Superconductivity over a century

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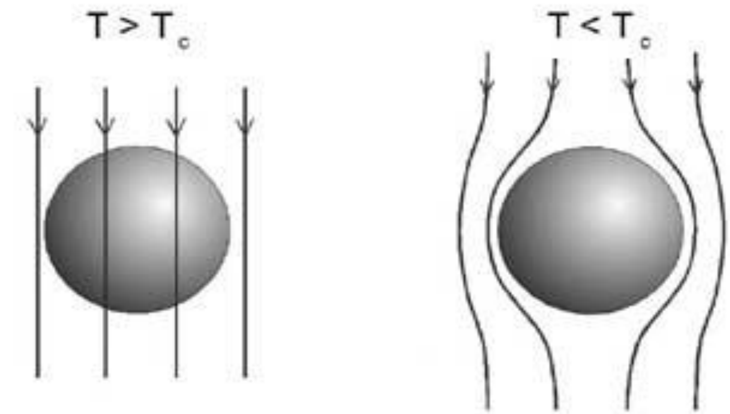
- **Introduction**
- **Conventional superconductor**
- **High temperature superconductivity**
- **Recent development, chiral p-wave and topological superconductor**

Colloquium at National Tsinghua Univ., June 5 , 2013

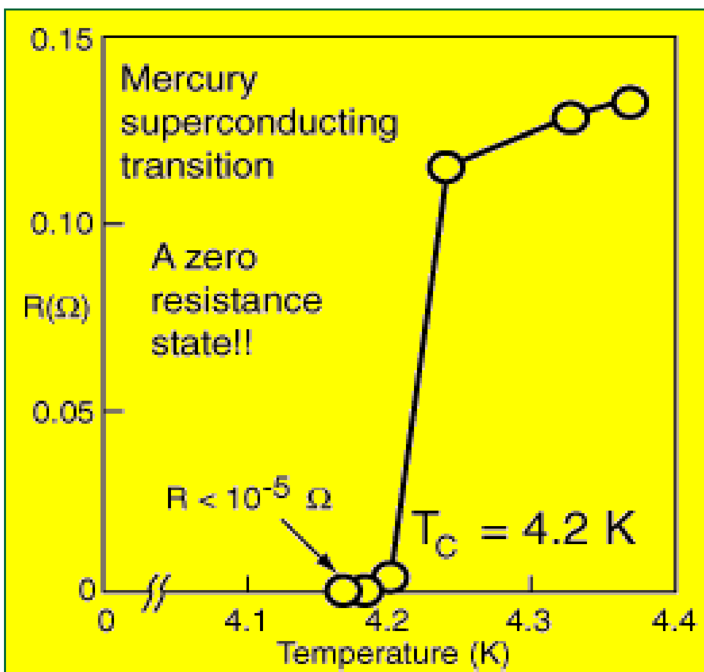
Superconductivity

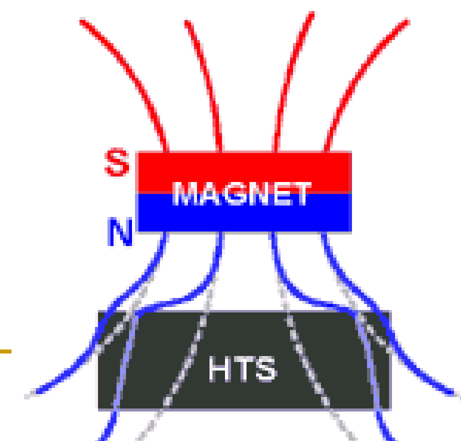
(Onnes,1911)

Meissner effect (1930's): Repel magnetic field

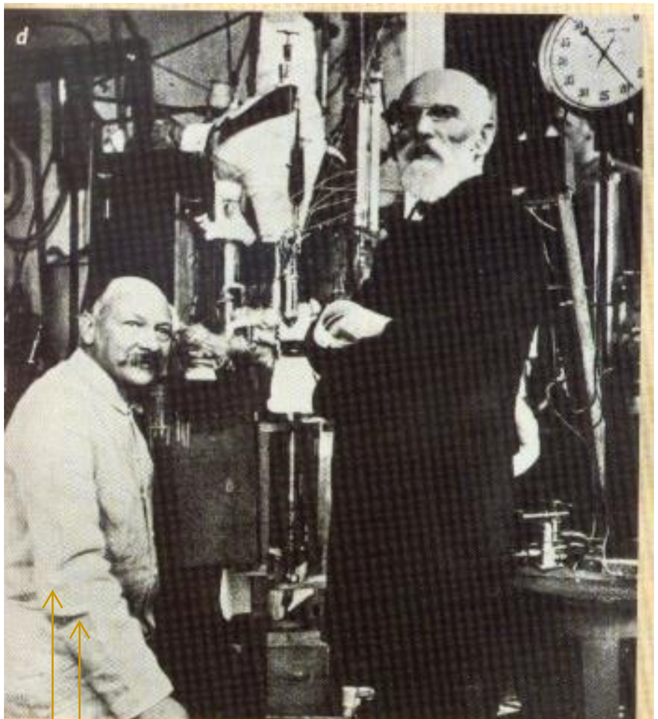


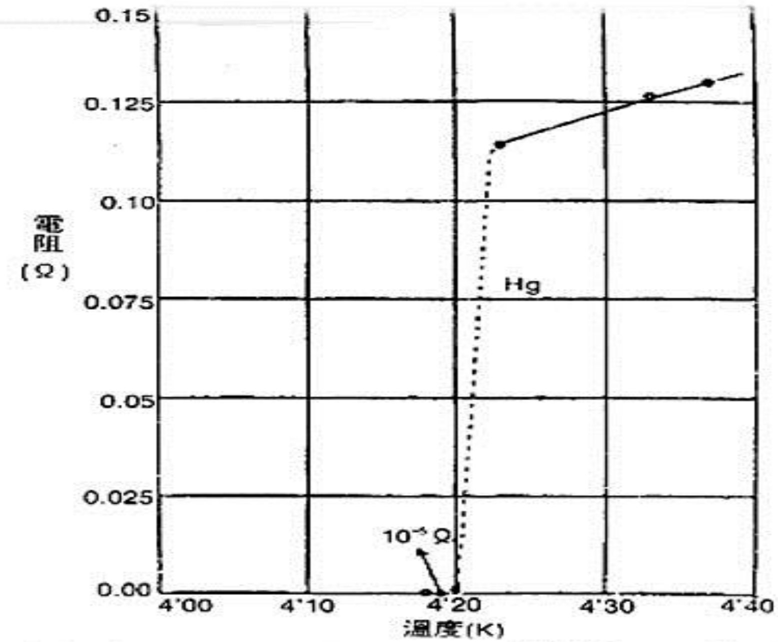
Zero electric resistance





Discovery of superconductivity, 1911



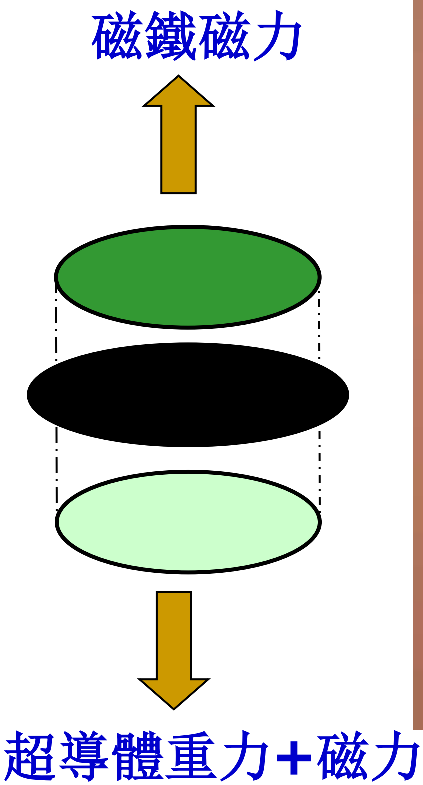


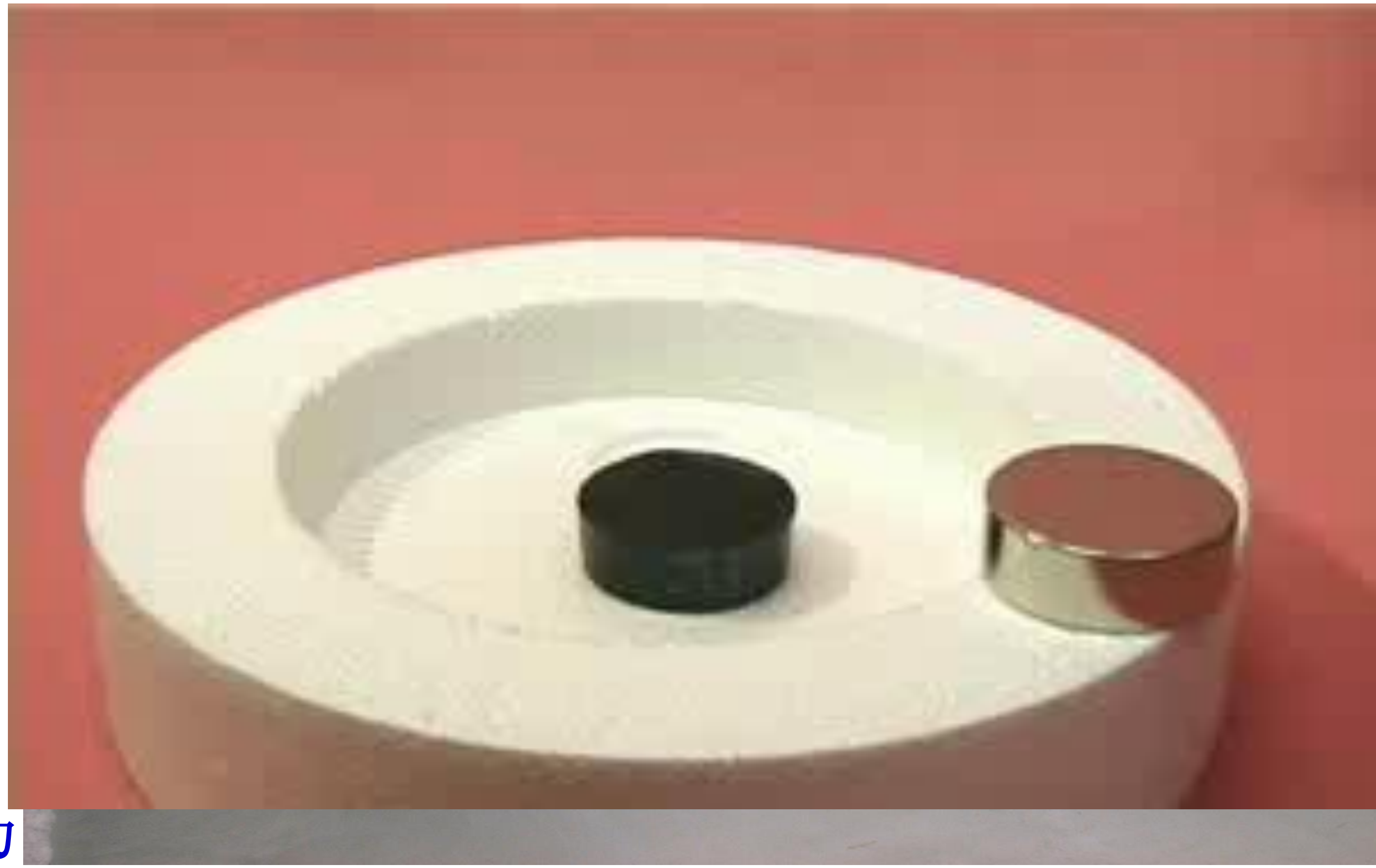
超導態首次發現:
Kamerlingh-Onnes測量汞的低溫電阻數據

1913 Nobel prize in Physics

for "his investigations on the properties of matter at low temperatures which led, inter alia, to the production of ***liquid helium".***

