High-Temperature Superconductivity and Strong Correlations

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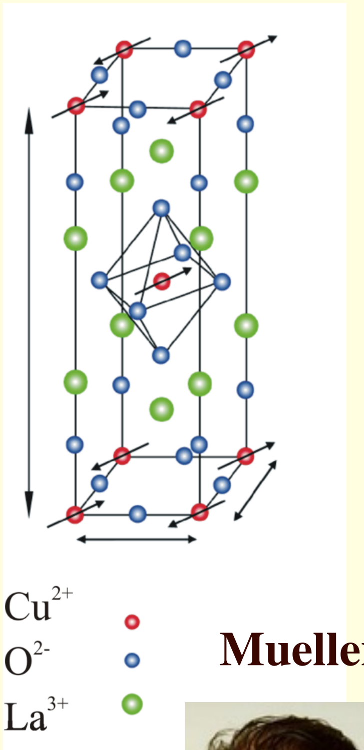
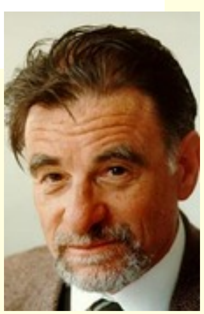
Outline

- High-T_c superconductivity: A general survey
- High-T_c cuprates as strongly correlated electron systems
- Mott physics: Basic organizing principles
- Examples
- Understanding of the phase diagram
- Summary and conclusion

Discovery of high-T_c superconductors

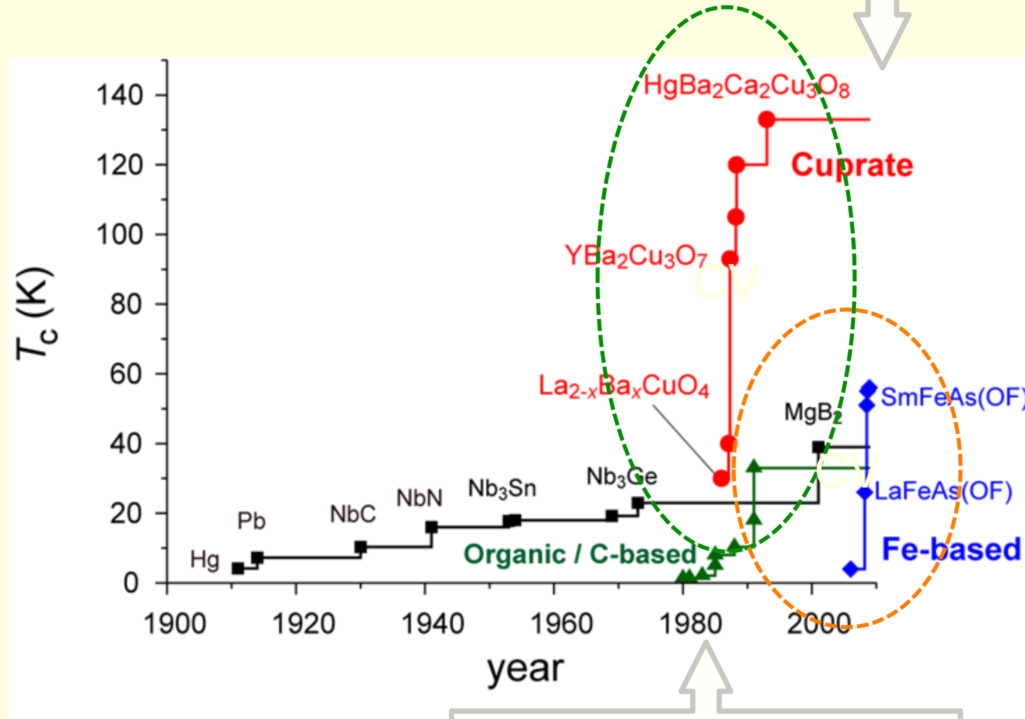


Mueller



Bednorz

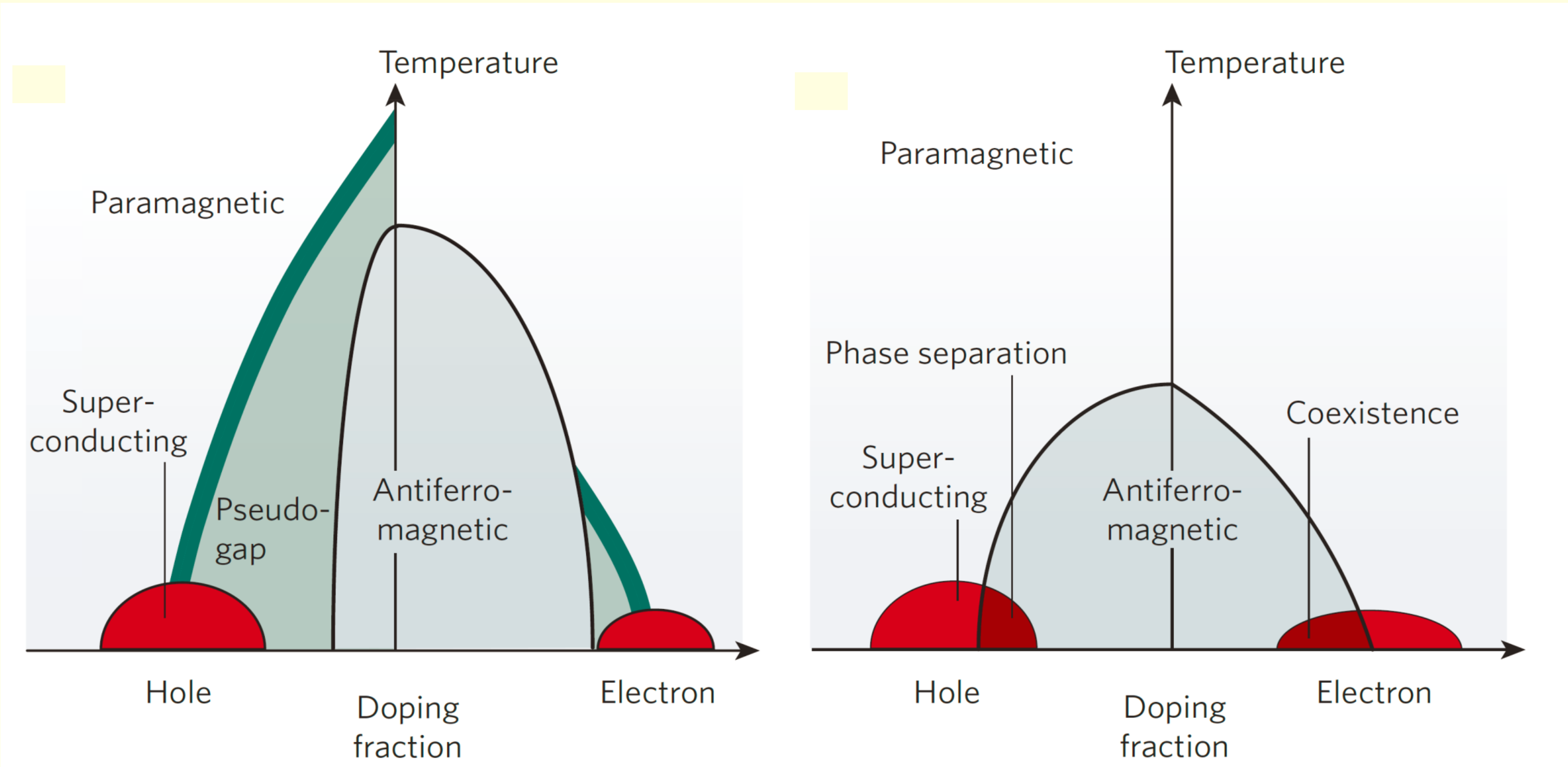
2008 Fe-based



1986 Cu-based

Phase Diagram of High Temperature Superconductors

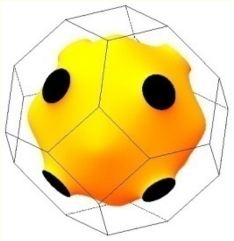
Cu-Based Superconductors **Fe-Based Superconductors**



