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MAX-PLANCK-GESELLSCHAFT

Electronic liquid crystals

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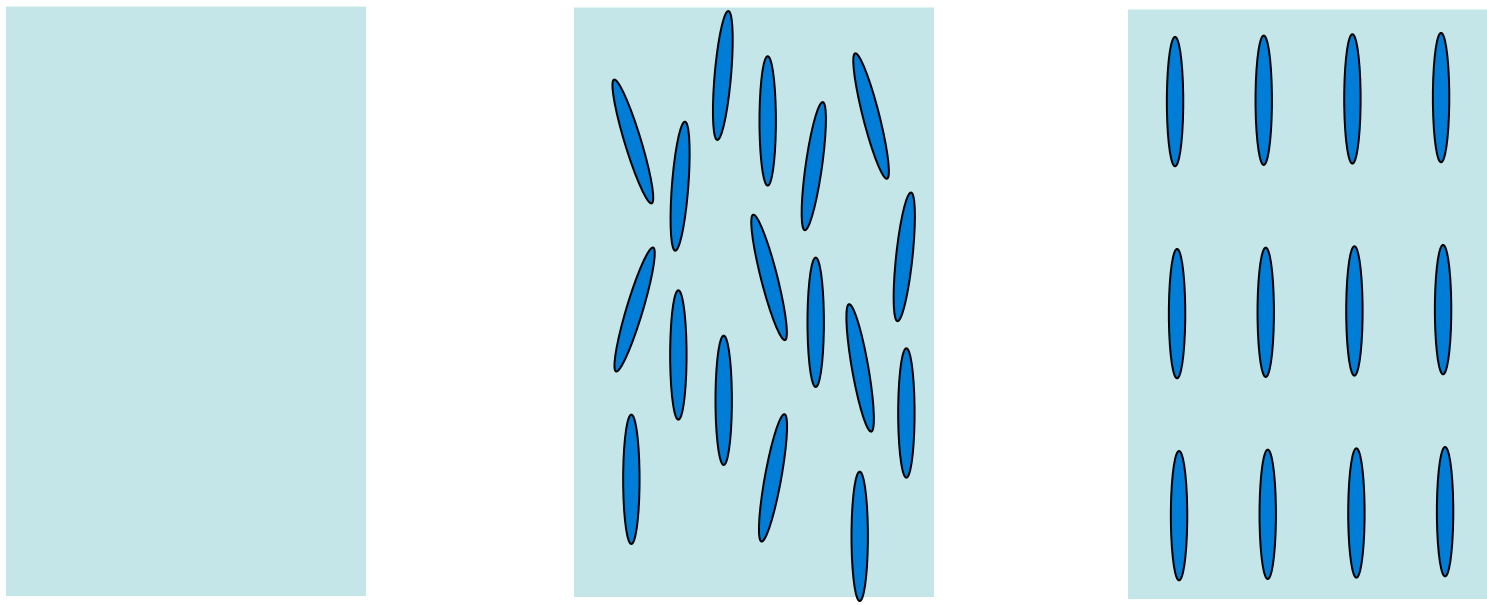
*Review on nematic electronic fluids: E. Fradkin, S.A. Kivelson, M.A. Lawler, J.P. Eisenstein & A.P. Mackenzie, Ann. Rev. Cond. Matt. Phys. **1**, 153 (2010)*

Liquid crystals: ‘Structured liquids’



Isotropic: full symmetry

Nematic: orientational but not translational symmetry breaking

Smectic: orientational *and* translational symmetry breaking

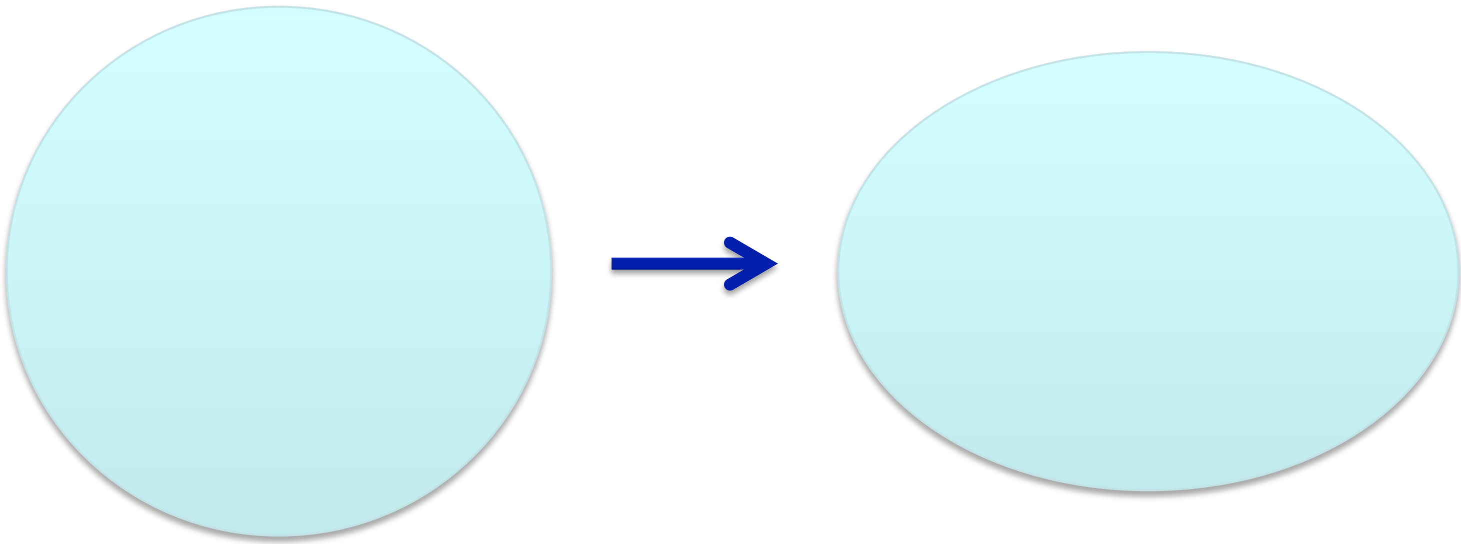
Kivelson, Fradkin & Emery, Nature ***393****, 550 (1998):* is there a productive analogy with textured electronic liquids?

Point particles so no ‘nematogens’; would have to be interaction-driven.

Anisotropic electron fluids – a *k*-space picture

*I.I. Pomeranchuk, JETP **8**, 361-2 (1959) 'On the Stability of a Fermi Liquid'*

The full-symmetry Fermi liquid is stable only as long as none of the Landau parameters is negative and large. If one is, a phase transition to a lower symmetry can take place. Example:

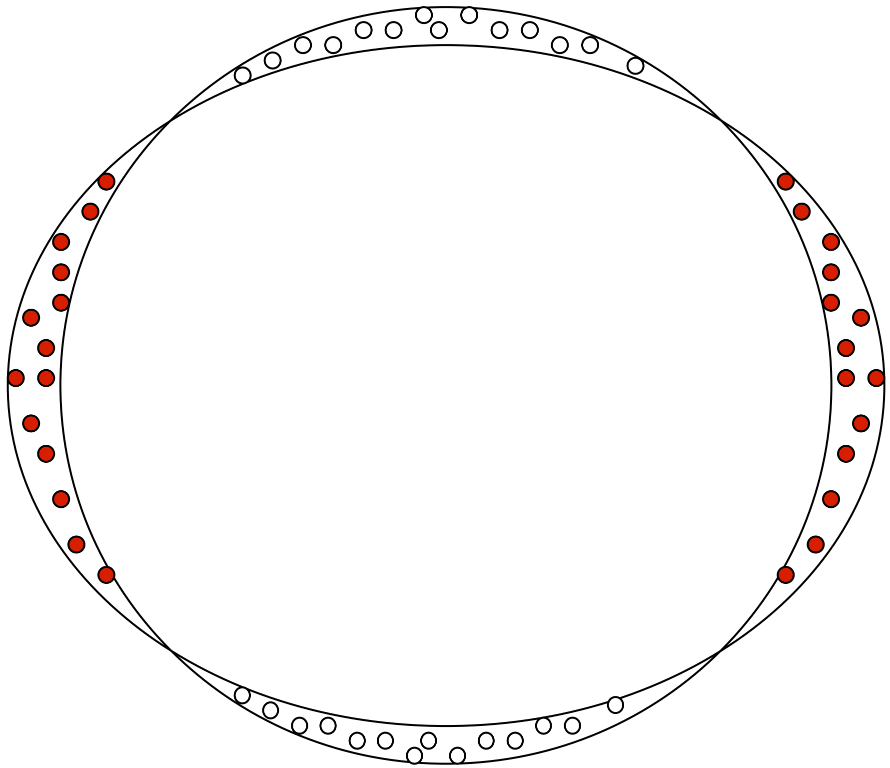


As expected, an instability of this kind depends on details of the quasiparticle dispersion and many-body interactions.

In the electronic liquid crystal nomenclature this is an electronic nematic.

