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Metamagnetism of the bilayer ruthenate $Sr_3Ru_2O_7$

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4. Field angle as a novel tuning parameter.
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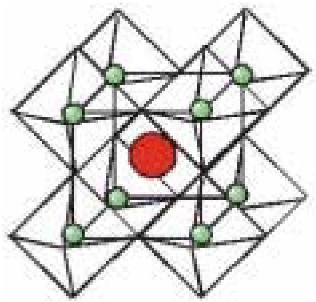
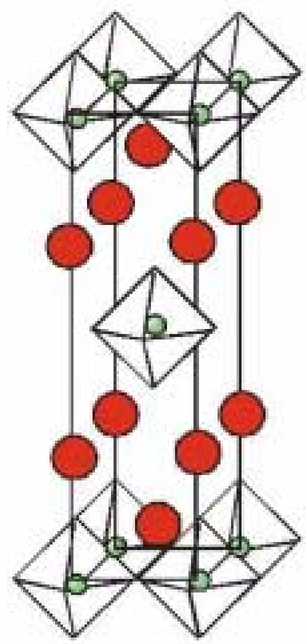
The layered perovskite ruthenates $Sr_{n+1}Ru_nO_{3n+1}$

$SrRuO_3$: 3D itinerant ferromagnet

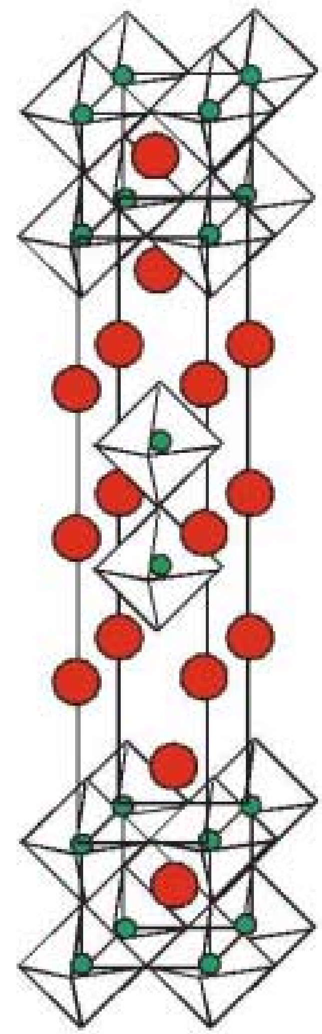


n=∞

Sr_2RuO_4: highly 2D Fermi liquid and unconventional superconductor. Pauli paramagnet.

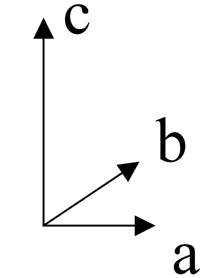


n=1



n=2

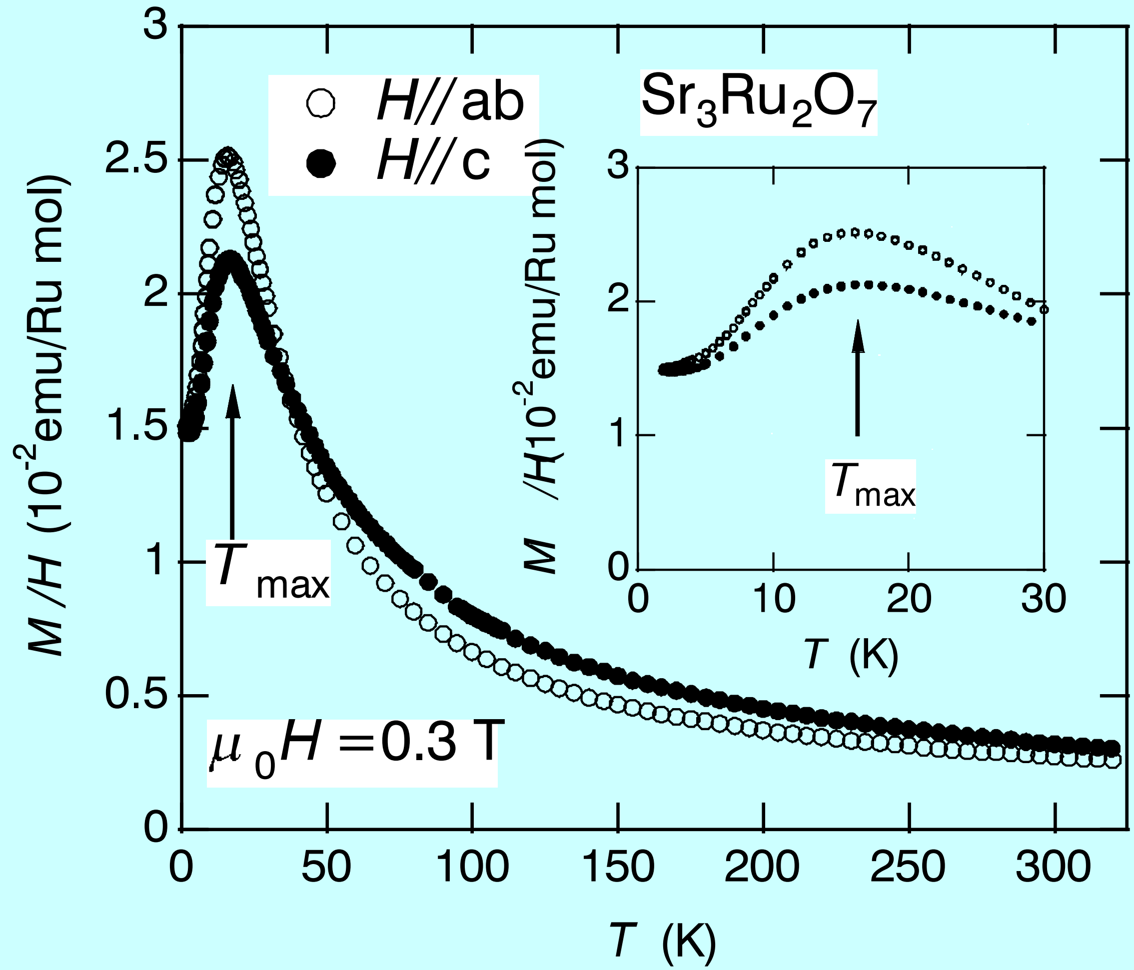
$Sr_3Ru_2O_7$: intermediate properties expected



Basic properties of $Sr_3Ru_2O_7$

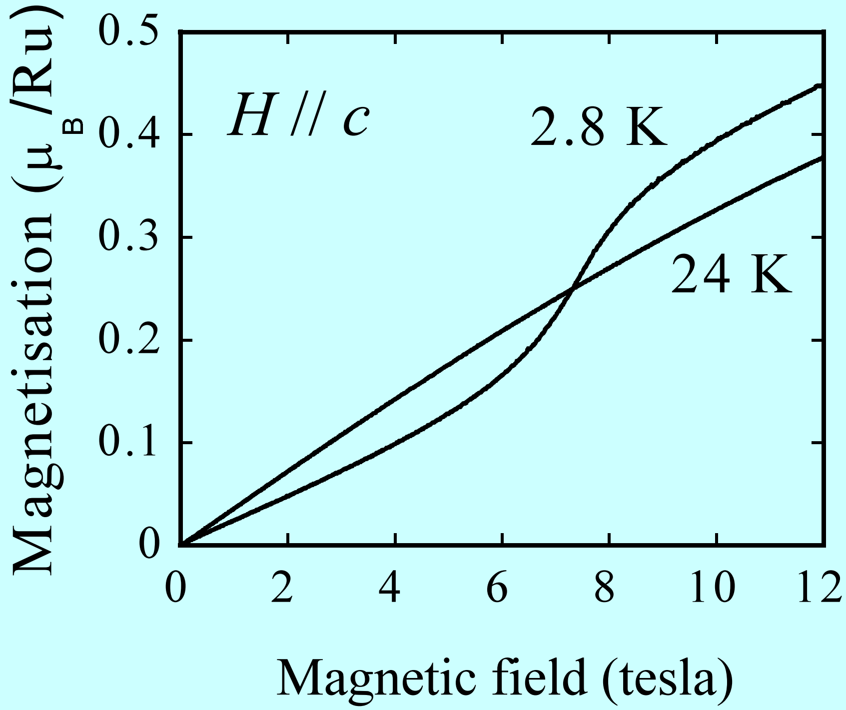
At low temperature and low applied magnetic field, it is an anisotropic Fermi liquid ($\rho_c / \rho_{ab} \approx 100$).

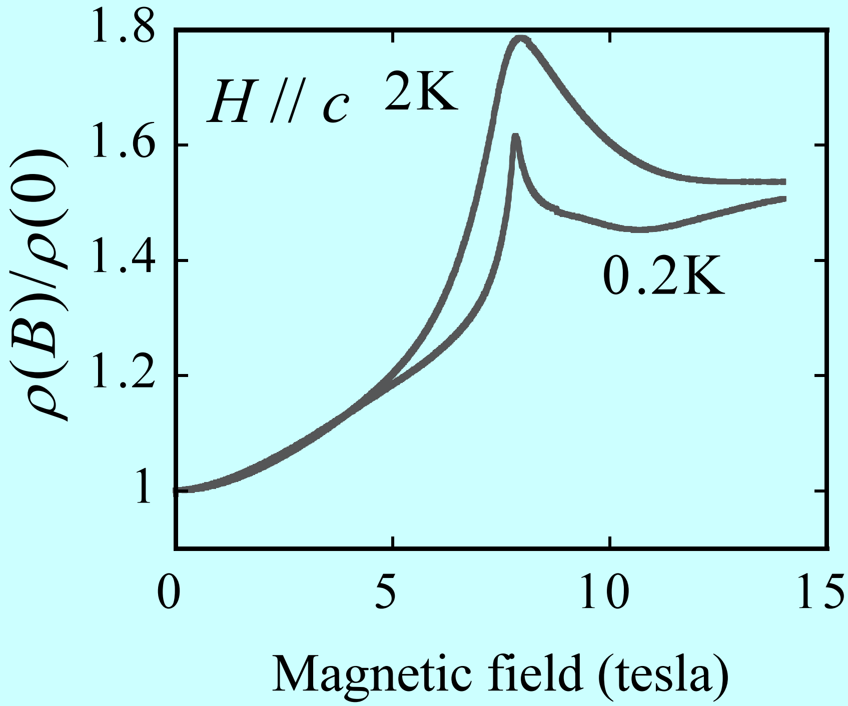
Low-T susceptibility is remarkably isotropic and T-independent: strongly enhanced Pauli paramagnet on verge of ferromagnetism?



