Dynamical charge and spin fluctuations: is this the glue in cuprates?

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Theory: S. Caprara, C. Di Castro, G. Mazza, G. Seibold, J. Lorenzana
Raman Expts: R. Hackl's group

What is the interaction mediator? The "glue" issue

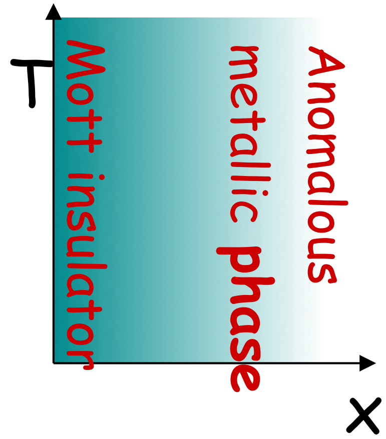
doping a Mott insulator produces

a non-FL **phase** and pairing result from

•RVB (Anderson,Lee, Nagaosa, Wen)

•Stripes (Emery,Kivelson,Zaanen,..)

⇒Instantaneous interactions are more relevant (U,J,....)



Quantum **instability** (QCP) of the metallic phase:

•Stripes - Charge ordering (Rome), $q_c \approx (0,\pm\pi/2), (\pm\pi/2,0)$

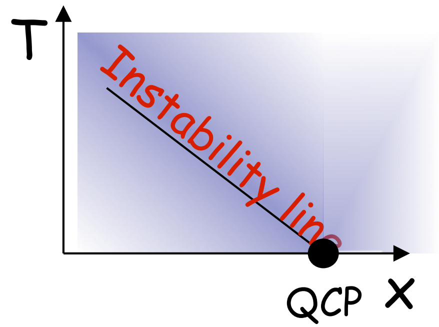
•Circulating currents (Varma), $q_c=0$

•Pomeranchuk-nematic instability (Metzner), $q_c=0$

•retarded spin waves (Chubukov,Pines,....)

due to proximity to AF-QCP, $q_c \approx (\pi,\pi)$

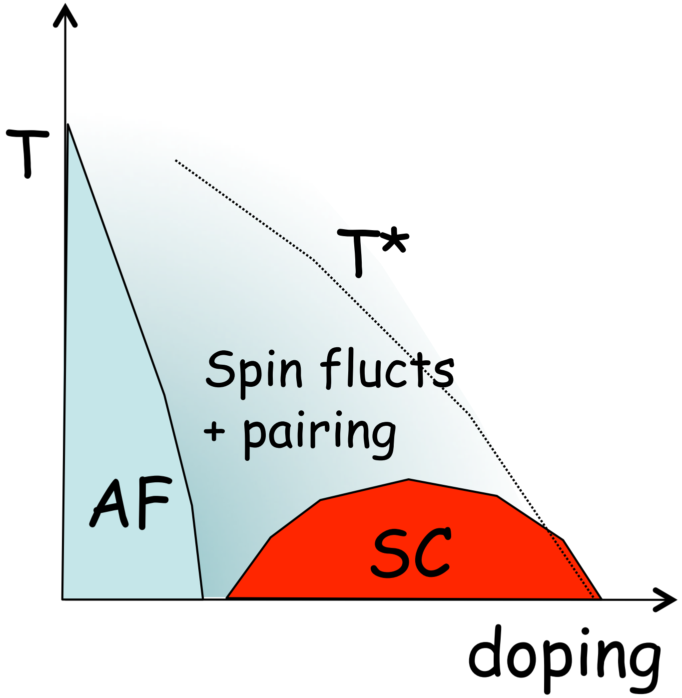
⇒Crucial role of retarded critical interactions



If retarded (i.e. low-energy) modes are there the issue is:
How to identify them? What is their typical wavevector related to the ordered phase?

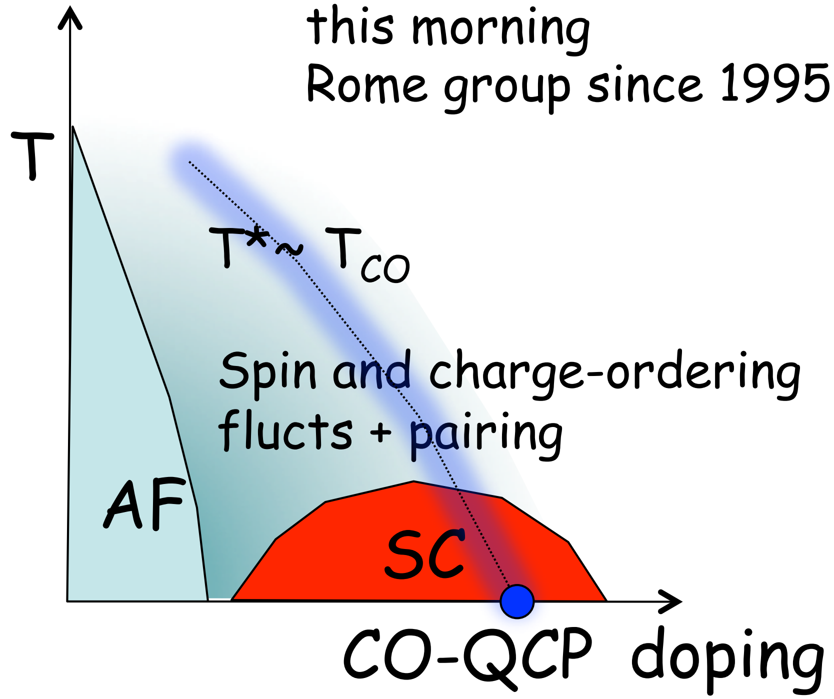
A "traditional" view: spin and charge modes only

First possibility: spin glue
Physics ruled by spin flucts. only
Pines, Chubukov, …since early nineties



Is this all? After all stripes are there…

Cf. Di Castro's talk this morning
Rome group since 1995



Q: what are more relevant? Spin-modes, charge-modes or both?

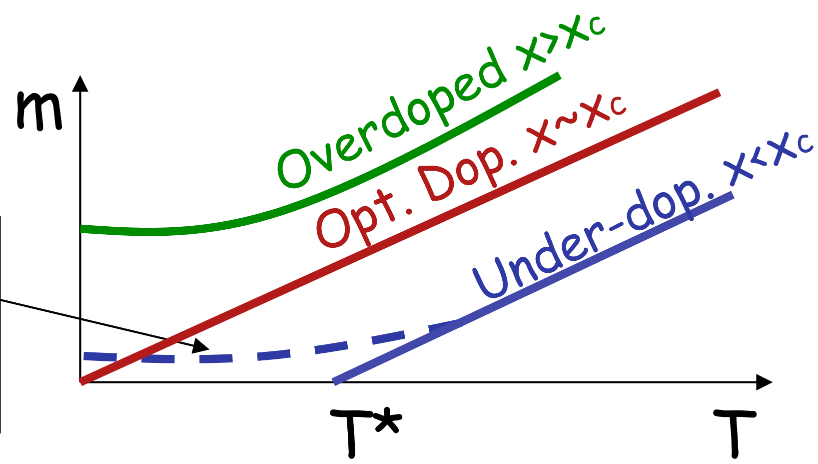
The nearly critical modes (charge and spin) mediate a retarded interaction

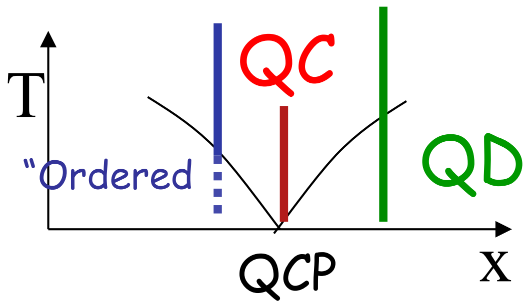
$$D(\vec{q},\omega) = -\frac{1}{m + \nu|\vec{q} - \vec{q}_c|^2 - i\omega - \frac{\omega^2}{\overline{\Omega}}}$$

For small m and ω is strongly peaked at q_c

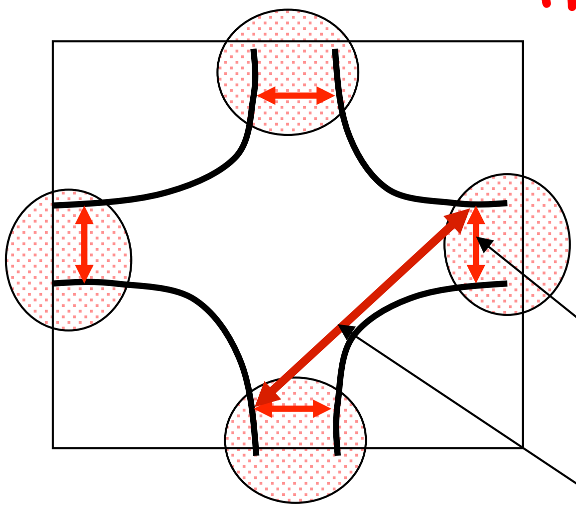
$m \sim \xi^{-2}$ depends on proximity to the "missed instability"

If order is not truly
static-long-range
m never vanishes





Can we identify the relevant collective modes with Raman?



LSCO: we focus on large dopings $x \geq 0.15$ to avoid PG effects

$$q_c \approx \left(\pm\frac{\pi}{2},0\right),\left(0,\pm\frac{\pi}{2}\right)$$

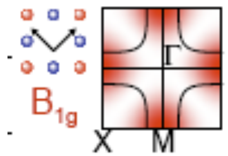
$$q_s \approx (\pm\pi,\pm\pi)$$

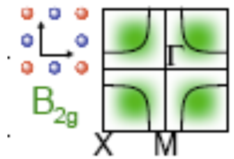
Nearly critical modes strongly couple hot regions of the FS

In Raman spectroscopy one can select the probed k-space
With specific form factors in the vertices:

B_{1g} $\gamma_k = \cos(k_x) - \cos(k_y)$

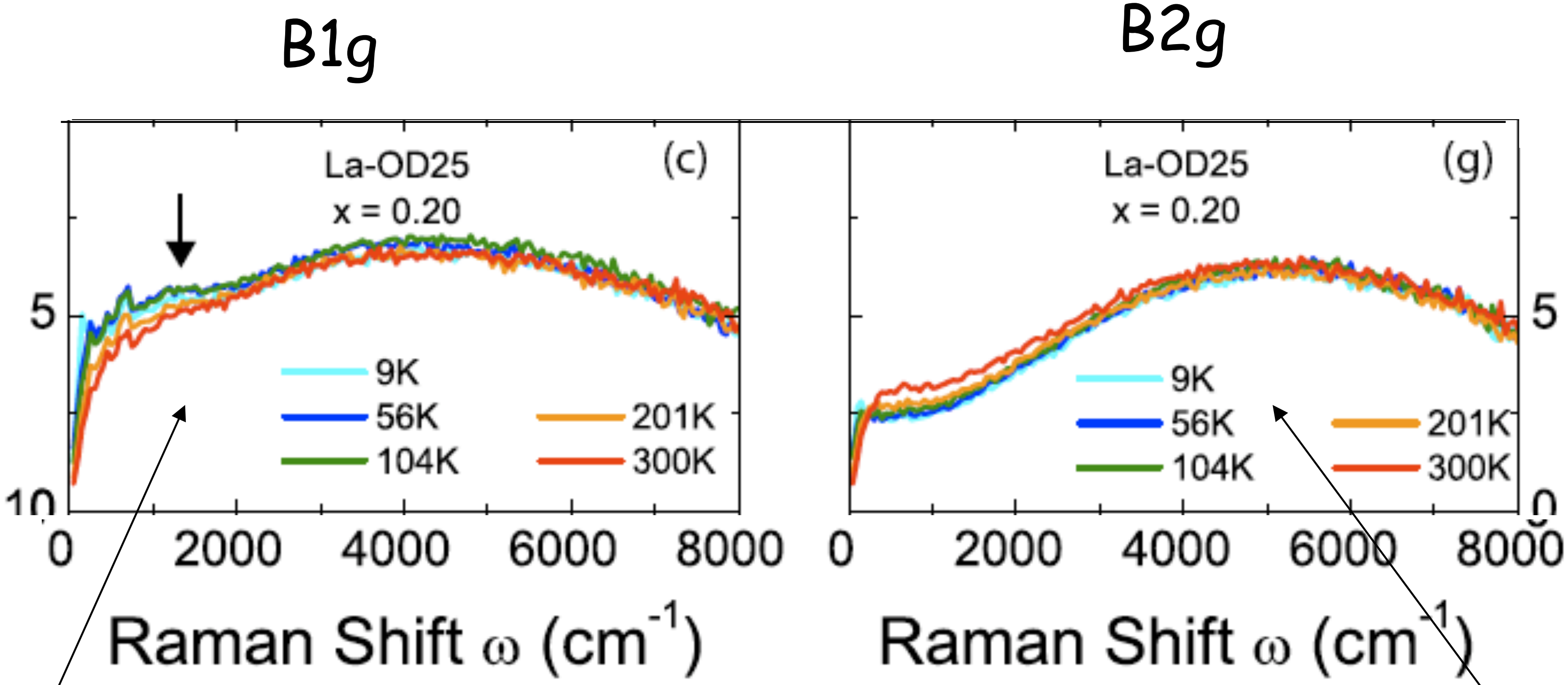
B_{2g} $\gamma_k = \sin(k_x)\sin(k_y)$





Spin and CO coll. modes: similar hot spots,but different q_c's
Is it possible to distinguish their effects?

What can we learn from the whole spectra?



