University of St Andrews
School of Physics and Astronomy

Spontaneous resistive anisotropy at high fields in $Sr_3Ru_2O_7$

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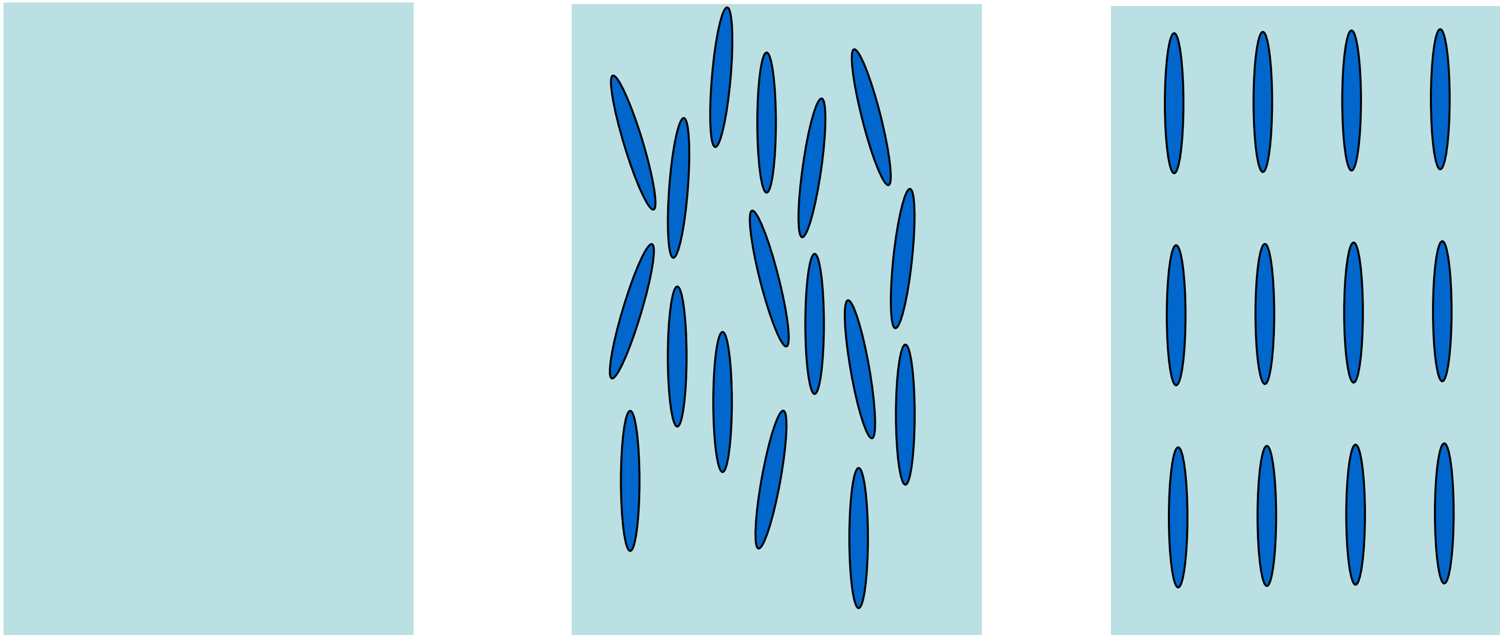
Introduction: Terminology

Liquid crystal



Isotropic | Nematic | Smectic

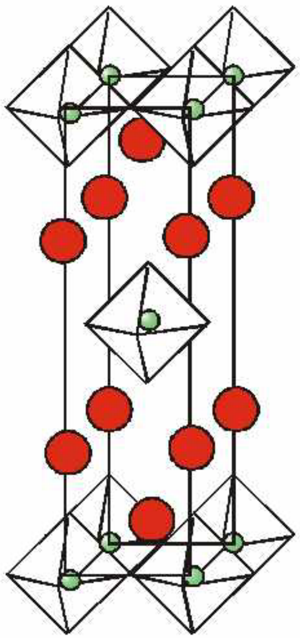
Metal

Electron fluid fully respects lattice symmetries

Lattice symmetries ‘broken’ by conduction electrons; nematic breaks them more weakly than smectic.

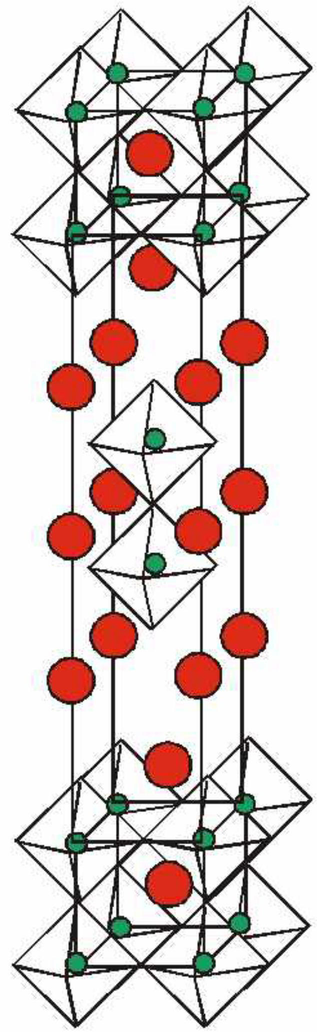
Introduction: Materials

The Ruddlesden-Popper Series: $Sr_{1+n}Ru_nO_{1+3n}$

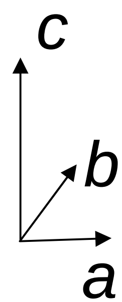


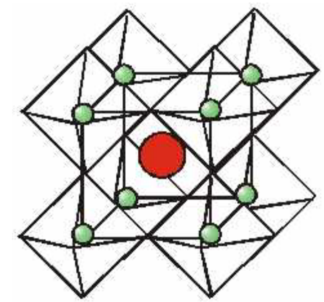
n=1

quasi-2d
Paramagnetic Fermi liquid
Triplet superconductor



n=2





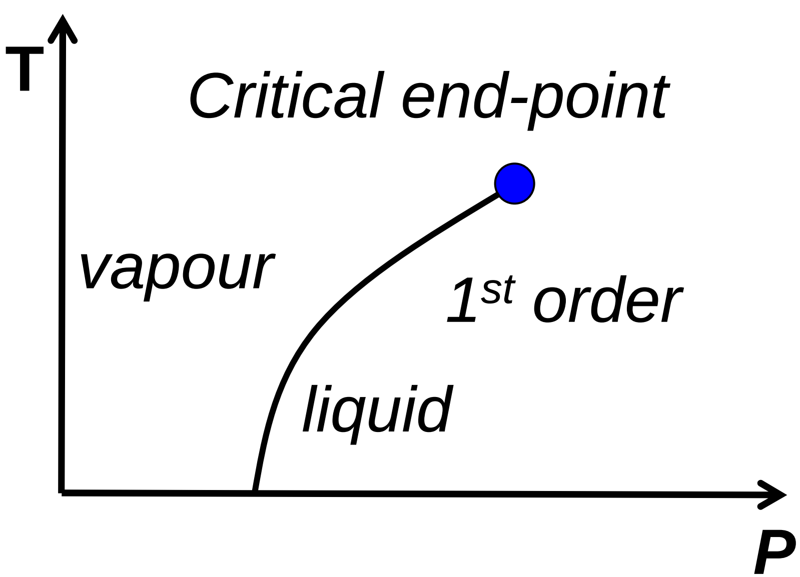
n=∞

3d
Ferromagnetic,
T_c=160K

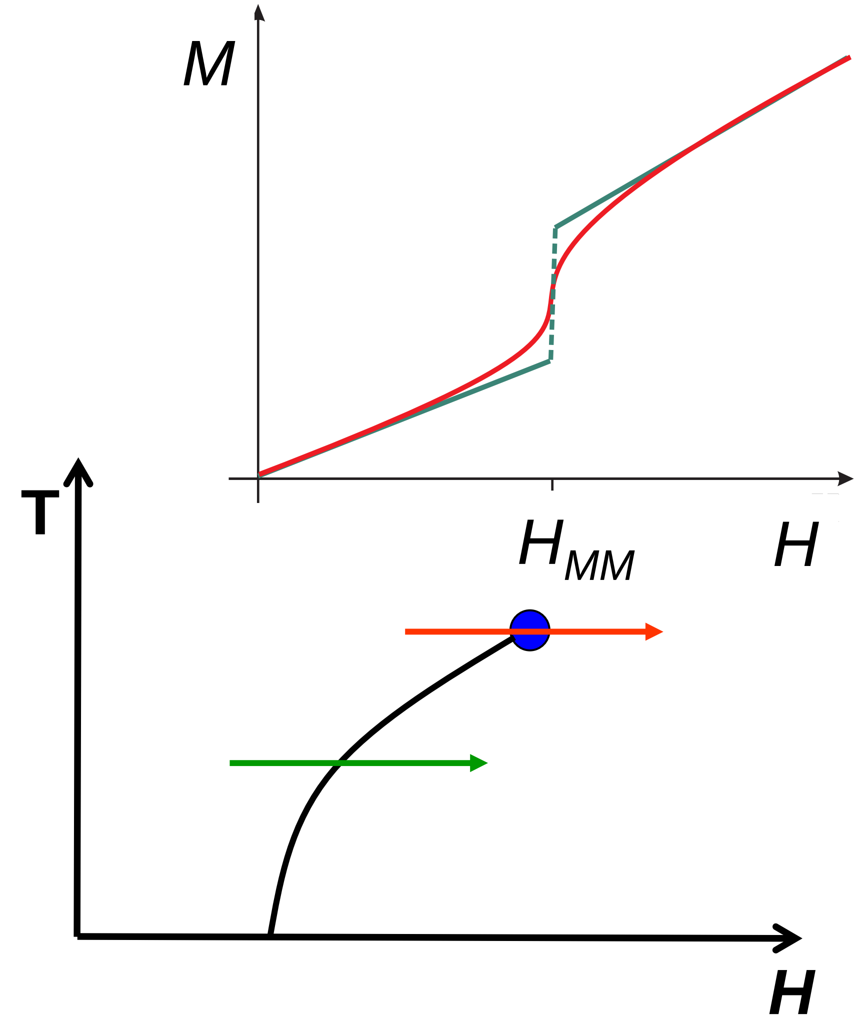
Introduction: Metamagnets and vapour-liquid transition

