Workshop on Theory and Practice of
Adiabatic Quantum Computers and Quantum Simulations
22-26 August 2016, ICTP Trieste

High-Tc Josephson junctions for quantum computation

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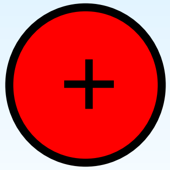
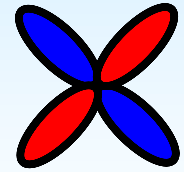
Outline

- **Introduction**

  Superconductivity: conventional unconventional

  s-wave 

  d-wave 

  Josephson junctions

- **Qubits & (d-wave) high-Tc Josephson junctions**

- **Devices with hundreds/thousends of high-Tc junctions**

  Flux-flow MW/THz generators

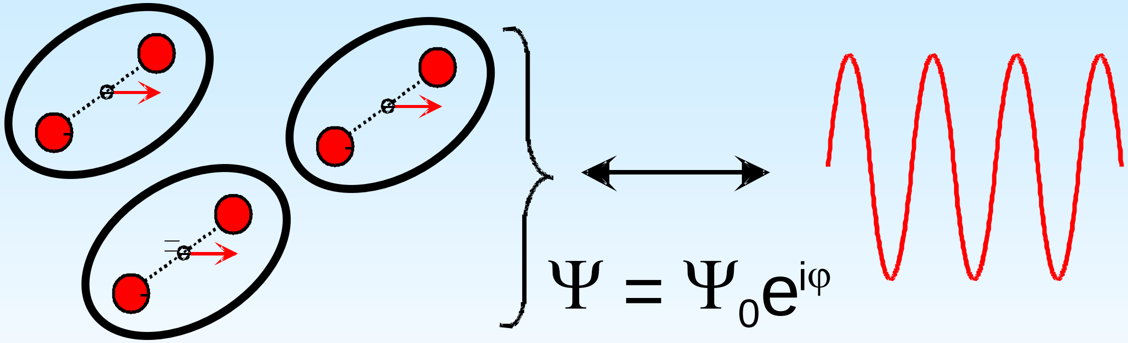
  Transistors

  Magnetic sensors (SQUIDs, SQIFs)

  Quantum computers?

Superconductivity: conventional & unconventional

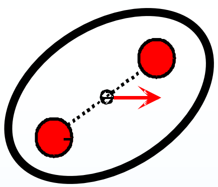
Cooper pairs



Superconducting order parameter

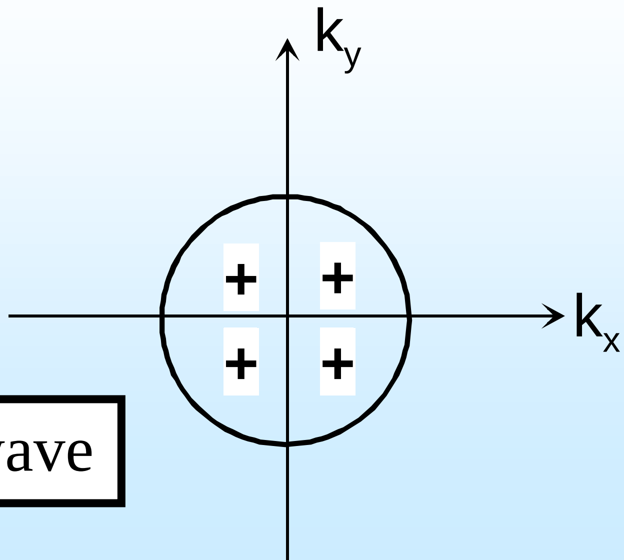
Conventional

pairing mechanism: electron-phonon interaction



total spin S=0

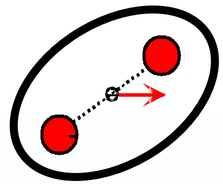
orbital angular momentum L=0



s-wave

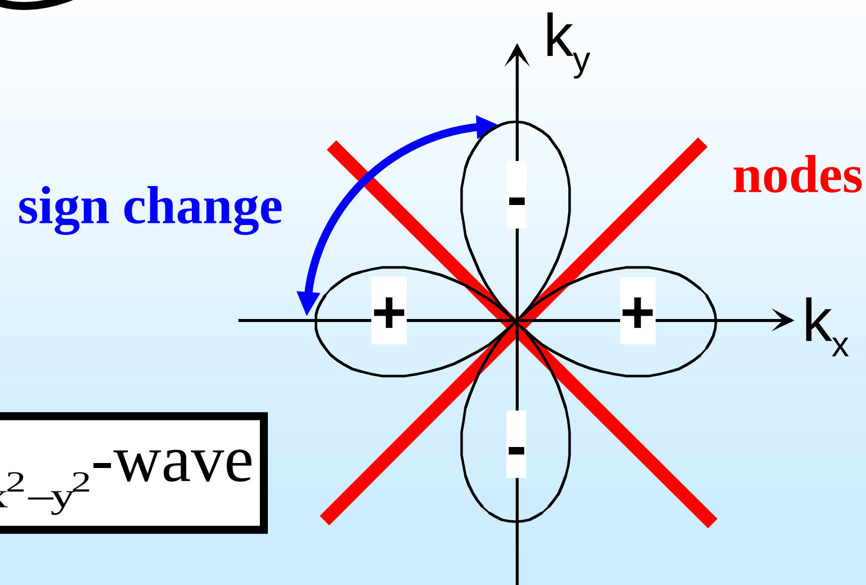
Unconventional

pairing mechanism ?



