Thermodynamics near magnetically tuned quantum critical points – past work and future prospects

Andy Mackenzie

University of St Andrews, Scotland

Recent collaborators

A. Rost[1], J.-F. Mercure[1], S. A. Grigera[1,3], R. S. Perry[1,2], R.A. Borzi[3], J. Bruin[1], A.S. Gibbs[1], D. Slobinsky[1], I.A.S. Langley[1], S. Raghu[4], S.A. Kivelson[4]

[1] University of St Andrews
[2] University of Edinburgh
[3] CONICET La Plata
[4] Stanford University

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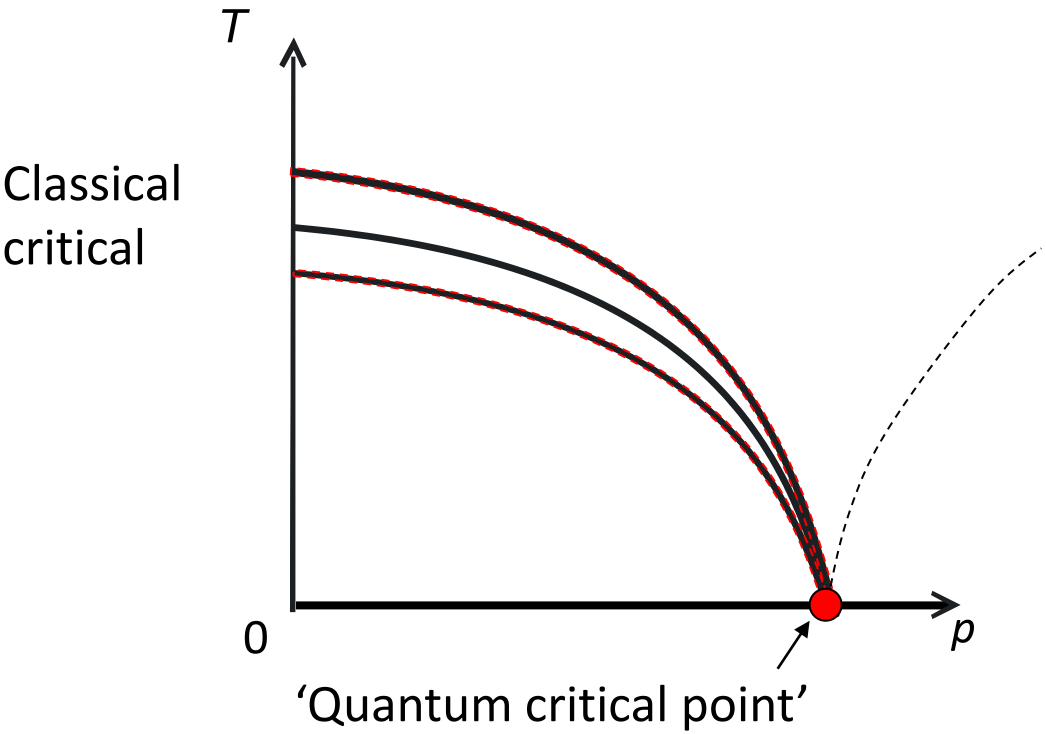
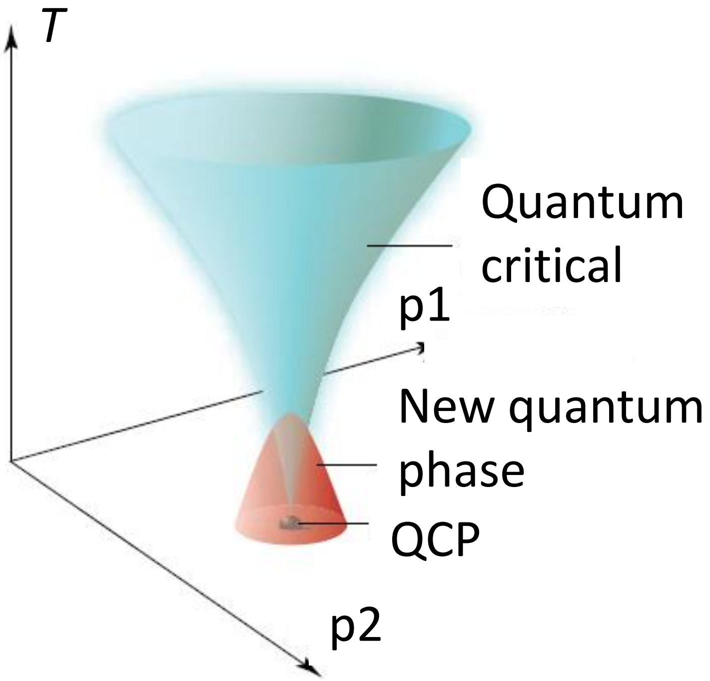
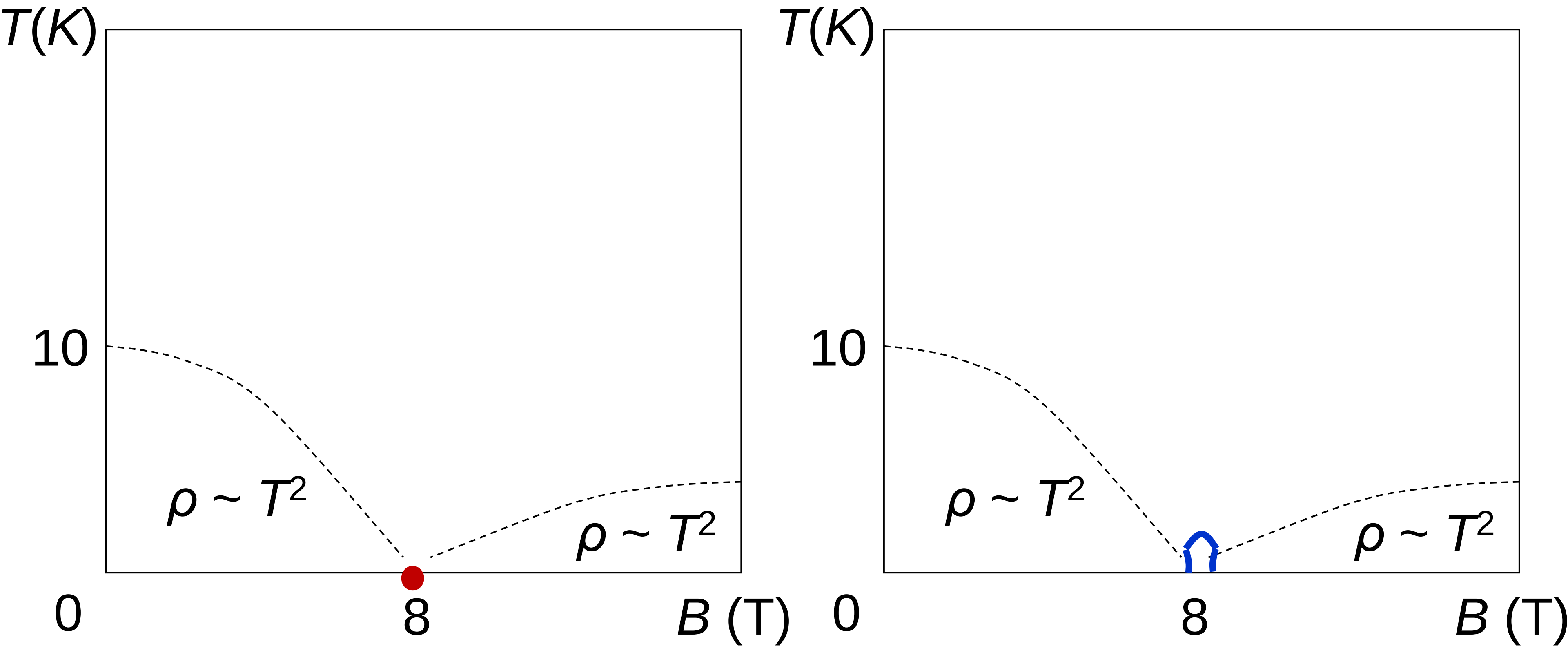
Quantum critical points and phase formation





1. At mean-field level, flatten the free energy landscape favouring the original phase.
2. In a metal, induce a mass divergence that favours order.
3. Create fluctuations that can act as 'binding bosons' for new superconductors.