*S.I. Ikeda, Y. Maeno, S. Nakatsuji, M. Kosaka and Y. Uwatoko, Phys. Rev. B **62**, R6089 (2000).*

Basic signatures of metamagnetism in $Sr_3Ru_2O_7$



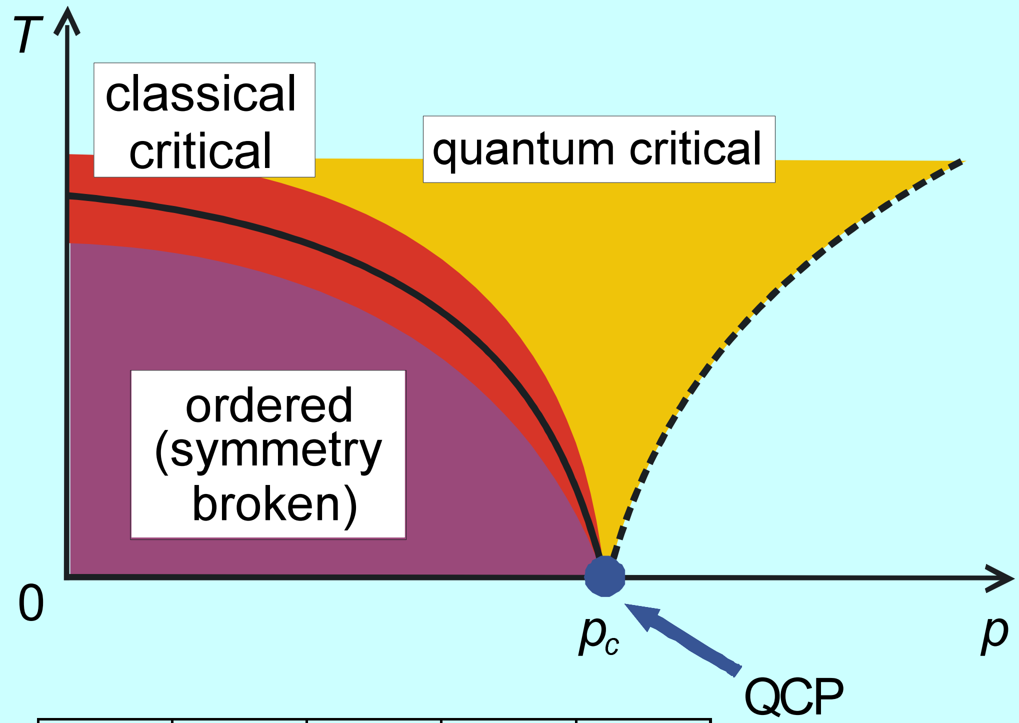


Superlinear rise in magnetisation accompanied by peak in magneto-resistance. Low temperature transport data show a very sharp feature.

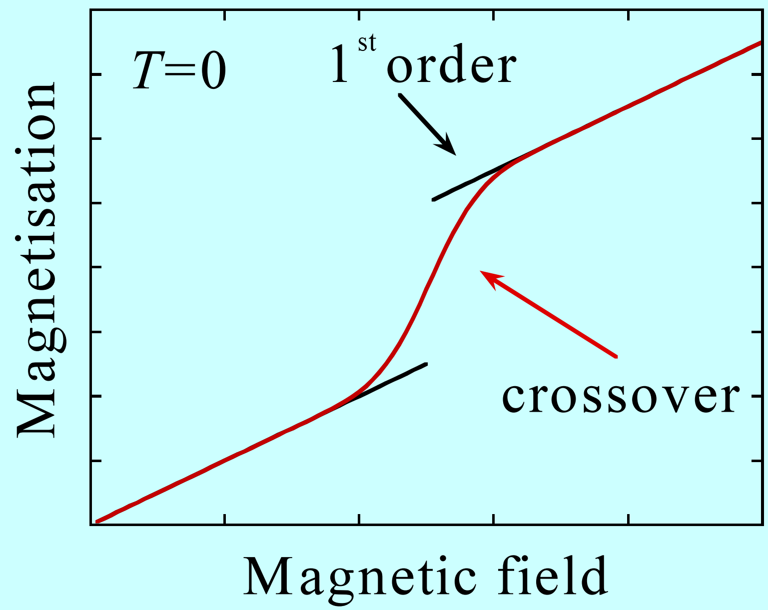
R.S. Perry, L.M. Galvin, S.A. Grigera, L. Capogna, A.J. Schofield , A.P. Mackenzie, M. Chiao, S.R. Julian, S. Ikeda, S. Nakatsuji, Y. Maeno and C. Pfleiderer, Phys. Rev. Lett. ***86****, 2661 (2001)*

Is metamagnetic quantum criticality possible?

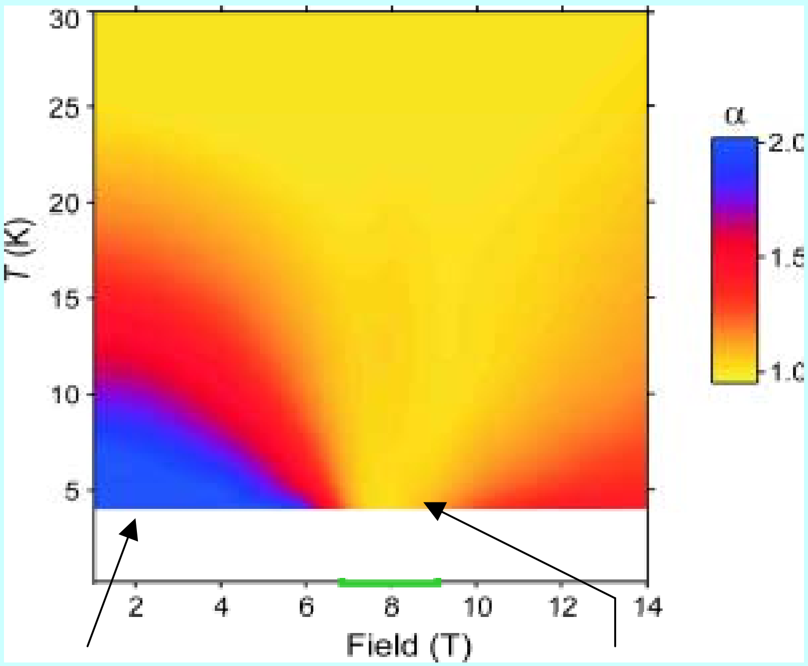
Quantum criticality is usually associated with a second order phase transition at zero *T*, but 2nd order phase transitions are associated with diverging susceptibilities and *spontaneously broken symmetries*.



Surely metamagnetism must be a first-order transition or crossover, since there can be no spontaneous symmetry breaking?

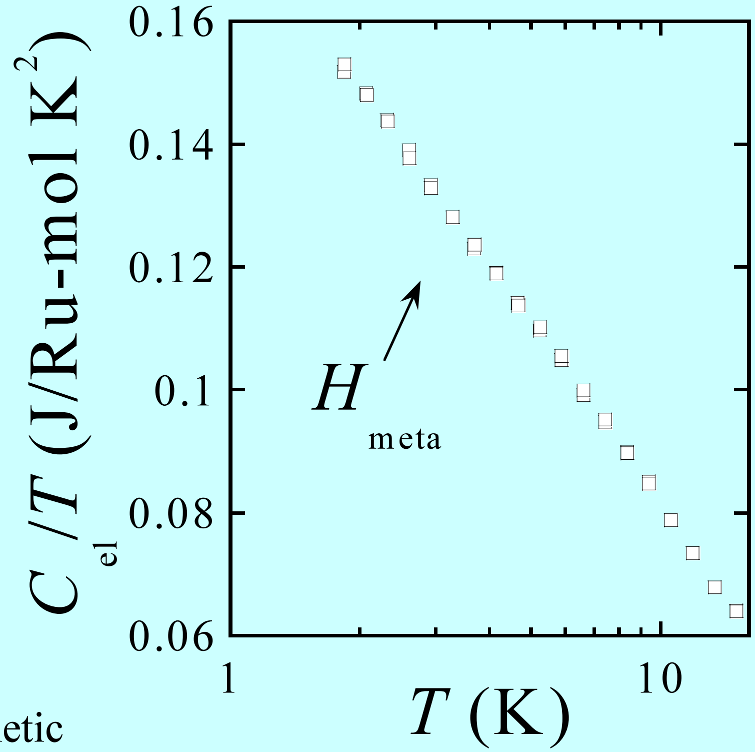


Indications of quantum critical / non-Fermi liquid behaviour associated with the metamagnetism of $Sr_3Ru_2O_7$



Fermi liquid:
$\rho \sim \rho_{res} + AT^2$

Near $H_{metamagnetic}$
$\rho \sim$ *linear* in T



Also log T divergence of C/T near $H_{metamagnetic}$

Not the only example of a link between metamagnetism and non-Fermi liquid behaviour

Some other systems studied so far:

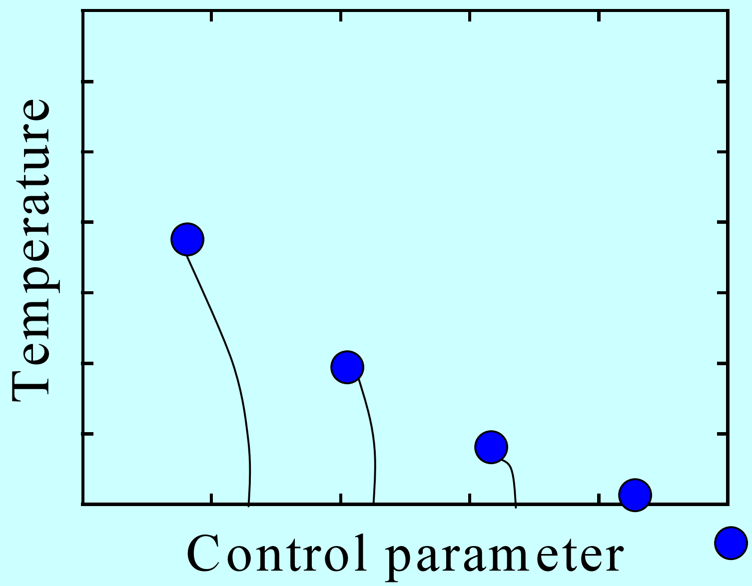
UPt_3 *e.g. Kim et al., Solid State Comm.* ***114****, 413 (2000) and references therein*

$CeRu_2Si_2$, $CeFe_2Ge_2$, $CeNi_2Ge_2$

e.g. Sugawara et al., J. Phys. Soc. Jpn. ***68****, 1094 (1999)*
Flouquet et al., Physica B ***215****, 77 (1995)*
Flouquet et al., Physica B ***319****, 251 (2002)*
Kambe et al., Solid State Comm. ***95****, 449 (1995);* ***96****, 175 (1995)*
Aoki et al., J. Magn. Mag. Mat. ***177****, 271 (1998)*
Julian et al., J. Magn. Mag. Mat. ***177****, 265 (1998)*

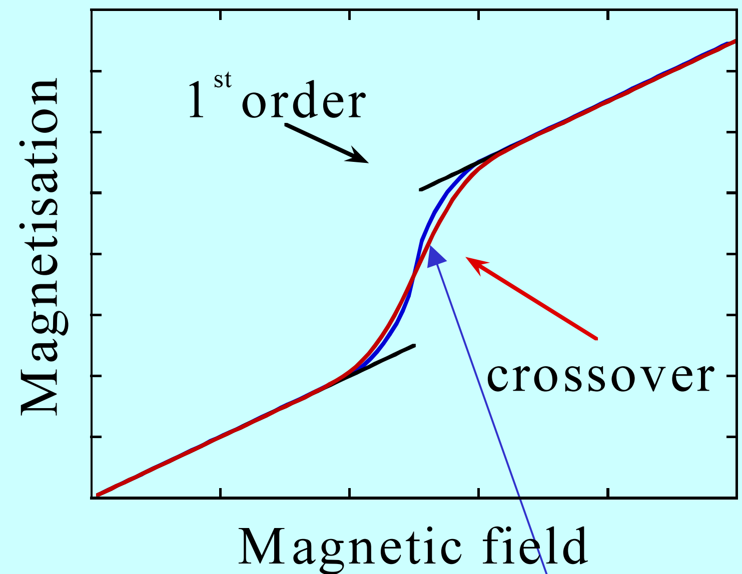
We should not forget the critical end-point

A line of first order transitions can have a critical end-point.



