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Band Superconductivity in Periodic Constricted Nanoribbon Structures

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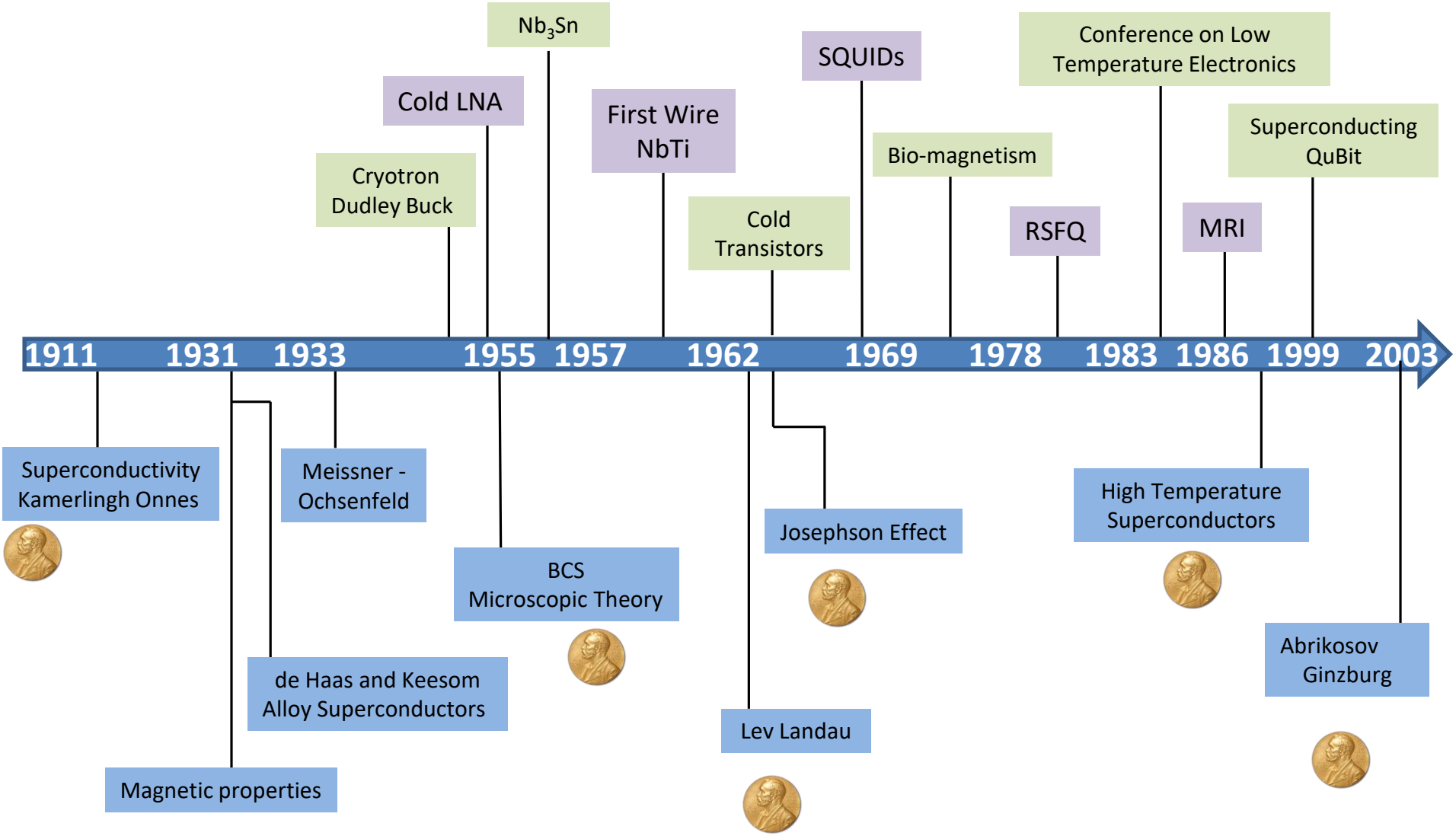
WHY SUPERCONDUCTIVITY



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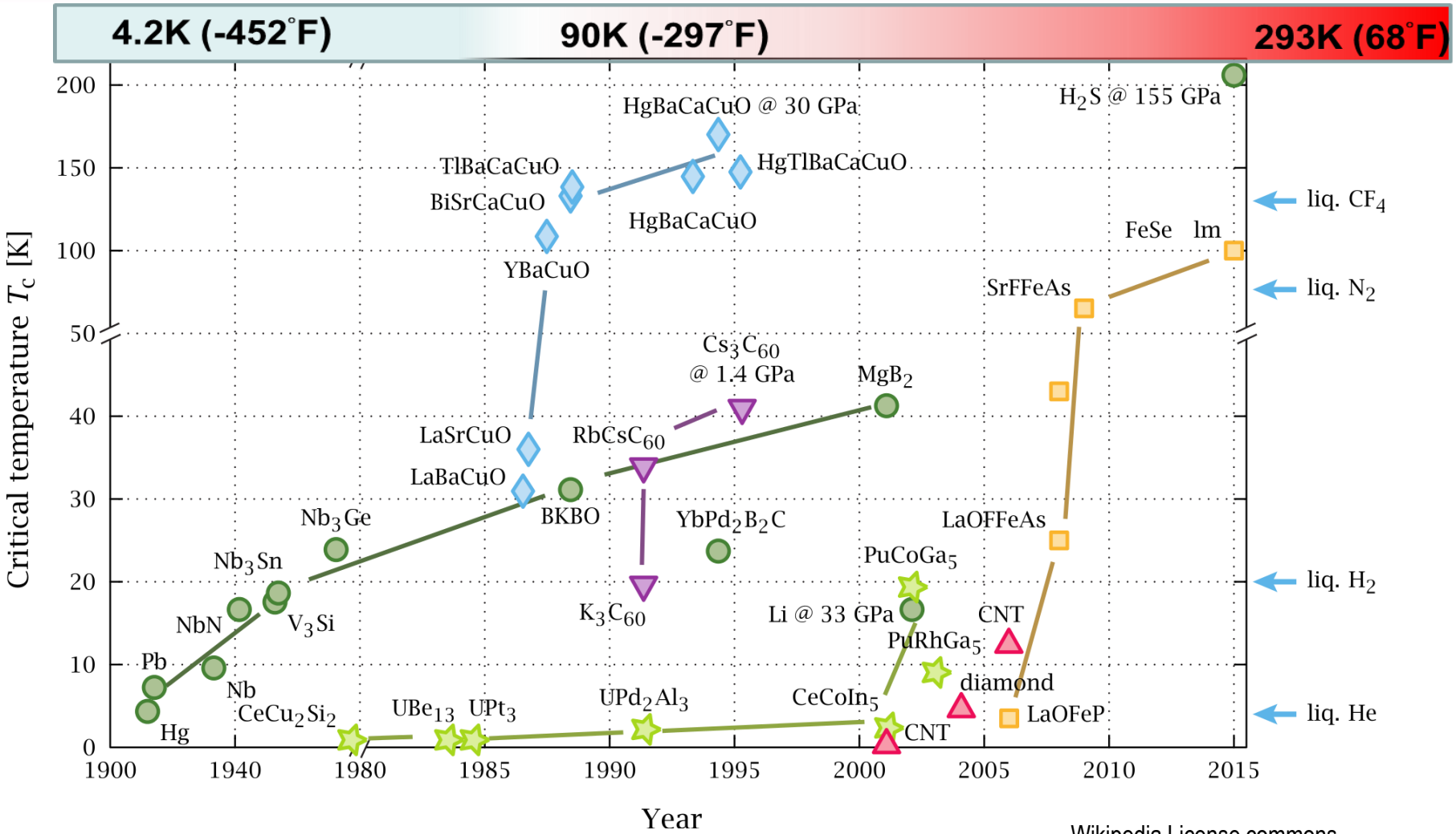
SUPERCONDUCTING MATERIALS

It's Cold!