$Sr_3Ru_2O_7$: a quantum critical phase diagram

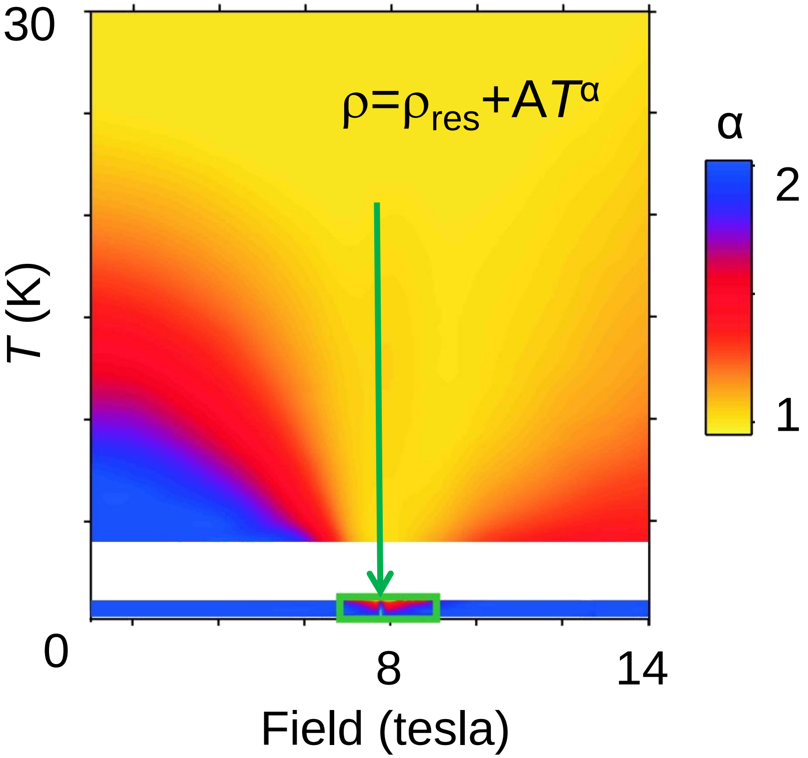


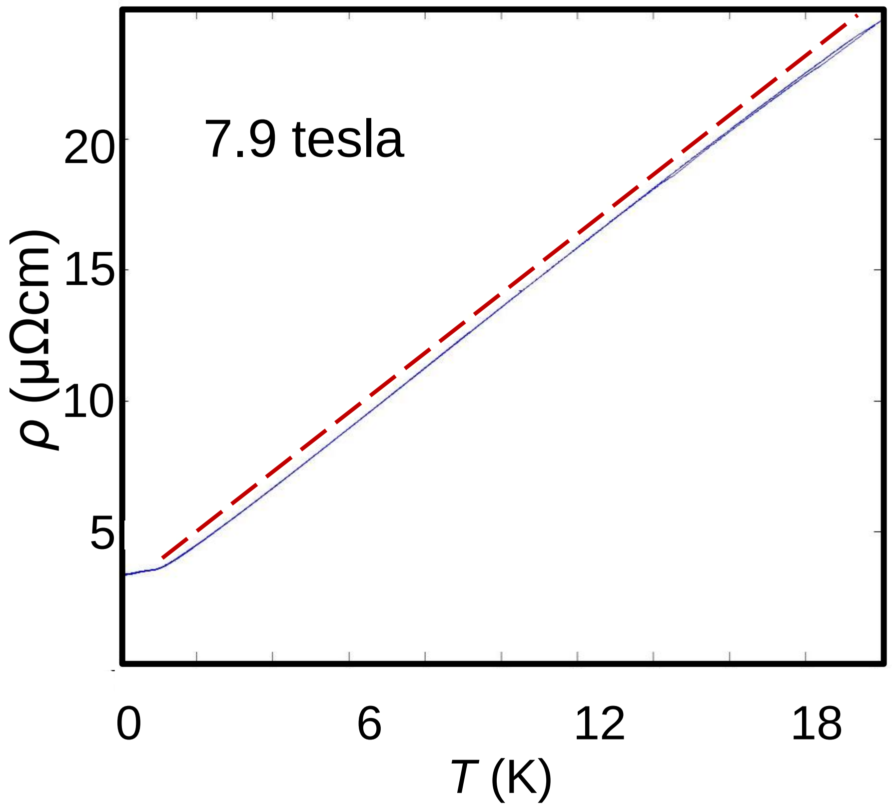
m.f.p. ~ 300 Å: apparent QCP

m.f.p. ~ 3000 Å: approach to QCP cut off by formation of a new phase *but* overall phase diagram retains signatures of quantum criticality

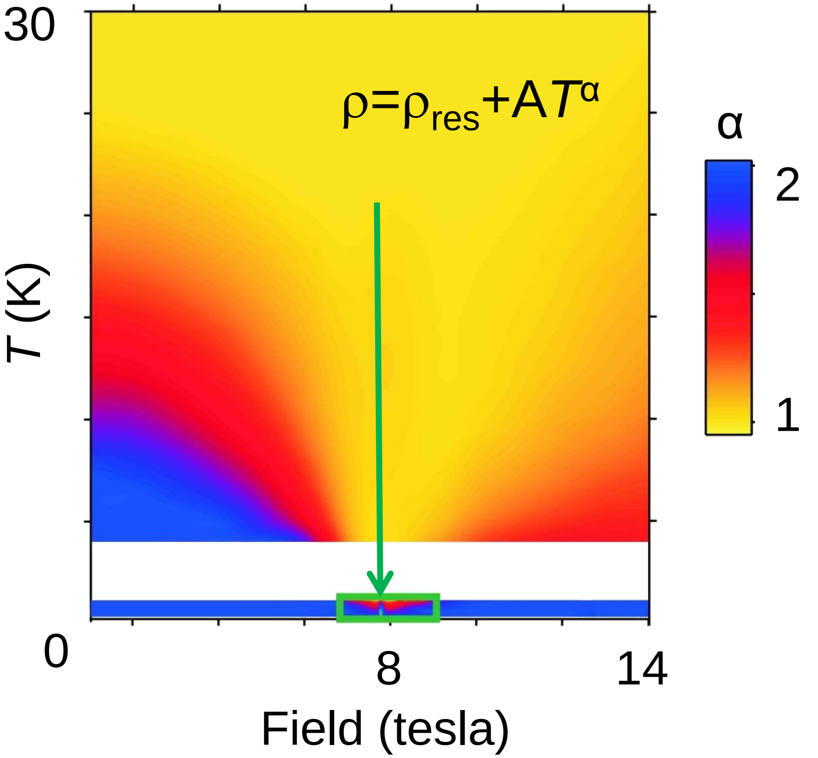
S.A. Grigera et al., Science ***294****, 321 (2001); ibid* ***306****, 1154 (2004).*

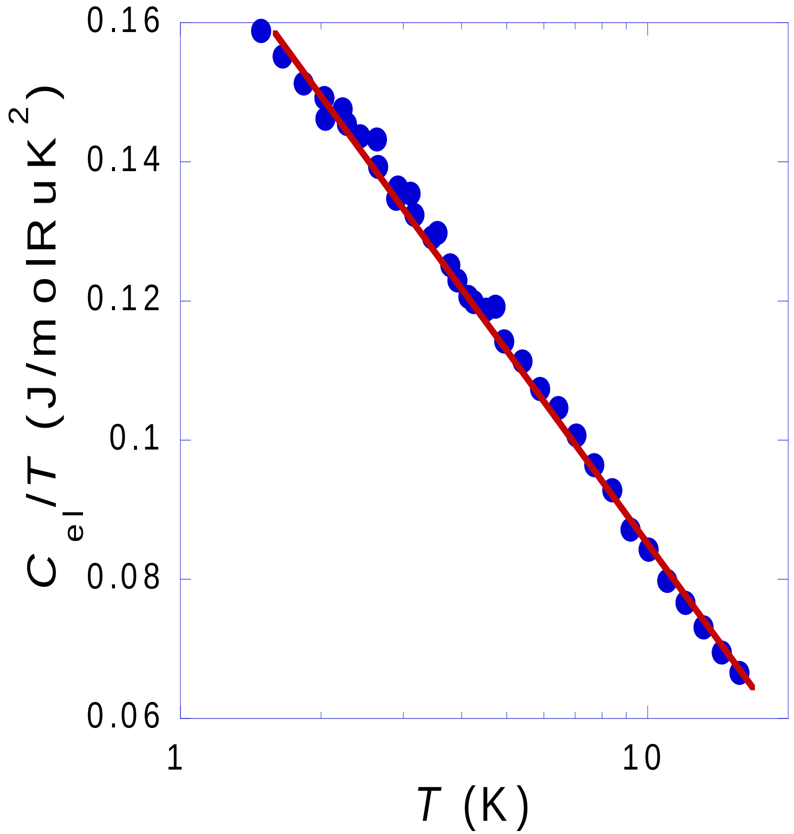
The phase in $Sr_3Ru_2O_7$ forms out of a quantum critical background



