# Hidden Order and Nexus between Quantum Criticality and Phase Formation : The Case of $URu_2Si_2$

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# Main Collaborators

| | |
|---|---|
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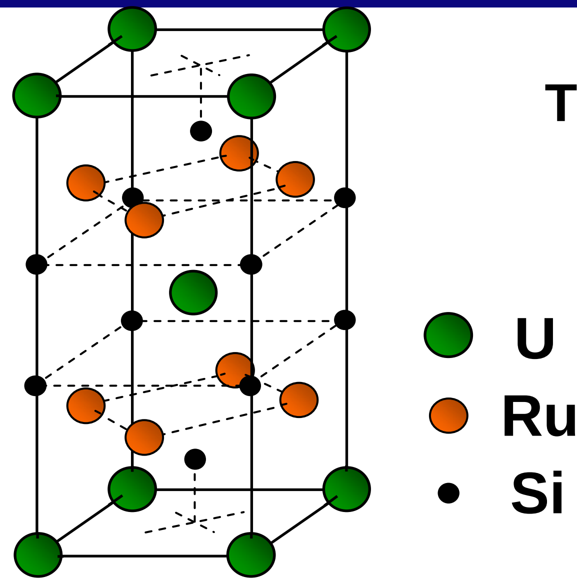
# Outline

- Introduction to $URu_2Si_2$ and Hidden Order (HO)
- Pressure Tuning : Neutron Diffraction and NMR
- Theories, Models and Conjectures over HO
- Destruction of HO with Field : Magnetization and Transport Properties – Phase Diagram
- Effects of Rh-doping
- Simplified Phase Diagram – only Phase II
- Nexus between Quantum Criticality and Phase Formation
- Characterization of Phase II via C(T,H) and MCE

# Introduction

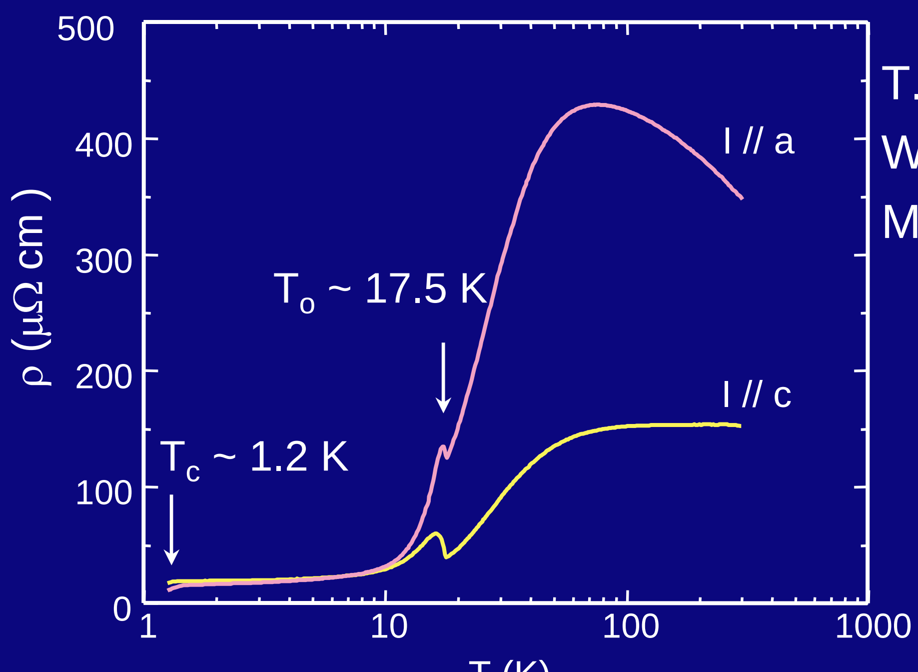
## $URu_2Si_2$




**$ThCr_2Si_2$ bct - type ( I4/mmm )**

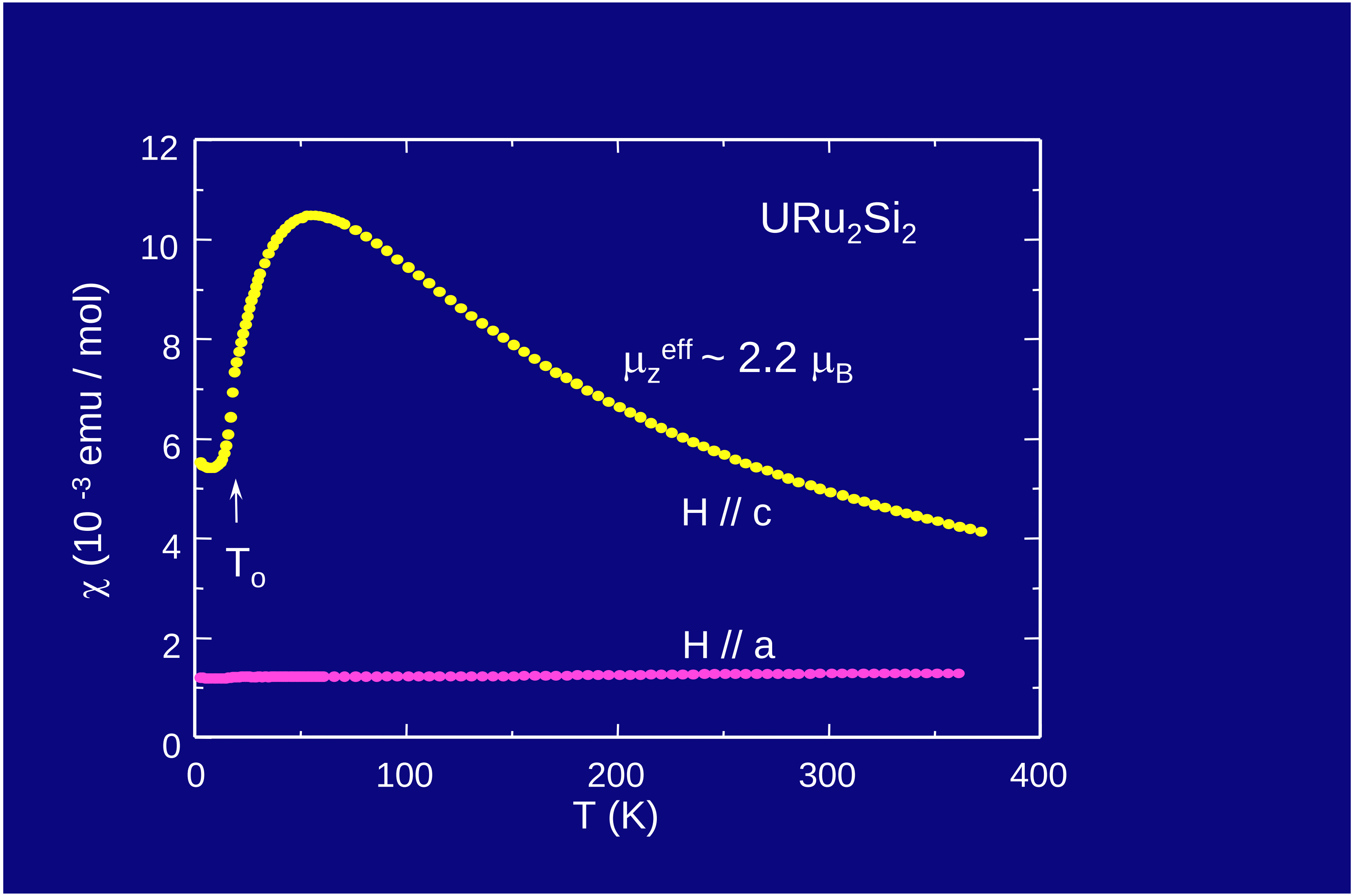
**a = 4.127 (Å)**
**c = 9.570 (Å)**

Coexistence of HO with SC

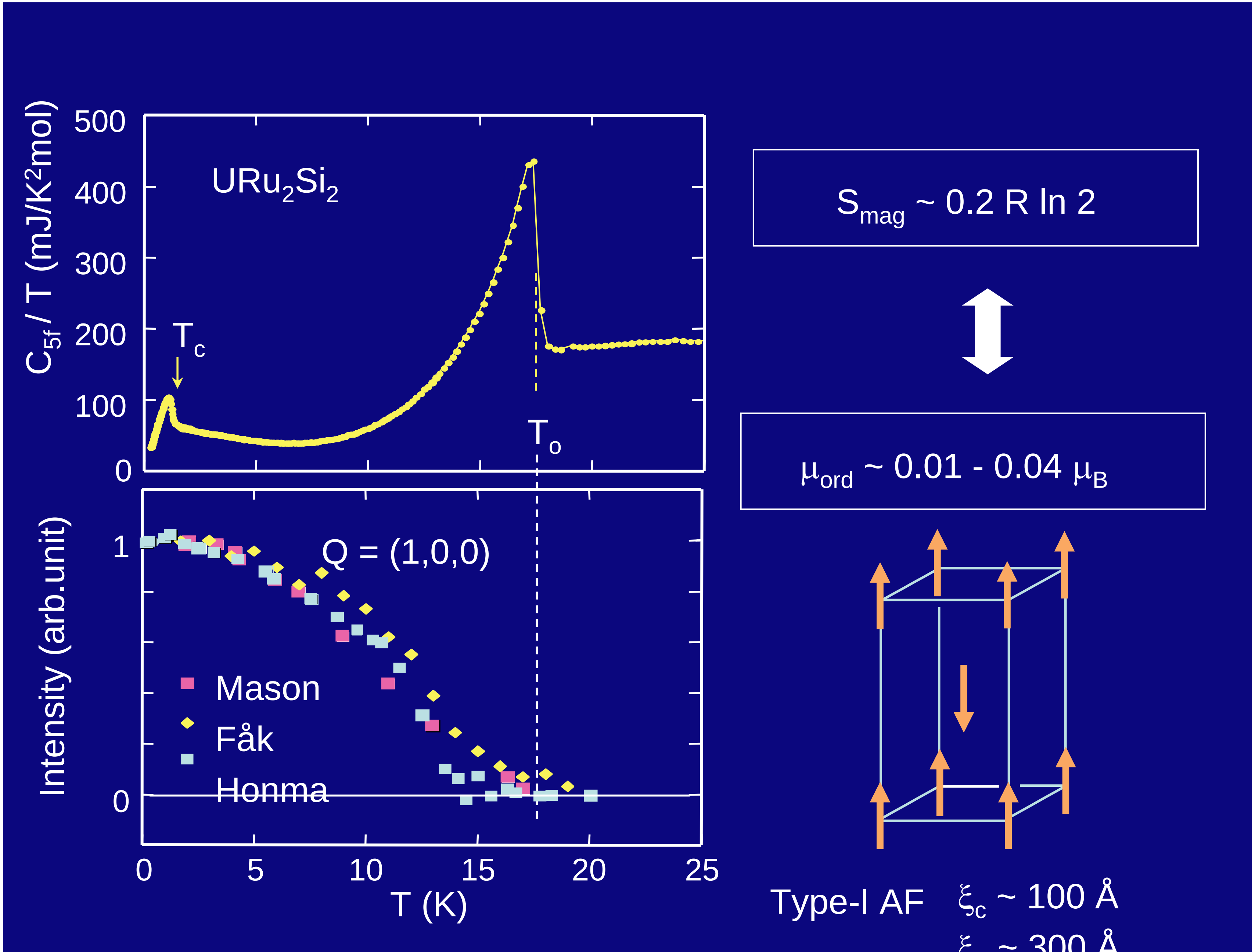



T.T.M. Palstra et al.(1985)
W. Schlabitz et al.(1986)
M.B. Maple et al.(1986)

