Cuprate high temperature superconductivity

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Physics 250 (Special topics: spectroscopies of quantum materials)

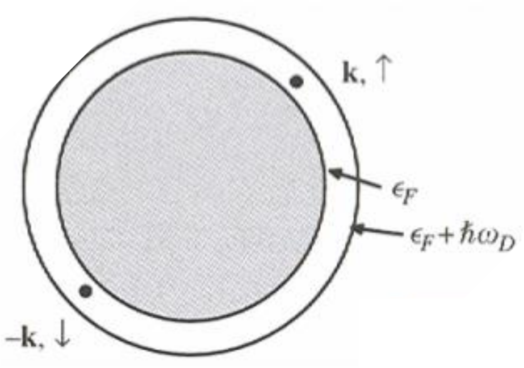
UC Davis, Fall 2016

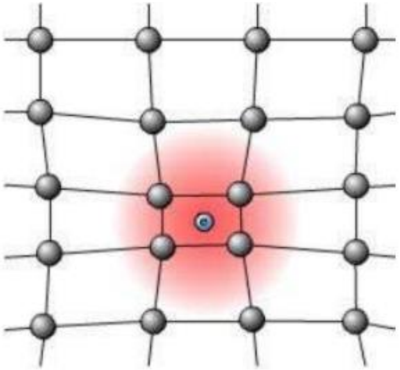
Goals of lecture

- Understand why/how cuprates are different from BCS superconductors (and which aspects are not different)
- Understand historical/scientific context of cuprates
- Be familiar with key area of cuprate research as highlighted in temperature-doping phase diagram
    - d-wave superconducting gap
    - Pseudogap
    - Antiferromagnetism
    - Strange metal

One slide review of BCS (conventional) superconductors

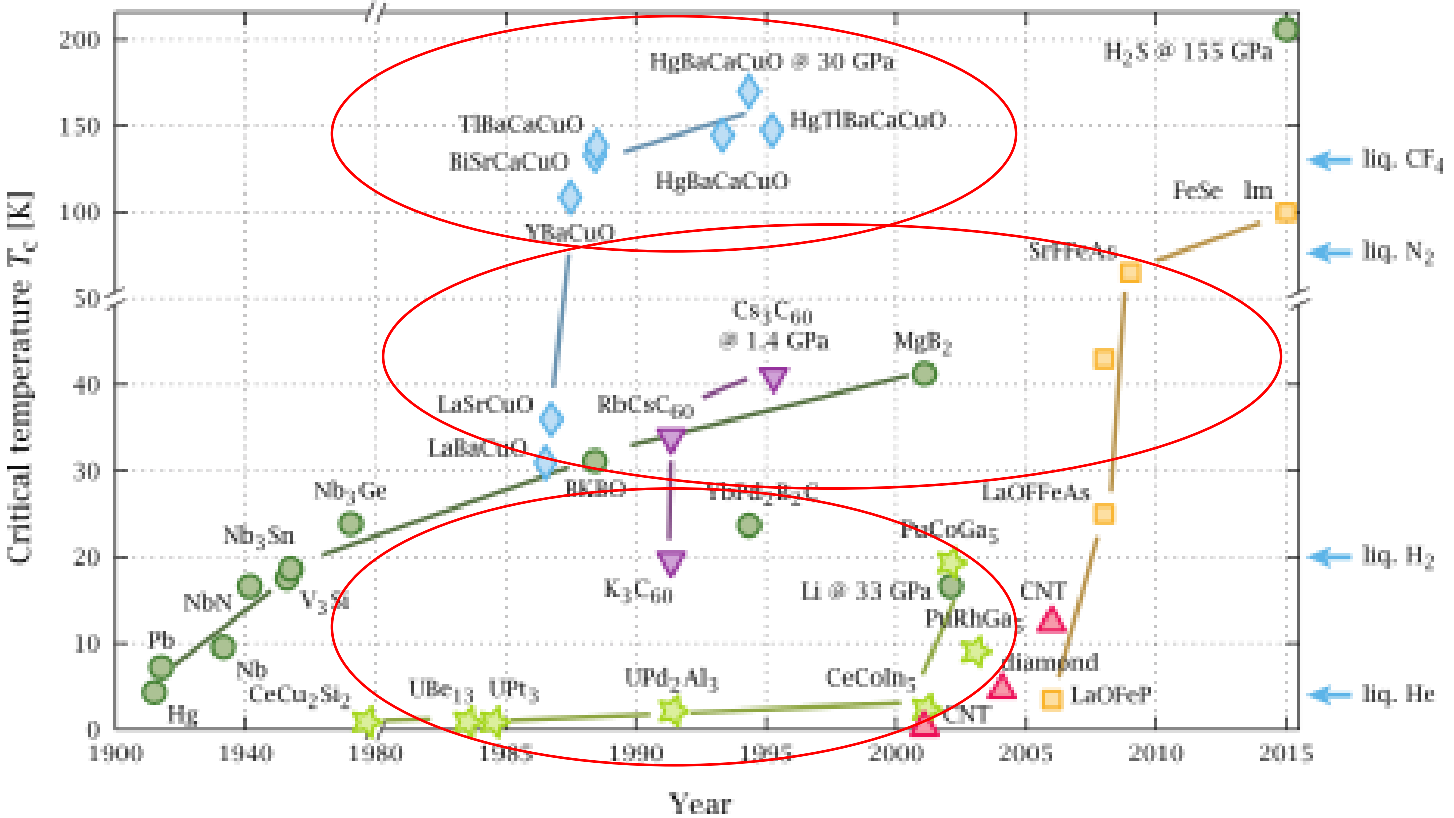
- Fermi surface is unstable to small attractive potential
- In superconductors described by BCS theory, this pairing potential is provided by retarded interaction with lattice vibrations (phonons)
- $T_c \sim \omega_D e^{-1/N(E_F) g_{eff}}$
- Complex wavefunction ($\Psi \sim \Delta e^{i\theta}$)reflects that superconducting state is characterized by both pairing ($\sim\Delta$) and phase coherence





Images from: http://www.mpipks-dresden.mpg.de/~ieremin/teaching/wroclaw1.pdf

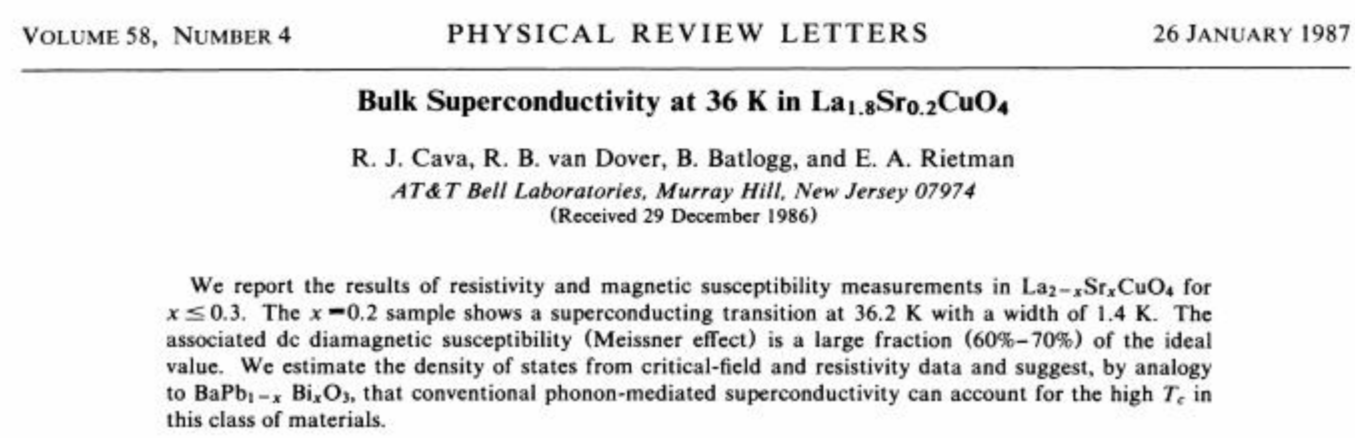
What is high T_c?



- T_c>77K (boiling point of liquid nitrogen)
- T_c>30K (former BCS "limit")
- T_c large relative to Fermi energy
- Mechanism unknown (not BCS)

Image source: https://en.wikipedia.org/wiki/High-temperature_superconductivity

Discovery of cuprate superconductivity in 1986



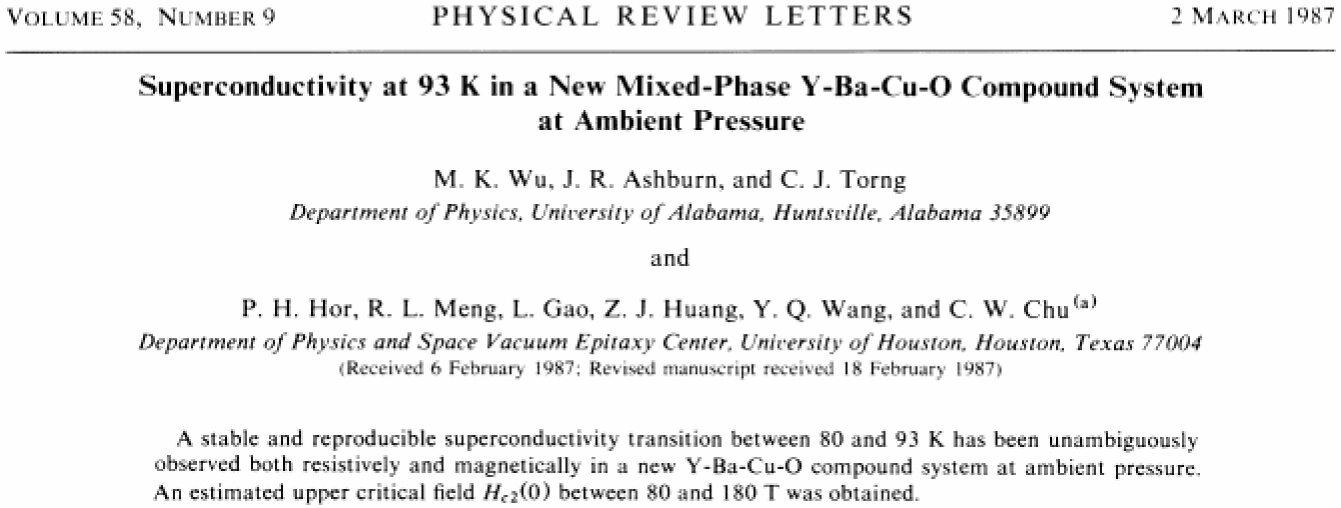
VOLUME 58, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1987

Bulk Superconductivity at 36 K in $La_{1.8}Sr_{0.2}CuO_4$

R. J. Cava, R. B. van Dover, B. Batlogg, and E. A. Rietman
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 29 December 1986)

We report the results of resistivity and magnetic susceptibility measurements in $La_{2-x}Sr_xCuO_4$ for $x \leq 0.3$. The $x=0.2$ sample shows a superconducting transition at 36.2 K with a width of 1.4 K. The associated dc diamagnetic susceptibility (Meissner effect) is a large fraction (60%–70%) of the ideal value. We estimate the density of states from critical-field and resistivity data and suggest, by analogy to $BaPb_{1-x}Bi_xO_3$, that conventional phonon-mediated superconductivity can account for the high T_c in this class of materials.



