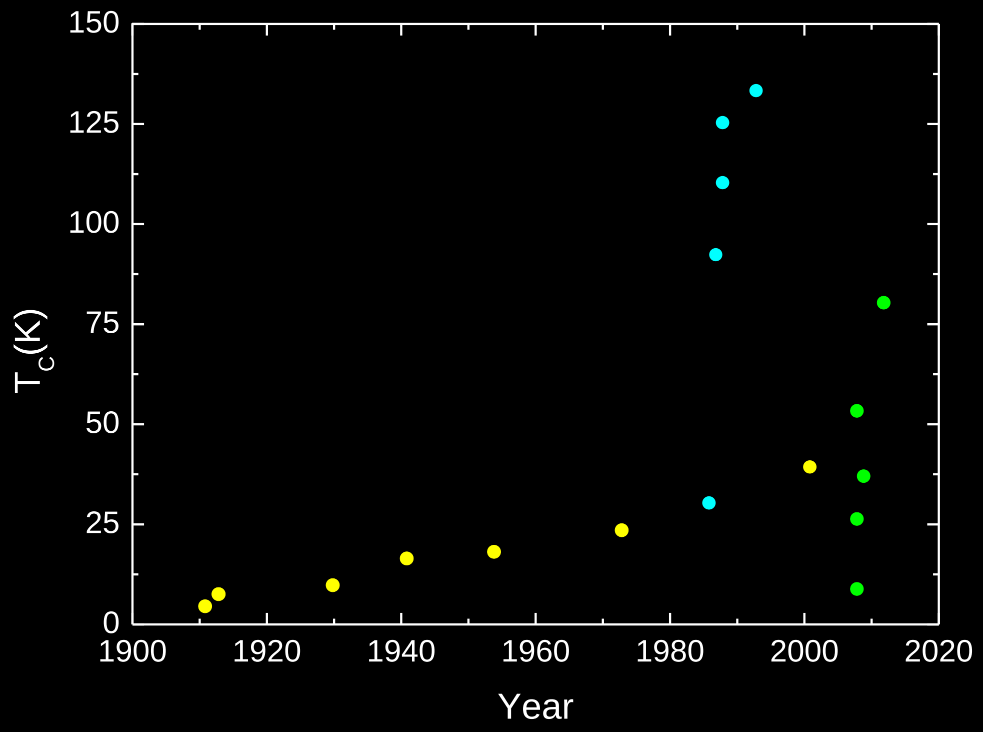
High T_c Superconductivity



Outline

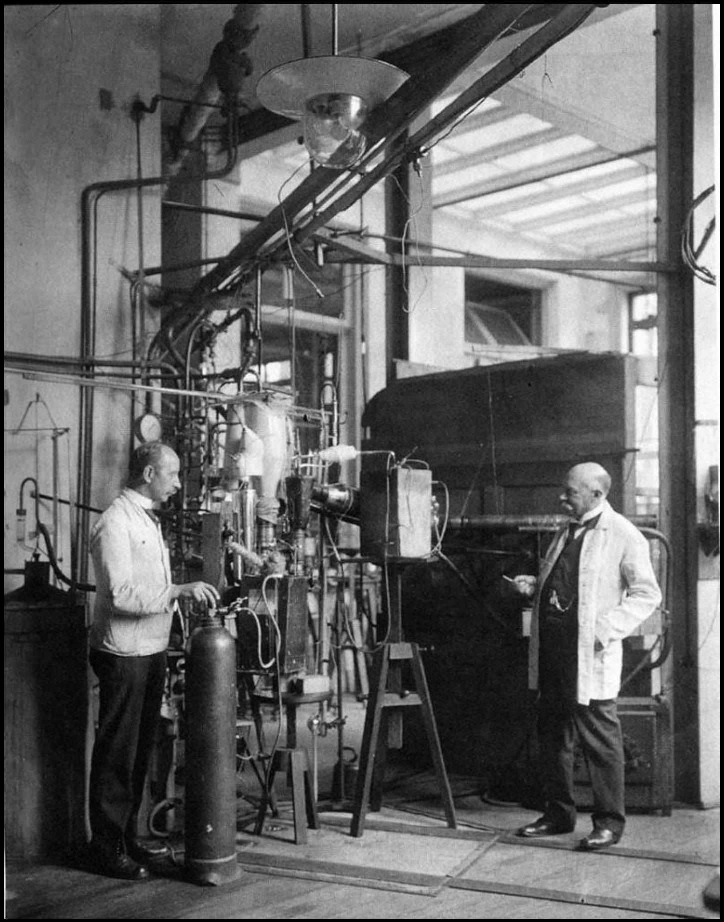
1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High T_c Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

Outline

1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

Helium Liquefaction in 1908

July 10, 1908



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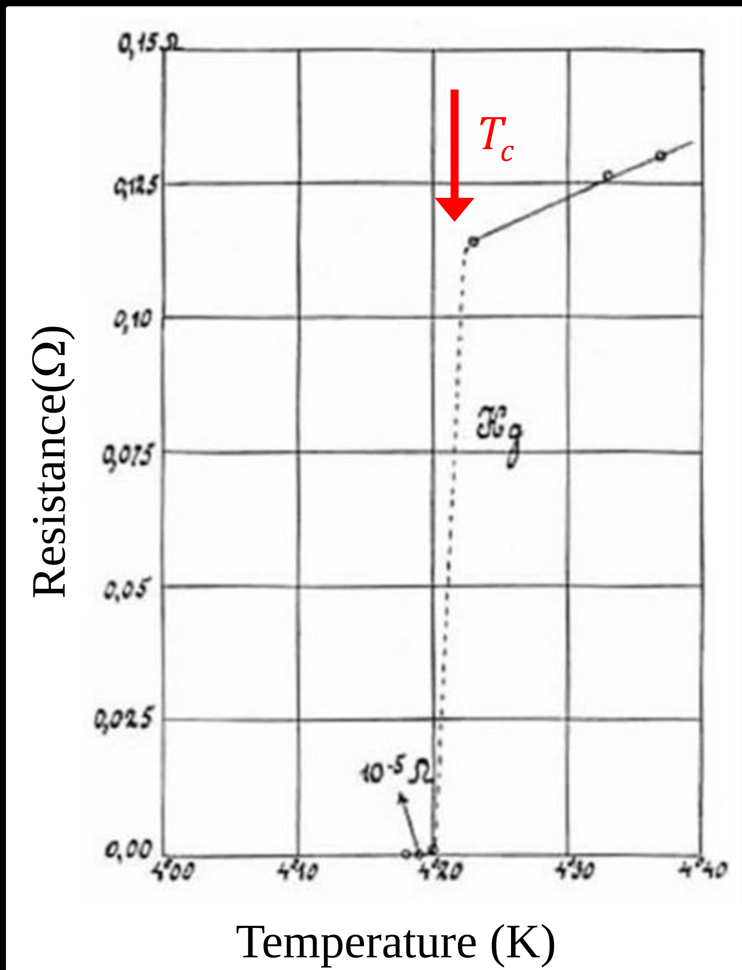
Heike Kamerlingh Onnes

Nobel Prize, 1913

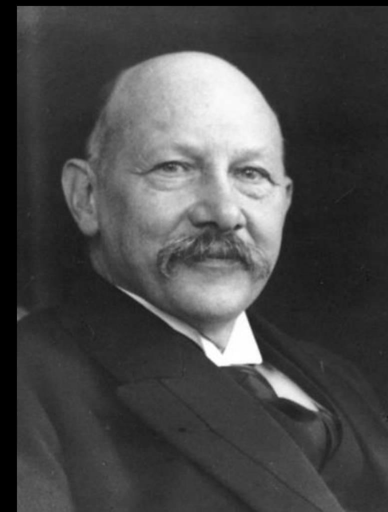
“Door meten tot weten”
(Knowledge through measurement)

Discovery of Superconductivity in 1911

April 8, 1911



H. Kamerlingh Onnes, *Commun. Phys. Lab. Univ. Leiden. Suppl.* **29** (Nov. 1911).



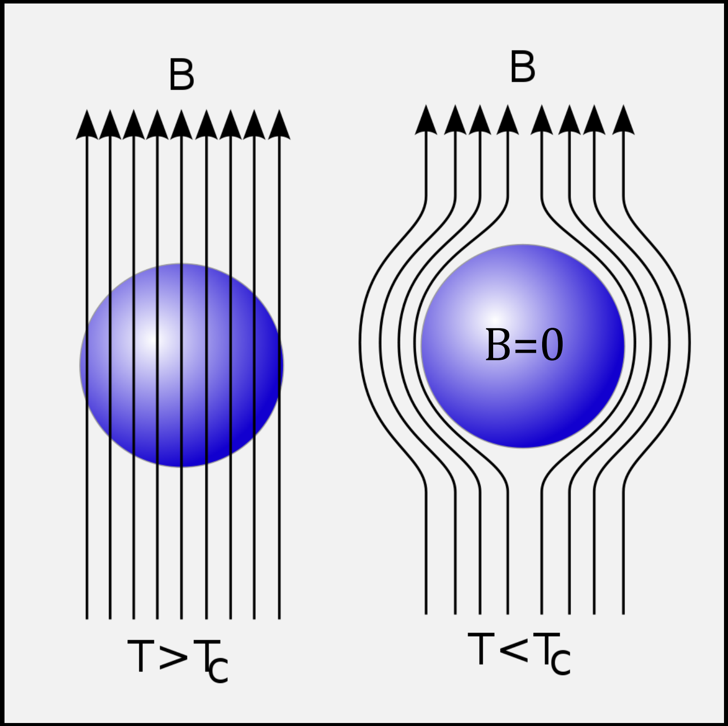
Heike Kamerlingh Onnes

Nobel Prize, 1913

"Door meten tot weten"
(Knowledge through measurement)

The Meissner Effect in 1933

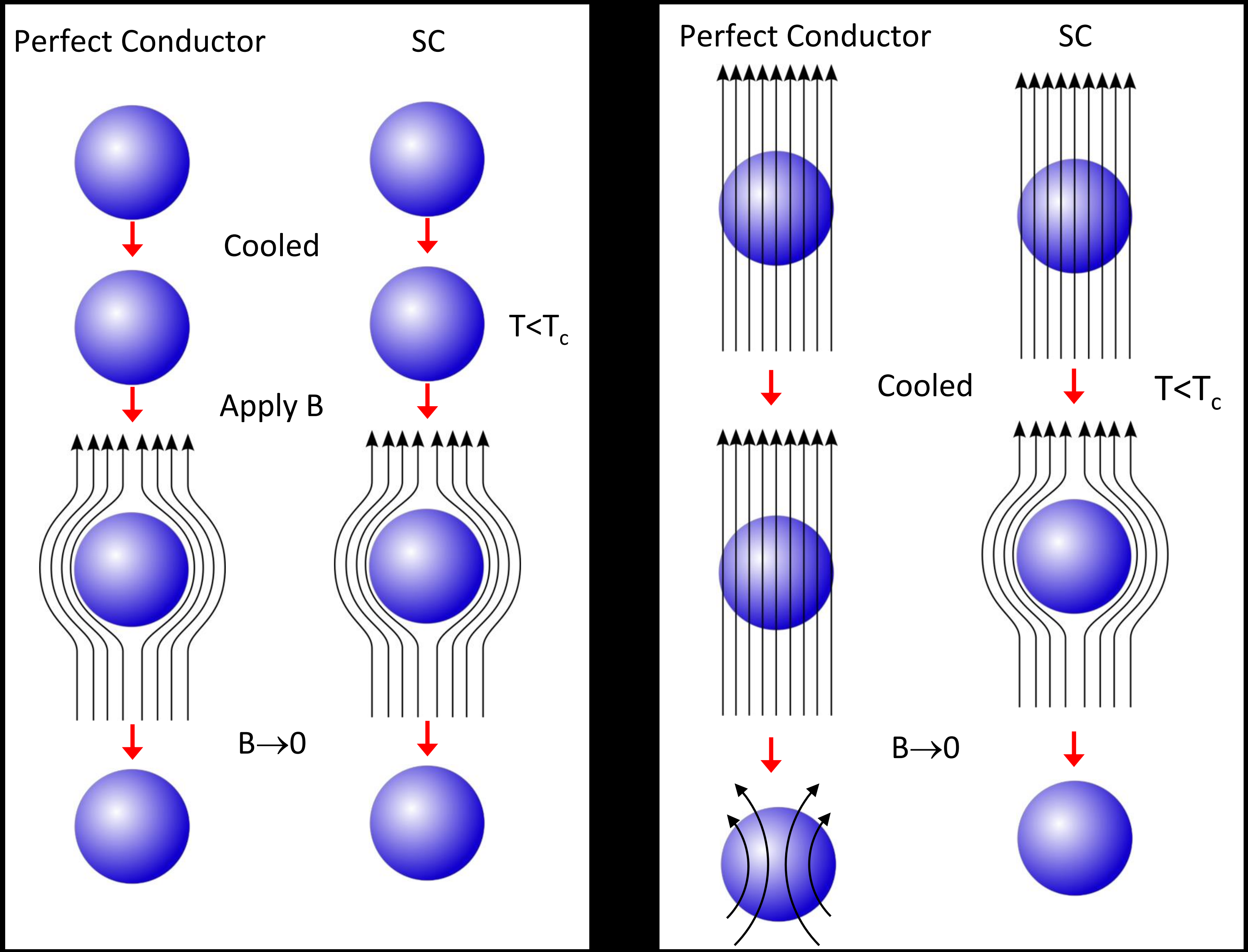
Perfect diamagnetism



Walther Meißner

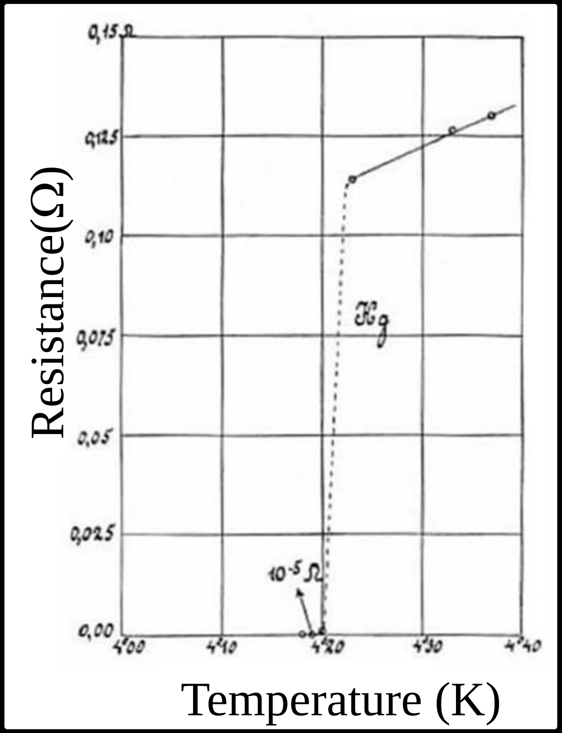
Robert Ochsenfeld

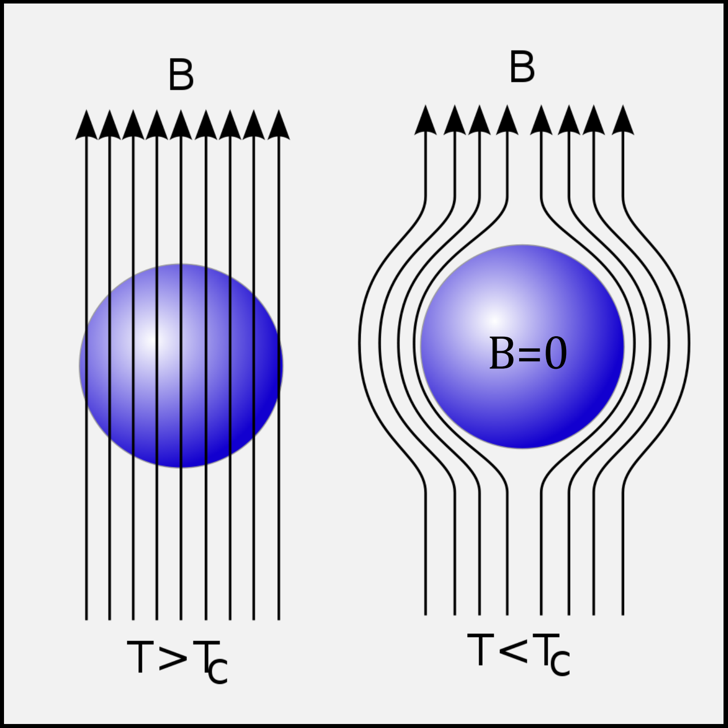
Perfect Conductor vs Superconductor



Basic Properties of Superconductors

Zero electrical resistance + Meissner effect





Periodic Table of Superconductivity

ambient pressure superconductor: T_c(K) / T_c^{max}(K) / P(GPa)

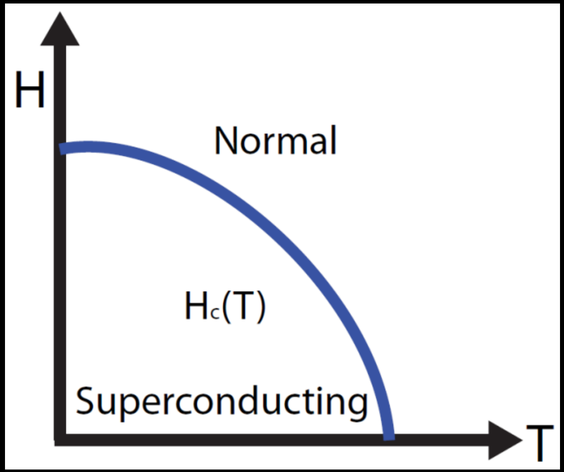
high pressure superconductor: T_c^{max}(K) / P(GPa)

H																	He
Li 0.0004 14 30	Be 0.026 3.7 30											B 11 250	C	N	O 0.6 100	F	Ne
Na	Mg											Al 1.14	Si 8.2 15.2	P 13 30	S 17.3 190	Cl	Ar
K	Ca 29 217	Sc 19.6 106	Ti 0.39 3.35 56.0	V 5.38 16.5 120	Cr	Mn	Fe 2.1 21	Co	Ni	Cu	Zn 0.875	Ga 1.091 7 1.4	Ge 5.35 11.5	As 2.4 32	Se 8 150	Br 1.4 100	Kr
Rb	Sr 7 50	Y 19.5 115	Zr 0.546 11 30	Nb 9.50 9.9 10	Mo 0.92	Tc 7.77	Ru 0.51	Rh .00033	Pd	Ag	Cd 0.56	In 3.404	Sn 3.722 5.3 11.3	Sb 3.9 25	Te 7.5 35	I 1.2 25	Xe
Cs 1.3 12	Ba 5 18	insert La-Lu	Hf 0.12 8.6 62	Ta 4.483 4.5 43	W 0.012	Re 1.4	Os 0.655	Ir 0.14	Pt	Au	Hg-α 4.153	Tl 2.39	Pb 7.193	Bi 8.5 9.1	Po	At	Rn
Fr	Ra	insert Ac-Lr	Rf	Ha													
		La-fcc 6.00 13 15	Ce 1.7 5	Pr	Nd	Pm	Sm	Eu 2.75 142	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu 12.4 174	
		Ac	Th 1.368	Pa 1.4	U 0.8(β) 2.4(α) 1.2	Np	Pu	Am 0.79 2.2 6	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

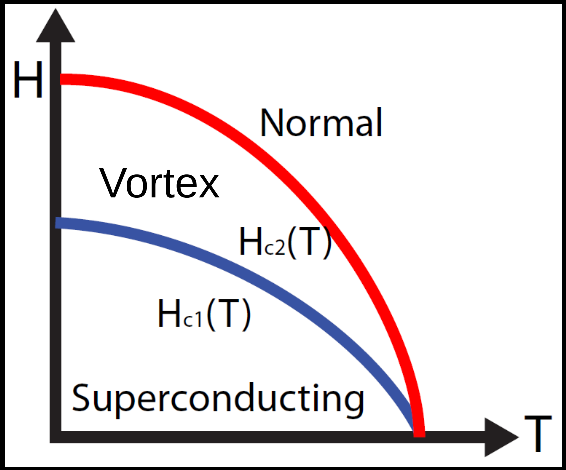
M. Debessai *et al.*, J. Phys.: Conf. Series 215, 012034 (2010).

Type I & II Superconductors

Type I : Al, Pb…



Type II : Nb, NbTi, Nb_3Sn and HTSC



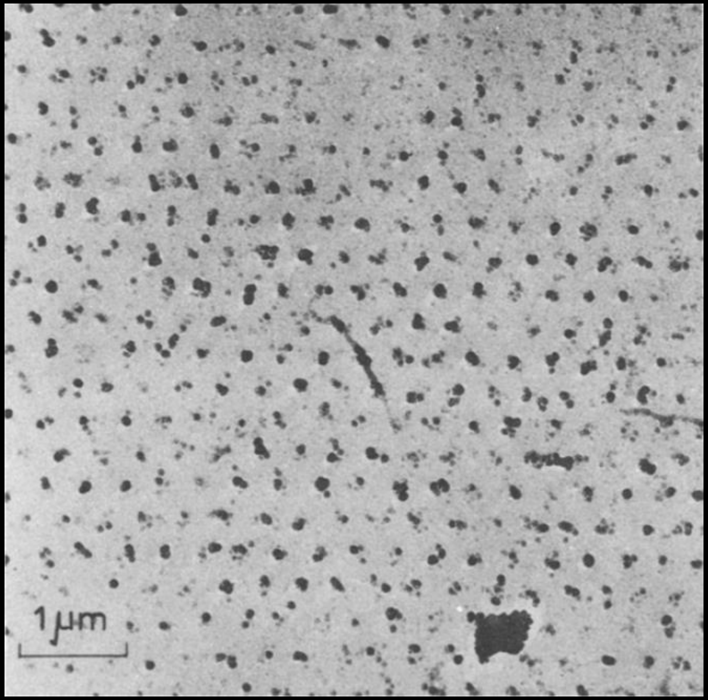
Lev V. Shubnikov

found type-II SC in Pb-Bi alloy in 1935. Excuted in 1937.

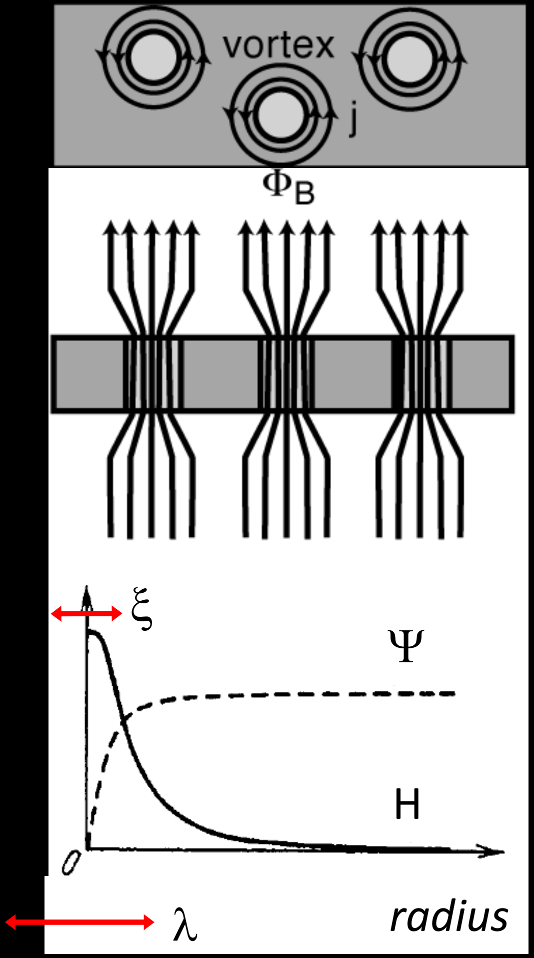
J. N. Rjabinin, L.W. Schubnikow, Physikalische Zeitschrift der Sowjetunion 7, 122 (1935)

Superconducting Vortices

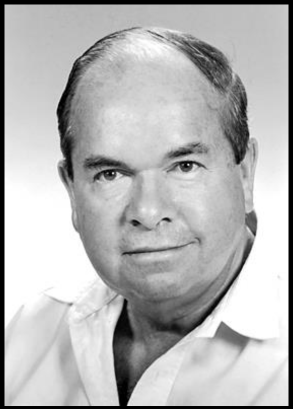
Decoration image of vortex lattice



U. Essmann and H. Trauble, Physics Letters 24A, 526 (1967)



Alexei A. Abrikosov



Nobel Prize 2003

A. A. Abrikosov, Doklady Akademii Nauk SSSR 86, 489 (1952)
A. A. Abrikosov, Sov. Phys. JETP **5**,1174 (1957)

Vortex-Current Interaction

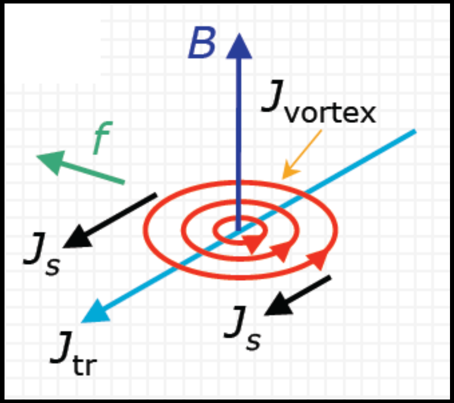
- Lorentz force on J_S due to the interaction between J_S and B.

$$f = \int J_s \times B \, d^2r = J_{tr} \times \int B \, d^2r = J_{tr} \times (\phi_0 \hat{B})$$

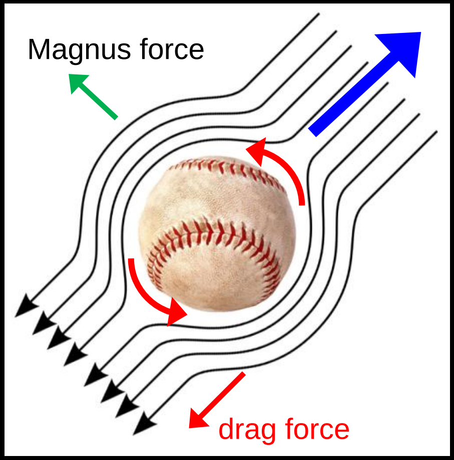
- Vortex motion implies that the vortex is subject to a power input per unit volume of vortex of characteristic radius r_B

$$P = \frac{f\,v}{\pi r_B^{\,2}} = J_{tr} \frac{\phi_0}{\pi r_B^{\,2}} v = \underbrace{J_{tr}\, B}_{\text{Lorentz force per unit volume}} v$$

- Vortex motion leads to dissipation! R≠0 !
- Vortex pinning is crucial for applications.

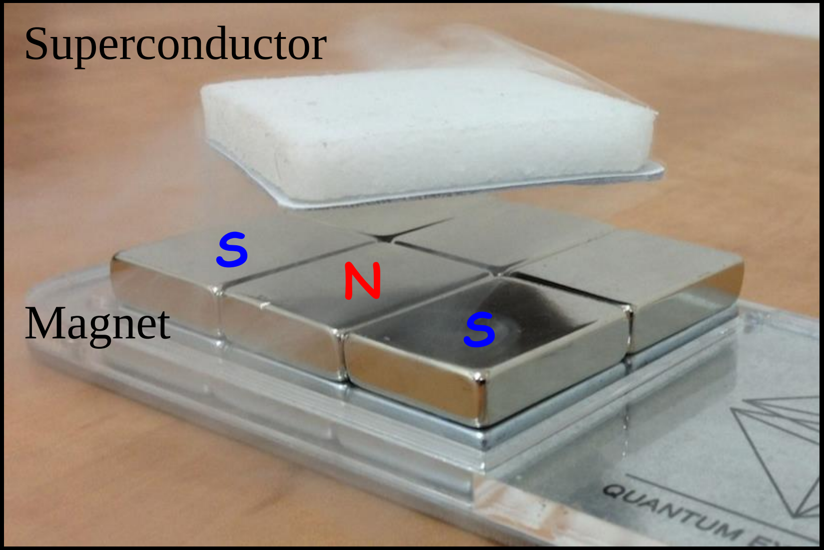


Magnus force

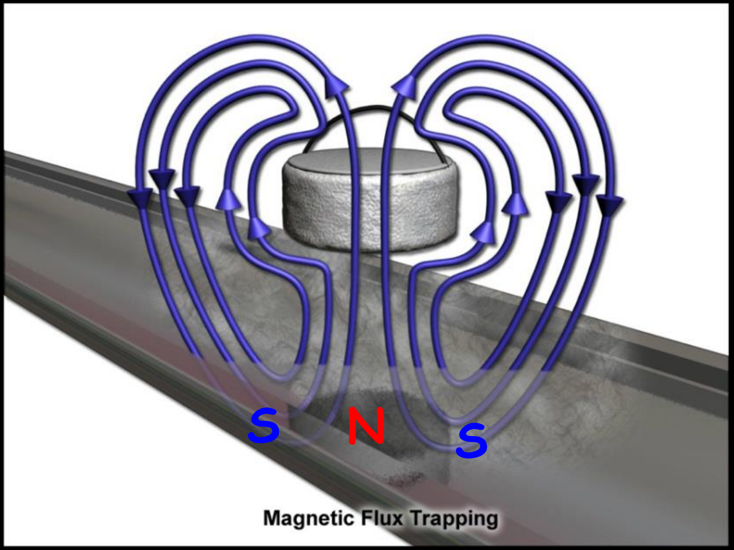


Quantum Levitation

Magnetic flux pinning is key.
Unstable for type I superconductors.