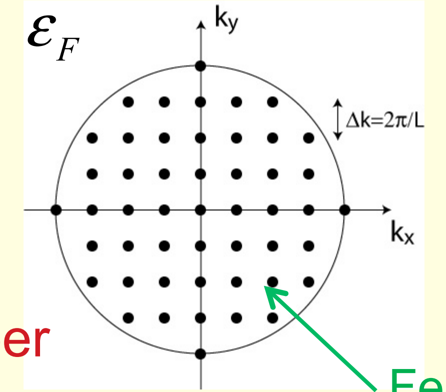
charge doping only

charge doping, isovalence doping, pressure,

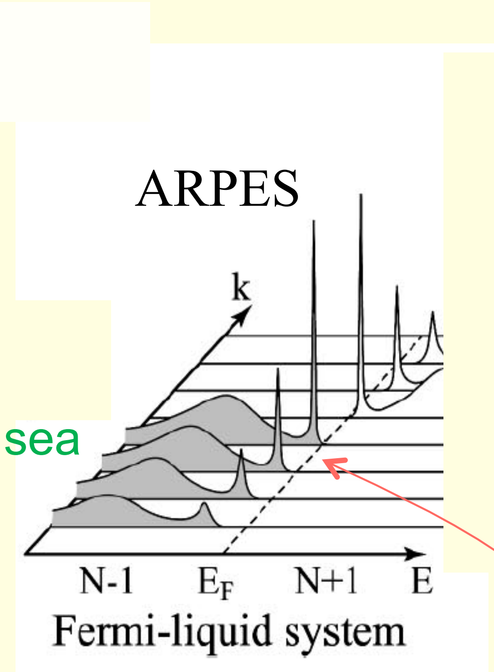
Landau paradigm



Fermi surface of copper

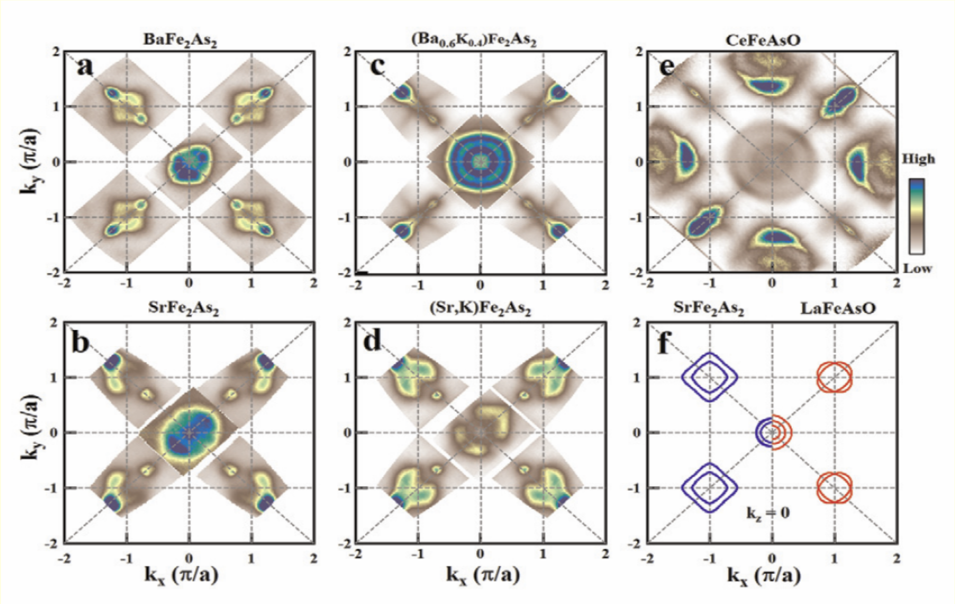


Fermi sea



$$\varepsilon_k \, , \; Z_k$$

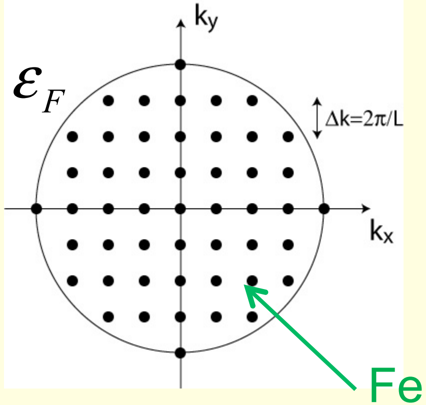
Fe-based SC

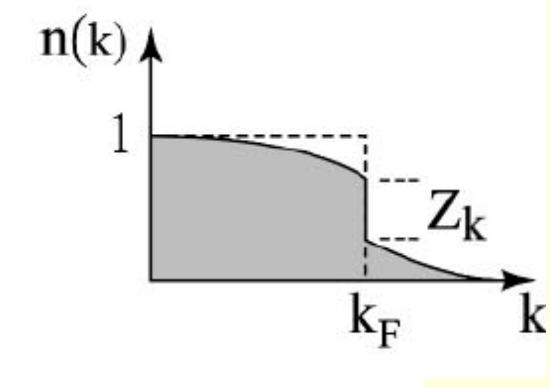


X. J. Zhou et al.

Phys. Status Solidi A (2010)

Landau's Fermi Liquid





Fermi degenerate temperature $T_F = E_F / k_B$

$E_F \sim 1eV \approx 10{,}000K$

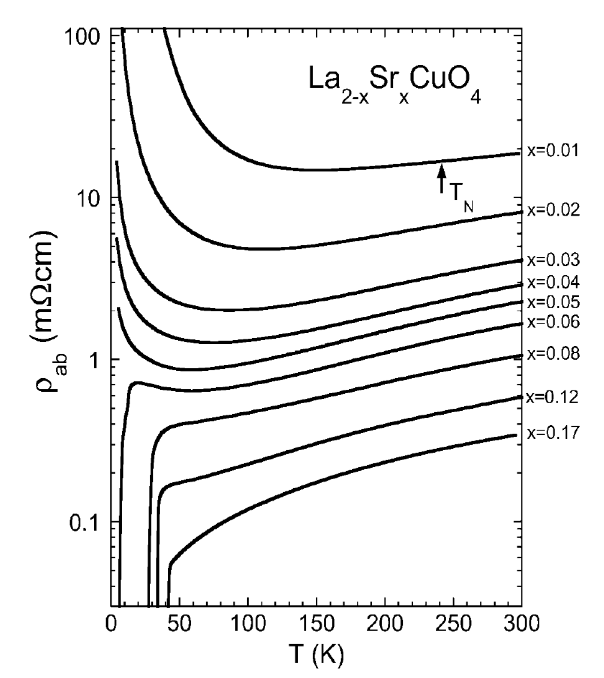
$T << T_F$ typical Fermi liquid behavior:

$\rho \propto T^2 / E_F$	Quasiparticle
$C_v = \gamma T$	Sommerfeld constant
$\chi_s = const.$	Pauli susceptibility
$1/T_1 \propto T$	Korringa behavior

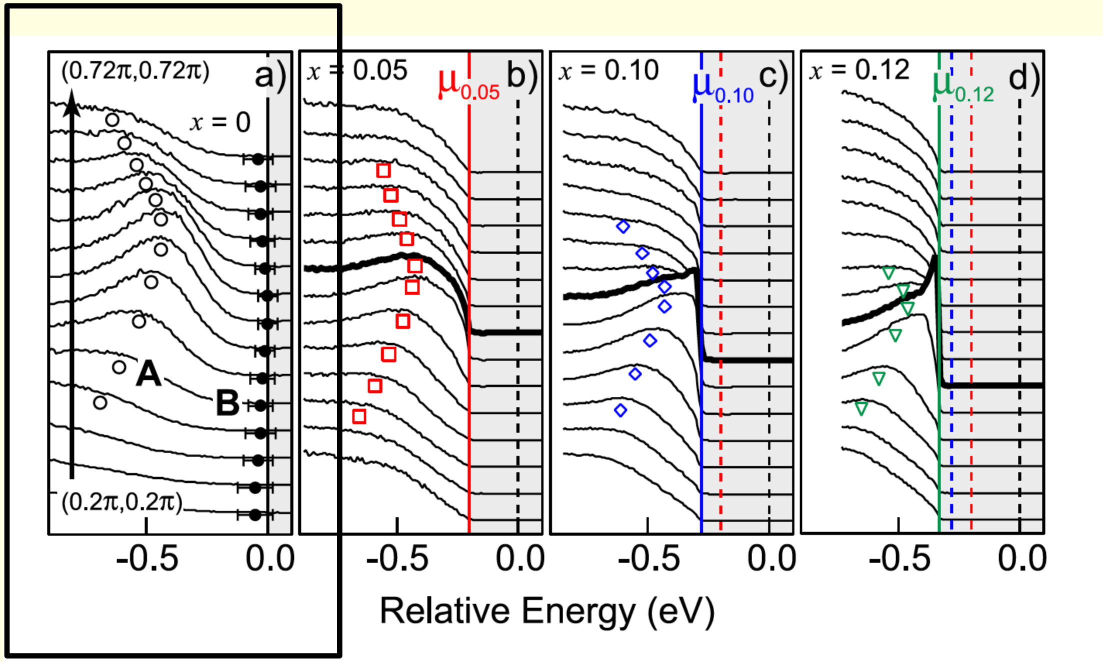
Cuprate superconductors

charge localization
at low doping

ARPES result: A broad peak at x=0



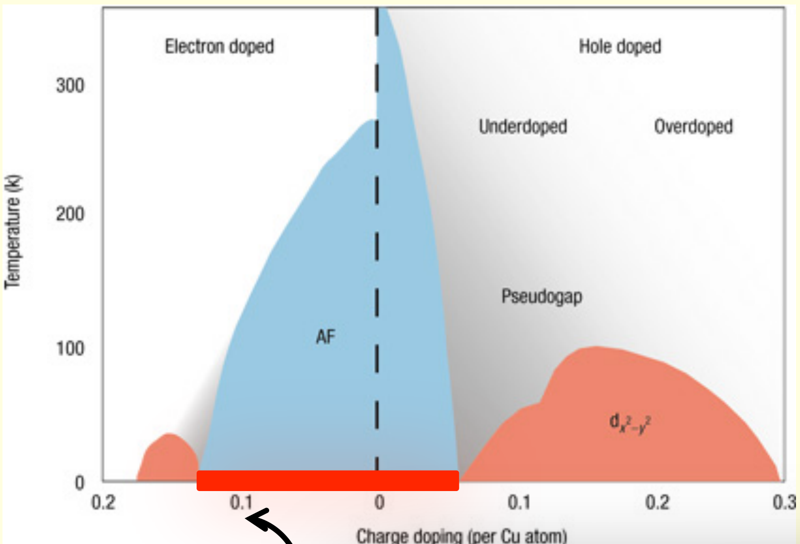
$Ca_2CuO_2Cl_2$

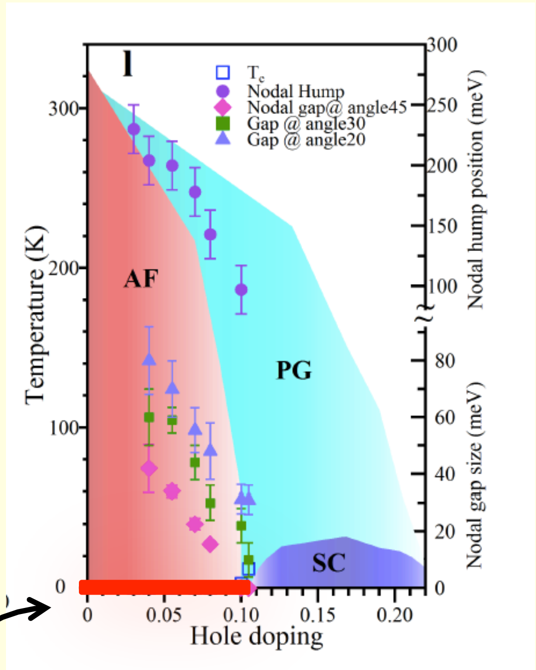


Ando et al, PRL 87, 017001 (2001)