VOLUME 58, NUMBER 9 PHYSICAL REVIEW LETTERS 2 MARCH 1987

Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure

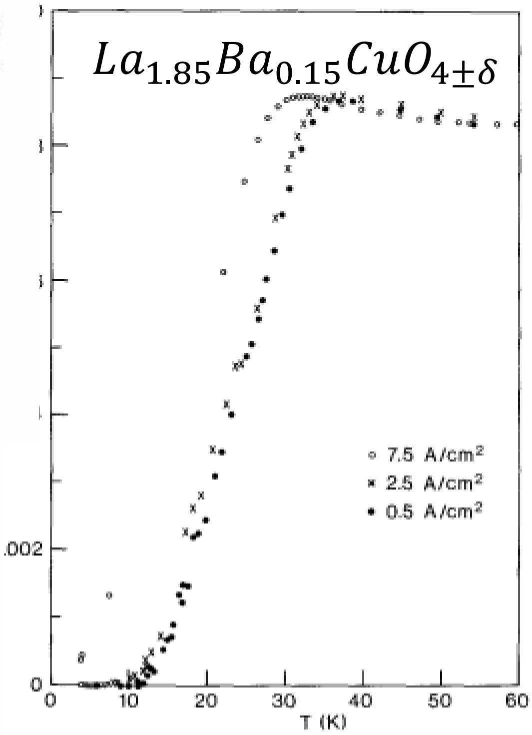
M. K. Wu, J. R. Ashburn, and C. J. Torng
Department of Physics, University of Alabama, Huntsville, Alabama 35899

and

P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu[a]
Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004

(Received 6 February 1987; Revised manuscript received 18 February 1987)

A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field $H_{c2}(0)$ between 80 and 180 T was obtained.



$La_{1.85}Ba_{0.15}CuO_{4\pm\delta}$

Bednorz & Muller, Z. Phys. B - Condensed Matter 64, 189-193 (1986)

Woodstock of physics

- Coordinates: March meeting 1987, NYC, ~11 months after discovery of high-Tc
- Videos from this historic meeting available at https://www.youtube.com/watch?v=JcprXckcGrc&list=PLgxD9DiwxLGpdSqKDIRlPjg0MoEveCKhH&index=1 courtesy of APS

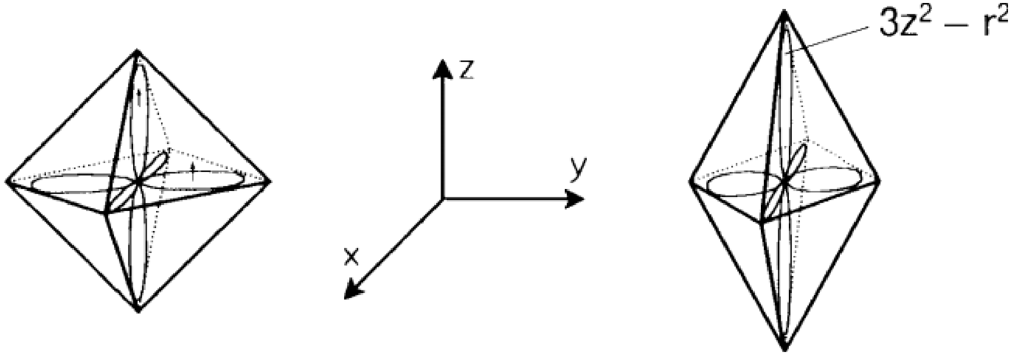
Speaker: Neil Ashcroft

Cuprate high-T_c in context: how they were discovered

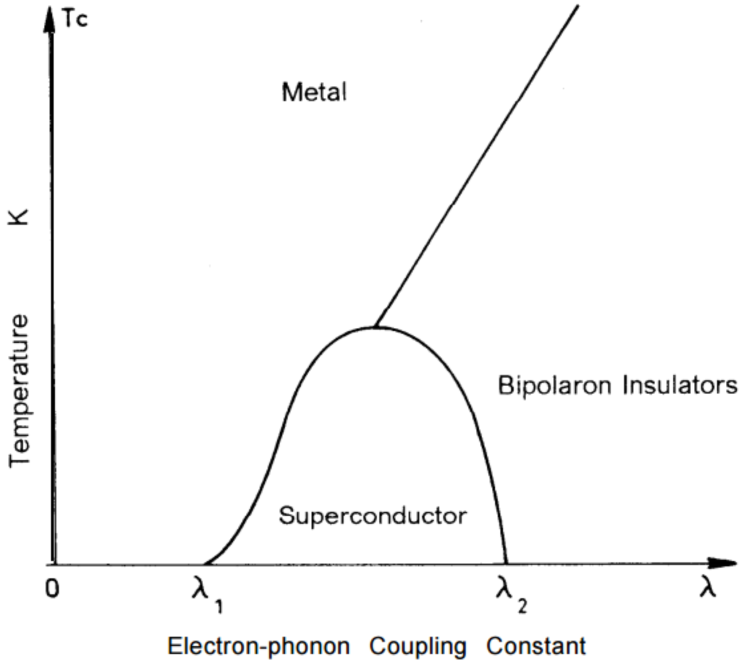
- Motivating results: superconductivity in other oxides
  - $SrTiO_{3-\delta}$ $(T_c = 0.3\ K)$
  - $Li_{1+x}Ti_{2-x}O_4$ $(T_c = 13\ K)$
  - $BaPb_{1-x}Bi_xO_3$ $(T_c = 13\ K)$
- In BCS theory: $k_B T_c \propto \hbar\omega_D e^{-\frac{1}{N(E_F)V^*}}$
  - ω_D=Debye frequency (often large in oxides)
  - $N(E_F)$=density of states at Fermi level
  - V^*=electron-phonon coupling
- Strategy: enhance electron-phonon coupling by trying to push perovskite materials close to a structural phase transition

Source: Nobel prize lecture of Bednorz and Muller, 1987, available at:
http://www.nobelprize.org/nobel_prizes/physics/laureates/1987/bednorz-muller-lecture.pdf

Cuprate high-T_c in context: how they were discovered

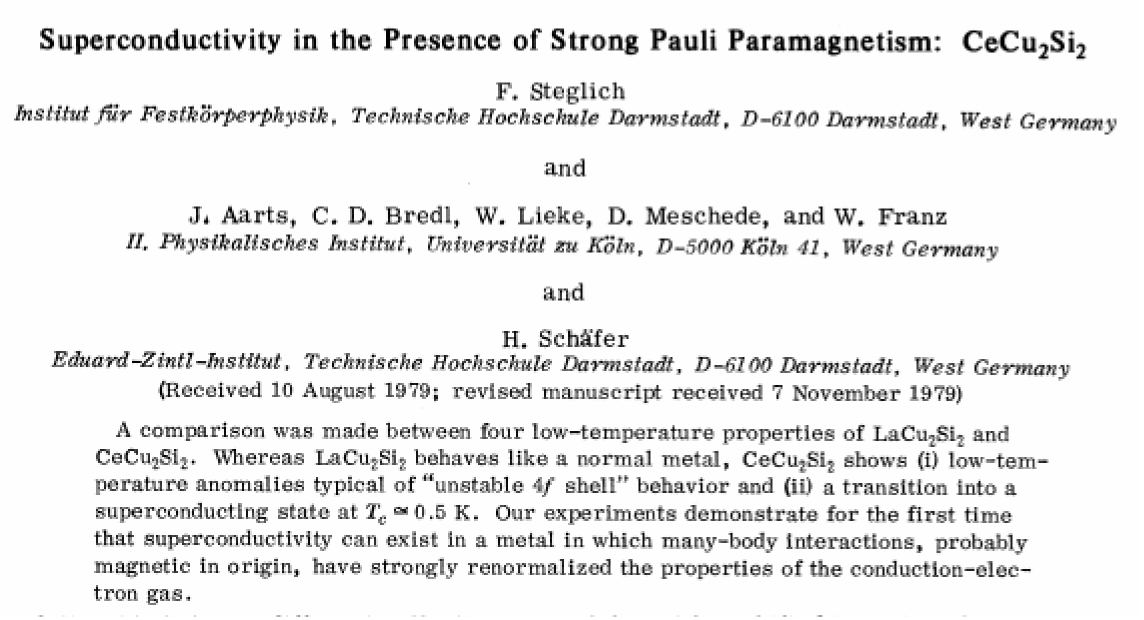


Jahn-Teller Effect: Elongation of the Octahedron



- Nobel prize lecture of Bednorz and Muller, 1987, available at: http://www.nobelprize.org/nobel_prizes/physics/laureates/1987/bednorz-muller-lecture.pdf
- B. K. Chakraverty, J. Physique Lett. 40, L99 (1979)

Cuprate high-Tc in context: what else was going on in the field at the time



Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

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and

J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz
II. Physikalisches Institut, Universität zu Köln, D-5000 Köln 41, West Germany

and

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Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany
(Received 10 August 1979; revised manuscript received 7 November 1979)

A comparison was made between four low-temperature properties of $LaCu_2Si_2$ and $CeCu_2Si_2$. Whereas $LaCu_2Si_2$ behaves like a normal metal, $CeCu_2Si_2$ shows (i) low-temperature anomalies typical of "unstable 4*f* shell" behavior and (ii) a transition into a superconducting state at $T_c \simeq 0.5$ K. Our experiments demonstrate for the first time that superconductivity can exist in a metal in which many-body interactions, probably magnetic in origin, have strongly renormalized the properties of the conduction-electron gas.

Discovery of heavy fermion superconductivity in 1979

- Approximation that electrons are much 'faster' than ions doesn't necessarily hold
- Proximity to magnetism
- Strong intellectual influence on field of high-Tc

Comparison to conventional superconductors: what stays and what goes

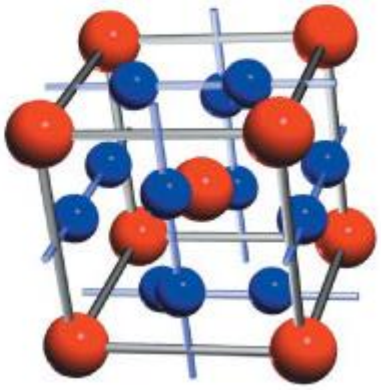
- Ginzburg-Landau phenomenological description ✓
  - Coherence length, ξ ✓
  - Magnetic penetration depth, λ ✓
- BCS theory ✗
  - Superconducting gap ✓ (though not s-wave)
  - Complex order parameter ✓(though distinction between pairing and phase coherence may be important)
  - Cooper pairs✓ (and singlet too)
  - Fermi surface instability ✗ (T>Tc state probably not a Fermi liquid)
  - ‘Pairing glue’=electron-phonon coupling ✗ (pairing glue is debated, including if there is one at all, but if there is a ‘glue’ it is probably not phonons)
  - Isotope effect ✗ (inconclusive, doping dependent)

Why cuprates are(?) different from BCS: high Tc

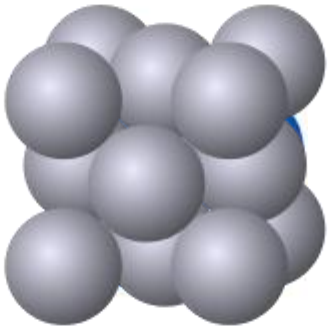
$$T_c \propto \omega_{ph} e^{-\frac{1}{N(0)V}}$$

