Dimensional Crossover of Charge-Density Wave Correlations in the Cuprates

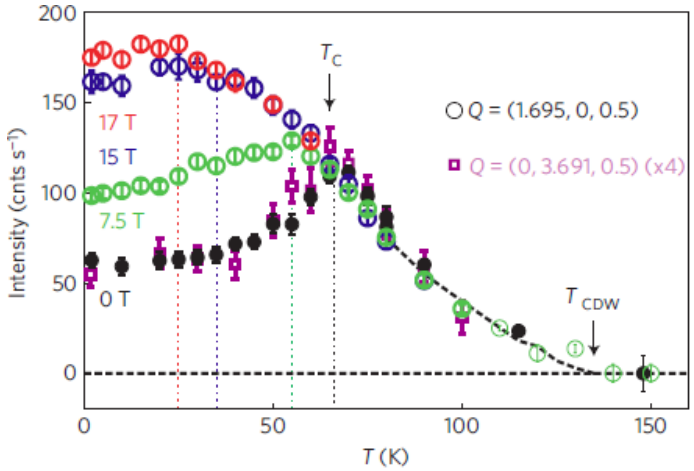
Yosef Caplan
Dror Orgad

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

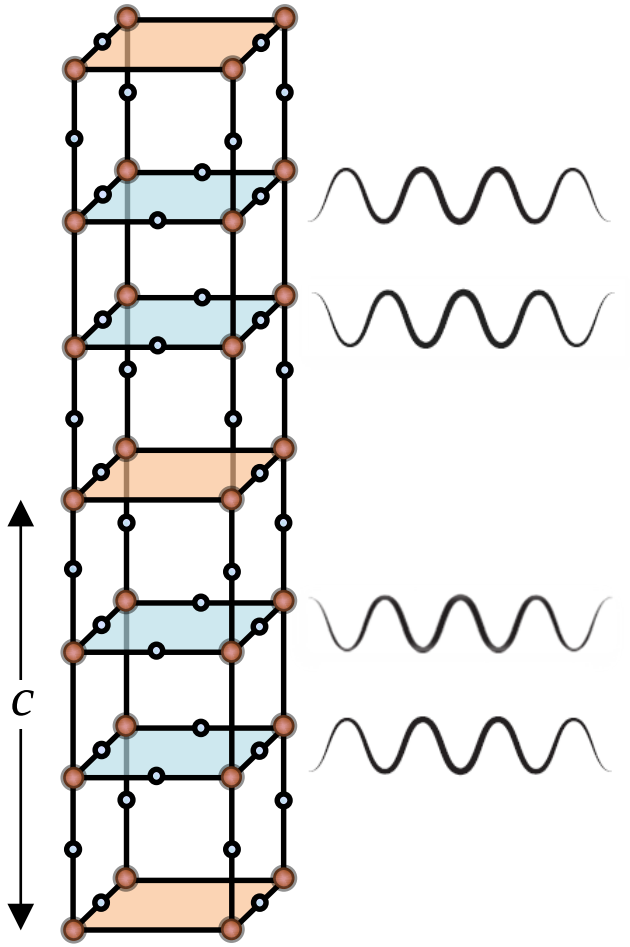
Evidence for short-range CDW order

- Short-ranged: $\xi_a \approx 20a, \quad \xi_c \approx 0.6c$
- $l = 0.5$
- Bidirectional
- Competes with superconductivity

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



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

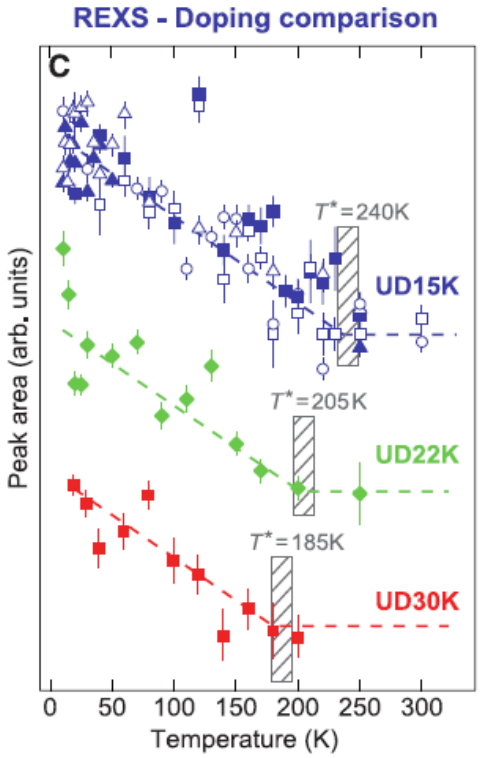


Forgan *et al*. (Nat. Commun. 2015)

Evidence for short-range CDW order

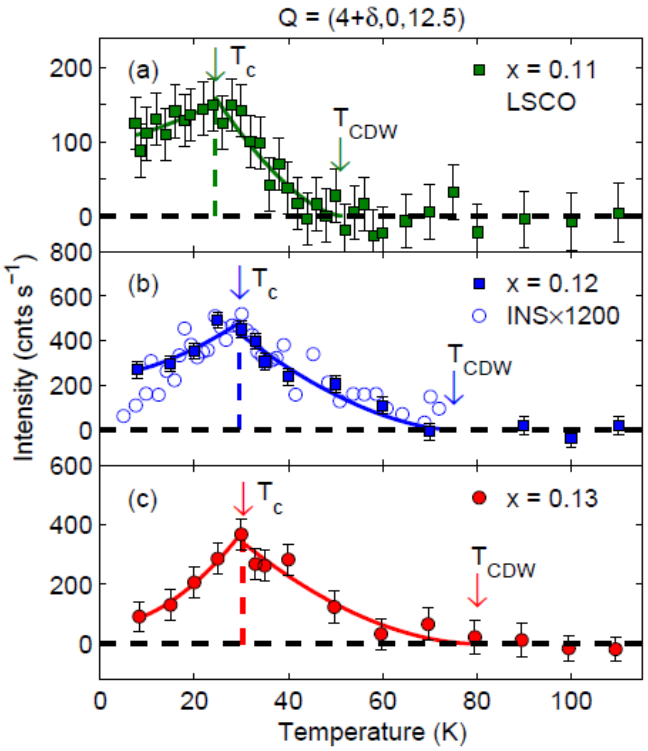
A similar signal is observed in other cuprates

Bi2201



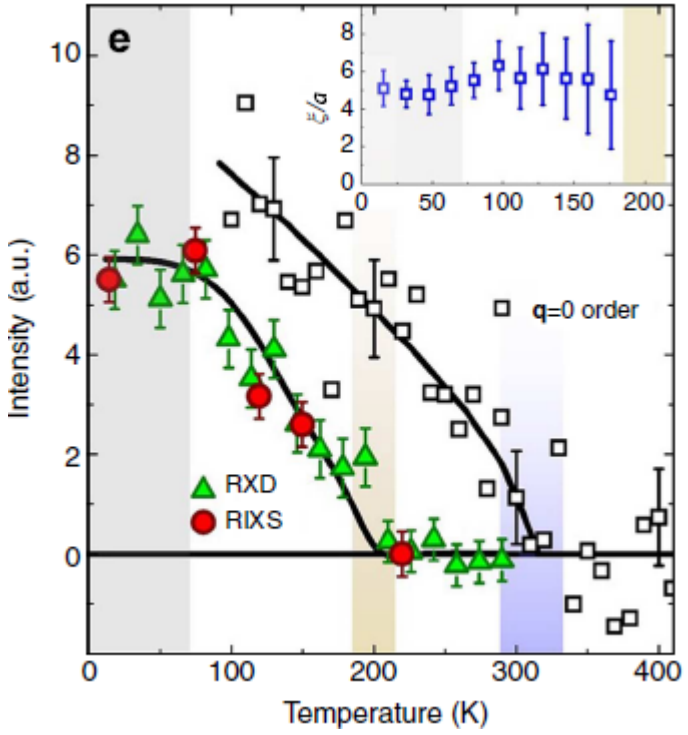
Comin *et al*. (Science 2014)

LSCO



Croft *et al*. (PRB 2014)

Hg1201

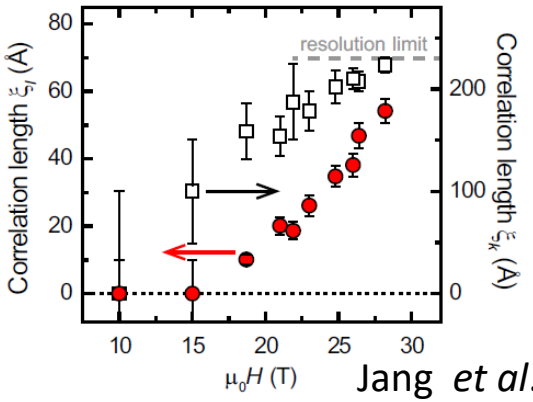


Tabis *et al*. (Nat. Commun. 2014)

Evidence for long-range CDW order

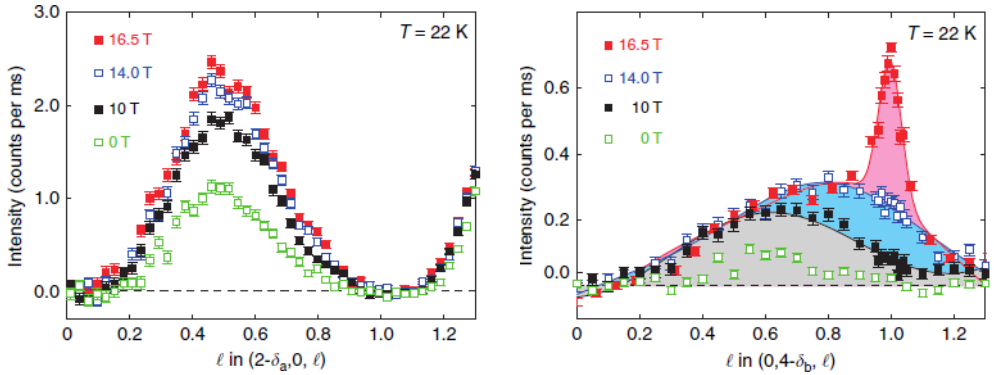
High field x-ray diffraction: ortho-II and ortho-VIII YBCO