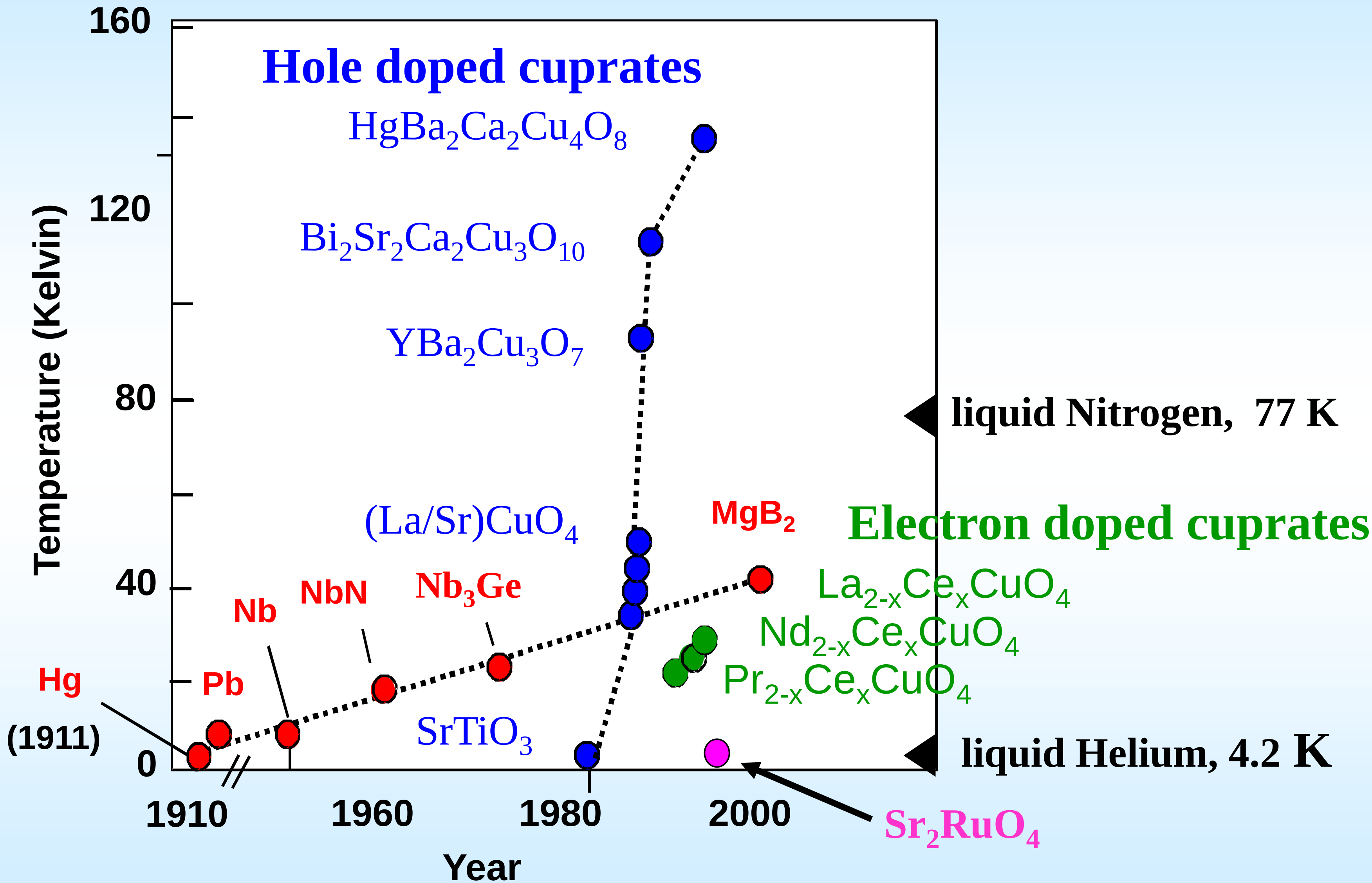
total spin S=0

orbital angular momentum L=2



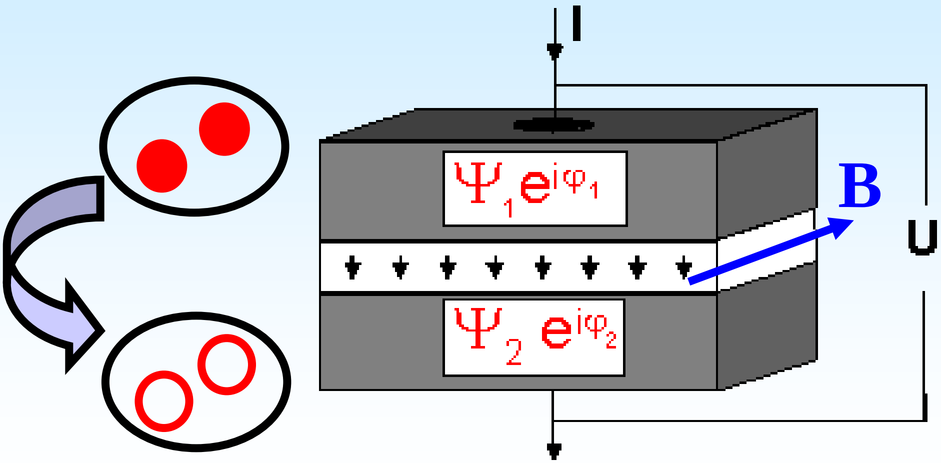
$d_{x^2-y^2}$-wave

Discovery of superconductors: critical temperature vs. time

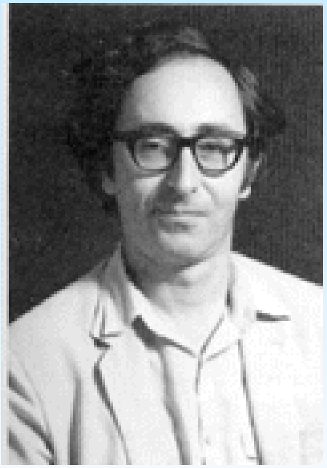


Conventional superconductors

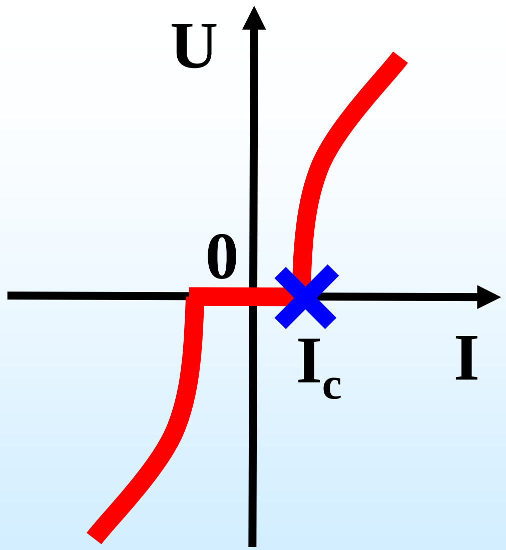
Josephson junction: dc effect

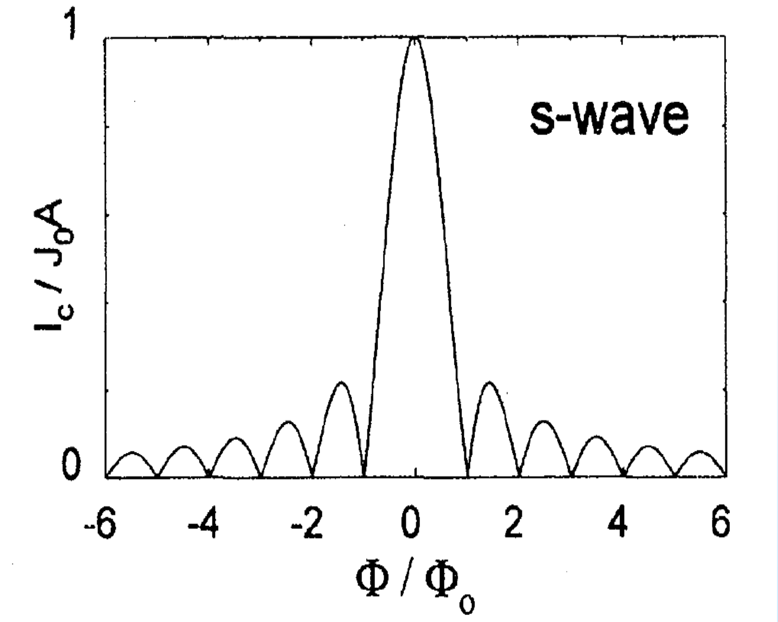


$$J = J_c \sin(\varphi_2 - \varphi_1)$$



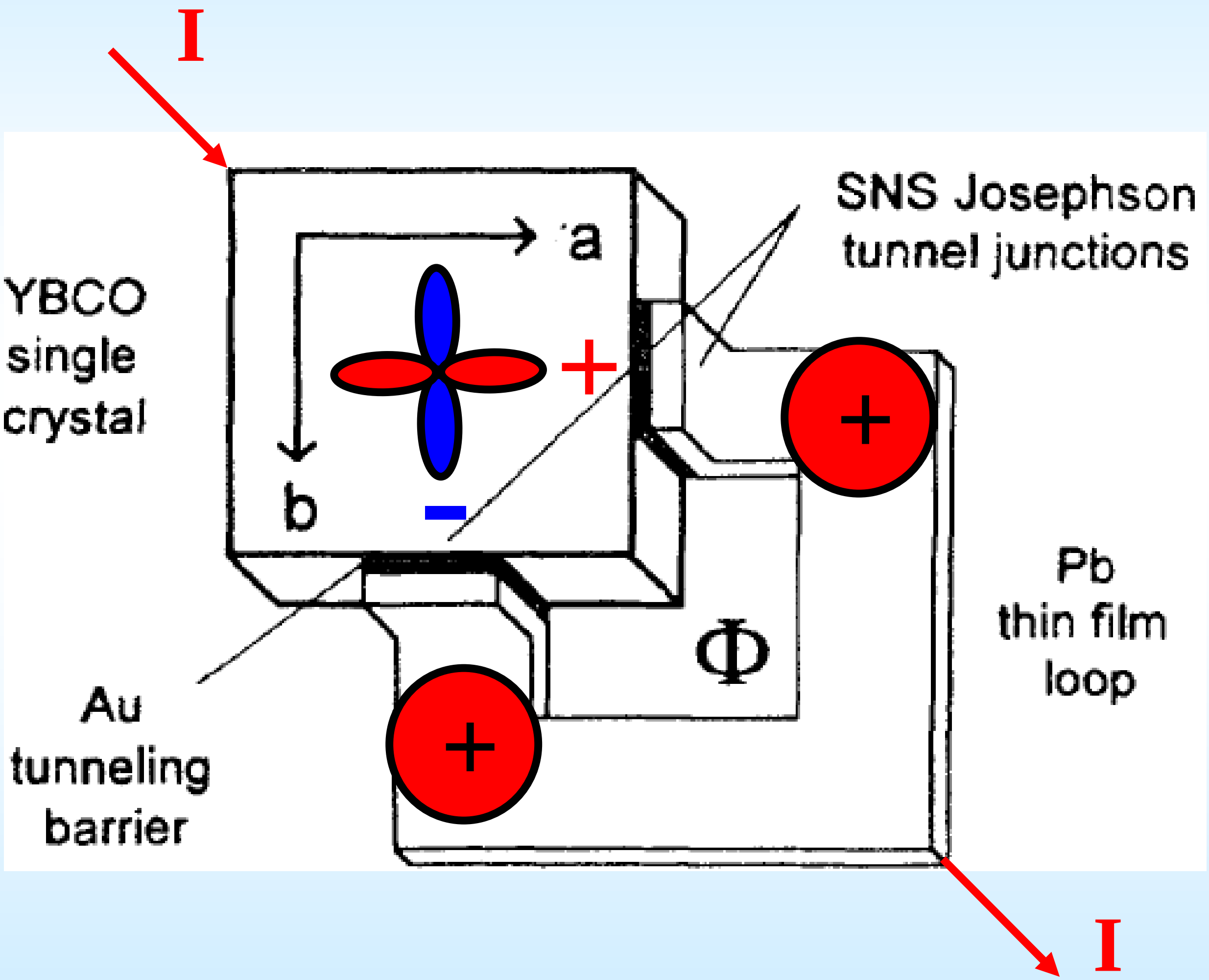
B. D. Josephson,
Cambridge (1962)