ω_{ph}	**Typical phonon frequency**
$N(0)$	**Density of states at Fermi level**
V	**Net attractive pairing potential**

Nb_3Ge



Pb

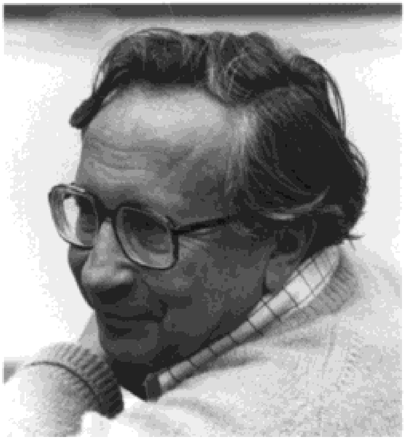


	Nb_3Ge	Pb
Observed T_c	23	7.2
Predicted Max T_c	28	9.2

W. L. McMillan Phys. Rev. **167** 331 (1968)

- Origin of rumor that Tc couldn’t be higher than 30K within BCS theory (which McMillan never said)
- Now there are multiple examples of BCS superconductors with high-T_c including MgB_2 (T_c=40K) and H_2S under pressure (T_c=203K)

Why cuprates are different from BCS superconductors: Matthias' rules



Bernd Mattias

Mattias' Rules (1963)—heuristic guidance for finding superconductors

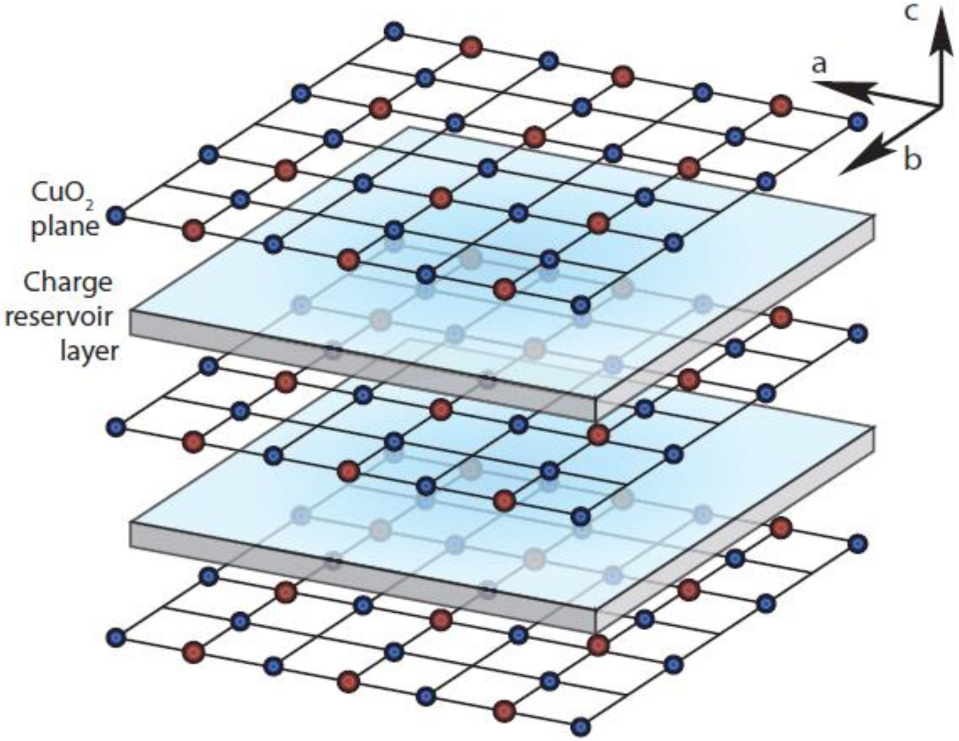
- Metals and intermetallic compounds
- Cubic crystal symmetry
- No magnetism
- No insulators
- No oxides

Cuprates violate most of these 'rules'

Matthias *et al.* Rev. Mod. Phys. 35 p1 (1963)

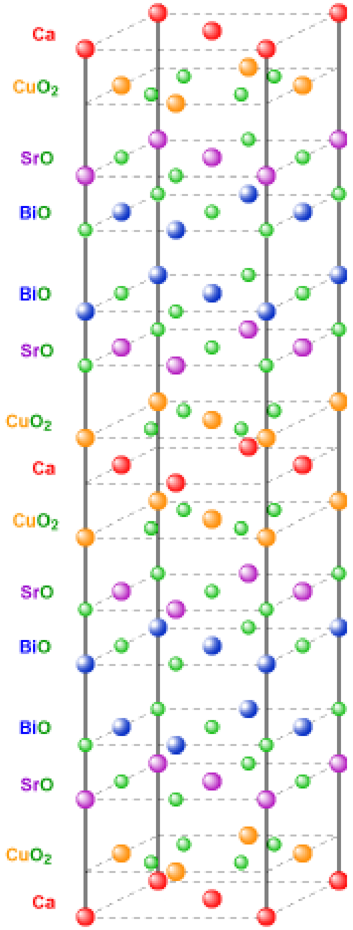
Cuprate Crystal structure

Schematic



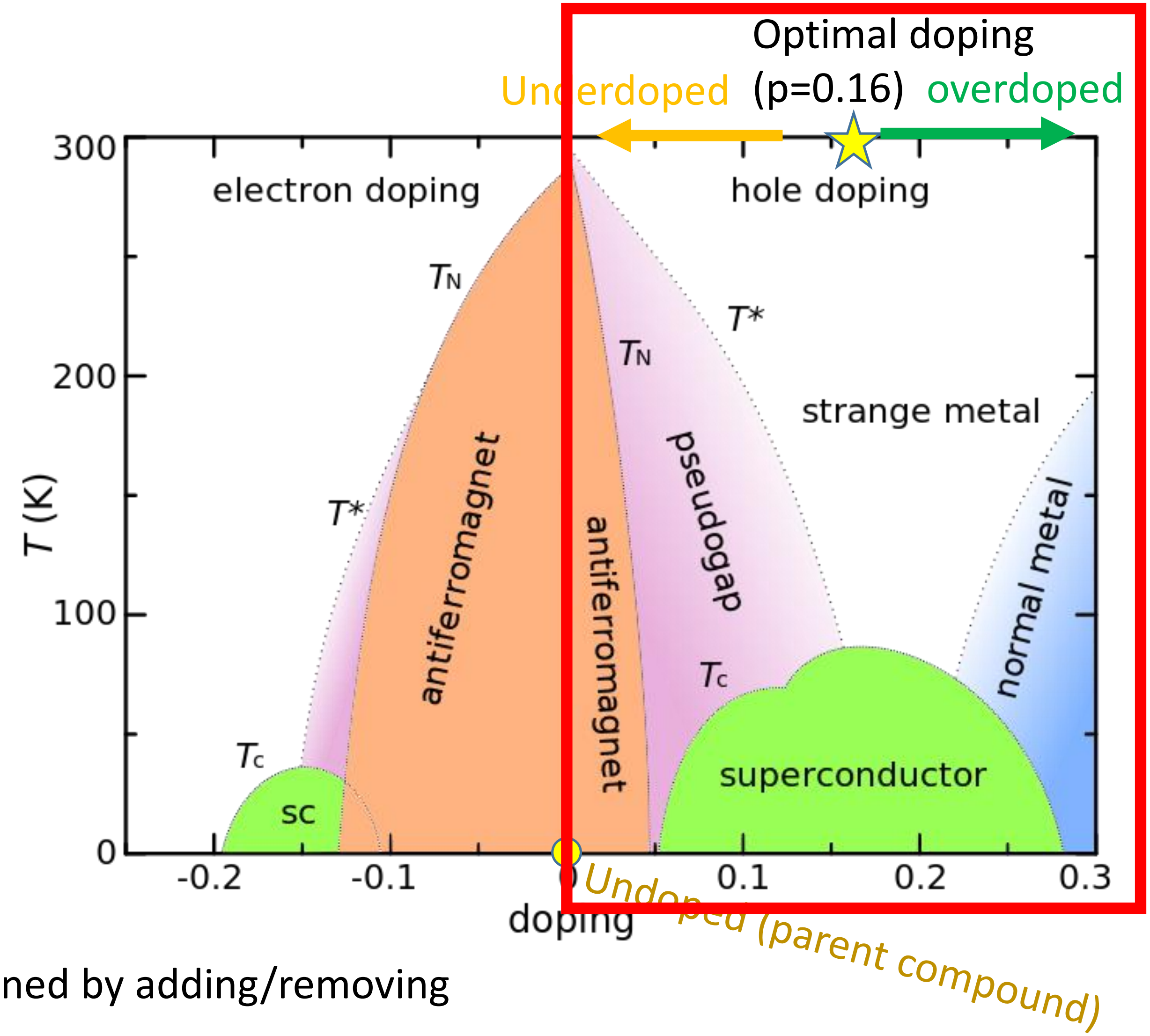
- Building blocks: CuO_2 planes
- CuO_2 planes provide near-E_F electrons which are involved in superconductivity
- Intervening layers provide doping and interlayer coupling

Realistic schematic



By James Slezak, CC-BY-SA-3.0 or CC BY 2.5 , via Wikimedia Commons

Cuprate phase diagram



Optimal doping (p=0.16)

Underdoped

overdoped

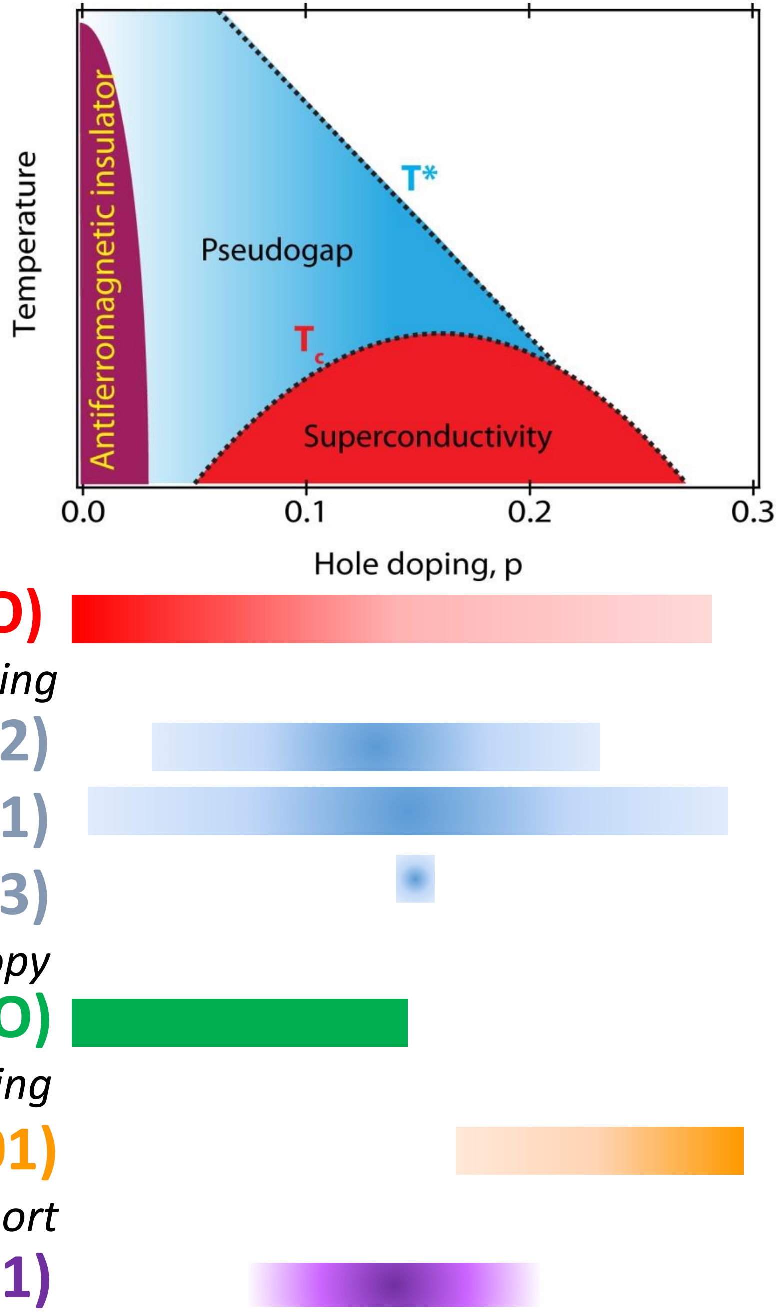
Undoped (parent compound)

