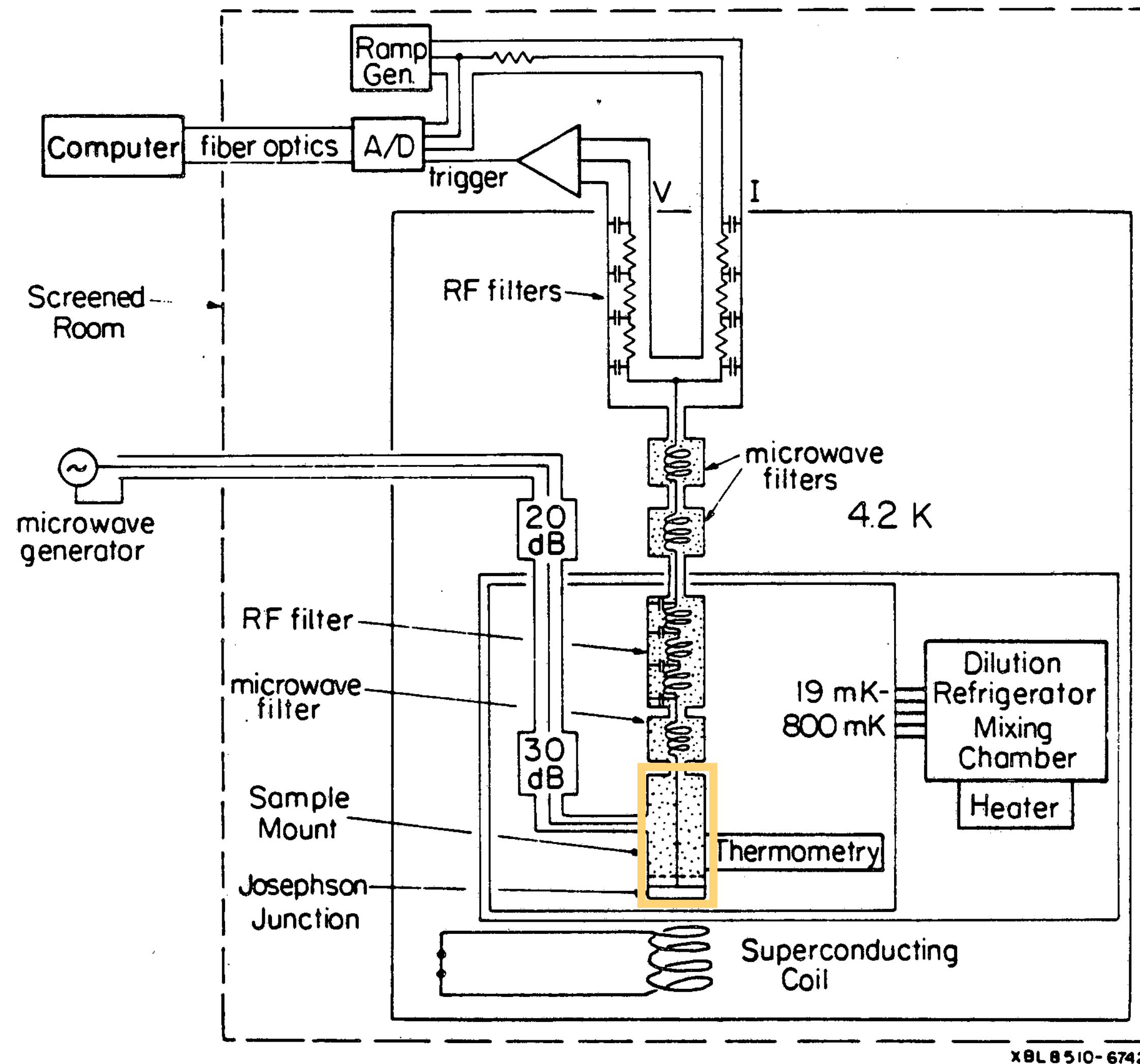
Très froid (Helium liquide 4.2K = -269°C)

Très très froid (^4He 1K = -272°C)

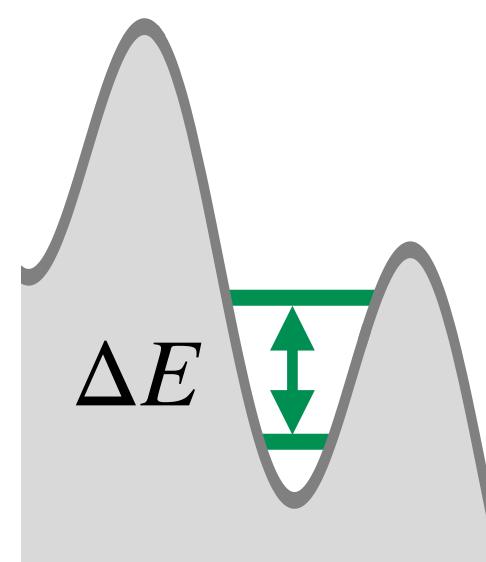
Ultra froid (dilution de $^4\text{He}/^3\text{He}$ 20 mK = -273.13°C)