- Longer-ranged
- $l = 1$

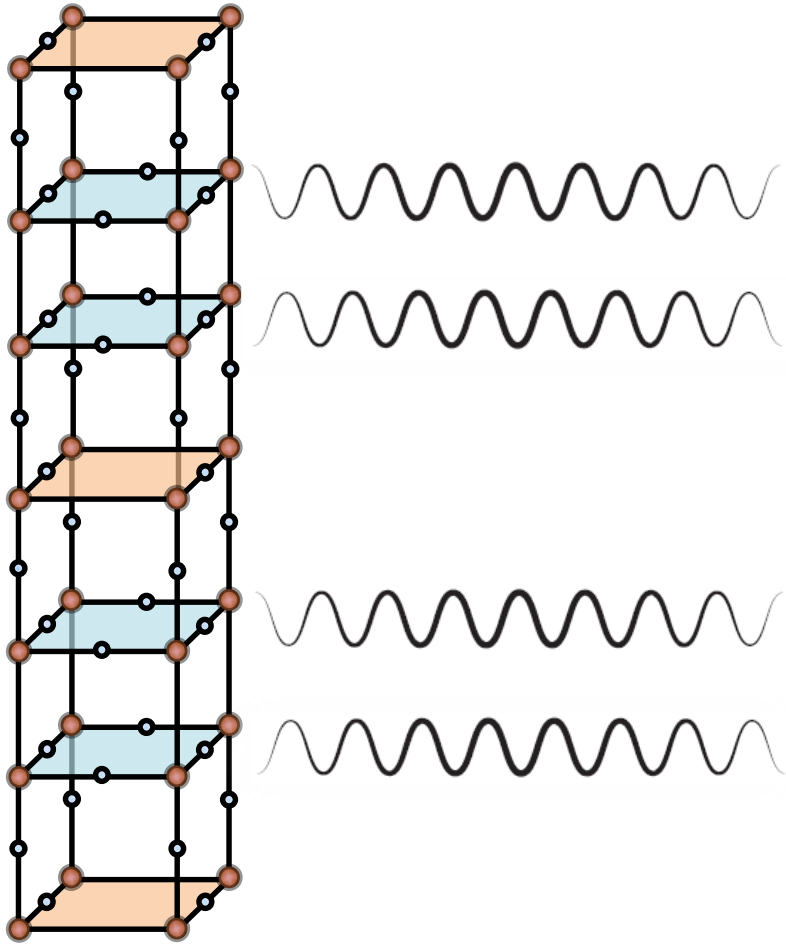


Jang *et al*. (PNAS 2016)

- Unidirectional



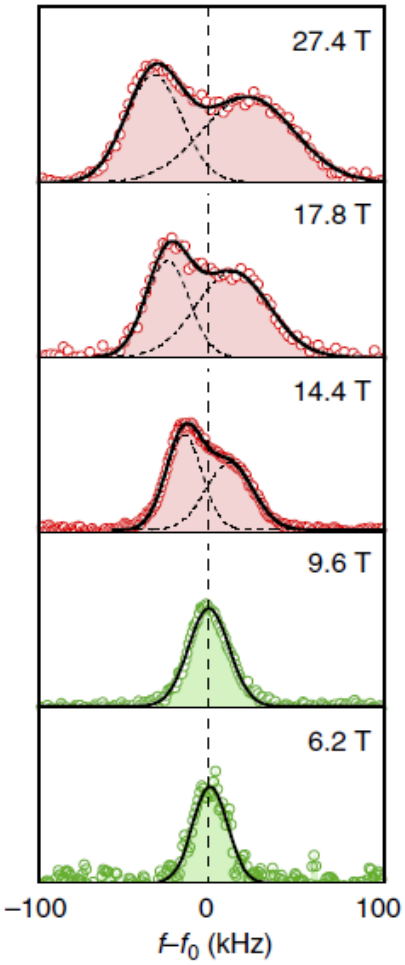
Chang *et al*. (Nat. Commun. 2016)

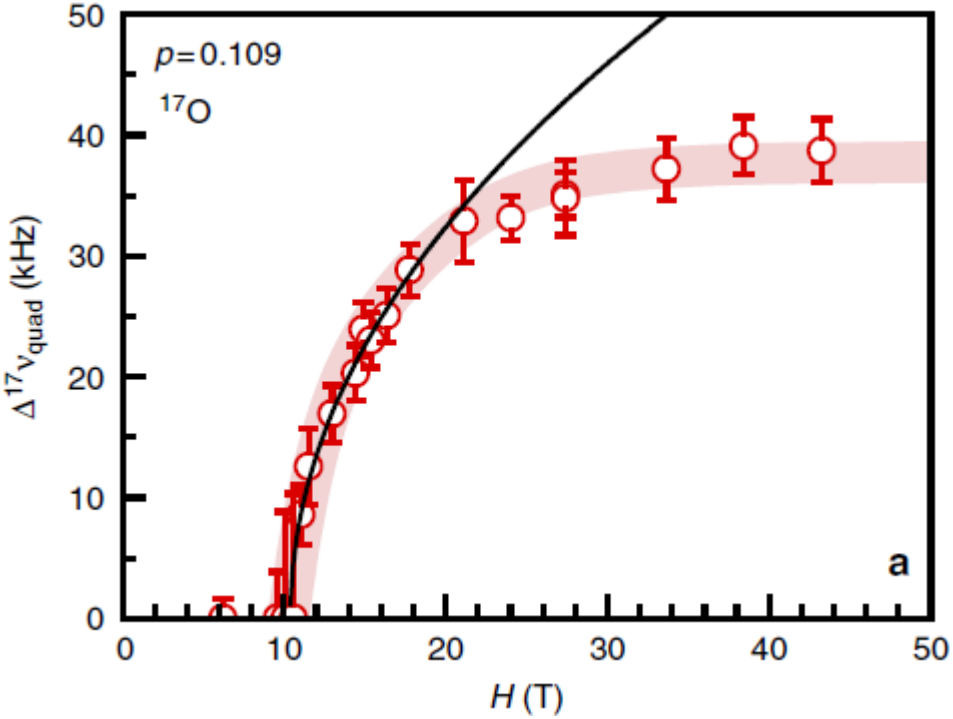


Gerber *et al*. (Science 2015)

Evidence for long-range CDW order

Splitting of NMR lines

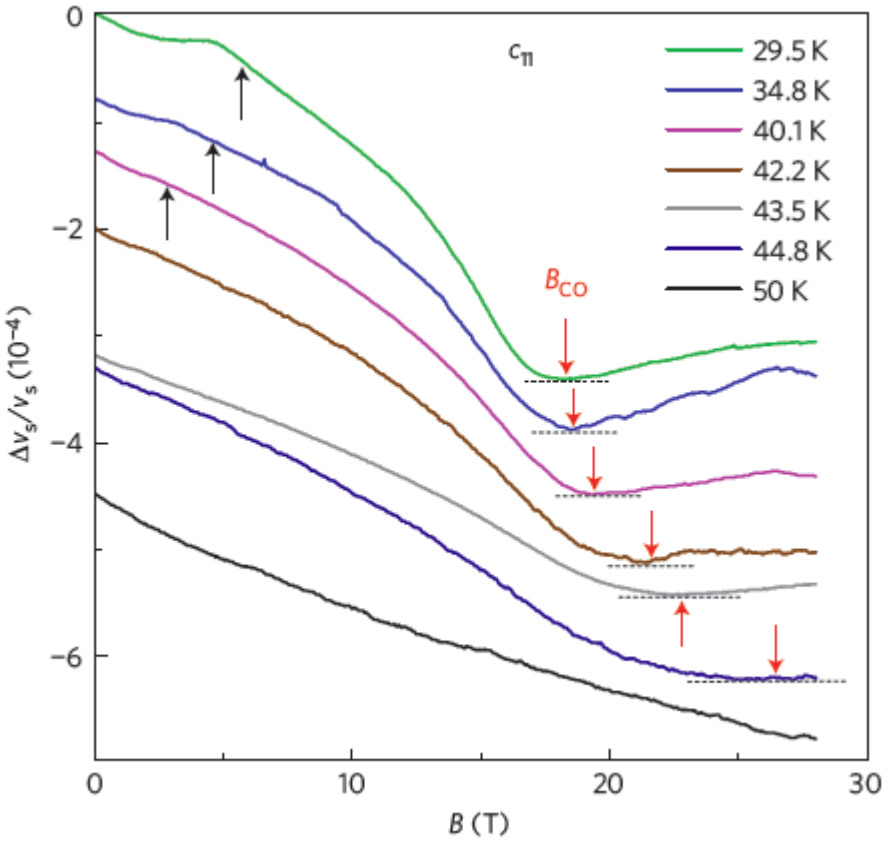


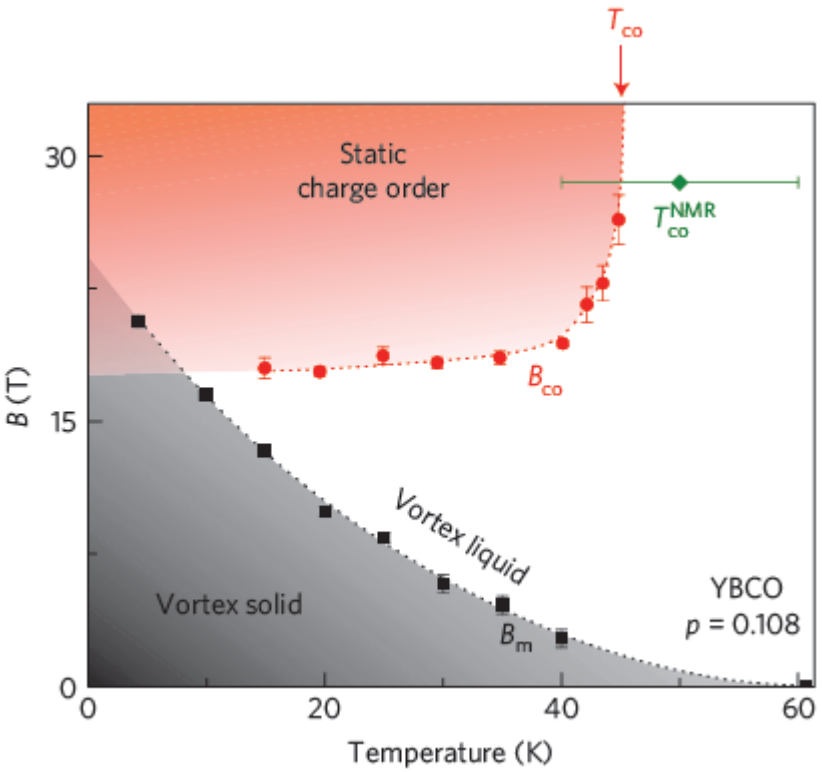


Wu *et al*. (Nat. Commun. 2013)