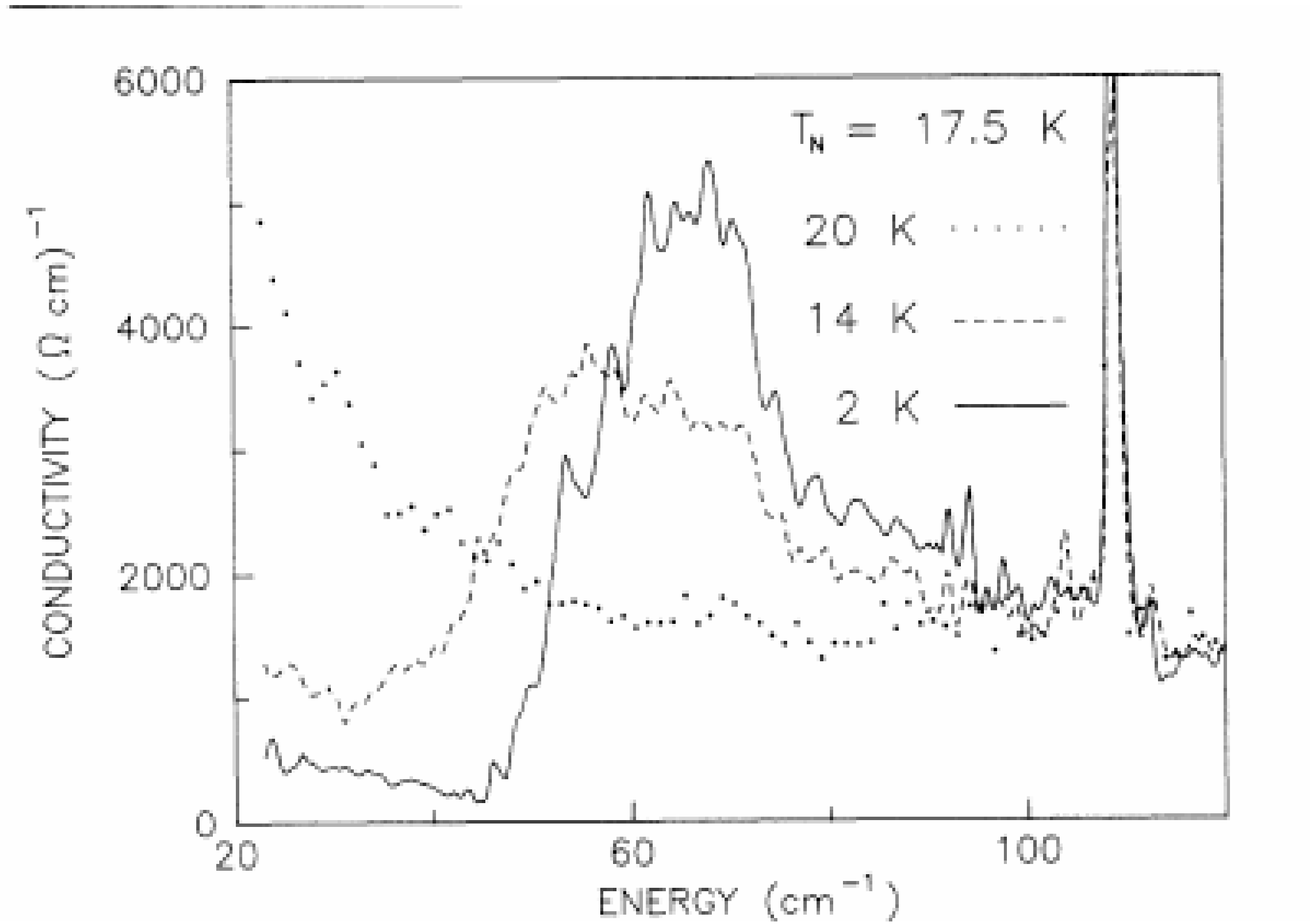
# Magnetic susceptibility



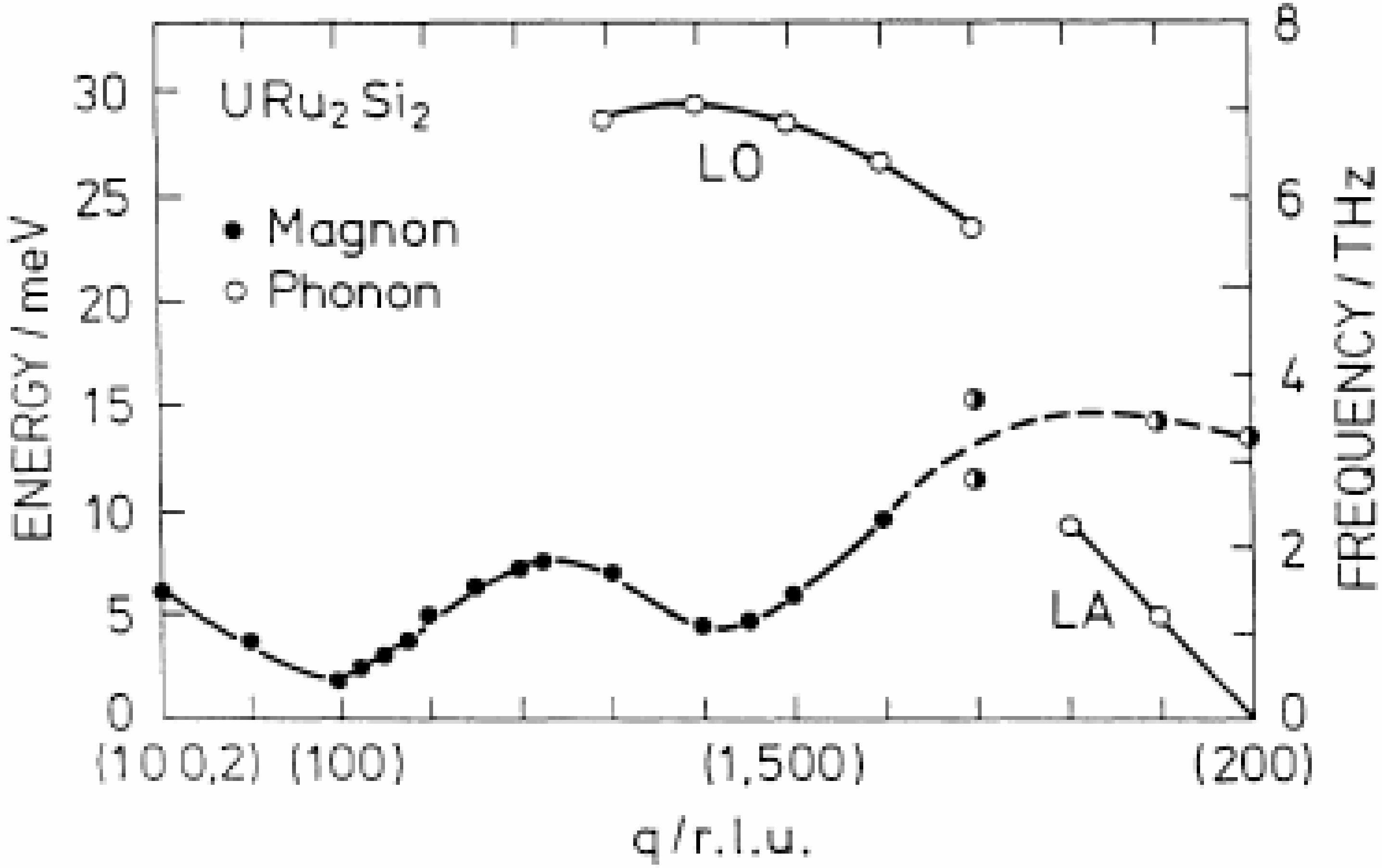
# Specific heat vs. magnetic Bragg-peak intensity