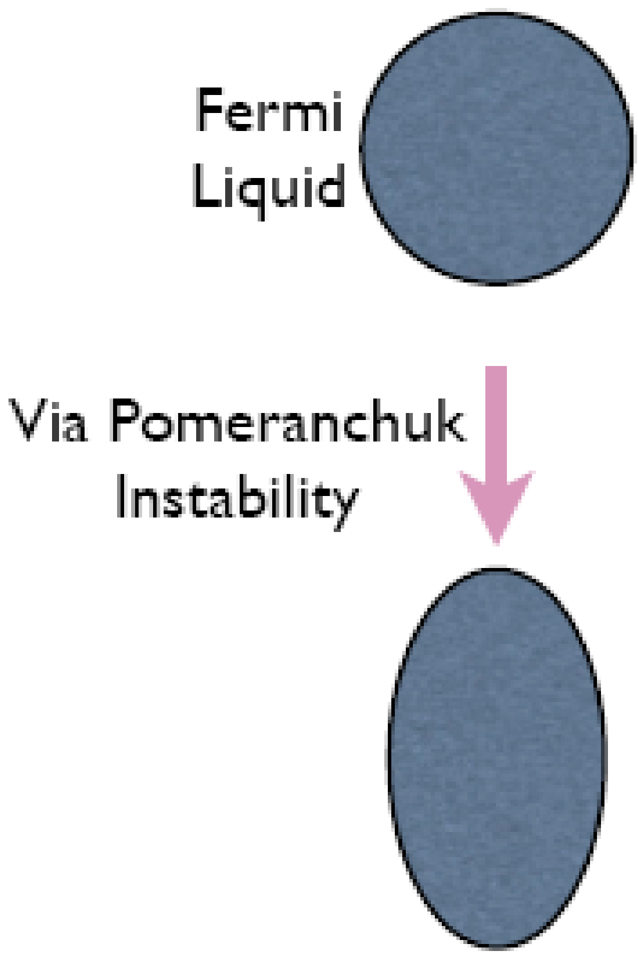
Analogy with unconventional superconductivity

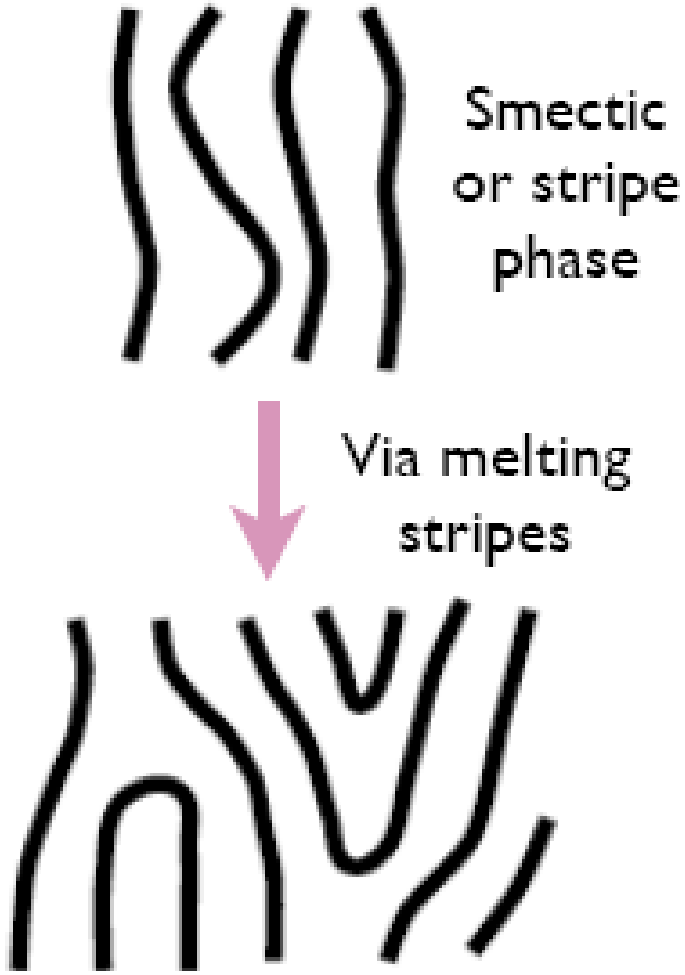
Think of the instability as a kind of particle-hole pairing



$N_\ell = \sum_{\mathbf{k}} n(\mathbf{k}) \exp[i\ell\theta(\mathbf{k})]$; here ℓ = 2 and this is a '*d-wave distortion in the particle-hole channel*'

The electronic nematic in a second limit





Weak coupling

k-space picture

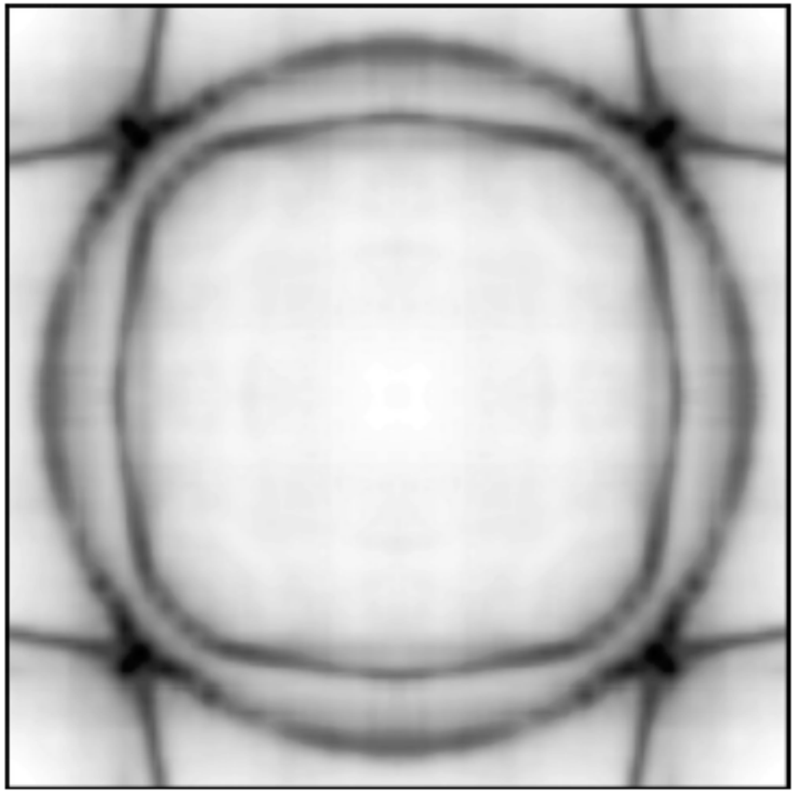
‘BCS’ limit

Strong coupling

Real space picture

‘BEC’ limit

Effect of a lattice in a real solid



Real Fermi surface of a three-band metal measured by photoemission

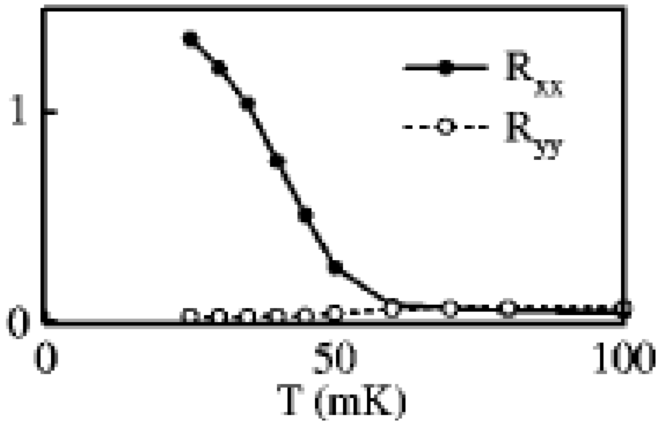
1. Usually correlation physics is primarily sensitive to *U* and *W*

For electronic liquid crystal physics the lattice potential *V* is explicitly important. Crudely, want *U*, *V* & *W* to be similar. This is quite rare, because it is not easy to tune *V* and *W* independently.

2. The highest symmetry in the problem is that of the lattice but as long as *W* is finite there *must* be a lattice response to a new electronic symmetry.

The question becomes whether the valence electrons or the lattice drive the symmetry lowering.