- Properties tuned by adding/removing electrons
- Focus on hole-doped side for now

Image source: By Holger Motzkau - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=27862441

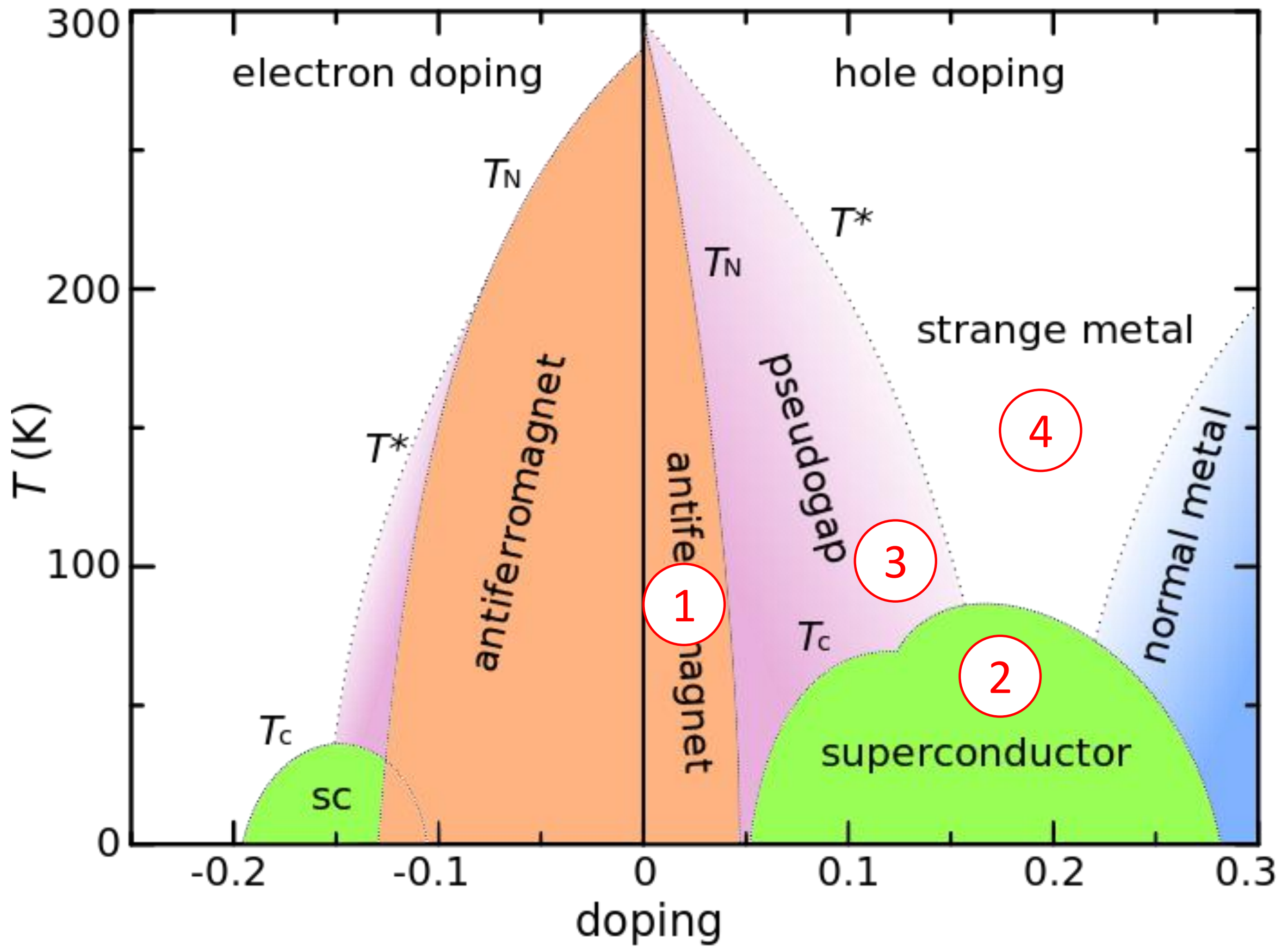
Hole-doped cuprate materials

(not an exhaustive list)

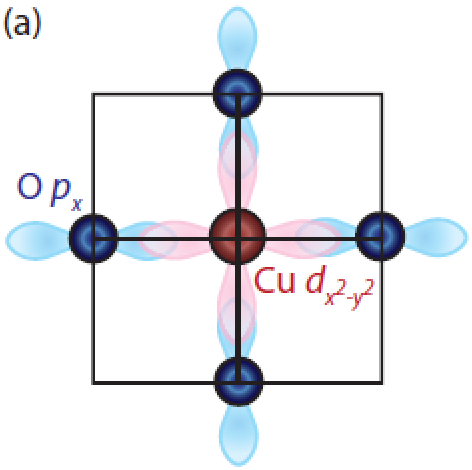


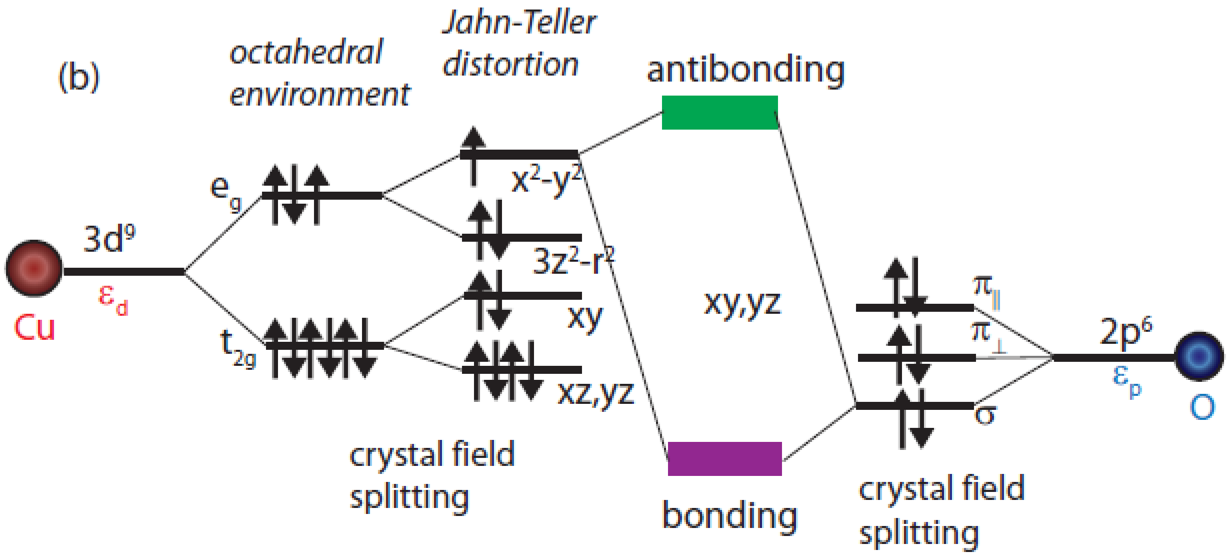
	$T_{c,max}$
$La_{2-x}Sr_xCuO_4$ (LSCO) *Neutron scattering*	36K
$Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212)	98K
$Bi_2Sr_2CuO_{6+\delta}$ (Bi-2201)	40K
$Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) *ARPES, scanning tunneling microscopy*	110K
$YBa_2Cu_3O_{7-x}$ (YBCO) *Transport, neutron and x-ray scattering*	92K
$Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201) *Transport*	95K
$HgBa_2CuO_{4+\delta}$ (Hg-1201) *Transport, neutron*	95K

Traversing the phase diagram



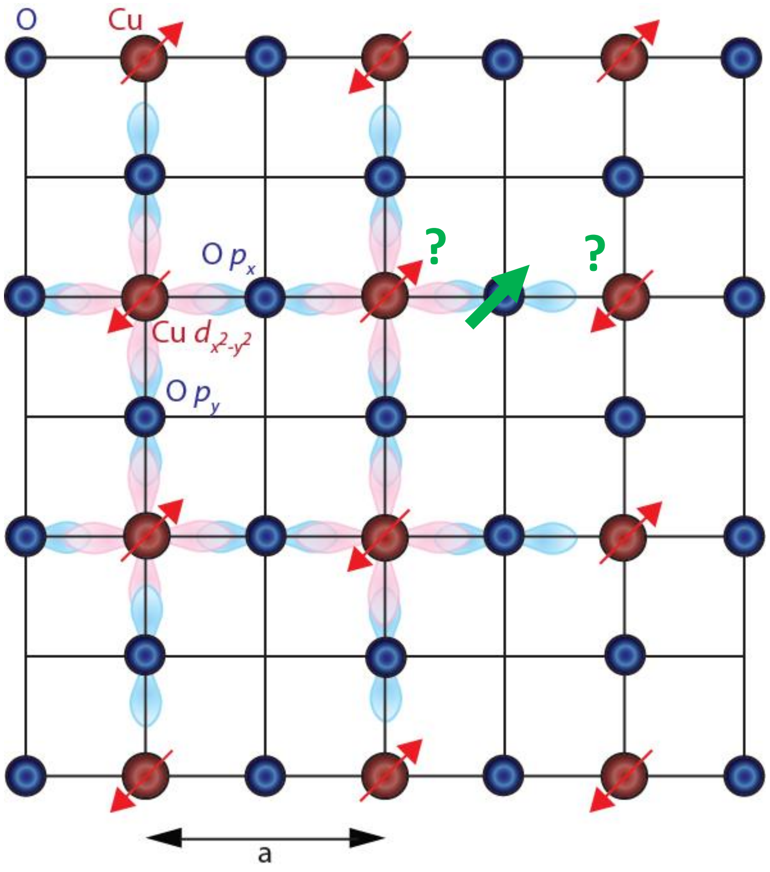
1. Antiferromagnetic **insulator**





- Cuprate electronic structure derived from $Cu - d_{x^2-y^2}$ orbitals and $O - p_{x,y}$ orbitals
- 1 electron per unit cell: expected to be a metal
- But undoped cuprates are insulators because **coulomb repulsion** causes localization
- Cuprate superconductors are examples of **strongly correlated electron materials** where pairwise **coulomb repulsion between every electron cannot be ignored**