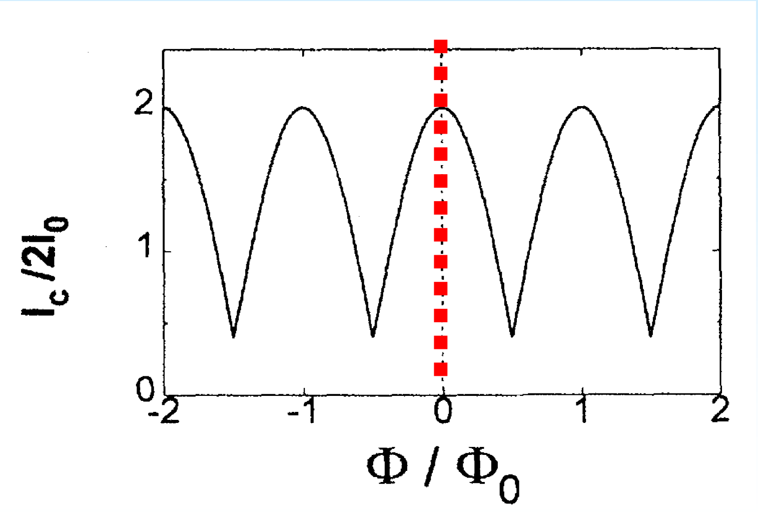


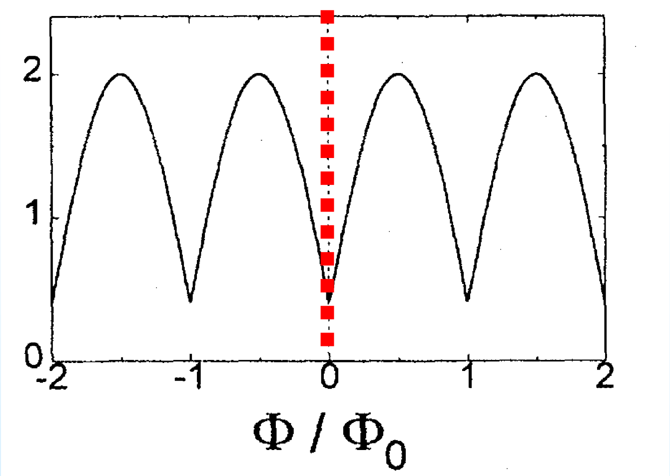


π-junction: s-wave & d-wave superconductors

$$I = -I_c \sin(\varphi_2 - \varphi_1) = I_c \sin(\varphi_2 - \varphi_1 + \pi)$$

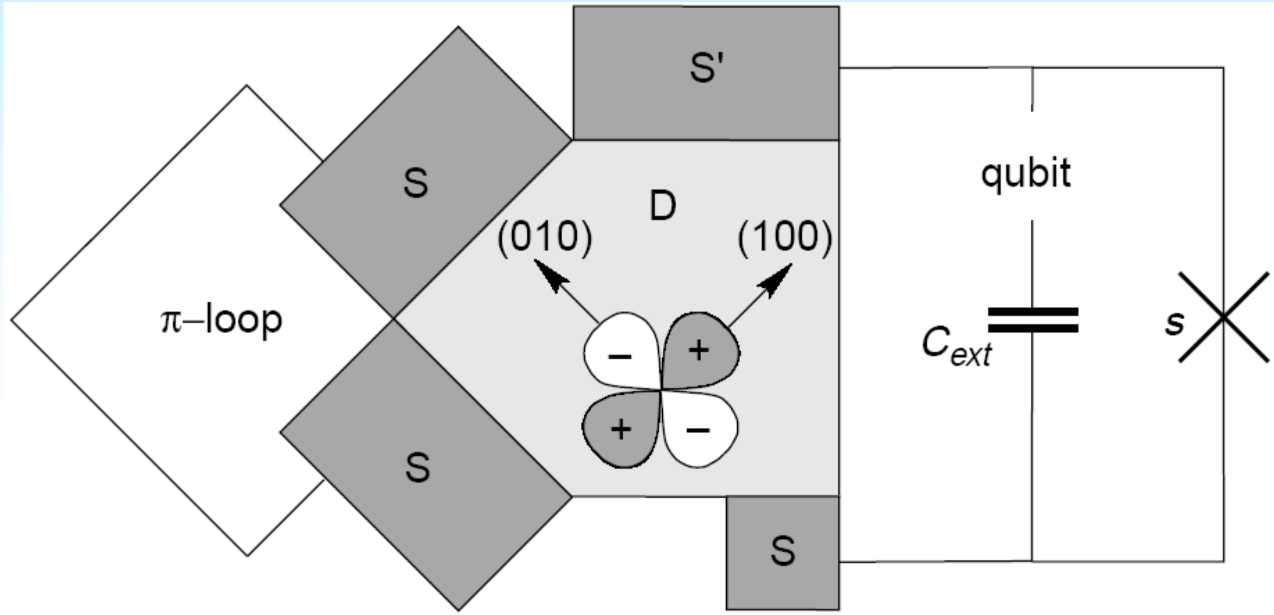




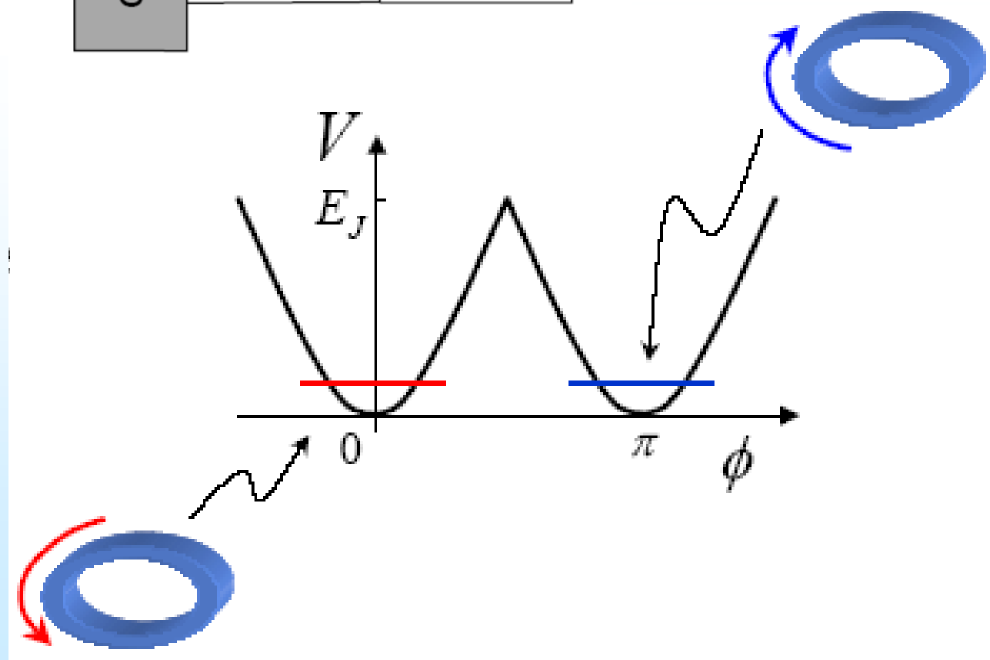


D.Wollman, Van Harlingen, W.Lee, D.M.Ginsberg, A.J.Leggett, *Phys.Rev.Lett.* 71, 2134 (1993)

π-junction & Qubits



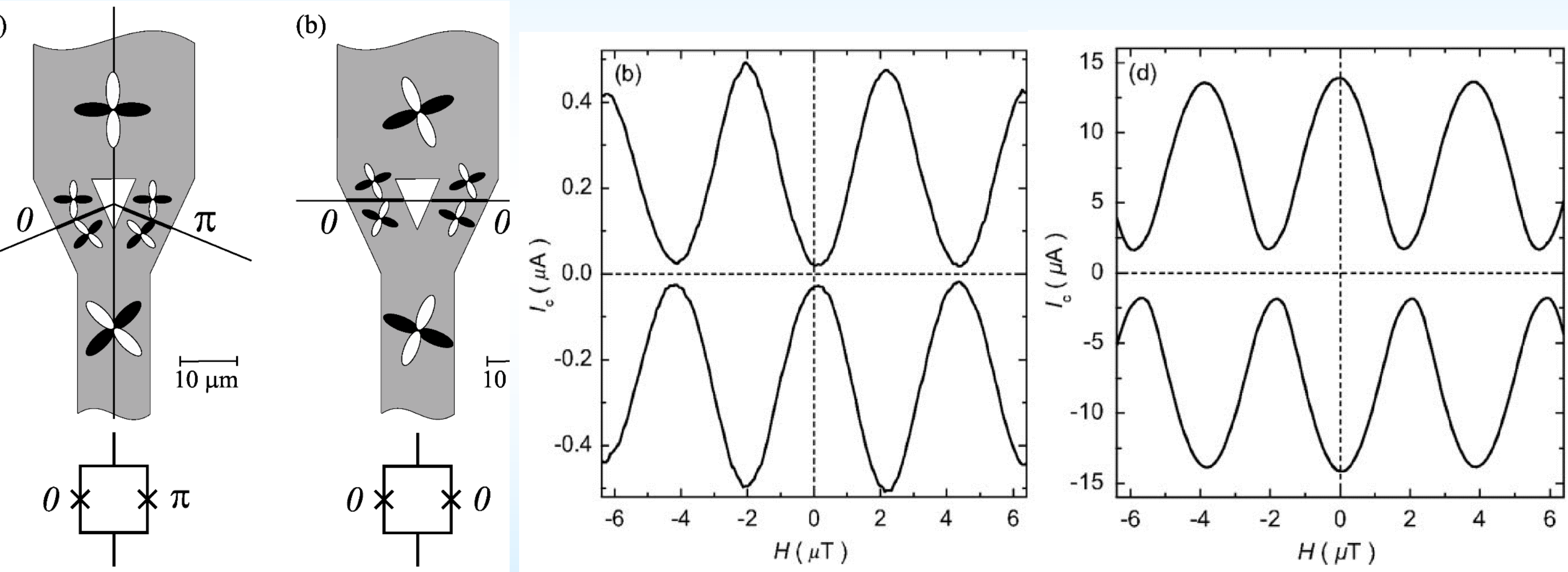
Quantum computation:
a qubit with 2 persistent
current states



L. B. Ioffe et al., *Nature* **398,** 679 (1999)

π-junctions: d-wave superconductors only!