Expérience cryogénique



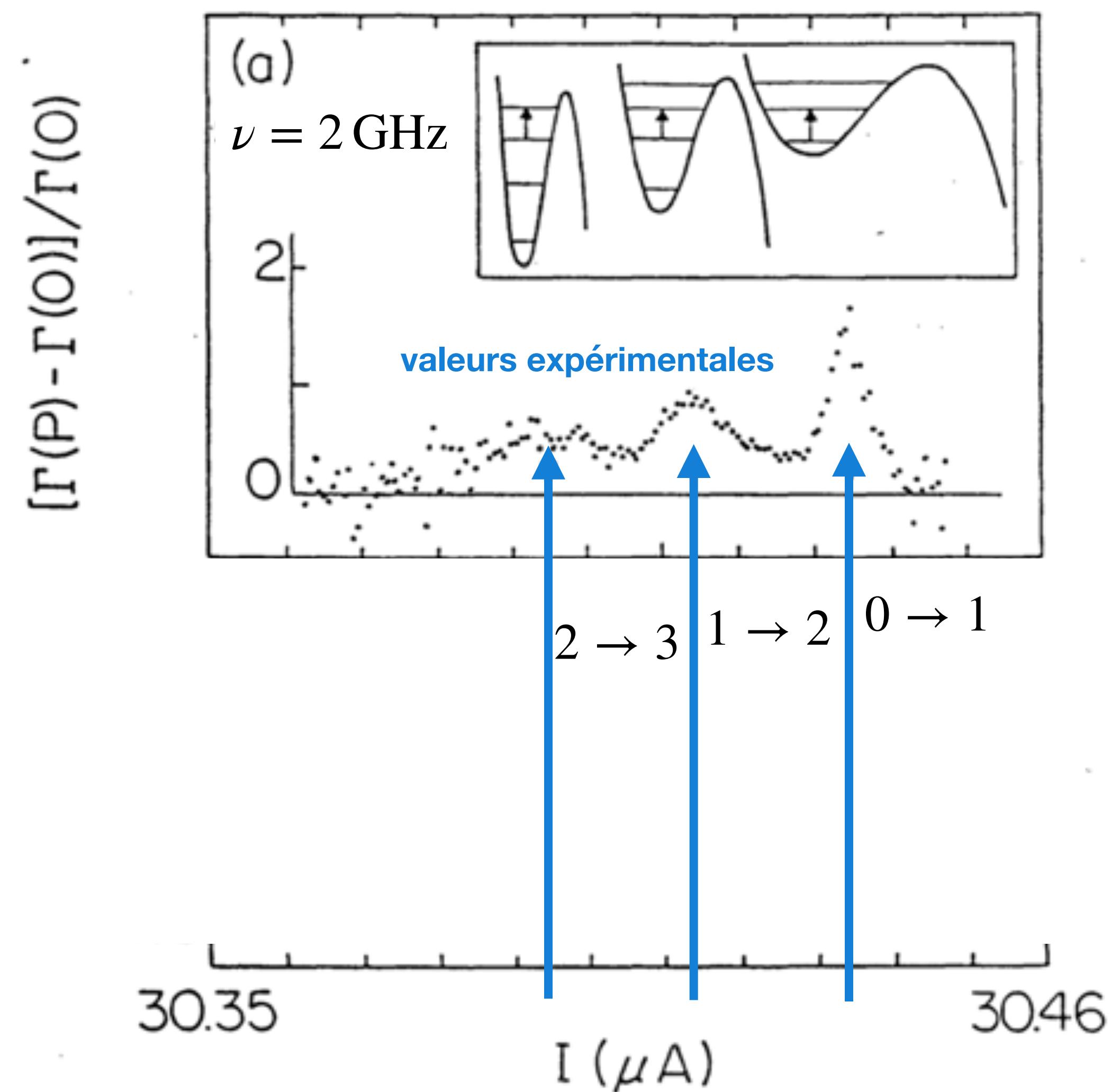
Travail pionnier: Quantification des états



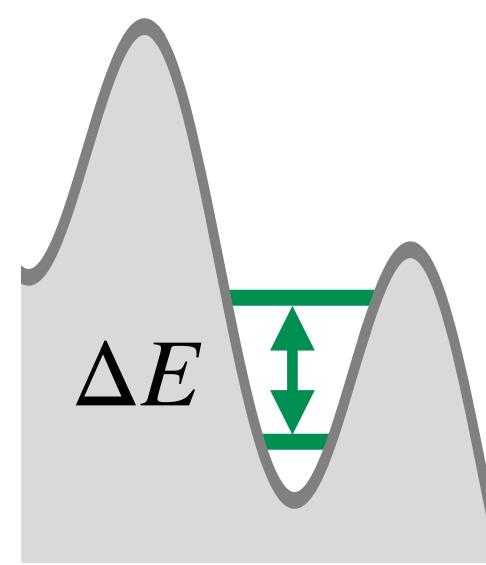
Jonction de Josephson stimulée par un générateur micro-ondes