© Quantum Experience ltd.



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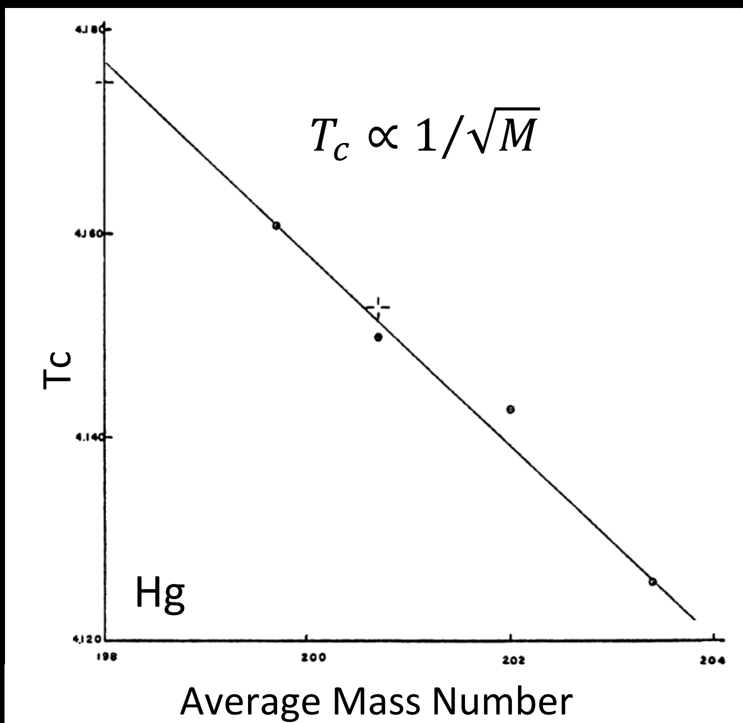
The Origin of Conventional Superconductivity

Isotope Effect in 1950

- Lattice vibration is a part of the SC process.
- A crucial step to a microscopic theory.

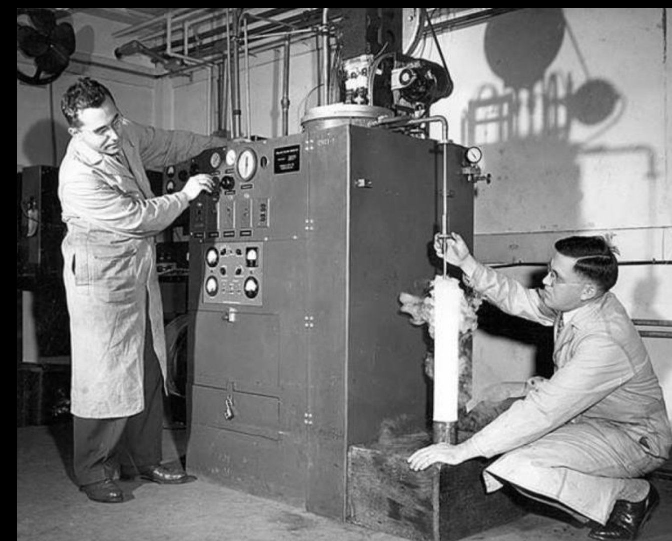


Emanuel Maxwell, Phys. Rev. 78, 477 (1950)
C.A. Reynolds et al., Phys. Rev. 78, 487 (1950)

Emanuel Maxwell

© MIT

Bernard Serin & Charles Reynolds



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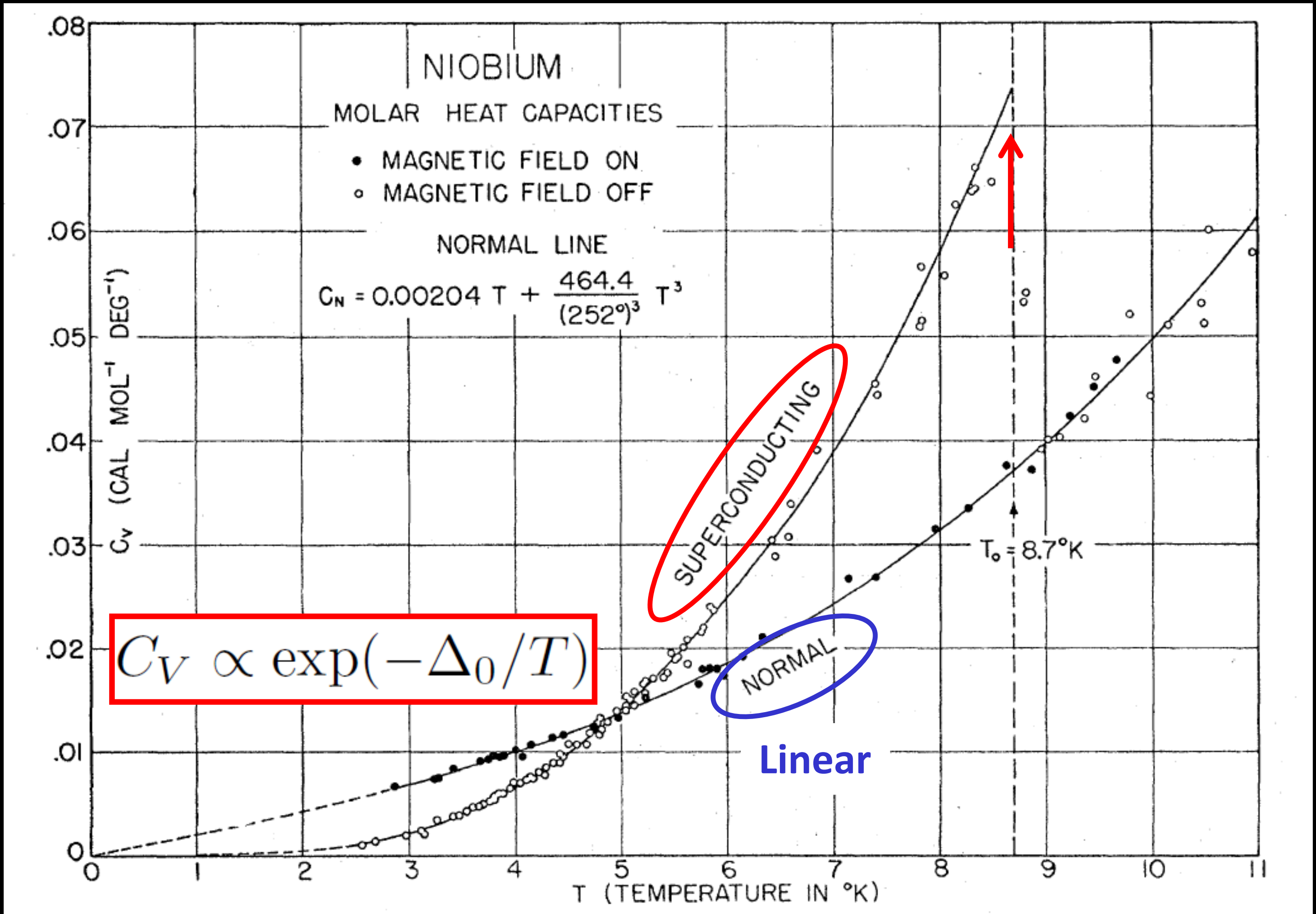
Evidence for Energy Gap in 1953

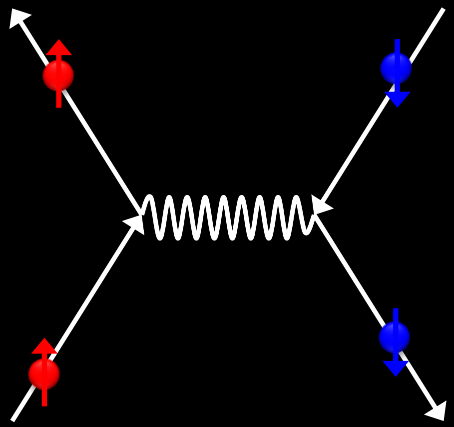
Another motivation for the BCS theory of superconductivity.



A. Brown, M. W. Zemansky, and H. A. Boorse, Phys. Rev. 92, 52 (1953)
B. B. Goodman, Proc. Phys. Soc. (London) **A66**, 217 (1953)

BCS Theory in 1957

Cooper Pairs



Exchange boson:
Lattice Vibration Mode

Microscopic theory for SC

John Bardeen

Leon Cooper

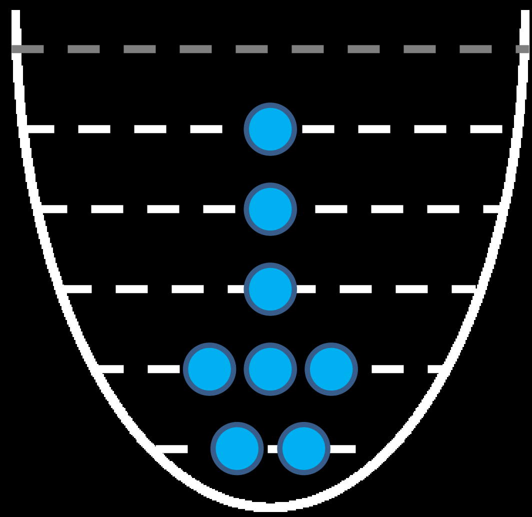
Robert Schrieffer

Nobel Prize 1972

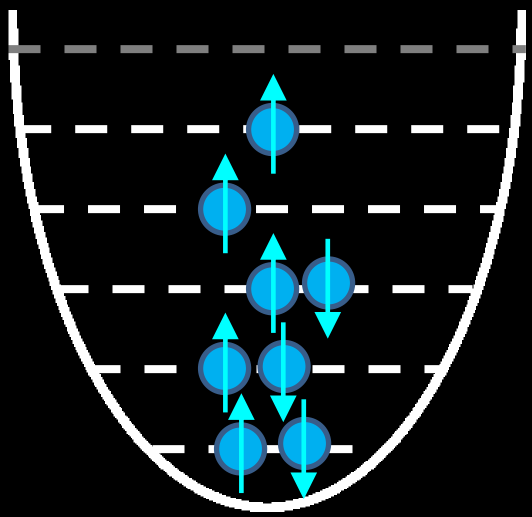
J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957)

Bosons vs Fermions

Bosons



Fermions



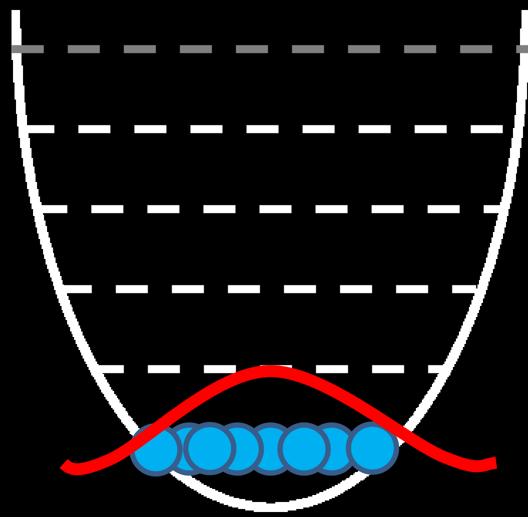
Pauli Exclusion Principle

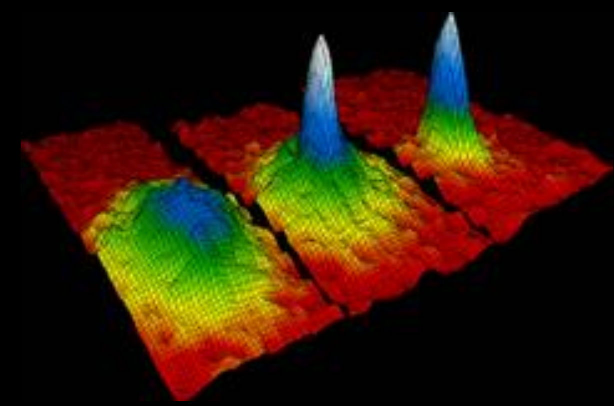
Wolfgang Pauli

Nobel Prize 1945

Bose-Einstein Condensation

T↓ Bosons

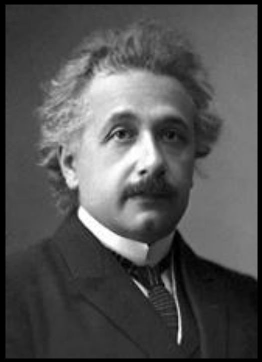




Predicted in 1924

Satyendra Nath Bose

Albert Einstein

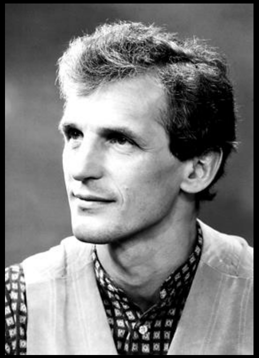


BEC in Rb and Na in 1995

Eric Cornell

Carl Wieman

Wolfgang Ketterle

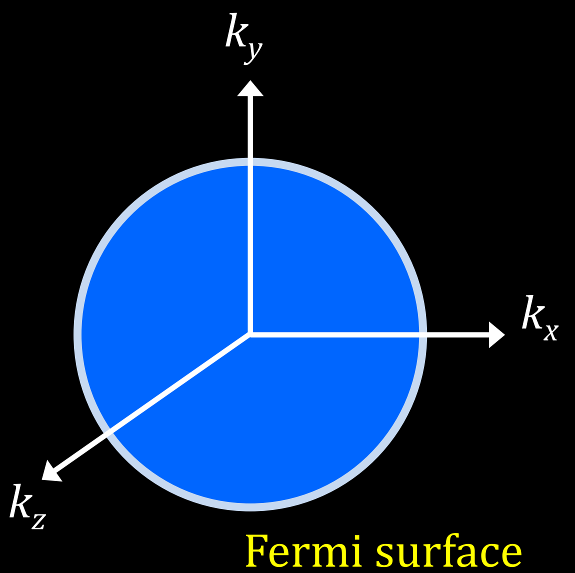


Nobel Prize 2001

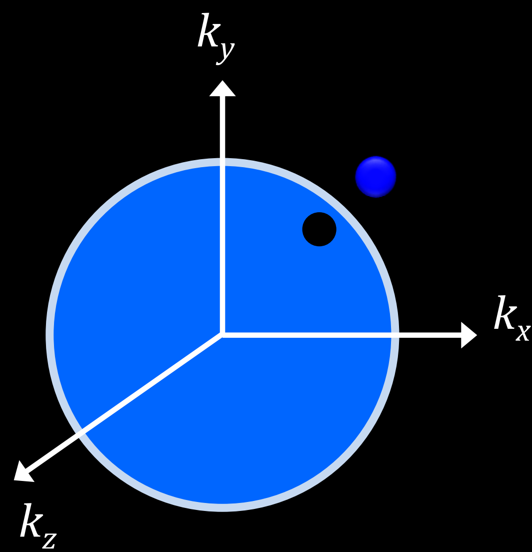
Normal Metallic State

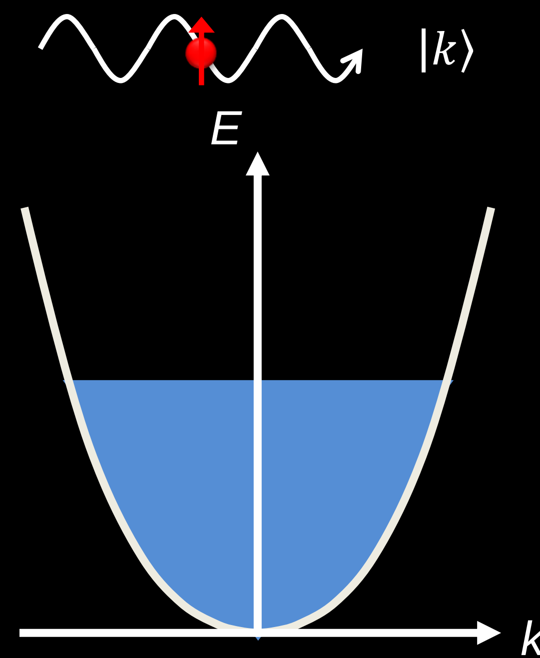
Electrons in wave-like states in momentum-space (*k*-space)

Free electron gas



Fermi liquid



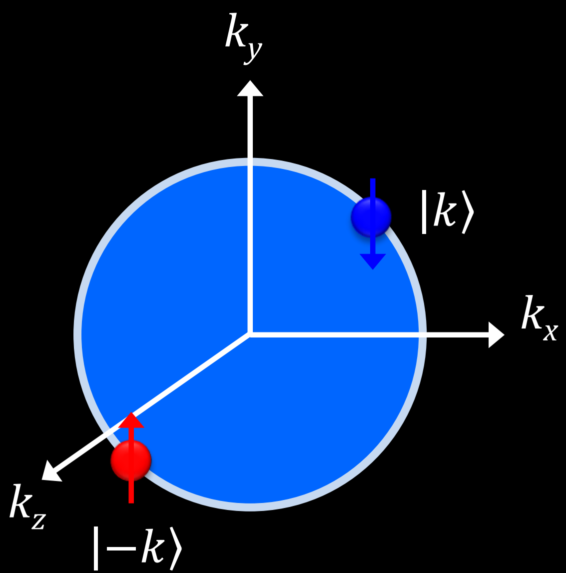


$$p = \hbar k = h/\lambda$$

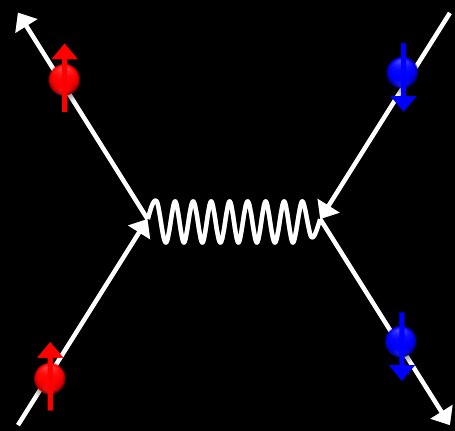
$$E = \frac{\hbar^2 k^2}{2m}$$

Superconducting Ground State

Normal state

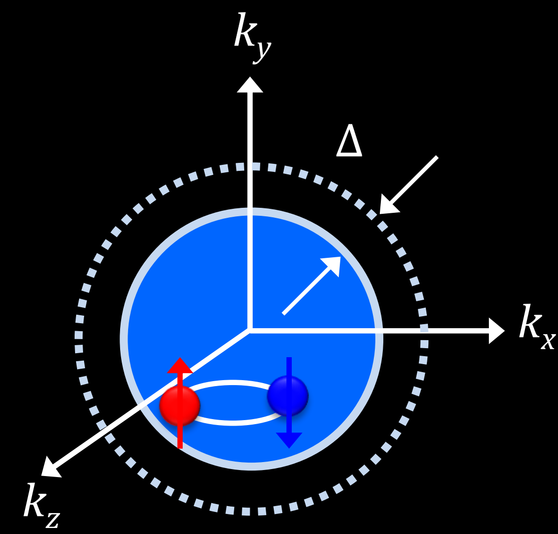


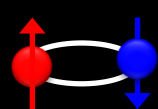
Cooper Pairs



Exchange boson:
Lattice Vibration Mode

Superconducting ground state

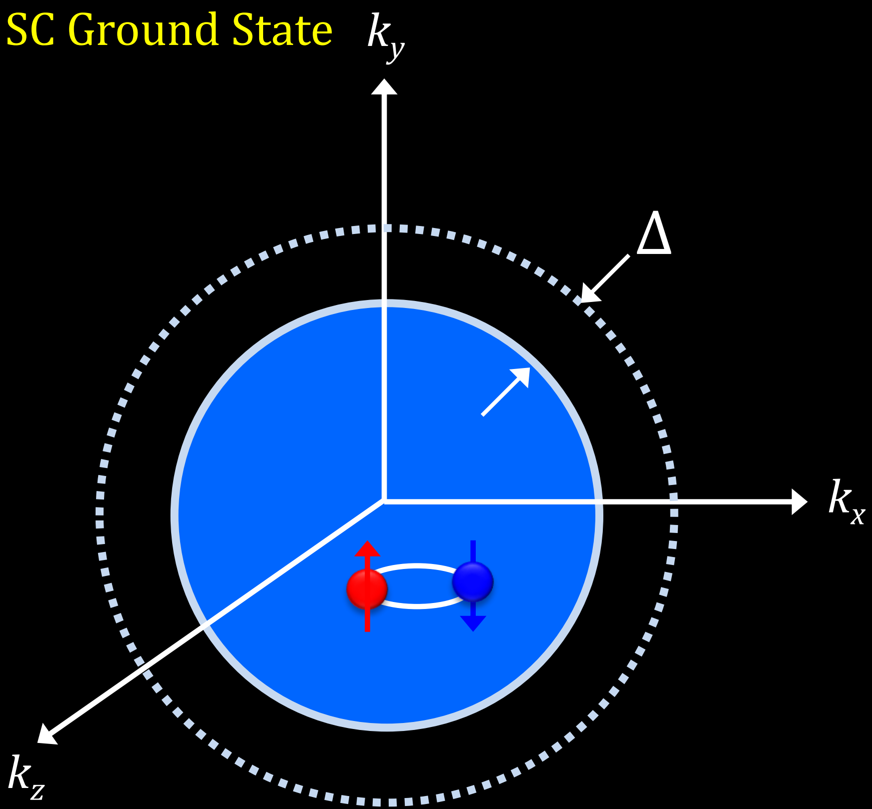




- Spin singlet
- L=0; S=0
- Binding energy: Δ

Superconducting Ground States

SC Ground State



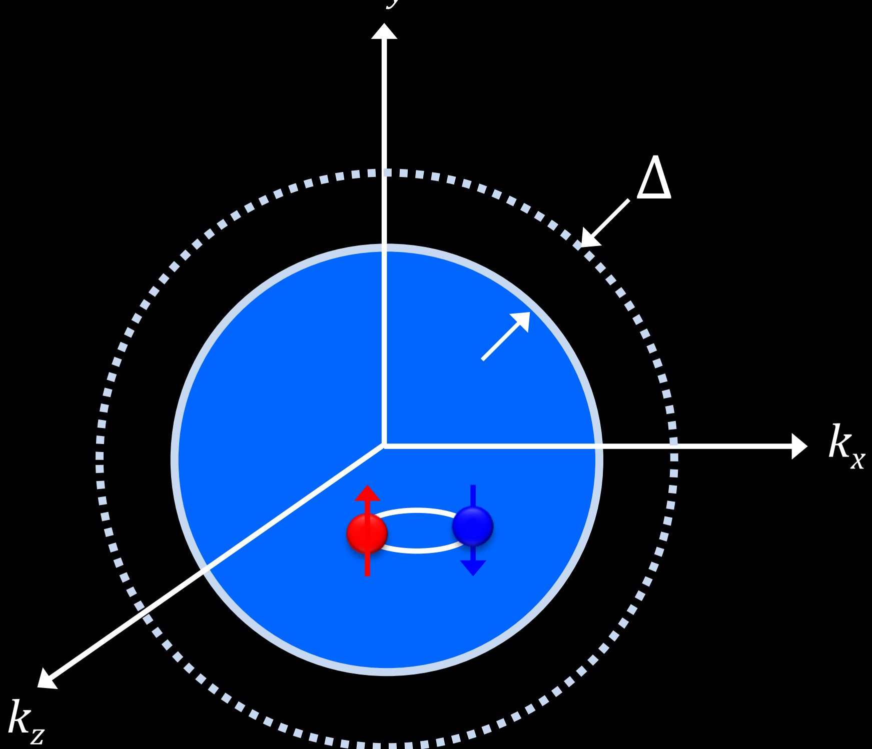
$$\Psi_{BCS} = \prod_k \left(u_k + v_k c^*_{k\uparrow} c^*_{-k\downarrow}\right) | 0 >$$

u_k and v_k : coherence factor

BCS, Phys Rev 108, 1175 (1957)

Superconducting Excited States

SC Ground State

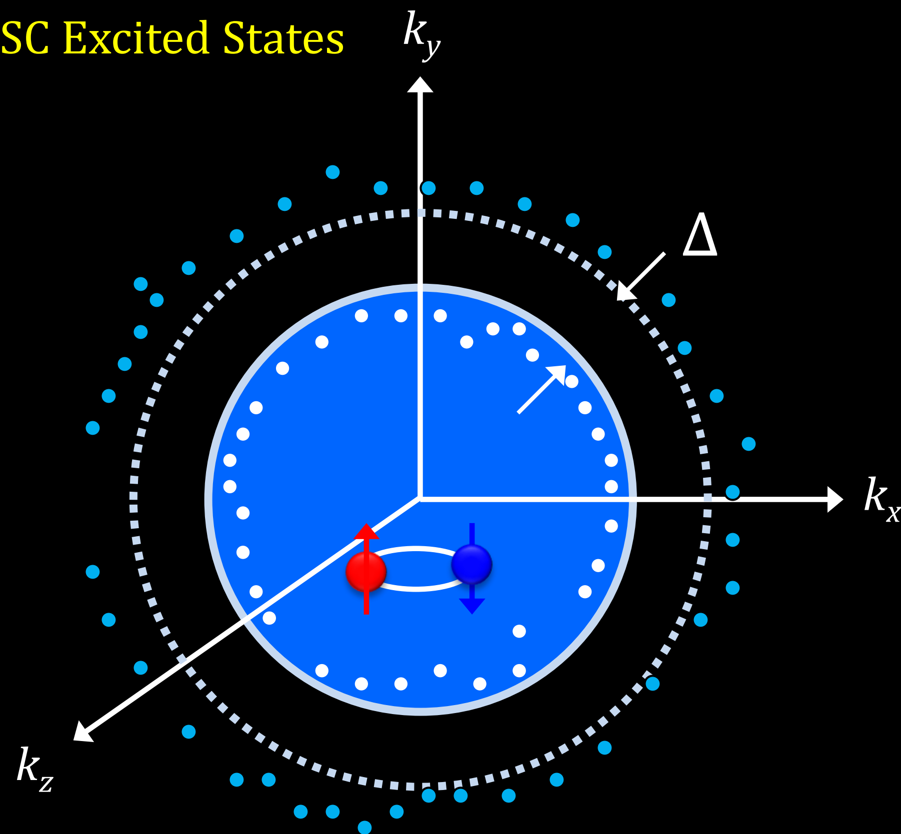


$$\Psi_{BCS} = \prod_k \left(u_k + v_k c^*_{k\uparrow} c^*_{-k\downarrow}\right) | 0 >$$

u_k and v_k : coherence factor

BCS, Phys Rev 108, 1175 (1957)

