Title: Long-range order and pinning of charge-density waves in competition with superconductivity

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Abstract: <p>Recent experiments show that charge-density wave correlations are prevalent in underdoped cuprate superconductors. The correlations are short-ranged at weak magnetic fields but their intensity and spatial extent increase rapidly at low temperatures beyond a crossover field. Here we consider the possibility of long-range charge-density wave order in a model of a layered system where such order competes with superconductivity. We show that in the clean limit, low-temperature long-range order is stabilized by arbitrarily weak magnetic fields. This apparent discrepancy with the experiments is resolved by the presence of disorder. Like the field, disorder nucleates halos of charge-density wave, but unlike the former it also disrupts inter-halo coherence, leading to a correlation length that is always finite. Our results are compatible with various experimental trends, including the onset of longer range correlations induced by inter-layer coupling above a characteristic field scale.</p>

Long-range order and pinning of charge-density waves in competition with superconductivity

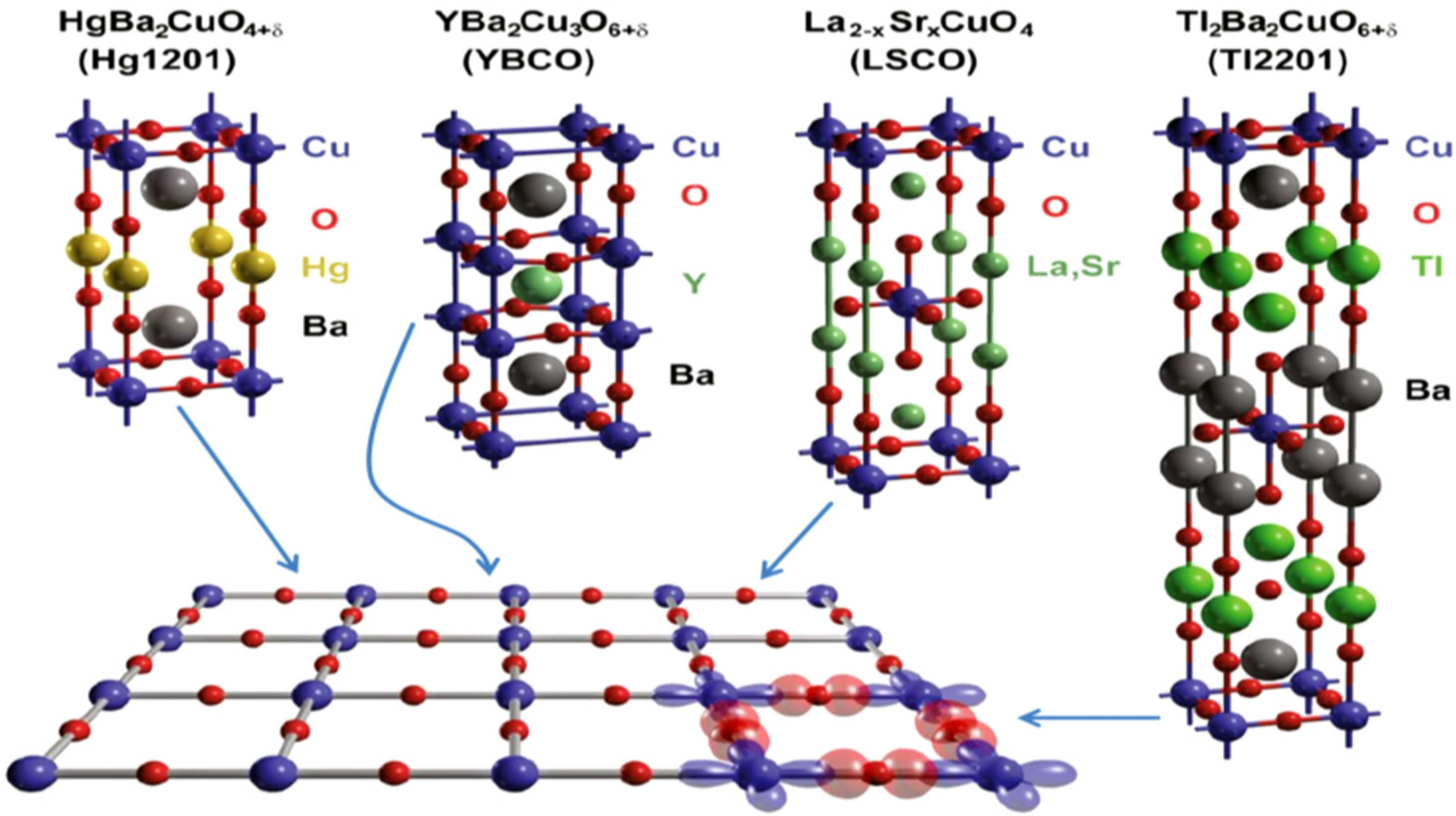
Gideon Wachtel

with

Yosef Caplan and Dror Orgad

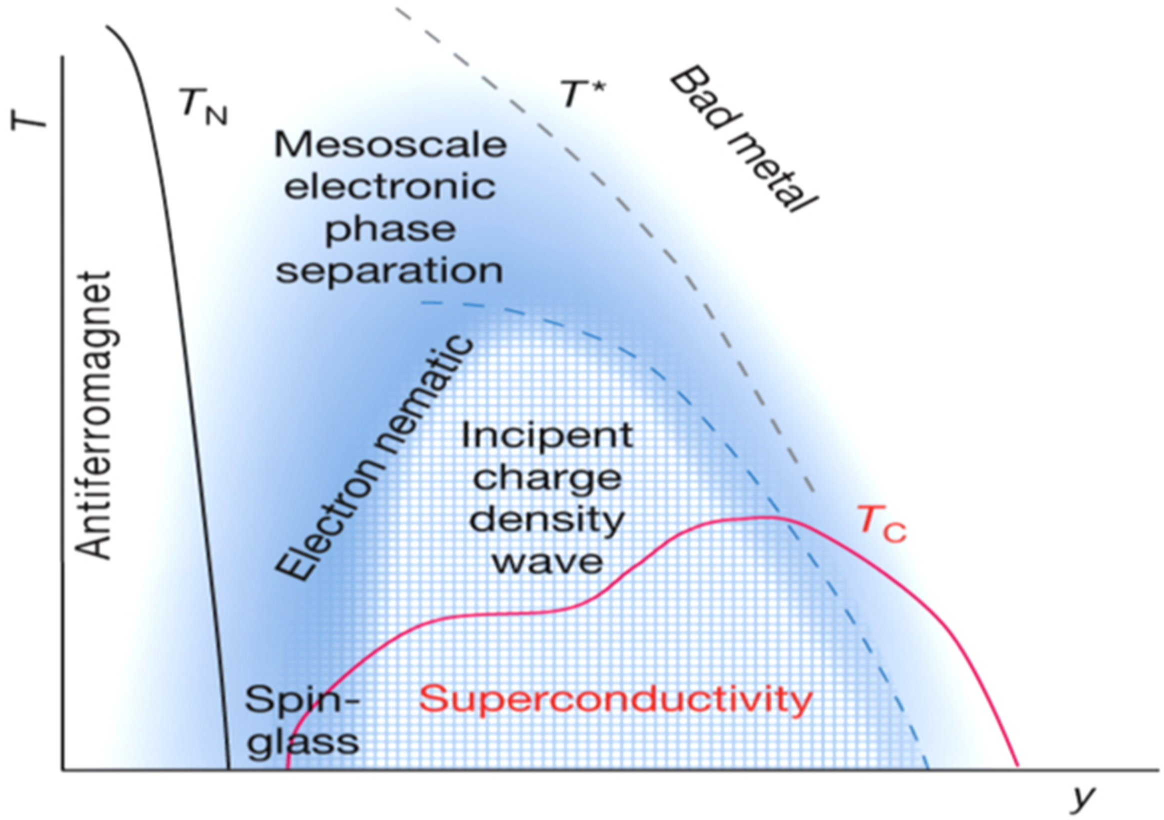
האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

Cuprate high-temperature superconductors

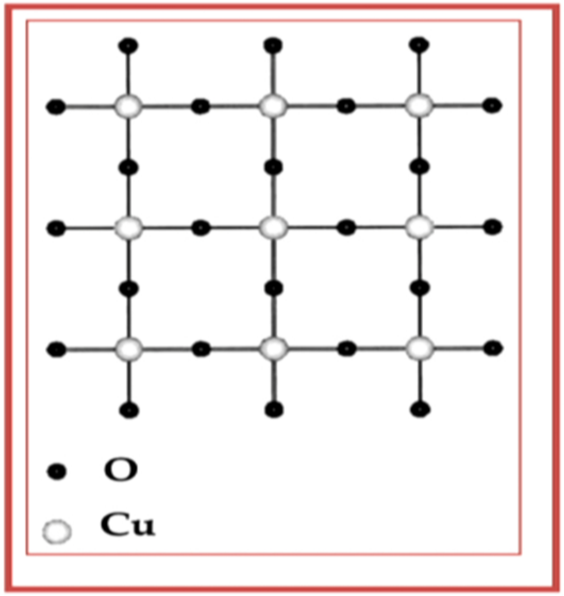


Barisic *et al*. (PNAS 2013)

Cuprate high-temperature superconductors



Fradkin and Kivelson (Nat. Phys. 2012)



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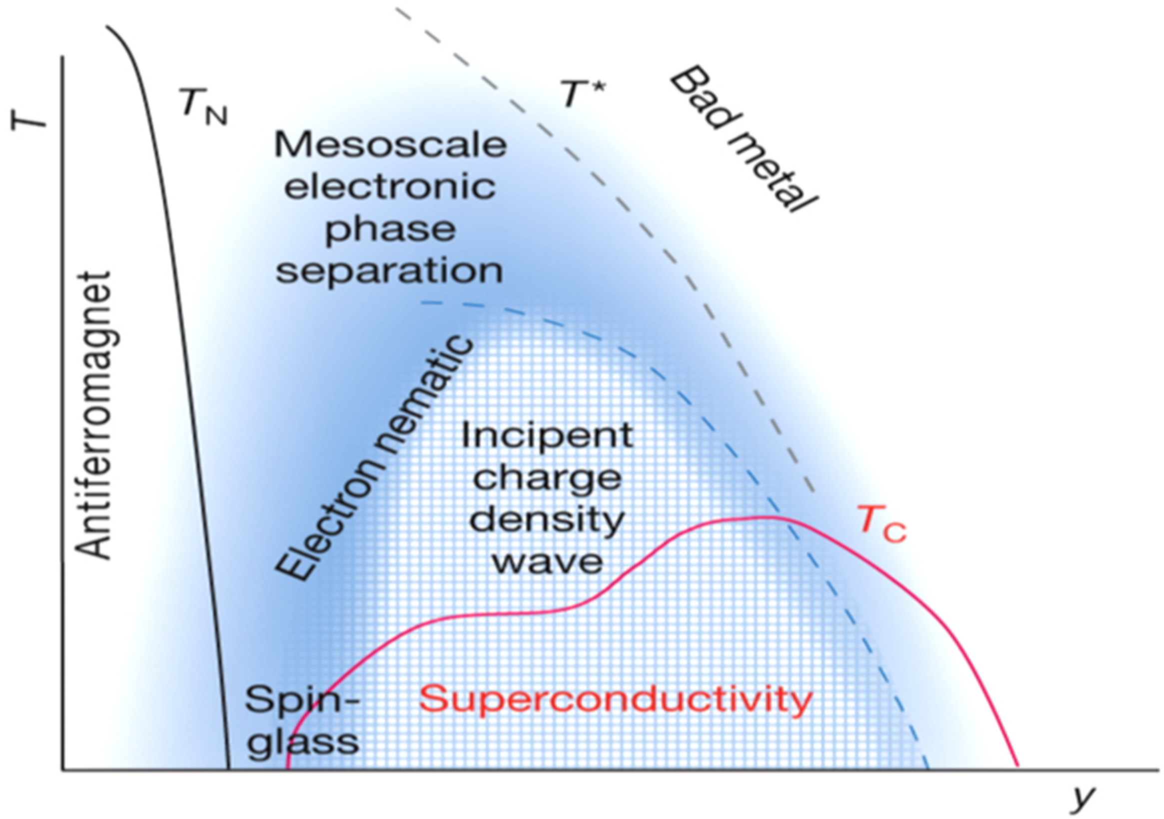

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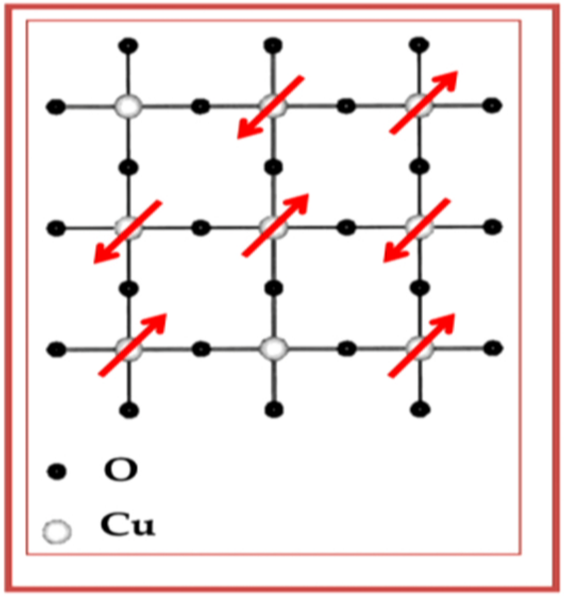
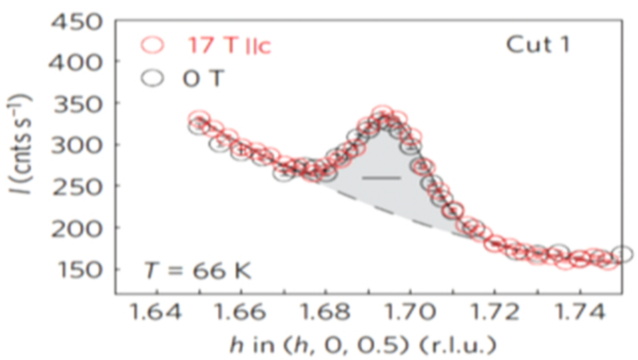
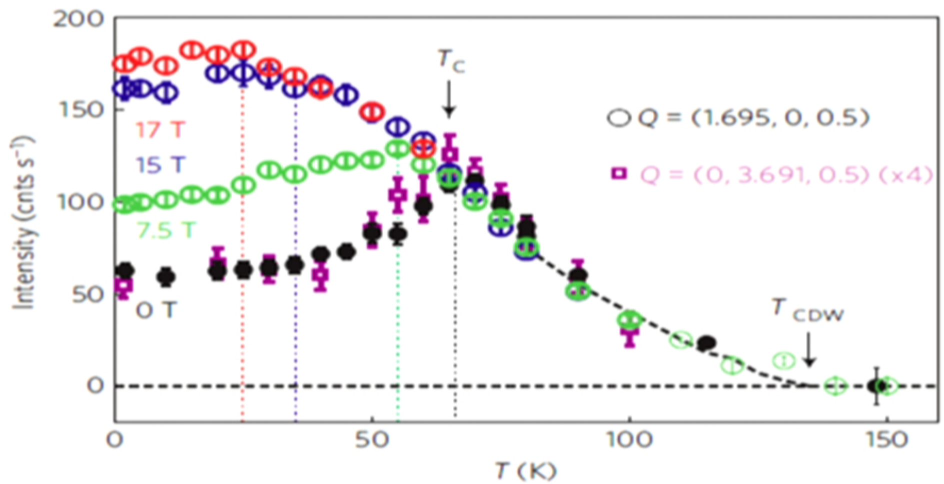


