Properties of valence-bond stripes in cuprates

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Matthias Vojta
(Köln)

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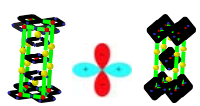
	Oliver Rösch
	Alexander Wollny
Santa Barbara:	Ribhu Kaul
Rolla:	Thomas Vojta

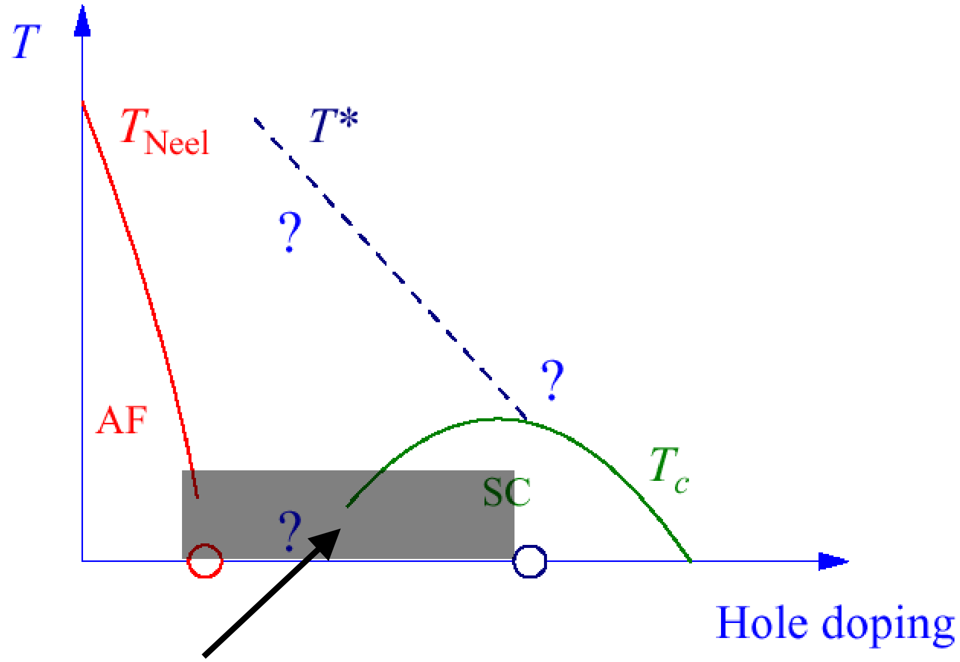
Deutsche Forschungsgemeinschaft DFG

SFB 608



Santa Barbara, June 2009

Conservative cuprate phase diagram



Stripes, dominated by **bond order** and competing with superconductivity.

1. **Valence-bond stripes, neutrons & STM**

   Stripes co-exist with nodal quasiparticles below T_c

2. **Fermi surface reconstruction and Nernst effect**

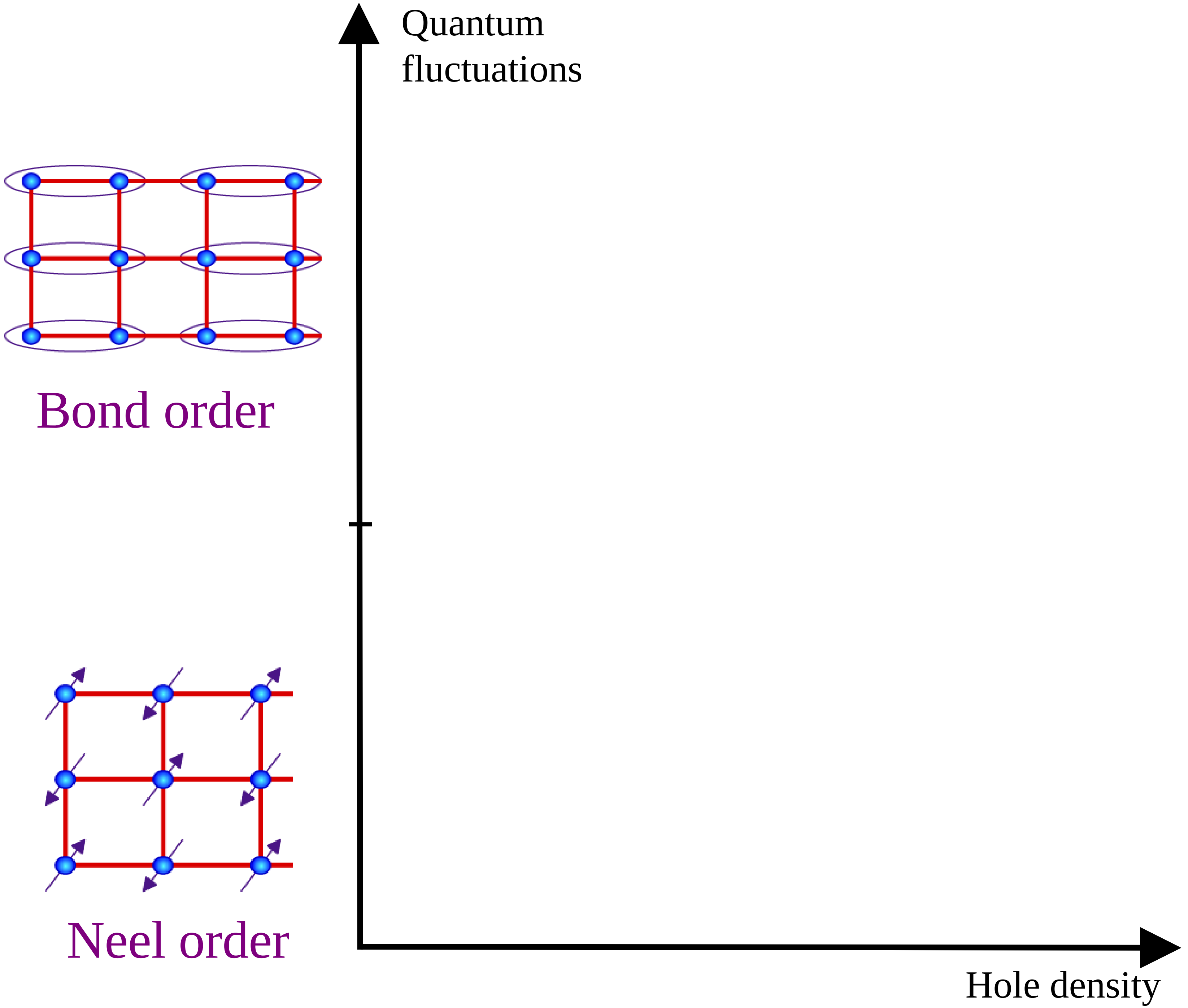
   Low-temperature Nernst effect from stripes

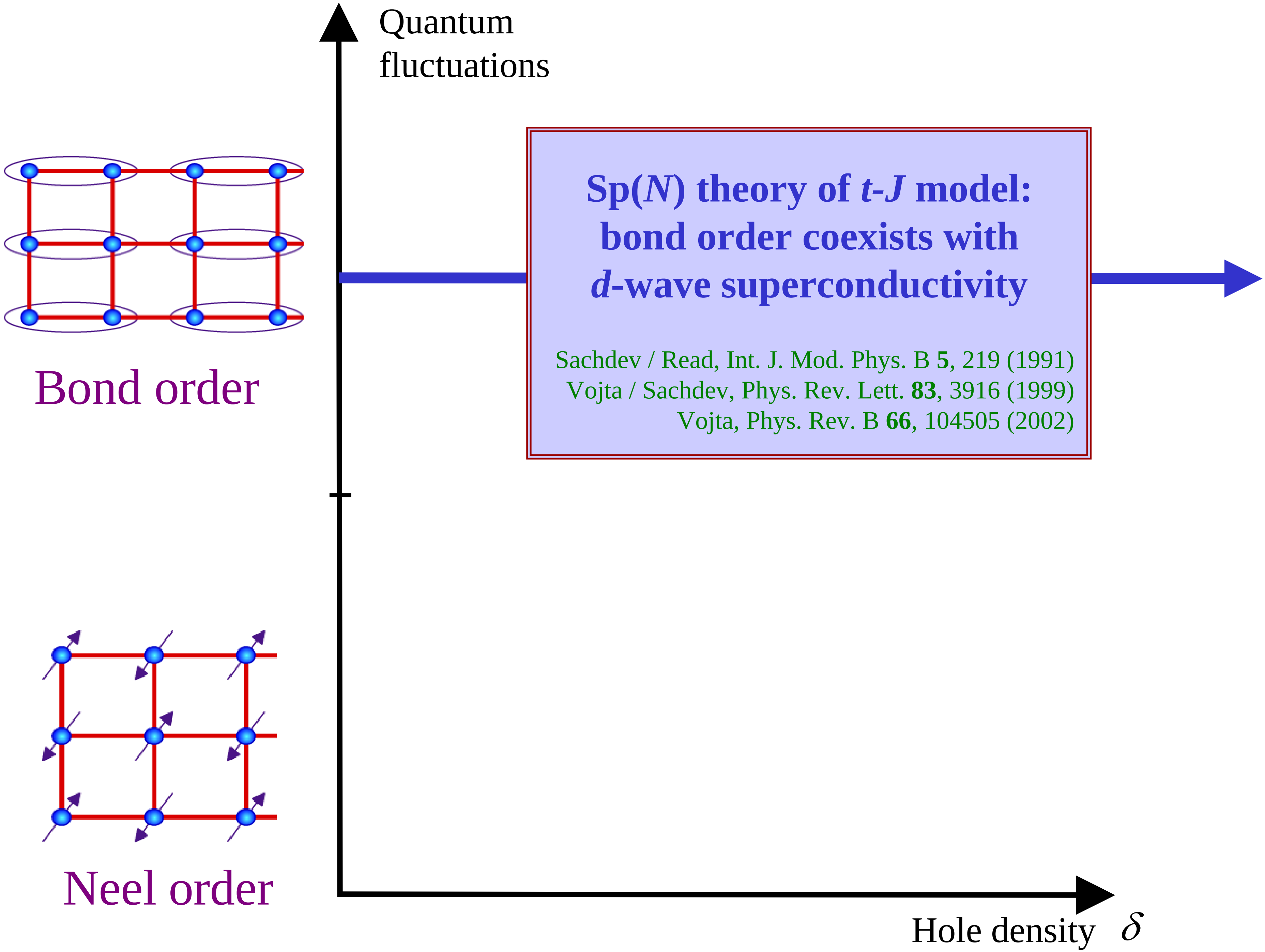
3. **Interlayer Josephson tunneling**

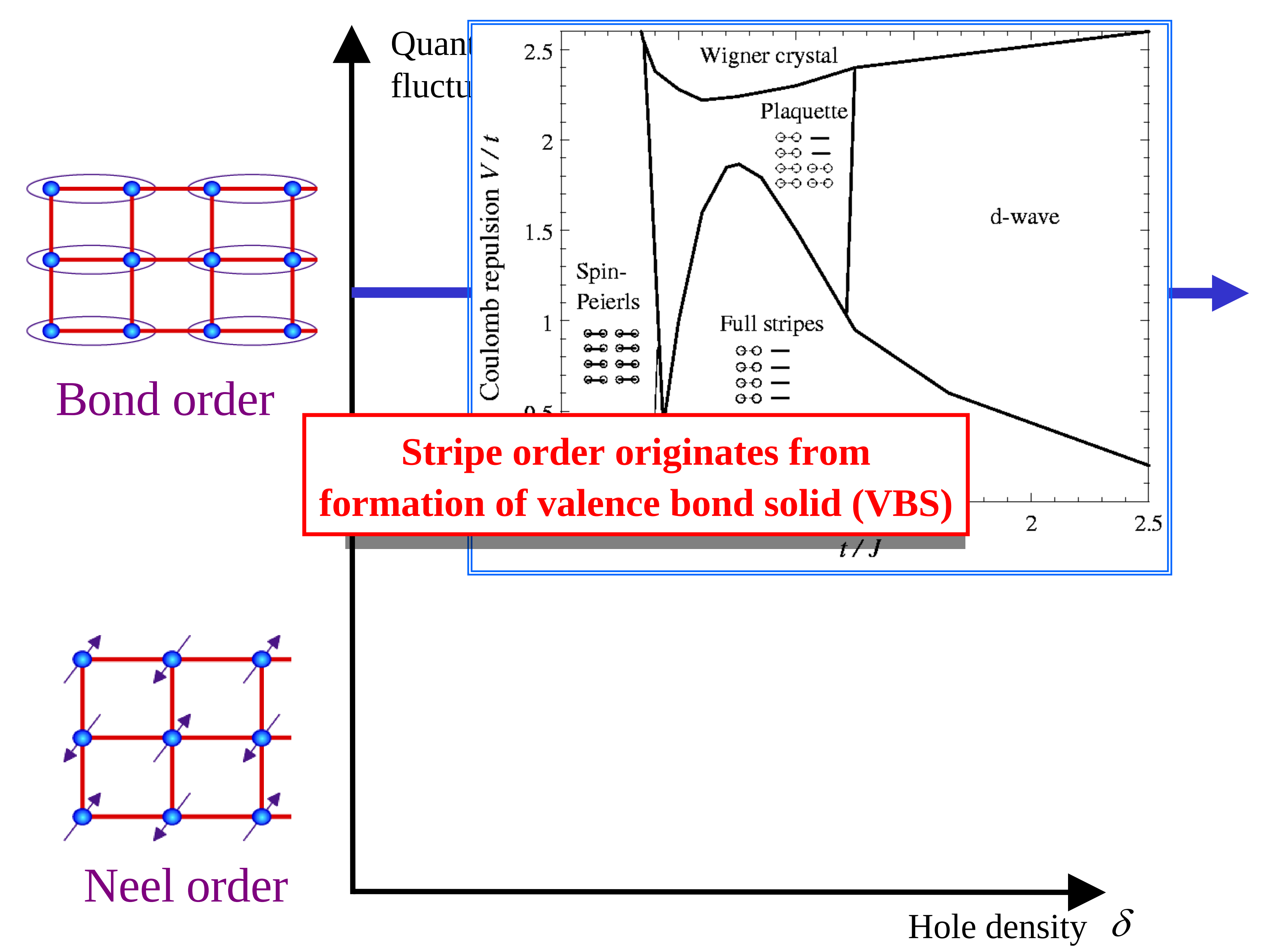
   Could a uniform condensate be compatible with quasi-2d pairing?

Stripy review: arXiv:0901.3145
To appear in Adv. Phys.