Famous early observations in GaAs 2D electron gases



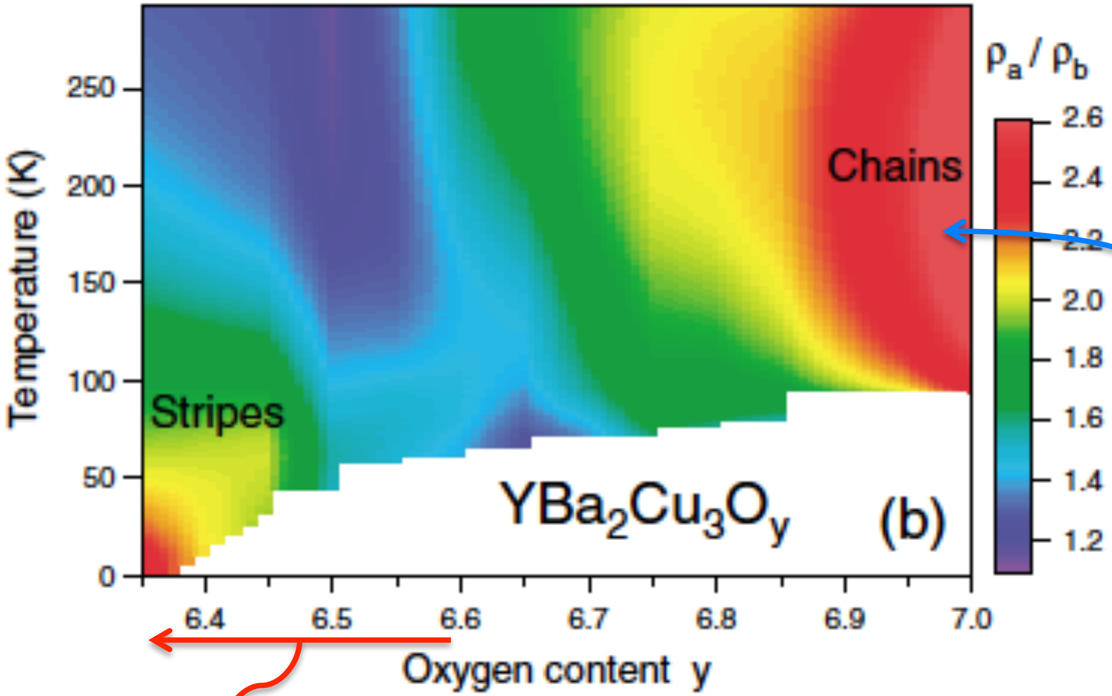
Spontaneous resistive anisotropy in a high purity 2-DEG at low Landau level.

Low density semiconductor so *U, V* are small. Intuitively *W* would be larger.

However, Landau quantisation quenches *W* so for at least two low Landau levels the conditions are right for liquid crystalline physics.

M.P. Lilly, K.B. Cooper, J.P. Eisenstein, L.N. Pfeiffer & K.W. West, Phys. Rev. Lett. ***82****, 394 (1999); ibid* ***83****, 824 (1999)*

Transport in high T_c cuprate superconductors also shows electronic anisotropy, but it is subtle.



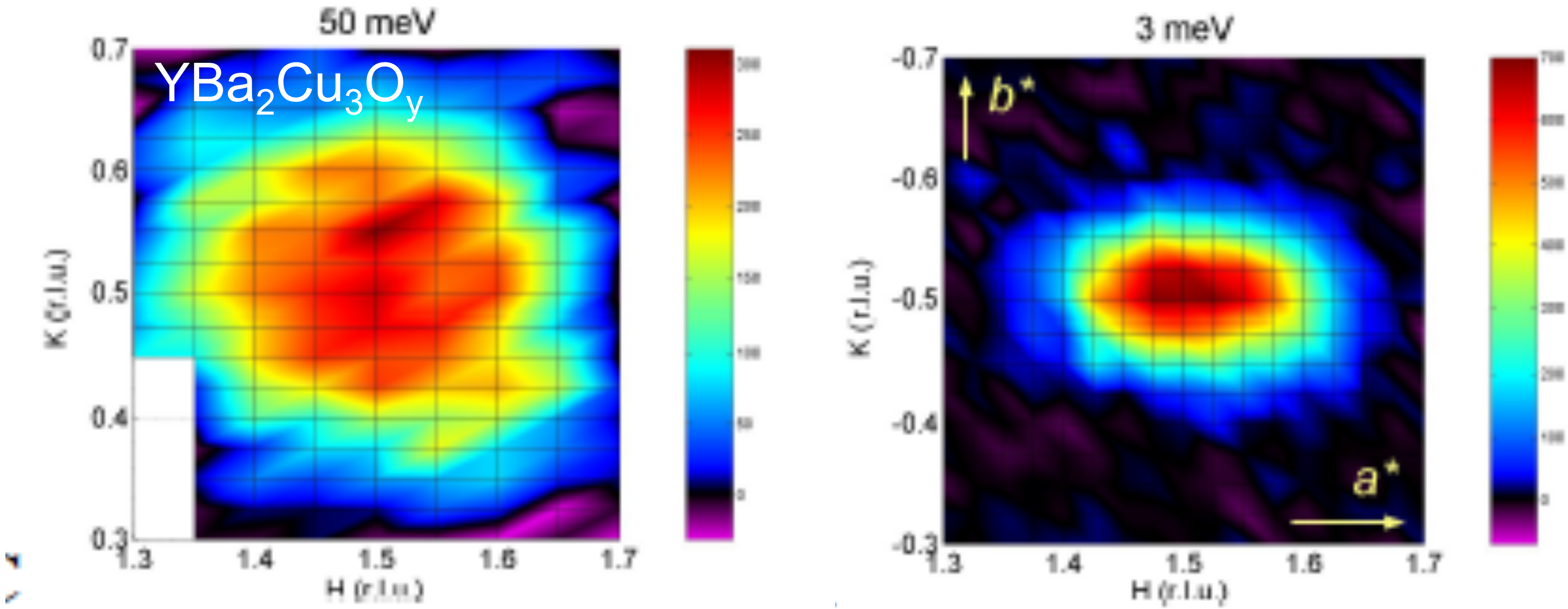
$YBa_2Cu_3O_y$ is quite strongly orthorhombic, so no surprise to see anisotropic transport, but..

Structurally driven anisotropy

Orthorhombicity is decreasing but electronic anisotropy is increasing

Y. Ando, K. Segawa, S. Koyima and A.N. Lavrov, Phys. Rev. Lett. ***88****, 137005 (2002)*

Anisotropy of the spin response in untwinned crystals



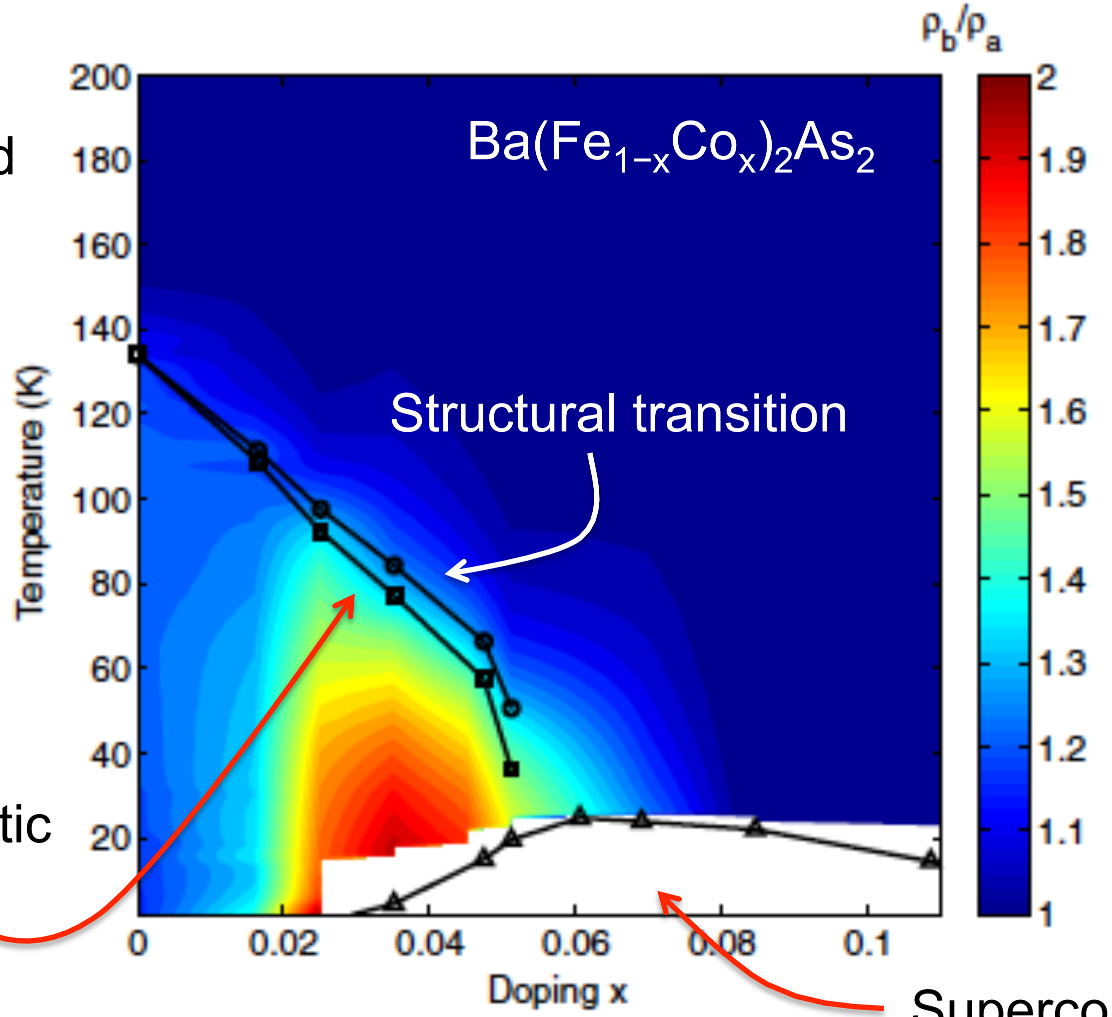
*V. Hinkov, D. Haug, B. Fauque, P. Bourges, Y. Sidis, A. Ivanov, C. Bernhard, C. T. Lin, and B. Keimer, Science **319**, 597 (2008)*

Anisotropy also seen in thermoelectric coefficients.

