The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

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2157-9

Workshop on Principles and Design of Strongly Correlated Electronic Systems

2 - 13 August 2010

Thermodynamic Studies of $Sr_3Ru_2O_7$

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Thermodynamic studies of $Sr_3Ru_2O_7$

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Recent collaborators

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Contents

1. $Sr_3Ru_2O_7$ and the phase diagram of itinerant ferromagnetism

2. Thermodynamic probes used in our group: magnetisation, quantum oscillations, specific heat and magneto-caloric effect

3. Quantum critical entropy pileup

4. A novel phase with nematic transport properties and additional degrees of freedom

5. Broader perspectives: relevance to surface spectrosopy, electronic nematics, heavy fermion physics and beyond.

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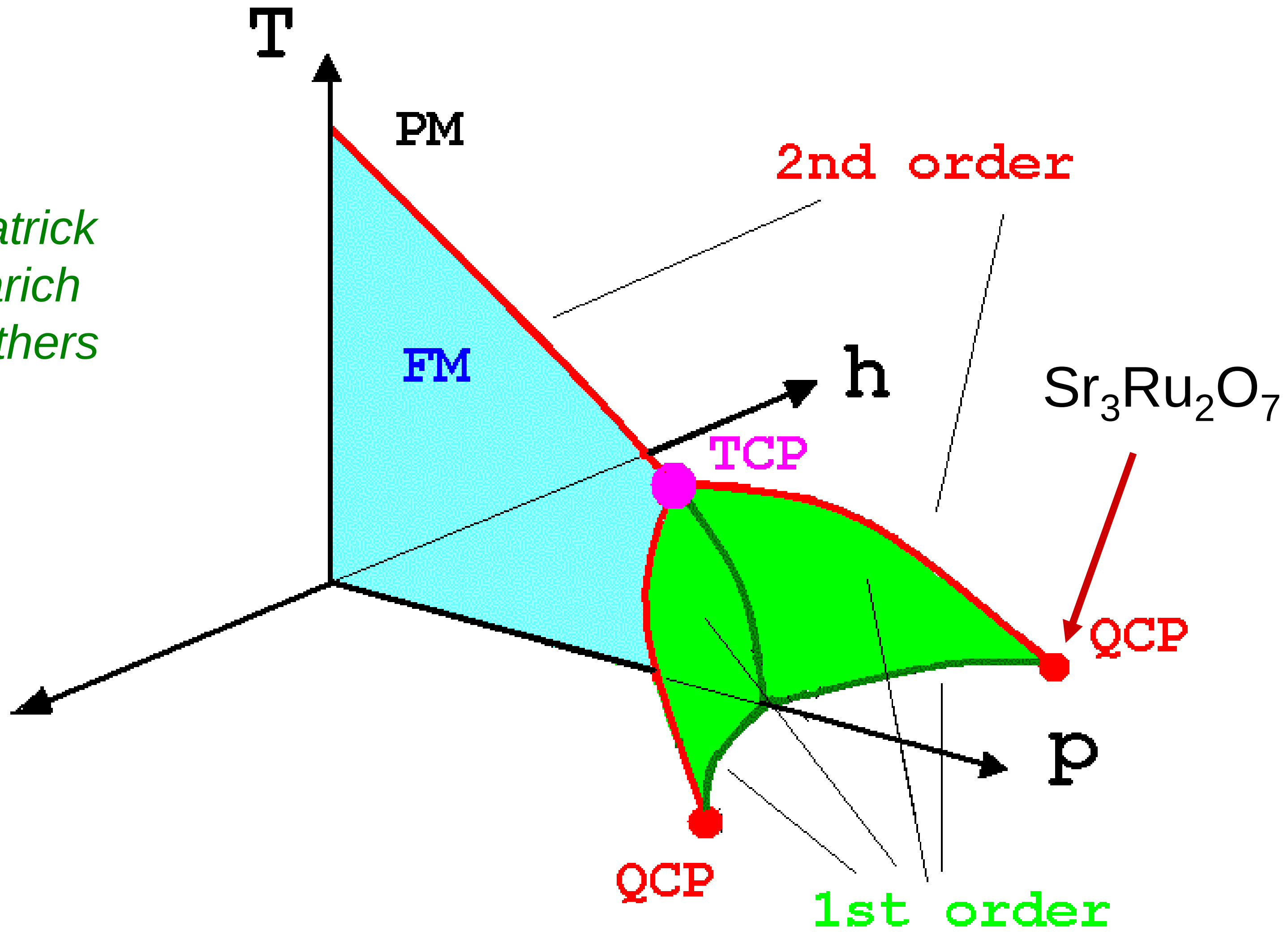
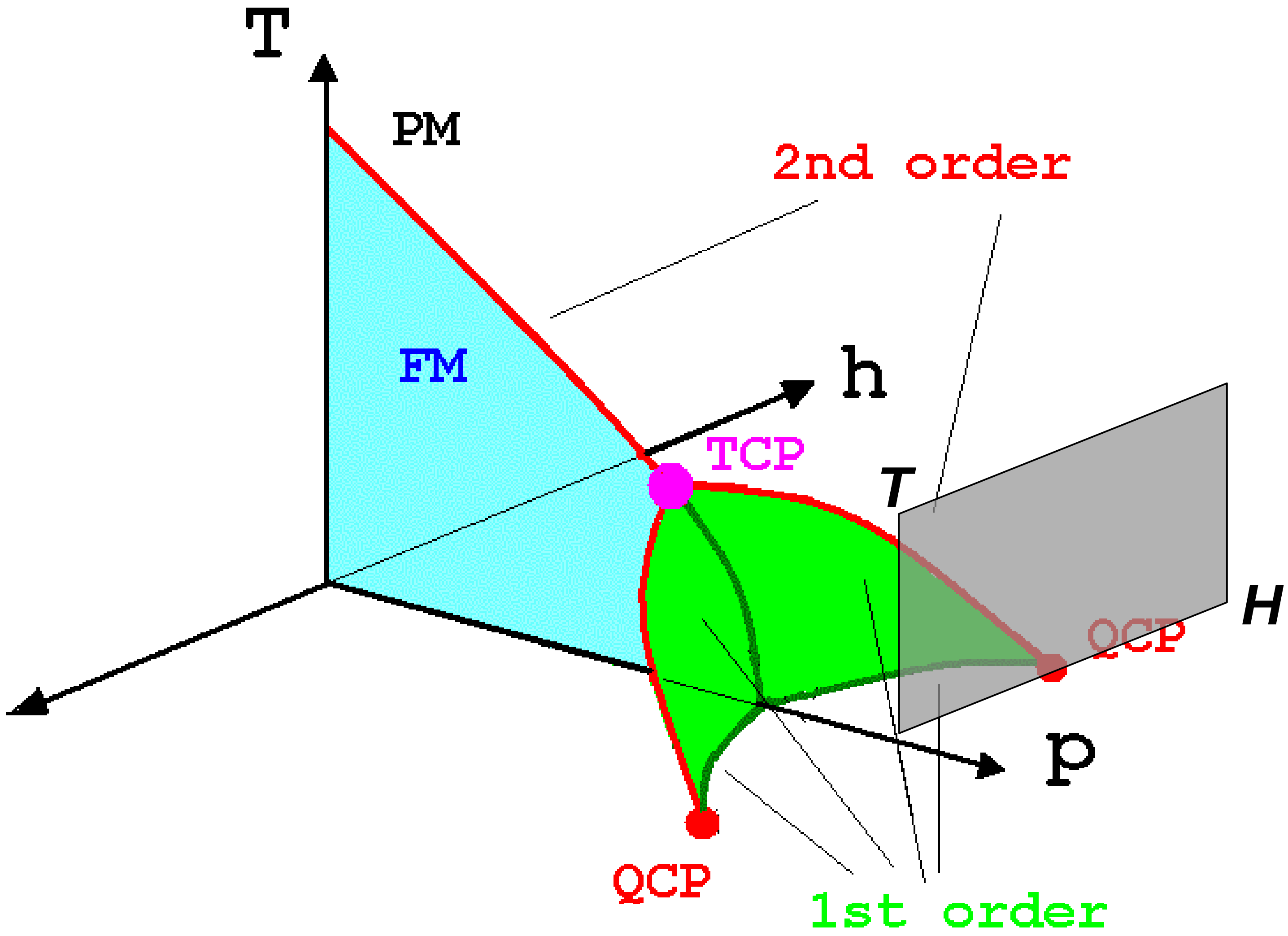
$Sr_3Ru_2O_7$ in the phase diagram of itinerant ferromagnetism