condition de résonance

$$\Delta E = \hbar\omega = h\nu$$



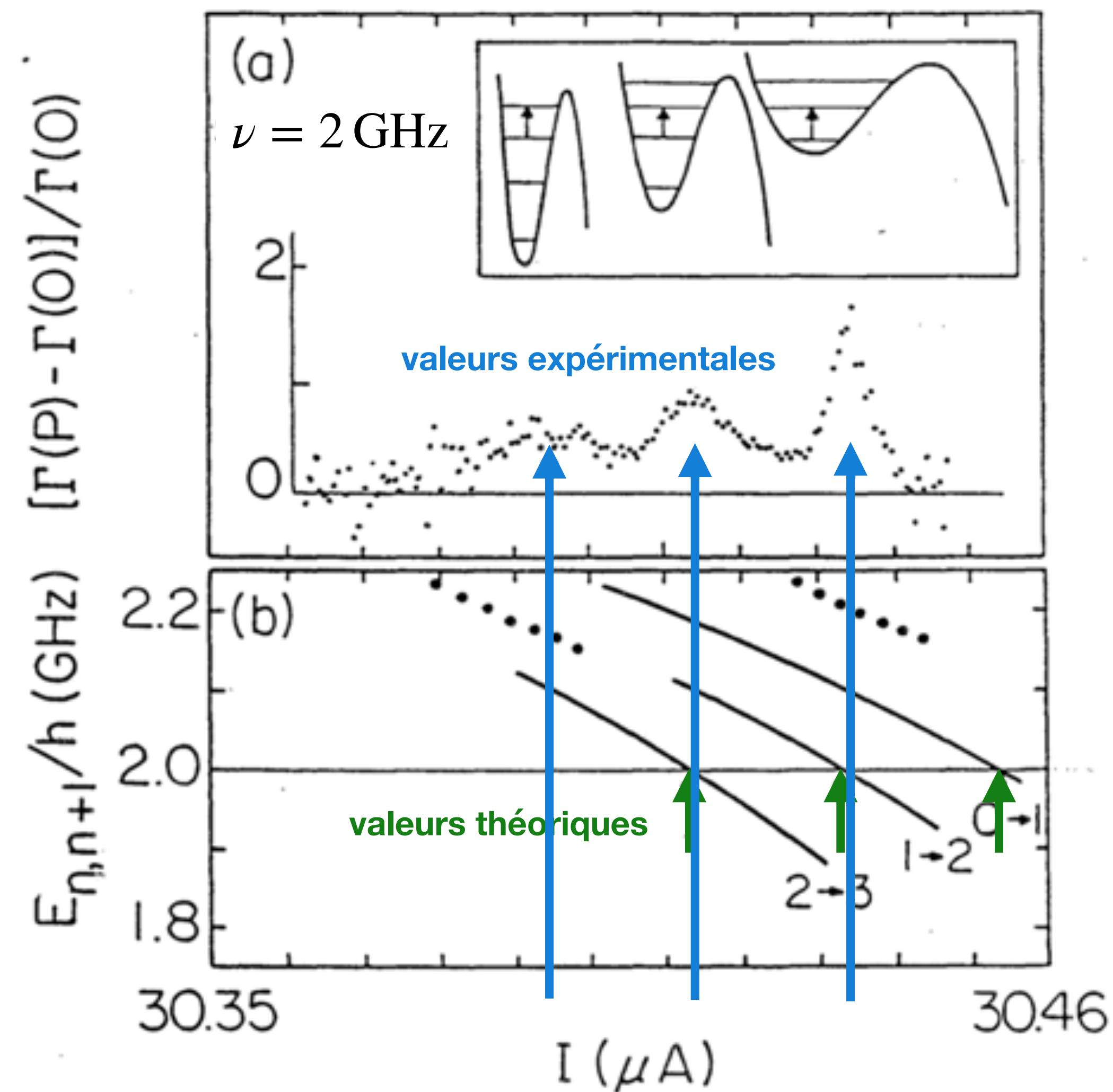
Travail pionnier: Quantification des états



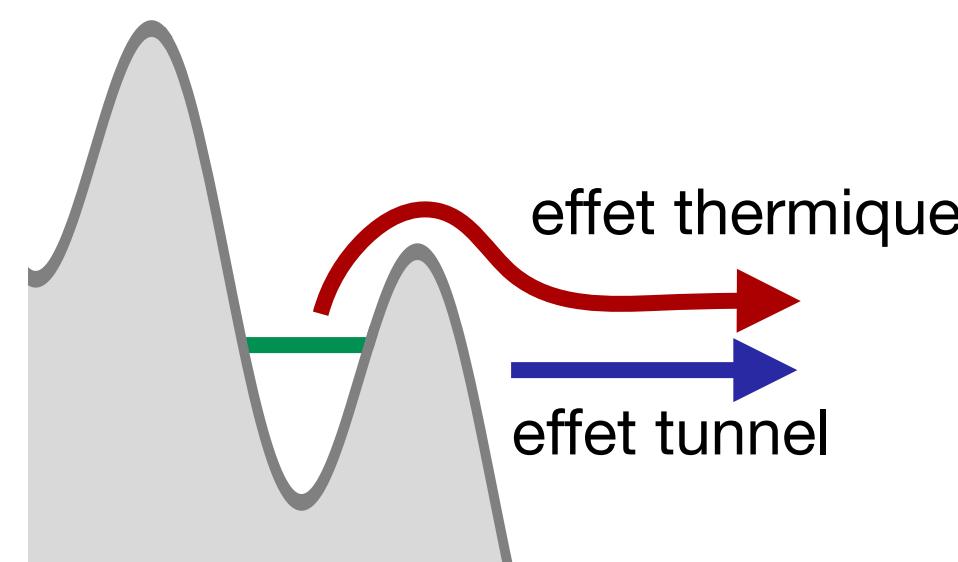
Jonction de Josephson stimulée par un générateur micro-ondes

