The Physics of YBCO (and other high-temperature superconductors)

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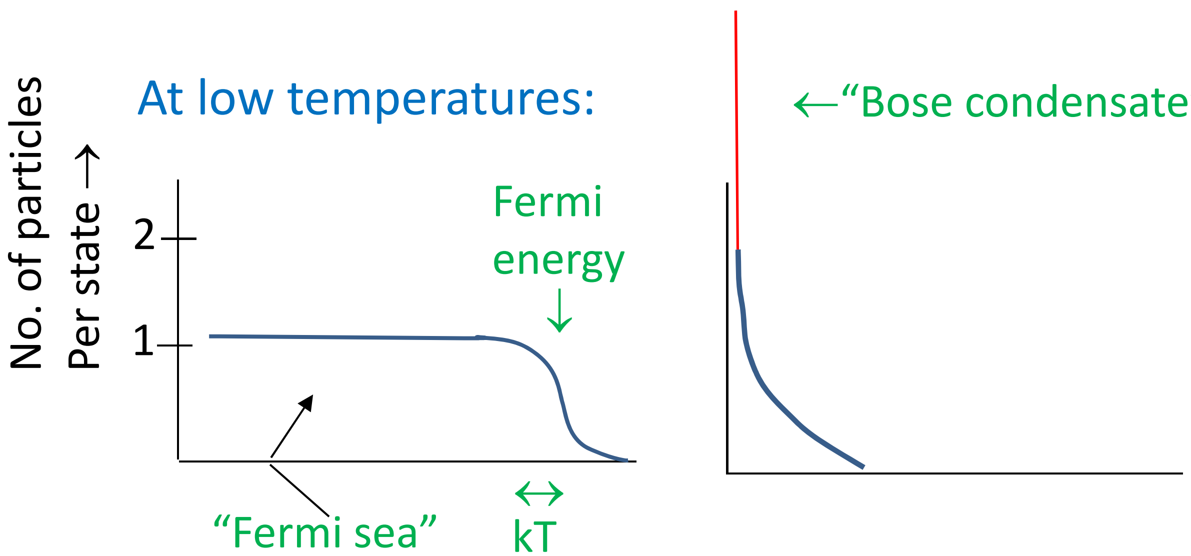
PHYSICS OF SUPERCONDUCTIVITY

"Spin" of elementary particles $= \frac{n}{2}\frac{h}{2\pi}$

$0, \; 1, \; 2....$ bosons

$\frac{1}{2}, \frac{3}{2}, \frac{5}{2} ....$ fermions

At low temperatures:



Electrons in metals: spin ½ ⇒ fermions

But a compound object consisting of an even number of fermions has spin 0, 1, 2 ... ⇒ boson.

(Ex: $2p + 2n + 2c = {}^4He$ atom)

⇒ can undergo Bose condensation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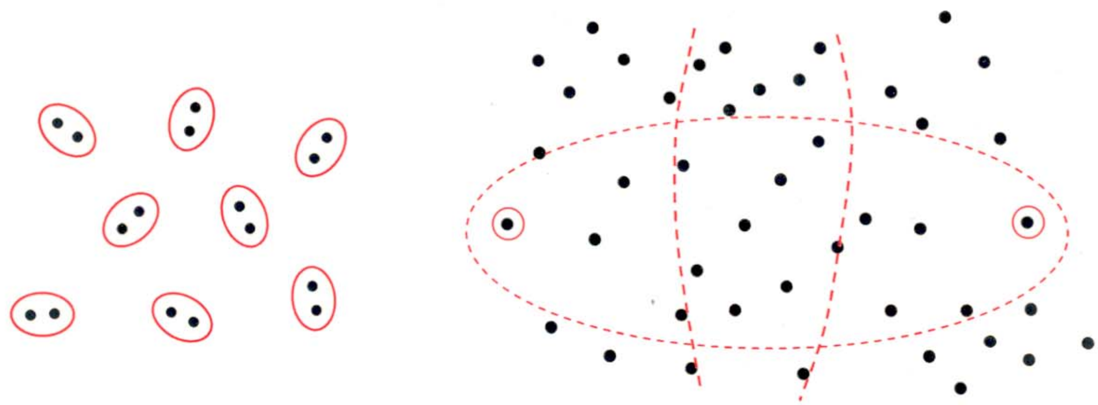
Molecule of the Year
the Bose-Einstein Condensate