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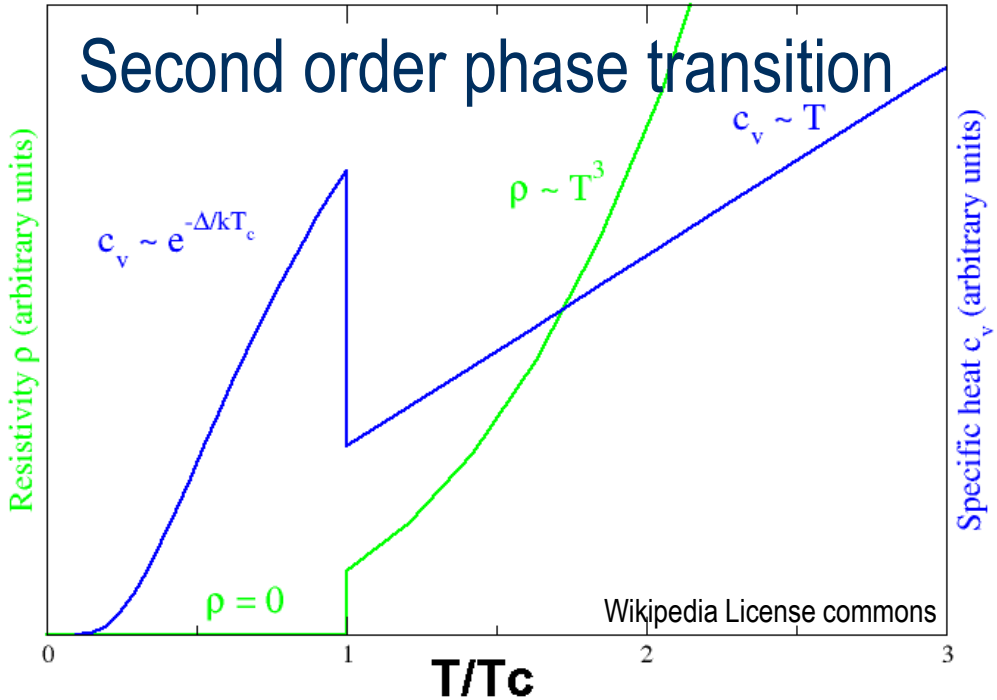
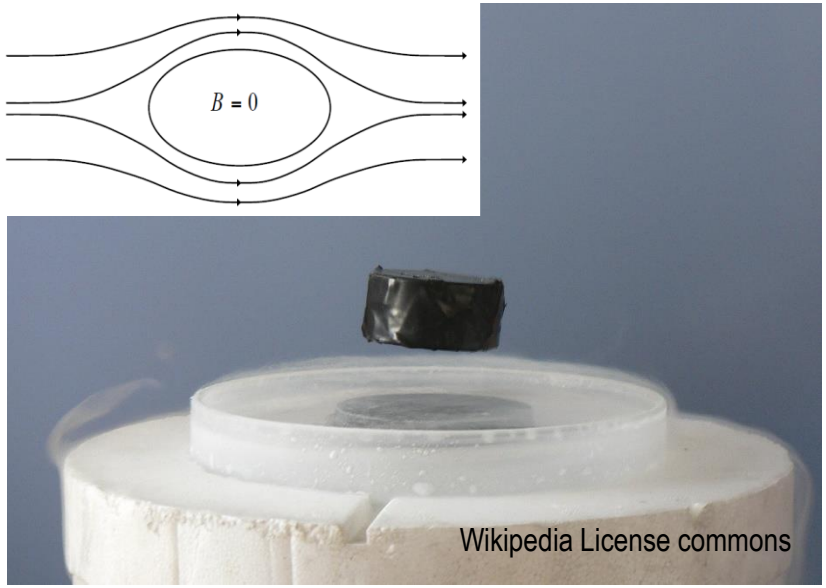
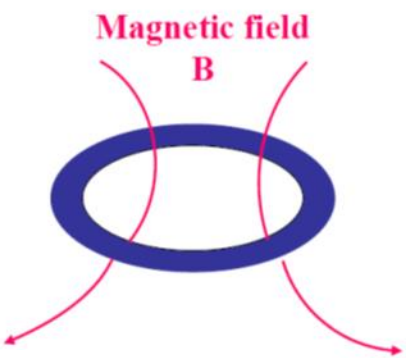
SUPERCONDUCTIVITY PROPERTIES



Macroscopic Quantum Effect





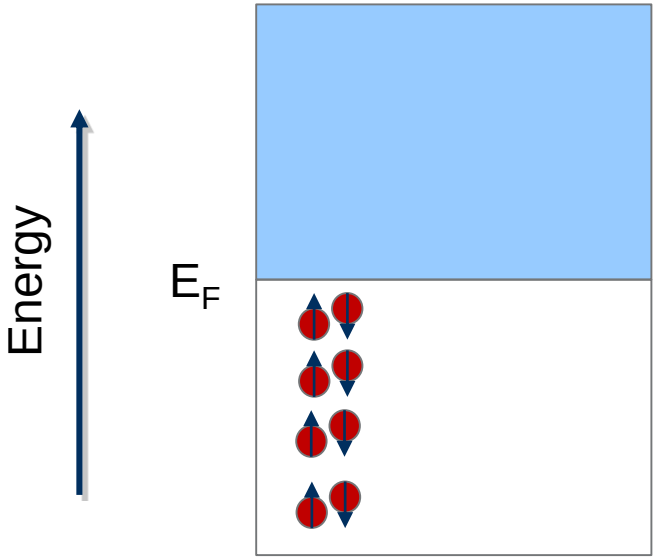
Magnetic flux is quantized in units of

$$\Phi_0 = {}^{h}/_{2e} = 2.07 \text{ x } 10^{-15}\ weber$$

ENERGY GAP

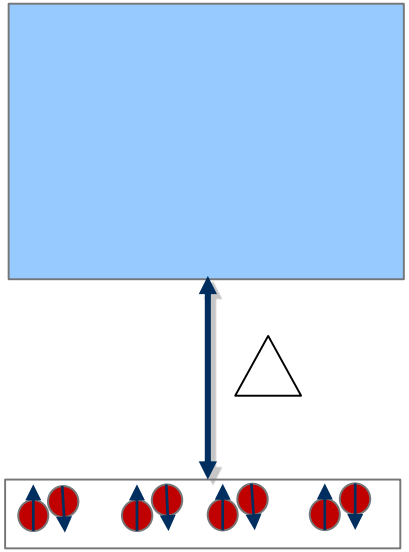
Metals

- Fermions
- Quantum states are an exclusive club



Superconductors

- Bosons
- Democratization of quantum states©



Condensation of pairs at the same energy level
A wave function representing a system with N particles (the order parameter)

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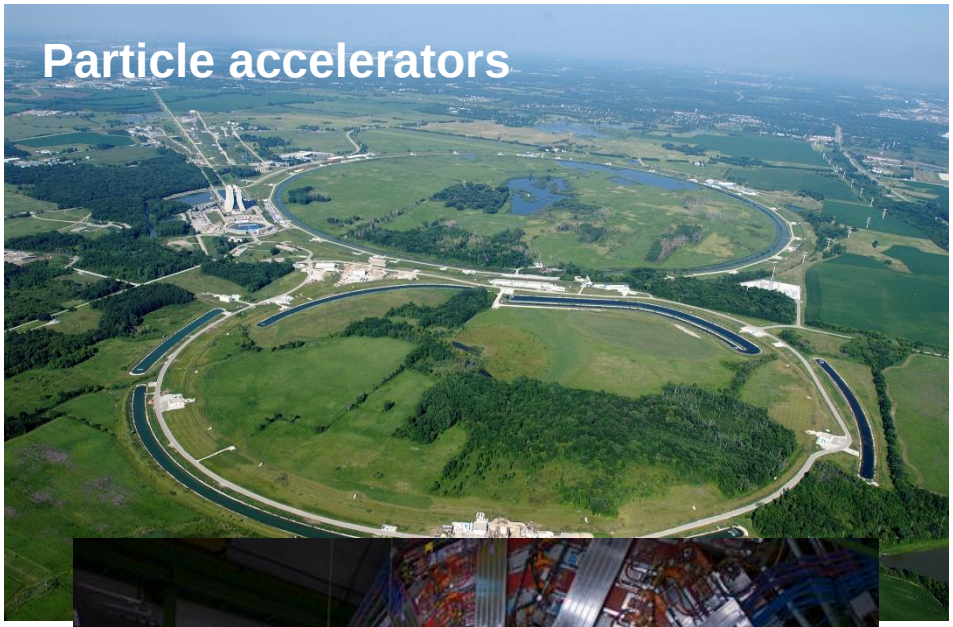
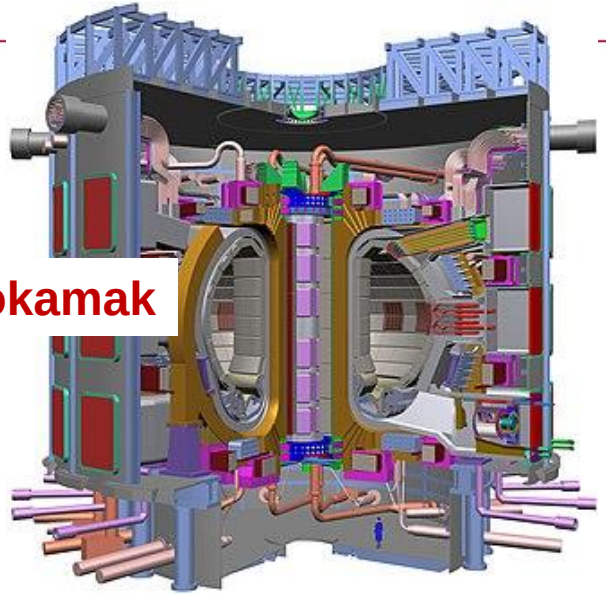
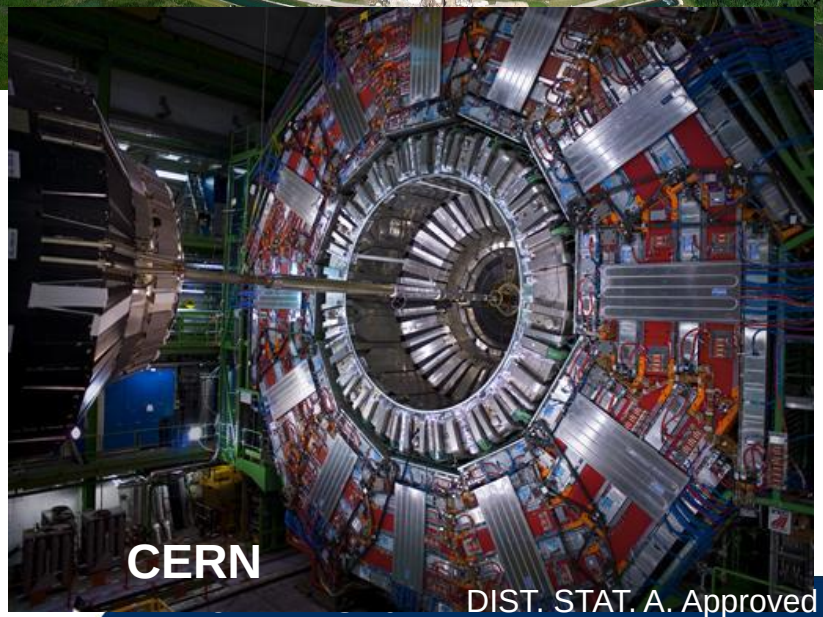
SUPERCONDUCTING MAGNETS