Mapping between both systems

P, T, ρ ⇔ *H, T, M*

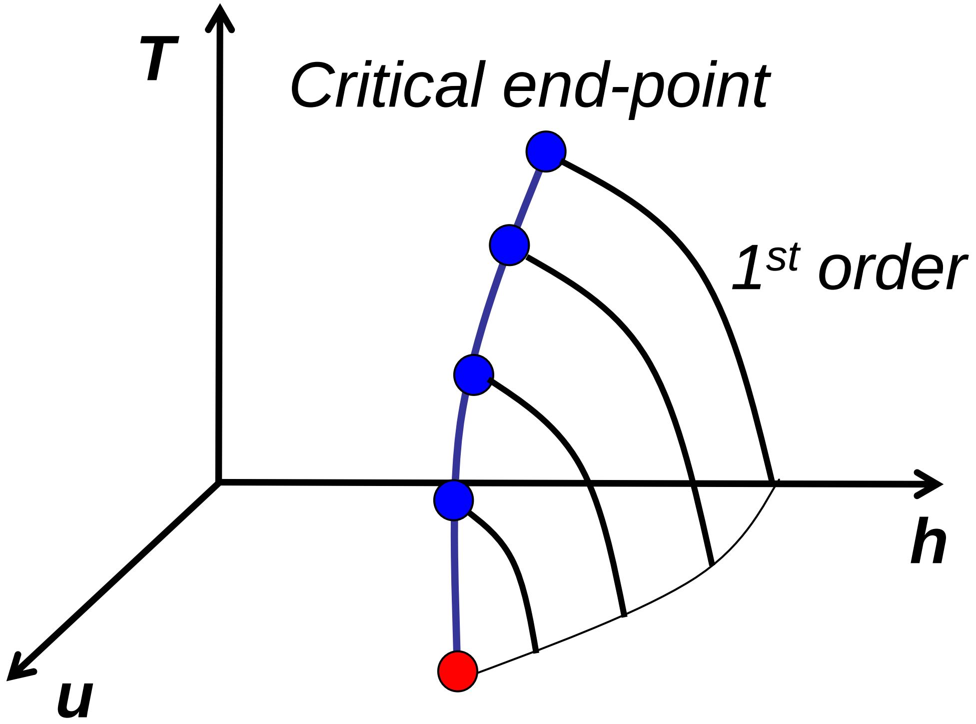


Jump in M vs H (ρ vs P)

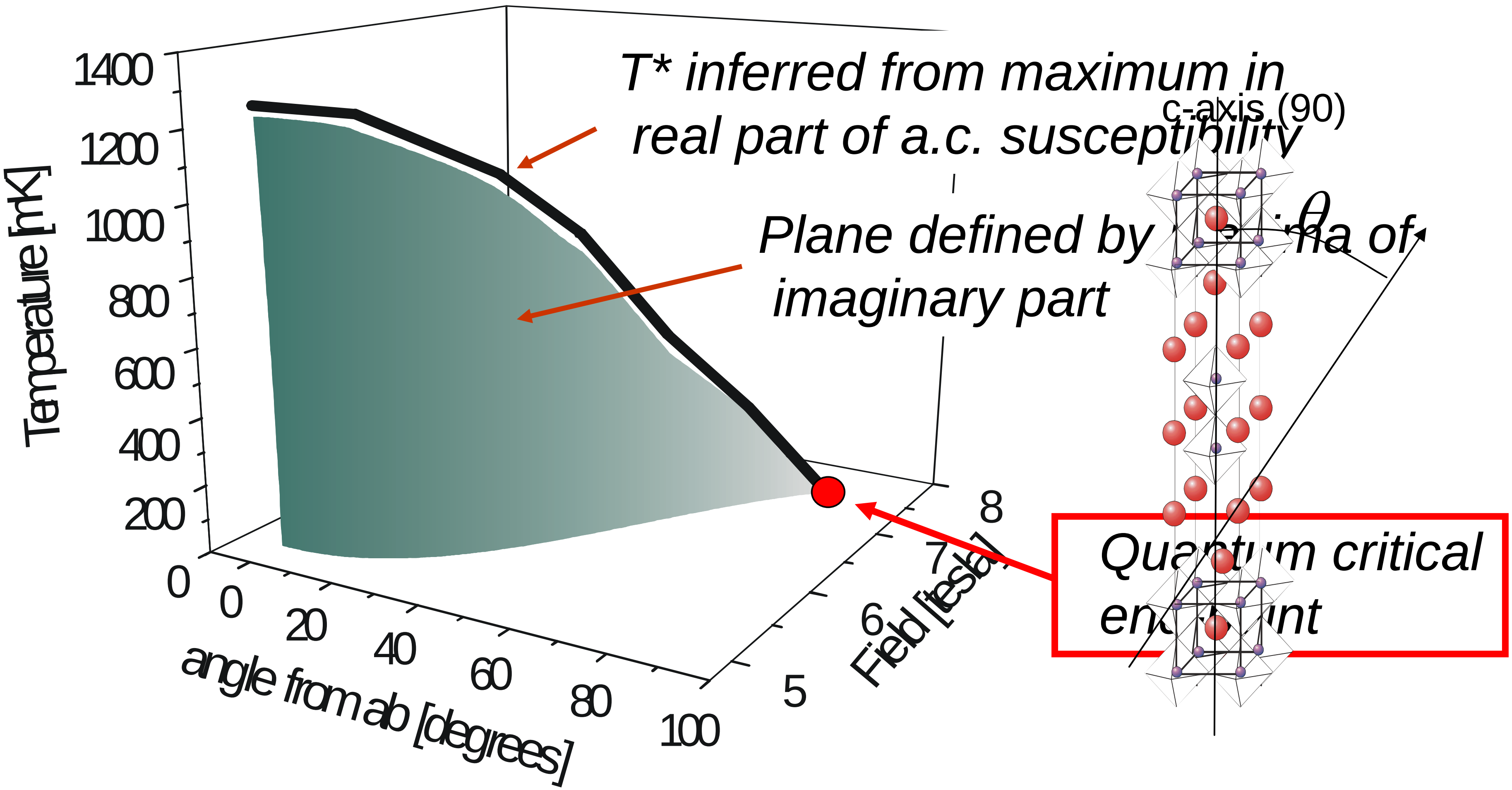


Introduction: Metamagnets and Quantum critical points

Important difference with water: The transition can be tuned to *T*=0.



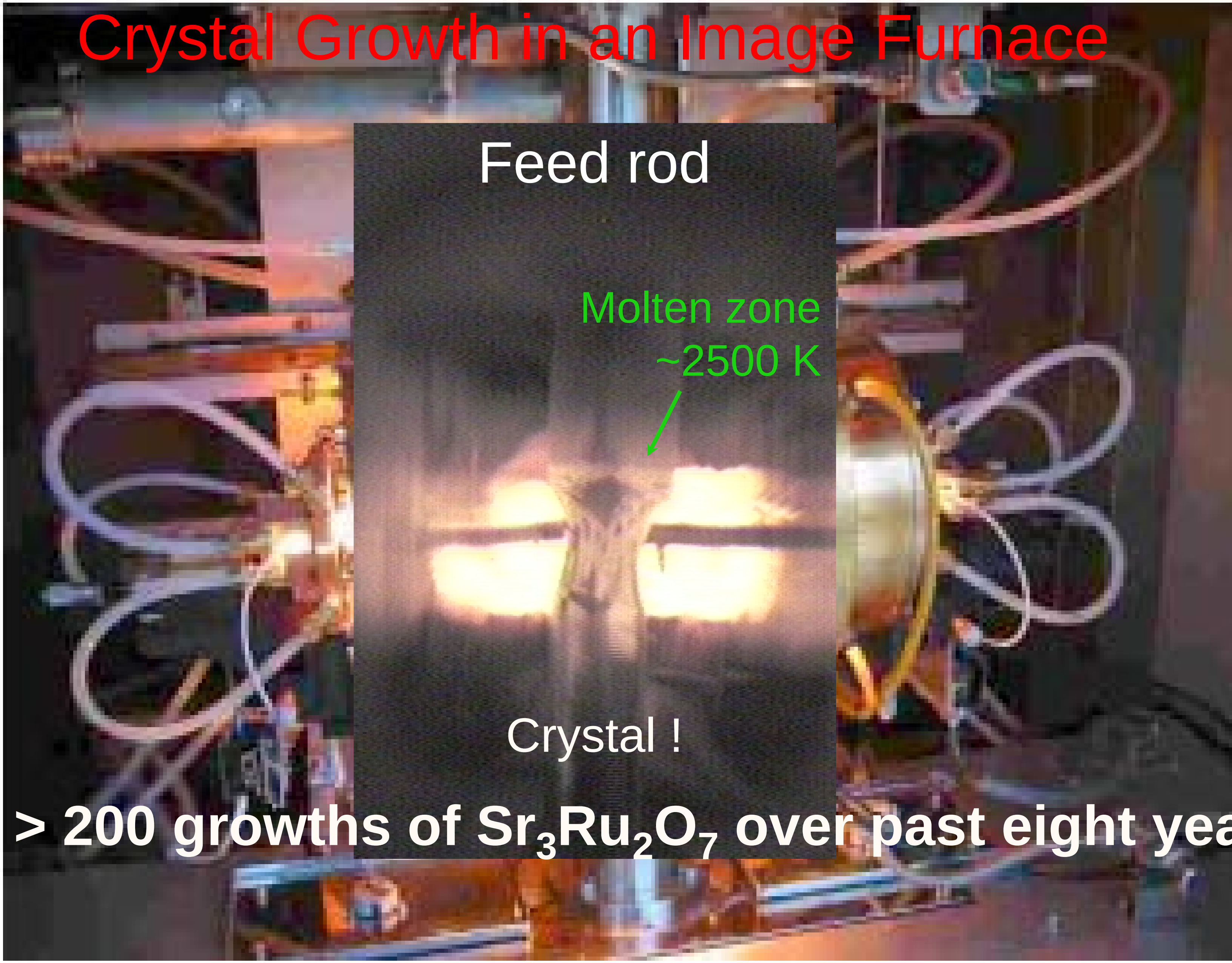
Experimental phase diagram of “clean” $Sr_3Ru_2O_7$