R. Daou, J. Chang, D. LeBoeuf, O. Cyr-Choiniere, F. Laliberte, N. Doiron-Leyraud, B. J. Ramshaw, R. Liang, D. A. Bonn, W. N. Hardy, and L. Taillefer, Nature 463, 519 (2010)

Qualitatively similar observations in pnictide superconductors

Crystals pre-stressed to suppress twinning

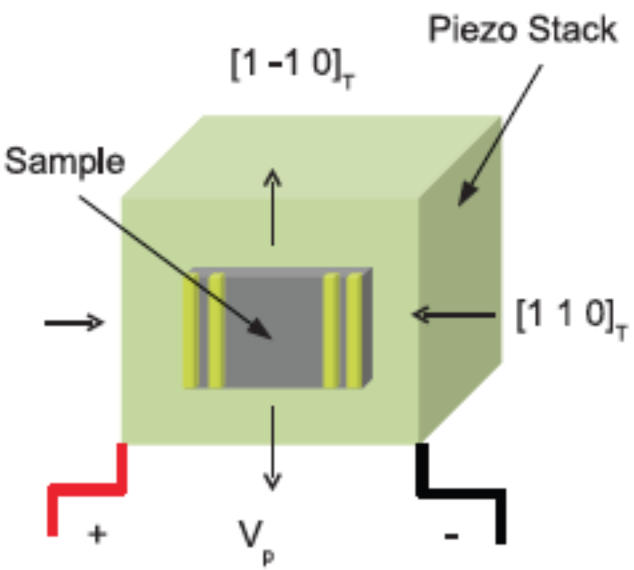


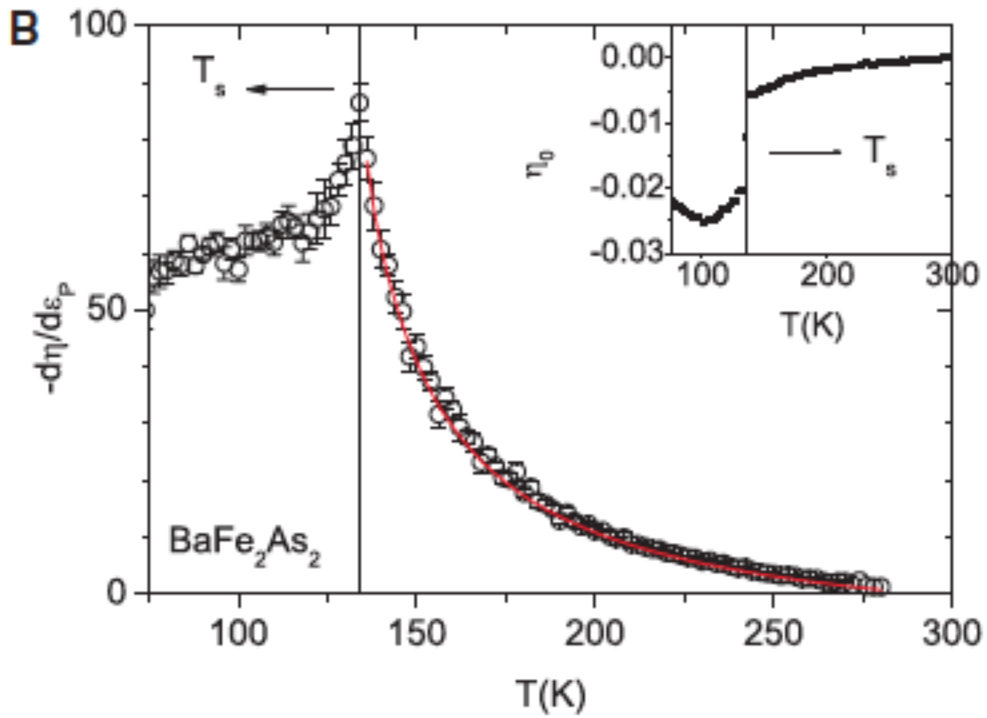
Antiferromagnetic transition

Superconductivity

*J.-H. Chu, J.G. Analytis, K. De Greve, P. McMahon, Z. Islam, Y. Yamamoto and I.R. Fisher Science **329**, 824 (2010)*

Identify purely electronic effects by working at constant strain

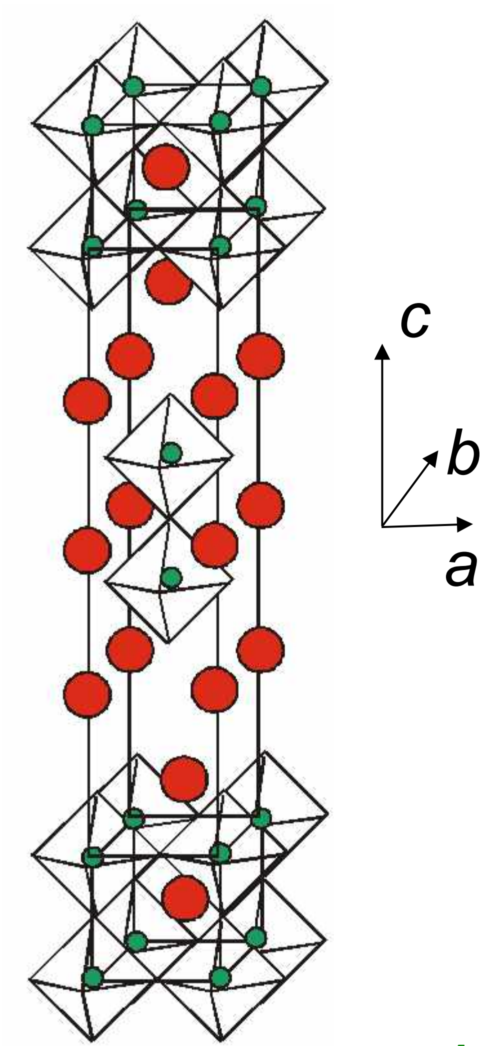




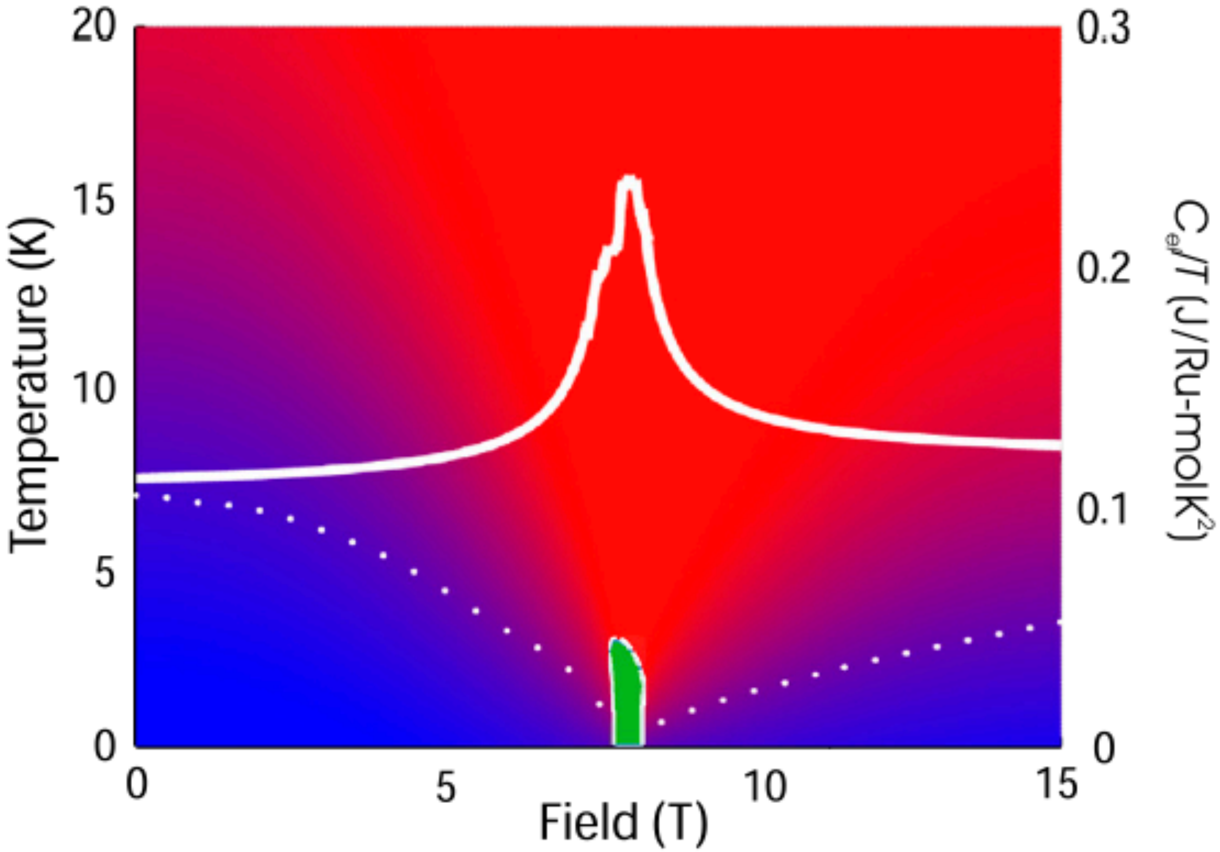
Idea – if the electrical anisotropy were caused by structural distortion, its temperature dependence would be nulled by preventing the structural change by holding the strain constant.