Evidence for local CDW order

Hard x-ray diffraction: ortho-VIII $YBCO_{6.67}$



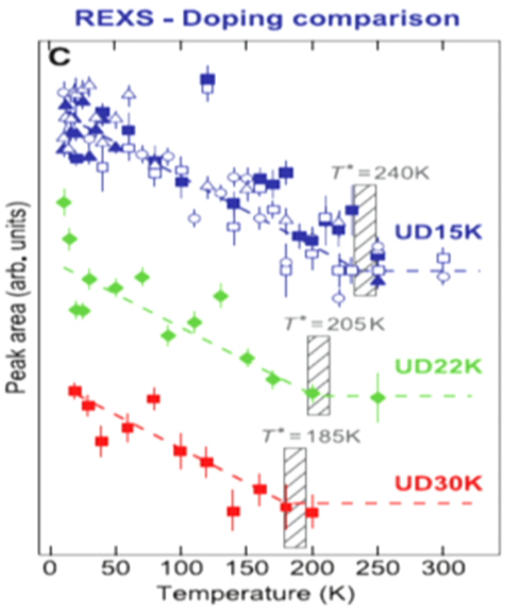


Chang *et al*. (Nat. Phys. 2012)

Evidence for local CDW order

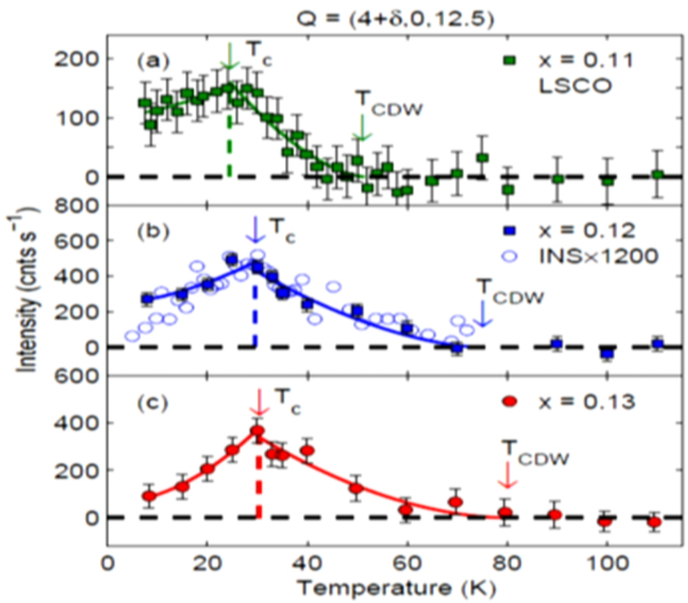
A similar signal is observed in other cuprates

Bi2201



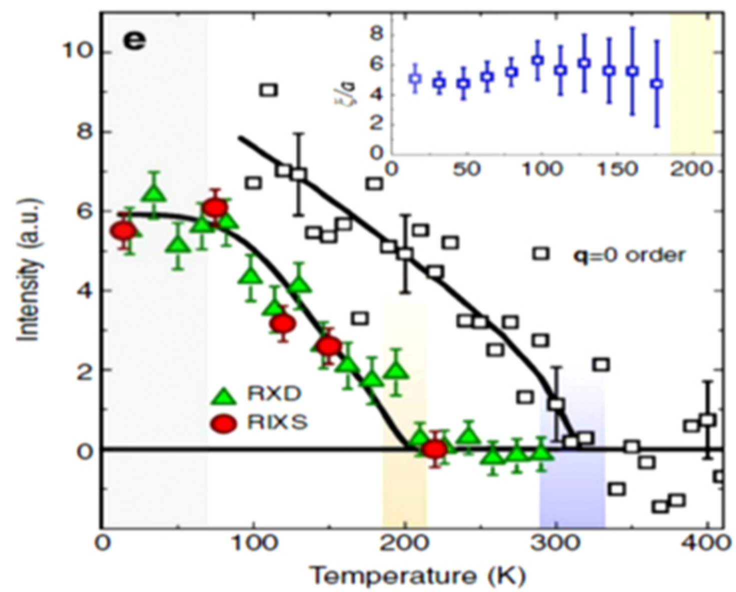
Comin *et al*. (Science 2014)

LSCO



Croft *et al*. (PRB 2014)

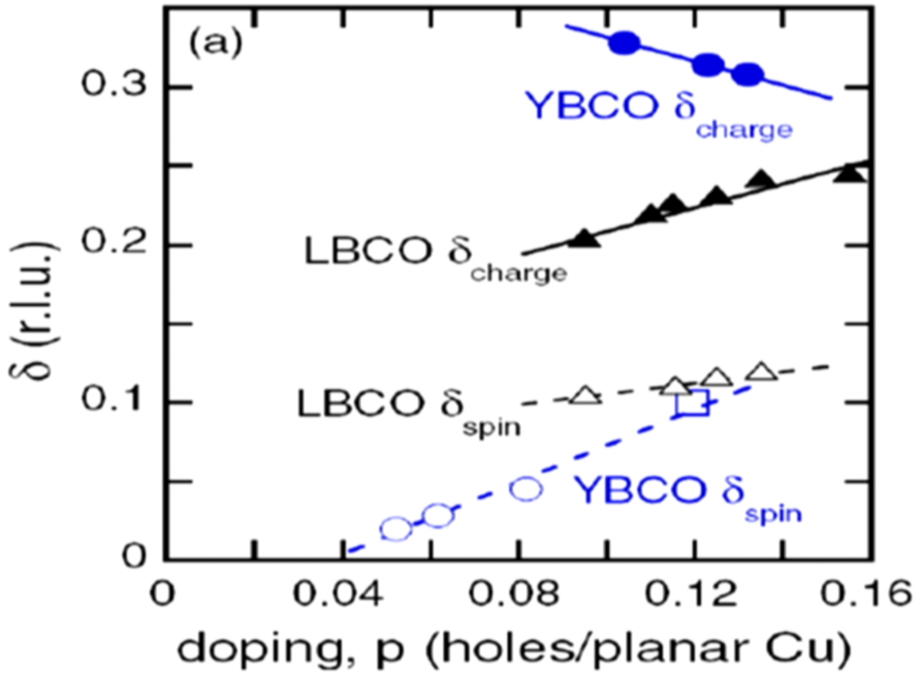
Hg1201



Tabis *et al*. (Nat. Comm. 2014)

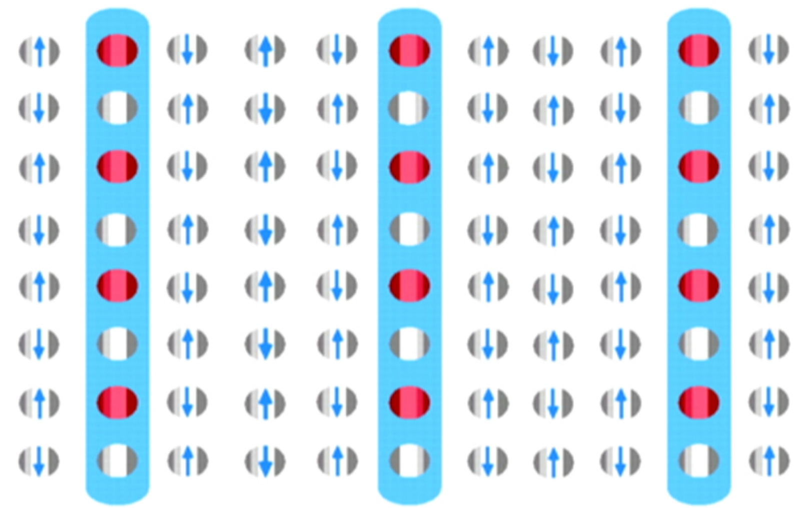
Evidence for local CDW order

There are some differences



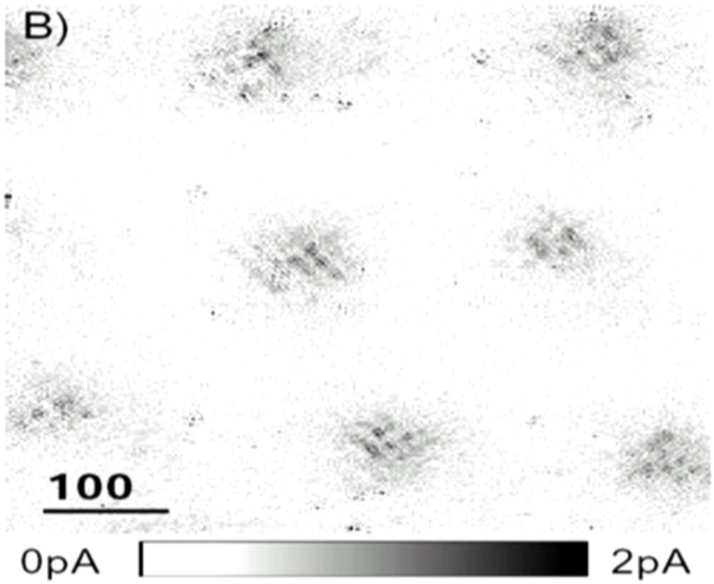
Blackburn *et al*. (PRL 2013)

LBCO

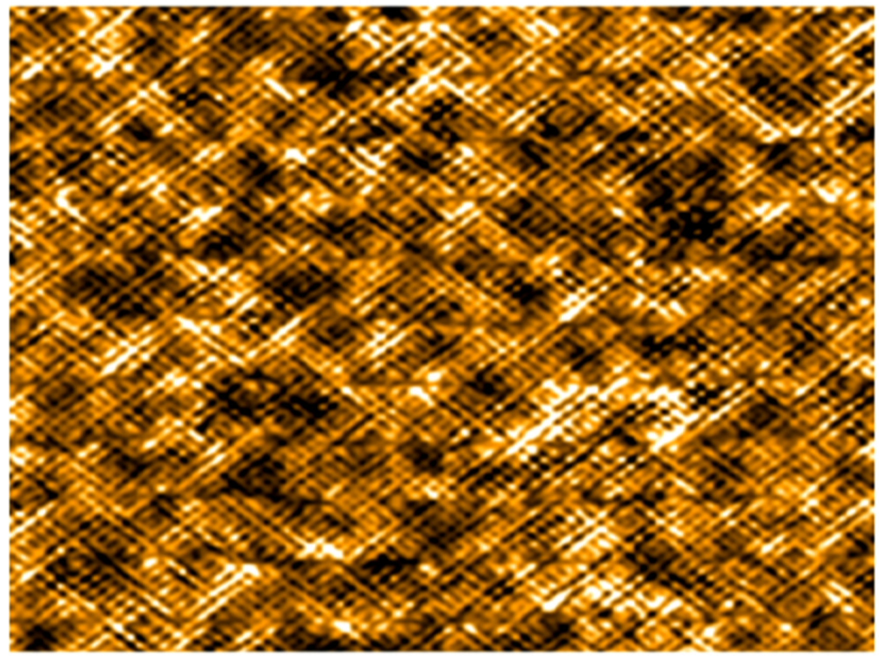


Evidence for local CDW order

STM imaging of BSCCO



Hoffman *et al*. (Science 2002)

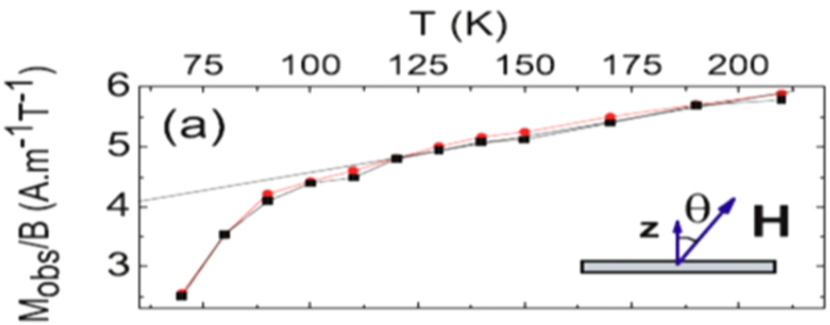


Fujita *et al*. (PNAS 2014)

Evidence for fluctuating SC above Tc

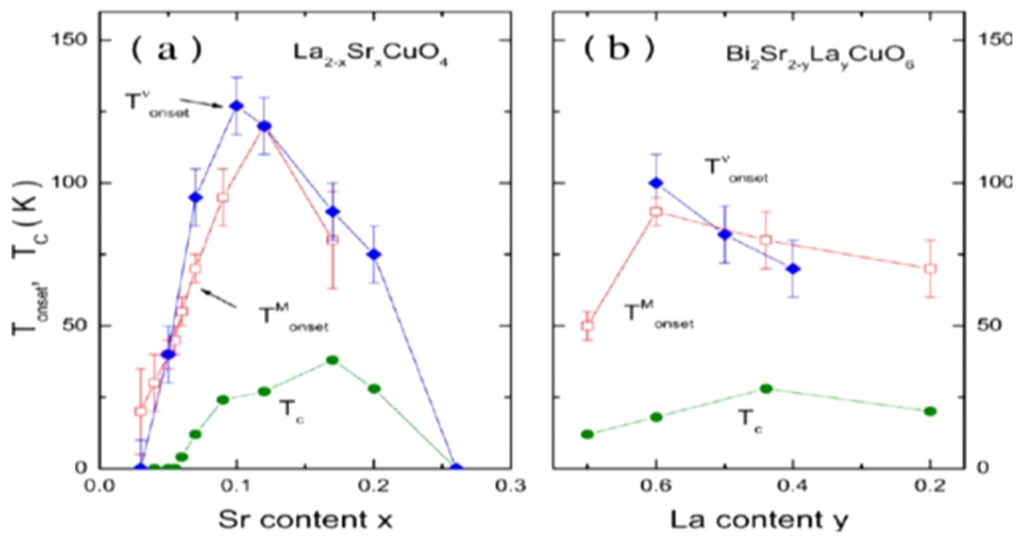
Torque magnetometry

Ortho-II YBCO (Tc=61K)



Yu *et al*. (arXiv:1402.7371)

LSCO BSLCO



Contested by others

Li *et al*. (PRB 2010)