1. **Antiferromagnetic** insulator

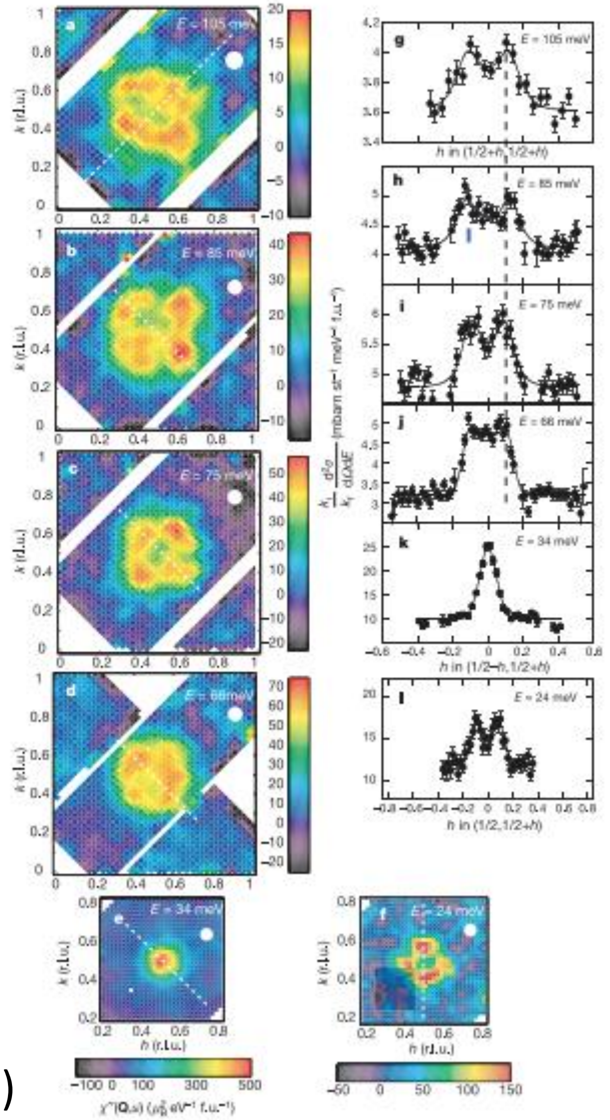


- Antiferromagnetic order on Cu site mediated by superexchange interaction through oxygen p-orbitals
- Hole doping **frustrates** magnetic order quickly killing antiferromagnetism

Echoes of parent compound

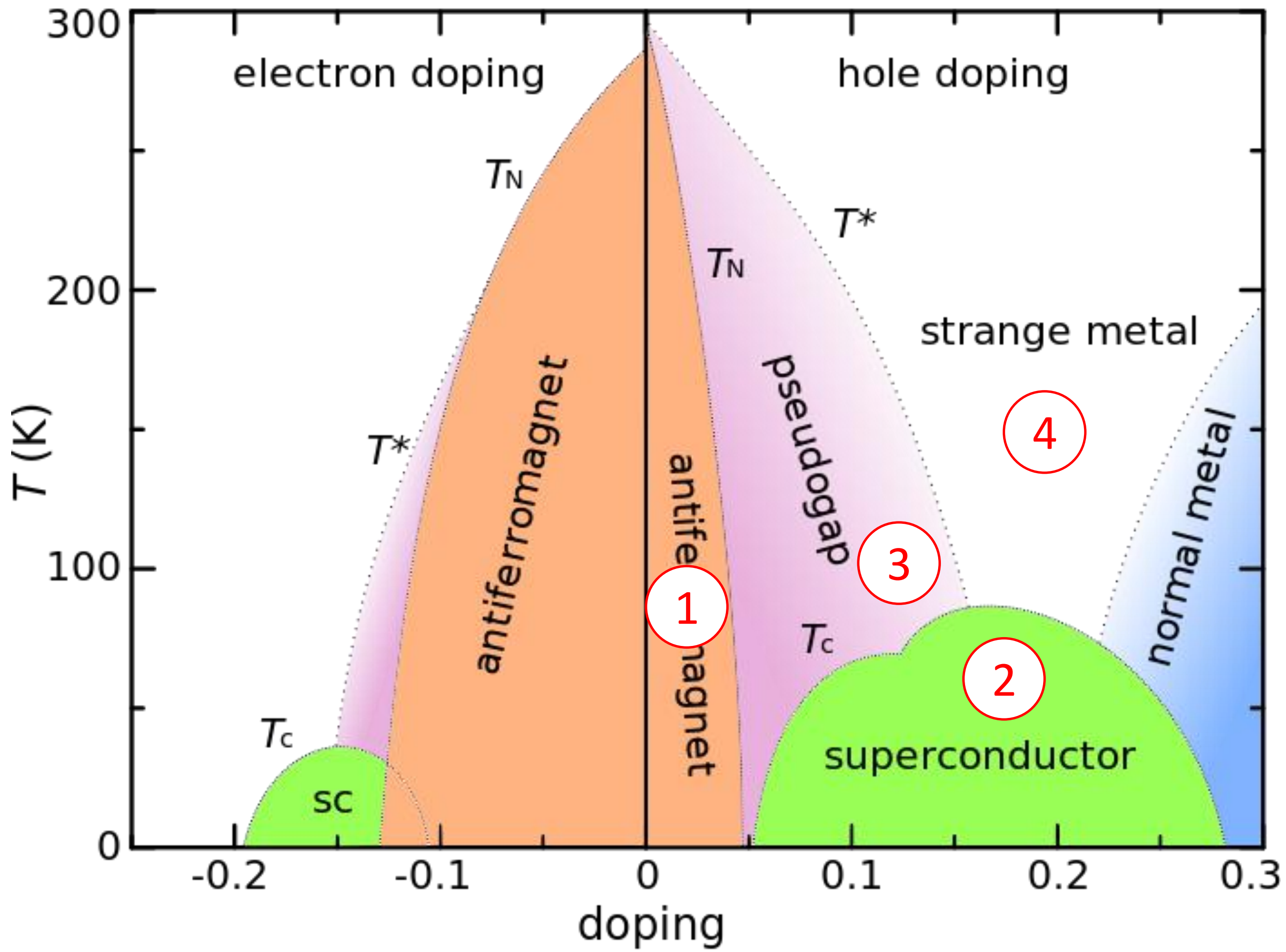
- Correlations
- Excitations near AF
    - Long range AF order: elastic scattering at **q=**(1/2, 1/2)
    - At higher dopings: inelastic scattering at **q=**$(\frac{1}{2}\pm\delta, \frac{1}{2}\pm\delta)$ often connected to possible pairing mechanism

Neutron scattering: spin fluctuations



Hayden *et al*. Nature **429** (2004)

Traversing the phase diagram



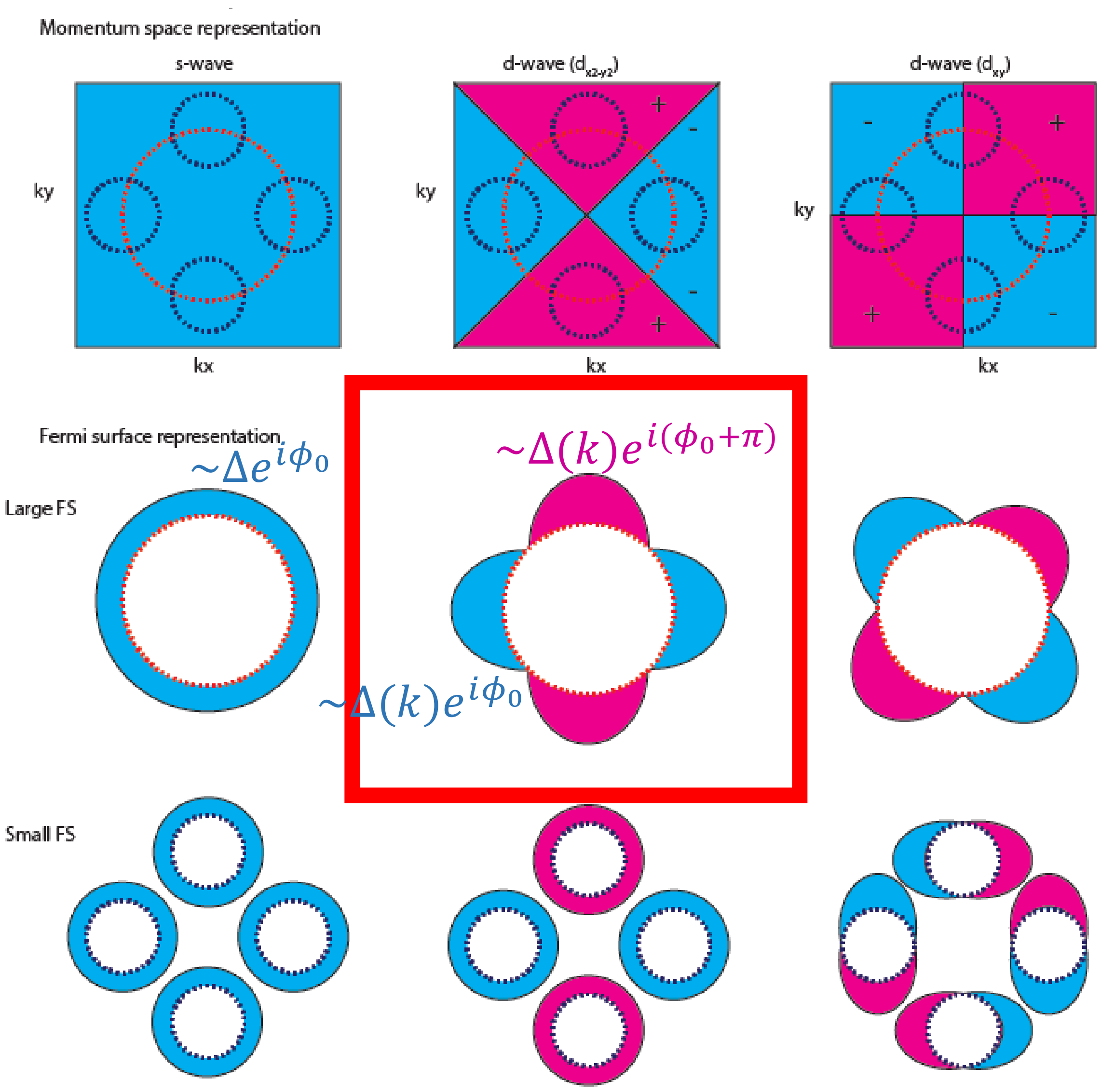
2. d-wave superconducting gap

- Superconducting wavefunction has spin part and orbital (spatial) part
- Antisymmetric spin singlet Cooper pairs are accompanied by even-parity orbital angular wavefunction (L=0, s-wave; L=2, d-wave;) and symmetric spin triplet Cooper pairs are accompanied by odd-parity orbital wave function (L=1, p-wave; L=3, f-wave;)
- For p,d,and f wave superconductors the **phase** and/or momentum-dependence of superconducting wave function matters