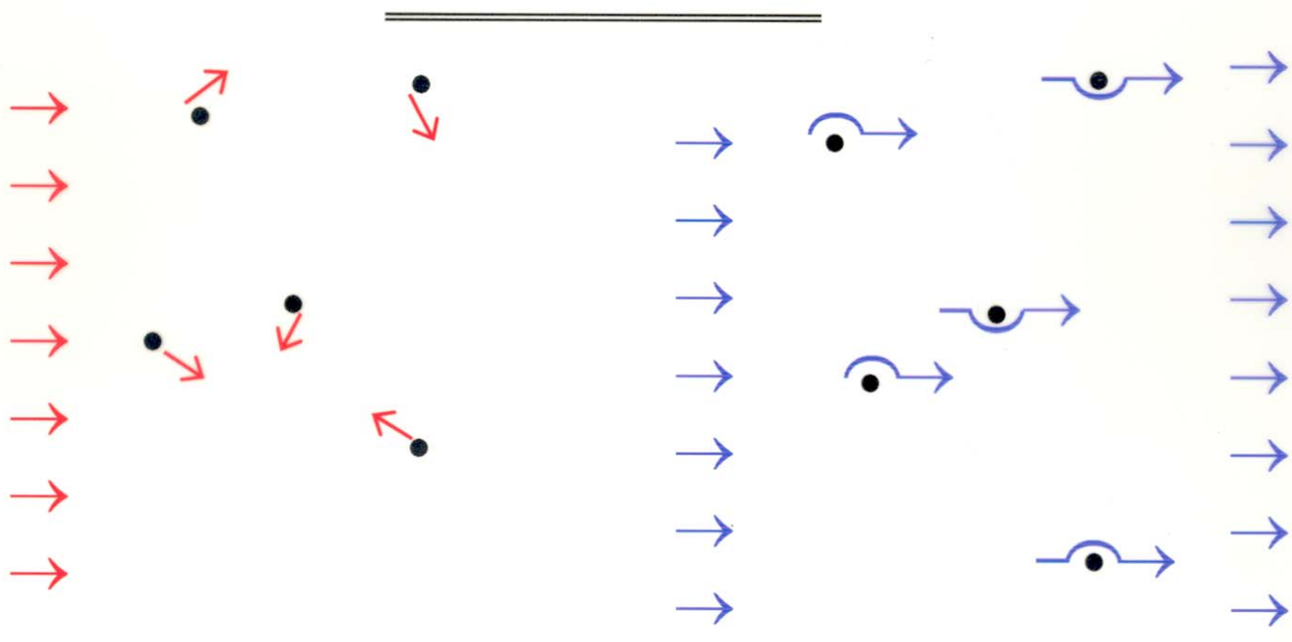
Pairing of electrons:



"di-electronic molecules" Cooper Pairs

In simplest ("BCS") theory, Cooper pairs, once formed, must automatically undergo Bose condensation!