Could this end point be tuned to become quantum critical?

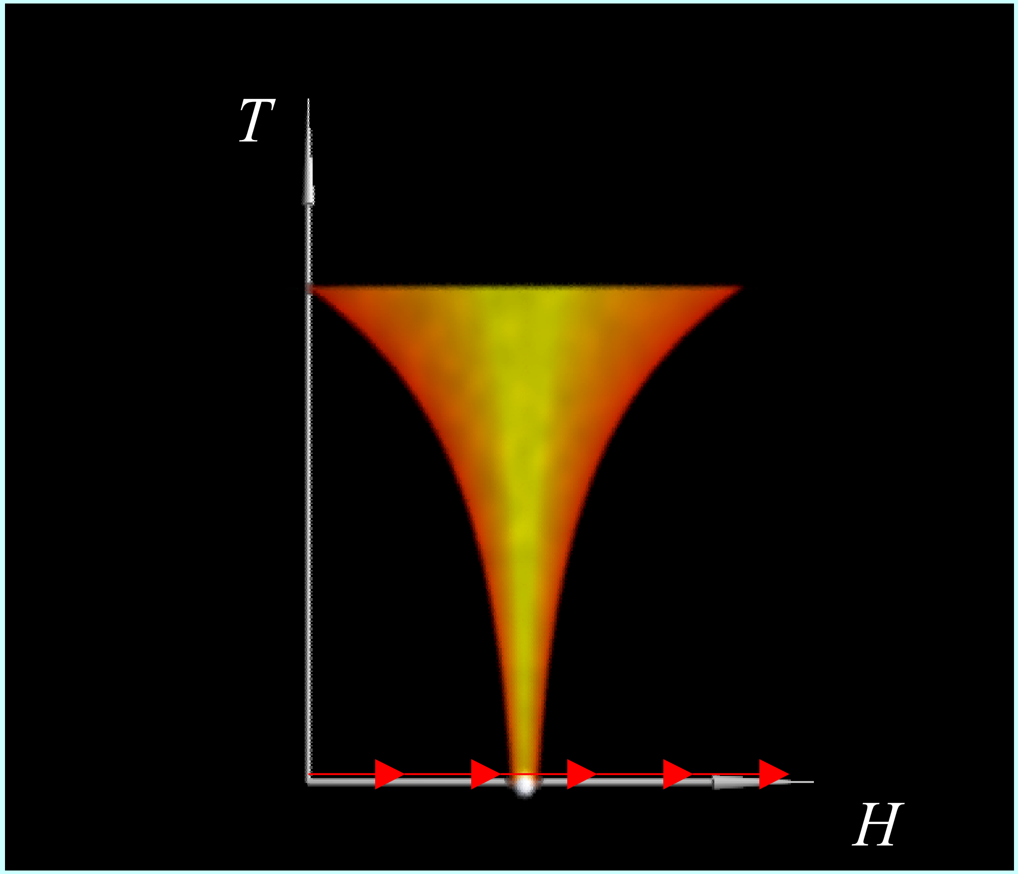
Magnetisation at the critical point



Continuous function with infinite derivative

Idea a): could metamagnetic $Sr_3Ru_2O_7$ be naturally quantum critical for *H* // *c* ?

Quantum criticality in the (H,T) plane of an itinerant system with no symmetry broken phase.

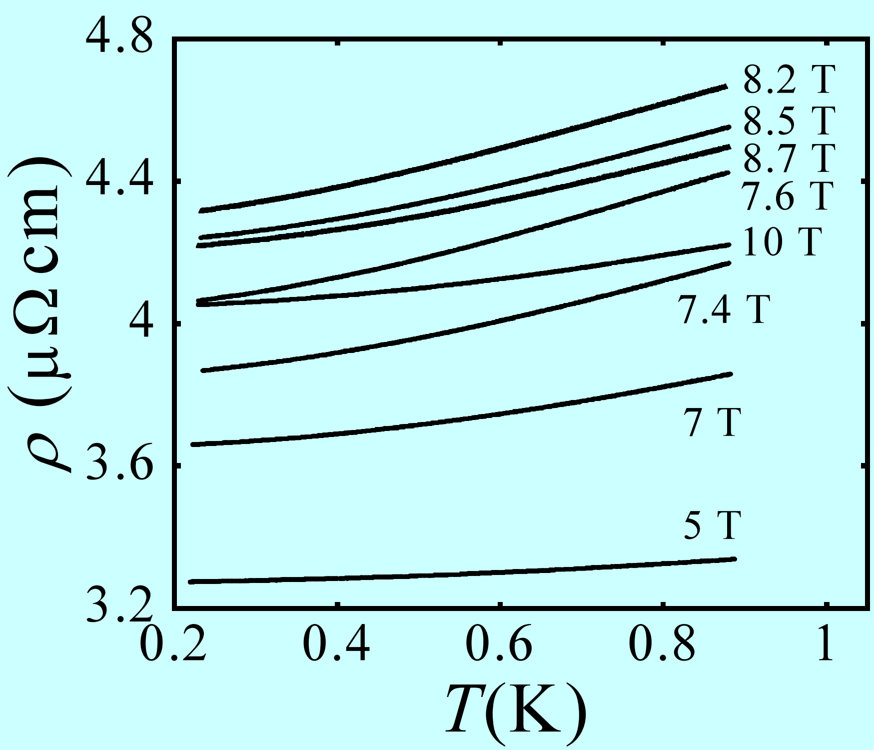


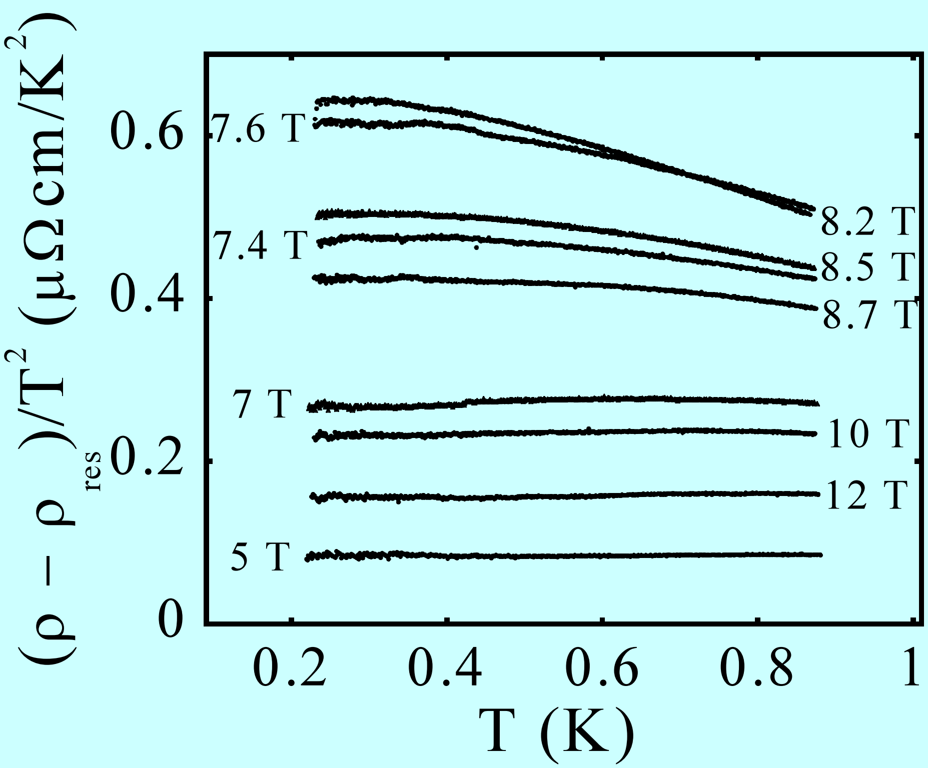
Nice speculation, but more evidence needed.

Go to very low temperature ($T < 250$ mK) and look for evidence for diverging fluctuations as a function of magnetic field.

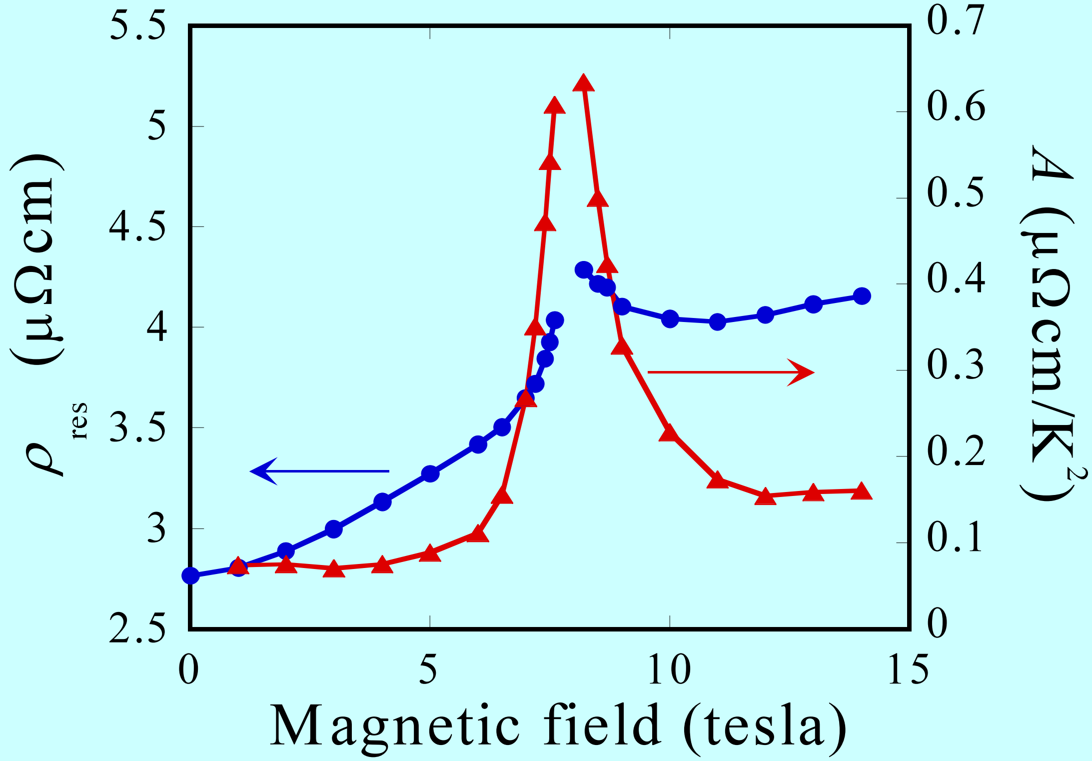
Method: study transport at low temperatures for *H* // c