*J.-H. Chu, H.-H. Kuo, J.G. Analytis & I.R. Fisher, Science **337**, 710 (2012)*

The layered perovskite metal $Sr_3Ru_2O_7$

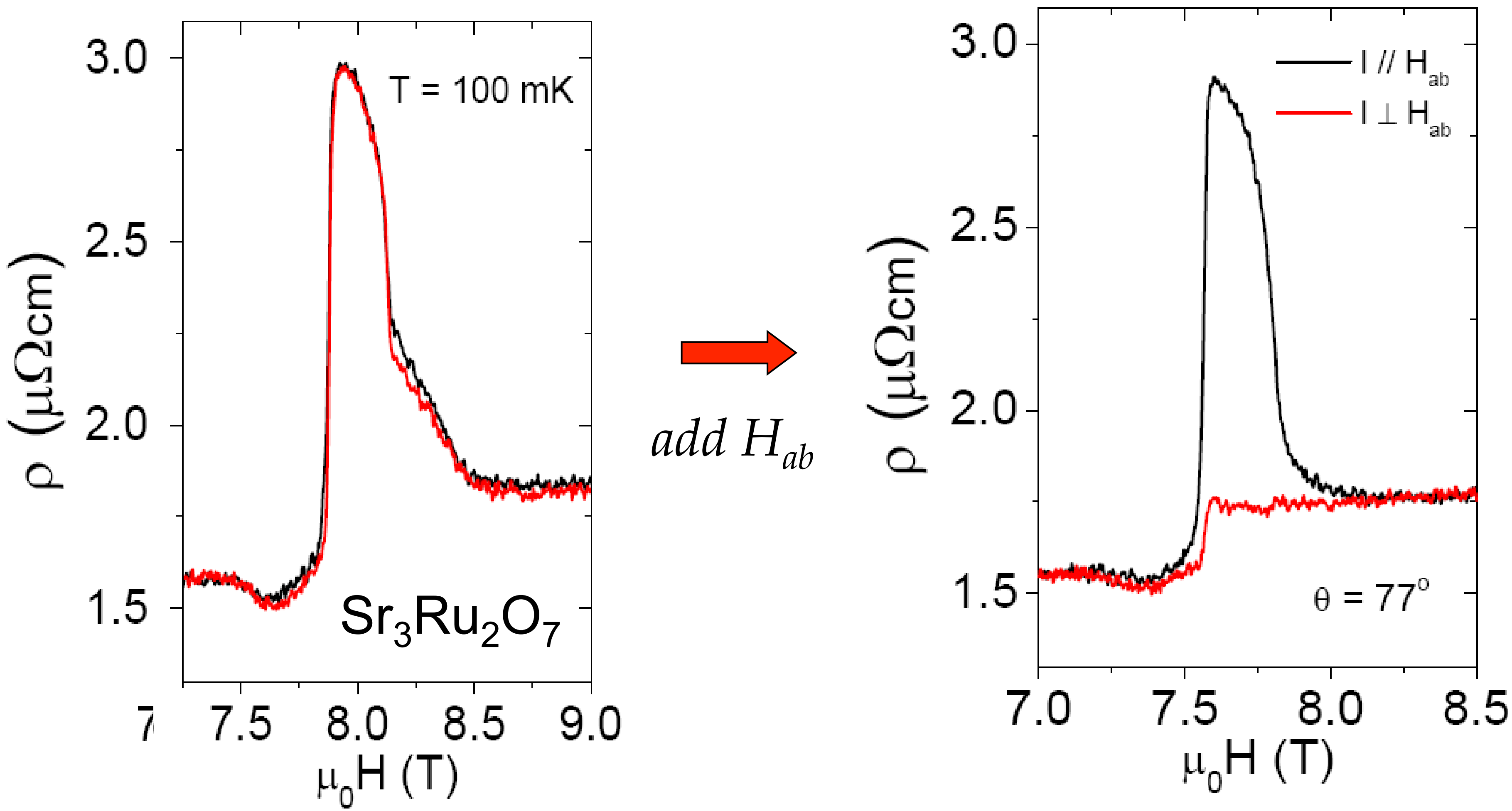


Quasi–2D metal



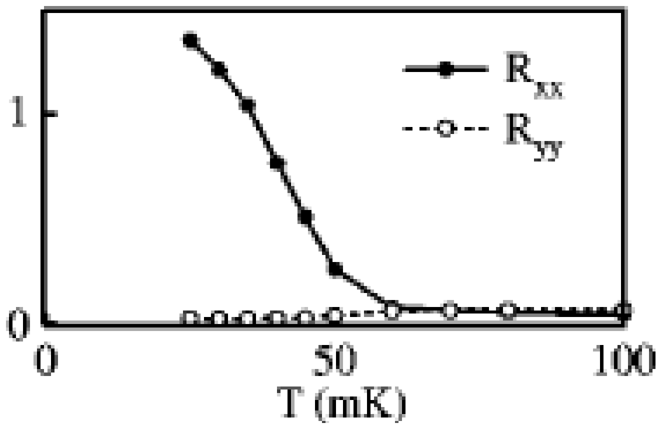
A.W. Rost, S.A. Grigera, J.A.N. Bruin, R.S. Perry, D. Tian, S. Raghu, S.A. Kivelson & A.P. Mackenzie, Proc. Nat. Acad. Sci. ***108****, 16549 (2011)*

Anisotropic resistivity stimulated by in-plane magnetic field

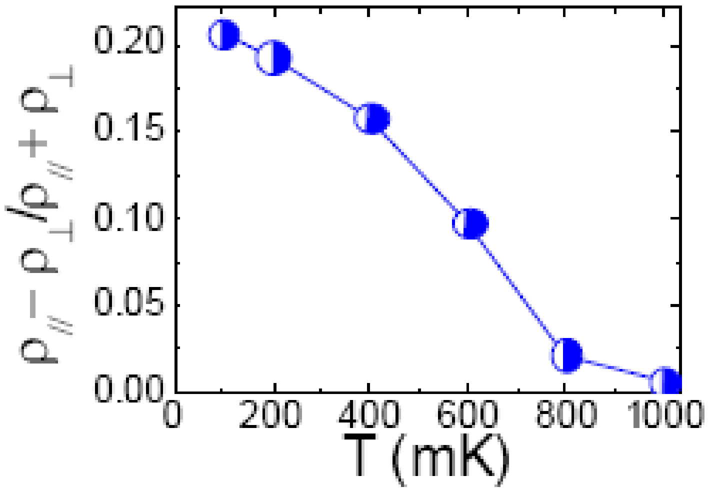


*R.A. Borzi, S.A. Grigera, J. Farrell, R.S. Perry, S. Lister, S.L. Lee, D.A. Tennant, Y. Maeno & A.P. Mackenzie, Science **315**, 214 (2007)*