Belitz,
Kirkpatrick
Lonzarich
and others

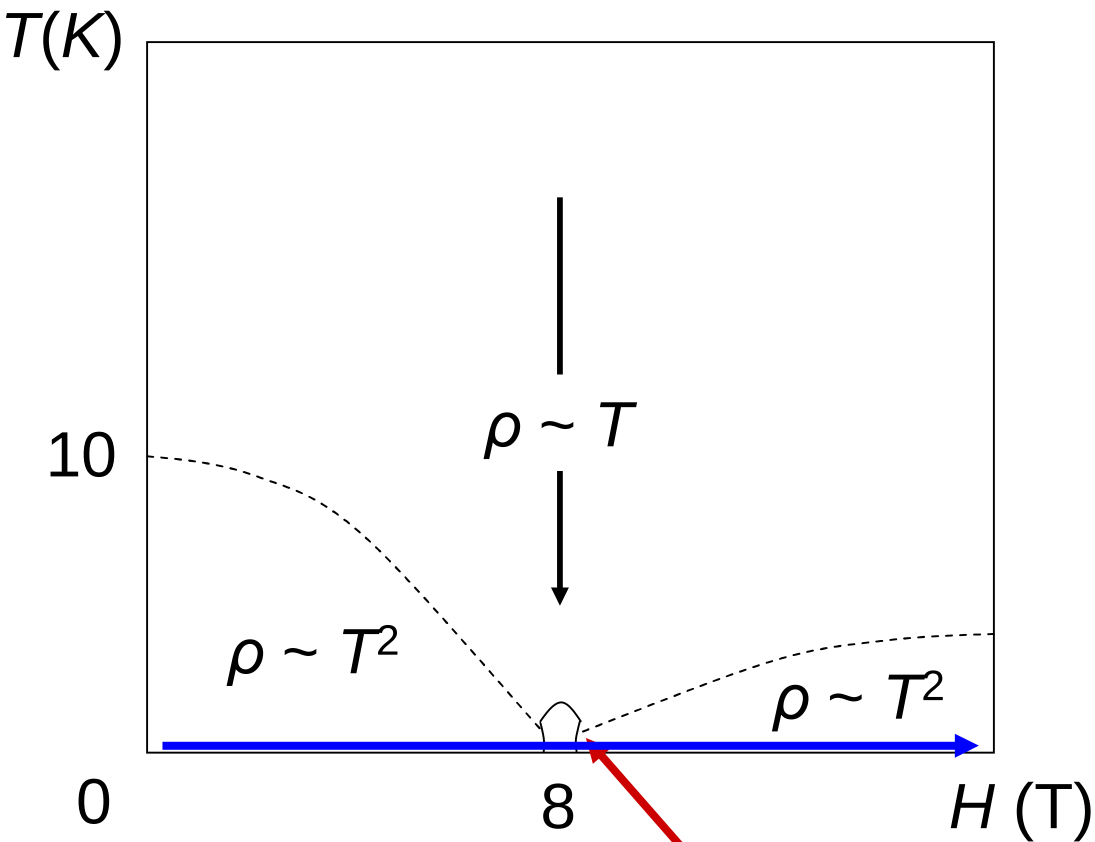


Data presented in this talk



Relevant electronic shells are Ru 4*d* and O 2*p*; no *f* electrons

Quantum critical transport phase diagram



Approach to QCP cut off by novel phase formation in purest crystals

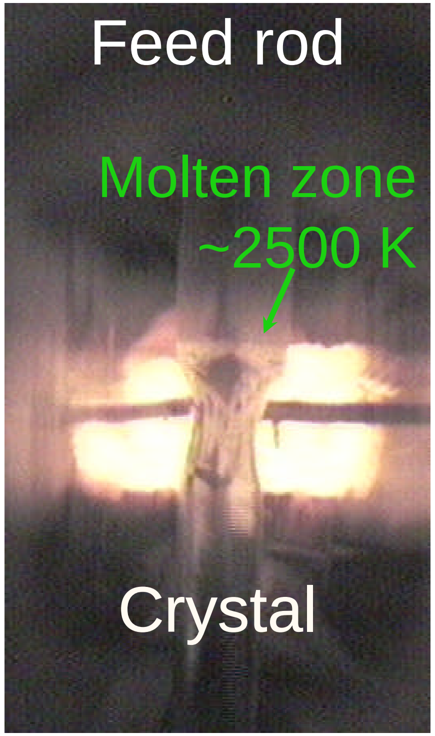
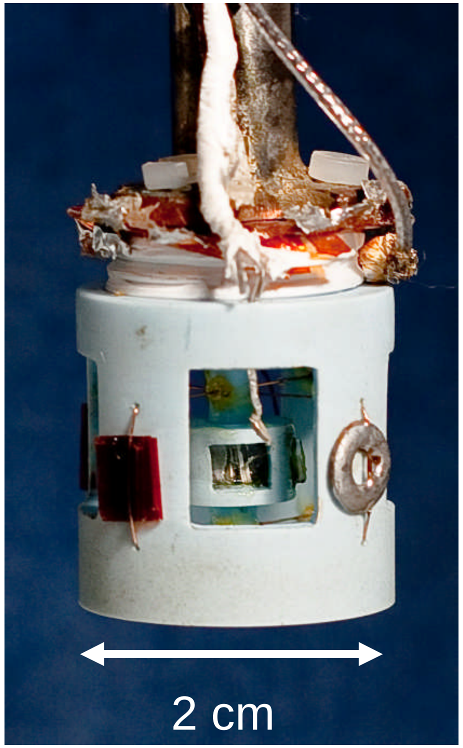


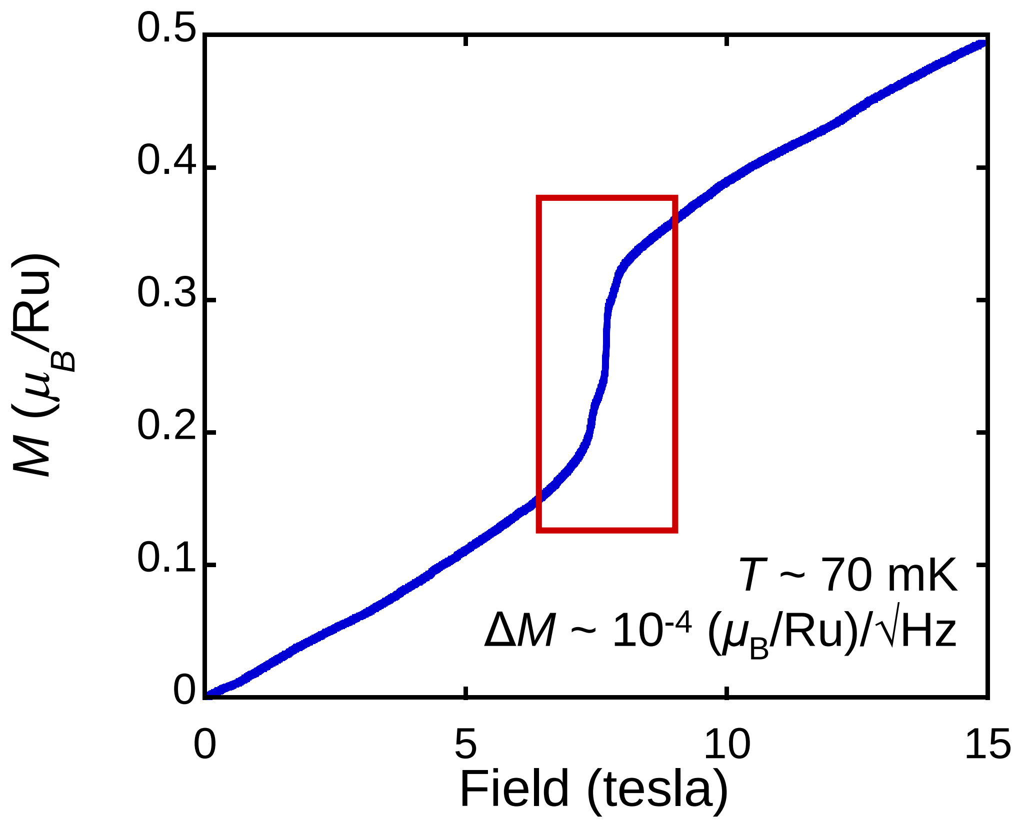
Image furnace grown single crystals now with mean free paths greater than 3000 Å

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

*R.S. Perry & Y. Maeno, J. Cryst. Growth **271**, 134 (2004)*

Low temperature magnetisation of $Sr_3Ru_2O_7$

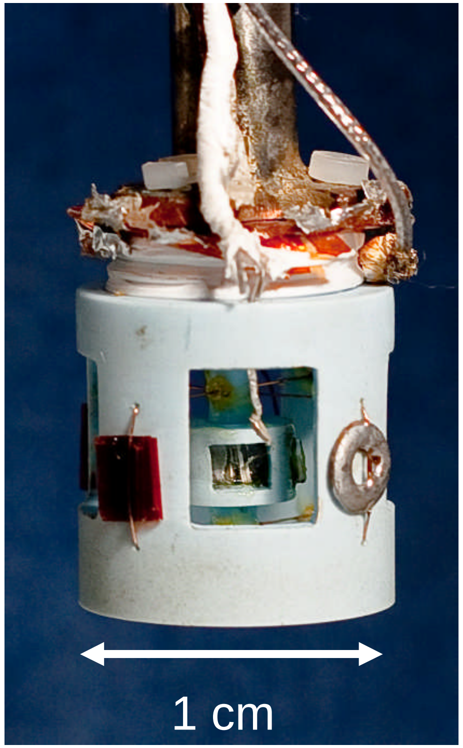


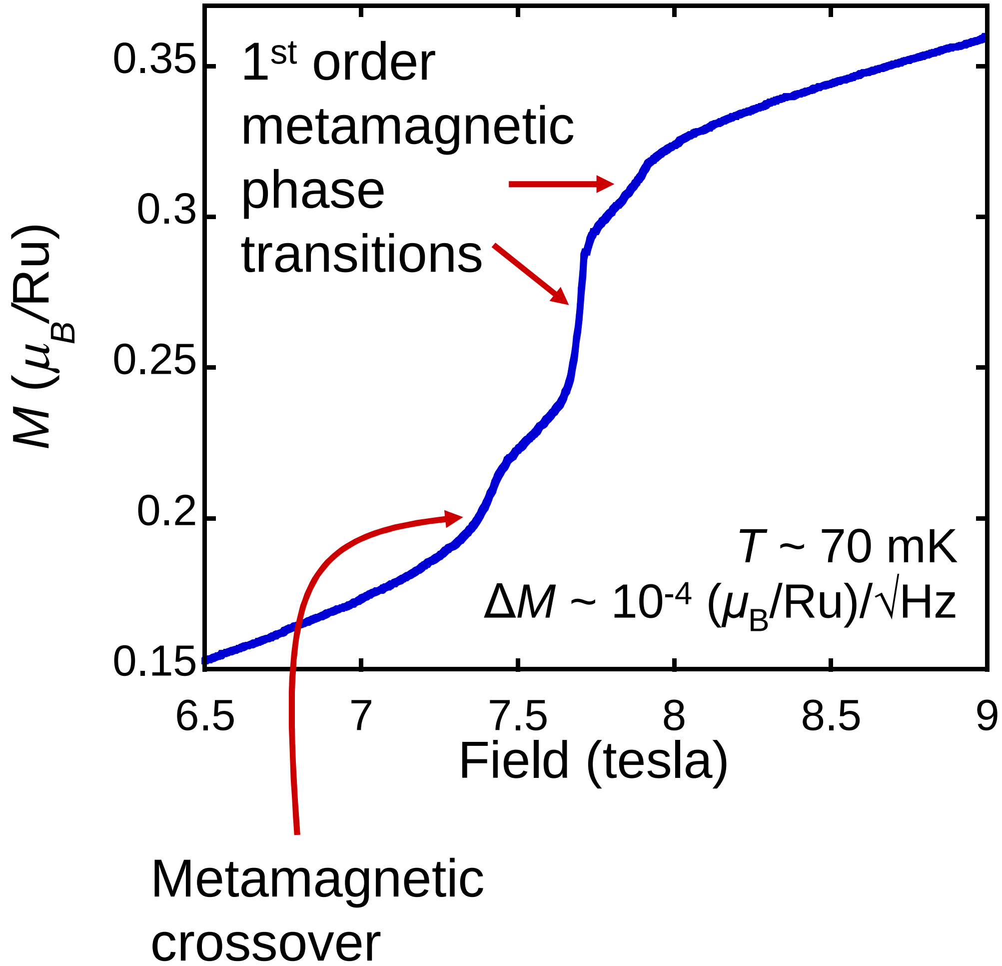


Lightweight plastic construction Faraday force magnetometer with independent sample temperature measurement, capacitive displacement sensing and reversible field gradient for isolation of torque and magnetisation signals.

