Charge ordering and quantum criticality in the phase diagram of the cuprates

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Workshop on “Emergent materials and highly correlated electrons”
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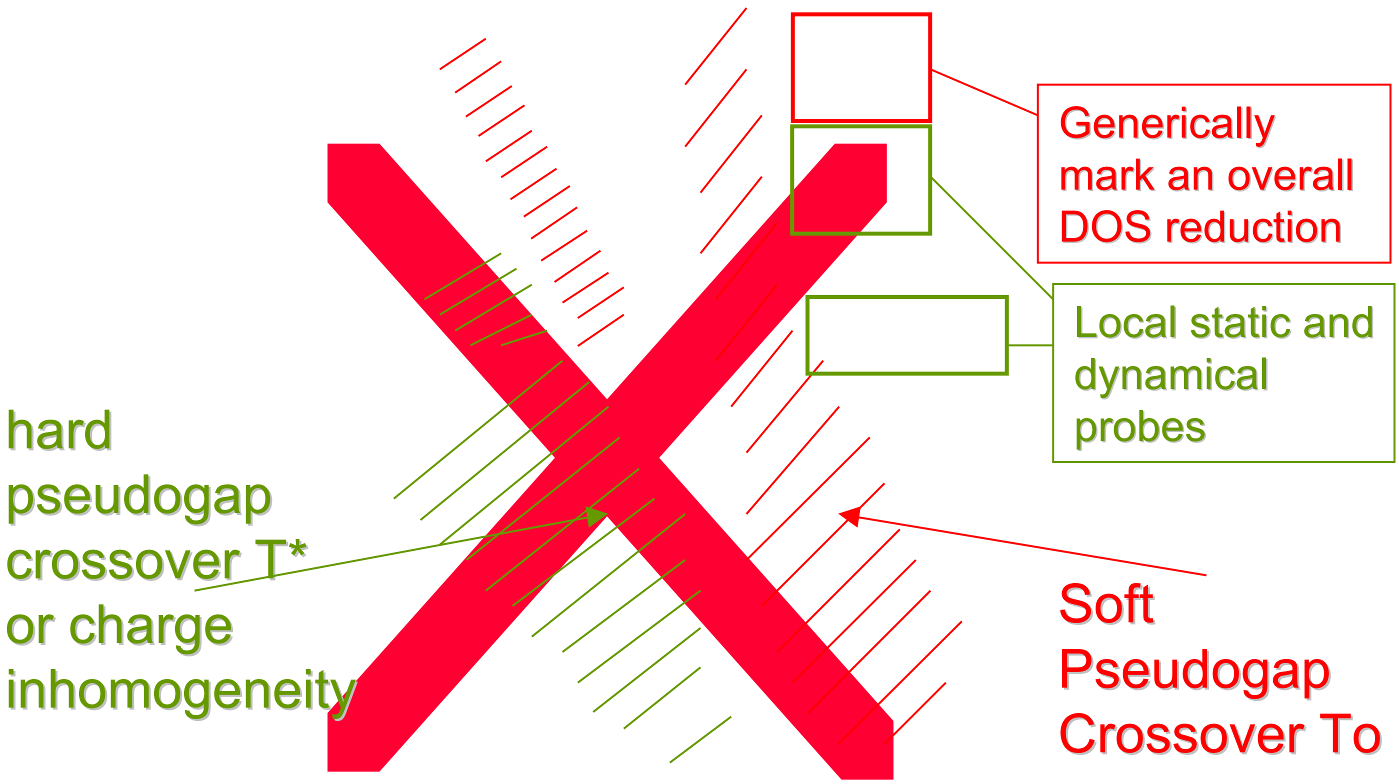
Experimental collection on LSCO

Gutmann et al., cond-mat/0009141



- Two distinct pseudogap crossovers at quite different temperature scales
- Large spread in the pseudogap and/or local inhomogeneity crossover T*

Outline

- The Charge-Ordering (CO) Quantum Critical Point (QCP) scenario

  (C. Castellani, C. Di Castro, M.G)