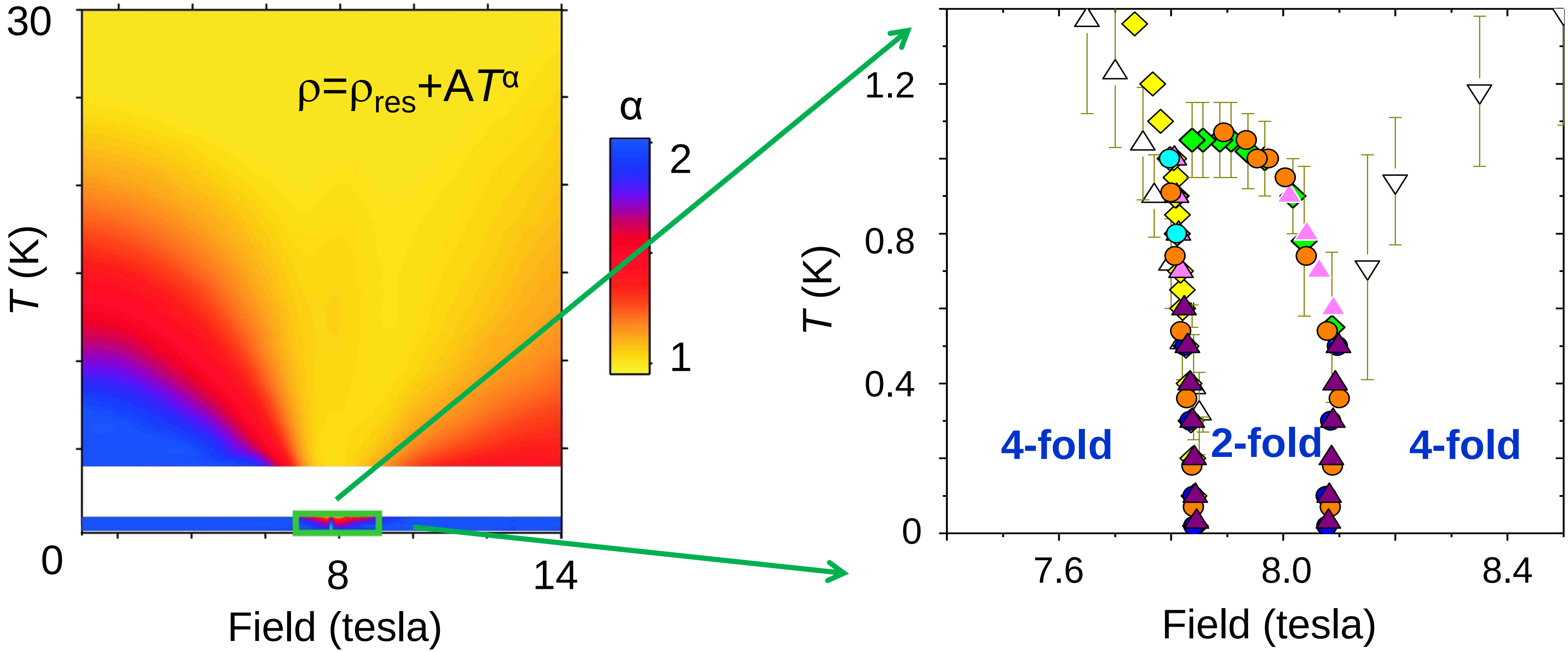


The phase in $Sr_3Ru_2O_7$ forms out of a quantum critical background





‘Nematic’ properties

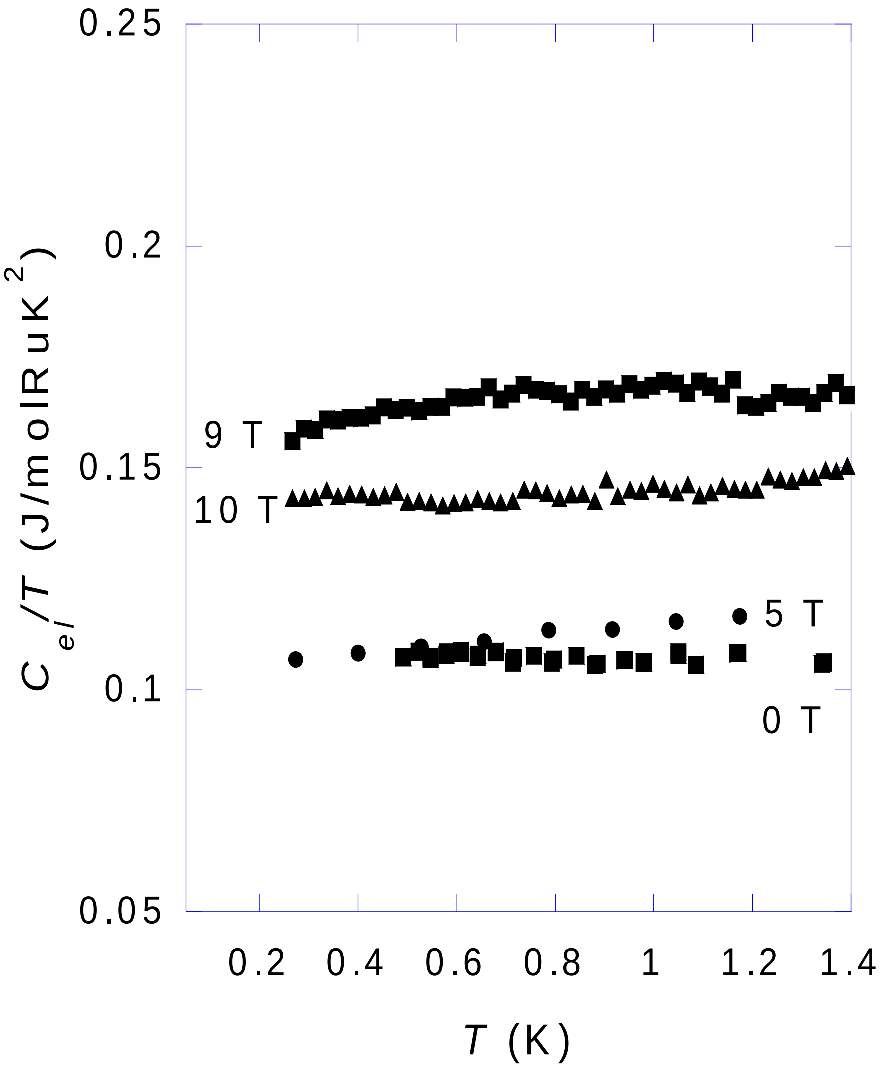


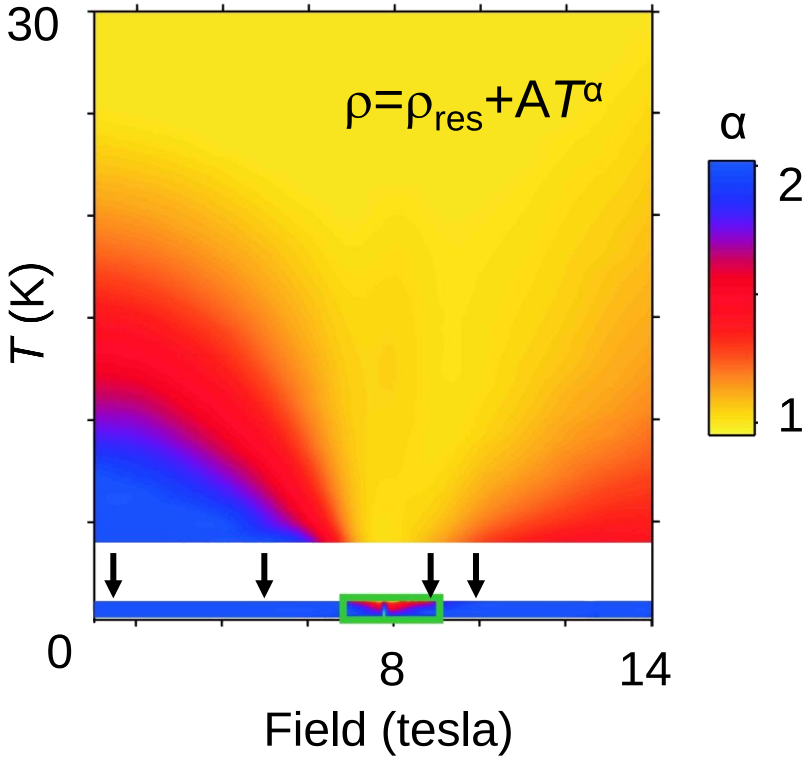
Nematic order now widely seen in the vicinity of superconductivity in cuprates and pnictides.

Unusual form of phase formation – the transition is not from a Fermi liquid; indeed it happens at a similar temperature to the crossovers to conventional Fermi liquids at lower and higher fields.

S.A. Grigera et al., Science ***306****, 1155 (2004); R.A. Borzi et al., Science* ***315****, 214 (2007)*

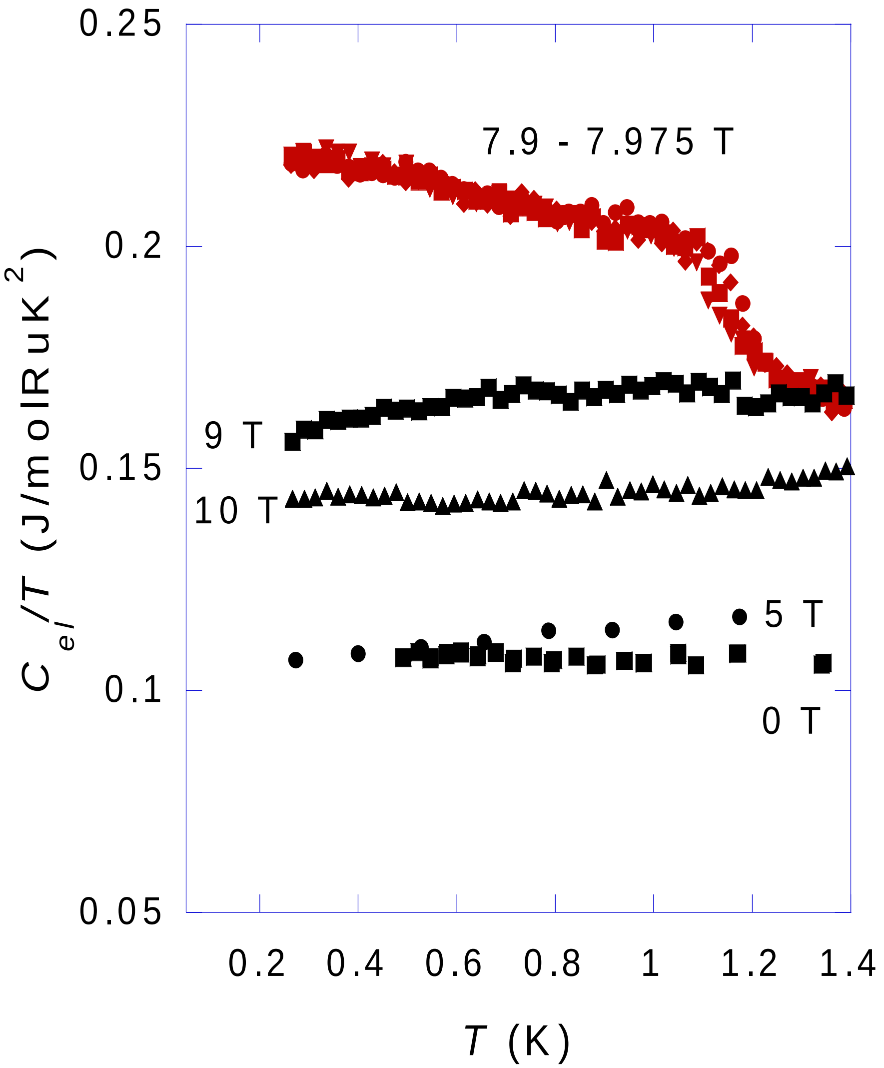
Low temperature specific heat and phase formation

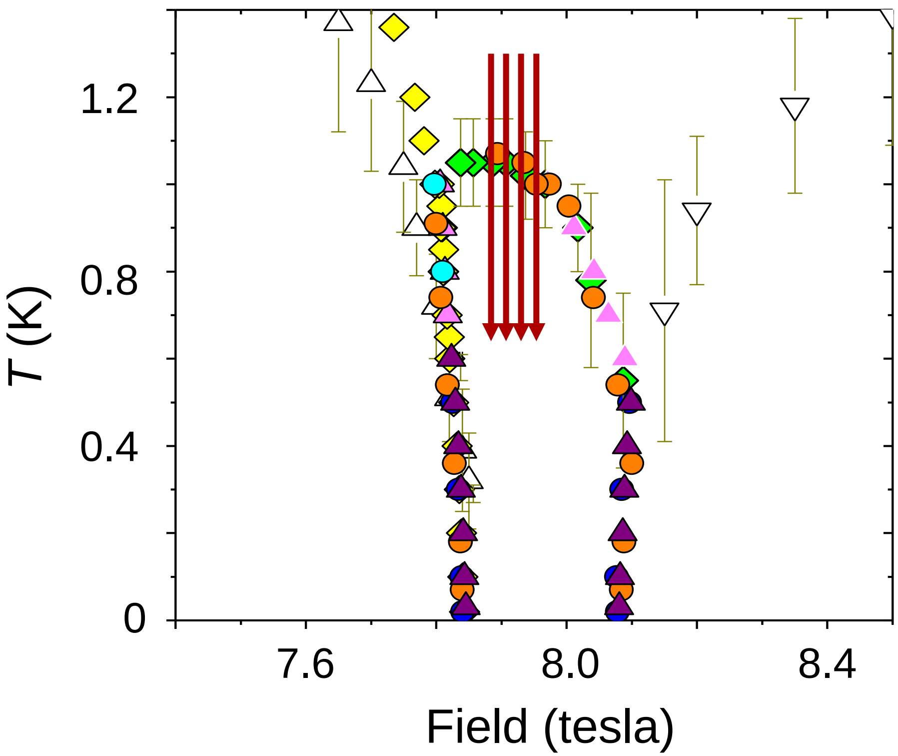




Away from the phase: approximately constant as a function of T (Fermi liquid).