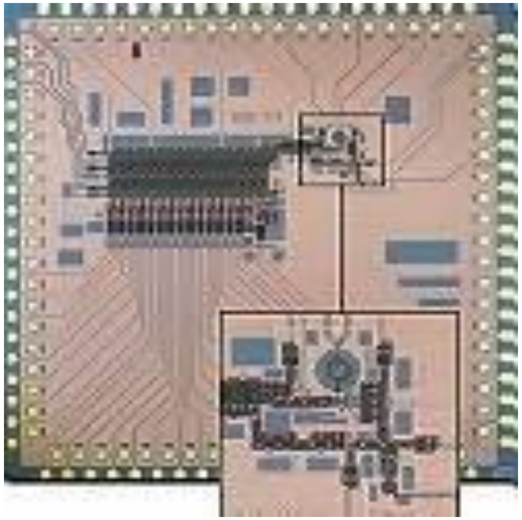
Meissner Effect





Applications of Superconductors

Magnetic-Levitation Train



Superconducting Microchip

Power transportation
No heat, no energy cost

Superconductivity: once mysterious phenomenon

- A quantum phenomenon
- Need also new concept:

  Spontaneous symmetry broken

  Cooper pairs & BCS theory
- New challenges

  - high temperature superconductivity

  - other unconventional superconductivity (topological superconductor)

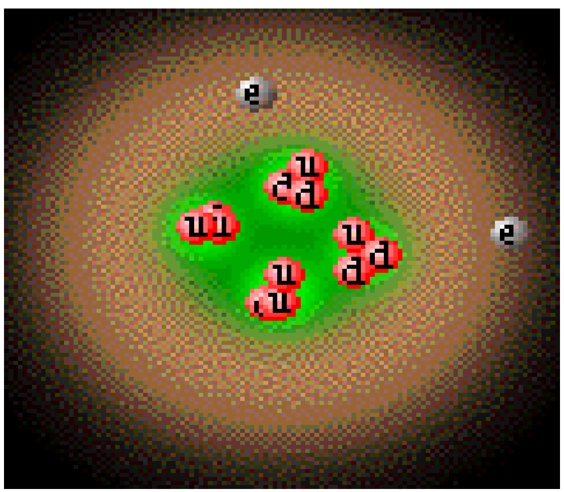
Two kinds of identical particles

Fermions

(spin 1/2, 3/2, 5/2, etc.)

- Cannot occupy the same state
- Pauli exclusion principle

Antisocial



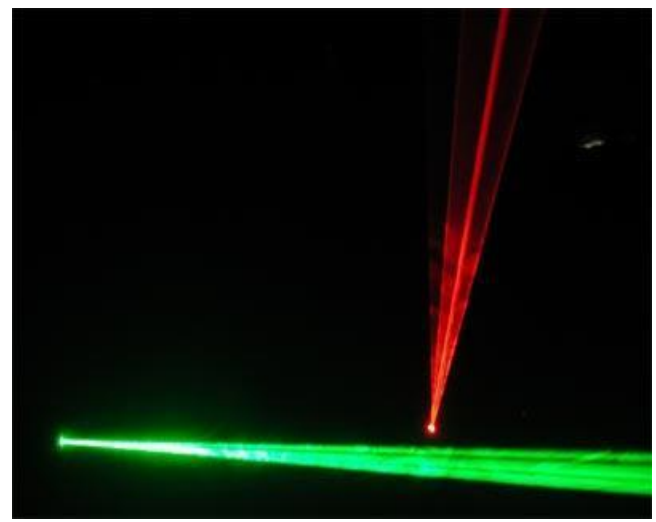
Electrons are Fermions

Bosons

(spin 0, 1, 2, etc.)

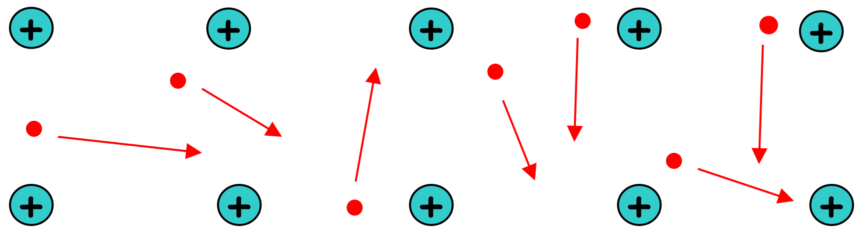
- Can occupy the same space at the same time

All Follow the Crowd



Photons are bosons → lasers

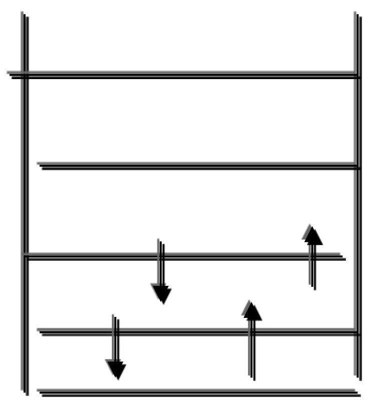
Basics of Condensed Matter Physics



Quantum Mechanics

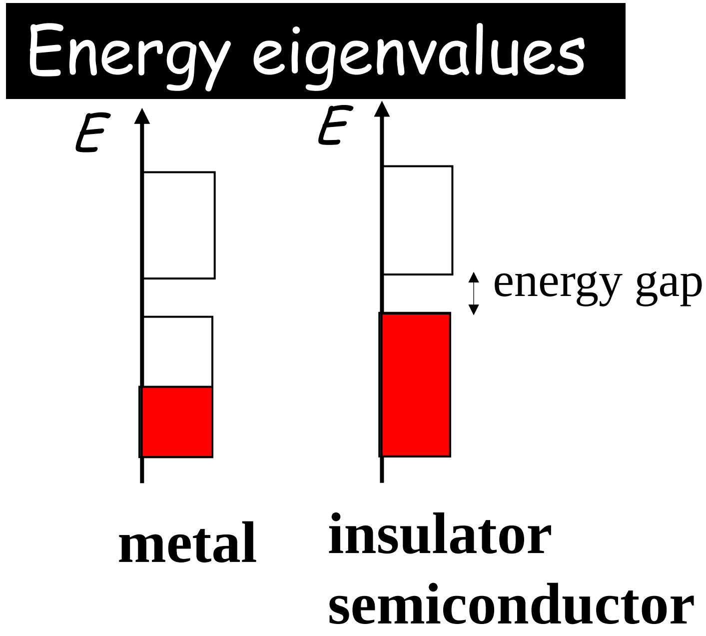
Electrons, Ions and Coulomb-interaction:

Fermi surface



Band picture - electrons in momentum space

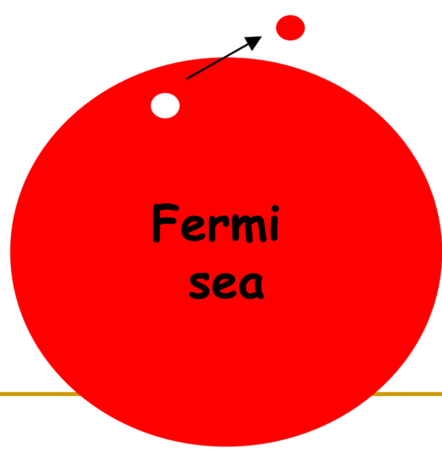
- **Odd number of electrons/unit cell**
  --- metal
- **Even number of electrons/unit cell,**
  --- can be insulator or semiconductor



Independent electron picture

-- Landau's Fermi liquid (1956)

For interacting fermion system, low energy excitations are quasi-particles, similar to free fermions.



Spontaneous symmetry broken

- Order parameters

Order parameter in magnetism

A magnet, all spins up or all down, symmetric.

The state: all spins up, breaks symmetry

Laws symmetric respect to matter & anti-matter

The Nature: matter rather than anti-matter

- Superconducting state:

Complex order parameter |\Psi|exp(i\phi)

- Phenomenological theory for superconductivity: Ginzburg-Landau theory (1950's) – 1/3 Nobel prize in 2003

Theory for conventional superconductivity

Bardeen- Cooper-Schrieffer theory (BCS theory)

--- metal: Landau Fermi liquid theory, free electron systems

--- electrons form Cooper pairs due to attraction (k, spin-up↑; -k, spin-down ↓)

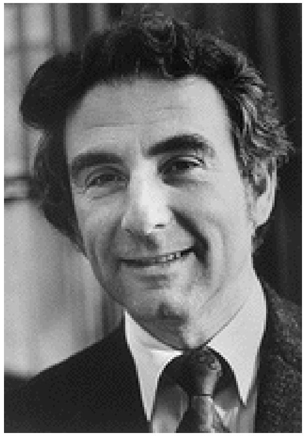
----metal unstable against infinitesimal electron pairing interaction

--- electron-lattice coupling leads to e-e attractive interaction

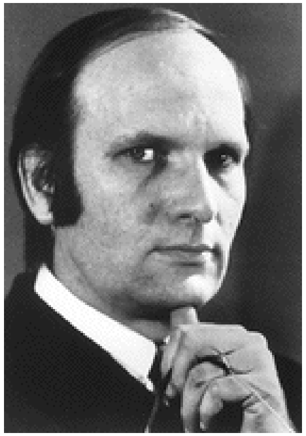
Confirmed in experiments later, and is one of the most beautiful theory in physics

BCS Theory for Conventional Superconductivity, 1956

John Bardeen



Leon Cooper

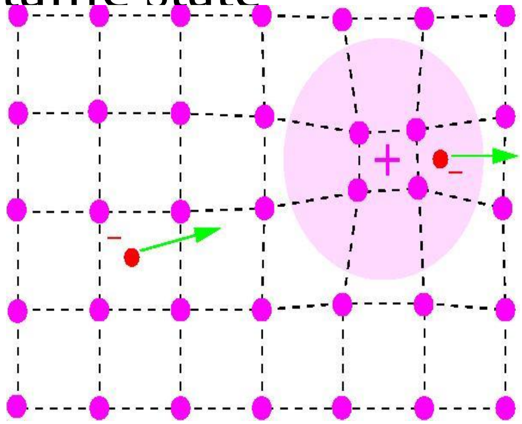


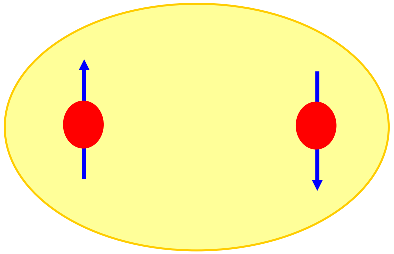
Bob Schrieffer

Cooper pairs of electrons formed by an attraction,
instability of the metallic state

1972 Nobel prize

Conventional pairing
attractive interaction of electrons in a metal thru electron-phonon interaction

