Nernst effect in the cuprates

Stockholm, July 2010

Nernst effect in the cuprates

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Harvard: Subir Sachdev

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Nernst effect due to quasiparticles/vortices

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Stripe order enhances the Nernst effect

3) Nernst effect and rotational symmetry breaking

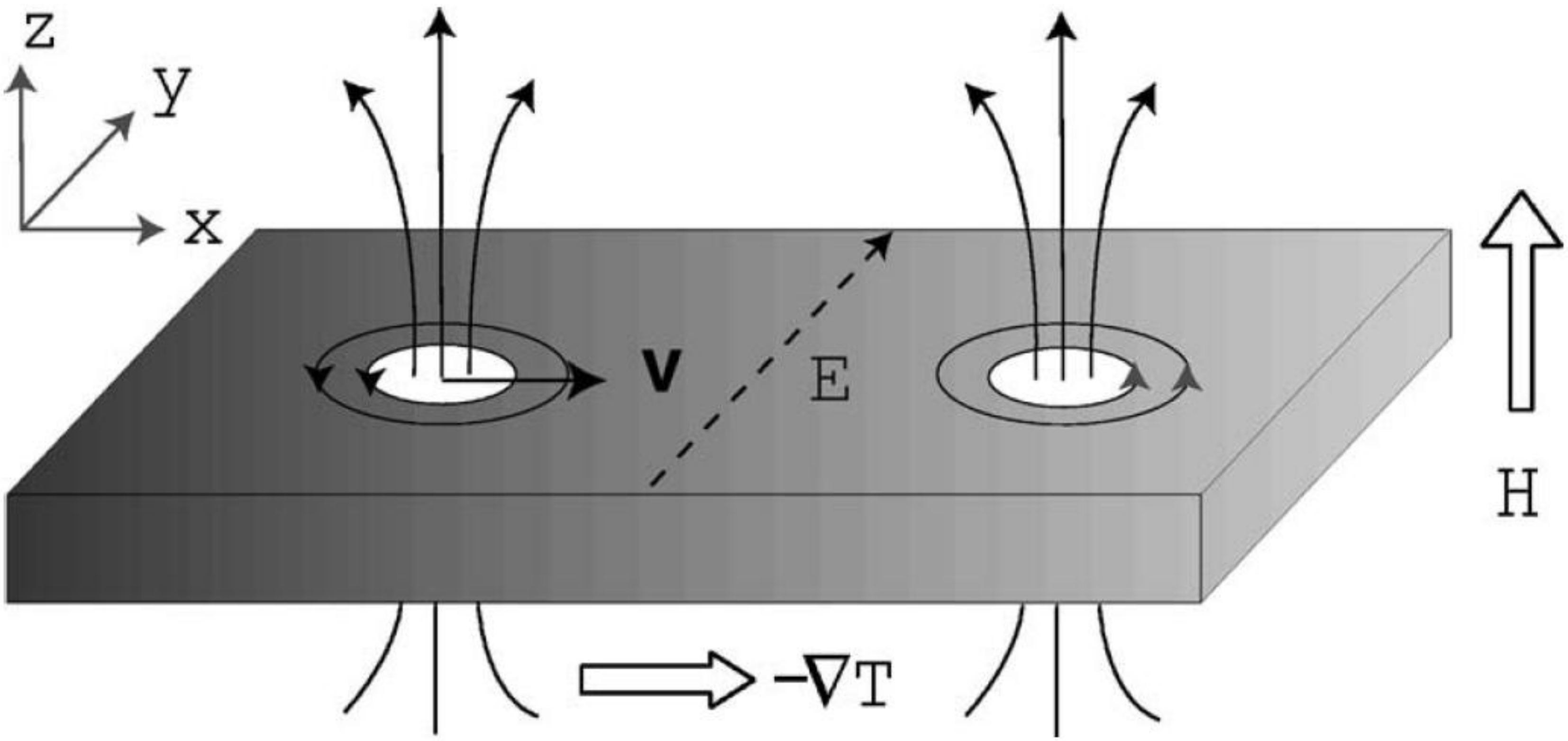
Important new insights into the pseudogap phase

Nernst effect and cuprates

The Nernst effect

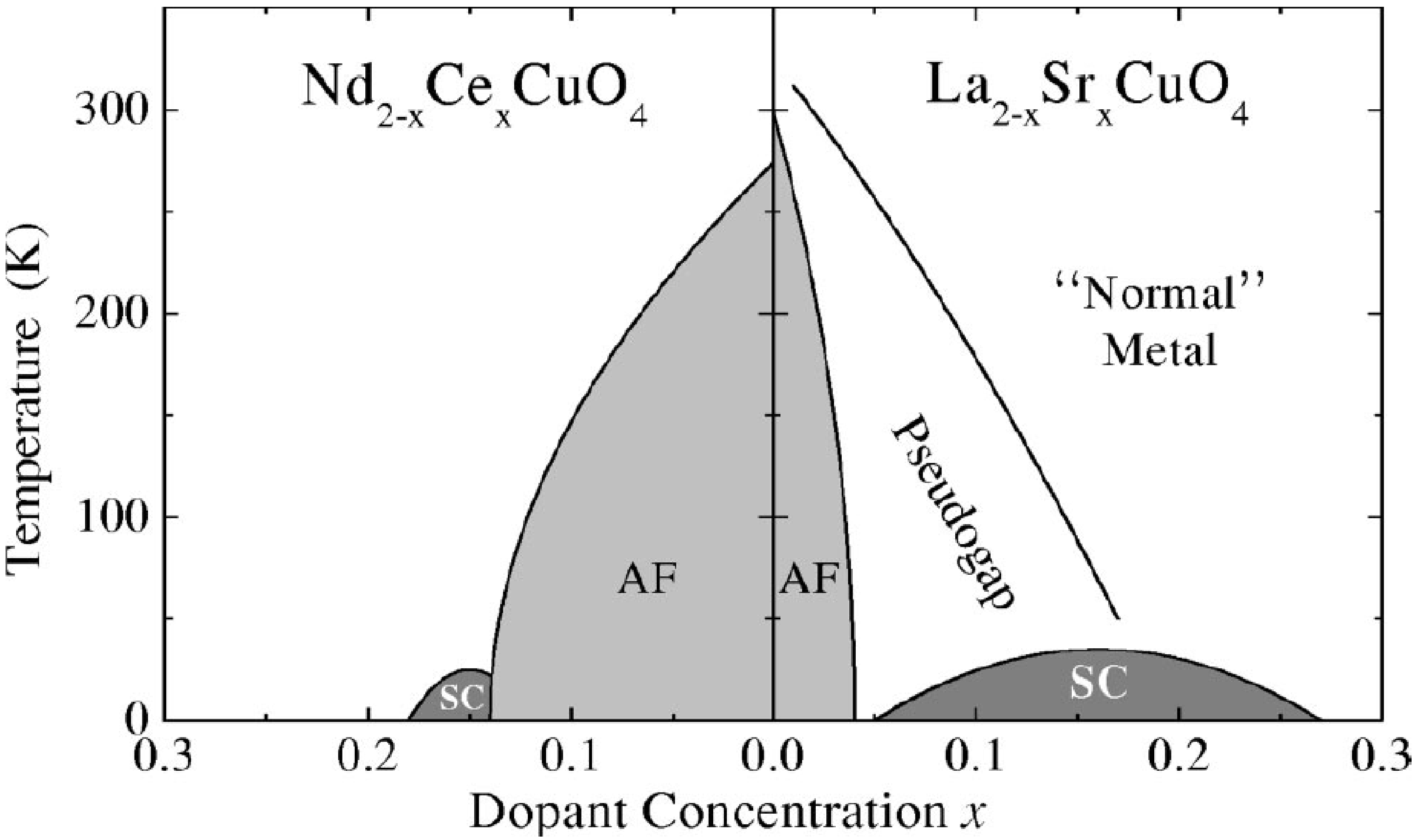
- Thermoelectric phenomenon observed in strong magnetic fields
- Very small and featureless in metals
- Important role for correlated electron systems only recently due to discovery of large Nernst signal in cuprate materials
- Potential of new insights into origin of cuprate phase diagram