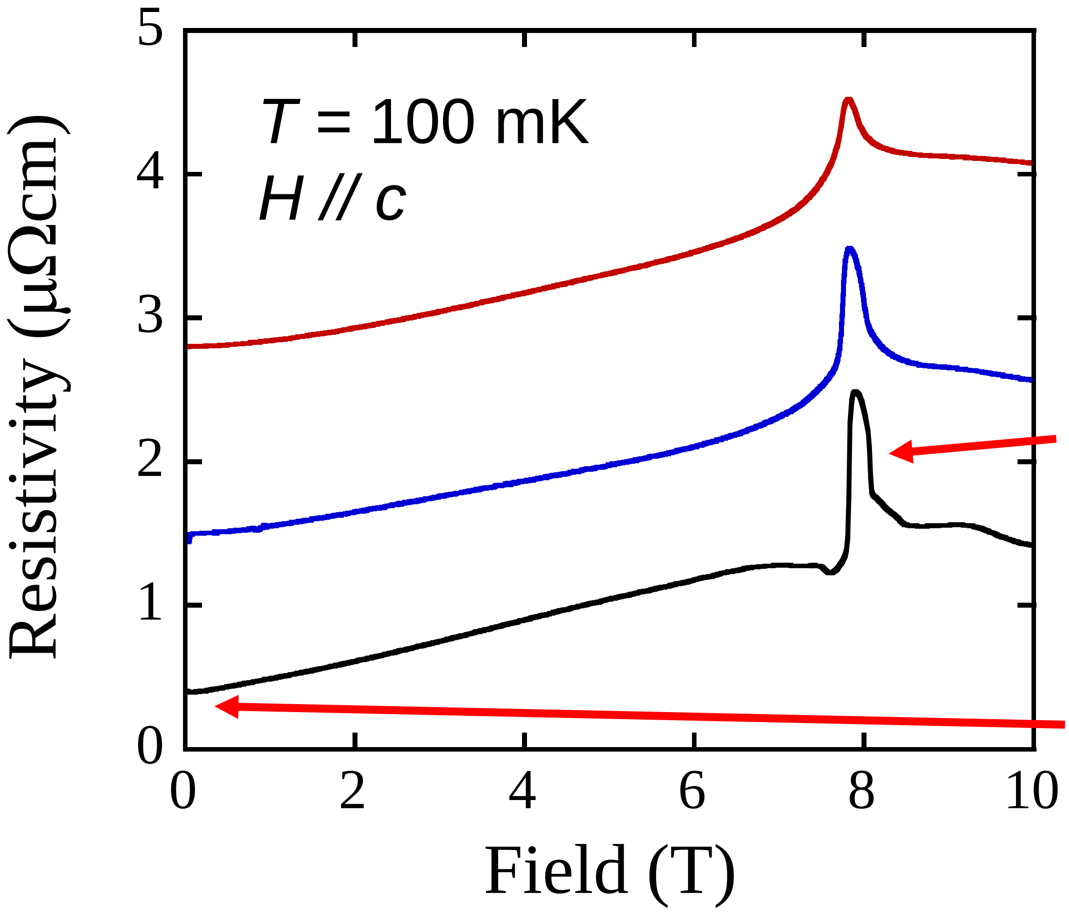
S.A. Grigera, R.S. Perry, A.J. Schofield, M. Chiao, S.R. Julian, G.G. Lonzarich, S.I. Ikeda, Y. Maeno, A.J. Millis, A.P. Mackenzie, Science **294**, 329 (2001)

S.A. Grigera, R.A. Borzi, A.P. Mackenzie, S.R. Julian, R.S. Perry & Y. Maeno, Phys. Rev. B **67**, 214427 (2003).

Crystal Growth in an Image Furnace



Effect of increasing crystal purity



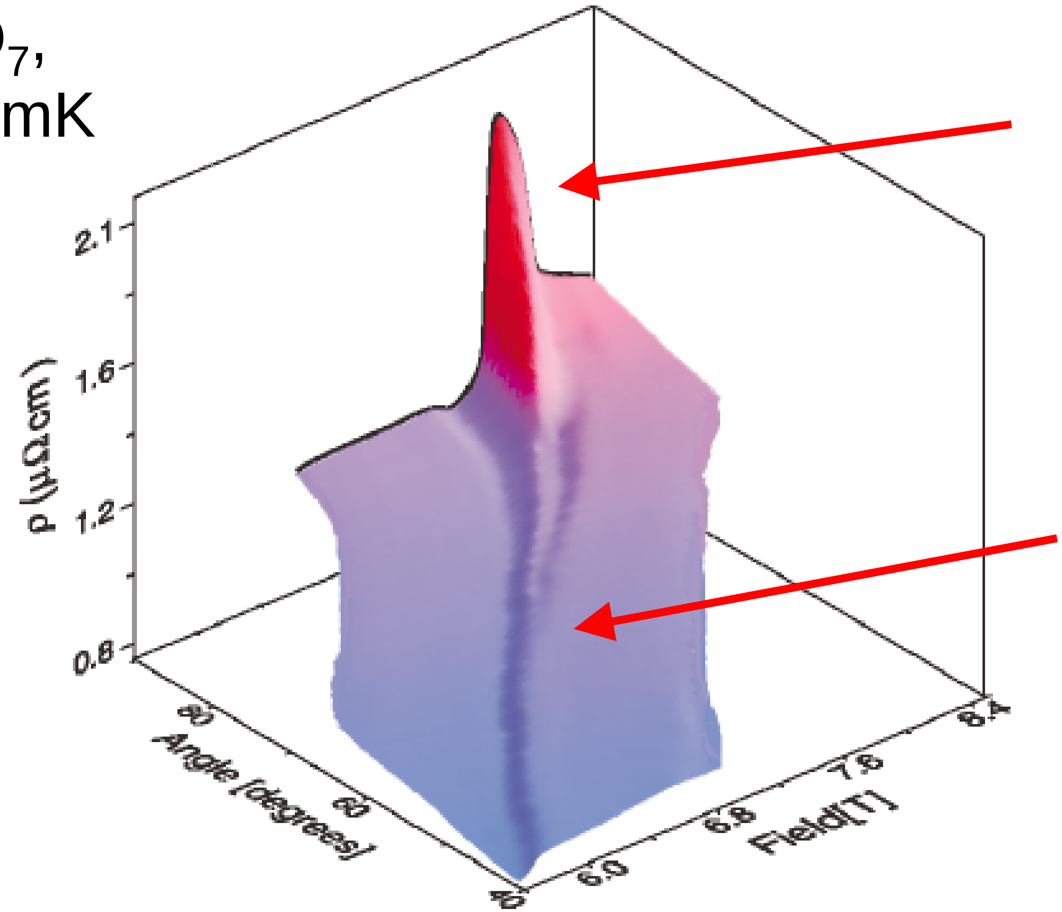
Sharply defined resistive anomaly in the best samples

Mean free paths > 3000 Å

R.S. Perry, K. Kitagawa, S.A. Grigera, R.A. Borzi, A.P. Mackenzie, K. Ishida and Y. Maeno, Phys. Rev. Lett. ***92****, 166602 (2004).*

Transport data from best samples

$Sr_3Ru_2O_7$,
T = 100 mK



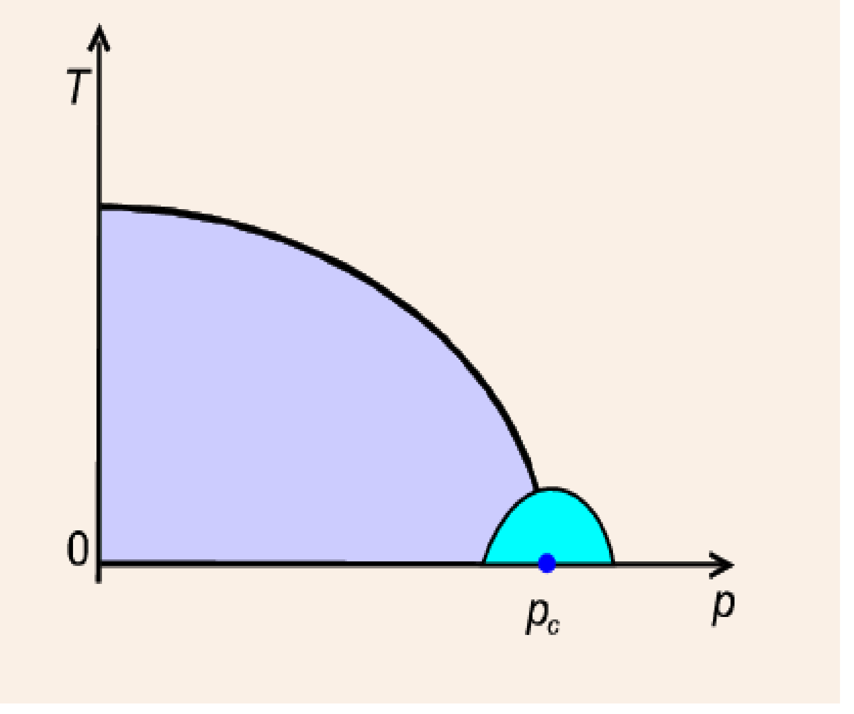
Large increase in resistivity for fields aligned nearly along c axis

Bifurcation of first-order phase lines visible in resistivity and proven to exist using magnetic susceptibility.

A.G. Green, S. A. Grigera, R.A. Borzi, R.S. Perry, A. P. Mackenzie & B.D. Simons, Phys. Rev. Lett. 95, 086402 (2005).

A. I. Larkin and S. A. Pikin, Zh. Eksp. Teor. Fiz. ***56****, 1664 (1969)*

Quantum criticality driven phase formation?



- Superconductivity in $CeIn_3$ and $CePd_2Si_2$.

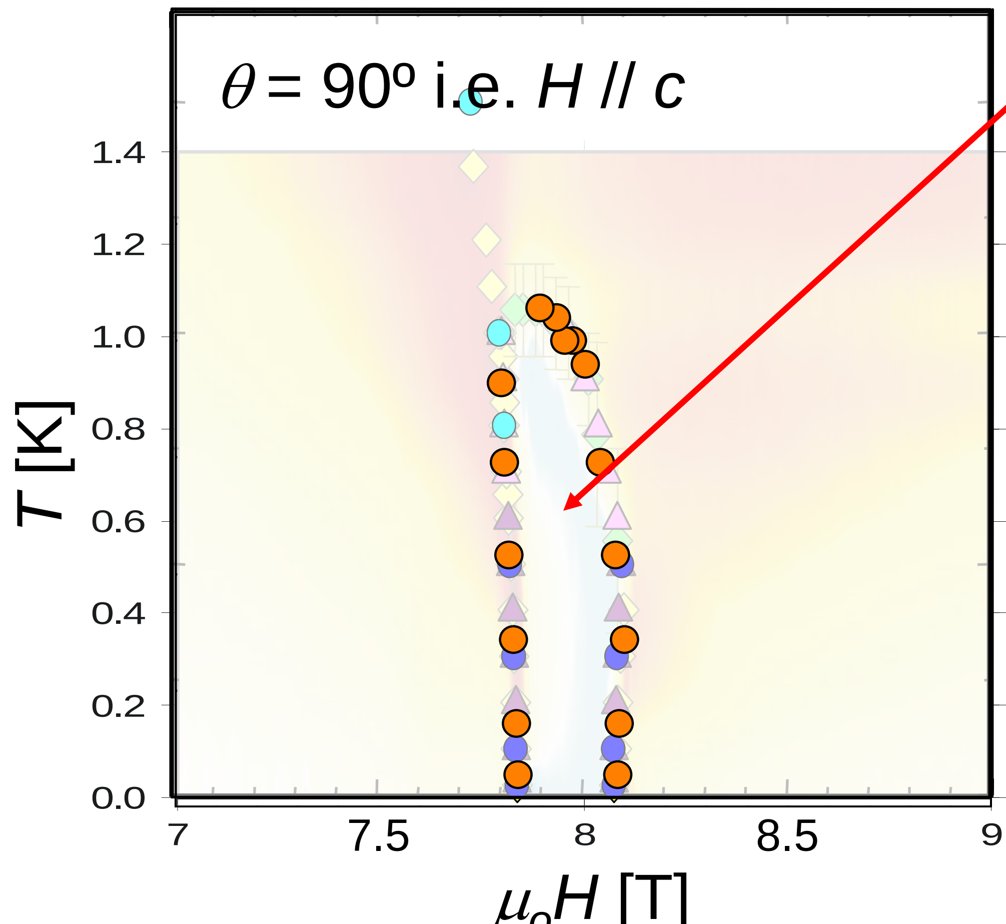
*N.D. Mathur, F.M. Grosche, S.R. Julian, I.R. Walker, D.M. Freye, R.K.W. Haselwimmer and G.G. Lonzarich, Nature **394**, 39 (1998)*

- High-field phases in URu_2Si_2.