•The soft-to-hard pseudogap formation

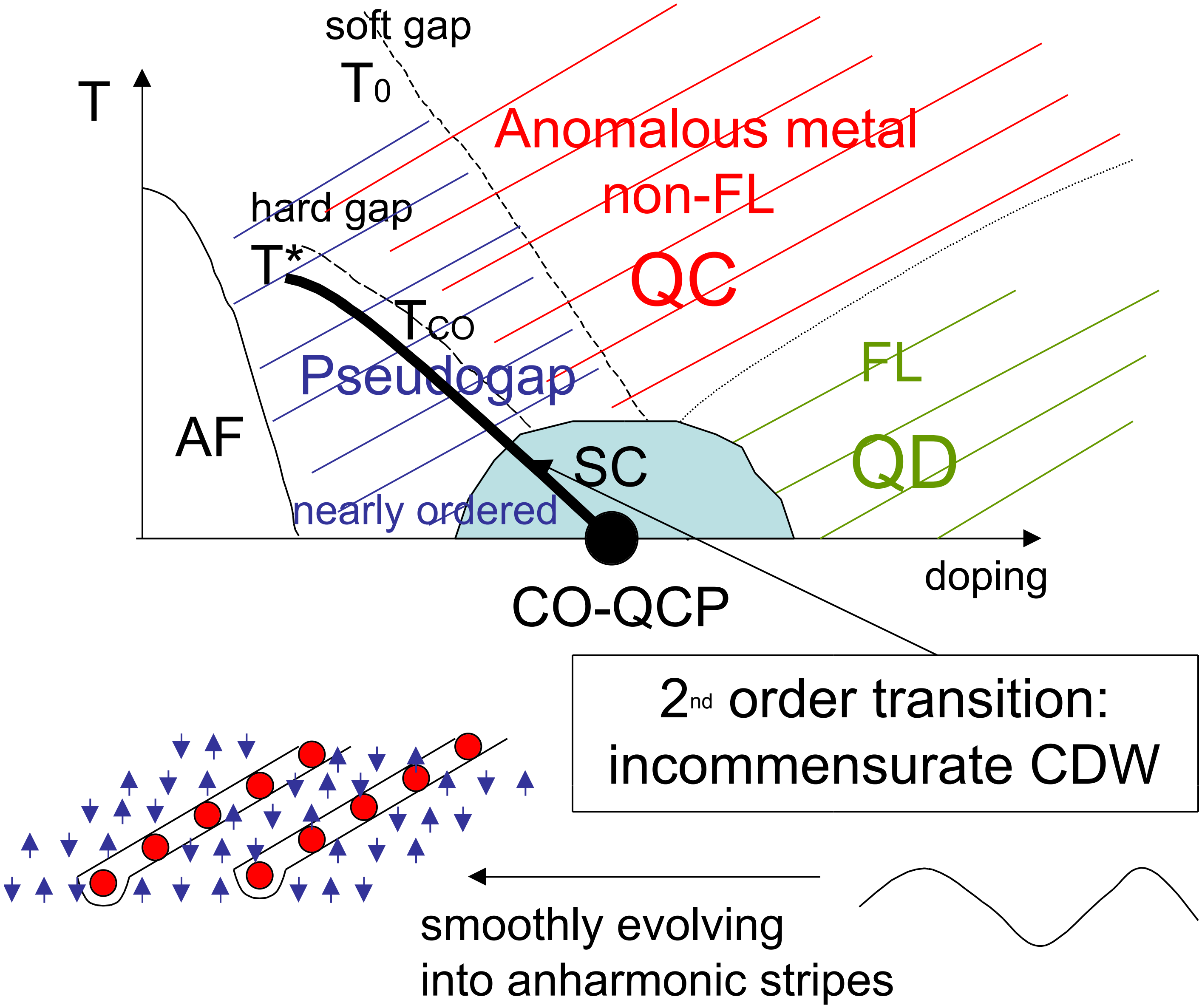
- The role of CO fluctuations beyond mean field
- The role of time resolution in experiments
- Isotope Effects on the pseudogap crossovers

S. Andergassen, S. Caprara, C. Di Castro, M.G.,PRL 87, 056401(2001)

•Anomalous finite-frequency absorption $\sigma(w)$

S. Caprara, C. Di Castro, S. Fratini, M.G., PRL 88, 147001 (2002)

•A “critical” discussion and summary



Main features of the normal state:

-Overdoping more or less FL

-Optimal doping: no energy scales but T

-Underdoping: excess of energy scales
pseudogap Δ_g, T_0, T*

Crucial consequence

Near Tco(x) there are critical charge fluctuations

$$\langle \phi(q,\omega)\phi(-q,-\omega)\rangle \cup \frac{1}{\nu\left|\vec{q}-\vec{q}_c\right|^2+\left|\omega_n\right|+m(T,x)}$$

$$m(T,x) \cup \begin{cases} a(x-x_c) & \text{in low-T (QD) region} \\ bT & \text{in high-T (QC) region} \\ & \text{Note: T is the relevant energy scale} \\ c(T-T_{CO}) & \text{in underdoped region} \\ & \text{above } T_{CO} \sim T^* \end{cases}$$

Singular quasiparticle scattering amplitude

- Non-FL behavior
- Pseudogaps
- Strong pairing near T_{CO}

  T*-Tc bifurcation
- Specific spectroscopic features

  (e.g. ARPES, $\sigma(\omega)$,...)

Strong correlations

Phase separation is easy

+ Coulomb forces

phase separation on local basis

STRIPES

Emery Kivelson '93
Rome group '93

second-order instability

CO-QCP

Castellani, Di Castro, M.G., PRL(1995)

singular scattering
strong k-dependence

3 regions in
phase diagram

p-h

- CDW scattering opens pseudogap
- non-FL metal

p-p

- p-p pairing at T*
- k-dependence of the gap Δ_{pg}

A specific model: Hubbard-Holstein

$H_{kin} = -t \sum \left(c^{+}_{i\sigma} c_{j\sigma} + H.c. \right) - t' \sum \left(c^{+}_{i\sigma} c_{j\sigma} + H.c. \right)$ kinetic energy