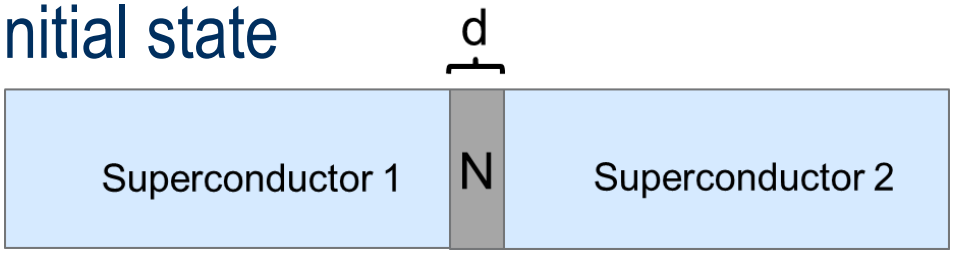






JOSEPHSON JUNCTIONS

Initial state



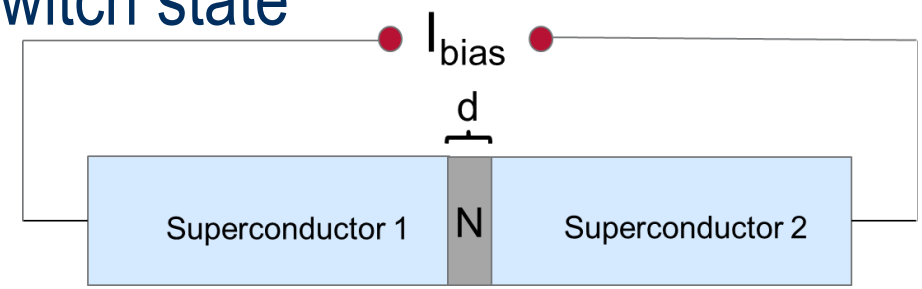
$$i\hbar\dot{\psi}_1 = E_1\psi_1 \qquad i\hbar\dot{\psi}_2 = E_1\psi_2$$

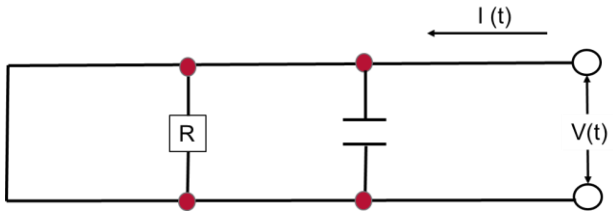
Josephson Junction Equations

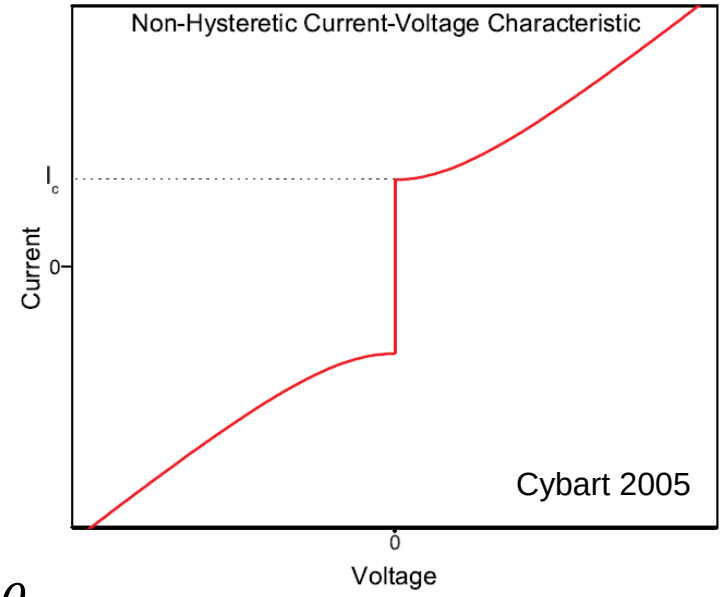
$$i = i_0 \sin\Delta\theta$$

$$\Delta\dot{\theta} = \frac{2eV}{\hbar}$$

Switch state







$$I = \frac{V}{R_n} C\frac{\partial V}{\partial T} + I_C \sin\Delta\theta$$

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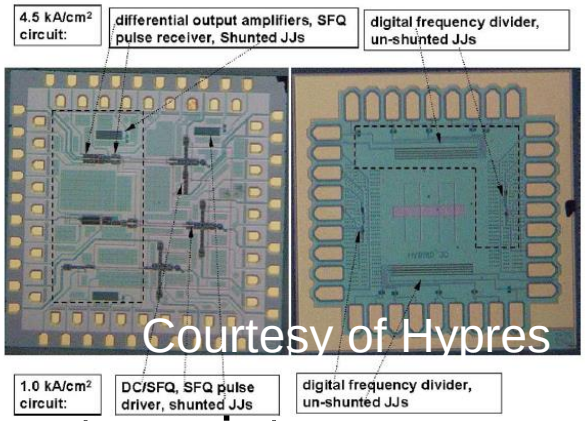
DIGITAL APPLICATIONS

- Rapid Single Flux Quantum Logic (RSFQ)
  - Josephson junctions operating as ultrafast switches (pS)
  - Extremely low dissipation (greater circuit density)
  - Low attenuation and dispersion over chip distance (high speeds)
- 1967 – 1990 Various attempts USA/Europe/Japan
- Multi-layer fabrication process
- Integration with semiconductors
- Commercially available
  - Less parameter deviation
  - Simpler fabrication than semiconductors transistor



Courtesy of Hypres

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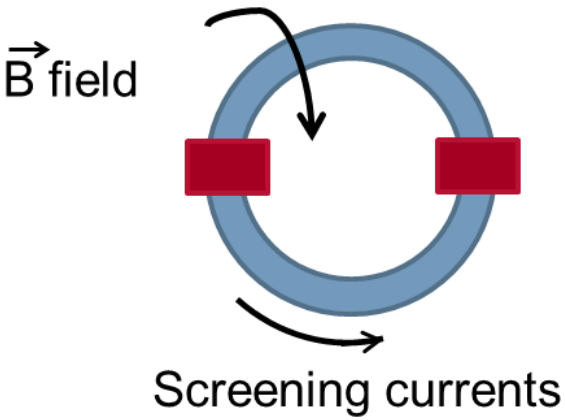
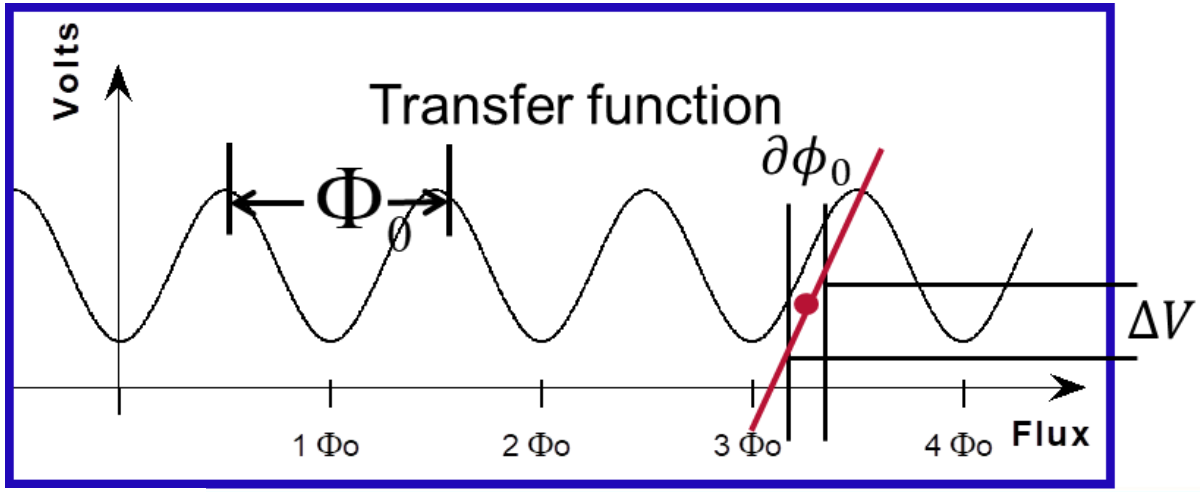
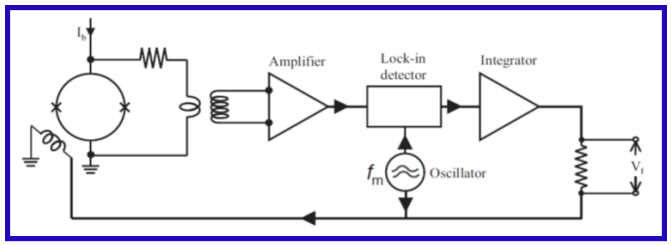
SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE (SQUID)

- Two Josephson junctions connected by a superconducting loop
- Highly sensitivity magnetic sensor
  - I-V modulated by magnetic flux
  - Period of the Flux Quantum Φ_0
  - Flux-to-voltage transfer function $V_\Phi \equiv \partial V/\partial \Phi$
- Low dissipation (Superconductivity)
- Low noise (Low temperatures)