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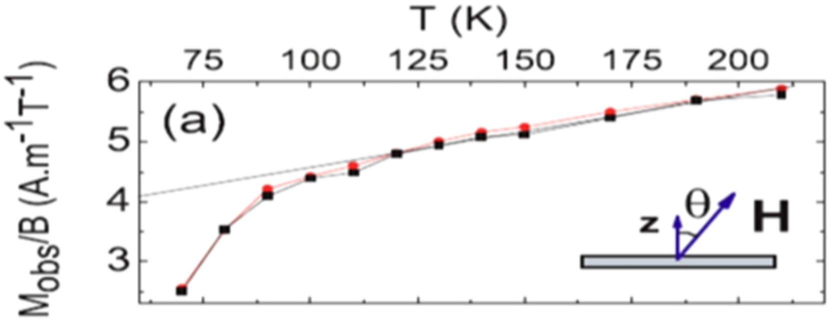

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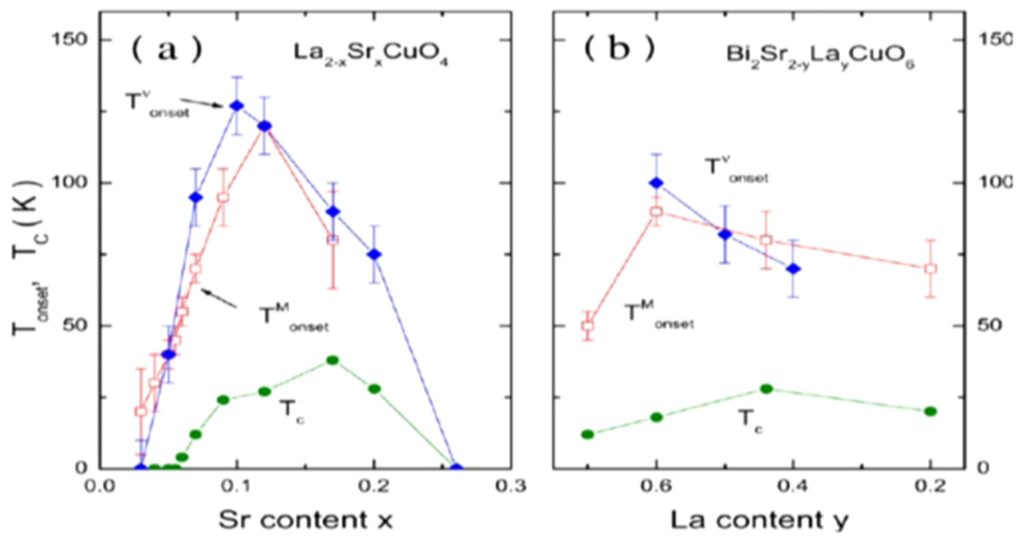

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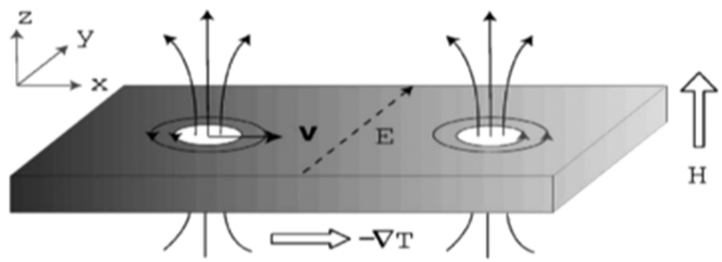
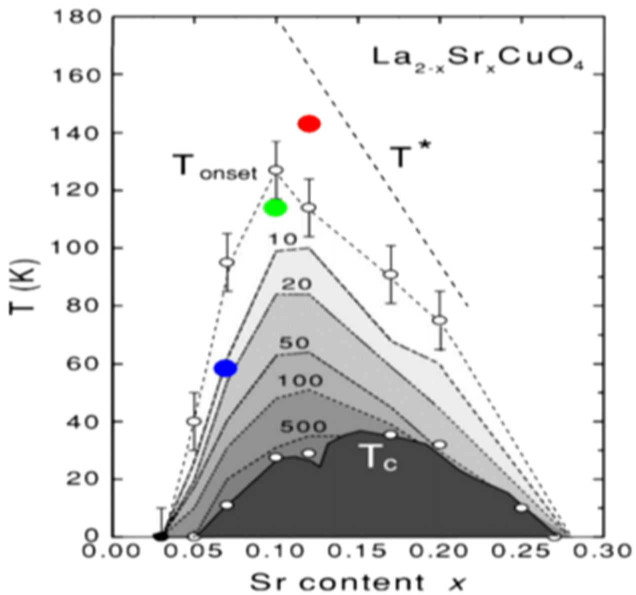


Nernst effect

Wang et al. (PRB 2006)



Contested by others

Gaussian fluctuations in Eu-LSCO

Chang et al. (Nat. Phy. 2012)

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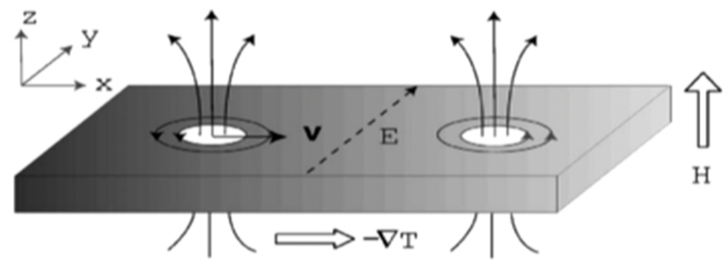

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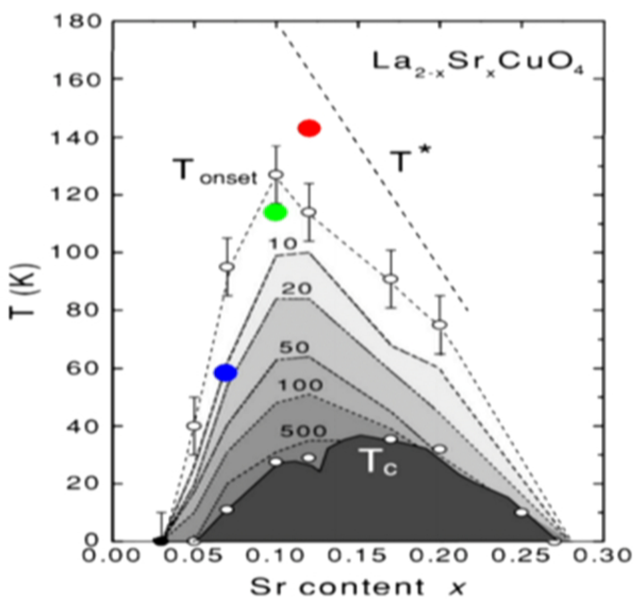

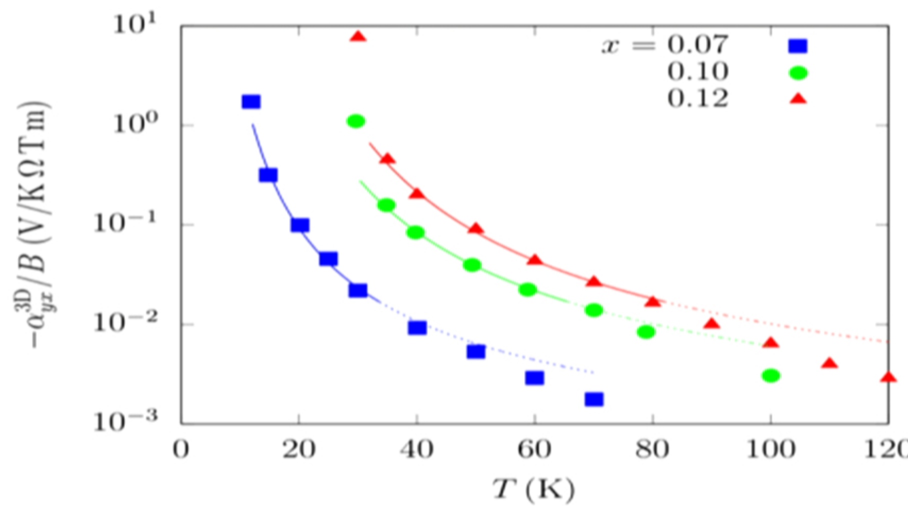

$$\alpha_{yx} = -\frac{2ek_B}{h}\frac{\varepsilon_c}{k_B T}\frac{B}{\phi_0}\frac{r_0^2}{2}\, e^{\varepsilon_c/k_B T}$$

GW and Dror Orgad (PRB 2014)

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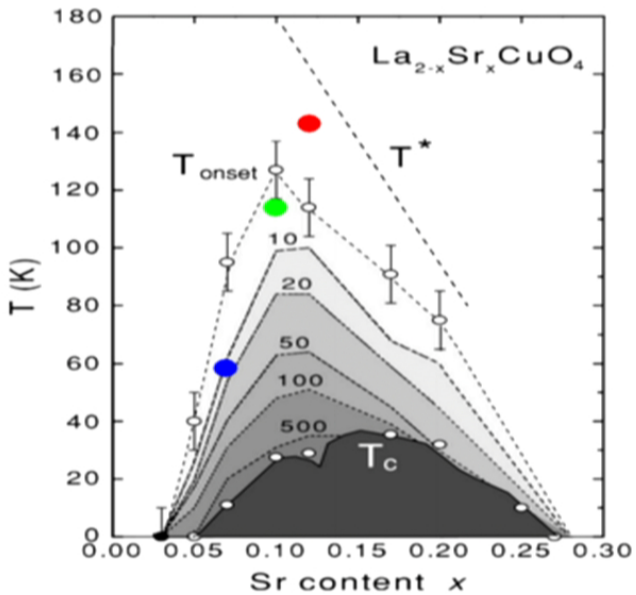

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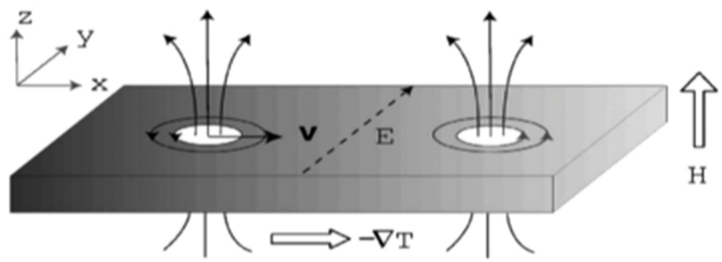

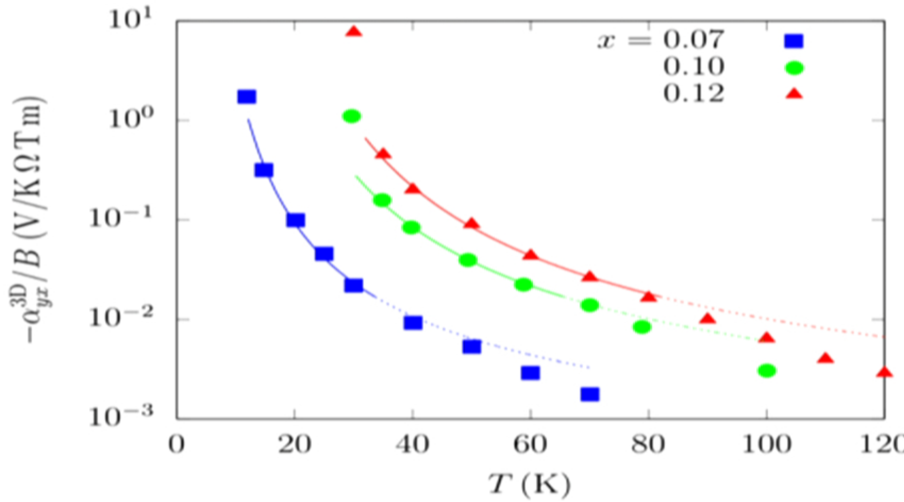

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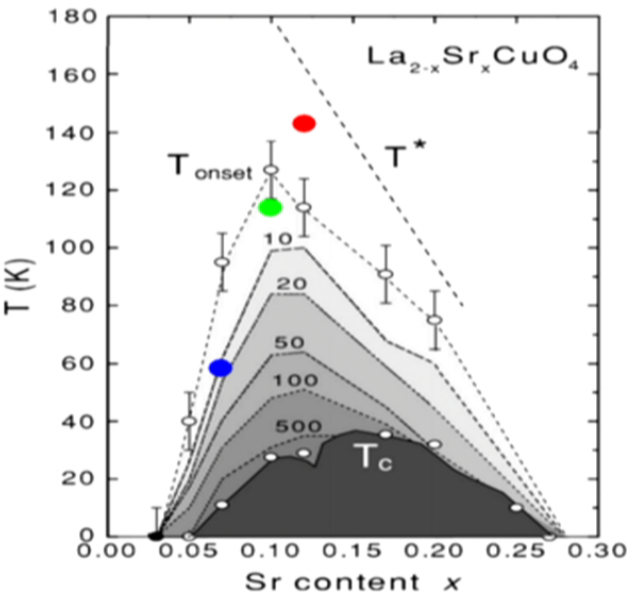