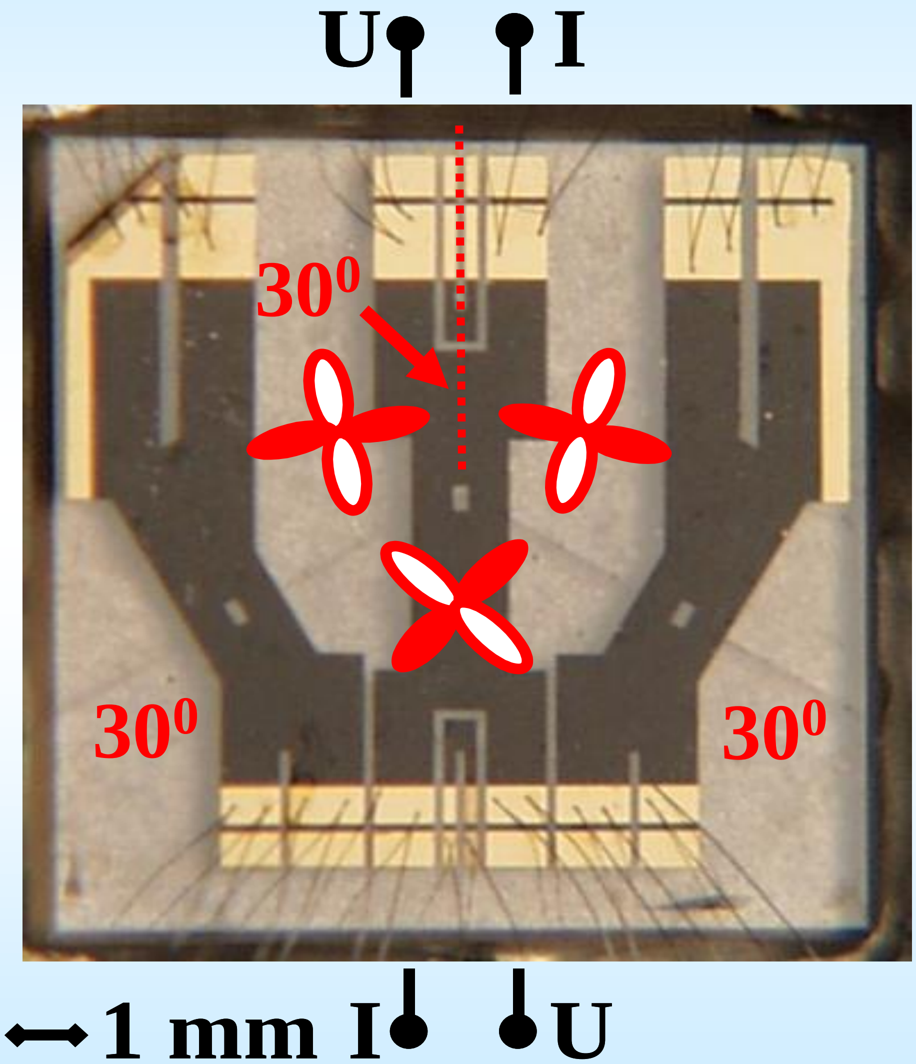
hole-doped $YBa_2Cu_3O_7$

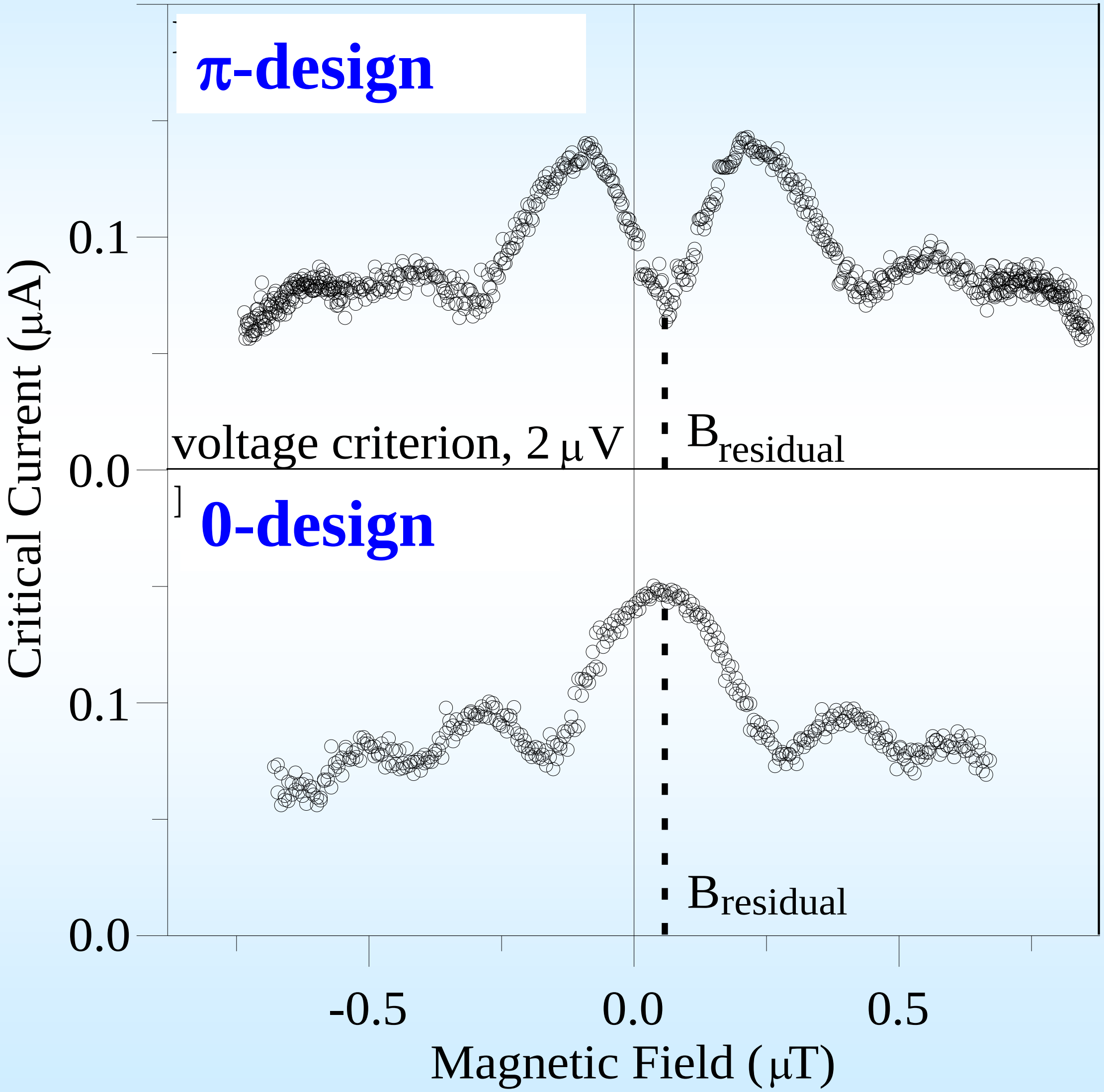


R.R.Schulz, B. Chesca, et al., *Appl. Phys. Lett.* **76**, 912 (2000)

π-junctions: d-wave superconductors only!

electro-doped $La_{2-x}Ce_xCuO_4$





B. Chesca et al., *Phys. Rev .Lett.* **90**, 057004 (2003)

Devices with hundreds/thousends of high-Tc junctions

Flux-flow MW/THz generators
Transistors
Magnetic sensors (SQUIDs, SQIFs)

Quantum computers ?

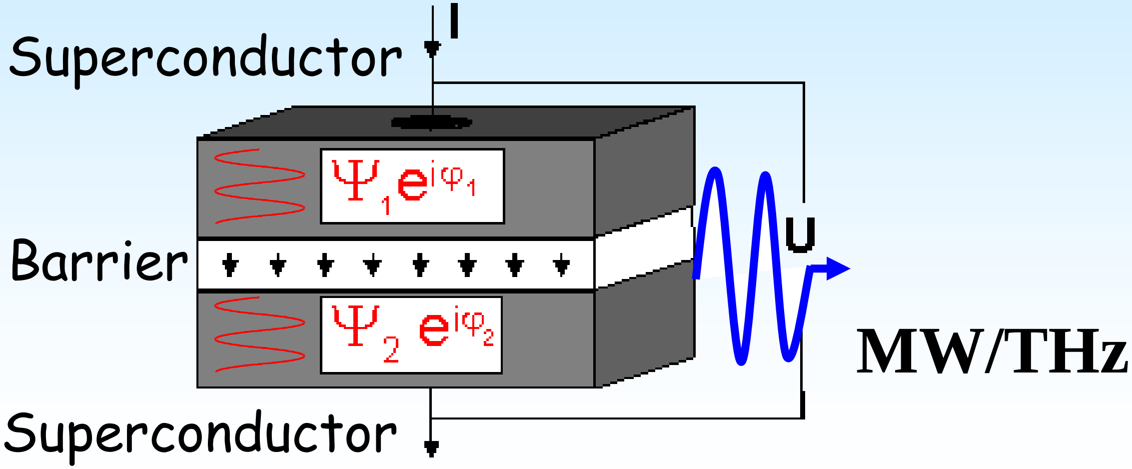
Flux-flow MW/THz generators

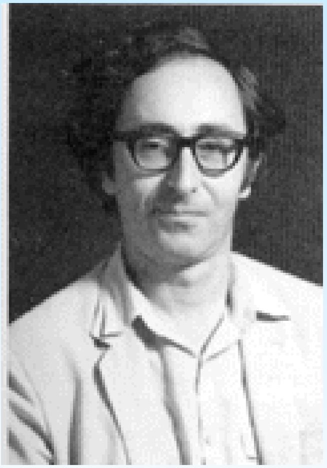
why superconducting generators?