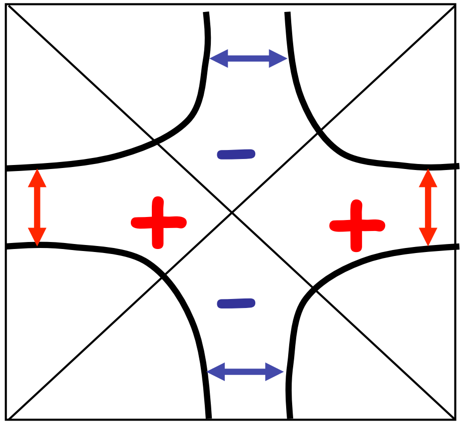
More rounded: two close humps

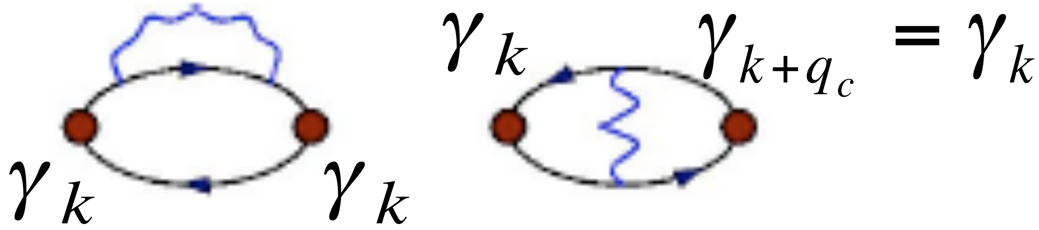
Step+hump structure

Different shapes in the two channels below ~4000 cm^{-1}:
Just fermiology or different scattering mechanisms?

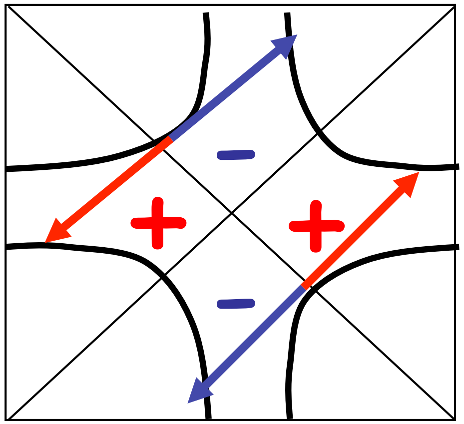
Symmetry arguments for the leading contribution to χ''

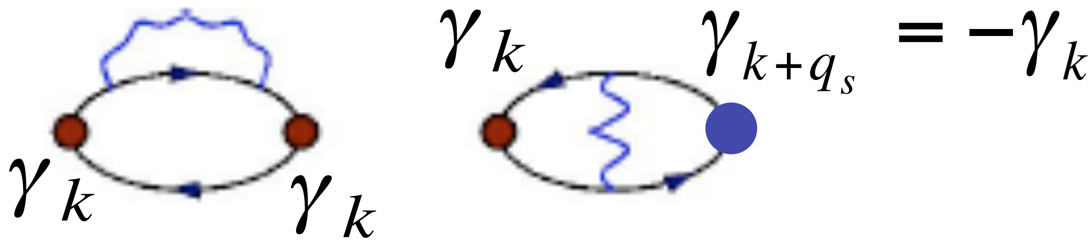
B_{1g}: $\gamma_k = \cos(k_x) - \cos(k_y)$





The two diagrams cancel at leading order
(like transport with scattering at q~0)





The two diagrams add at leading order
(like transport with scattering at $q \sim 2k_F$)

Not just a sketch: realistic q_c, q_s and Fermi surfaces are used

Similar arguments hold in the B_{2g} channel

At leading order (i.e. critical mode, low energy, linearized bands, vertices evaluated at E_F...)

	SPIN	CHARGE
B_{1g}	ALLOWED	FORBIDDEN
B_{2g}	FORBIDDEN	ALLOWED

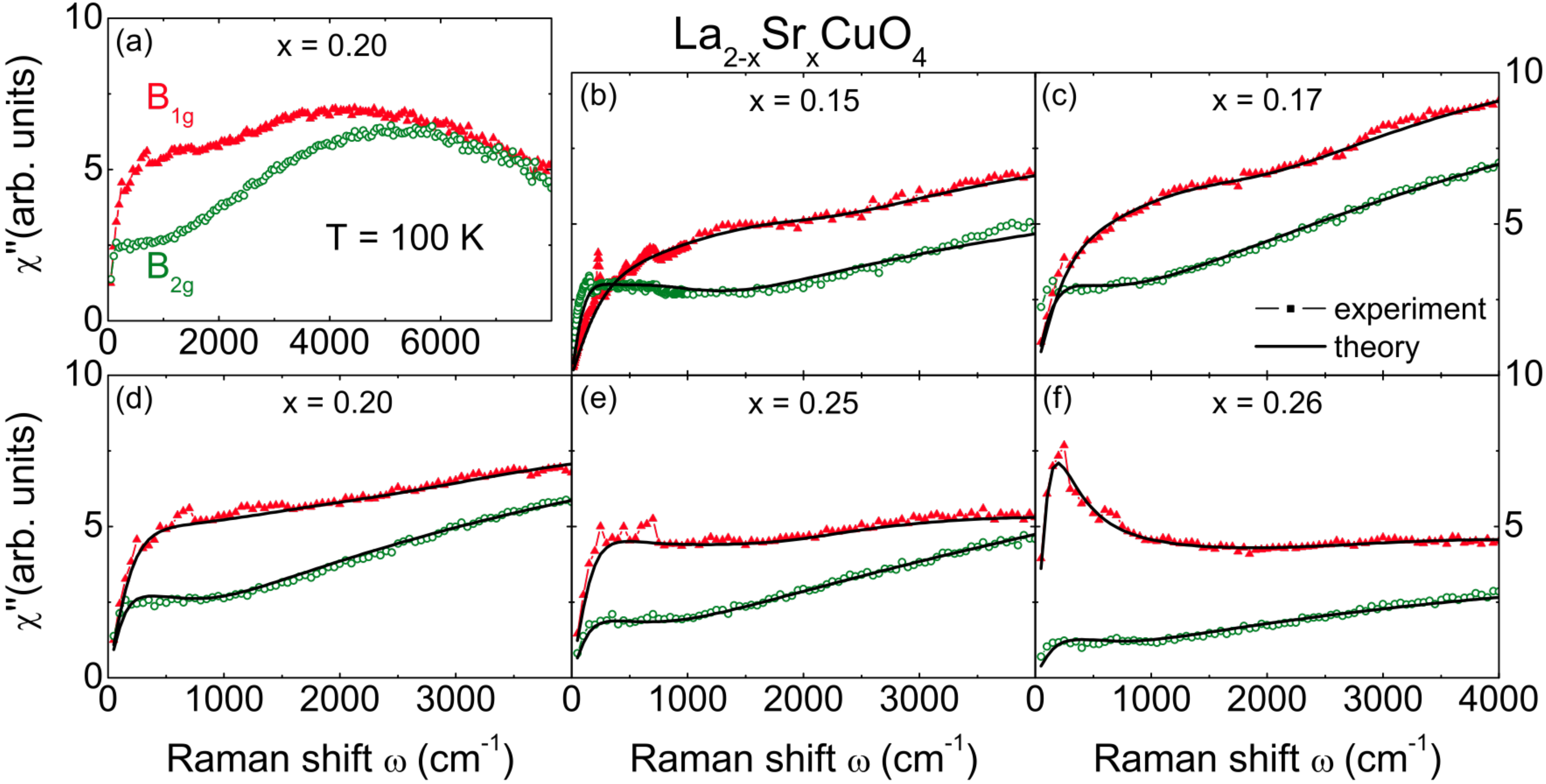
This suggests that different B_{1g} and B_{2g} spectra are due to different modes

Of course at large energies (say above 1000-2000 cm^{-1}) and far from criticality the "forbidden" modes come in and the spectra become equal in the two channels

Fitting the LSCO spectra

T~100 K

Caprara et al. PRB 2011



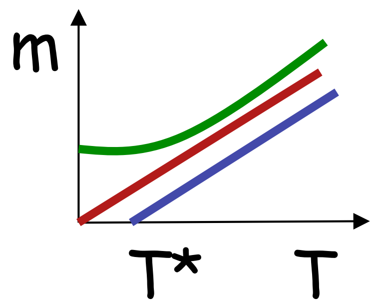
Temperature dependence

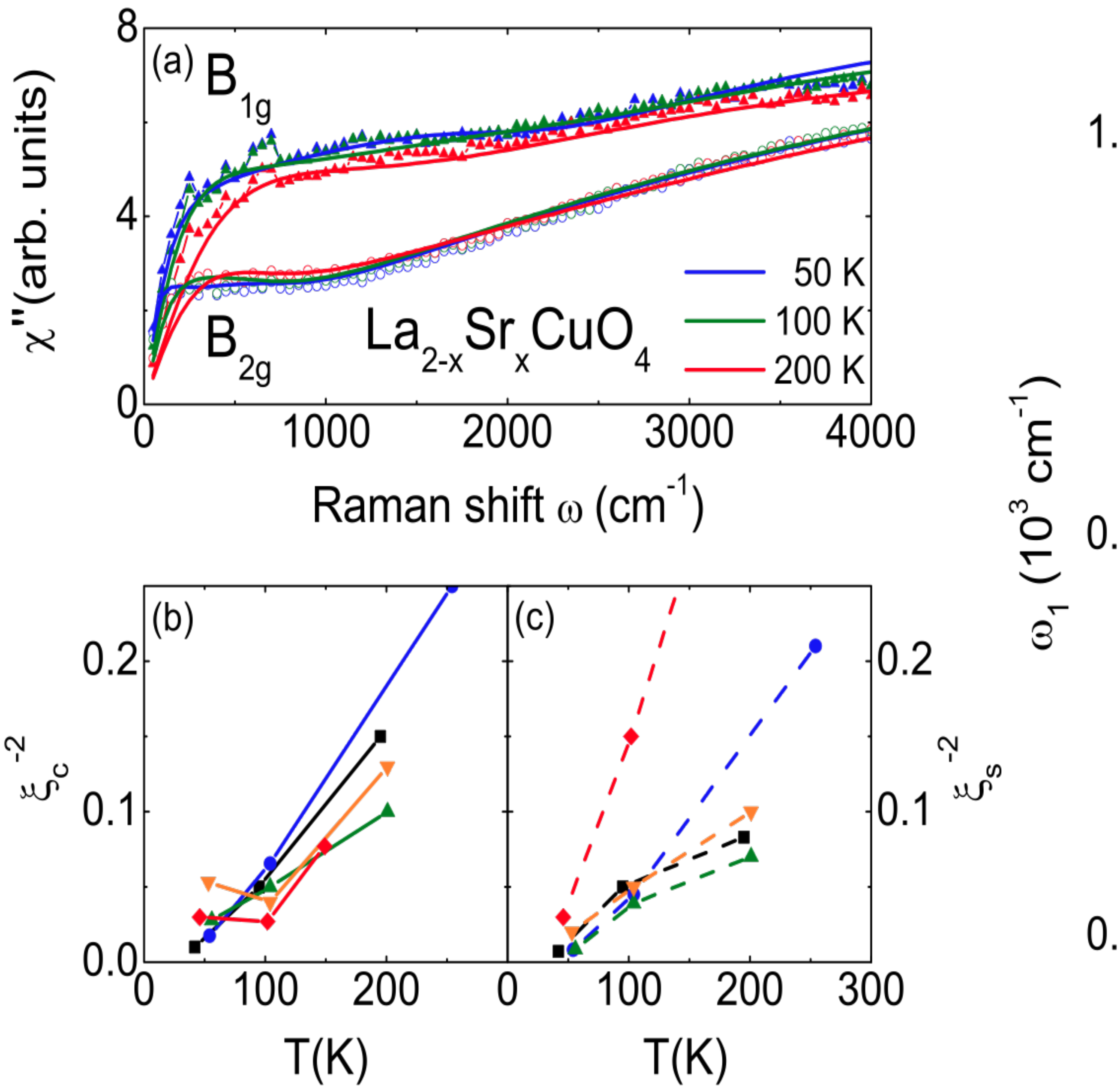
Caprara et al. PRB 2011

$La_{1.80}Sr_{0.20}CuO_4$

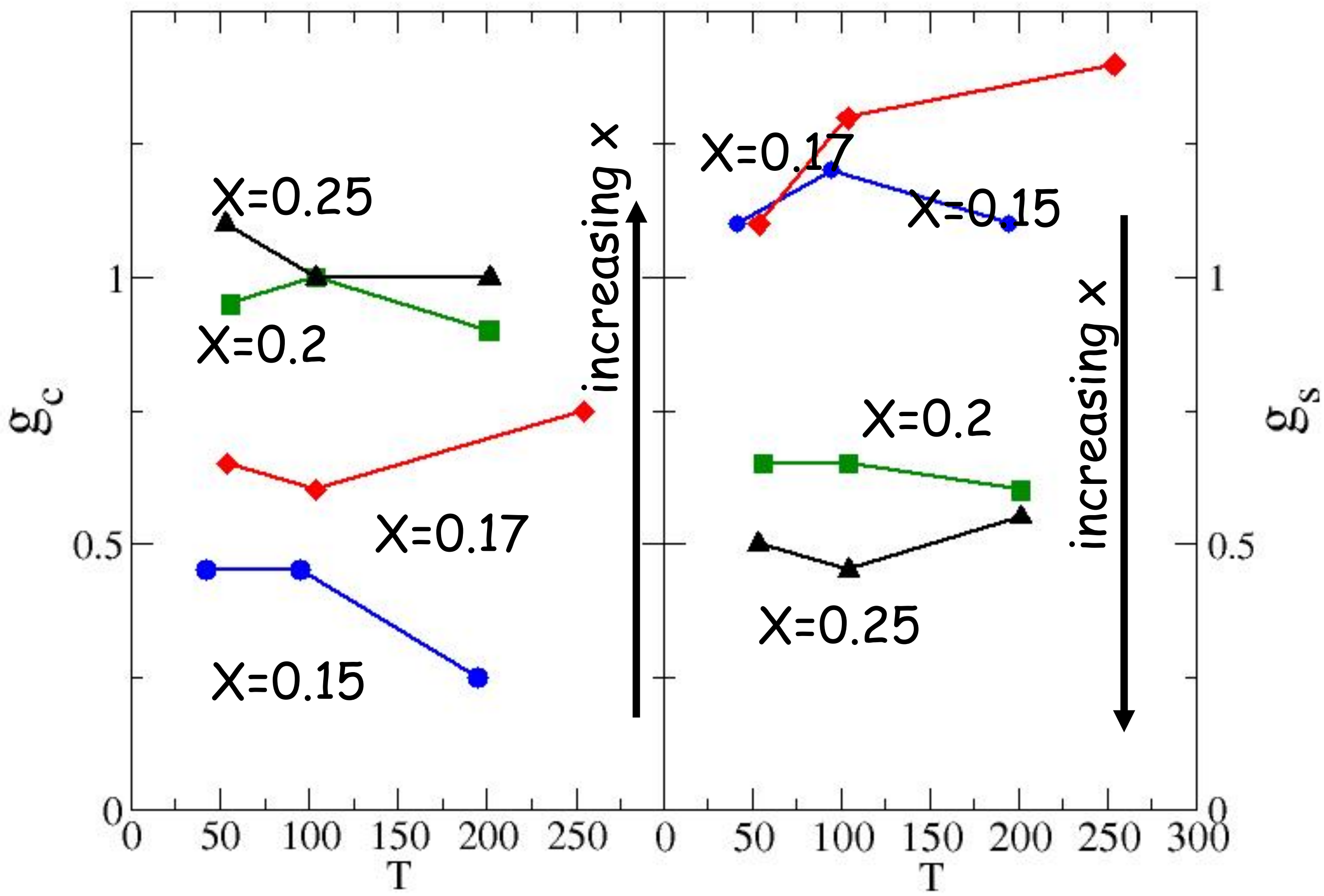
Weak T dependence:
m(T) compensates
bose factor effects