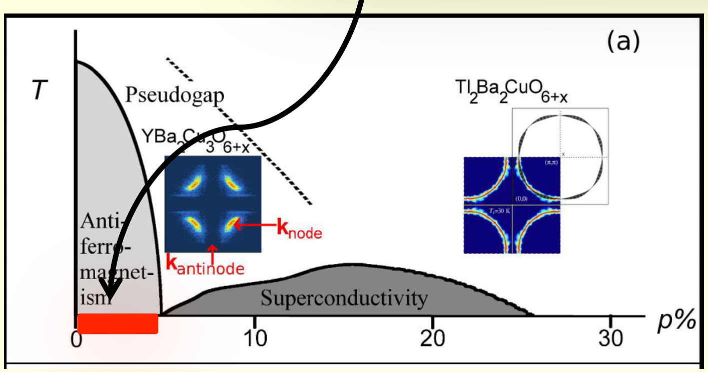
K. M. Shen et al, PRL 93, 267002 (2004)

Cuprate superconductors





charge localization



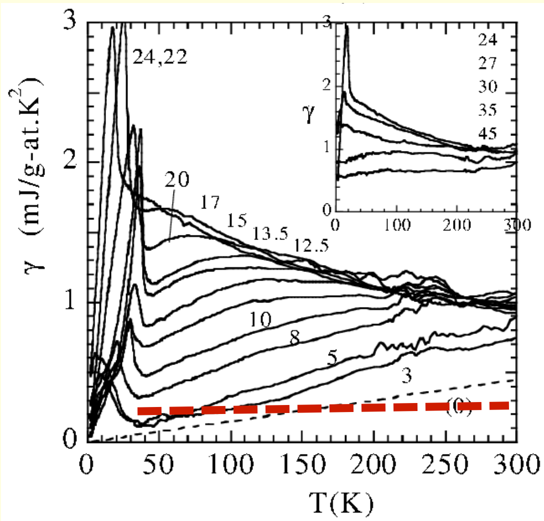
La-Bi2201

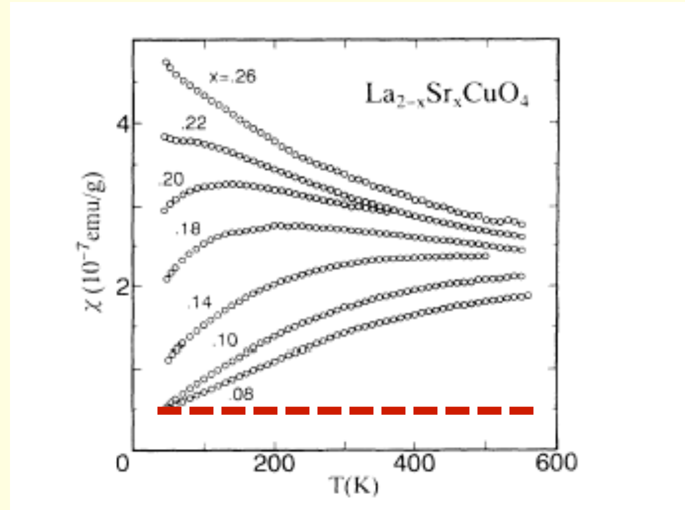
Peng, et al., *arXiv:1302.3017* (2013)

Sebastian, et al., *Reports on progress in physics* **75**, 102501 (2012)

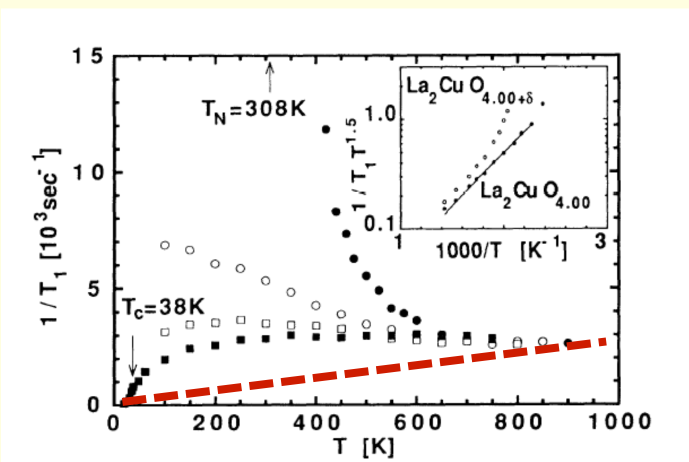
$La_{2-x}Sr_xCuO_4$

Spin susceptibility (T. Nakano, et al. (1994))





Specific heat (Loram et al. 2001)



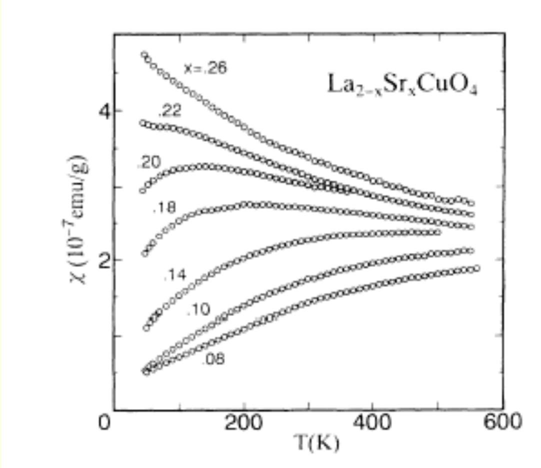
Cuprates systematically violate

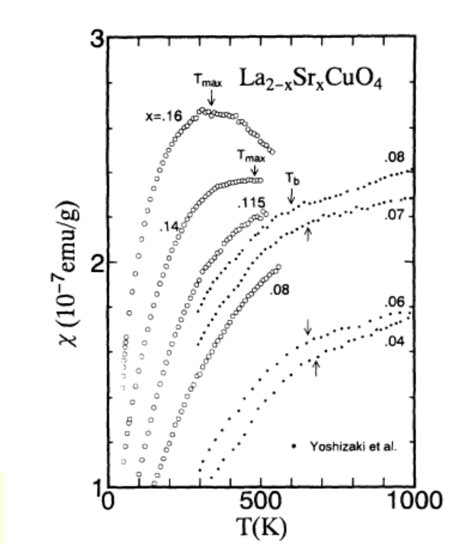
the Fermi liquid behavior!

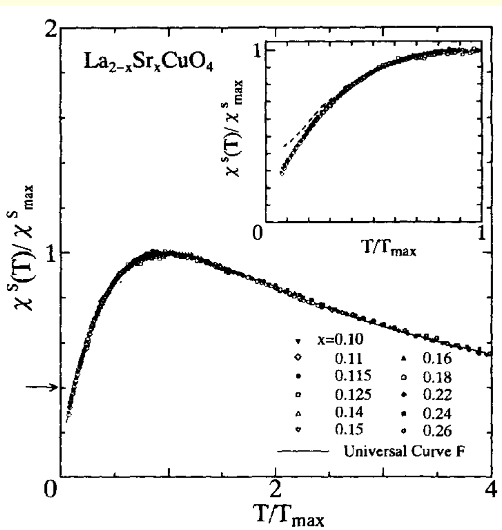
NMR spin-lattice relaxation rate (T. Imai et al. (1993))