Intriguing similarity with GaAs 2D devices



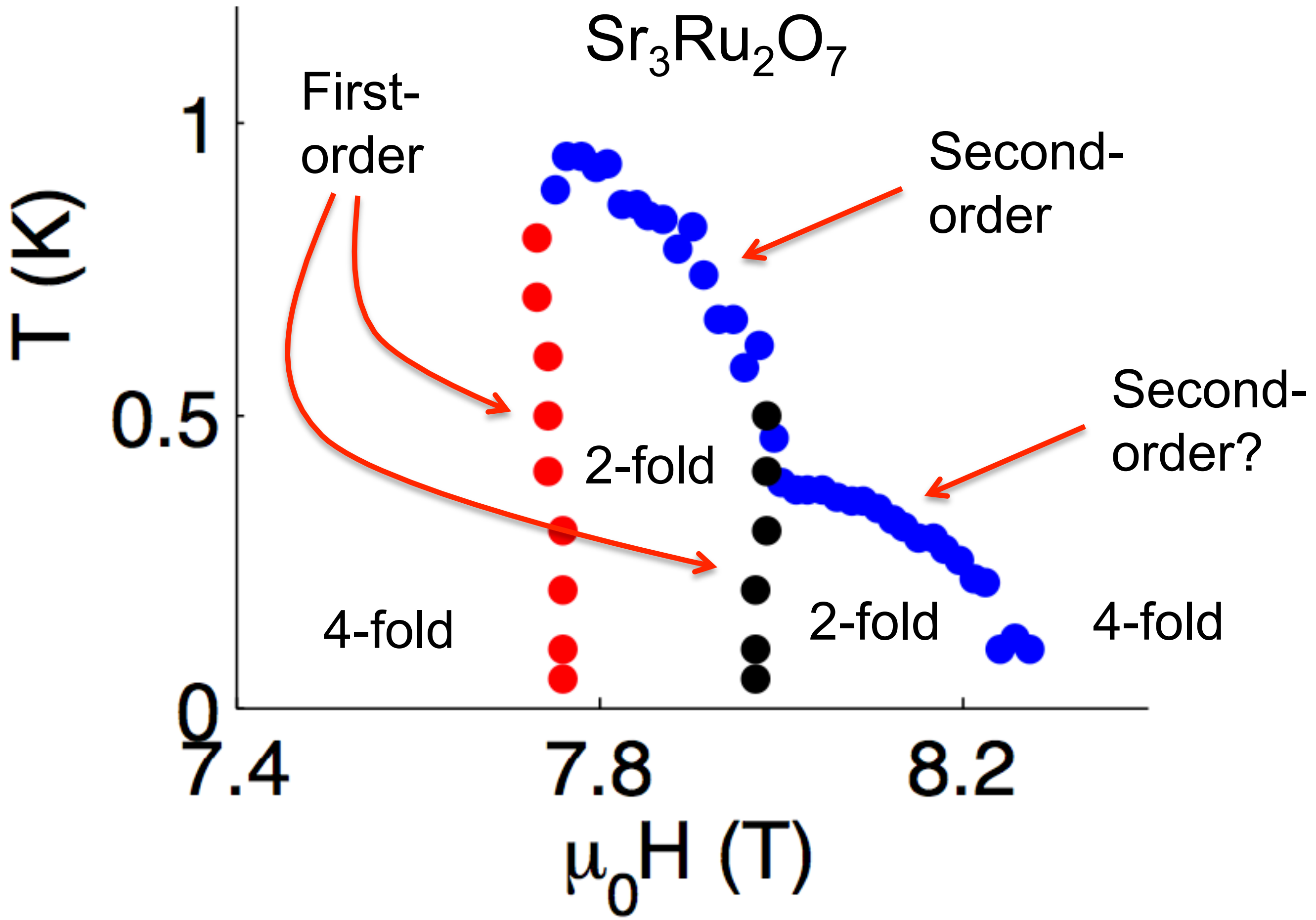
Resistive anisotropy in a high purity 2-DEG at low Landau level.



Resistive anisotropy in a high purity $Sr_3Ru_2O_7$ single crystal but at quite *high* Landau level.

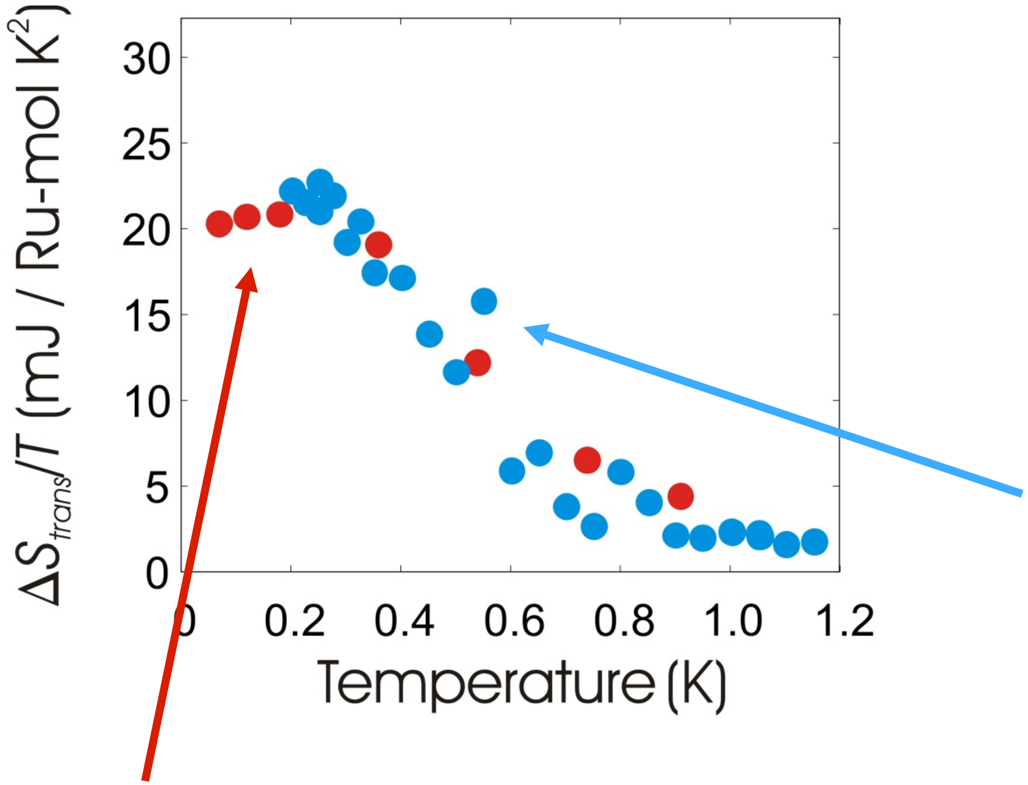
Idea – the quantum critical tuning, rather than Landau quantisation, is quenching the bandwidth *W.*

Phase diagram deduced from transport and thermodynamics



*J.A.N. Bruin, R.A. Borzi, S.A. Grigera, A.W. Rost, R.S. Perry and A.P. Mackenzie, Phys. Rev. B **87**, 161106 (2013).*

Entropy jumps on entering phase from low field



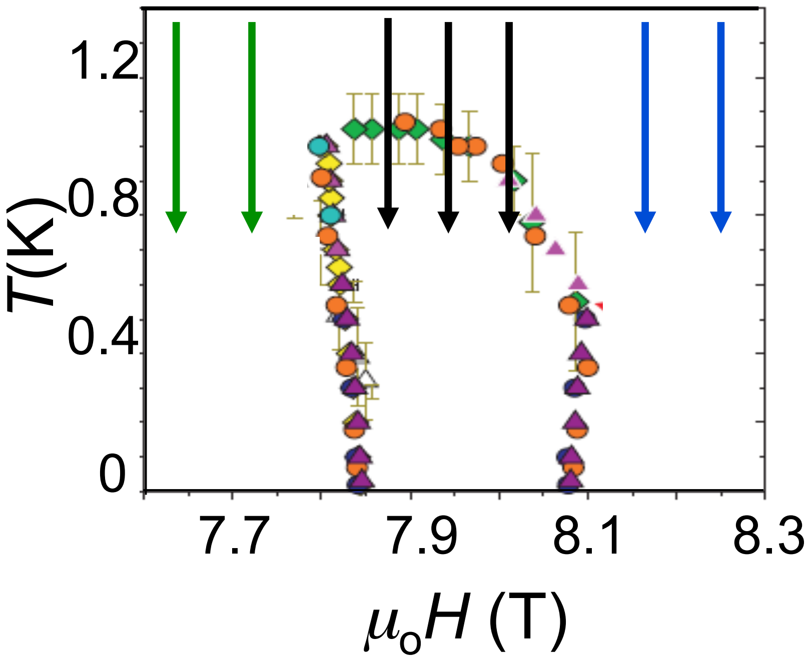
Entropy jump at first order phase boundary from direct analysis of magneto-caloric effect data

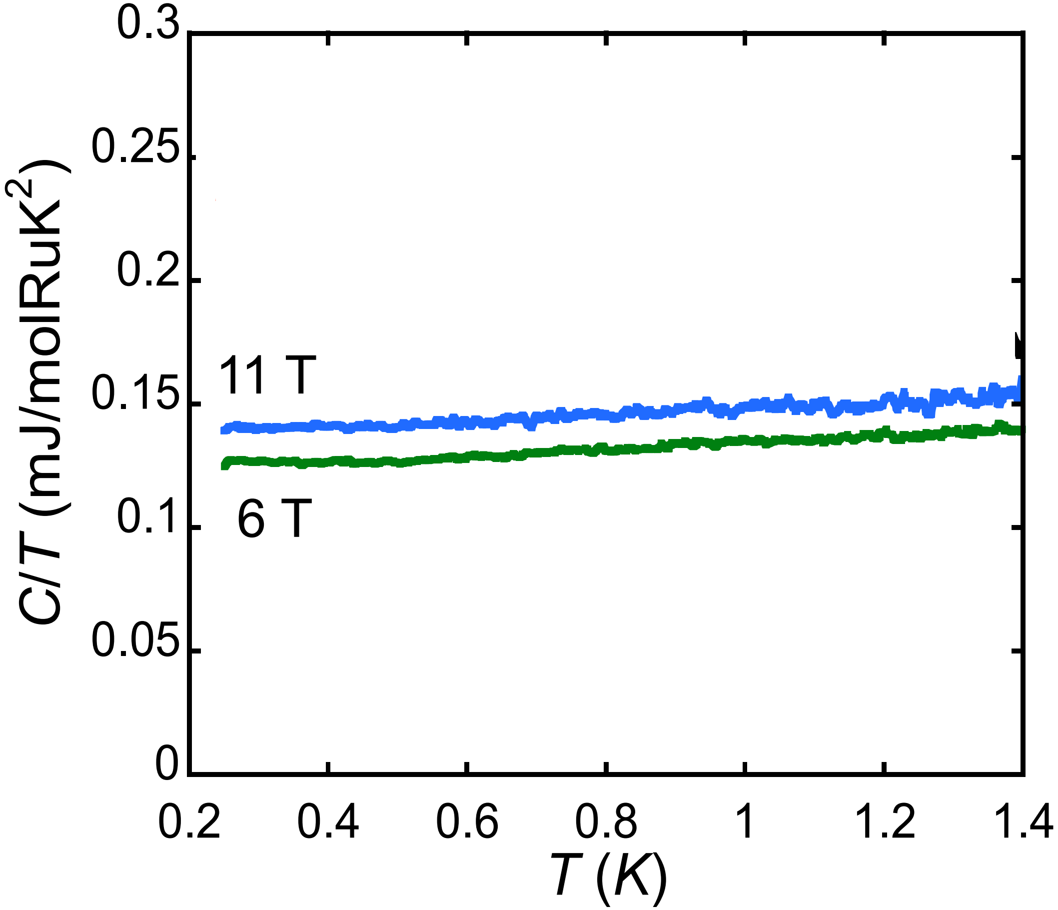
Entropy jump determined independently from magnetisation data and Clausius Clapeyron relation