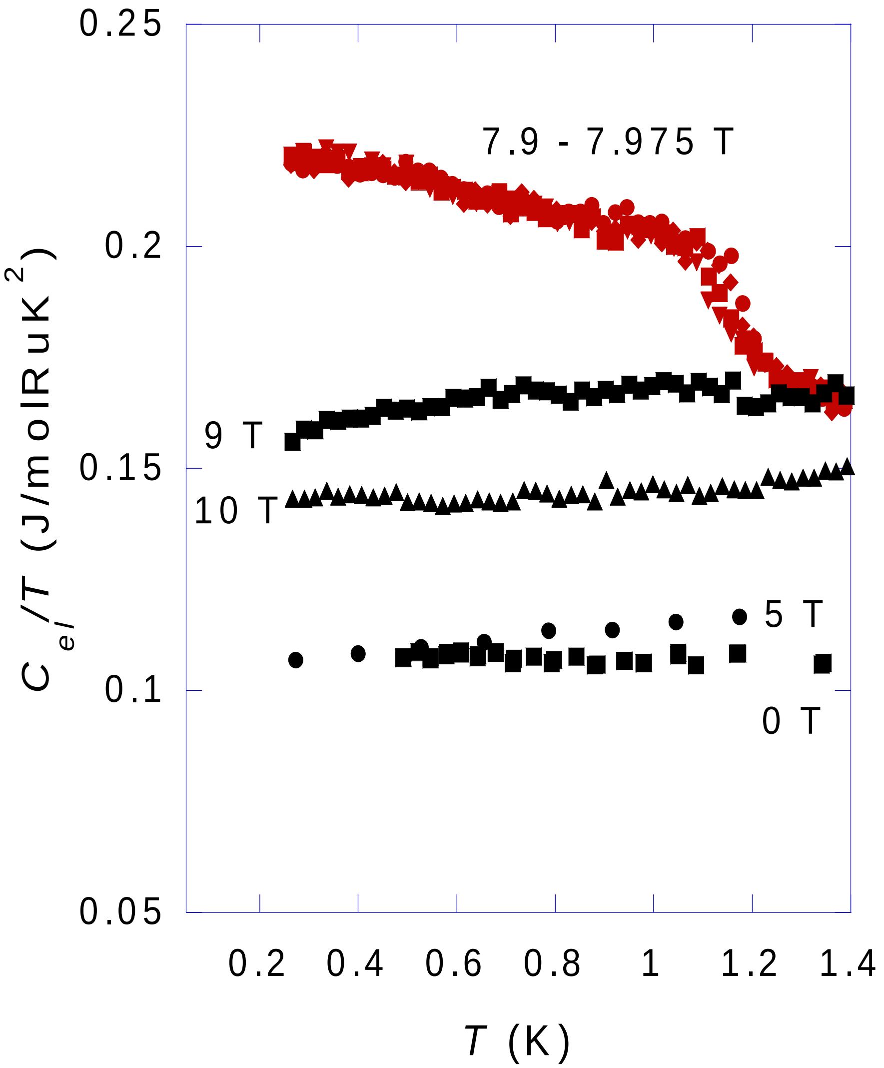
Low temperature specific heat and phase formation

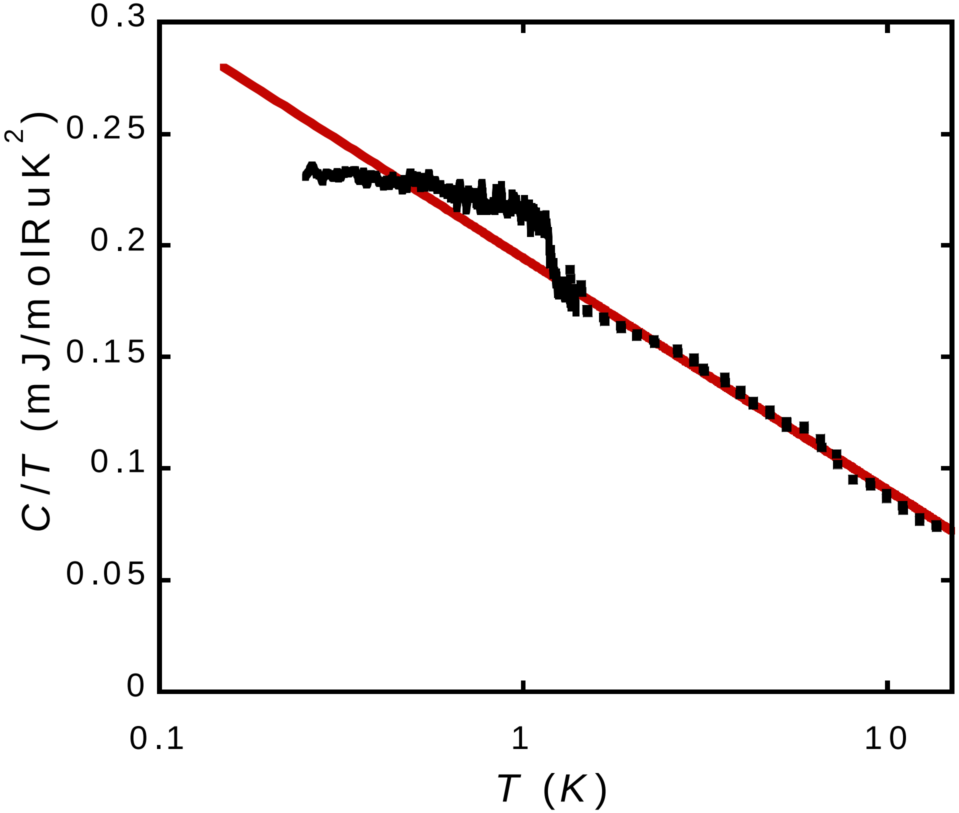




Cool into the phase: see rise in *C*/*T* even below T_c.

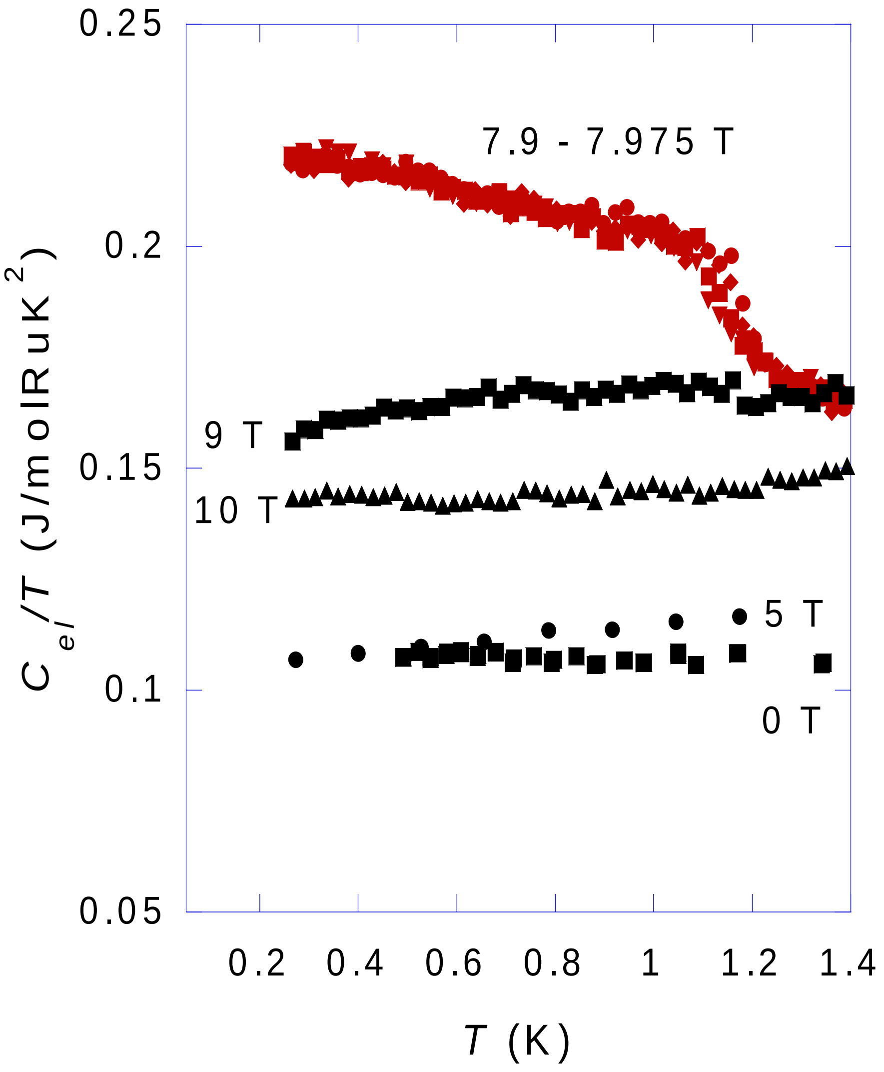
Low temperature specific heat and phase formation

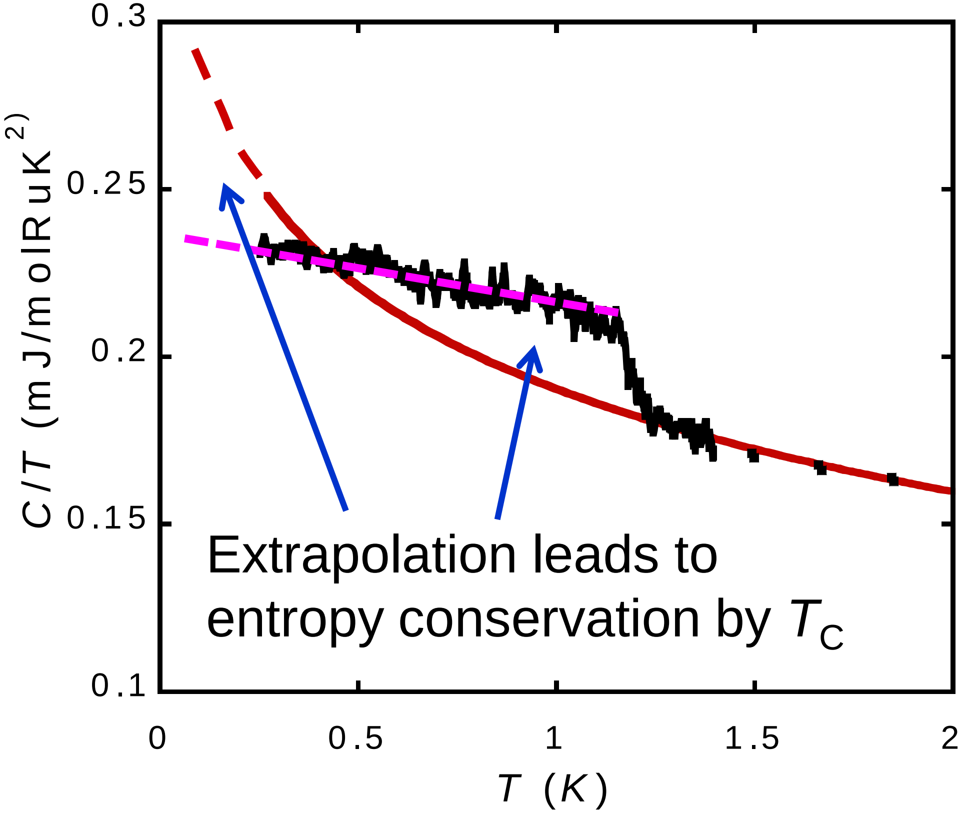




Background logarithmic divergence almost certainly plays a role in determining the observed behaviour.