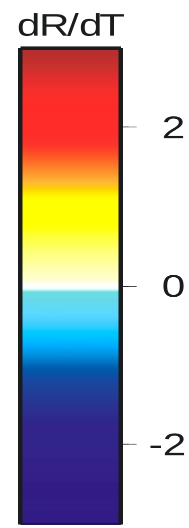
*e.g. K.H. Kim et al., Phys. Rev. Lett. **93**, 206402 (2004)*

Thermodynamic evidence for phase formation

- Resistivity: $d\rho/dH$ and $d^2\rho/dT^2$
- Susceptibility: χ' and χ''
- Magnetostriction: $\lambda(H)$
- Magnetisation



Note that within the 'phase' the resistivity has a mildly non-metallic temperature dependence



S.A.Grigera, P. Gegenwart, R. Borzi, F. Weickert, A. Schofield, R. Perry, A. Green, Y.Maeno & A.P.Mackenzie Science ***306***, *1154 (2004).*

Could domain formation explain the anomalous resistivity?

Broken symmetry

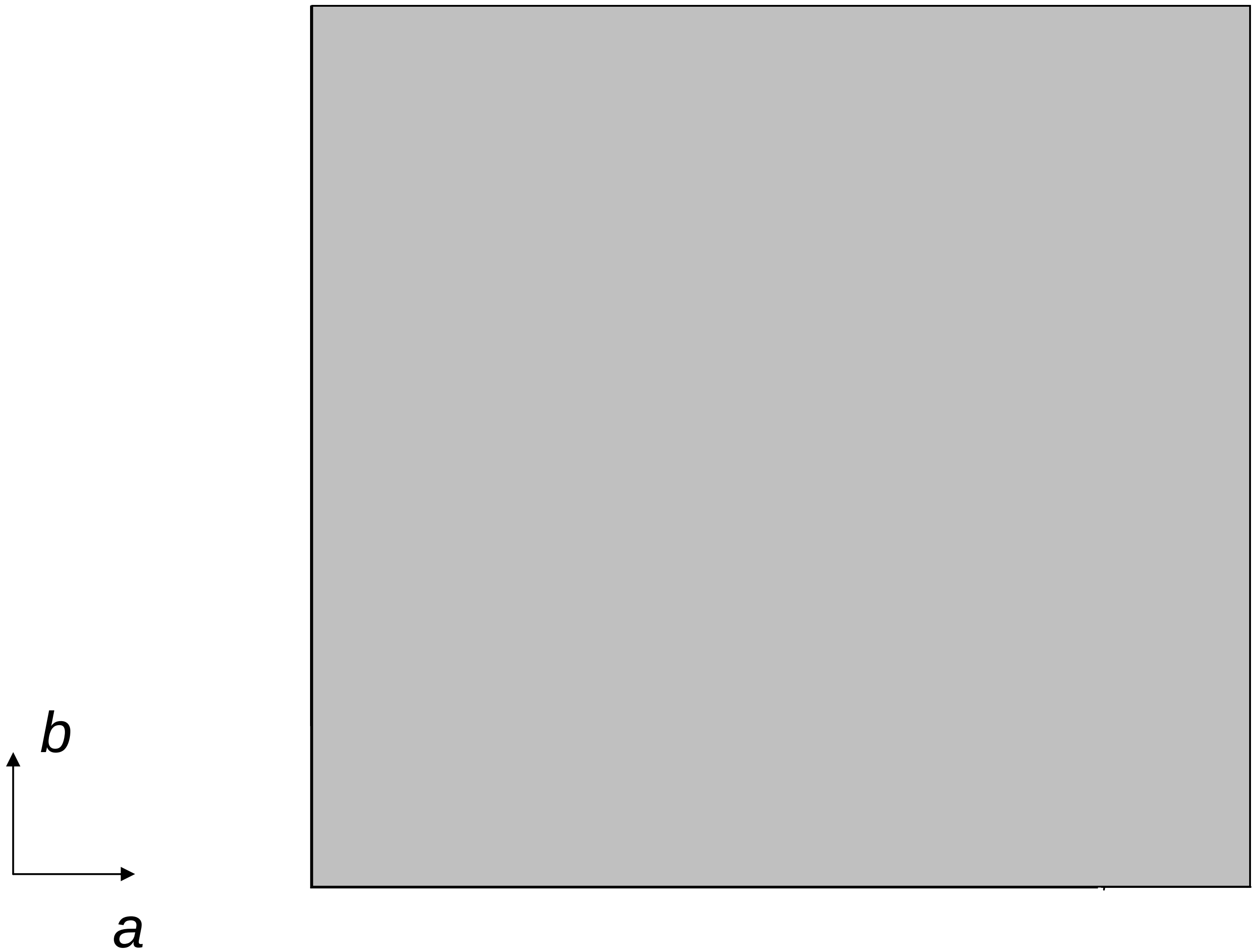
Domains of the symmetry broken possibilities

Example: Ferromagnetism

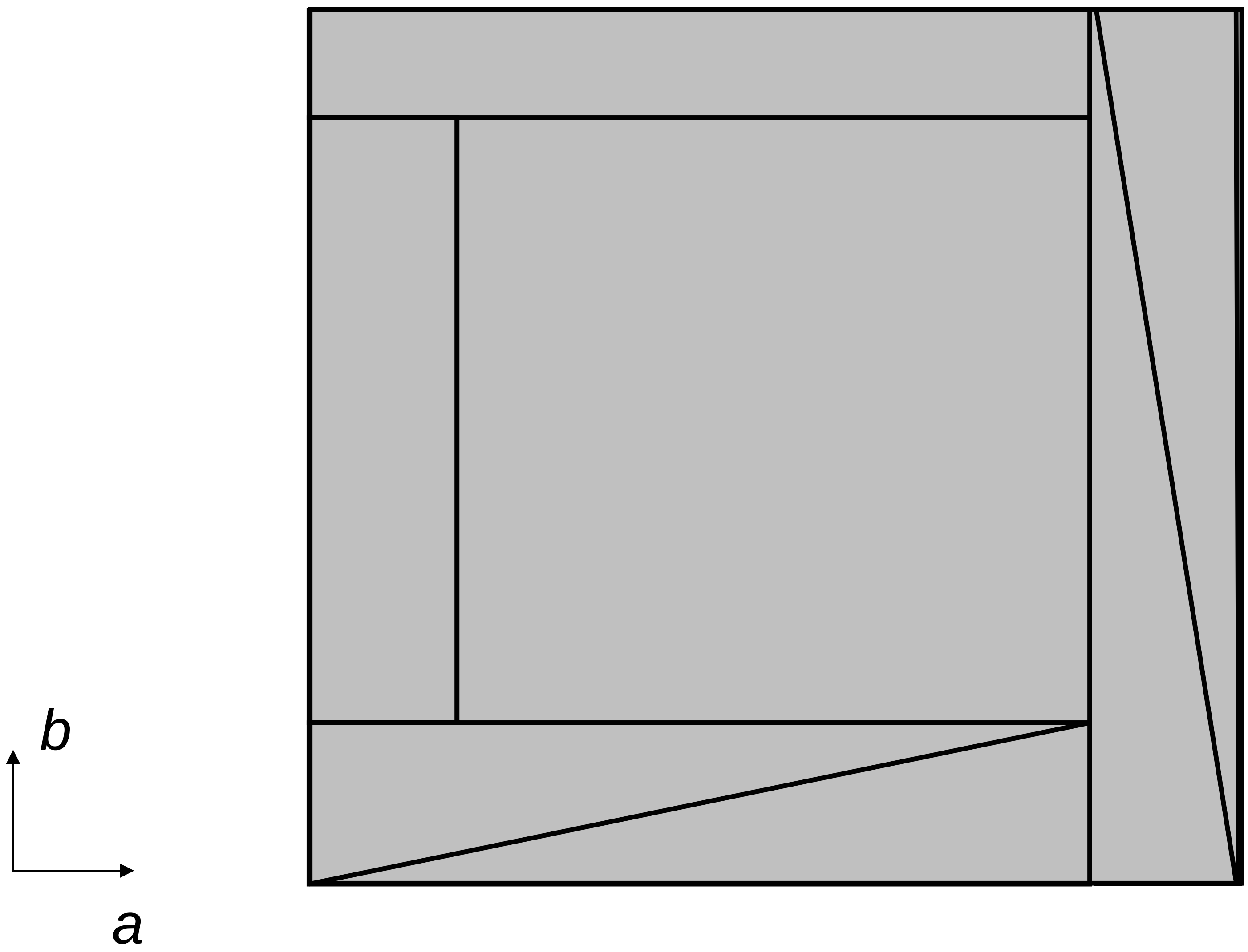
$+M$ $-M$ *domains*

Idea – could the in-plane fields in rotated samples couple to domains and give anisotropic transport?