Evidence for long-range CDW order

Sound velocity anomaly





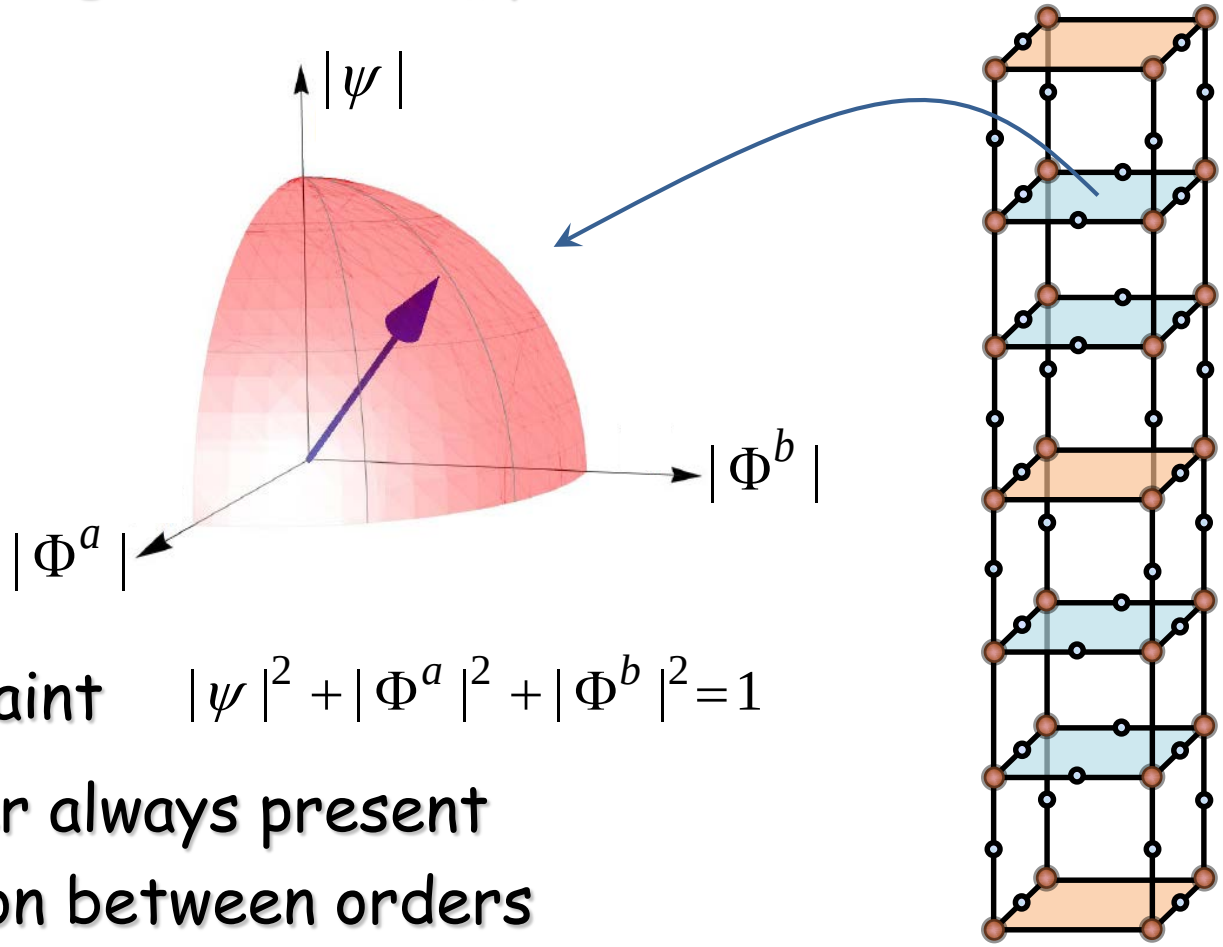
LeBoeuf *et al*. (Nat. Phys. 2012)

Questions

- Are the two orders distinct or related ?
- Do they microscopically coexist or do they phase separate ?
- What is the source of their different *c*-axis correlations ?
- Why are the short-range correlations bidirectional and the longer-range order unidirectional ?
- Is a transition to true long-range order expected at higher fields ?

The model

We study a nonlinear sigma model of a 6-component order parameter, residing on the CuO_2 planes,



with the constraint $|\psi|^2 + |\Phi^a|^2 + |\Phi^b|^2 = 1$

- Local order always present
- Competition between orders

The model

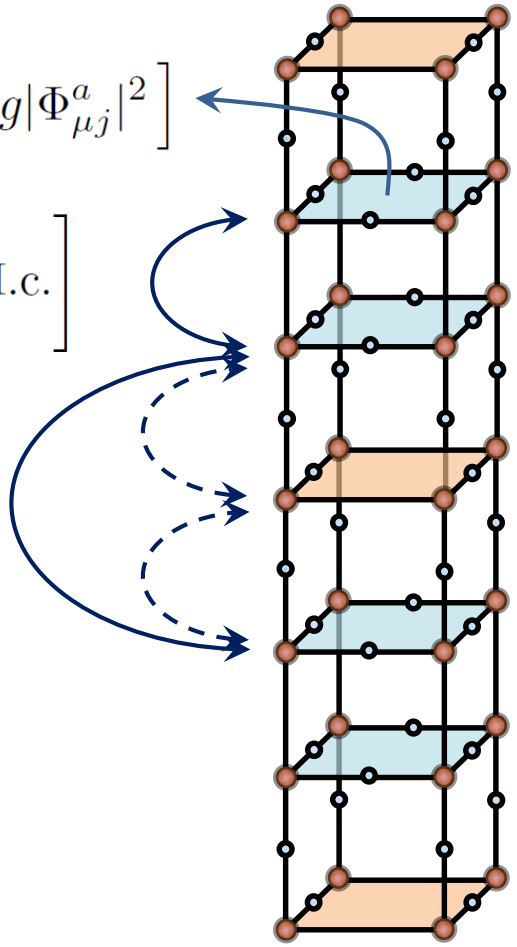
We study a nonlinear sigma model of a 6-component order parameter, residing on the CuO_2 planes.

$$\frac{\rho_s}{2}\int d^2r\Big[\,|(\boldsymbol{\nabla}+2ie\mathbf{A})\psi_{\mu j}|^2+\lambda|\boldsymbol{\nabla}\boldsymbol{\Phi}_{\mu j}|^2+g|\boldsymbol{\Phi}_{\mu j}|^2+\Delta g|\Phi^a_{\mu j}|^2\,\Big]$$

$$\frac{\rho_s}{2}\int d^2r\left[\tilde{U}\,\boldsymbol{\Phi}^\dagger_{0j}\boldsymbol{\Phi}_{1j}\;-\tilde{J}\psi^*_{0j}\psi_{1j}+\text{H.c.}\right]$$

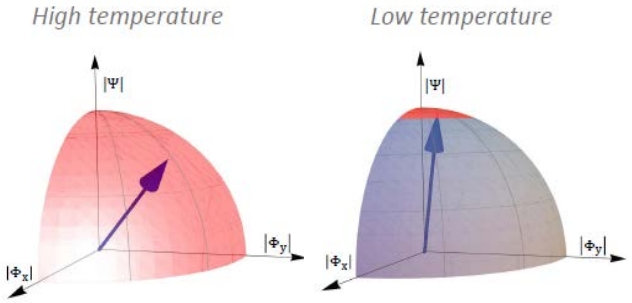
$$\frac{\rho_s}{2}\int d^2r\left[U\boldsymbol{\Phi}^\dagger_{1j}\boldsymbol{\Phi}_{0j+1}\;-J\psi^*_{1j}\psi_{0j+1}+\text{H.c.}\right]$$