natural

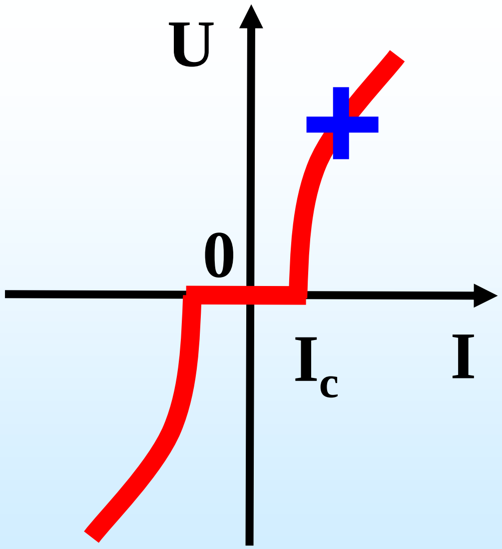
frequency is tunable (voltage, B field)

Josephson junction: ac effect





B. D. Josephson,
Cambridge (1962)

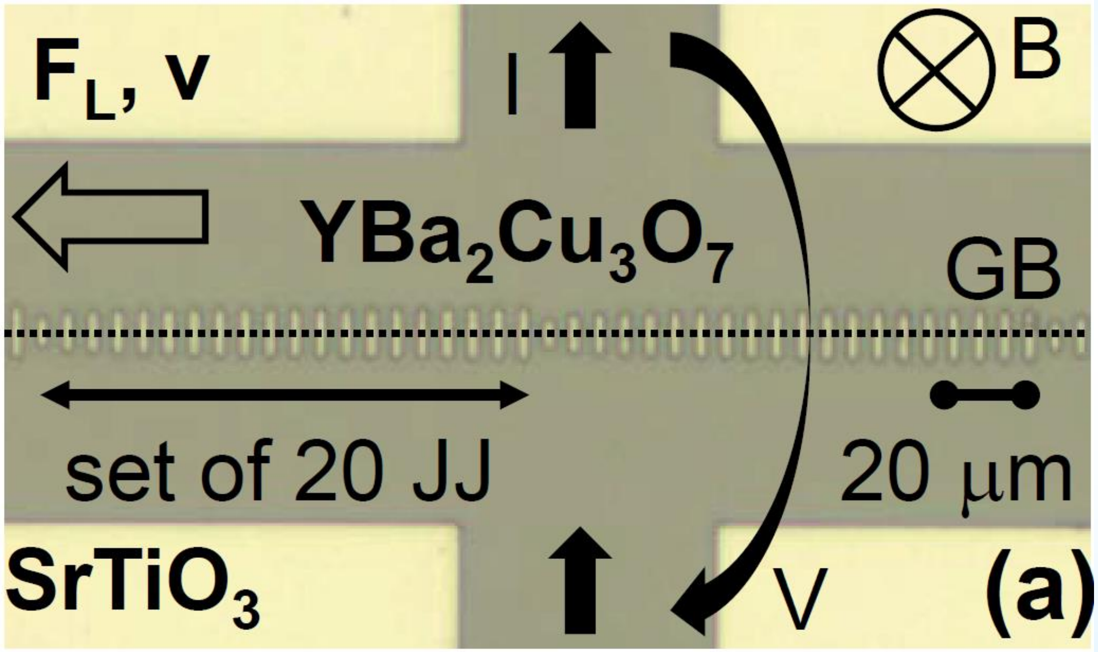


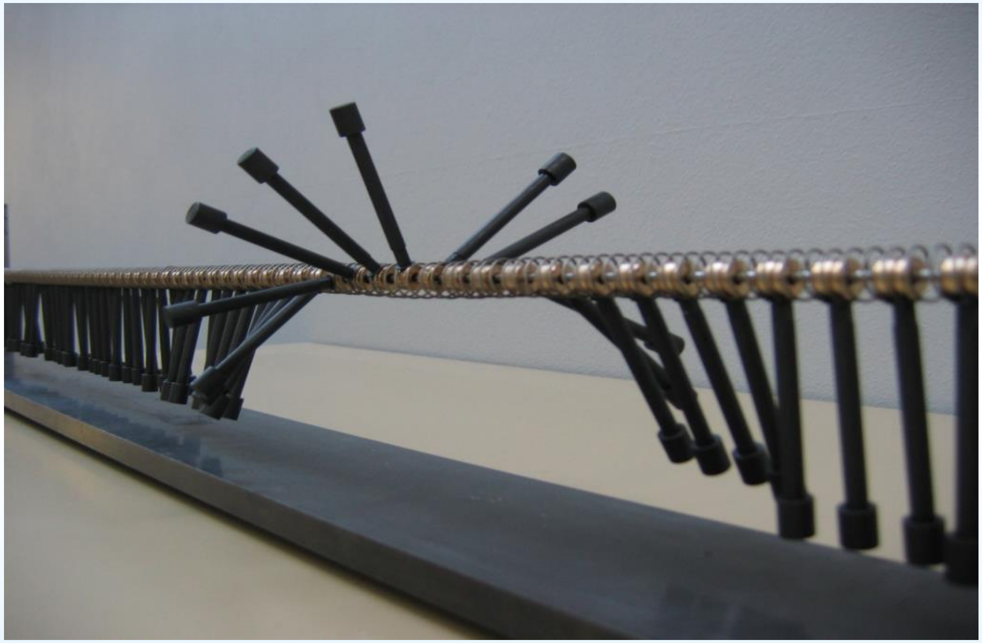
supercurrent oscillates locally
natural MW/THz generator

22 x 20 asymmetrical Josephson junction array

JJ array = chain of N identical pendulums driven by a constant torque

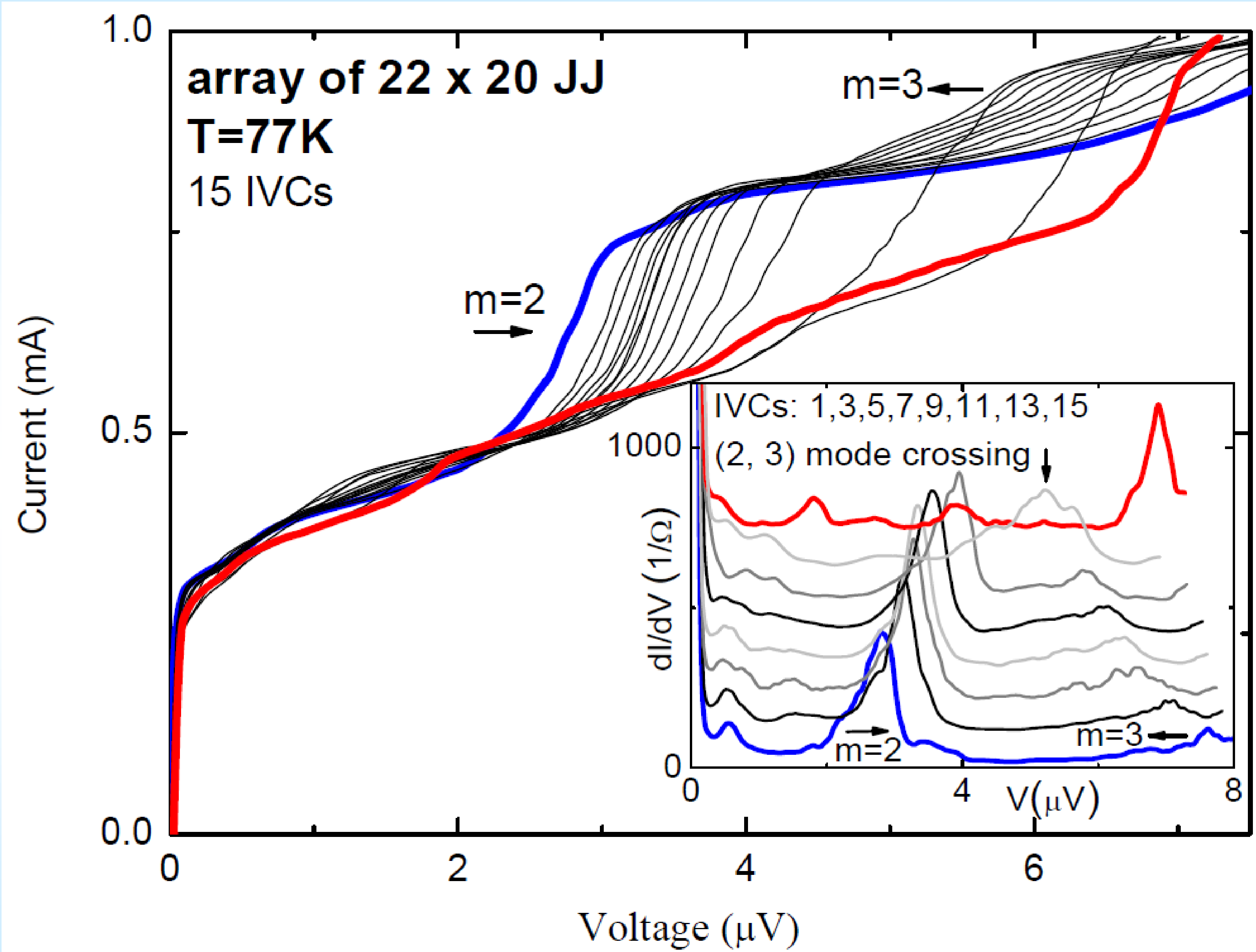
each pendulum is damped & free to move transverse to the axis of the chain
coupled to its nearest neighbours by torsional springs
has an identical behaviour except for a constant shift in time.