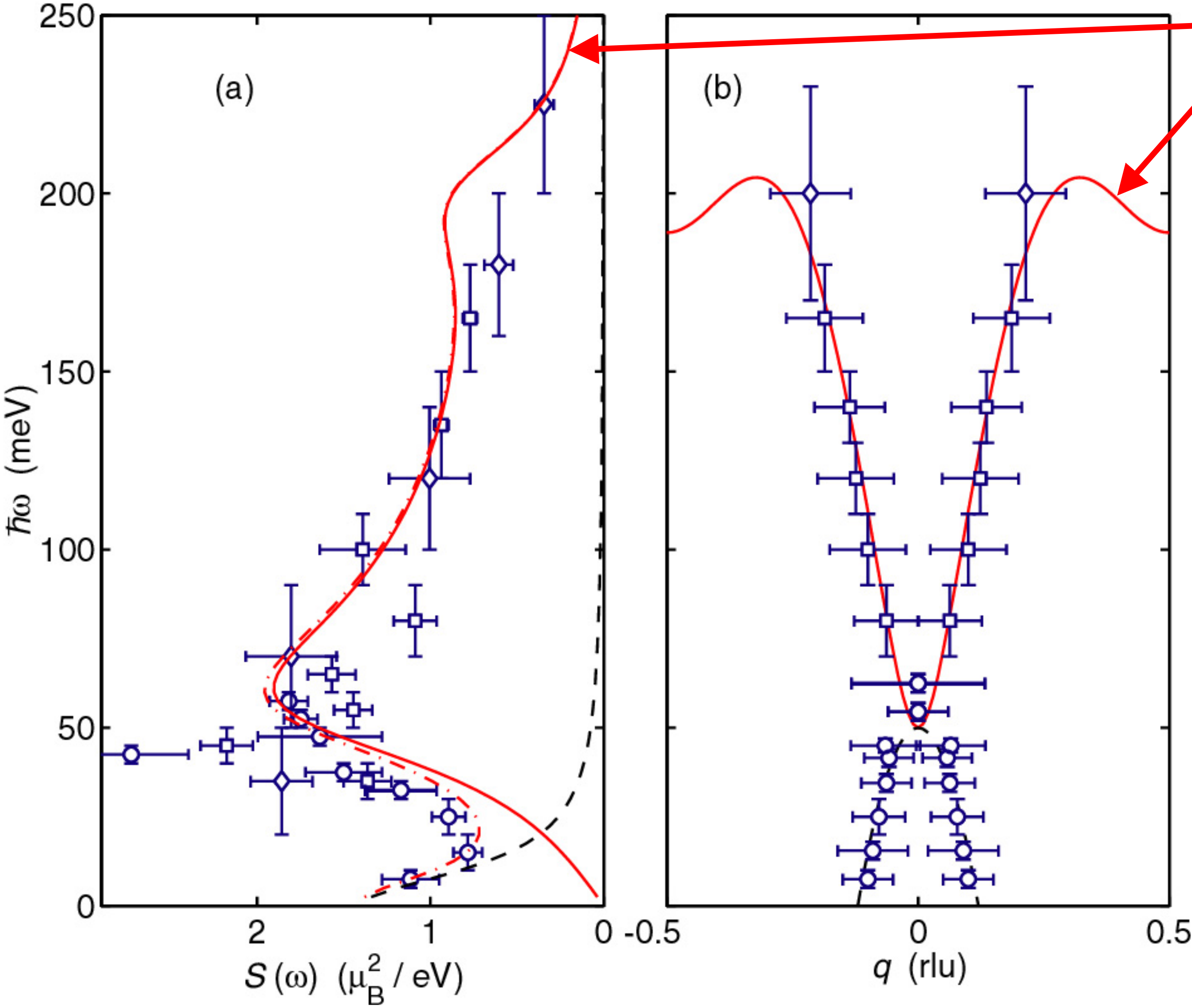
Valence-bond stripes


Quantum
fluctuations
Bond order
Neel order
Hole density

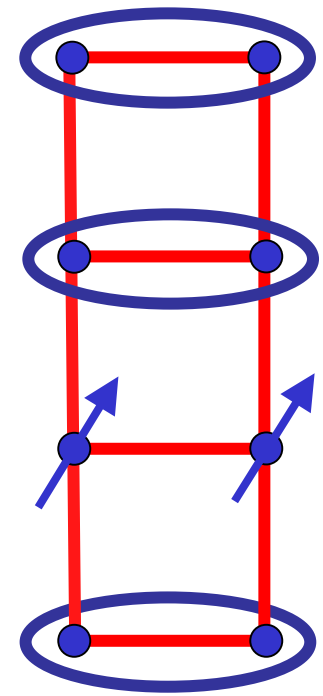

Quantum fluctuations
Sp(N) theory of t-J model: bond order coexists with d-wave superconductivity
Sachdev / Read, Int. J. Mod. Phys. B 5, 219 (1991)
Vojta / Sachdev, Phys. Rev. Lett. 83, 3916 (1999)
Vojta, Phys. Rev. B 66, 104505 (2002)
Bond order
Neel order
Hole density δ


Quant
fluctu
Wigner crystal
Plaquette
d-wave
Spin-
Peierls
Full stripes
Coulomb repulsion V / t
2.5
2
1.5
1
2
2.5
t / J
Bond order
Neel order
Hole density δ
Stripe order originates from
formation of valence bond solid (VBS)

$La_{15/8}Ba_{1/8}CuO_4$: Neutron scattering

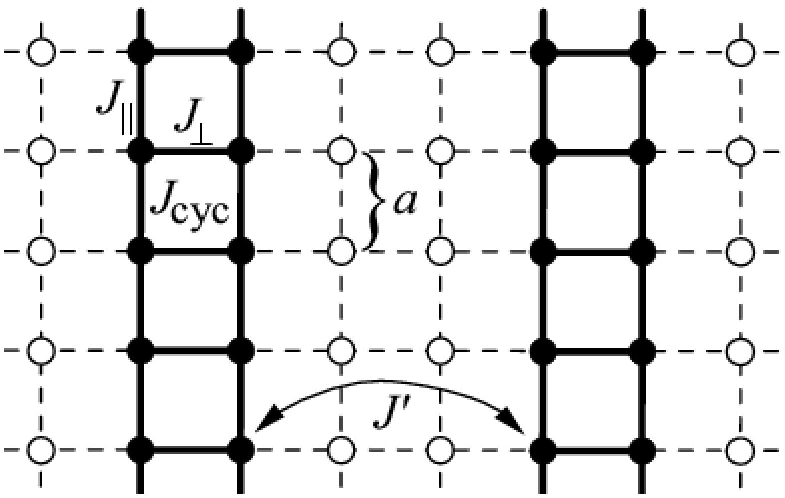


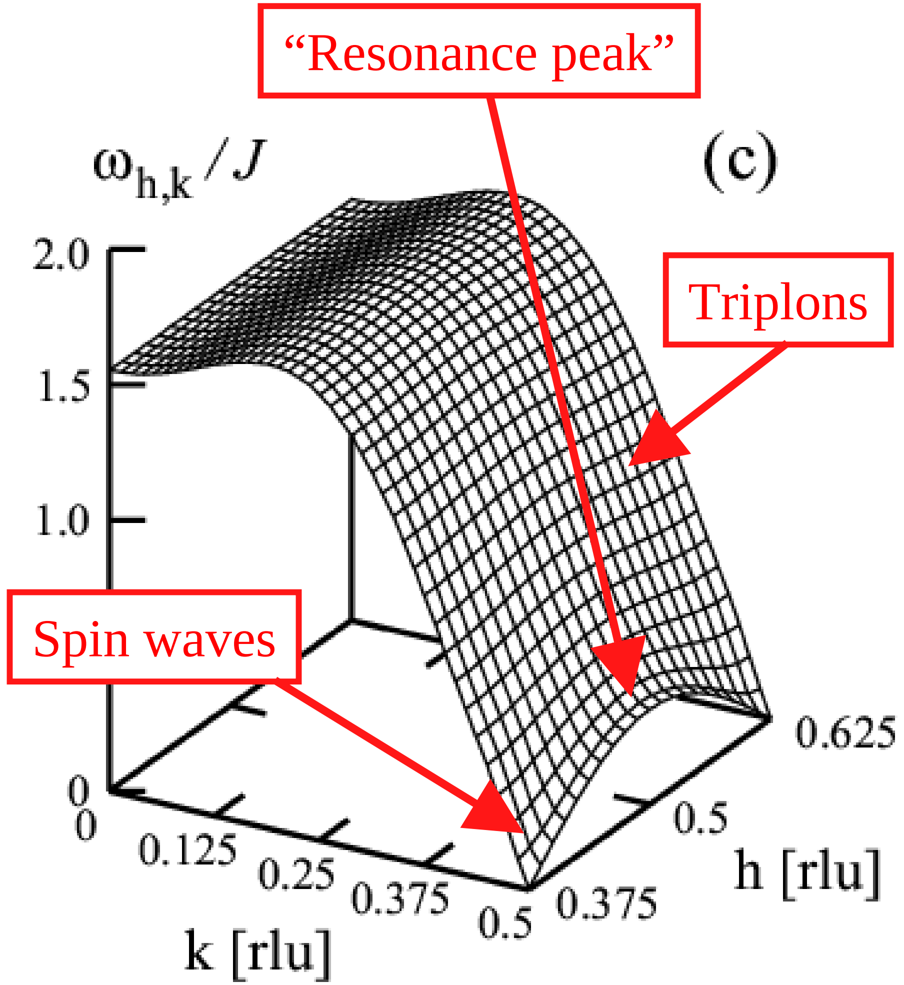
Red lines: triplon excitation of a 2 leg ladder with exchange *J*=100 meV



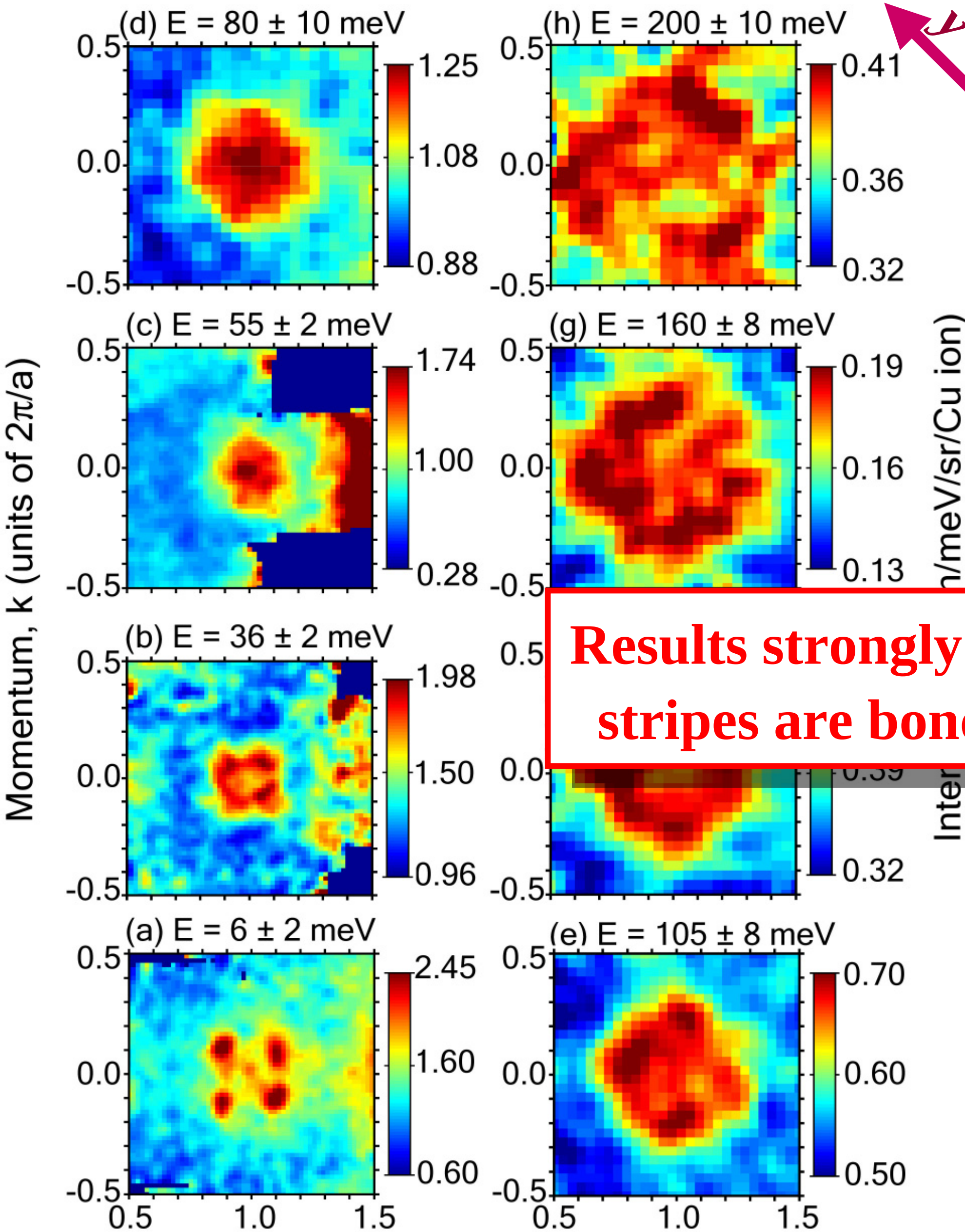
Tranquada *et al*, Nature **429**, 534 (2004)