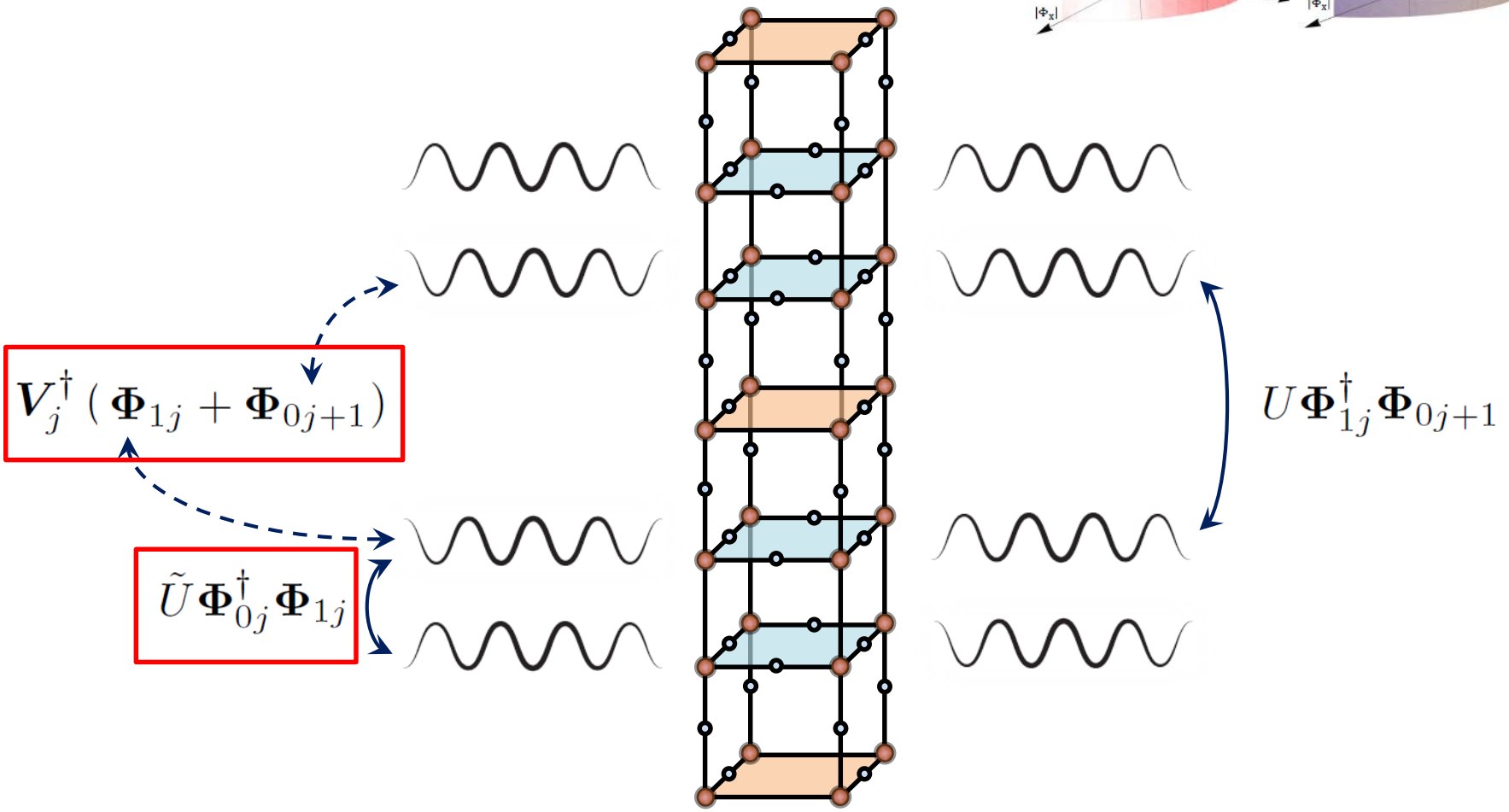
$$\frac{\rho_s}{2}\int d^2r\left[\boldsymbol{V}^\dagger_j\,(\,\boldsymbol{\Phi}_{1j}+\boldsymbol{\Phi}_{0j+1}\,)+\text{H.c.}\right]$$



The physics at B=0

$$\frac{\rho_s}{2}\int d^2r\Big[\,|(\boldsymbol{\nabla}+2ie\mathbf{A})\psi_{\mu j}|^2+\lambda|\boldsymbol{\nabla}\boldsymbol{\Phi}_{\mu j}|^2+g|\boldsymbol{\Phi}_{\mu j}|^2+\Delta g|\Phi^a_{\mu j}|^2\Big]$$



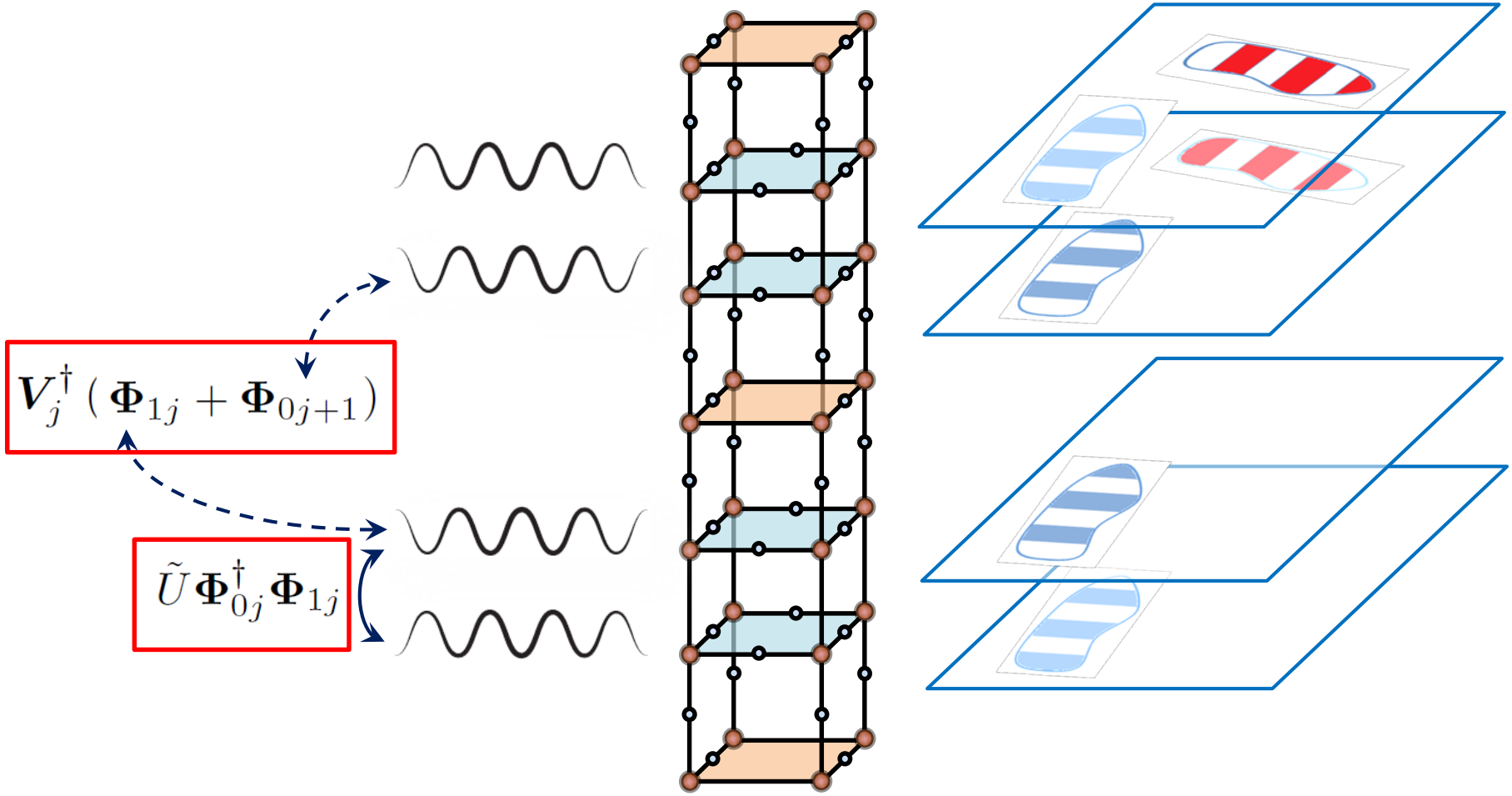


The physics at B=0

$$\frac{\rho_s}{2}\int d^2r\Big[\,|(\boldsymbol{\nabla}+2ie\mathbf{A})\psi_{\mu j}|^2+\lambda|\boldsymbol{\nabla}\boldsymbol{\Phi}_{\mu j}|^2+g|\boldsymbol{\Phi}_{\mu j}|^2+\Delta g|\Phi^a_{\mu j}|^2\Big]$$

$\boldsymbol{V}_j^\dagger\,(\,\boldsymbol{\Phi}_{1j}+\boldsymbol{\Phi}_{0j+1}\,)$

$\tilde{U}\,\boldsymbol{\Phi}^\dagger_{0j}\boldsymbol{\Phi}_{1j}$



Large-N analysis

The CDW correlation matrix

$$G^{\alpha}_{\mu\mu'}(\mathbf{q},l)=\frac{1}{2N_cA}\int d^2rd^2r'\sum_{jj'}e^{-i[\mathbf{q}\cdot(\mathbf{r}-\mathbf{r}')+2\pi(j-j')l]}\overline{\langle\Phi^{\alpha}_{\mu j}(\mathbf{r})\Phi^{*\alpha}_{\mu' j'}(\mathbf{r}')\rangle}$$

$$G^{\alpha}_{00}(0,l)=G^{\alpha}_{11}(0,l)=\frac{T}{\rho_s}\frac{\epsilon_\alpha}{\epsilon_\alpha^2-\epsilon_\perp^2(l)}+\frac{V^2}{[\epsilon_\alpha+\epsilon_\perp(l)]^2}+\frac{4V^2\epsilon_\alpha\tilde{U}\sin^2\pi l}{[\epsilon_\alpha^2-\epsilon_\perp^2(l)]^2}$$

$$\epsilon_\alpha=g+\Delta g\delta_{\alpha a}+J+\tilde{J}\qquad\epsilon_\perp(l)=[U^2+\tilde{U}^2+2U\tilde{U}\cos 2\pi l]^{1/2}$$