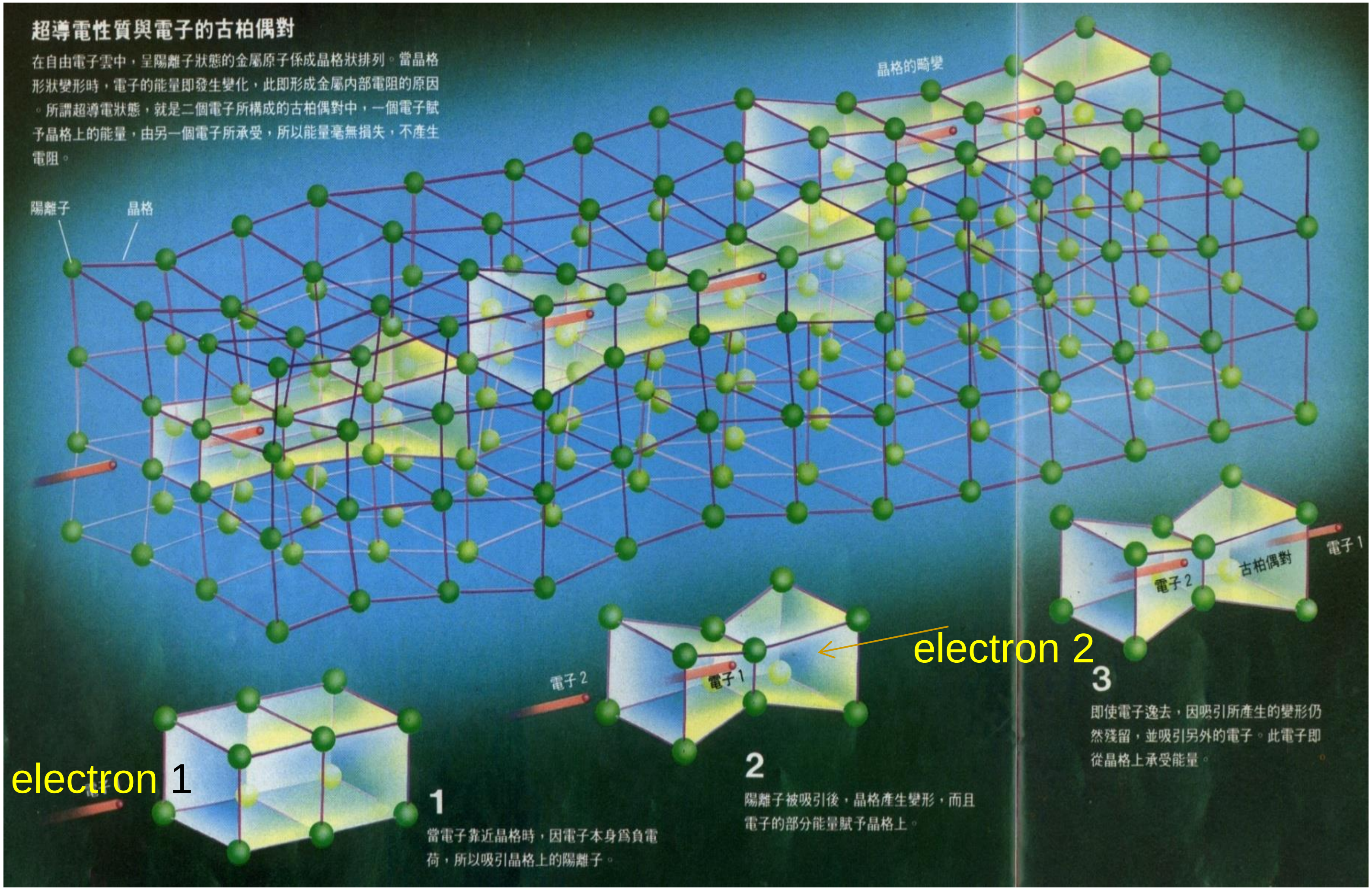




angular momentum l =0
spin singlet

Electrons in metal can pair via the lattice

Cartoon Picture of BCS Theory



牛頓雜誌 56期 1988年 1月號

Conventional (BCS) Superconductivity

Macroscopic Coherent Pair Wave Function forms at T < Tc

$$|\Psi_{BCS}\rangle = \prod_k (u_k + v_k c^+_{k,\uparrow} c^+_{-k,\downarrow})|0\rangle$$

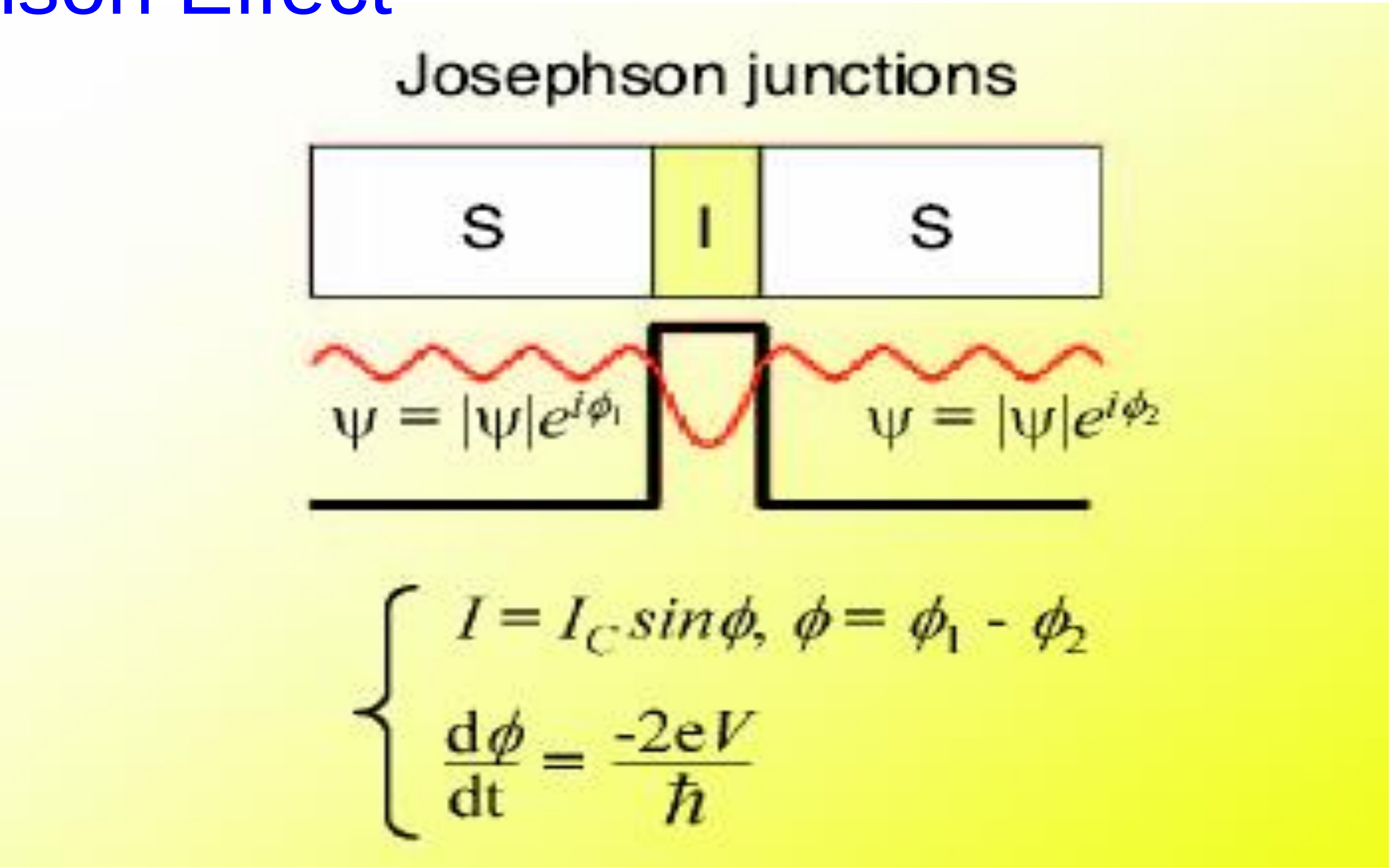
Pairing amplitude constant around Fermi surface

Energy gap function: $\Delta_{\sigma,\sigma_1}(\vec{k}) = \Delta_0(\uparrow\downarrow - \downarrow\uparrow)/\sqrt{2}$

Specific Heat C(T) vanishes exponentially as T ->0

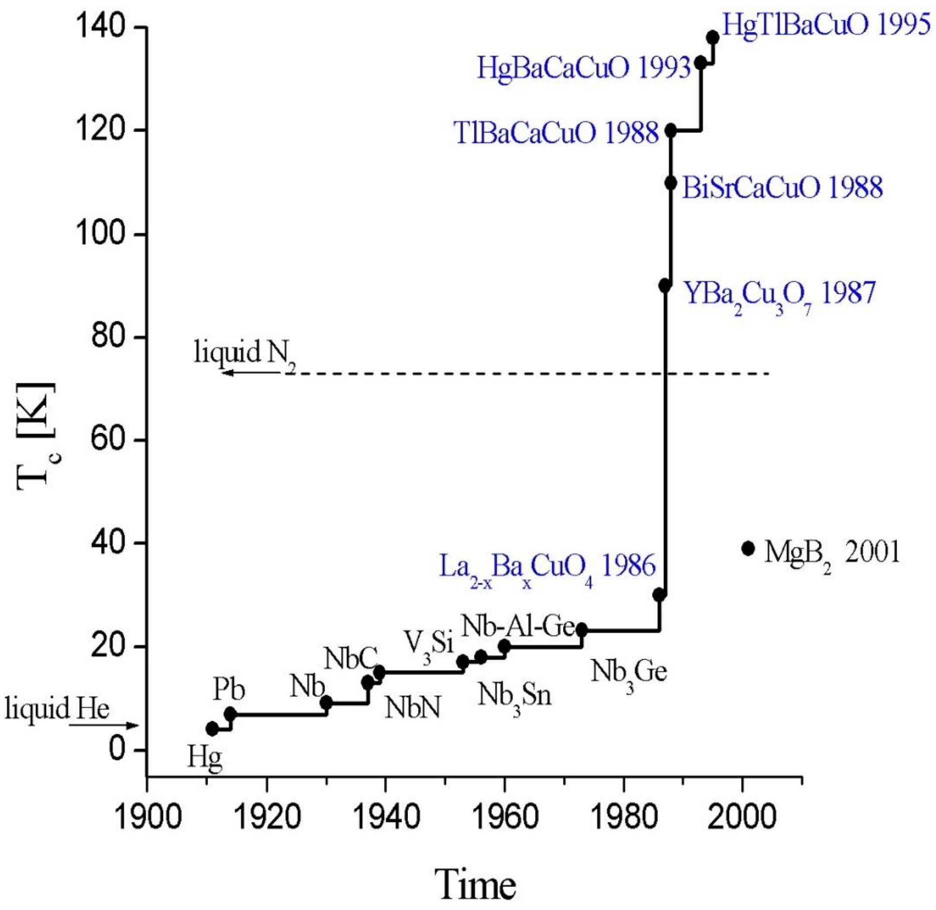
BCS theory explains all features of conventional superconductors

Josephson Effect



Josephson was a student when he predicted the effect, Nobel prize 1973

Discovery of High Temperature Superconductivity

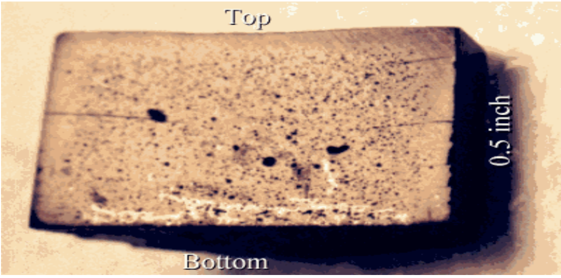


Tc up to 133K

1986: J.G. Bednorz & K.A. Müller

$La_{2-x}Ba_xCuO_4$ T_c =35 K

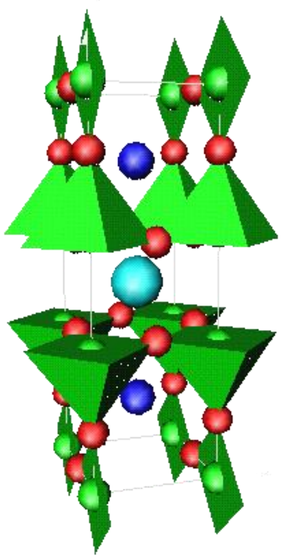
1987 Nobel prize



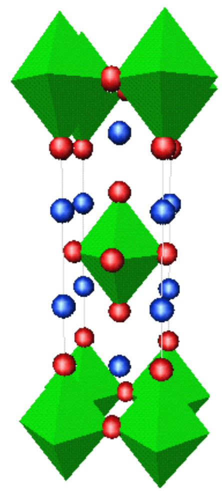
Ceramic, Insulator at normal state

How does it superconduct??