Minimal model: Coupled spin ladders



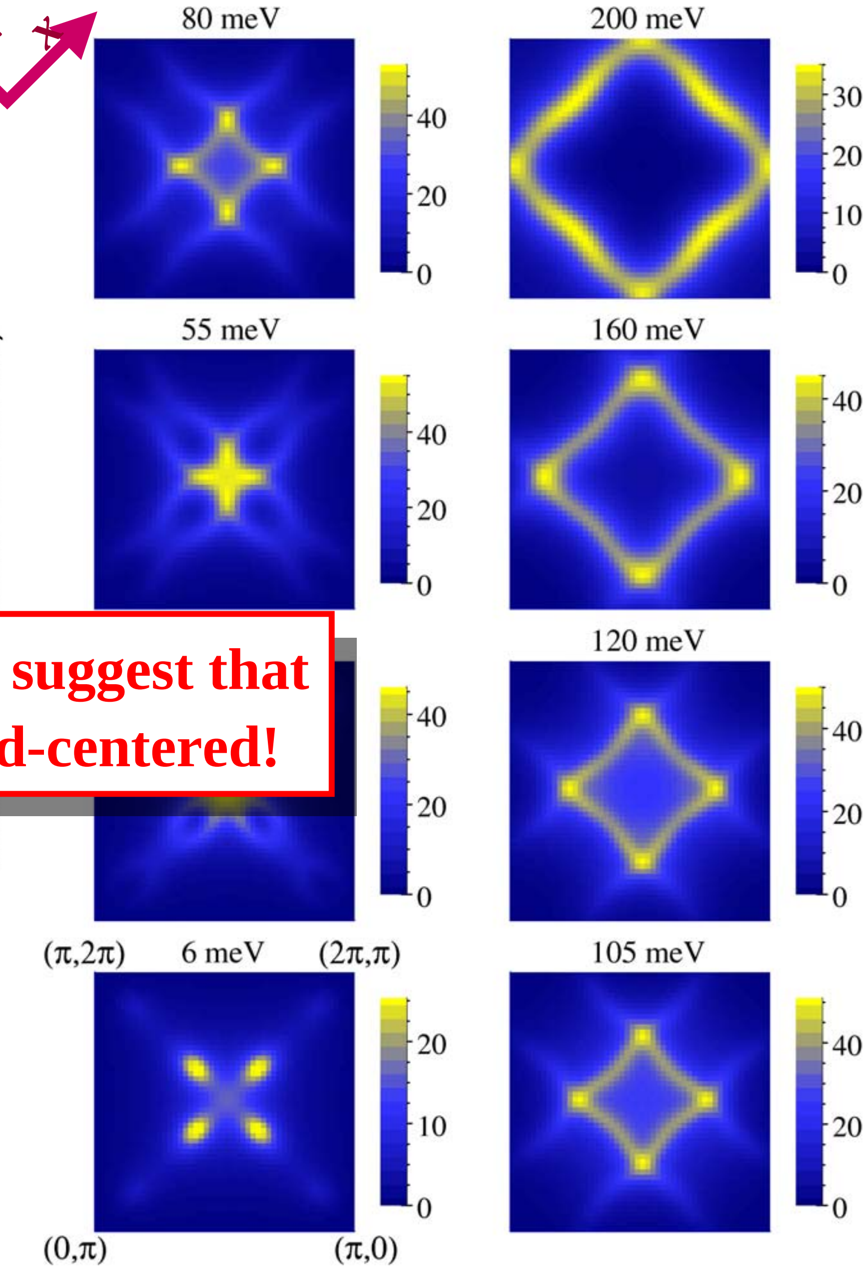


Vojta / Ulbricht, PRL **93**, 127002 (2004)
Uhrig *et al.*, PRL **93**, 183004 (2004)
Vojta / Sachdev, JPCS **67**, 11 (2006)



Results strongly suggest that stripes are bond-centered!

J. M. Tranquada *et al.*, Nature **429**, 534 (2004)



Bond operator theory of coupled-ladder model,
M. Vojta and T. Ulbricht, PRL **93**, 127002 (2004)

What about fluctuating stripes?

Spin excitations in a dynamically fluctuating stripe phase

Spin fluctuations near (π,π) described by φ^4 theory on a lattice:

$$\mathcal{S}_0 = \int d\tau \sum_j \left[\frac{1}{2} \left(\frac{\partial \varphi_{j\alpha}}{\partial \tau} \right)^2 + \frac{s}{2} \varphi_{j\alpha}^2 + \frac{u}{4} \left(\varphi_{j\alpha}^2 \right)^2 \right] + \int d\tau \sum_{\langle jj' \rangle} \frac{c^2}{2} \left(\varphi_{j\alpha} - \varphi_{j'\alpha} \right)^2$$

coupled to local charge density Q:

$$\mathcal{S}_x = \int d\tau \sum_j \Big[\lambda_1 Q_x(\mathbf{r}_j) \varphi_{j\alpha}^2 + \lambda_2 Q_x(\mathbf{r}_{j+x/2}) \varphi_{j\alpha} \varphi_{j+x,\alpha} + \lambda_3 Q_x(\mathbf{r}_j) \varphi_{j-x,\alpha} \varphi_{j+x,\alpha} + \lambda_4 Q_x(\mathbf{r}_{j+y/2}) \varphi_{j\alpha} \varphi_{j+y,\alpha} \Big]$$

Q is parametrized as

$$Q_x(\mathbf{r}) = \phi_x(\mathbf{r}) e^{i\mathbf{K}_x \cdot \mathbf{r}} + \phi_x^*(\mathbf{r}) e^{-i\mathbf{K}_x \cdot \mathbf{r}}$$

Static charge order: ϕ = const

Vojta / Sachdev, JPCS **67**, 11 (2006)

Vojta / Vojta / Kaul, PRL **97**, 097001 (2006)

Spin excitations in a dynamically fluctuating stripe phase

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$$\mathcal{S}_x = \int d\tau \sum_j \Big[\lambda_1 Q_x(\mathbf{r}_j)\varphi_{j\alpha}^2 + \lambda_2 Q_x(\mathbf{r}_{j+x/2})\varphi_{j\alpha}\varphi_{j+x,\alpha} + \lambda_3 Q_x(\mathbf{r}_j)\varphi_{j-x,\alpha}\varphi_{j+x,\alpha} + \lambda_4 Q_x(\mathbf{r}_{j+y/2})\varphi_{j\alpha}\varphi_{j+y,\alpha} \Big]$$

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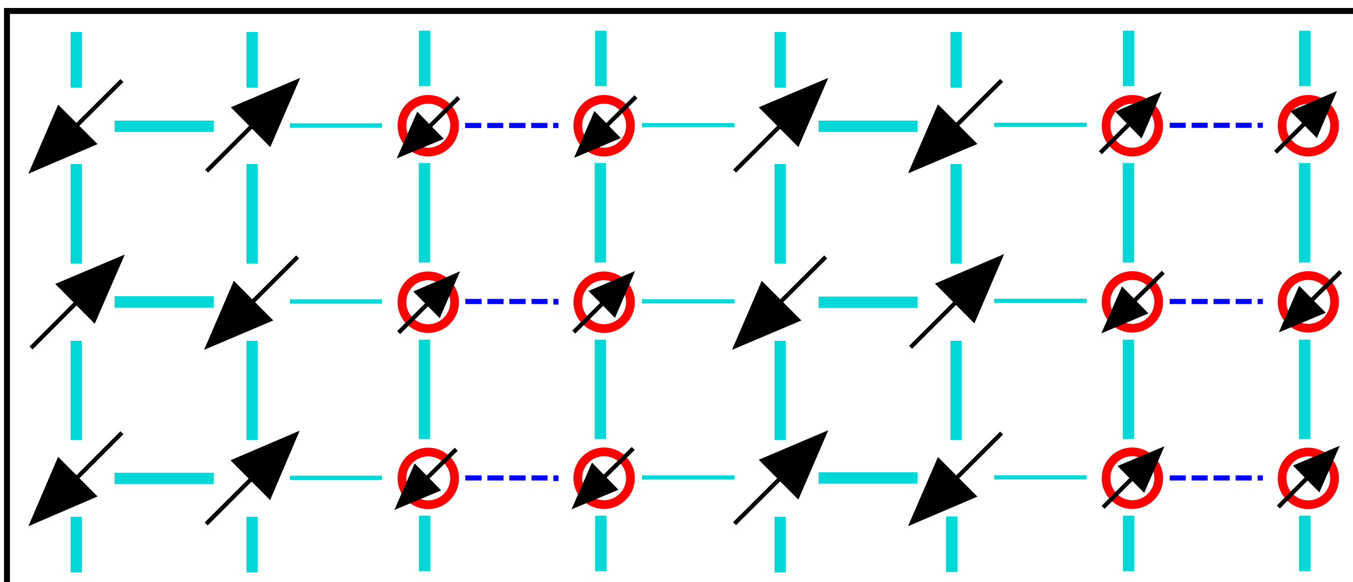
$$Q_x(\mathbf{r}) = \phi_x(\mathbf{r}) e^{i\mathbf{K}_x \cdot \mathbf{r}} + \phi_x^*(\mathbf{r}) e^{-i\mathbf{K}_x \cdot \mathbf{r}}$$



67, 11 (2006)
Vojta / Vojta / Kaul, PRL 97, 097001 (2006)

Spin excitations in a dynamically fluctuating stripe phase

Spin fluctuations near (π,π) described by φ[4] theory on a lattice:

$$\mathcal{S}_0 = \int d\tau \sum_j \left[\frac{1}{2} \left(\frac{\partial \varphi_{j\alpha}}{\partial \tau} \right)^2 + \frac{s}{2} \varphi_{j\alpha}^2 + \frac{u}{4} \left(\varphi_{j\alpha}^2 \right)^2 \right] + \int d\tau \sum_{\langle jj' \rangle} \frac{c^2}{2} \left(\varphi_{j\alpha} - \varphi_{j'\alpha} \right)^2$$

coupled to local charge density *Q*:

$$\mathcal{S}_x = \int d\tau \sum_j \left[\lambda_1 Q_x(\mathbf{r}_j) \varphi_{j\alpha}^2 + \lambda_2 Q_x(\mathbf{r}_{j+x/2}) \varphi_{j\alpha} \varphi_{j+x,\alpha} + \lambda_3 Q_x(\mathbf{r}_j) \varphi_{j-x,\alpha} \varphi_{j+x,\alpha} + \lambda_4 Q_x(\mathbf{r}_{j+y/2}) \varphi_{j\alpha} \varphi_{j+y,\alpha} \right]$$

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Static charge order: ϕ = const

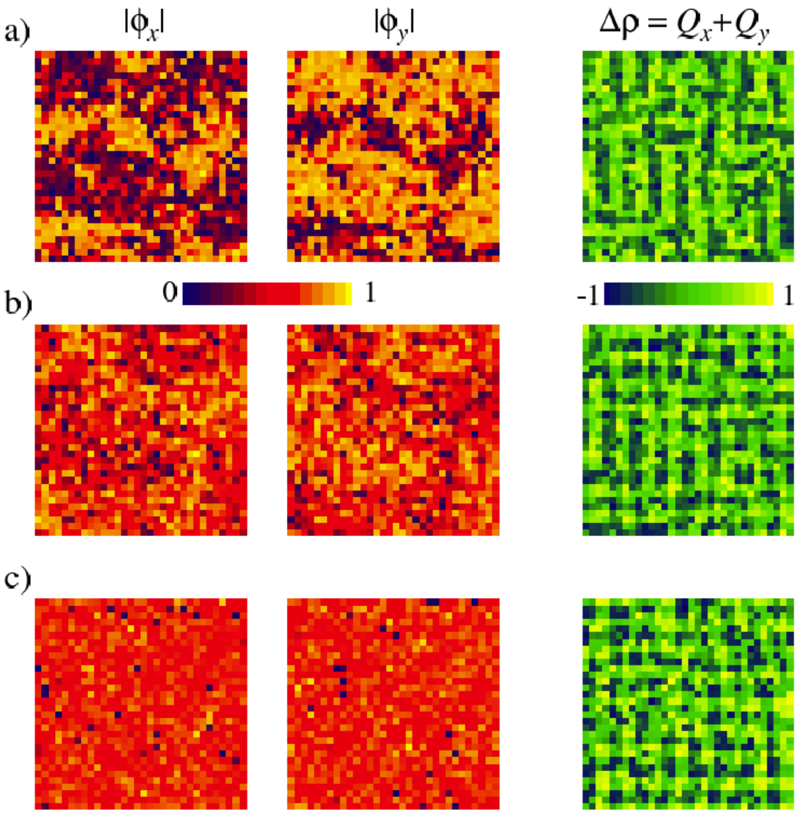
Fluctuating charge order:

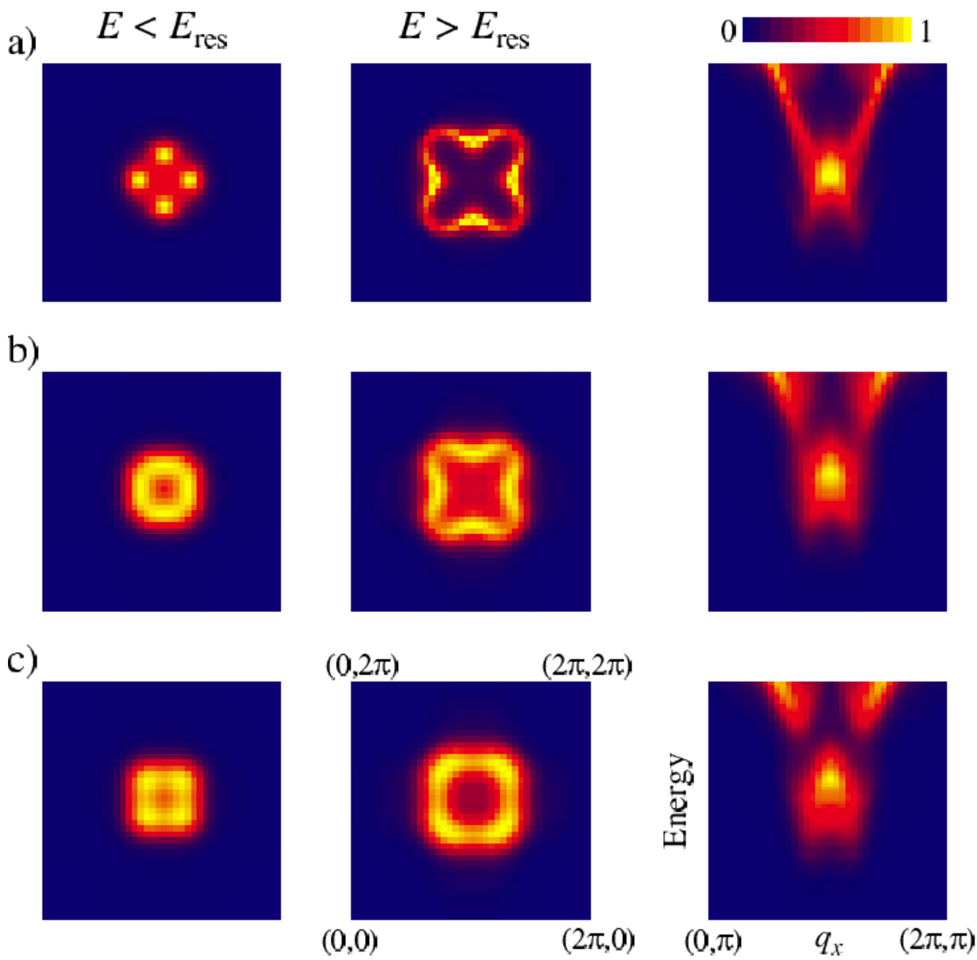
$$\mathcal{S}_\phi = \int d\tau d^2\mathbf{r} \Big[|\partial_\tau \phi_x|^2 + |\partial_\tau \phi_y|^2 + c_1^2 |\partial_x \phi_x|^2 + c_2^2 |\partial_y \phi_x|^2 + c_1^2 |\partial_y \phi_y|^2 + c_2^2 |\partial_x \phi_y|^2 + i\delta \phi_x^* \partial_x \phi_x + i\delta \phi_y^* \partial_y \phi_y + s_1 \left(|\phi_x|^2 + |\phi_y|^2 \right) + u_1 \left(|\phi_x|^4 + |\phi_y|^4 \right) + v |\phi_x|^2 |\phi_y|^2 + w \left(\phi_x^4 + \phi_x^{*4} + \phi_y^4 + \phi_y^{*4} \right) \Big]$$

Decides between stripes and checkerboard!