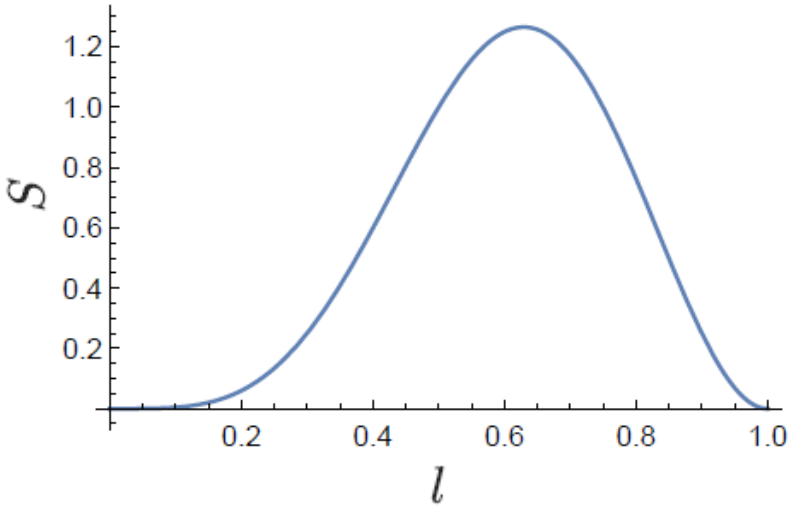
Temperature term peaks at integer l

Disorder terms peak at half-integer l, as long as $\epsilon_\alpha > 3U+\tilde{U}$

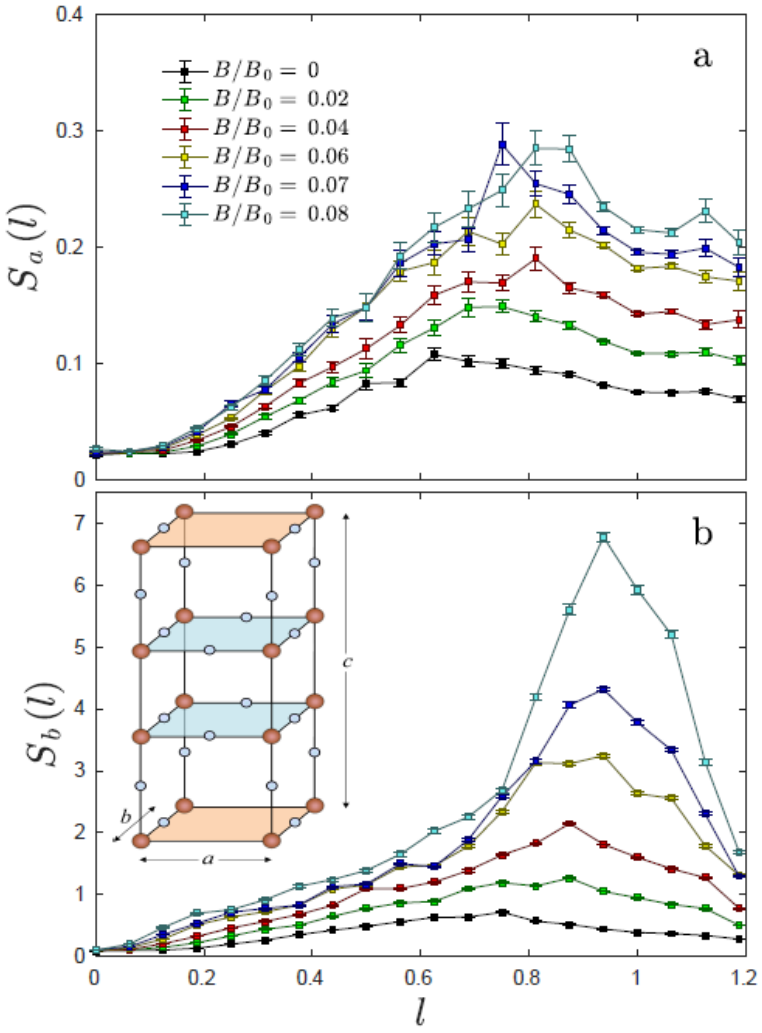
dominate if $V^2 > 2UT/\rho_s$

The structure factor

Large-N analysis

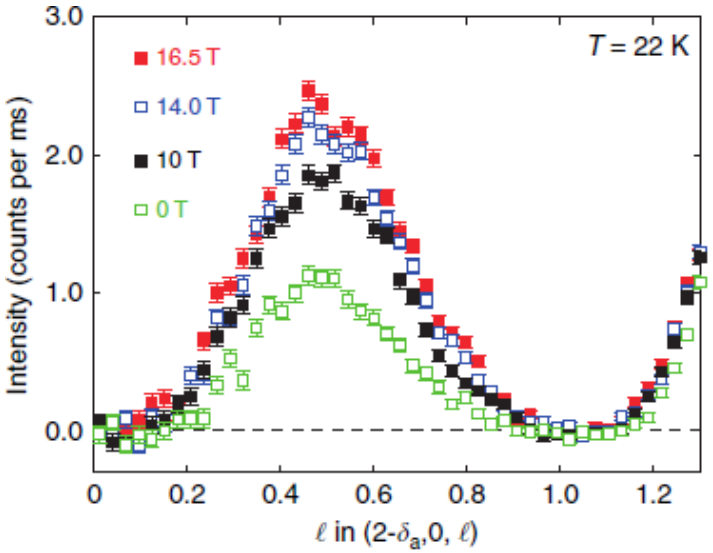


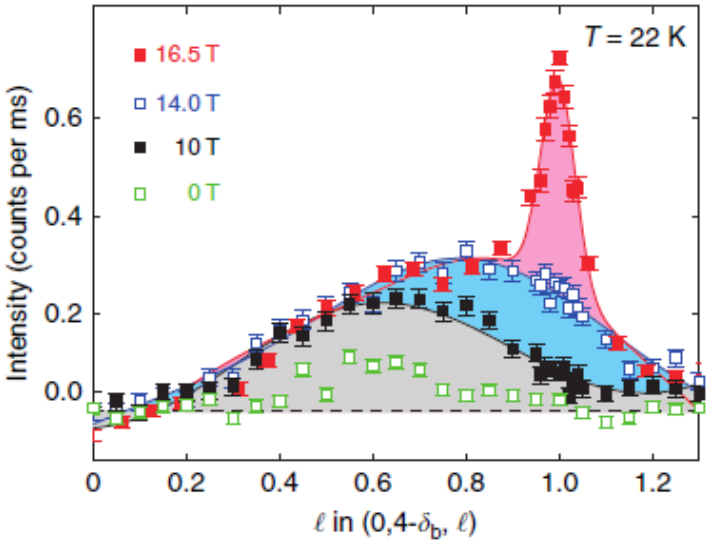
Monte Carlo



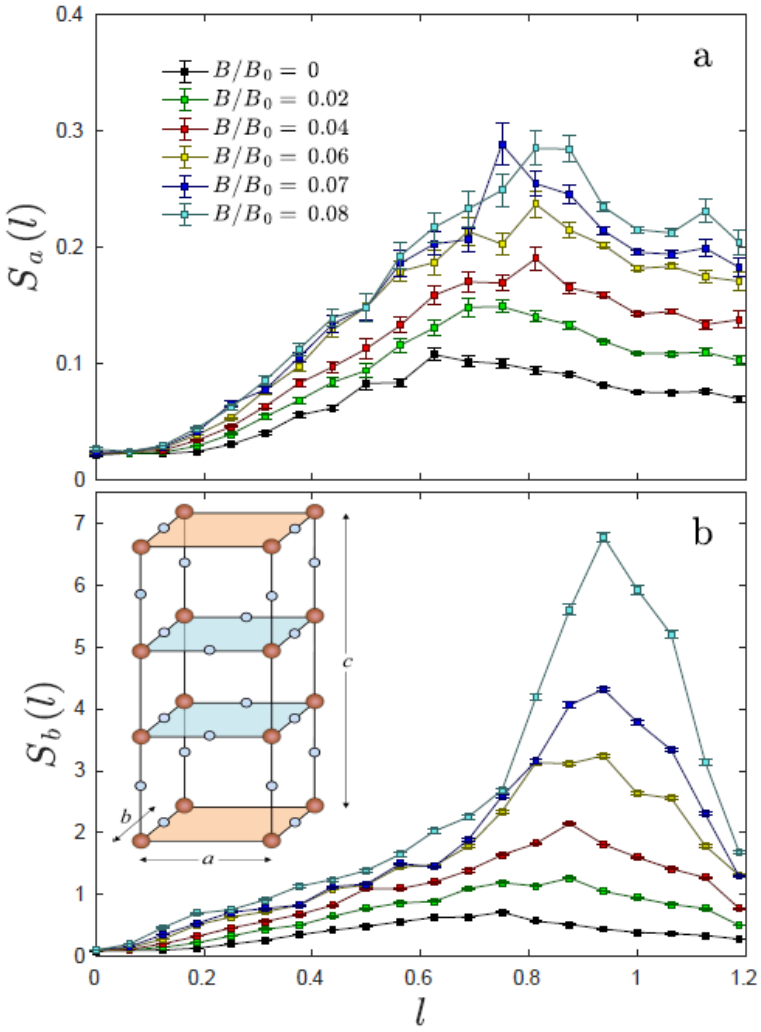
The structure factor

Chang *et al*. (Nat. Commun. 2016)