# Pseudo-gap in $URu_2Si_2$ measured through optical conductivity, D. A. Bonn et al. PRL (1988)

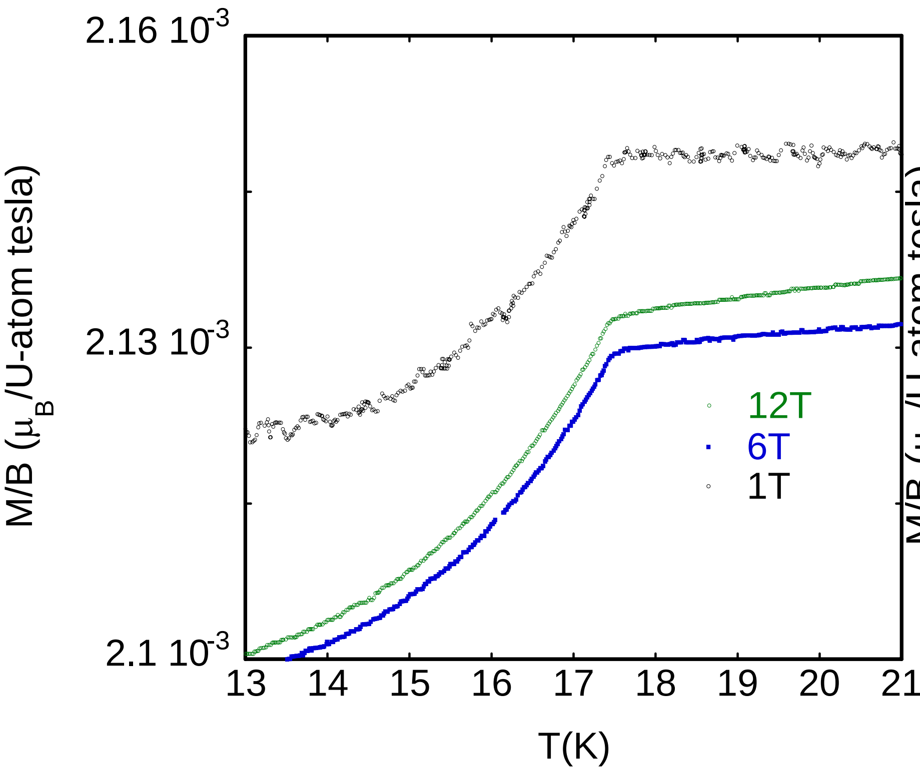


# Zone-center gap in $URu_2Si_2$ measured through neutron scattering, C. Broholm et al. PRL (1987) & PRB (1991)

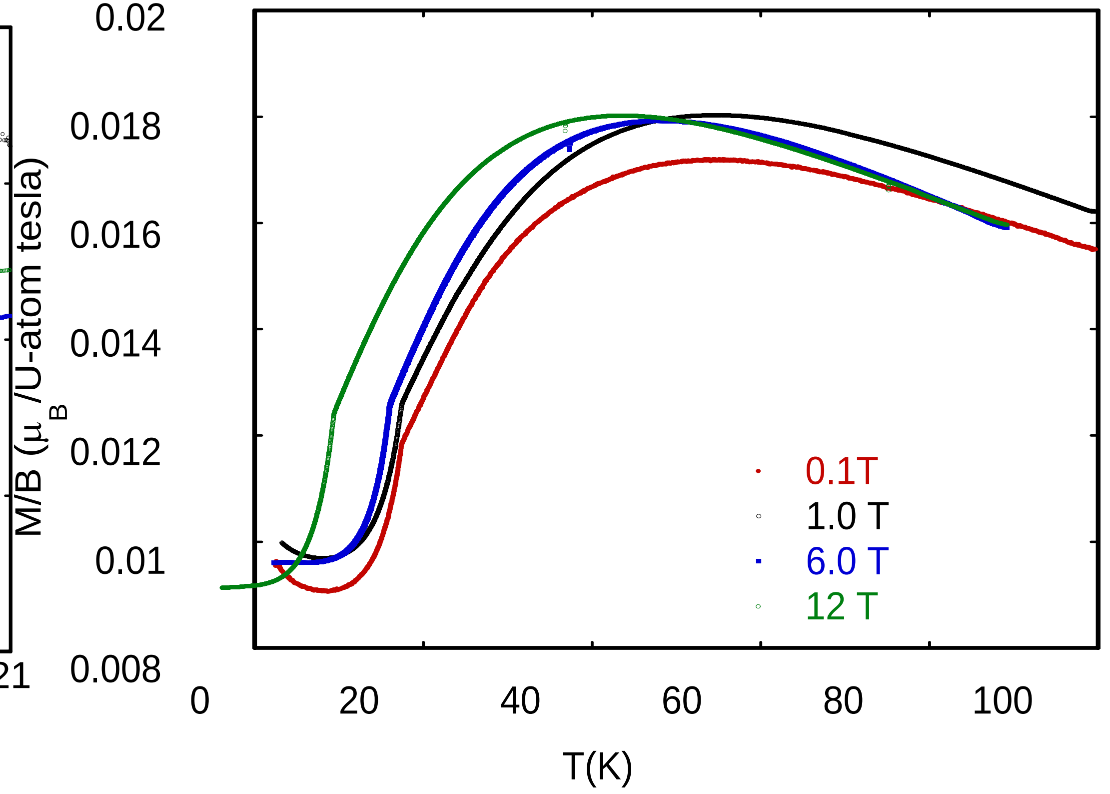



Similarity between optics and neutrons suggests magnetic excitations are strongly coupled to charge excitations

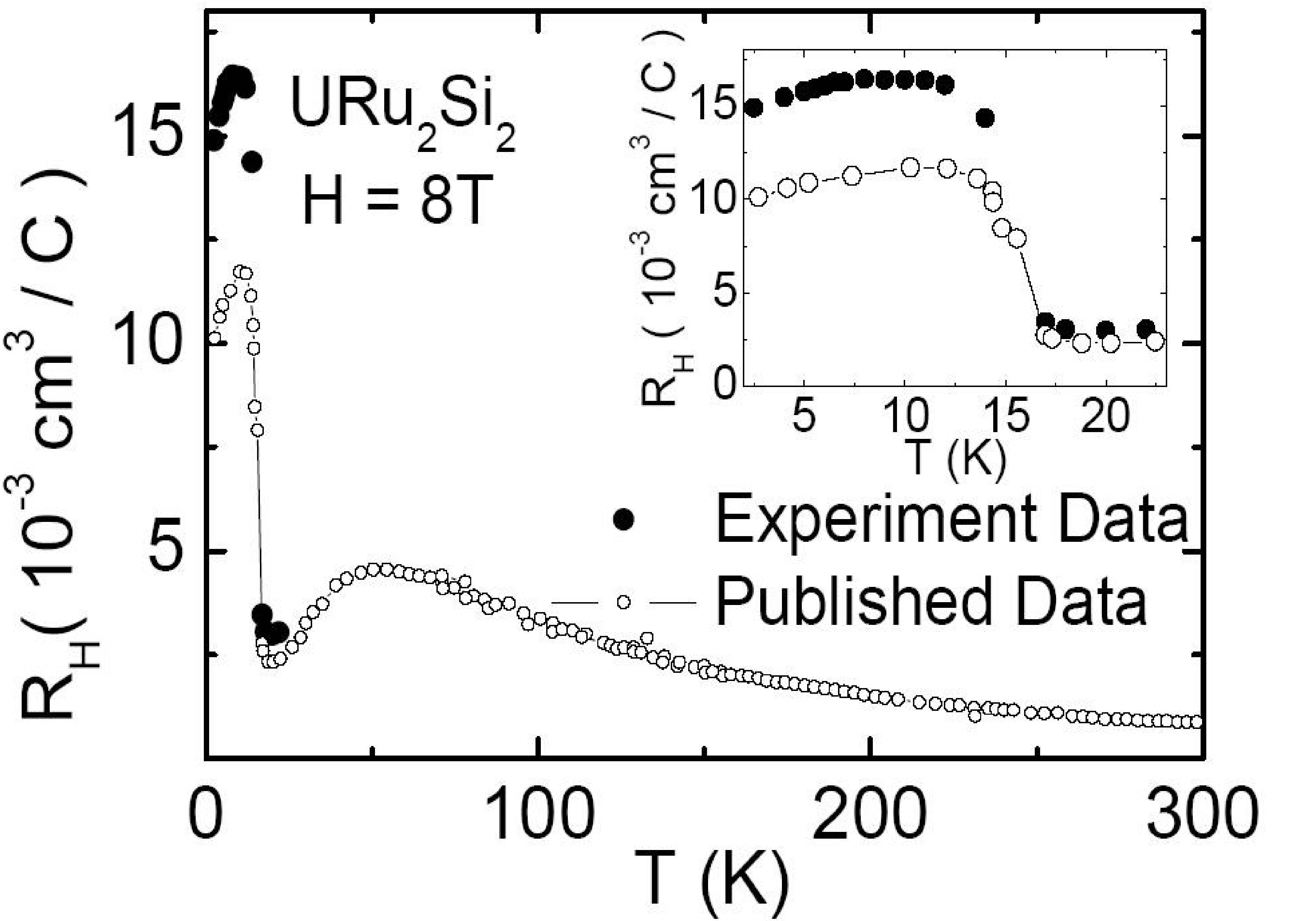
# Magnetization as function of temperature, C. Pfleiderer et al. to be published (2005)