$$\frac{dH_c}{dT_c} = -\frac{\Delta S}{\Delta M}$$

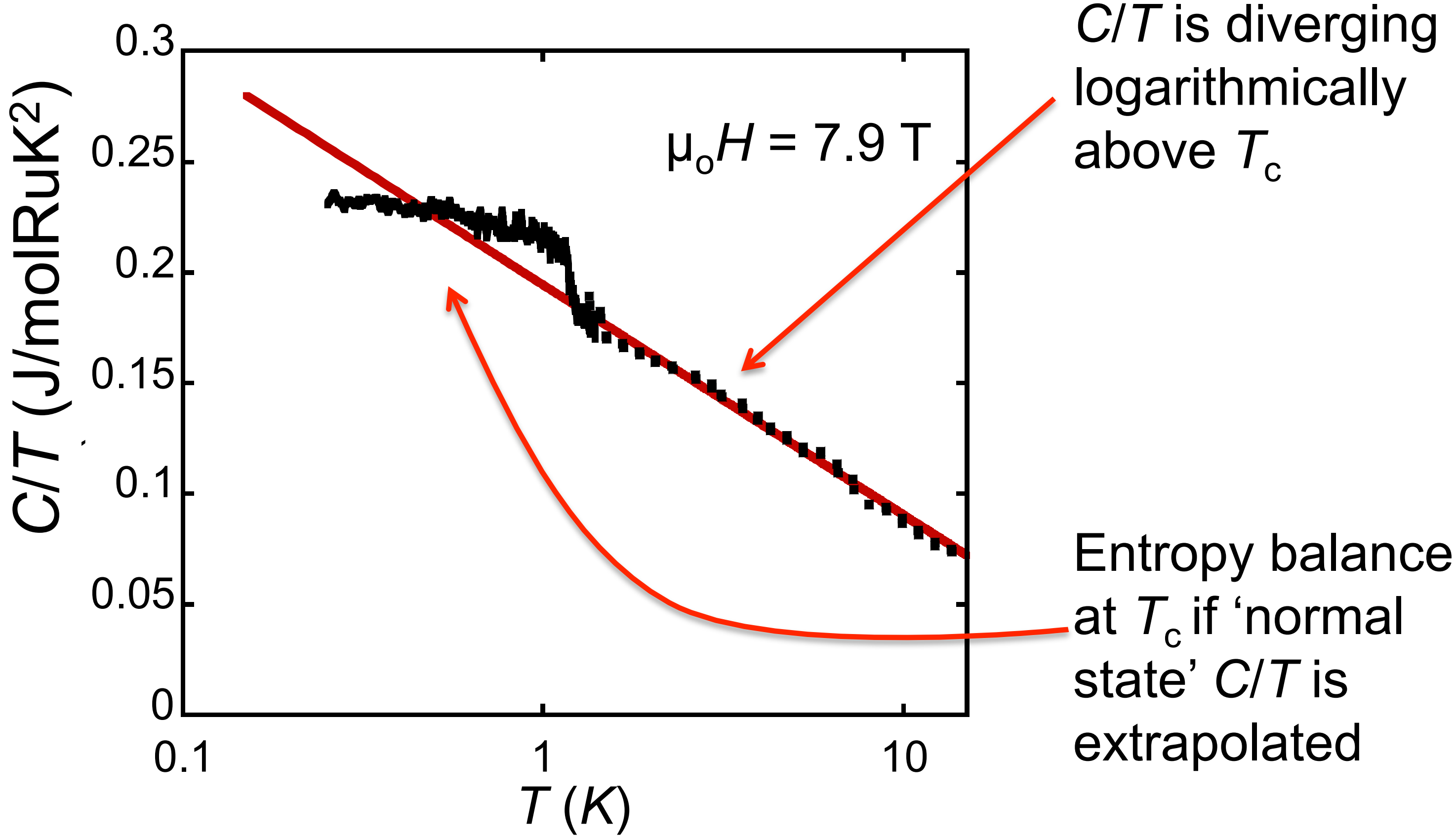
*A.W. Rost, R.S. Perry, J.F. Mercure, A.P. Mackenzie & S.A. Grigera, Science **325**, 1360 (2009).*

Also unusual specific heat signature of entry to phase as a function of T



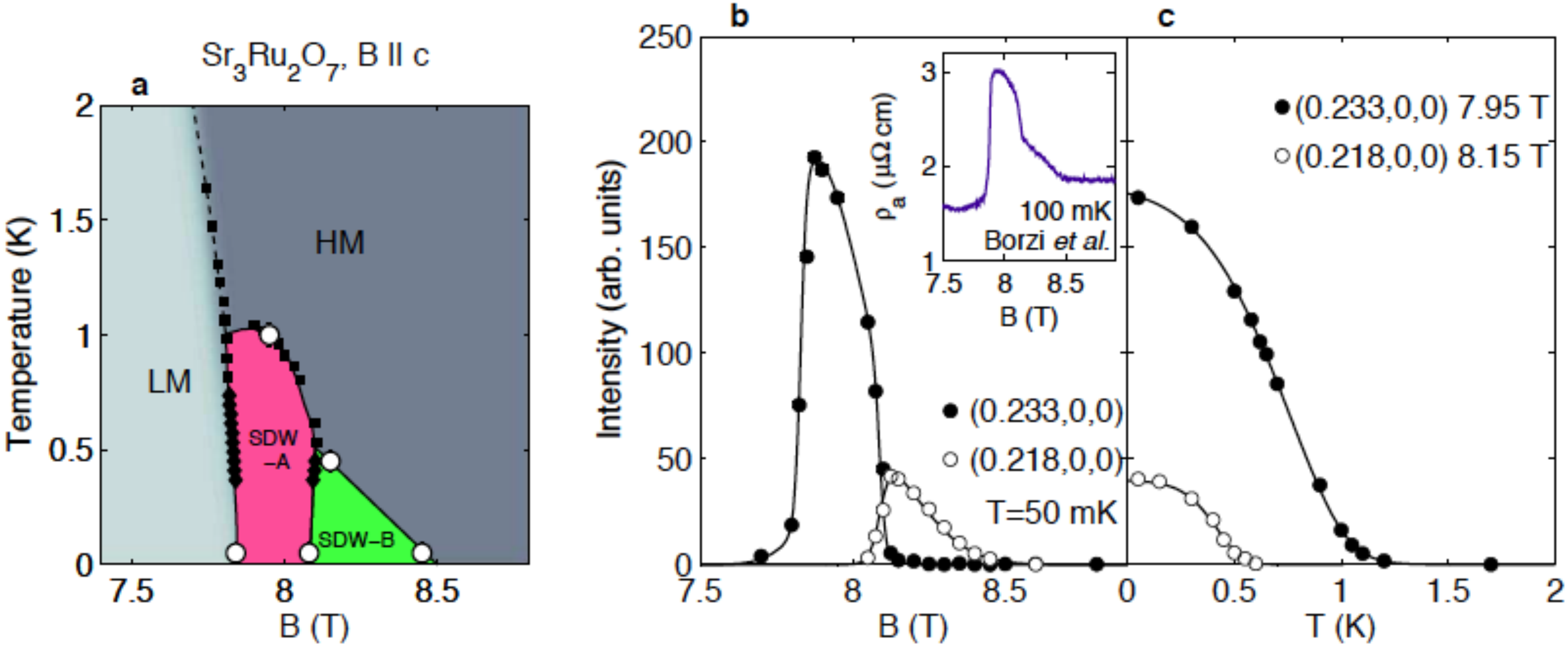


Also unusual specific heat signature of entry to phase as a function of *T*



Although the phase is metallic and thermodynamically well-defined, it seems to be associated with degrees of freedom additional to those of a standard Fermi liquid. Also not obviously a gapping transition.