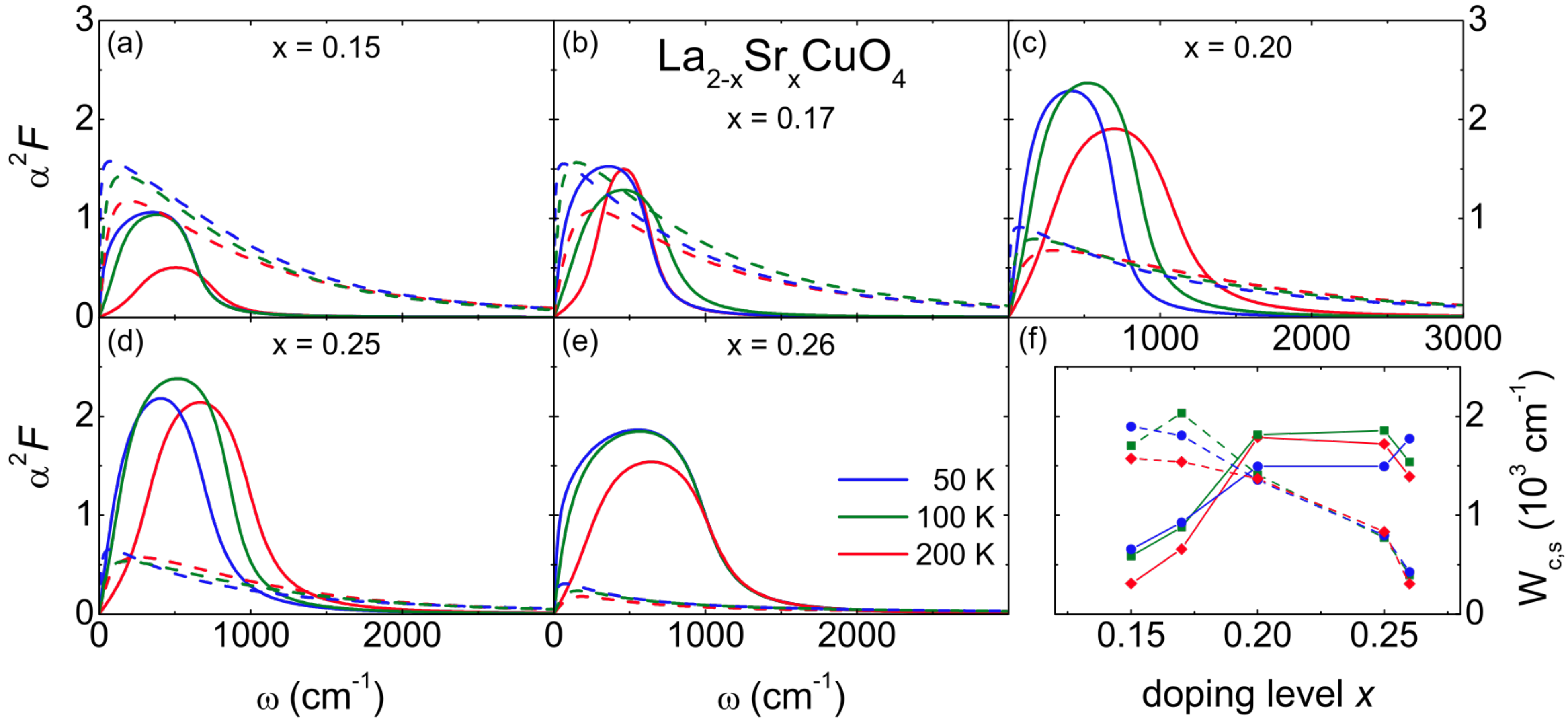
Similar coherence
lengths for charge
and spin fluts.
~2-10 lattice units





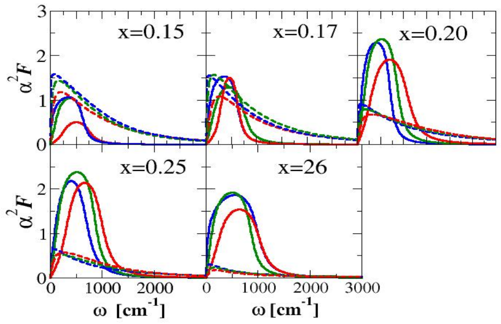
How the CM's couple to the quasiparticles?



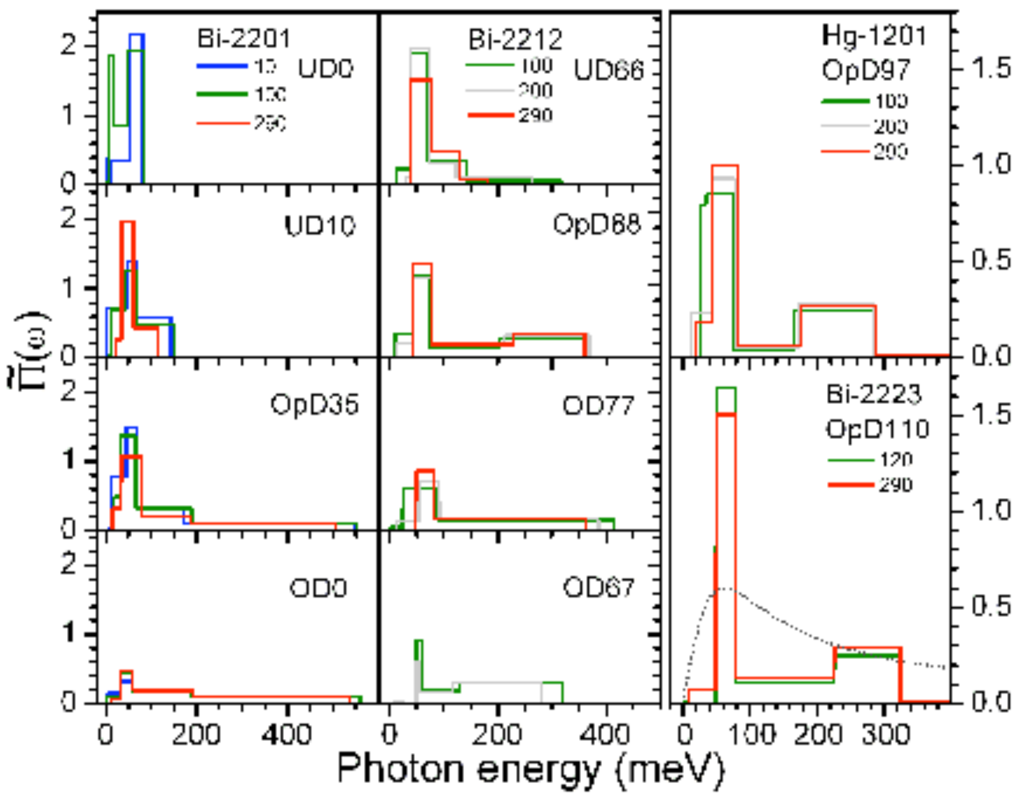


- The spin glue decreases with doping
- The charge glue increases with doping
- All charge glue functs. are centered at phononic energies (~500 cm^{-1}), but have larger weights at low T because of the CO instability which softens the phonon around q_c

How do we compare with optics?



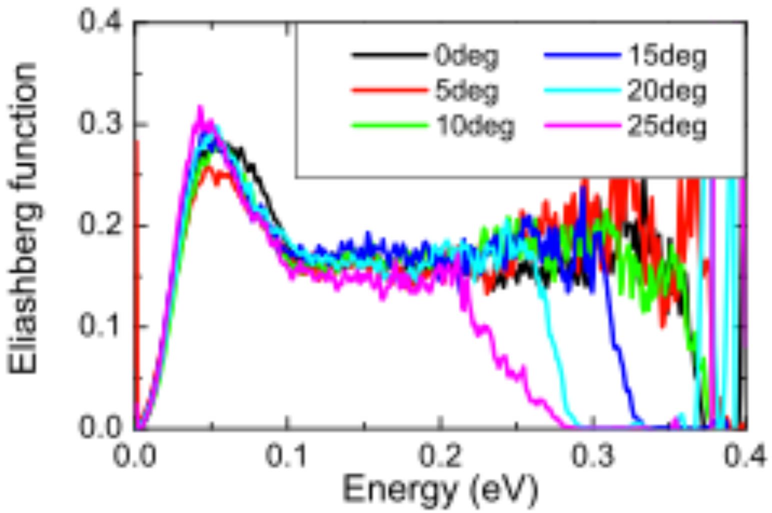
In optics no “selection rules”: both modes contribute



Van Heumen et al., PRB 2009 and arXiv:0807.1730

Bi-2212 different from LSCO?

ARPES



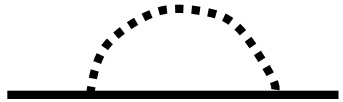
Bok et al. PRB 2010

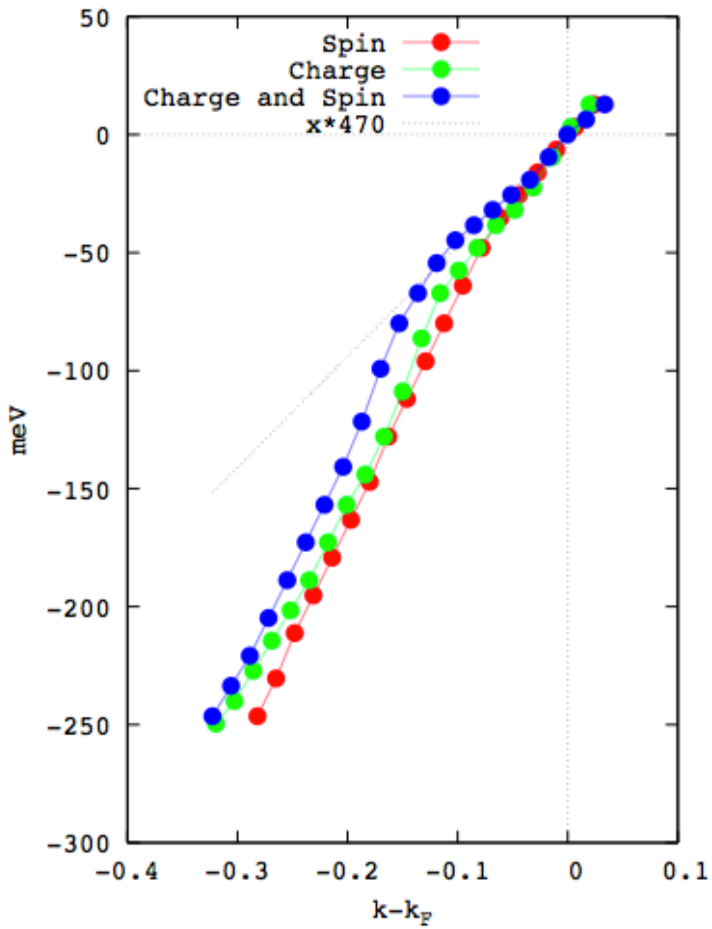
Again two features in α^2F:
A peak at phonon-like energies
and a broad continuum

How do we account for the prominent experimental features in ARPES, kinks and waterfalls?
We now know that both spins and charge modes are present and we know the major characteristics of the modes…

KINKS

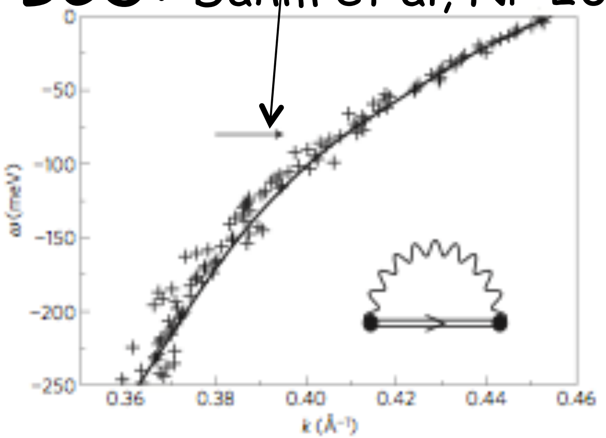
Old idea: collective modes give kinks in electronic dispersion
Engelsberg, Schrieffer PRB 63 (phonons);
Eschrig, Norman, PRL 2000 (spin modes)
Seibold, MG, PRB 2001 (charge modes)
Now we use the input from Raman expts for parameters of spin and charge CM