SC Excited States



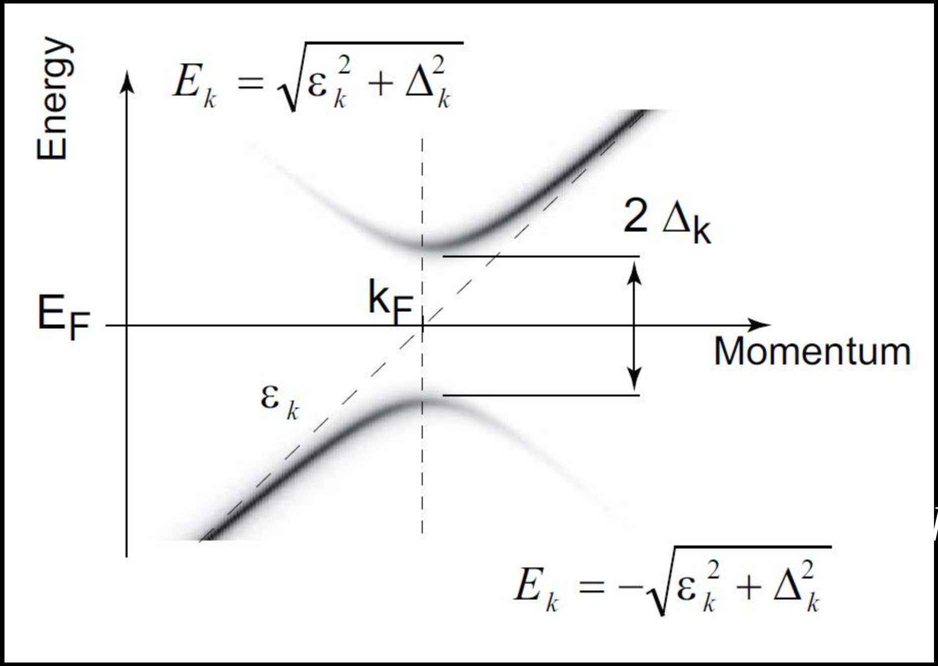
Bogoliubov quasiparticle

$$\gamma^*_{k\uparrow} = u_k c_{k\uparrow} + v_k c^*_{-k\downarrow}$$

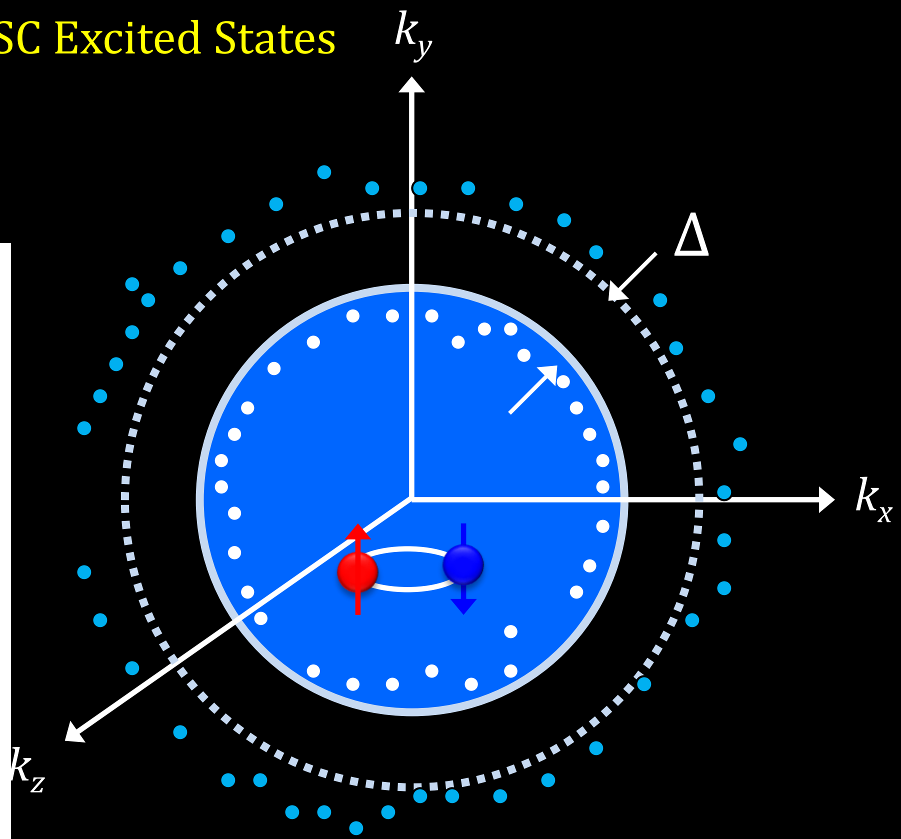
Bogoliubov, Nuovo Cimento 7, 794 (1958)

Superconducting Excited States

$$E_{\pm}(\vec{k}) = \pm\sqrt{\varepsilon(\vec{k})^2 + \Delta(\vec{k})^2}$$



SC Excited States



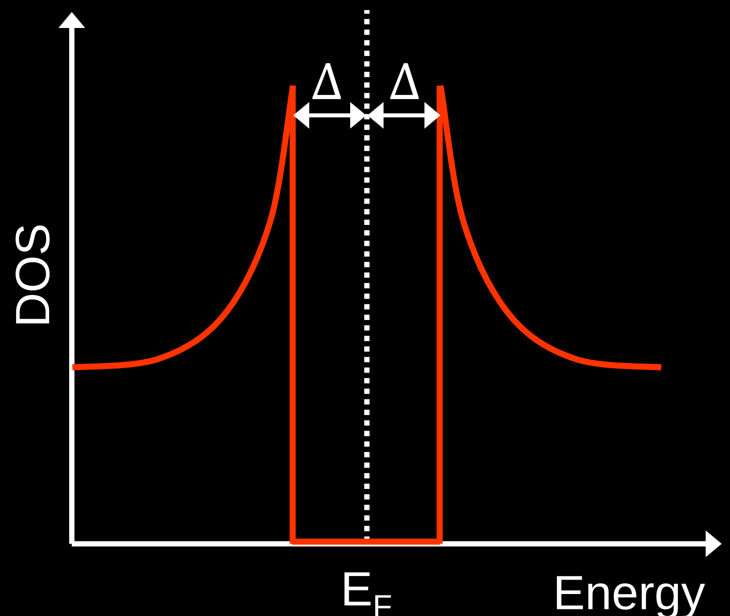
Bogoliubov quasiparticle

$$\gamma^*_{k\uparrow} = u_k c_{k\uparrow} + v_k c^*_{-k\downarrow}$$

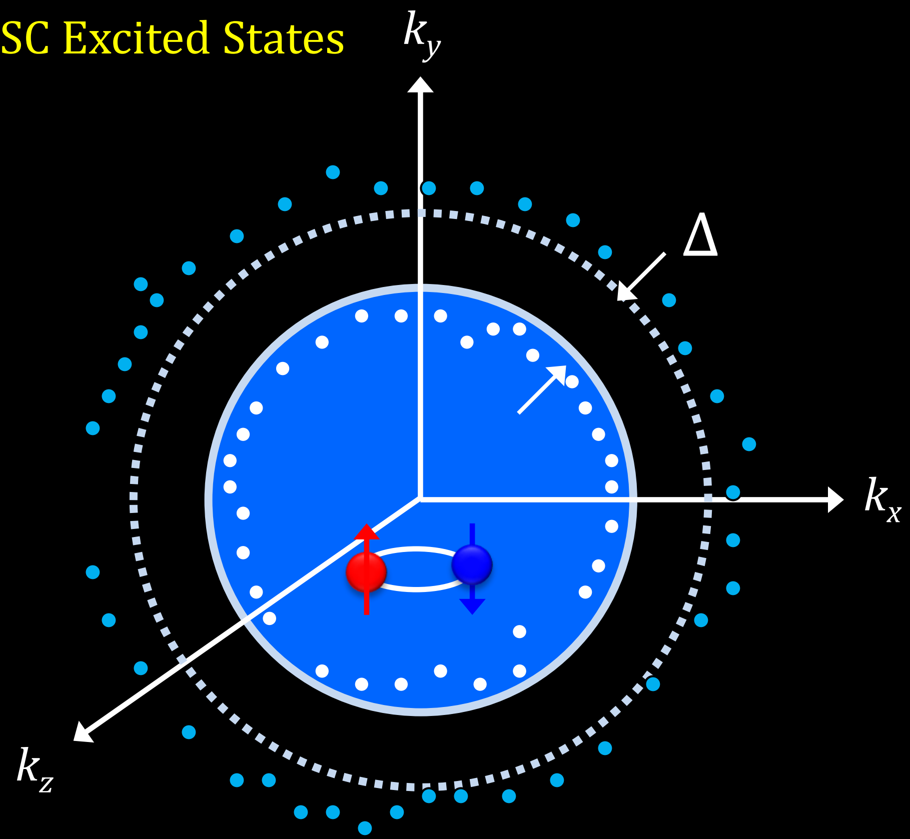
Bogoliubov, Nuovo Cimento 7, 794 (1958)

Superconducting Excited States

Superconducting energy gap=2Δ
(T=0)



SC Excited States



Bogoliubov quasiparticle

$$\gamma^*_{k\uparrow} = u_k c_{k\uparrow} + v_k c^*_{-k\downarrow}$$

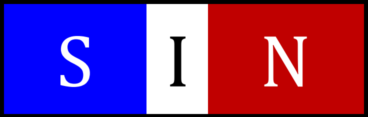
Bogoliubov, Nuovo Cimento 7, 794 (1958)

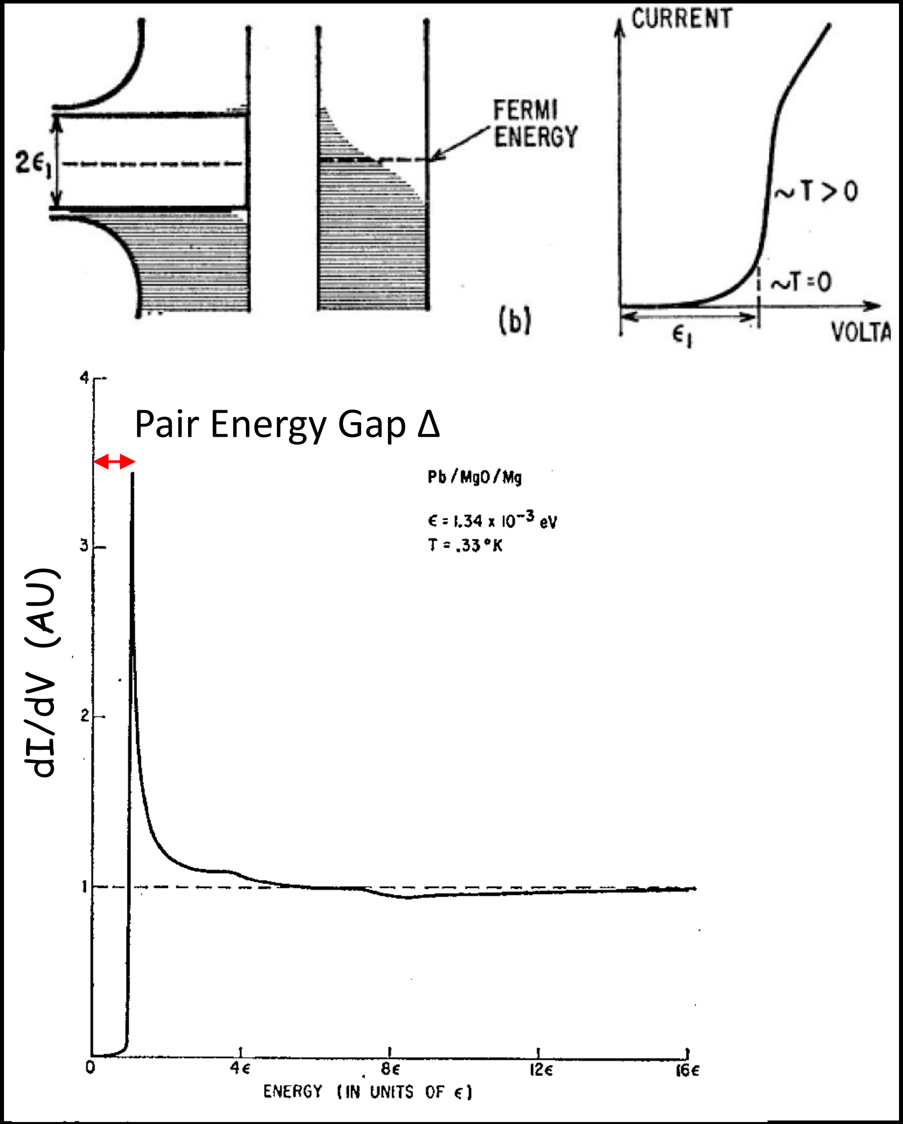
Superconducting Energy Gap in 1960

Ivar Giaever

Nobel Prize in 1973

Tunneling junction





I. Giaever, Phys. Rev. Lett. 5, 147 (1960)
I. Giaever, Phys. Rev. 126, 941 (1962)

Superconducting Gap

Pair wave function : $\Psi_{kss'} = \langle \Psi_{BCS} | c_{-ks'} c_{ks} | \Psi_{BCS} \rangle = g(k)\, \chi_{ss'}$

Spin part : $\chi_{ss'}$ $(\uparrow\downarrow - \downarrow\uparrow)$ $S = 0$

$(\uparrow\uparrow, \uparrow\downarrow + \downarrow\uparrow, \downarrow\downarrow)$ $S = 1$

Orbital part : $g(k)$ $\psi(\mathbf{r}) \propto \sum_{\mathbf{k}} \frac{\Delta(\mathbf{k})}{\sqrt{\epsilon(\mathbf{k})^2 + \Delta(\mathbf{k})^2}} \exp(-i\mathbf{kr})$

Spin	Orbital
anti-symmetric (S = 0)	symmetric (s, d, …)
symmetric (S = 1)	anti-symmetric (p, f, …)

l = 0 : s wave (conventional SC)

l = 1 : p wave (superfluid ^{3}He)

l = 2 : d wave (cuprate SC)

If $l > 0$, $\psi(0) = 0$

→ { repulsive interaction; $\Delta(k)$ must change its sign }

Gap Equation

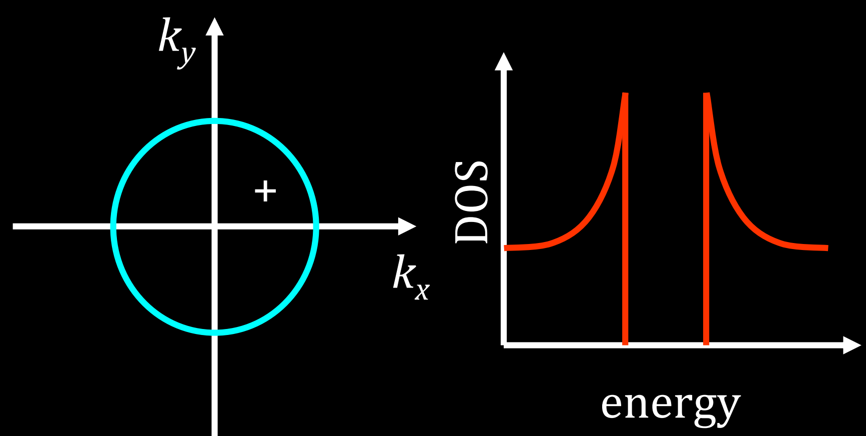
$$\Delta(\mathbf{k}) = -\frac{1}{2}\sum_{\mathbf{q}} V(\mathbf{q}) \frac{\Delta(\mathbf{k})}{\sqrt{\epsilon(\mathbf{k}+\mathbf{q})^2 + \Delta(\mathbf{k}+\mathbf{q})^2}} \tanh \frac{\sqrt{\epsilon(\mathbf{k}+\mathbf{q})^2 + \Delta(\mathbf{k}+\mathbf{q})^2}}{2k_B T}$$

Pairing interaction

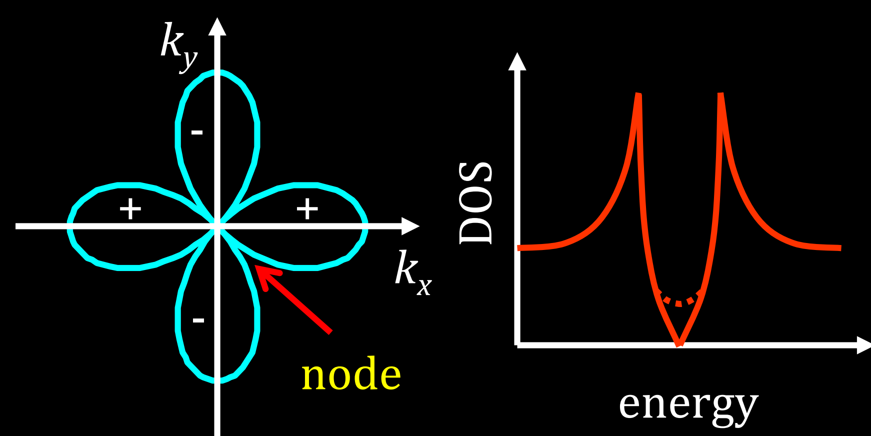
In conventional BCS, $V(\mathbf{q}) = -|V| < 0$: Δ is always positive.

If $V(\mathbf{q} = \mathbf{Q}) > 0$ plays a role, $\Delta(\mathbf{k})$ and $\Delta(\mathbf{k}+\mathbf{Q})$ have a different sign.

s wave



d wave



Flux Quantization Theory in 1950

* We note that in order for Ψ to be a single-valued function, as required by quantum mechanics, it is necessary that the moduli of χ fulfill a kind of quantum condition:

$$<\chi> = \oint \bar{\mathrm{p}}_s \cdot \mathrm{ds} = Kh$$

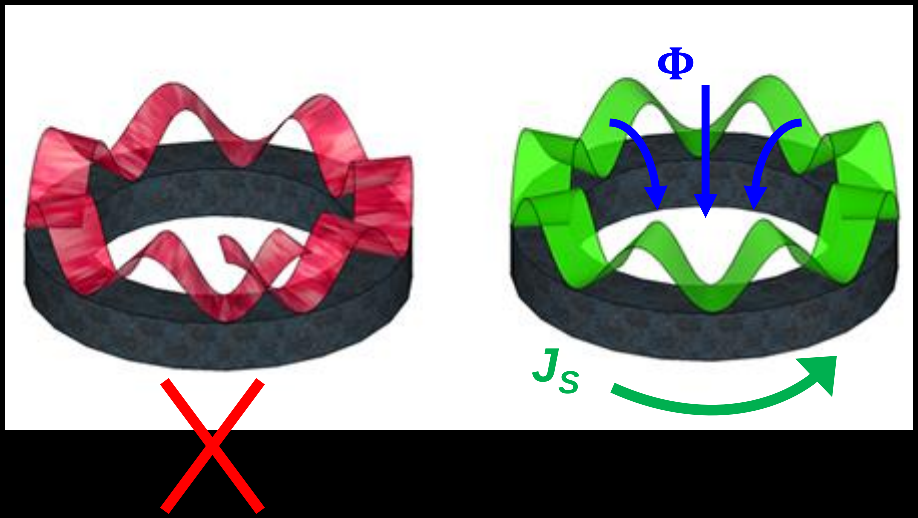
where K must be an integer. This means that there exists a universal unit for the fluxoid:

$$\Phi_1 = hc/e \simeq 4 \cdot 10^{-7} \text{ gauss} \cdot \text{cm}^2$$

Fritz London

©Duke Univ.

Superconducting ring



Superfluids, Macroscopic Theory of Superconductivity, Structure of Matter Vol. 1 (Wiley, New York, 1950)

Flux Quantization Experiments in 1961

Bascom Deaver

William Fairbank

©APS ©Duke Univ.

Robert Doll

Martin Näbauer

©Walther-Meißner-Institute

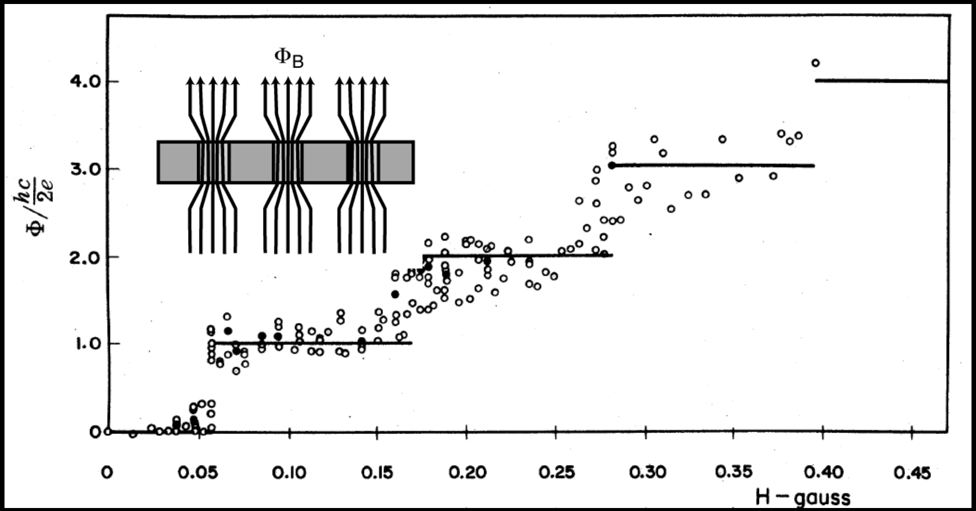
$|\Phi| = n\,{}^{hc}/_{2e} = n\Phi_{0},$

where $\Phi_{0} = 2.0 \times 10^{-15} Tesla - m^2$

Each vortex carries one flux quanta

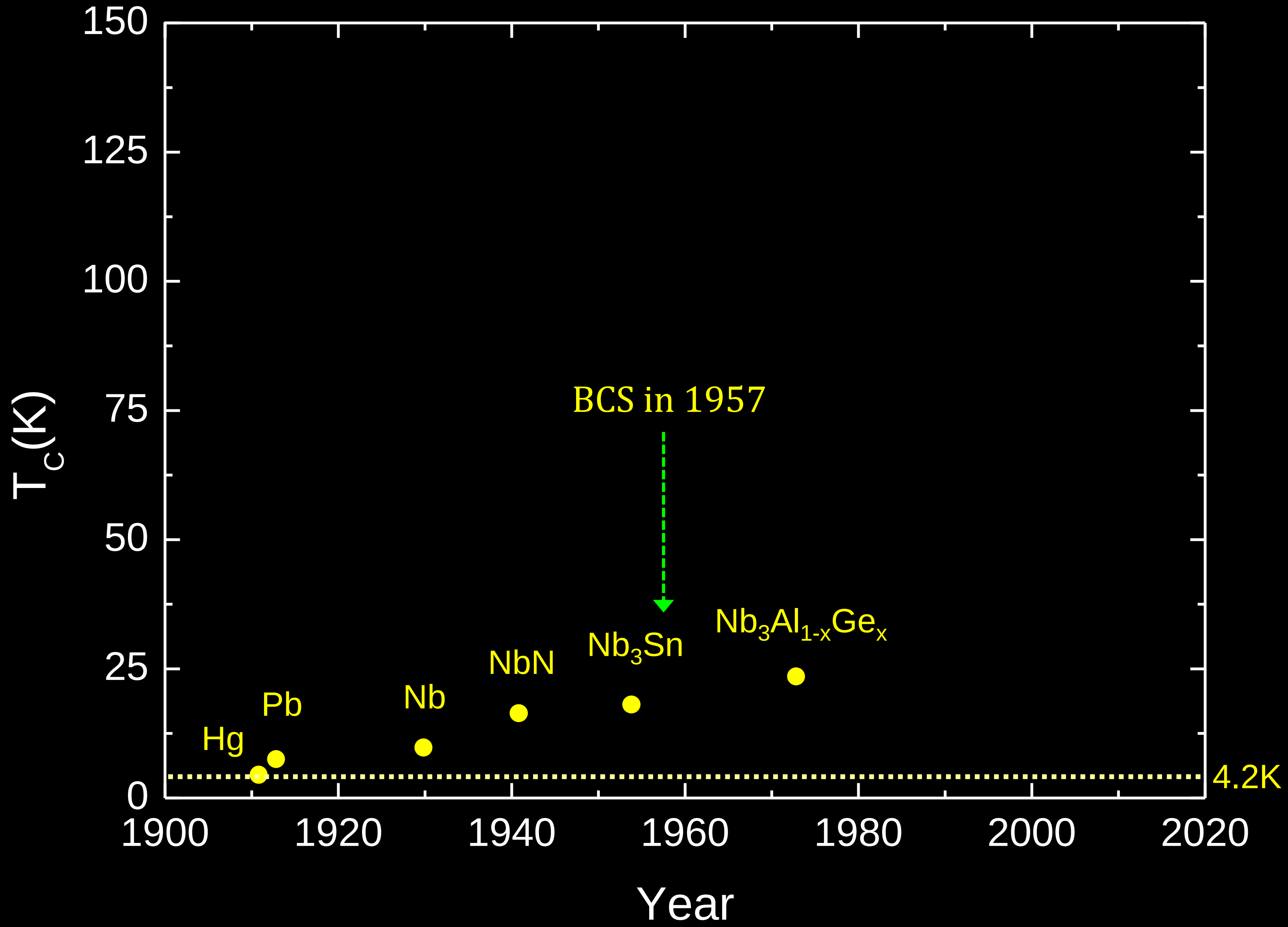
SC carriers are 2e!

Confirmation of Cooper pairs!

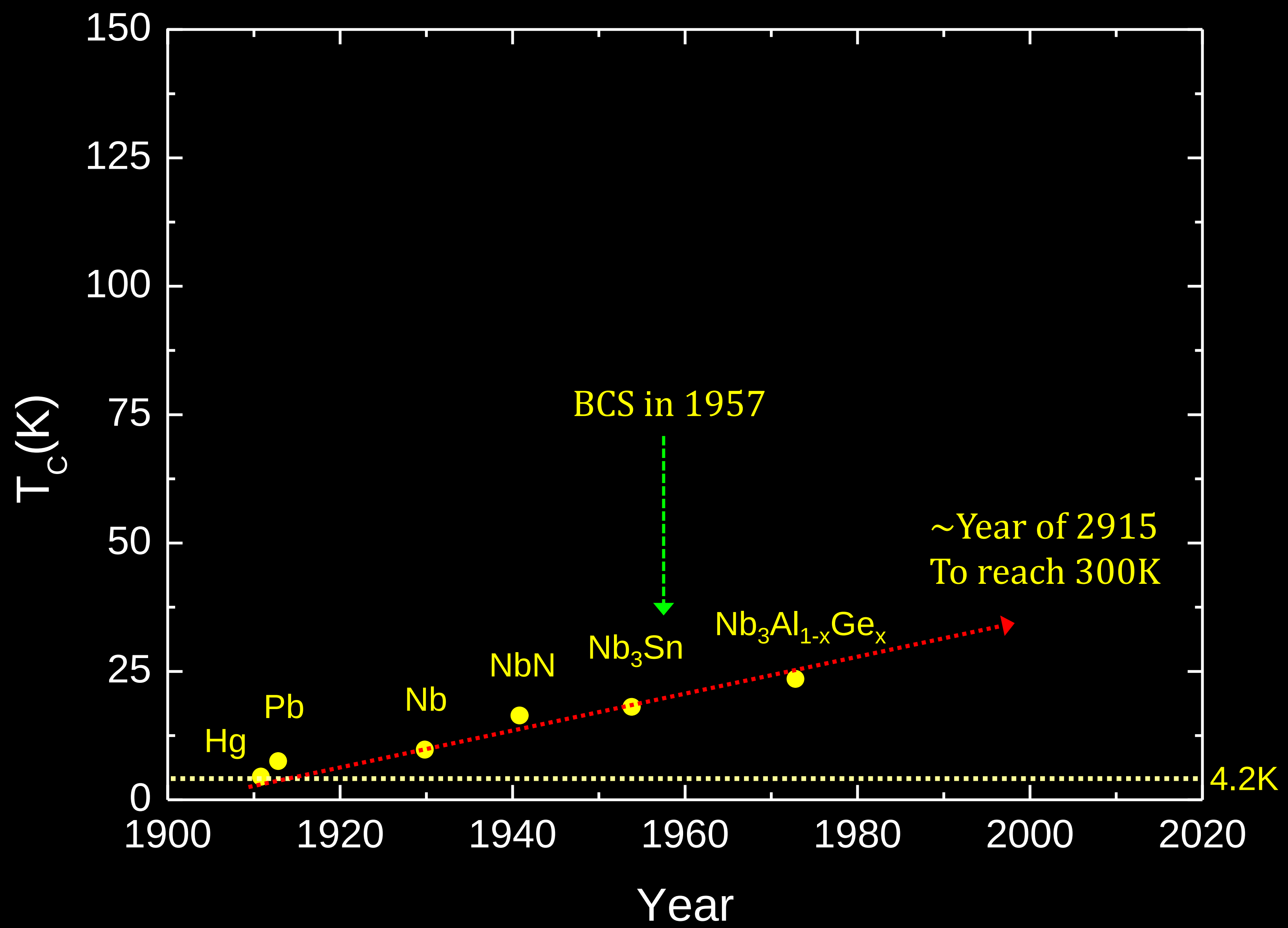


B. D. Deaver and W. M. Fairbank, PRL **7**, 43 (1961)
R. Doll and M. Näbauer, PRL **7**, 51 (1961)

History of Conventional SC



History of Conventional SC



Matthias's Rules for Searching High TC SC

Bernd Matthias

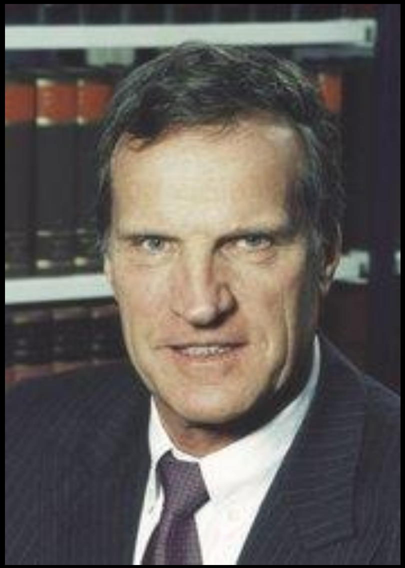
By Joel Broida©

1. Stay away from insulators; transition metals are better.
2. There are favorable electron/atom ratios.
3. High symmetry is good; cubic symmetry is best.
4. Stay away from Oxygen
5. Stay away from magnetism
6. Stay away from theorists.