Low temperature specific heat and phase formation

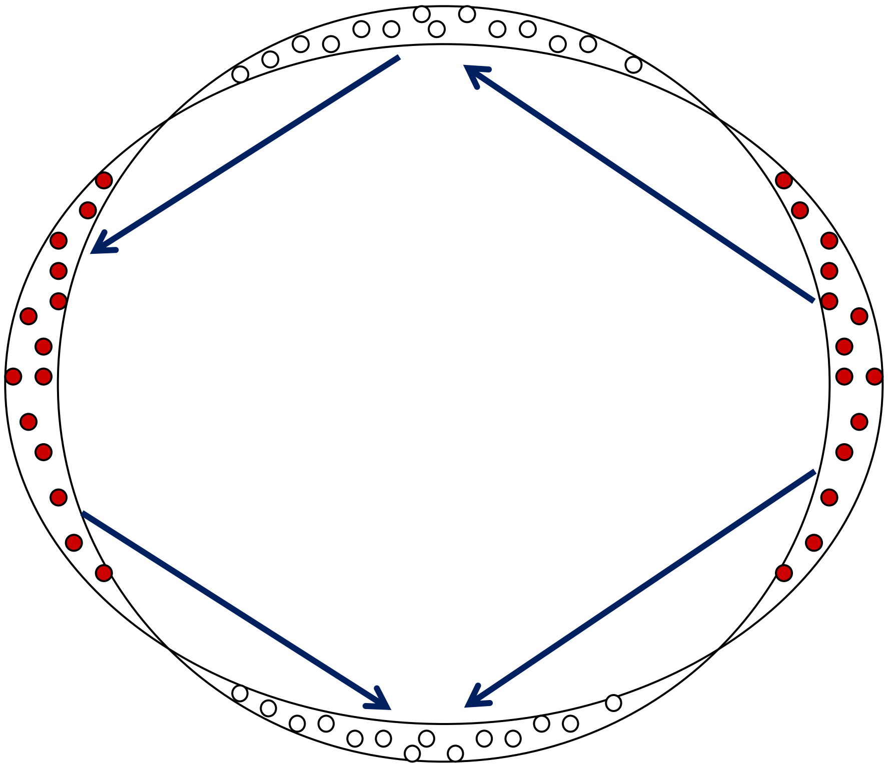




Extrapolation leads to entropy conservation by T_C

N.B. Entropy conservation is achieved by extrapolating the logarithmically diverging C/T.

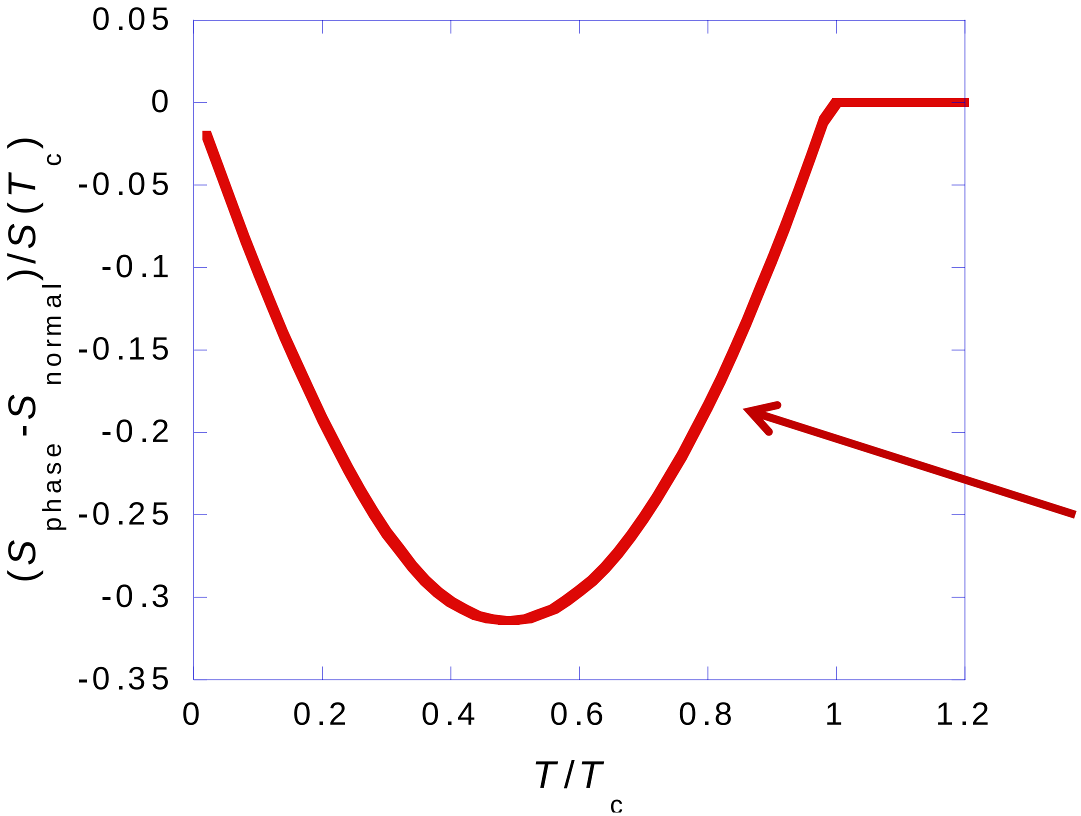
Possible microscopic model for phase: Pomeranchuk distortion



Appealing because it would give a natural explanation for 4-fold to 2-fold symmetry lowering and for the very strong observed disorder dependence.

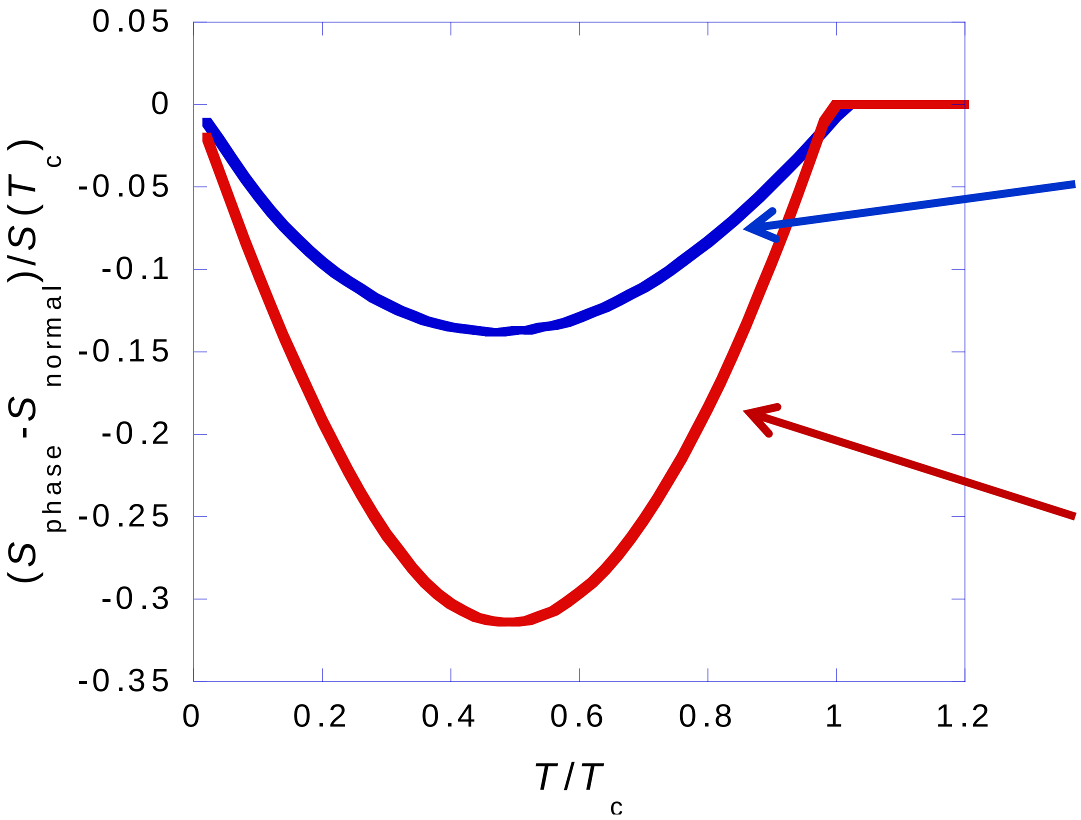
Weak back-coupling to the lattice is expected in such a picture; a part in 10^6 effect was observed very recently [*C. Stingl, R.S. Perry, Y. Maeno & P. Gegenwart, Phys Rev. Lett.* ***107****, 026404 (2011)*].