D. Slobinsky, R.A. Borzi, R.S. Perry, S.A. Grigera et al.

Low temperature magnetisation of $Sr_3Ru_2O_7$

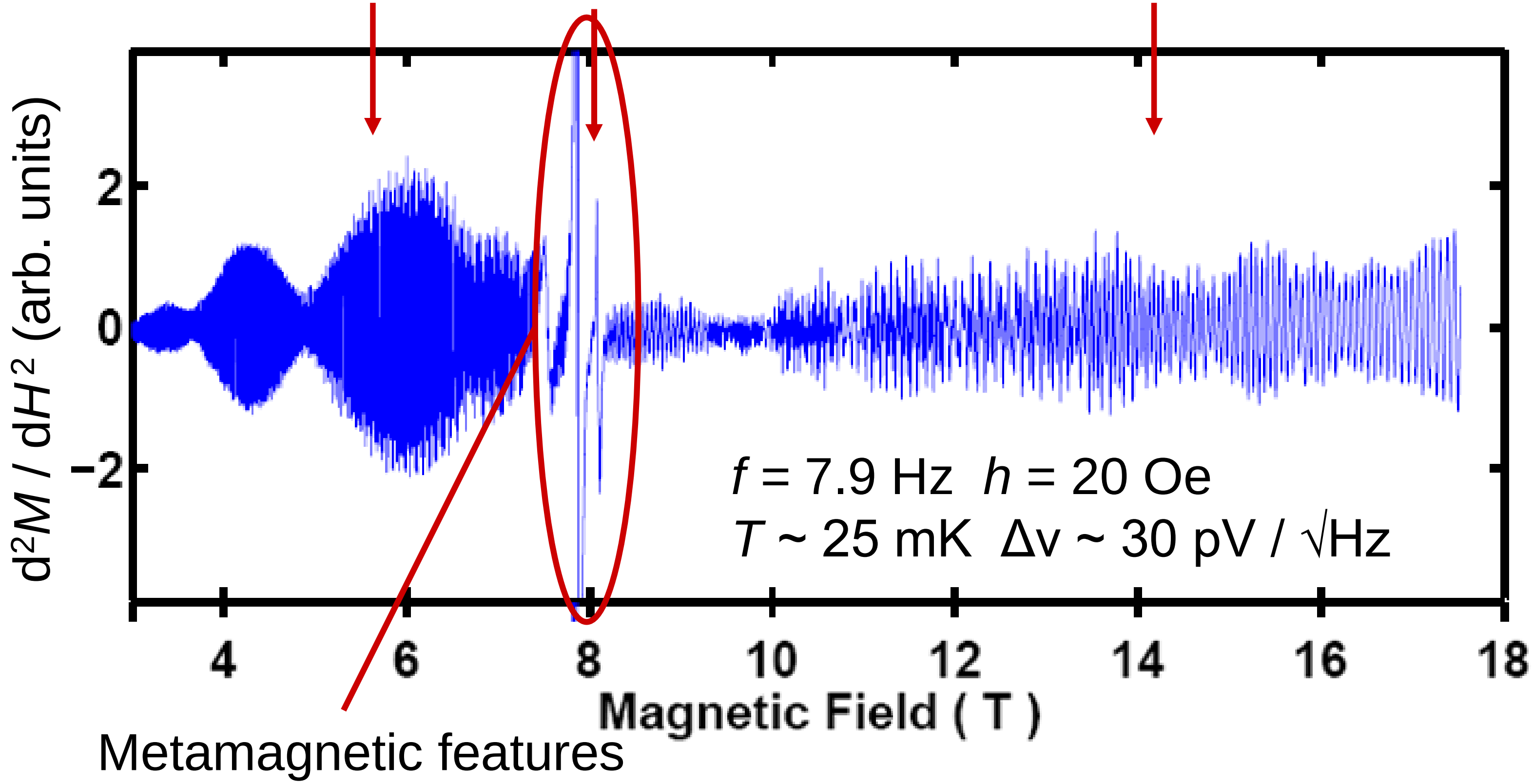




D. Slobinsky, R.A. Borzi, R.S. Perry, S.A. Grigera et al.

The de Haas – van Alphen Effect in $Sr_3Ru_2O_7$

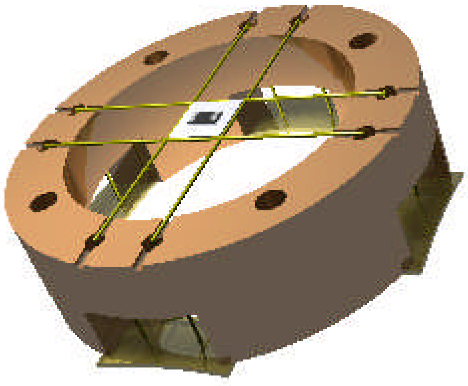
dHvA oscillations seen below, above and within the transition region.



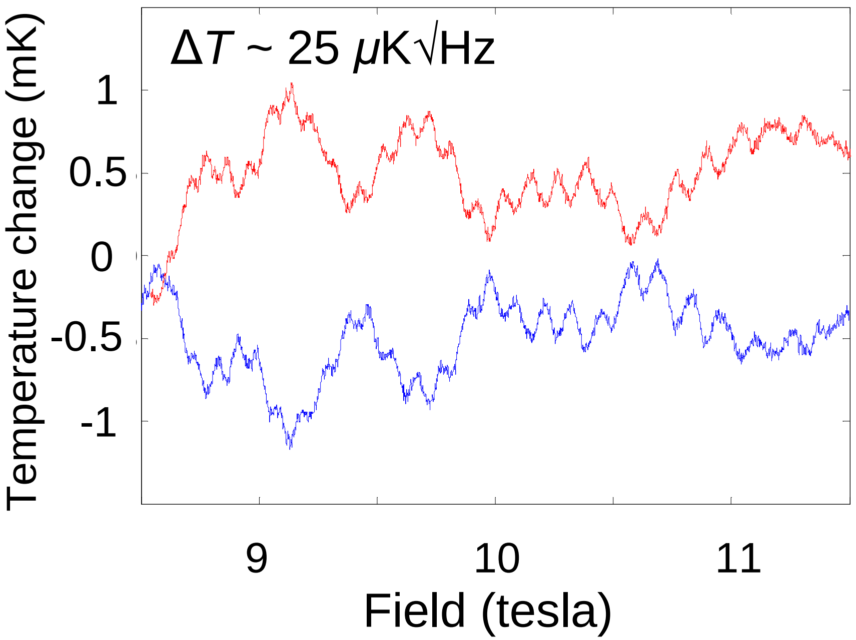
The $Sr_3Ru_2O_7$ phase diagram comprises a series of metallic fluids.

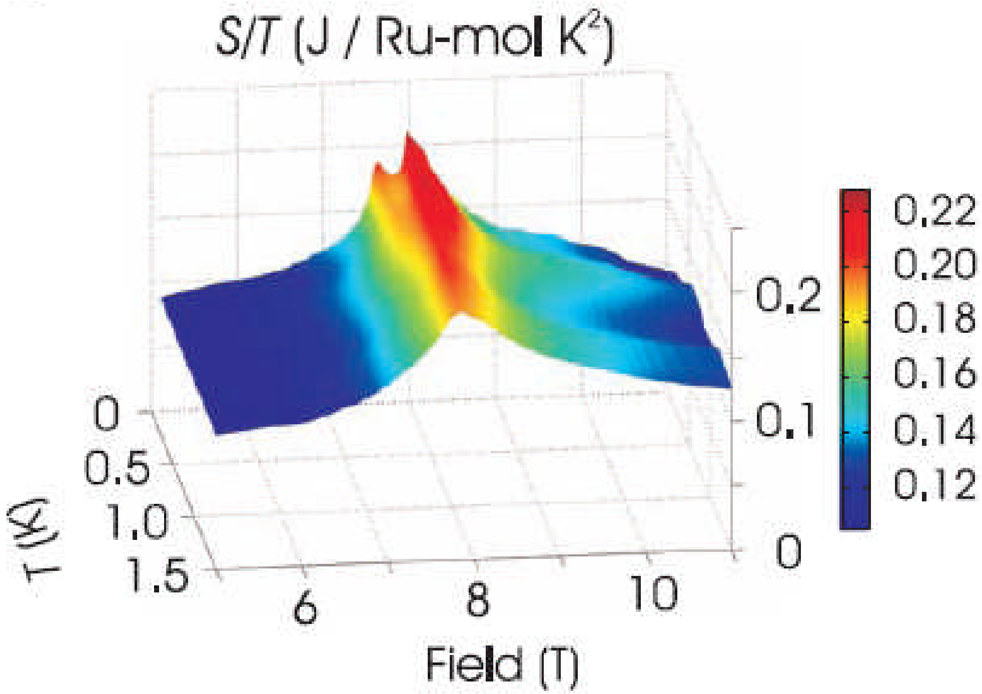
St. Andrews – Cambridge collaboration: J.F. Mercure et al., Phys. Rev. Lett. ***103****, 176401 (2009); Phys. Rev. B* ***81****, 235103 (2010).*

Combined magneto-caloric effect / specific heat in $Sr_3Ru_2O_7$



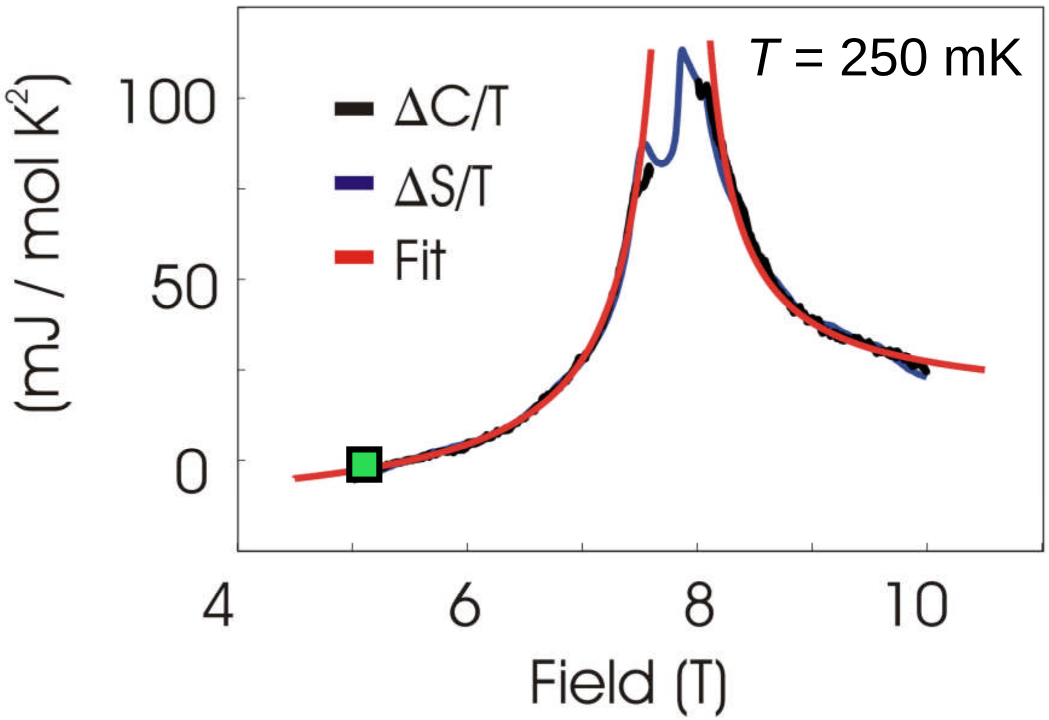
Silver platform suspended from tensioned kevlar fibres with variable thermal coupling to bath. Combination of precision and capability to take data rapidly.