Flux Lock loop

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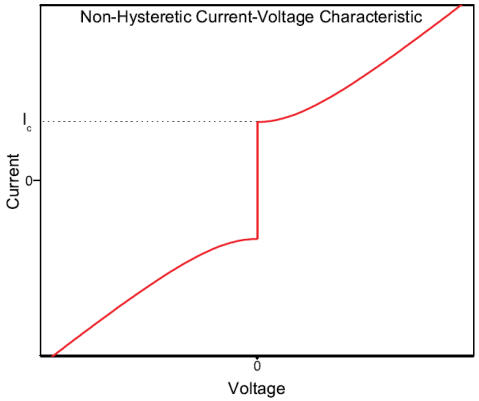
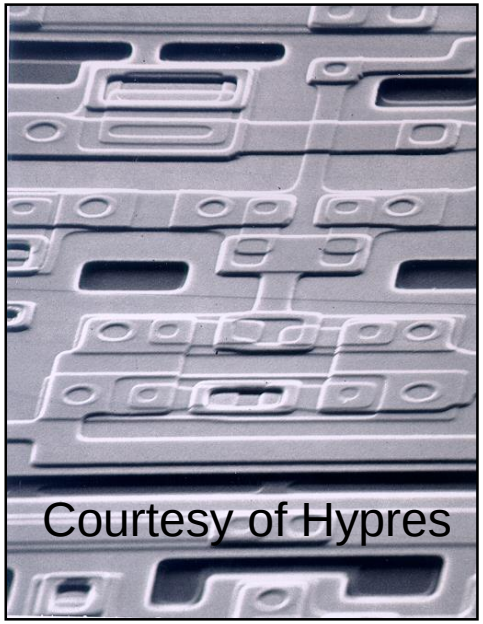
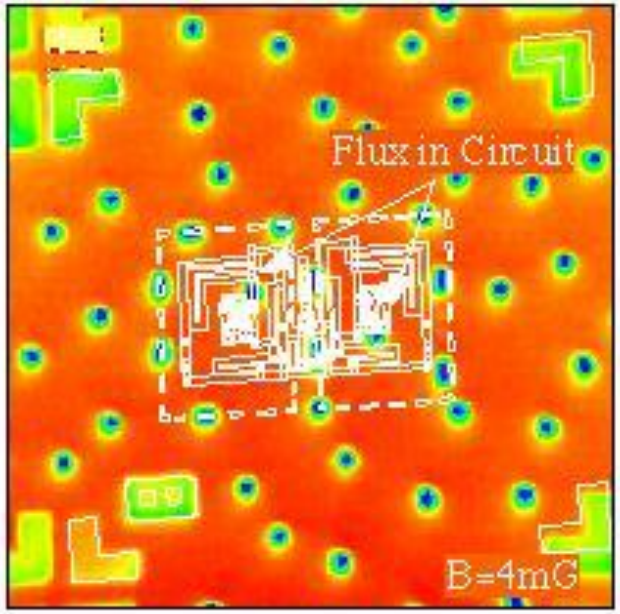
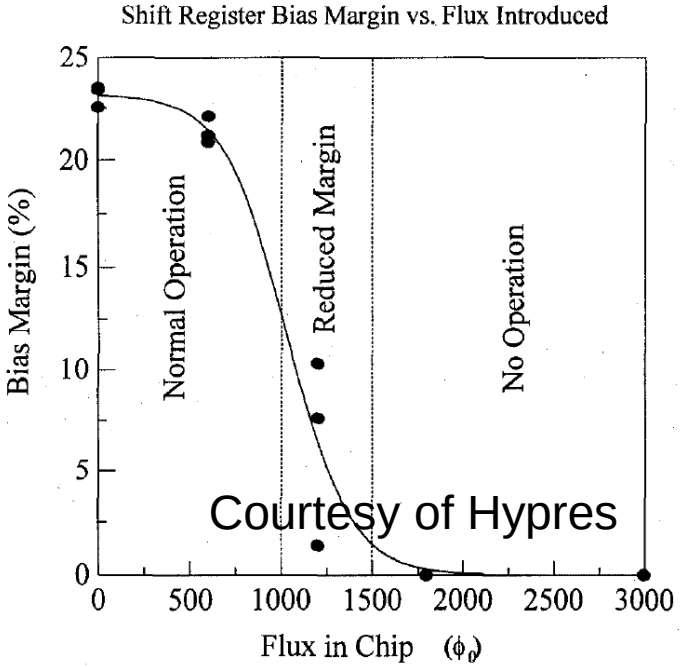
NO BED OF ROSES!

- Cryogenic memory is required to tap benefits
- Most electronics is custom designed
- Switching prone to errors
- No “transistor gain”
- Magnetic flux trap



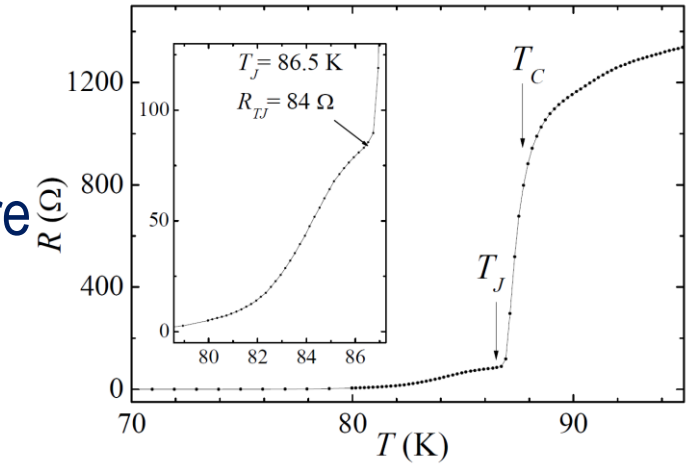






What about High Temperature Superconductors (HTS) ????

- Better candidate for practical applications $YBa_2Cu_3O_{7-\delta}$
  - Critical Temperature = 90K
  - Higher Thermal noise
  - Noise and currents increase with Temperature
  - Critical current spread



- Ceramic Material
  - Extremely laborious to make controlled junctions
  - Not scalable – Mass production does not exist (will ever?)
  - Highly anisotropic properties
  - Can't eliminate Grain boundaries
  - Enhanced magnetic flux trapping challenges

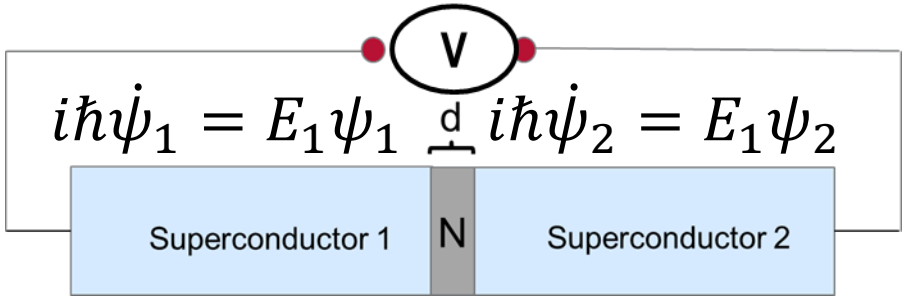
SHIELDED APPLICATIONS ONLY QUANTUM COMPUTING

- Josephson Qubits

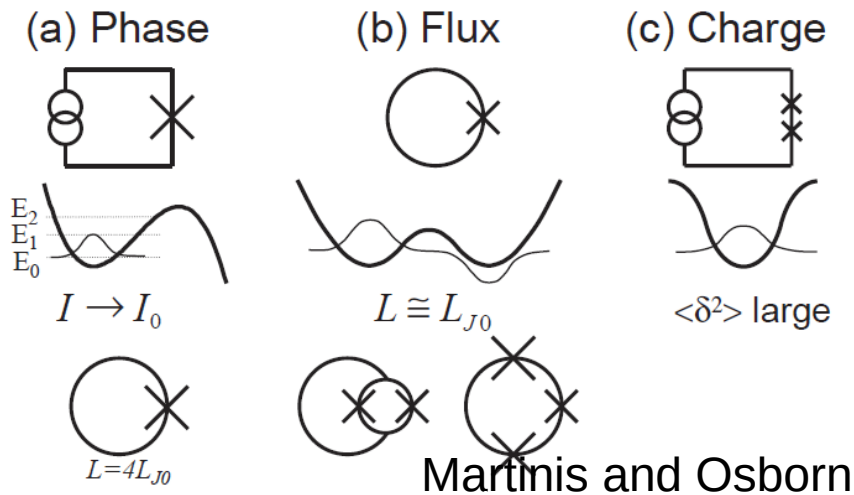
  Circuits with macroscopic quantum effects