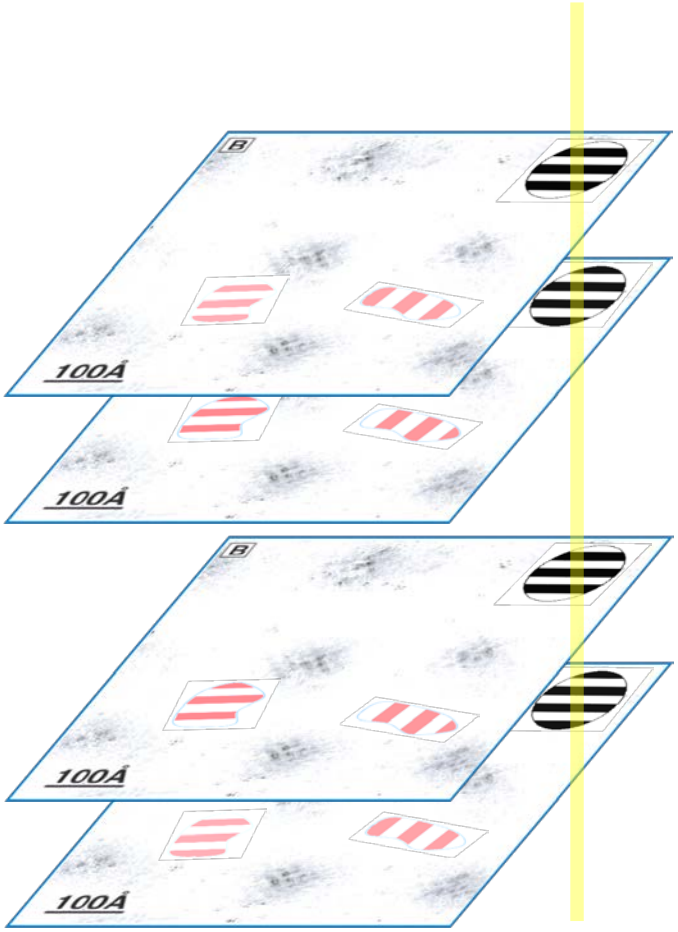


Monte Carlo



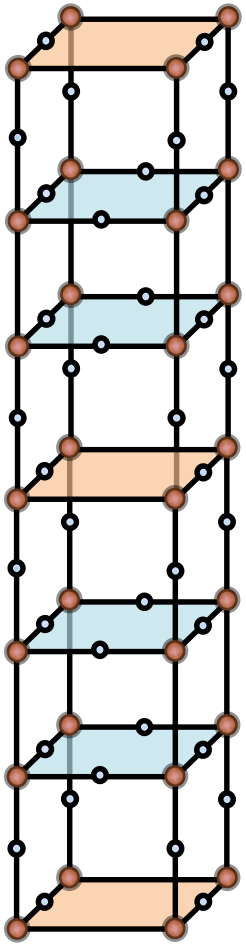
The physics at B>0

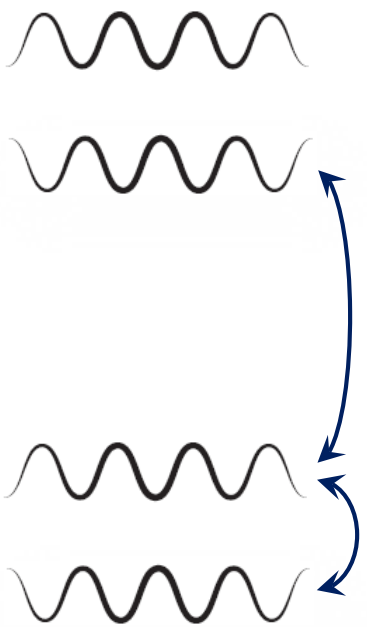
$$\frac{\rho_s}{2}\int d^2r\Big[\,|(\boldsymbol{\nabla}+2ie\mathbf{A})\psi_{\mu j}|^2+\lambda|\boldsymbol{\nabla}\boldsymbol{\Phi}_{\mu j}|^2+g|\boldsymbol{\Phi}_{\mu j}|^2+\boxed{\Delta g|\Phi^a_{\mu j}|^2}\,\Big]$$



STM on BSCCO

Hoffman *et al*. (Science 2002)