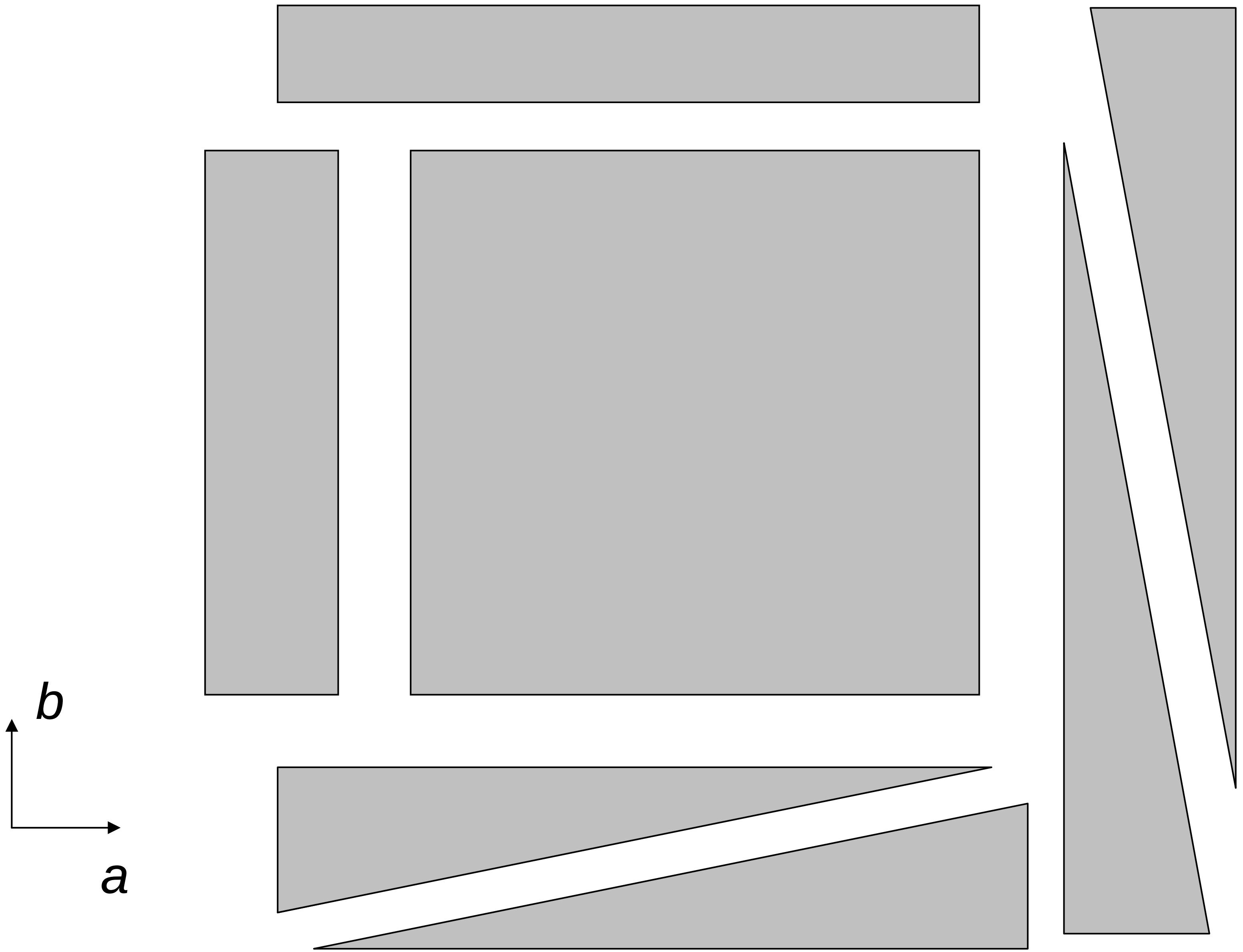
Domain scattering is a tricky business – great care required



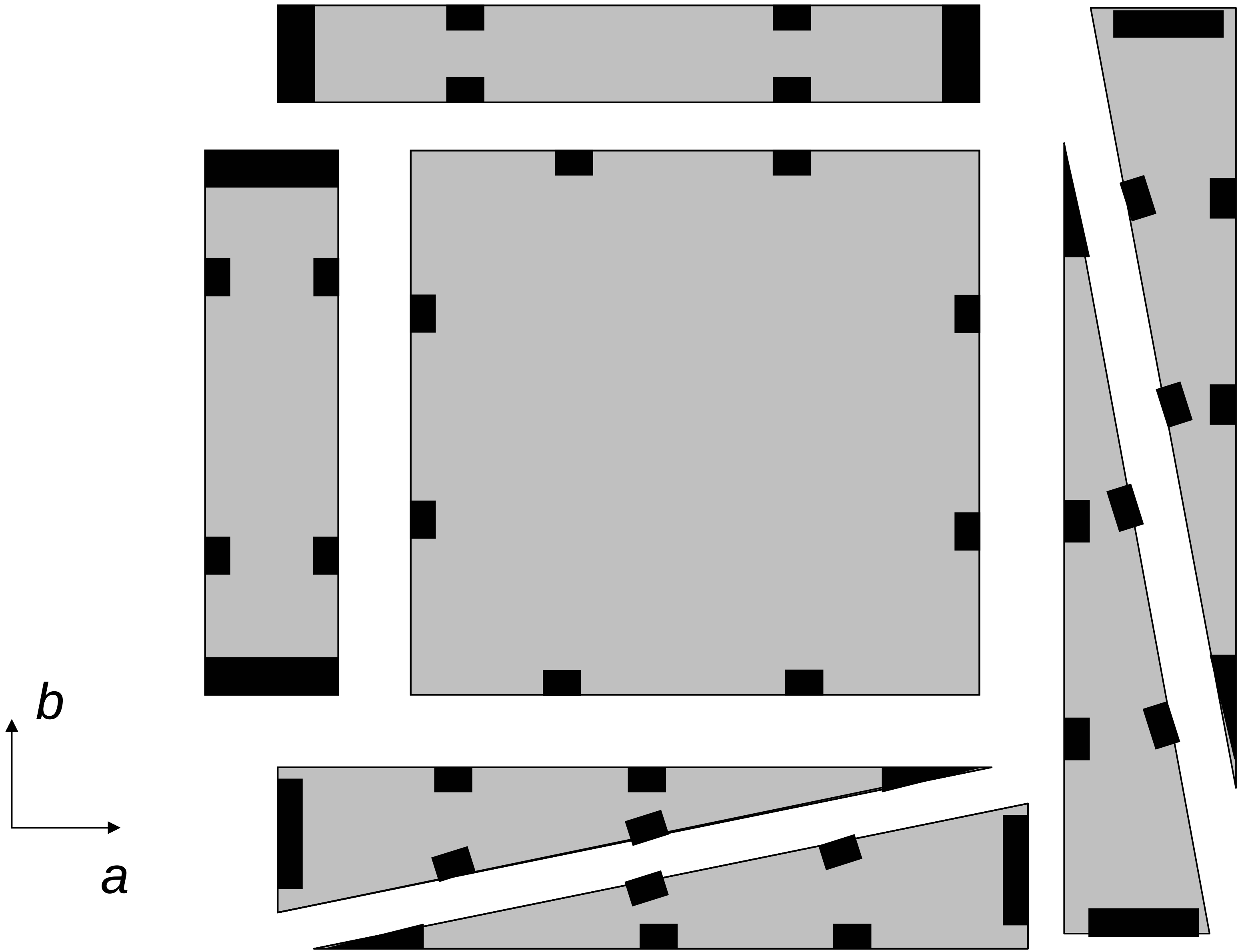
Domain scattering is a tricky business – great care required



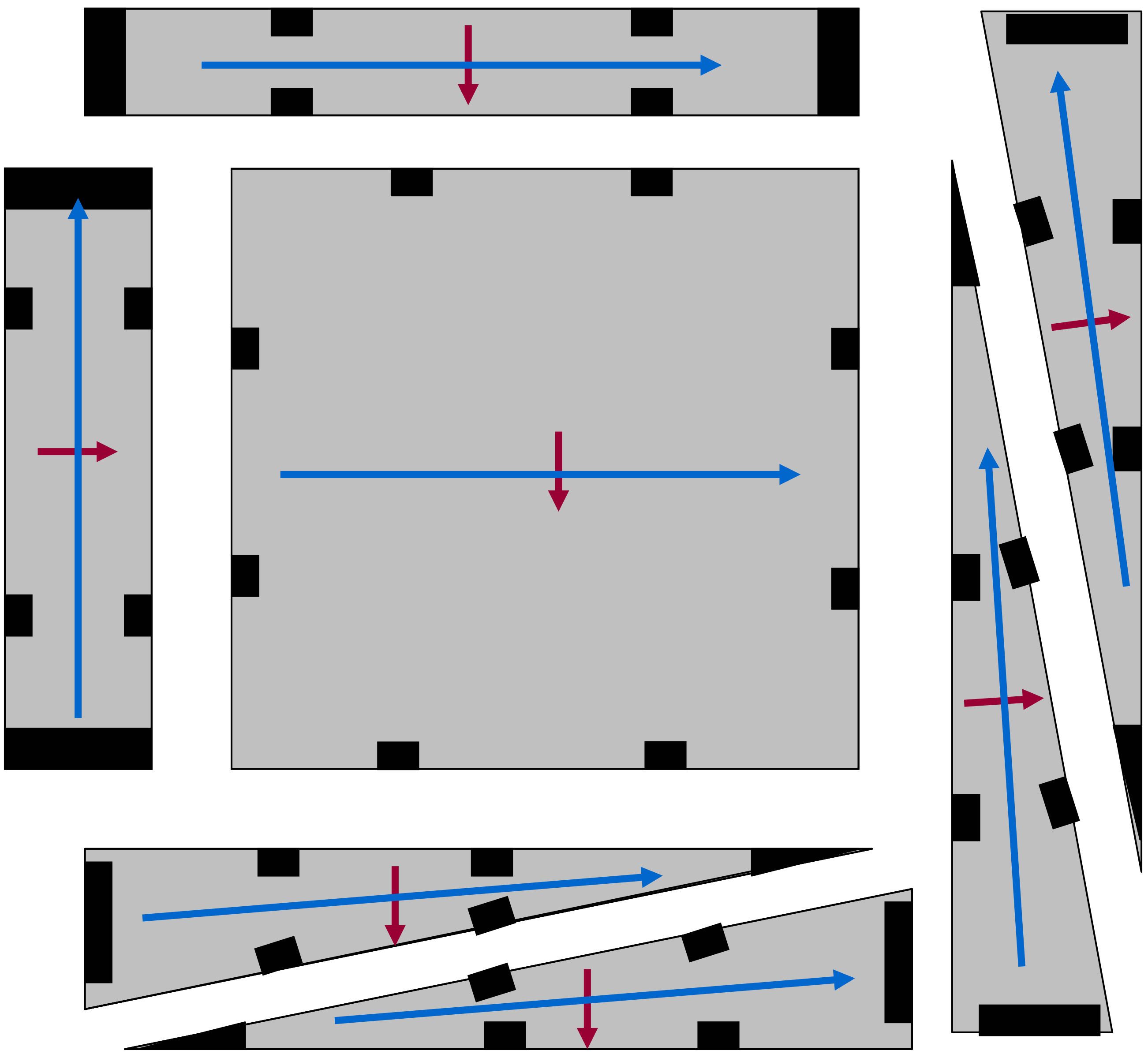
Domain scattering is a tricky business – great care required