W. E. Pickett , Physica B **296**, 112 (2001)
I. I. Mazin, Nature **464**, 183 (2010)

The Beginning of Unconventional SC: Heavy Fermion SC

Enormous effective mass of their charge carriers. This is achieved by a sharp spike in the DOS at the Fermi surface, to as much as 1000 times the density of states in Cu.



Frank Steglich

F. Steglich *et al.*, Phys. Rev. Lett. 43, 1892 (1979)

The Woodstock of Physics : Discovery of Cuprates

Possible High T_c Superconductivity in the Ba – La – Cu – O System

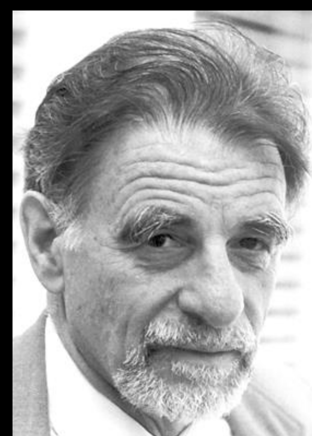
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

Z. Phys. B – Condensed Matter 64,189 (1986)

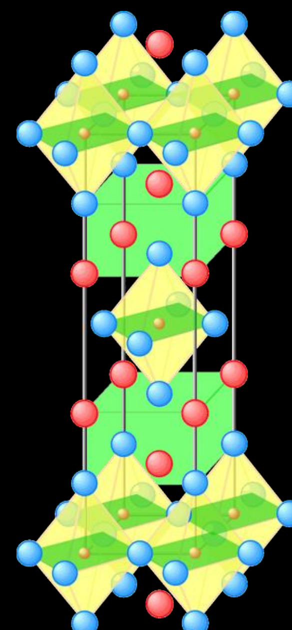
J. Georg Bednorz

K. Alex Müller



Nobel Prize 1987

$La_{2-x}Ba_xCuO_4$, Tc=30K



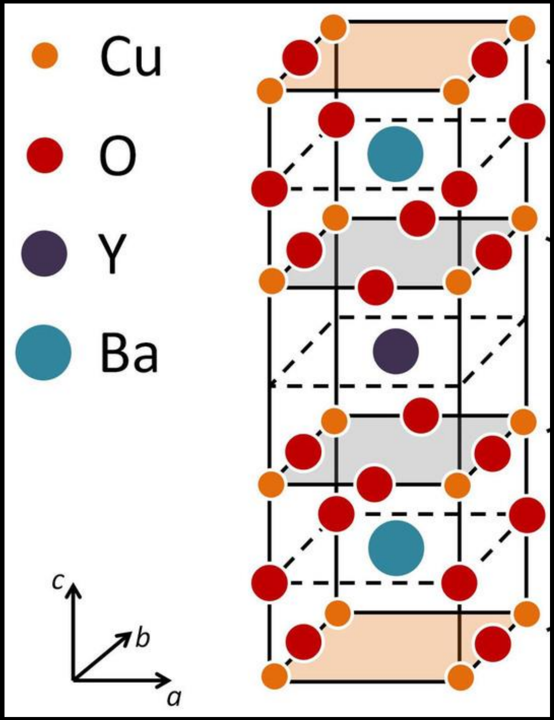
The Woodstock of Physics : Discovery of Cuprates

Tc>77K !

朱經武

吳茂昆

$YBa_2Cu_3O_{7-\delta}$, T_c~93K



CuO chain

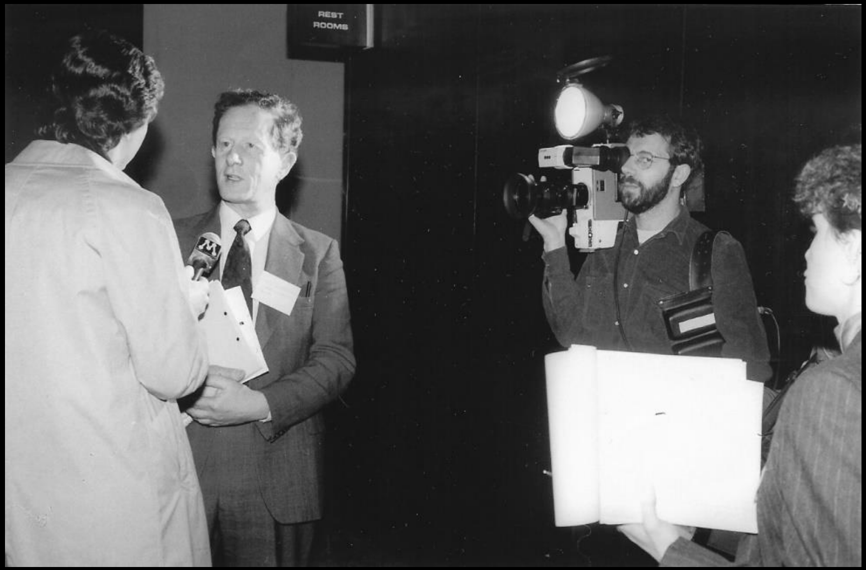
BaO

CuO plane

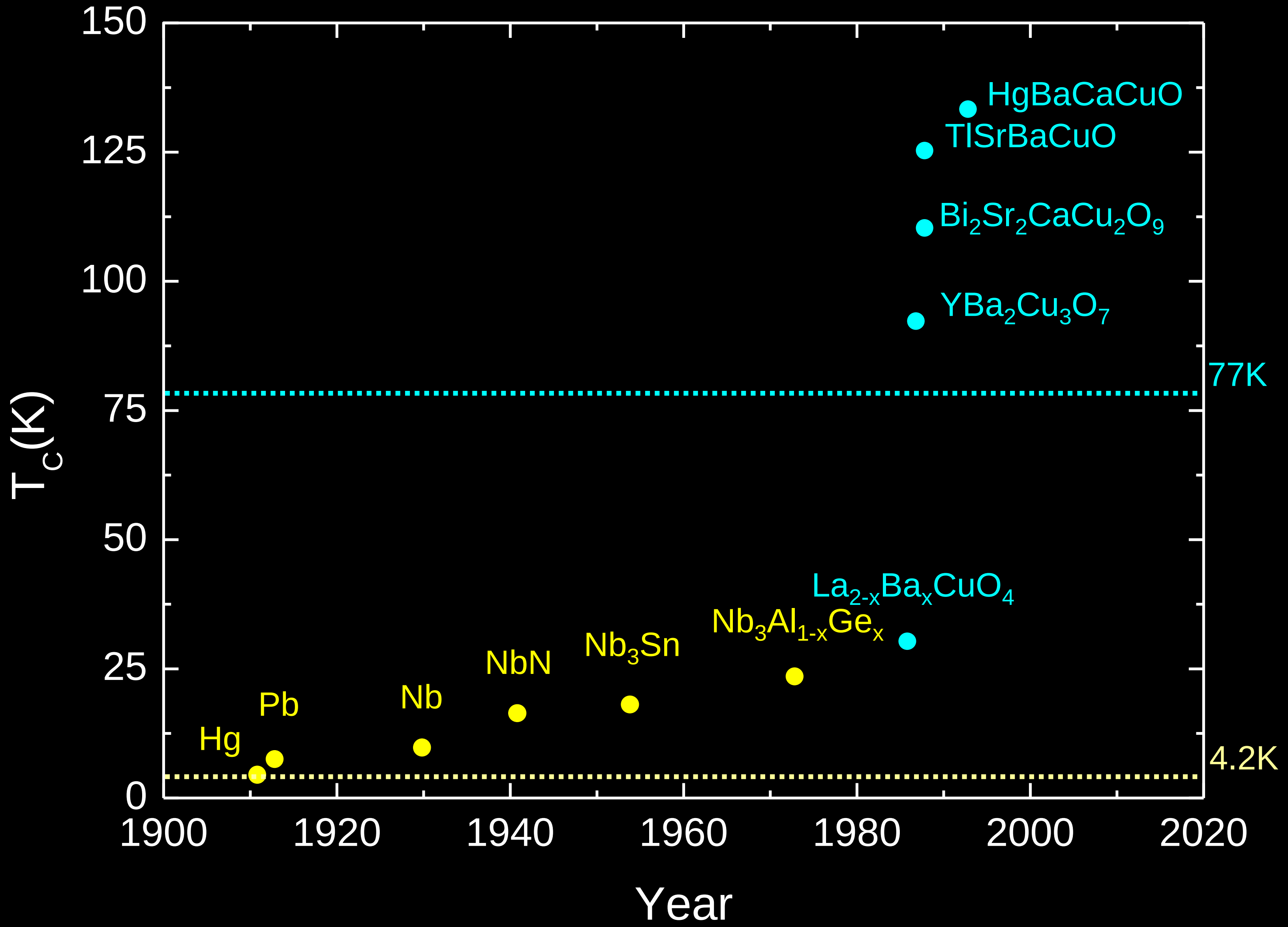
M. K. Wu *et al.*, PRL **58**, 908 (1987)

Woodstock of Physics - March Meeting 1987

“The stores and the bars were all ‘Physicists welcome,’ ” said Paul M. Grant, who headed the superconductivity research at I.B.M.’s Almaden Research Center in San Jose. He recalled a discotheque in Chelsea with a long line of people waiting to get in. “The bouncers took anybody that had a physical society badge on to the front,” Dr. Grant recalled, “and we got in gratis. Can you imagine what a culture shift? We had a hell of a good time.” – NY Times



History of Superconductors



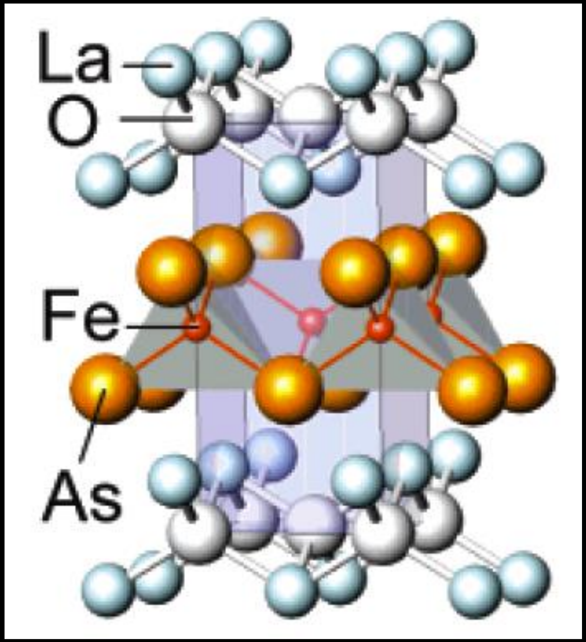
The Discovery of Fe-based Superconductors (FeSC)

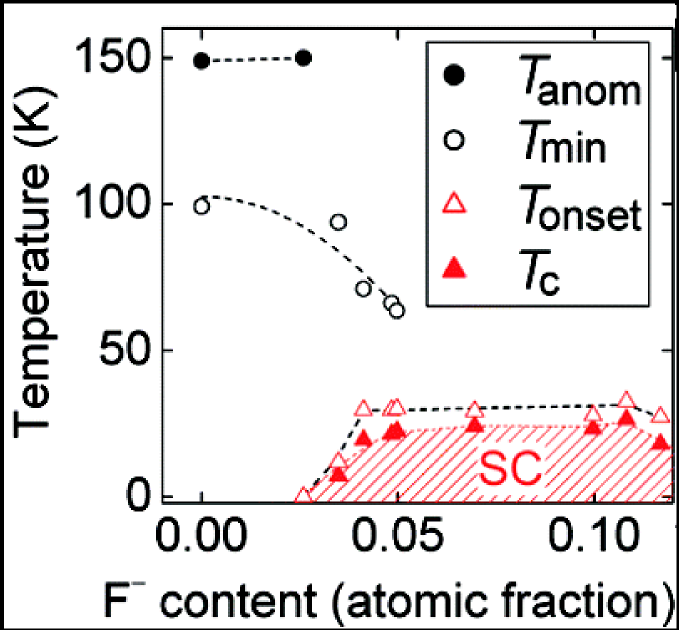
2006 : $LaFeP(O_{1-x}F_x)$, T_C~5K

2007 : LaNiPO, T_C~3K

Feb 23, 2008 : $LaFeAs(O_{1-x}F_x)$, T_C~26K

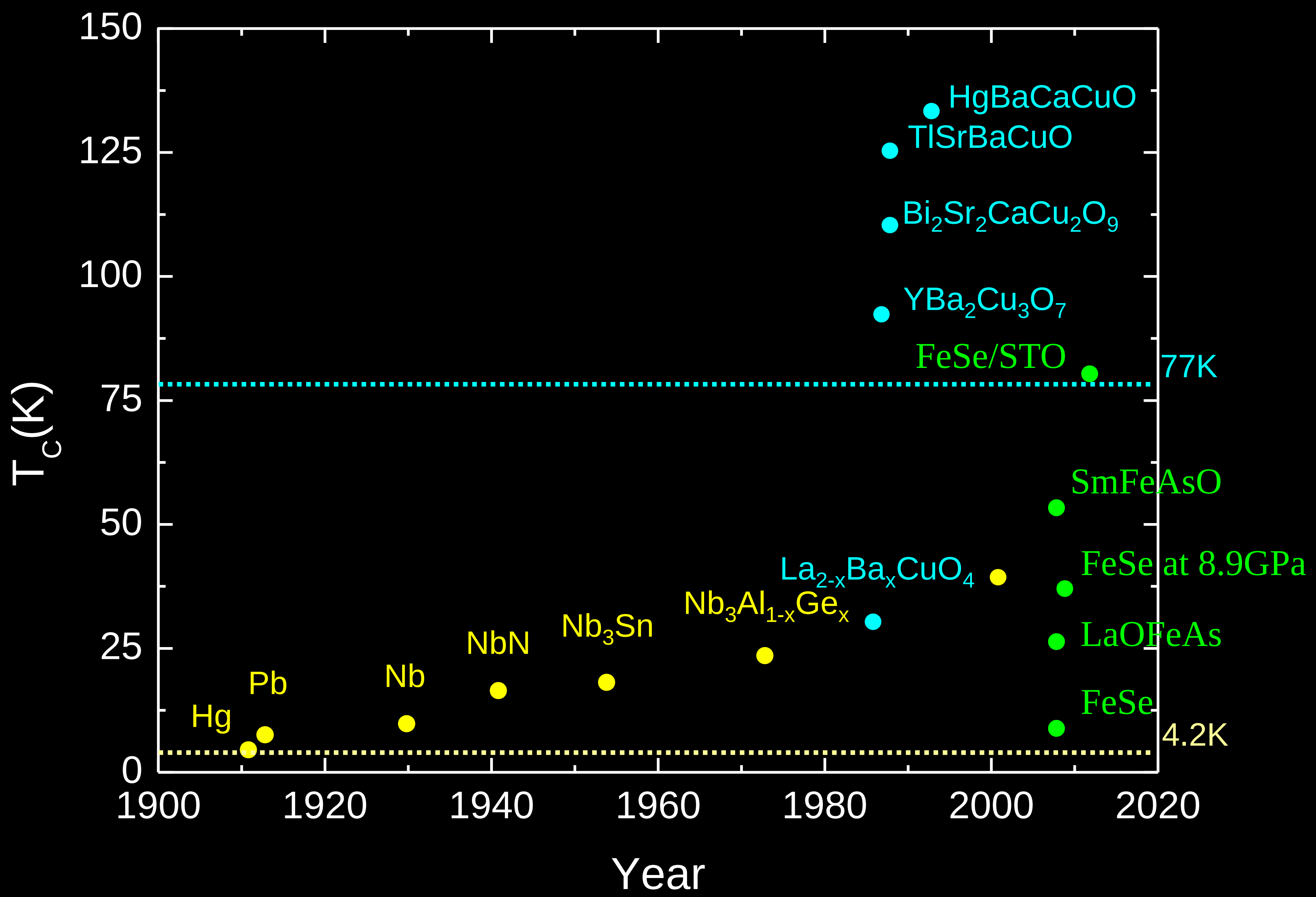
Hideo Hosono





Y. Kamihara *et al.*, JACS. **128**, 10012 (2006)
T. Watanabe *et al.*, JACS. **46**, 7719 (2007)
Y. Kamihara *et al.*, JACS. **130**, 3296 (2008)

History of Conventional and High T_C Superconductors

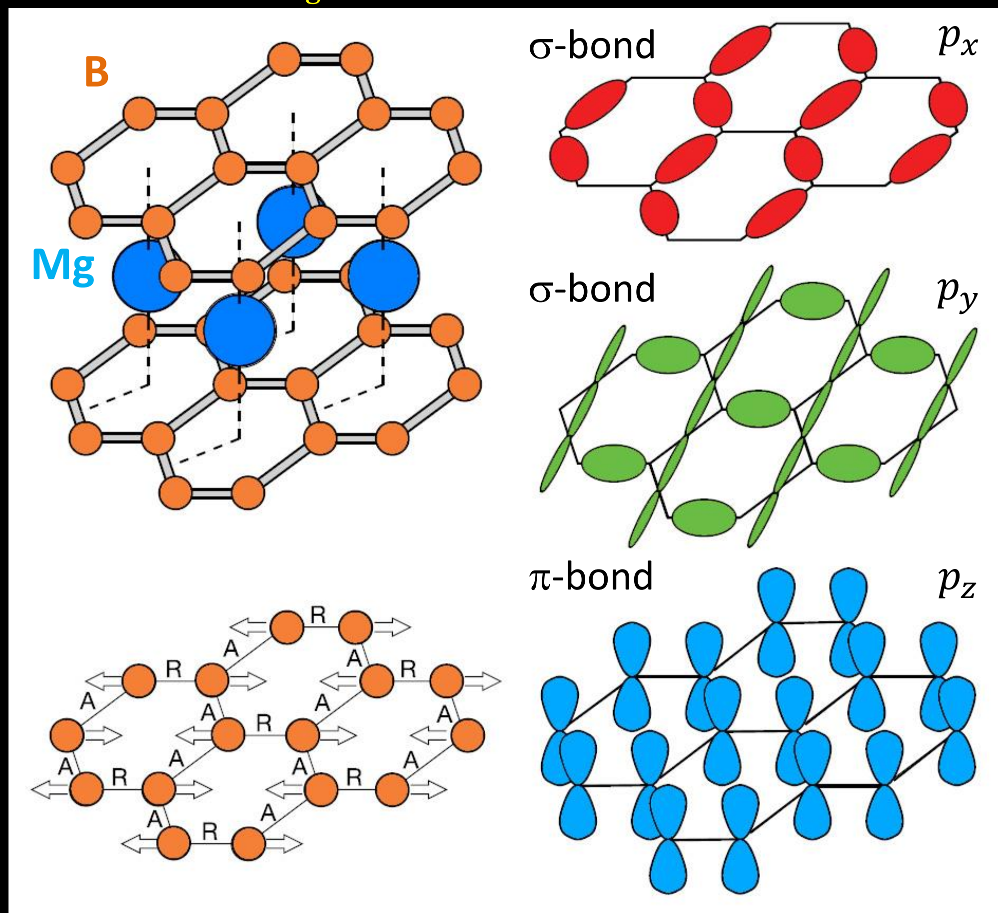


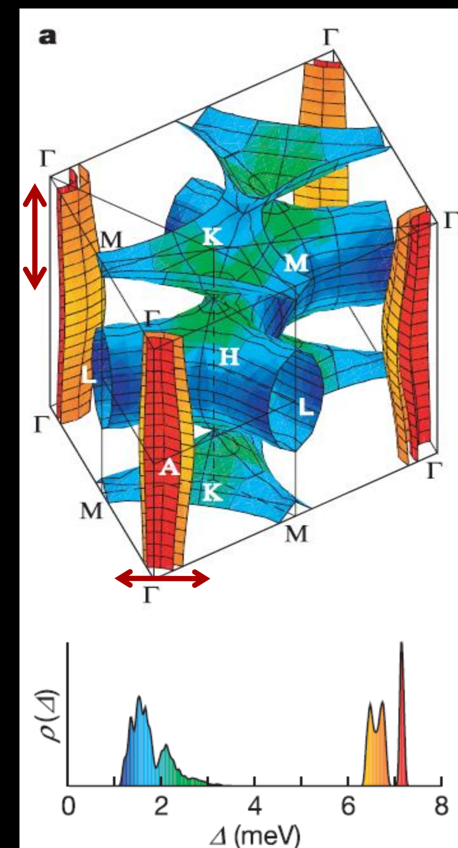
Honorable Mention : MgB_2 in 2001

Tc=39K
Two superconducting gaps
Strong *sp*[2] bonding and hybridization
E_{2g} phonon and σ bond coupling leads to high Tc

Jun Akimitsu
秋光純

©青山学院大学



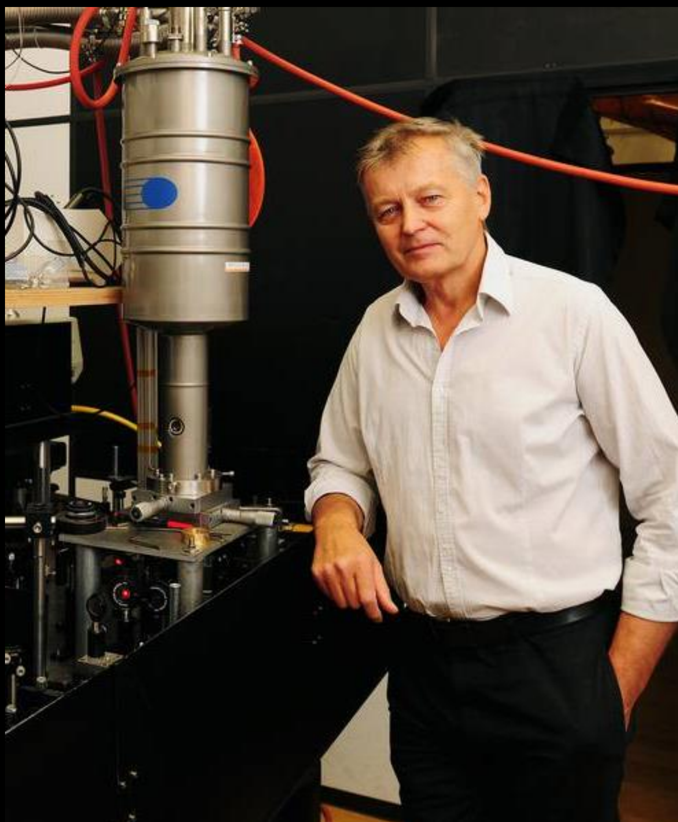


J. Nagamatsu *et al*., Nature 410, 63 (2001)
Amy Liu *et al*., PRL 87, 087005 (2001)
H.J. Choi *et al*., Nature 418, 758 (2002)

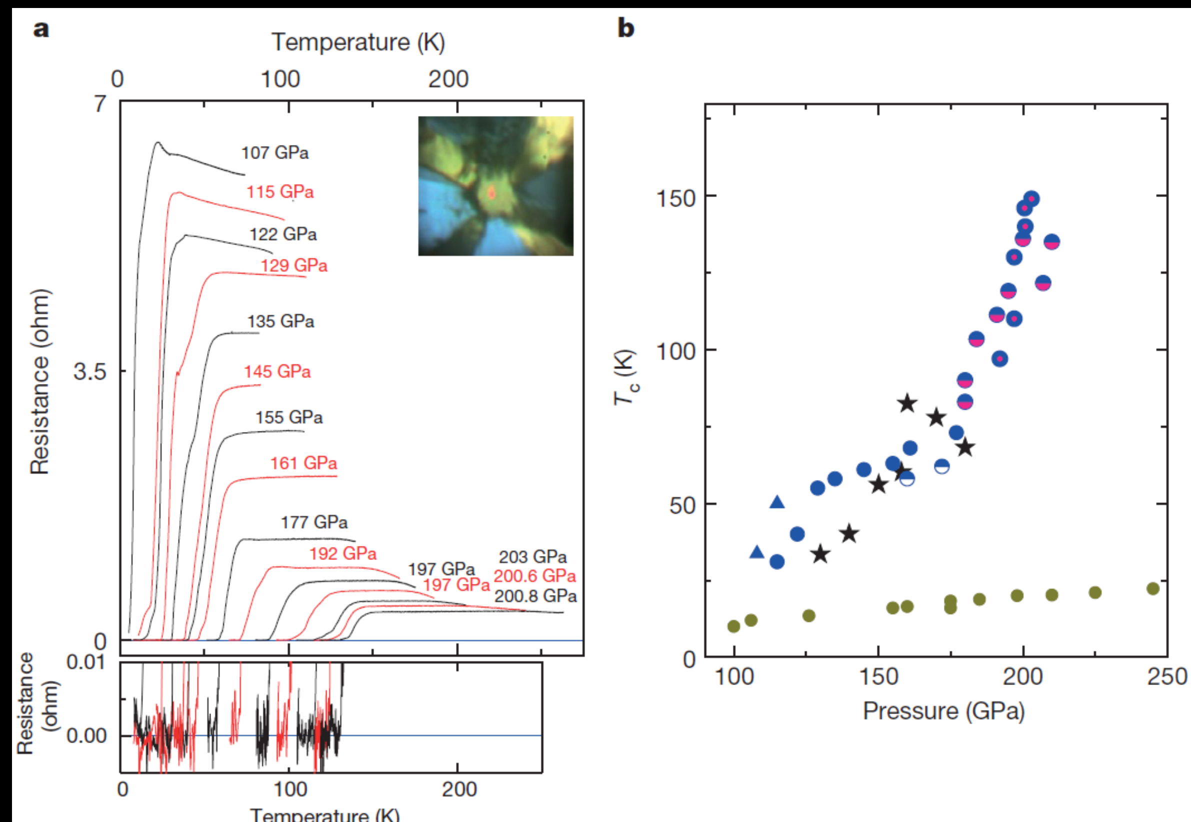
Honorable Mention : H_3S in 2015

T_C=203K under High Pressure
Likely H-rich H_3S
Conventional superconductor?