Vojta / Sachdev, JPCS **67**, 11 (2006)
Vojta / Vojta / Kaul, PRL **97**, 097001 (2006)

Spin excitations in a dynamically fluctuating stripe phase

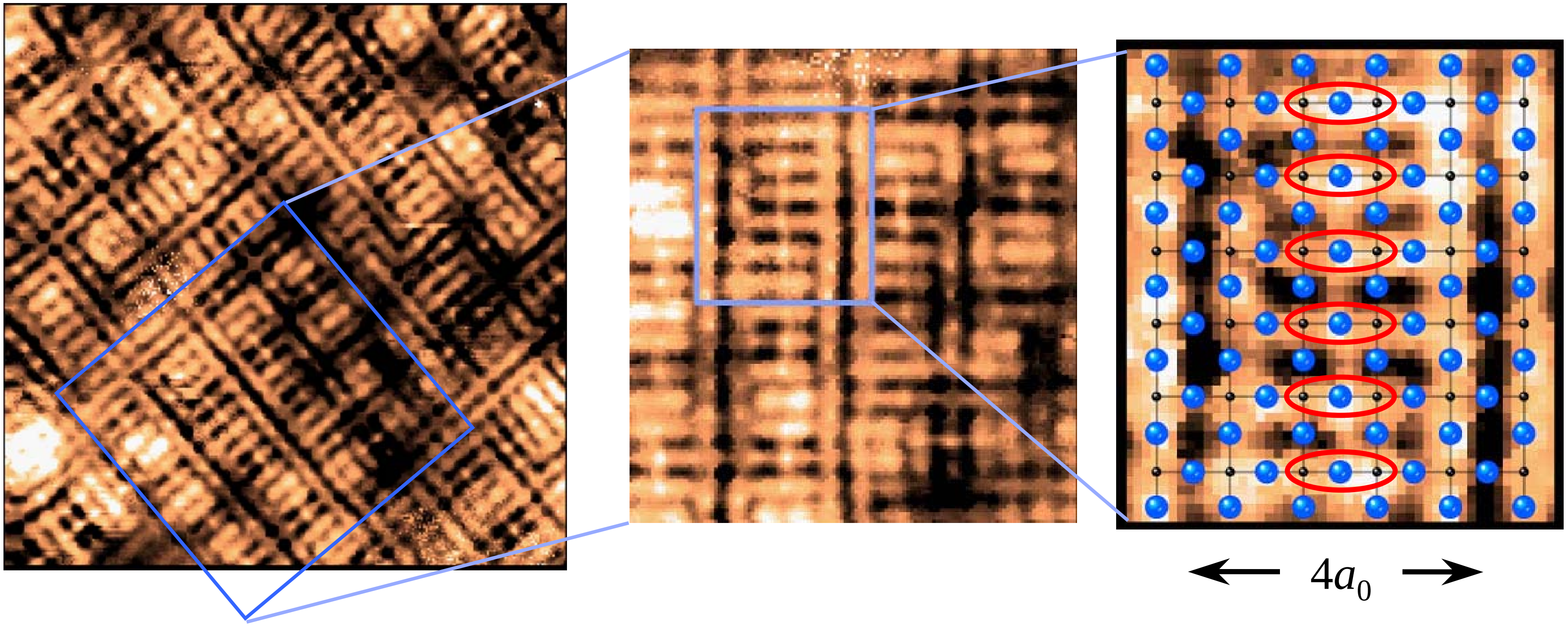




Vojta / Vojta / Kaul, PRL **97**, 097001 (2006)

STM: Local static order in superconducting state

R map (asymmetry) at 150 meV

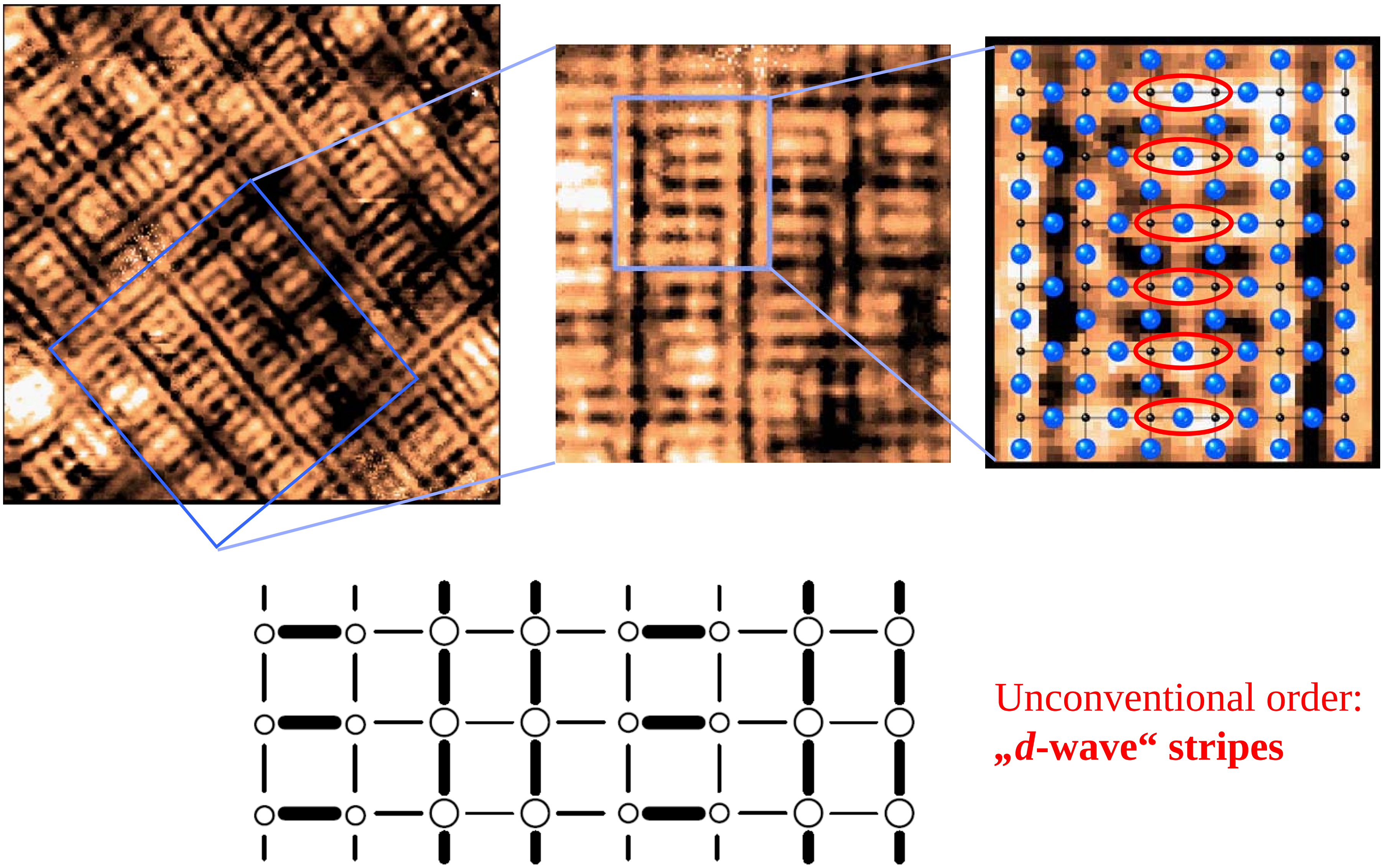


Period-4 nanodomains with contrast on Cu-Cu bonds:

Valence bond solid (glassy)

Kohsaka et al., Science **315,** 1380 (2007)

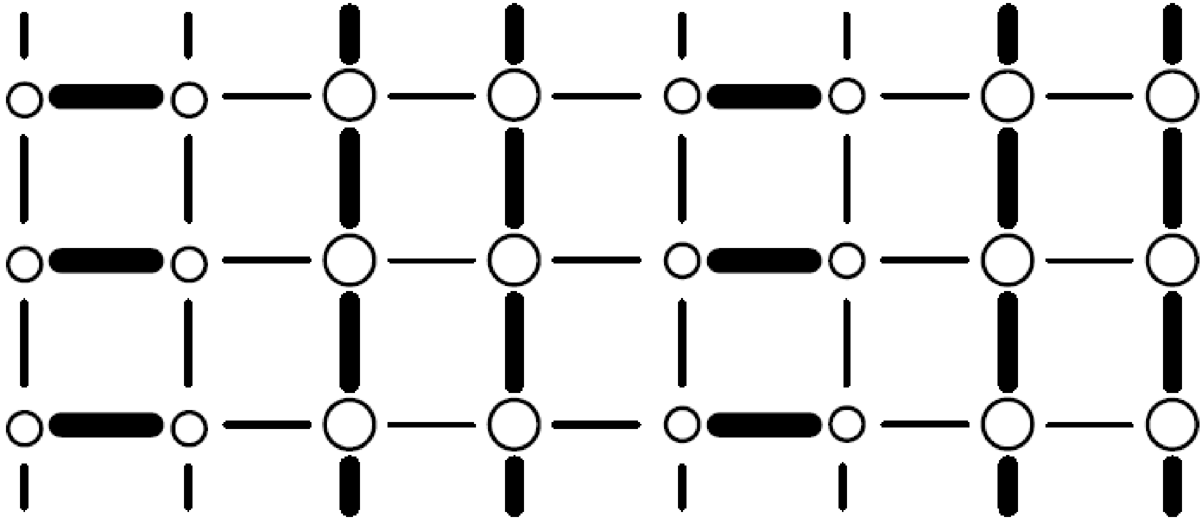
Order has stripe character!



Unconventional order:
„*d*-wave" stripes

Vojta / Rösch, PRB **77**, 094504 (2008)

„*d*-wave“ stripes



$\phi_1(\mathbf{k}) = \langle c_{\mathbf{k}\uparrow} c_{-\mathbf{k}\downarrow} \rangle$ Homogeneous pairing

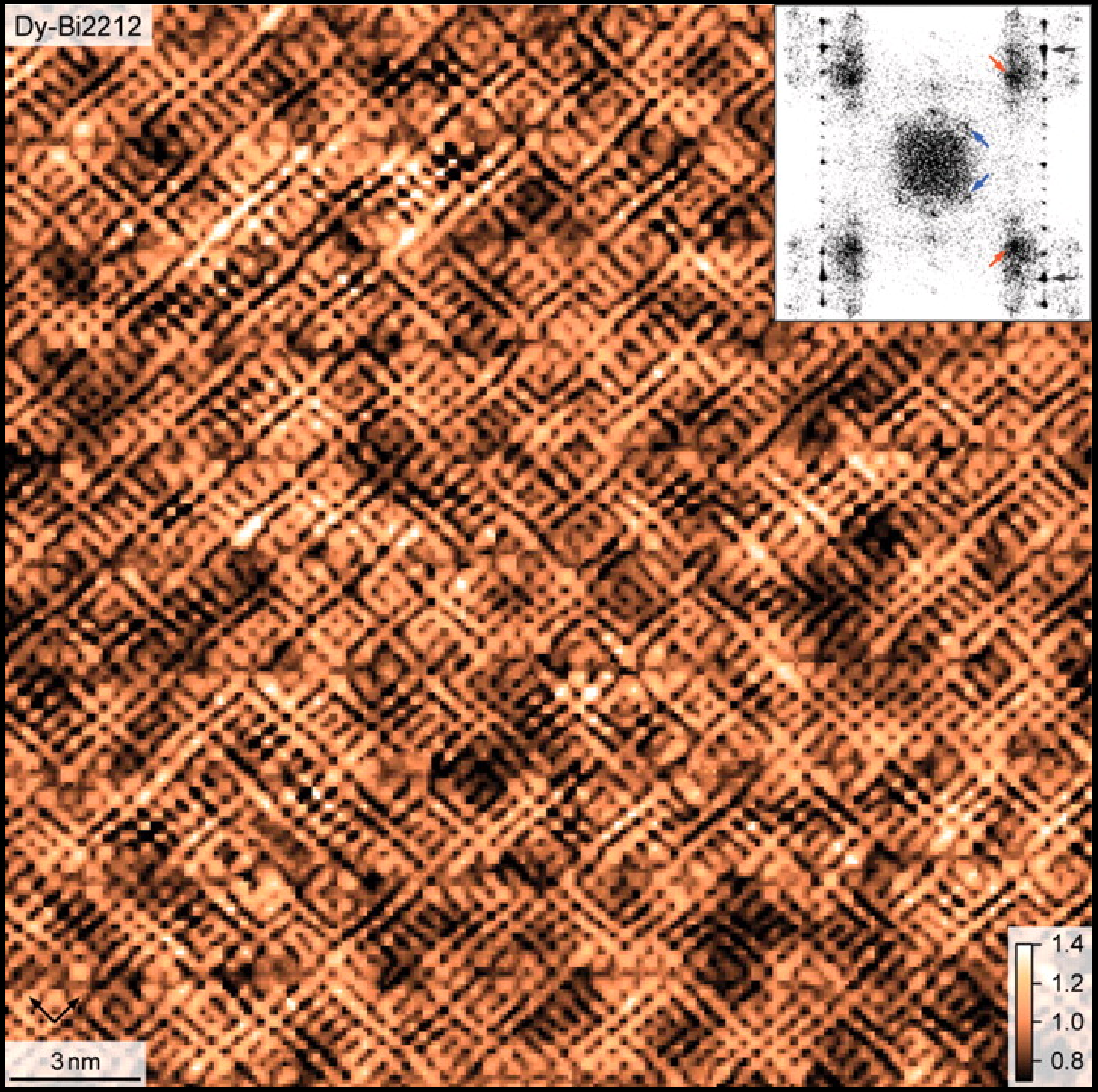
$\phi_2(\mathbf{k}) = \langle c^\dagger_{\mathbf{k}+\mathbf{Q},\sigma} c_{\mathbf{k}\sigma} \rangle$ Charge/bond modulation $\sim \cos k_x - \cos k_y$

$\phi_3(\mathbf{k}) = \langle c_{\mathbf{k}+\mathbf{Q},\uparrow} c_{-\mathbf{k}\downarrow} \rangle$ Modulated pairing (FFLO)

Vojta / Rösch, PRB **77**, 094504 (2008)

Order is static, but short-ranged (random field pinning).