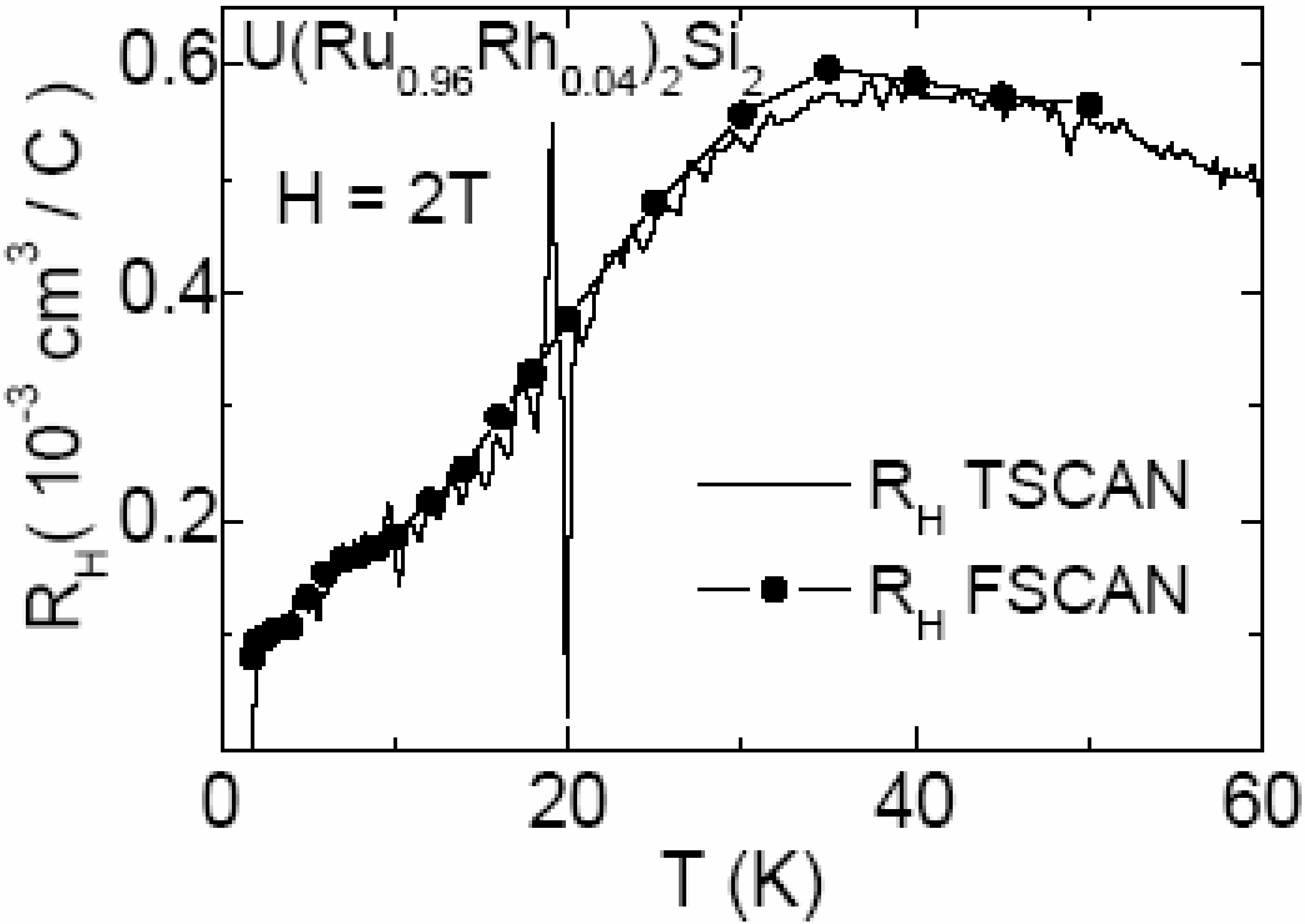



ab-plane



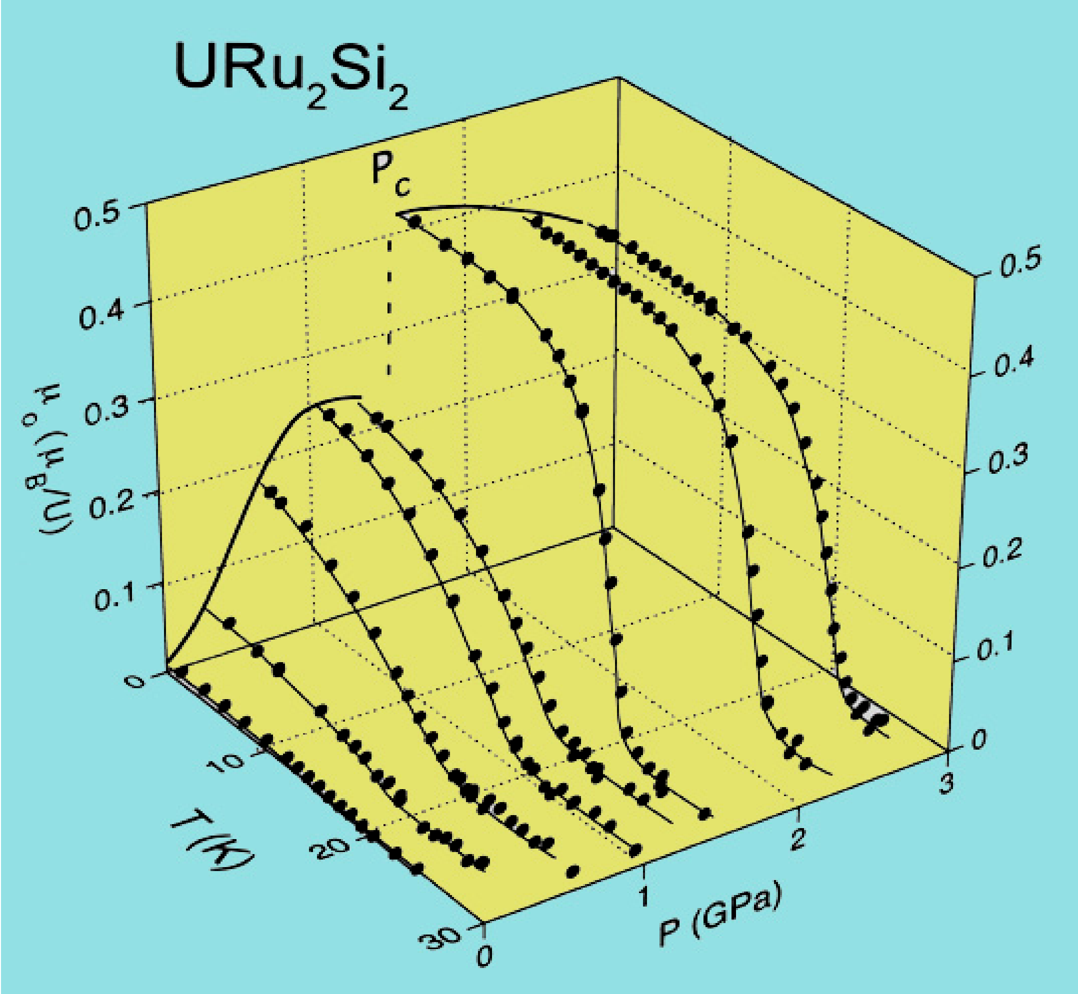

c-axis


URu2Si2
H = 8T
RH ( 10-3 cm3 / C )
T (K)
Experiment Data
Published Data
0
100
200
300
5
10
15
20
0



U(Ru0.96Rh0.04)2Si2
H = 2T
RH ( 10-3 cm3 / C )
0.2
0.4
0.6
0
20
40
60
T (K)
RH TSCAN
RH FSCAN

# • Neutron scattering under hydrostatic pressure




**H. Amitsuka, M. Sato, N. Metoki, M. Yokoyama, K. Kuwahara, T. Sakakibara, H. Morimoto, S. Kawarazaki, Y. Miyako, and JAM**

**PRL 83 (1999) 5114**

# $^{29}$Si NMR in Aligned Powder

Matsuda, *et al*., PRL 87 (2001) 87203
NMR, under pressure [*P*-induced IAF]

Bernal et al., PRL 87 (2001) 196402
Ambient Pressure [Internal Field]

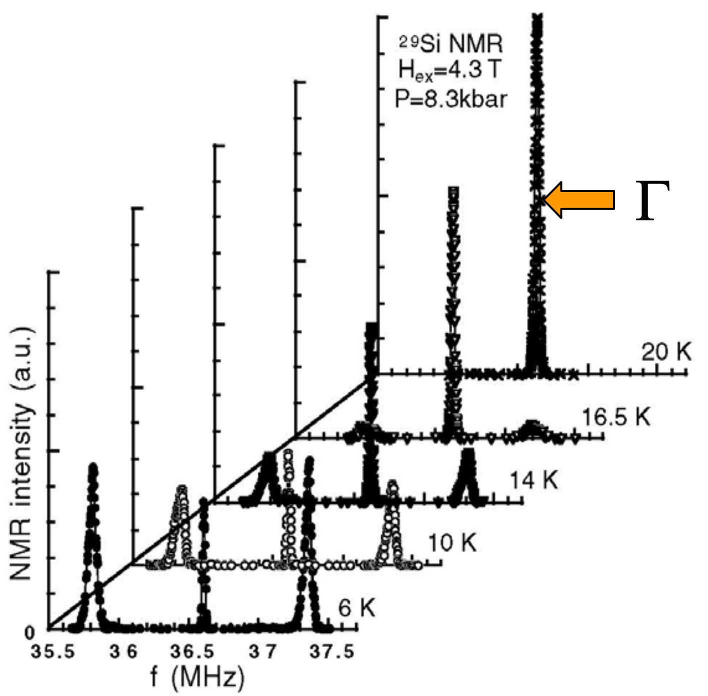
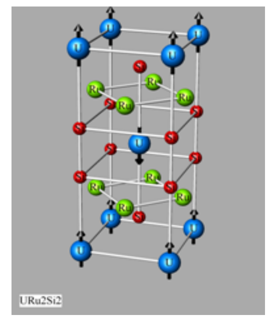
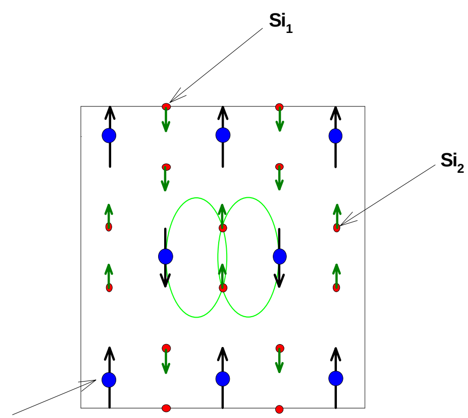
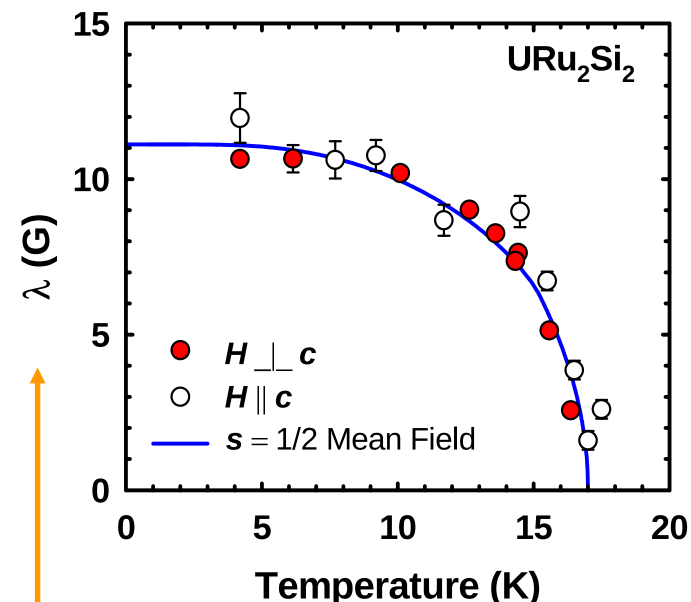



FIG. 1. $T$ evolution of $^{29}$Si NMR spectrum for $H_{ex} \parallel c$ axis at 8.3 kbar.




(110)

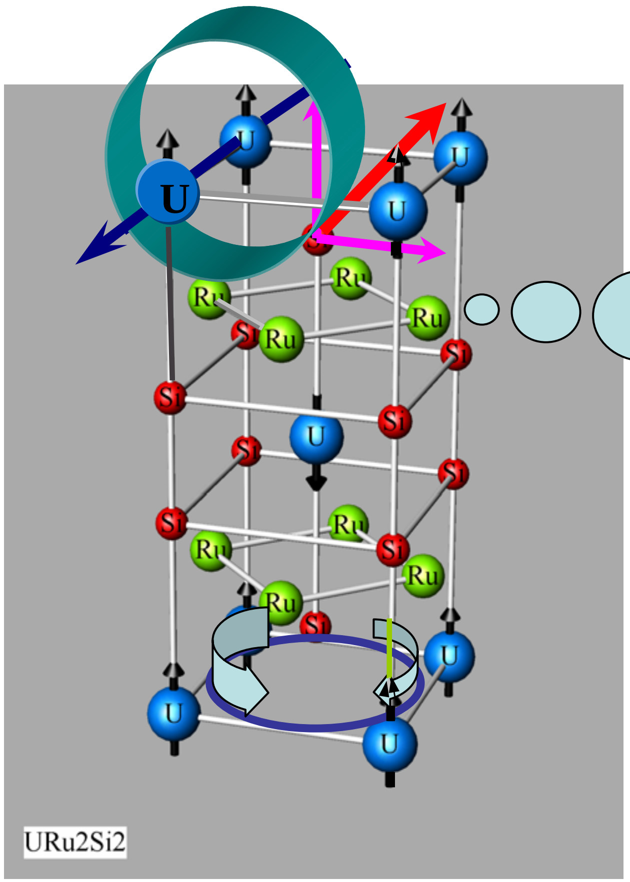



OAF?