A vortex corresponds to a soliton propagating along the chain. Each pendulum hangs almost straight down for much of the time, but when the soliton passes by, the pendulum overturns rapidly and oscillates for the period between passing solitons. These oscillations are the analogue of the *EM* radiation excited by the vortex. A resonance occurs if the pendulum oscillates precisely an integer number of times (*m*) between successive passages of the soliton;

Flux-flow @ 77 K: MW is 0.1 μW @ (1.5-25) GHz



B. Chesca, D. John, and C. Mellor, *Supercond. Sci. Technol.* **27**, 085015 (2014)

Transistors

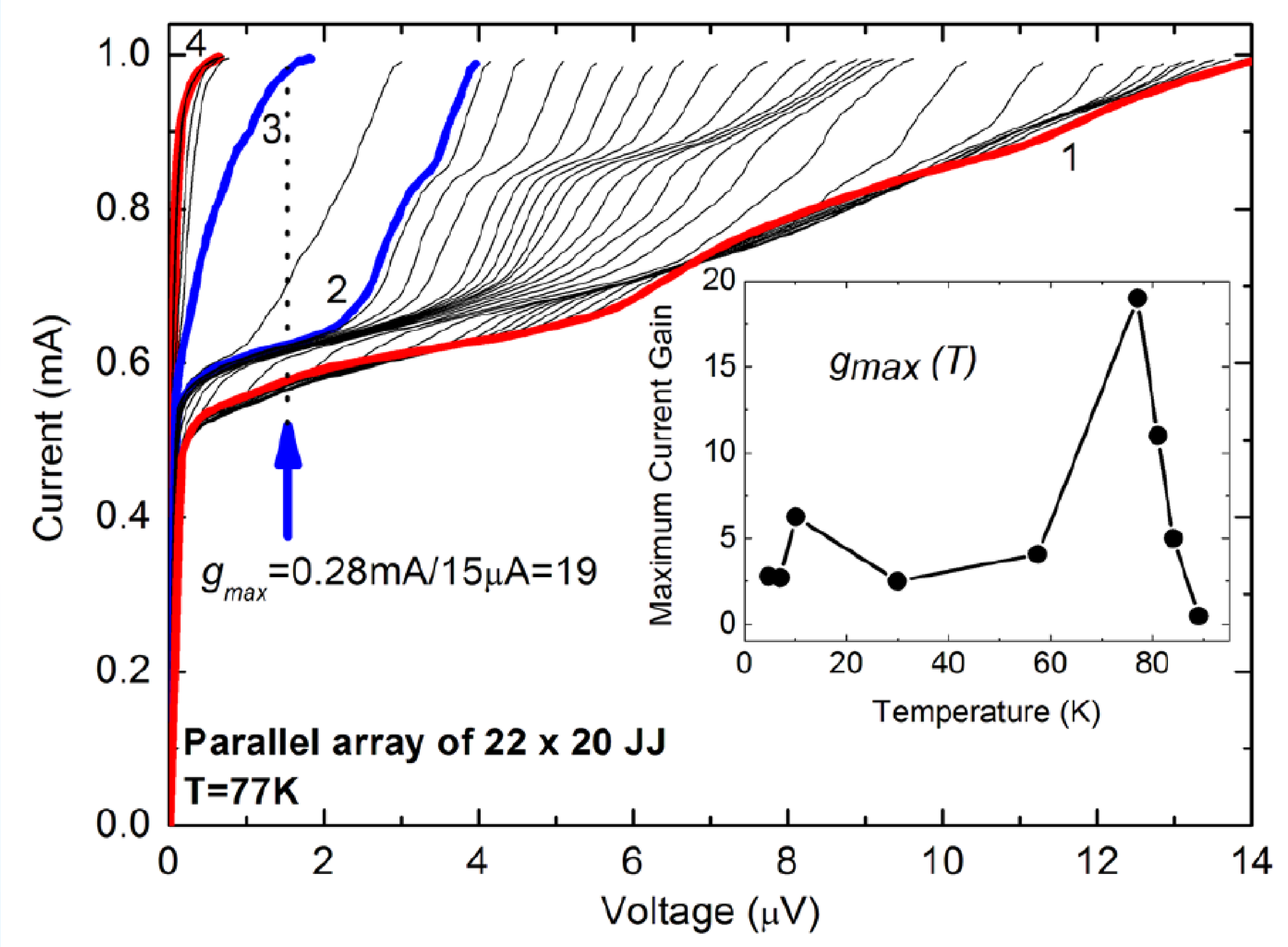
why superconducting transistors?

high switching speed

low power dissipation

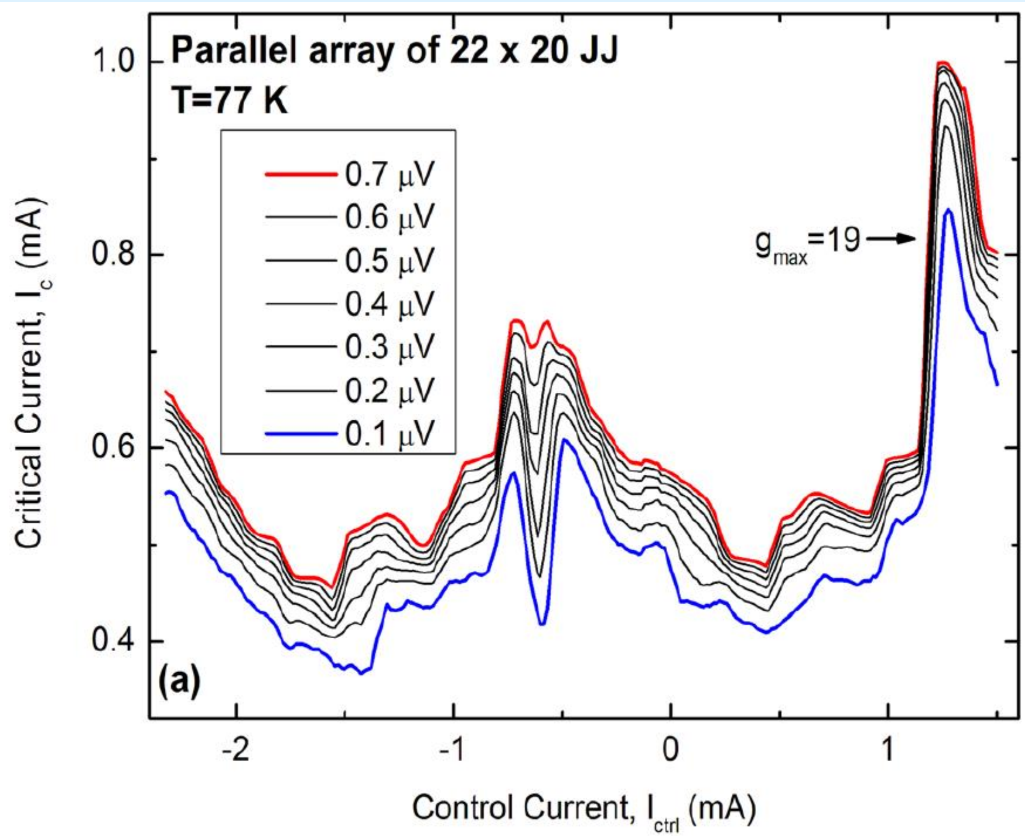
low noise

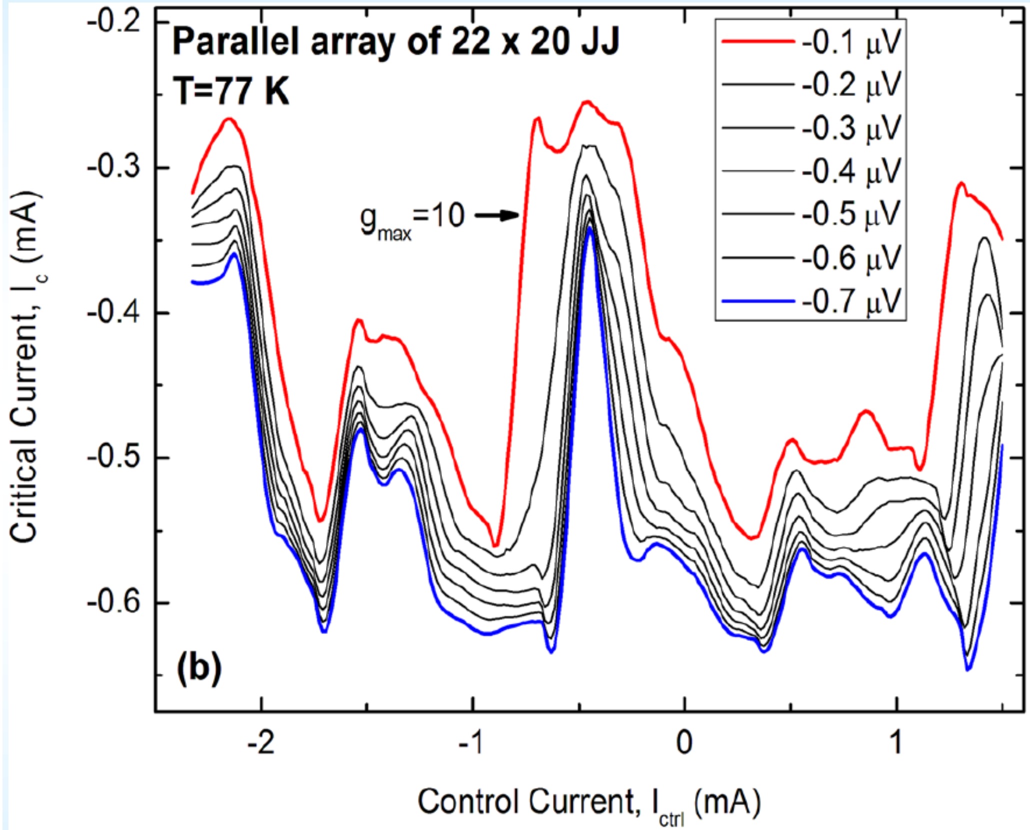
Flux-flow resonances: ideal for high-gain transistors



B. Chesca, et al, *Appl. Phys. Lett.* **103**, 092601 (2013)

$I_c(I_{ctrl})$ at 77K: highly asymmetric





B. Chesca, D. John, M. Kemp, J. Brown, and C. Mellor, *Appl. Phys. Lett.* **103**, 092601 (2013)

Magnetic sensors: SQUIDs & SQIFs

Why superconducting magnetic sensors?