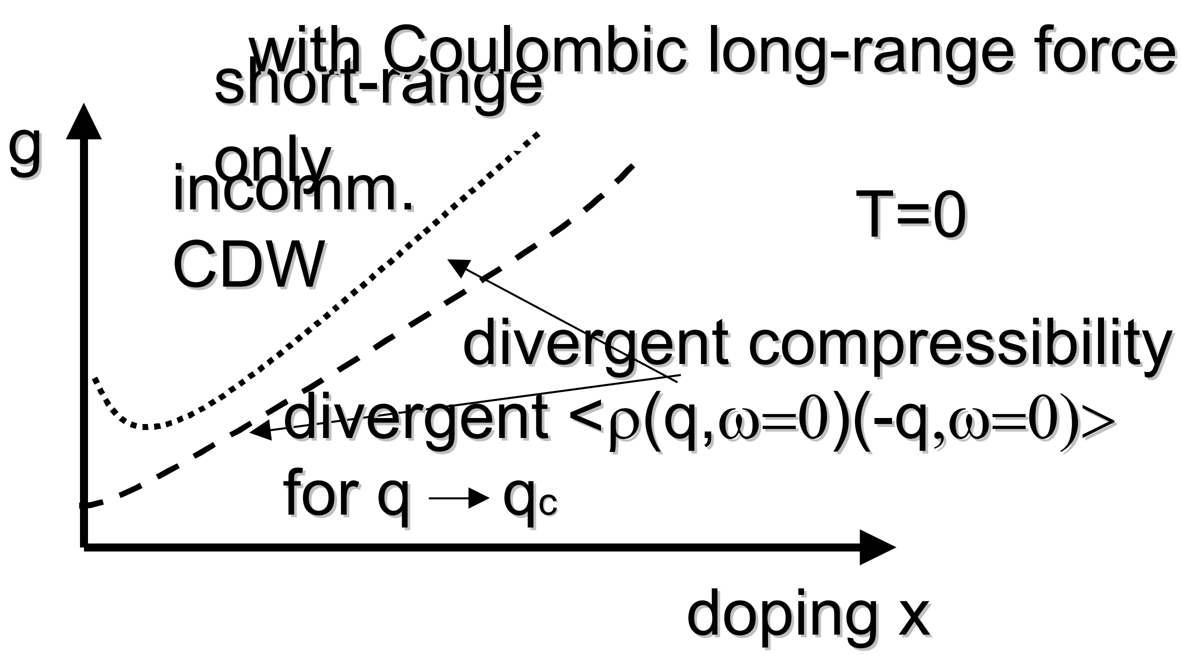
$H_U = U \sum n_{i\uparrow} n_{i\downarrow}$ (strong) local Hubbard repulsion

$H_{e-ph} = \omega_0 \sum a^{+}_i a_i + g \sum n_i \left(a^{+}_i + a_i \right)$ Holstein e-ph coupling

$H_{Coulomb} = \frac{1}{2} \sum V_C\left(\left| i - j \right| \right) c^{+}_{i\sigma} c_{i\sigma} c^{+}_{j\sigma'} c_{j\sigma'}$ Coulomb e-e repulsion

U is large in cuprates ⇨ U ♦ × large-N and slave-bosons

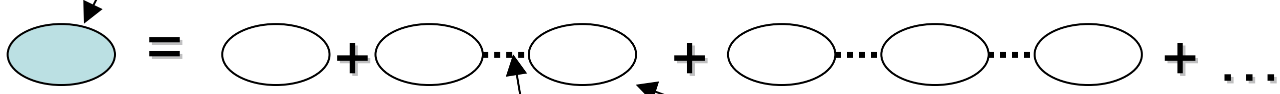
Mean-field results



Mean-field results with long-range repulsion

- At T=0 there is a CDW instability for $\lambda<1$
- for reasonable parameters the CO-QCP is near x_{opt}
- At the CO-QCP the density-density response function $\chi=\langle\rho(q,\omega=0)\rho(-q,\omega=0)\rangle$ diverges at q_c

$$\chi(q,\omega)=\frac{\chi_0(q,\omega)}{1+V_{eff}(q,\omega)\chi_0(q,\omega)}$$ RPA-like form



V_{eff} effective interaction between QP's: includes U (slave bosons), phonons, Coulomb repulsion

χ_0 Lindhardt polarization bubble

The full Hubbard-Holstein model is still too difficult ⇨ Effective low-energy model

$$\tilde{H}=\sum_{k\sigma}\varepsilon_k c^+_{k\sigma}c_{k\sigma}+\gamma\sum_{kq\sigma}\left(c^+_{k+q\sigma}c_{k\sigma}\phi_q+H.c.\right)$$

Quasiparticles coupled to charge collective modes with effective interaction

$$\Gamma(q,\omega)=V_{eff}(q)/\left(1+V_{eff}(q)\chi_0(q,\omega)\right)$$

- QP band structure to match ARPES;
- V_{eff} and χ_0 determined by the model at T=0;
- At T=0 all model parameters but γ are determined.