Order coexists with well-defined low-energy quasiparticles.



Monte-Carlo simulation of short-range ordered bond-centered *d*-wave stripes

Homogeneous *d*-wave superconductor:

$$\mathcal{H}_0 = \sum_{\mathbf{k}} (\epsilon_{\mathbf{k}} - \mu) c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \Delta_{\mathbf{k}} (c_{\mathbf{k}\uparrow} c_{-\mathbf{k}\downarrow} + h.c.)$$

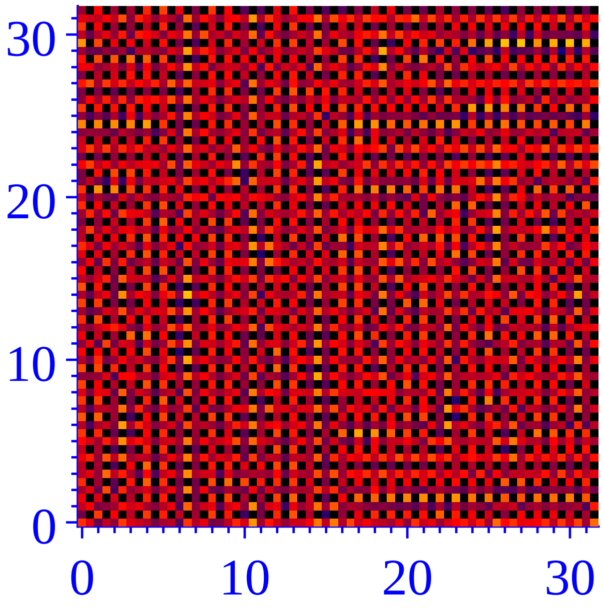
coupled to local „charge density“ order parameter *Q*:

$$\mathcal{H}_x = \sum_i \kappa_1 Q_x(\mathbf{r}_i) c^\dagger_{i\sigma} c_{i\sigma} + \kappa_2 Q_x(\mathbf{r}_i + x/2) c^\dagger_{i\sigma} c_{i+x,\sigma} + \kappa_3 Q_x(\mathbf{r}_i + y/2) c^\dagger_{i\sigma} c_{i+y,\sigma}$$
$$+ \kappa_4 Q_x(\mathbf{r}_i + x/2)(c_{i\uparrow} c_{i+x,\downarrow} + h.c.) + \kappa_5 Q_x(\mathbf{r}_i + y/2)(c_{i\uparrow} c_{i+y,\downarrow} + h.c.)$$

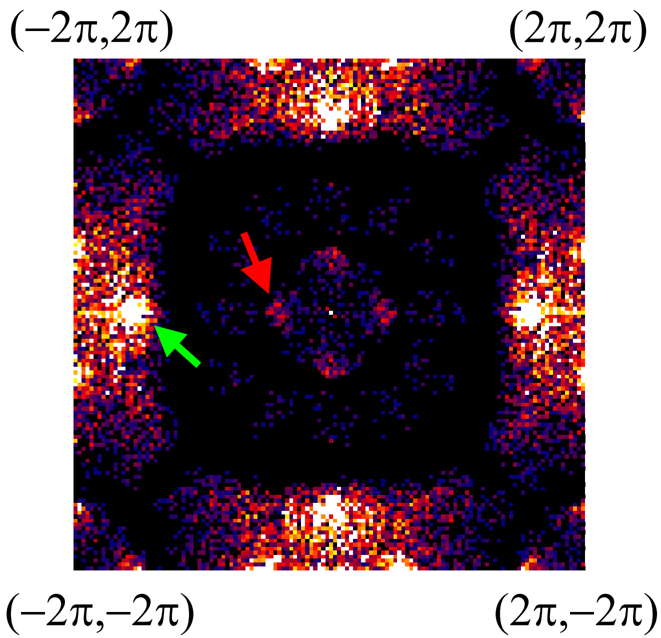
Vojta, PRB **78**, 144508 (2008)

Monte-Carlo simulation of short-range ordered bond-centered *d*-wave stripes

Real-space density
(one run)

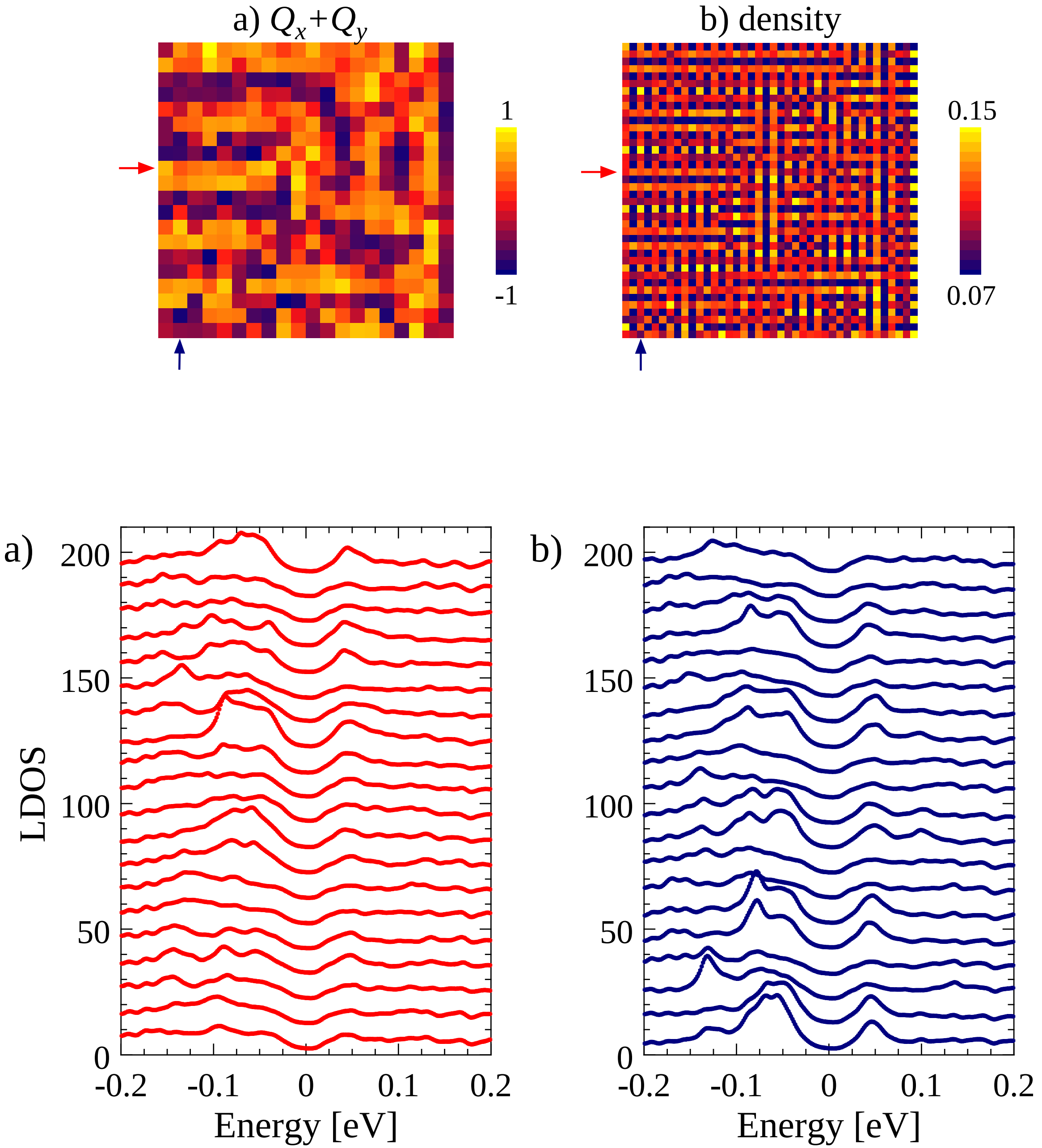


Fourier-transformed density
(config average)

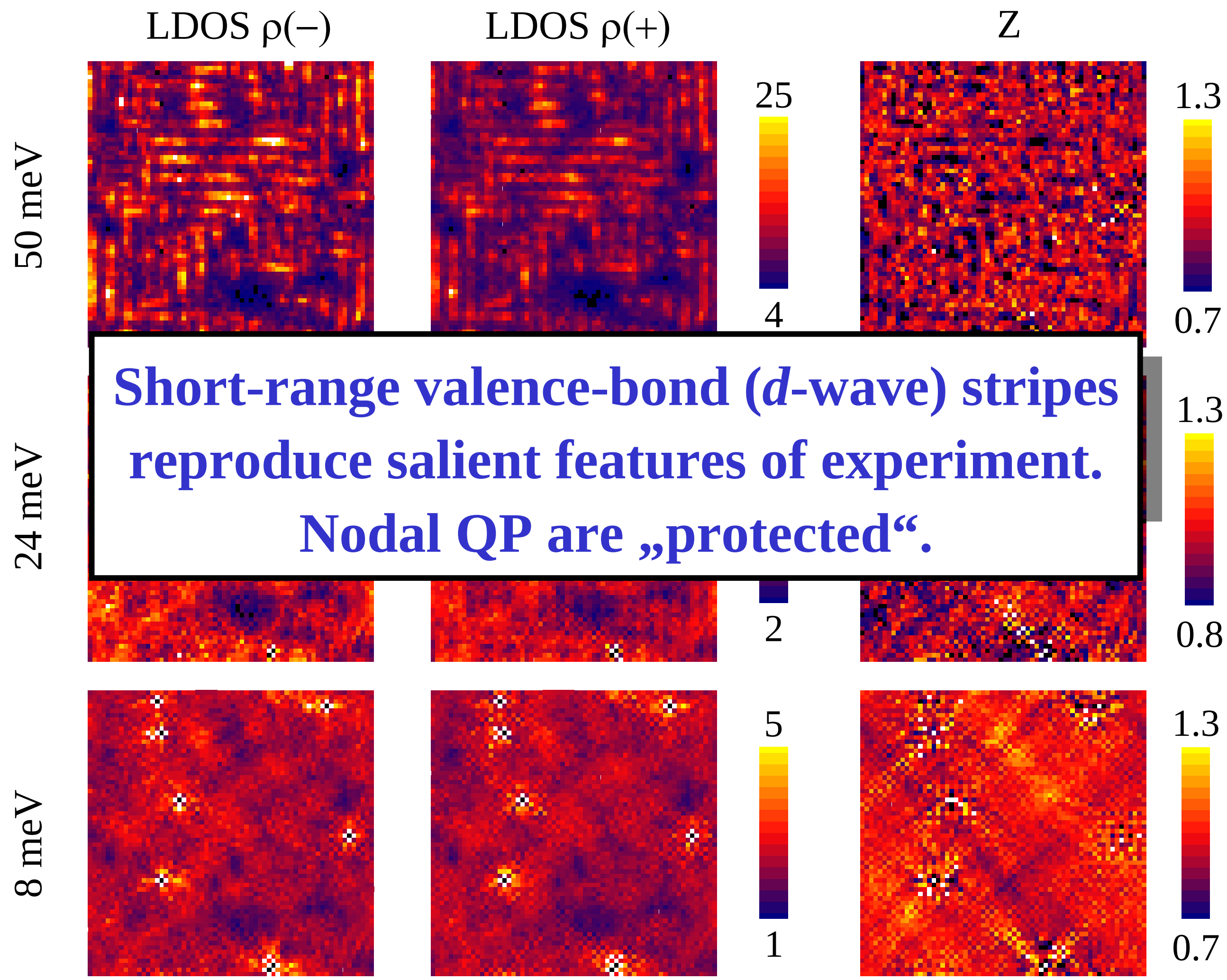


Vojta, PRB **78**, 144508 (2008)

LDOS spectra



Add impurities



Short-range valence-bond (*d*-wave) stripes reproduce salient features of experiment. Nodal QP are „protected“.

LDOS shows **quasiparticle interference** features at low energies (<< gap), but stripe signatures at high energies.