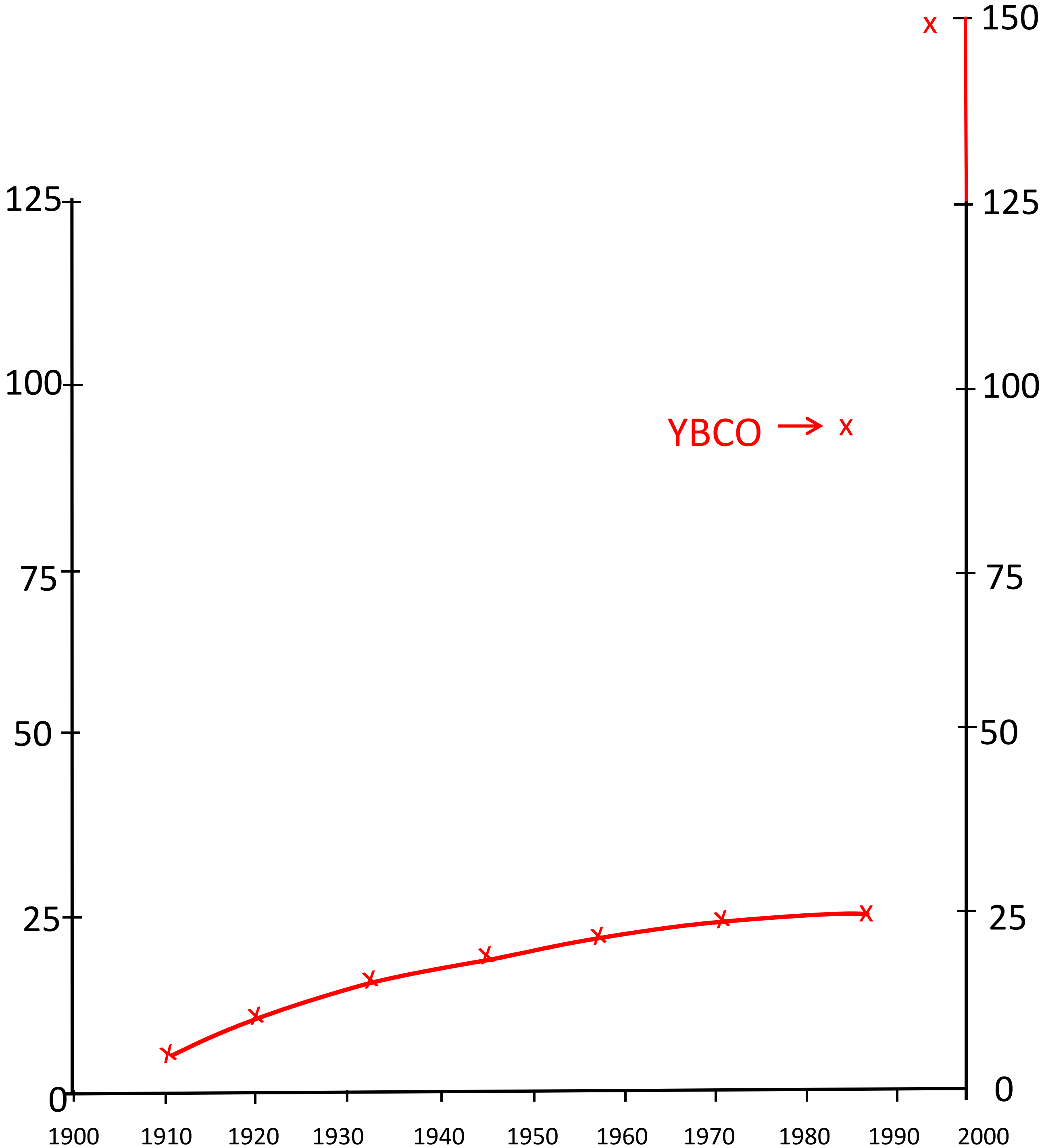
⇒ must all do exactly the same thing at the same time (also in nonequilibrium situation)