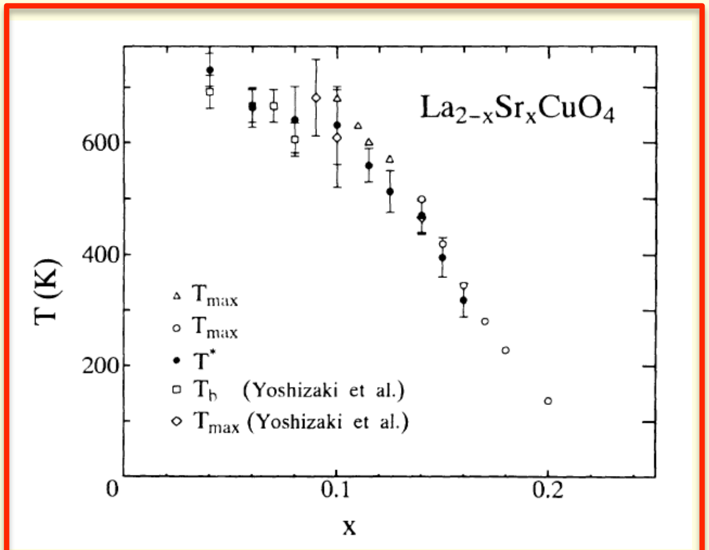
Uniform spin susceptibility

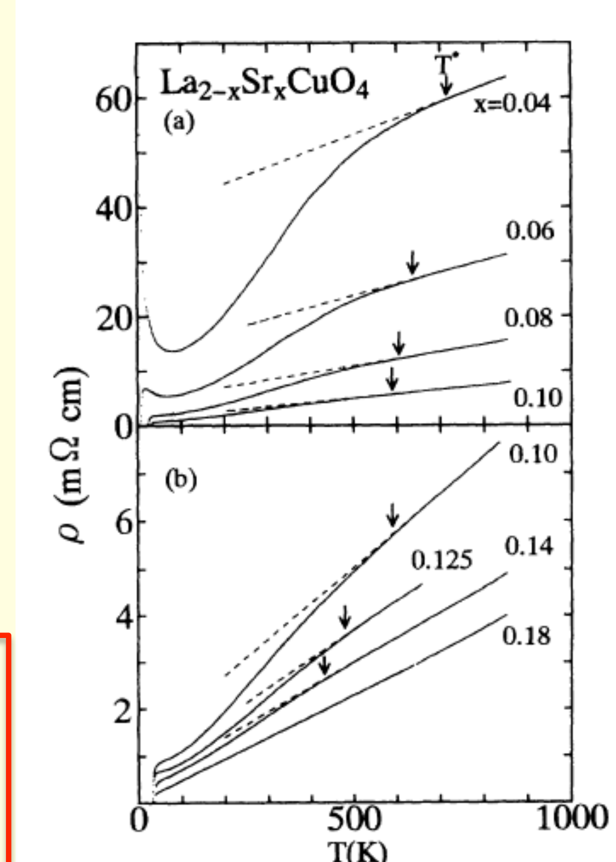
Resistivity measurement





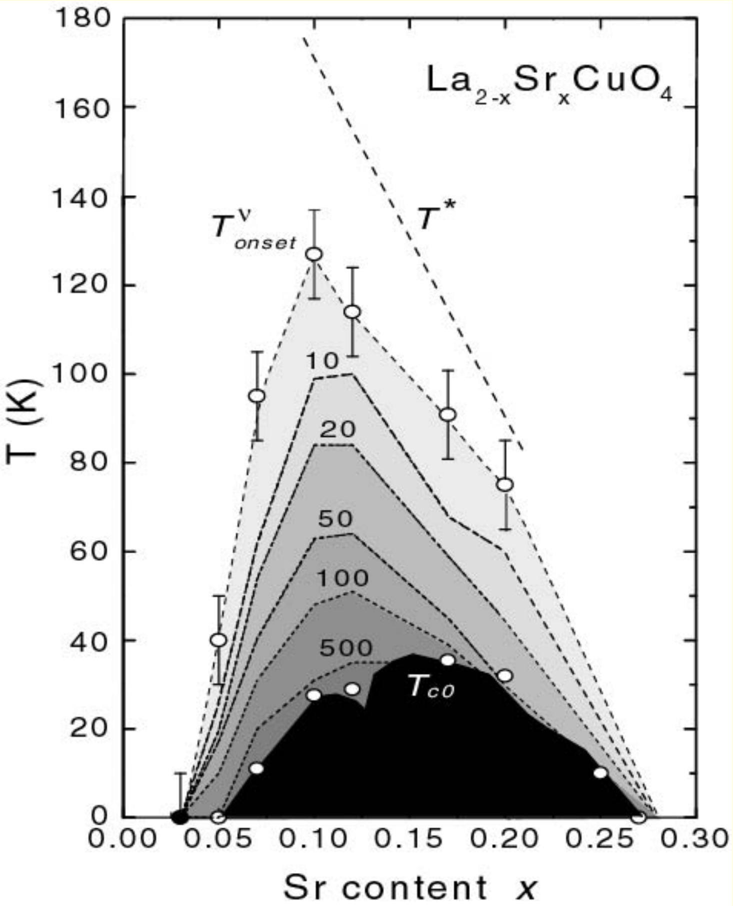






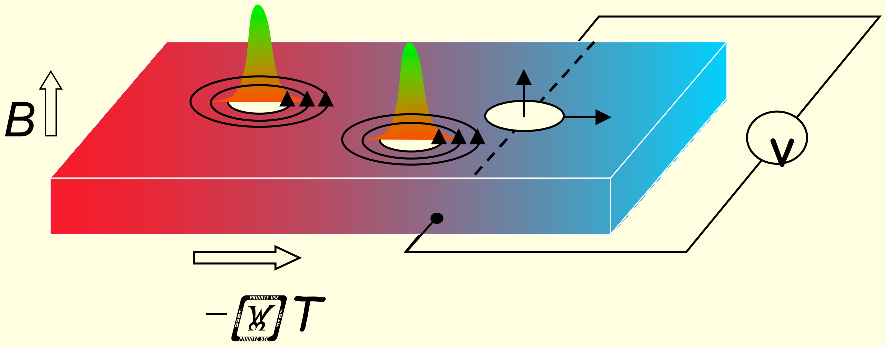
T. Nakano, et al.
PRB49, 16000(1994)

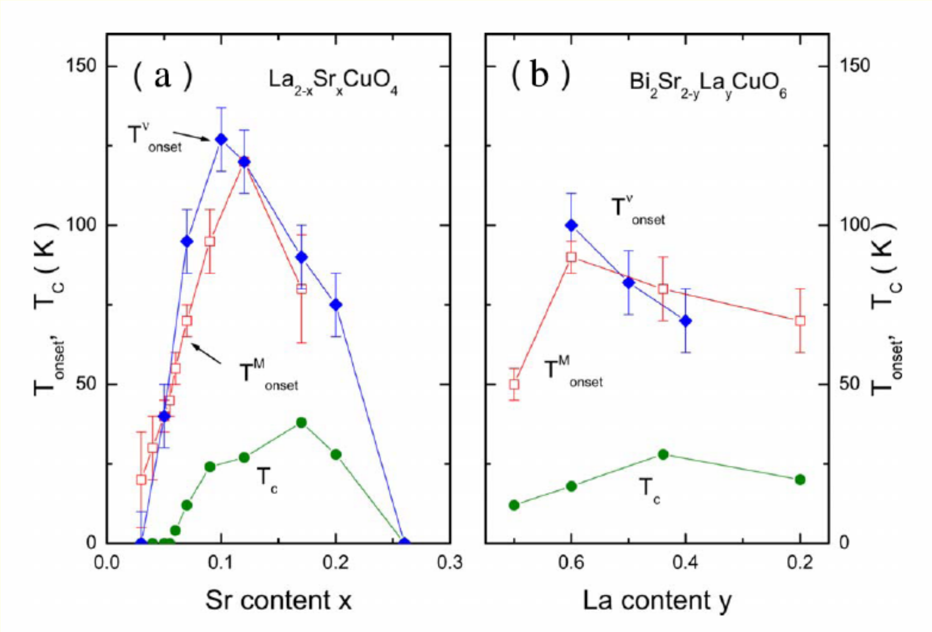
Vortex Nernst effect and diamagnetism in the pseudogap regime