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

Low *T* field-dependent specific heat and entropy in $Sr_3Ru_2O_7$



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

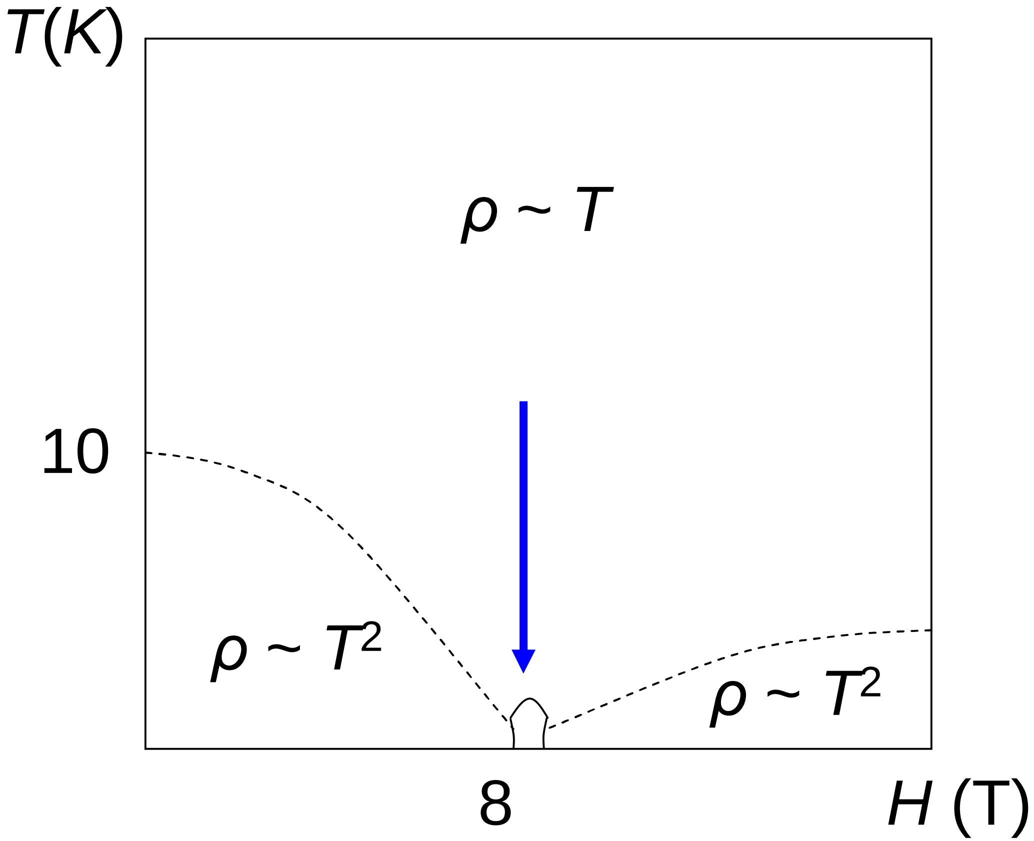
Fermions: $C = \gamma T$

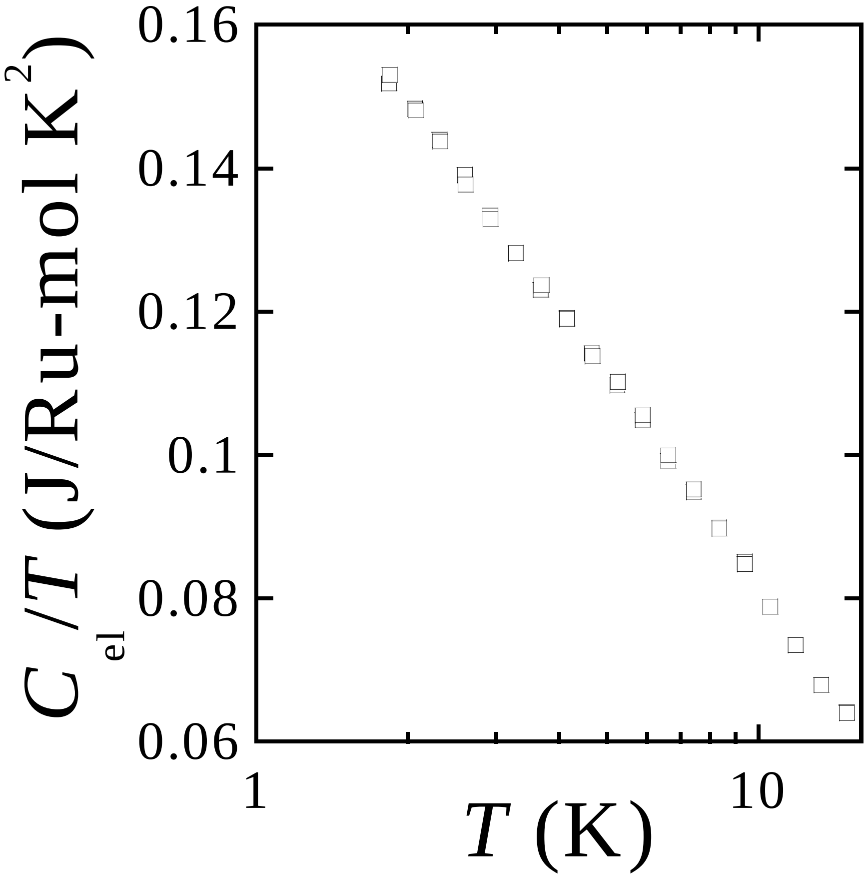
$\therefore S(T') = \gamma T' = C(T')$

Consistent with a mass diverging Fermi liquid (but no direct dHvA observation of a strongly field-dependent mass).

See also L.J. Zhu et al., Phys. Rev. Lett. ***91****, 066404 (2003)*

Logarithmically diverging *C*/*T* above the critical field

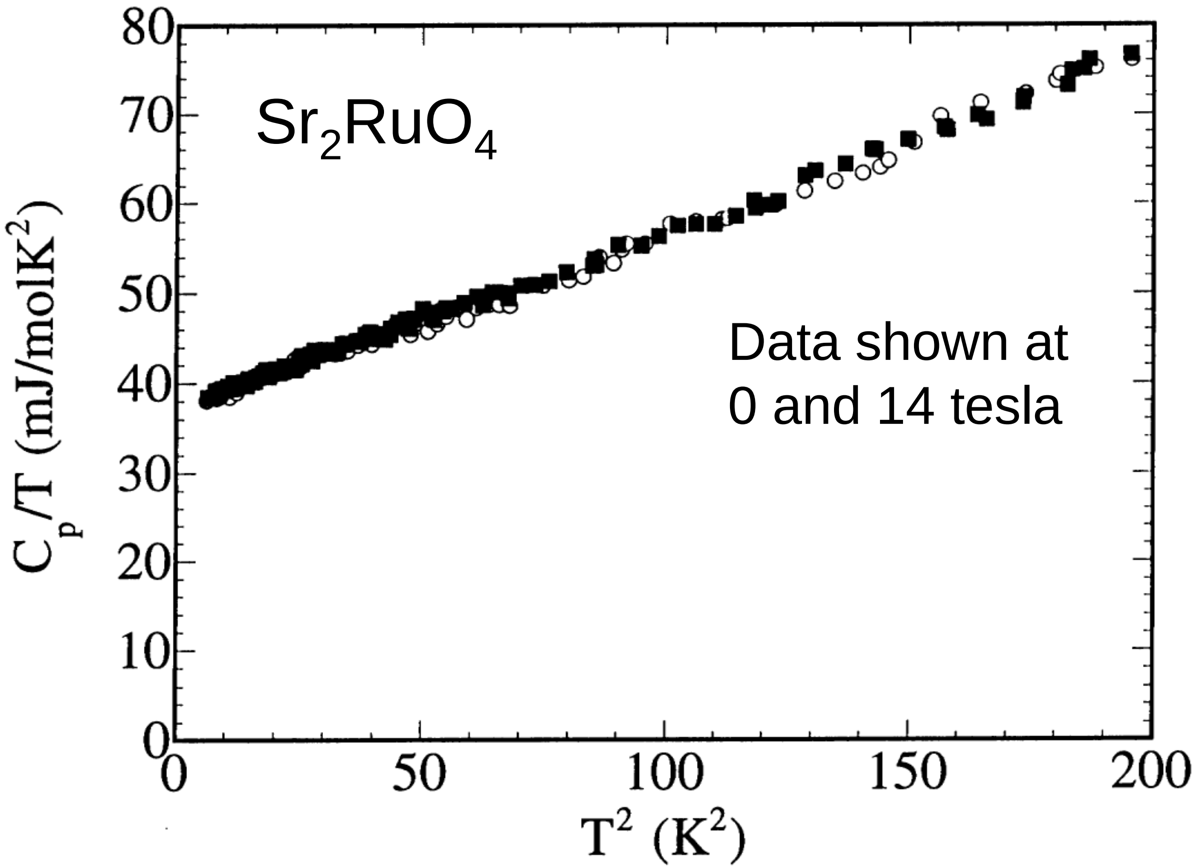




Conclusion – the overall phase diagram of $Sr_3Ru_2O_7$ bears the main qualitative hallmarks of quantum criticality in the vicinity of metamagnetism.

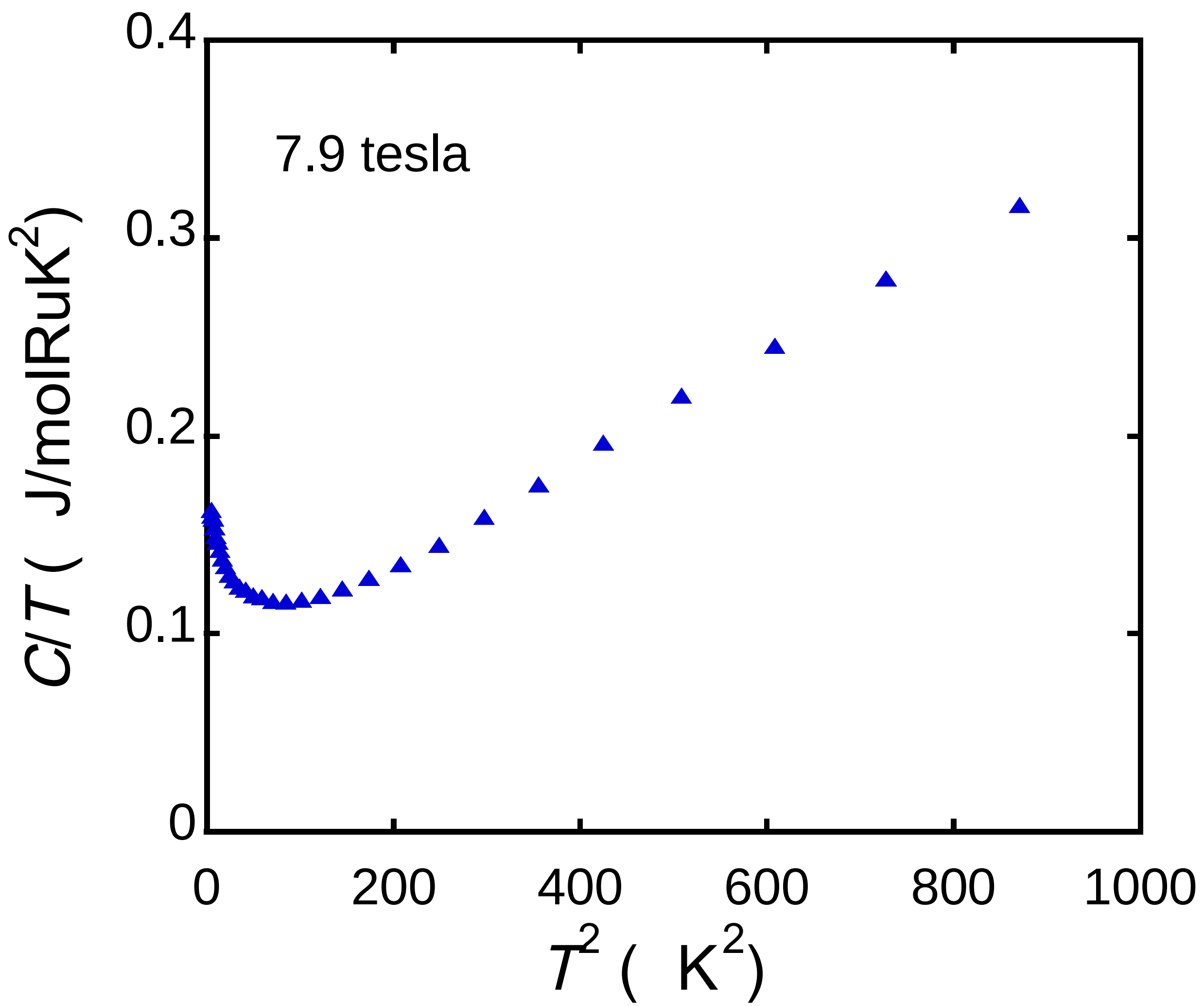
What is the root of this logarithmic divergence?