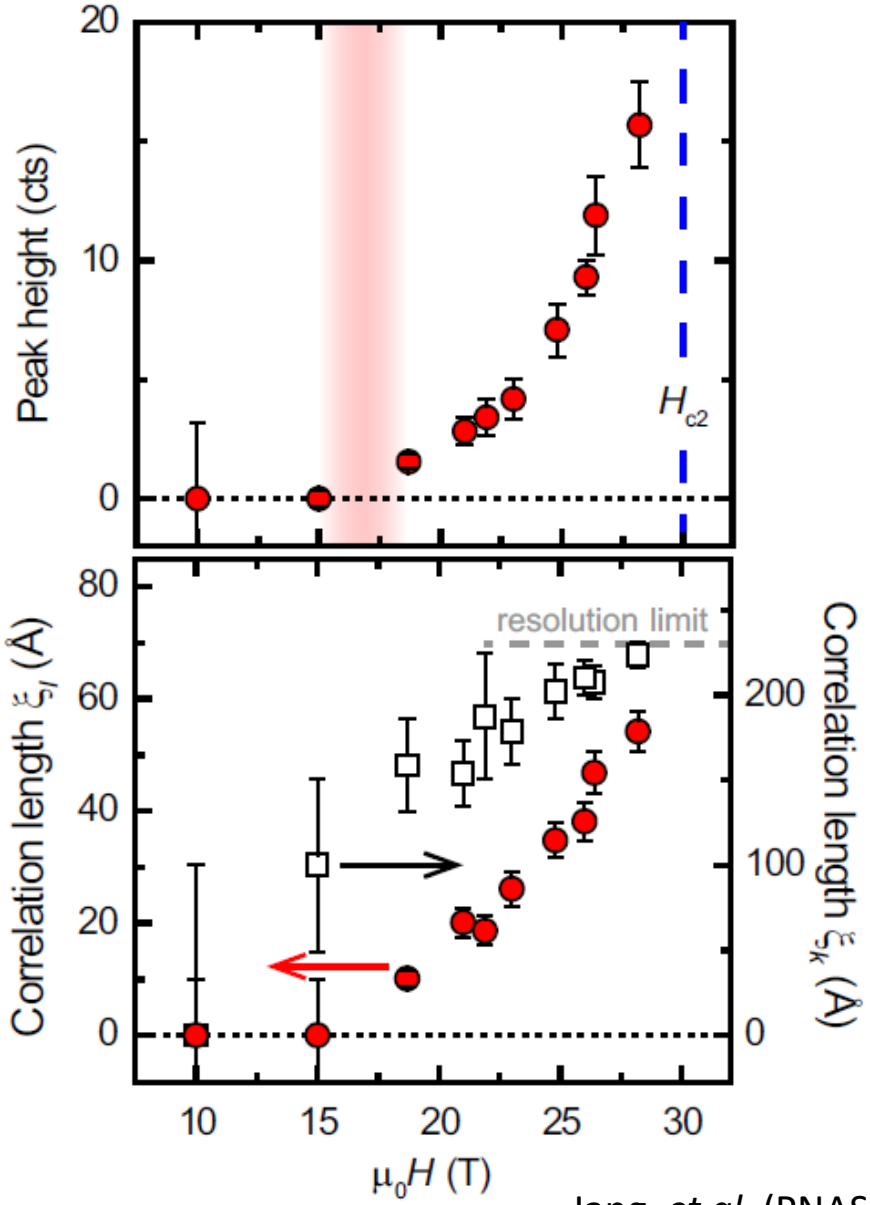


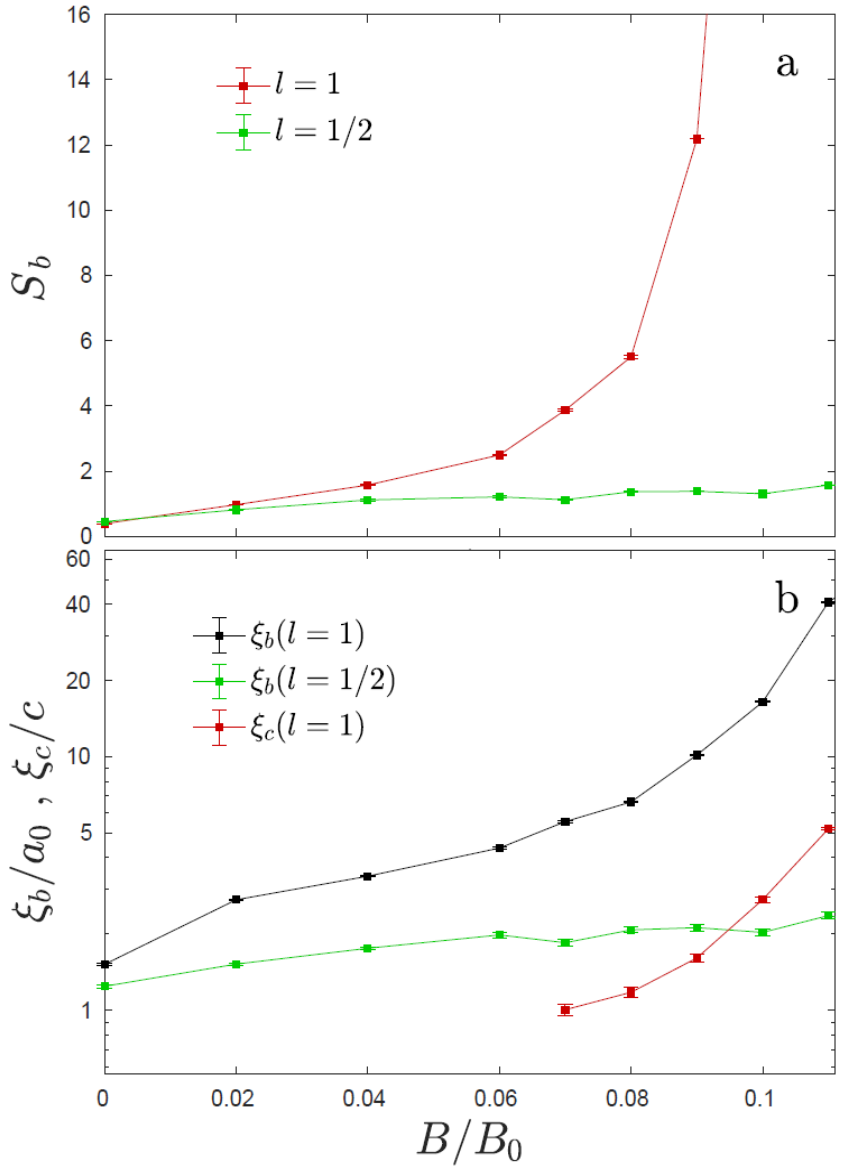


$U\boldsymbol{\Phi}^\dagger_{1j}\boldsymbol{\Phi}_{0j+1}$

$\tilde{U}\boldsymbol{\Phi}^\dagger_{0j}\boldsymbol{\Phi}_{1j}$

B-dependence

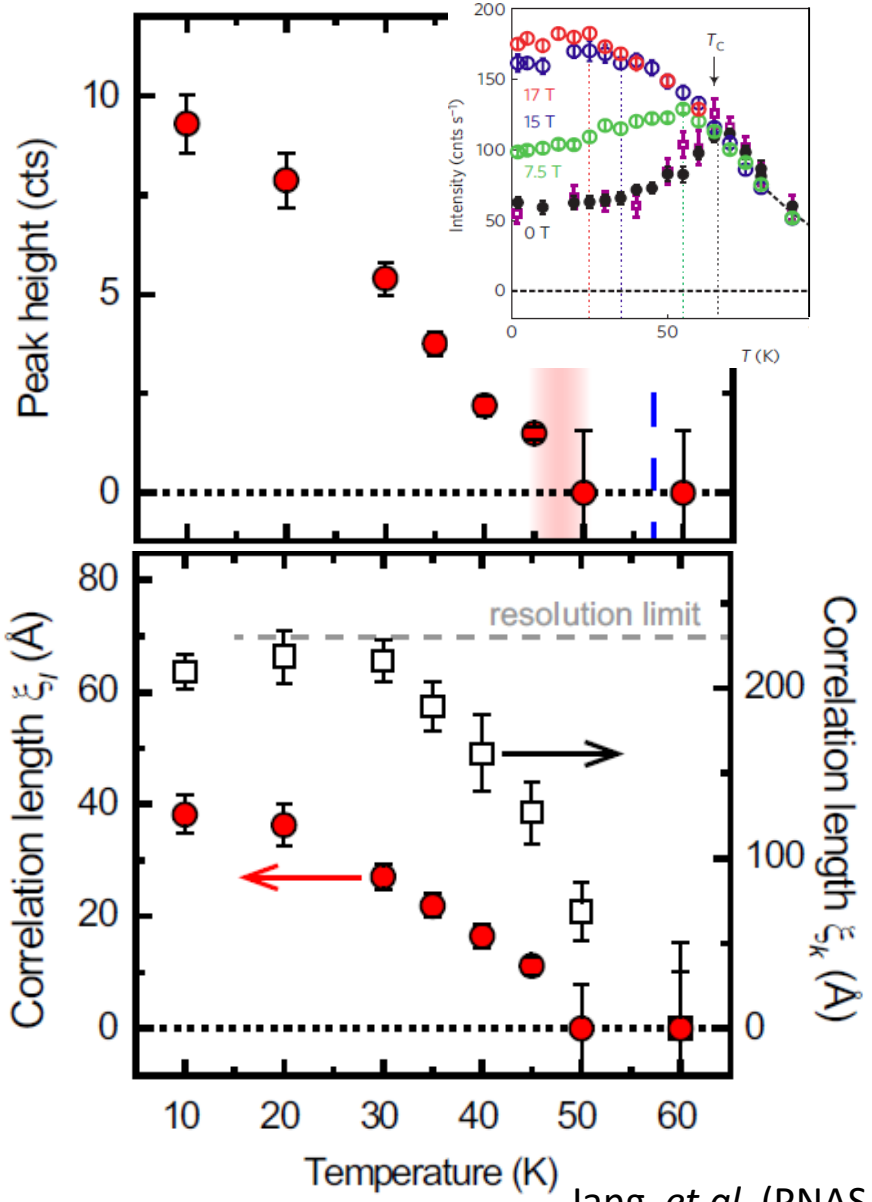


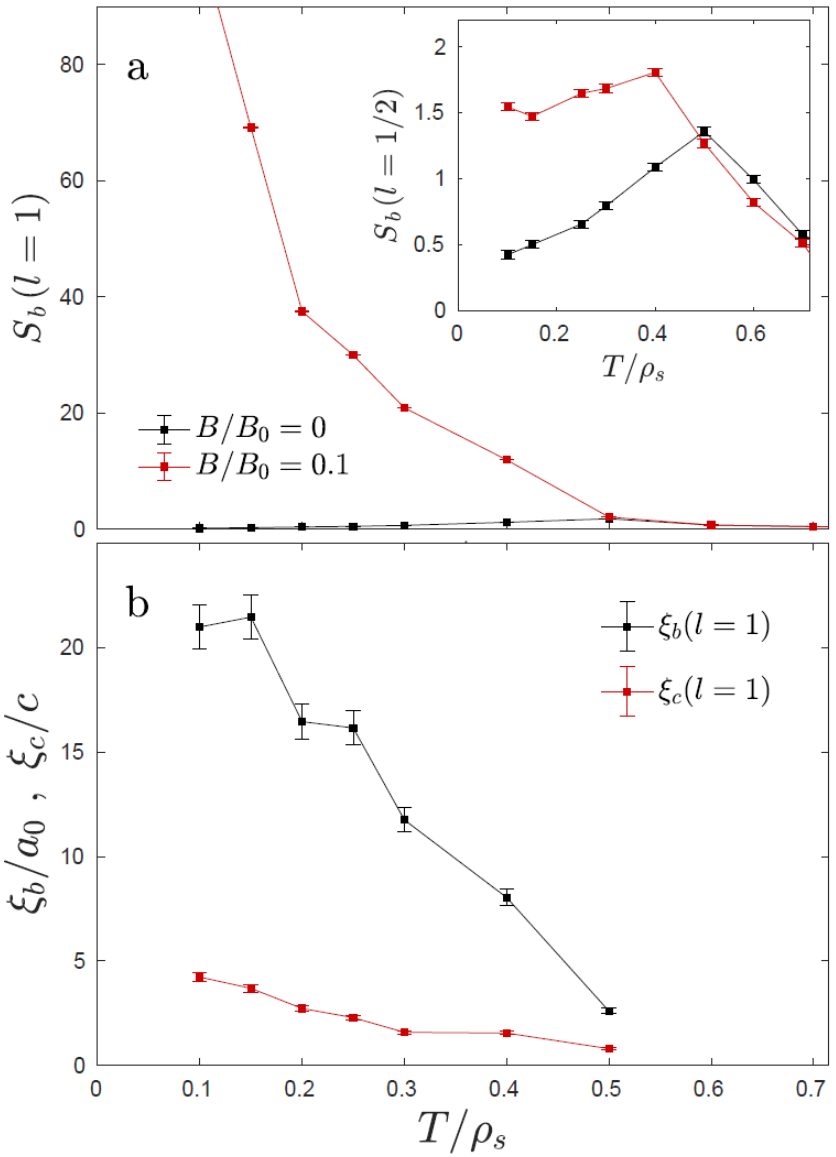


Jang *et al.* (PNAS 2016)

T-dependence

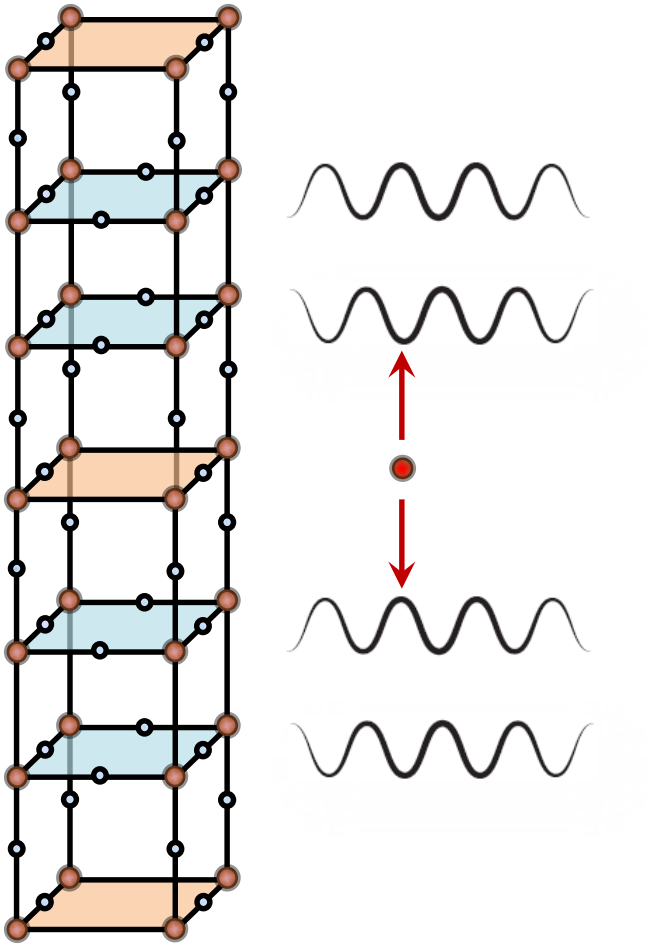
Chang *et al*. (Nat. Phys. 2012)





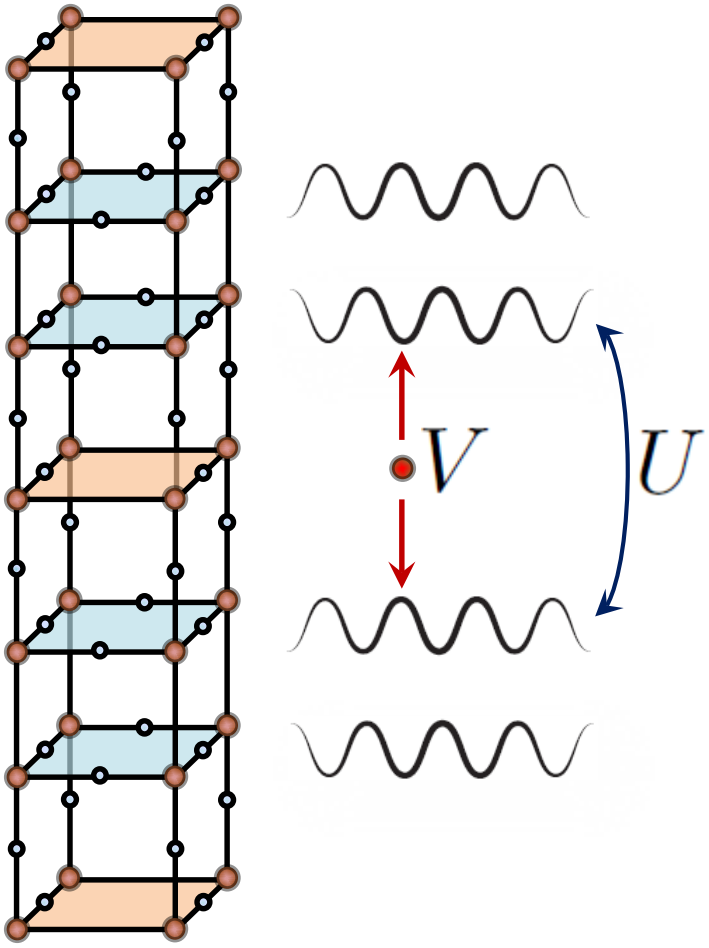
Jang *et al*. (PNAS 2016)