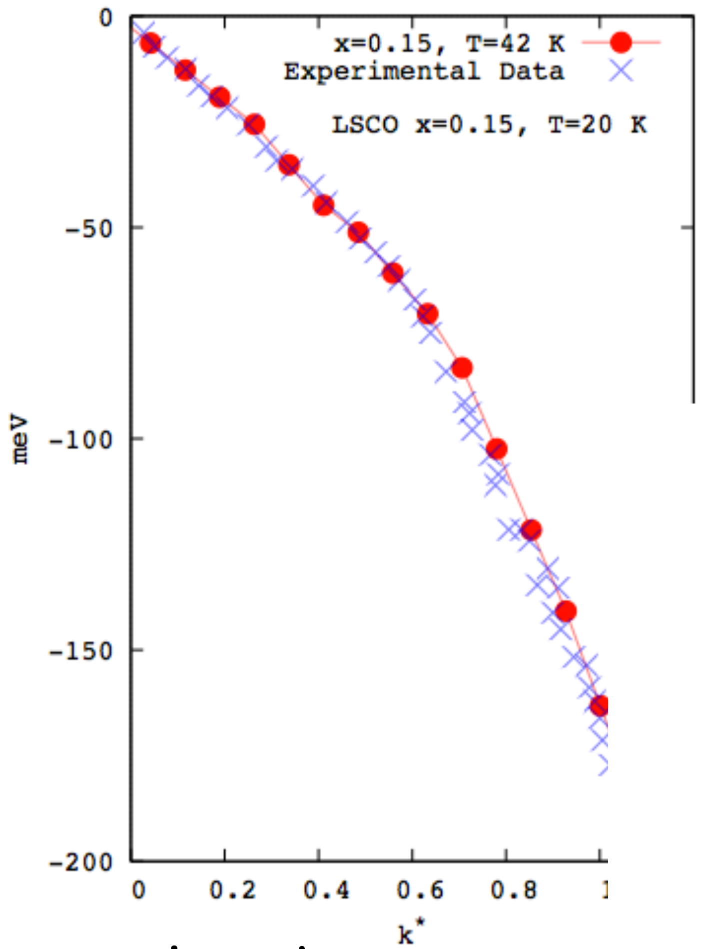


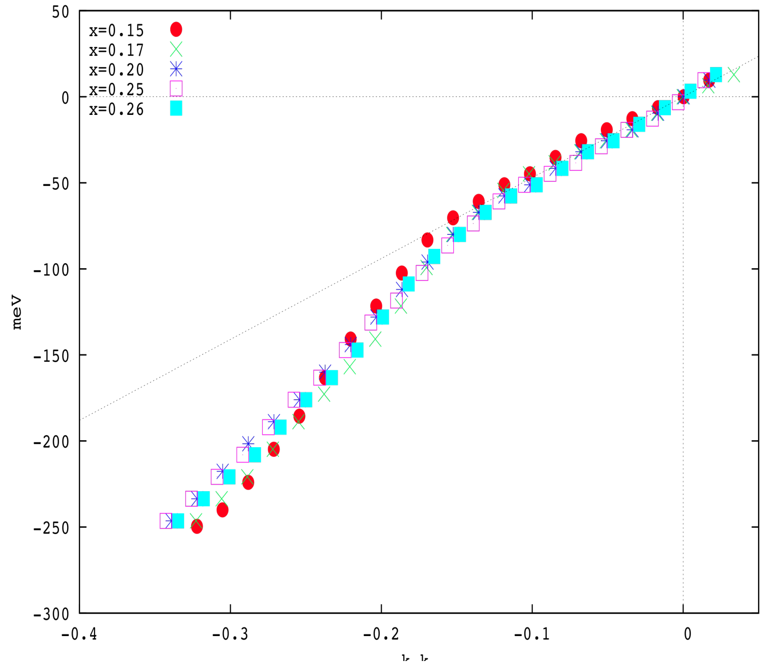
Diagonal (nodal) cut above Tc:
Spin modes too broad and diffusive might work well for YBCO, not for LSCO. Charge modes too narrow range. Together work well

YBCO: Dahm et al, NP 2010

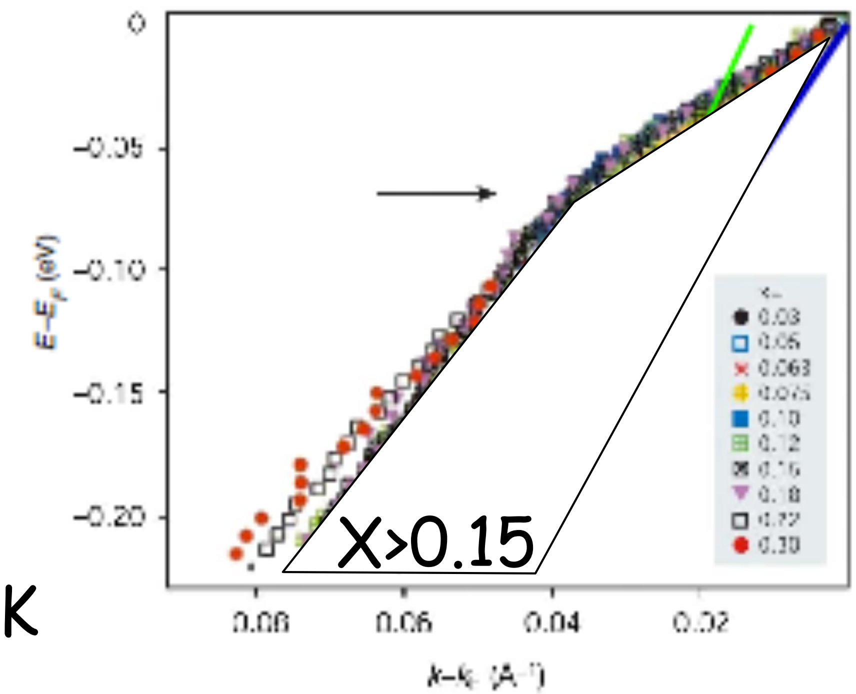


Theoretical dispersion with charge and spin describe well expts.



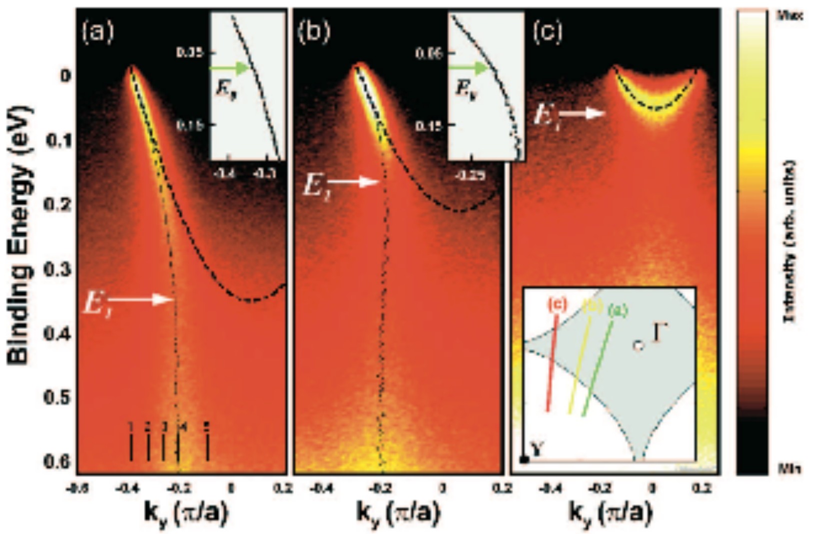


Also doping evolution seems OK

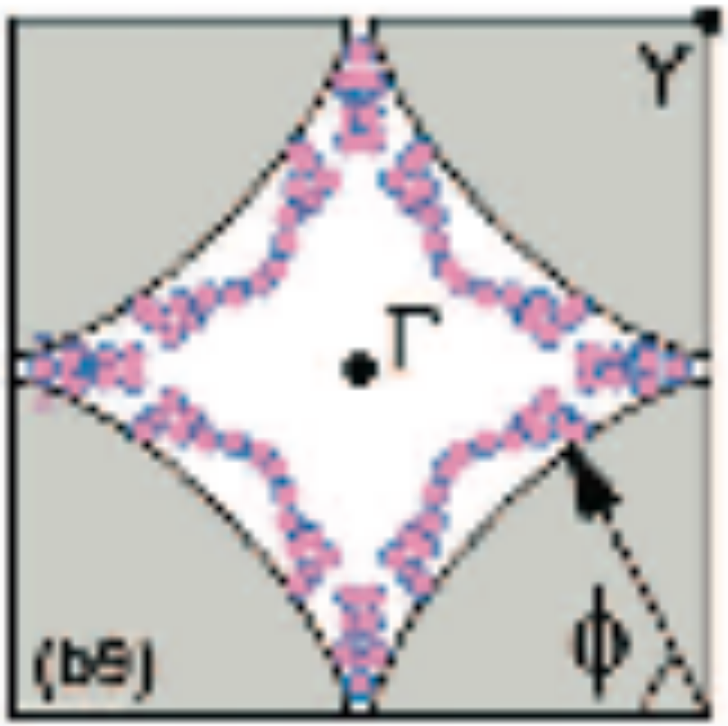


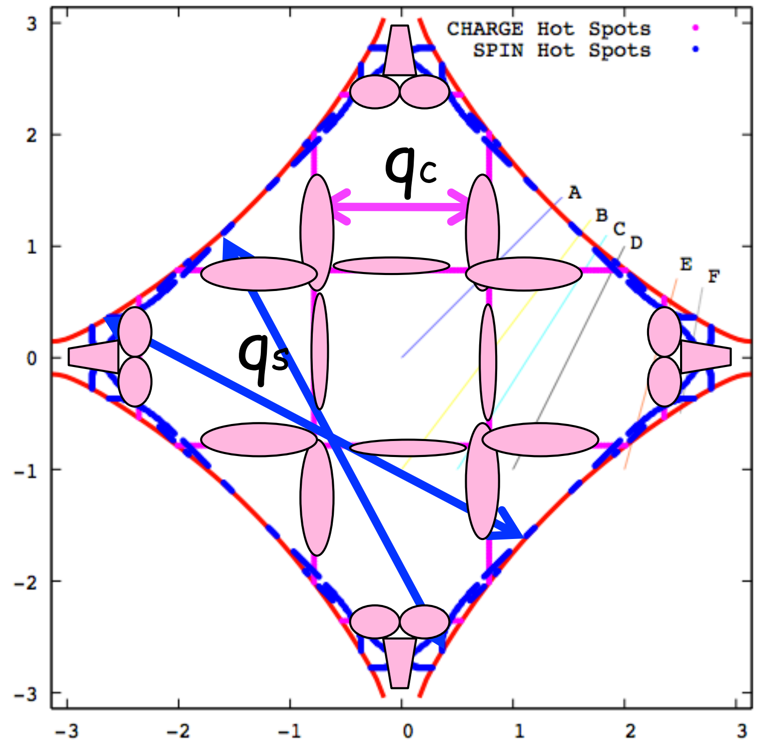
Sahrakorpi et al, PRB 2008

WATERFALLS

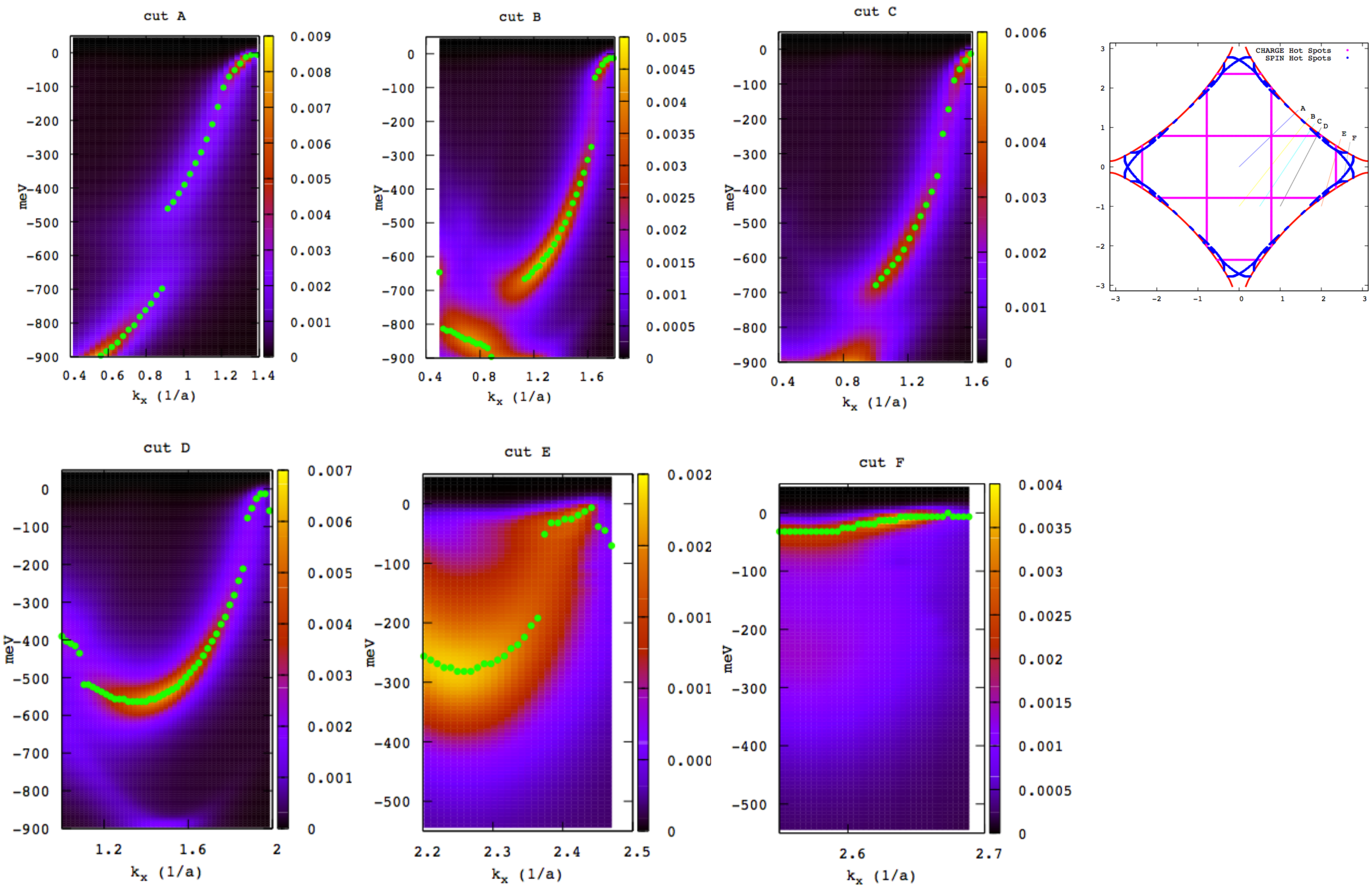


Waterfalls in LSCO at x=0.17
Chang et al PRB 2007





G. Mazza et al., in preparation



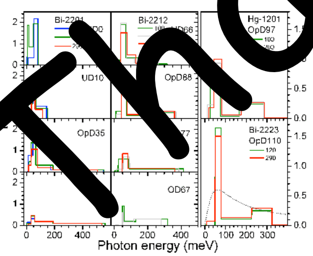
Conclusions

Raman experiments can be a powerful tool to detect scattering mechanisms which are large at finite wave-vectors: 