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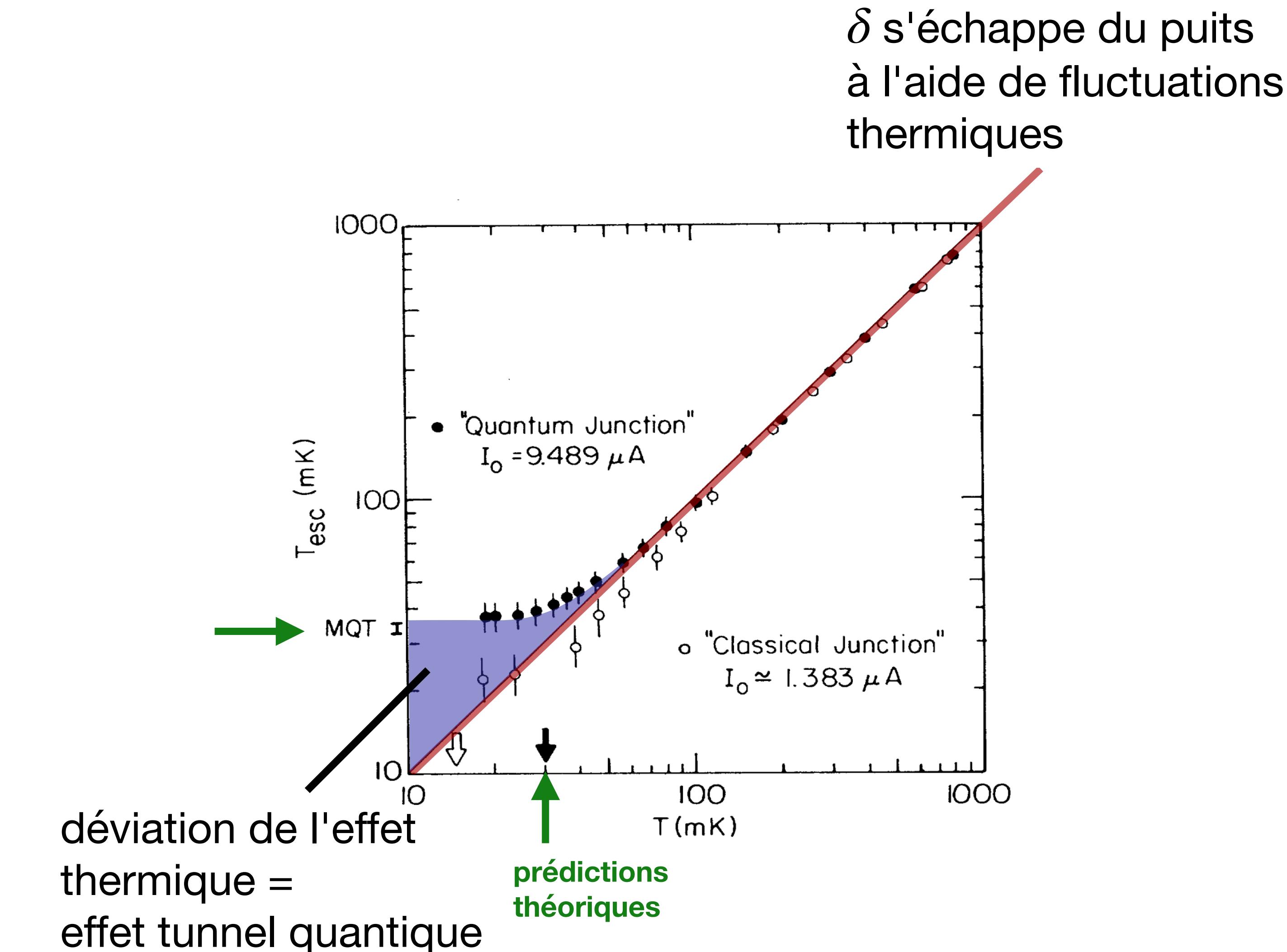