Nernst effect



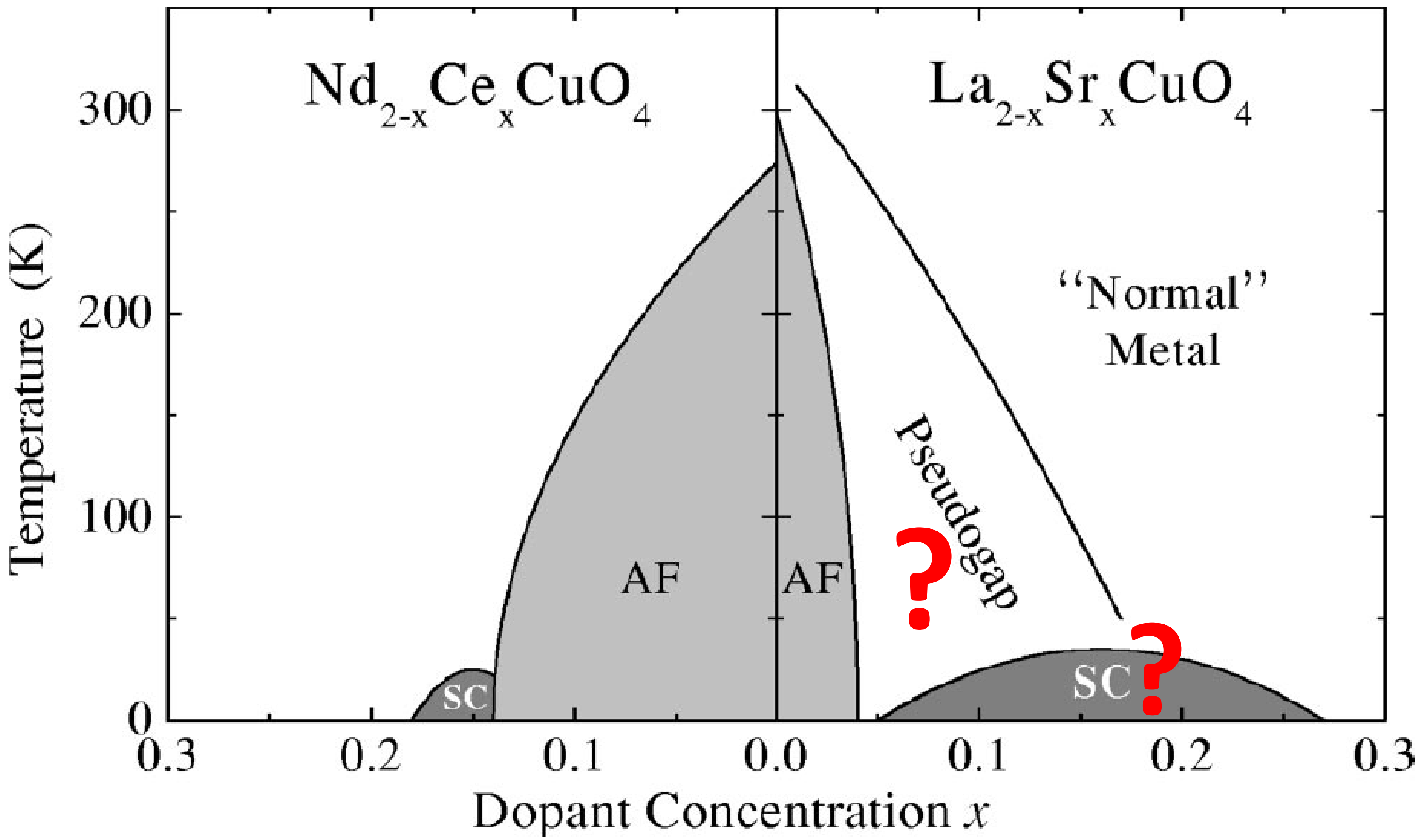
Thermal analogon to Hall effect

The cuprates



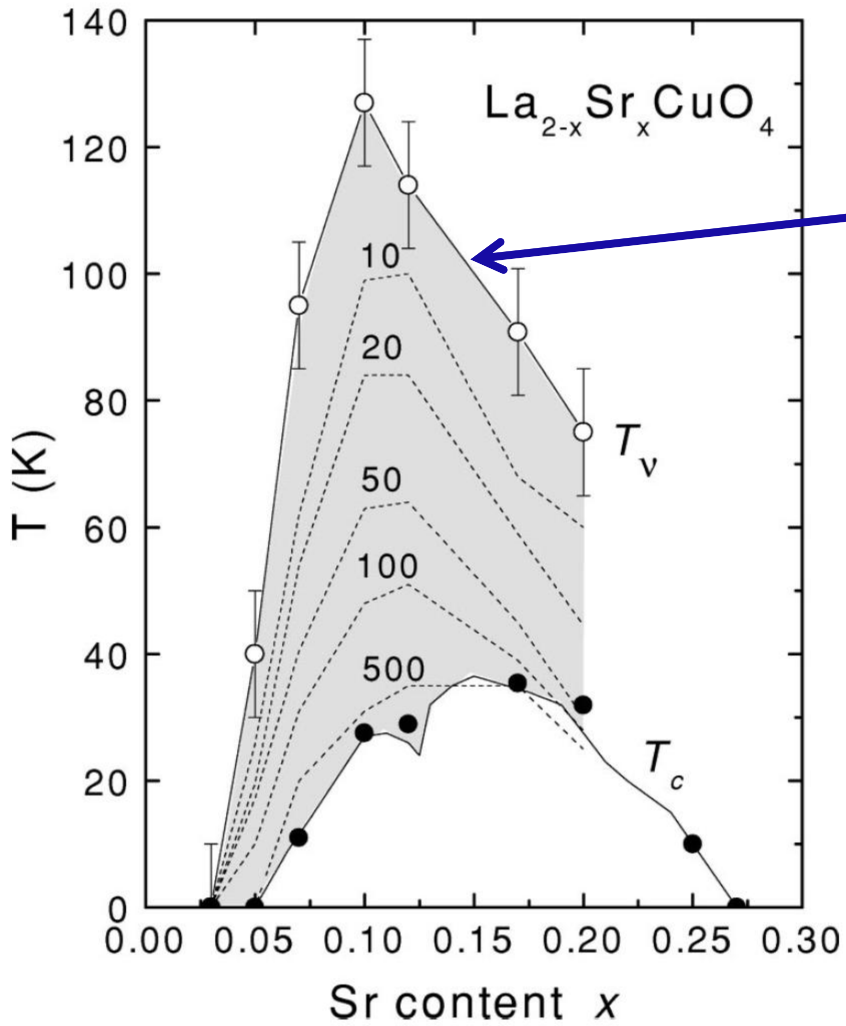
Damascelli et al., RMP **75**, 473 (2003)

The cuprates



Damascelli et al., RMP **75**, 473 (2003)

Nernst effect near superconducting dome

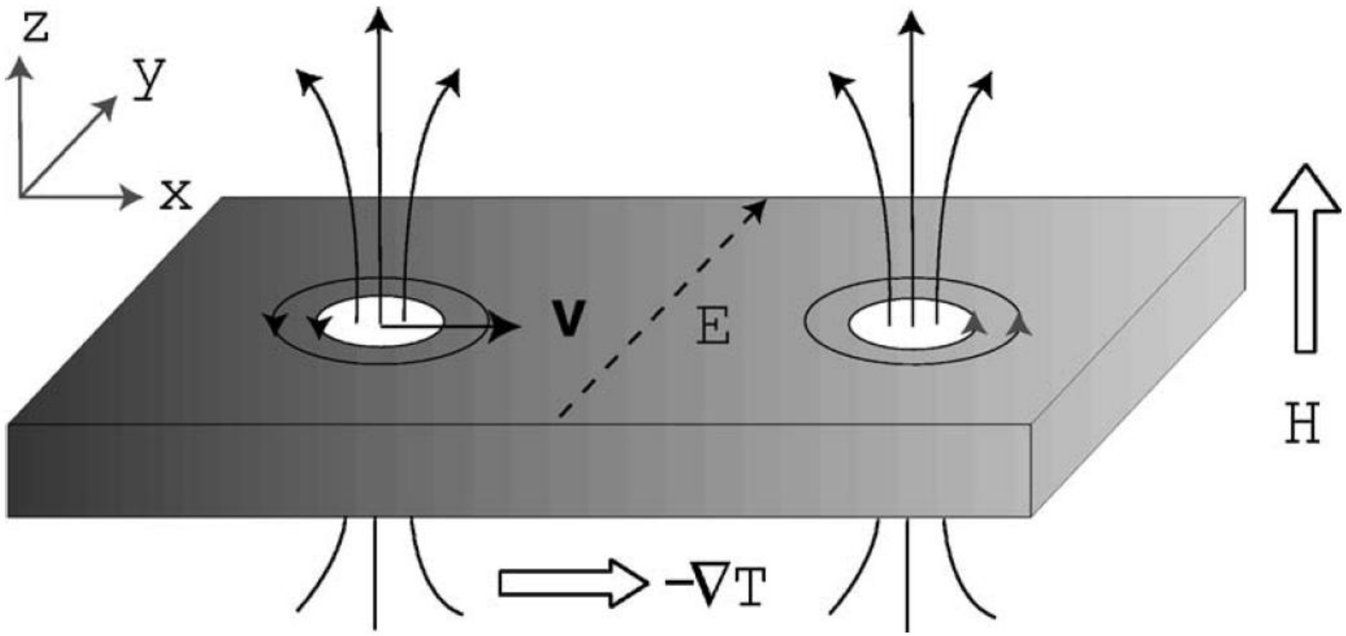


contours of constant ν [nV/KT]

Vortices in thermal gradient produce strong Nernst signal

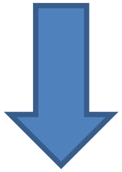
Wang et al. PRB **64**, 224519 (2001)