Entropy evolution below T_c for new phases



Fully gapped system, e.g. density wave, s-wave superconductor

Entropy evolution below T_c for new phases

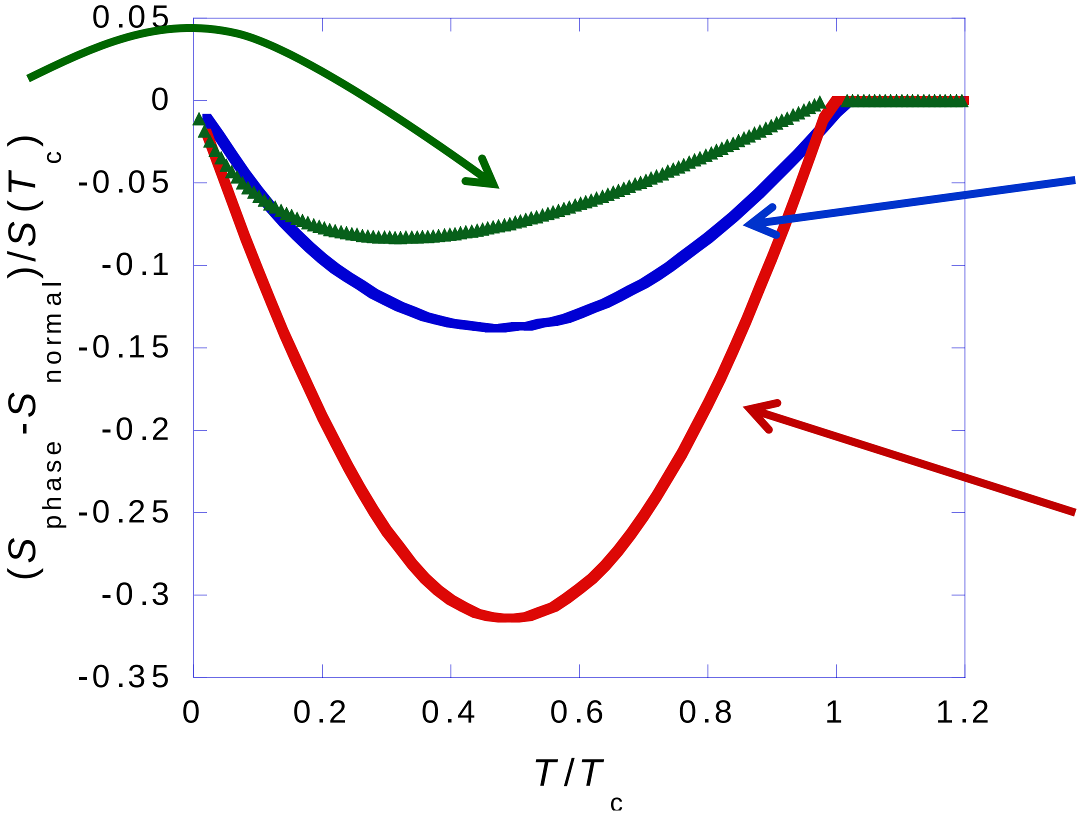


Phase formation without gapping, e.g. idealised mean-field Pomeranchuk distortion

Fully gapped system, e.g. density wave, s-wave superconductor

Entropy evolution below T_c for new phases

Our data



Phase formation without gapping, e.g. idealised mean-field Pomeranchuk distortion

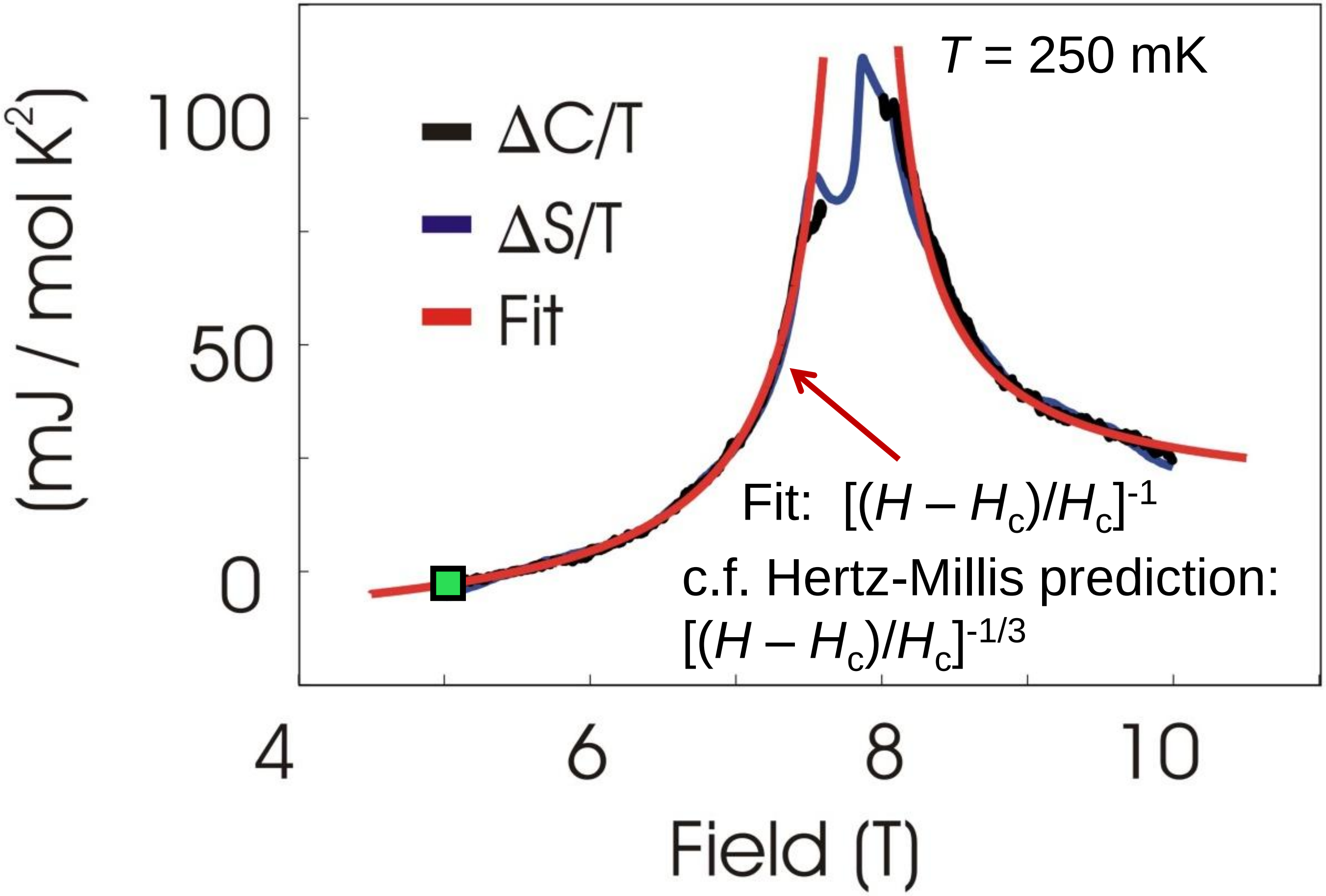
Fully gapped system, e.g. density wave, s-wave superconductor

Data seem consistent with a second order phase transition which does not open an energy gap, plus some extra degrees of freedom beyond mean-field.

A. W. Rost, S. A. Grigera, J. A. N. Bruin, R. S. Perry, D. Tian, S. Raghu, S. A. Kivelson, A. P. Mackenzie arXiv:1108.3554; to appear in Proc Nat Acad Sci USA (2011)

Field dependence of the entropy

Combining measurements of specific heat and magneto-caloric effect:



T = 250 mK

Fit: $[(H - H_c)/H_c]^{-1}$

c.f. Hertz-Millis prediction: $[(H - H_c)/H_c]^{-1/3}$

$$S(T') = \int_0^{T'} \frac{C}{T} dT$$

Fermions:

$$C = \gamma T$$

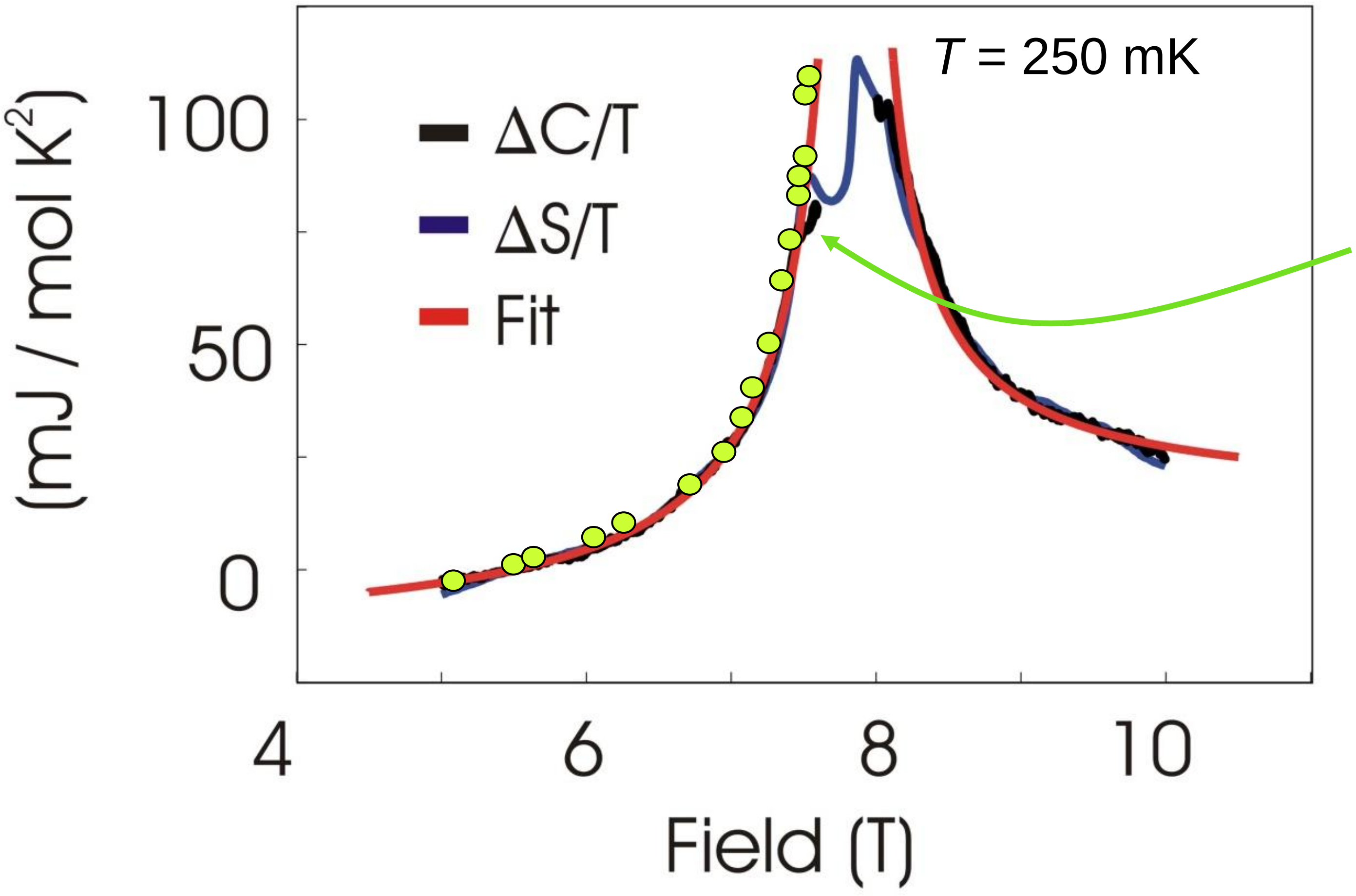
$$\therefore S(T') = \gamma T' = C(T')$$