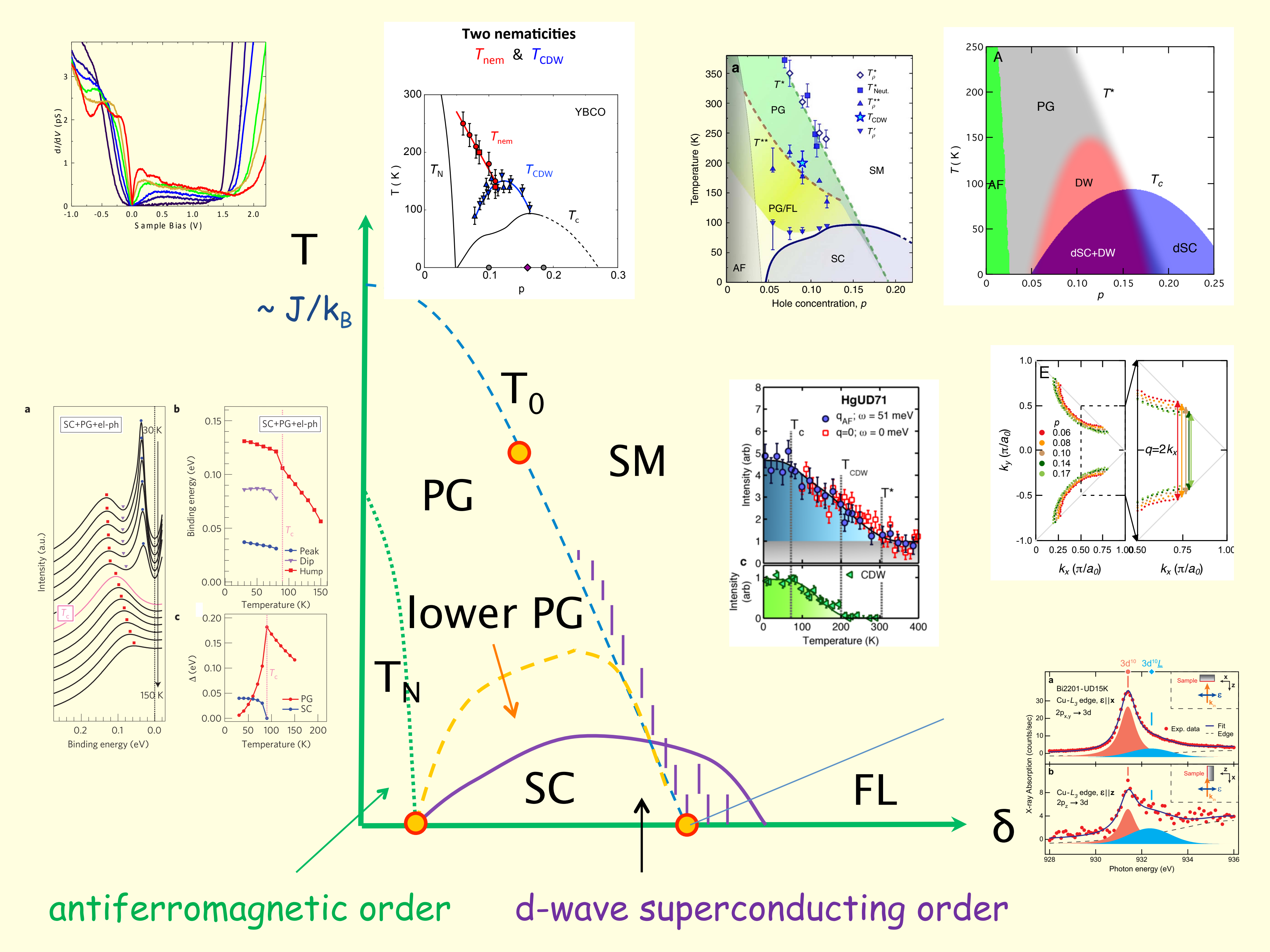
Xu et al., Nature (2000),

Wang et al., PRB (2001).





LI *et al.* PHYSICAL REVIEW B **81**, 054510 (2010)


T
~ J/k_B
T_0
PG
SM
lower PG
T_N
SC
FL
δ
antiferromagnetic order
d-wave superconducting order
Two nematicities
T_nem & T_CDW
YBCO
T_nem
T_CDW
T_N
T_c
T (K)
p
Temperature (K)
Hole concentration, p
T*
T**
PG/FL
AF
T(K)
A
DW
dSC+DW
dSC
T_c
Sample Bias (V)
dI/dV (pS)
SC+PG+el-ph
Binding energy (eV)
Intensity (a.u.)
Binding energy (eV)
Temperature (K)
Peak
Dip
Hump
Δ (eV)
PG
SC
HgUD71
q_AF; ω = 51 meV
q=0; ω = 0 meV
Intensity (arb)
CDW
Temperature (K)
E
q=2k_x
k_x (π/a_0)
k_y (π/a_0)
Bi2201-UD15K
Cu-L_3 edge, ε||x
Cu-L_3 edge, ε||z
Exp. data
Fit
Edge
Sample
X-ray Absorption (counts/sec)
Photon energy (eV)

Pseudogap physics: `normal state'

pseudo spin gap (short-range antiferromagnetic order)

Fermi surface reconstruction (Fermi arc & antinodal)

charge modulation: stripes, CDW,

nematicities

transport (resistivity, Nernst effect, quantum oscillation in magnetic field...)

thermodynamic properties (specific heat, spin susceptibility, diamagnetism)

....

Essential question: Any intrinsic connection between the pseudogap phase and high-Tc superconductivity?

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瞎子摸大象—唯象理论方法

General strategy:

$$H\psi = E\psi$$

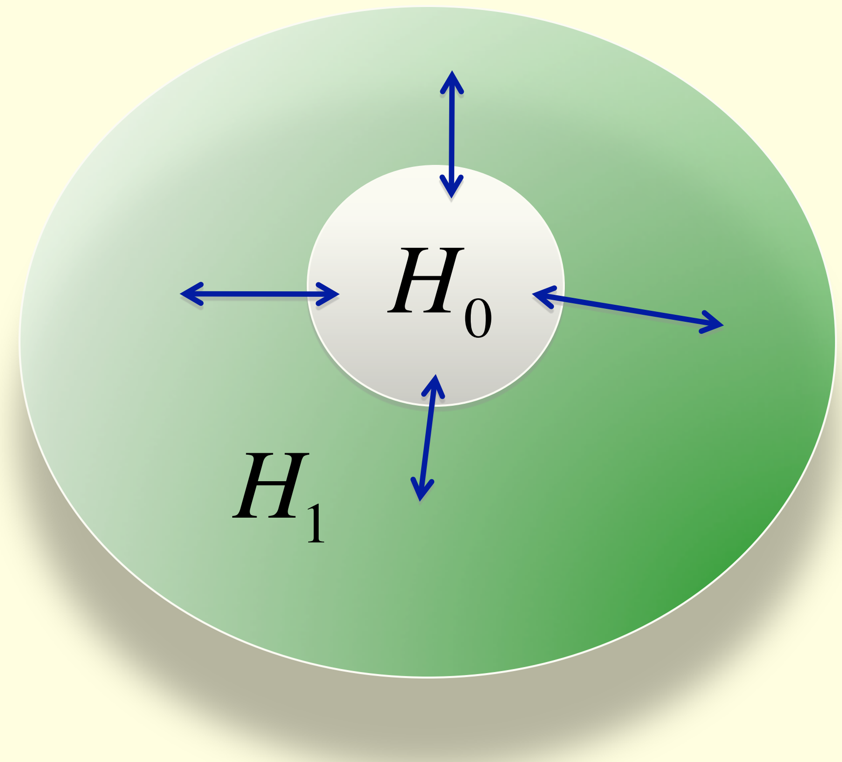
reduced problem which is solvable:

$$H_0\tilde{\psi} = \tilde{E}\tilde{\psi}$$

adiabatic continuity:

$$H_0 + H_1 \Rightarrow H$$

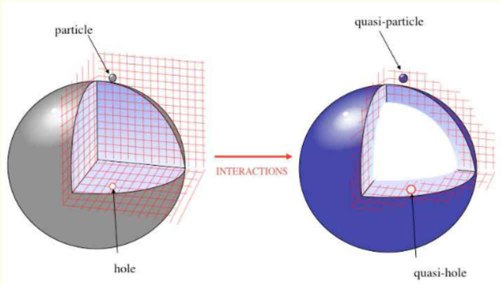
H_0 or $\tilde{\psi}$ should account for the systematic essential features of anomalous properties with the rest as perturbative results from H_1



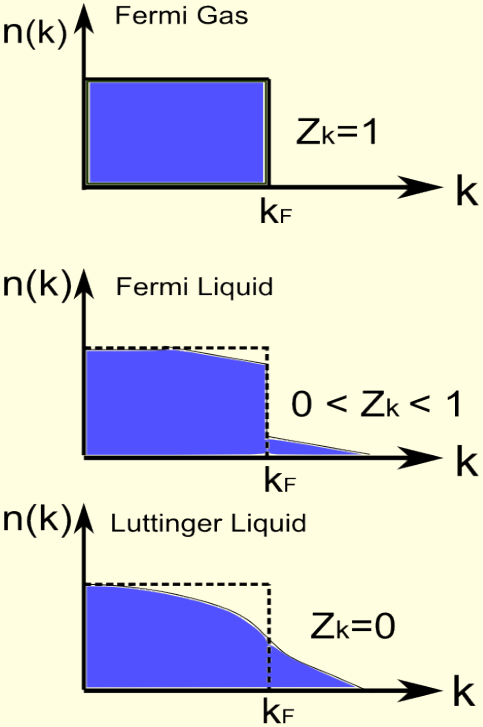
Fermi Gas State for Fermion Liquids

Fermion signs

$$\psi(x_1, x_2, \ldots) = -\psi(x_2, x_1, \ldots)$$



Landau Fermi Liquid



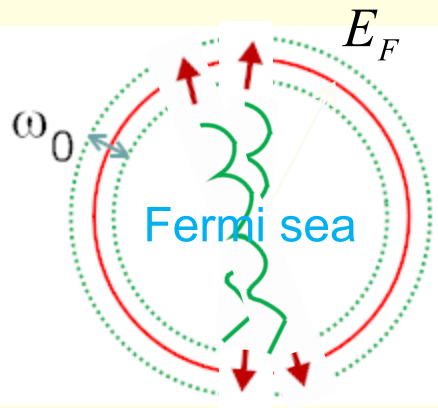
$$T \ll T_F \qquad T_F = E_F / k_B$$

$\rho \propto T^2 / E_F$	Quasiparticle
$C_v = \gamma T$	Sommerfeld constant
$\chi_s = const.$	Pauli susceptibility
$1/T_1 \propto T$	Korringa behavior

BCS theory for superconductivity

electron pairing by "glueon": phonon, AF fluctuations, ...

$$T_c = \omega_0 e^{-\frac{1+\lambda}{\lambda-\mu^*}}$$



λ -- coupling constant

μ^* -- Coulomb pseudopotential

ω_0 -- characteristic energy of the glueon

Strong coupling theory

Pb:	T_c=7.19 K	λ=1.55,	μ*=0.13,	ω_0=4.8 meV
Nb_3Ge:	T_c=21.2 K	λ=1.73,	μ*=0.12,	ω_0=10.7 meV

High-T_c cuprates: T_c ~ 160 K

FeAs based superconductors: T_c ~ 56 K

typical energy scales: $\Theta_D \sim 300K$ $J \sim 300 - 1,500K$

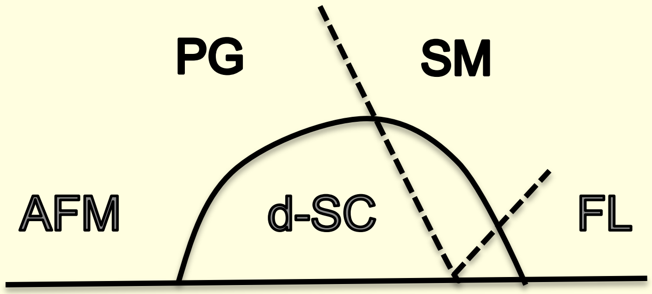
What is the gluon in the iron-based superconductors?