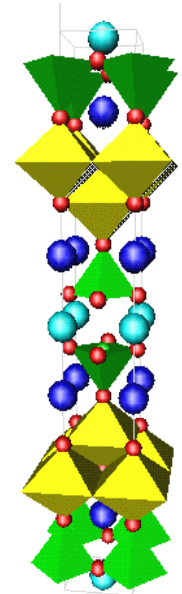
Structures of High Temperature Superconductors



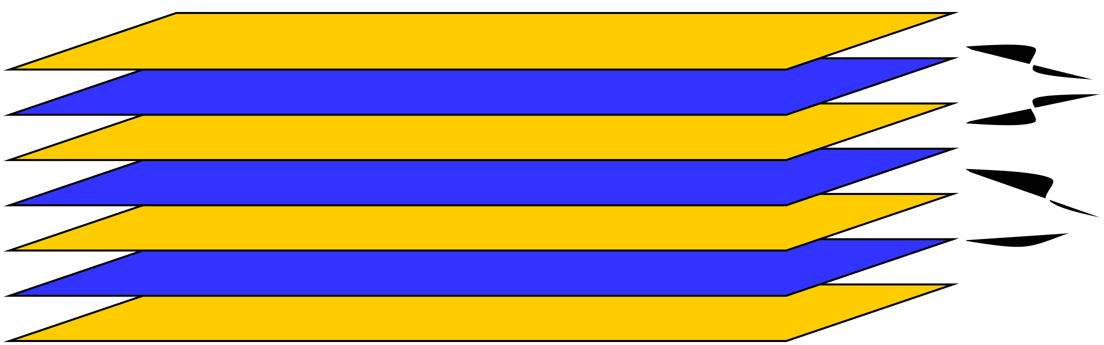
LSCO



YBCO

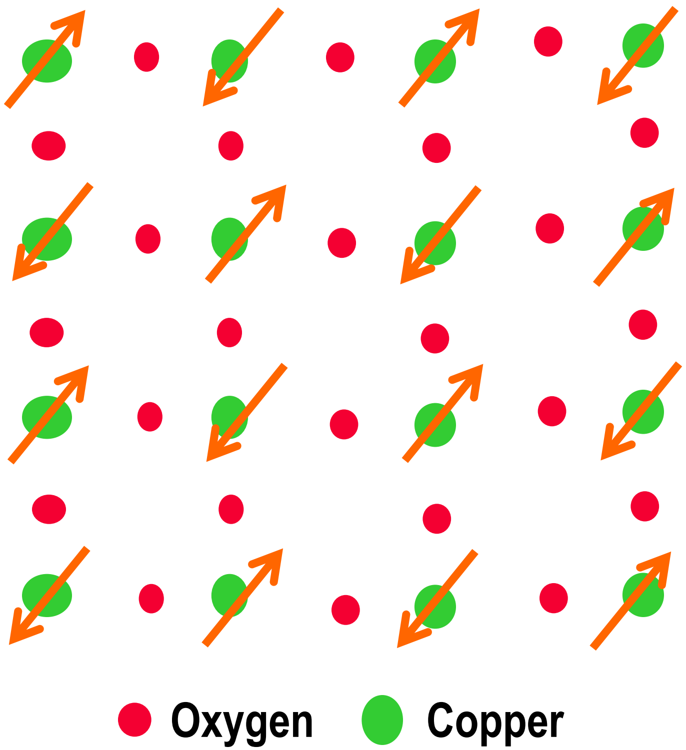


HgCuO



Layered structure → quasi-2D system

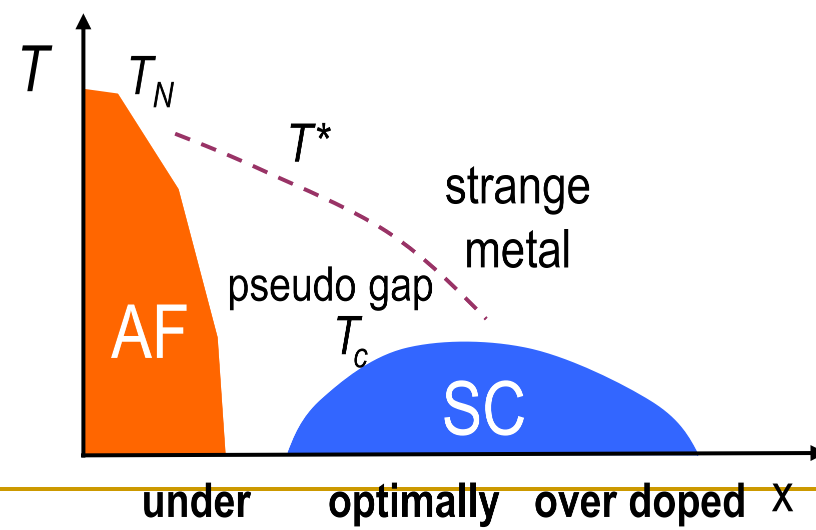
High Tc Superconducting Cu-oxides



Chemical doping introduces carriers: superconductivity

- **Near magnetic insulator**
- **D-wave pairing symmetry.**
- **Metallic not simple Fermi liquid**

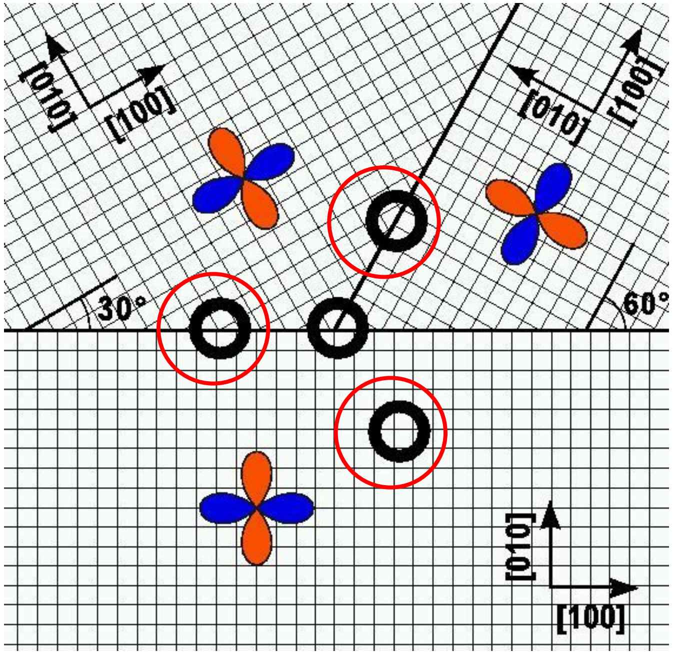
CuO_2 Planes Important, “Undoped” is half-filled antiferromagnetic state, Naive band theory fail to describe strongly correlated system



Generic Phase Diagram

Gap Symmetry of High Temperature Superconductors
d_{x2-y2} symmetry

Tri-Crystal Geometry

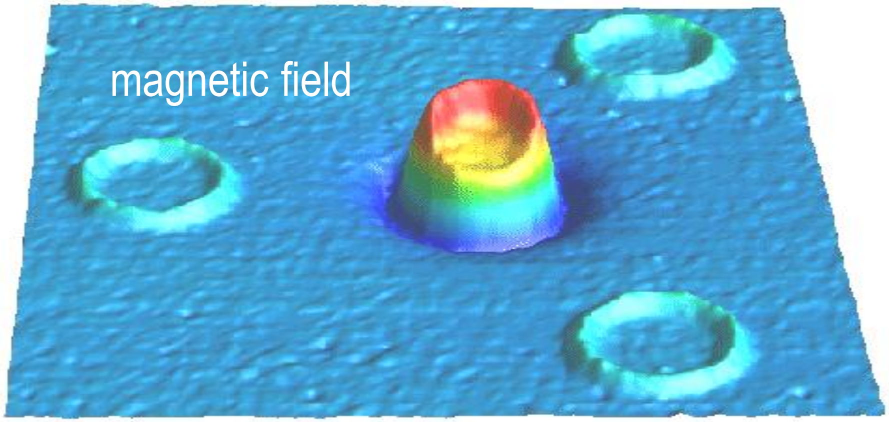


Tsuei, Kirtley Chi et al. (1995)

Superconducting loop ∅ = 60 μm
$YBa_2Cu_3O_7$ T_c = 92 K

Odd number of π-shifts

frustrated loops lead to a current in groundstate



SQUID-scanning-microscope measures the magnetic field that results from the current

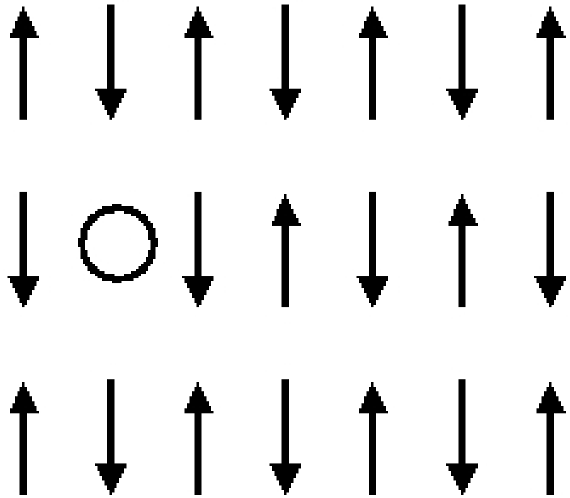
Highly challenging problem

Many talented physicists tried to understand high Tc, including over 10 Nobel laureates. Not yet solved

Mysteries of High Temperature Superconductivity

- Ceramic superconductors, not metallic
- Magnetism nearby (antiferromagnetism)
- Very robust against randomness
- Don't follow BCS theory