Phenomenological explanation



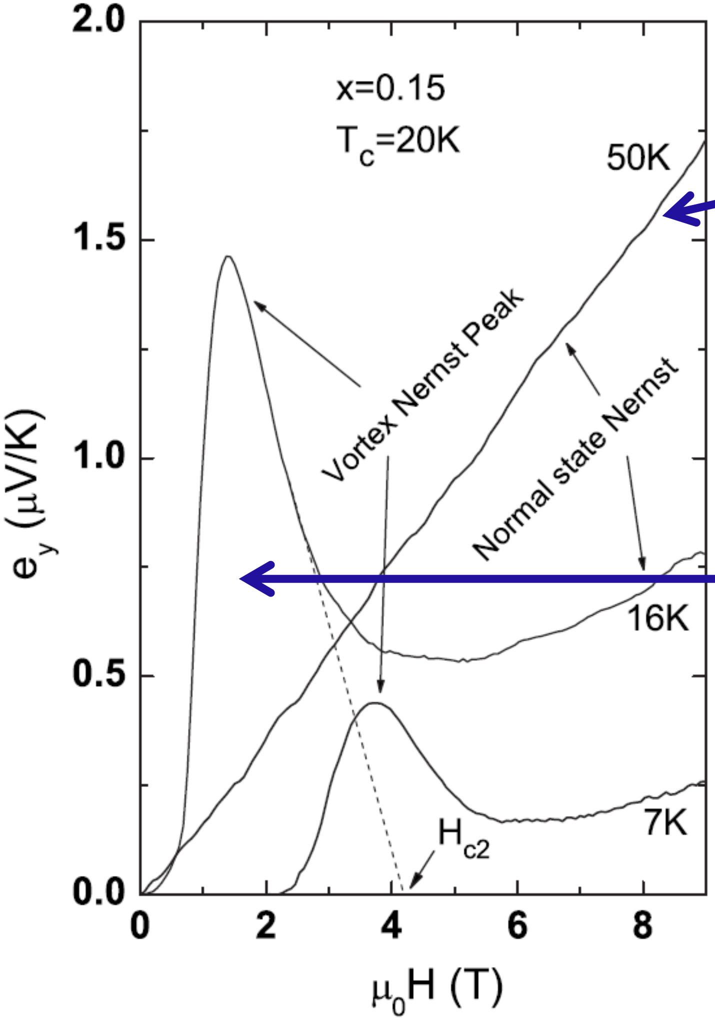
Josephson equation: $2eV_J = \hbar\dot{\Theta}$

# of drifting vortices: $\dot{\Theta} = 2\pi \dot{N}_V$



Transverse Voltage

Quasiparticle Nernst effect



Nernst effect linear in magnetic field: normal state quasiparticles

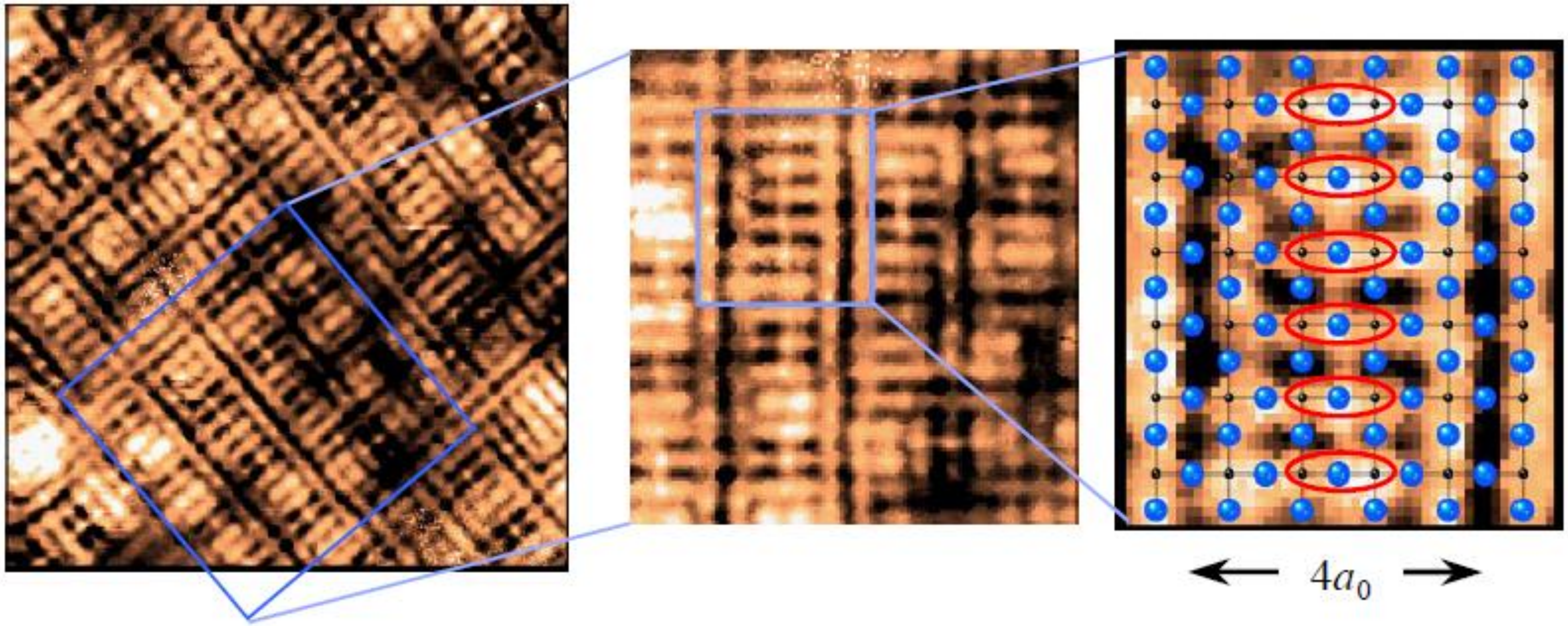
Vortex Nernst effect, suppressed in strong magnetic fields

Li and Greene PRB **76**, 174512 (2007)

Nernst effect and stripe order

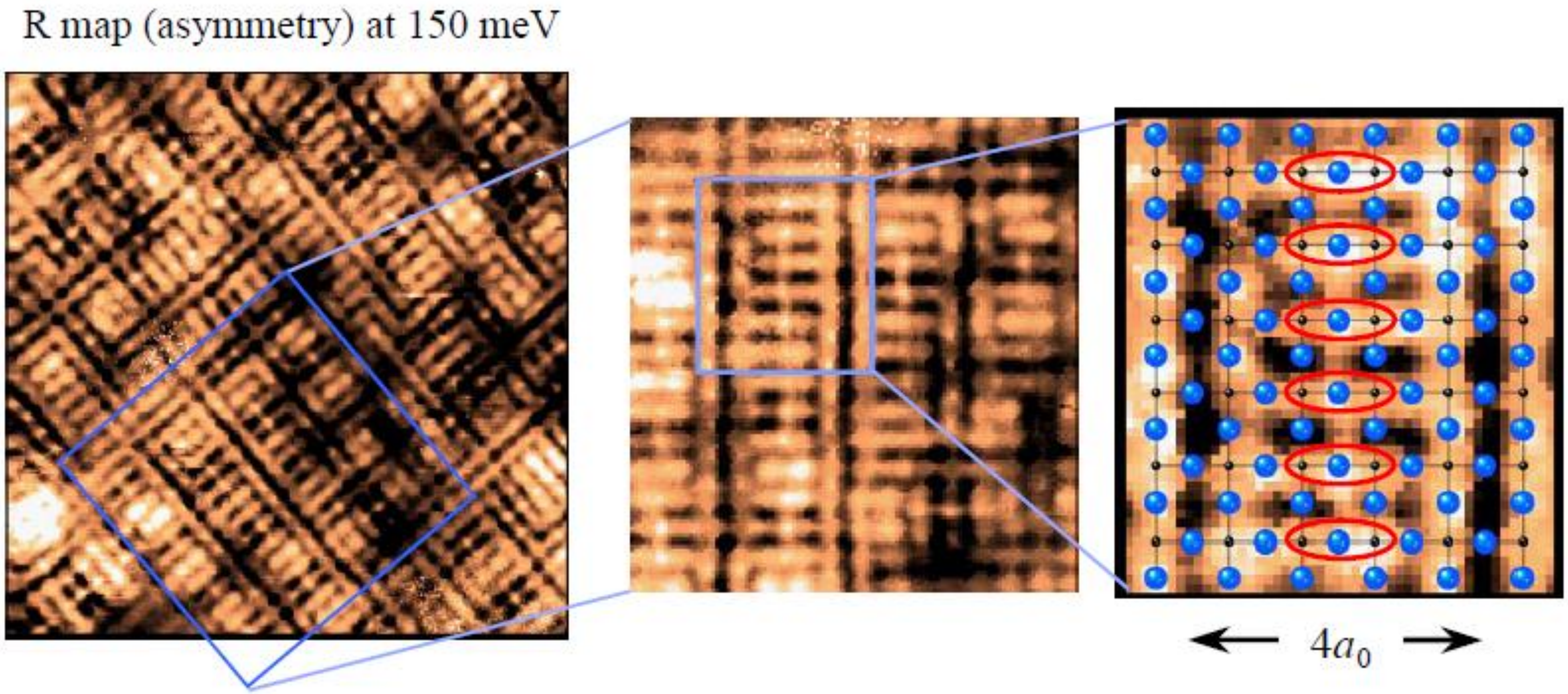
Stripe order

R map (asymmetry) at 150 meV

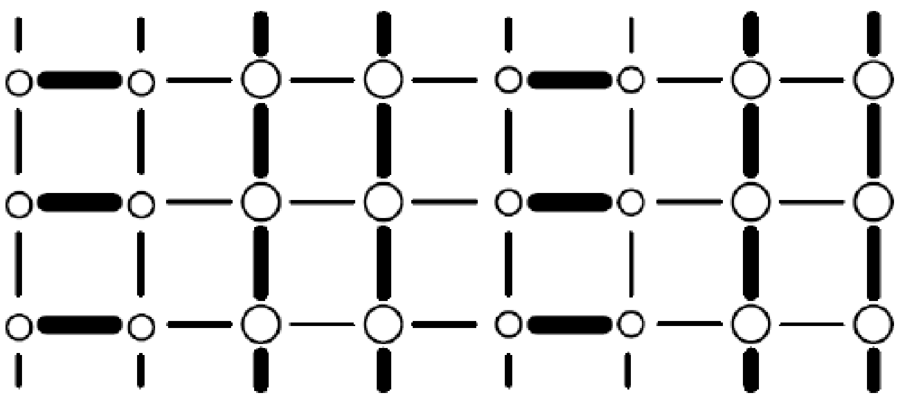


Kohsaka et al., Science **315**, 1380 (2007)