Domain scattering is a tricky business – great care required

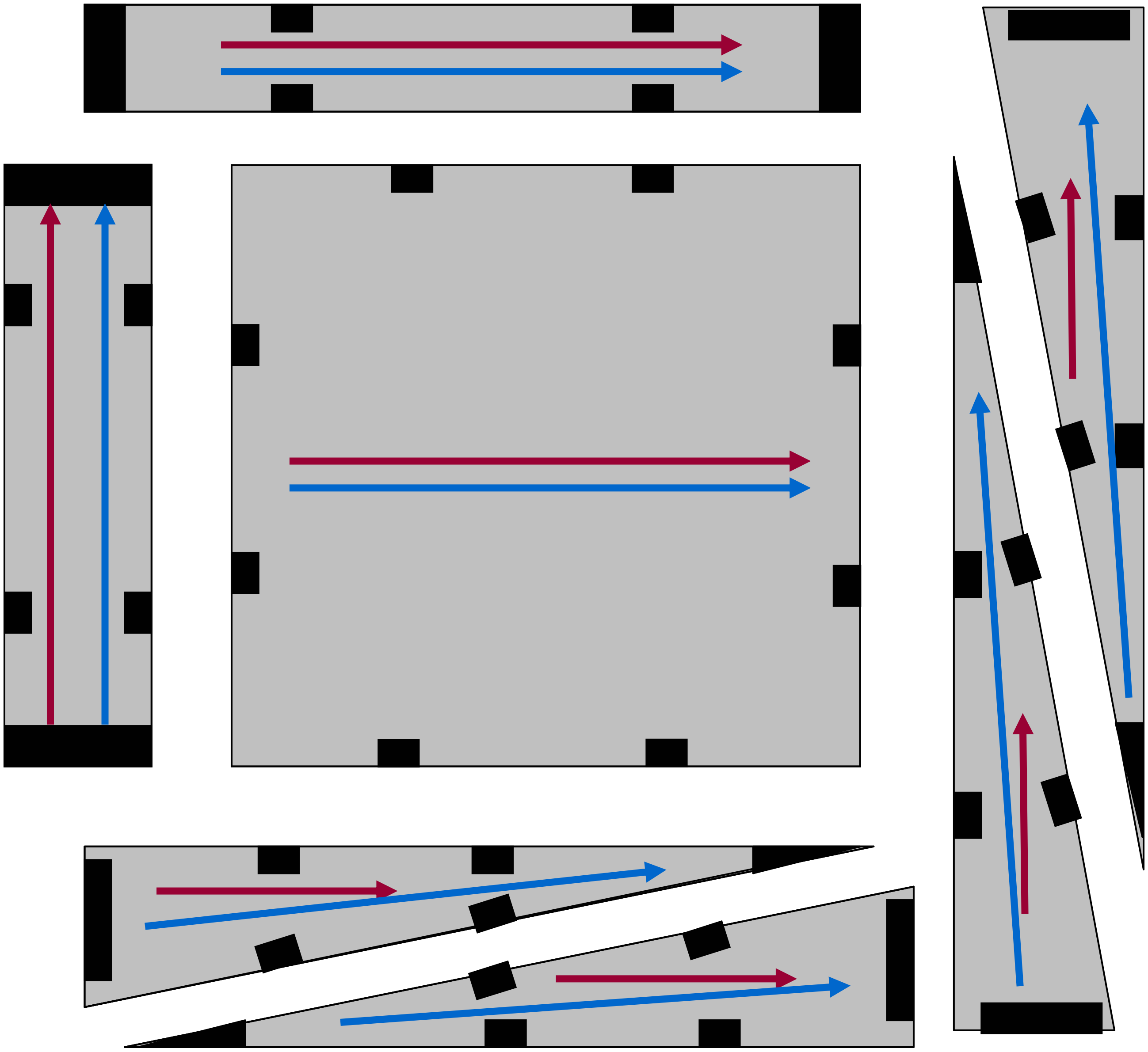


Domain scattering is a tricky business – great care required



Then the measurements must cover bewildering combinations of relative orientations of **J**, $\mathbf{H}_{ab}$ and sample shape etc.

Domain scattering is a tricky business – great care required



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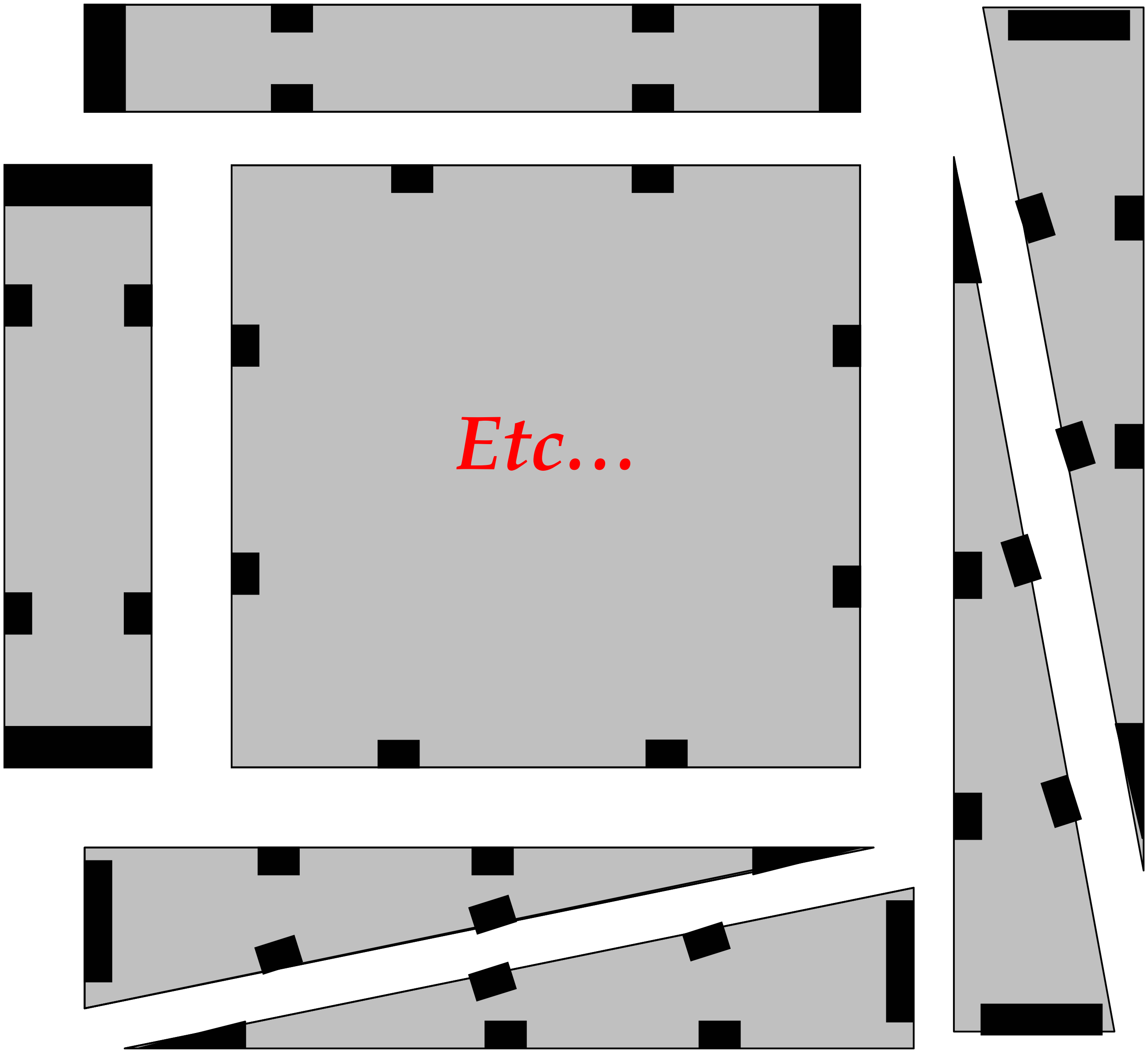
Domain scattering is a tricky business – great care required



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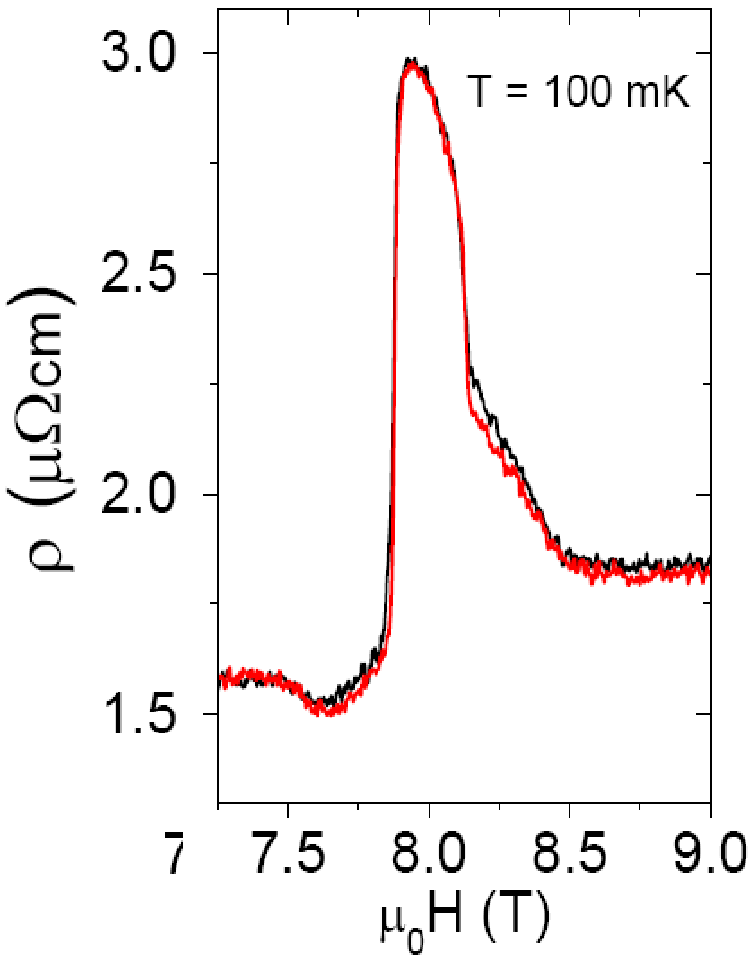
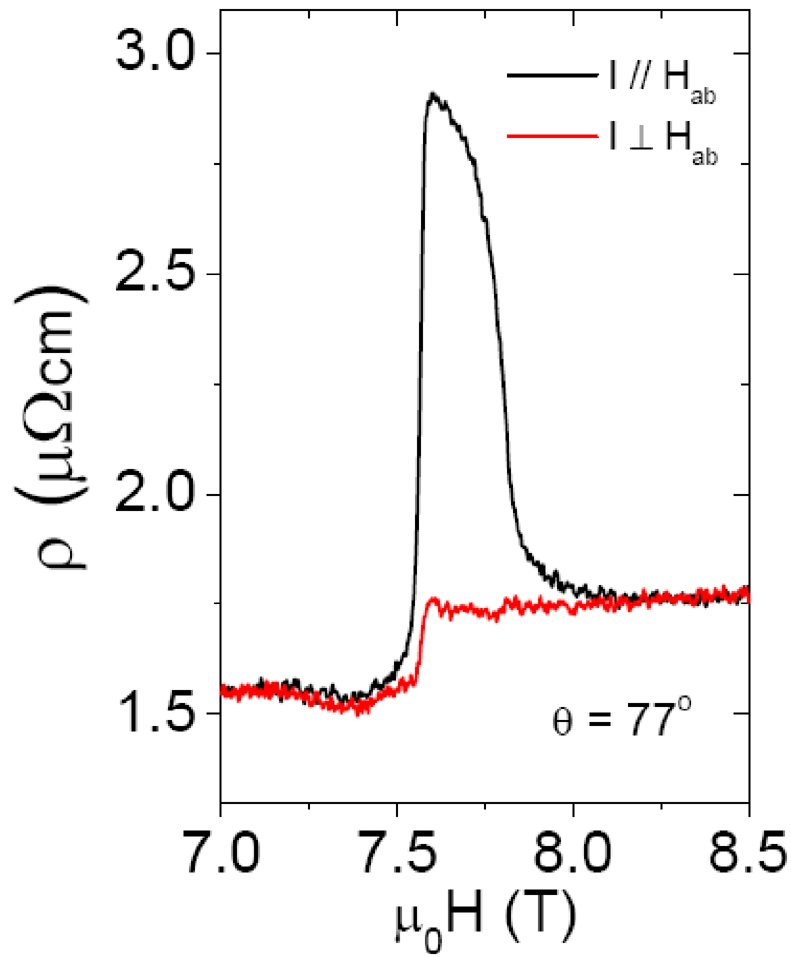
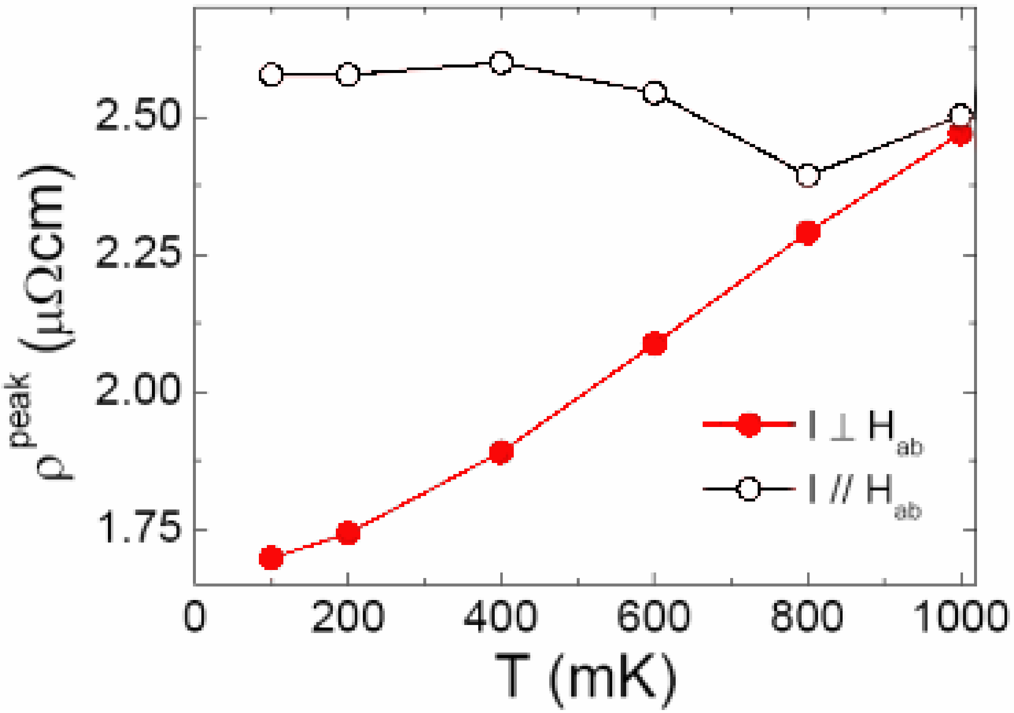
Anisotropic resistivity