A.W. Rost et al., Science ***325****, 1360 (2009)*

J. Zaanen, Nature Journal Club Nov 2009

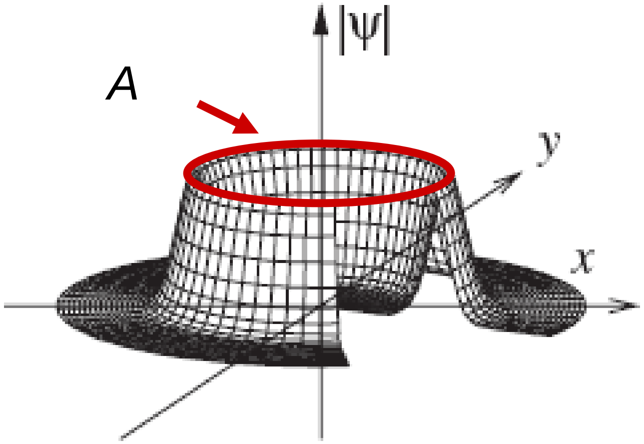
Field dependence of the entropy

Ours does not turn out to be the first observation of this power:



ΔC/T for $CeRu_2Si_2$ (data reported by Grenoble and Osaka groups without comment in the 1990s)

Quantum oscillations – the Onsager-Lifshitz interpretation



Bohr-Sommerfeld condition for orbital motion

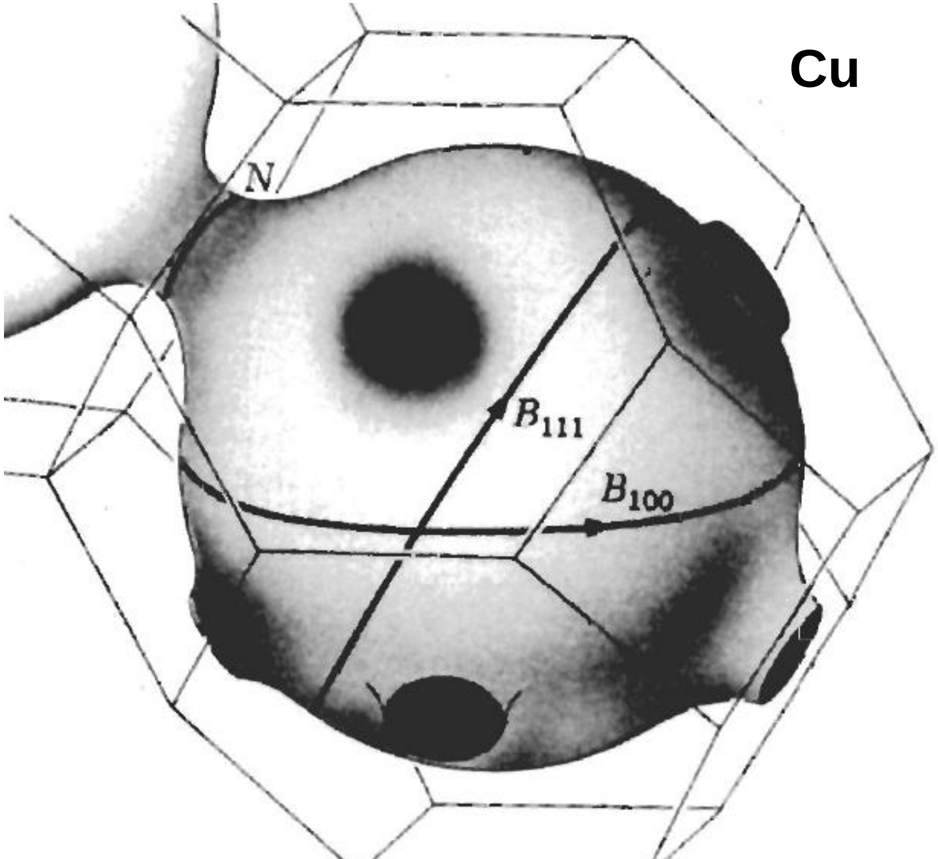
Orbit area in real space is quantised such that flux $\Phi = AH_z = n\,\Phi_o$

‘whereby we recognize a fundamental unit equal to the flux from one of Dirac’s hypothetical magnetic poles’

1950 – 70: Two decades of mapping 3D Fermi surfaces of ‘simple’ metals.

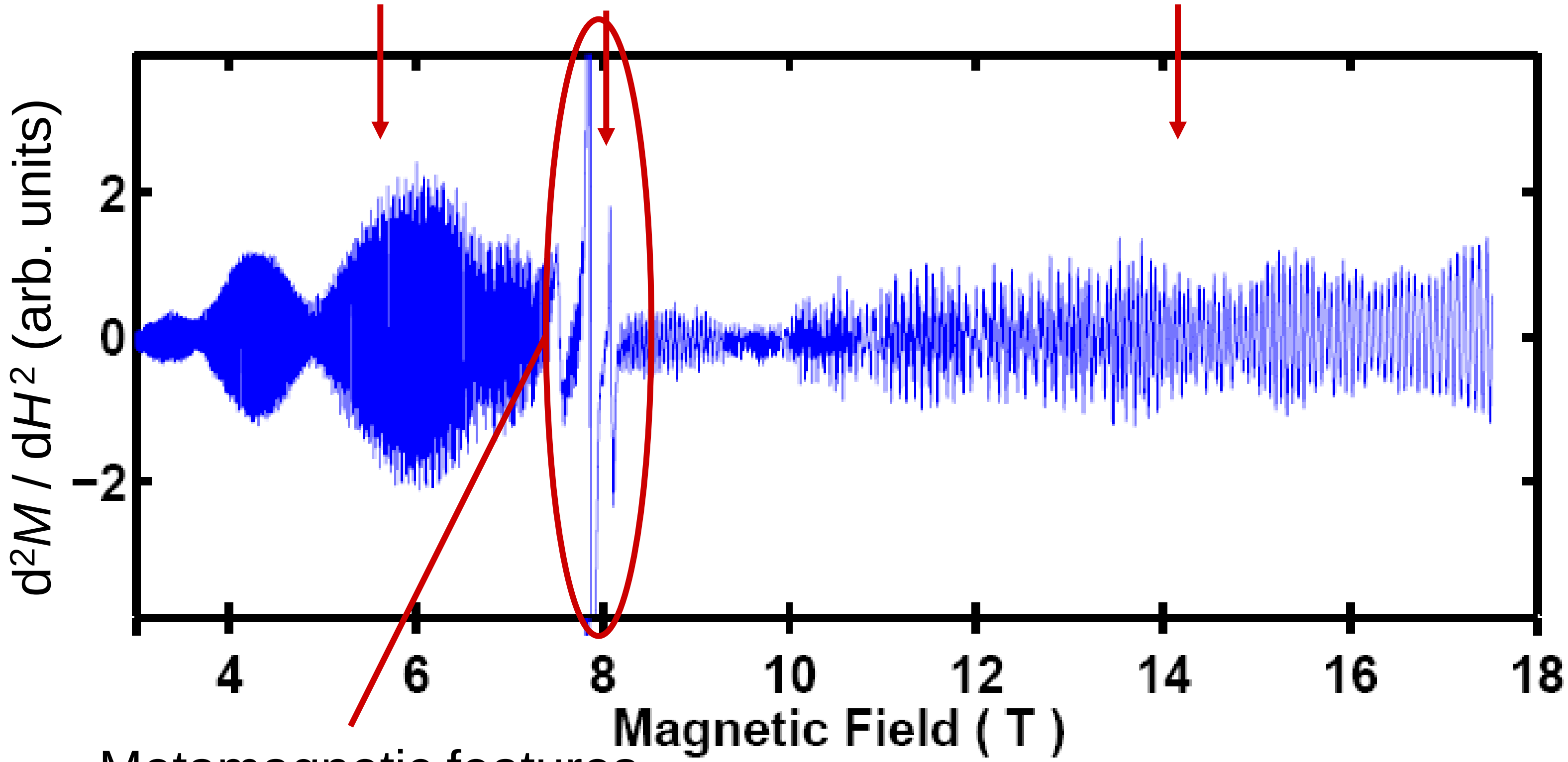
Onsager – Lifshitz relation in *k* space:

$$A_F = \frac{2\pi e F}{\hbar}$$



The de Haas – van Alphen Effect in $Sr_3Ru_2O_7$

dHvA oscillations seen below, above and within the transition region.