Consider the total *C*/*T* in a related system that is a conventional Fermi liquid

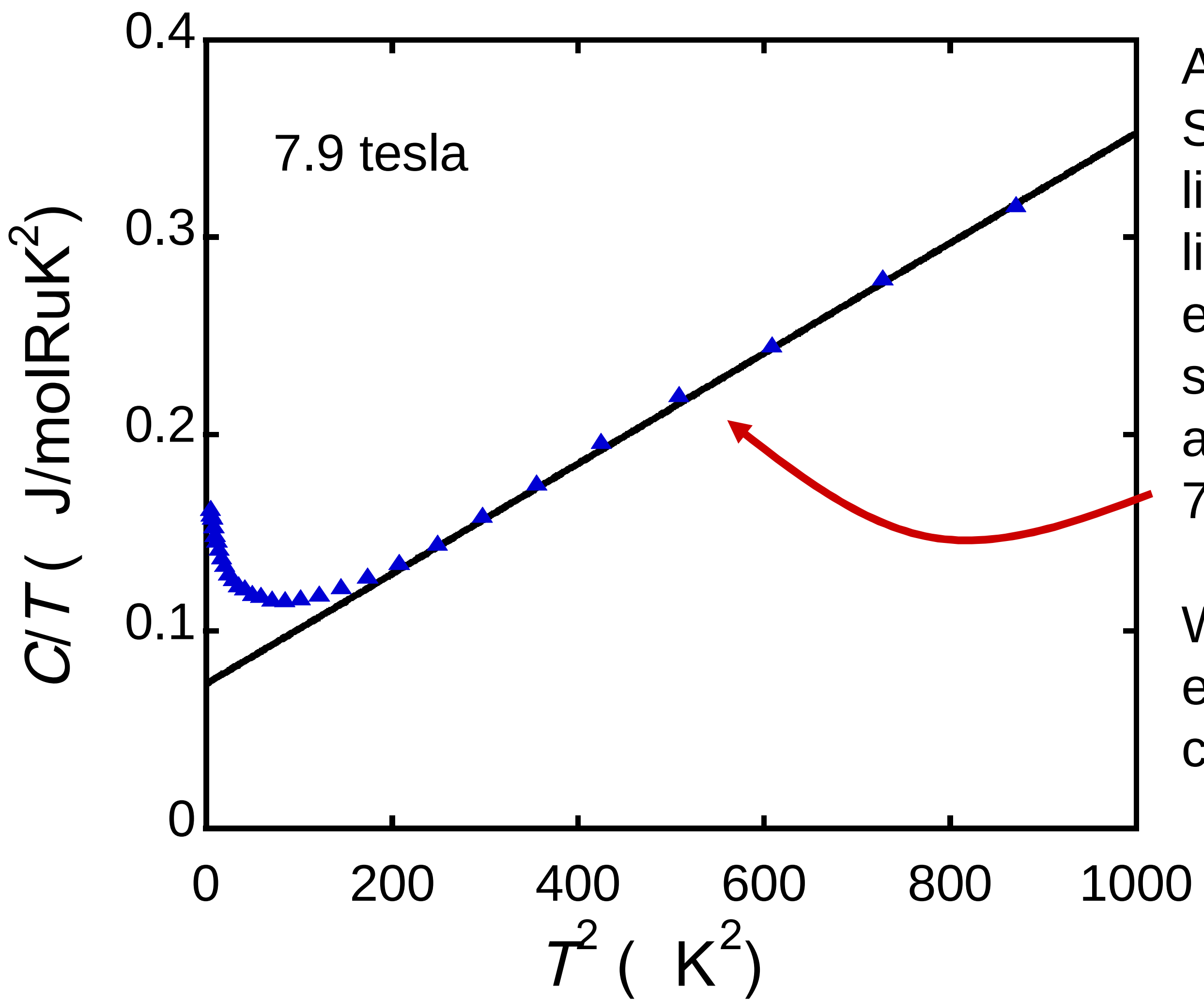


A.P. Mackenzie et al., J. Phys. Soc. Jpn. ***67****, 385 (1998)*

Contrast with $Sr_3Ru_2O_7$ at the critical field



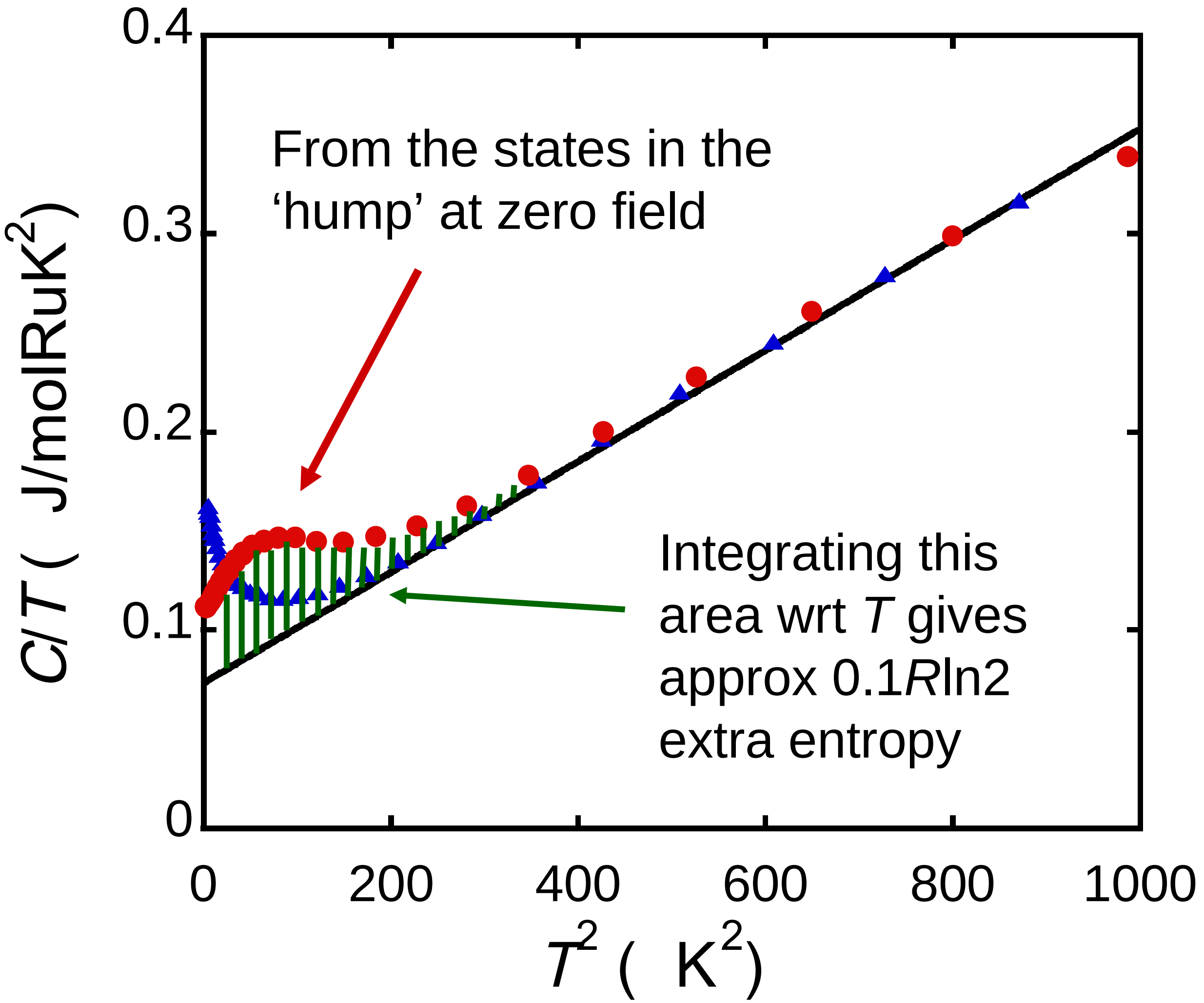
Contrast with $Sr_3Ru_2O_7$ at the critical field



Above ~15 K, $Sr_3Ru_2O_7$ looks like a Fermi liquid with an electronic specific heat of approximately 75 mJ/molK^2.

Where did the extra states come from?

Contrast with $Sr_3Ru_2O_7$ at the critical field



Towards a microscopic understanding in $Sr_3Ru_2O_7$

Key question seems to be the microscopic origin of the 10K energy scale.

It is NOT, apparently, a rigid band feature through which one simply Zeeman shifts.