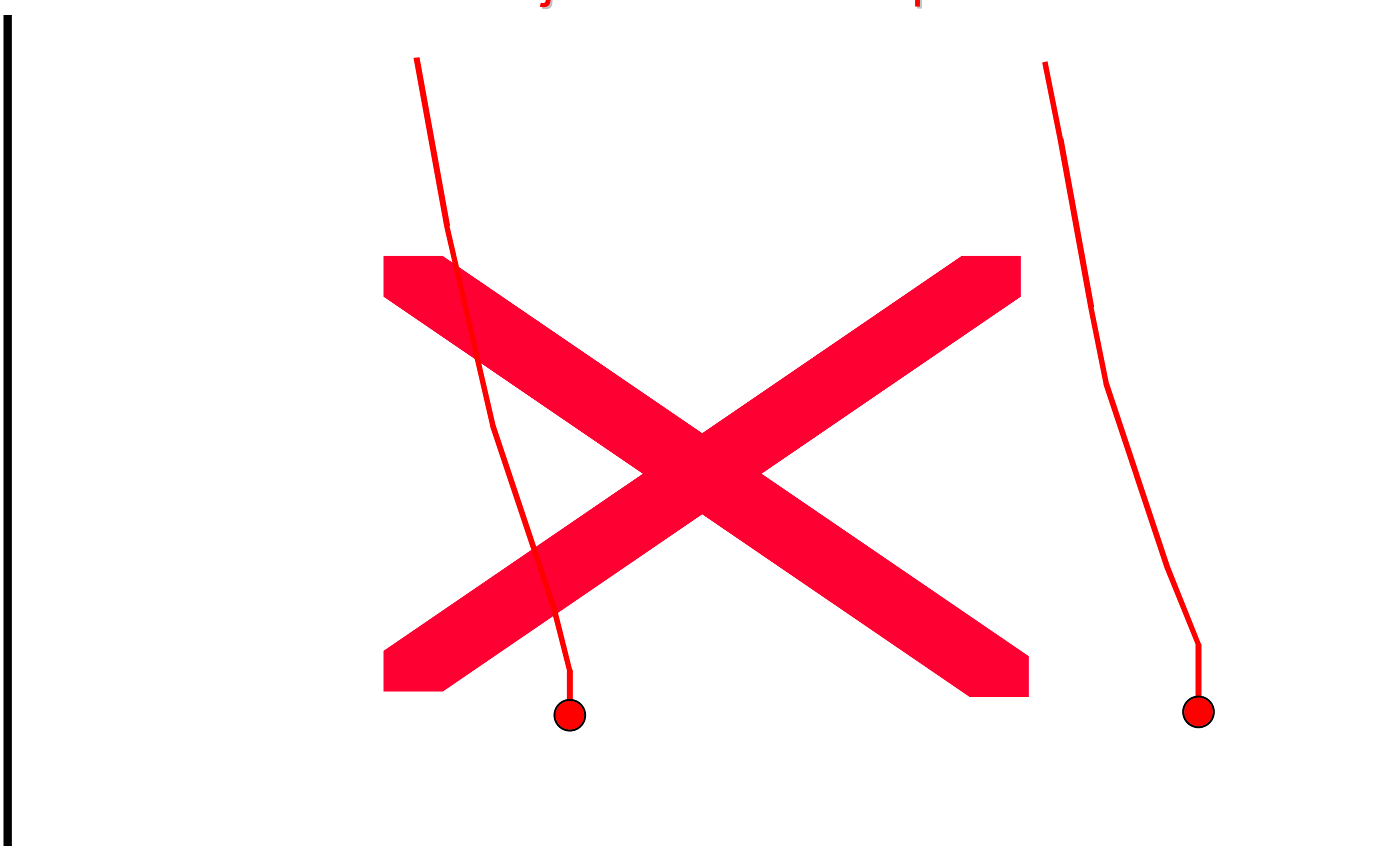
Finite-temperature mean field

Within mean-field (RPA) the CO instability is given by

$$1 + V_{eff}(q_c)\chi_0\left(q_c, \omega; T_{CO}^{(0)}\right) = 0$$

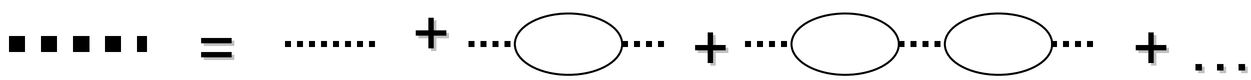
giving the critical line $T_{CO}^{(0)}(x)$ ending in a QCP at $x_c^{(0)}$ where $T_{CO}^{(0)}\left(x_{CO}^{(0)}\right) = 0$

Notice: the QP-CM coupling γ is fixed to place $x_c^{(0)}$ at T=0. The curve $T_{CO}^{(0)}(x)$ is then determined by the T-dependence of $\chi_o(q_c, \omega = 0; T)$ without further adjustment of the parameters

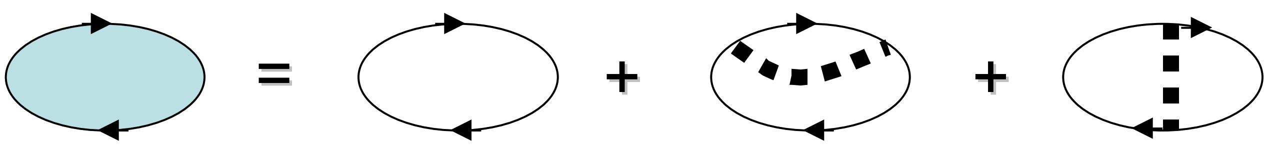


Beyond mean field: corrections due to nearly critical CO fluctuations

critical CO fluctuation propagator



dresses the Lindhard polarization bubble



The mass m of the fluctuation propagator is dressed

$$m = m_0 + 12uT \sum_{q} \sum_{\omega<\omega_0} \frac{1}{m + \nu \left|\vec{q} - \vec{q}_c\right|^2 + \left|\omega_n\right|}$$

ω_0 is an UV frequency cutoff for the CO critical fluctuations of the order of the phonon frequency

[M.G. and C.Castellani, PRB (1994); F. Becca et al., PRB (1996)]