Name	S	L	Examples
s-wave	0	0	Nb, NbTi, Nb_3Ge, maybe pnictides
p-wave	1	1	Sr_2RuO_4
d-wave	0	2	Cuprates, probably $CeCoIn_5$
f-wave	1	3	Probably UPt_3

Good resource: Mackenzie and Maeno, Rev Mod Phys **75** (2003)

2. d-wave superconducting gap



Picture will depend on crystal symmetry and fermiology

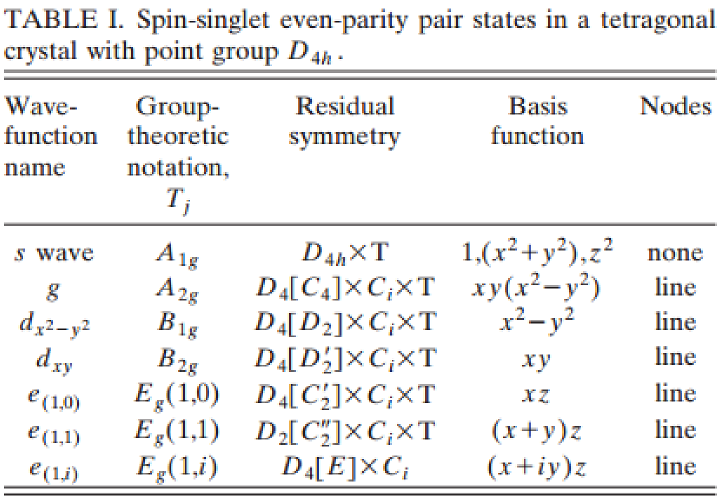
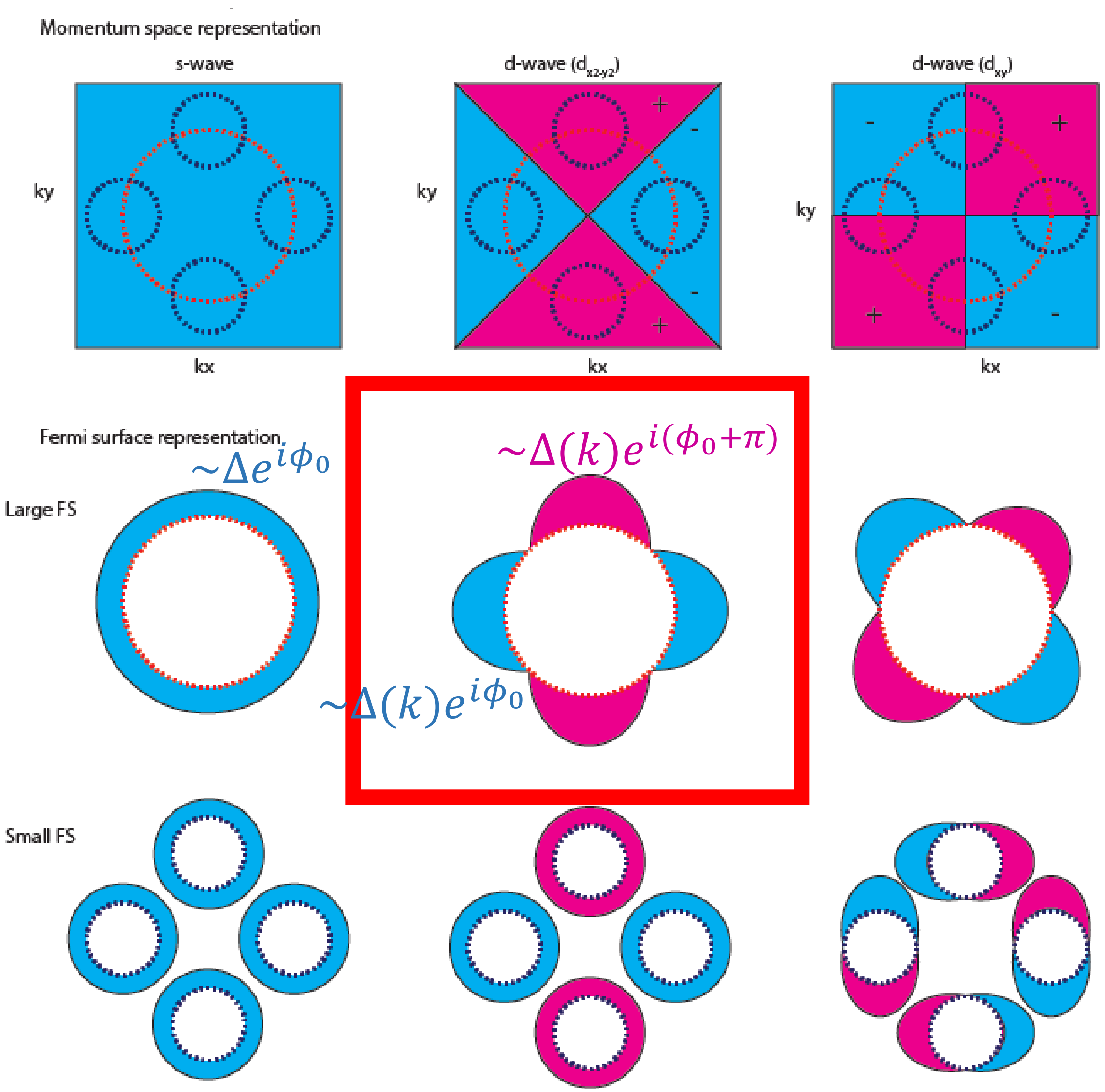


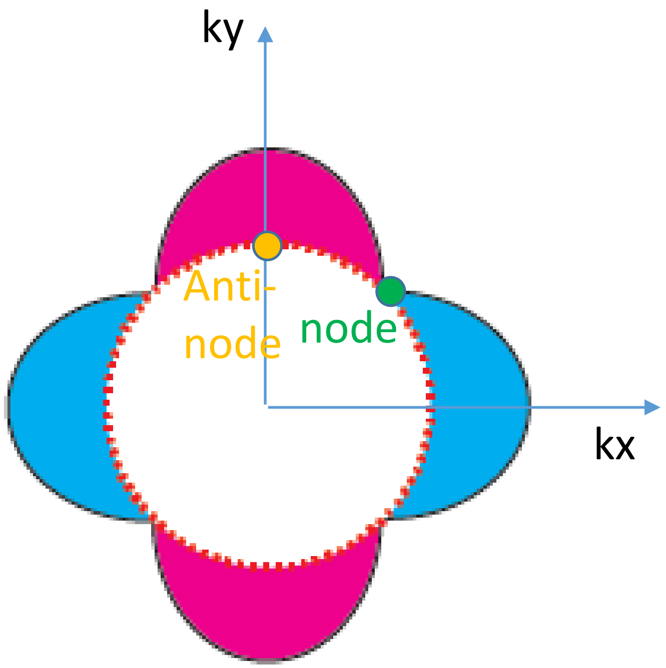
TABLE I. Spin-singlet even-parity pair states in a tetragonal crystal with point group D_{4h}.

Wave-function name	Group-theoretic notation, T_j	Residual symmetry	Basis function	Nodes
s wave	A_{1g}	$D_{4h}\times T$	$1,(x^2+y^2),z^2$	none
g	A_{2g}	$D_4[C_4]\times C_i\times T$	$xy(x^2-y^2)$	line
$d_{x^2-y^2}$	B_{1g}	$D_4[D_2]\times C_i\times T$	x^2-y^2	line
d_{xy}	B_{2g}	$D_4[D_2']\times C_i\times T$	xy	line
$e_{(1,0)}$	$E_g(1,0)$	$D_4[C_2']\times C_i\times T$	xz	line
$e_{(1,1)}$	$E_g(1,1)$	$D_2[C_2'']\times C_i\times T$	$(x+y)z$	line
$e_{(1,i)}$	$E_g(1,i)$	$D_4[E]\times C_i$	$(x+iy)z$	line

Tsuei and Kirtley, Rev. Mod. Phys. **72** 969 (2002)

2. d-wave superconducting gap



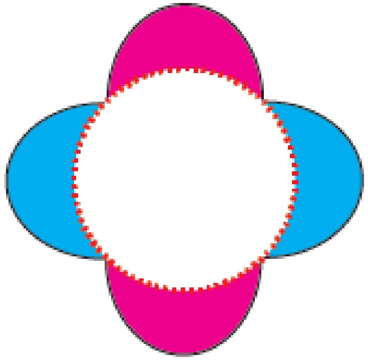


$$\Delta(\mathrm{k}) = \Delta_0(cosk_x - cosk_y)$$

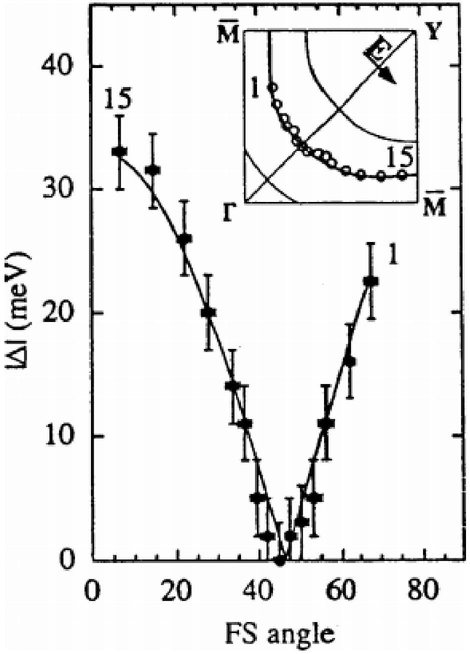
2. d-wave superconducting gap

Many different experiments, guided by theory, required to confirm gap symmetry!

- Node-sensitive spectroscopy
- Node-sensitive thermodynamics/transport
- Phase sensitive experiment

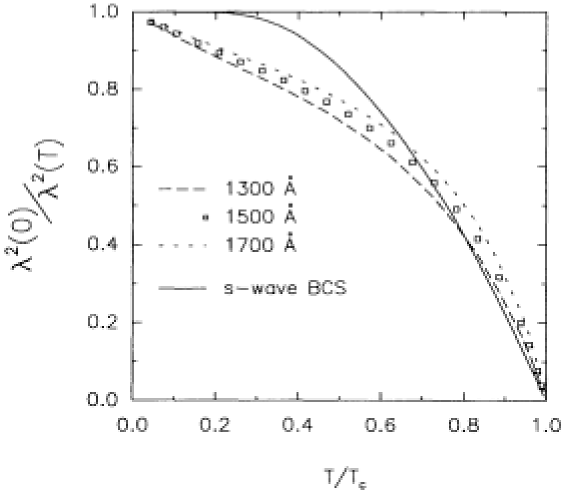


ARPES



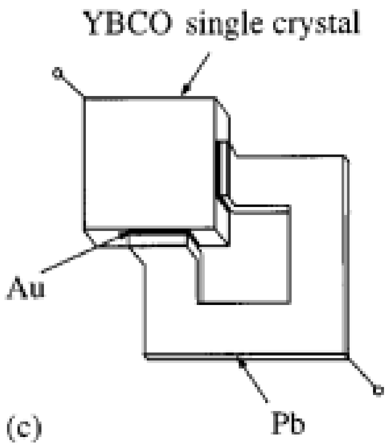
Ding *et al.* PRB (1996)

Calculation, not data!