087203-2

$$\Gamma^2(H,\theta,T) = \alpha^2 M^2(H,\theta,T) + \lambda^2(T)$$

# Orbital Antiferromagnet




Is the internal field also isotropic at Ru sites?

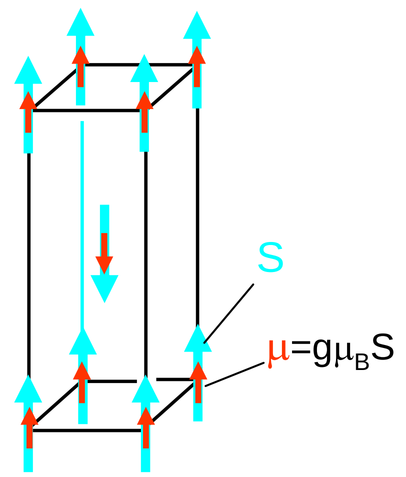
U-U Bond Current Direction

Resultant Magnetic Field

# Hidden Order Unique Enough to Stimulate New Ideas:

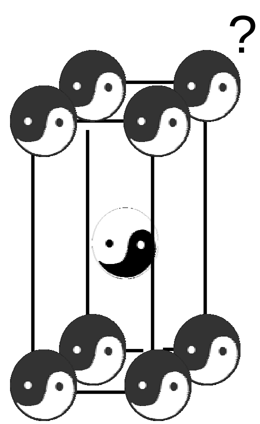
## Dipolar order with small g values

| | | |
|---|---|---|
| crystal fields | Niewenhuys | '86 |
| quant. spin fluctuation | Sikkema et al. | '96 |
| duality: loc./itin. | Okuno, Miyake | '98 |
| spin-orbital cancellation | Yamagami | '99 |
| fragile AF order | Bernhoeft et al. | '02 |




## Non-dipolar order

| | | |
|---|---|---|
| quadrupole | Miyako et al. | '91 |
| triple spin | Barzykin, Gor'kov | '93 |
| quadrupole ($\Gamma_4$) | Santini, Amoretti | '94 |
| quadrupole ($\Gamma_5$) | H. A., Sakakibara | '94 |
| structural distortion | Barzykin, Gor'kov | '95 |
| U dimer | Kasuya | '97 |
| d-wave SDW | Ikeda, Ohhashi | '98 |
| quadrupole ($\Gamma_5$) | Shimizu, Ohkawa | '99 |
| bond order - OAF | Chandra et al. | '01 |
| unconventional SDW | Virosztek, Maki, Dóra | '02 |

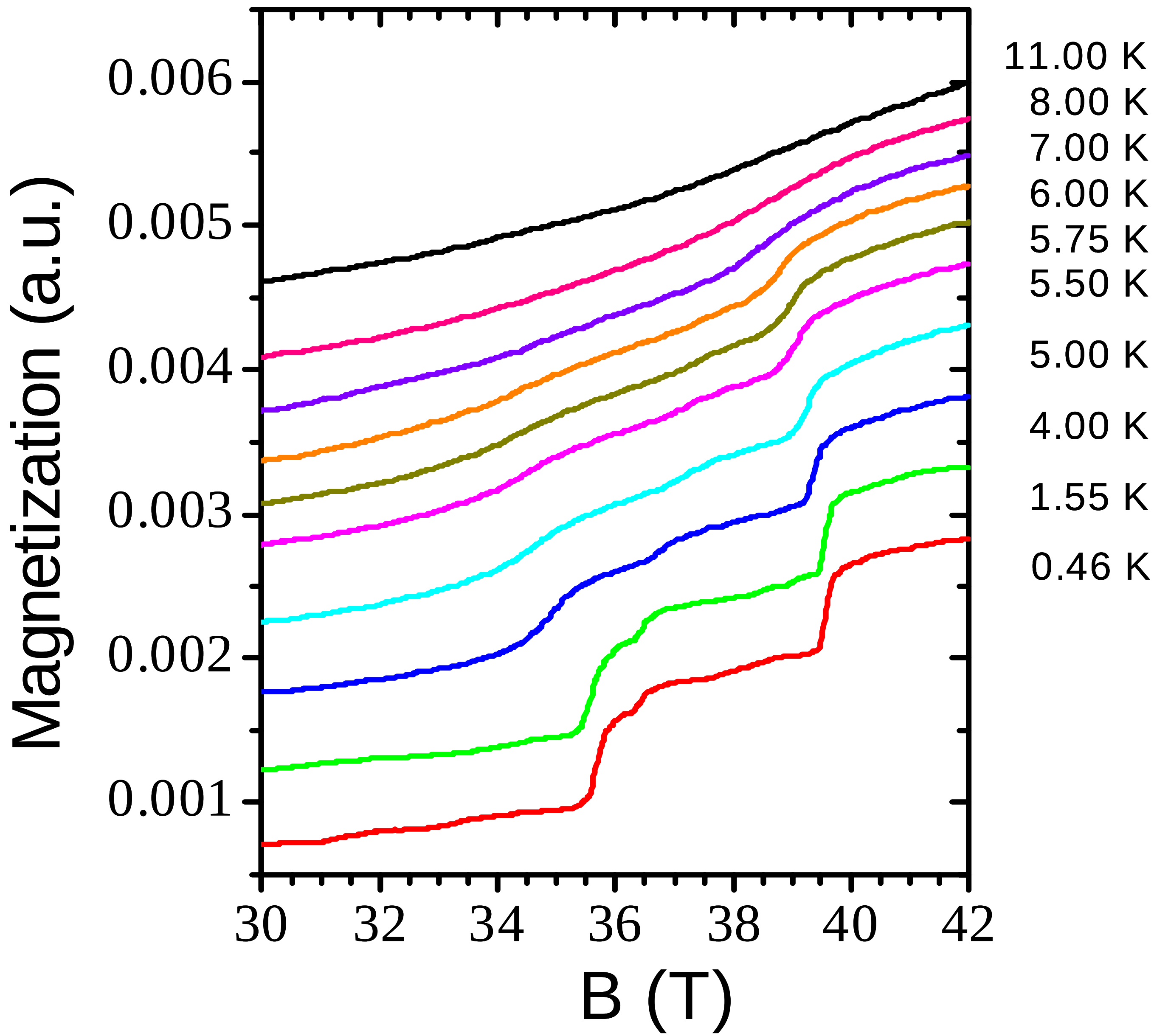


# Hidden Order Unique Enough to Stimulate New Ideas:

## Non-translational-symmetry breaking

| | | |
|---|---|---|
| Landau-Pomeranchuk | Varma | '03/'05 |
| Valency transition | Gor'kov | '04 |
| Octupolar | Kiss & Fazekas | '05 |
| SDW | Mineev & Zhitomir. | '05 |
| Falicov-Kimble | Zlatic | '05 |
| Itinerant quadrupole | Harrison et al. | '05 |
| Itinerancy & HO | Tripathi & $(PC)^2$ | '05 |

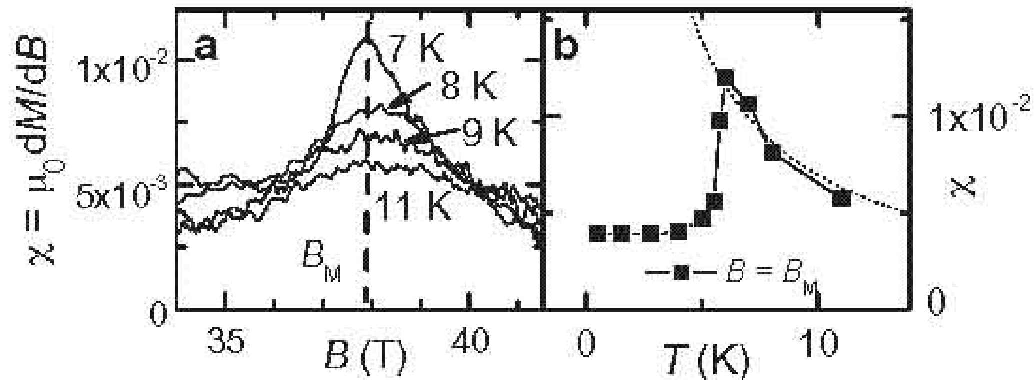
# Switching to the Metamagnetic Transition in $URu_2Si_2$




N. Harrison, M. Jaime, and JAM, PRL **90**(2003)

# What happens as $T$ is lowered?

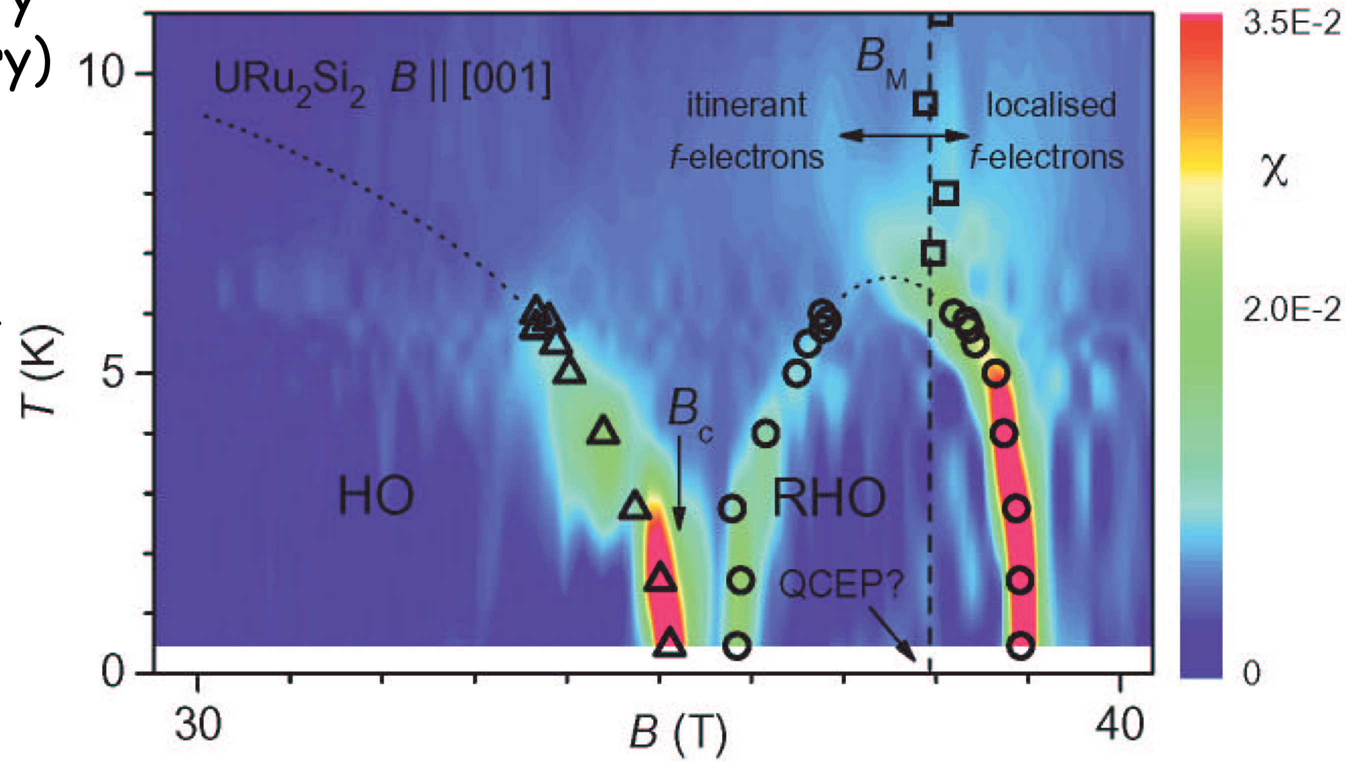
$\chi$ exhibits divergence for $T > 6$ K as for $CeRu_2Si_2$, $Sr_3Ru_2O_7$ and $UPt_3$