Vojta, PRB **78**, 144508 (2008)

Fermi-surface reconstruction
and Nernst effect

Vol 458 | 9 April 2009 | doi:10.1038/nature07931 nature

LETTERS

Enhancement of the Nernst effect by stripe order in a high-T_c superconductor

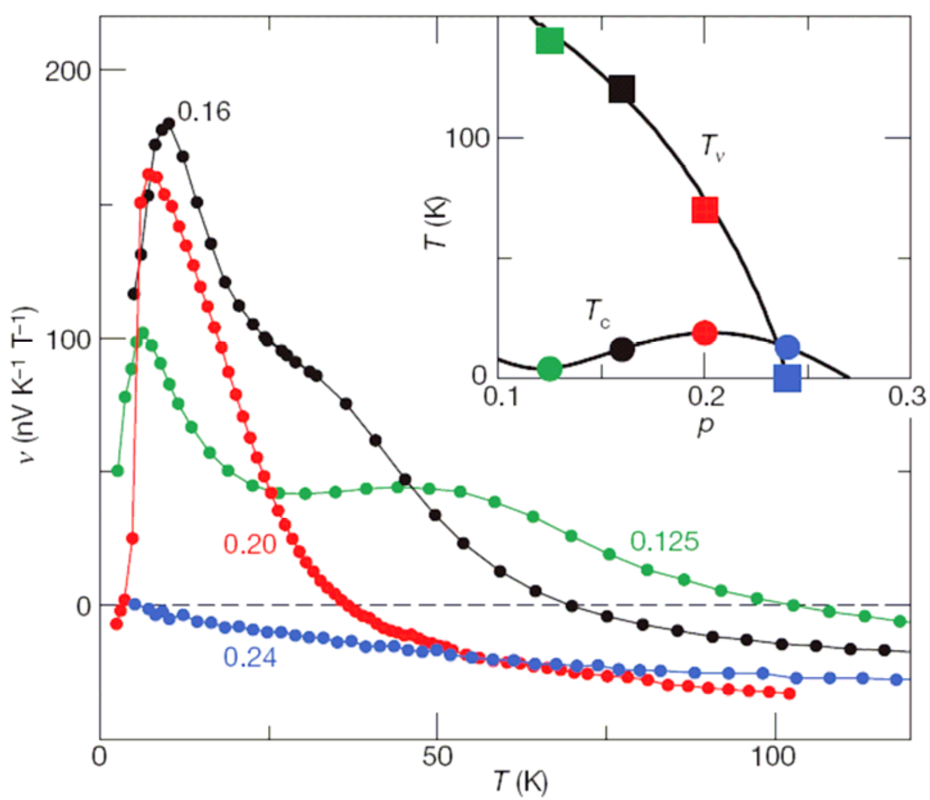
Olivier Cyr-Choinière[1]*, R. Daou[1]*, Francis Laliberté[1], David LeBoeuf[1], Nicolas Doiron-Leyraud[1], J. Chang[1], J.-Q. Yan[2]†, J.-G. Cheng[2], J.-S. Zhou[2], J. B. Goodenough[2], S. Pyon[3], T. Takayama[3], H. Takagi[3,4], Y. Tanaka[5,3] & Louis Taillefer[1,6]

Eu-LSCO
Nd-LSCO

Nernst signal shows two „peaks“:

1) Superconducting fluct at low *T*

2) Fermi surface reconstruction at higher *T*



Cyr-Choiniere *et al.*, Nature **458**, 743 (2009)

Mean-field/Boltzmann calculation

Mean-field stripe Hamiltonian (CDW+SDW)

Boltzmann equation for transport coefficients,
relaxation time approx. with *k*-independent τ (for impurity-dominated scattering)

Linear response
$$\begin{pmatrix} \vec{J} \\ \vec{Q} \end{pmatrix} \begin{pmatrix} \hat{\sigma} & \hat{\alpha} \\ T\hat{\alpha} & \hat{\kappa} \end{pmatrix} = \begin{pmatrix} \vec{E} \\ -\vec{\nabla} T \end{pmatrix}$$

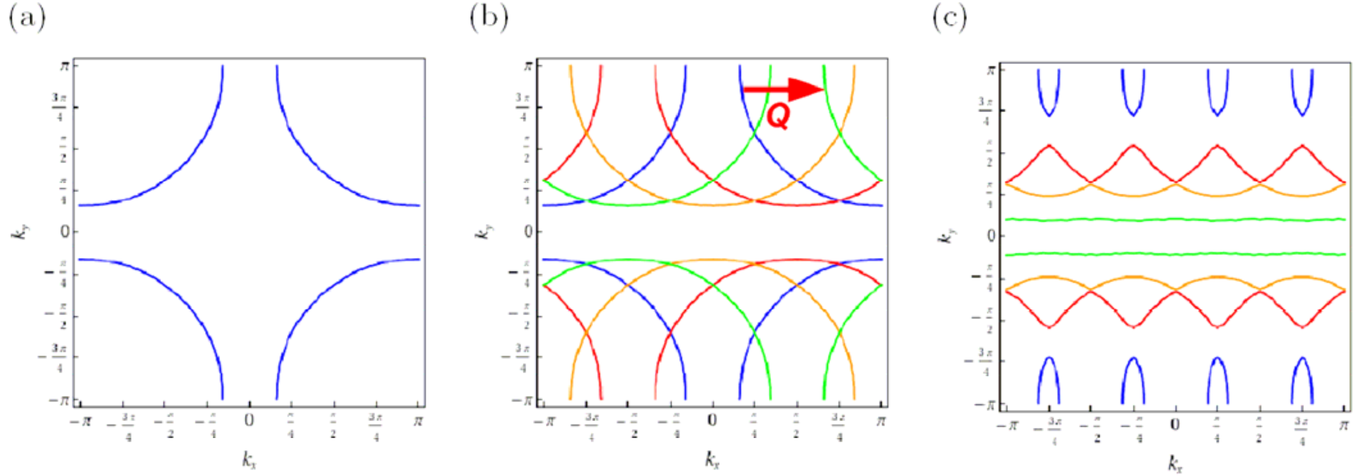
Nernst signal:
$$\vec{E} = -\hat{\vartheta} \nabla T$$
(no charge current, *B* field || z)

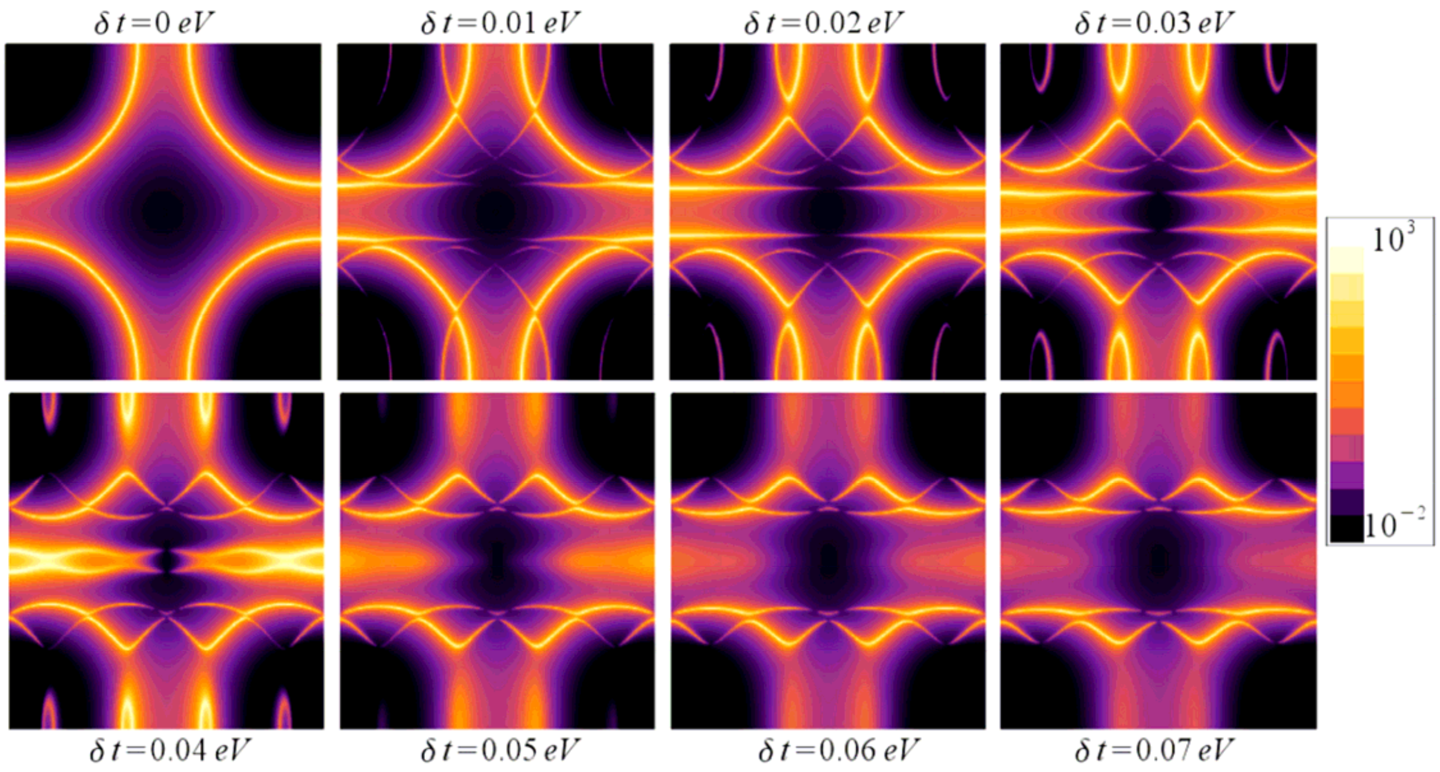
$$\vartheta_{yx} = -\frac{\sigma_{xx}\alpha_{yx} - \sigma_{yx}\alpha_{xx}}{\sigma_{xx}\sigma_{yy} - \sigma_{xy}\sigma_{yx}}$$

Nernst coefficient:
$$\nu = \vartheta_{yx}/B$$
(~*T* at low *T*)

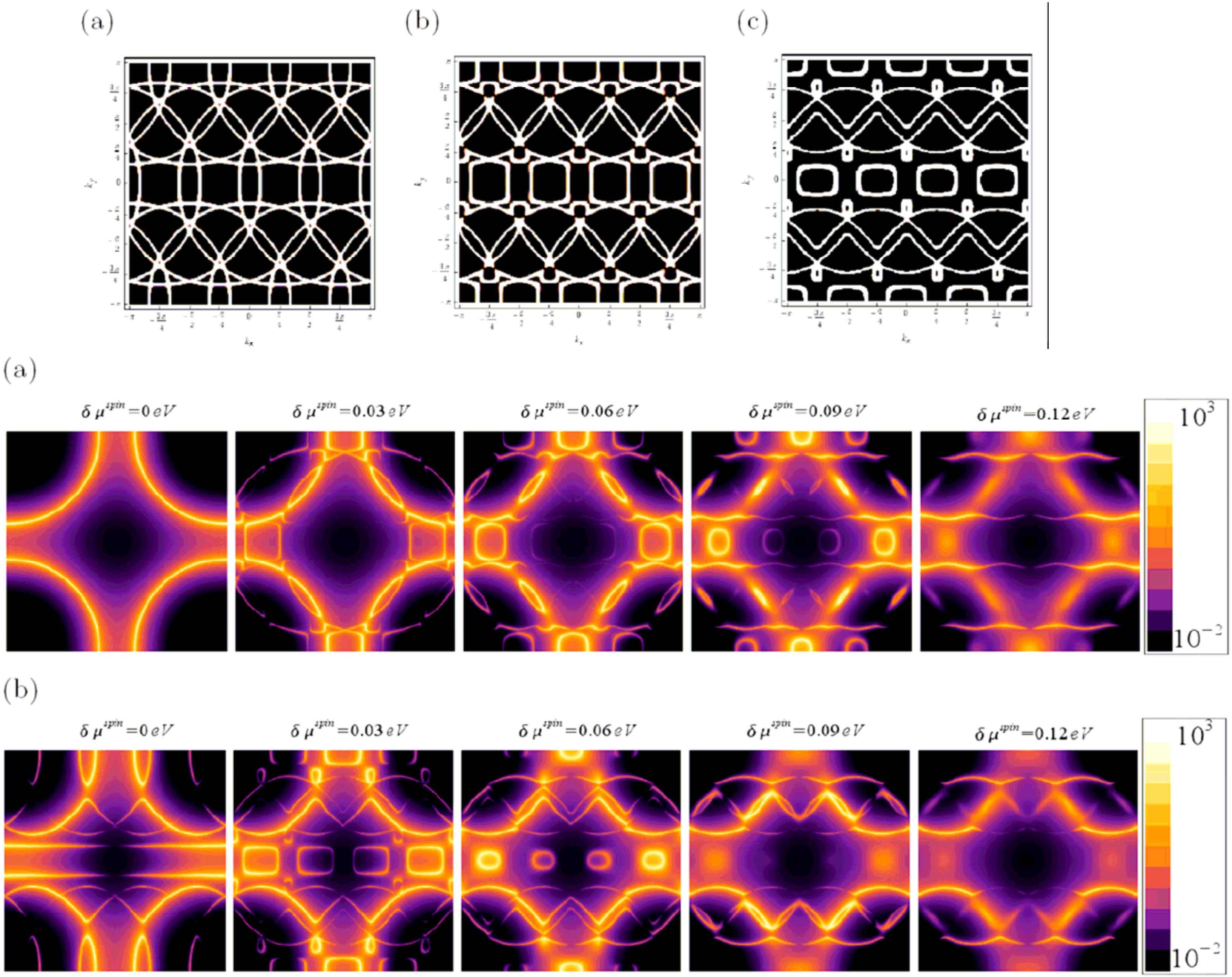
Hackl / Vojta / Sachdev, unpublished

Fermi surface reconstruction: CDW only (period 4)