The equation for the critical line is given by

$$m\left(T_{CO}, x\right) = 0$$

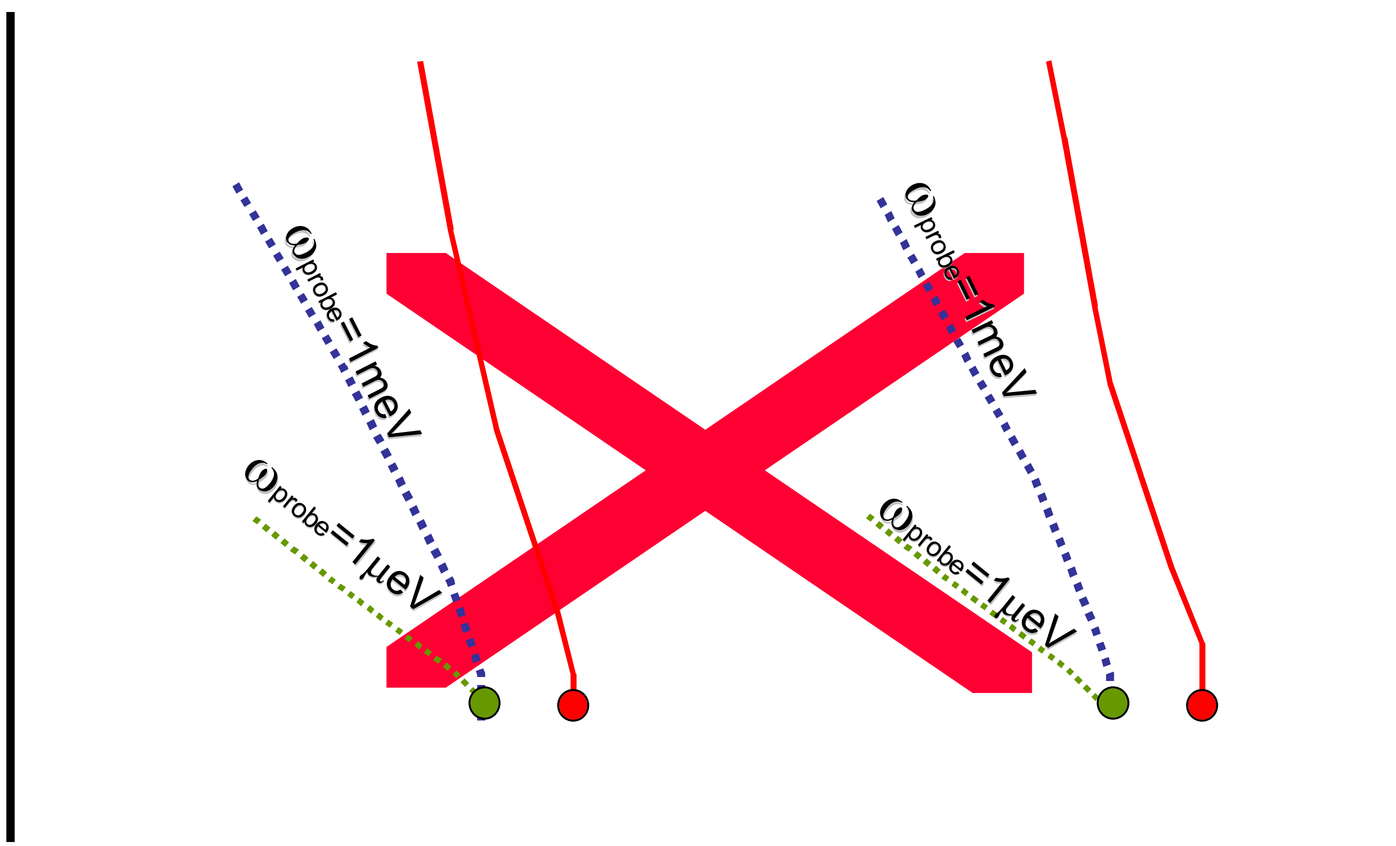
Beyond mean field: corrections due to nearly critical CO fluctuations

At T=0 the mean-field QCP $x_c^{(0)}$ is reduced by the fluctuations

$$x_{CO}^{(0)} - x_{CO} \propto \omega_0$$

x_{CO} $x_{CO}^{(0)}$ x

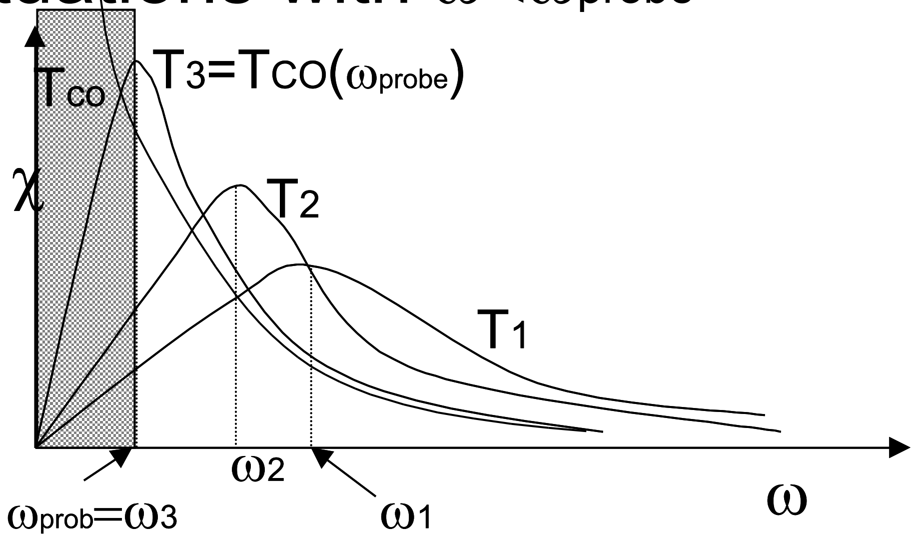
At T>0 the mean-field critical line $T_{CO}^{(0)}(x)$ is shifted to the corrected critical line $T_{CO}(x)$



Why probes with different time-scales give different T*'s for the same class of materials?