  Entanglement quantized energy levels, superposition of states

- $E_{quantum} << E_{thermal}$
  - Induction + Capacitance
  - Non-Linear Josephson inductor
  - Possible to tune the energy states to lowest one



$$I_J = I_0 \sin\delta \qquad \delta = \phi_1 - \phi_2$$

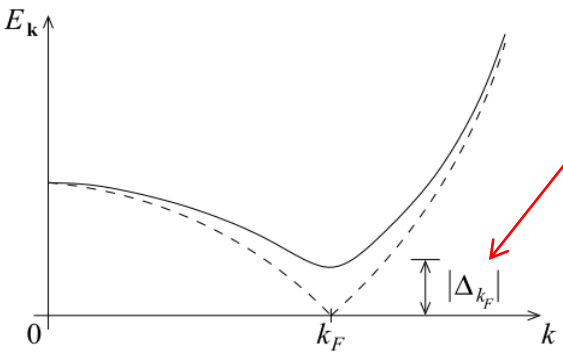


Martinis and Osborne

EXPLORING OTHER OPTIONS FOR QuBITS

▼ Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity

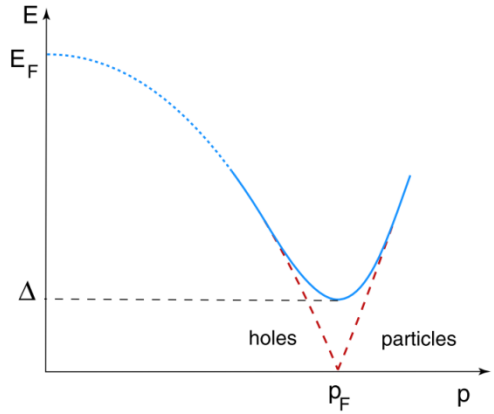
$$H_{\mathrm{BCS}} = \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}}\, c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} - \sum_{\mathbf{k}} \Delta^{*}_{\mathbf{k}}\, c_{-\mathbf{k},\downarrow} c_{\mathbf{k}\uparrow} - \sum_{\mathbf{k}} \Delta_{\mathbf{k}}\, c^{\dagger}_{\mathbf{k}\uparrow} c^{\dagger}_{-\mathbf{k},\downarrow} + \mathrm{const.}$$

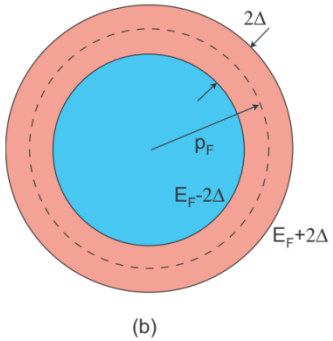


SC gap

$$\Delta_0(0) \cong 2\omega_D \exp\left(-\frac{1}{V_0 D(E_F)}\right).$$

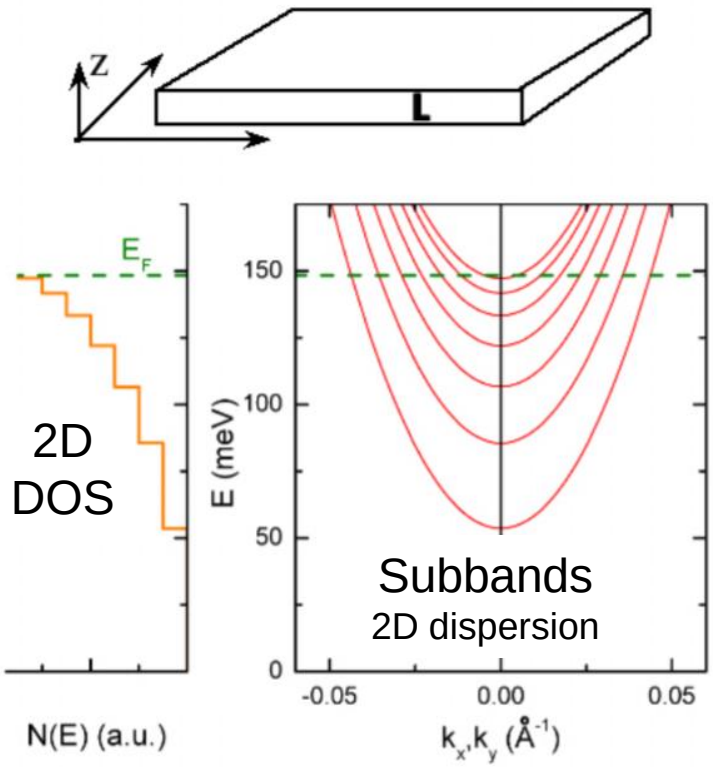
Density of states DOS



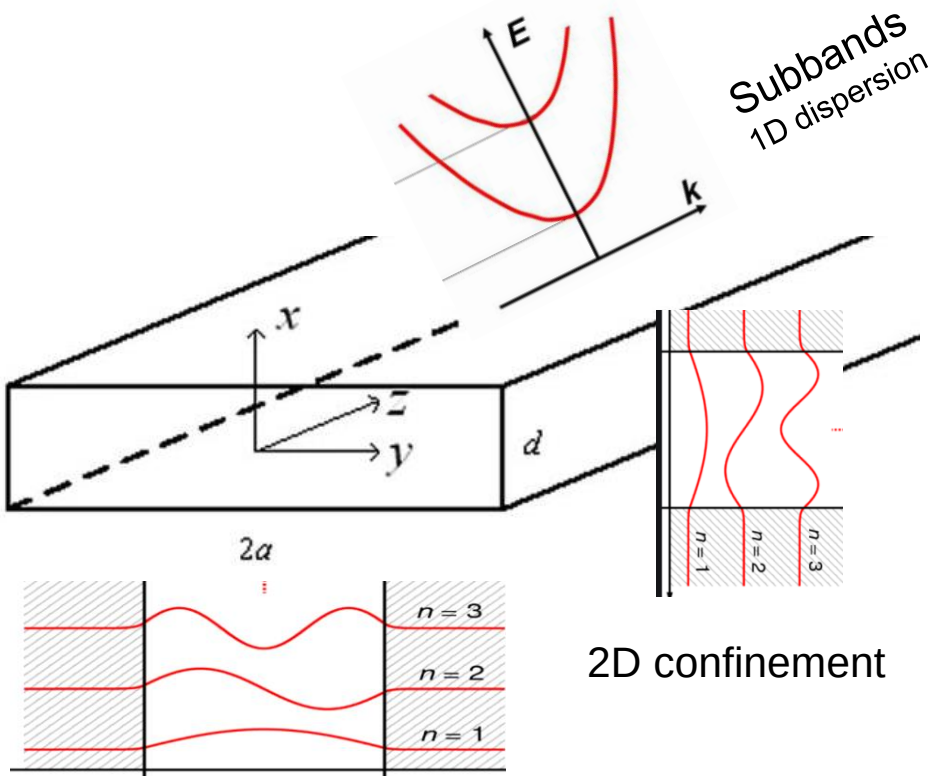


SUPERCONDUCTING THIN FILMS

Thin films (2D)

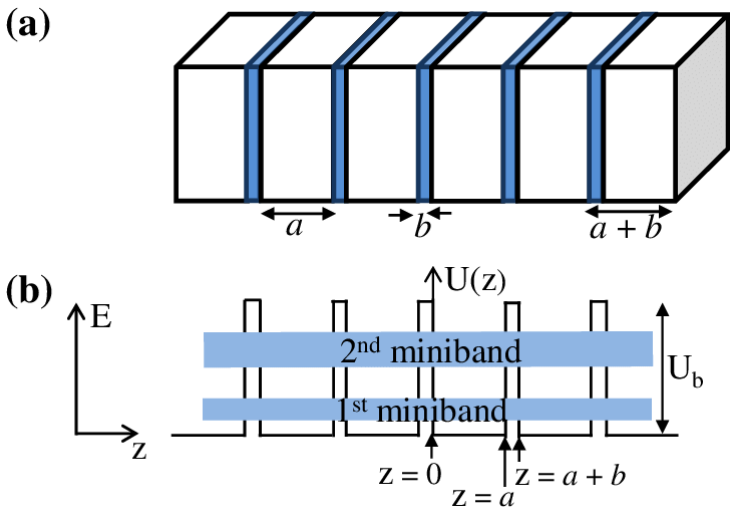


Nanoribbon (quasi-1D)

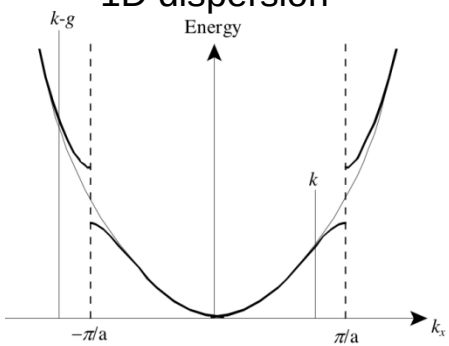


MODULATION IN SUPERCONDUCTING NANOWIRES

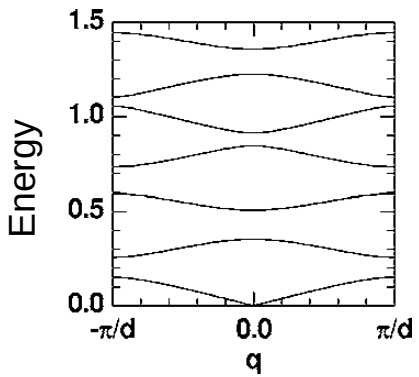
1D superlattices



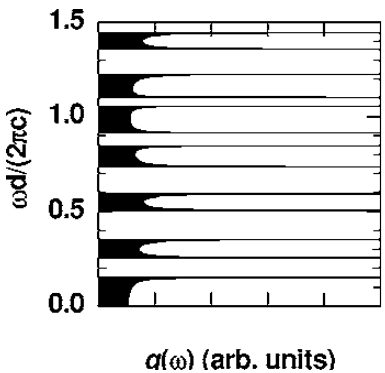
1D dispersion



Miniband formation

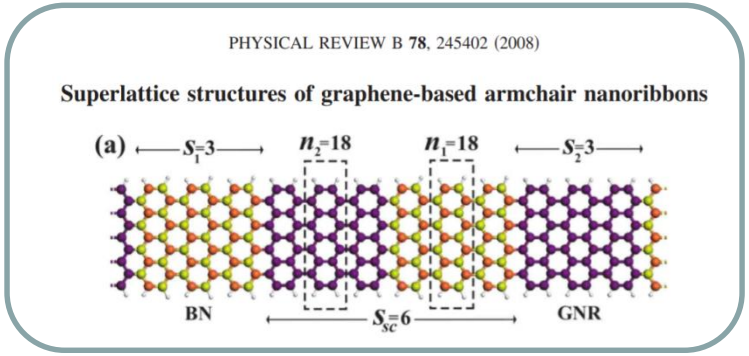


Miniband dispersion



Miniband DOS

Possible realization



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Controlling SC by MODIFYING THE DENSITY OF STATES