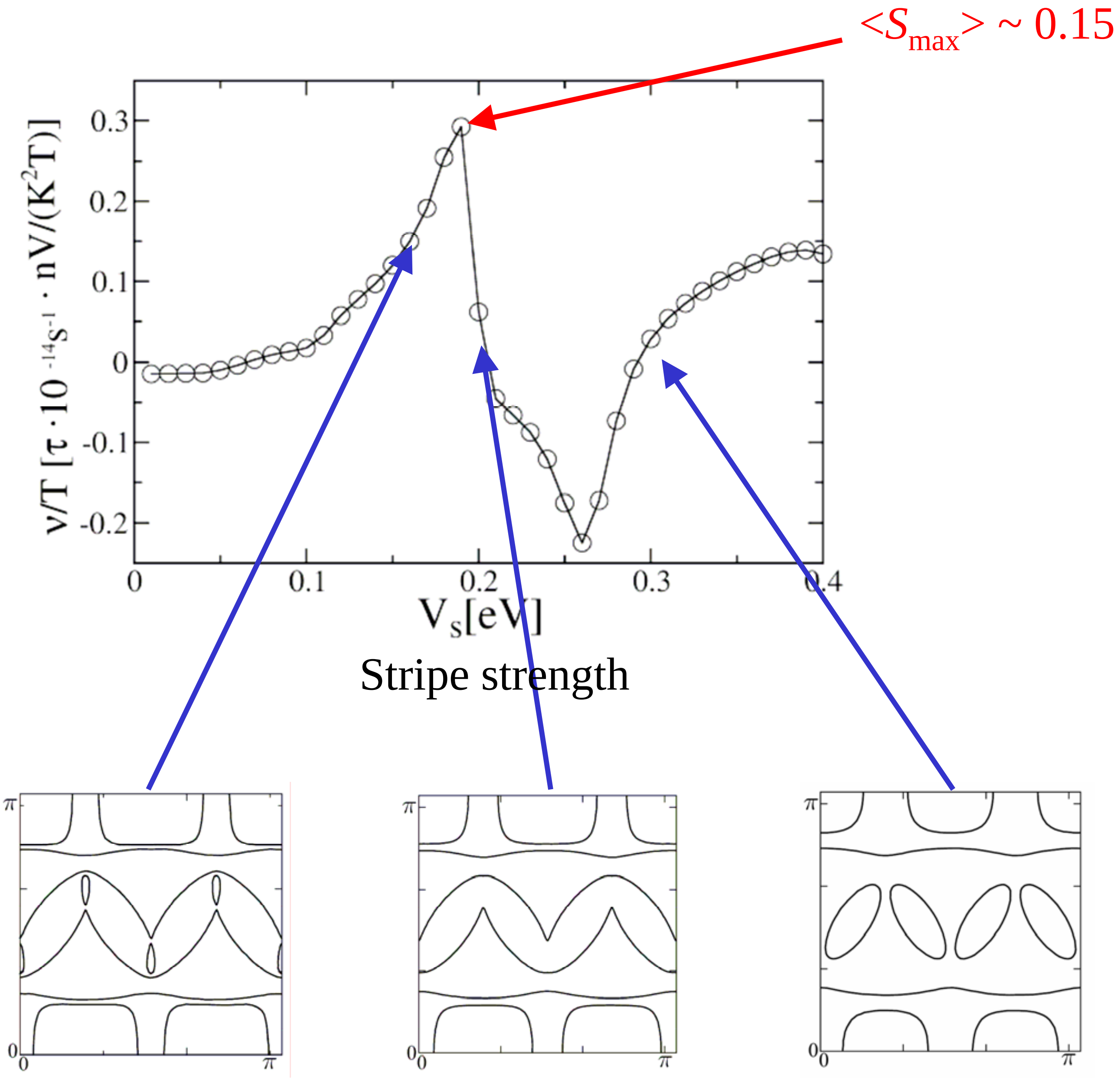




Fermi surface reconstruction: CDW + SDW (period 8)

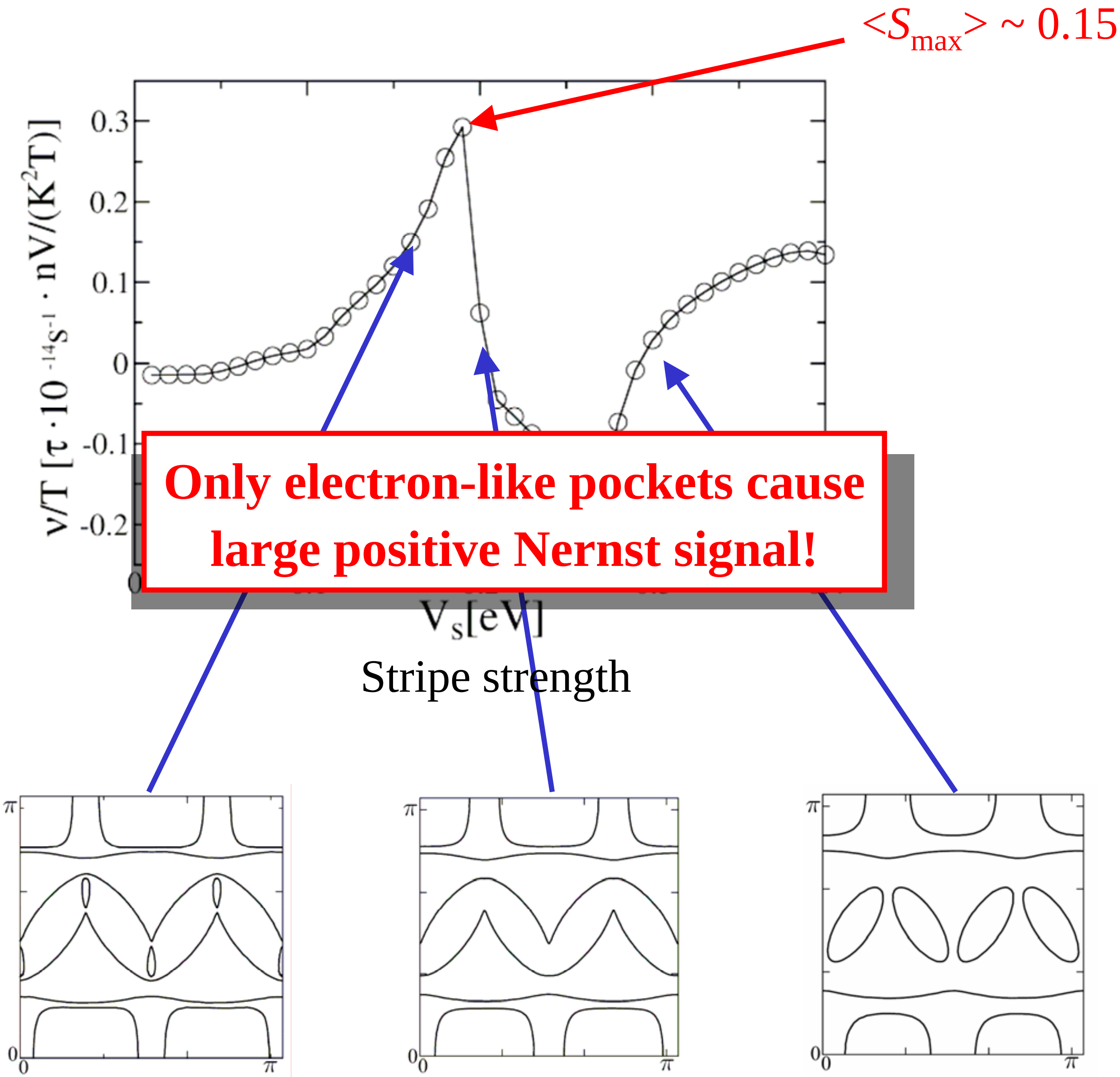


Nernst signal for CDW+SDW (period 8)



Hackl / Vojta / Sachdev, unpublished

Nernst signal for CDW+SDW (period 8)

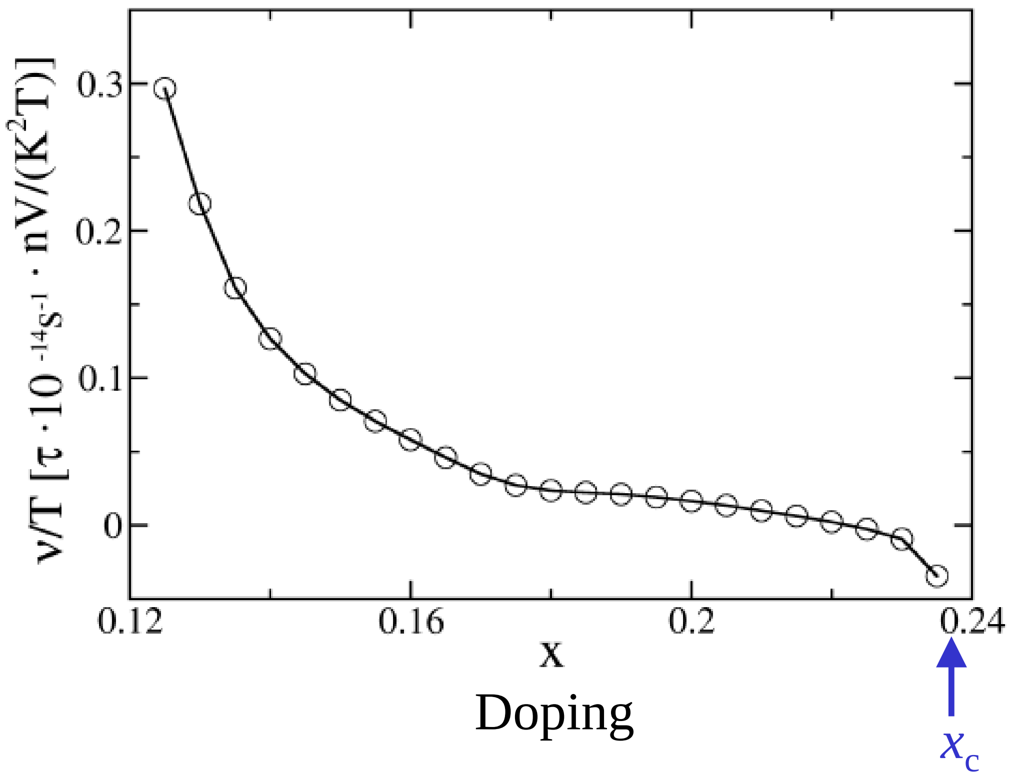


Hackl / Vojta / Sachdev, unpublished

Nernst signal for CDW+SDW (period 8)

Assuming a mean-field dependence of the stripe order parameter on doping

$$V_s(x) = V_0 \sqrt{1 - x/x_c}$$

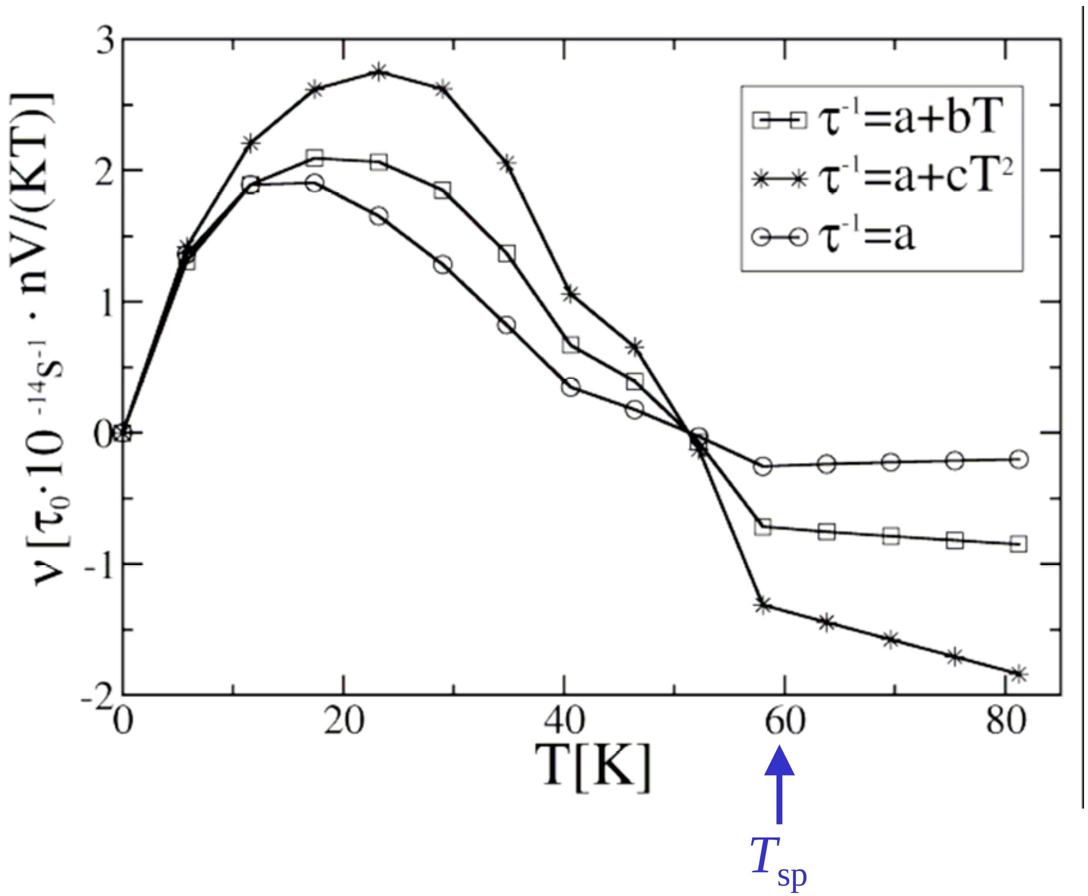


Hackl / Vojta / Sachdev, unpublished

Nernst signal for CDW+SDW (period 8)

Assuming a mean-field dependence
of the stripe order parameter on temperature

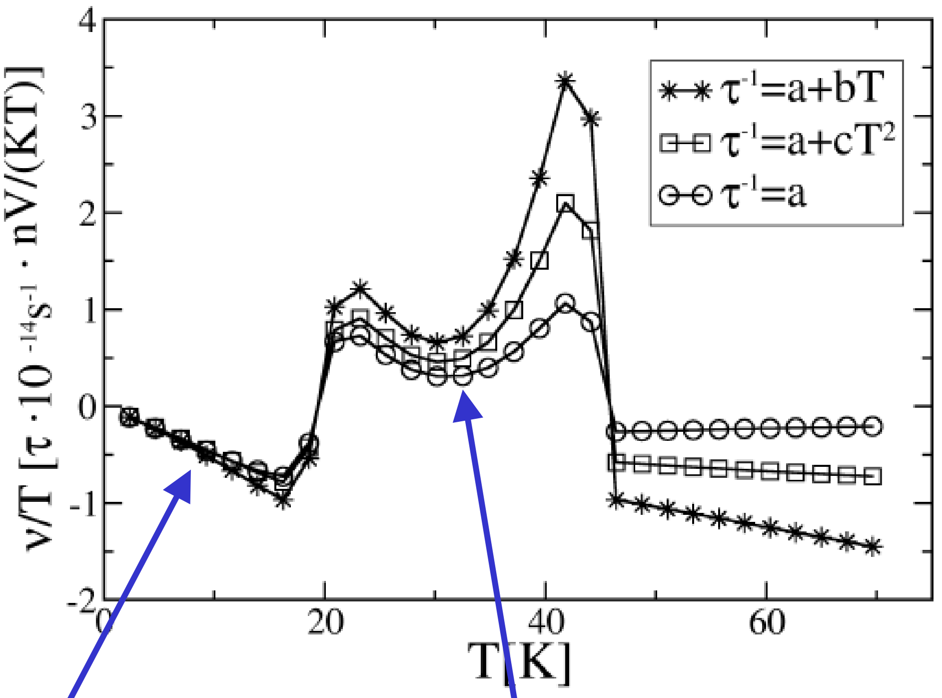
$$V_s(x) = V_0\sqrt{1 - T/T_{sp}}$$



Hackl / Vojta / Sachdev, unpublished

Eletron pockets are needed for positive Nernst signal!