K. Iwaya et al., Phys. Rev. Lett. ***99****, 057208 (2007)*

J. Farrell et al., Phys. Rev. B ***78****, 180409 (2008)*

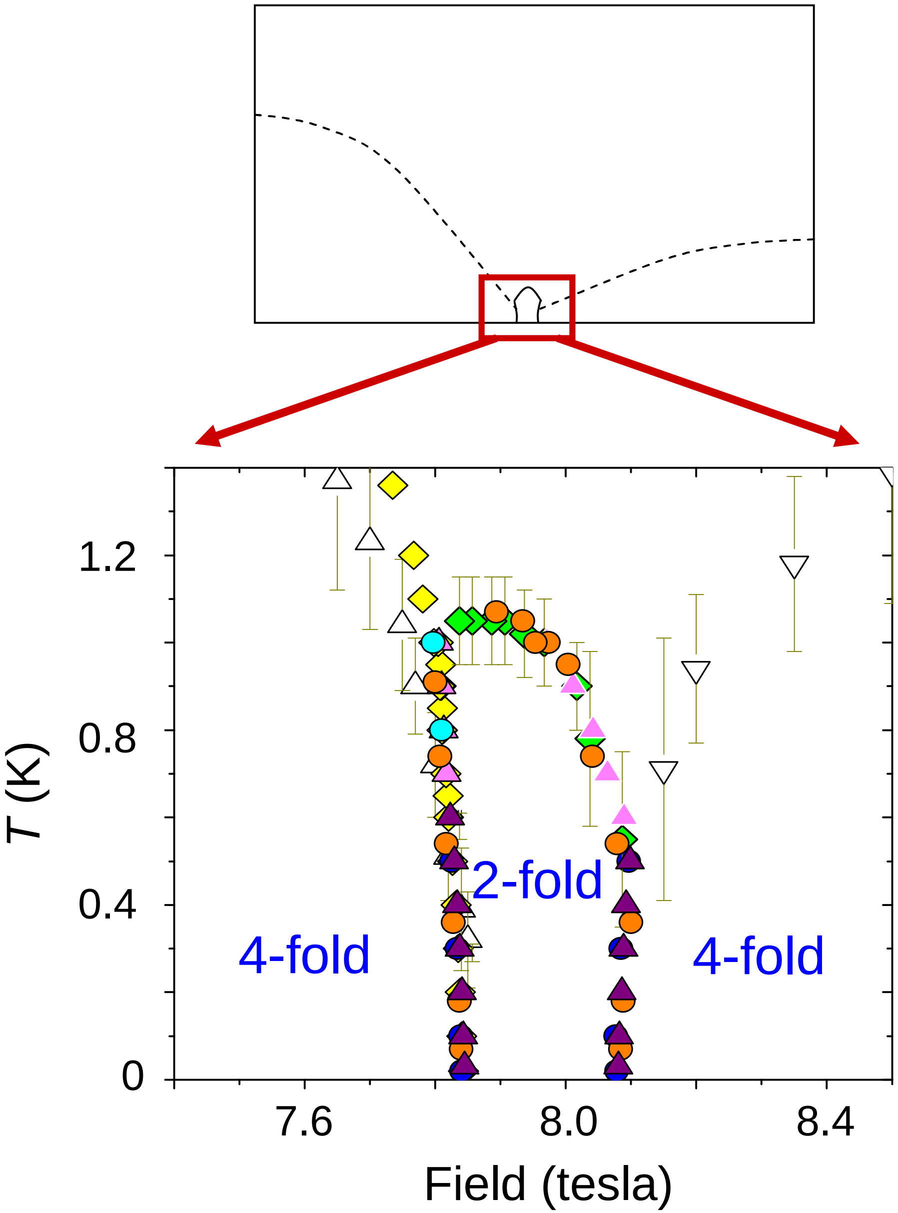
Spin-orbit coupling almost certainly plays a role.

e.g. W.C. Lee and C. Wu, preprint (2010)

The low temperature, purity dependent nematic phase

Critical mean free path for observation of phase: 1000 Å.

Equivalent scattering rate ~ $T_c \Rightarrow$ phase is anisotropic in *k*-space



*S.A. Grigera et al., Science **306**, 1154 (2004).*

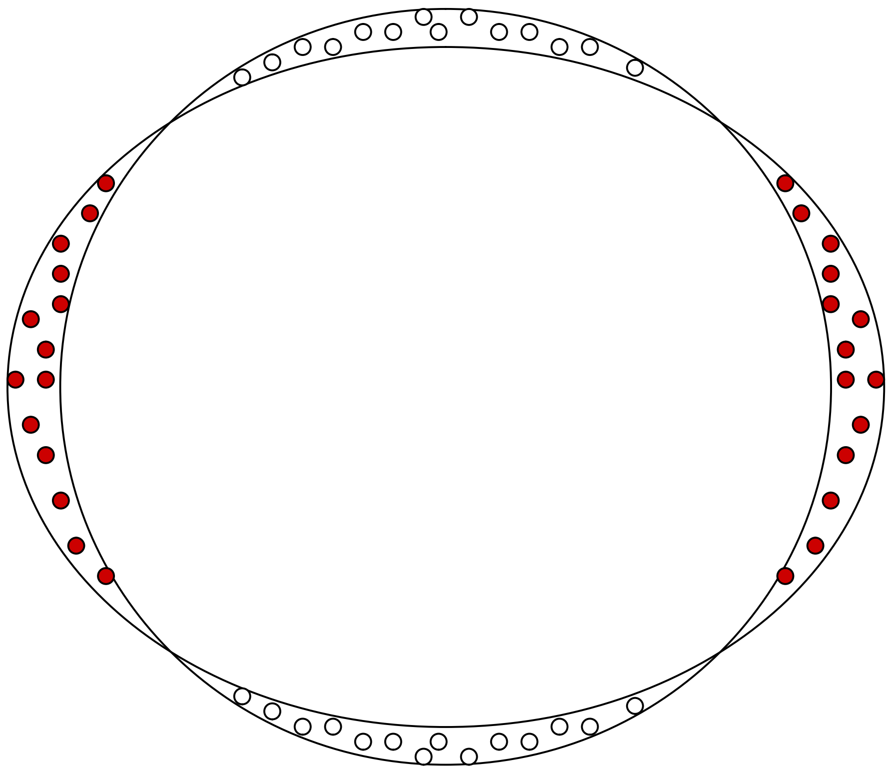
*P. Gegenwart et al., Phys. Rev. Lett. **96**, 136402 (2006).*

*R.A. Borzi et al., Science **315**, 214 (2007)*

*E. Fradkin et al., arXiv:0910.4166; Ann. Rev. Cond. Matt. Phys. **1**, 153 (2010).*

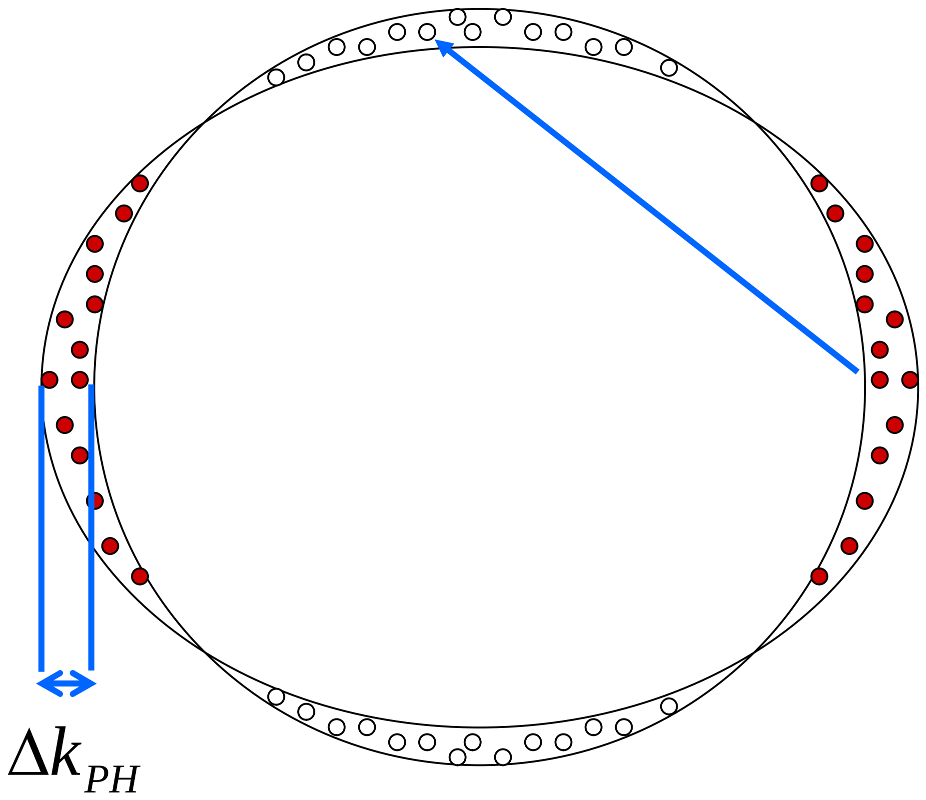
Analogy with unconventional superconductivity

Imagine a weak 'Pomeranchuk distortion'



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

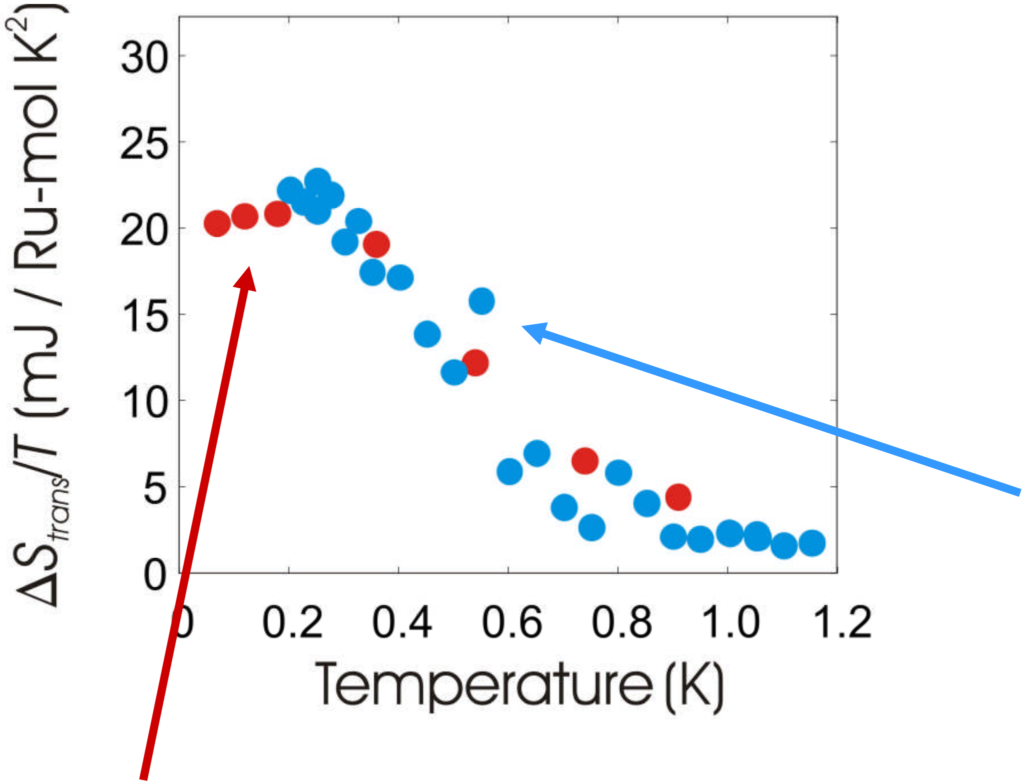
Consequence: sensitivity to disorder



Condition for destruction of state: $v_F \Delta k_{PH} \approx \Delta_{PH} \approx \dfrac{h}{\tau}$

Explicit calculation: *A.F. Ho and A.J. Schofield, EPL **84**, 27007 (2008)*

Quantitative thermodynamic consistency via application of the Clausius-Clapeyron relationship for 1st order transitions