Pergamon

Solid State Communications, Vol. 102, No. 5, pp. 369–374, 1997

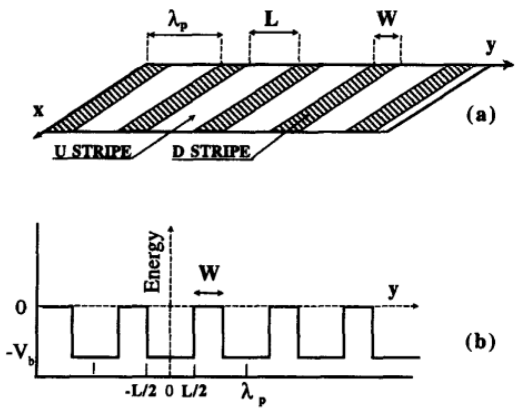
0038–1098/97 $17.00+.00

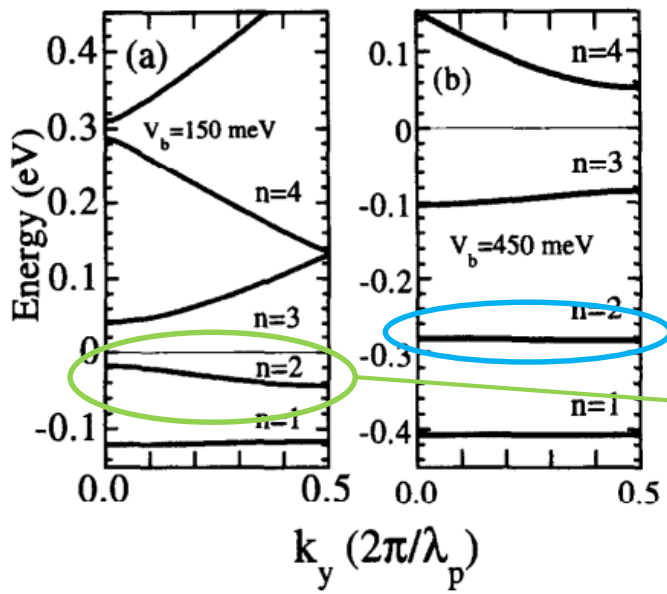
PII: S0038–1098(97)00011-2

$$\Delta_0(0) \cong 2\omega_D \exp\left(-\frac{1}{V_0\, D(E_F)}\right).$$

HIGH T_c SUPERCONDUCTIVITY IN A SUPERLATTICE OF QUANTUM STRIPES

A. Bianconi,[a] A. Valletta,[a] A. Perali[a] and N.L. Saini[b]





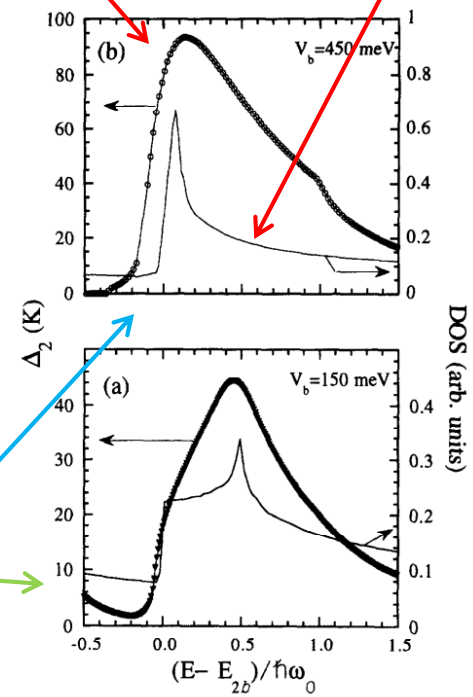
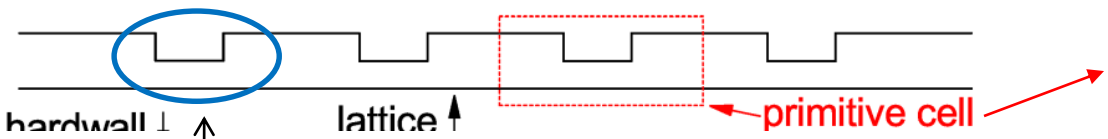
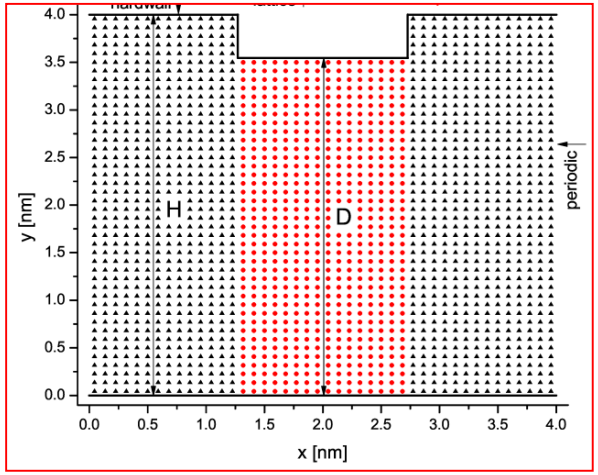


Fig. 6. The superconducting gap Δ_2 at $n = 2$ shape resonance as a function of the energy separation from the

PROPOSED MODEL TO CONTROL DOS

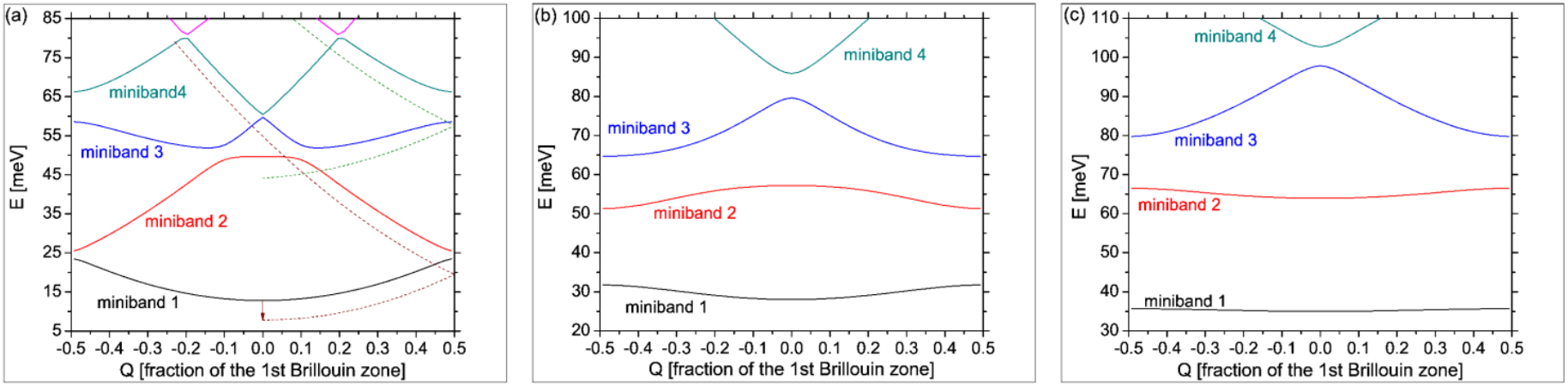
Periodically constricted nanoribbon





Constrictions – play the role similar to gates

Dispersions – Varying the constriction



(~a free nanoribbon) → → increasing constriction → → (~aligned quantum dots)

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Bogoliubov-de Gennes Equations

The BdG equations, describing the superconductivity, have the form of:

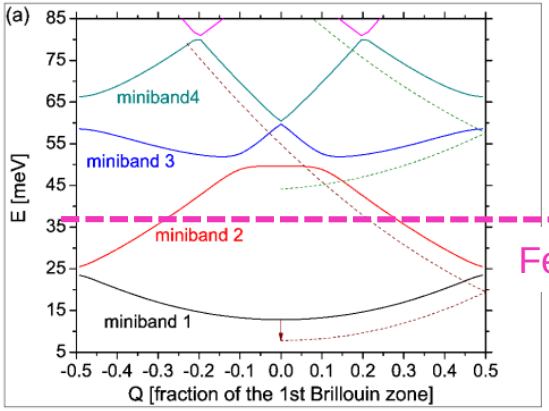
$$\begin{pmatrix} -\frac{\hbar^2}{2m}\nabla^2 - E_F & \Delta(\vec{r}) \\ \Delta^*(\vec{r}) & \frac{\hbar^2}{2m}\nabla^2 + E_F \end{pmatrix} \begin{pmatrix} u_\eta(\vec{r}) \\ v_\eta(\vec{r}) \end{pmatrix} = E_\eta \begin{pmatrix} u_\eta(\vec{r}) \\ v_\eta(\vec{r}) \end{pmatrix},$$