Near 'conventional' QCP: Below some T_{FL}, $\rho \sim \rho_{res} + AT^2$, with T_{FL} falling and A diverging as the system is tuned to criticality. In $Sr_3Ru_2O_7$, both are indeed seen to show this qualitative behaviour:





Strong evidence for a metamagnetic quantum critical end-point in $Sr_3Ru_2O_7$

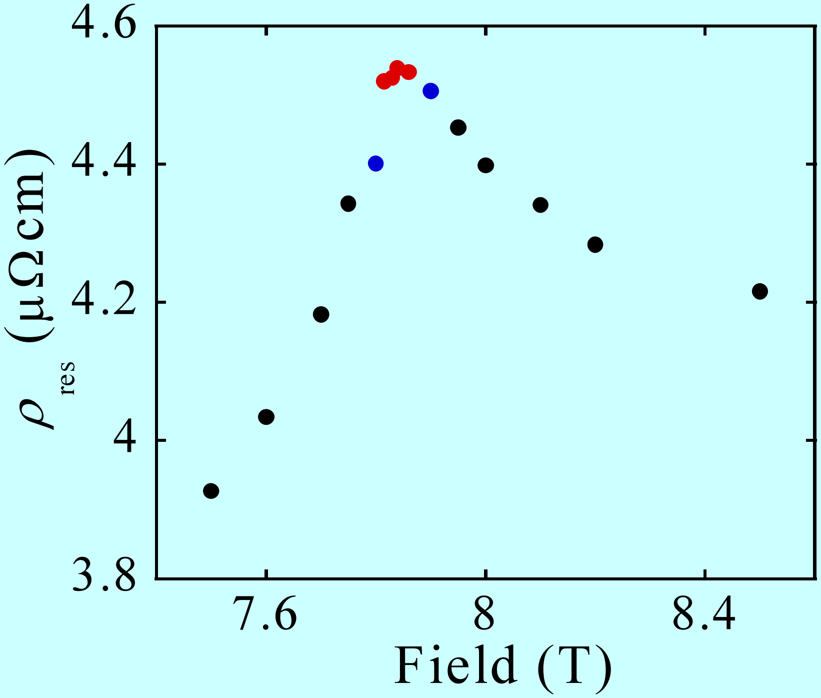


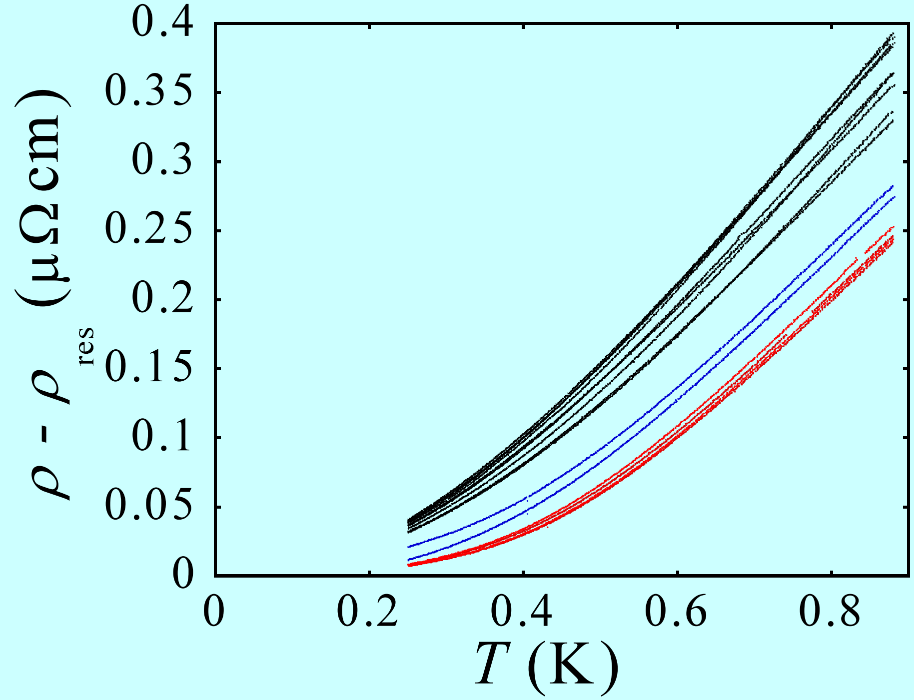
Plot of *A* vs. field gives evidence for divergent critical fluctuations.

A quantum critical point with magnetic field as the tuning parameter.

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

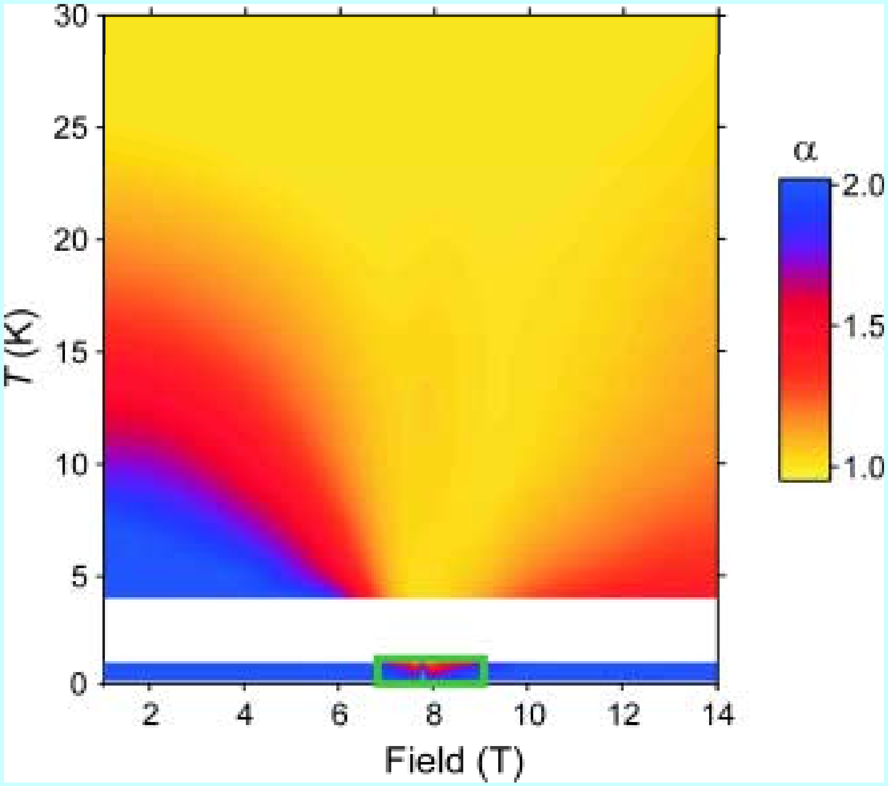
What happens really close to the transition field?

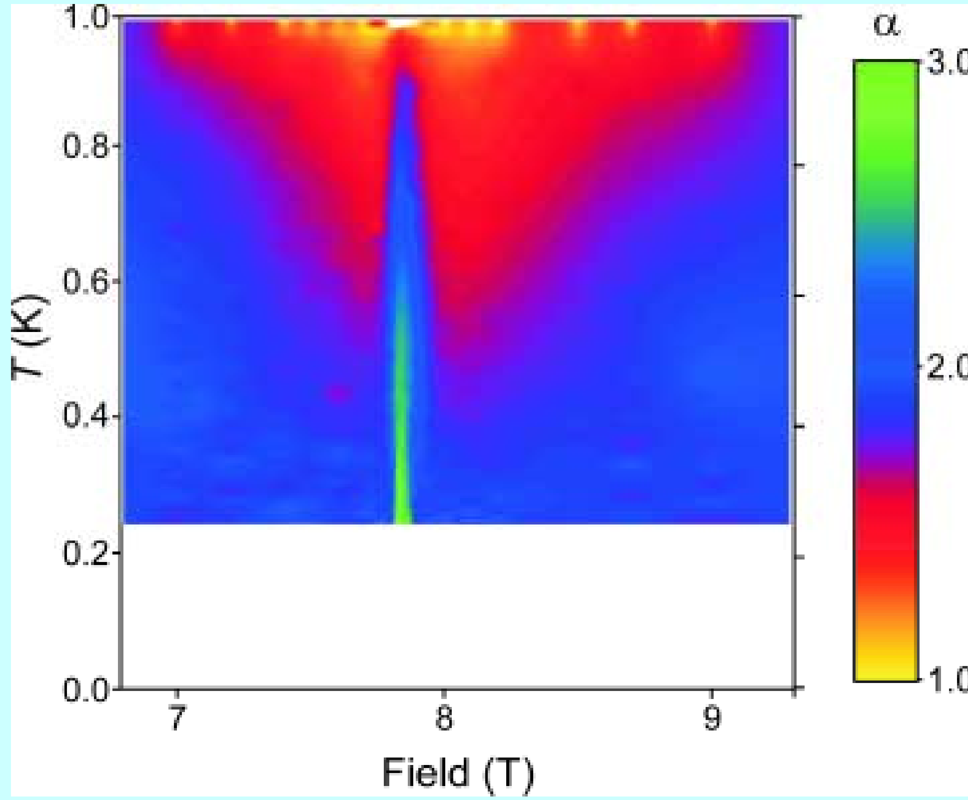




Narrow range of field with much flatter temperature dependence than T^2

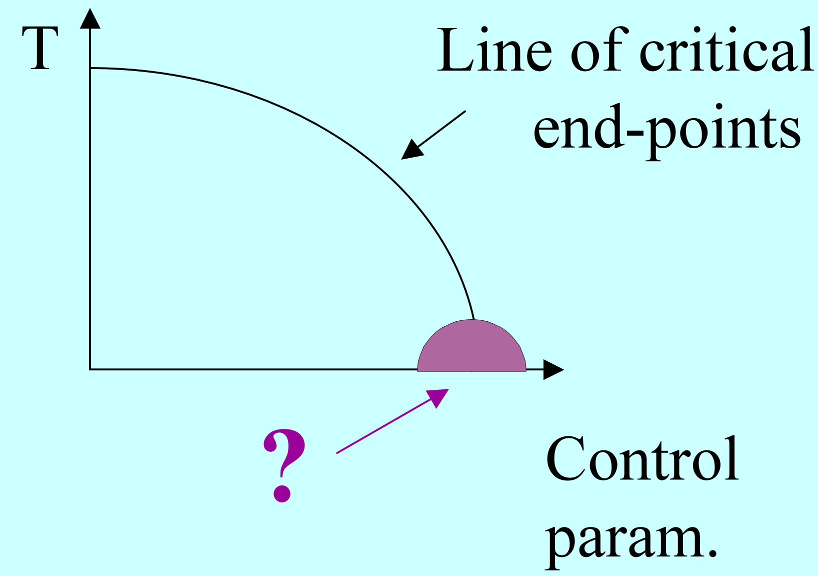
Return to the empirical phase diagram





$\rho = \rho_{res} + AT^{\alpha}$ with $\alpha > 2$ from a purely electronic mechanism is a) *not* a trivial consequence of critical fluctuations, and b) *not* easy to explain in terms of standard metallic theories.