Mikhail Eremets



© Max-Planck-Institut für Chemie

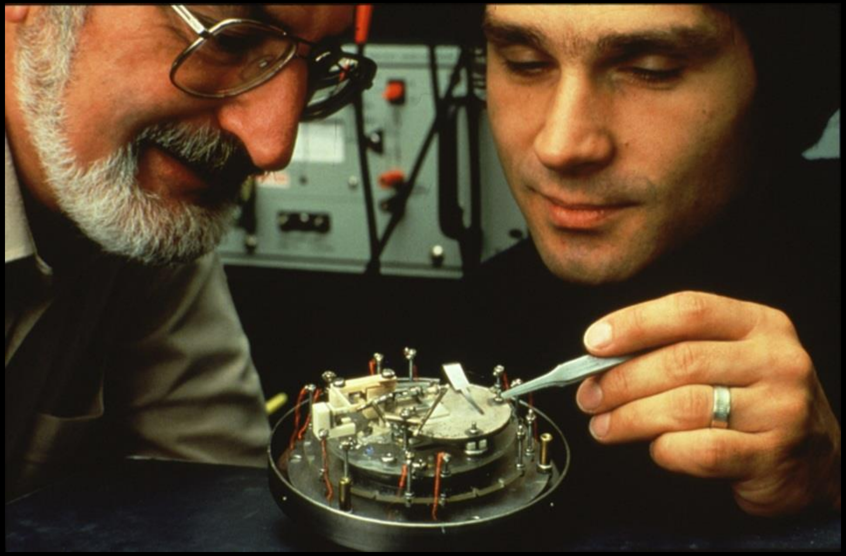


A. P. Drozdov *et al.*, Nature 525, 73 (2015)

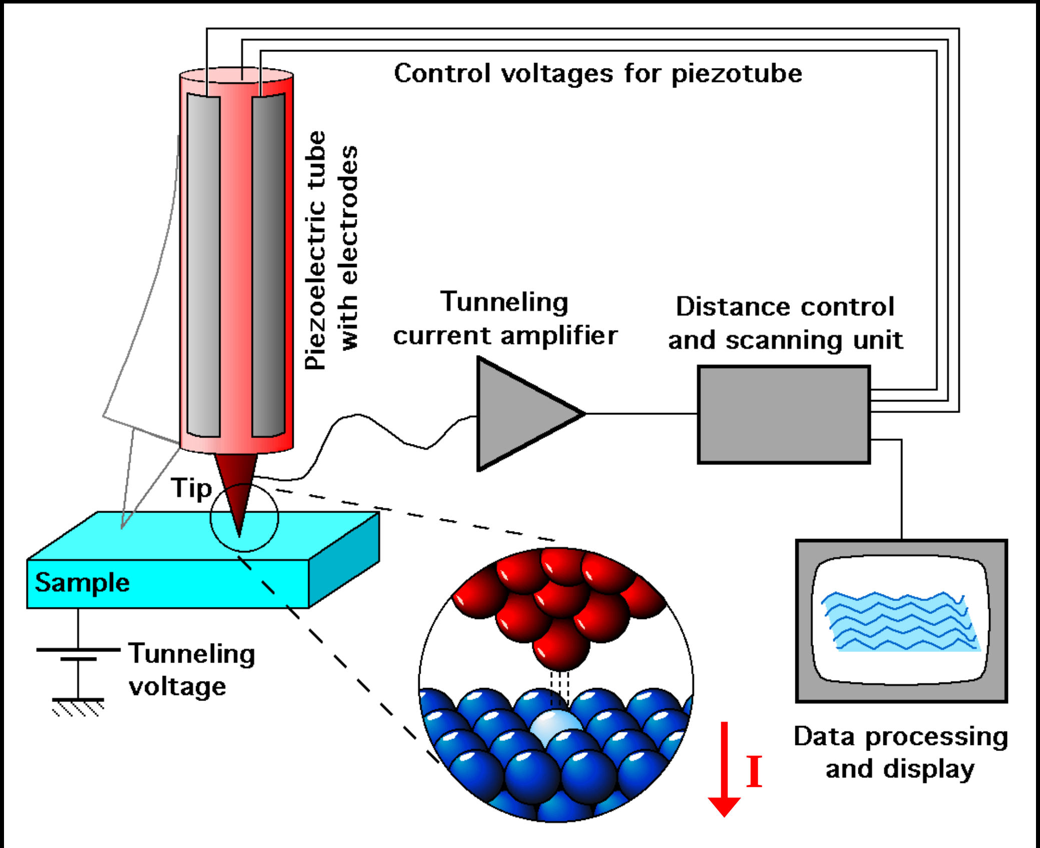
1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

Scanning Tunneling Microscope (STM)

Heinrich Rohrer & Gerd Binnig



Nobel Prize in 1986 ©IBM



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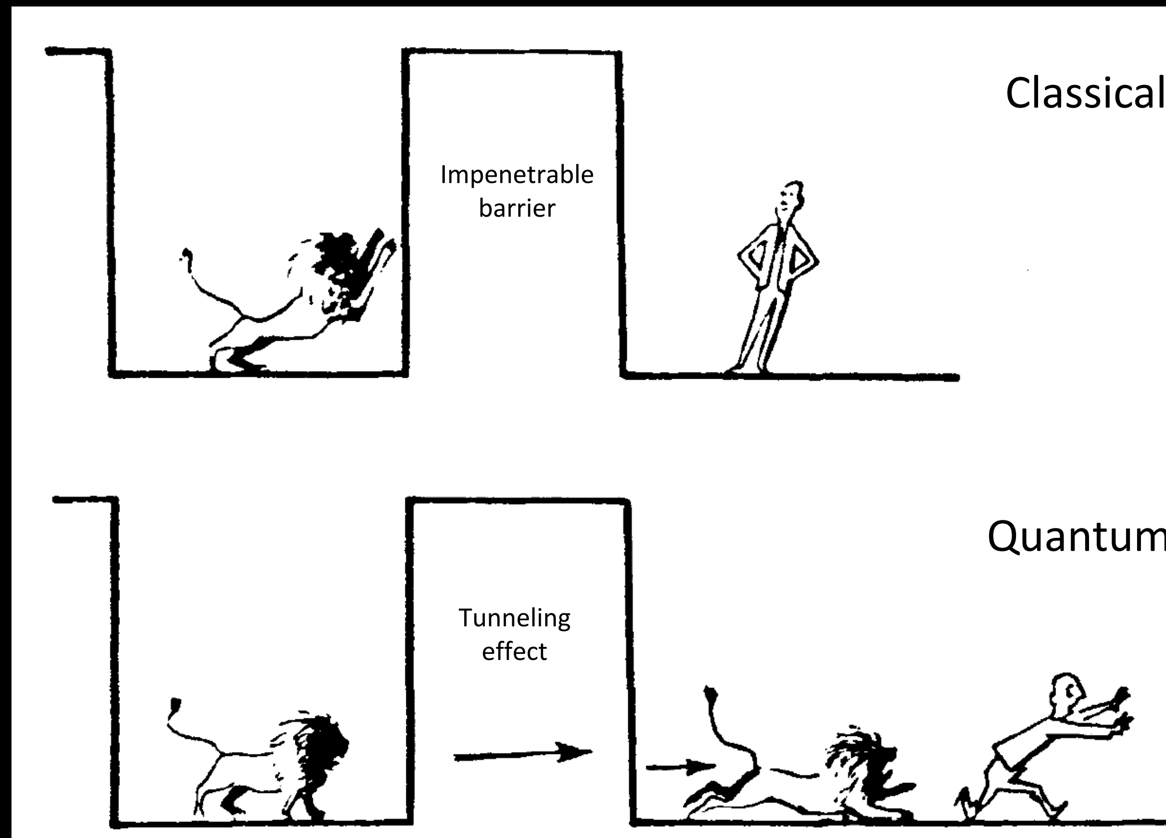
Quantum Tunneling

Erwin Schrödinger

Nobel Prize in 1933



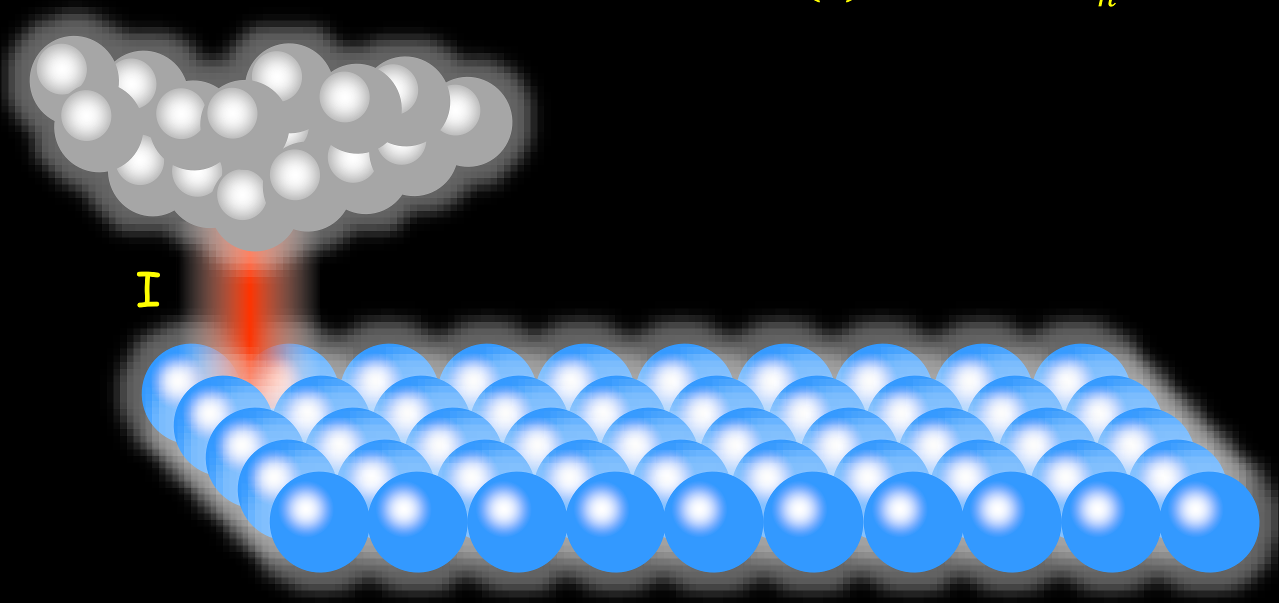
$$-\frac{\hbar^2}{2m}\nabla^2\Psi(\vec{r},t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{r},t)$$

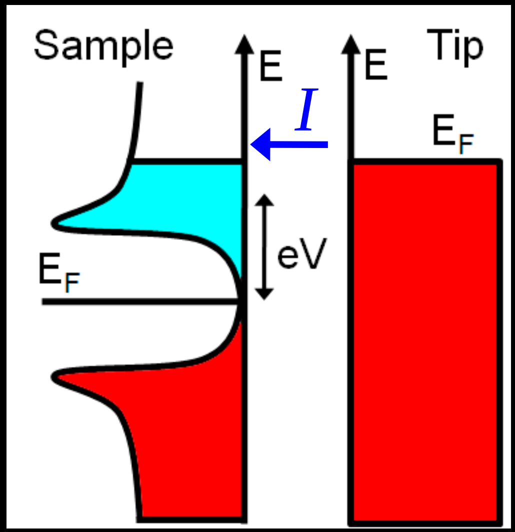
B. Bleaney, Contemp. Phys. 25, 315 (1984)

Tunneling current

$$I(\vec{r}, z, V) \propto \exp(-2\kappa(\vec{r})z) \int_0^{E=eV} LDOS_{sample}(\vec{r}, E)dE$$

where $\kappa(\vec{r}) = \sqrt{2m\phi(\vec{r})}/\hbar \sim 1\text{Å}^{-1}$

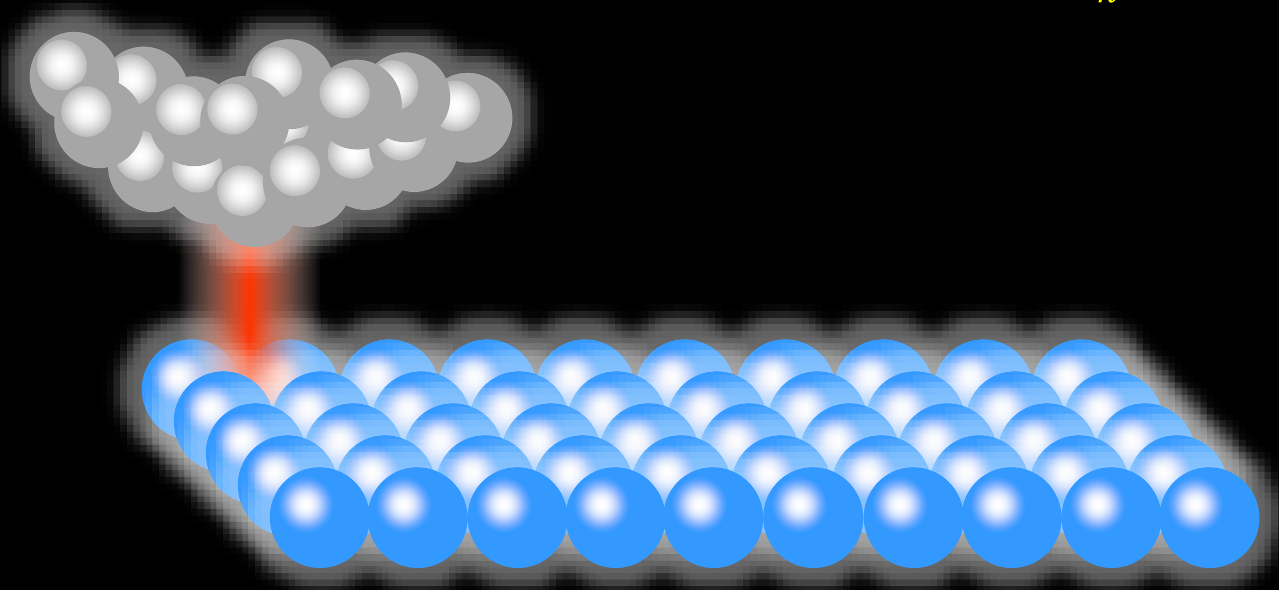


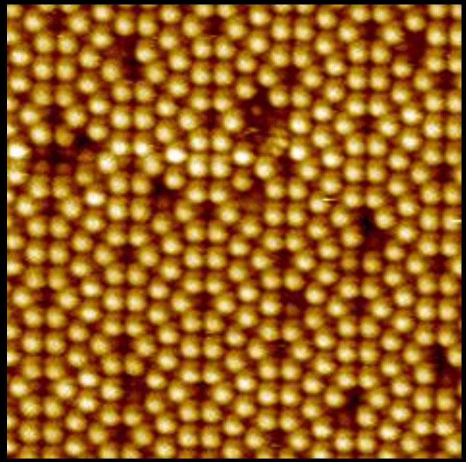


Constant Current Topography

$$I(\vec{r},z,V) \propto \exp(-2\kappa(\vec{r})z)\int_0^{E=eV} LDOS_{sample}(\vec{r},E)dE$$

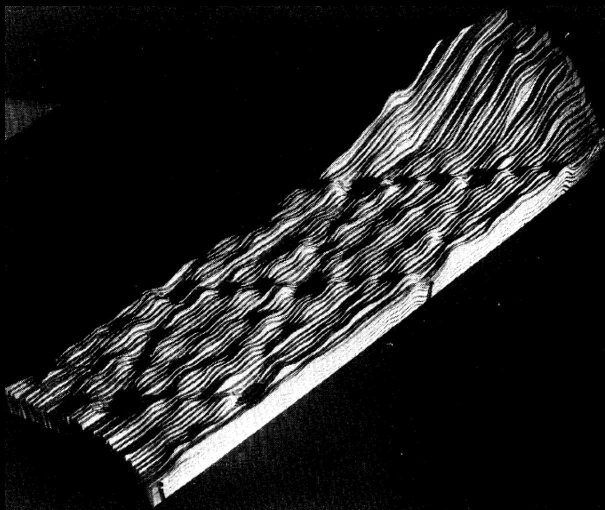
where $\kappa(\vec{r}) = \sqrt{2m\phi(\vec{r})}/\hbar \sim 1\text{Å}^{-1}$



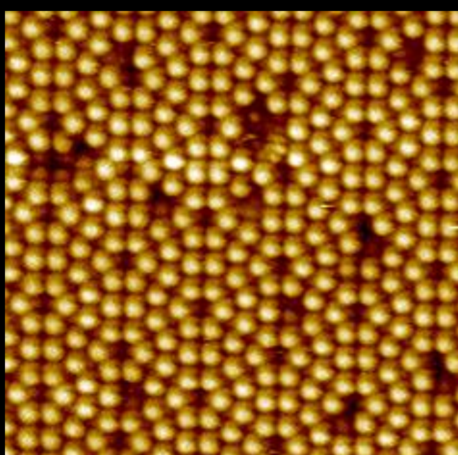


Si(111) 7x7

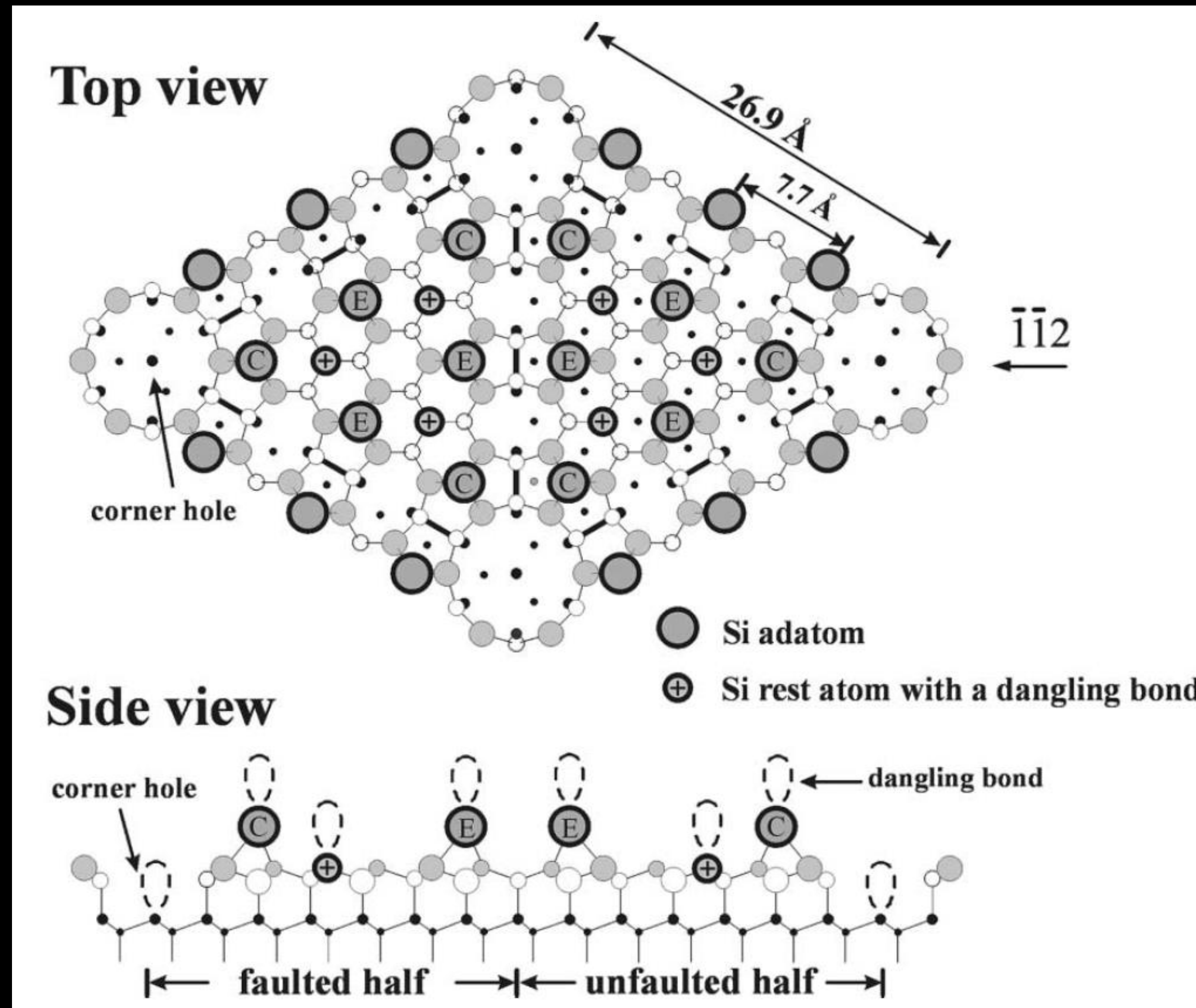
Si(111) 7x7 Structure



G. Binning *et al.*, Phys. Rev. Lett. 50, 120 (1983)



DAS Model

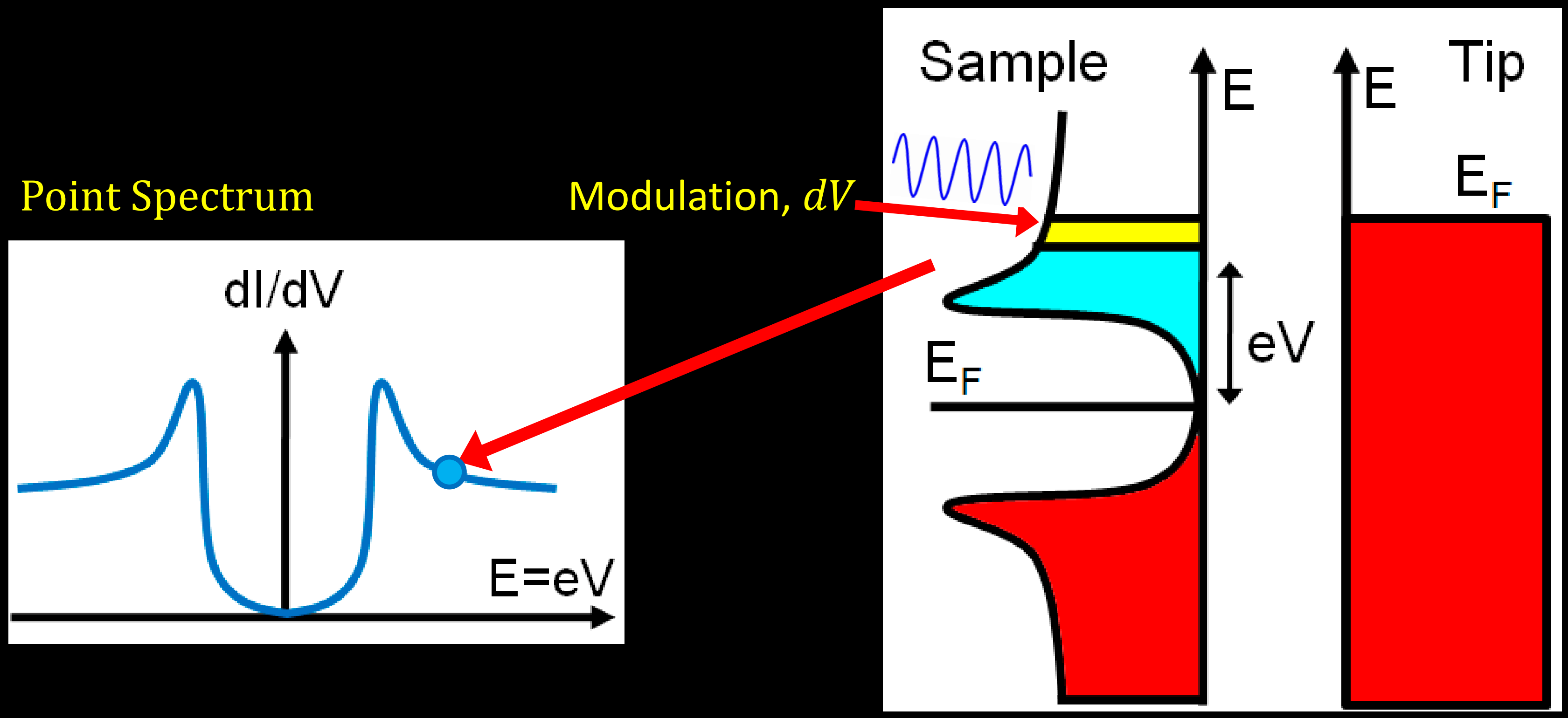


K. Takayanagi *et al.*, Surf. Sci. 164, 367 (1985)

Tunneling Spectroscopy

$$\text{Local Density of States}: \frac{dI}{dV}(\vec{r}, V) \propto LDOS_{sample}(\vec{r}, E = eV)$$

$$I(V + \Delta V \sin \omega t) = I(V) + \frac{dI}{dV} \Delta V \sin \omega t + \ldots$$

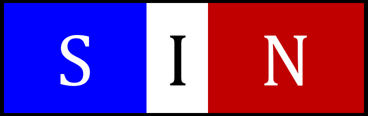


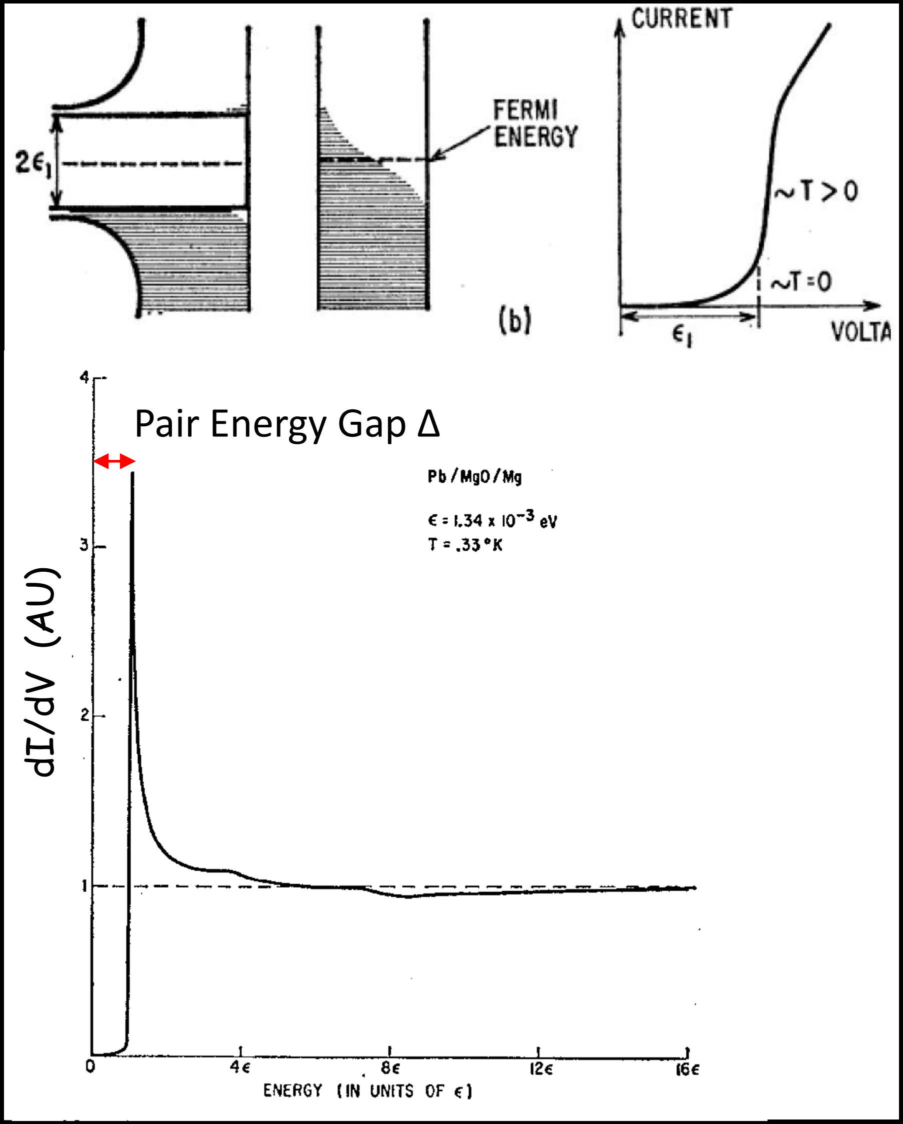
Superconducting Energy Gap in 1960

Ivar Giaever

Nobel Prize in 1973

Tunneling junction

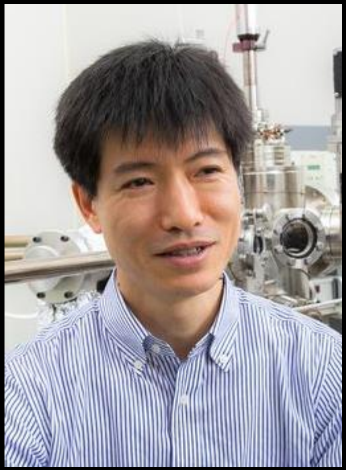




Ivar Giaever, Phys. Rev. Lett. 5, 147 (1960)
I. Giaever, Phys. Rev. 126, 941 (1962)

Superconducting Energy Gap by STM

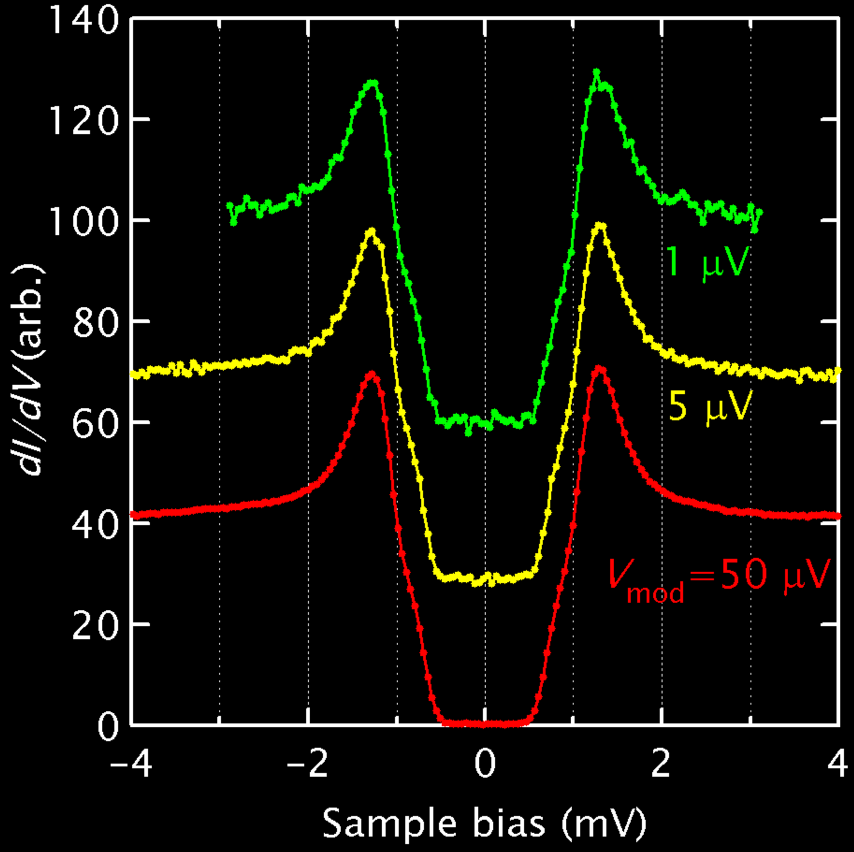
Tetsuo Hanaguri



©RIKEN

Energy resolution is thermally limited.