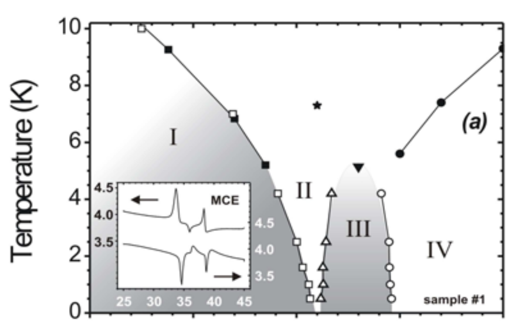

H decreasing

THEN SUDDENLY

crossover splits for $T < 6$ K ($T$-stability crucial for discovery)

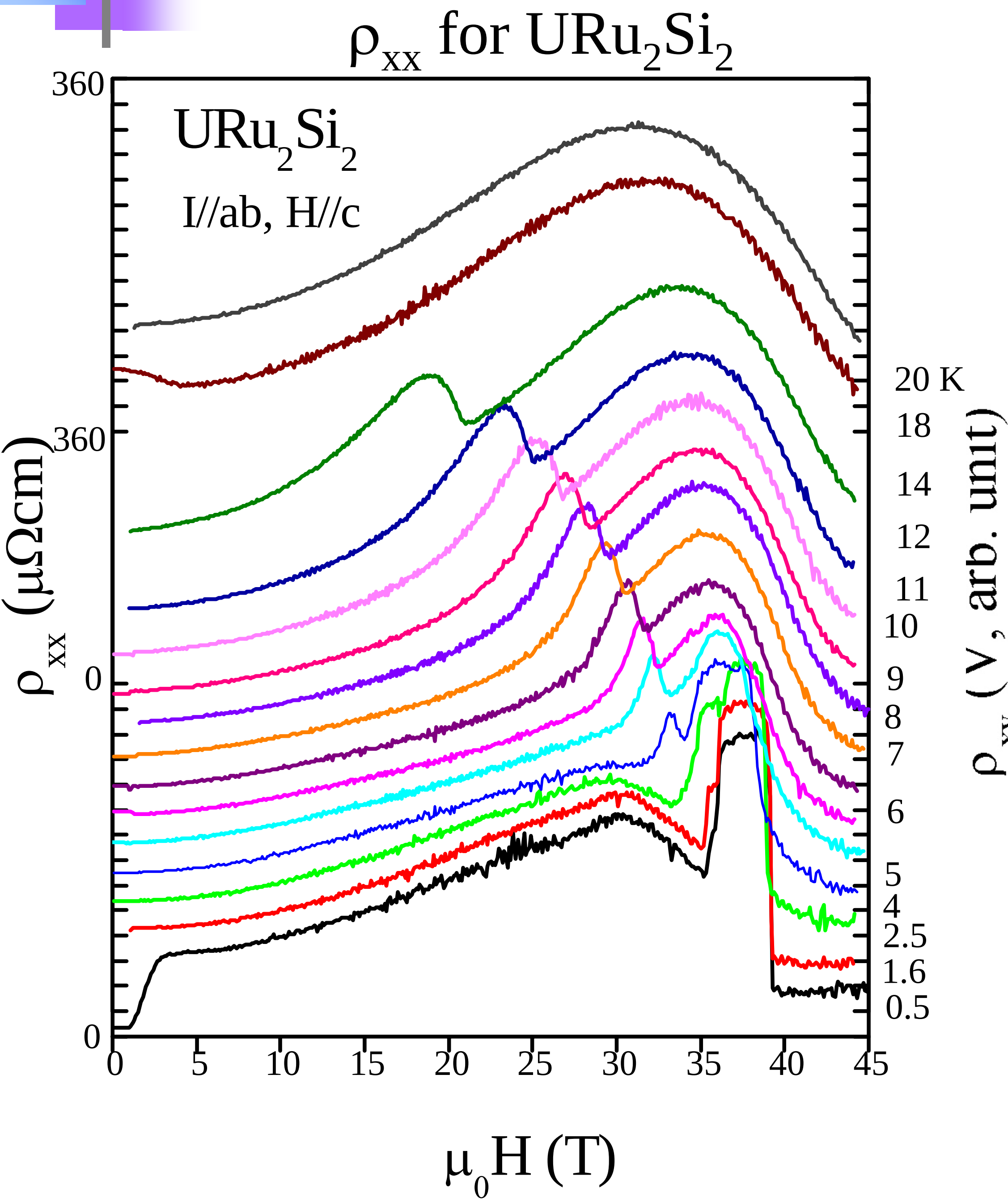


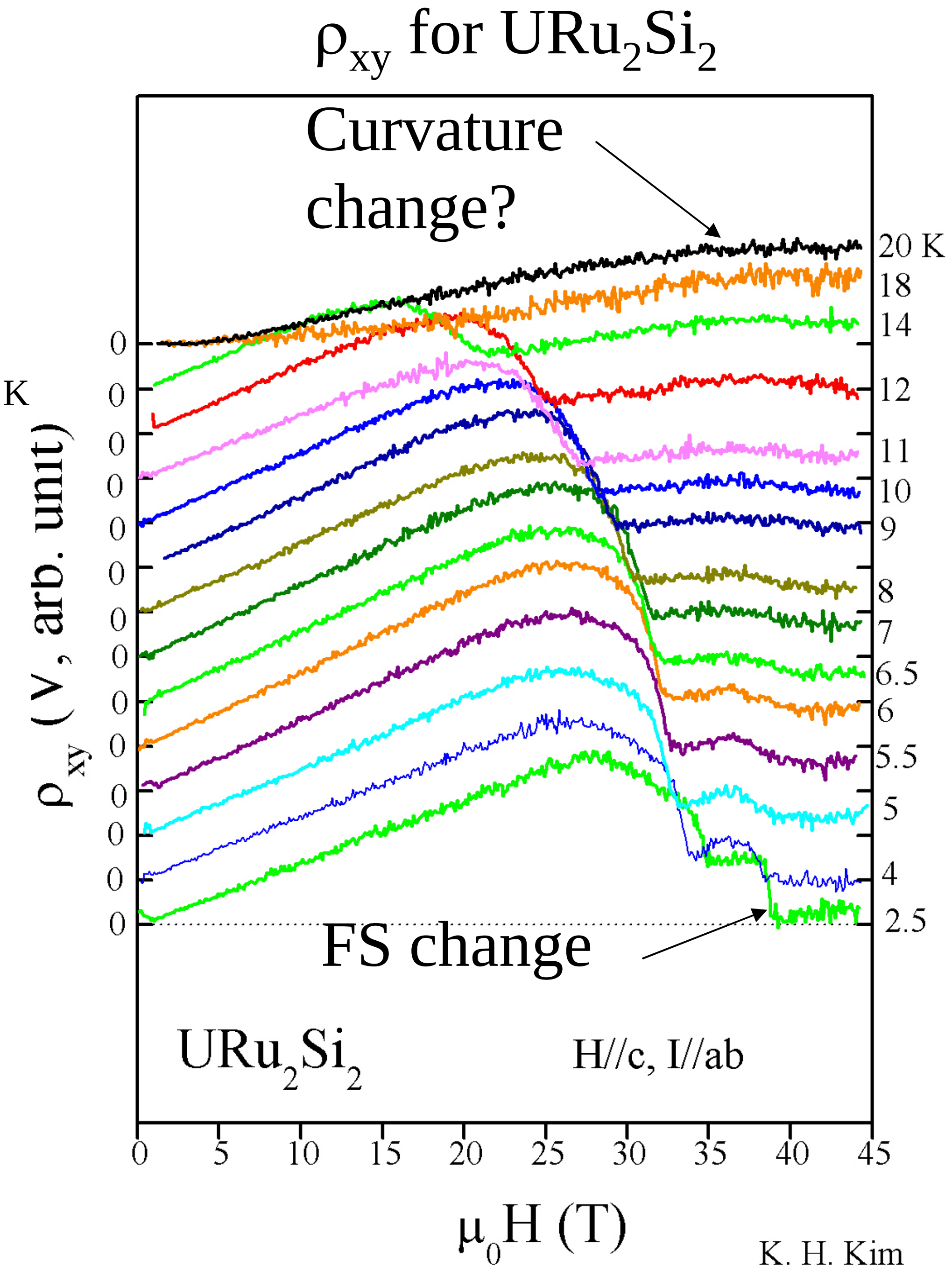

Transitions consistent with specific heat measurements [Jaime et al. **PRL 89**, 287201(2002)]




CAN FIELD-INDUCED QCP INSTIGATE NEW PHASES?