Doped Antiferromagnetic Mott Insulator



Hole Motion is Frustrated

Basic or minimum model for high Tc

---- Anderson 87’; Zhang & Rice, 88

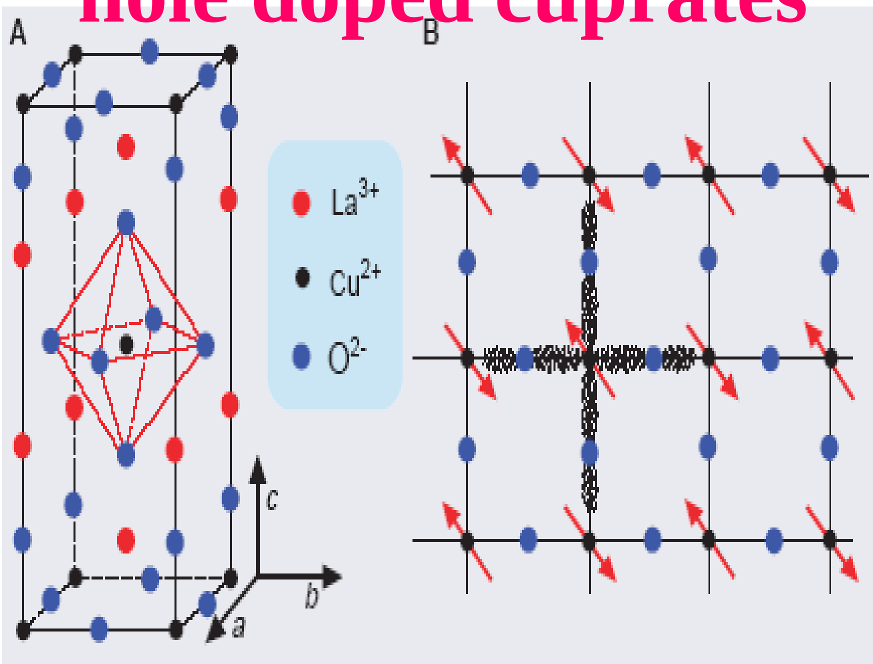
Merit:

- **reproduce AFM-Mott insulator for the half-filling;**
- **agreements with many expts.:**
  - **photoemission, quasiparticle;**
  - **neutron scatterng, spin fluctuation;**
  - **interband gap in infrared optical.**

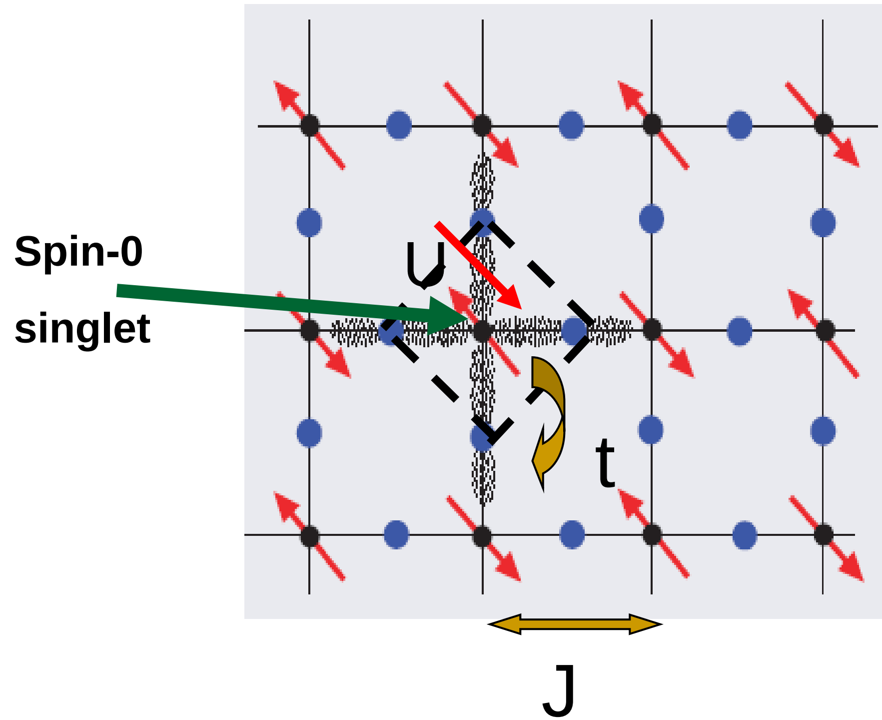
Challenging problem in theory:

doped Mott insulator, perturbation does not work

Zhang-Rice Singlet – charge carrier in hole doped cuprates



Crystal structure and electronic structure of undoped cuprates



doped with one additional hole--- Zhang & Rice, 1988

Plain Vanilla Version of RVB

(low T theory for high Tc based on ground state and elementally excitations)

Anderson, Lee, Randeria, Rice, Trivedi, Zhang, 2004

Hamiltonian:

$$H = -t\sum_{\langle i,j \rangle} c^{+}_{i,\sigma} c_{j,\sigma} + J\sum_{\langle i,j \rangle} \vec{S}_i \bullet \vec{S}_j$$

Constraint: 0, or 1 electron each site

State:

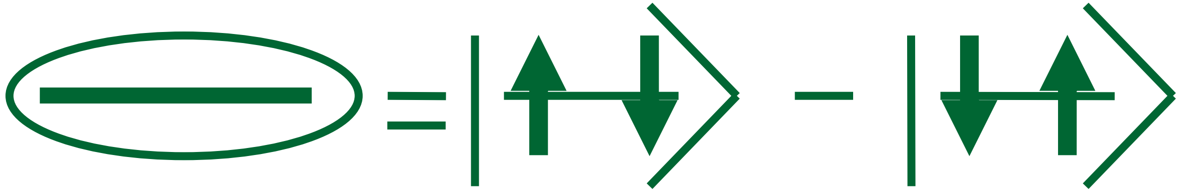
$$\left| RVB \right\rangle = P \left| BCS \right\rangle$$

P: Projection to keep 0 or 1-el at each site

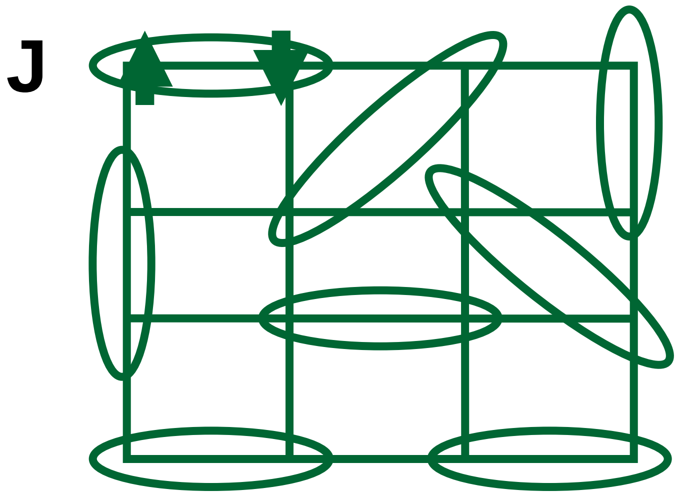
RVB = resonant valence bond

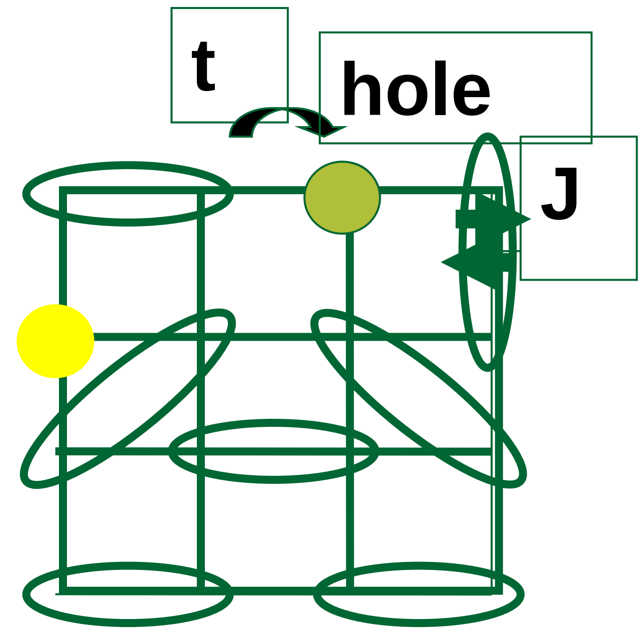
1. Model
2. Variational calculations (numerical or mean field)
3. Results

magnetic singlet (valence bond)



Quantum spin liquid



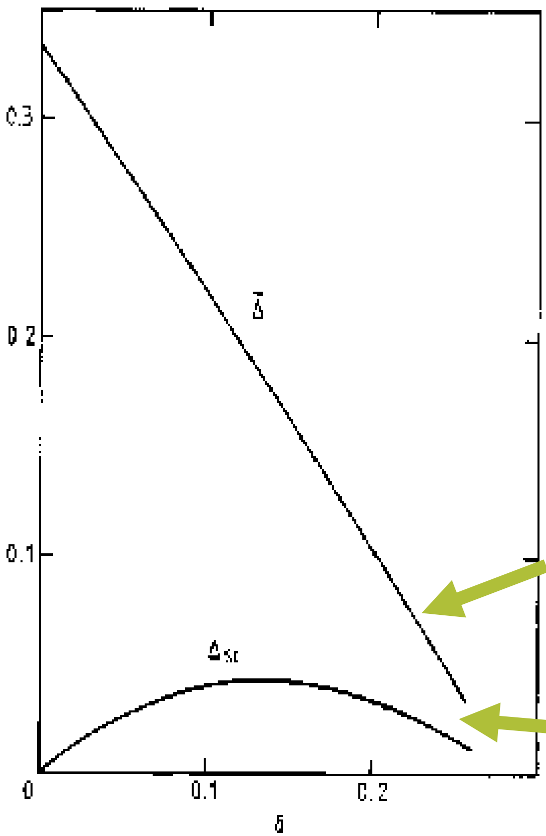


A snap shot of RVB insulator

Doped RVB (Supercond)

Pseudogap v.s. SC order

Theory (1988)



$$\Psi_{RVB}^{q.p.} = P\Psi_{BCS}^{q.p.}$$

$$E_k = \sqrt{\xi_k^2 + (\tilde{\Delta}(\cos k_x - \cos k_y))^2}$$

$$\Delta_{SC} = g_t \tilde{\Delta} \approx 2\delta \tilde{\Delta}, g_t = \frac{2\delta}{1+\delta}$$

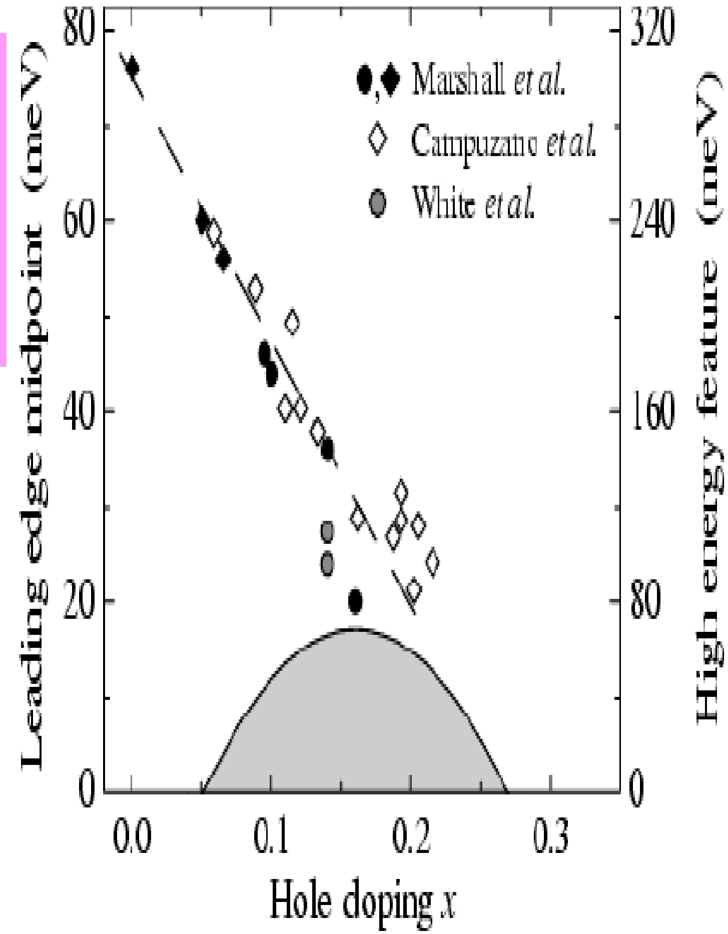
amplitude of excitation energy

SC order parameter

hole concentration

t/J = **5**

Experiment



Fe-based superconductivity

- Doped LaAsFeO, BaFe_2As_2, FeSe …
- Tc as high as 55K, next to Cu-oxides
- Multi-orbitals, multi Fermi pockets
- Pairing symmetry: likely anti-phase s-wave
- Likely due to magnetic interaction, similar to Cu-oxides, but strength is weak

Room temperature superconductivity

- This remains to be the dream task for material scientists working on superconductivity. Huge possible applications.
- We may need new ideas from young people like you.