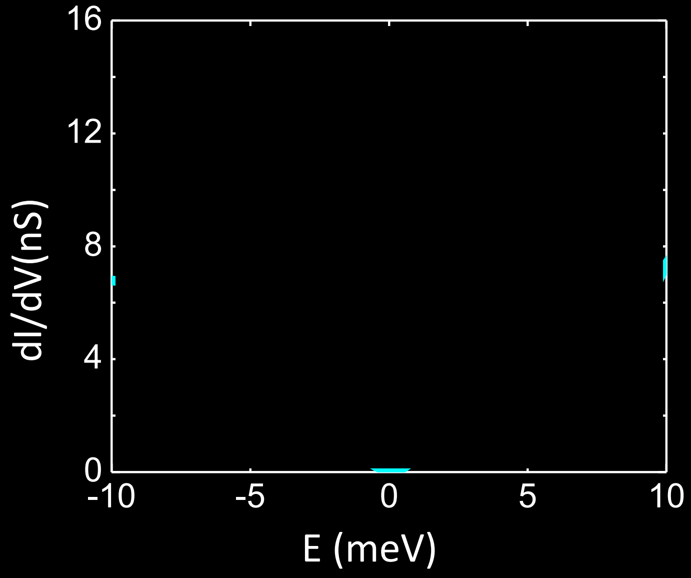
2H-$NbSe_2$, T_c = 7.1 K, measured at $T \sim 0.4$K

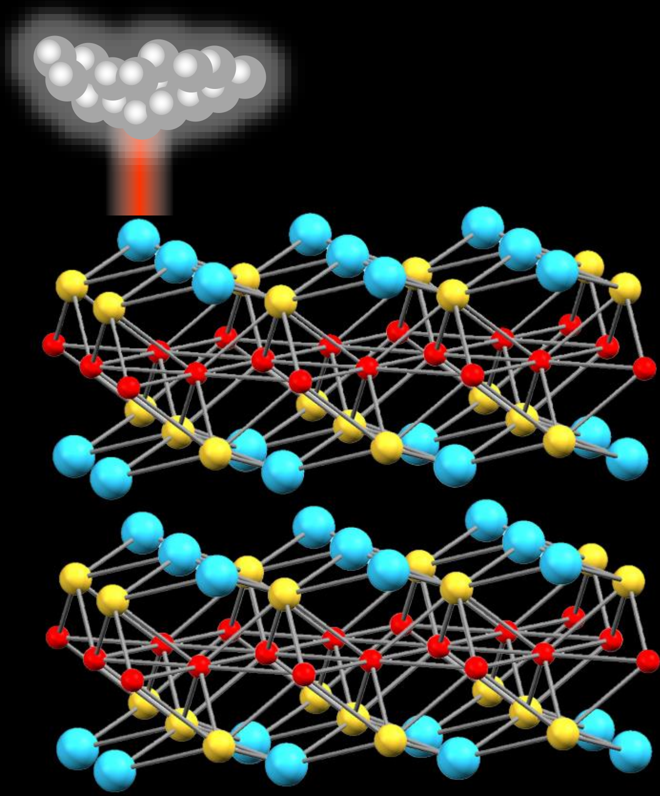


Scanning Tunneling Spectroscopy (STS) Mapping

Atomic resolution energy resolved conductance images, g(r,E) ∝ LDOS(r,E)

Energy resolution ≤ 0.35meV at T=1.2K

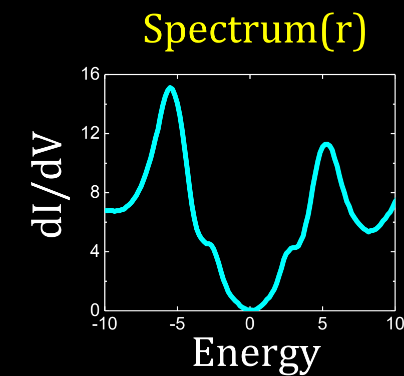


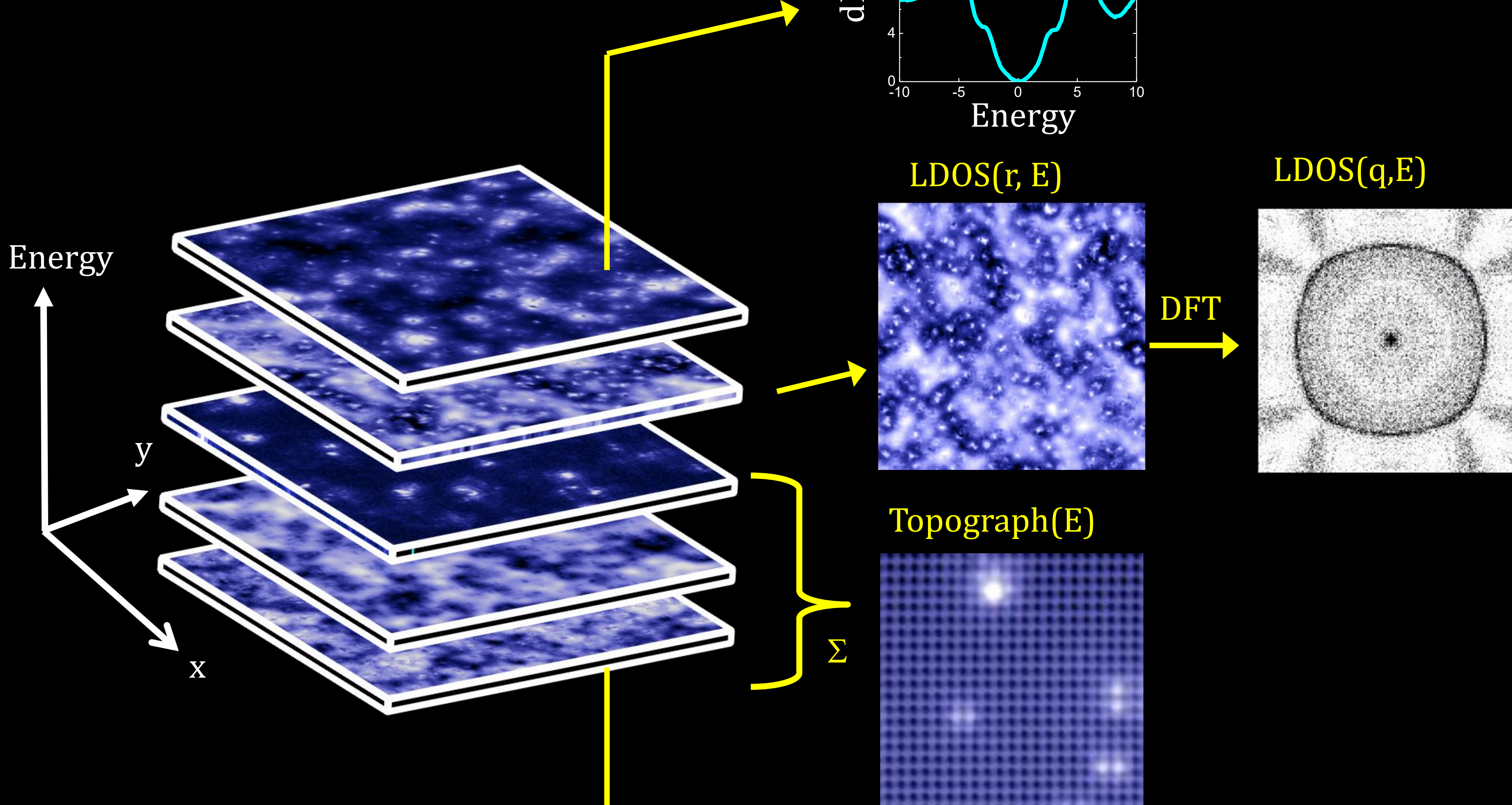


LiFeAs

Atomic Resolution Energy Resolved Images, LDOS(r,E)

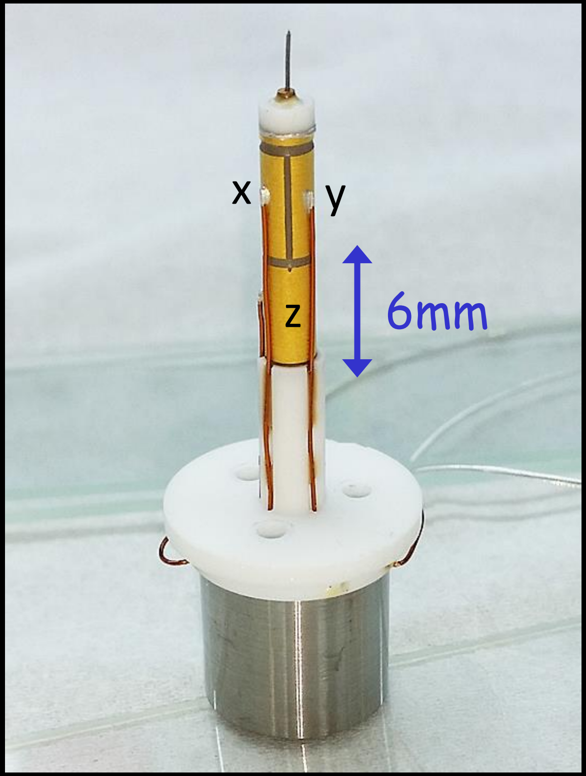
~5M dI/dV(r,E):
>50ms each with S/N~100
Total measurement > 72 hours
Requires < 10^{-15} m STM-tip vibration



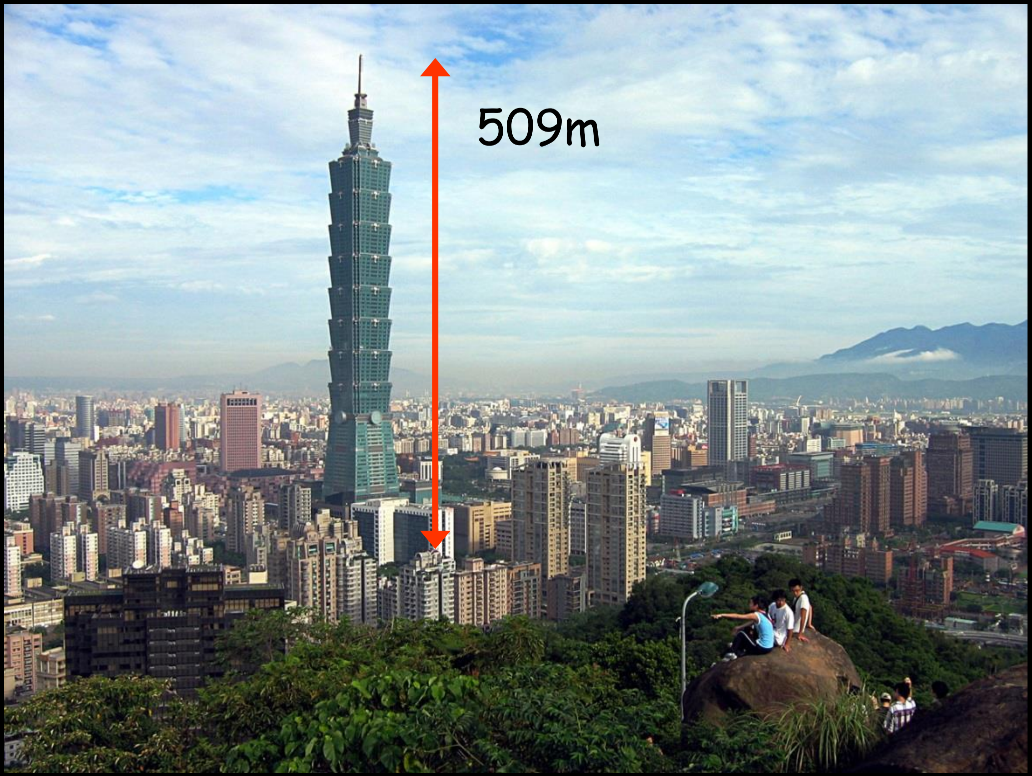


Our Resolution and Stability

STM Tip on Piezo Scanner



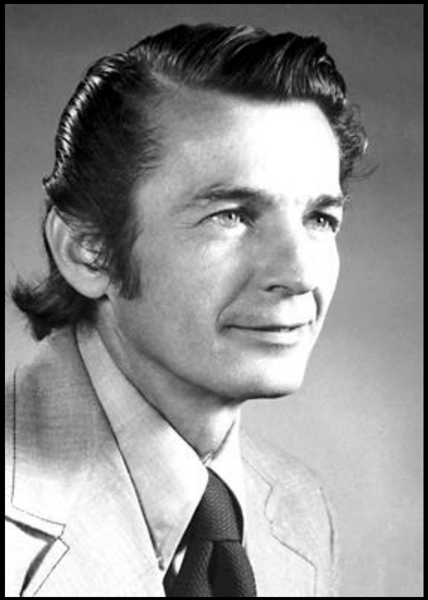
Taipei 101



@Wikipedia

0.5pm/6mm → 42nm/509m!

Ivar Giaever



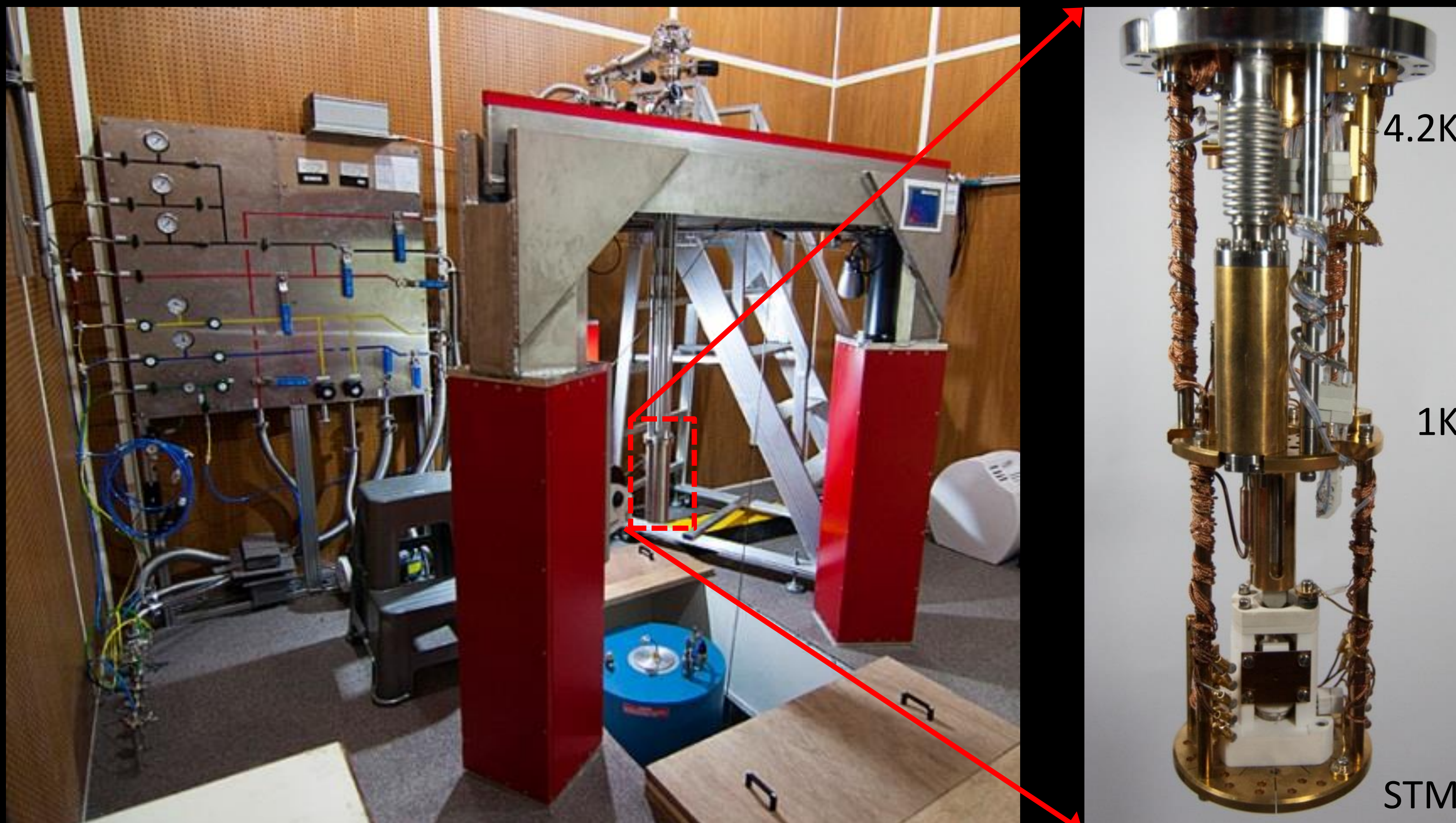
Nobel Prize 1973

The best way to do science is not to buy a big piece of expensive equipment and use it to do research. There are lots of other people who have the same big expensive equipment. The best way to do science is if you can make your own equipment, make your own thing.

- Ivar Giaever, BCS@50 Conference, 2007

1.6K-9Tesla Cryogenic UHV STM @ Academia Sinica

100% Homemade!



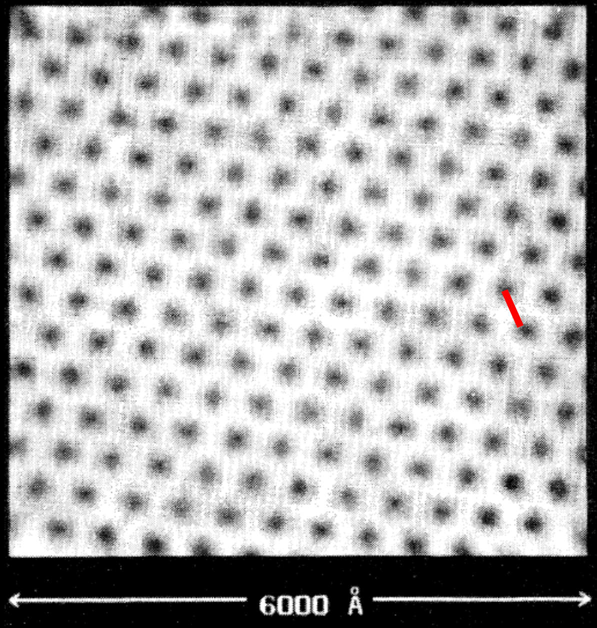
http://www.phys.sinica.edu.tw/~chuangtm/

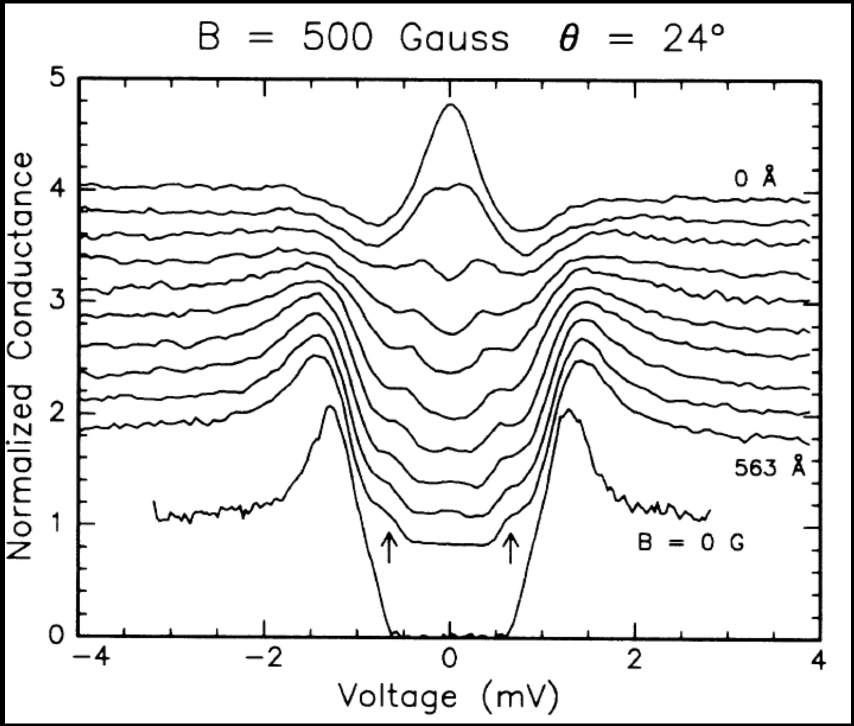
Vortex Imaging of $NbSe_2$ by STM

Harald F. Hess

© www.janelia.org

2H-$NbSe_2$: T_c = 7.1 K, T_{CDW} = 29 K



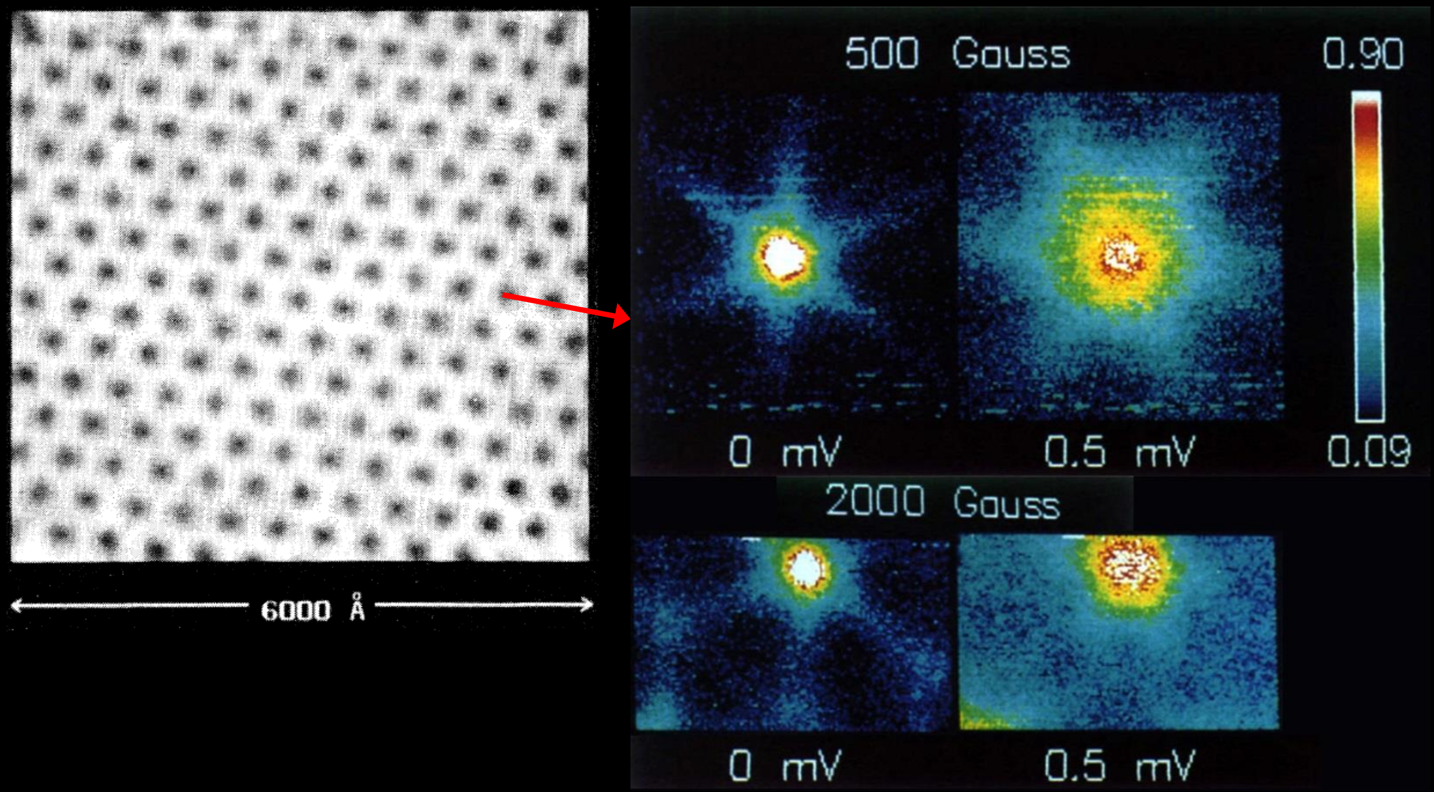


H. F. Hess *et al.*, PRL 62, 214 (1989).
H. F. Hess *et al.*, PRL 64, 2711 (1990).

Vortex Imaging of $NbSe_2$ by STM

Harald F. Hess

2H-$NbSe_2$: T_c = 7.1 K, T_{CDW} = 29 K

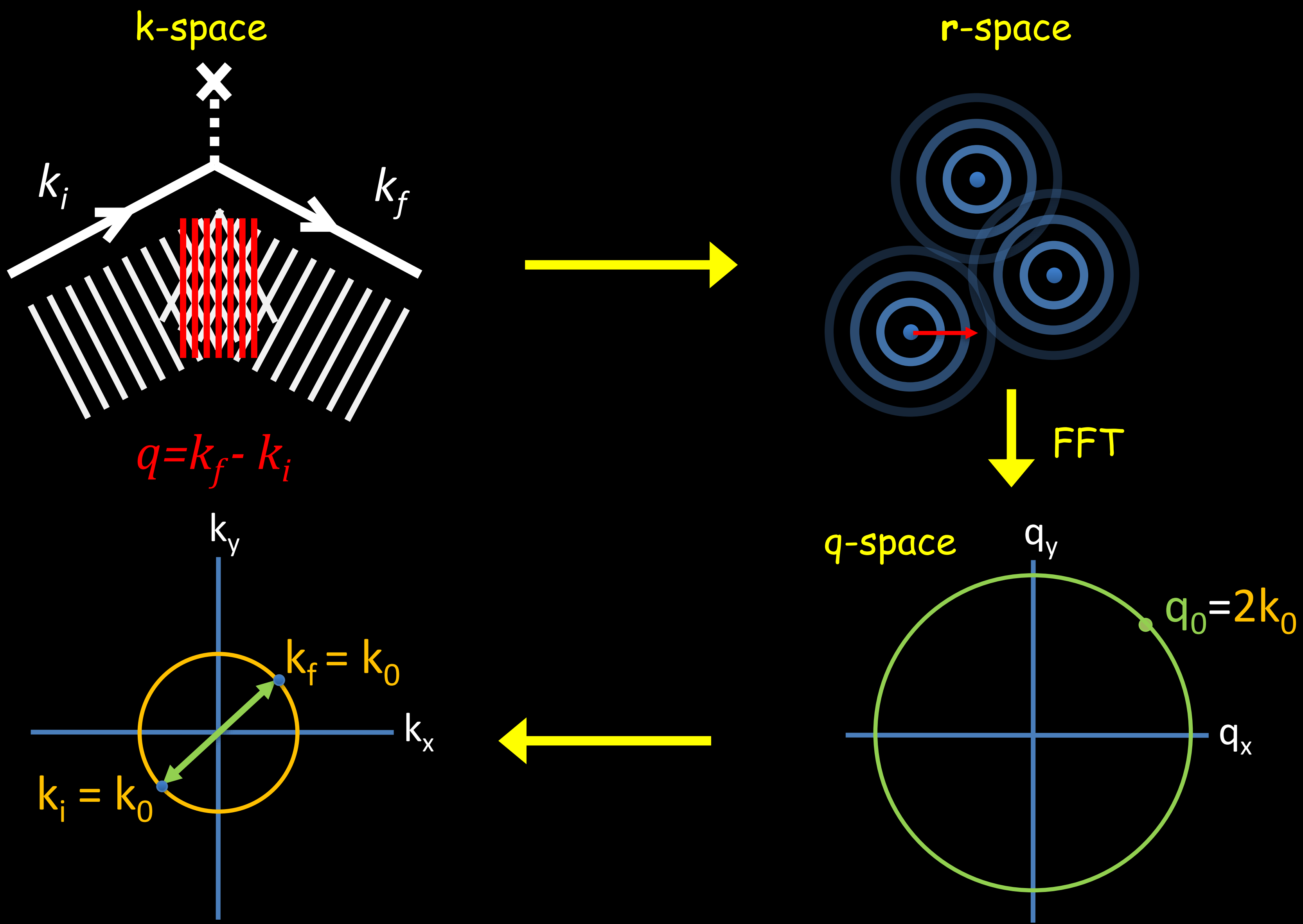


H. F. Hess *et al.*, PRL 62, 214 (1989).
H. F. Hess *et al.*, PRL 64, 2711 (1990).

Quasiparticle Scattering Interference (QPI)