# Hall Effect Results for $URu_2Si_2$ in Pulsed Magnet

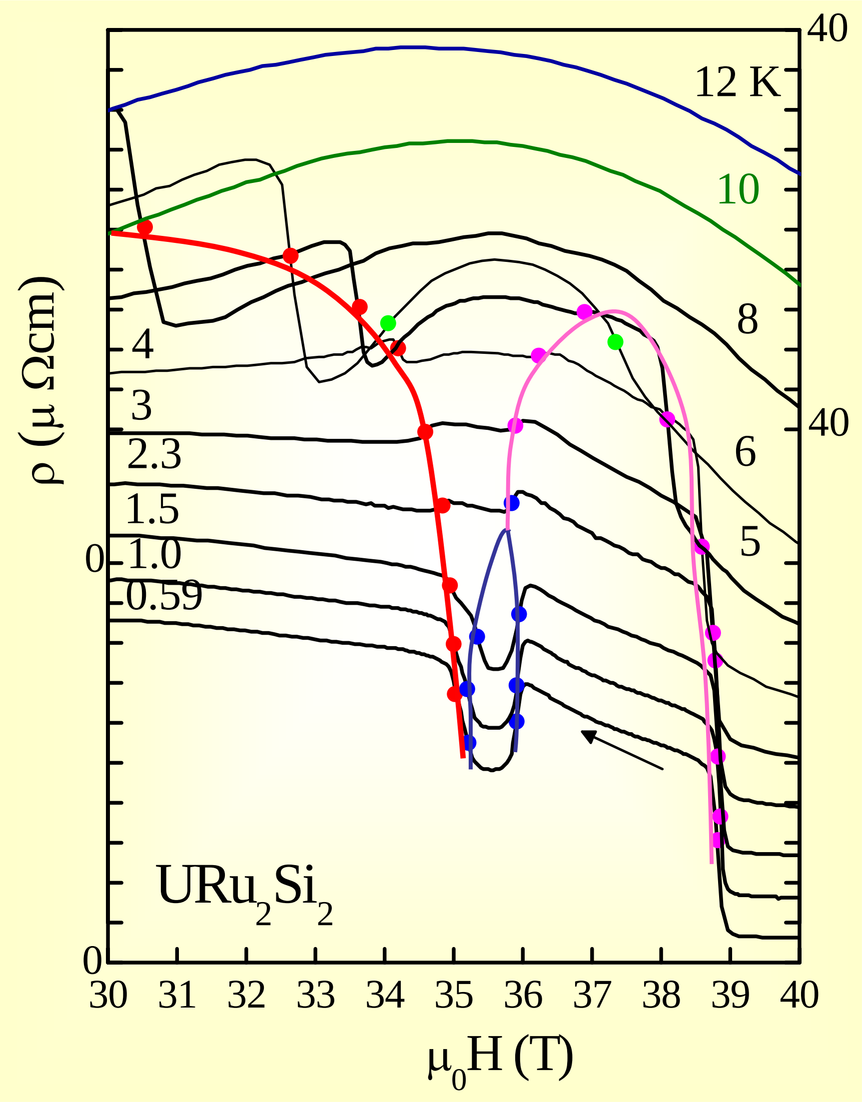


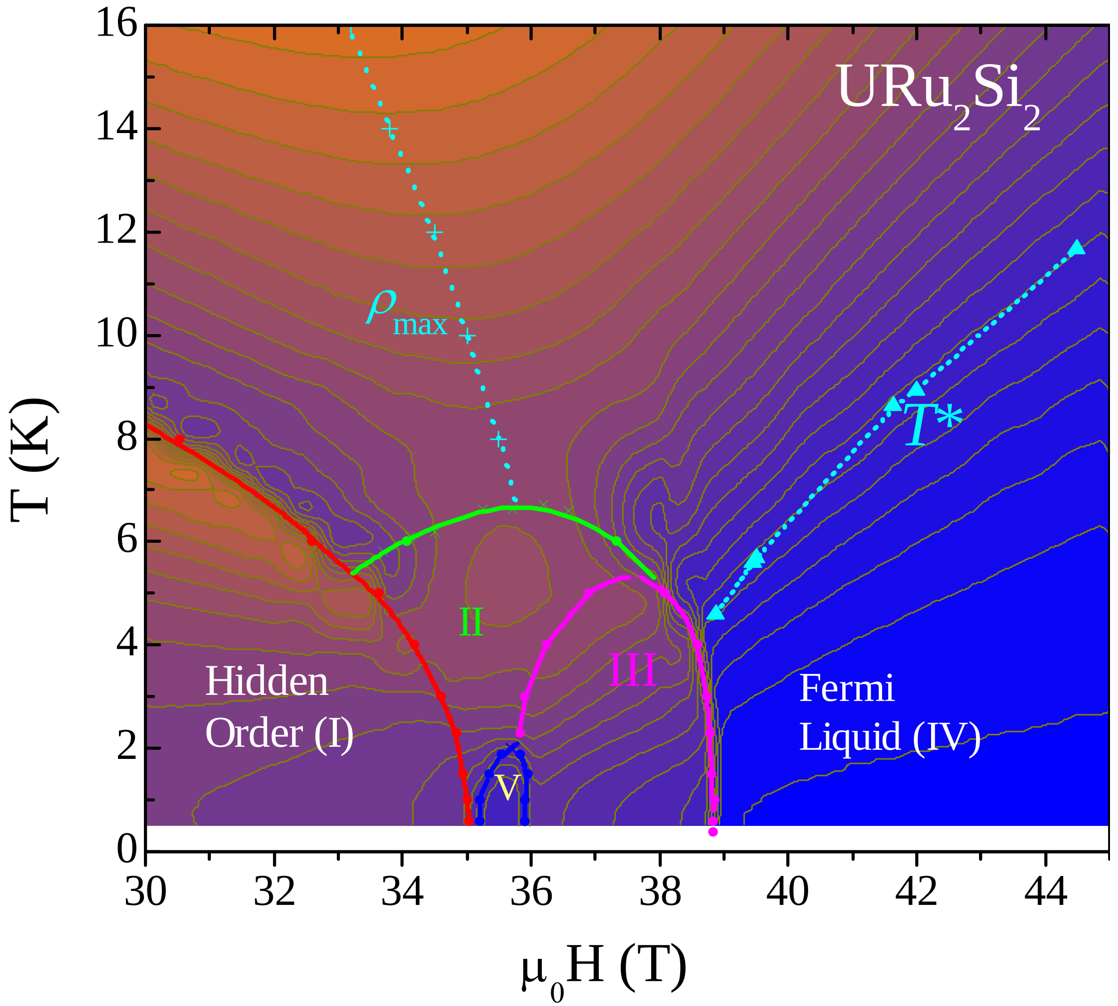




K. H. Kim
10/13/03

Fig. 1. Kim, Harrison, and Mydosh

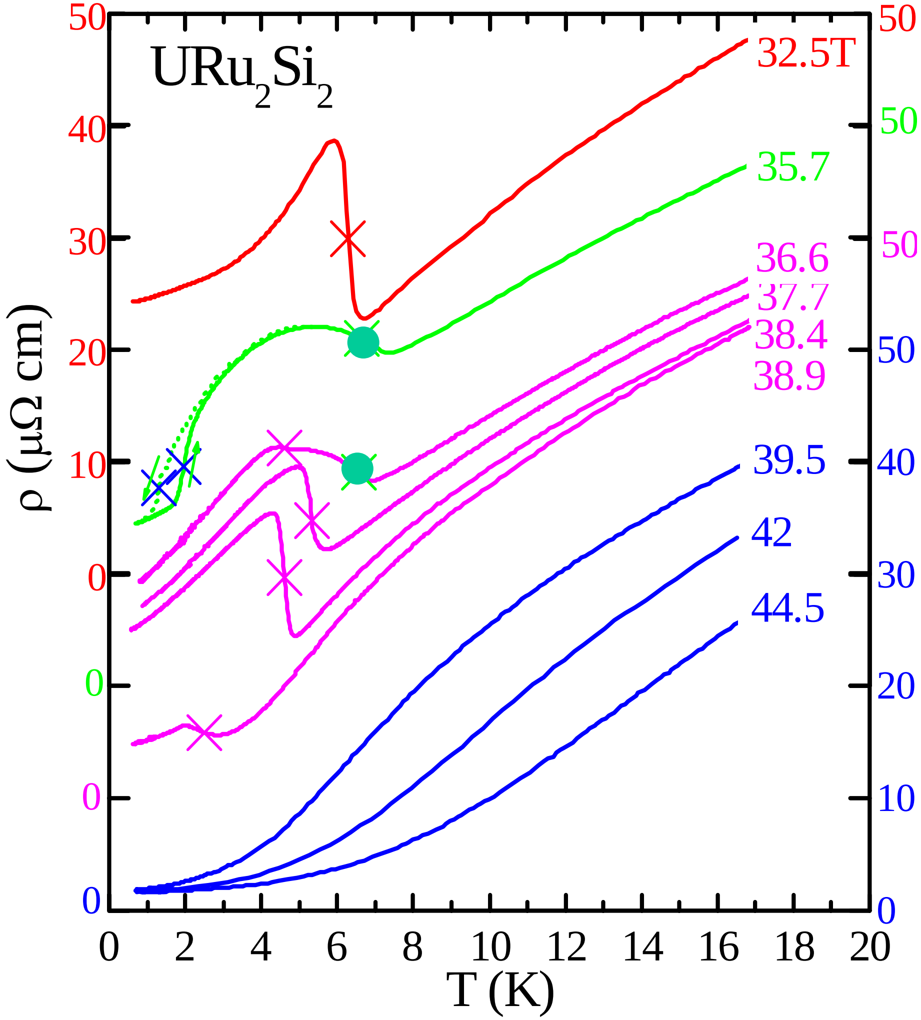
# Multiple phases nearby a QCP: H decreasing