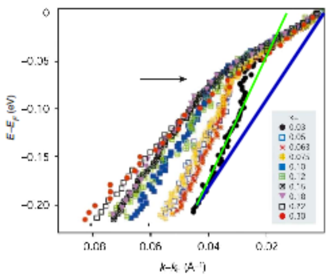
In LSCO one can see spin and charge scattering at work separately

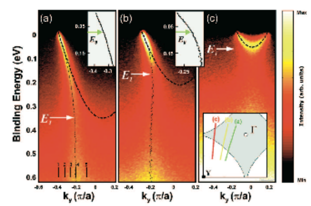
- In optimally-overdoped LSCO the spin glue decreases with doping (but is still strong at x=0.15), the charge glue increases with doping. Who is the main character of this comedy? Open question…
- The spin+charge physics also seems to account for

Optics

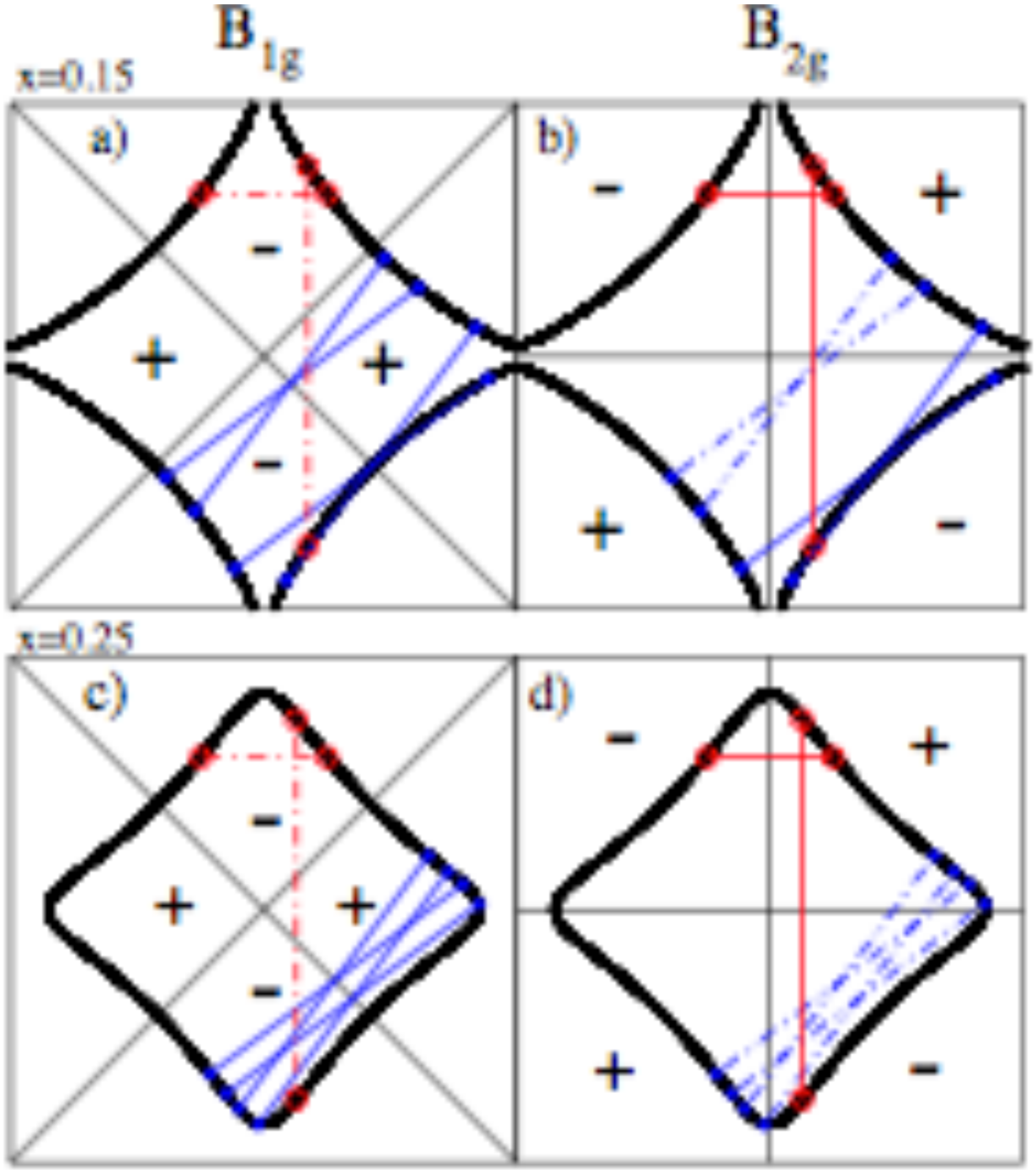


ARPES

Kinks 

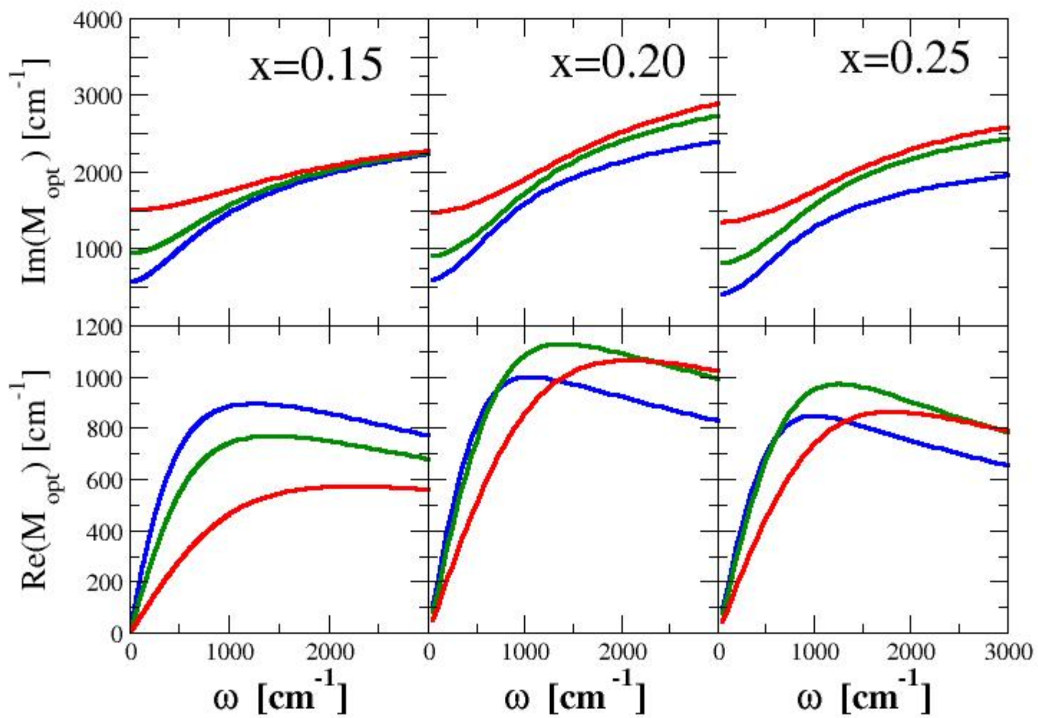
and waterfalls 

Thank you



B1g
B2g
x=0.15
a)
b)
x=0.25
c)
d)

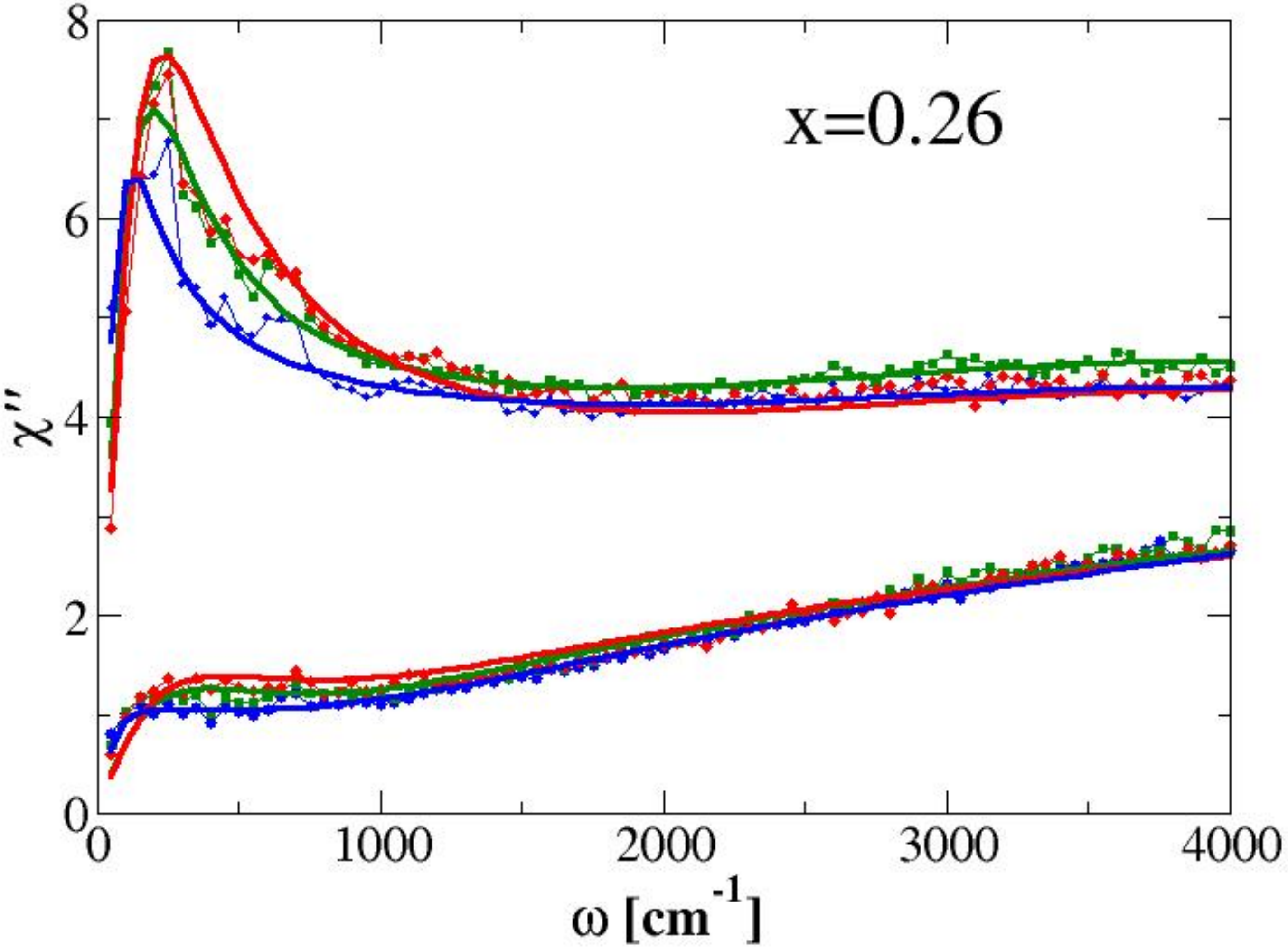
- Two modes are present (agrees with van Heumen et al. PRB 2009)
- The phonon-CO mode has some T dependence (doesn't agrees with van Heumen et al.)
- The phonon-CO mode does not disappear in overdoped LSCO (different with respect to BSCCO? What happens at even larger dopings?