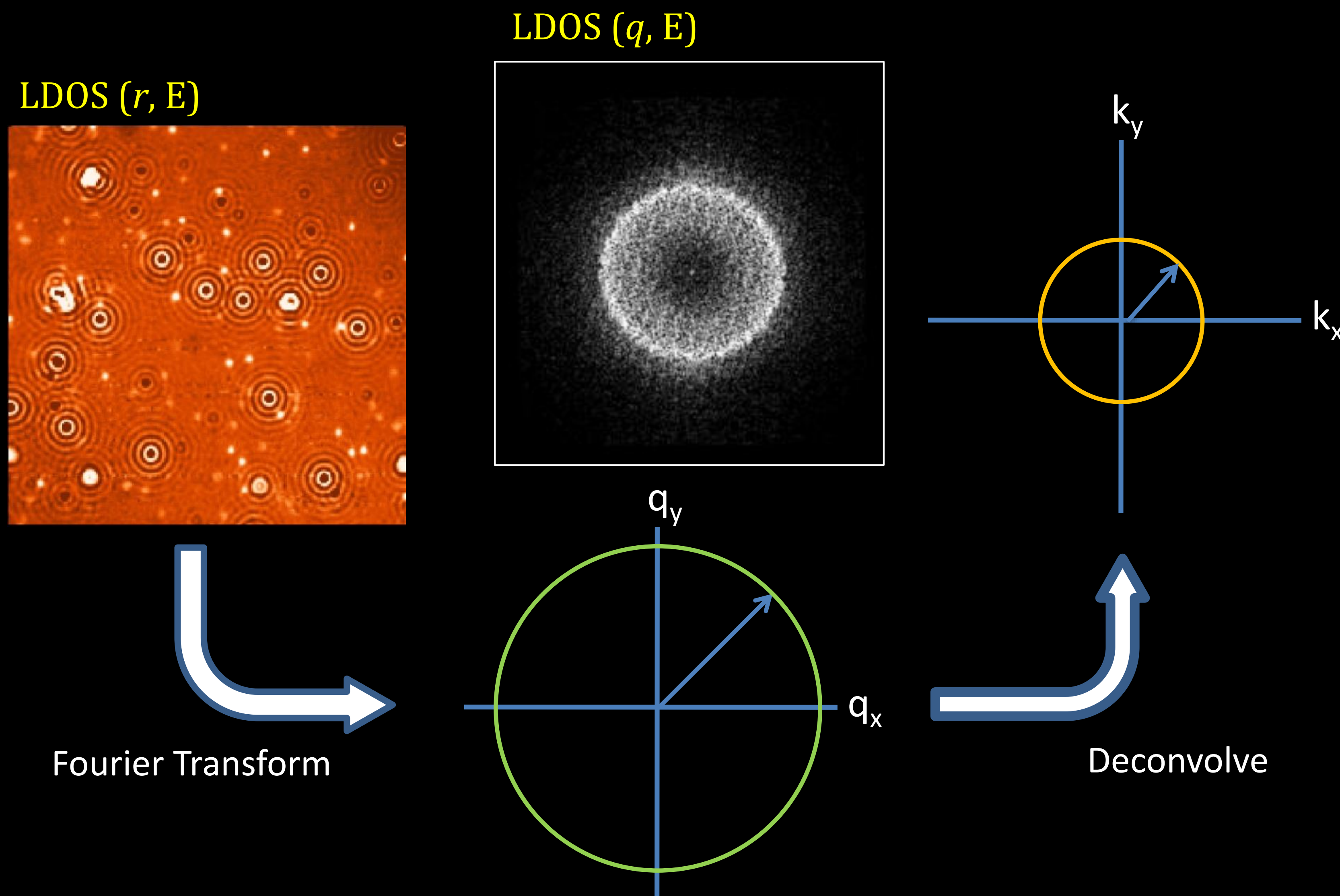
A path to determining momentum space structure by STM

Quasiparticle Scattering Interference (QPI)



Y. Hasegawa and Ph. Avouris, PRL 71, 1071 (1993).
M.F. Crommie *et al.*, Nature **363**, 524 (1993)

Inferring Band Structure from QPI

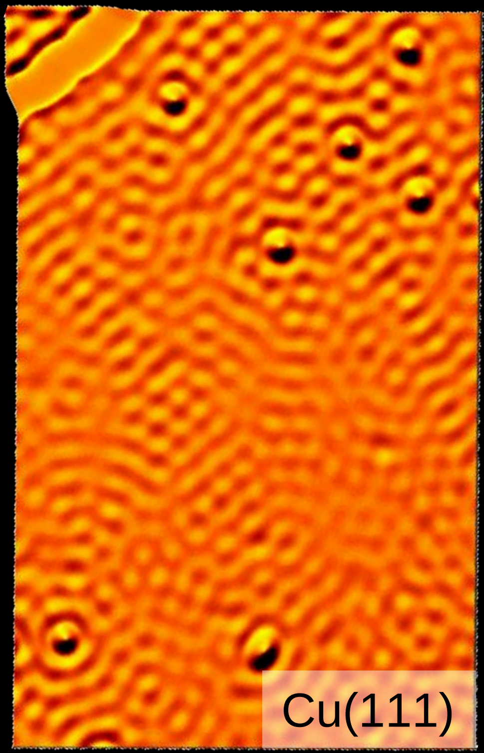


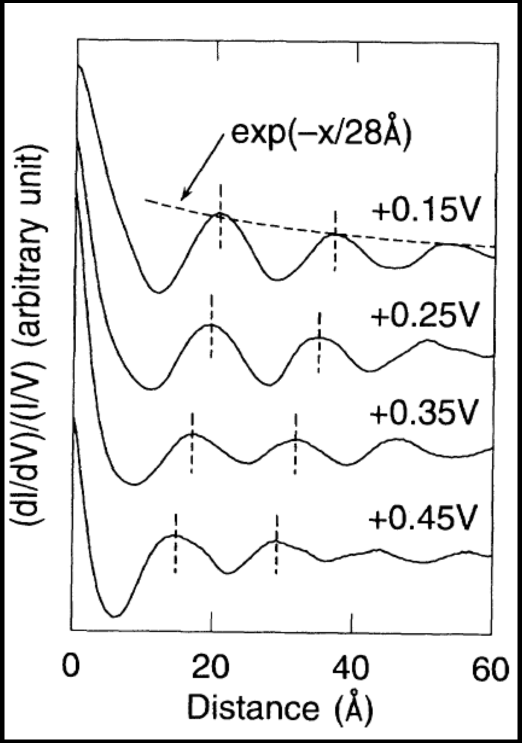
QPI on Simple Metals

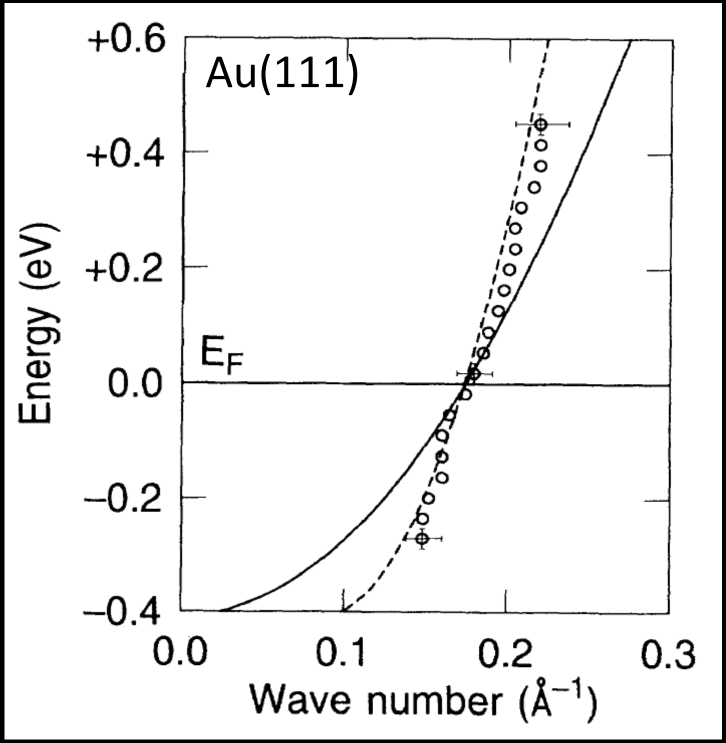
Landau quasiparticle standing waves at the surface of a 2D electron gas system.

Scattering off impurities and edges.

Dispersion relation of Bloch electrons







Y. Hasegawa and Ph. Avouris, PRL 71, 1071 (1993).
M.F. Crommie *et al.*, Nature **363**, 524 (1993)

Atomic Scale Visualization of Novel Materials by STM

Advantages:

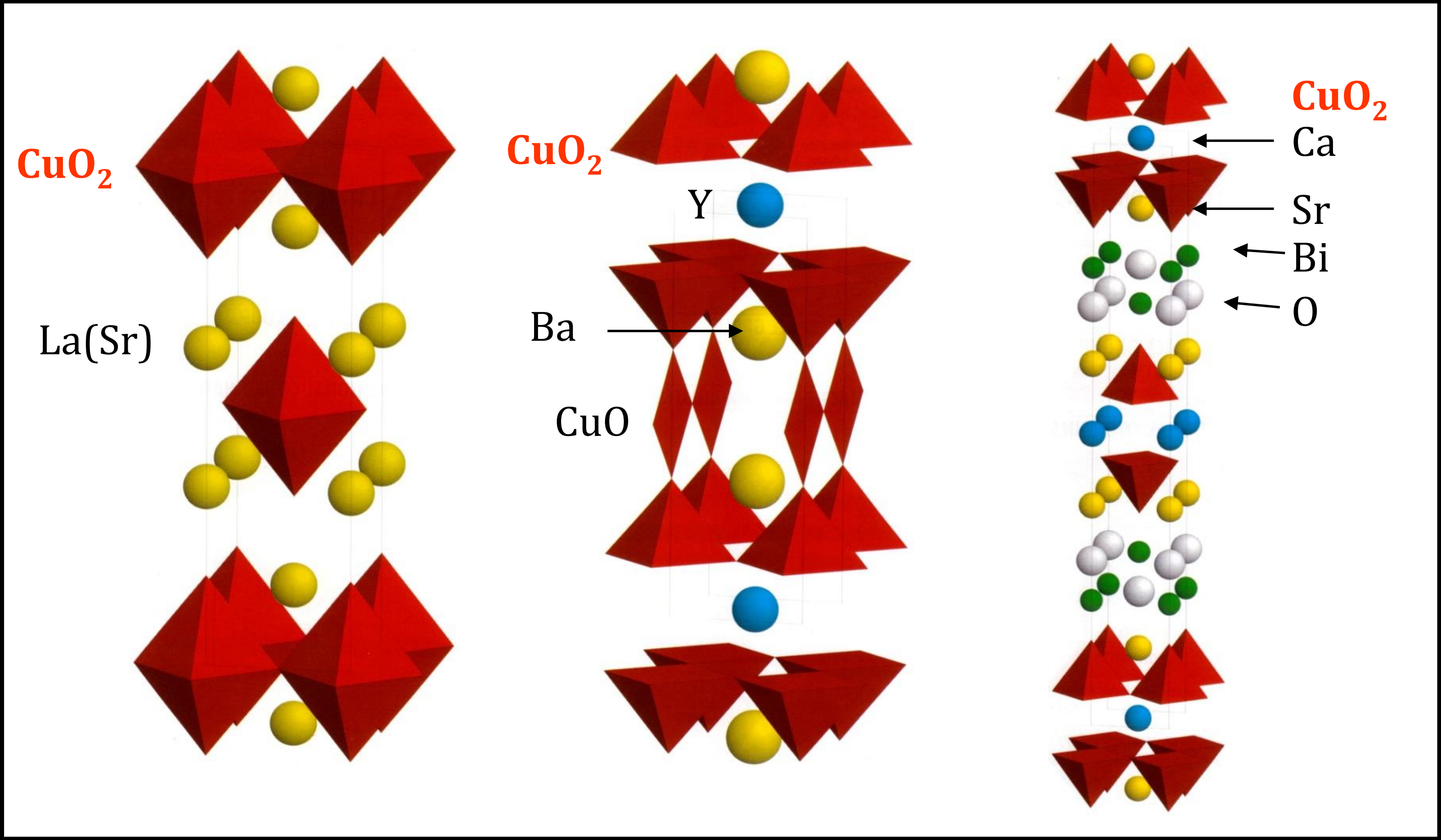
- Both occupied and empty states can be explored.
- Both real and momentum spaces can be explored.
- Magnetic-field compatible.
- Excellent energy resolution at low temperature

Disadvantages:

- Quasi-particle scatterers are necessary.
- Measurement takes VERY long time.

1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

High Tc Cuprate Superconductors (CuSC)



$La_{2-x}Sr_xCuO_4$
(LSCO)

(T_c^{max} ~ 40 K)

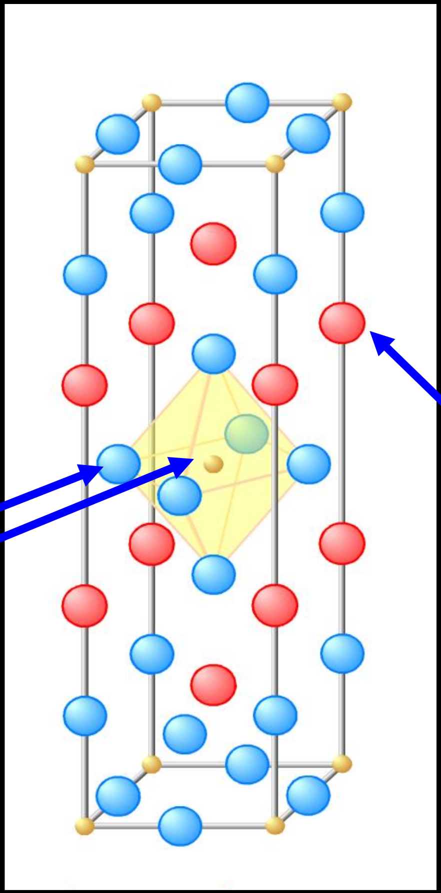
$YBa_2Cu_3O_y$
(YBCO)

(T_c^{max} ~ 93 K)

$Bi_2Sr_2CaCu_2O_y$
(Bi2212 or BSCCO)

(T_c^{max} ~ 95 K)

$La_{2-x}Ba_xCuO_4$

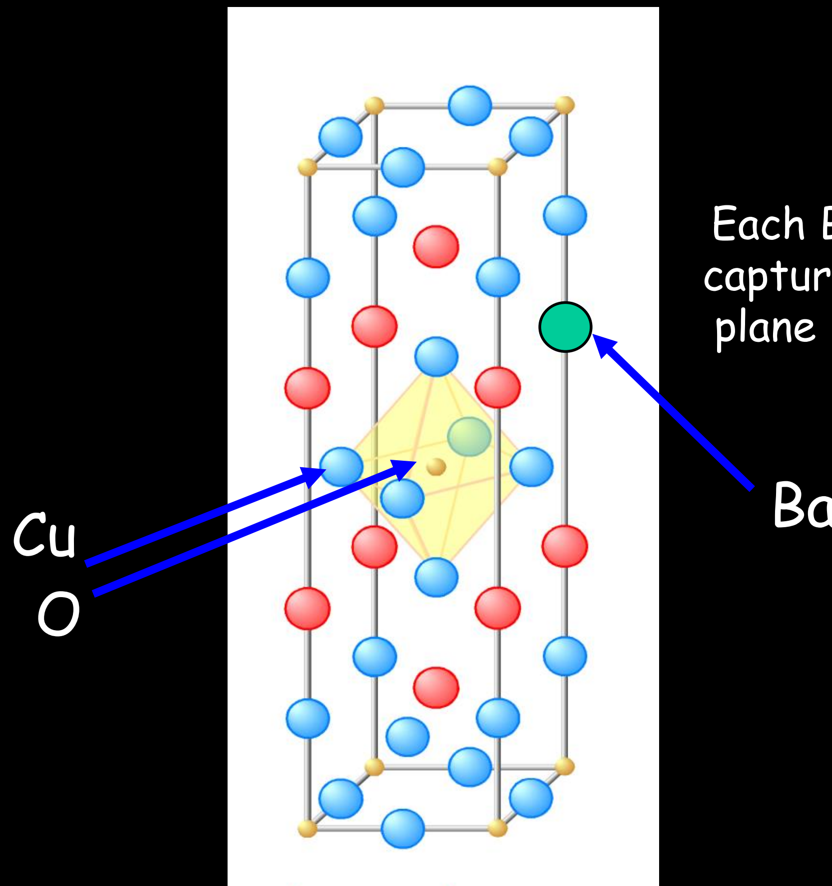


Antiferromagnetic

Mott Insulator

Z. Phys. Rev. **B** **64** 189 (1986)

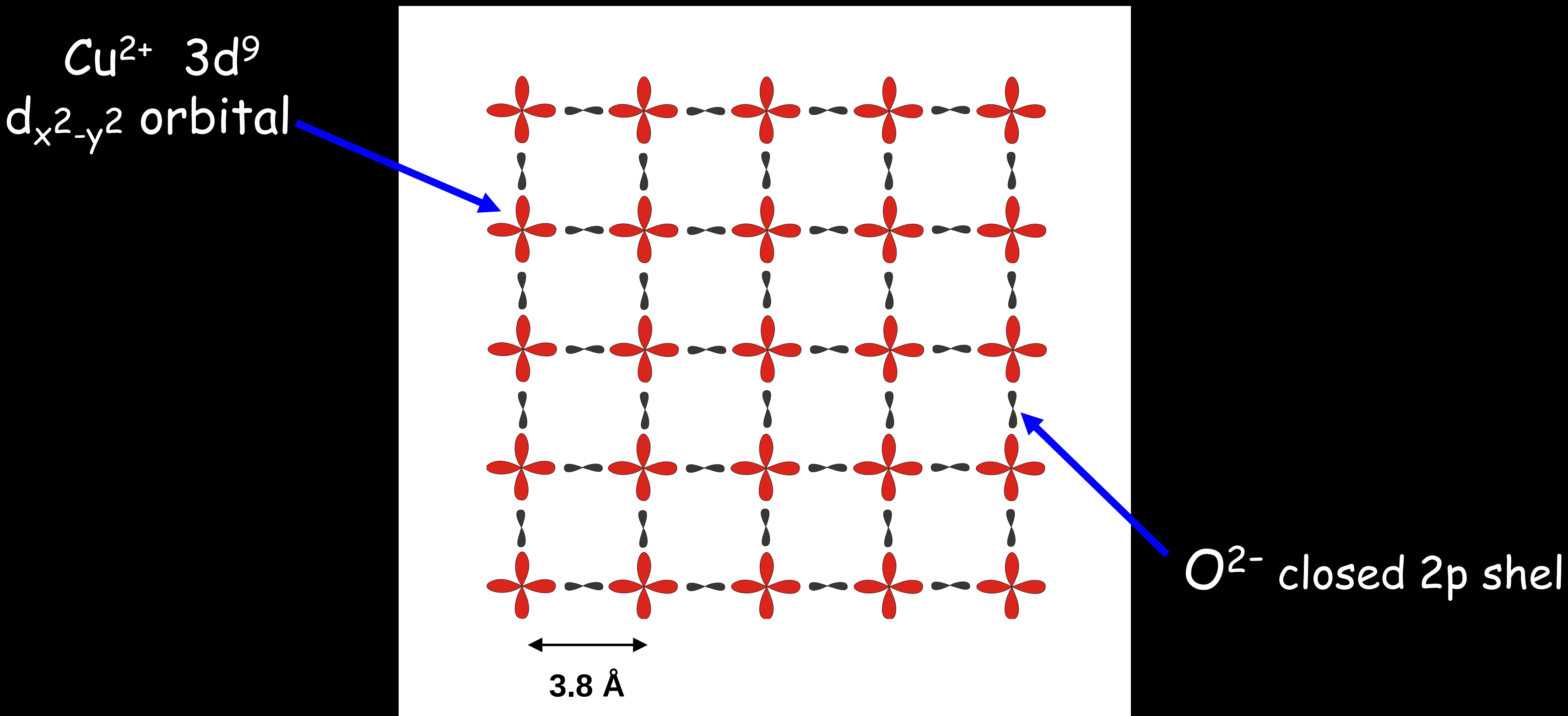
$La_{2-x}Ba_xCuO_4$

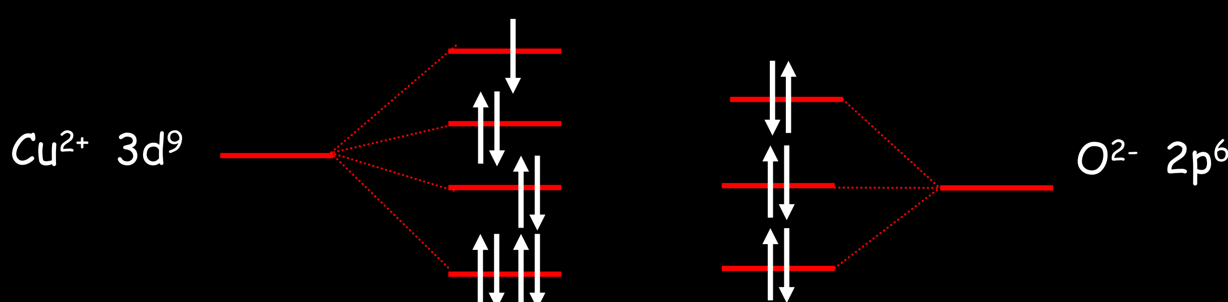


Each Ba atom substituted for Sr captures and electron from CuO_2 plane leaving *p* holes per unit cell

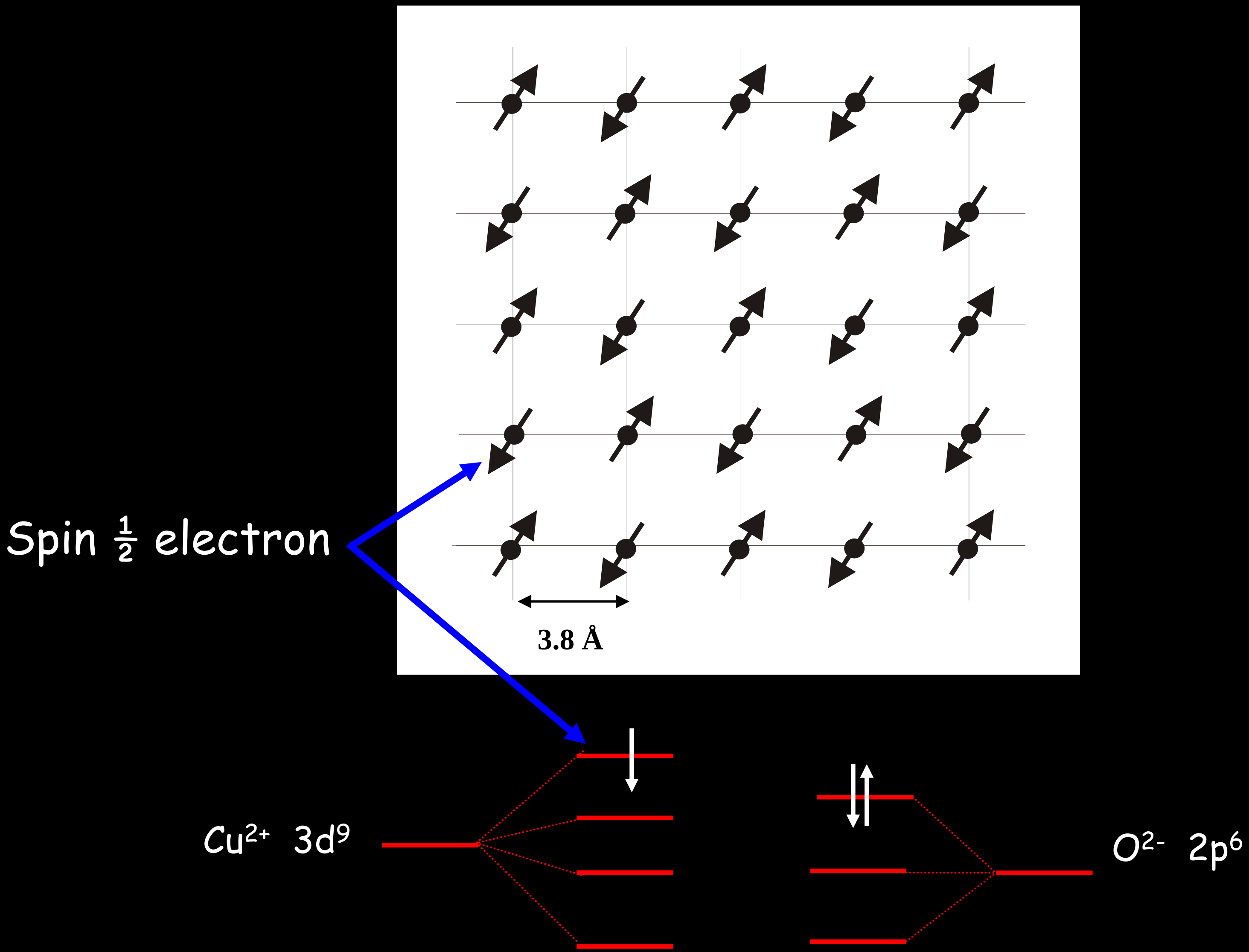
Z. Phys. Rev. **B 64** 189 (1986)

CuO_2: Charge transfer yields a Cu-$3d^9$ $d_{x^2-y^2}$ band

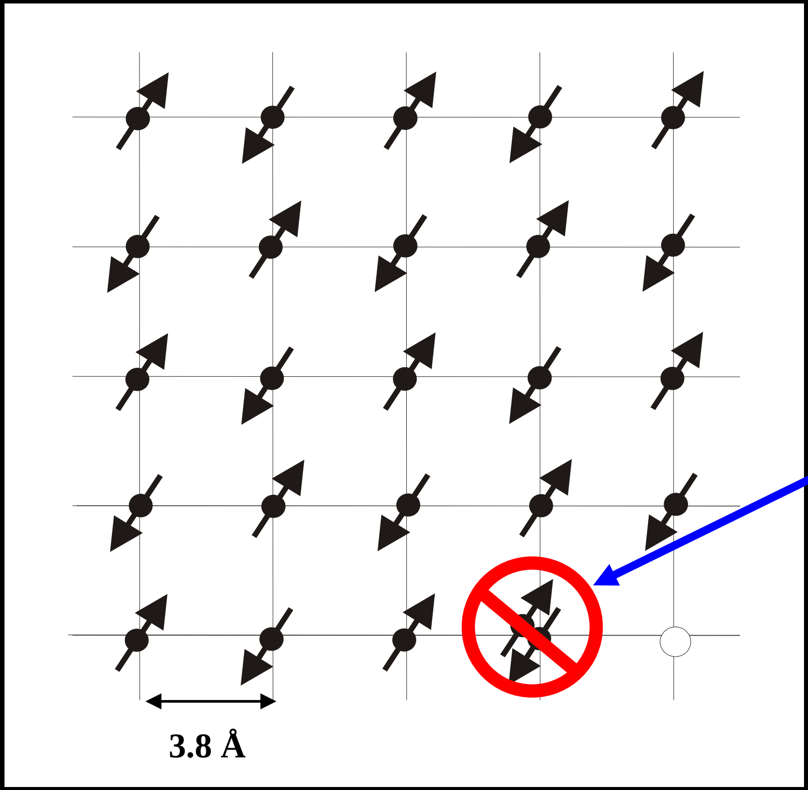




Half filling: Antiferromagnetic Mott Insulator



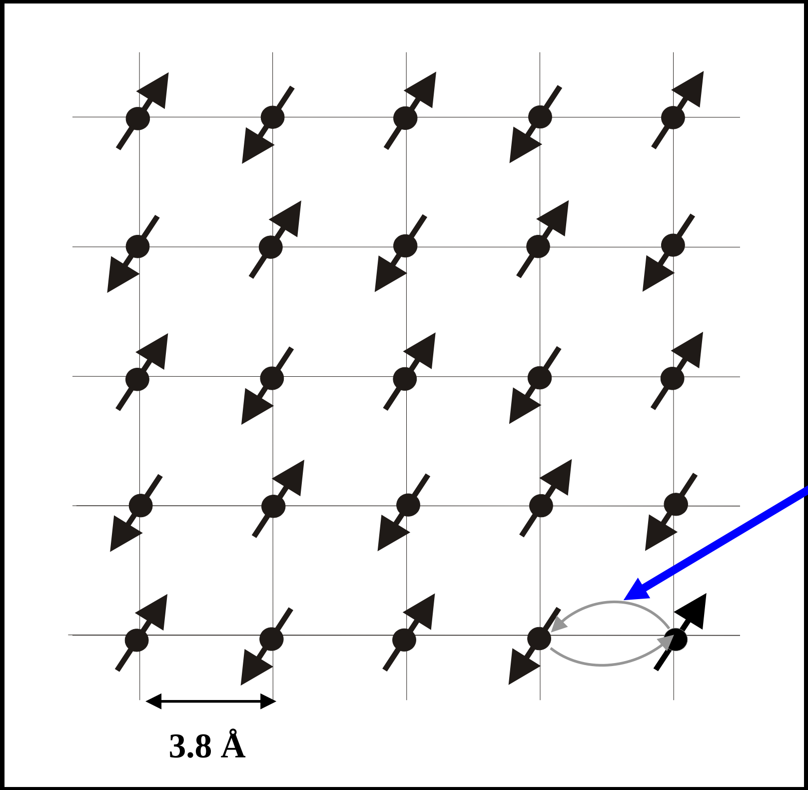
Mott Insulator: Repulsive Coulomb U~3eV



No double occupancy allowed..