Period-10 stripe order with $V_s(x) = V_0\sqrt{1 - T/T_{\rm sp}}$



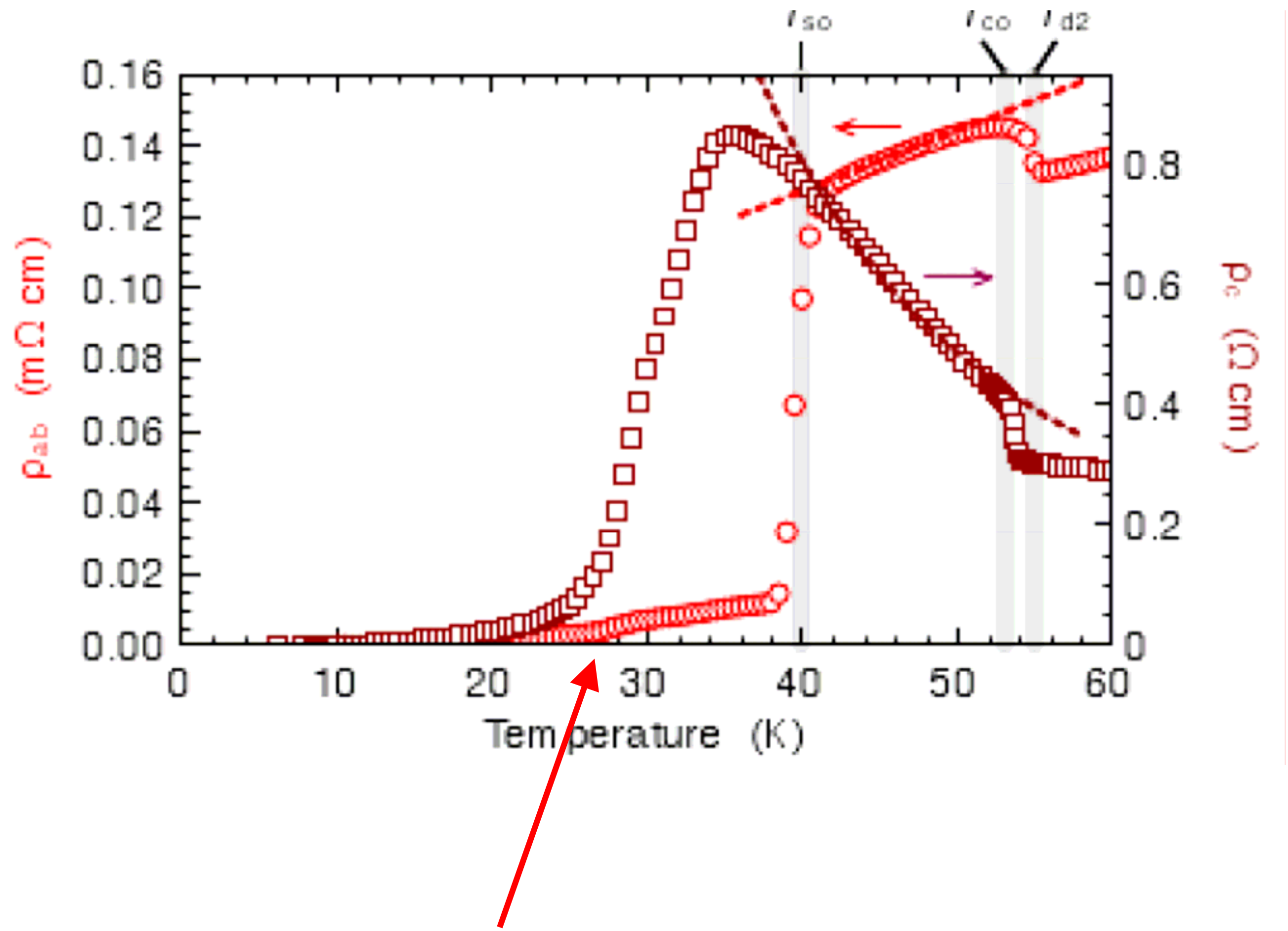
Only hole pockets

Electron pockets

Hackl / Vojta / Sachdev, unpublished

Inter-layer Josephson coupling

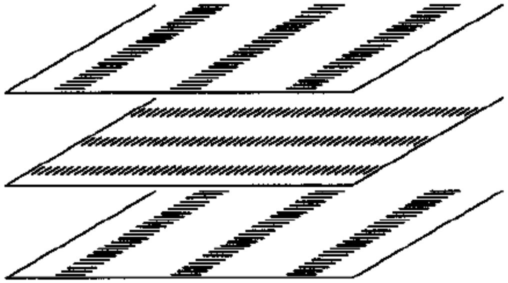
LBCO resistivity



Fluctuating 2d pairing
in the presence of stripes?

Inter-layer Josephson coupling

Inter-layer tunneling: $$t_\perp(\mathbf{k}) = \frac{t_\perp}{4}(\cos(k_x) - \cos(k_y))^2$$



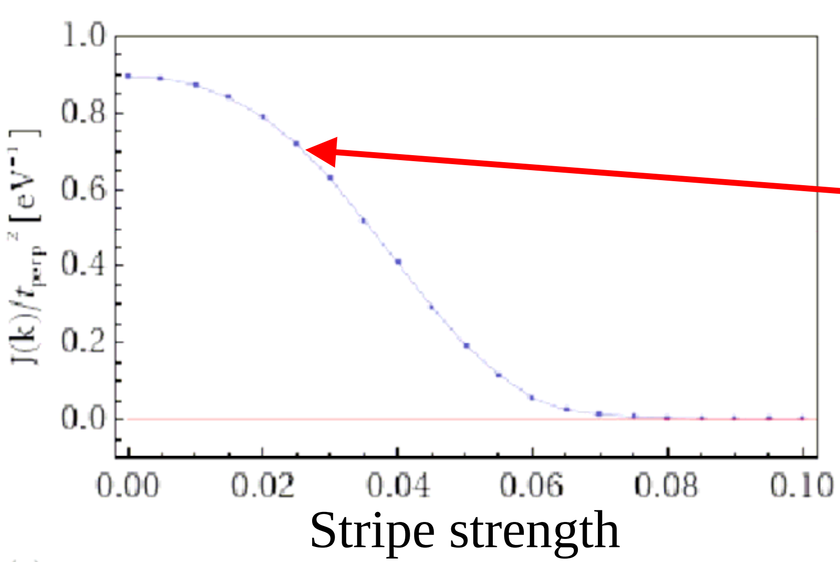
Calculate free-energy correction from $t_\perp$, with phase difference $\Delta\theta$

$$\Delta F^{(2)}(\Delta\theta) = -J_J\left(1 + \cos(\Delta\theta)\right)$$

Quasiparticle calculation:

$$\Delta F^{(2)} = \frac{1}{\beta N}\sum_{\mathbf{k}n} t_\perp(\mathbf{k})^2 \sum_{\alpha,\beta=0}^{1} (-)^{\alpha+\beta} \mathcal{G}^{1,\alpha\beta}_{\Psi\mathbf{k}n} \mathcal{G}^{2,\beta\alpha}_{\Psi\mathbf{k}n}$$

Inter-layer Josephson coupling: Results

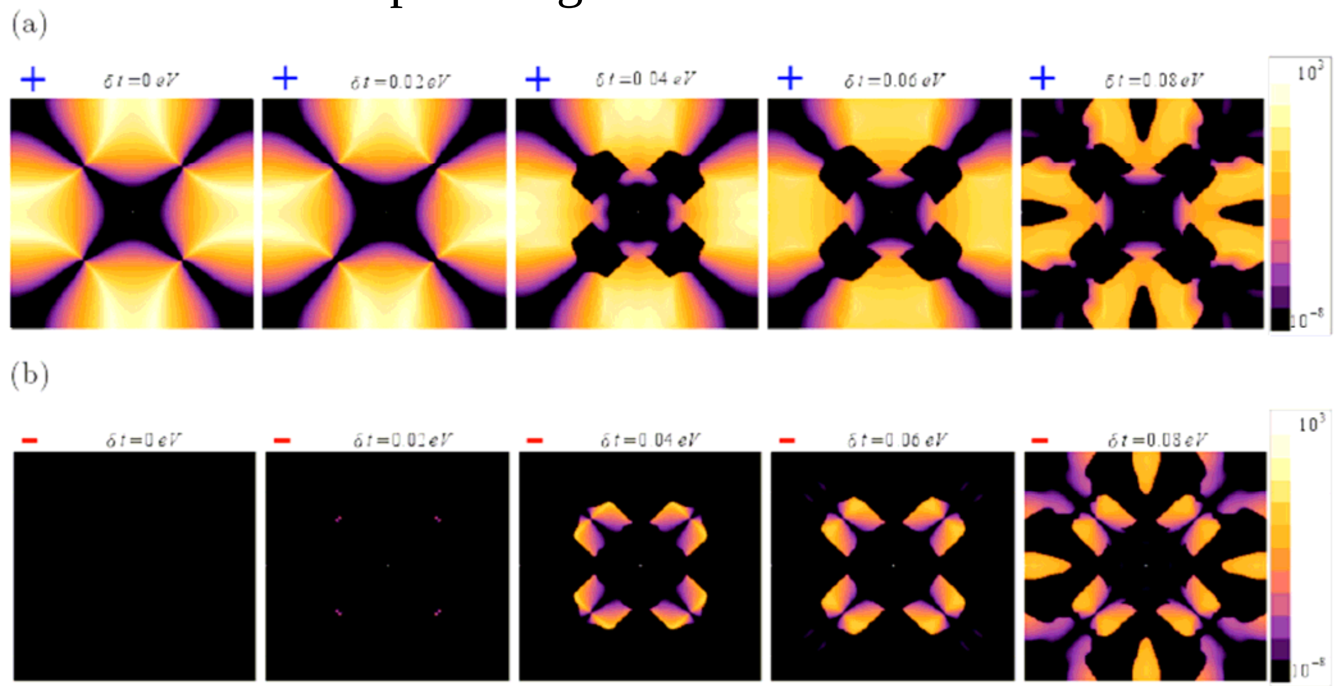


Charge modulation of about 25%

Momentum-resolved contributions to J_J

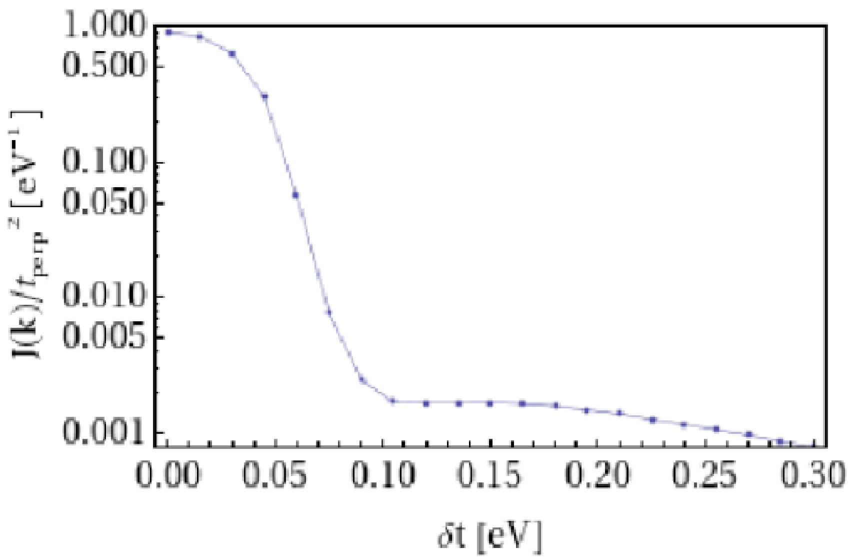
pos

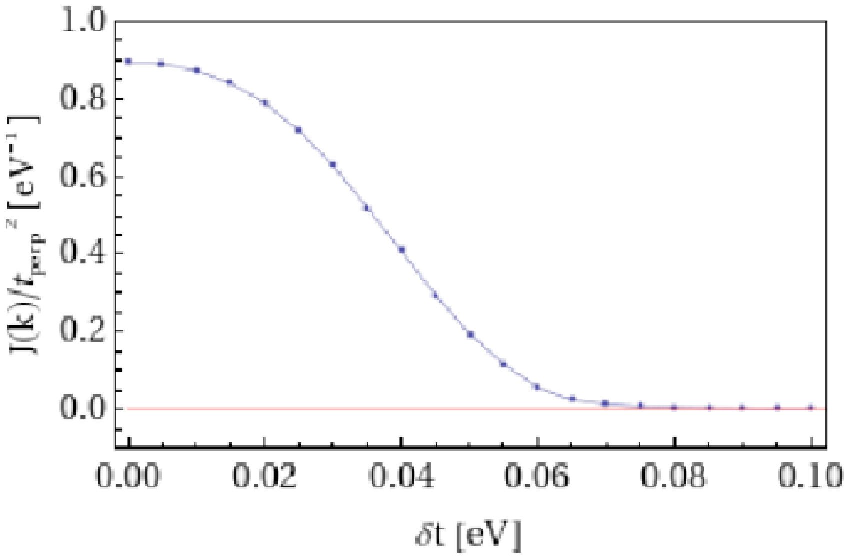
neg



Wollny / Vojta, unpublished

Inter-layer Josephson coupling: Results





Orthogonal stripes with primarily uniform pairing show strongly reduced inter-layer Josephson coupling.

But: Effect may be too small ...

Caveat of mean-field calculations: Assume coherent antinodal QP.

Chairman‘s questions

Momentum-space dichotomy and stripes

Disordered valence-bond stripes (strong scattering of antinodals, protected nodals) may explain part of it.

Are stripes a surface artefact?

Perhaps, but tendency toward stripes is very likely **not** ...

How to observe fluctuating stripes?

Ideally: Observation of dynamic charge mode in clean samples (little pinning)

Alternatively: Study of disorder (pinning) dependence of static charge order

Are stripes a red herring?

Perhaps, in the sense that they are not responsible for large T_c and linear $\rho(T)$.

But: They tell us something about underdoped cuprates (**local moments, not FL-based**)

Conclusions

1. Tendencies toward **stripe/bond order** common to underdoped cuprates; often static component is impurity-pinned and weak

2. Nodal quasiparticles are protected:
   Ordering phenomena have ***d*-wave form factor.**
   Microscopically: The action is on the oxygen!!!

3. Pocket-induced Nernst signal and
   reduced inter-layer Josephson coupling may be
   relevant for explaining various experiments.

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