Hardy *et al,* PRL **70** (1993)

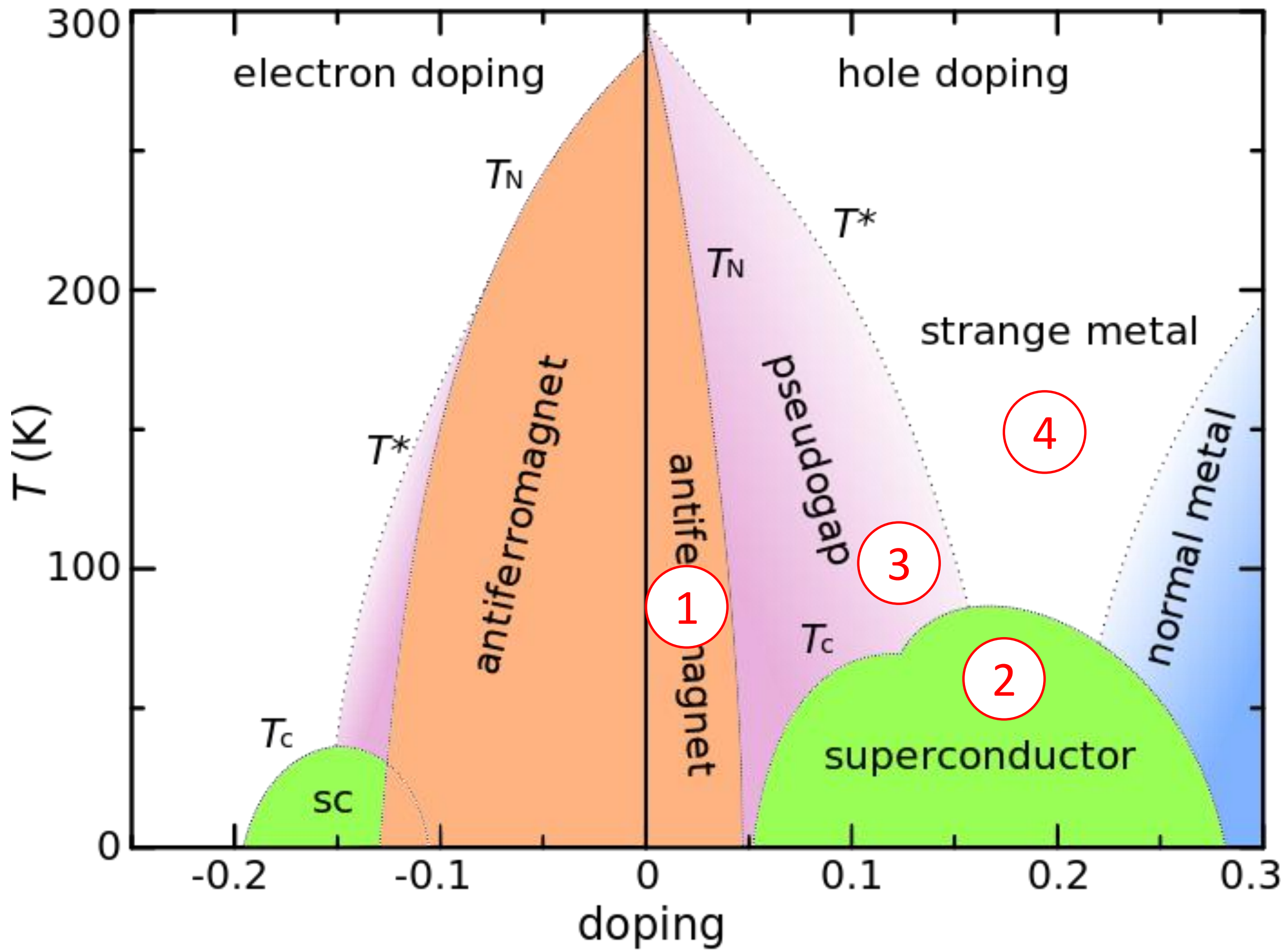
"corner SQuID"



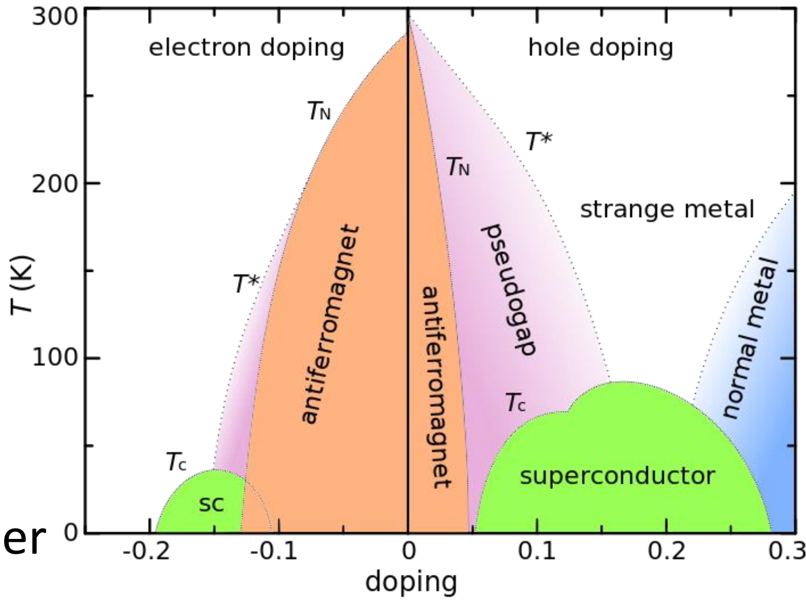
Wollman *et al.* PRL (1993)

Tsuei and Kirtley, Rev. Mod. Phys. **72** 969 (2002)

Traversing the phase diagram



3. Pseudogap



What is **a** pseudogap

- A gap whose DOS doesn't go to zero
- Depletion of DOS at E_F in the absence of order (Mott*)
- A miniminum in the DOS where the conduction and valence band of amorphous semiconductor overlap (Mott)
- A gap due to fluctuating short-range order

What is **the** pseudogap in the cuprates?

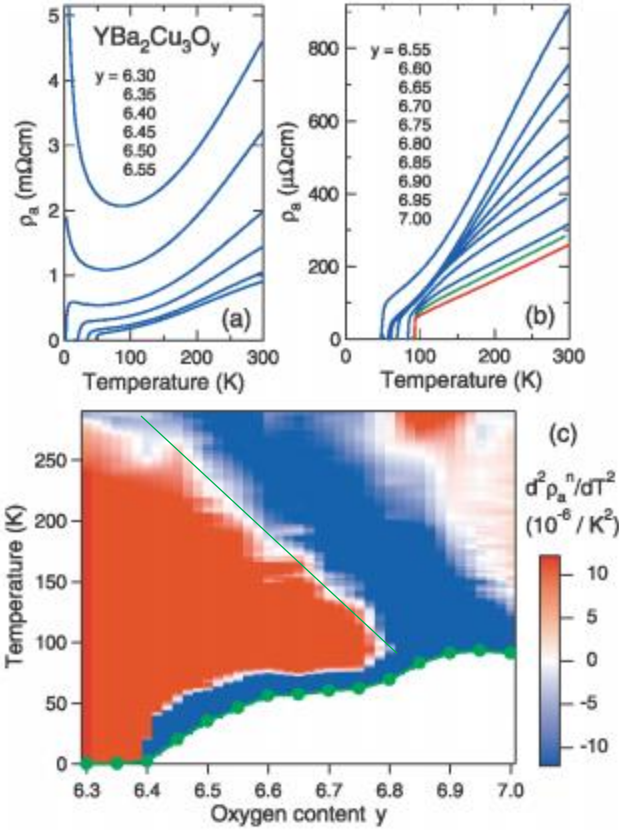
- The abnormal normal state in cuprates characterized by the properties outlined in coming slides

*Mott *et al,* Electronic Processes in non-crystalline materials, Oxford University Press (1979)

3. The pseudogap

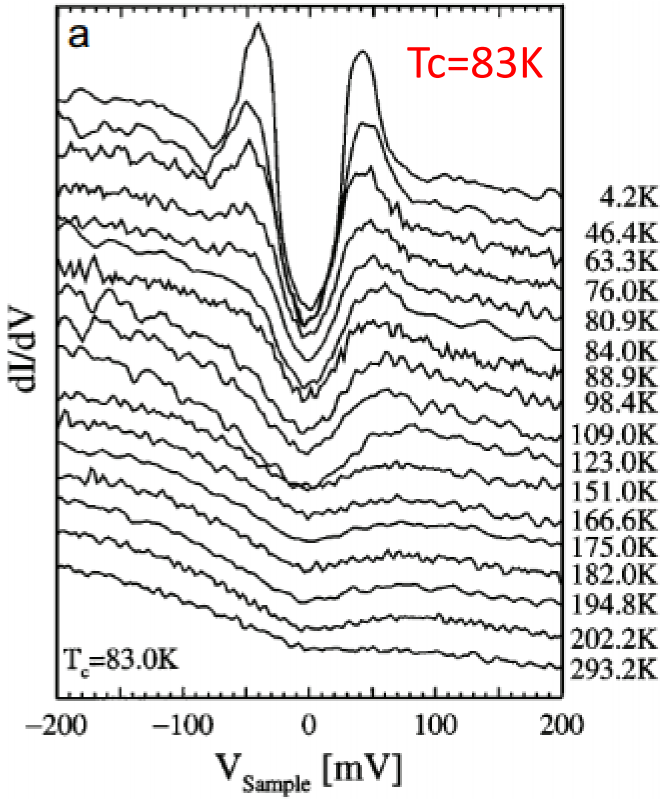
The pseudogap is apparent in every experimental technique that couples to low-energy electrons, but its identify is mysterious

In-plane resistivity



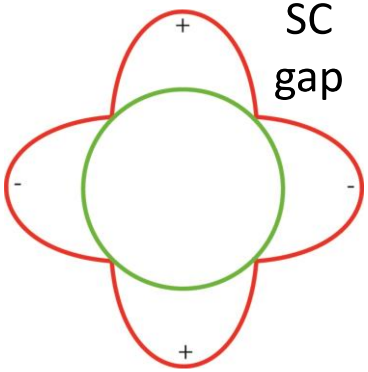
Ando et al, PRL **93** (2004)

STM

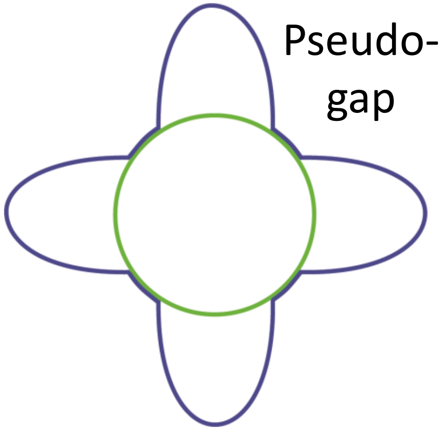


Renner *et al*, PRL **80** (1998)