Electron-like

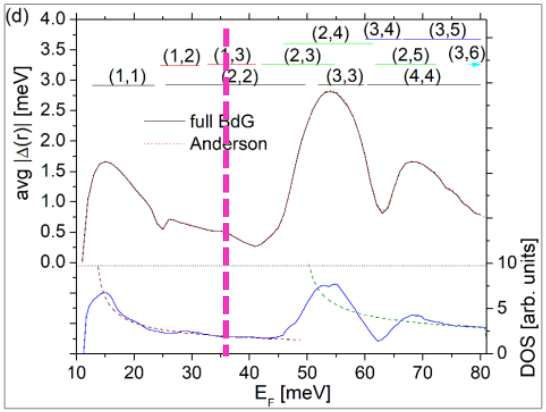
Hole-like

Self-consistent

$$\Delta(r) = \frac{g}{N_0} \sum_Q \sum_{\{n:E_{Q,n}<E_C\}} u_{Q,n}(\vec{r}) v^*_{Q,n}(\vec{r})$$



Fermi level



$$\Delta_0(0) \cong 2\omega_D \exp\left(-\frac{1}{V_0\, D(E_F)}\right).$$

SC gap ~ DOS

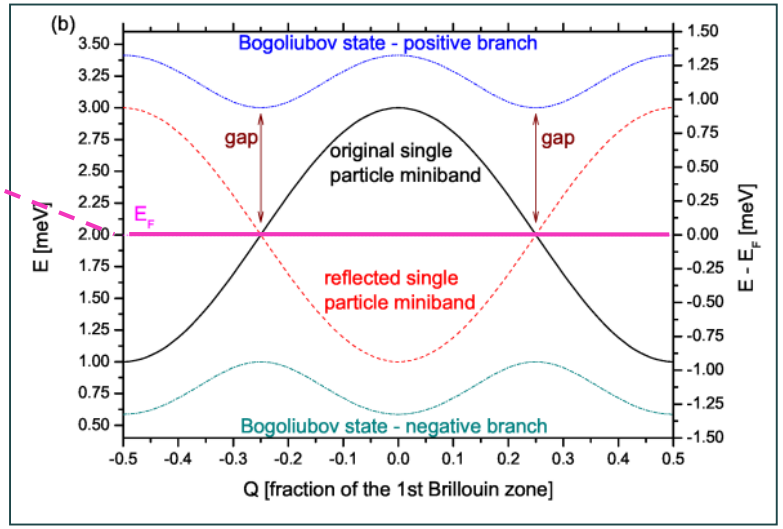


Illustration:
Gap formation at the Fermi level

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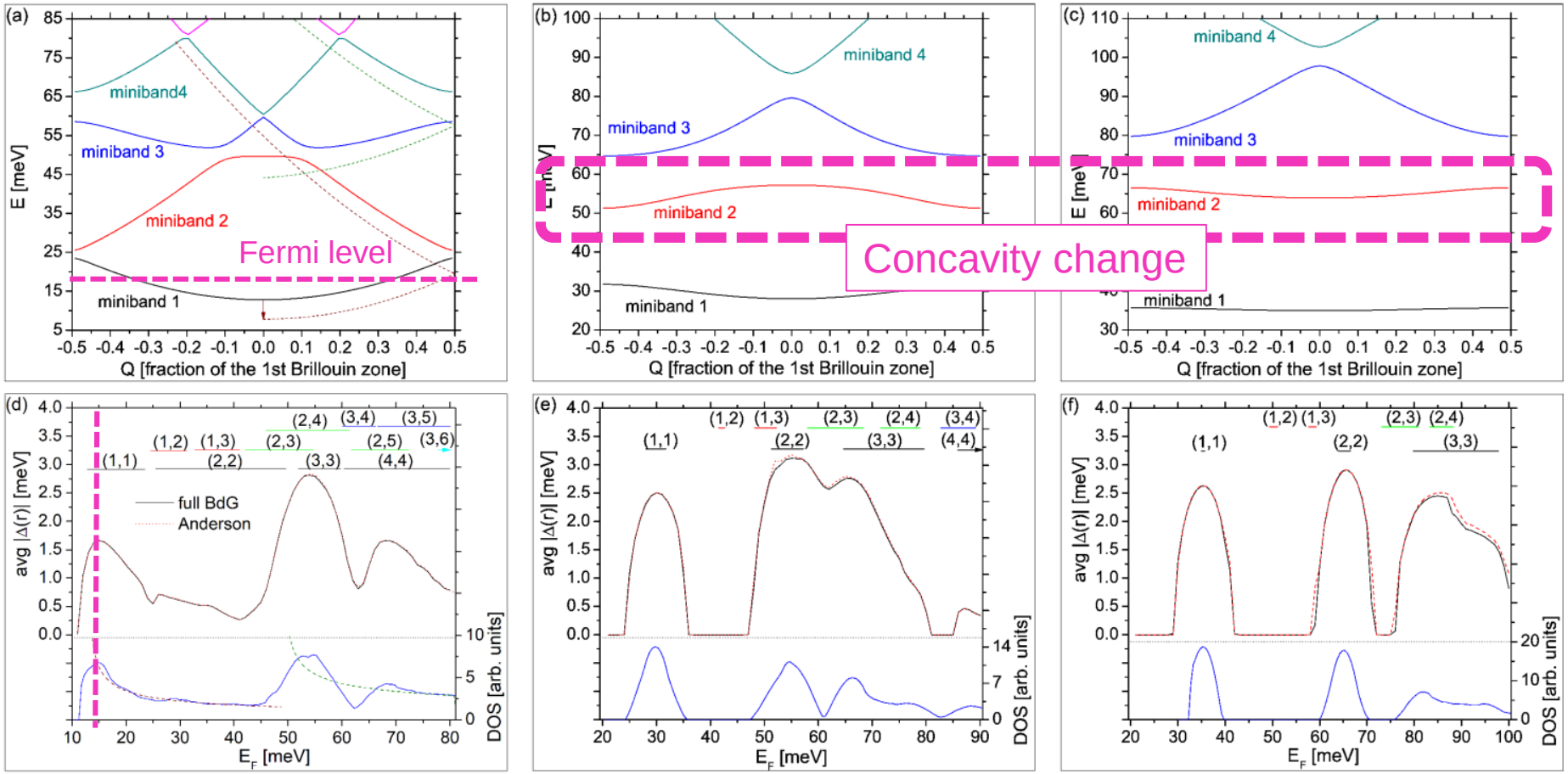
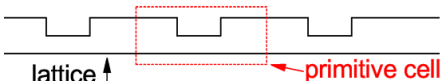
RESULTS

Average gap versus Fermi energy – Varying constriction



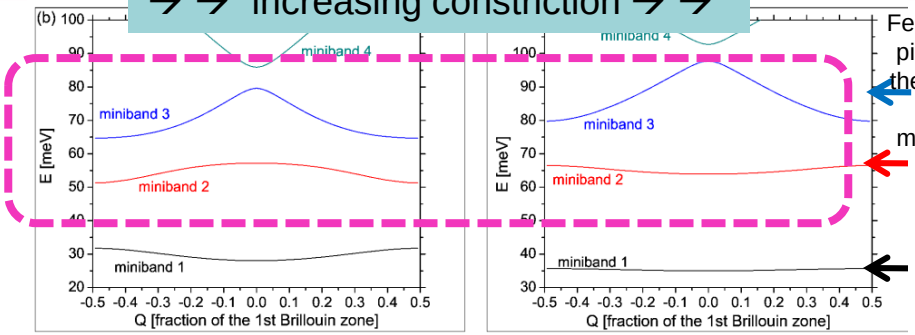
(~a free nanoribbon) → → increasing constriction → → (~aligned quantum dots)



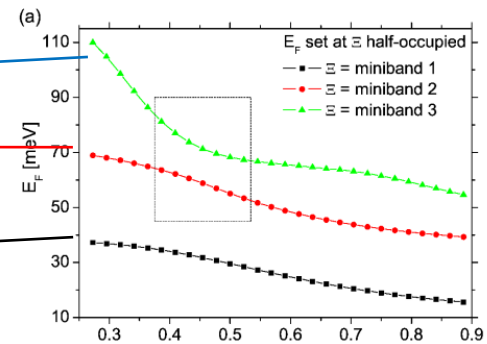
EFFECTS ON THE MINIBANDS MIXING

Geommetric effect "shape resonance"