Important qualitative feature:

The T dependence of $1/\tau$ at high ω increases with x

T-independent mode and couplings wouldn't produce it

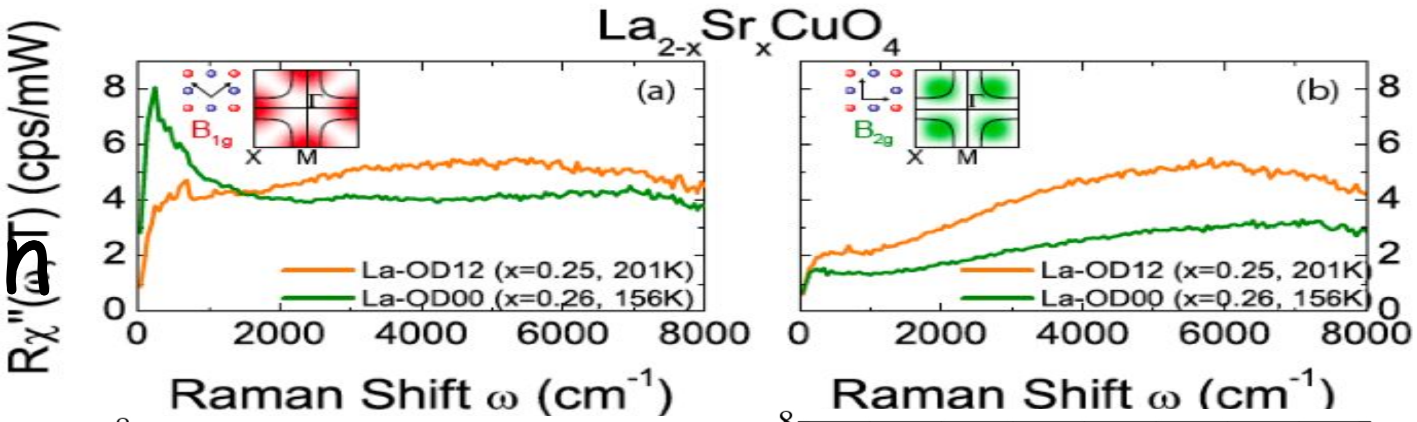


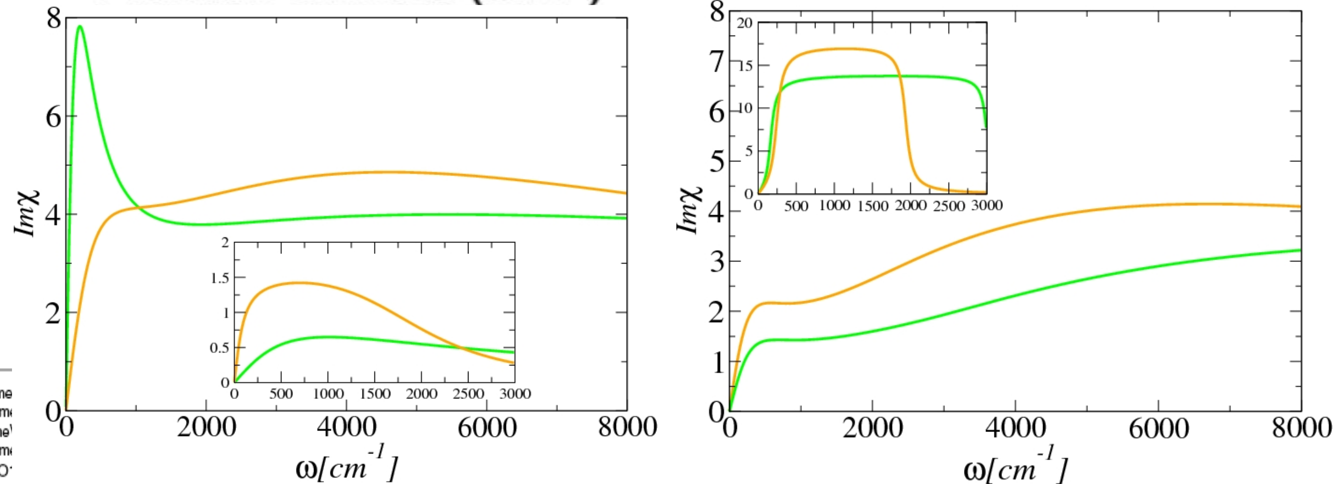
x=0.26
χ''
ω [cm-1]
0
1000
2000
3000
4000
0
2
4
6
8

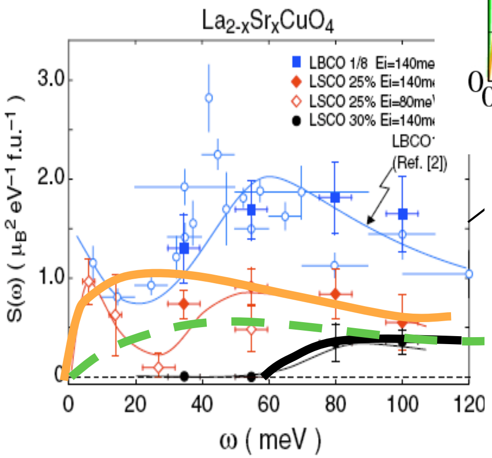
High doping

Charg

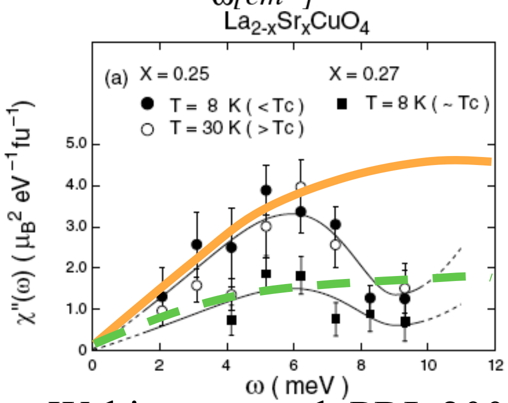
SPin







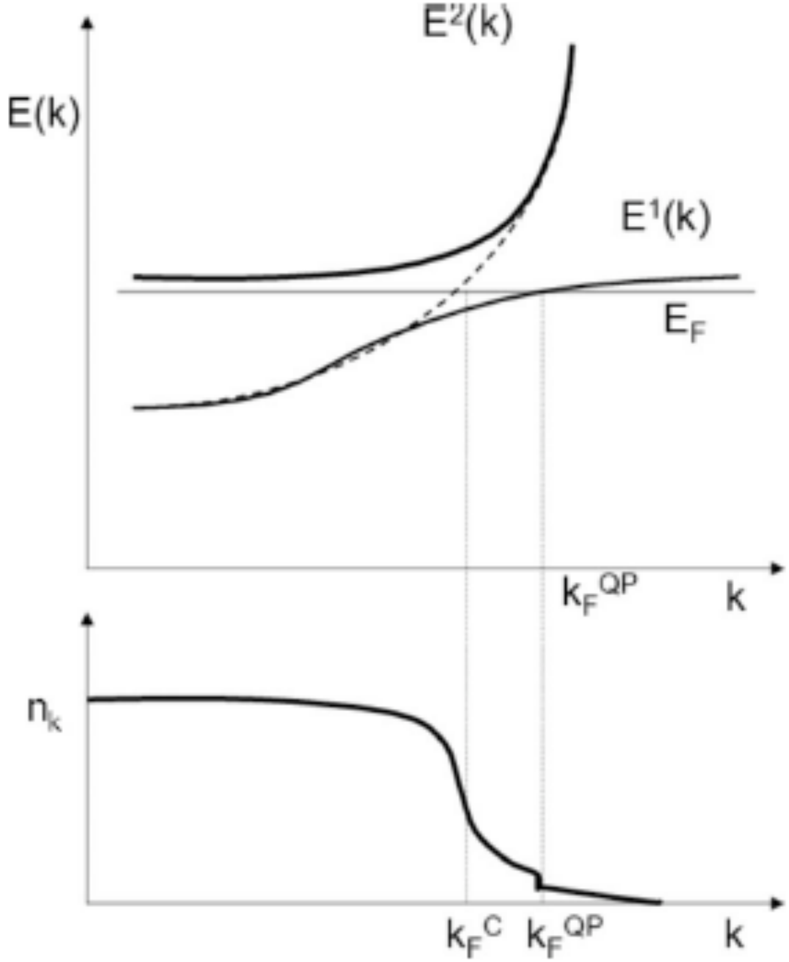
Wakimoto, et al, PRL 2(



Wakimoto, et al, PRL 2004

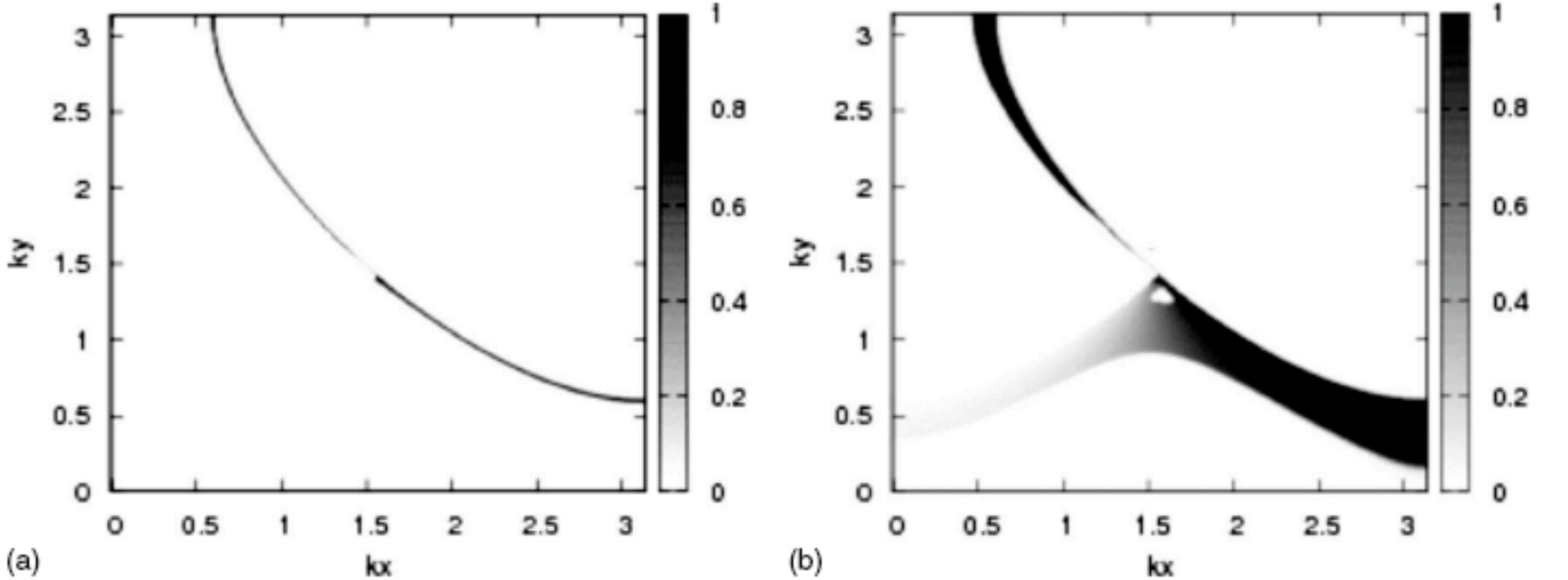
Check with neutrons:

Qualitative agreement with Neutron structure factors… From x=0.25 to x=0.27 spin χ''(ω) is reduced by factor 2



$$n_{\mathbf{k}} \equiv \int d\omega A(\mathbf{k},\omega) f(\omega),$$

2D toy model with qc=(π,0)



Ordered and disordered eggbox (checkerboard)

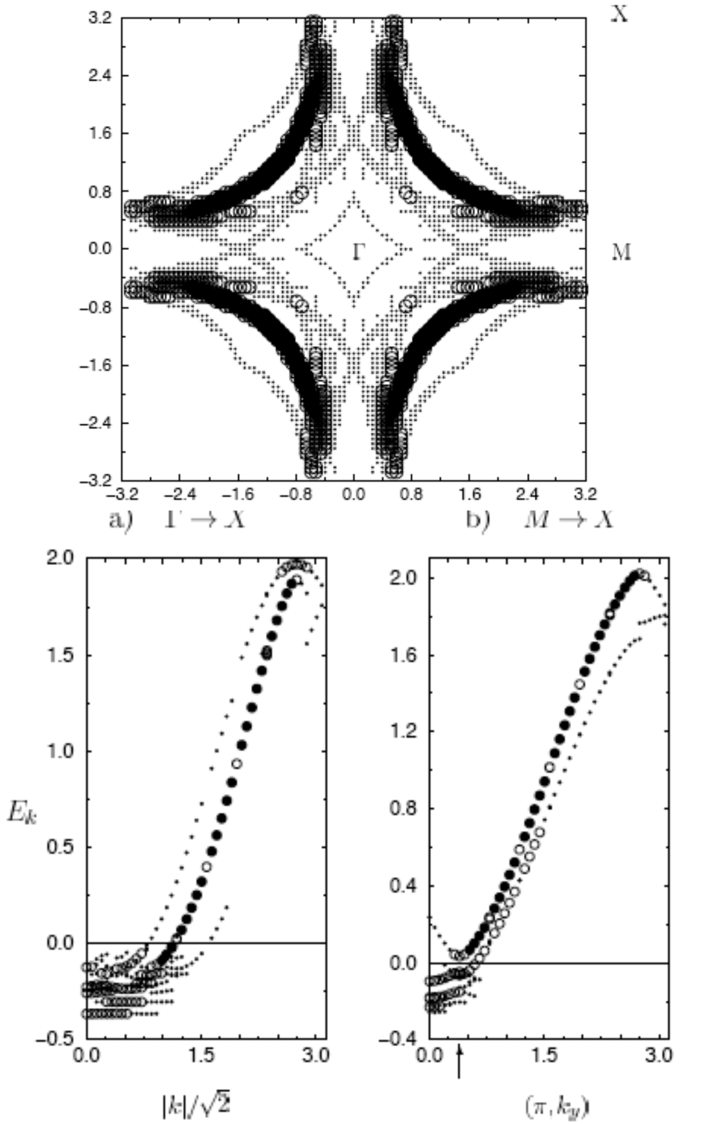
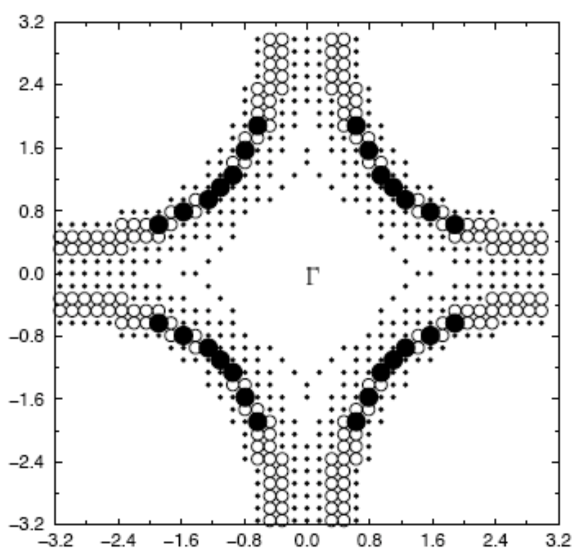


Fig. 7. Bandstructure in the full Brillouin zone corresponding to the Fermi surface in Figure 1. Intensities: $I > 50\%$: full points, $10\% < I < 50\%$: circles, $1\% < I < 10\%$: small dots. (a) $\Gamma \le k \le X$, (b) $M \le k \le X$.