Even and odd parities of Cooper pair

- A Cooper pair: 2 electrons, total wavefunction antisymmetric with interchange electrons:

  spin =0, even parity;

  spin=1, odd parity
- Conventional superconductors, high Tc cuprates and pnictides all have even parity, the total spin of two electrons is zero.
- P-wave superconductivity ?

Superfluid helium -3

helium-3 contains 2 protons and 1 neutron, so it is a fermion. No electric charge

At very low T, superfluid. Discovery: David M. Lee, Douglas D. Osheroff and Robert C. Richardson ; Nobel prize 1996

Theory: Anthony Leggett, Nobel prize 2003

- In astrophysics
- Pairing in fermionic ultracold atoms

^{3}He- Isotope with Fermionic Nucleus 2p+1n

effective mass $m^*/m \approx 4$
spin susceptibility: $\chi^*/\chi \approx 9$ } ⟺ **strong correlations close to solid phase**

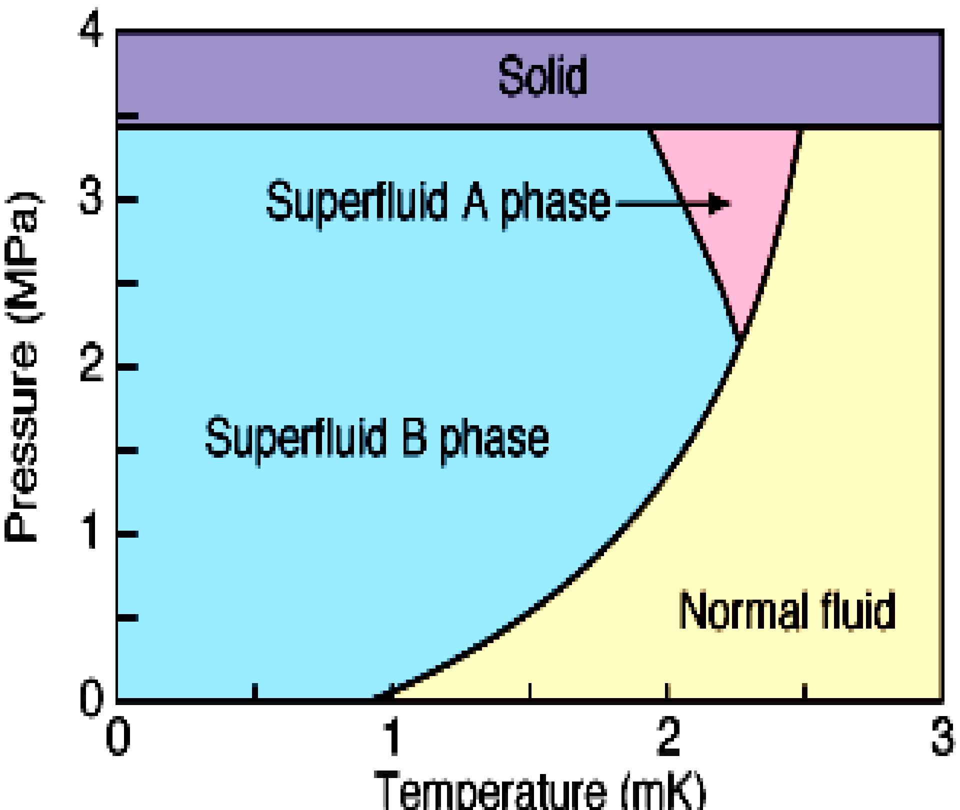
Superfluid : p-wave, 1971

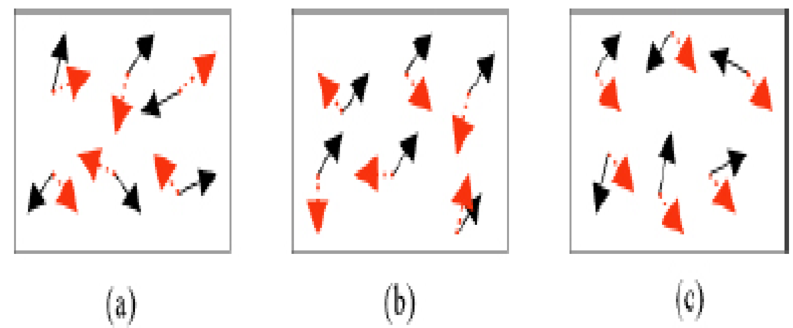
$$\Delta_{\sigma,\sigma_1}(\vec{k}) = \Delta_0(k_x + ik_y)(\uparrow\downarrow + \downarrow\uparrow)/\sqrt{2}$$

Lee, Osheroff & Richardson

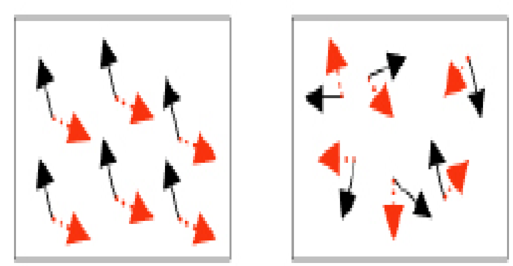
Cooper pairing: odd parity spin triplet

$$\ell = 1 \qquad S = 1$$





black arrow spin; red arrow: orbital



B-phase

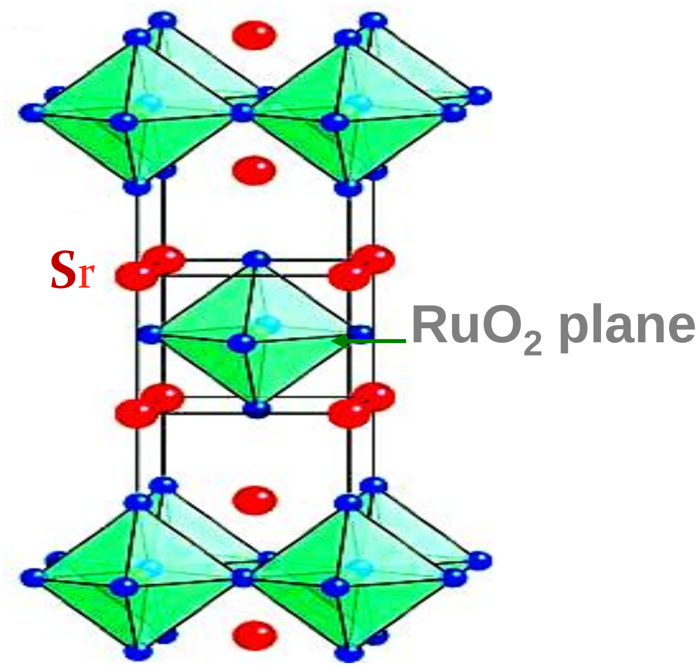
A-phase: time reversal broken

Ruthenate

Highly anisotropic, 2D

Y. Maeno, et al. (1994)

Sr_2RuO_4



Same 2D crystal structure as cuprate 214

- Likely p-wave superconductivity
- (Px + iPy)
- Evidence for odd parity,
- time reversal symmetry broken,

But edge current has not been seen.

Integer Quantum Hall Effect

VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance

K. v. Klitzing
Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany, and Hochfeld-Magnetlabor des Max-Planck-Instituts für Festkörperforschung, F-38042 Grenoble, France

- 1980 年 Klitzing教授在强磁场下MOS晶体管二维电子气中发现整数量子霍尔效应。

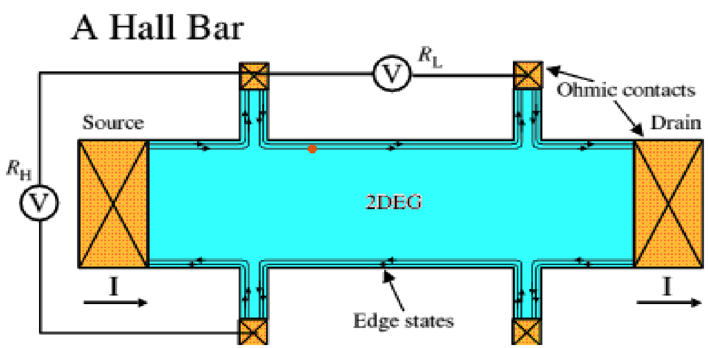
1985

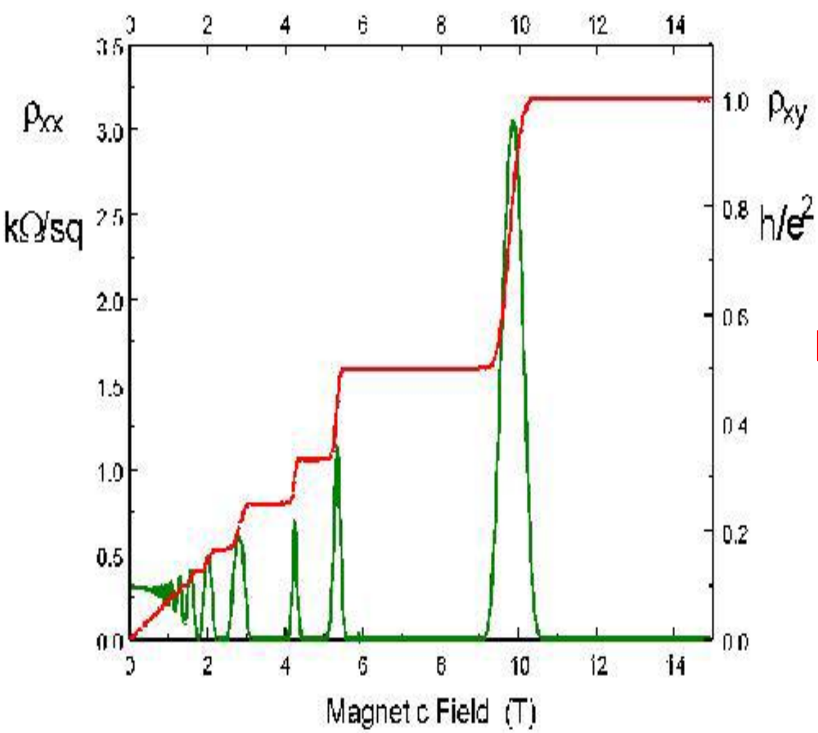
Klaus von Klitzing

The Nobel Prize in Physics 1985 was awarded to Klaus von Klitzing *"for the discovery of the quantized Hall effect".*

http://www.nobelprize.org/nobel_prizes/physics/laureates/1985/

Quantum Hall effect





$$\rho_{xy} = R_Q / n \quad \text{n = integer}$$

- R_Q Quantized resistance

$$R_Q = h / e^2 = 25.812\,807\ \text{k}\Omega$$

Geometry and topology

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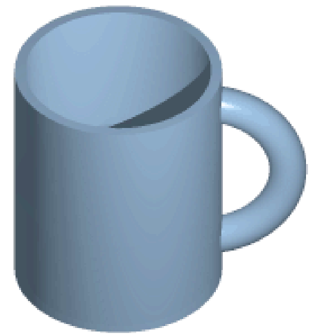