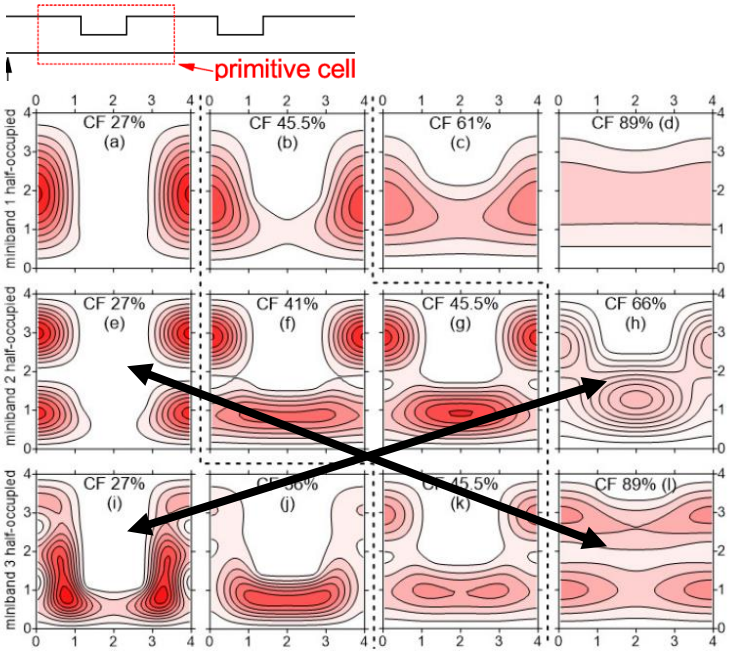
→ → increasing constriction → →



Fermi level pinned at the middle of the miniband



← ← increasing constriction ← ←

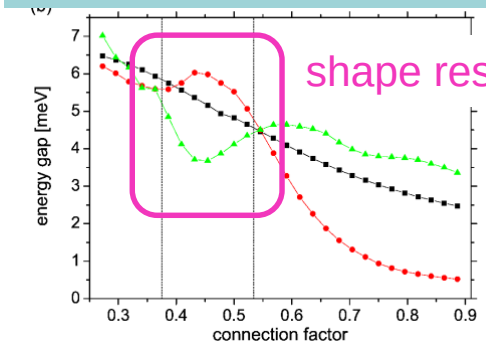


Miniband-1

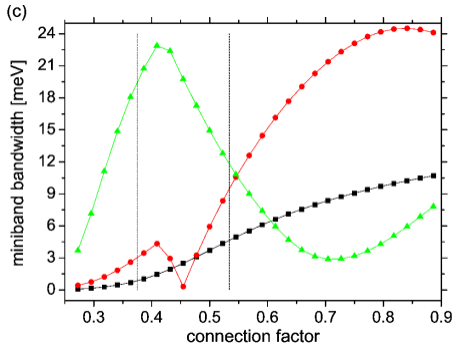
Miniband-2

Miniband-3

← ← increasing constriction ← ←



Average gap

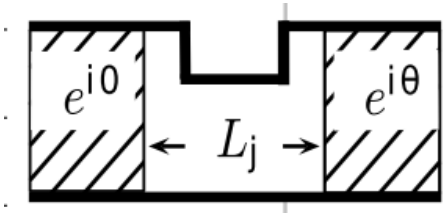


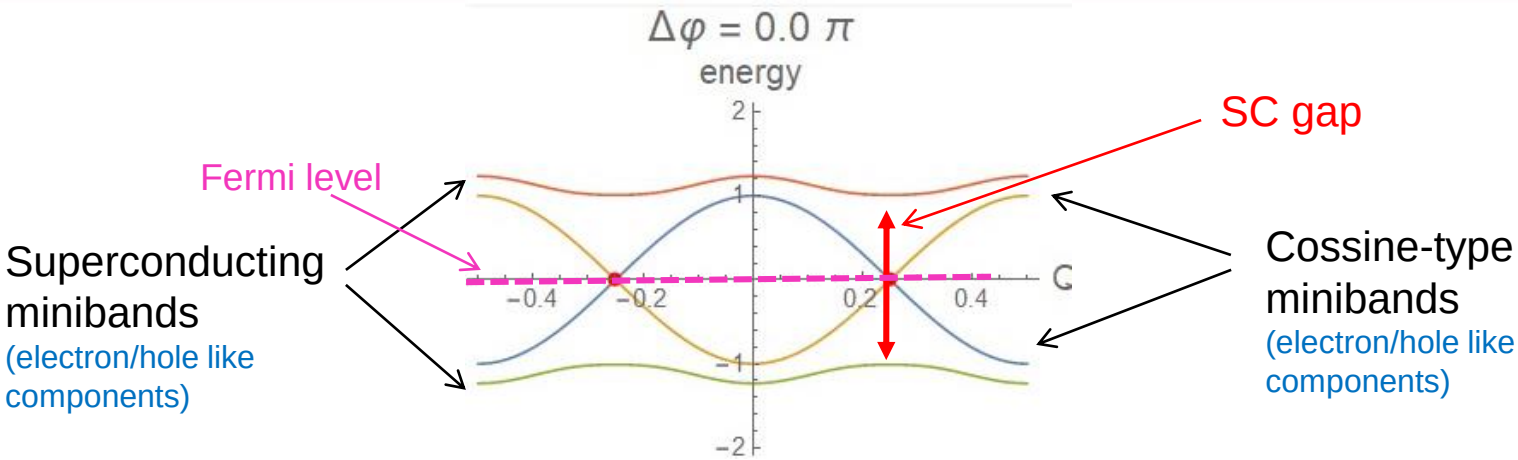
Miniband width

~1/DOS

Phase Effects

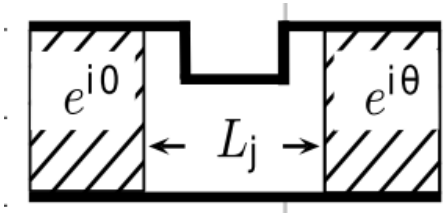
Simple example – cossine-type miniband

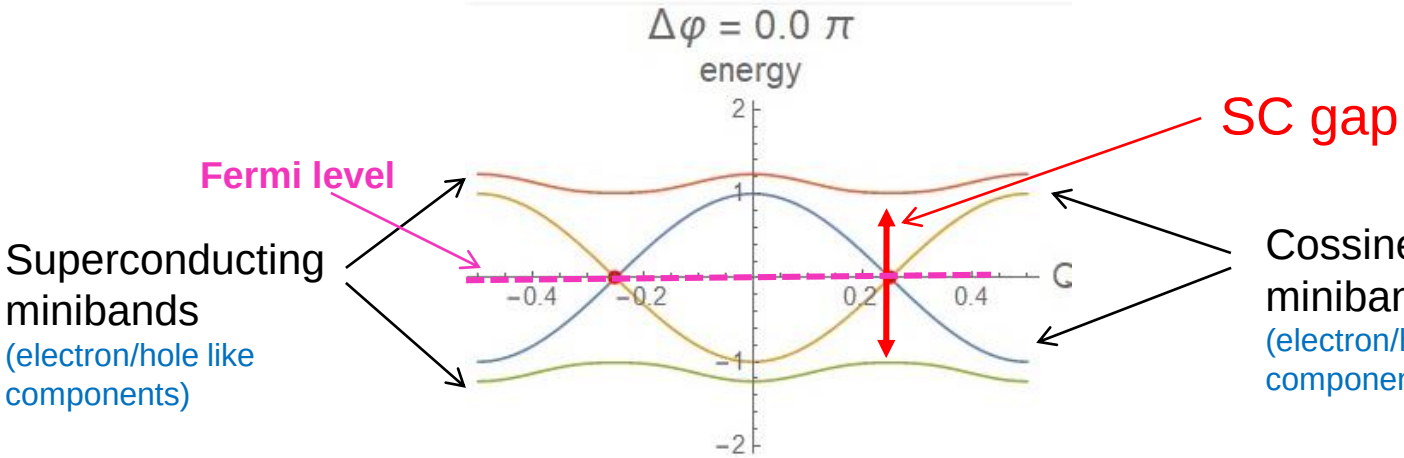




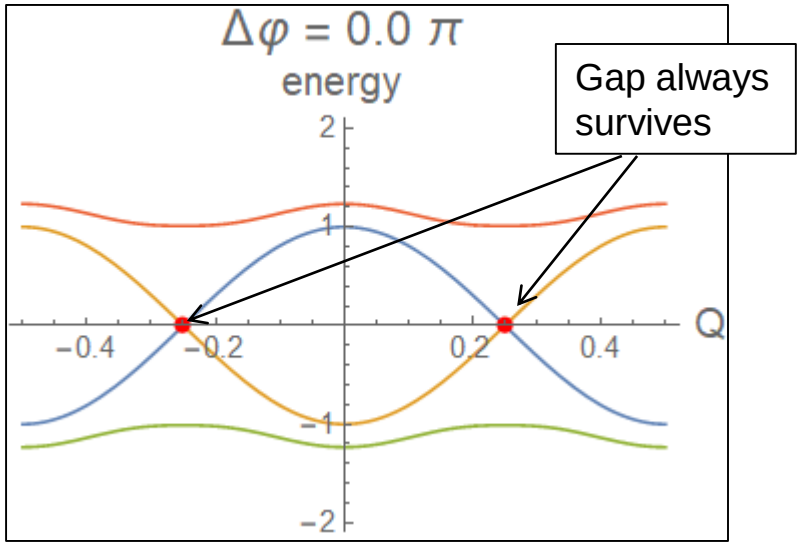
Phase Effects

Simple example – cossine-type miniband

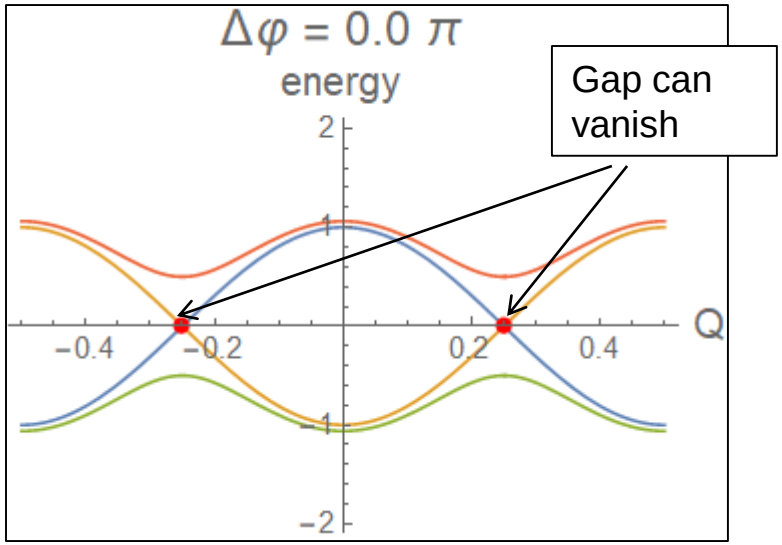




Larger SC gap



Smaller SC gap



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FINAL CONSIDERATIONS

- Nanoribbons can provide a better control of the current-phase relation in junctions/SQUIDs
- The extra control can be applied to QuBits for quantum hardware
- Semiconductor people can work well with experimental physicists!