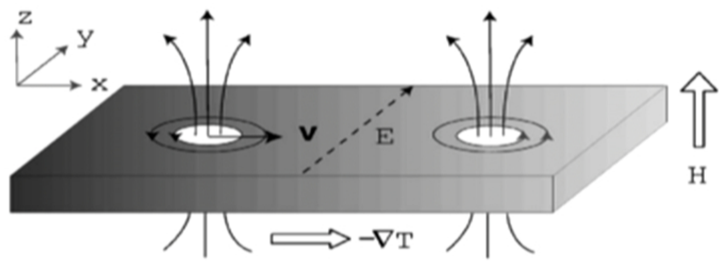

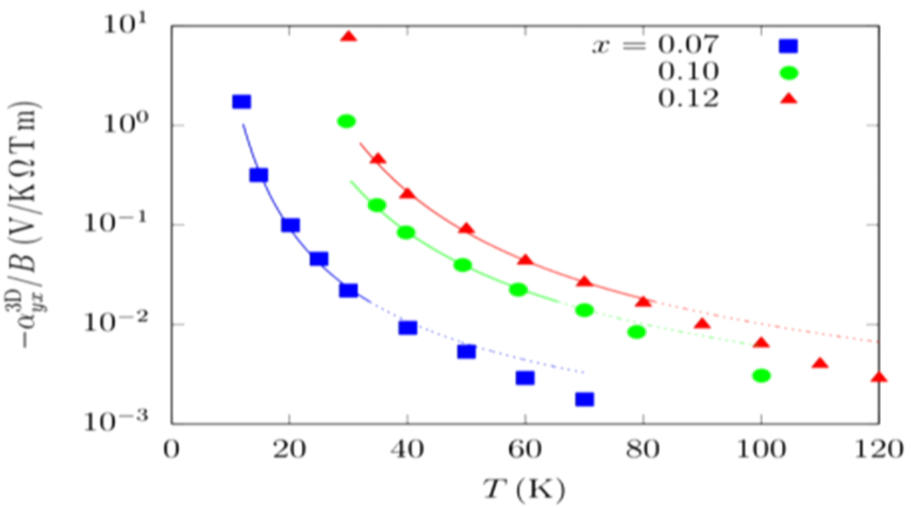

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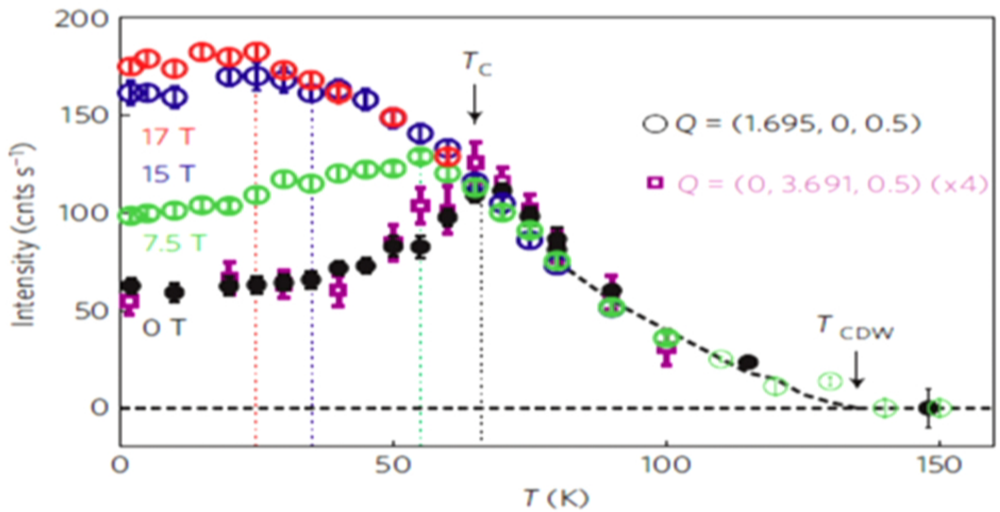
$$\alpha_{yx} = -\frac{2ek_B}{h}\frac{\varepsilon_c}{k_BT}\frac{B}{\phi_0}\frac{r_0^2}{2}\,e^{\varepsilon_c/k_BT}$$

GW and Dror Orgad (PRB 2014)

CDW and SC orders seem to compete



Chang *et al*. (Nat. Phys. 2012)

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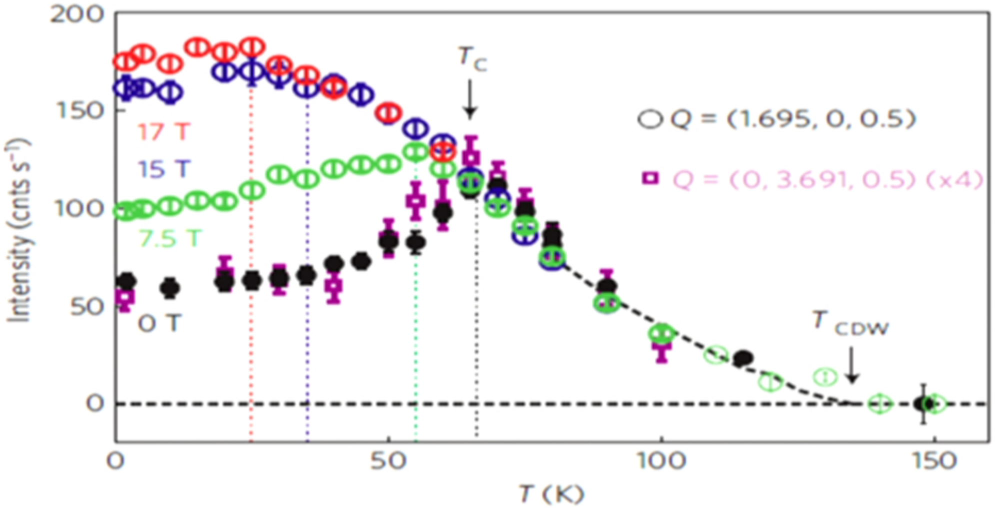
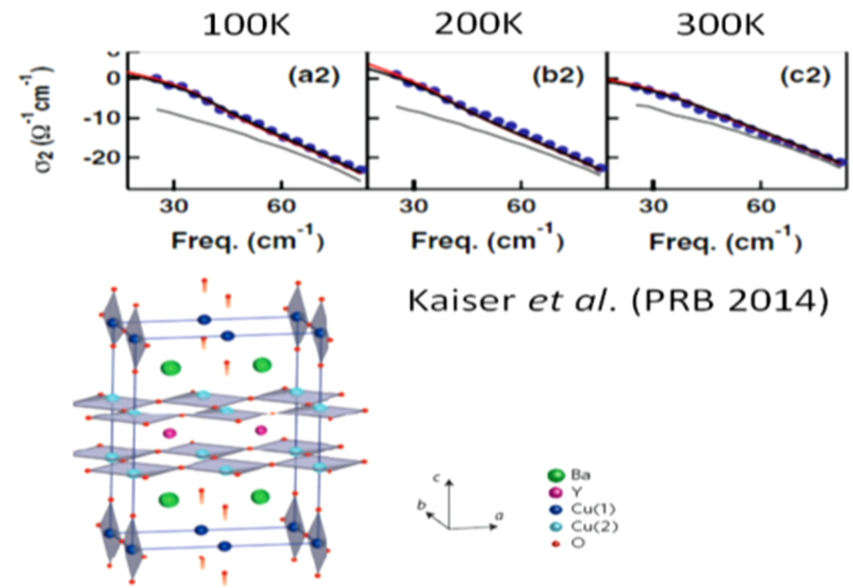


Chang *et al*. (Nat. Phys. 2012)

Enhanced c-axis coherent transport in YBCO by 20THz irradiation



Kaiser *et al*. (PRB 2014)

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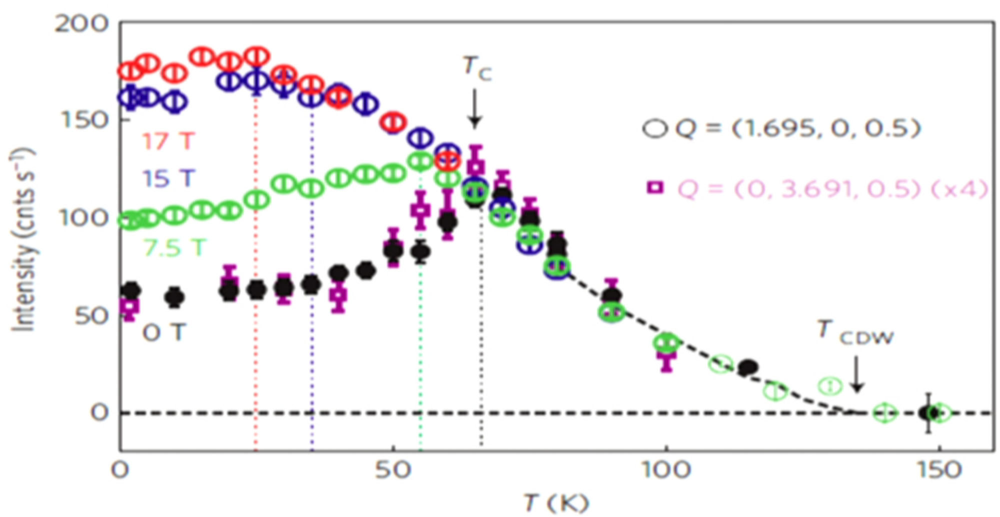

Chang *et al*. (Nat. Phys. 2012)

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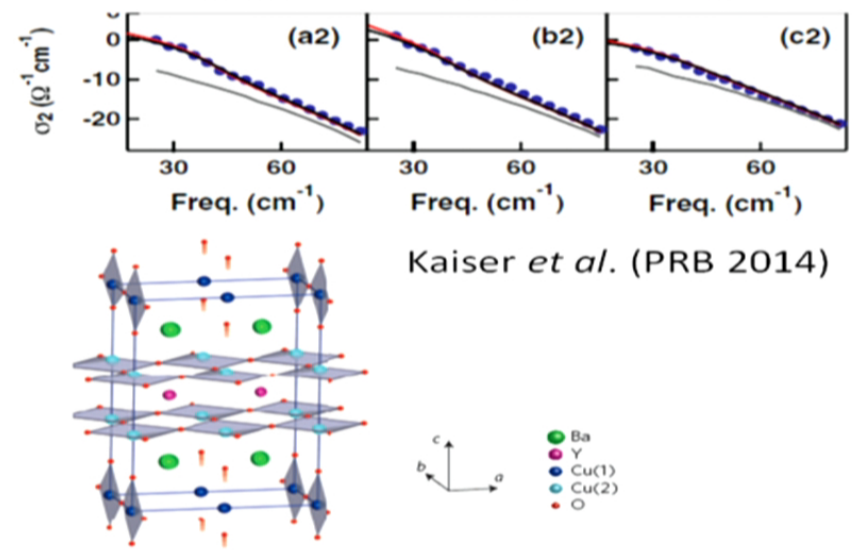

Kaiser *et al*. (PRB 2014)

Similar results in LBCO interpreted as due to melting of charge order

CDW and SC in quasi-1D

In 1D SC and CDW fluctuations coexist and are both enhanced by the opening of a spin gap

SC :

$$\Psi_{R\uparrow}\Psi_{L\downarrow} - \Psi_{R\downarrow}\Psi_{L\uparrow} \propto \cos(\sqrt{2\pi}\phi_s)e^{-i\sqrt{2\pi}\theta_c}$$

CDW :

$$\Psi^{\dagger}_{R\uparrow}\Psi_{L\uparrow} + \Psi^{\dagger}_{R\downarrow}\Psi_{L\downarrow} \propto \cos(\sqrt{2\pi}\phi_s)e^{-i\sqrt{2\pi}\phi_c}$$

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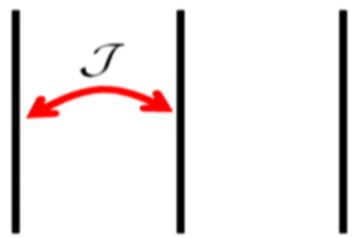
CDW : $$\Psi^{\dagger}_{R\uparrow}\Psi_{L\uparrow} + \Psi^{\dagger}_{R\downarrow}\Psi_{L\downarrow} \propto \cos(\sqrt{2\pi}\phi_s)e^{-i\sqrt{2\pi}\phi_c}$$

They compete for long-range order in the coupled qusi-1D system

$$\chi_{\rm sc} \approx \Delta_s T^{K_c^{-1}-2}$$



$$\chi_{\rm cdw} \approx \Delta_s T^{K_c-2}$$

The model

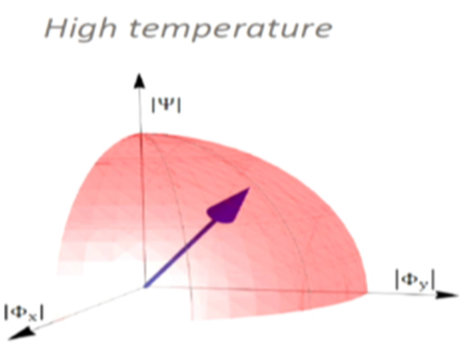
Following Hayward et al. (Science 2014) we study a nonlinear sigma model of a six-component order parameter

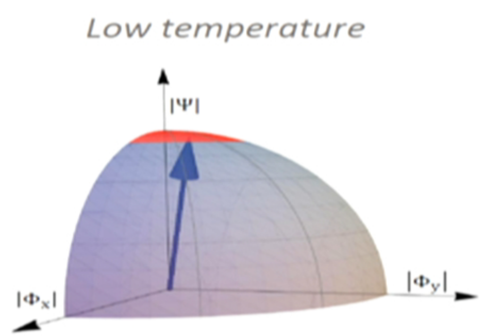
SC	Ψ	$\begin{cases} n_1 \\ n_2 \end{cases}$
CDW_x	Φ_x	$\begin{cases} n_3 \\ n_4 \end{cases}$
CDW_y	Φ_y	$\begin{cases} n_5 \\ n_6 \end{cases}$

$$H_0 = \frac{\rho_s}{2} \int d^2r \left\{ |(\nabla + 2ie\boldsymbol{A})\psi|^2 + \sum_{\alpha=3}^{6} [\lambda(\nabla n_\alpha)^2 + g n_\alpha^2 - 2V_\alpha n_\alpha] \right\}$$

where the competition is encapsulated by the constraint

$$\sum_{\alpha=1}^{6} n_\alpha^2 = 1$$



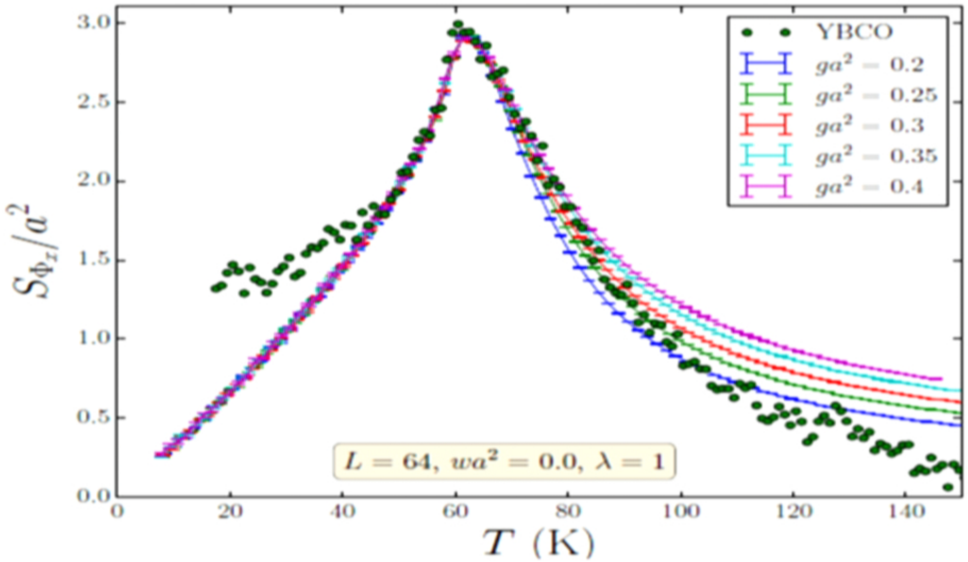


The model

Hayward et al. (Science 2014) studied the model for a 2D clean system at zero magnetic field, and showed that it reproduces a peak in the CDW structure factor

$$S_{\Phi_x} = \frac{1}{L^2} \int d^2r d^2r' \langle \Phi_x^* (\boldsymbol{r}) \Phi_x(\boldsymbol{r}') \rangle$$

corresponding to the x-ray diffraction peak intensity



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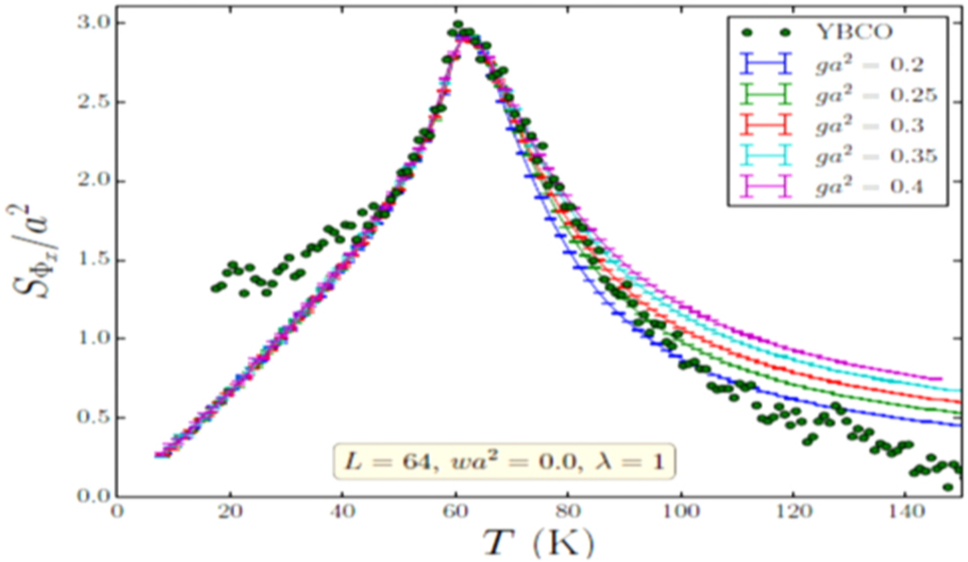