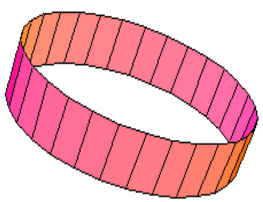

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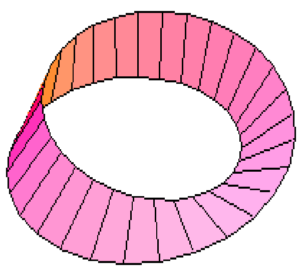
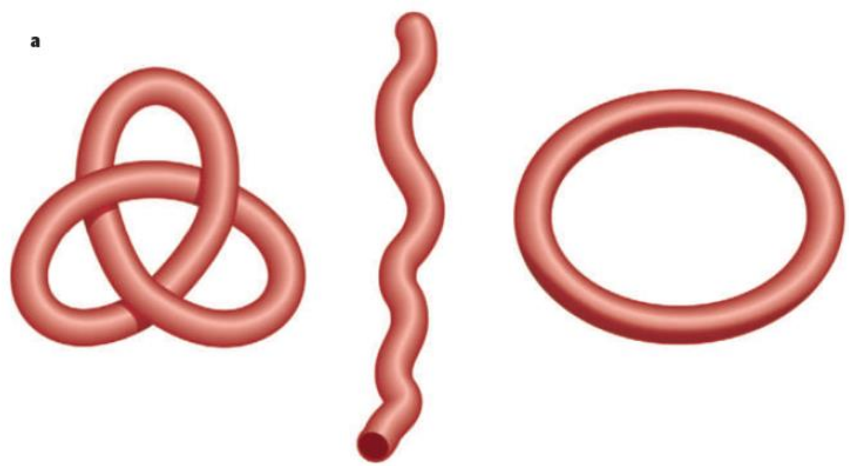
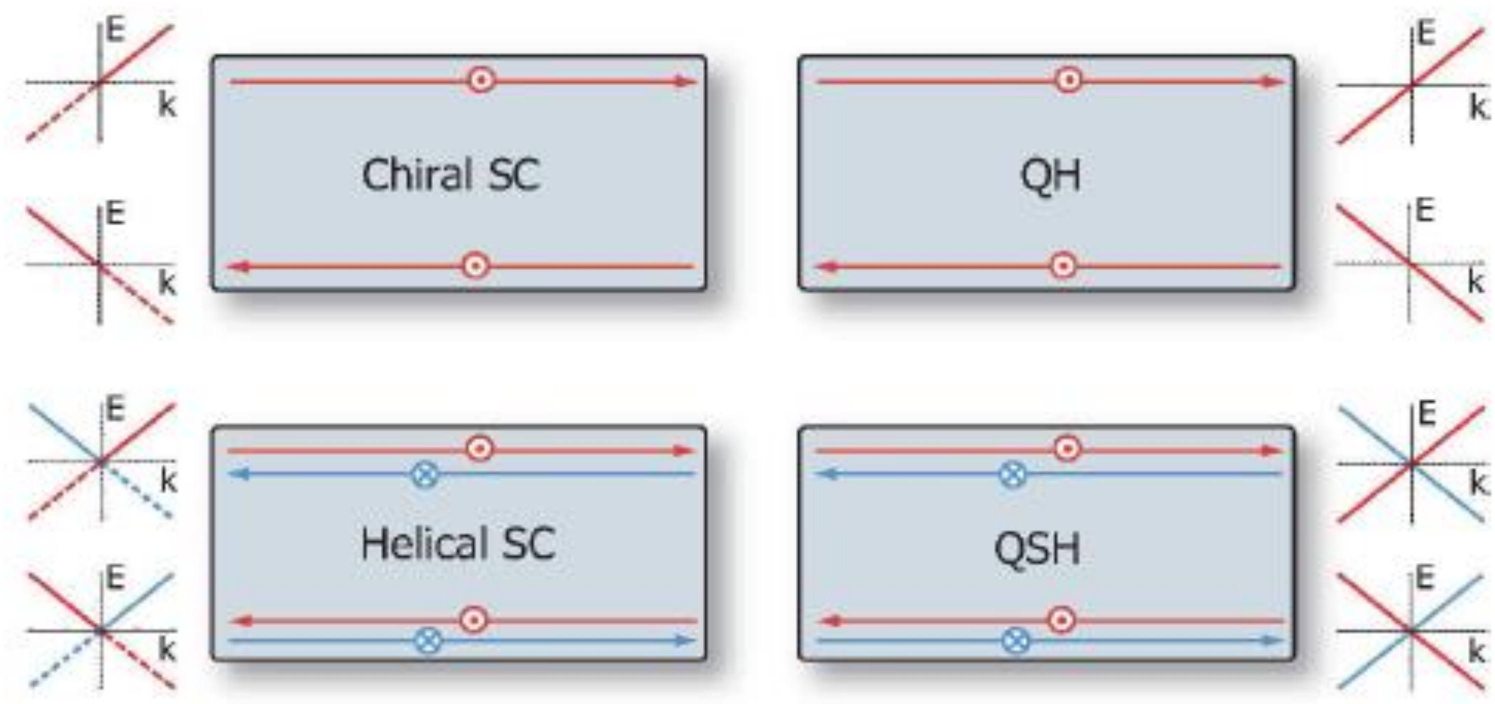




J. E. Moore, （2010）

Topological superconductor & quantum Hall or quantum spin Hall effects



Just beginning of research in topological insulator/superconductor

Search for Majorana particles

particle = its antiparticle.

Summary

- Superconductivity, a remarkable phenomenon. Basic understanding of “conventional superocnductivity”
- High temperature superconductivity, remain a major challenge in physics. Related physics: Mott insulator, spin liquid, …
- Chiral p-wave superconductivity, Sr2RuO4

  topological superconductor, … new challenges

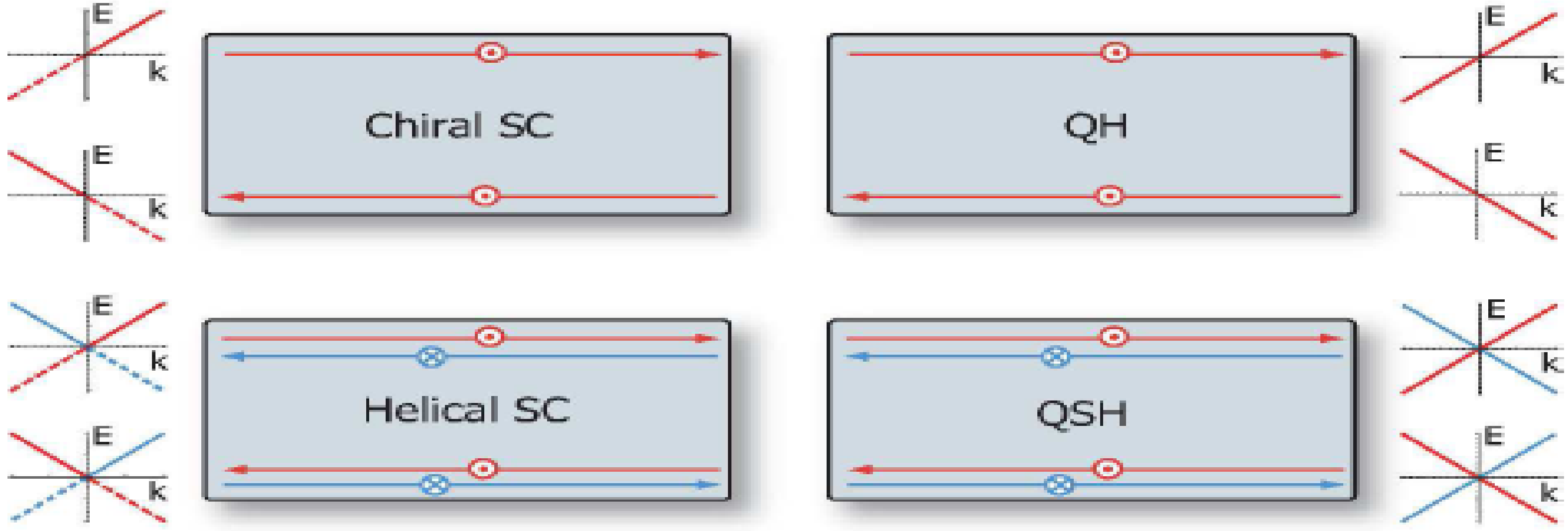


FIG. 40 (Top row) Schematic comparison of 2D chiral superconductor and QH state. In both systems, TR symmetry is broken and the edge states carry a definite chirality. (Bottom row) Schematic comparison of 2D TR invariant topological superconductor and QSH insulator. Both systems preserve TR symmetry and have a helical pair of edge states, where opposite spin states counter-propagate. The dashed lines show that the edge states of the superconductors are Majorana fermions so that the $E < 0$ part of the quasiparticle spectrum is redundant. In terms of the edge state degrees of freedom, we have symbolically QSH = $(\mathrm{QH})^2$ = $(\mathrm{Helical\ SC})^2$ = $(\mathrm{Chiral\ SC})^4$.