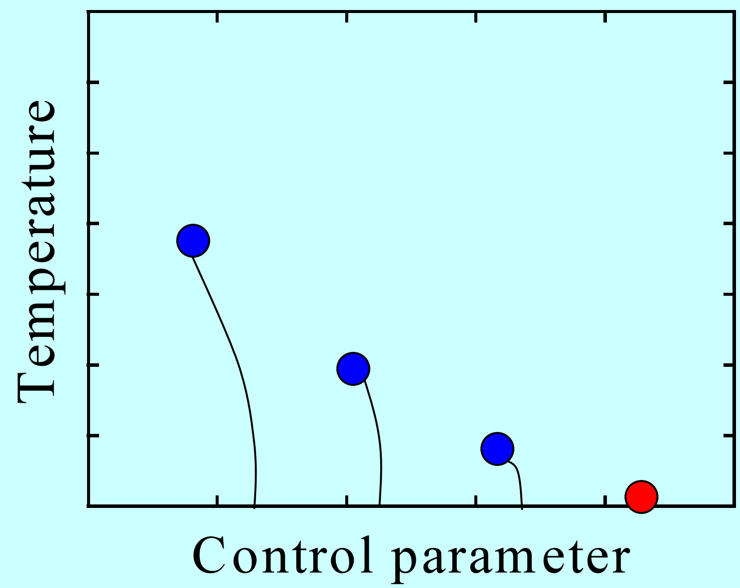
Novel ordered states are known to form in the vicinity of QCPs in clean systems. What would happen at high field near a metamagnetic QCP?



Reminder of our basic picture:

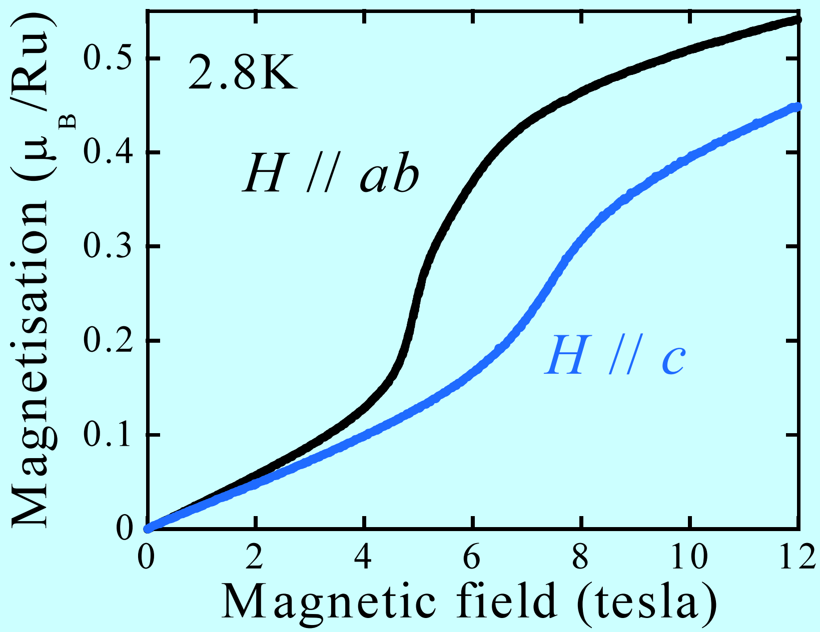
Tuneable critical end-point sitting very near $T = 0$.

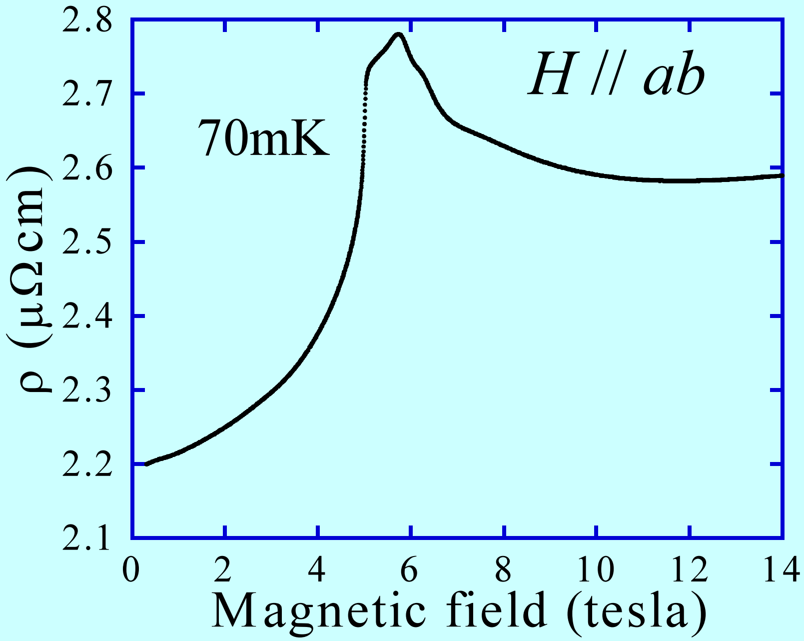
Can we obtain explicit evidence for a tuneable end-point?



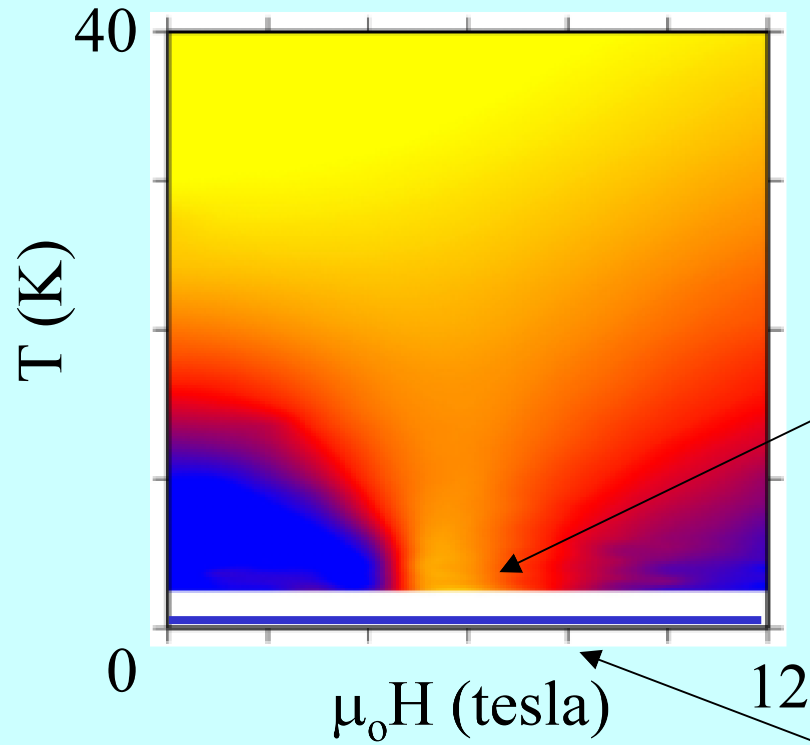
Idea b): Could field angle be a kind of tuning parameter?

Metamagnetism has some anisotropy, with slightly lower field scale and more structure for *H // ab:*





‘High temperature’ transport shows wide region without T^2 transport:

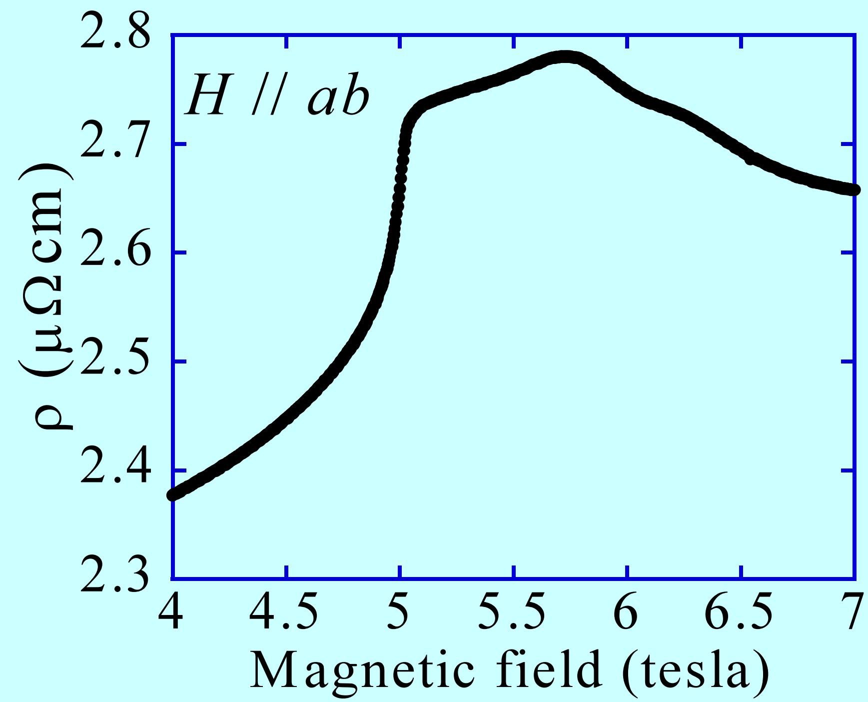


Line of criticality?

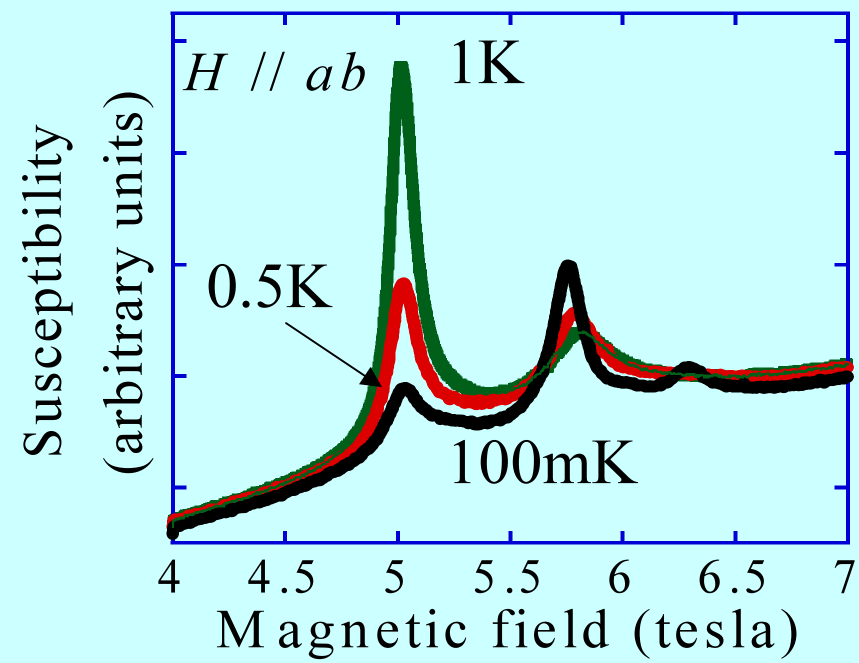
Low T transport: T^2 seen below 1K across entire field range.