Stripe order



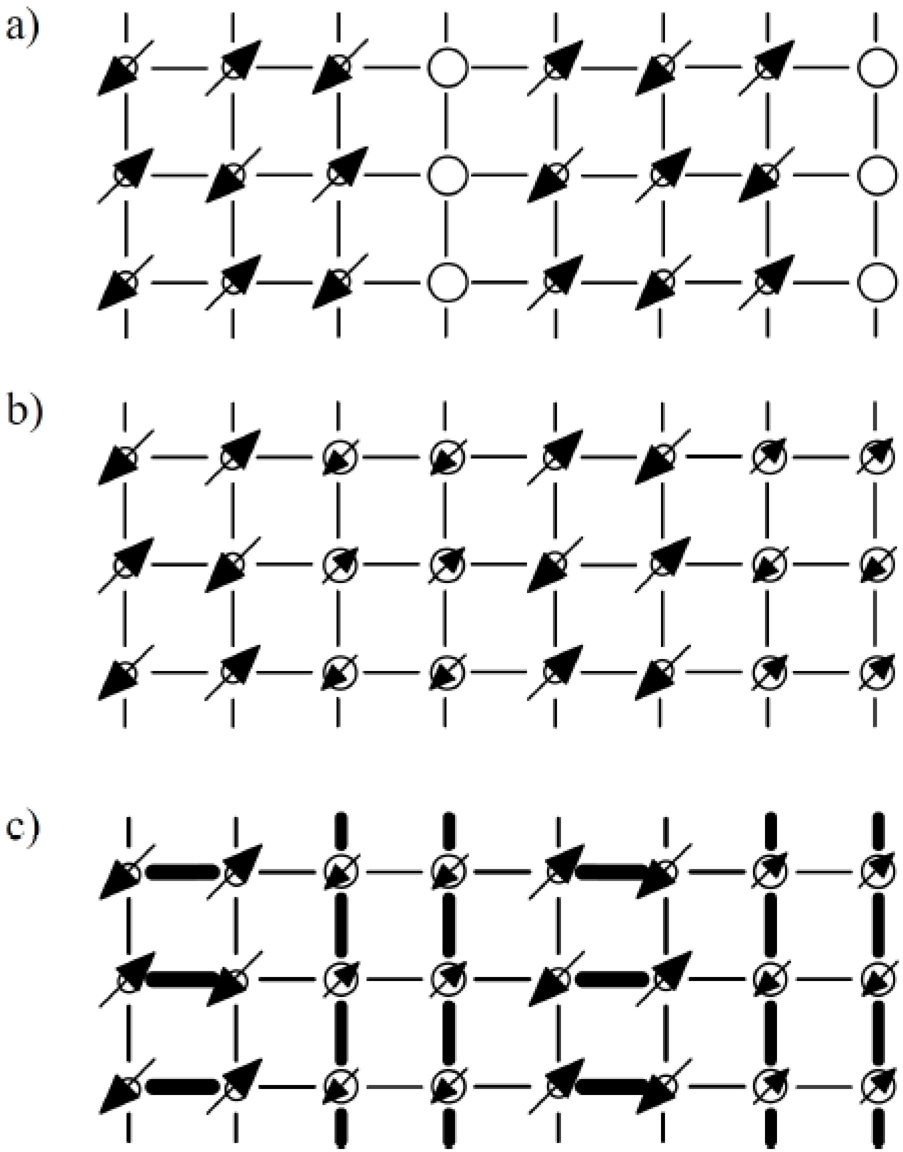
Kohsaka et al., Science **315**, 1380 (2007)



Unconventional order:
„*d*-wave“ stripes

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

Stripe order



On mean-field level:
provides scattering potential
for quasiparticles

$$\hat{V}_{s,c} = \sum_{\vec{k}\sigma} V_{s,c}(\vec{k}) c^{\dagger}_{\vec{k}+\vec{Q}_{s,c}\sigma} c_{\vec{k}\sigma} + h.c.$$

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

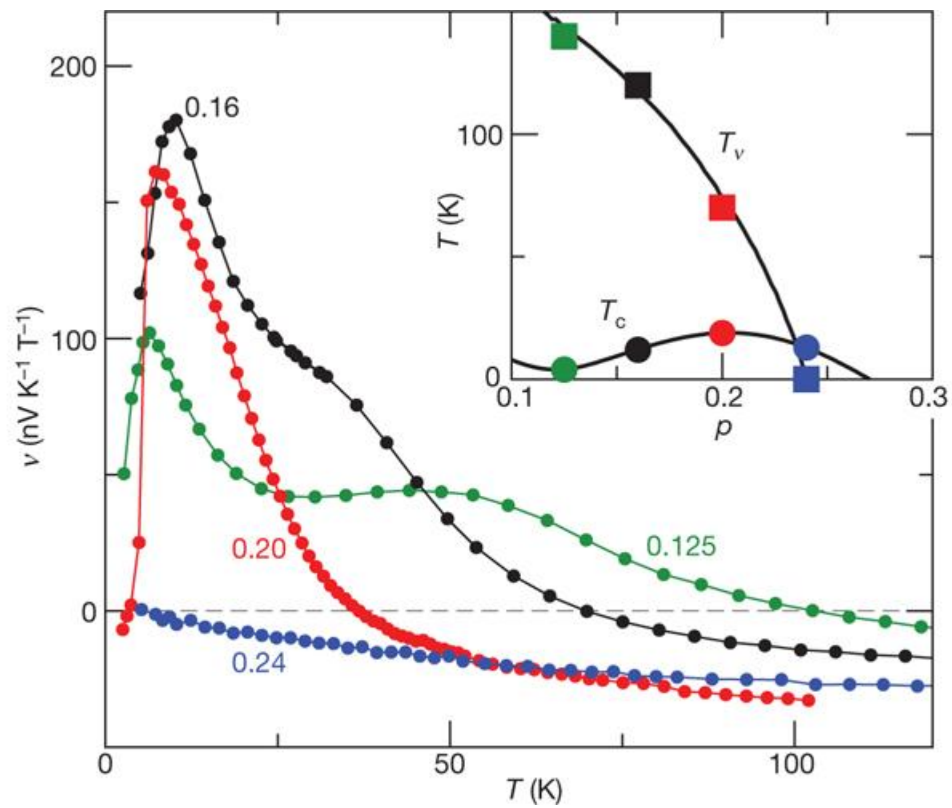
Olivier Cyr-Choinière[1]*, R. Daou[1]*, Francis Laliberté[1], David LeBoeuf[1], Nicolas Doiron-Leyraud[1], J. Chang[1], J.-Q. Yan[2]†, J.-G. Cheng[2], J.-S. Zhou[2], J. B. Goodenough[2], S. Pyon[3], T. Takayama[3], H. Takagi[3,4], Y. Tanaka[5,3] & Louis Taillefer[1,6]

Eu-LSCO
Nd-LSCO

Nernst signal shows two „peaks“:

1) Superconducting fluc. at low T

2) Fermi surface reconstruction at higher T



Cyr-Choniere Nature **458**, 743 (2009)

Theoretical question:

To what extent can this peak structure of
the Nernst effect be explained
in terms of normal state quasiparticles?