We would like to study the effects of:
magnetic fields, disorder and interlayer couplings

Y. Caplan, GW, and D. Orgad (PRB 2015)
See also: Nie et al. (PRB 2015)

Results for the 2D clean system

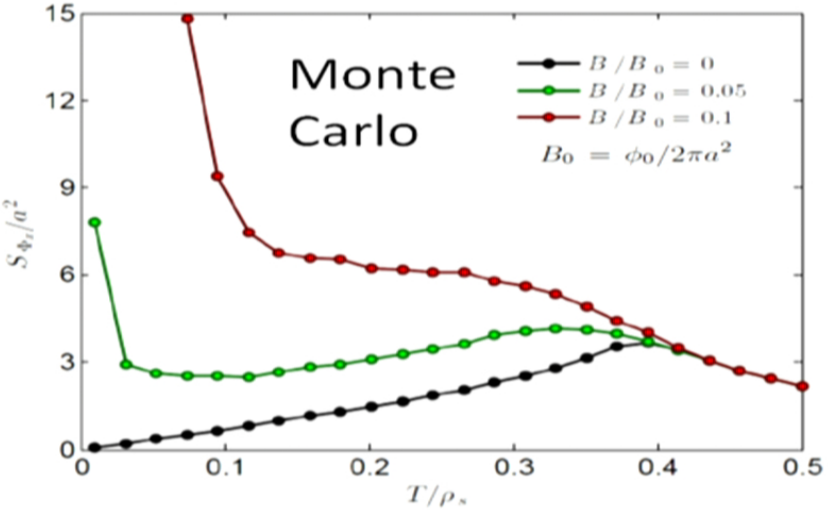
Large N analysis: B = 0 : $S_{\Phi_x} = \dfrac{2T}{g\rho_s}$

Y. Caplan, GW, and D. Orgad (PRB 2015)

B > 0 : results depend on the order of limits

Low T and B →0 $$S_{\Phi_x} = \frac{2T}{g\rho_s} + A_1\left[1 - \left(\frac{A_2}{\rho_s} + \frac{1}{T_{MF}}\right)T\right]\frac{B}{g^2\phi_0}$$

Low B and T→0 $$S_{\Phi_x} = A_3 \frac{T}{t\rho_s}\frac{B}{g\phi_0} e^{c_2 \frac{t}{g}\rho_s\left(\frac{1}{T}+\frac{1}{T_{MF}}\right)}$$ $$t \sim g e^{-c_1\sqrt{g\phi_0/B}}$$



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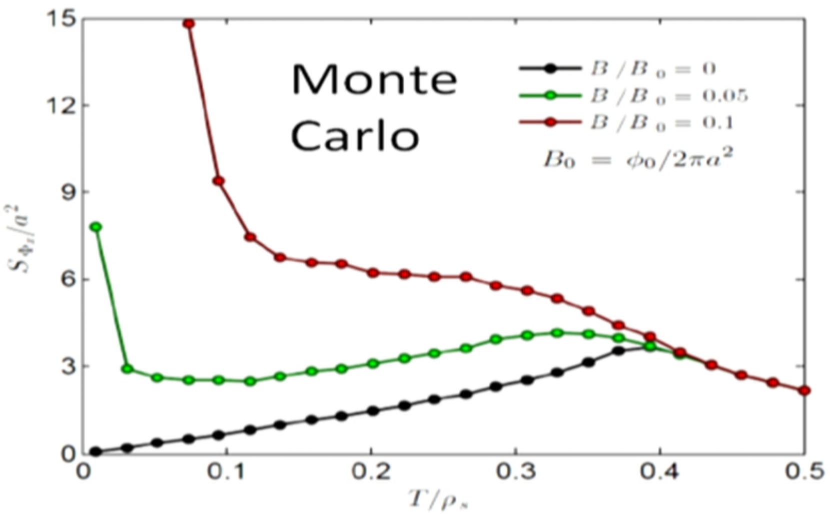

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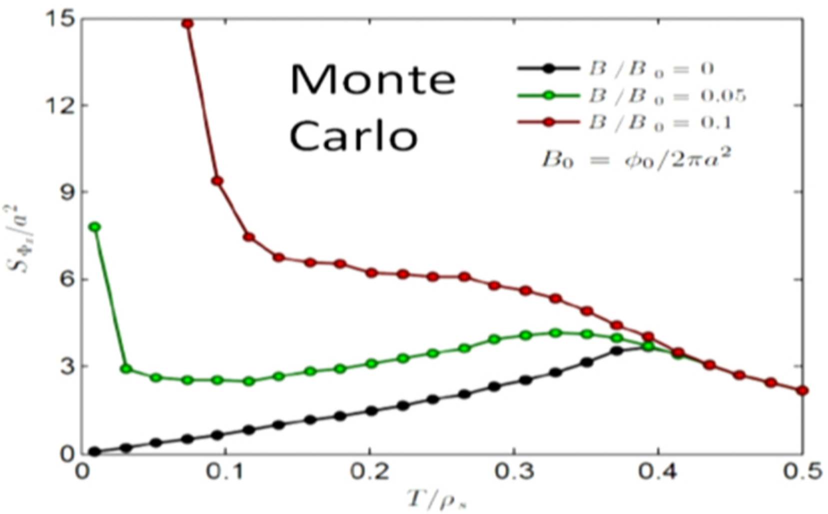

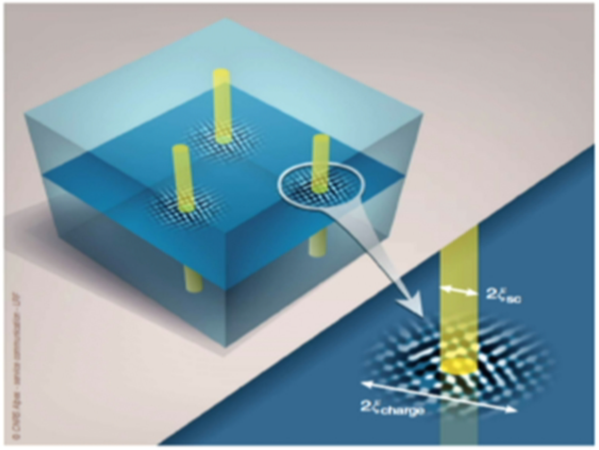

Wu *et al*. (Nat. Comm. 2013)

Results for the 2D clean system

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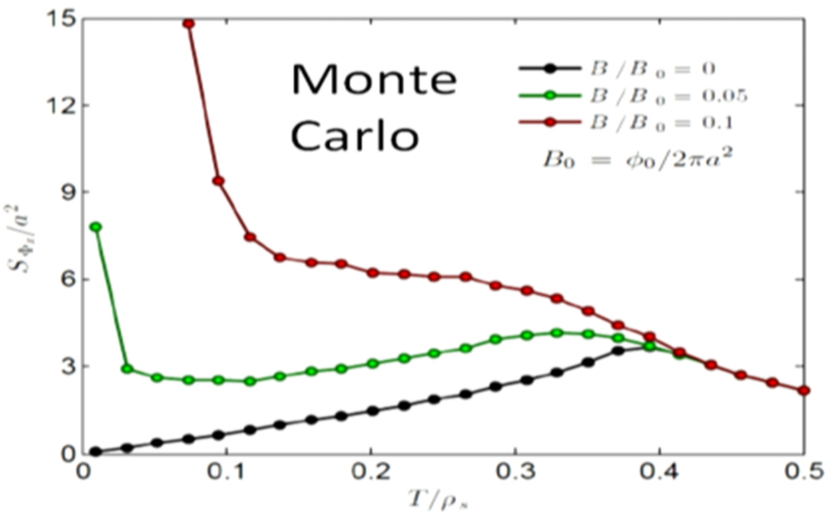

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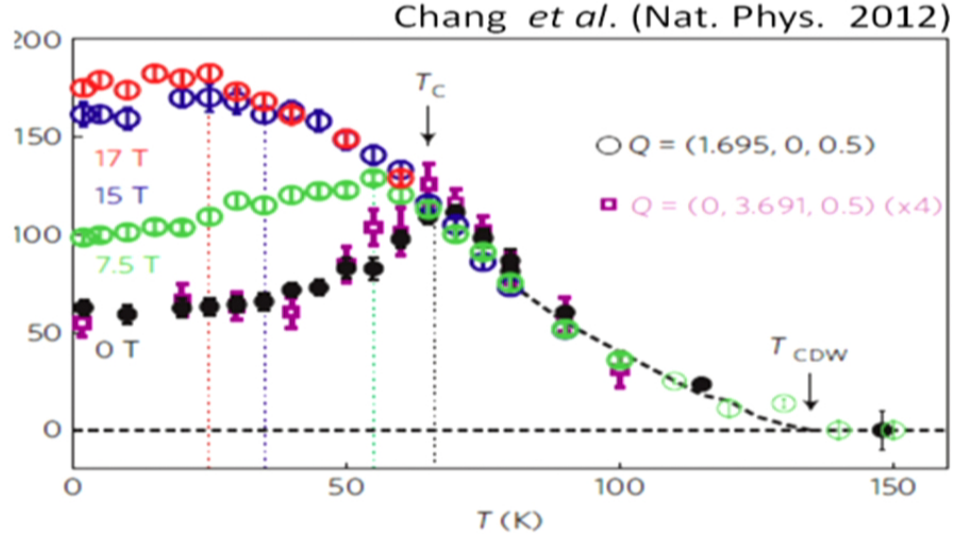
Chang *et al.* (Nat. Phys. 2012)

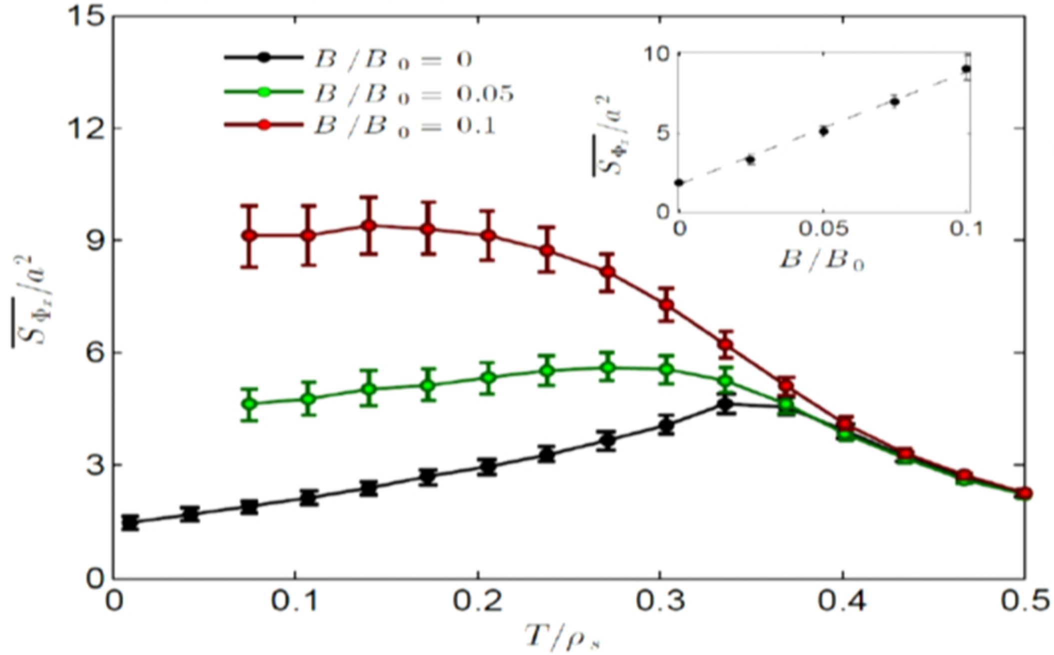


Results for the 2D disordered system

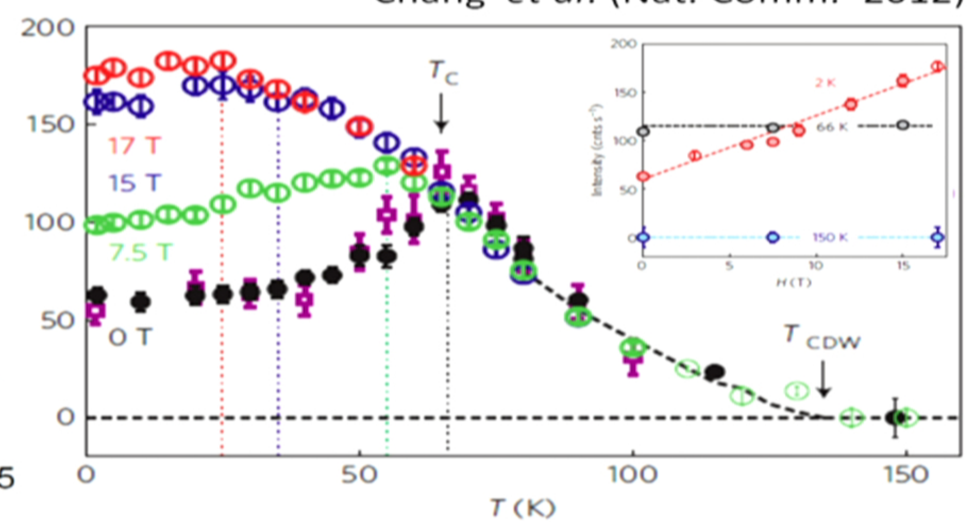
Large N + replica

$$\overline{S_{\Phi_x}} = \frac{2T}{g\rho_s} + \frac{2V^2}{g^2} + A_1\left[1 - \left(\frac{A_2}{\rho_s} + \frac{1}{T_{MF}}\right)T - A_4\frac{V^2}{g}\right]\frac{B}{g^2\phi_0}$$