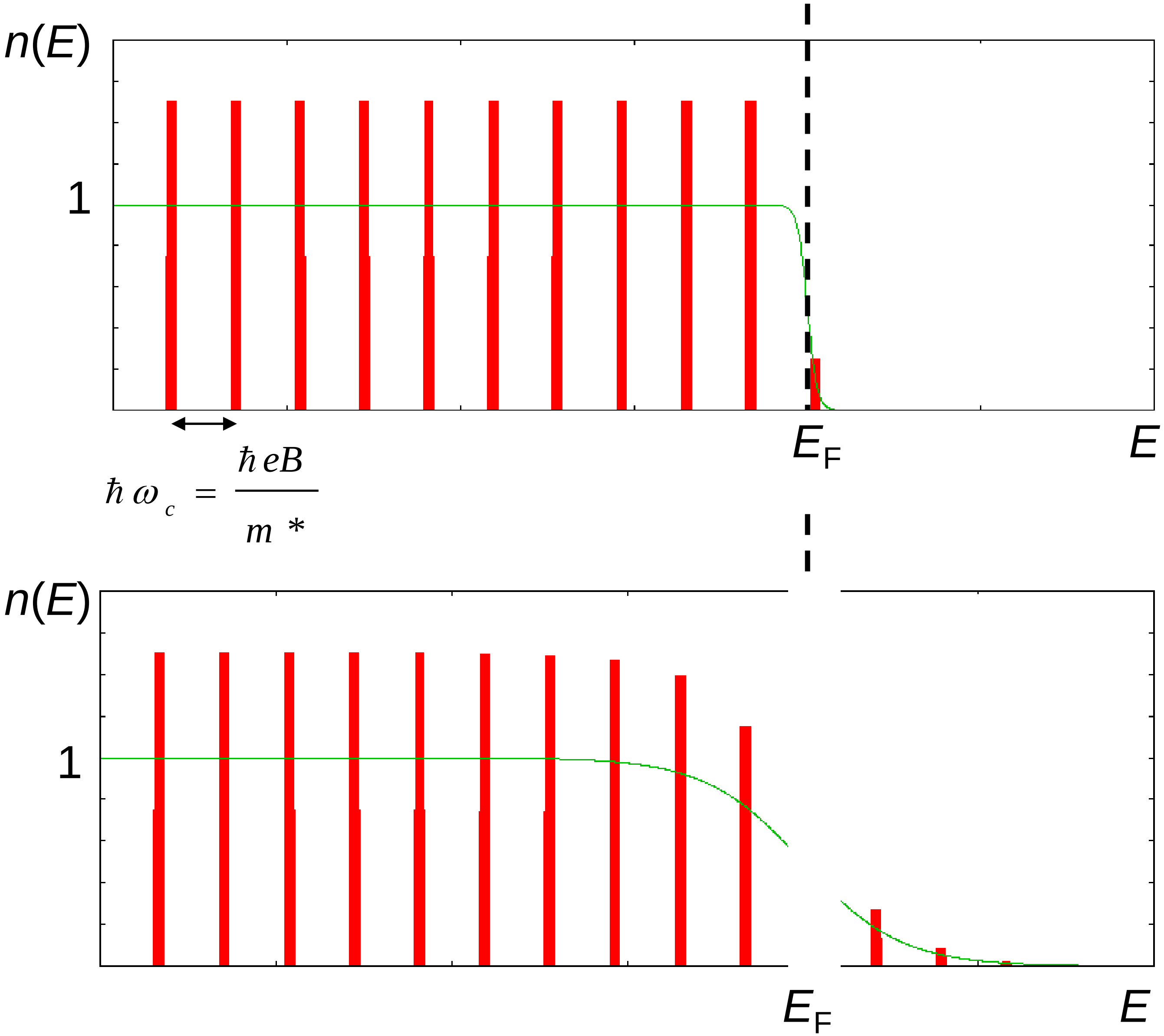
Metamagnetic features

The $Sr_3Ru_2O_7$ phase diagram comprises a series of metallic fluids; the basic picture is one of itinerant rather than localised magnetism.

St. Andrews – Cambridge collaboration: J.F. Mercure et al., Phys. Rev. Lett. ***103****, 176401 (2009)*

Condition to see oscillations: narrow Fermi function

Illustration given in two dimensions



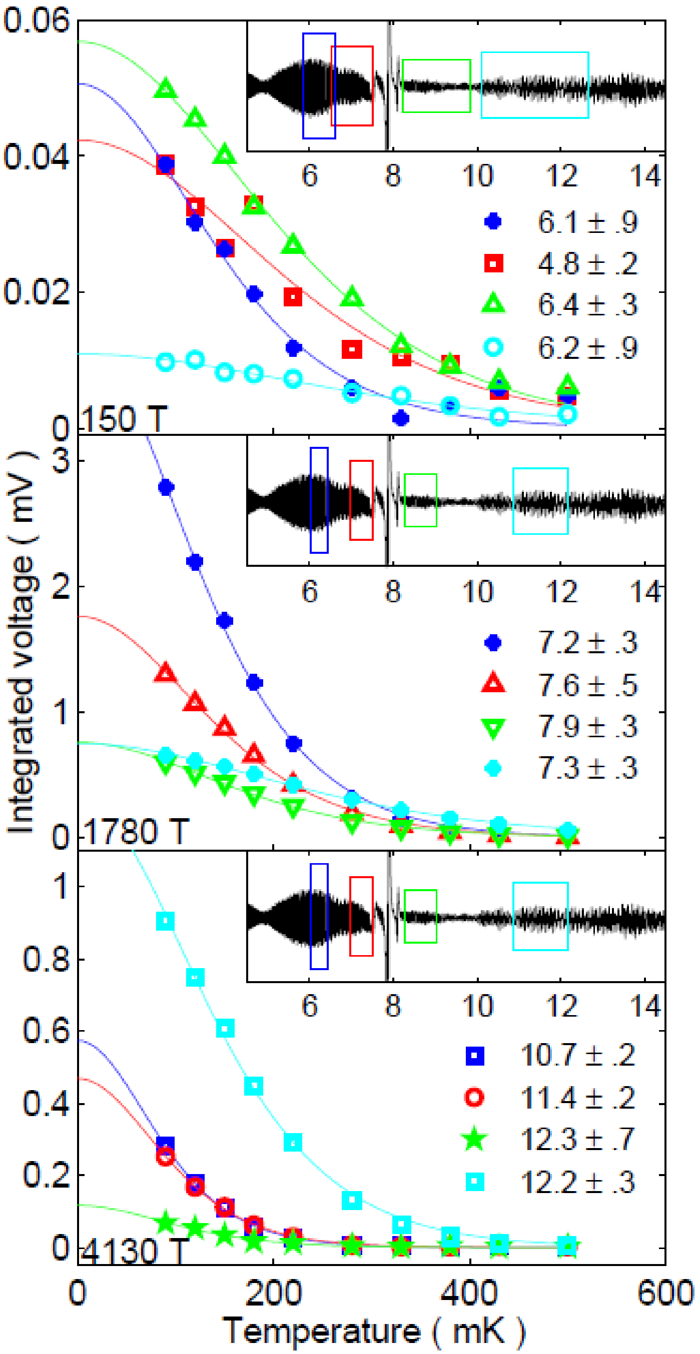
$$\hbar\omega_c = \frac{\hbar eB}{m^*}$$

Consequence: if the carriers in an exotic metal are charged and obey Fermi-Dirac statistics, the oscillatory amplitude *A*(*T*) follows the well-known Lifshitz-Kosevich form:

$$A(T) = \frac{\pi\lambda}{\sinh(\pi\lambda)}$$

where

$$\pi\lambda = \frac{2\pi^2 m^* k_B T}{e\hbar B}$$



Lifshitz-Kosevich behaviour is observed in $Sr_3Ru_2O_7$

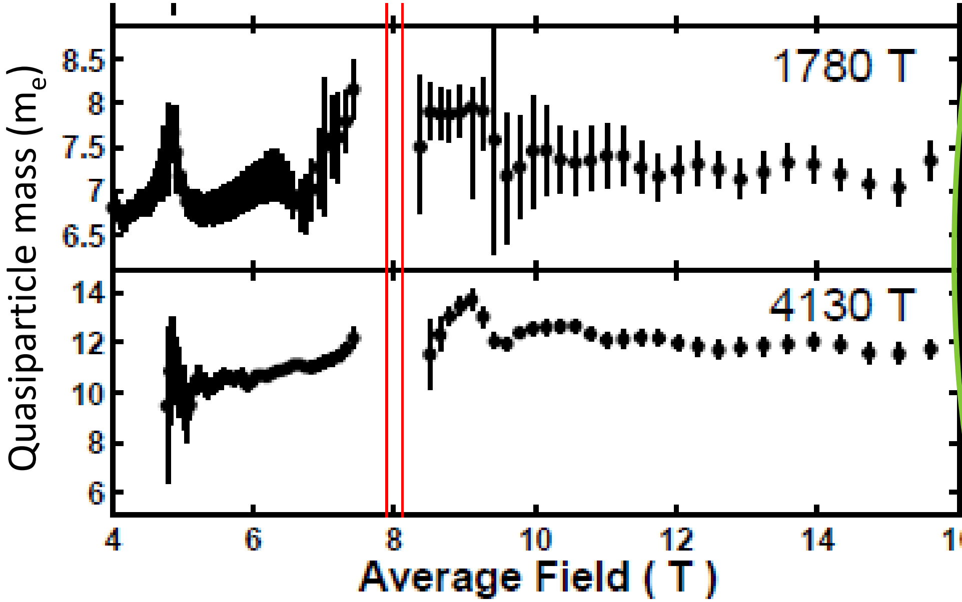
Many dHvA frequencies, in qualitative agreement with known complex Fermi surface.

No matter what field ranges we analyse, the Lifshitz-Kosevich form for the temperature dependence of the oscillations is obeyed within our experimental error.

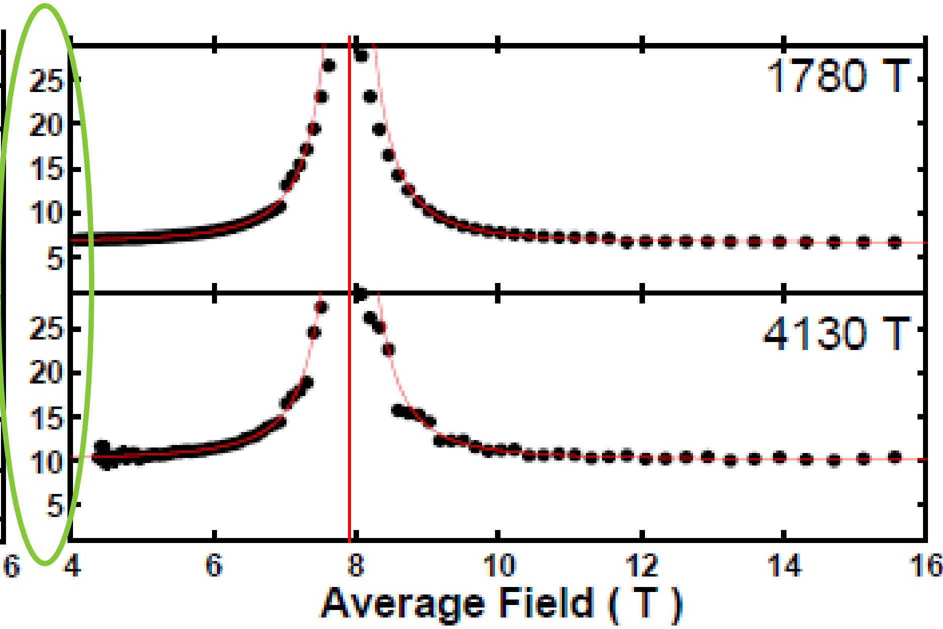
BUT

We do not see the mass associated with any frequency show the field dependence of the specific heat:

Numerical tests show that our analysis procedure is up to the job.



Analysis of our actual data



Analysis of simulated data of similar signal-to-noise ratio and including a mass increase similar to that indicated by the specific heat

For one tiny frequency (110 T) we cannot tell whether or not there is a mass increase using our current data set – we will be testing this in future.

*J.-F. Mercure et al., Phys. Rev. B **81**, 235103 (2010).*

Conclusions

- High purity $Sr_3Ru_2O_7$ has proved to be an unexpected playground for the study of phase formation in quantum critical systems.
- The opportunity to study its thermodynamic properties particularly useful.
- The evidence available so far suggests that there is no ground state entropy in $Sr_3Ru_2O_7$.
- More examples of thorough thermodynamic characterisation of phases formed directly from quantum critical ‘soup’ are highly desirable.

Future work

- Seek more examples of magnetically tuned systems, and investigate power law behaviour of entropy vs. field at lower temperatures.
- Study the relationship between quantum oscillation masses and thermodynamic potentials in the vicinity of magnetic QCPs