Could there be a first order transition and finite temperature critical end-point for this field orientation?

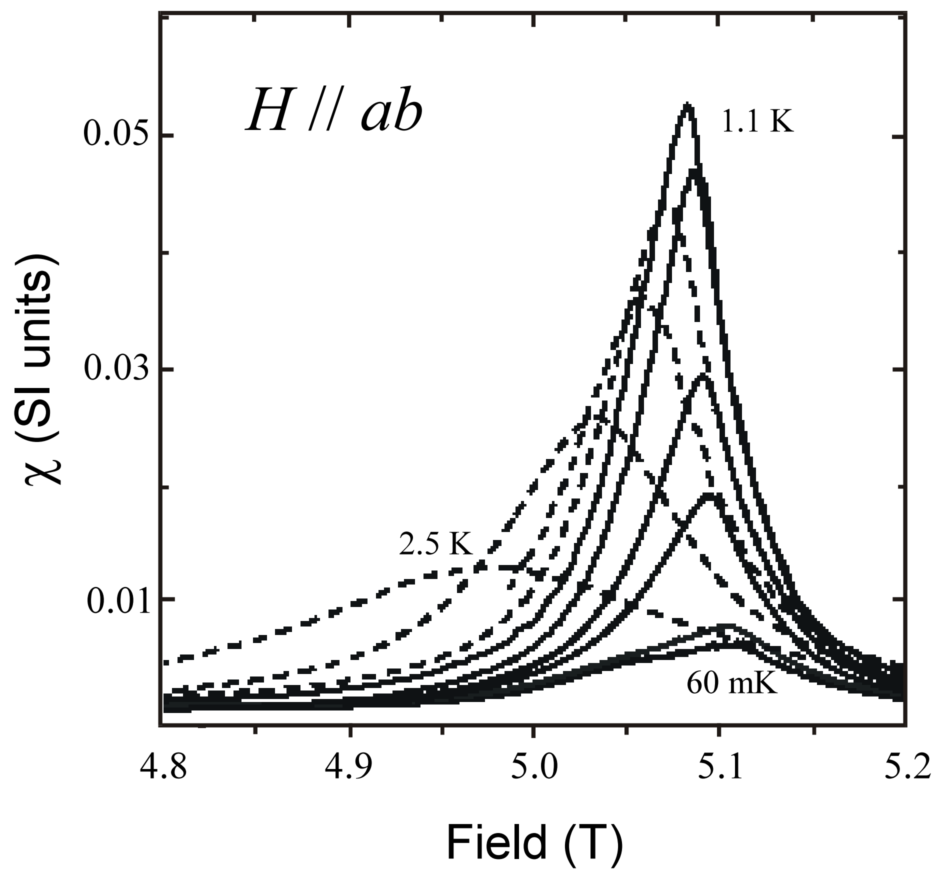
Address issue with study of differential susceptibility χ:

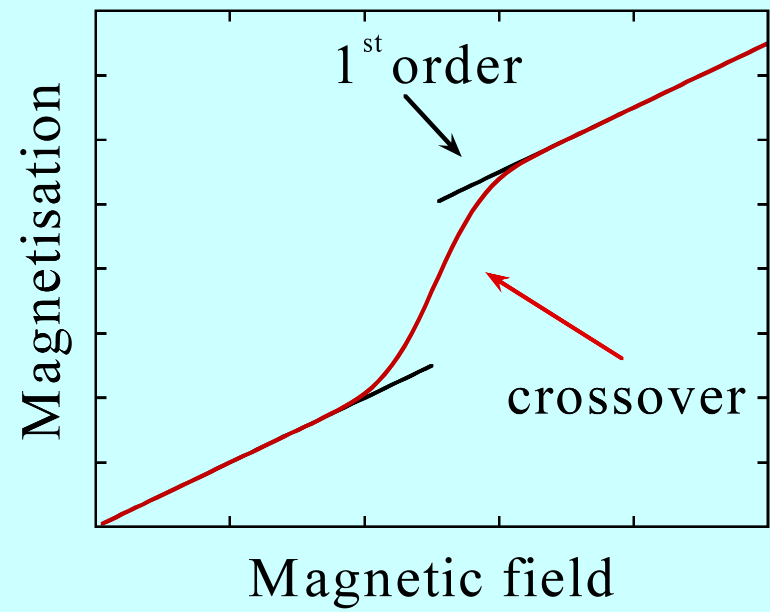


Structure in ρ is accompanied by features in χ.



Susceptibility peak observed just above 1K: evidence for first-order transition

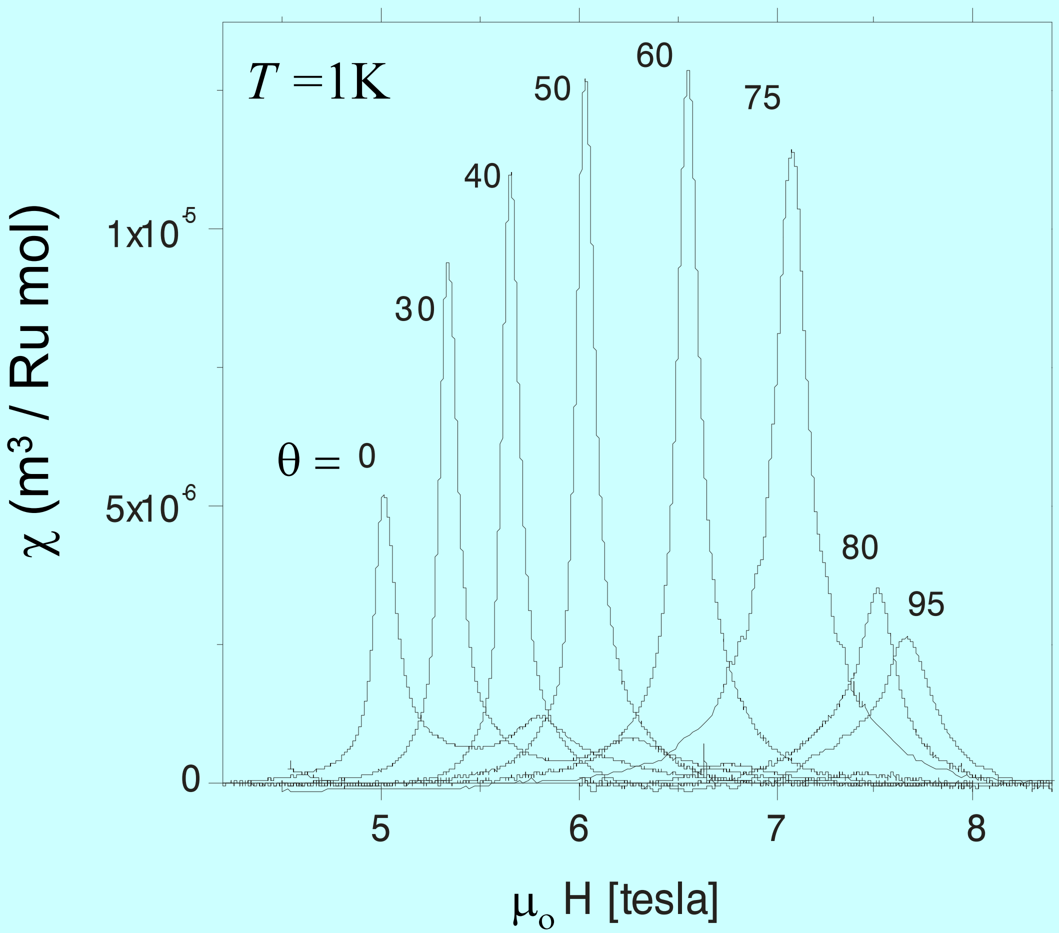




M. Chiao, C. Pfleiderer, R. Daou, A. McCollam, S.R. Julian, G.G. Lonzarich, R.S. Perry, A.P. Mackenzie and Y. Maeno, preprint (2002)

Transport and susceptibility suggest first order behaviour below 1K for *H* // *ab* but not for *H* // *c*.

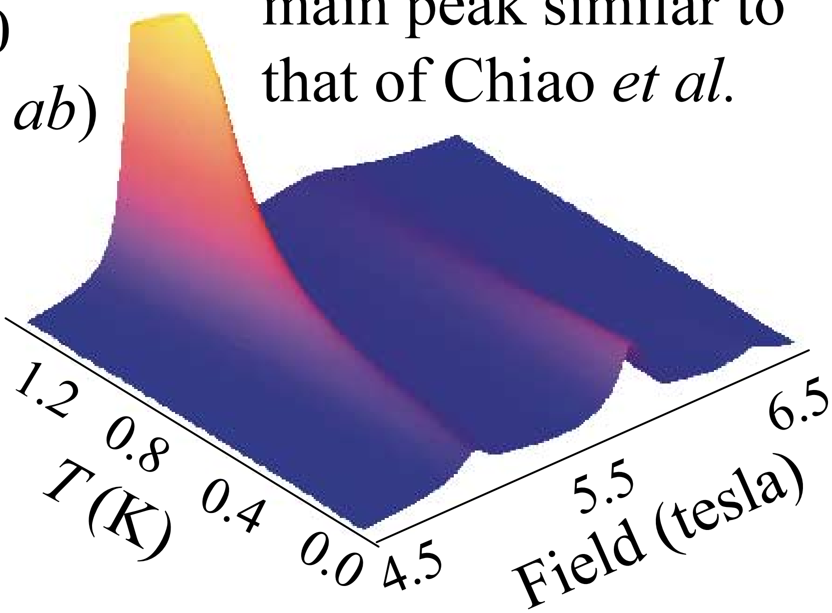
Motivation for study of susceptibility as a function of field angle θ from *ab* plane.