Semiclassical calculation

Quasiparticle Hamiltonian

$$H = \sum_{\vec{k}\sigma} \epsilon_{\vec{k}} c^{\dagger}_{\vec{k}\sigma} c_{\vec{k}\sigma} + \sum_{\vec{k}\sigma} V_{s,c}(\vec{k}) c^{\dagger}_{\vec{k}+\vec{Q}_{s,c}\sigma} c_{\vec{k}\sigma} + h.c.$$

Boltzmann equation

$$\left[-\frac{e}{\hbar c}(\mathbf{v_k} \times \mathbf{B}) \cdot \nabla_{\mathbf{k}} + \frac{1}{\tau(\epsilon_{\mathbf{k}})}\right] g_{\mathbf{k}} = \left[-e\mathbf{v_k}\mathbf{E} - (\varepsilon_{\mathbf{k}} - \mu)\mathbf{v_k}\frac{\nabla_r T}{T}\right]\left(-\frac{\partial f^0_{\mathbf{k}}}{\partial \varepsilon_{\mathbf{k}}}\right)$$

$$g(\mathbf{k}) = f(\mathbf{k}) - f_0(\mathbf{k})$$

Semiclassical calculation

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

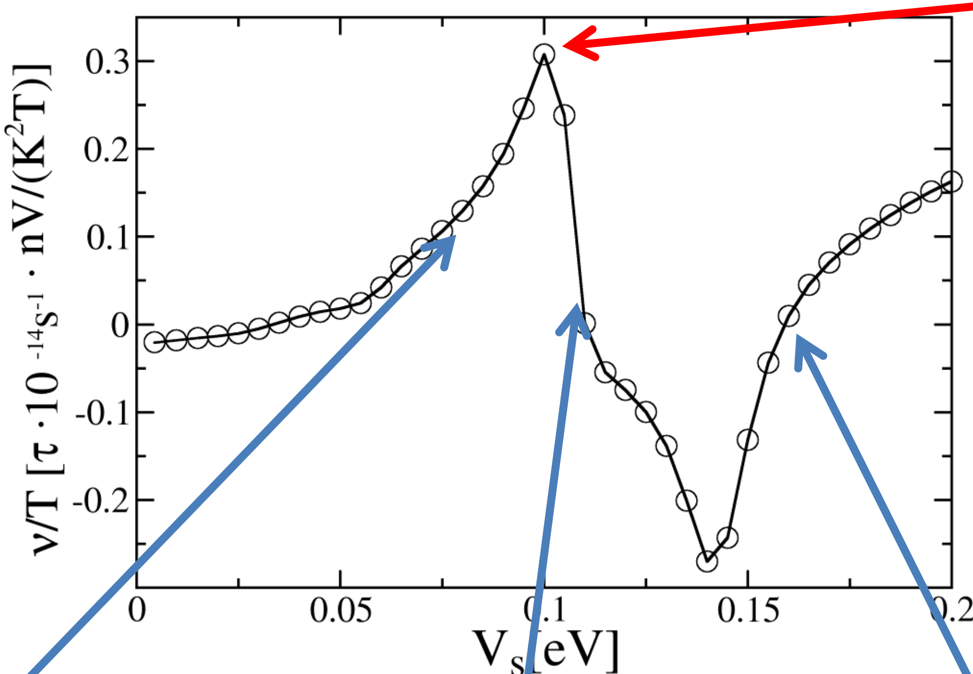
Nernst signal: $\vec{E} = -\hat{\vartheta}\nabla T$ (no charge current, B field || z)

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

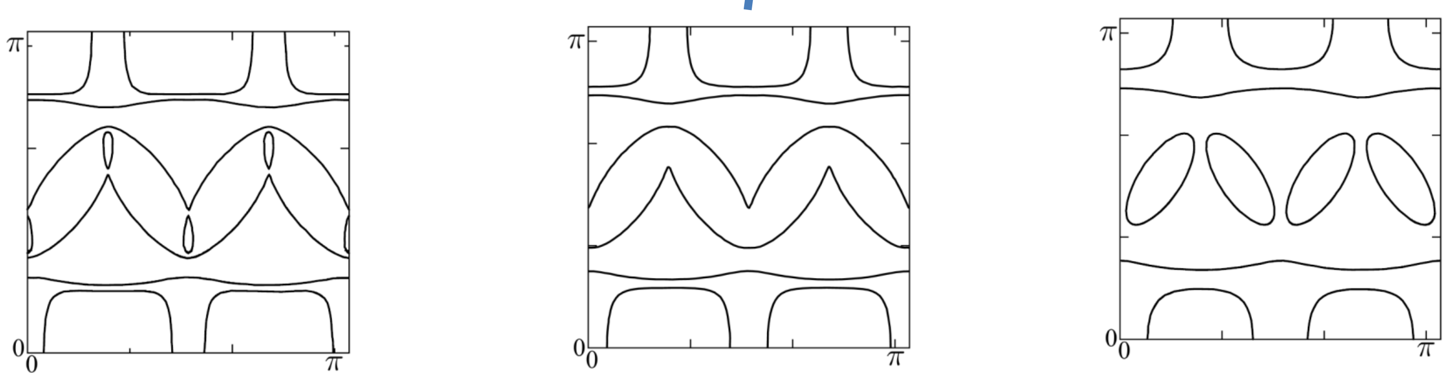
Nernst coefficient: $\nu = \vartheta_{yx}/B$ (~T at low T)

Nernst signal for CDW+SDW (period 8)

$\langle S_{max} \rangle \sim 0.15$

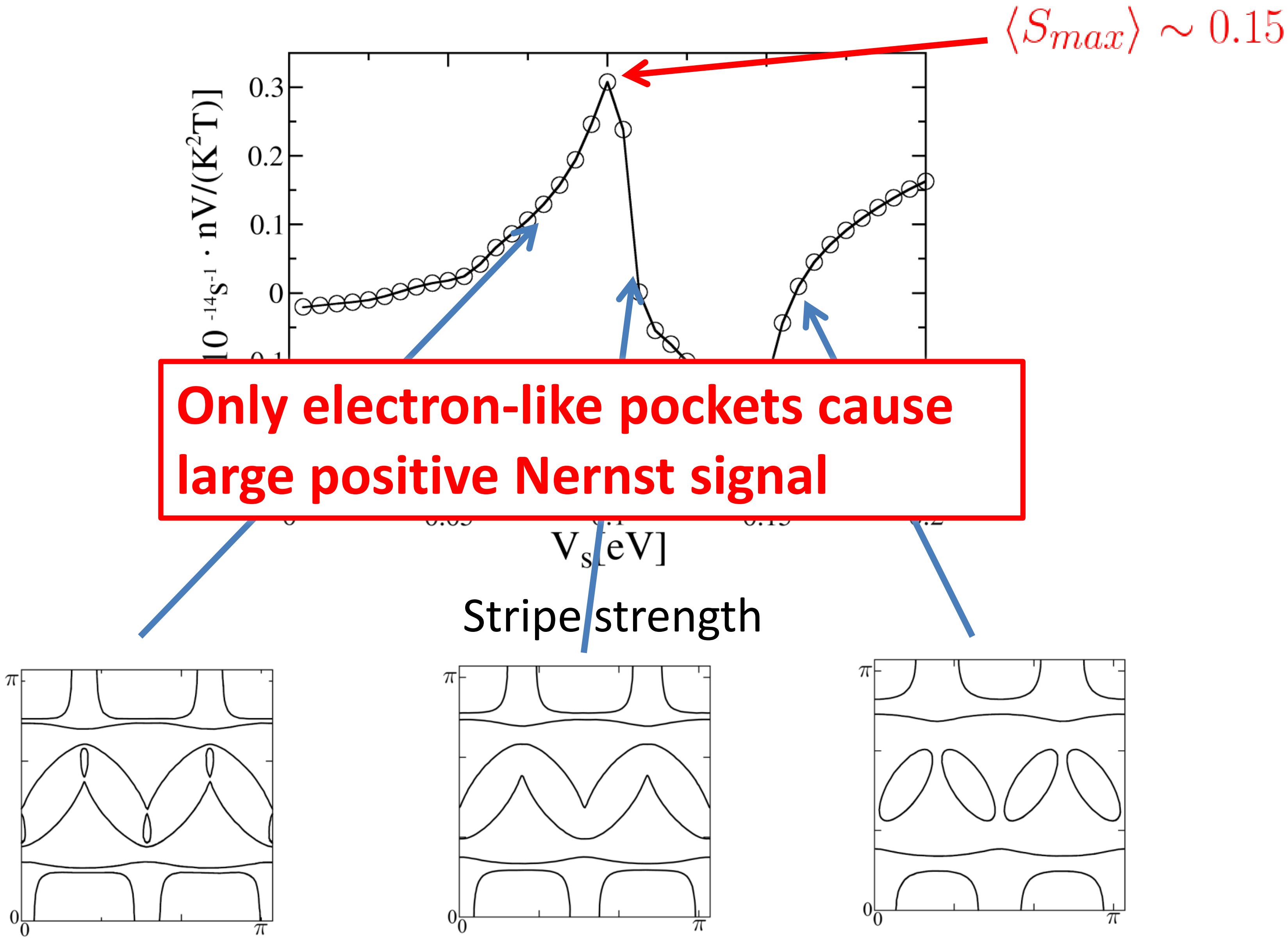


Stripe strength



Hackl/Vojta/Sachdev PRB **81**, 045102 (2010)

Nernst signal for CDW+SDW (period 8)