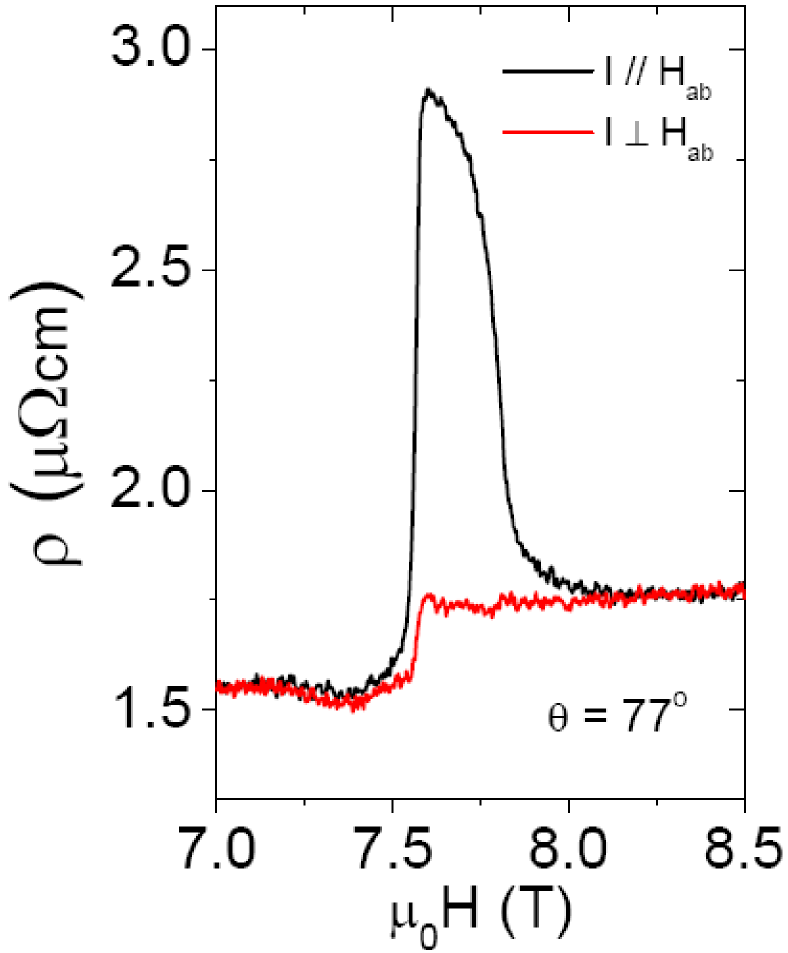


add H_{ab}

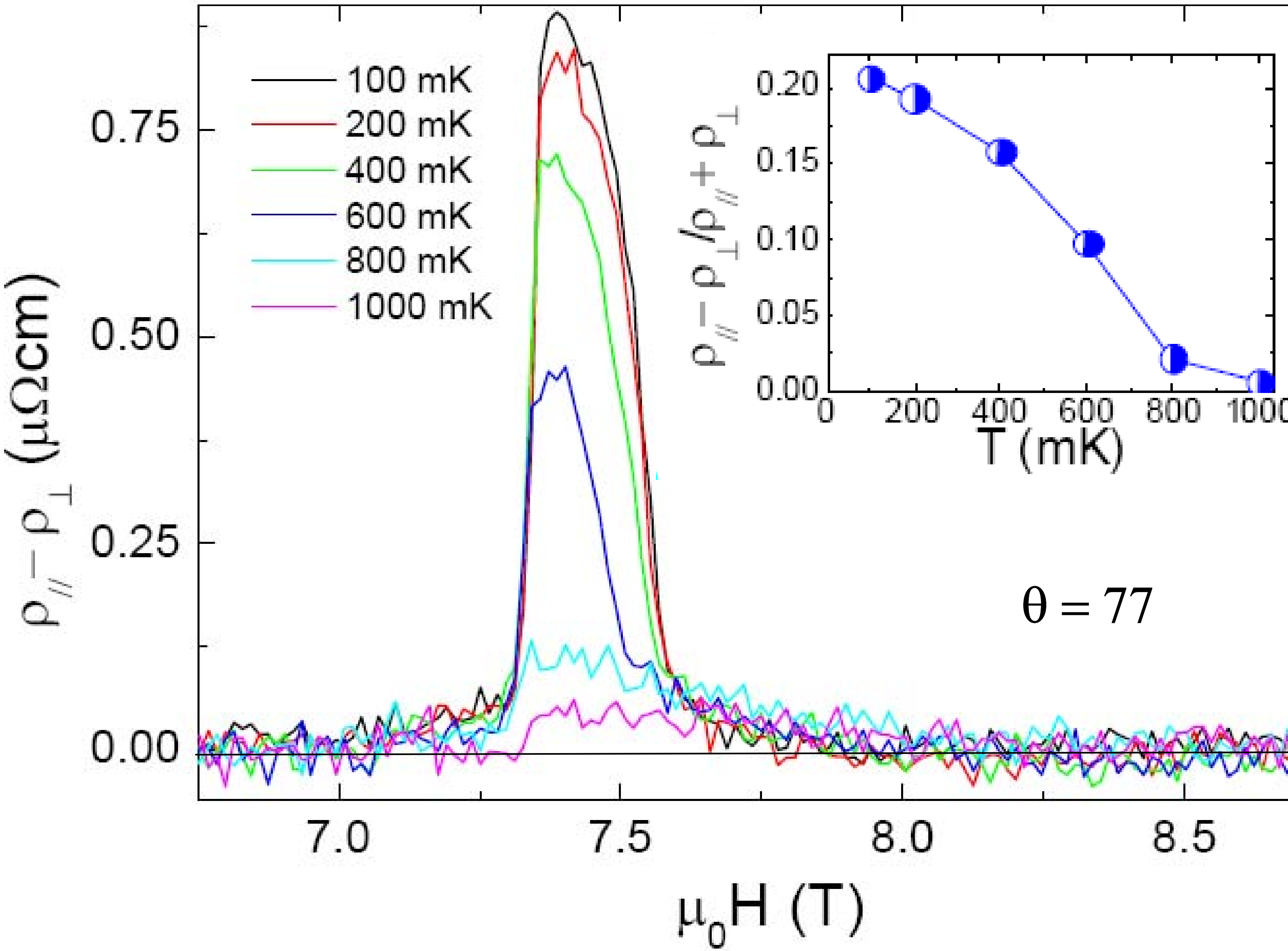


Anisotropic resistivity: temperature dependence



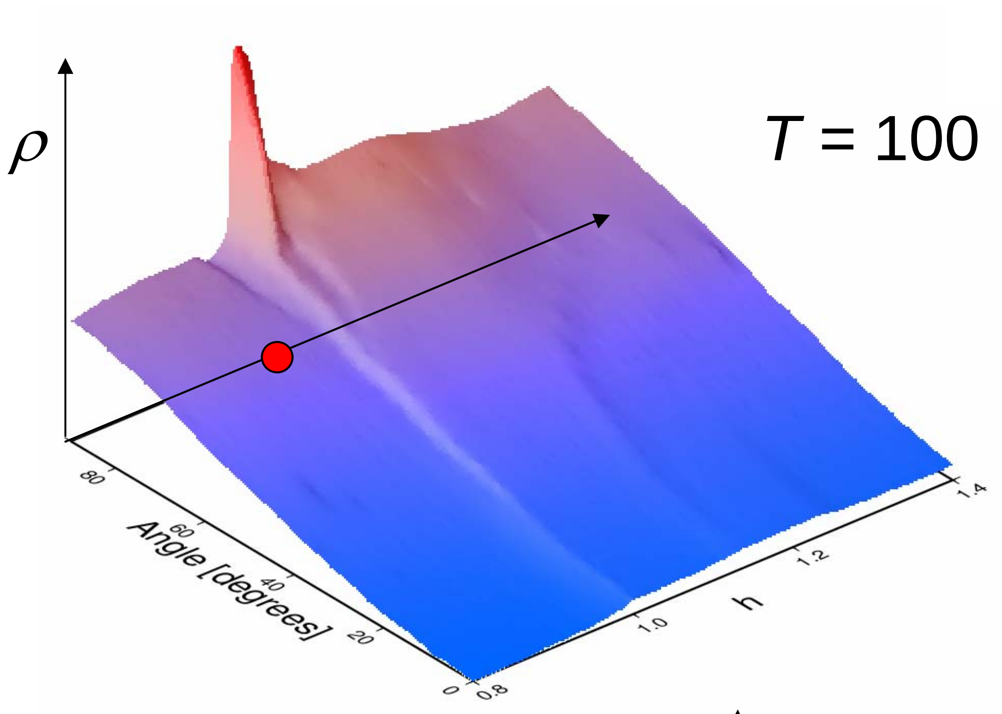


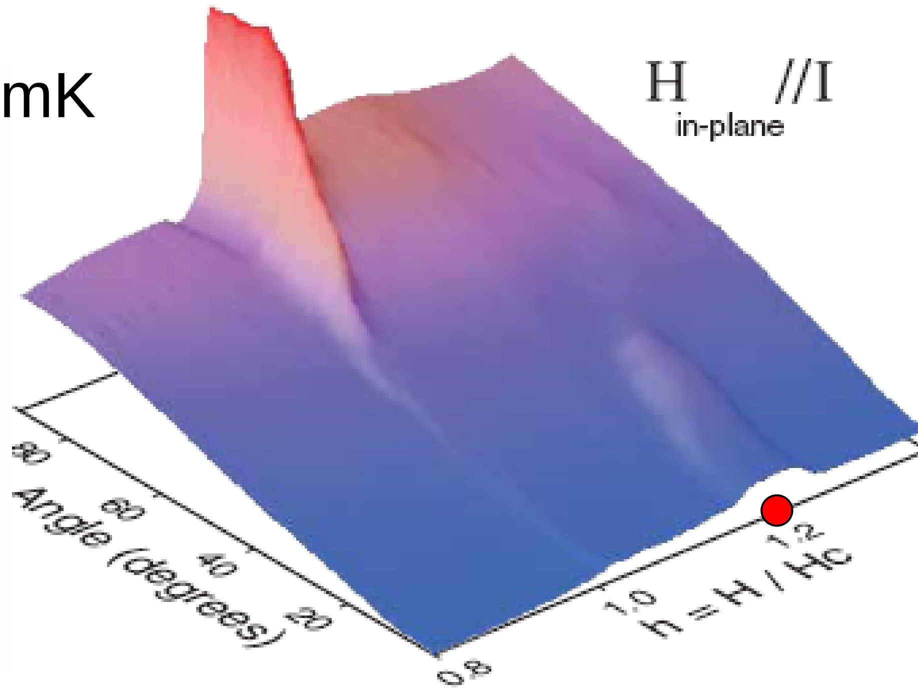
The anisotropy exists in a very limited region of the phase diagram



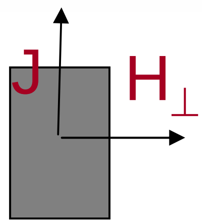
Going back to the 3D plots (now in reduced field $h = H / H_c$)

T = 100 mK

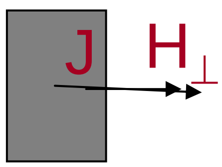




$J \perp H_{\perp}$



$J \,//\, H_{\perp}$



*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)*

Anisotropic **electronic** state

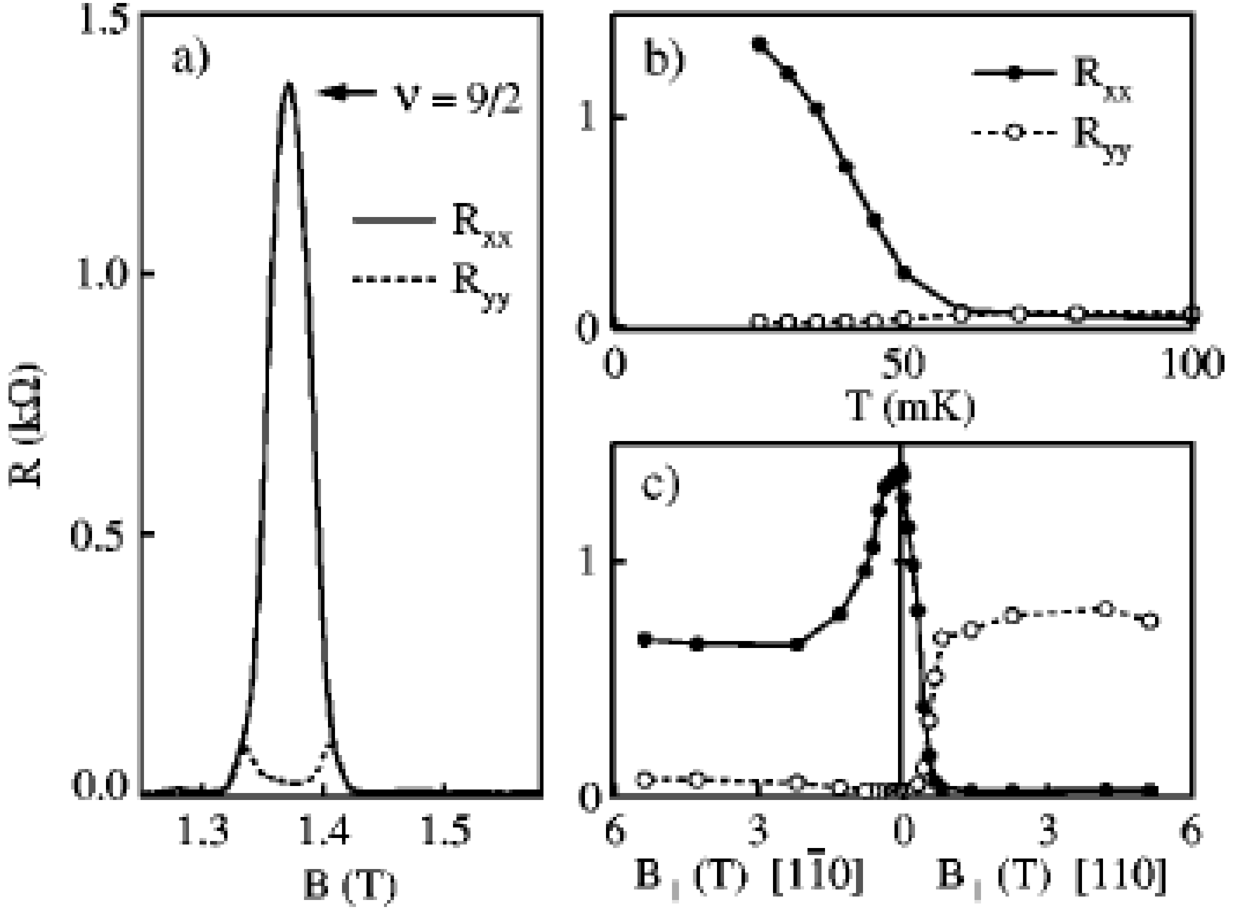
- The transport properties are clearly anisotropic

- Neutron experiments resolve no lowering of crystalline symmetry.

Intriguing similarity with GaAs 2D devices

M.P. Lilly et al., Phys. Rev. Lett. ***82****, 394 (1999); ibid* ***83****, 824 (1999)*

Interpreted (by theory community) in terms of very specific 2D Landau level physics.



Is there a more general way of looking at things?