Clear evidence for first-order behaviour from 3D plots of both real and imaginary parts of the susceptibility:

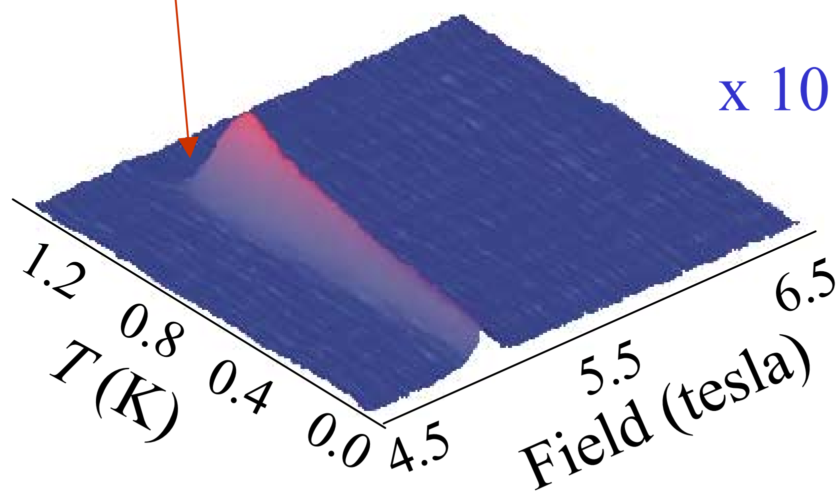
$\theta = 0$
(H // ab)

Maximum at T^* in main peak similar to that of Chiao *et al.*



Real part

Below T^* a peak in the imaginary part can be attributed to hysteretic dissipation.



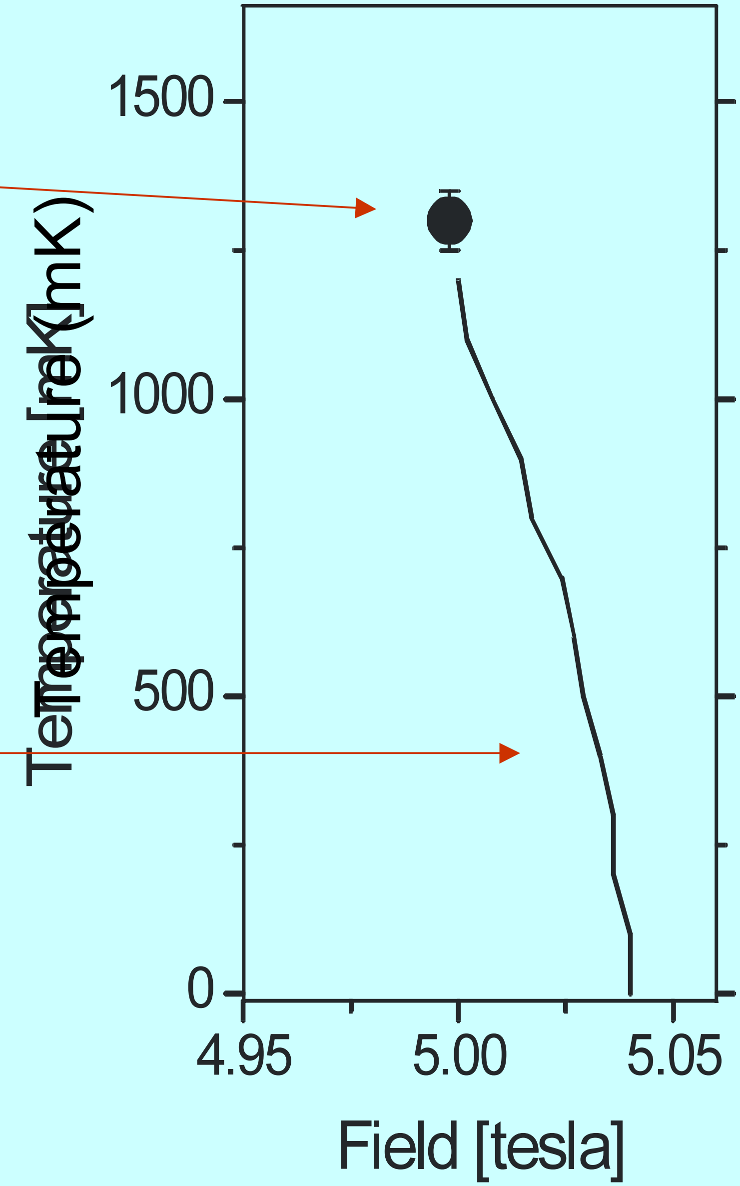
Imaginary part

S.A. Grigera, S.R. Julian, R.A. Borzi, R.S. Perry, Y. Maeno and A.P. Mackenzie (unpublished)

Data yield detailed and consistent information on 1st order transition line and its end-point

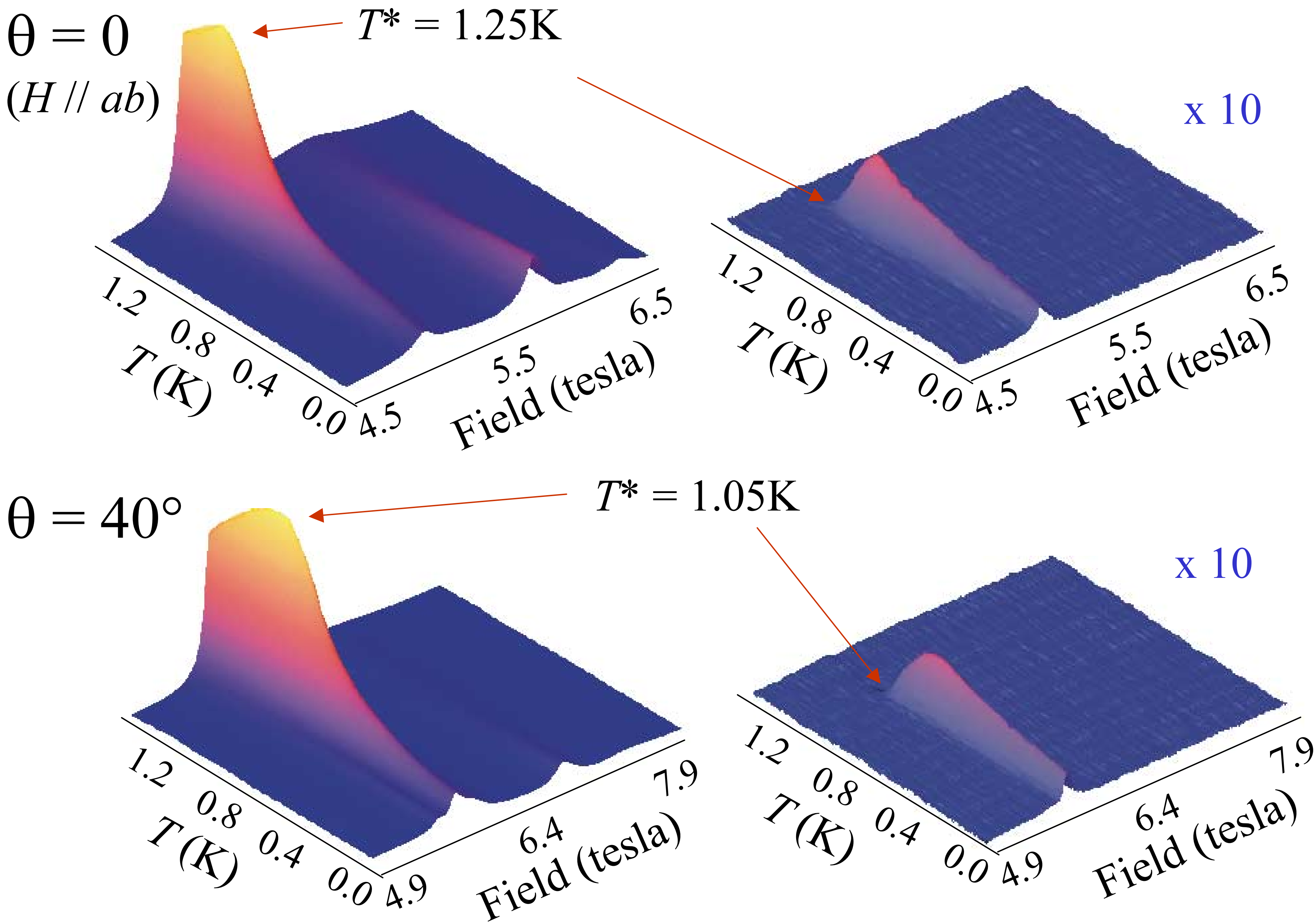
(T*, H*) defined from the overall maximum of the real part of χ

1st order transition line defined from (T,H) values of the maxima of the imaginary part of χ. Wiggles just reflect precision with which it can be identified.

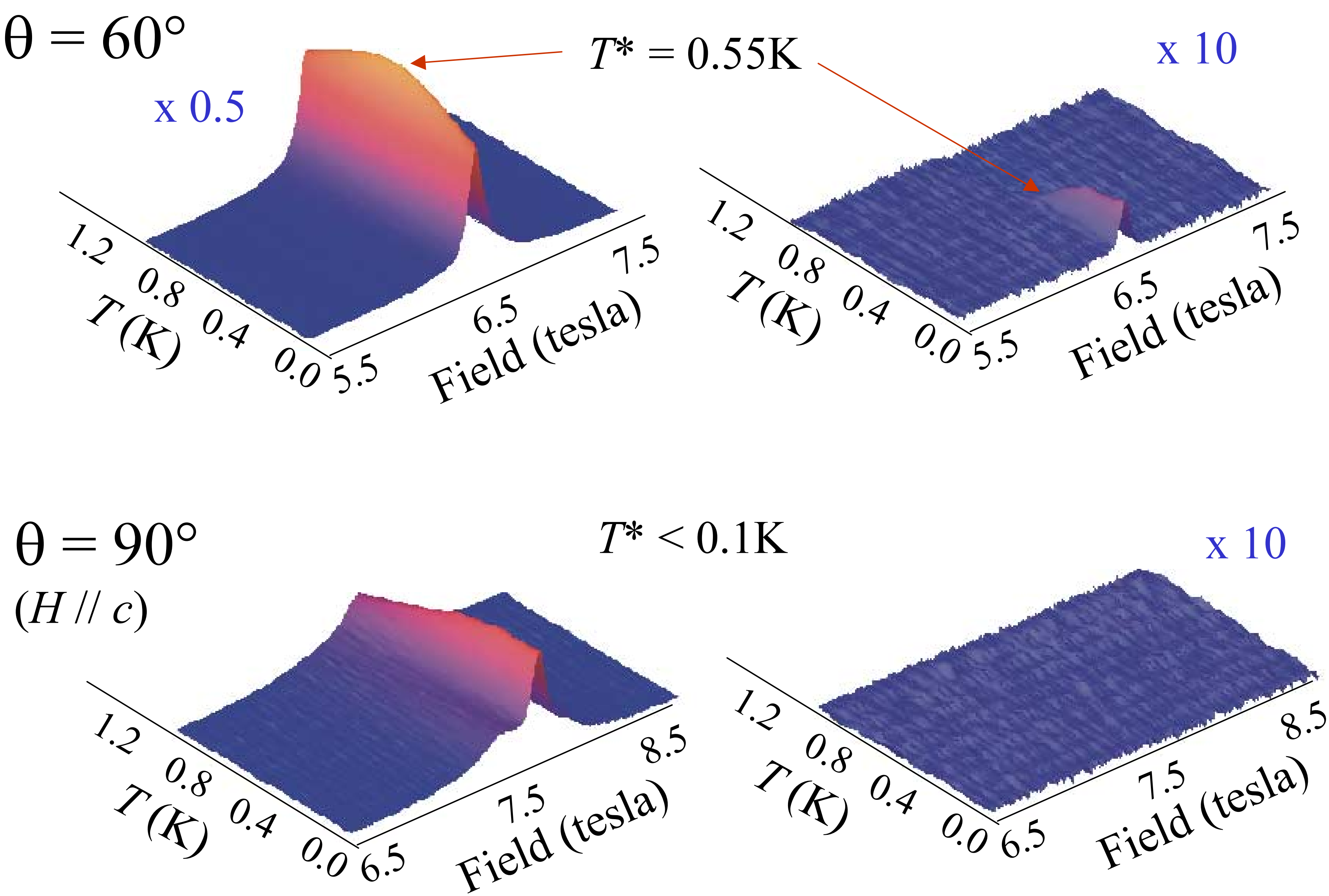


1st order line and end-point clearly identified for H // ab. Does angle indeed control (T*, H*)?