Single electrons in normal metal

Cooper pairs in superconductor

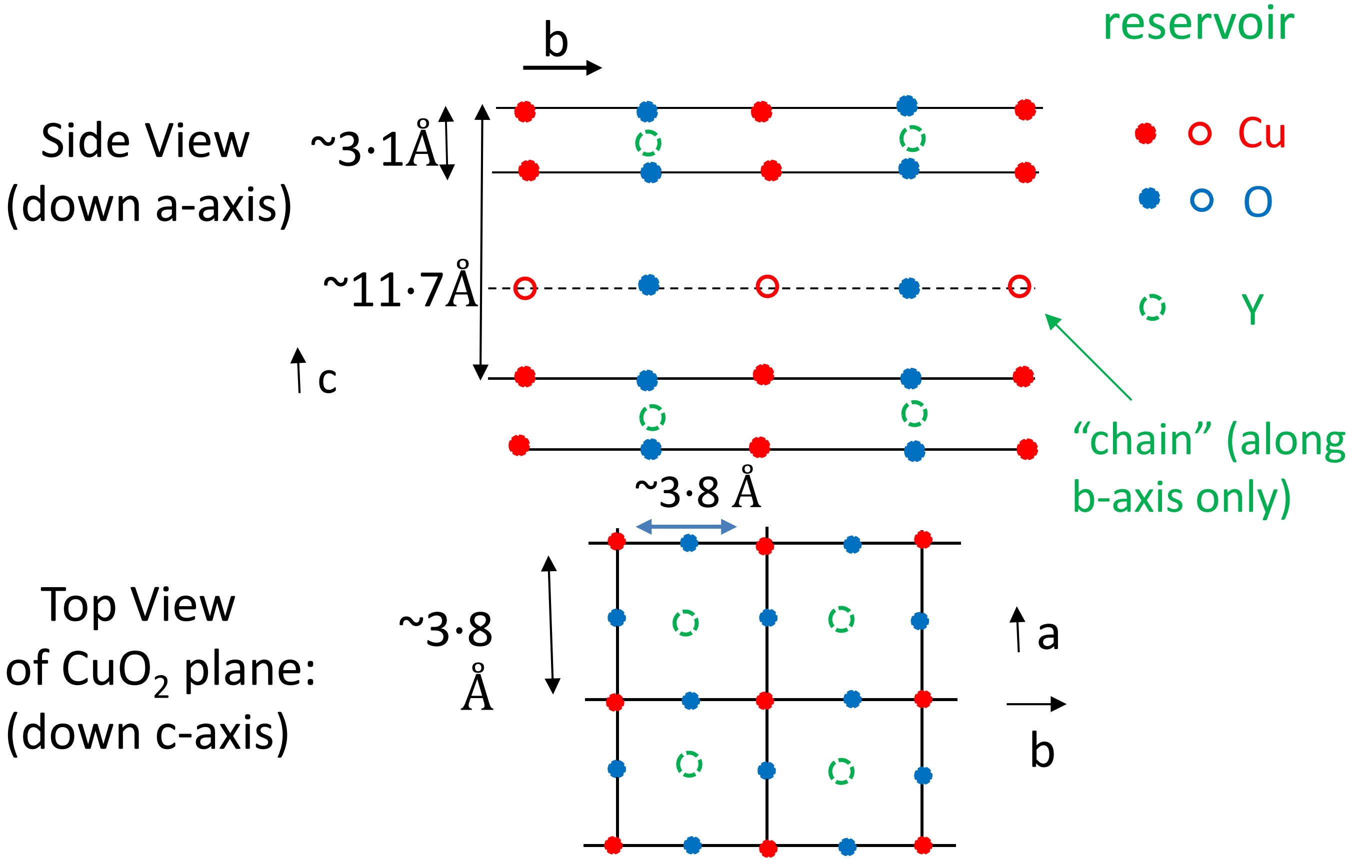
HISTORY OF THE HIGHEST TEMPERATURE ("T_c") AT WHICH SUPERCONDUCTIVITY KNOWN



$YBCO$– THE "E. COLI" (?) OF CUPRATE SUPERCONDUCTIVITY

$$YBCO \equiv YBa_2Cu_3O_{6+\delta} \equiv (CuO_2)_2\, Y(Ba_2CuO_{2-\delta})$$

planes intercalant charge reservoir



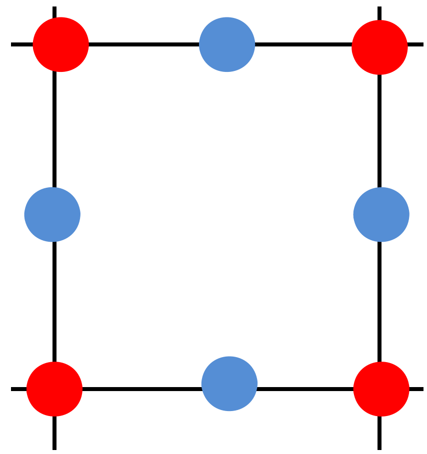
Some idiosyncracies of $YBCO$ among cuprates:

1. Relation between nonstoichiometry (δ) and doping of planar unit cell (p) complicated (contrast e.g.
$$La_2CuO_{4+\delta}, p = 2\delta)$$
2. No homologues (contrast e.g. $T\ell_2Ba_2Ca_nCu_{n+1}O_{4+3n+2}$)
3. Very non-negligible effect of chains (e.g. b-axis conductivity ≅ 2·5 a-axis one ⇒ one chain contributes as much as both planes!)