As of a few months ago – $Sr_3Ru_2O_7$ is actually a smectic

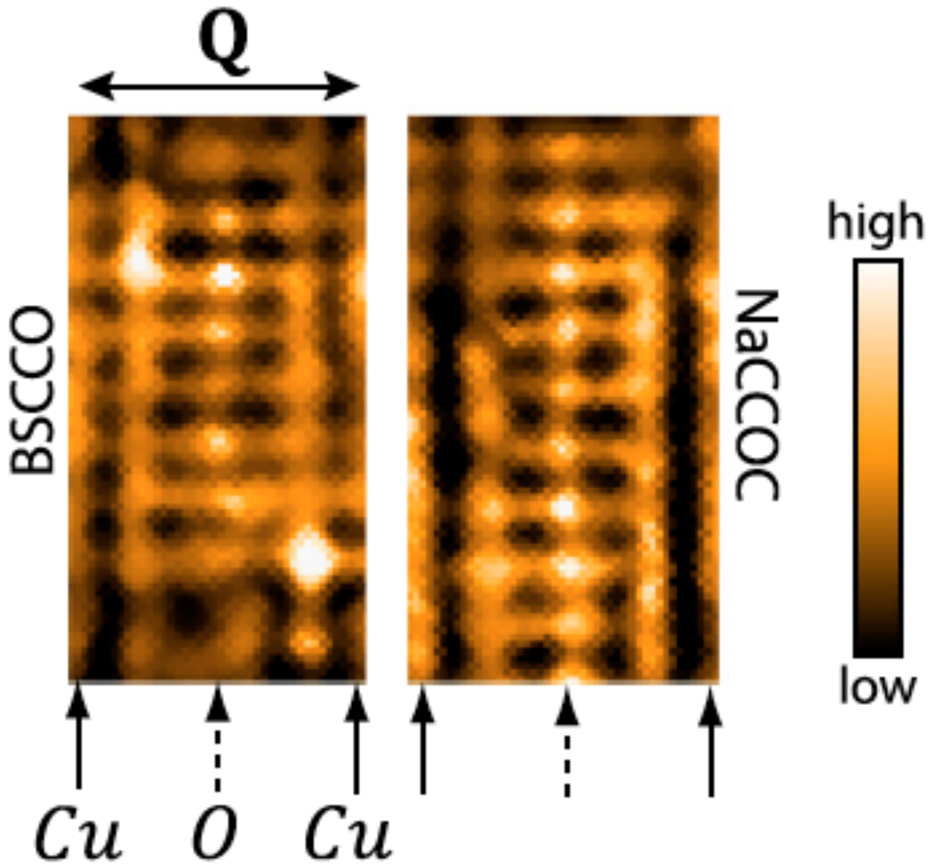


'Stripey' magnetic response detected by polarised neutron scattering.

Relationship with transport and thermodynamic properties not yet fully clear but this is an exciting development.

C. Lester, S. Ramos, R.S. Perry, T. P. Croft, R. I. Bewley, T. Guidi, P. Manuel, D.D. Khalyavin, E.M. Forgan and S.M. Hayden. arXiv 1409.7054v1

Huge topical interest in smectic structures – e.g. in cuprates



Atomically-resolved STM conductance patterns

K. Fujita, M. H. Hamidian, S.D. Edkins, C.K. Kima, Y. Kohsaka, M. Azumaf, M.Takano, H. Takagi, H. Eisaki, S.-I. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. S. Davis, Proc. Nat. Acad. Sci ***111****, E3026 (2014)*

Unconventional density wave (DW) : Bose condensation of particle-hole pairs

$$\langle c_\alpha^\dagger(\mathbf{r}_1) c_\alpha(\mathbf{r}_2)\rangle$$

$$= \left[\mathcal{P}(\mathbf{r}_1 - \mathbf{r}_2)\right] \times \Psi_{DW}\left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2}\right) e^{i\mathbf{Q}\cdot(\mathbf{r}_1+\mathbf{r}_2)/2}$$

Density wave **form factor** (internal particle-hole pair wavefunction)

$$\mathcal{P}(\mathbf{r}) = \int \frac{d^2k}{4\pi^2} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{r}}$$

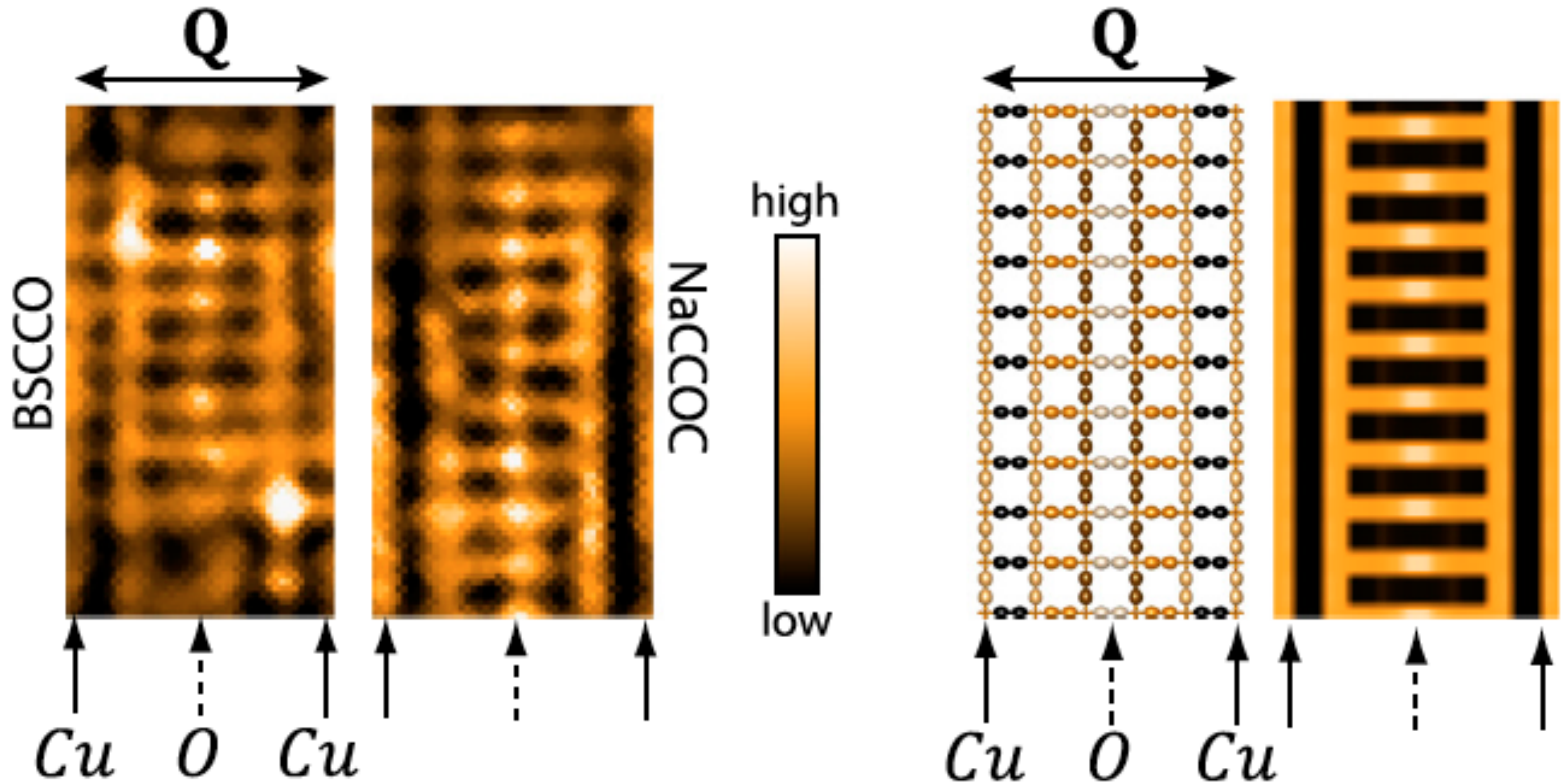
Time-reversal symmetry requires $\mathcal{P}(\mathbf{k}) = \mathcal{P}(-\mathbf{k})$.

We expand (using reflection symmetry for $\mathbf{Q}$ along axes or diagonals)

$$\mathcal{P}(\mathbf{k}) = \mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$$

M.A. Metlitski and S. Sachdev, *Phys. Rev.* B **85**, 075127 (2010)

Particle-particle vs particle hole: more than just a conceptual analogy?



D-form factor smectic…. Significant in terms of trying to identify the minimal microscopic Hamiltonian for high-T_c cuprate superconductors

D. Chowdhury and S. Sachdev, arXiv:1409.5430v1 and references therein

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Summary and conclusions

1. Electrons in metals can adopt a range of state analogous to liquid crystalline states of classical systems.

2. This is still a growing field of research, requiring new imaging techniques such as those that revolutionised soft matter physics.

3. Comparison between leading order instabilities in different channels offers the hope of identifying new ‘generic minimal Hamiltonians’ for interacting metals and superconductors.

4. We should not be too limited in imagining what might be possible….

How complex could pattern formation in electrons be?
Recall the ferrofluid in a magnetic field