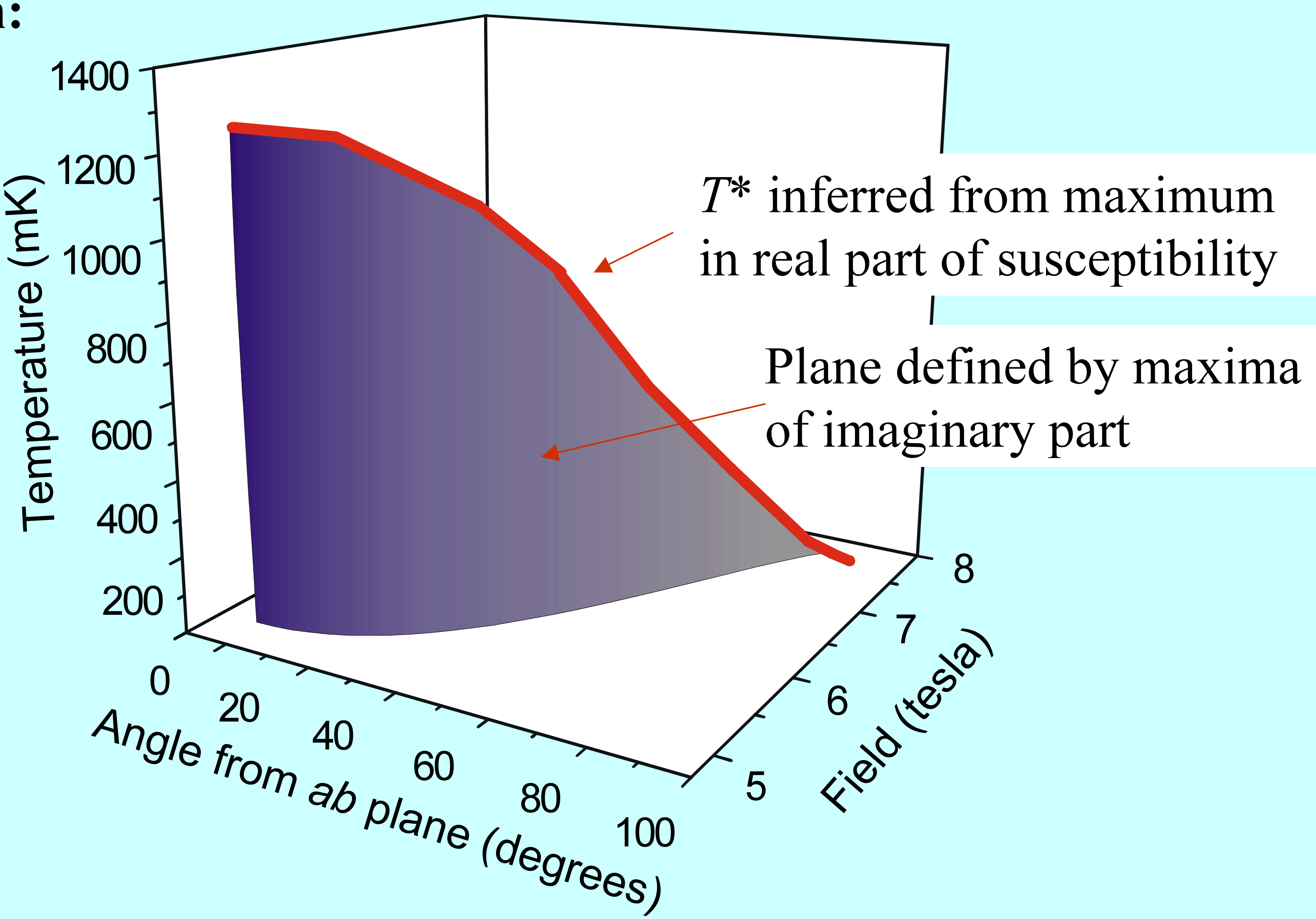
The effect of rotation is a smooth decrease of *T**



No evidence of first-order behaviour for *H* // *c*

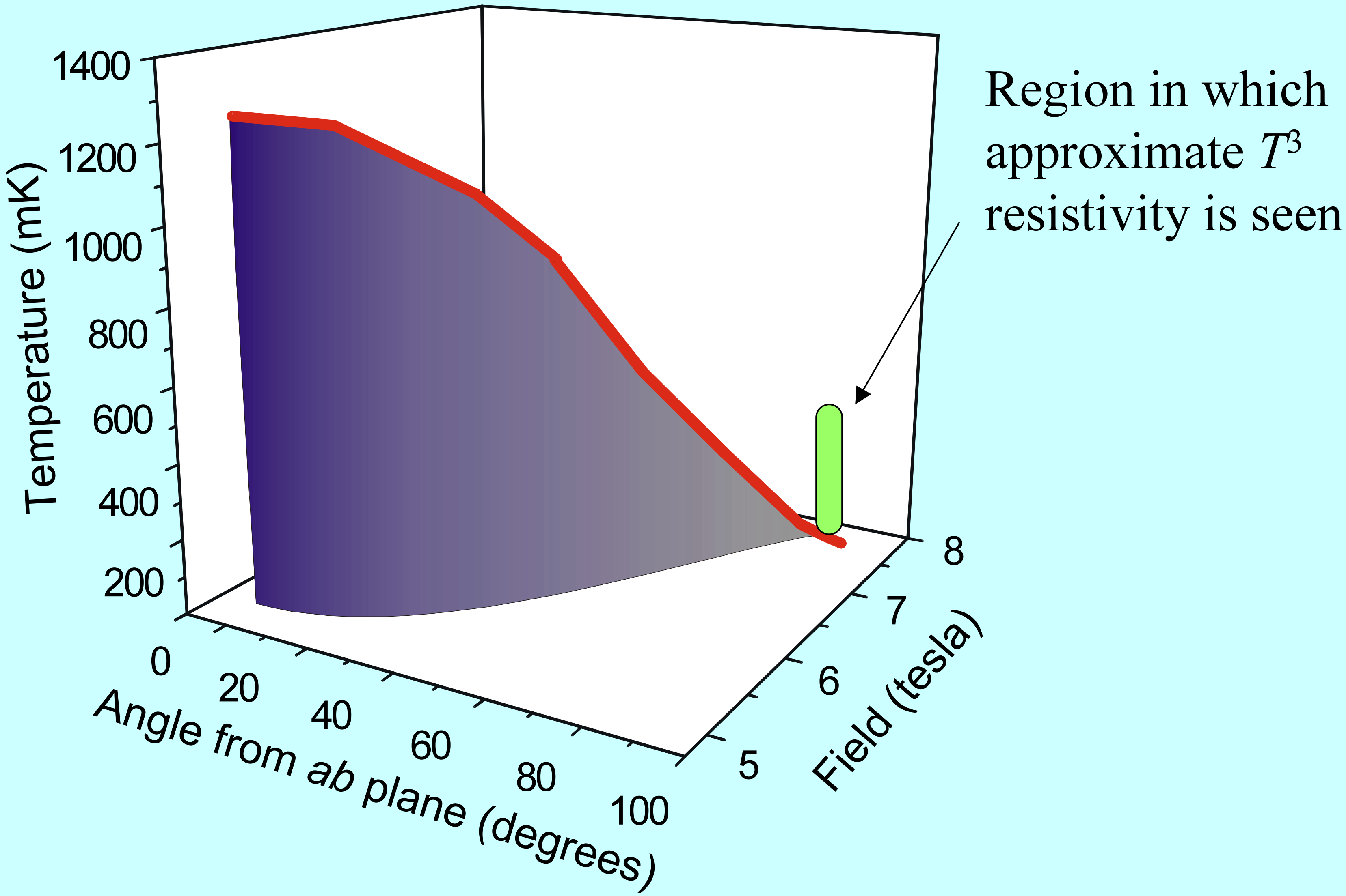


Collating all data allows construction of a purely empirical phase diagram:



Conclusion: The metamagnetic physics of $Sr_3Ru_2O_7$ *is* governed by a first order transition whose end-point (T^*, H^*) can be tuned by field angle, and sits at or very near $T = 0$ for H // c.

Note: There is no susceptibility evidence for first order behaviour in the region of anomalous transport:



Open question:

Are our observations consistent with a model based purely on proximity to ferromagnetism?

Not entirely. Main discrepancy is that although we observe a maximum in the real part of χ, we do not see the predicted divergence.

See e.g. A.J. Millis, A.J. Schofield, G.G. Lonzarich and S.A. Grigera, Phys. Rev. Lett. ***88****, 217204 (2002)*

Possible extrinsic reasons: Finite size effects, disorder, demagnetisation etc. need to be investigated.

Possible intrinsic reason: a ‘purely ferromagnetic’ model is not adequate.

Could the critical divergence be at a finite q rather than at $q = 0$?

There is no long-range order at high q in $Sr_3Ru_2O_7$, but there are nesting-related high-q fluctuations.

(L. Capogna, E.M. Forgan, S.M. Hayden, A. Wildes, J.A. Duffy, A.P. Mackenzie, R.S. Perry, S. Ikeda, Y. Maeno and S.P. Brown, preprint)

How easy is it to understand clear first-order behaviour in the static susceptibility on the basis of changes to finite-ω, finite-q fluctuations?

Would it explain discrepancies with the ‘standard model’ reported by Chiao *et al.,* who performed a scaling analysis of pressure-dependent transport?

Conclusions:

Metamagnetism in $Sr_3Ru_2O_7$ gives a route to quantum criticality with no symmetry-broken phase.

Transport and susceptibility data point to a basic picture in which the critical end-point of a line of first order transitions can be tuned towards T=0.

Field angle has been explicitly identified as an appropriate tuning parameter.

Although $Sr_3Ru_2O_7$ is nearly ferromagnetic, it is not clear that models based purely on proximity to ferromagnetism will be adequate to explain the behaviour of the $q = 0$ susceptibility.