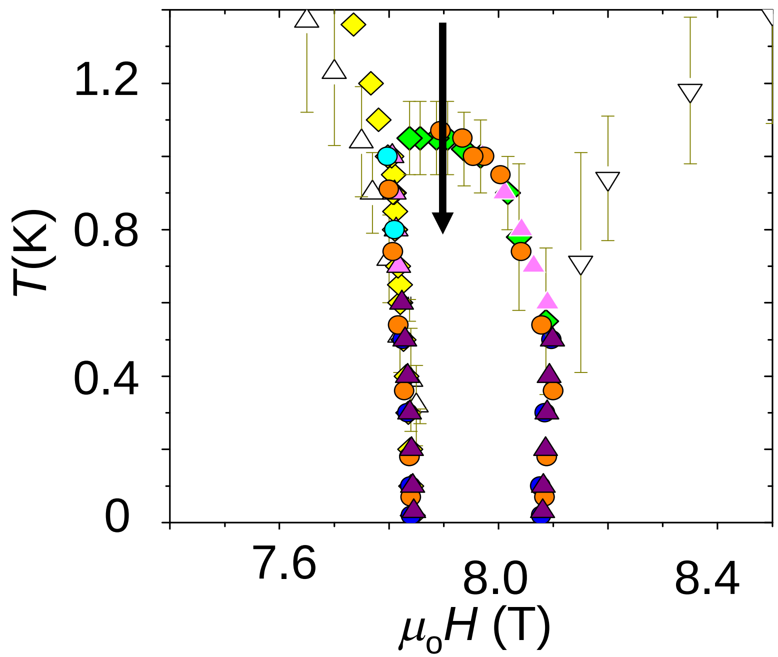


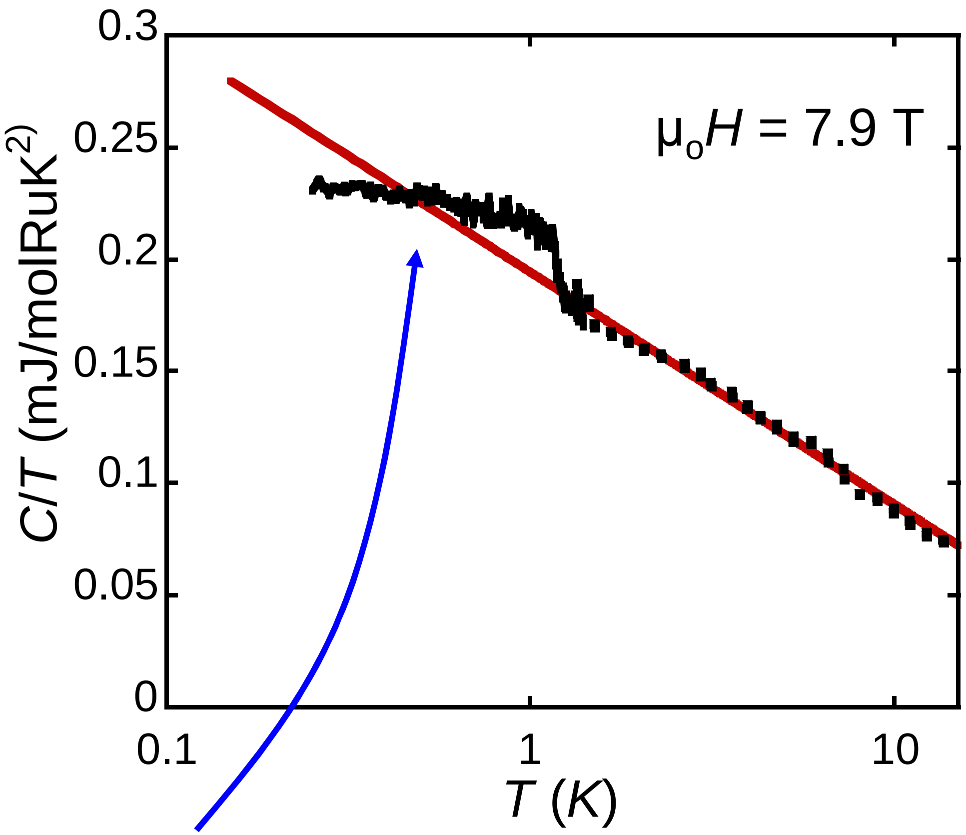
Entropy jump at first order phase boundary from direct analysis of MCE data

Entropy jump determined independently from magnetisation data and Clausius Clapeyron relation $\frac{dH_c}{dT_c} = -\frac{\Delta S}{\Delta M}$

Unusually, the entropy is higher within the phase than outside it.

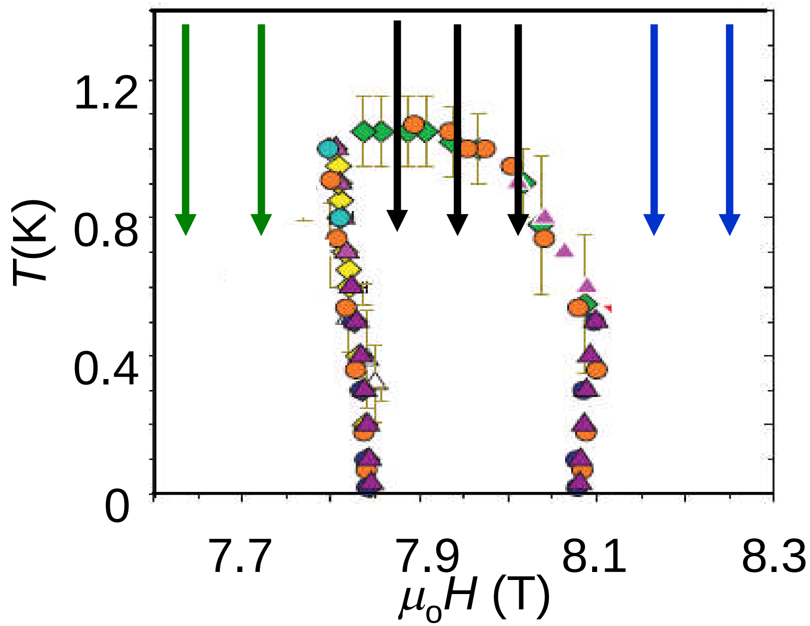
Specific heat on cooling into the phase

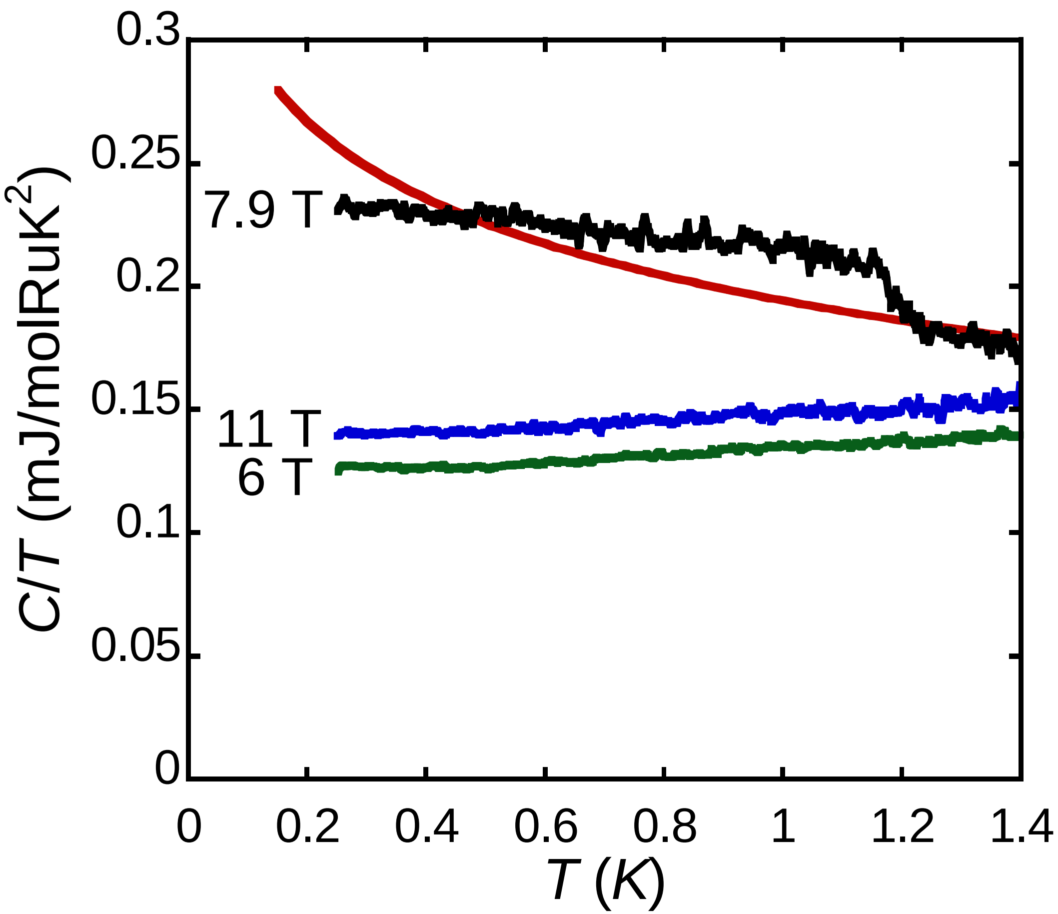




Even below T_c, C/T keeps rising as T decreases

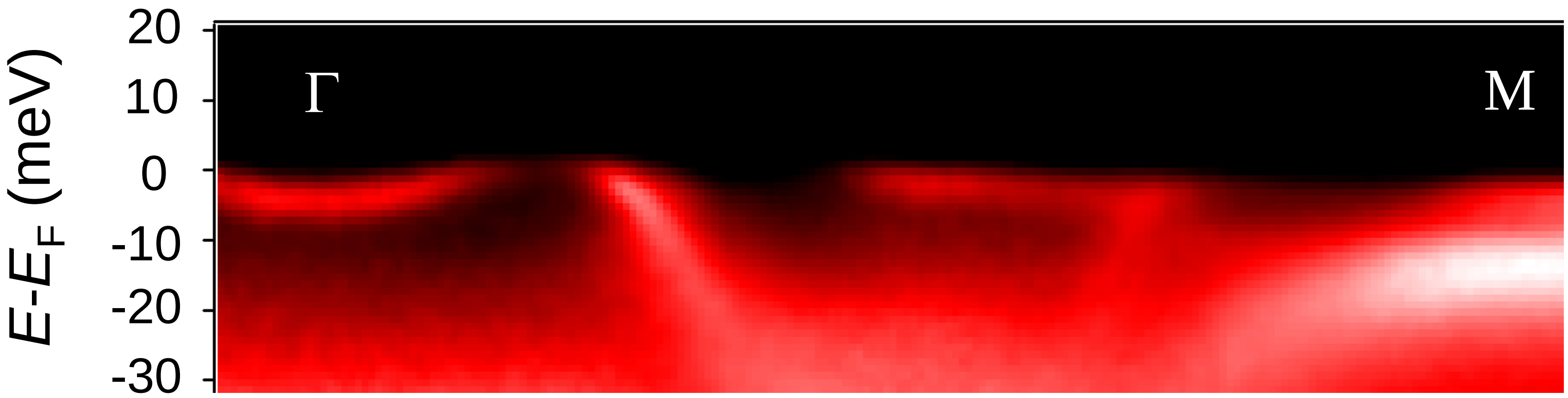
Rising *C*/*T* is a property of the phase and not its surroundings

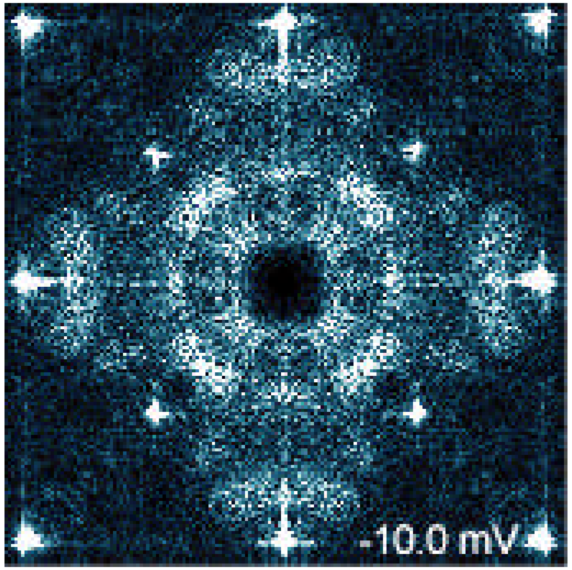




Although the phase is metallic and shows quantum oscillations, it seems to be associated with degrees of freedom additional to those of a standard Fermi liquid.