- Fermi surfaces are well defined (ARPES) and BCS theory may be applicable
- Tc is high (55K)
- SC and SDW phases are adjacent: magnetic origin of the gluon
- AF fluctuations persist over a wide temperature and doping regime

Mechanism of superconductivity in high-T_c cuprates: What is the most essential issue?

$H_0 \Leftrightarrow$ Ground state wavefunction = Cooper pair condensation

+ additional structure



- Cooper pair condensation

  BCS like: d-wave pairing symmetry;

  Bogoliubov nodal quasiparticle; GL equation (low-energy, long distance)

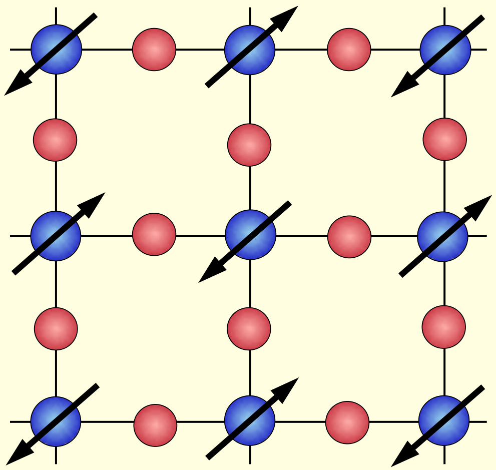
- additional structure (short-range, high-energy)

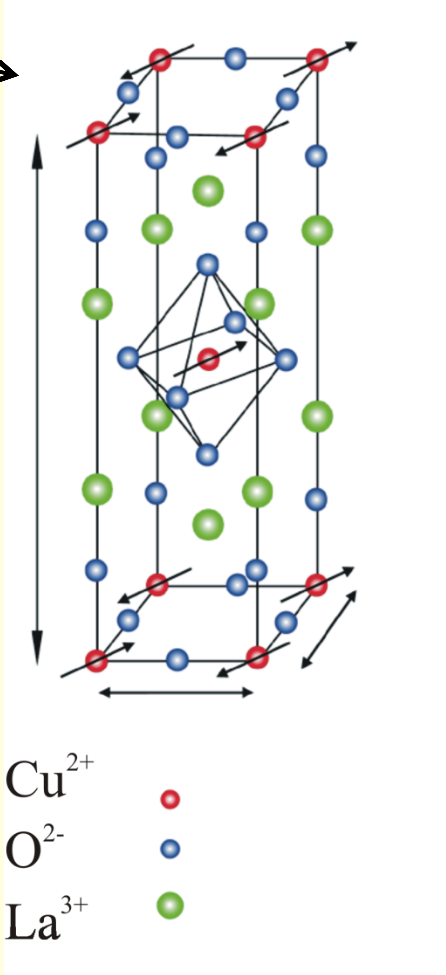
  non-FL–like: pseudogap, AF, strange metal, ...

  quantum order? long-range entanglement? fractionalization? competing order?

Half-filling: Low-energy physics is described by Heisenberg model

Pure CuO_2 plane





$$H = J \sum_{<ij>} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

large $J = 135$ meV

quantum spin $S = 1/2$

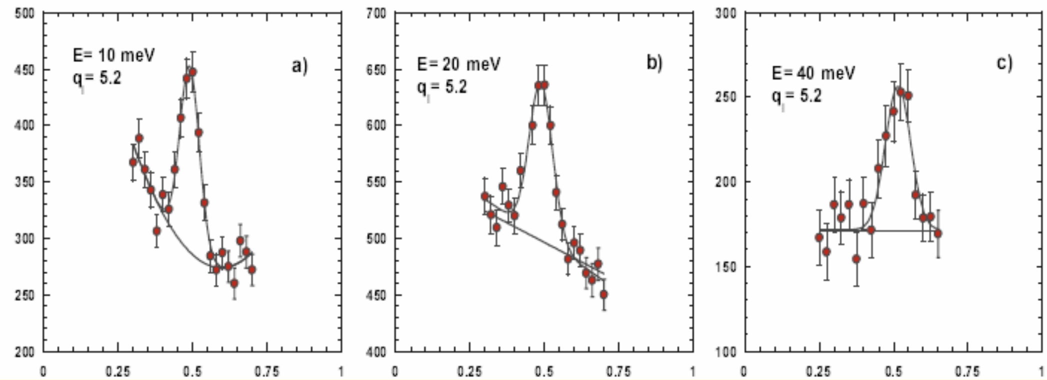
neutron scattering

$$S^{\alpha\beta}(Q,\omega) = \frac{1}{2\pi\hbar}\int_{-\infty}^{+\infty} dt\, \exp(-i\omega t) < S_Q^{\alpha} S_{-Q}^{\beta}(t) >$$

AF

$YBCO_{6.2}$

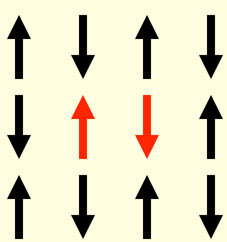
$T_N = 400$ K



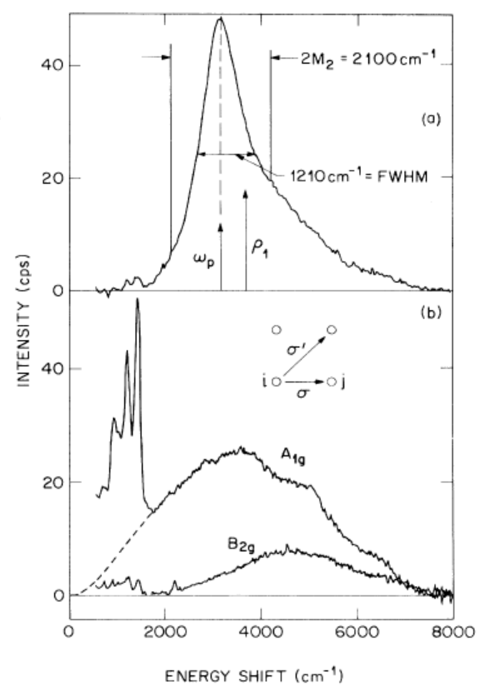
Raman scattering

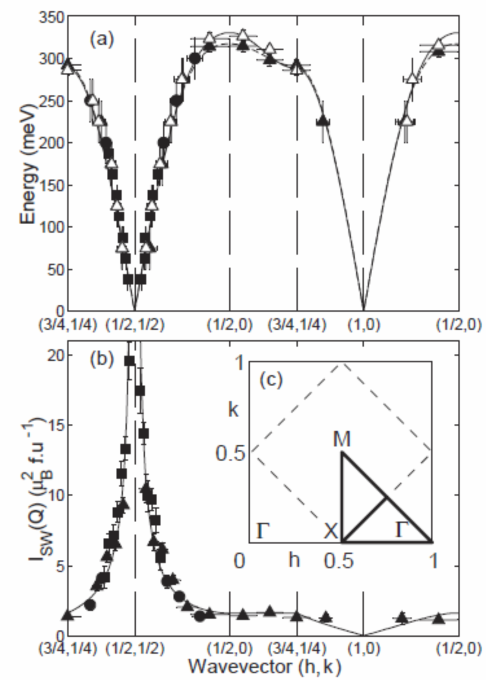
$$I(\omega) = \sum_i \delta(\omega - (E_i - E_0)) \,|\langle 0 | H_R | i \rangle|^2$$

$$H_R = \sum_{\langle ij \rangle} (\mathbf{E}_{\text{inc}} \cdot \boldsymbol{\sigma}_{ij})(\mathbf{E}_{\text{sc}} \cdot \boldsymbol{\sigma}_{ij}) \mathbf{S}_i \cdot \mathbf{S}_j$$



Spin flip breaks 6 bonds, costs 3J.