Monte Carlo



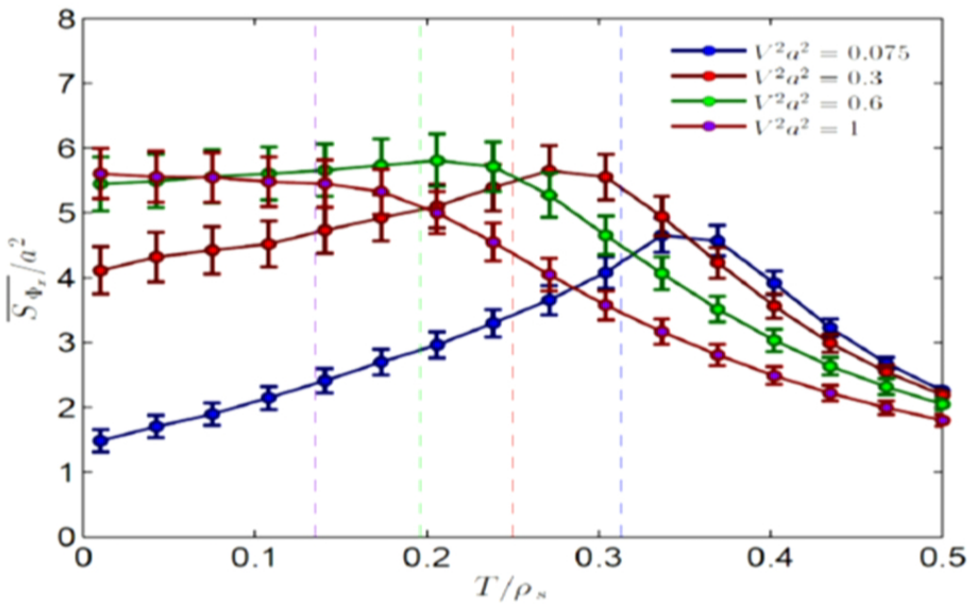
Chang *et al.* (Nat. Comm. 2012)



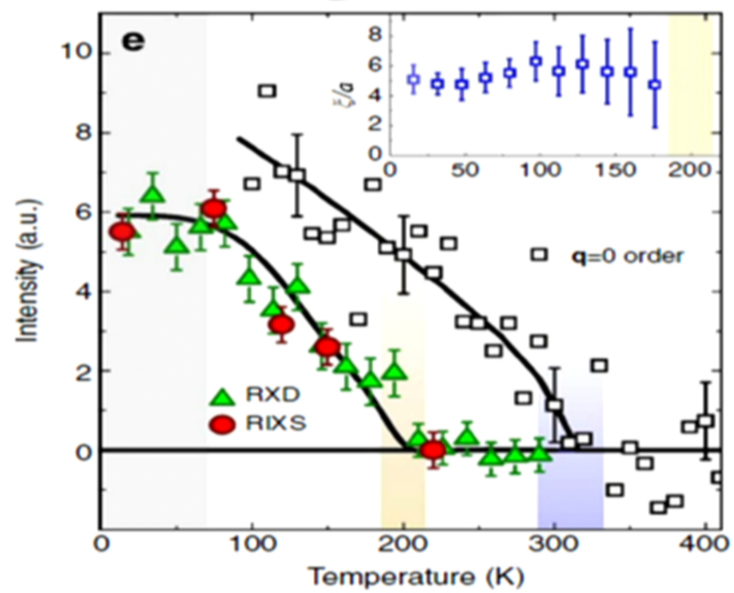
Results for the 2D disordered system

Increasing the disorder strength has similar effect to increasing B

B = 0



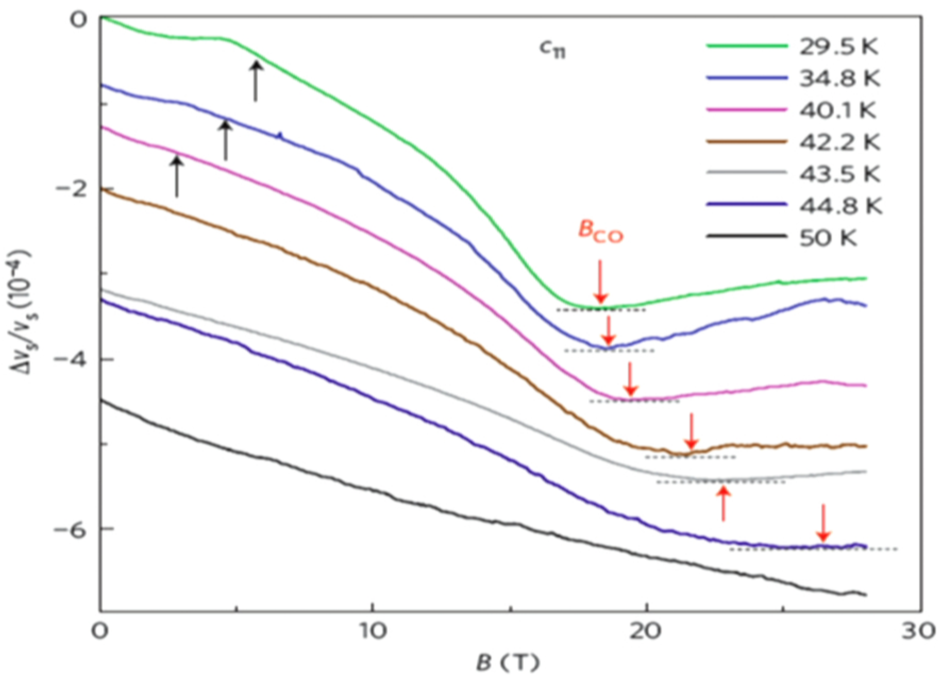
Hg1201

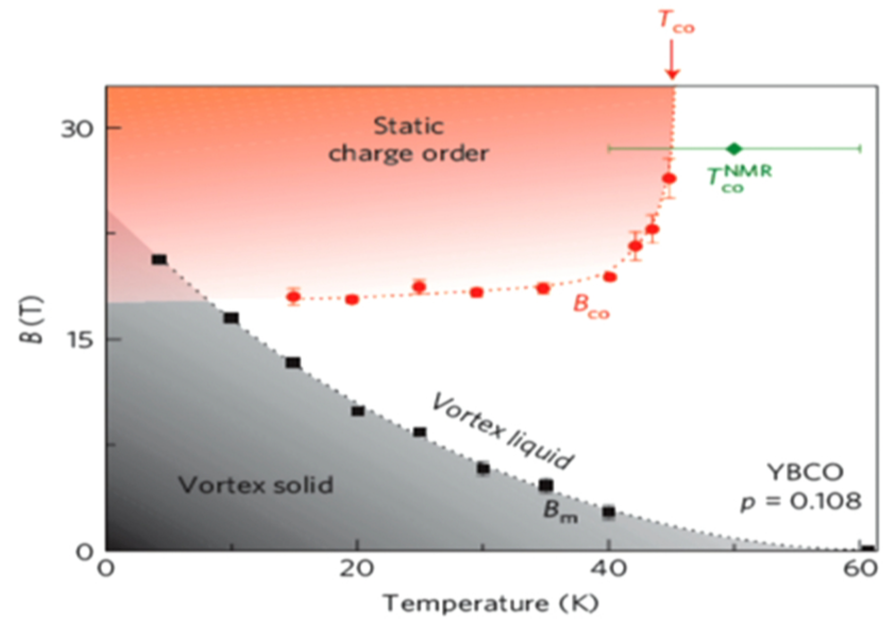


Tabis *et al*. (Nat. Comm. 2014)

Evidence for long-range CDW order

Sound velocity anomaly

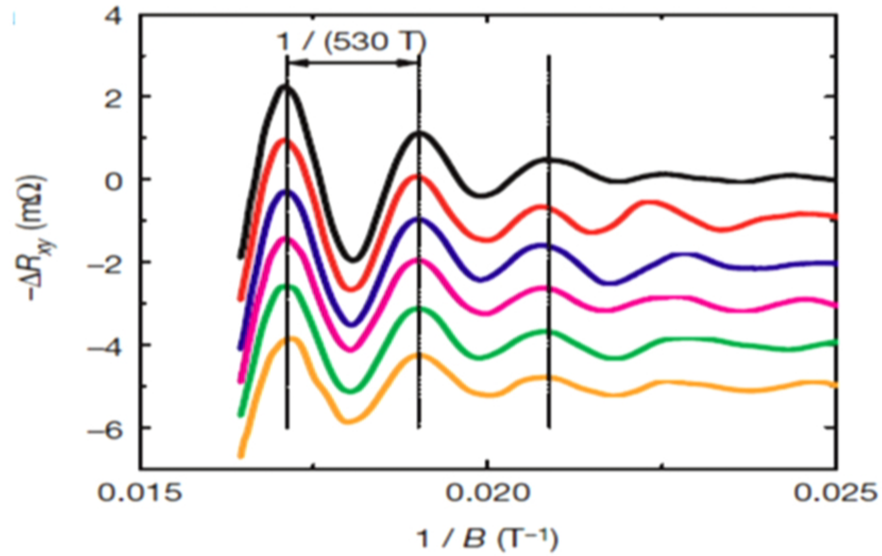




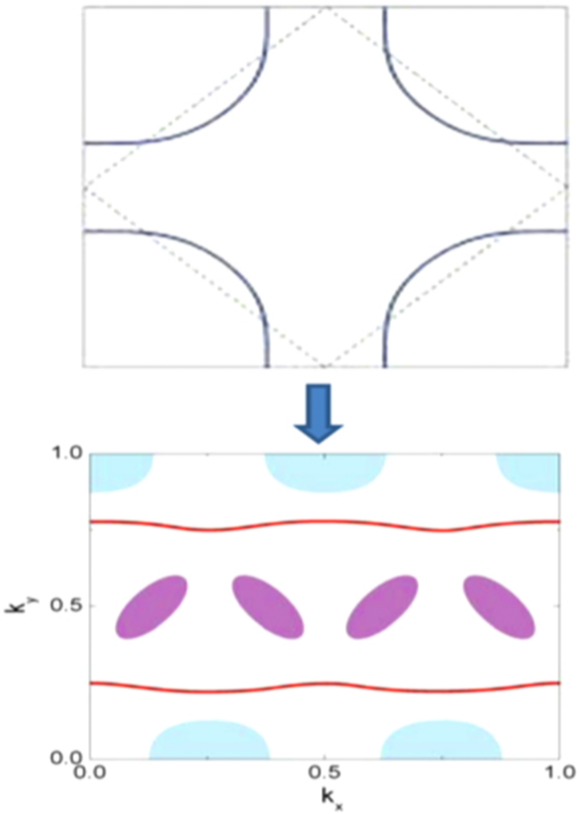
LeBoeuf *et al.* (Nat. Phys. 2012)

Evidence for Fermi-surface reconstruction

Quantum resistance oscillations at high magnetic fields



Doiron-Leyraud *et al*. (Nature 2007)



Millis and Norman(PRB 2007)

Evidence for Fermi-surface reconstruction

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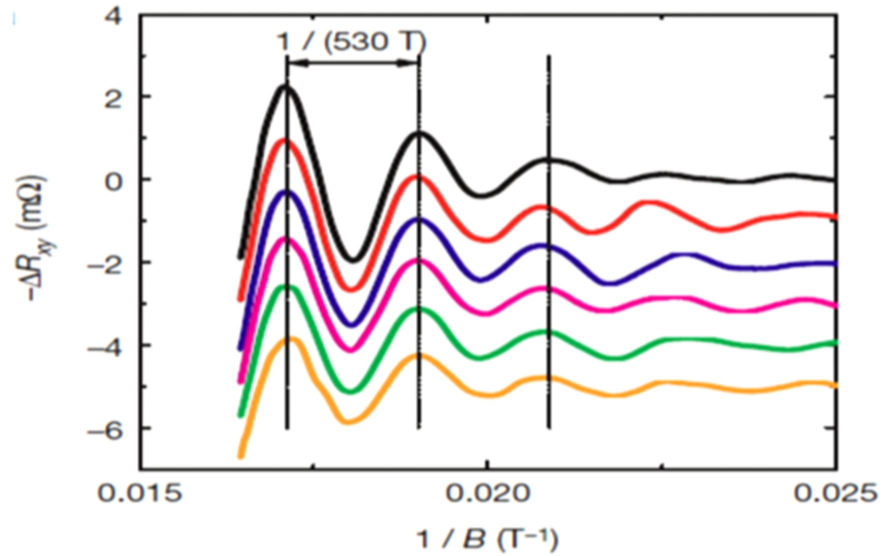
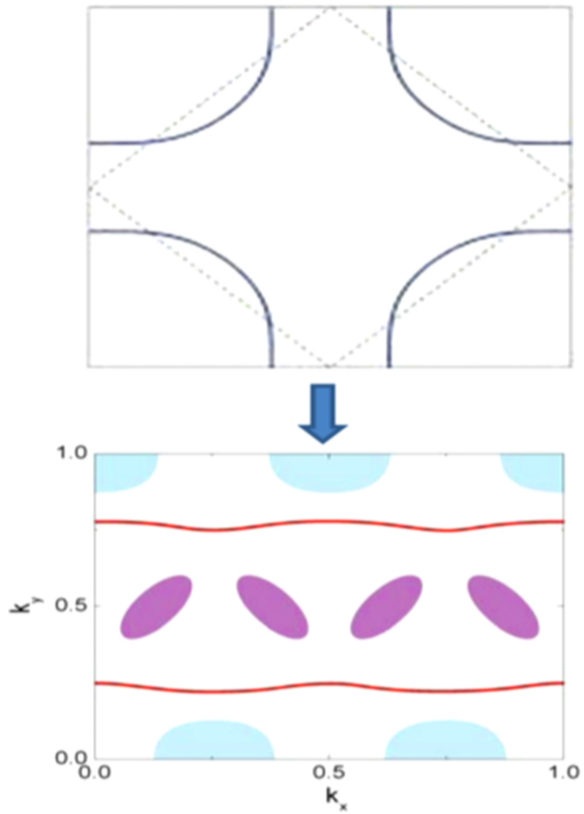