Policing surface spectroscopies of $Sr_3Ru_2O_7$





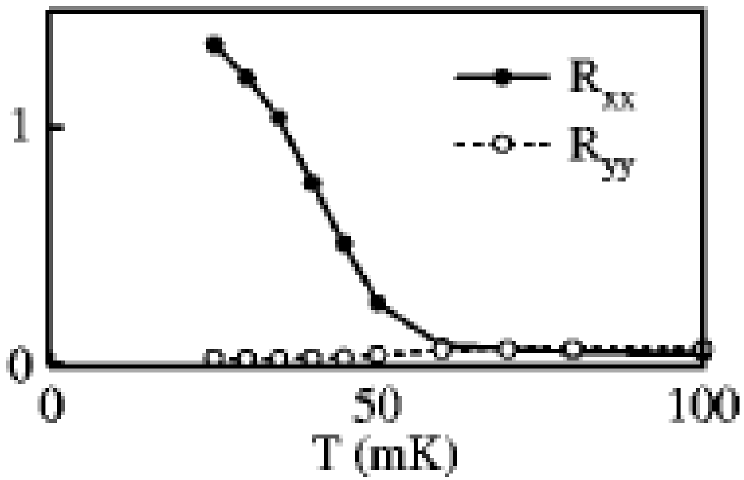
Bulk dHvA is consistent with characteristic velocities from Angle Resolved Photoemission and Spectroscopic Imaging Scanning Tunneling Microscopy.

A. Tamai et al., Phys. Rev. Lett. ***101****, 026407 (2008).*

J. Lee et al., Nature Physics ***11****, 800 (2009).*

W.C. Lee et al., Phys. Rev. B ***81****, 184403 (2010).*

Policing the increasing study of electronic nematicity



Theory: *S.A. Kivelson et al., Nature* ***393****, 550 (1998).*

S. Raghu et al., Phys. Rev. B ***79****, 214402 (2009).*

A.M. Berridge et al., Phys. Rev. Lett. ***102****, 136404 (2009).*

2DEGs: *M.P. Lilly et al., Phys. Rev. Lett.* ***82****, 394 (1999).*

Cuprates: *Y. Ando et al., Phys. Rev. Lett.* ***88****, 137005 (2002).*

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

V. Hinkov et al., Science ***319****, 597 (2008).*

R. Daou et al., Nature ***463****, 519 (2010).*

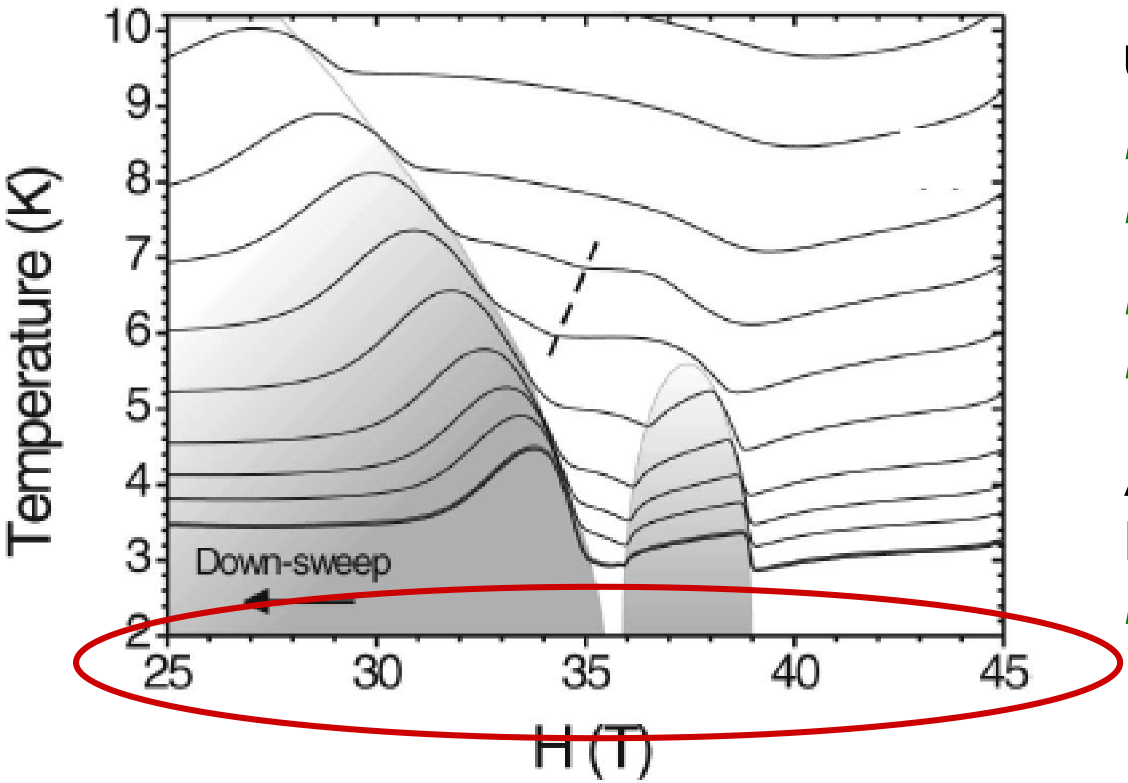
Pnictides: *T.M. Chuang et al., Science* ***327****, 181 (2010).*

J.H. Chu et al., arXiv:1002.3364 (2010).

$Sr_3Ru_2O_7$ is unique (to date) in giving access to detailed thermodynamic information relevant to this problem.

Comparison with metamagnetic *f*-electron systems

Reviews: *H. von Löhneysen et al., Rev. Mod. Phys.**79**, 1015 (2007)*
*G.R. Stewart, Rev. Mod. Phys **78**, 743 (2006)*



URu_2Si_2

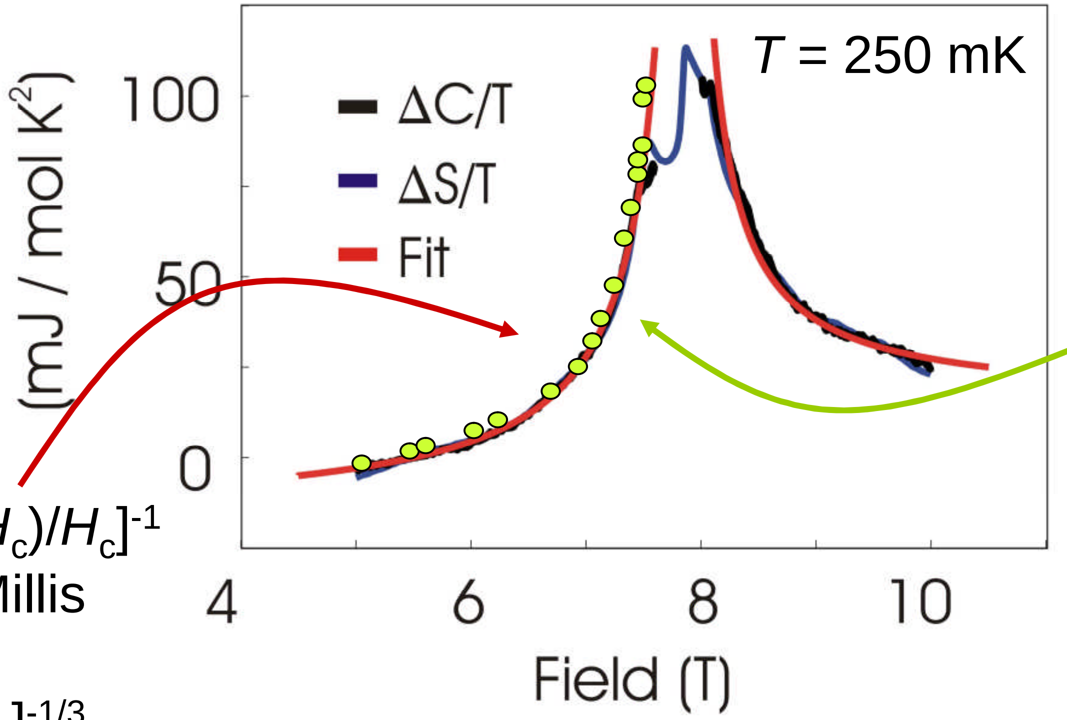
*M. Jaime et al., Phys. Rev. Lett. **89**, 287201 (2002)*

*N. Harrison et al., Phys. Rev. Lett. **90**, 096402 (2003)*

Also report of nematicity in hidden order phase
Matsuda group preprint

$CeRu_2Si_2$ *Y. Aoki et al., JMMM **177**, 271 (1998).*
*J. Flouquet et al., Physica B **319**, 251 (2002).*
*F. Weickert et al., Phys. Rev. B **81**, 134438 (2010).*

Field dependence of *C*, *S* is surprisingly strong



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

$\Delta C/T$ for $CeRu_2Si_2$ (data reported by Grenoble and Osaka groups)

Also, the scale of the entropy is interesting: the entropy by T_c of the nematic phase is ~5% of Rln2, similar to that at T_c in quite a wide range of unconventional superconductors *[Y.E. Yang et al., Nature **454**, 611 (2008)]*

Is there some something that we are missing with current approaches?
*S.A. Hartnoll et al., Phys Rev B **76**, 144502 (2007)*

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Conclusions

1. $Sr_3Ru_2O_7$ provides the opportunity to test and refine a number of modern ideas about quantum criticality and phase formation

2. The comparison with *f*-electron physics provides challenges and insights

3. High purity crystals and thermodynamic measurements are good for you!

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