ARPES



SC gap

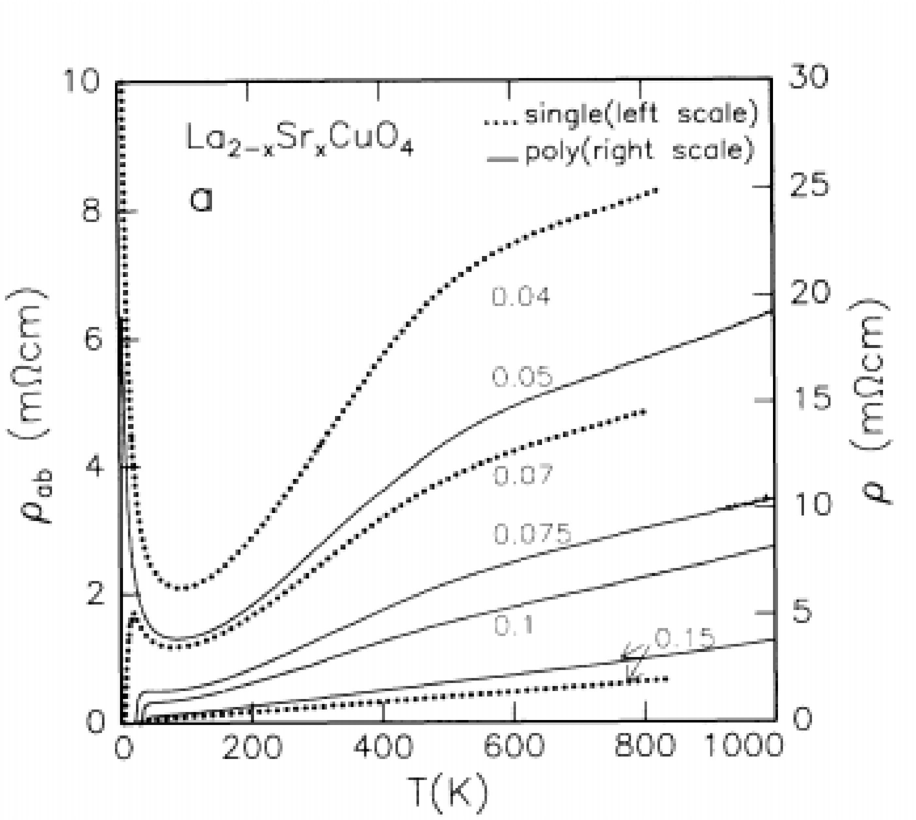


Pseudo-gap

3. The pseudogap: proposed explanations

- Phases that are well-understood in other contexts
  - Superconducting flucturations
  - CDW
- Other explanations
  - Nematic order (Kivelson + clique)
  - Orbital loop currents (C. M. Varma)
  - d-density wave (Chakravarty + Laughlin)
  - Amperean pairing (pair density wave) (P. A. Lee)
  - RVB (P. Anderson)
  - YRZ (Yang, Rice, Zhang)

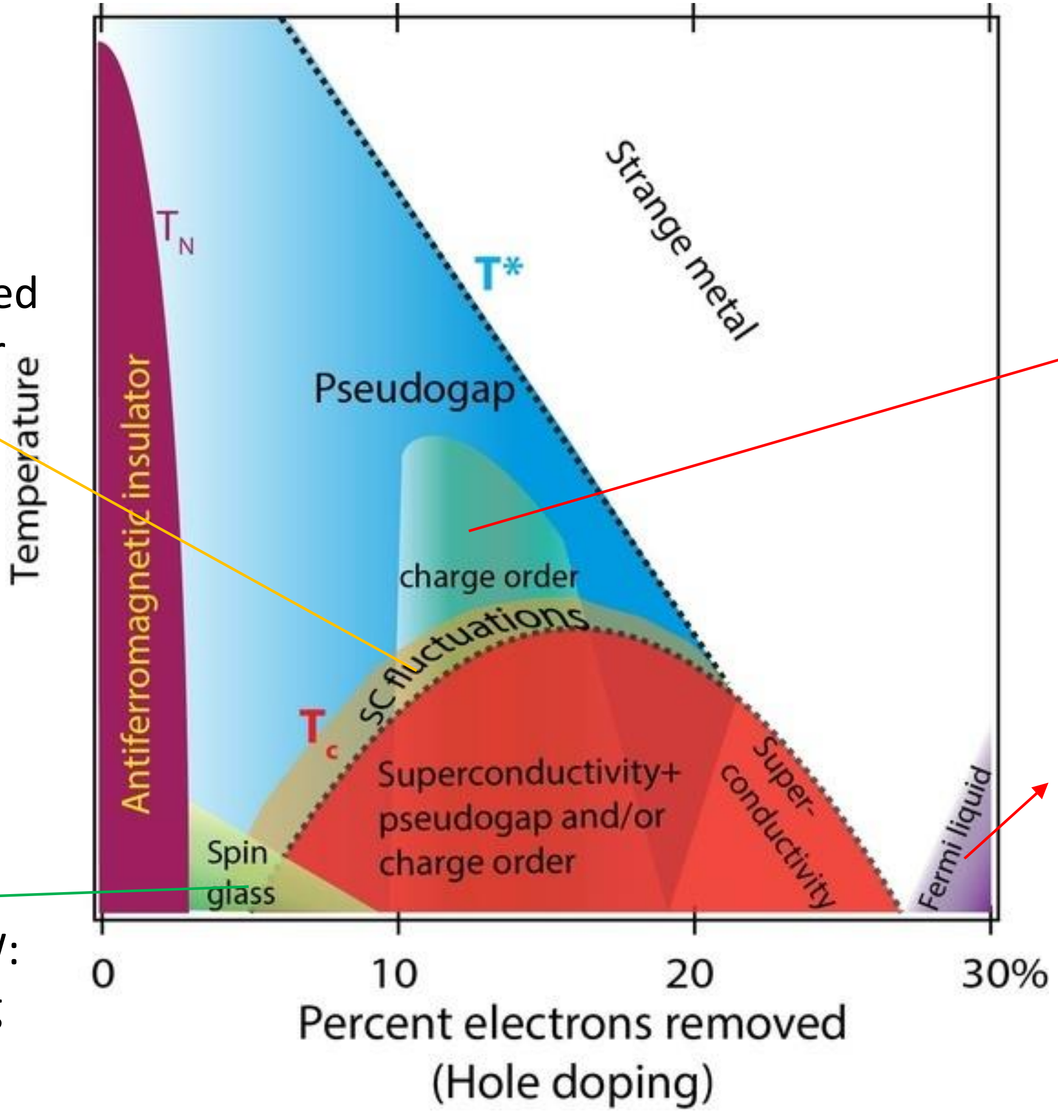
4. Strange metal



H. Takagi *et al.* PRL **69** (1992)

- Linear resistivity without saturation to very high temperatures
- mfp smaller than interatomic spacing

Other misc. phases



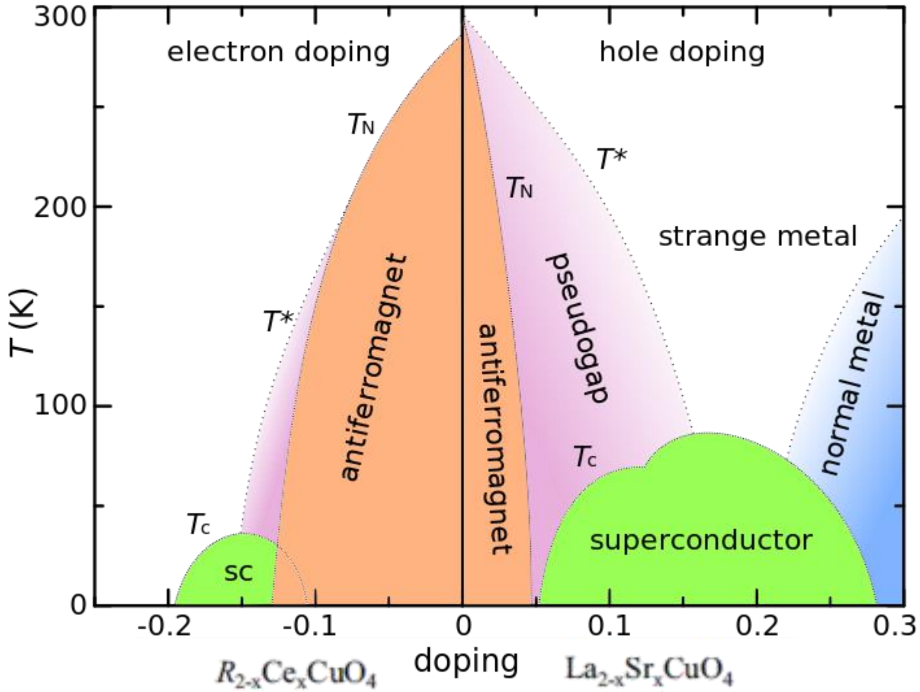
Phase-disordered superconductor

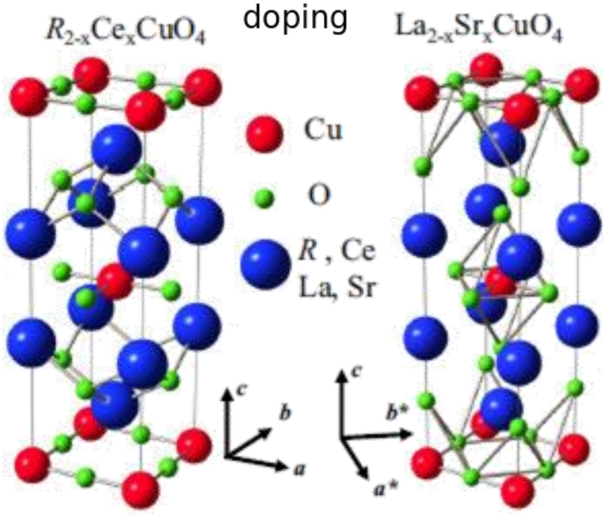
Recently, short-range charge order has been observed inside pseudogap

At high dopings, correlations are weak and ordinary metallic ground state prevails

Spin glass or SDW: slowly fluctuating short-range AF correlations

Electron-doped cuprates





- Most compounds have chemical formula $R_{2-x}Ce_xCuO_4$ (R=La, Pr, Nd, Sm)
- Slightly different superconductor
- Antiferromagnetism extends to higher doping and may coexist with superconductivity
- Antiferromagnetic correlations are important throughout phase diagram
- Likely also has d-wave superconducting gap
- Weaker correlations
- No mystery phases

Summary

- Cuprates were the first superconducting materials discovered with Tc exceeding the boiling point of liquid nitrogen
- Cuprates differ from their BCS predecessors in that the normal state is not understood and the pairing mechanism is still debated.
- Electronic correlations make the problem complicated
- Next lecture: ARPES studies of cuprates, with a focus on superconductivity and the pseudogap

Resources

- Superconductivity
  - Annet, *Superconductors, Superfluids, and Condensates*
  - Tinkham, *Introduction to Superconductivity*
- Cuprates
  - Order parameter: Tsuei and Kirtley, Rev. Mod. Phys. **72** 969 (2002)
  - STM: Fischer *et al*, Rev. Mod. Phys. **79** (2007)
  - ARPES: Damascelli *et al,* Rev. Mod. Phys. **75** (2003)
- Fun
  - L. Cooper and D. Feldman, eds, *BCS: 50 years*
  - Woodstock of physics: https://www.youtube.com/watch?v=JcprXckcGrc&list=PLgxD9DiwxLGpdSqKDIRlPjg0MoEveCKhH&index=1