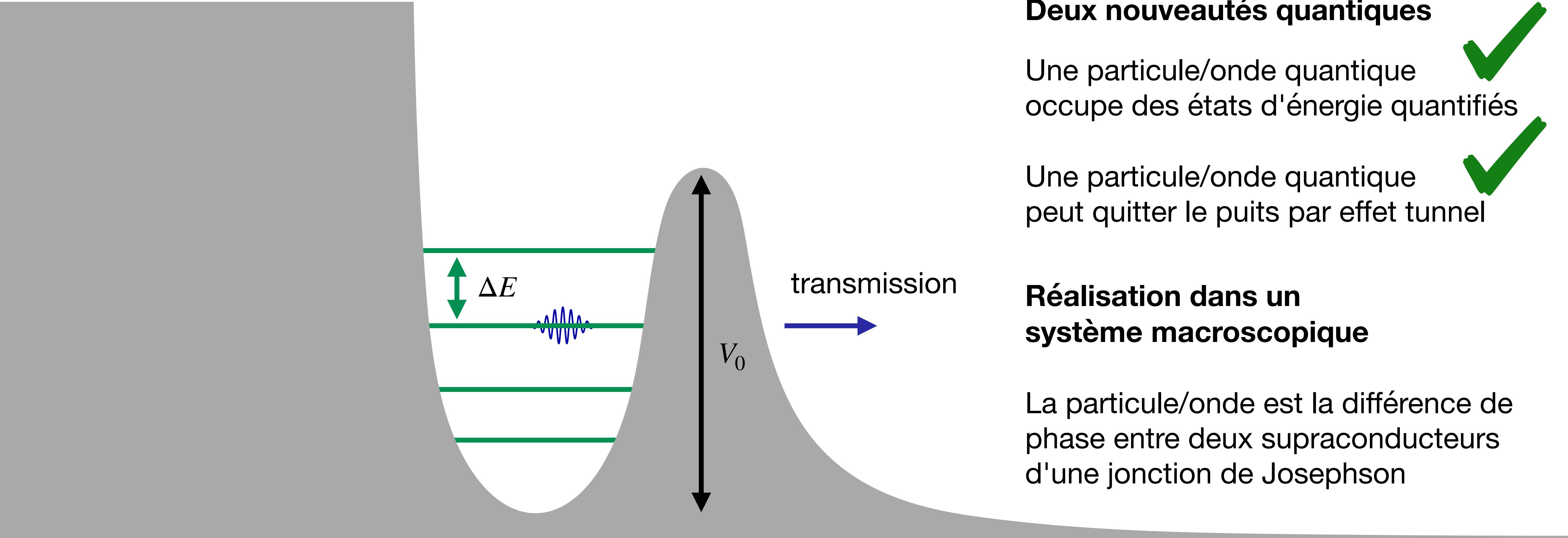
Travail pionnier: L'effet tunnel



Des fluctuations thermiques permettent de s'échapper **par dessus** la barrière.

À des températures très basses cet effet disparaît et permet de dévoiler l'effet quantique.