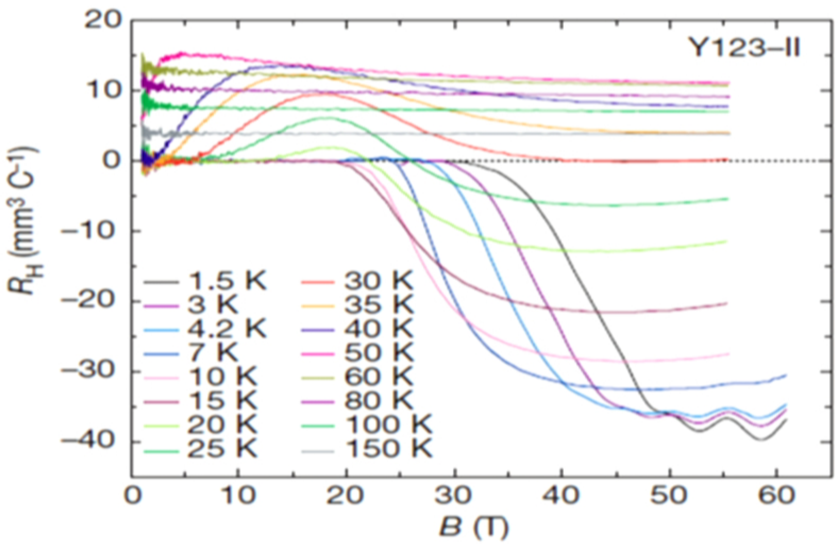
Doiron-Leyraud *et al*. (Nature 2007)

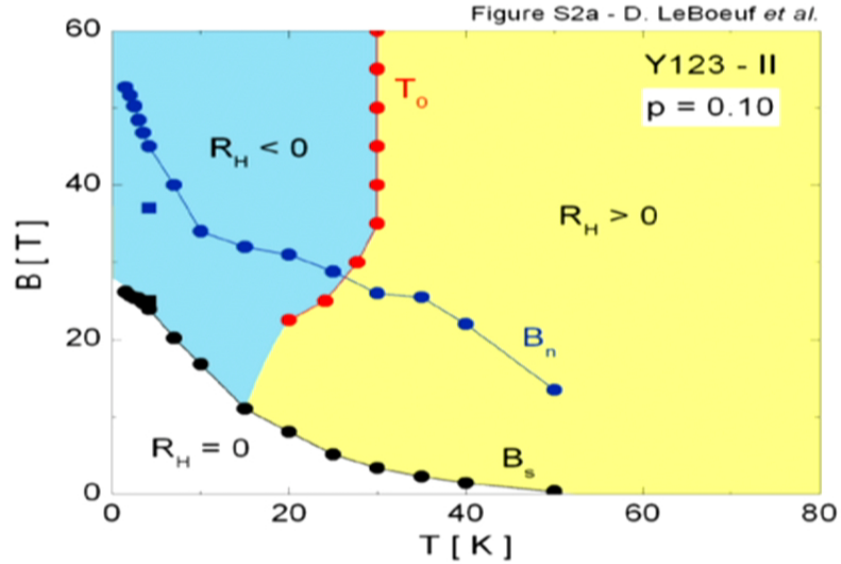


Millis and Norman(PRB 2007)

Evidence for Fermi-surface reconstruction

Change in the Hall coefficient





LeBoeuf *et al*. (Nature 2007)

Is there long-range CDW order in the 3D model ?

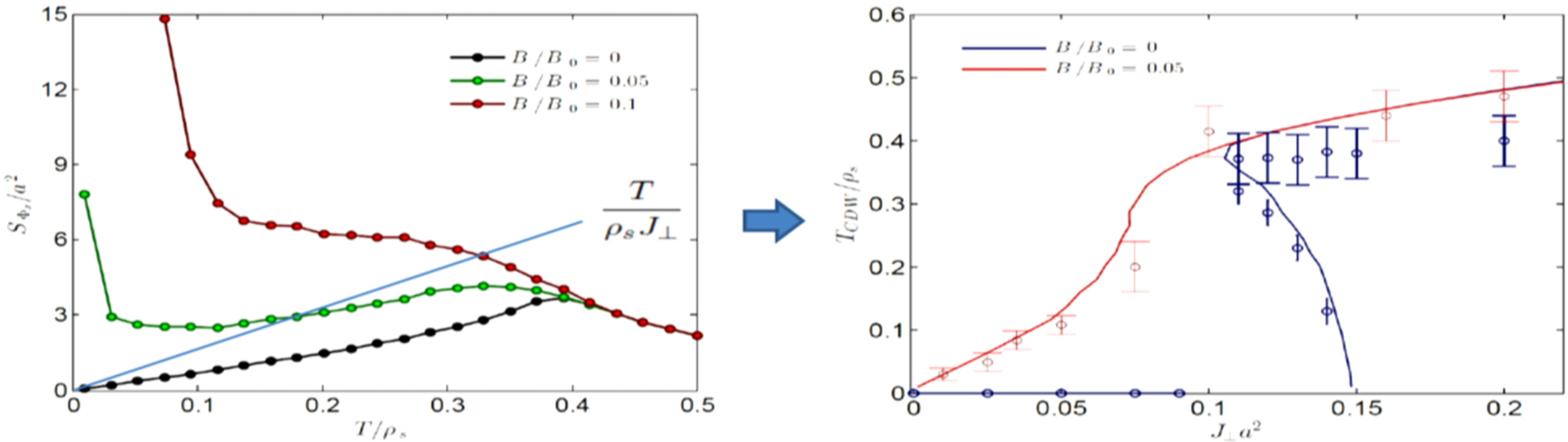
Consider the multi-layer model:

$$H = \sum_i H_0[\psi_i, n_{\alpha,i}] - \rho_s J_\perp \int d^2r \sum_{\alpha,i} n_{\alpha,i} n_{\alpha,i+1}$$

Within an inter-layer mean-field approximation the condition for onset of long-range CDW order at T_{CDW} is:

$$\frac{T_{CDW}}{2\rho_s J_\perp} = \chi(T_{CDW}) \equiv \frac{1}{L^2} \int d^2r \, d^2r' \left[\overline{\langle n_\alpha(\mathbf{r}) n_\alpha(\mathbf{r'}) \rangle} - \overline{\langle n_\alpha(\mathbf{r}) \rangle \langle n_\alpha(\mathbf{r'}) \rangle} \right]$$

Long-range CDW order in the clean 3D model



- For B = 0 ordering takes place only above a critical $J_\perp$
- When B > 0 the system orders for arbitrarily weak $J_\perp$

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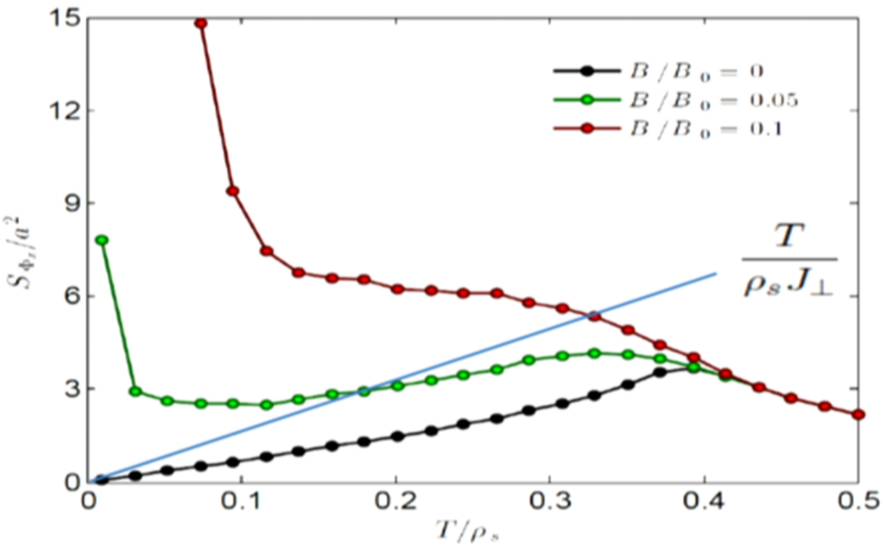

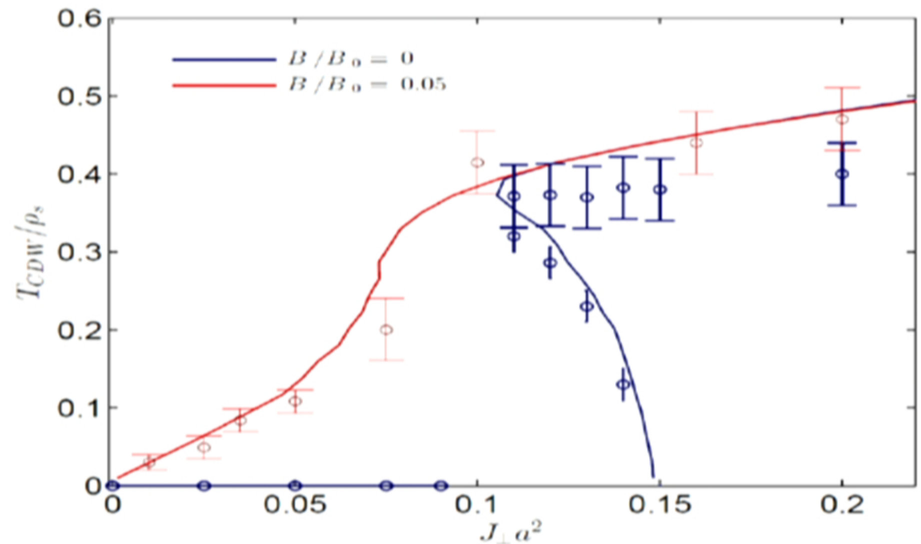

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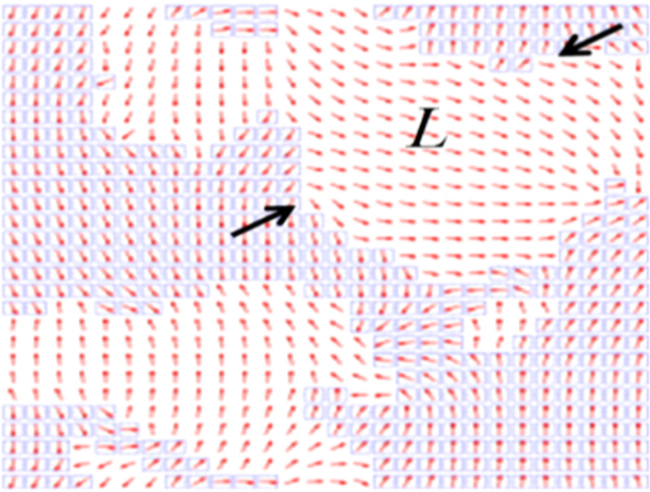
- When B > 0 the system orders for arbitrarily weak $J_\perp$

At odds with experiments

"Long-range" CDW order in the dirty 3D model

Imry-Ma (1975): No long-range order exists when a continuous order parameter is coupled to a random field in d < 4

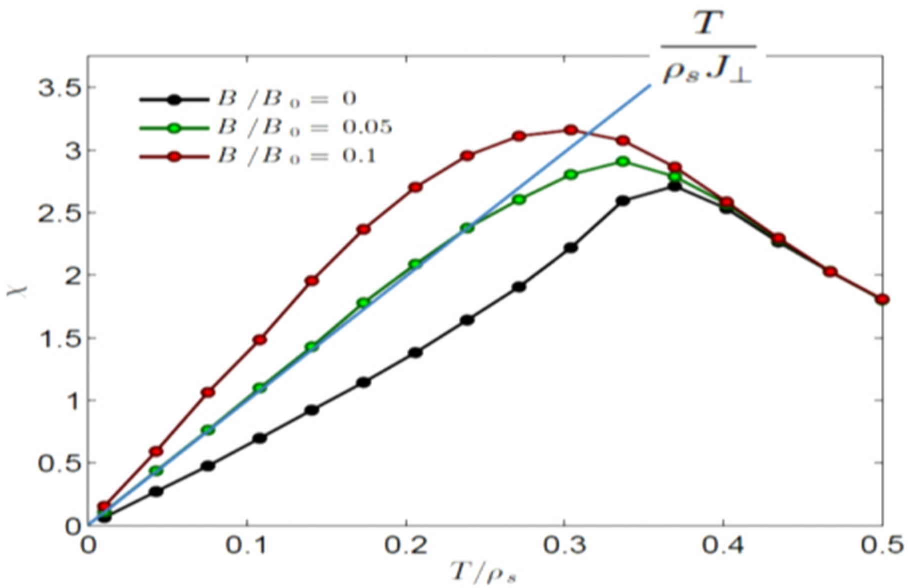


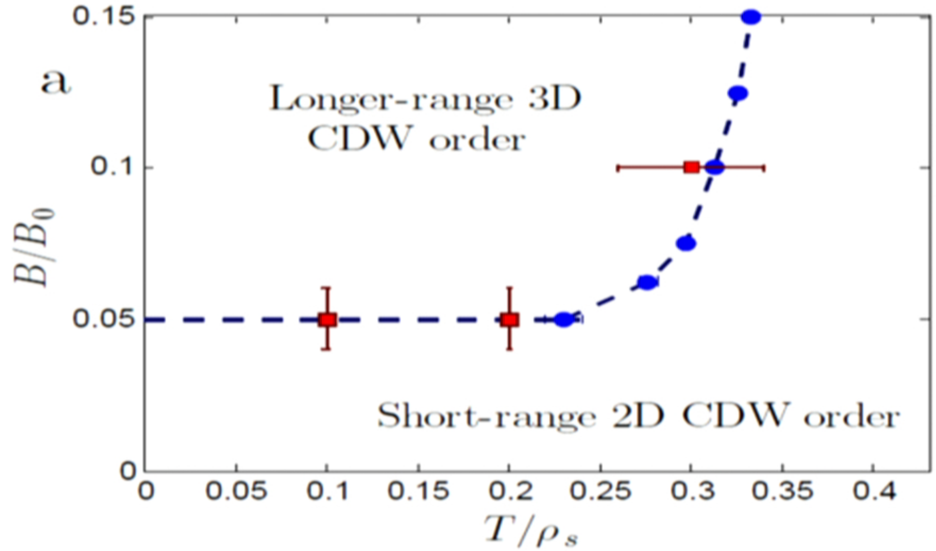
Domain wall energy $\sim L^{d-2}$

If the order parameters aligns along $\sum_{i \in dom} \vec{h}_i$ typically gains $\sim L^{d/2}$