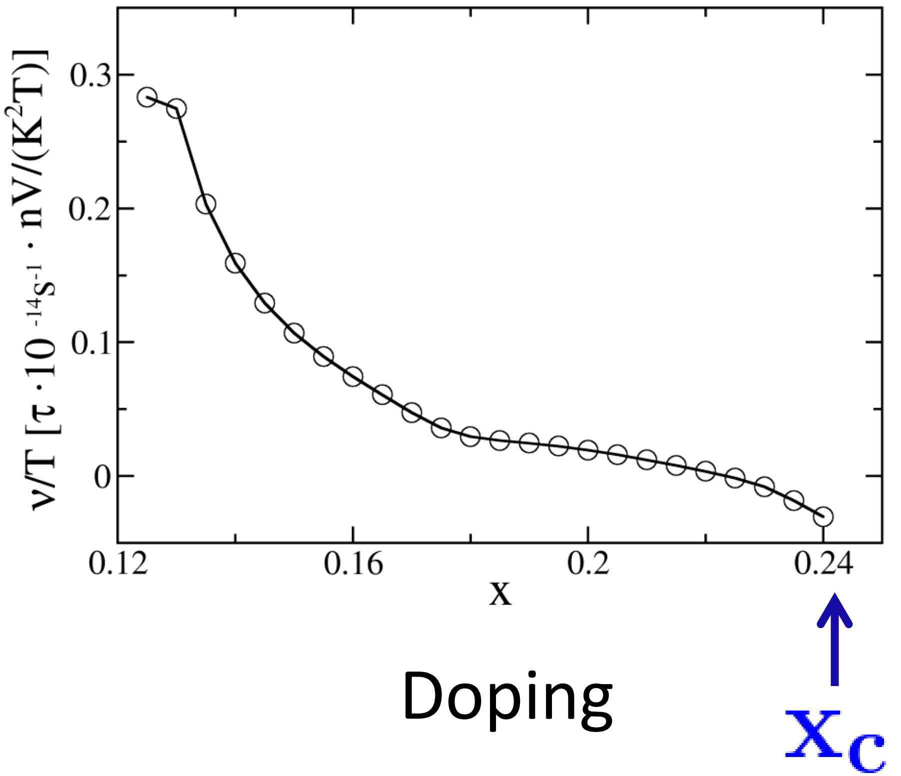
Only electron-like pockets cause large positive Nernst signal

Hackl/Vojta/Sachdev PRB **81**, 045102 (2010)

Nernst signal for CDW+SDW (period 8)

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

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

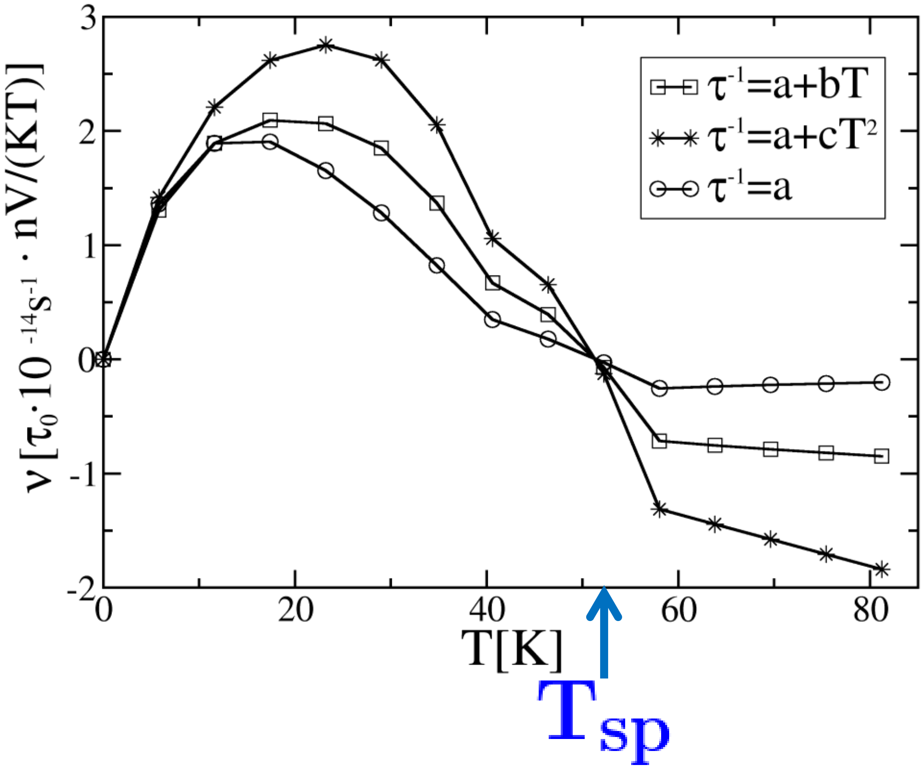


Hackl/Vojta/Sachdev PRB **81**, 045102 (2010)

Nernst signal for CDW+SDW (period 8)

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

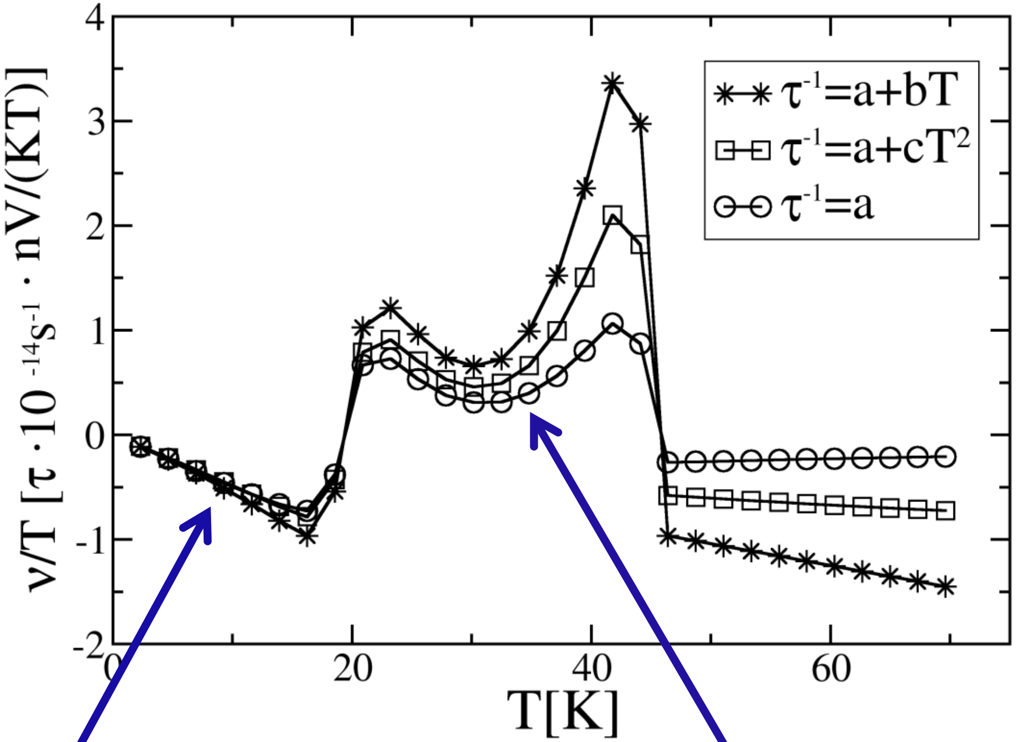
$$V_s(T) = V_0\sqrt{1 - T/T_{sp}}$$



Hackl/Vojta/Sachdev PRB **81**, 045102 (2010)

Nernst signal for CDW+SDW (period 10)

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



Only hole pockets

Electron pockets

Hackl/Vojta/Sachdev PRB **81**, 045102 (2010)

Intermediate conclusions

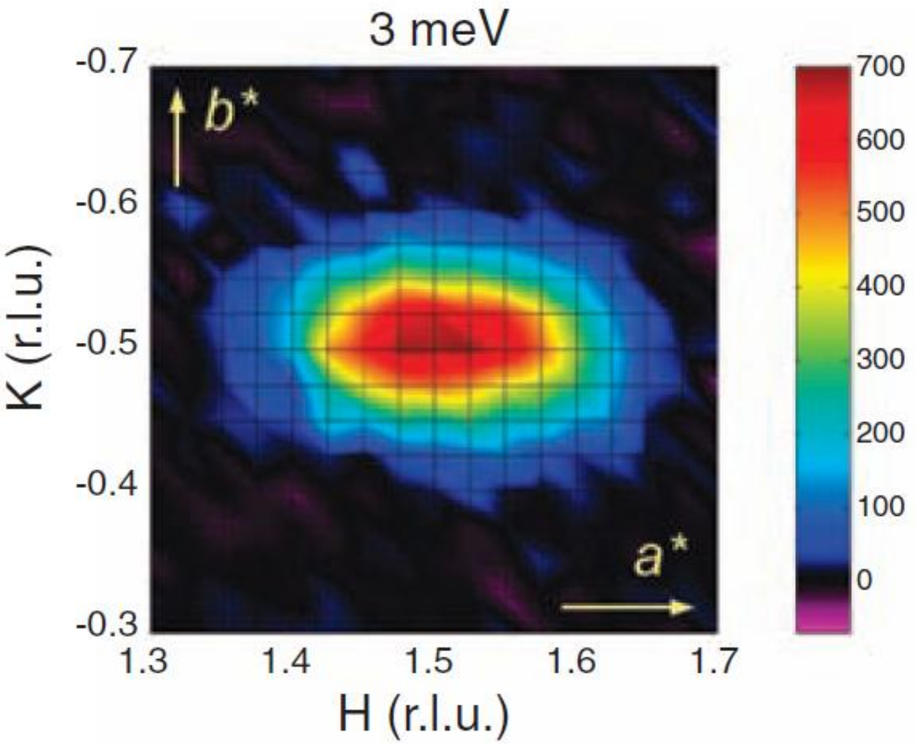
- Fermi surface reconstruction due to stripe order in agreement with enhanced positive Nernst signal

- Sign changes of Nernst signal as function of temperature predicted in underdoped region