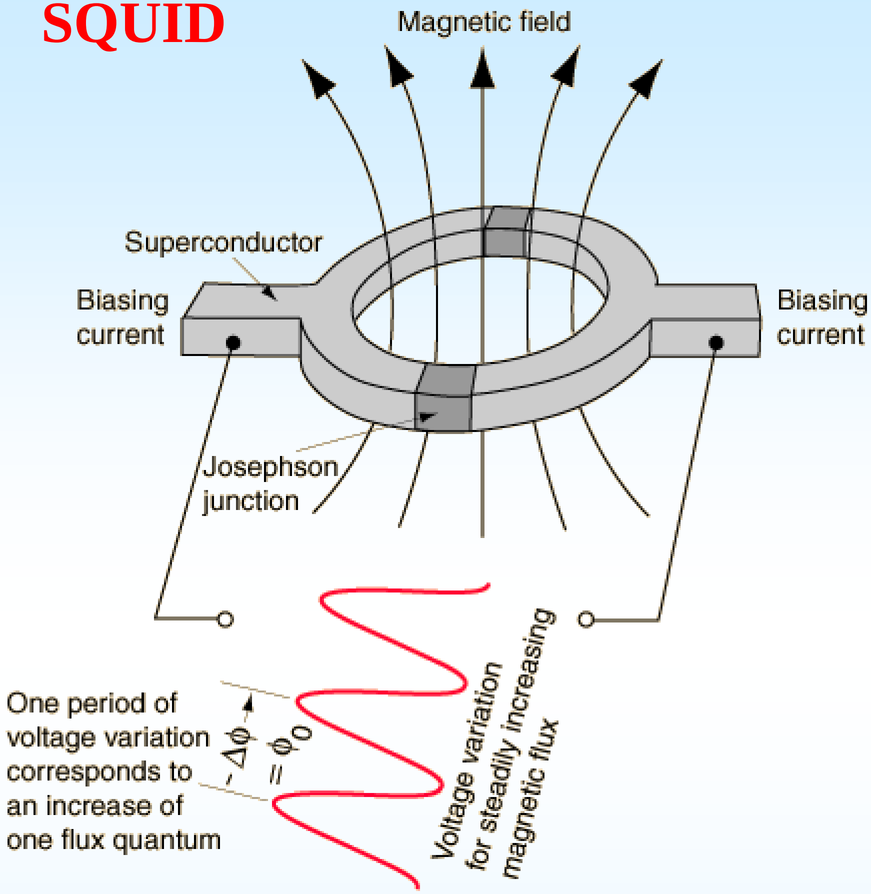
the best

getting less expensive:

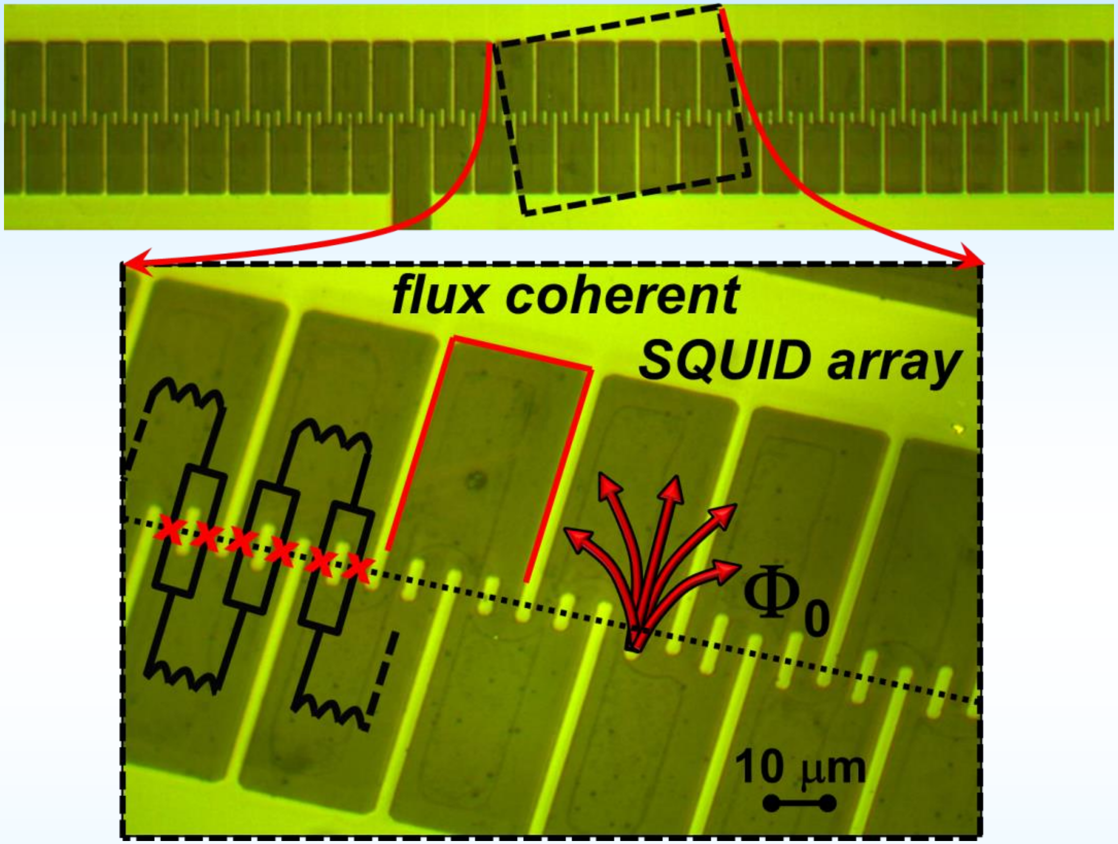
77K SQUID-arrays better than single-SQUID 4.2 K

SQUID arrays

SQUID



770 SQUID array

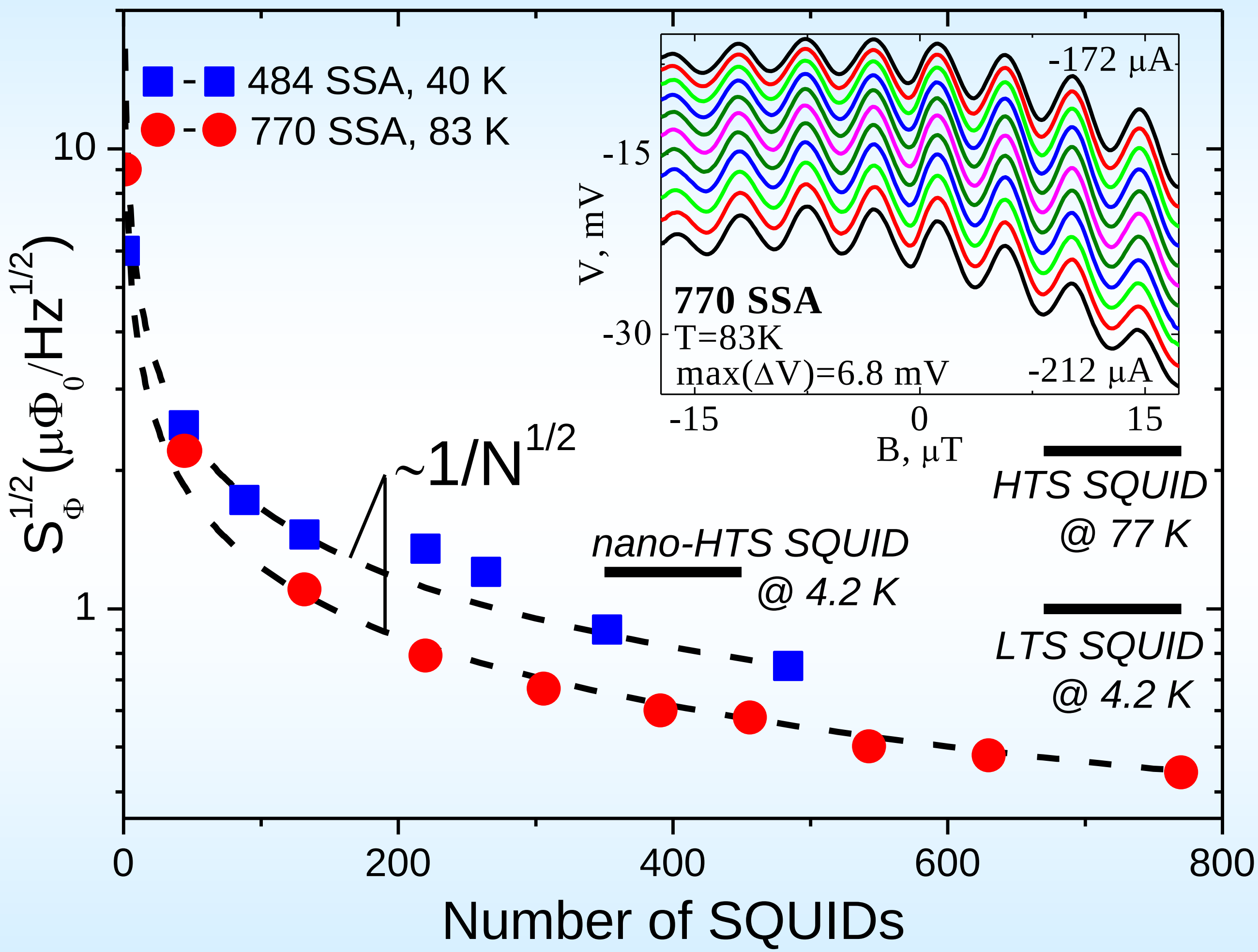


flux coherent & non-interacting SQUID array

$$\boxed{\begin{aligned} Noise_{Array} &= N^{1/2}\, Noise_{SQUID} \\ V_{Array} &= N\, V_{SQUID} \end{aligned}}$$