Transition to long-range order



	Disorder	
	Chain	Plane
Typical energy gain	$L^{d/2-1}$	$L^{d/2}$
Domain wall energy	L^{d-2}	L^{d-2}
Lower critical dimension	2	4

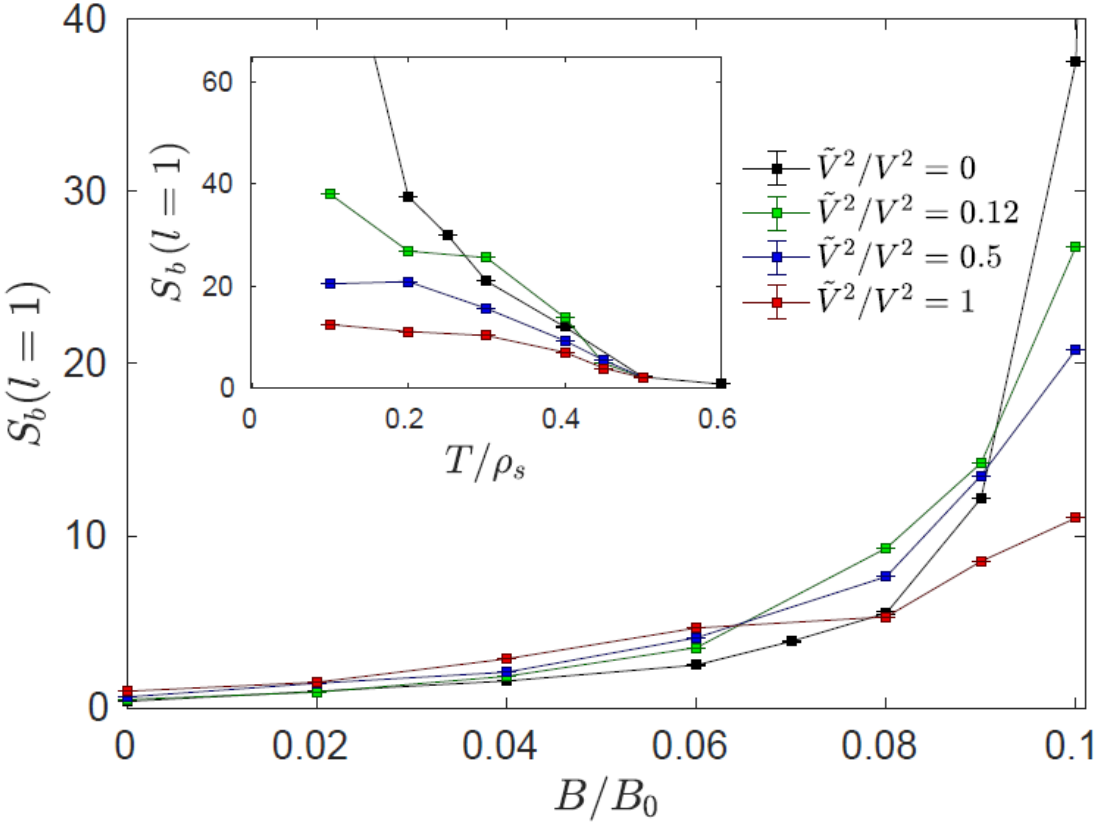
Transition to long-range order



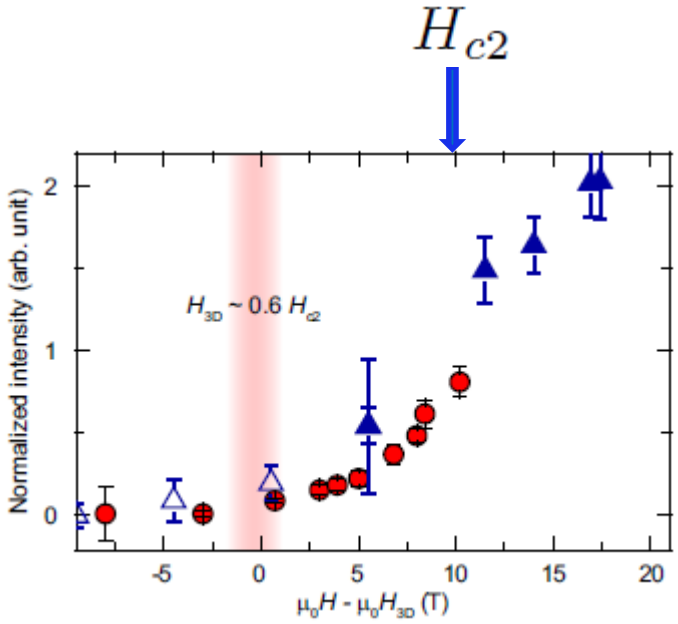
$$\frac{T_{CDW}}{\rho_s} = \kappa r_0^2 \sqrt{tU} - \frac{V^2}{2U}$$

$$\frac{B_{CDW} r_0^2}{\phi_0} \approx \ln^{-2}\left[\kappa^2 r_0^2 U \left(\frac{2U}{V^2}\right)^2\right]$$

Effects of in-plane disorder

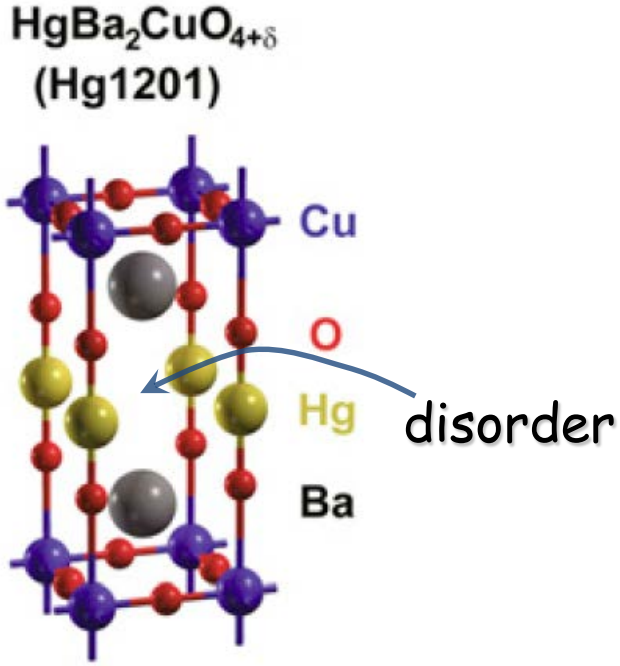


Consequences



Jang *et al*. (PNAS 2016)

Signs for local SC in ortho-VIII YBCO above H_{c2}



Low-field correlations should broadly peak near integer l.

At high fields should move to half-integer l

Questions and answers

- Are the two orders distinct or related ?
- Both are manifestations of the same CDW, and compete with SC.

- Do they microscopically coexist or do they phase separate ?
- They exist in distinct regions. The longer-range order appears around vortices.

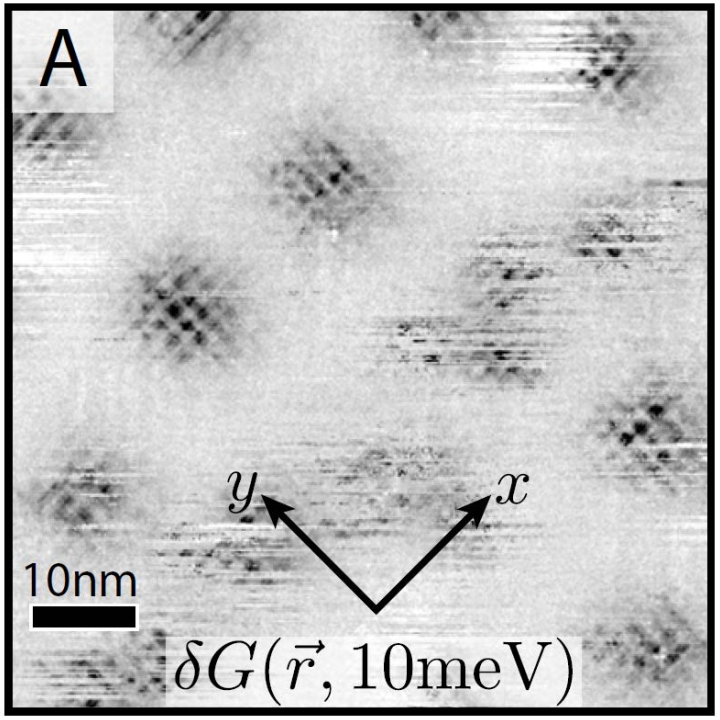
- What is the source of their different *c*-axis correlations ?
- The bilayer structure of YBCO and the conflicting ordering conditions set by the disorder and the Coulomb interaction.

- Why is the l=1/2 order bidirectional and the l=1 unidirectional ?
- The slight anisotropy induced by the chains hardly affects the weak l=1/2 correlations but suffices to orient the stronger l=1 order.

- Is a transition to true long-range order expected at higher fields ?
- Almost. Weak plane disorder turns it into a sharp crossover.

STM on BSCCO 2212

B= 8.5 T



Hamidian *et al*. (arXiv 2015)