- Further experiments for different dopings needed to check theoretical results

Nernst effect and rotational symmetry breaking

Electron nematic order in cuprates

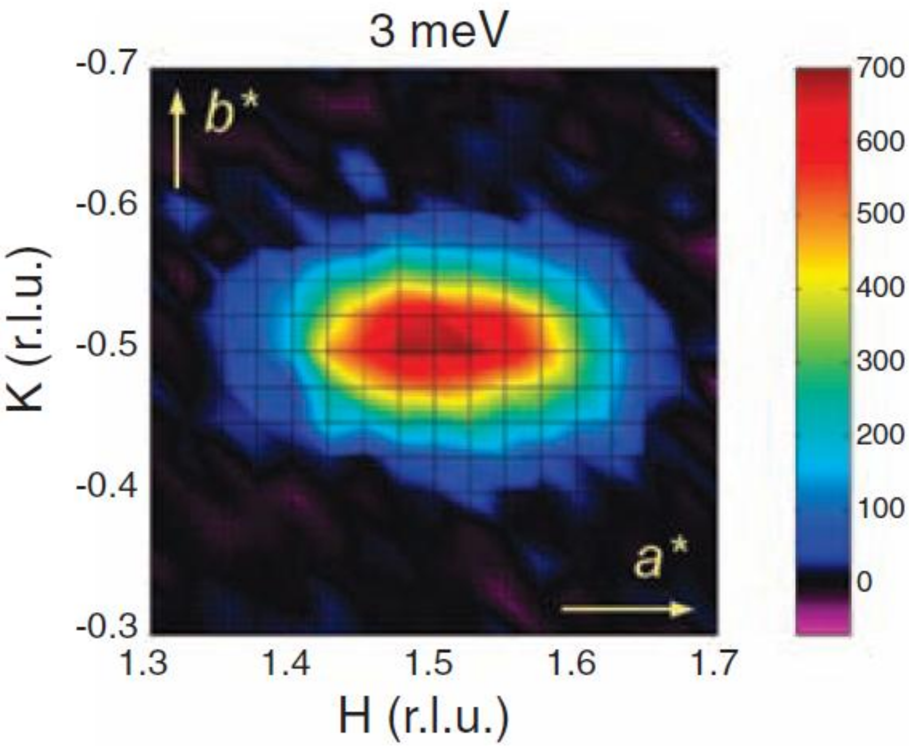


Electronic Liquid Crystal State in the High-Temperature Superconductor $YBa_2Cu_3O_{6.45}$

V. Hinkov,[1]* D. Haug,[1] B. Fauqué,[2] P. Bourges,[2] Y. Sidis,[2] A. Ivanov,[3] C. Bernhard,[4] C. T. Lin,[1] B. Keimer[1]

Anisotropic spin fluctuations detected

Electron nematic order in cuprates



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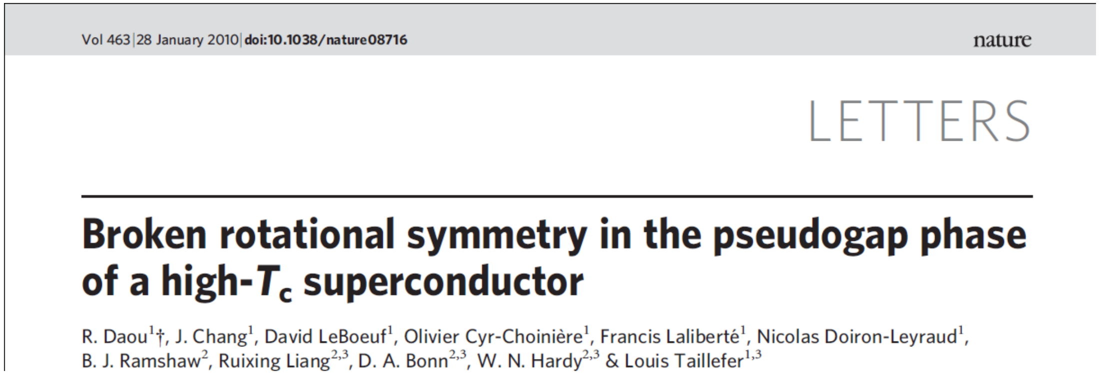
Anisotropic spin fluctuations detected

Electronic liquid-crystal phases of a doped Mott insulator

S. A. Kivelson*, E. Fradkin† & V. J. Emery‡

Proposed theoretically years before

Is the pseudogap phase a nematic phase?

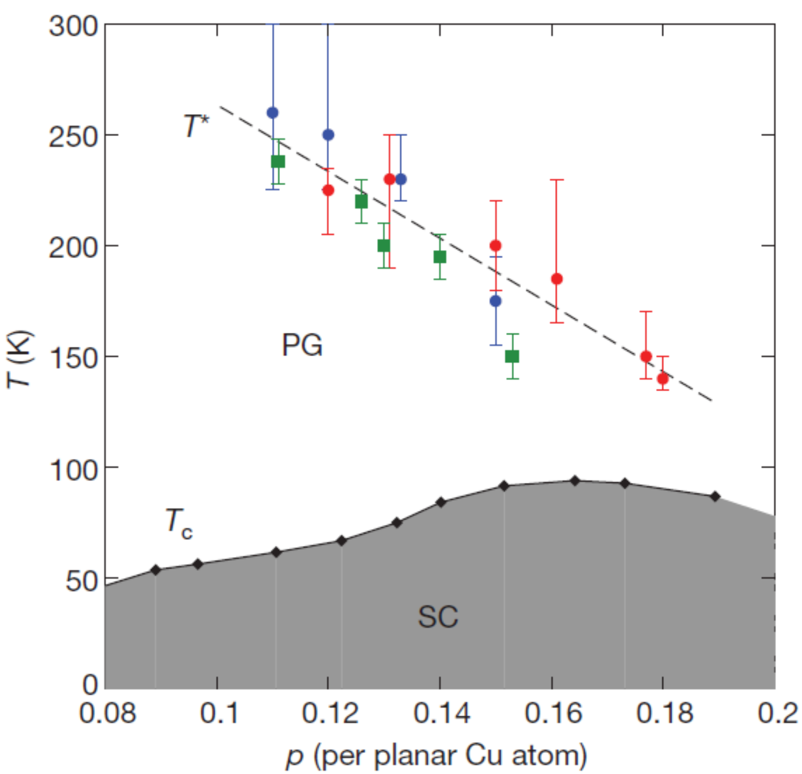

Vol 463|28 January 2010|doi:10.1038/nature08716 nature

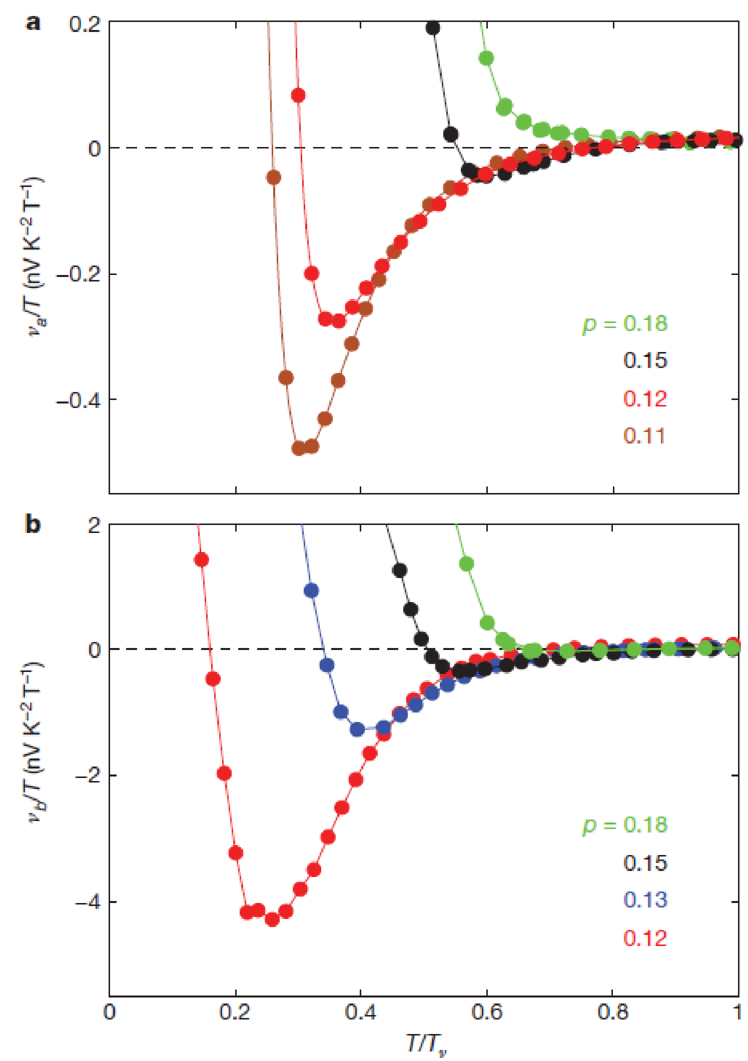
LETTERS

Broken rotational symmetry in the pseudogap phase of a high-T_c superconductor

R. Daou[1]†, J. Chang[1], David LeBoeuf[1], Olivier Cyr-Choinière[1], Francis Laliberté[1], Nicolas Doiron-Leyraud[1], B. J. Ramshaw[2], Ruixing Liang[2,3], D. A. Bonn[2,3], W. N. Hardy[2,3] & Louis Taillefer[1,3]