Why different probes (neutrons, NQR, NMR, ARPES,…) give different T* for the same class of materials?

- A probe with time-resolution $t_p=1/\omega_{probe}$ does not see the effect of fluctuations with $\omega<\omega_{probe}$



The system looks ordered at $T_{CO}(\omega_{probe})>T_{CO}$ even though slow fluctuations (with $\omega<\omega_{probe}$) restore symmetry

$T_{CO}(\omega_{probe})$ is a natural consequence of the dynamical character of the CO fluctuations

Standard BCS: $T_c = \omega_0 e^{-1/\lambda_{e-ph}}$

$\omega_0 \propto \frac{1}{\sqrt{M_{ion}}}$

doesn't depend on M_{ion}

Our case is different: IE induced by fluctuations

$$T_{CO}(x) = T_{CO}^{(0)}(x) - \boxed{} \cdots$$

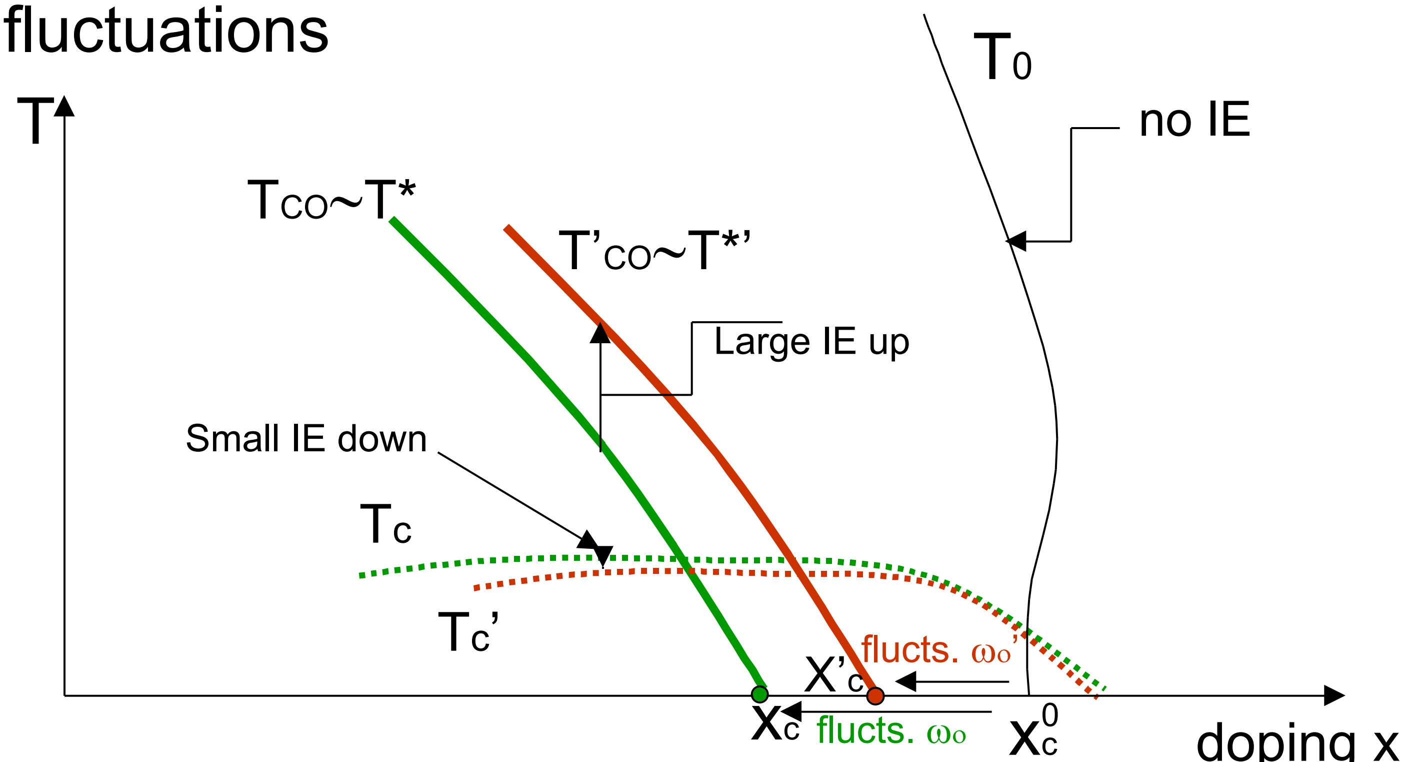
ω_0

CO flucts. only exist at $\omega<\omega_0$

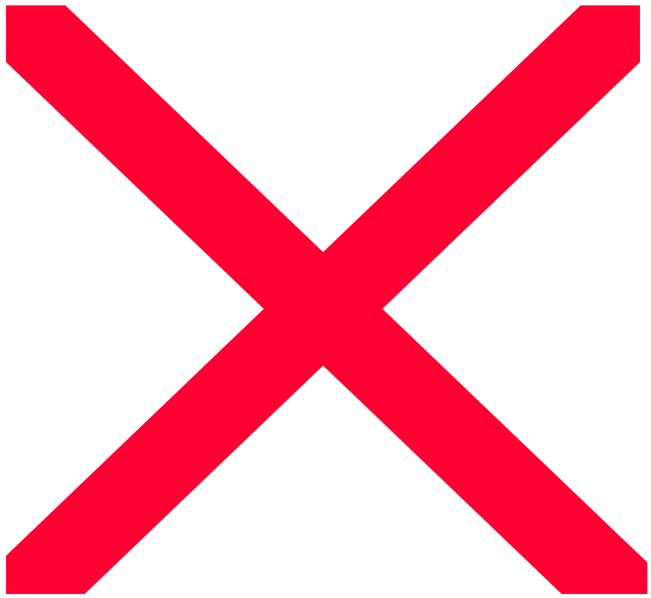
$T_0 \cup T_{CO}^{(0)}$ depends on λ_{e-ph} only:

No IE

The larger is ω_0 the more T_{CO} is reduced by fluctuations



- No IE for mean-field $T_{CO} \sim T_0$
- IE is similar to underdoping for T_c and T* (cf.Rubio Temprano et al. PRL (2000)



- Spread of T* depending on ω_{probe}
- Qualitative agreement for IE on T_c and T*
- if confirmed, ΔT^*_{fast} is too small (15-20K) with respect to neutron-scattering in $HoBa_2Cu_4O_8$ (~ 50K, Rubio-Temprano et al., PRL 2000) or ARPES in BSCCO (Lanzara, private commun.) and ΔT^*_{slow} is too large (2-5K) with respect to NMR (Williams et al. PRL 1998) and NQR (Raffa et al. PRL 1998) on $YBa_2Cu_4O_8$.

Anomalous optical absorption in the normal state of overdoped cuprates

S. Lupi et al. PRB 62, 12418 (2000)

Drude from σ_{dc}

Interesting low-ω region

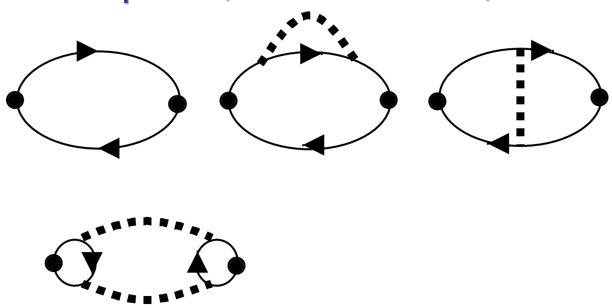
The absorption at low ω is NOT an anomalous Drude peak, but something else ….

Startseva et al., Physica C 321, 135 (1999)

Singley et al., PRB 64,224503 (2001)

A simple phenomenological interpretation

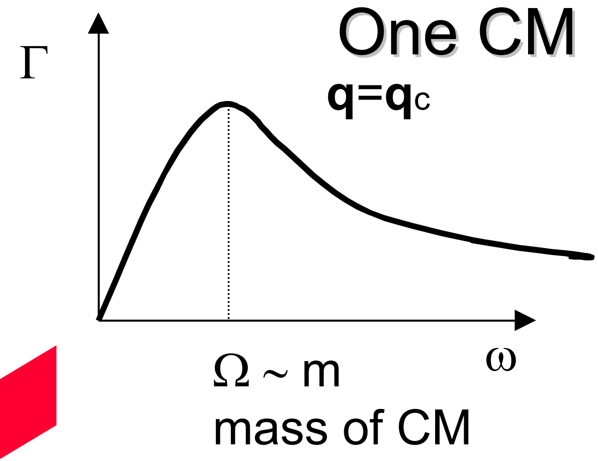
S. Caprara, C. Di Castro, S. Fratini, M.G., PRL88, 147001 (2002)



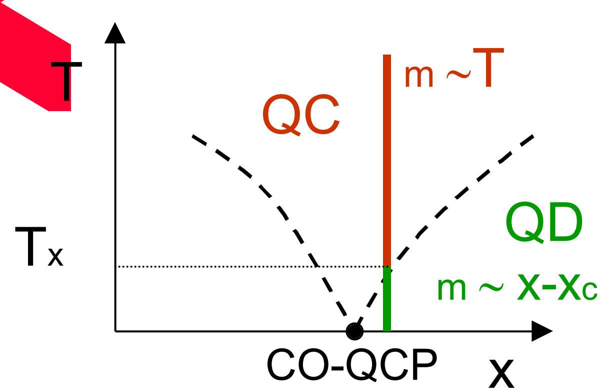
$$\sigma_{QP}(\omega) = \frac{\omega_p^2}{4\pi}\frac{1}{M_{QP}(\omega,T) - i\omega}$$

$$\sigma_{CM}(\omega) = \frac{i}{\omega}\chi_{CM}^{JJ}(\omega)$$

Convolution of two CM's



Temperature dependence?



For overdoped samples

$$\Omega \sim \begin{cases} T \text{ for } T>T_x \\ \text{Const. for } T<T_x \end{cases}$$

Scaling properties of $\sigma(\omega,T)$

A "critical" summary

- The CO-QCP scenario is based on the occurrence of (dynamical/local) charge inhomogeneities (stripes and so on).

- Do they exist? Yes in Nd-doped LSCO, likely yes in LSCO and YBCO. Recent controversial claims of charge textures from tunneling in BSCCO (Kapitulnik,…, Davis)

- Are they accidental? Actually there are high-Tc SC's like FET C_{60} with T_c >100K (if confirmed), where no QCP seems to be present: a seemingly "boring" FL-BCS behavior

  ⇒ other more general mechanisms can produce high-T_c: see SC near a MIT (Capone, Fabrizio, Castellani, Tosatti, Science (2002), see M. Fabrizio)

- Charge criticality may be unnecessary for high-T_c, but could explain the non-FL behavior and the pseudogaps.