N.F. Mott, ***Proc. Phys. Soc A62***, 416 (1949)

Antiferromagnetic: Superexchange J~0.14eV

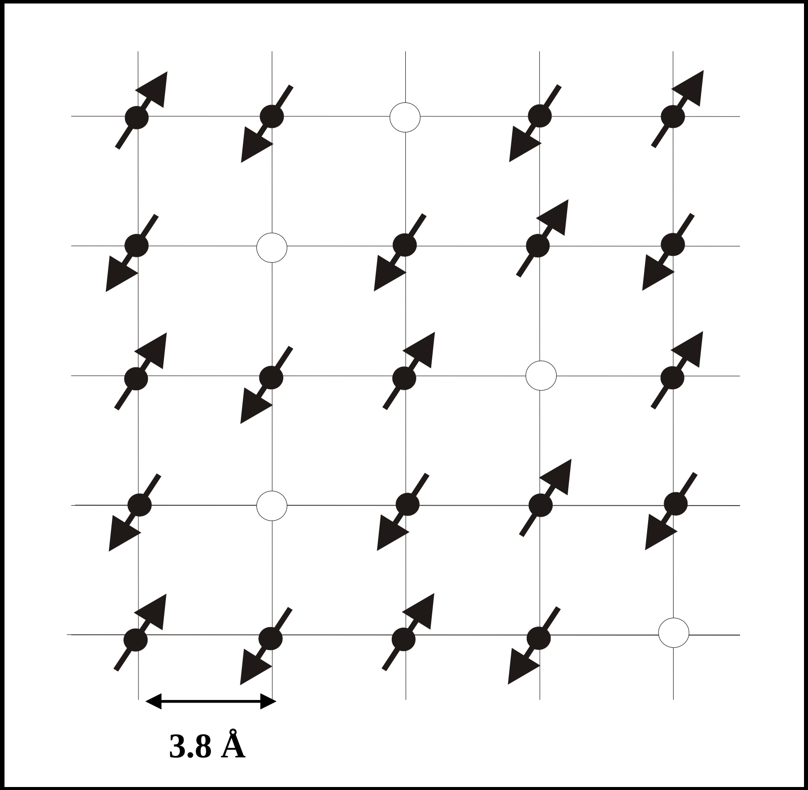


..except as a virtual process.

$$H = \frac{4t^2}{U}\sum_{<i,j>}\vec{S}_i \bullet \vec{S}_j - \frac{1}{4}n_i n_j$$

P. W. Anderson, ***Phys. Rev. 115***, 2 (1959)

Holes introduced $\Longrightarrow$ carriers become mobile

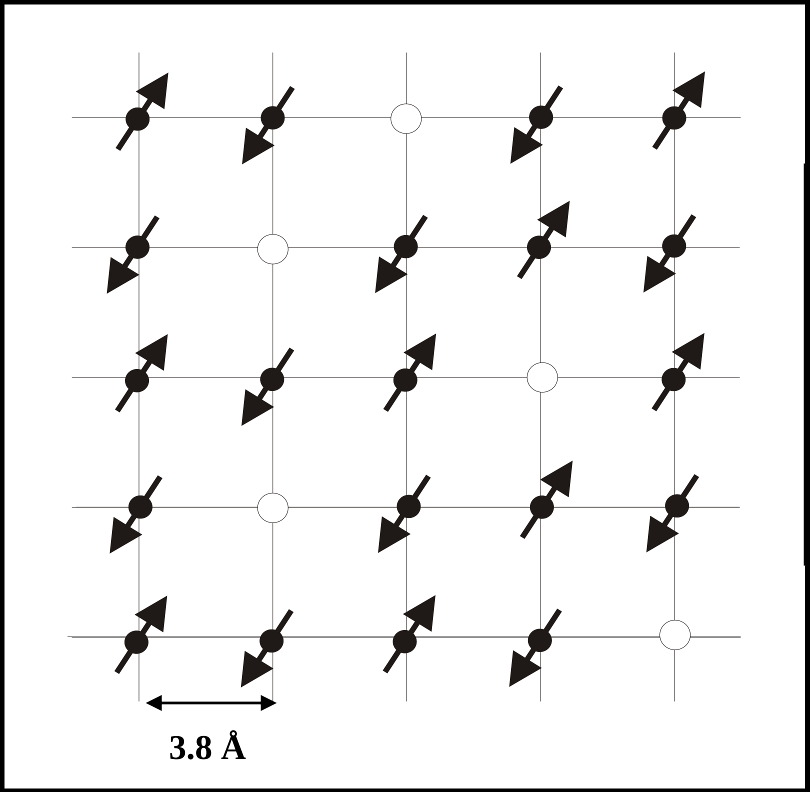


Dopant density p
= number of holes
per CuO_2 plaquette

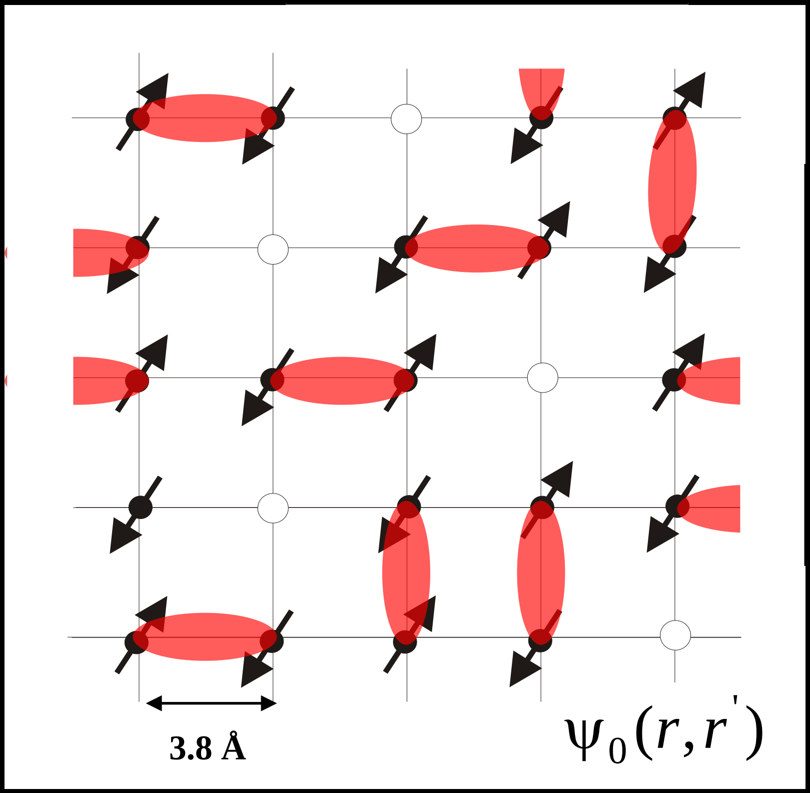
$$H = -t \sum_{<i,j>} (c_{i\sigma}^{\dagger} c_{j\sigma} + h.c.) \quad + \quad U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

J. Hubbard, ***Proc. Roy. Soc A276***, 238 (1963)

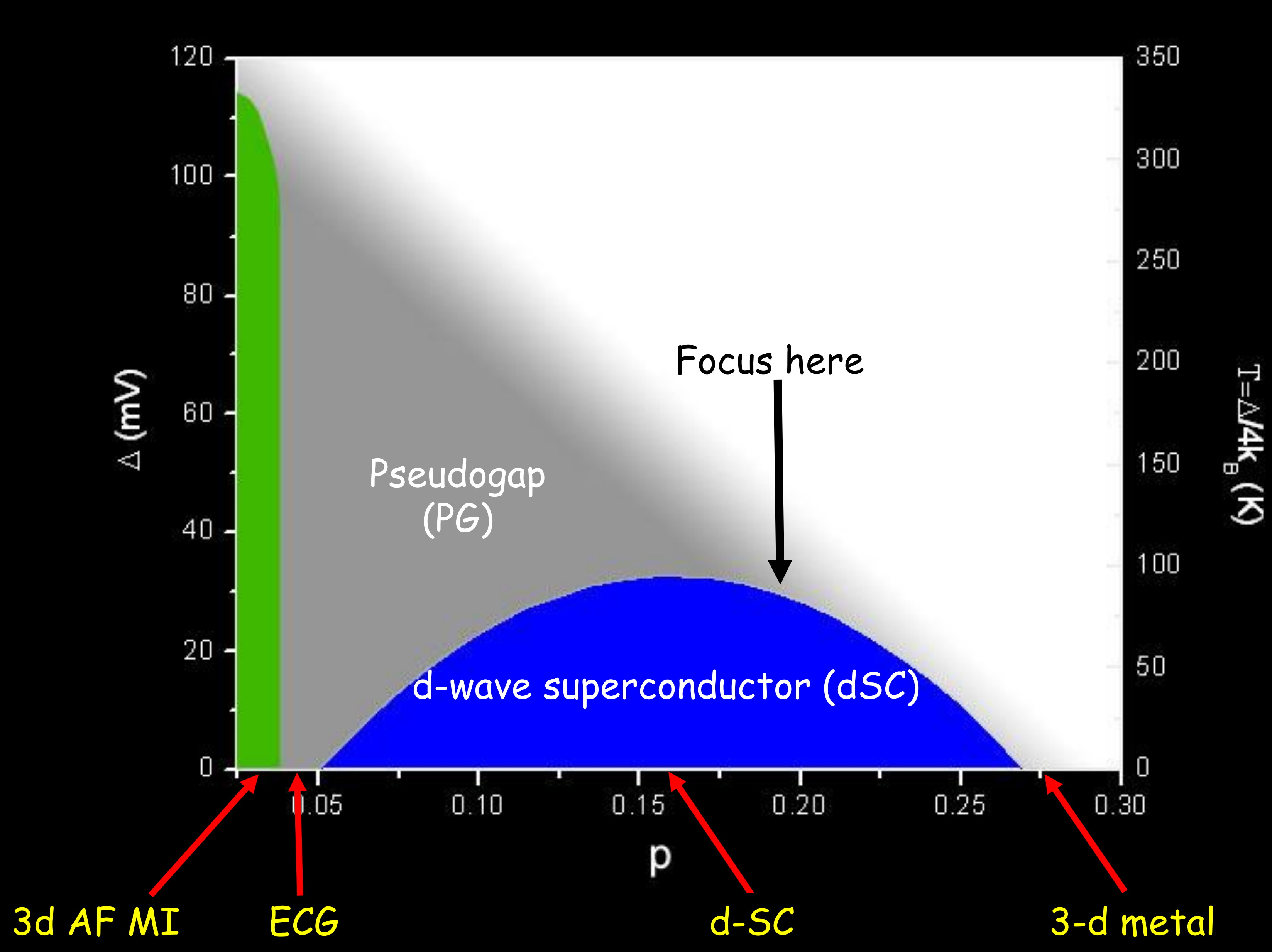
How could this state become superconducting?



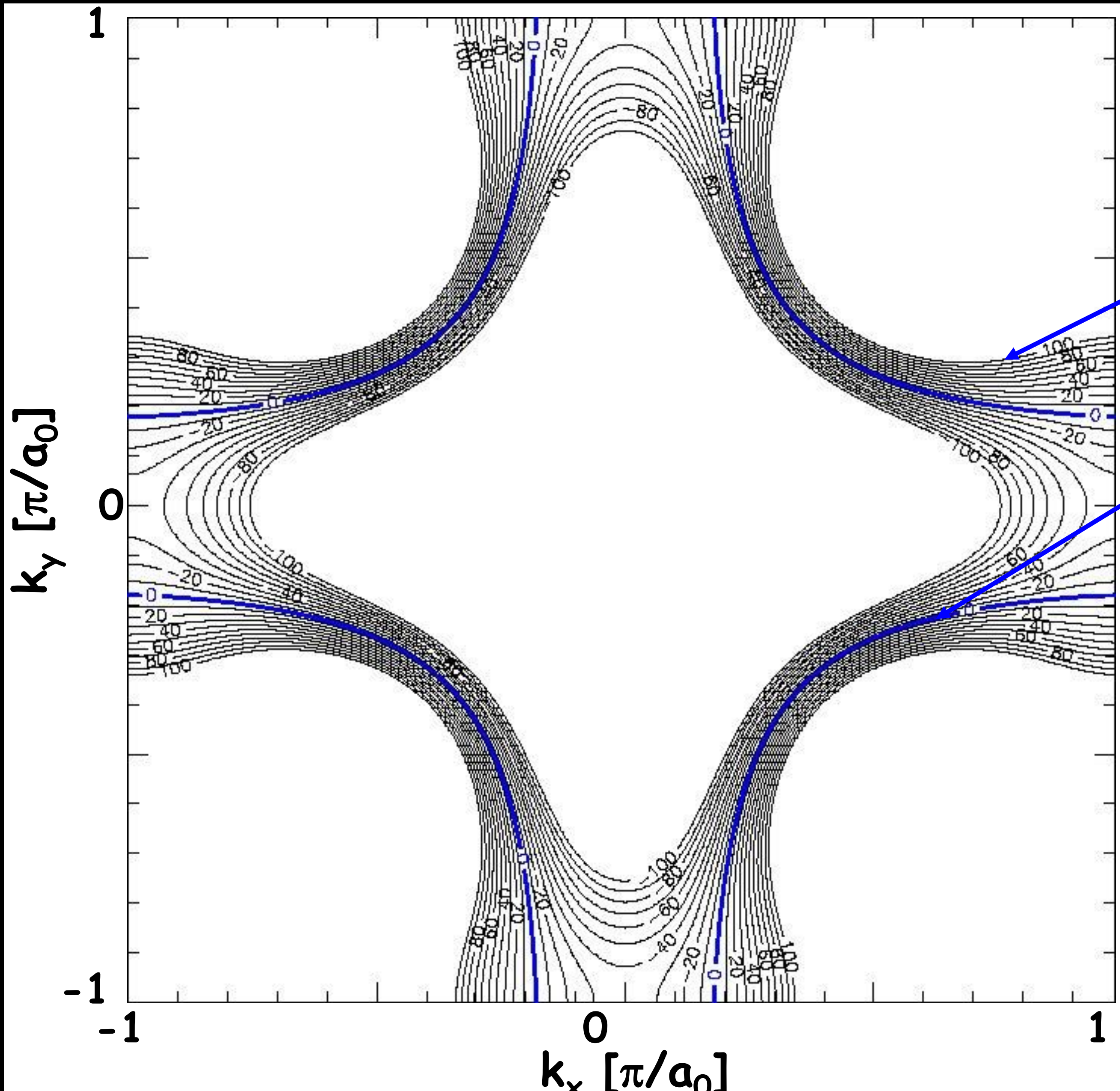
How could this state become superconducting?



Schematic Phase Diagram of Hole-doped Cuprates



Normal State Band Structure

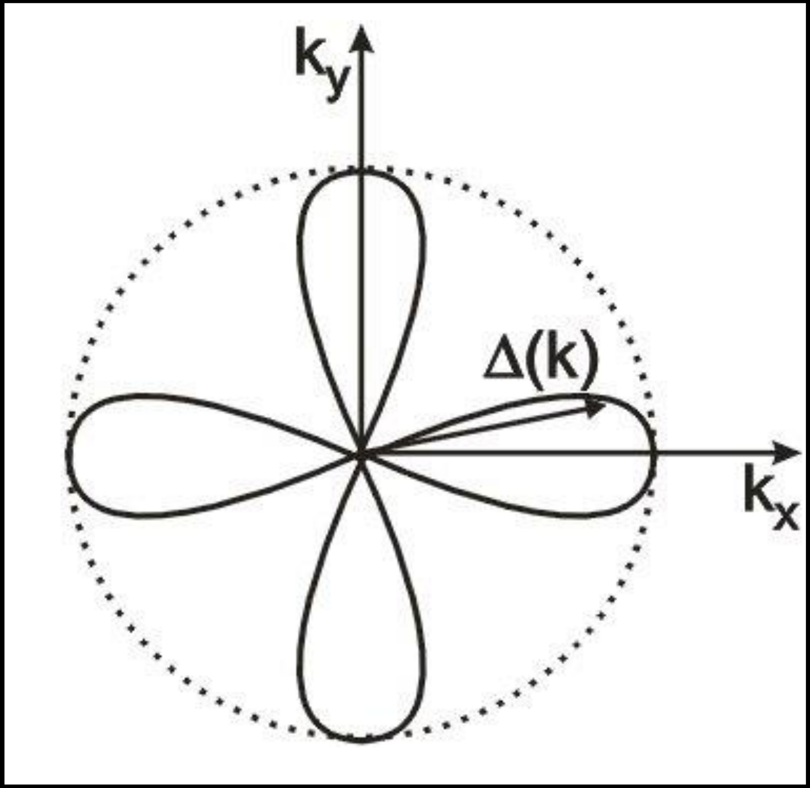


CEC (E): The location in k-space of states with energy E

Fermi Surface CCE(0)

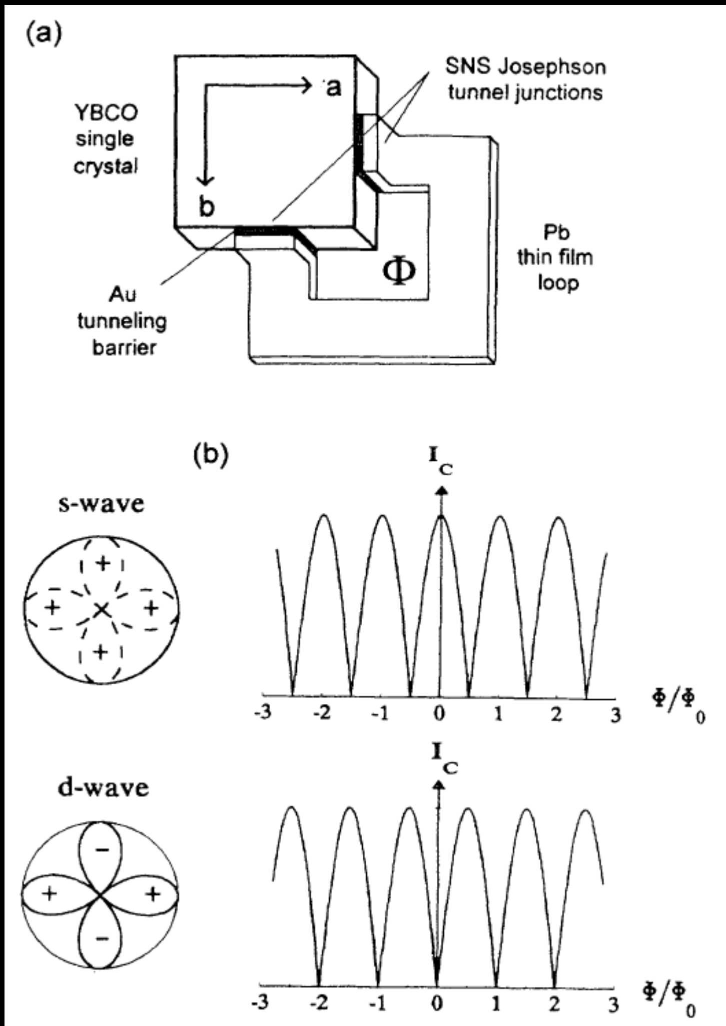
Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

The SC energy gap, $\Delta(\boldsymbol{k})$ has four nodes.

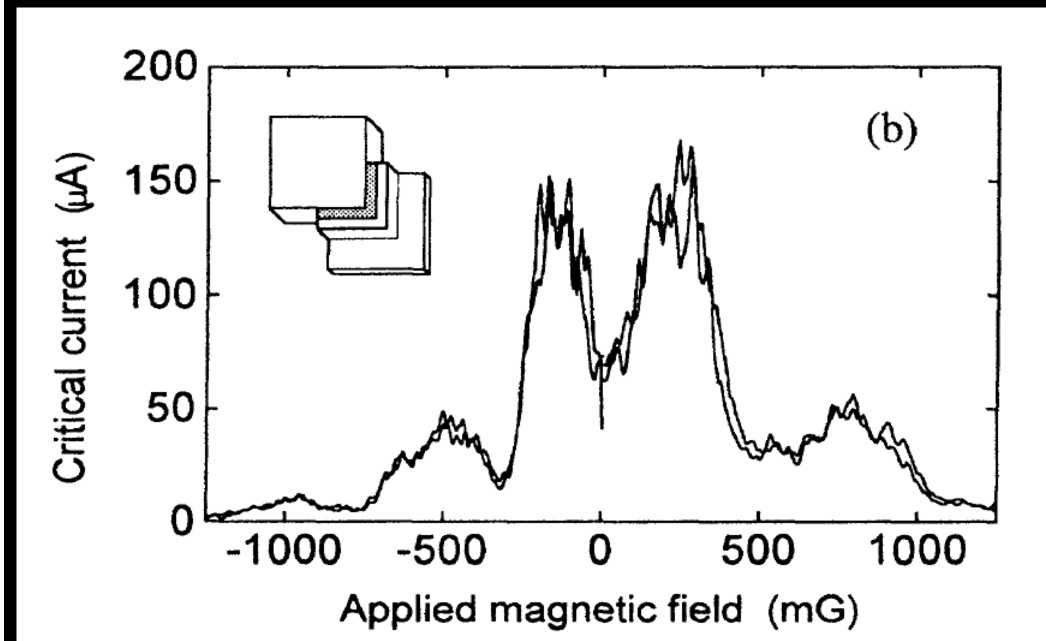


Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

DC SQUID



$$I_c(\Phi,\gamma) = J_0 A \left| \frac{\sqrt{\sin^2(\gamma\pi\Phi/\Phi_0) + [\cos(\pi\Phi/\Phi_0) - \cos(\gamma\pi\Phi/\Phi_0)]^2}}{\pi(\Phi/\Phi_0)} \right|$$



D. A. Wollman *et al.*, PRL 71, 2134 (1993)
D. A. Wollman *et al.*, PRL 74, 797 (1995)

Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

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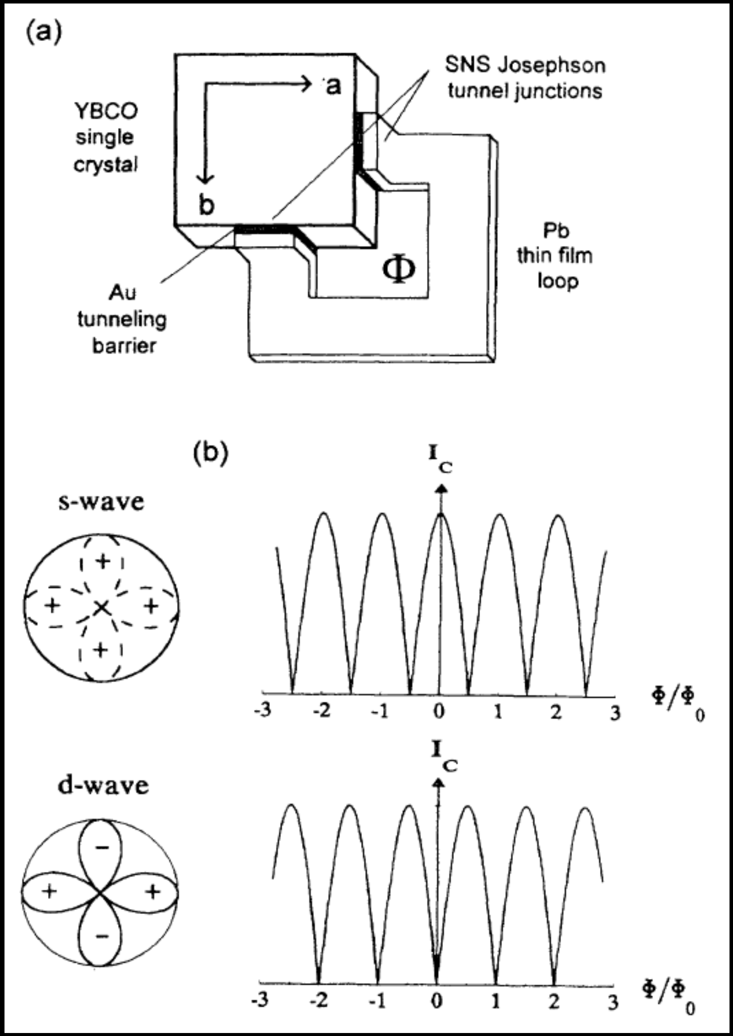
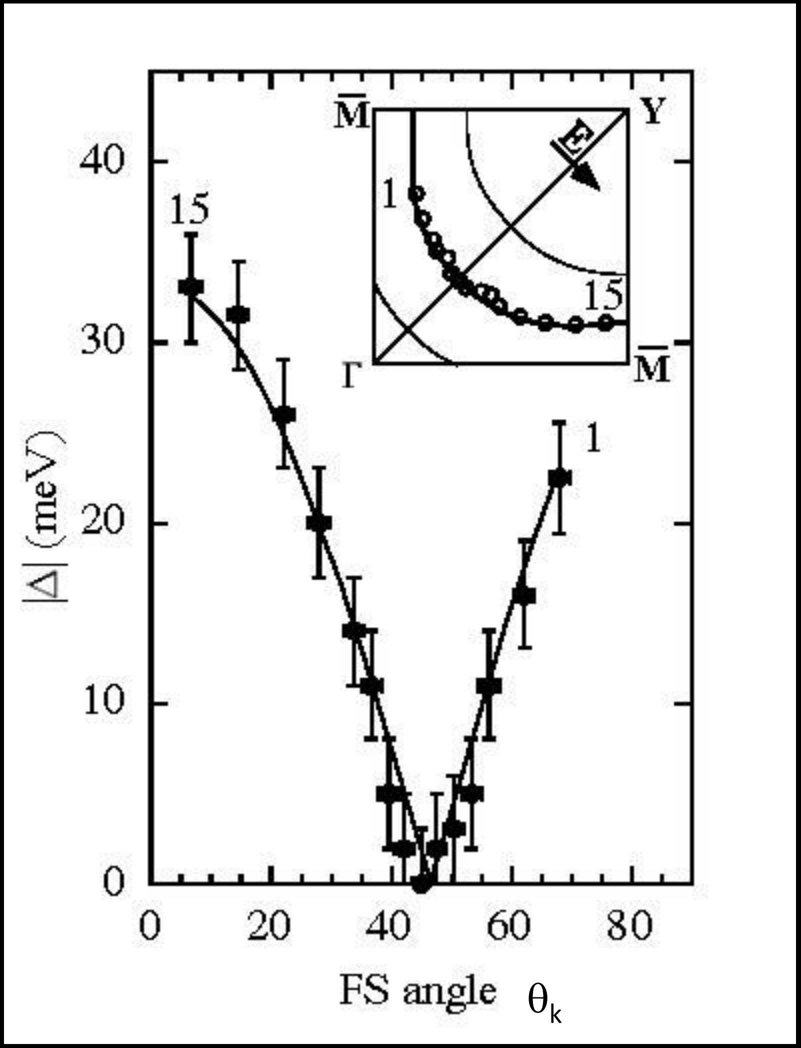


D. A. Wollman *et al.*, PRL 71, 2134 (1993)
D. A. Wollman *et al.*, PRL 74, 797 (1995)

ARPES



H. Ding *et al.*, PRB 54, 9678 (1996)
J. Mesot *et al.*, PRL 83, 840 (1999)