Seibold et al., EPJ B 2000

G. Seibold, M.G., and J. Lorenzana, PRL 2009

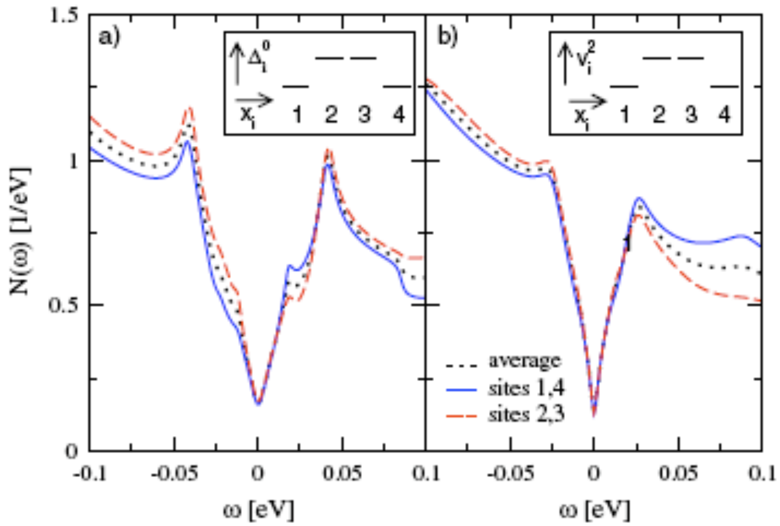


FIG. 2 (color online). LDOS for the model with (a) static CDW scattering ($\Delta_2^0 - \Delta_1^0 = 0.054$ eV) and (b) frequency dependent CDW scattering. The upper insets depict the modulations of $\Delta_{\mathbf{r}}^0$ (a) and $v_{\mathbf{r}}^2$ (b) in the unit cell. Further parameters: chemical potential $\mu = -0.23$ eV, (doping $x \approx 0.07$), $\Gamma = 1$ meV, and $\Omega = 1$ eV.

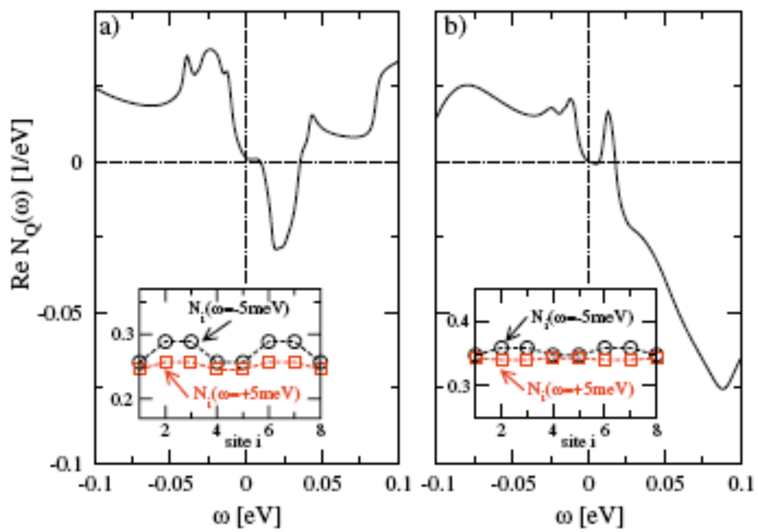


FIG. 3 (color online). Fourier-transformed LDOS at the CDW scattering vector, $\mathbf{Q} = \frac{2\pi}{4}$. (a) Static CDW scattering with $\Delta_2^0 - \Delta_1^0 = 0.054$ eV, (b) frequency dependent CDW scattering. The phase has been chosen such that $\text{Im}N_{\mathbf{Q}}(\omega) = 0$. Lower insets: LDOS at $\omega = +5$ meV (squares) and $\omega = -5$ meV (circles). Further parameters as in Fig. 2.

Understanding the effective interaction can shed light on the state: The "GLUE" issue

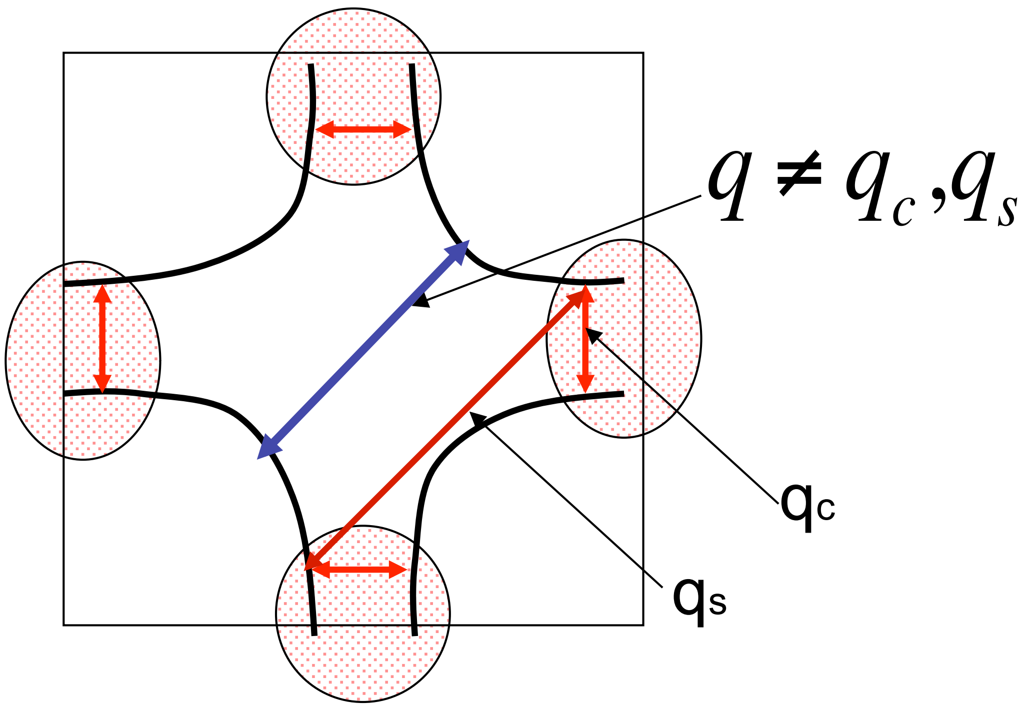
In particular, if retarded (i.e. low-energy) modes are present (point of view n.2), the issues are:
How to identify them?
How do they look like?
Can one determine the broken-symmetry phase?

e.g.

- Circulating currents ⇒ $q_c=0$ instability (C. M. Varma, since '94 on)
- AF spin waves ⇒ $q_c \approx (\pi,\pi)$ (A. Chubukov, D. Pines, ...)
- Pomeranchuk instability ⇒ $q_c=0$ instability (W. Metzner)
- Charge Ordering $q_c \approx (0,\pm\pi/2), (\pm\pi/2,0)$ (Rome, since 94+ε)
- ....

Hot and cold spots

Strongly k-dependent interaction mediated by Charge (but also spin) modes: clear distinction between hot and cold regions on the Fermi surface



Theory: Castellani et al PRL'95; Perali et al, PRB '96;….

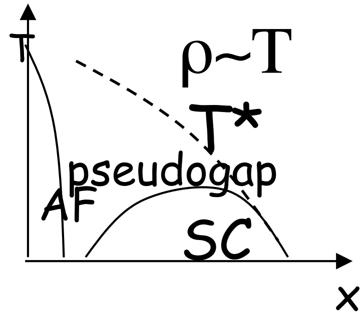
Experiments:

…nodal and antinodal QPs behave very differently……low energy scattering which operates primarily on antinodal QP… this may be associated with QP scattering across the nearly parallel segments of the FS near the antinodes ARPES ex. in LASCO .

Zhou et al. PRL 04
Vershinin et al Scince '04
Shen et al Science 05
…

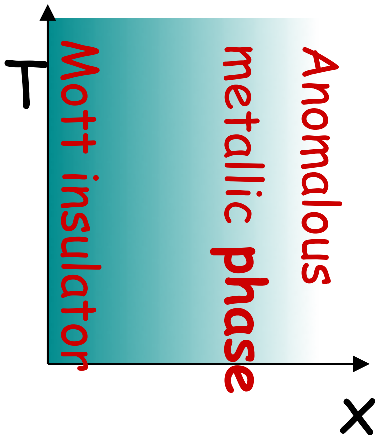
Spin and CO coll. modes: similar hot spots,but different q's
Is it possible to distinguish their effects?

Cuprates are anomalous metals ($\rho \sim T$, pseudogap,…)



Where all these anomalies come from?

Point of view n. 1:



•Non-FL anomalous **phase** "per se":

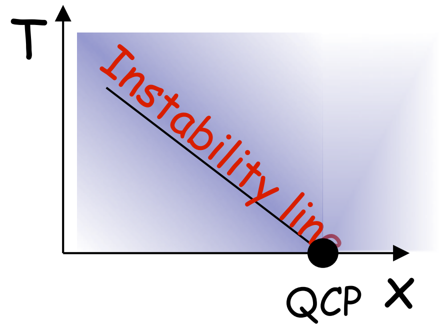
•RVB (P.W. Anderson, P. Lee, Nagaosa,Wen),

• 1d stripes (Emery, Kivelson,…)

Mottness is crucial

⇒Instantaneous interactions (U,J,…)

Point of view n. 2:



Proximity to **instability**

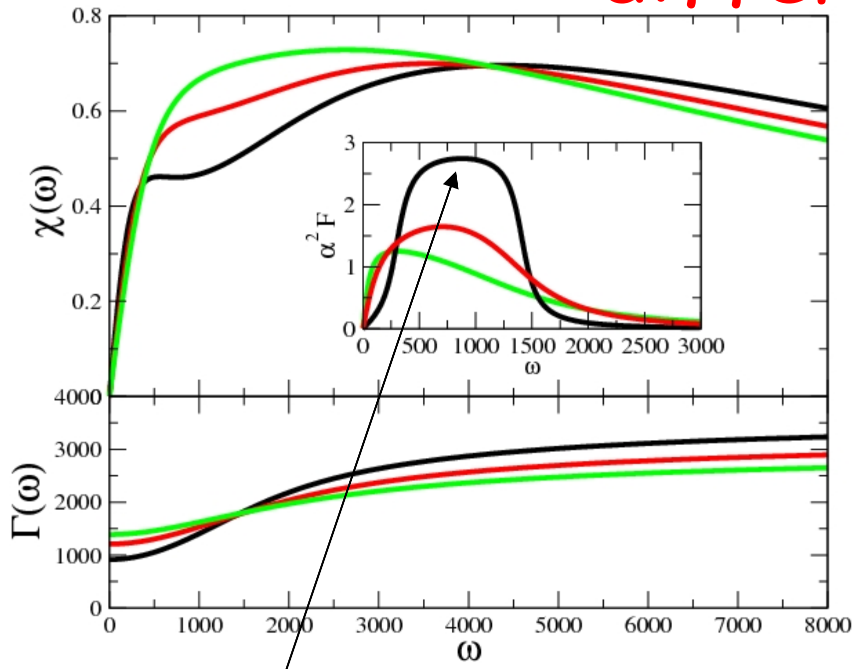
QCP people:

C.M. Varma, Rome, Chubukov, Pines,…

anomalies come from lots of quantum **fluctuations**

⇒Retarded critical interactions

How different modes generate different spectra?



Large $\overline{\Omega} \Rightarrow$ more diffusive mode

Small $\overline{\Omega} \Rightarrow$ less diffusive mode

m rules the amount of scattering at low energy….

Changing the mode (more or less diffusive, $\overline{\Omega}$,mass m,…) one changes the shape of spectra

Notice: more propagating modes may even have a Marginal-FL (flattish) form with initial slope ~1/m~T

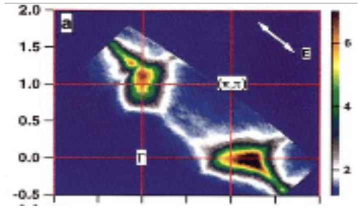
Dynamic character of CO **may** make it elusive

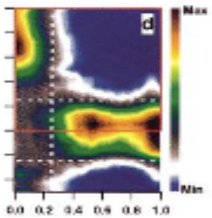
but not so much by now, cf. Z-X Shen talk.....