Nernst signal

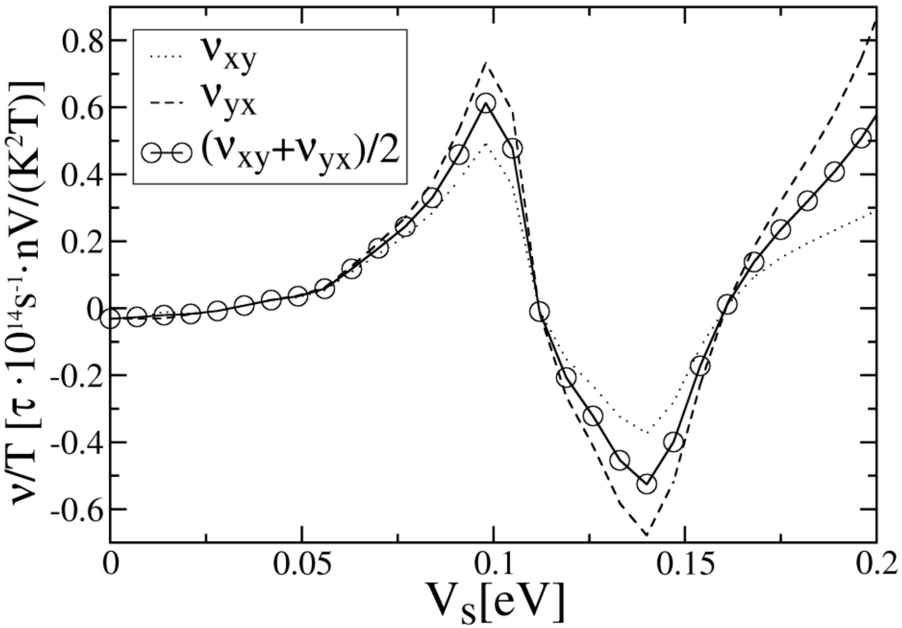




Stripe order is not enough

Anisotropy ratio too small (<=2 for relevant stripe potential strengths)

Example: period 8 stripe order



Electron nematic order

Nematic order distorts band structure

here: $d_{x^2-y^2}$ symmetry

(e.g., precursor of stripe phase)

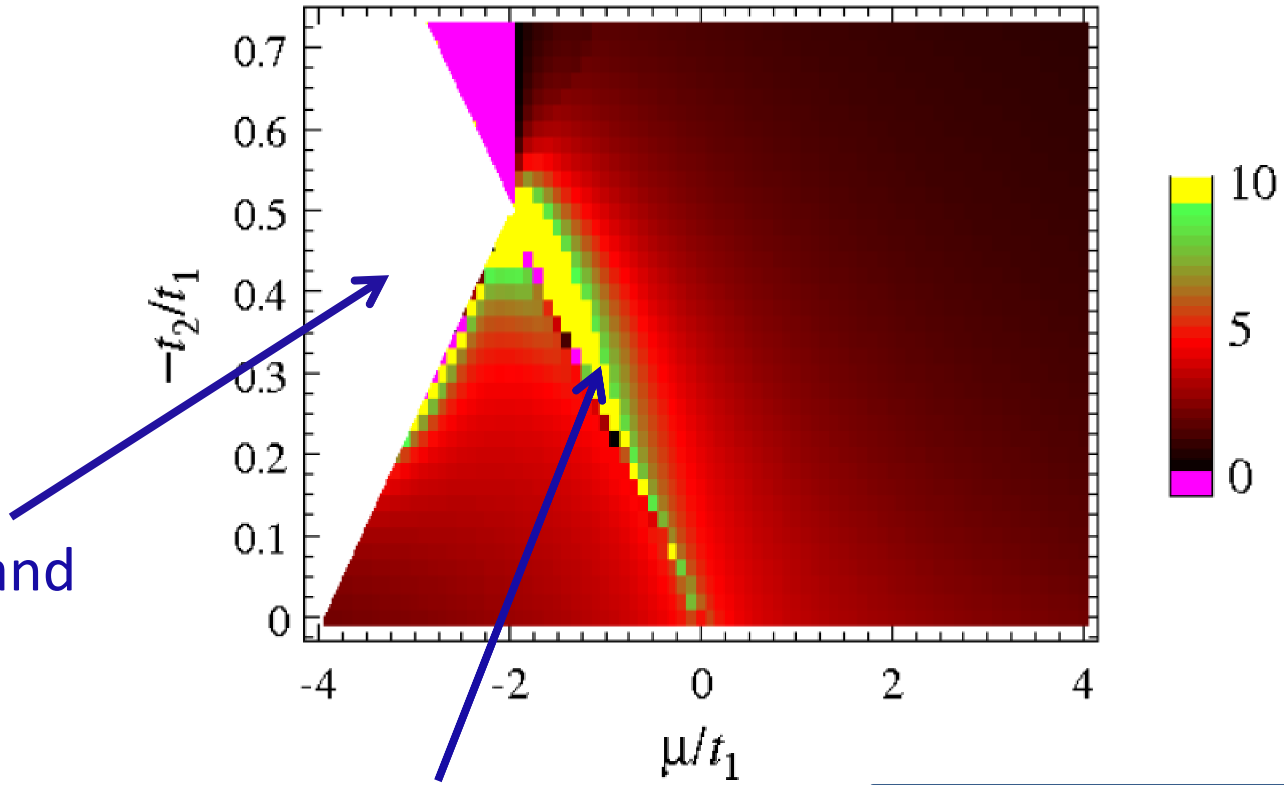
distorted hoppings:

$$t_{1x,y} = (1 \pm \epsilon/2)t_1$$
$$t_{3x,y} = (1 \pm \epsilon/2)t_3$$

Lattice symmetry: $C_4 \longrightarrow C_2$

Anisotropic Nernst effect

$$d(\nu_{yx} - \nu_{xy})/(\nu d\epsilon)$$



Empty band

Van Hove singularity

Amplified anisotropic response !

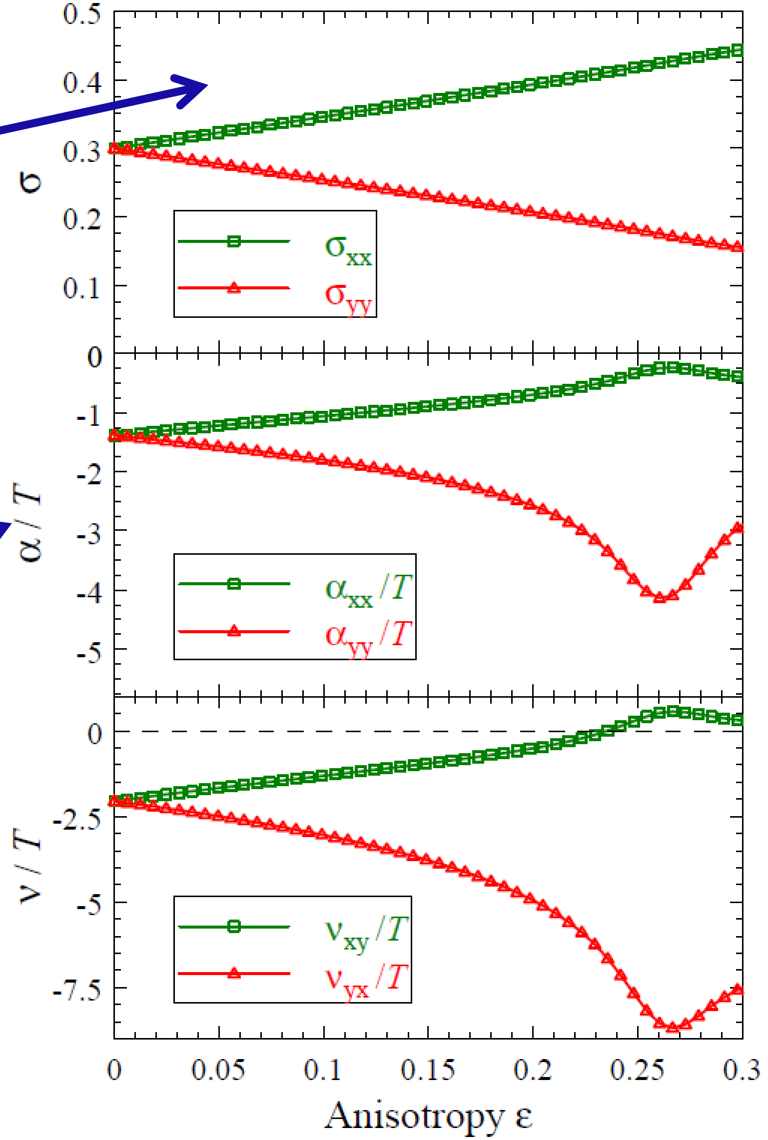
Hackl/Vojta Phys. Rev. B 80, 220514(R) (2009)

Anisotropic Nernst effect

Typical cuprate parameters;

Small anisotropy

Large anisotropy



Summary

Summary

- Strong enhancement of quasiparticle Nernst effect in strongly stripe ordered cuprates at doping x=1/8, qualitative agreement with experiment
- Proposed Nernst signal as unique tool for detection of broken rotational symmetry, e.g. also in $Sr_3Ru_2O_7$
- Results strengthen proposal of the identification of pseudogap phase as nematically ordered state