The CO-QCP is a standard theory of quantum symmetry breaking with ordering at a finite q_c: it shares many (positive and negative) features with the AF-QCP (cf. Chubukov, Pines, Sachdev, Norman,..)

- Phase diagram naturally splits in three (QC, QD, “ordered”) regions → Strong doping dependence;

- Strongly k-dependent interaction: clear distinction between hot and cold regions on the Fermi surface;

- Presence of critical (charge and spin) collective modes.

Particle-hole channel

- The (dynamical) CO below T_0 decreases the DOS and below T* opens pseudogap around $(\pi,0)$ and $(0,\pi)$ points (Seibold et al., EPJ B (2000));
- Non-trivial IE;
- Collective modes provide: peak-dip-hump structure in ARPES (Seibold, M.G., PRB (2001), cf. Eschrig, Norman, PRL (2000)) and direct absorption in $\sigma(\omega)$.

Particle-particle channel

- Critical modes mediate pairing in the d-wave channel

⇩

- strong x- and k-dependent pairing

⇩

- In underdoped coexist hot tightly bound pairs with either normal QP's (FS arcs above T_c) or cold weakly bound pairs (below T_c (Two-gap model, Perali et al, PRB (2000)).

however

The distinction between hot and cold regions opens serious problems (shared with QCP theories in heavy fermions):

- Some supposedly cold QP's show a non-FL behavior in ARPES (Valla et al., Science (1999));
- Cold QP's should short-circuit the hot ones

⇨ $\rho(T) \sim T^2$ (Hlubina, Rice PRB (1995))

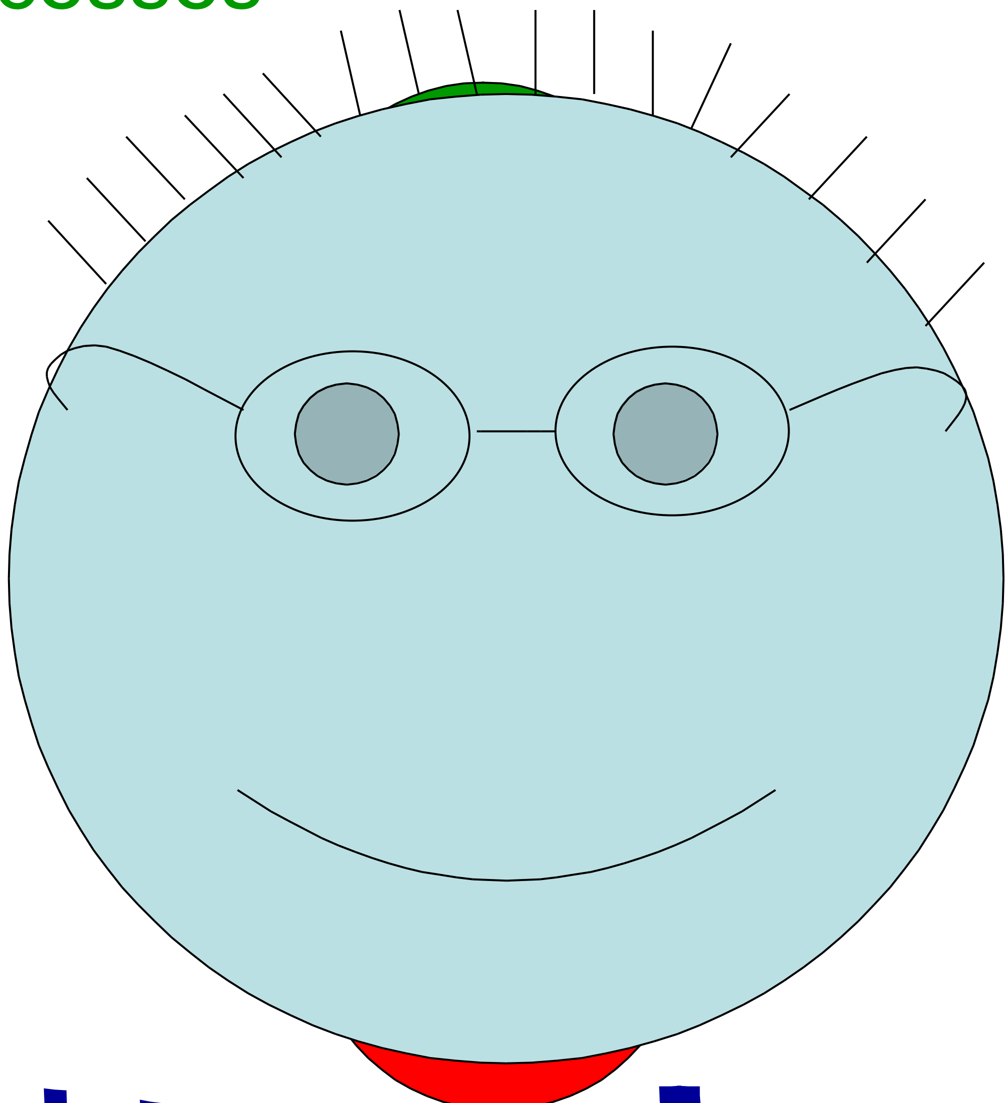
⇩

- Effects of disorder? (Rosch, PRL (1999))

- QCP with critical modes at $q_c=0$? (Circulating Currents, Varma; dDW,see D. Morr;…..)

- Local quantum criticality (see Q. Si, P. Coleman)?

CO-QCP has some partial successes



and

I am glad to be here to discuss with you

BUT