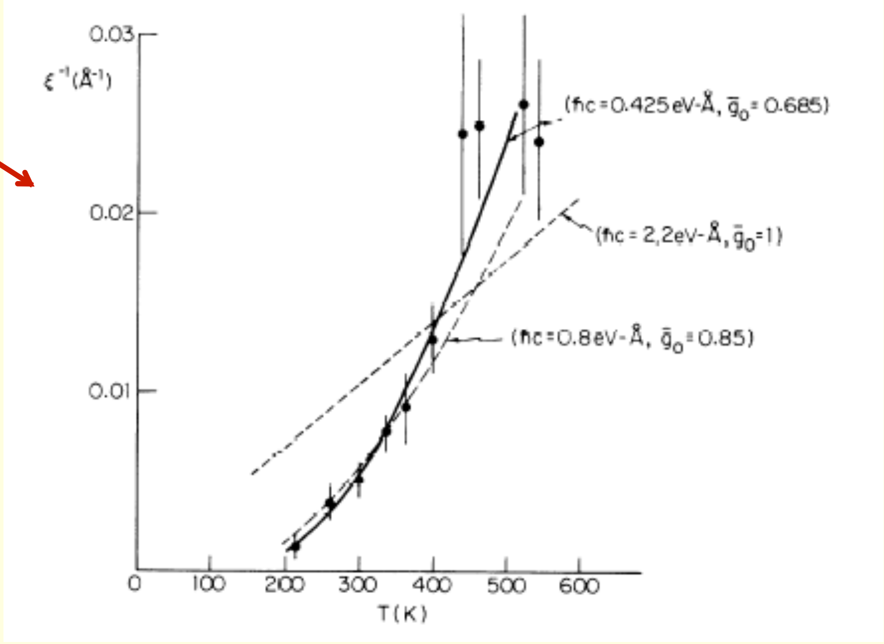




$J \sim$ 135 meV

Antiferromagnetism at x=0 is well described by the Heisenberg model

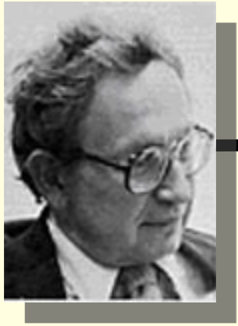
inverse spin-spin correlation length



Chakaravarty, Halperin, Nelson
PRL (1988)

Recent neutron-scattering data for the spin-correlation length in La_2CuO_4 can be fitted quantitatively with an analysis of the quantum mechanical nonlinear σ model in two space dimensions. The coupling constant must be chosen in the range where an isolated CuO_2 layer has antiferromagnetic order at $T=0$. The parameters are consistent with the spin-wave theory for the nearest-neighbor spin-$\frac{1}{2}$ Heisenberg antiferromagnet on a square lattice.

Cuprates = doped Mott Insulator



Anderson, Science 1987

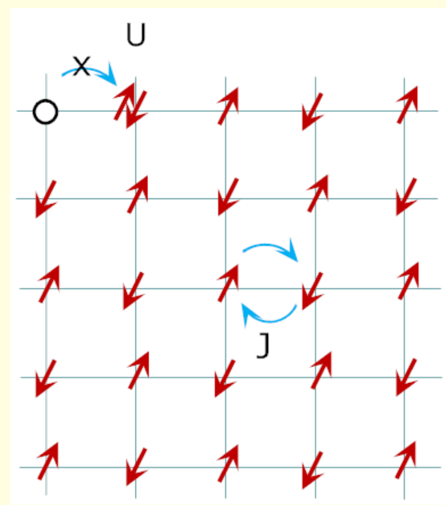
one-band large-U Hubbard/t-J model:

$$H_t = -t \sum_{<ij>\sigma} c^\dagger_{i\sigma} c_{j\sigma} + H.c.$$

$$H_J = \sum_{<ij>} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{n_i n_j}{4} \right)$$

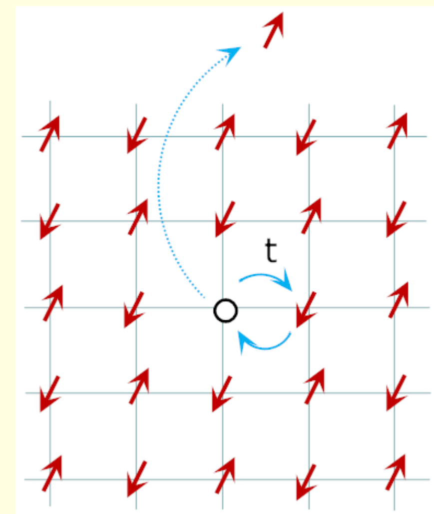
$$\sum_\sigma c^\dagger_{i\sigma} c_{i\sigma} \leq 1$$

Mott insulator



Heisenberg model

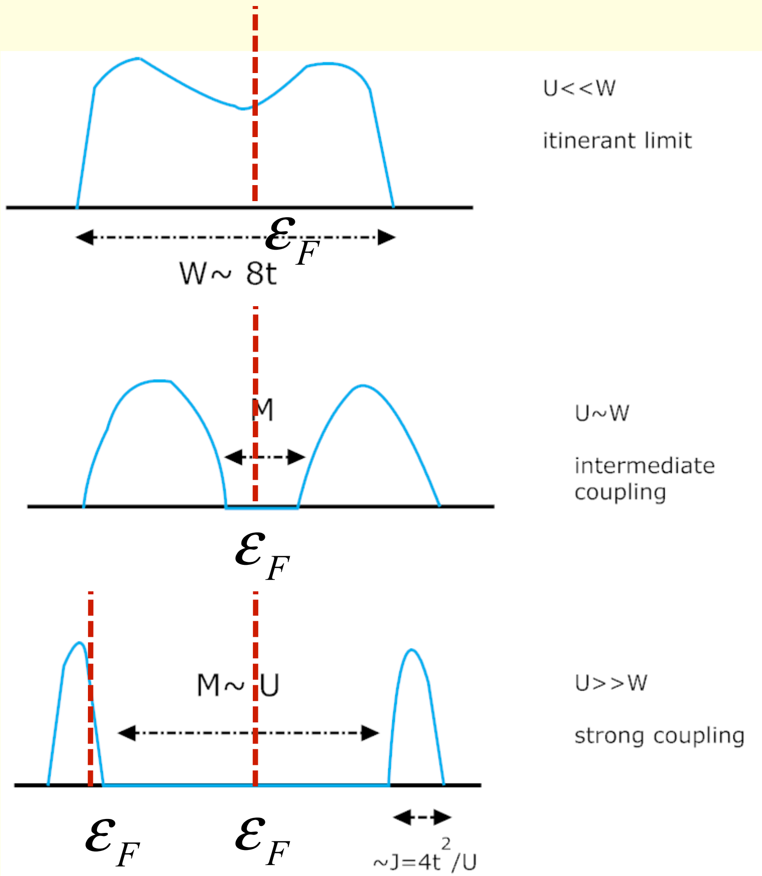
doped Mott insulator



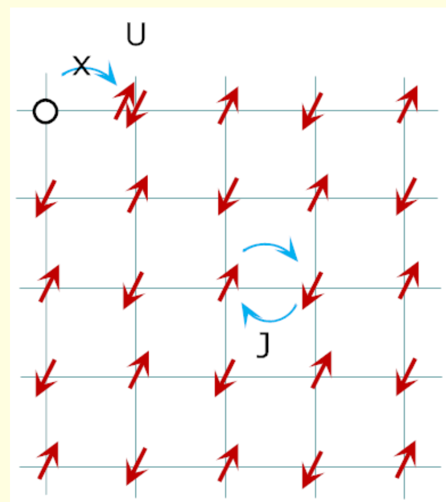
t-J model

Half-filling

Doping the Mott Insulator/ antiferromagnet

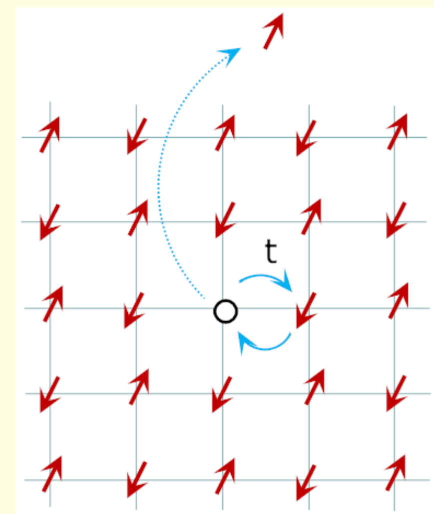


Mott insulator



Heisenberg model

doped Mott insulator

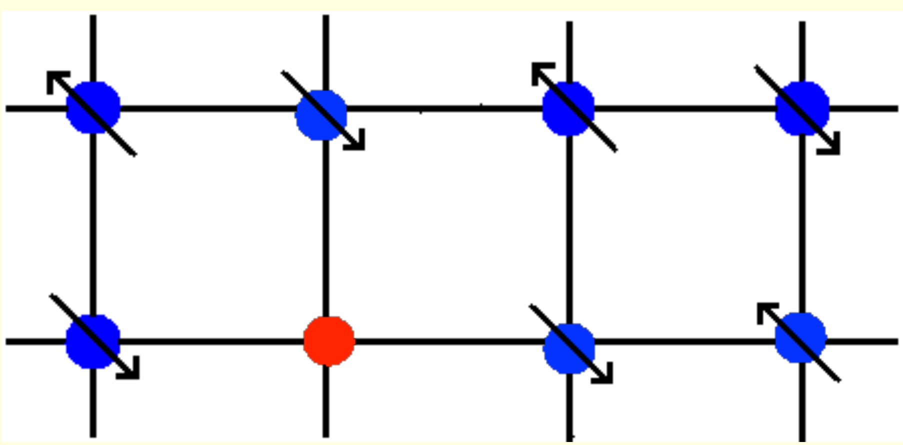


t-J model

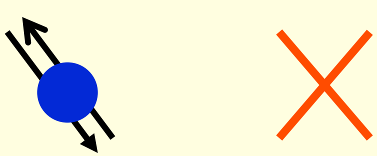
A minimal model for doped Mott insulators: t-J model

$$H = -t \sum_{\langle ij \rangle} \left(c_{i\sigma}^{\dagger} c_{j\sigma} + h.c. \right) + J \sum_{\langle ij \rangle} \left(\mathbf{S_i} \cdot \mathbf{S_j} - \frac{1}{4} n_i n_j \right)$$