Electron States in the C_UO_2 Planes

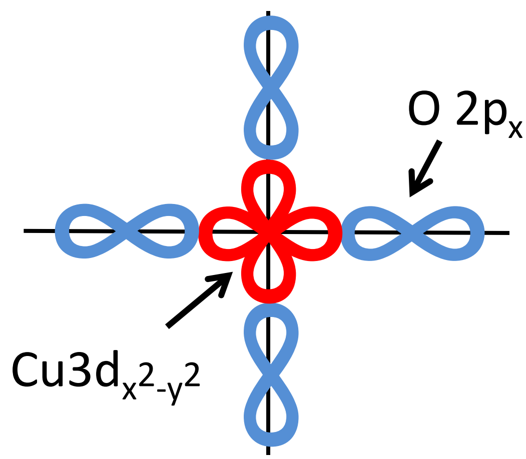
Cu: neutral atom has closed *s* and p shells plus $3d^{10}\,4s^1$

O : neutral atom has closed *s* shells plus $2p^4$

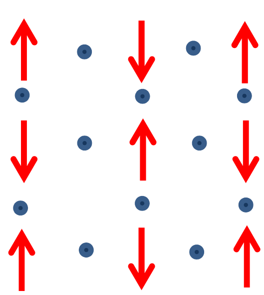


In “parent” compound $YBa_2Cu_3O_6$, Cu is ++ ($3d^9$)
O is – – ($2p^6$, closed shell), so one “hole” per CuO_2 unit.

(actually believed to be hybrid of Cu $3d_{x^2-y^2}$ and O $2p_{x,y}$ states)



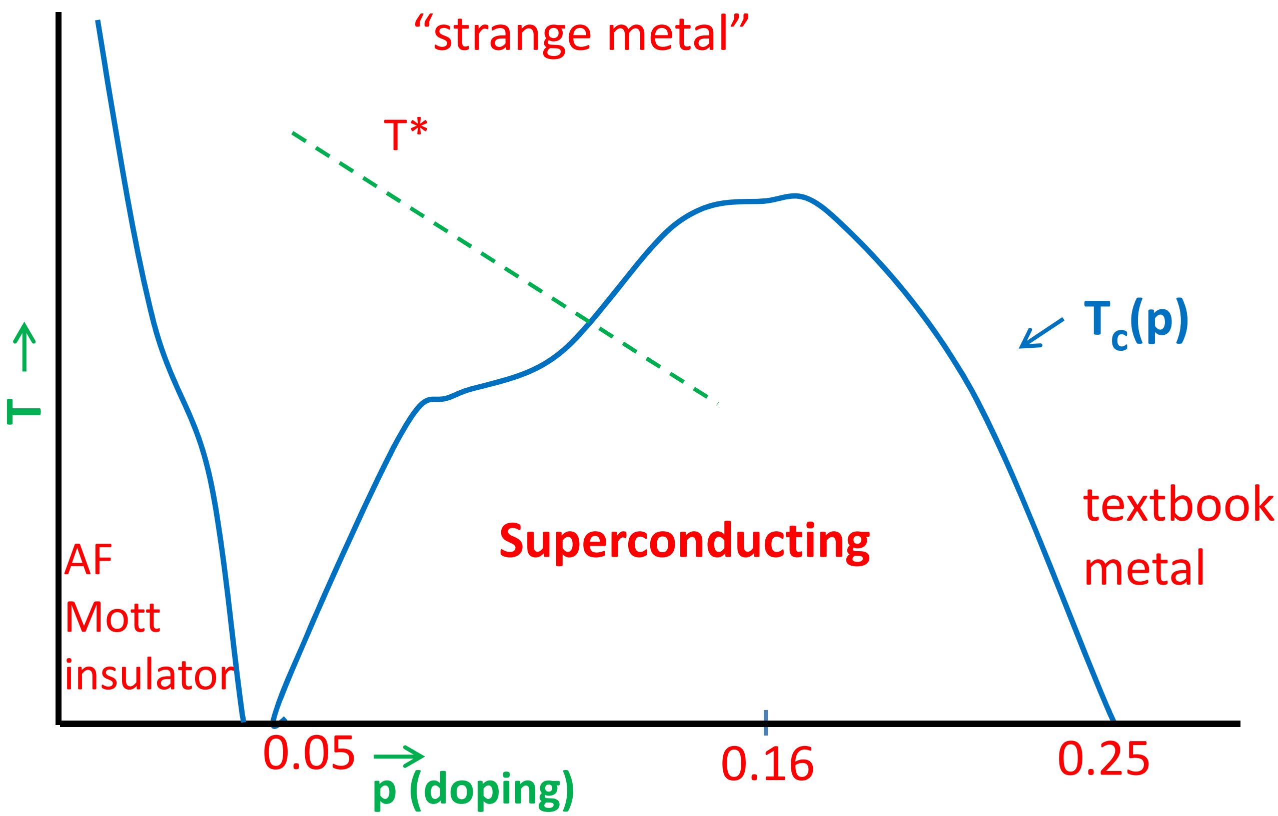
In parent compound, holes form Mott antiferromagnetic insulator:



When extra O is added (in chains) some of the extra holes created migrate to planes:

p ≡ number of extra holes per CuO_2 unit.
Almost universal belief: extra holes in CuO_2 planes are main actors in superconductivity of cuprates.

THE "CANONICAL" CUPRATE PHASE DIAGRAM (IN ZERO MAGNETIC FIELD)



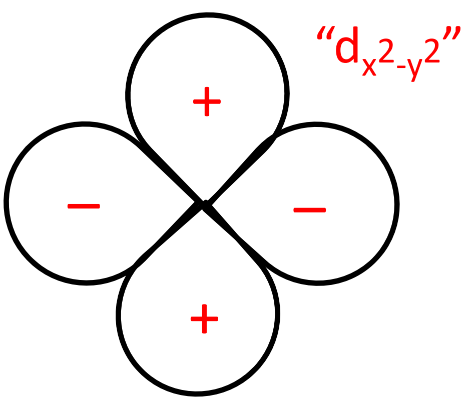
Note: (a) complete phase diagram not usually accessible in single system (including YBCO), so obtained by "pastiche"

(b) in YBCO, both superfluid density and condensation energy peak to right of $T_c^{(max)}$.

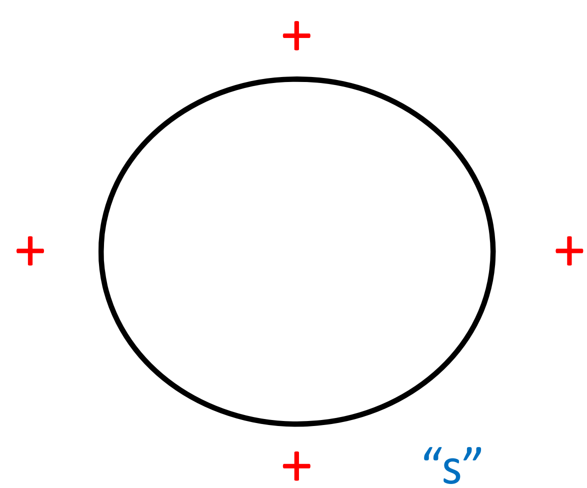
(c) nature of T* line unclear.

A Few Things We (THINK WE) Know About the Superconducting State of YBCO (and other cuprates)

1. Main locus of superconductivity is CuO_2 planes.
2. Mechanism of superconductivity is (as in traditional superconductors) formation and (pseudo-) Bose condensation of Cooper pairs.
3. Phonons (mostly) unimportant.
4. Primary mechanism of formation of Cooper pairs is single-plane (or at most single – multilayer).
5. Nature of Cooper pairs:
   (a) size: ~ 15-30 Å (contrast ~10^4 Å for Al!)
   (b) formed from time-reversed states (as in c.s.*)
   (c) spin state is singlet (↑↓-↓↑) (as in c.s.)
   (d) orbital state:



Contrast c.s.:



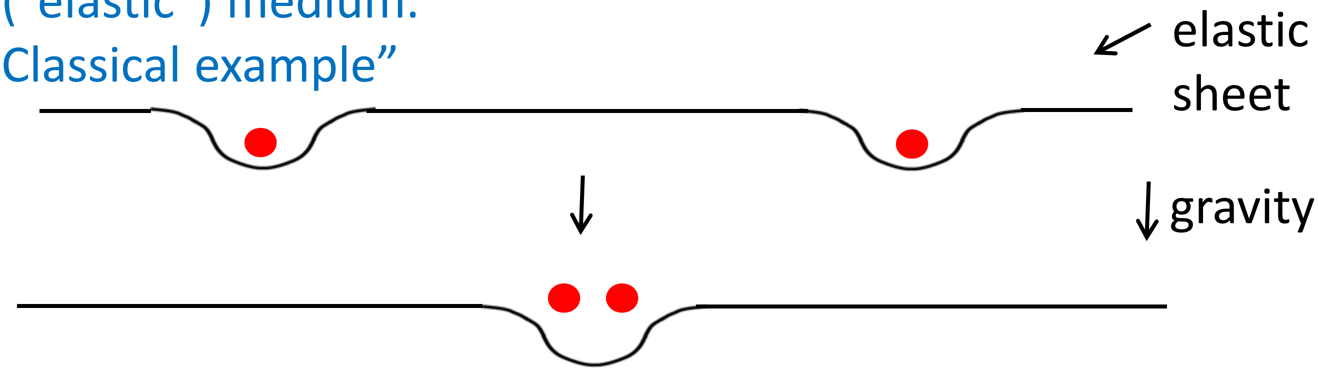
*conventional superconductor

The $64K question: What is the "Mechanism" of Formation of Cooper Pairs?

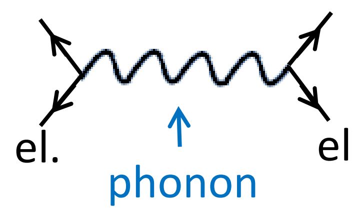
Scenario no. 1: Start with (nearly) noninteracting electrons.
provide mechanism of attraction.

One familiar way of doing this: couple linearly to deformable ("elastic") medium.

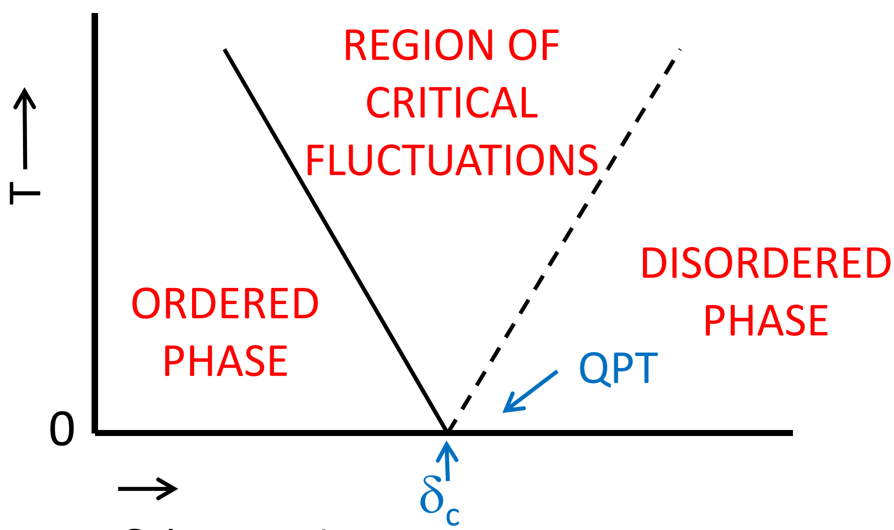
Classical example"



QM version of this is exchange of virtual low–energy excitation e.g. in traditional superconductors, a phonon:

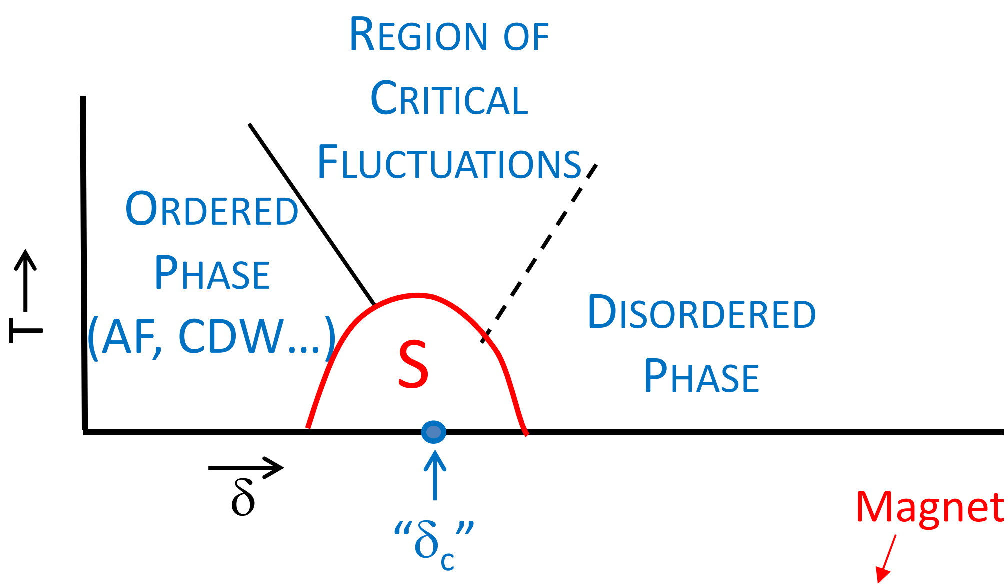


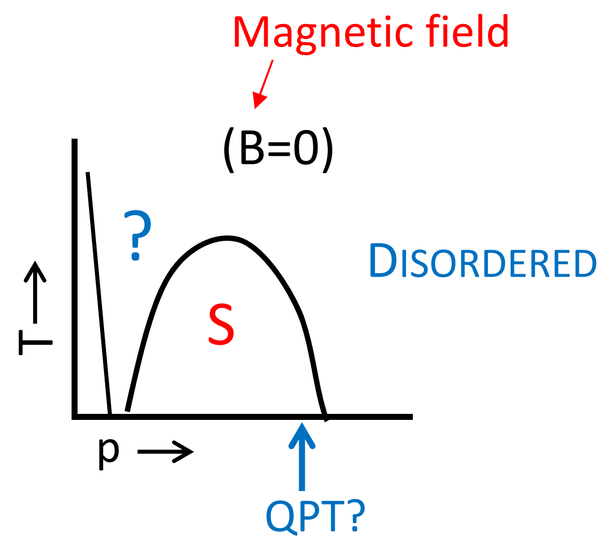
A plausible source of low-energy excitations : "quantum phase transition" (QPT)



δ (control parameter, e.g. pressure, magnetic field, doping….)

A Ubiquitous Phenomenon in Quasi-2D Systems (Heavy Fermions, TM Chalcogenides, Ferropnictides...)

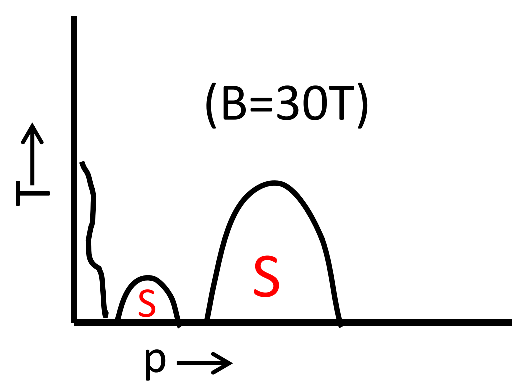




So, in cuprates,

(1) is there a QPT underlying the superconducting dome?
(2) if so, what is the nature of the ordered phase (and why is it so difficult to see directly)?
(3) is the mechanism of superconductivity the exchange of low–energy fluctuations associated with the QPT?

Very recent input: in high magnetic fields superconductivity dome splits ⇒ two different ordered phases??



Scenario no. 2: Start with strongly interacting electrons (i.e. with strong Coulomb repulsion), and by forming Cooper pairs reduce Coulomb repulsion. (e.g. by enhancing screening).

In any case, Coulomb energy is a sum of contributions from different q, ω. So:

(a) at the N$\rightarrow$S transition, is Coulomb energy saved or expended?

(b) in either case, in which regions of q and ω does most of the saving/expenditure occur?

Can in principle answer by electron energy loss spectroscopy (EELS) experiments – now starting.

SOME MAJOR UNKNOWNS ABOUT CUPRATE (and other high-temperature) SUPERCONDUCTIVITY:

1. Why is 2-dimensionality so important?
2. Why is proximity to a QPT so important?
3. Why is multiplicity of CuO_2 planes so important?
4. Will we ever find a robust room-temperature superconductor
   (a) in a cuprate or cuprate-related material
   (b) somewhere completely different?