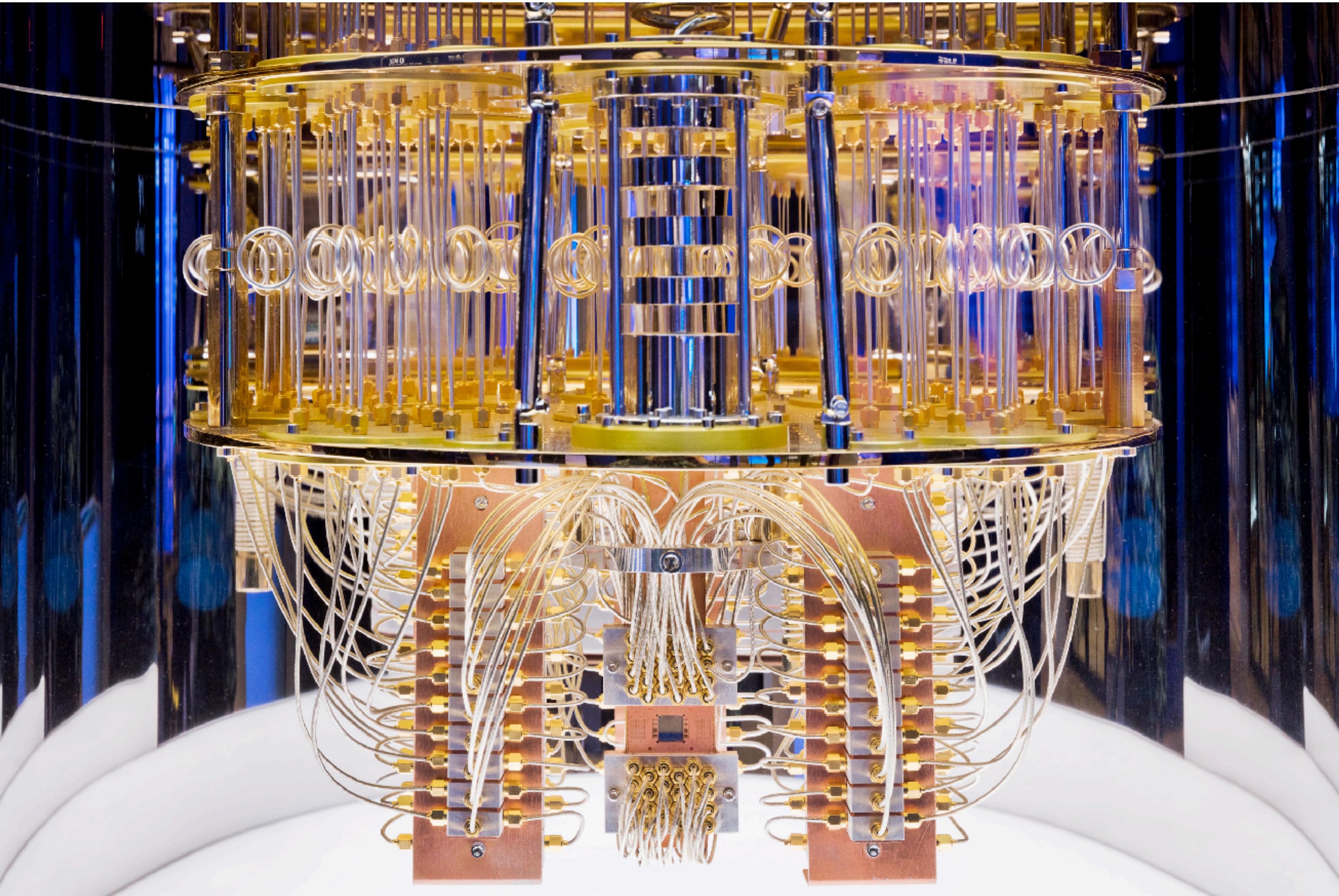




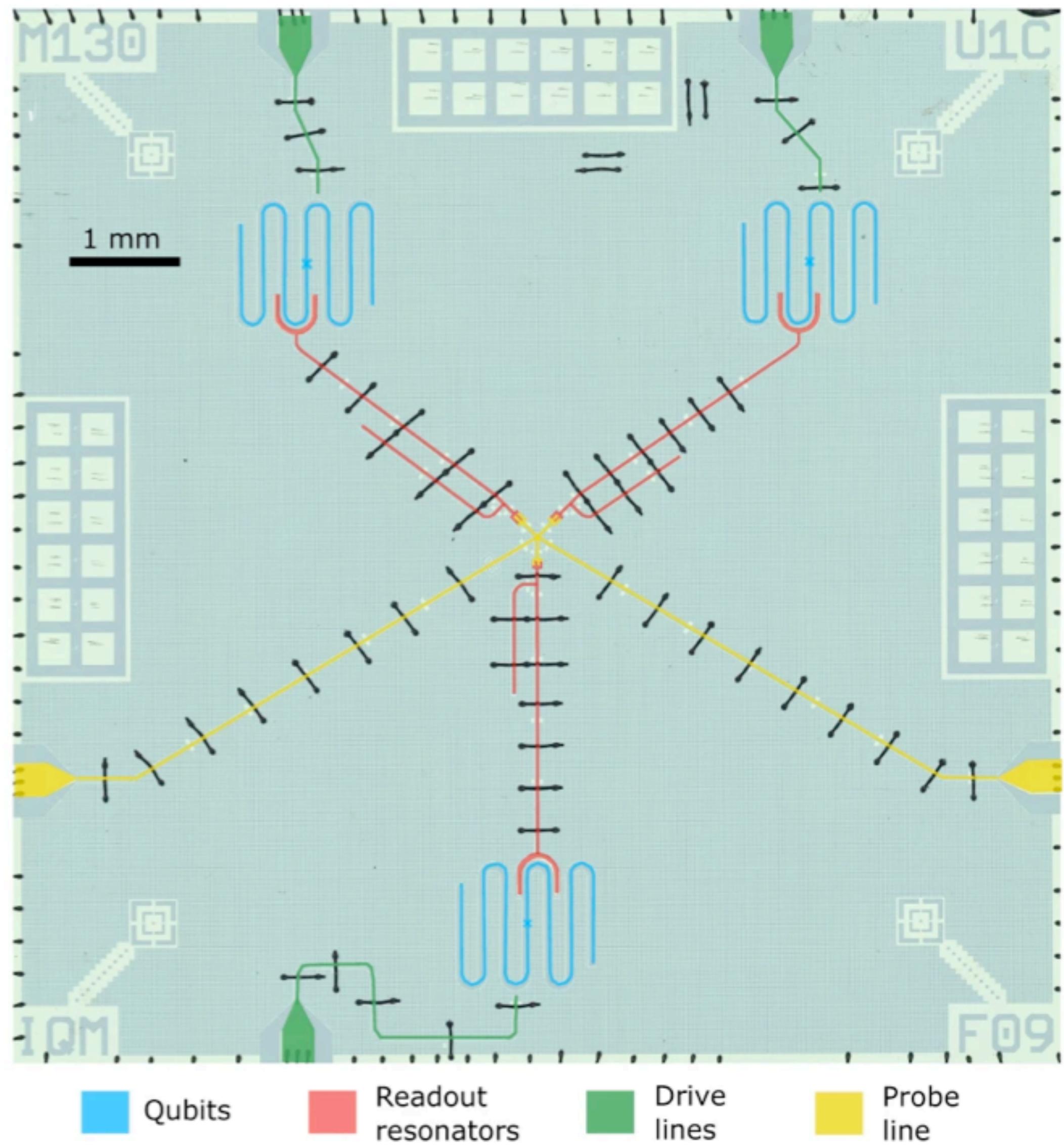
Développement vers des ordinateurs quantiques