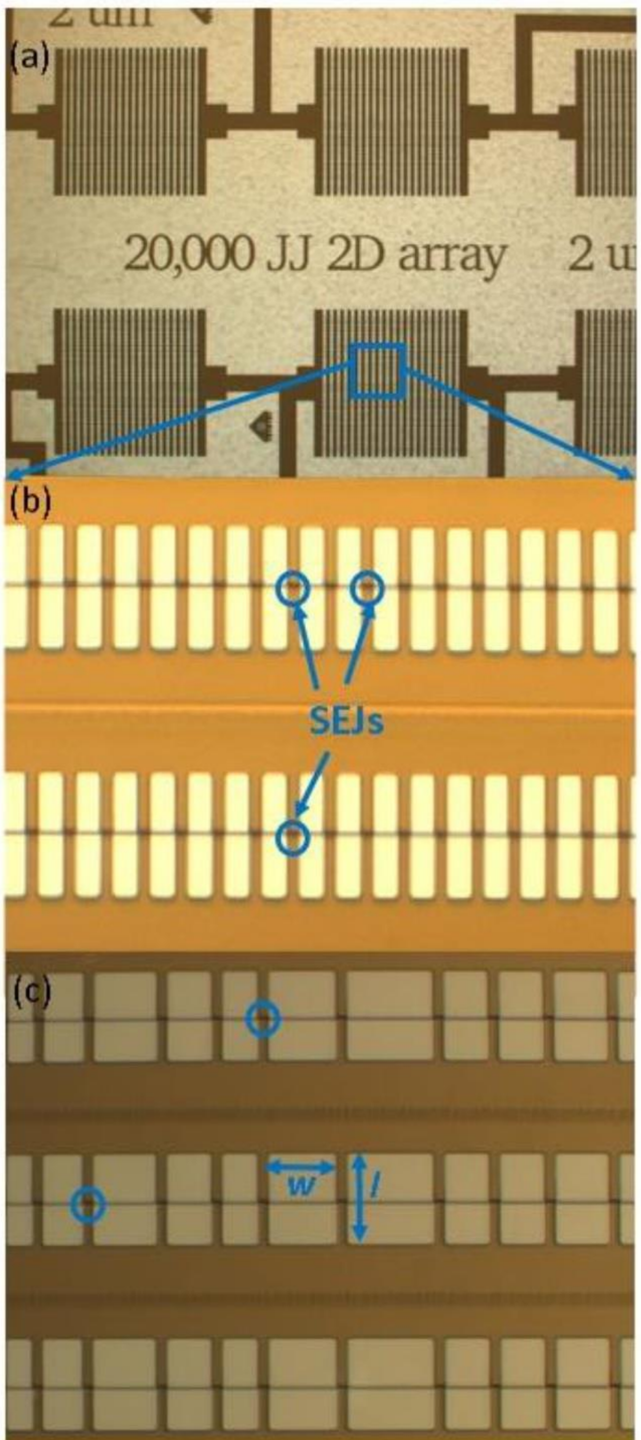
$$\Rightarrow \left[\frac{Noise}{V}\right]_{Array} = \frac{1}{N^{1/2}} \left[\frac{Noise}{V_{SQUID}}\right]$$

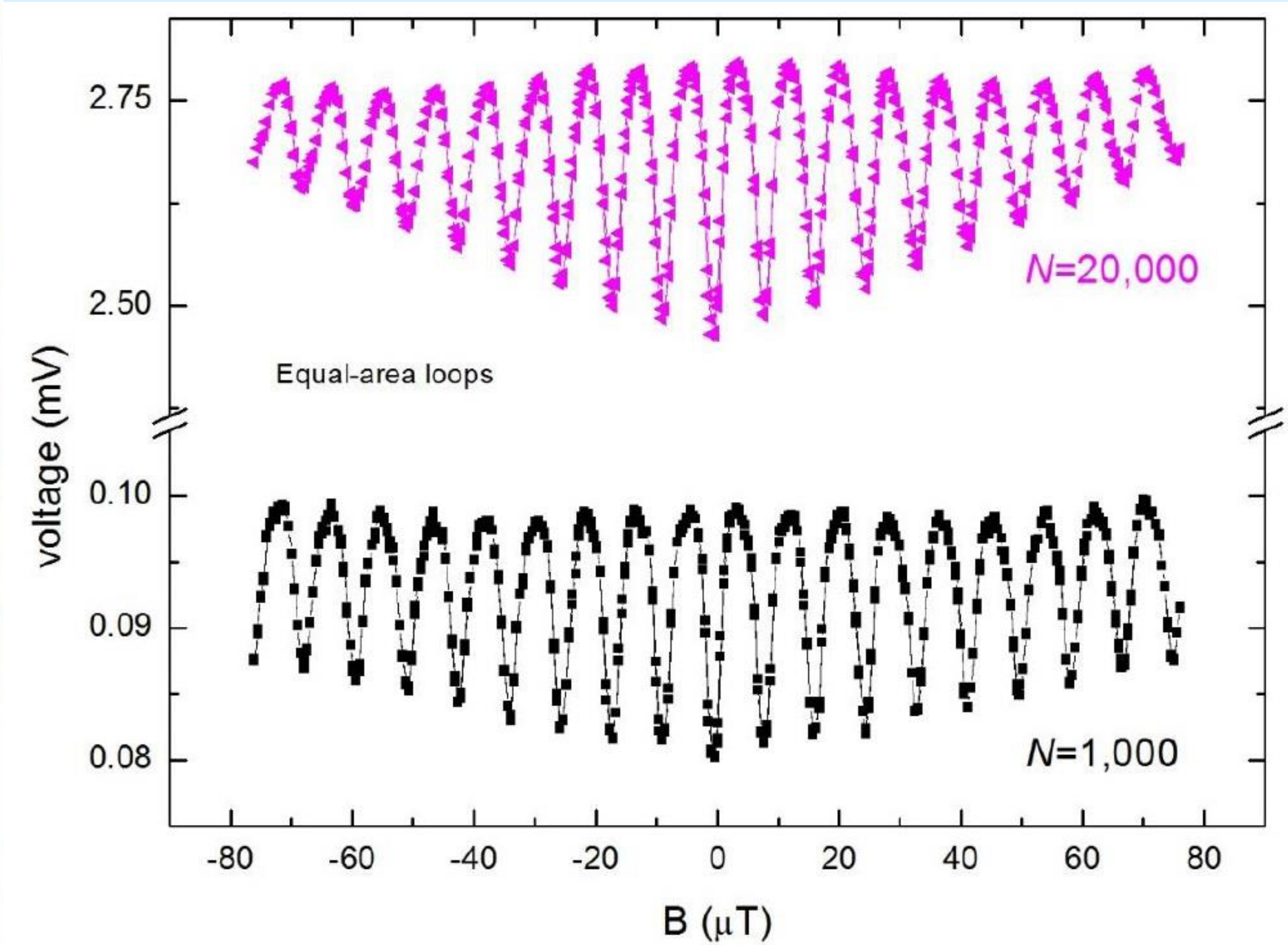
SQUID arrays @ 77K better than SQUIDs @ 4.2 K



B. Chesca, J. Daniel, C. Mellor, *Appl. Phys. Lett.* **107**, 162602 (2015)

2D 20000 SQUID arrays design



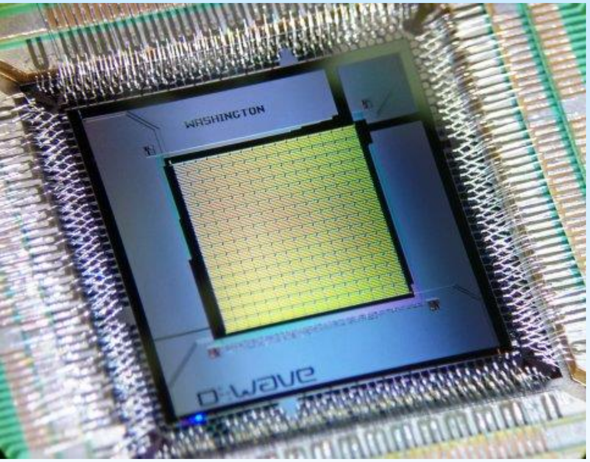


E. E. Mitchell et al,, *Supercond. Sci. Technol.* **29**, 06LT01 (2016)

Quantum Computers?

why superconducting Quantum Computers?

D-wave produced 2 (Google and NASA)



1000 qubit processor with 128K low-Tc Josephson junctions

Conclusions

High-Tc junctions: very significant progress

simple and reliable fabrication: bicrystal, step-edge
high performance devices with hundreds/thousands junctions

quantum computing with high-Tc junctions worth a try !