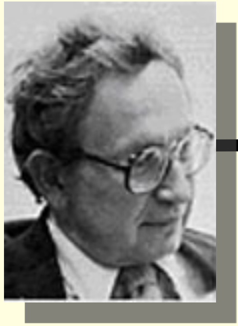
hopping **superexchange**



$$\sum_{\sigma} c_{i\sigma}^{+} c_{i\sigma} \leq 1$$



Cuprates = doped Mott Insulator



Anderson, Science 1987

one-band Hubbard model:

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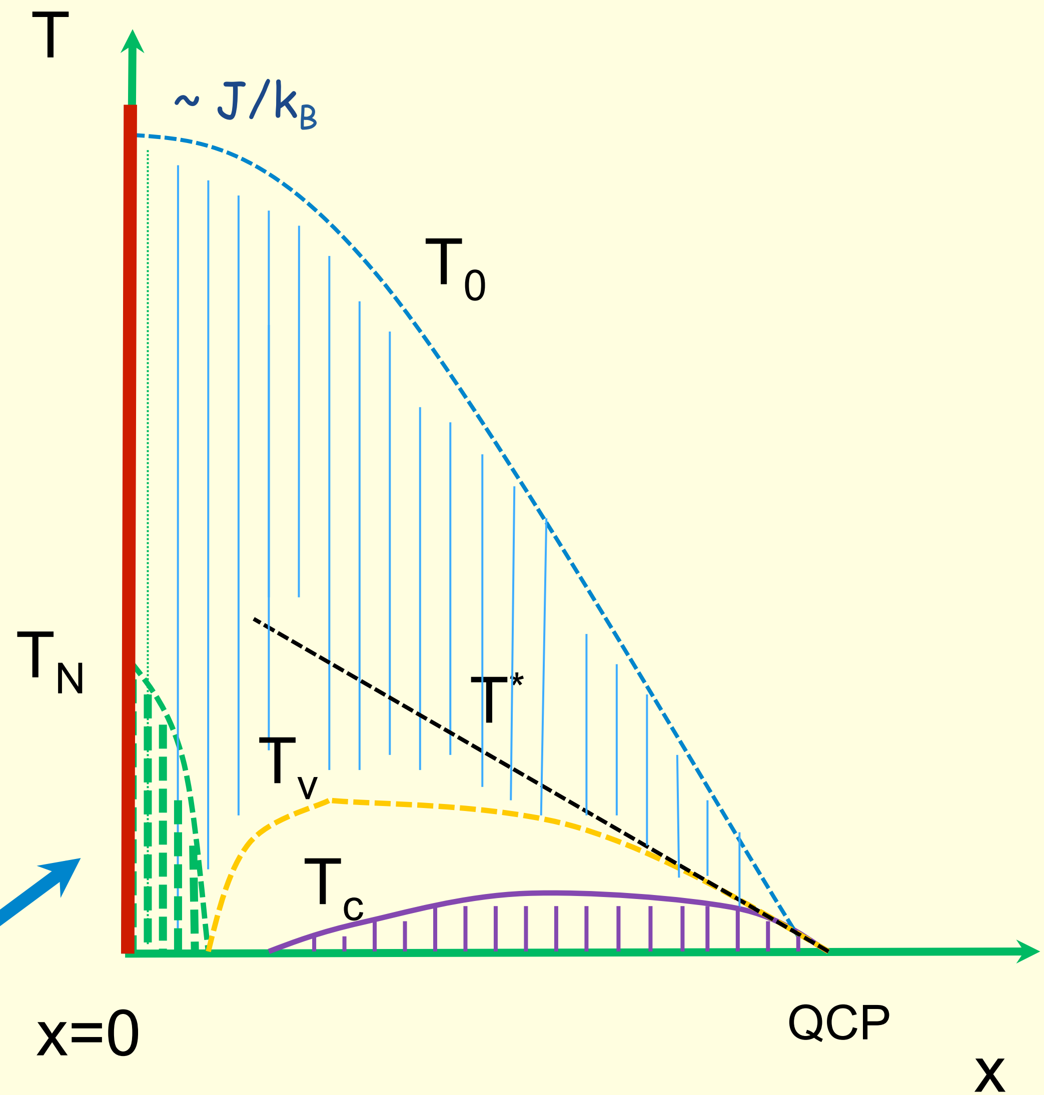
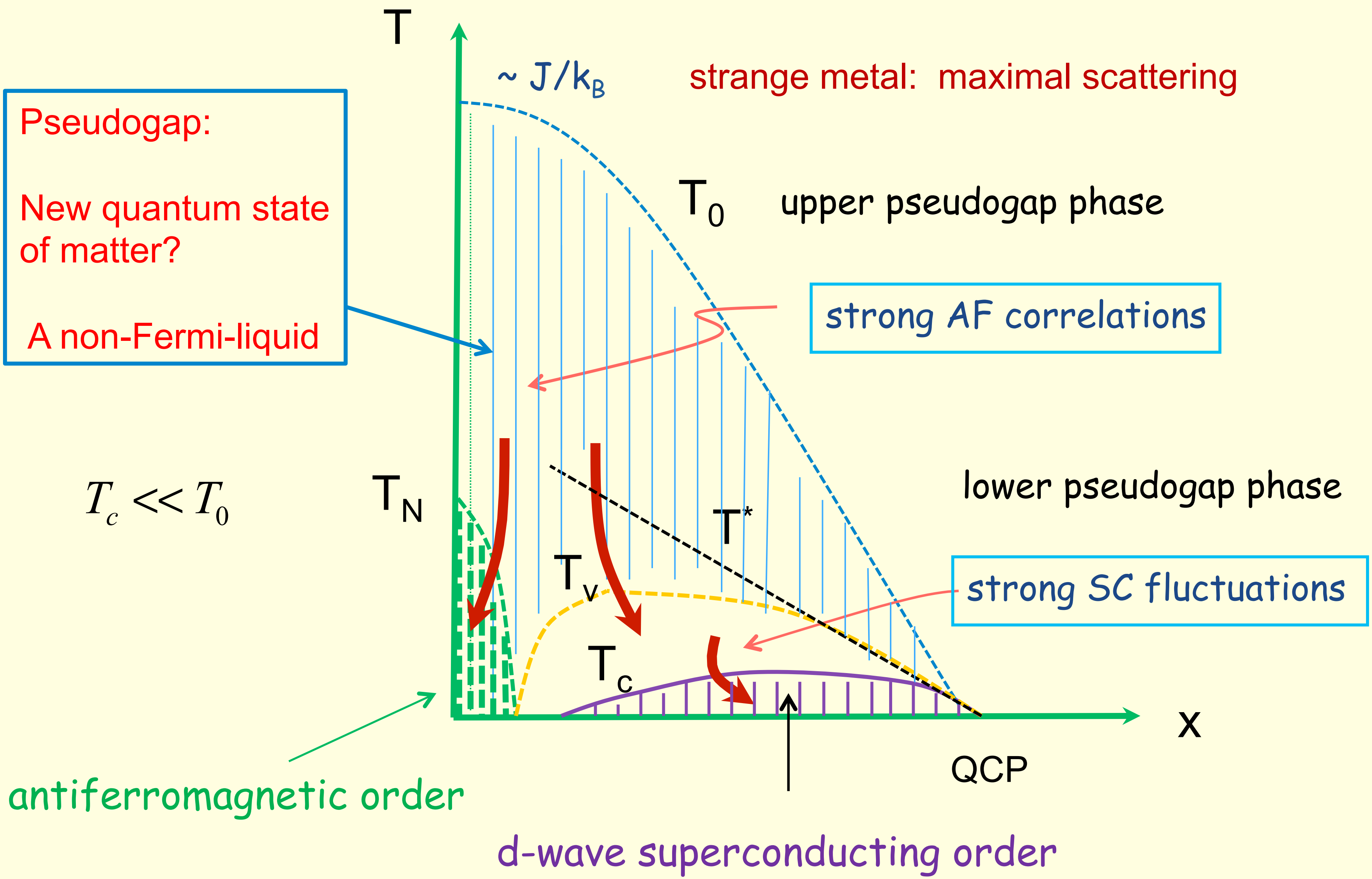
$$H_J = \sum_{<ij>} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \frac{n_i n_j}{4} \right)$$

$$\sum_\sigma c^\dagger_{i\sigma} c_{i\sigma} \le 1$$

Half-filling:
Mott insulator



Underdoped phase diagram



$T_c << T_0$

The Central Dogma

"Any correct theory must be consistent with anomalous behavior of a bewildering variety of experimental probes, in addition to the very basic requirement of being internally consistent, …, and *nothing else.*"

---P. W. Anderson

The theory of superconductivity in the high-Tc cuprates 1997 by Princeton University Press

Short summary of part I:

- Cuprate superconductors are different from iron-based superconductors: e.g. pseudogap phase

- Pseudogap state is firmly established by experiment as one of the most exotic phases in the cuprates which is closely related to high-T_c superconductivity

- Doped Mott insulator/antiferromagnet provides a suitable microscopic model to understand the cuprate physics