"Long-range" CDW order in the dirty 3D model

Mean-Field Phase Diagram





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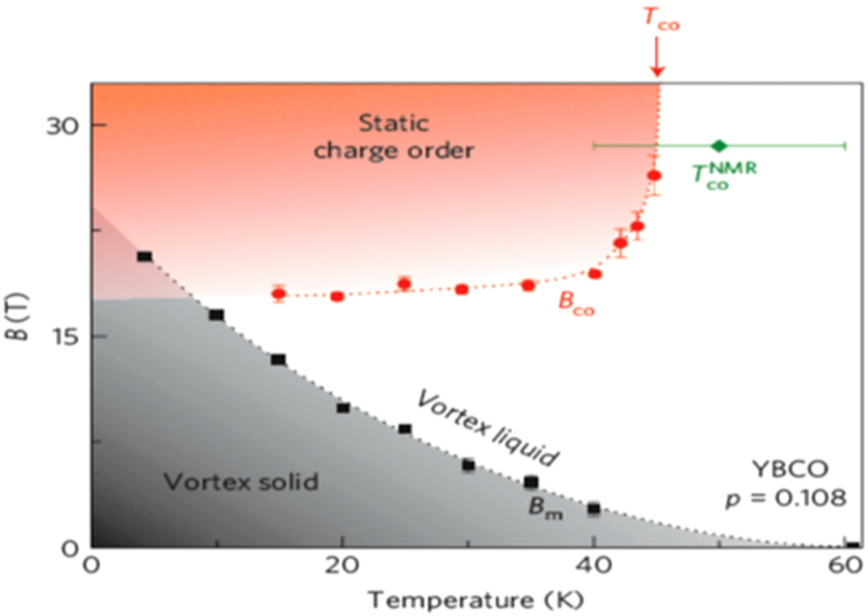
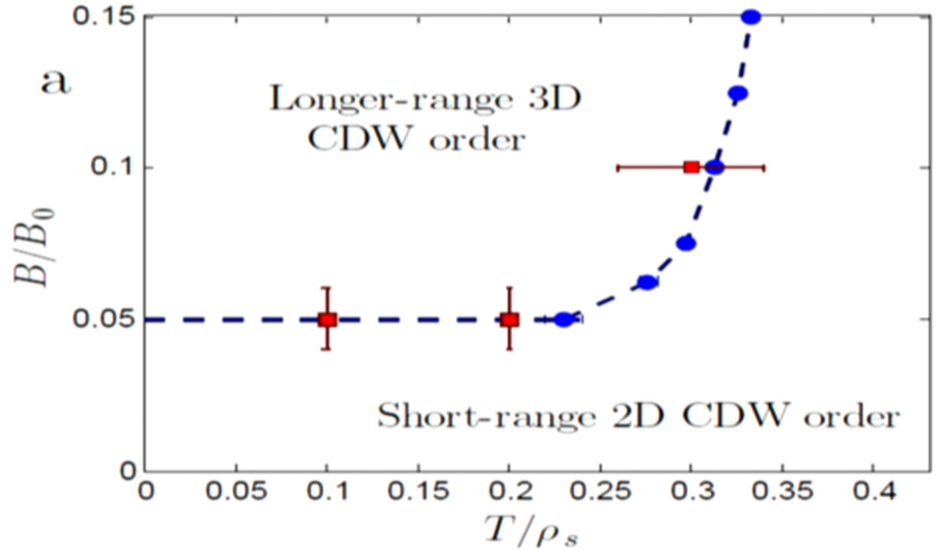
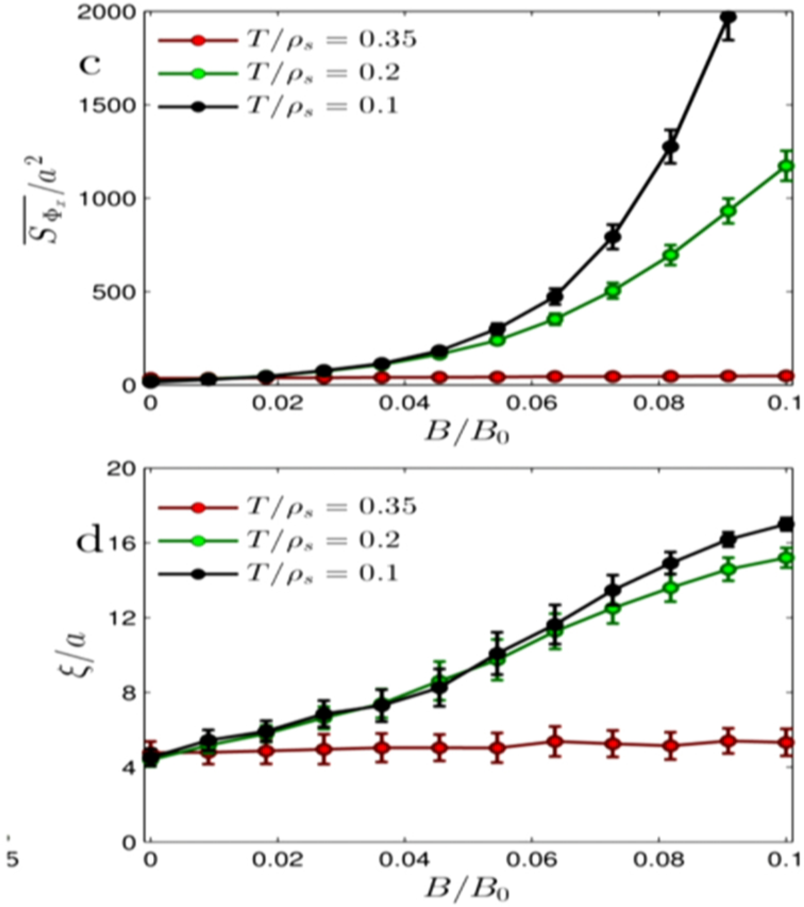


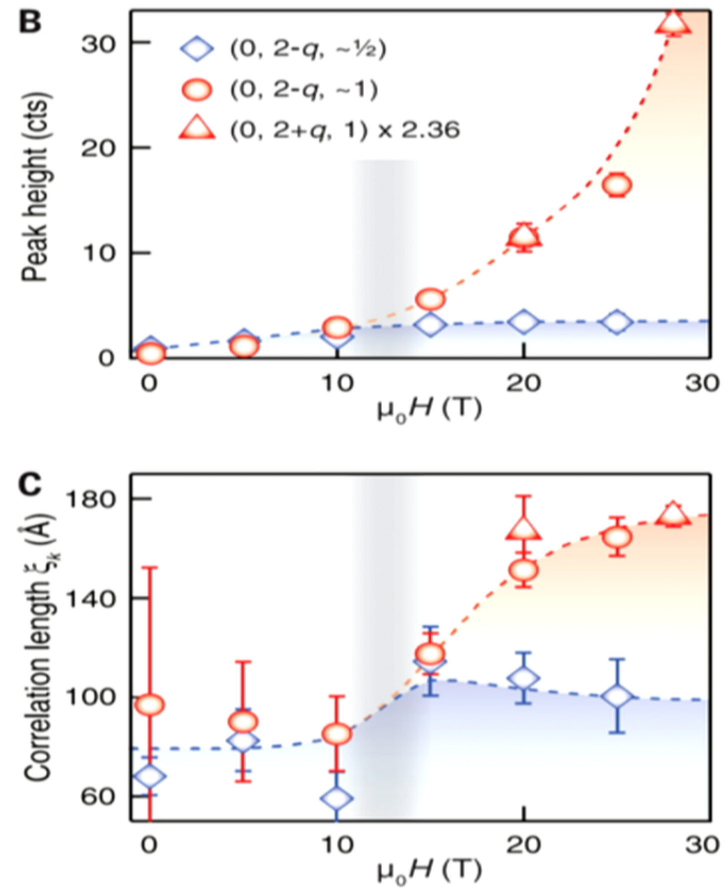


LeBoeuf *et al*. (Nat. Phys. 2012)

“Long-range” CDW order in the dirty 3D model



Gerber *et al.* (arXiv:1506.07910)



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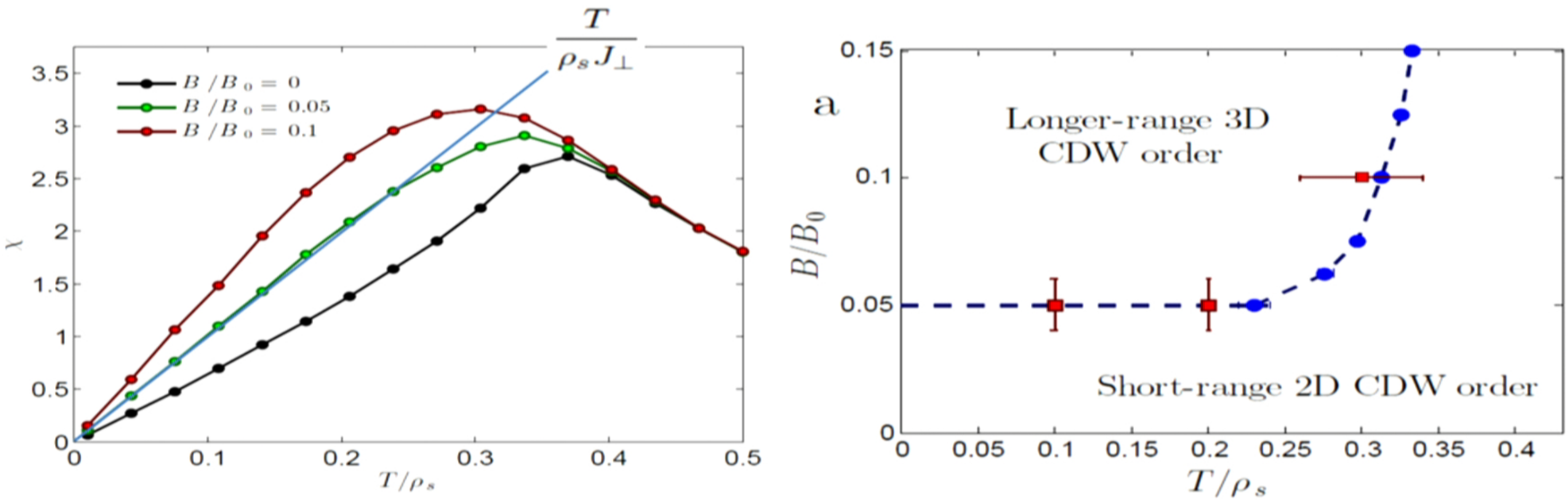

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Phase Fluctuations Redux

SC	Ψ	$\begin{cases} n_1 \\ n_2 \end{cases}$
CDW_x	Φ_x	$\begin{cases} n_3 \\ n_4 \end{cases}$
CDW_y	Φ_y	$\begin{cases} n_5 \\ n_6 \end{cases}$

$$H_0 = \frac{\rho_s}{2} \int d^2 r \left\{ |(\boldsymbol{\nabla} + 2ie\boldsymbol{A})\psi|^2 + \sum_{\alpha=3}^{6} [\lambda(\boldsymbol{\nabla} n_\alpha)^2 + g n_\alpha^2 - 2V_\alpha n_\alpha] \right\}$$

$$\sum_{\alpha=1}^{6} n_\alpha^2 = 1$$

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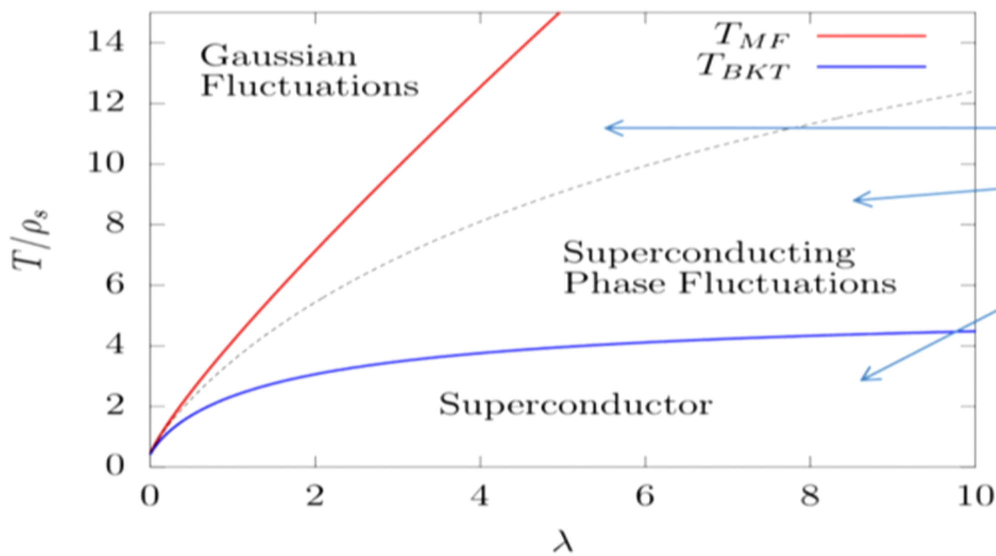
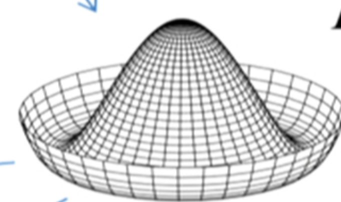
GW and Dror Orgad (PRB 2015)





$$F[\psi^*, \psi]$$

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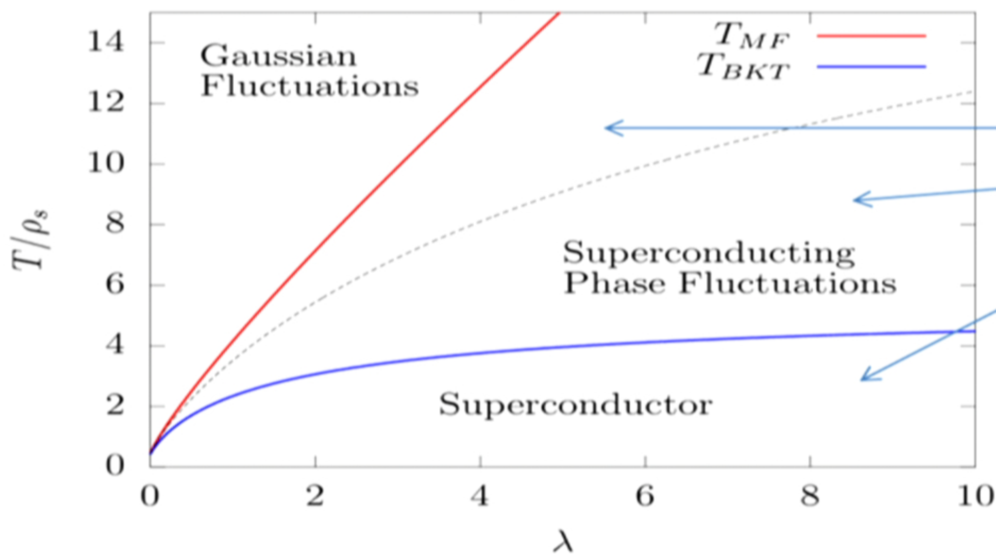

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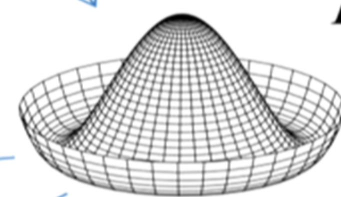

Phase fluctuations may have appreciable signatures at B = 0: Nernst, ARPES

Conclusions

- A non-linear sigma model of competing orders captures much of the experimental phenomenology in the cuprates.

Conclusions

• A non-linear sigma model of competing orders captures much of the experimental phenomenology in the cuprates.

• Disorder plays an essential role in establishing the observed x-ray signal in YBCO, and might be the reason behind the different T-behavior in Hg1201.

• The apparent ordering transition at high fields is, most likely, a dimensional crossover from short-range order within planes to much longer-range inter-plane order.