Working Together We Can
Advance
Into Higher Orbit
And Beyond ….
Thanks for
your attention

Pseudogap states in high Tc cuprates: Yang- Rice-Zhang theory

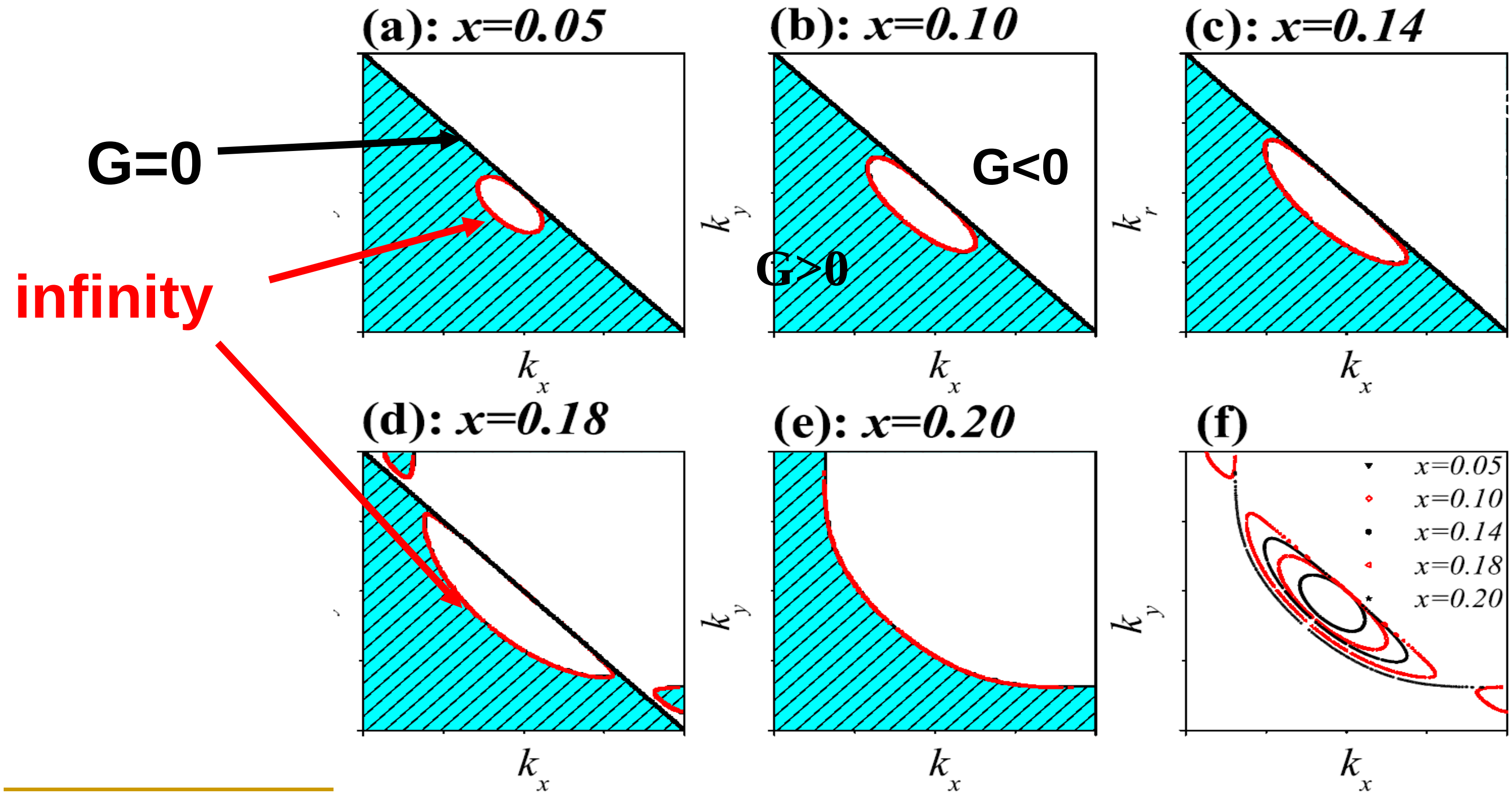
Review Article (2011)

A Phenomenological Theory of the Anomalous Pseudogap Phase in Underdoped Cuprates

Very different from normal metal

Fermi surface evolution (E=0) from YRZ

green dashed area: G>0, red: Fermi surface, white area: G<0

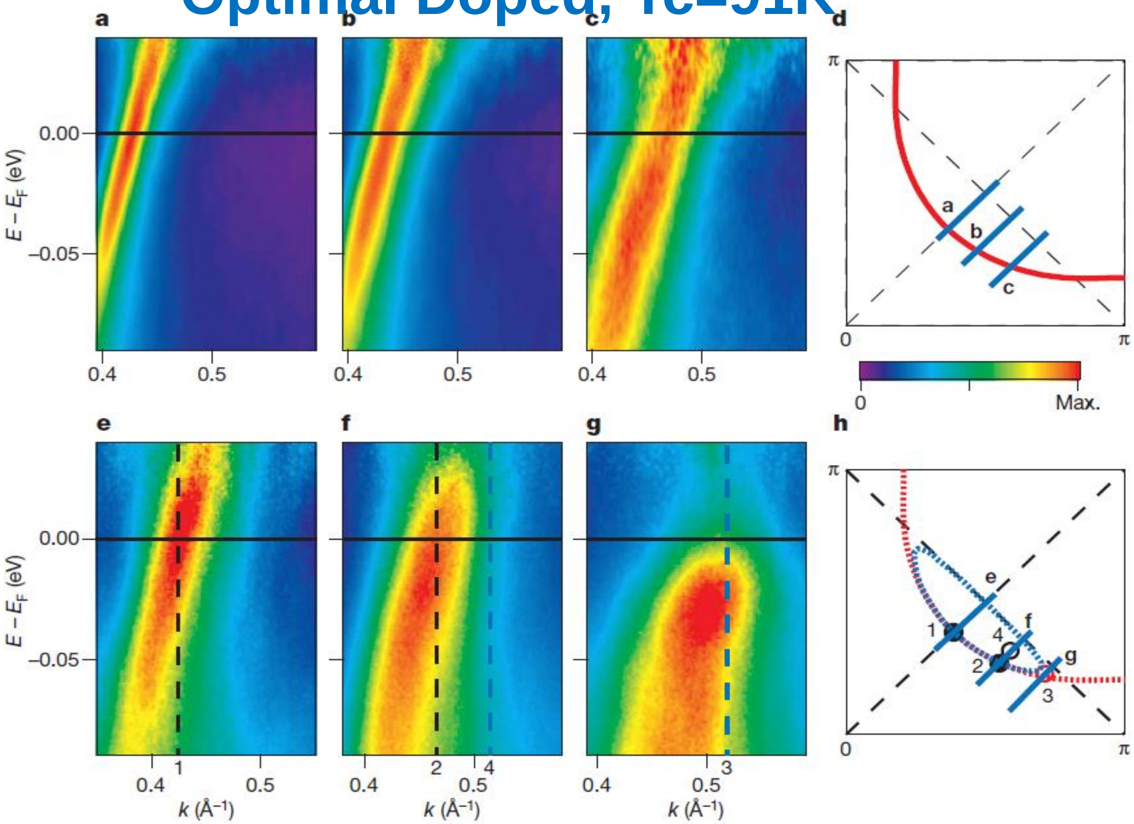


Full Fermi surface

Normal state spectra around node from ARPES: particle-hole asymmetry in BSCCO

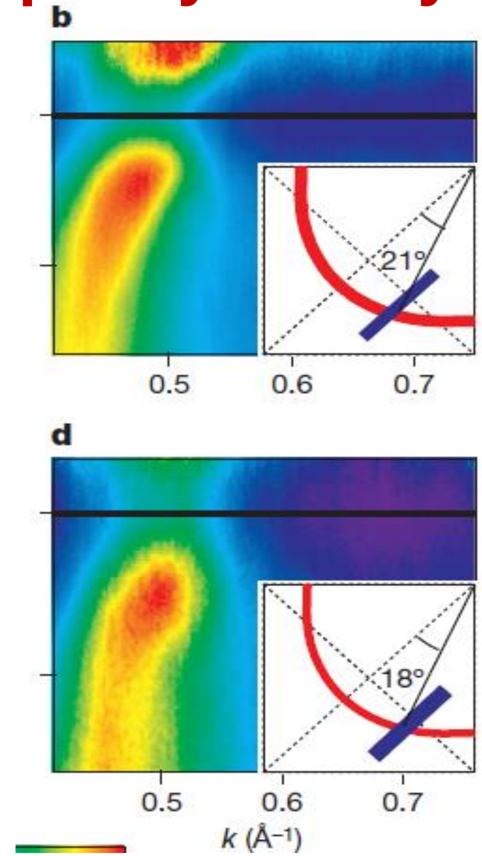
T= 140K (normal state)

Optimal Doped, Tc=91K



Under-doped: Tc=65K

SC State:
p-h symmetry



Arcs not related to thermal effect of nodal SC

H. B. Yang, P. Johnson et al., Nature, 2008

YRZ appears to explain many experiments for the underdoped cuprates:

ARPES,

STM,

Raman,

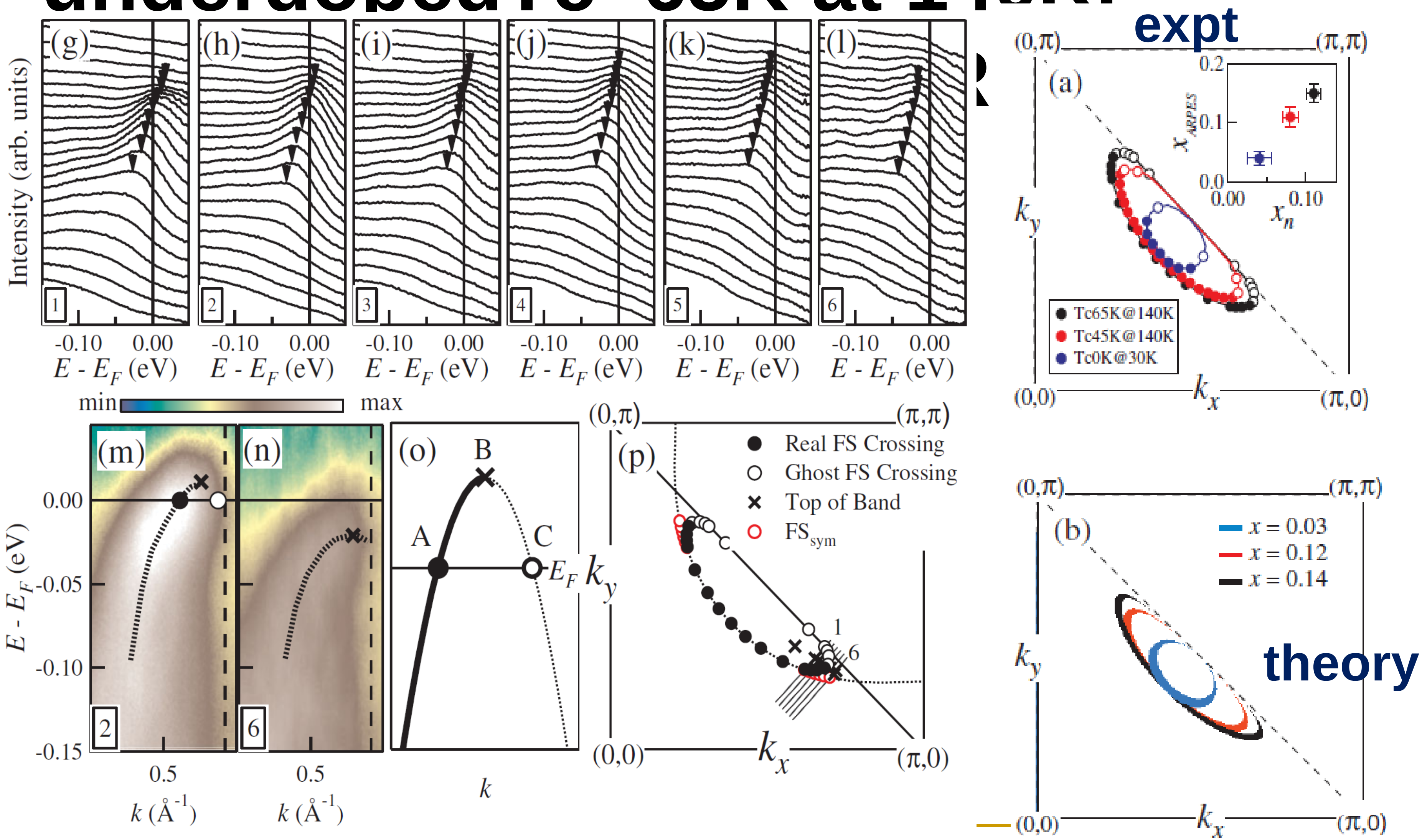
Specific heat,

Penetration depth,

Infrared,

Andreev reflection

AREPS on Bi2212 of underdopedTc=65K at 140K



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ARPES,

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