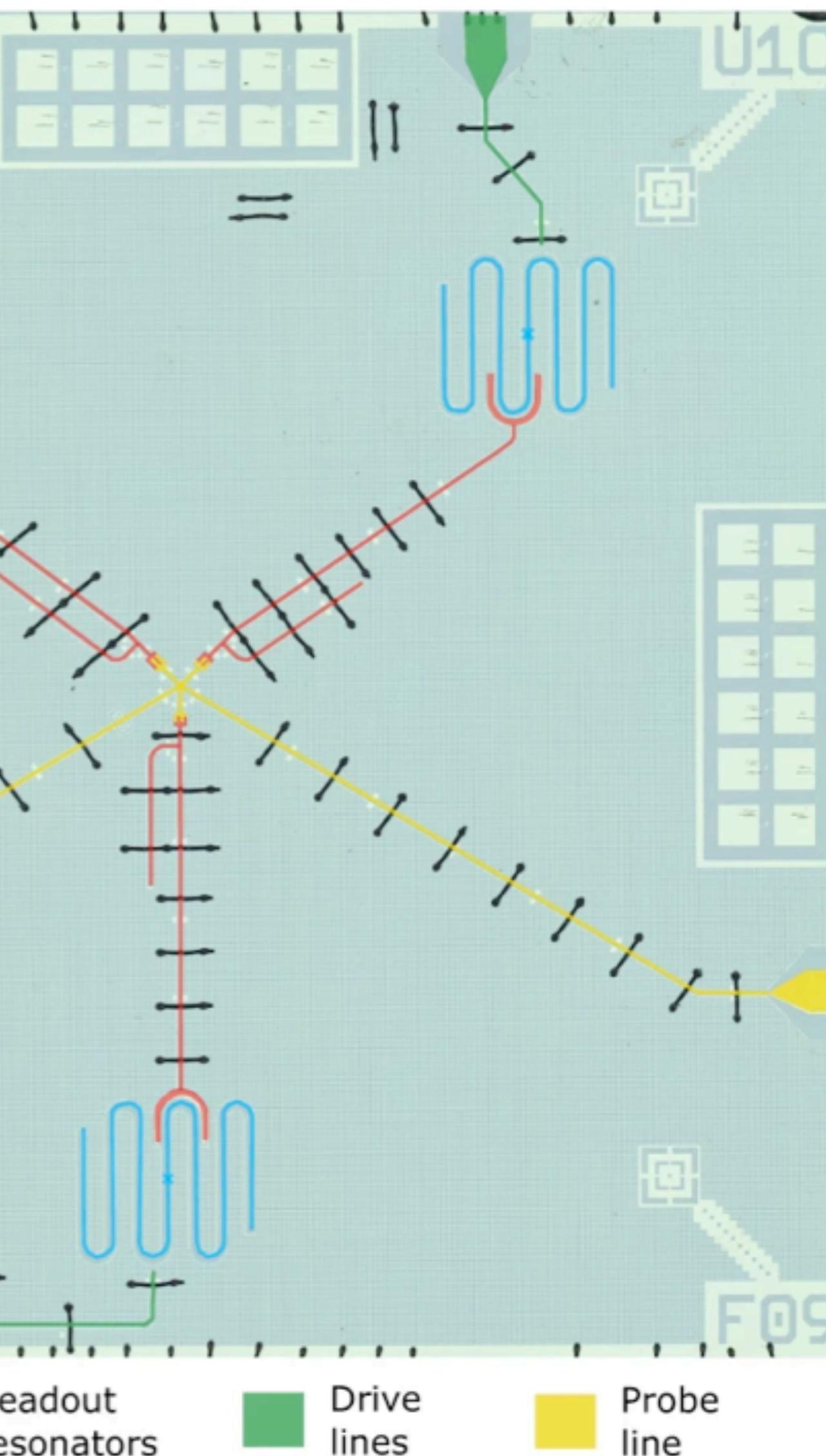
Développement vers des ordinateurs quantiques