An old example from ARPES

e.g. Nd-LSCO at x=0.15:

X.J. Zhou et al. PRL 2001

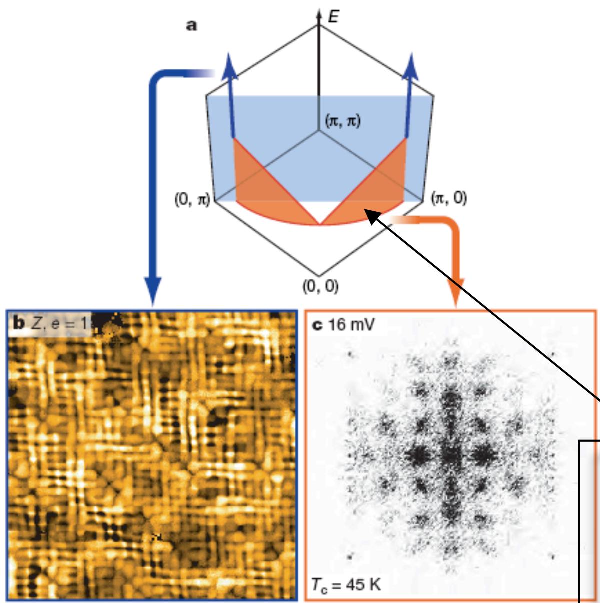


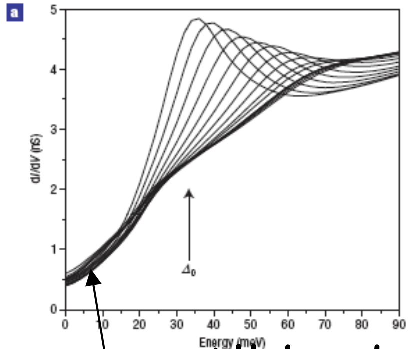


Large FS from low energy spectral weight only

Crossed FS (typical stripe signature) integrating SW up to 300 meV

STM





Non-dispersive Textured electronic Structure at higher energy > Δ_0

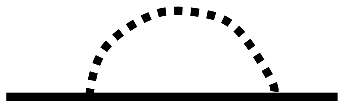
Alldredge et al. Nat.Phys. 2008

Uniform Bogoliubov structure of nodal QP's at low bias < Δ_0

Kohsaka et al., Nat.2008

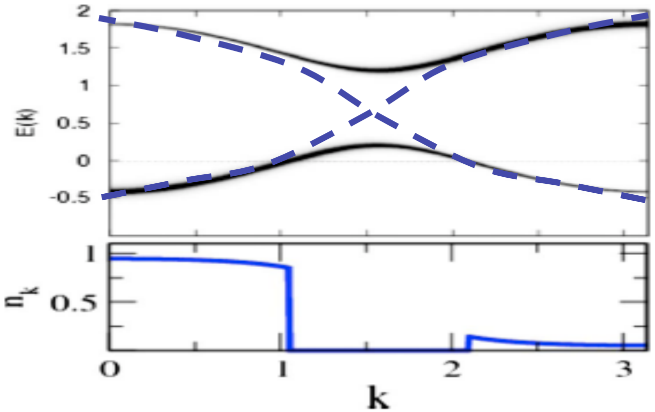
1D TOY MODEL WITH $q_c=\pi$

M.G. et al, PRB 09



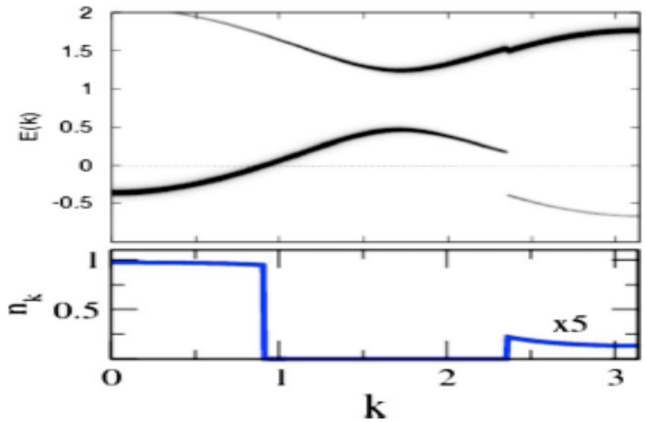
Mean field: $\chi''(q,\omega) \propto \delta(q-q_c)\delta(\omega)$

Cf. M. Imada yesterday



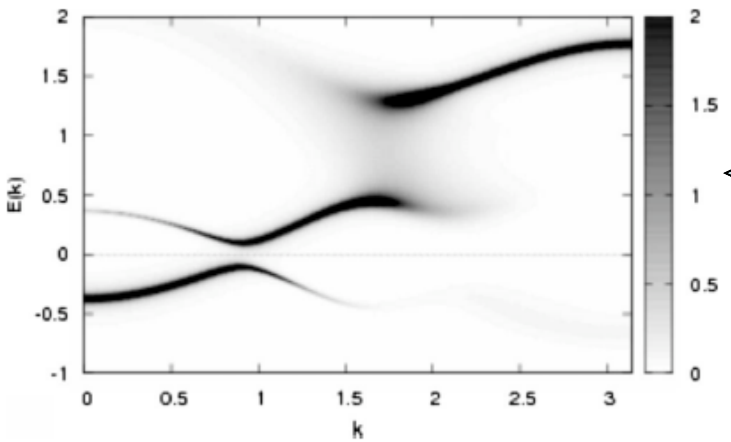
Dynamic flucts:

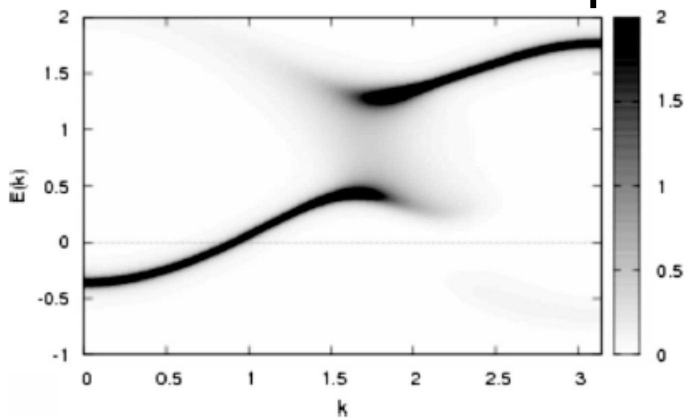
$$\chi''(q,\omega) \propto \delta(q-q_c)\delta(\omega-\omega_0)$$



$$\chi''(q,\omega) \propto \Lambda_q \Lambda_\omega$$

$+\Delta_{pp}$





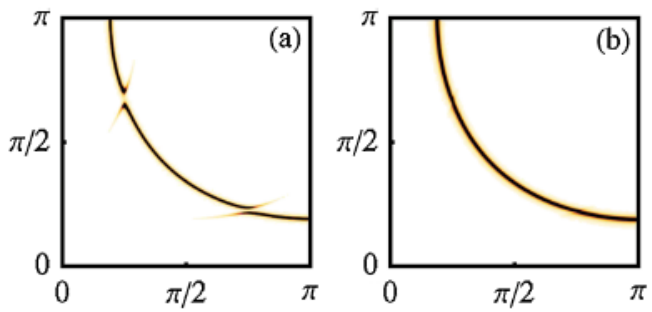
CO with dynamical order parameter Seibold et al. PRL 2009

$$\Sigma_{\mathbf{r}}^{\mathrm{CDW}}(\omega) = \Delta_{\mathbf{r}}(\omega) \equiv \Delta_{\mathbf{r}}^{0} + v_{\mathbf{r}}^{2} f(\omega).$$

Even when this is zero. CO can be static and lona-range

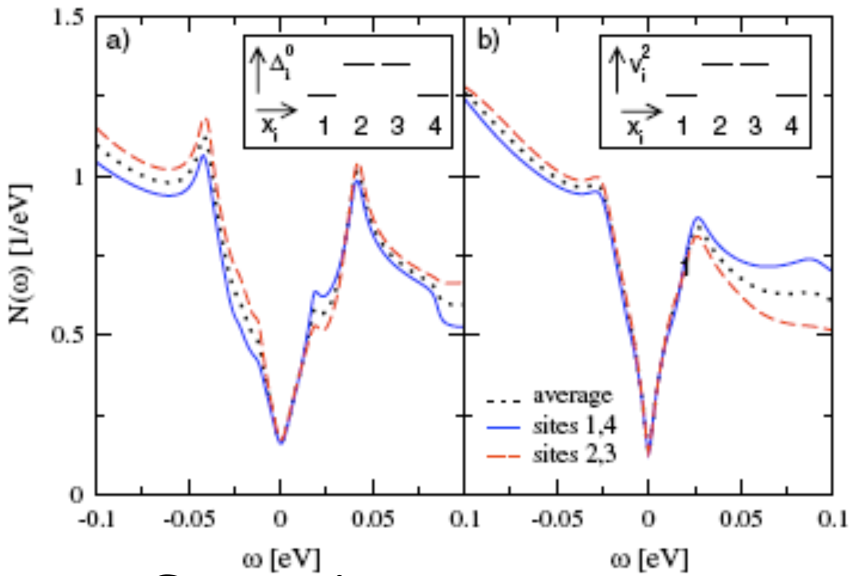
We assume MFL dynamics
$$f(\omega) = 2\omega \ln \frac{\Gamma + i\omega}{\Omega} + i\pi\Gamma,$$

vanishing at $\omega=0$



Static CO has shadow features

Dyn. CO has no shadow features



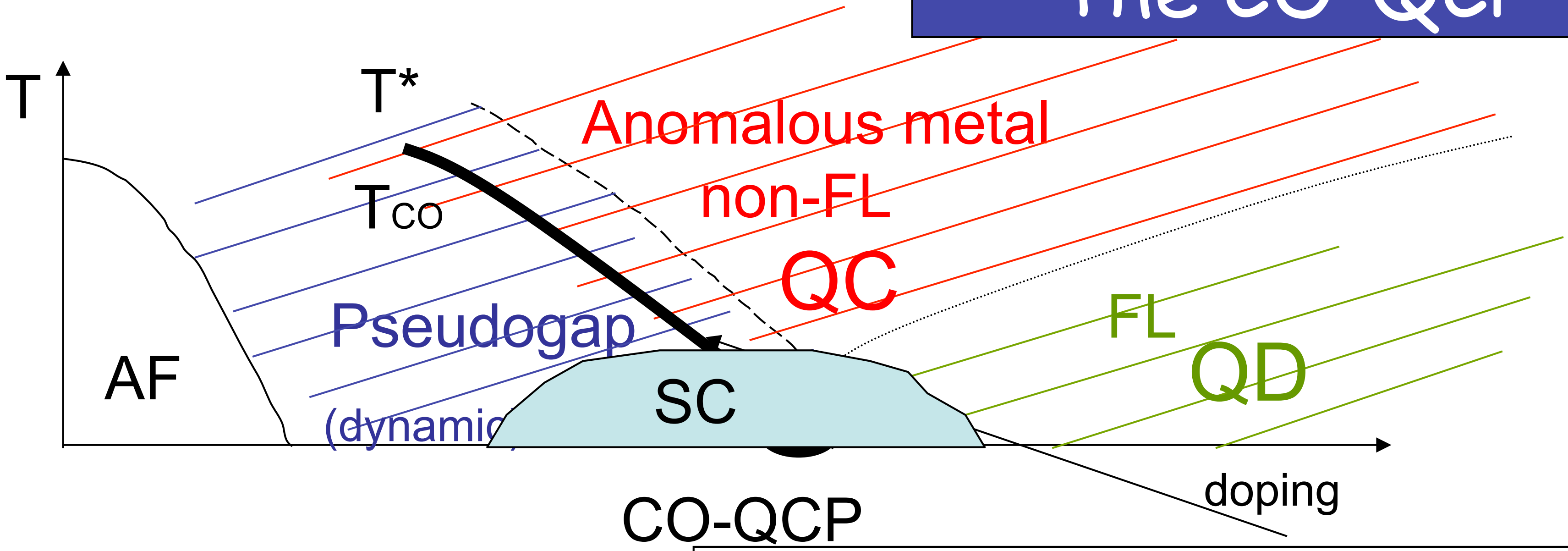
Opposite contrast reversal
For static and dyn, CO:
Dyn. CO agrees with expts.

Conclusions 1/2

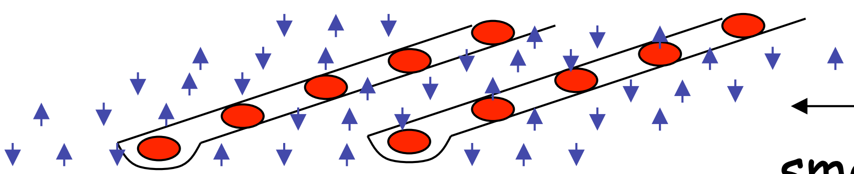
- Dynamical character of CO can account for the lack of shadow FS, uniformity of low-energy QP states, …

- Violation of p-h symmetry in the spectra at moderate energy can be a signature of CO. What happens at low energy? Where are the shadow bands?
  CO may appear or not….Help needed from expts.

The CO-QCP



Hidden 2nd order transition:
CO competing with pairing, disorder….



See C. Di Castro's talk

smoothly evolving
into anharmonic stripes (spin & charge)

Rome proposal C. Castellani,et al., PRL (1995) QCP at x=0.19

Major consequence: abundant critical charge (and spin) flucts

strongly temperature and momentum-dependent interaction

We aim to reproduce the (gross) features of the spectra with scattering due to charge and spin CM's

B_{1g} or B_{2g} Raman vertices

The CM's characterize the spectra via:

-a spectral "glue" function $\alpha^2F(\omega)$ depending on m(T), $\overline{\Omega}$

-T dependence from Bose function

The dynamics of the "glue" is a crucial issue

Understanding the dynamics of the effective interactions would shed light on

- Pairing mechanism
- Competing phase (if any) (e.g., $q_c \sim (\pi,\pi)$ –> spin, $q_c \sim (\pi/2,0)$ –> ch. Order, $q_c \sim 0$ –> circulating currents or Pomeranchuk, …)
- why the order is so elusive

……