Correlated electron physics is based on control of the interaction strength versus the bandwidth: *U/W*

- Very rare in real systems that we can increase *U/W* without also increasing the lattice potential *V.*

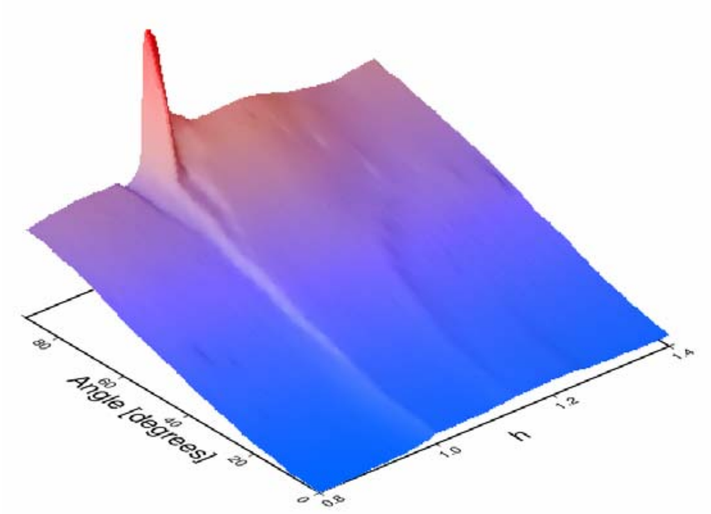
- Magnetic quantum critical points provide a way of doing this job.

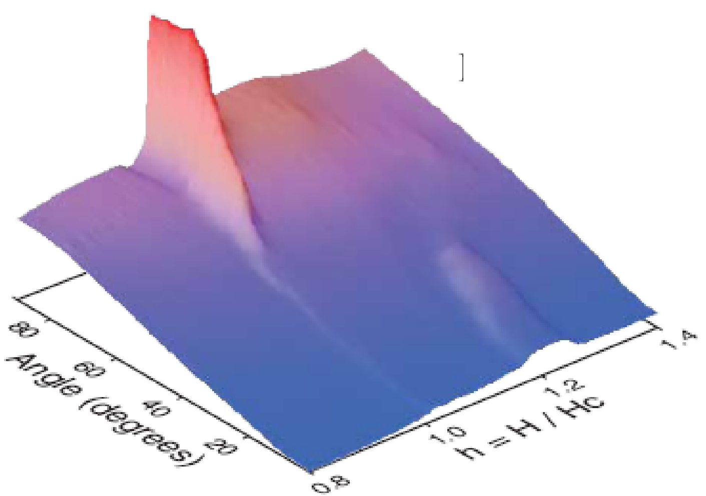
- Other new states almost certainly exist if we make the right materials and do the right experiments.

- Many of the interesting new ground states will be anisotropic in *k*-space: need better materials!

Conclusions

- The new phase boundaries that appear in extremely high purity $Sr_3Ru_2O_7$ enclose a region containing magnetically orientable domains which strongly affect charge transport.





- The phase boundaries themselves are invariant under changes in sample size and shape, and under the relative orientation of transport currents and in-plane fields.

- $Sr_3Ru_2O_7$ is an extremely promising candidate for STM spectroscopy.