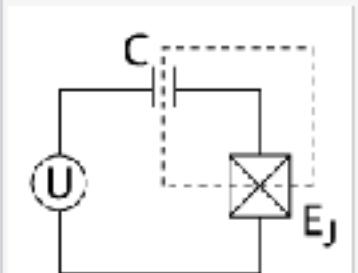
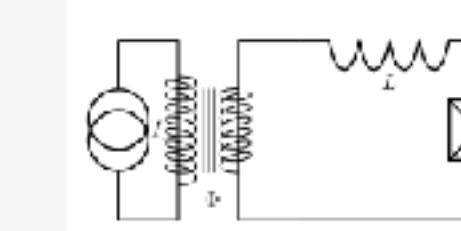
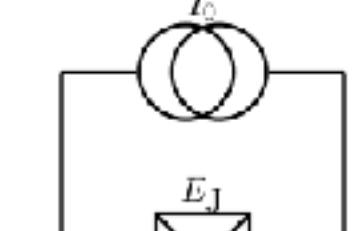
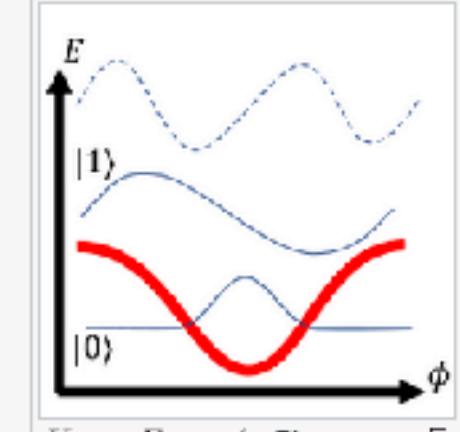
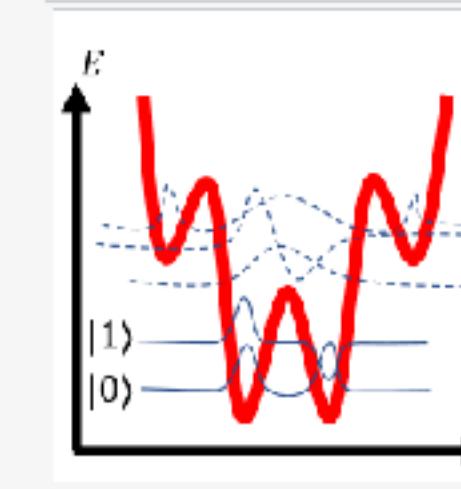
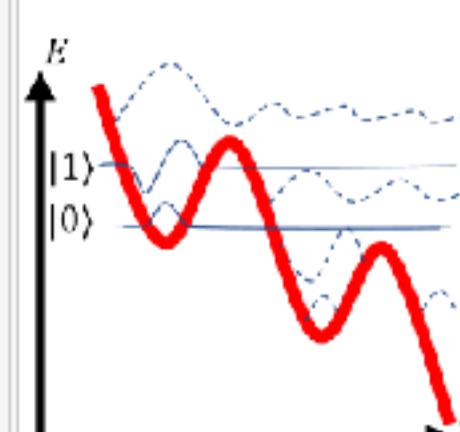


Développement vers des ordinateurs quantiques



Développement vers des ordinateurs quantiques



Type Aspect	Charge qubit	RF-SQUID qubit (prototype of the Flux Qubit)	Phase qubit
Circuit	 <p>Charge qubit circuit. A superconducting island (encircled with a dashed line) is defined between the leads of a capacitor with capacitance C and a Josephson junction with energy E_J, biased by voltage U.</p>	 <p>Flux qubit circuit. A superconducting loop with inductance L is interrupted by a junction with Josephson energy E_J. Bias flux Φ is induced by a flux line with current I_0.</p>	 <p>Phase qubit circuit. A Josephson junction with energy parameter E_J is biased by current I_0.</p>
Hamiltonian	$H = E_C(N - N_g)^2 - E_J \cos \phi$ <p>In this case N is the number of Cooper pairs to tunnel through the junction, $N_g = CV_0/2e$ is the charge on the capacitor in units of Cooper pairs number, $E_C = (2e)^2/2(C_J + C)$ is the charging energy associated with both capacitance C and Josephson junction capacitance C_J.</p>	$H = \frac{q^2}{2C_J} + \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{\phi^2}{2L} - E_J \cos\left[\phi - \Phi \frac{2\pi}{\Phi_0}\right]$ <p>Note that ϕ is only allowed to take values greater than 2π and is alternatively defined as the time integral of voltage along inductance L.</p>	$H = \frac{(2e)^2}{2C_J} q^2 - I_0 \frac{\Phi_0}{2\pi} \phi - E_J \cos \phi$ <p>Here Φ_0 is magnetic flux quantum.</p>
Potential	 <p>$U = -E_J \cos \phi$. Bias voltage is set such that $N_g = \frac{1}{2}$, minimizing the energy gap between $0\rangle$ and $1\rangle$, consequently distinguishing the gap from other energy gaps (e.g. gap between $1\rangle$ and $2\rangle$). The difference in gaps allows addressing transitions from $0\rangle$ to $1\rangle$ and vice versa only, without populating other states.</p>	 <p>$U = \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{\phi^2}{2L} - E_J \cos\left[\phi - \Phi \frac{2\pi}{\Phi_0}\right]$</p> <p>Bias flux is $\Phi = \Phi_0/2$. Different wells correspond to a distinct number of flux quanta trapped in the superconducting loops. The two lower states correspond to a symmetrical and anti-symmetrical superposition of zero or single trapped flux quanta, sometimes denoted as clockwise and counterclockwise loop current states: $0\rangle = [\psi_+\rangle + \psi_-\rangle]/\sqrt{2}$ and $1\rangle = [\psi_+\rangle - \psi_-\rangle]/\sqrt{2}$.</p>	 <p>$U = -I_0 \frac{\Phi_0}{2\pi} \phi - E_J \cos \phi$, also known as "washboard" potential. Bias current is adjusted to allow wells shallow enough to contain exactly two localized wave functions. A slight increase in bias current causes a selective "spill" of higher energy state ($1\rangle$), expressed with a measurable voltage spike (a mechanism commonly used for phase qubit measurement).</p>



Merci pour votre attention





Prix Nobel 2025