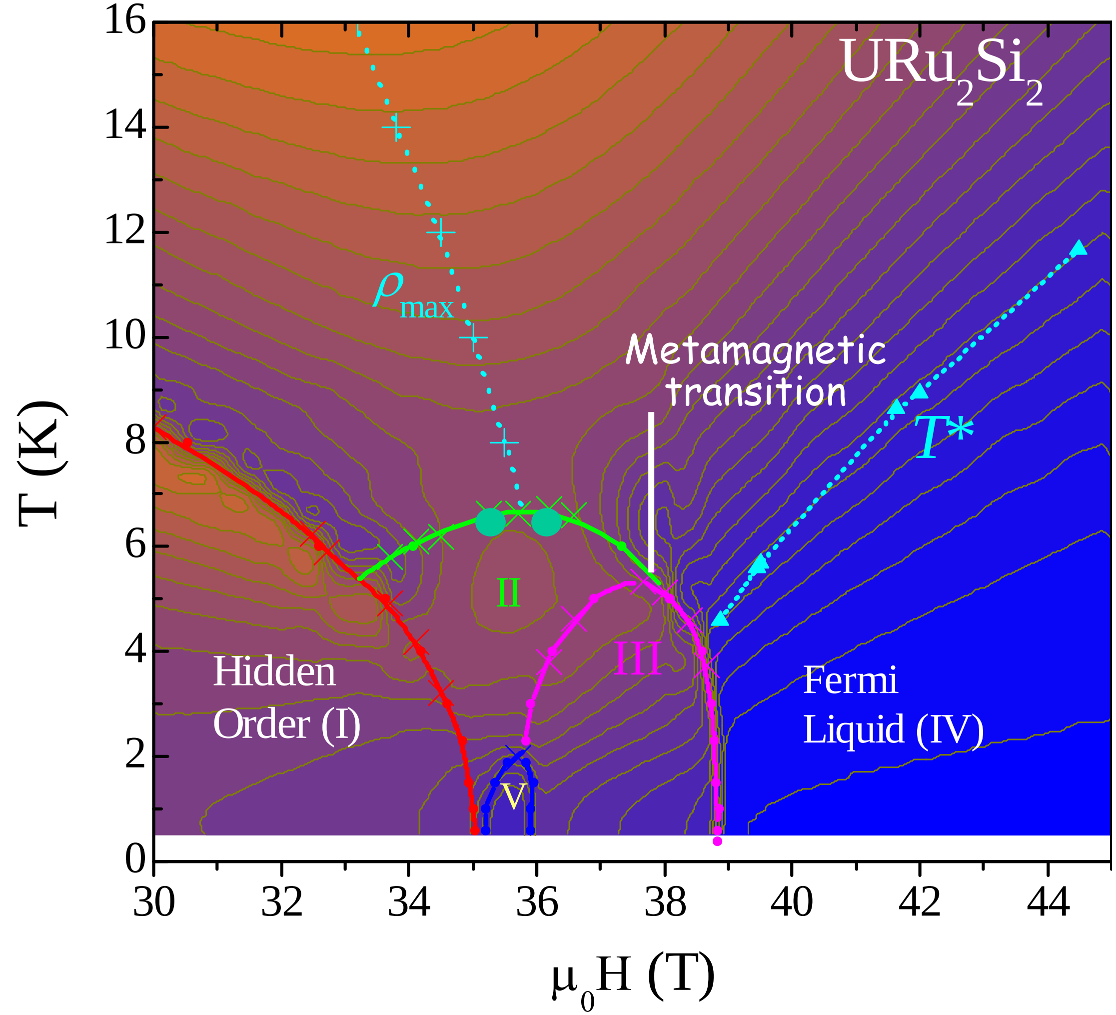



<u>**Phase transitions**</u> observed as extremities in $d\rho/dB$ and $d\rho/dT$ confirmed in $M$, $C$ and sound velocity $v_s$

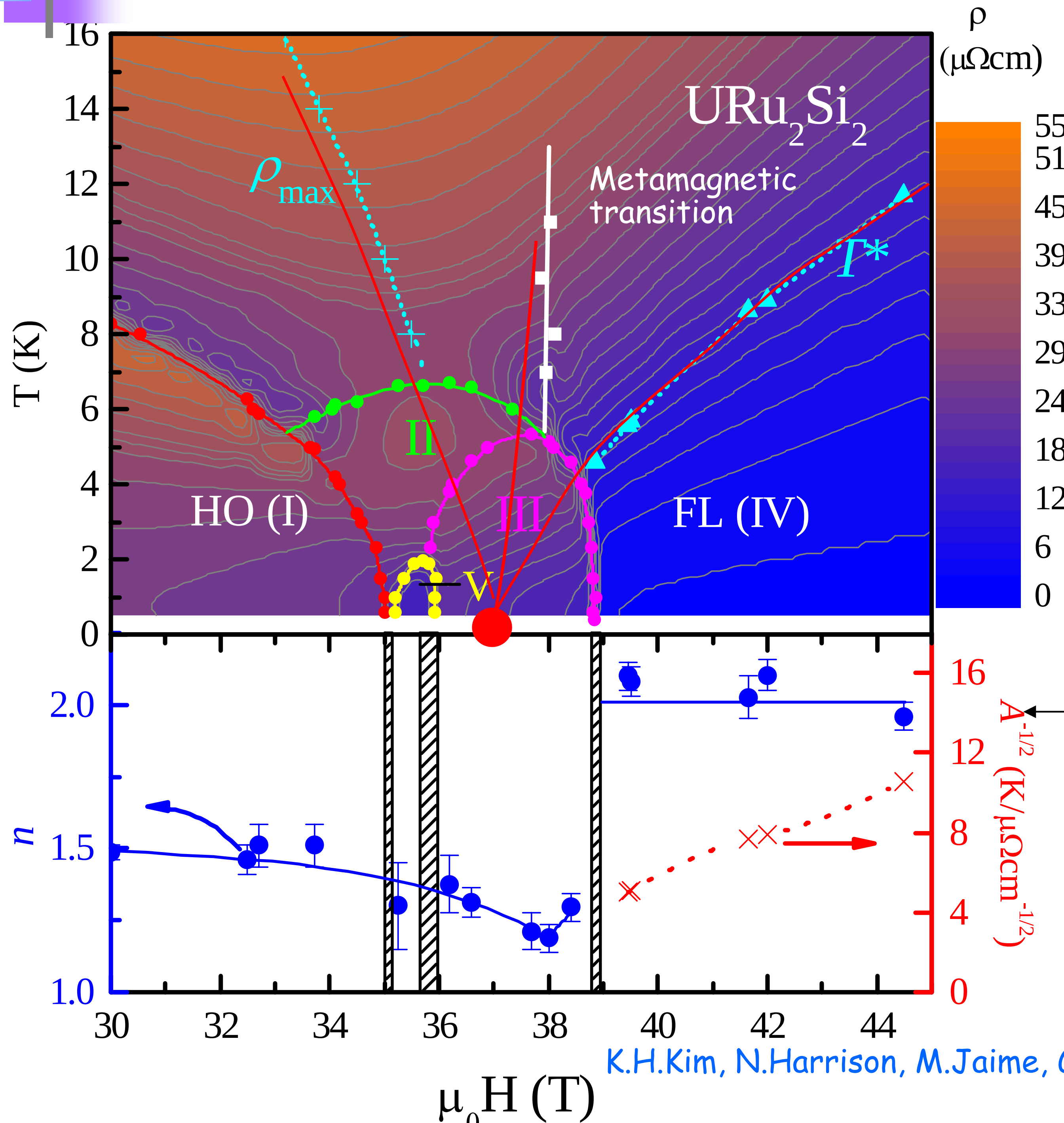
# Multiple phases nearby a QCP: H decreasing




**Multiple new phases** result from (1) multiple competing interactions and/or (2) close proximity of $B_M$ to Hidden Order phase

# Summary of Transport Results for $URu_2Si_2$




All the "smoking guns" indicate

$H_{QCP}$~37 T !!

**$URu_2Si_2$ :**

**Another example** of order created at quantum critical point ??

$\rho=\rho_0+AT^n$

~0.6K≤ $T$ ≤ 3 K

K.H.Kim, N.Harrison, M.Jaime, G.S.Boebinger and JAM. **PRL 91**, '03

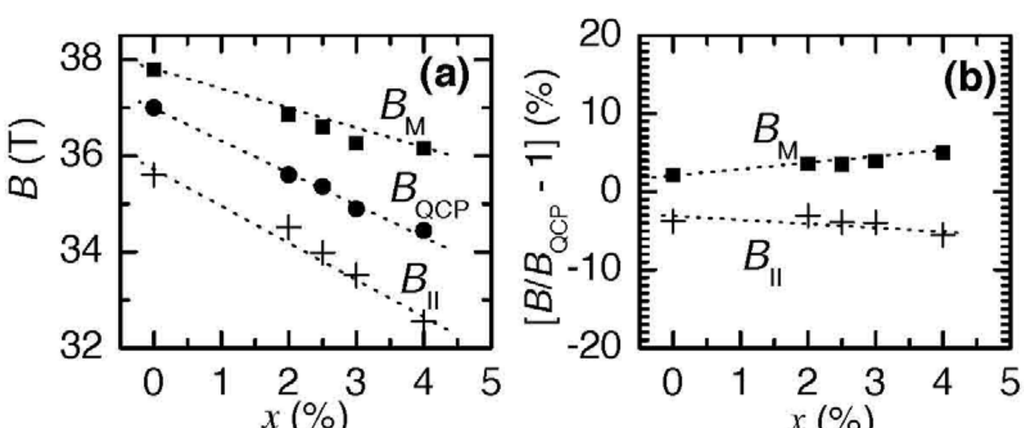
# Effects of Rh-doping in $URu_2Si_2$

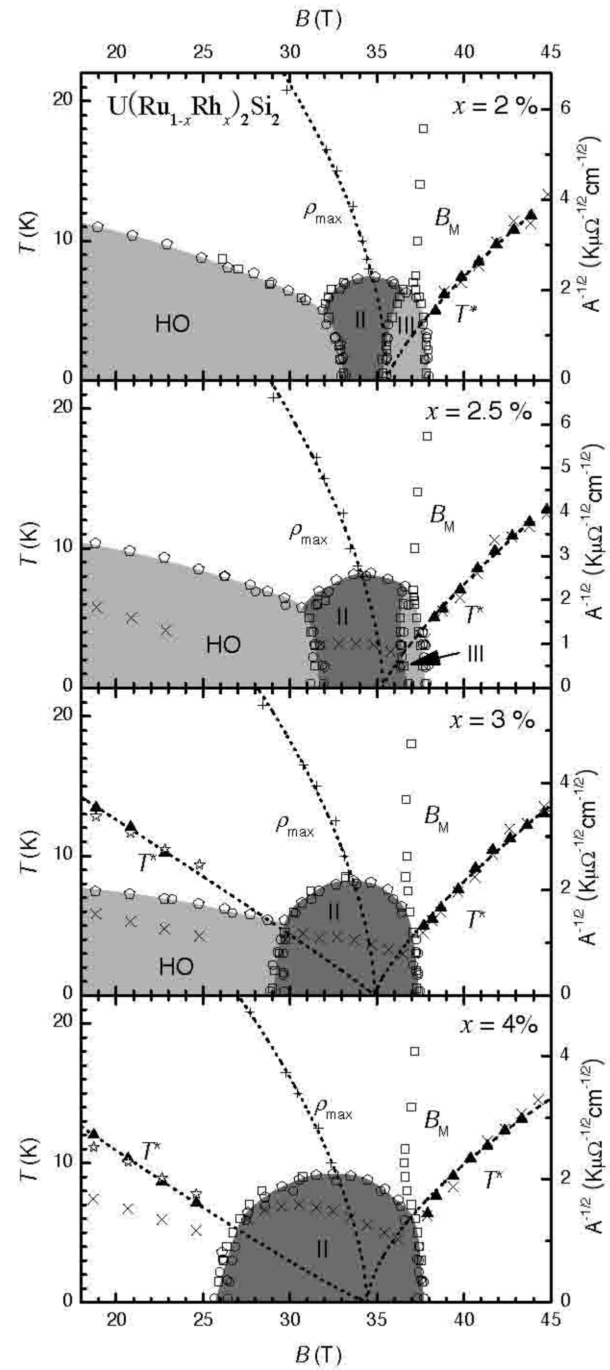
K.H.Kim, N.Harrison, H.Amitsuka, G.A.Jorge, M.Jaime and JAM, PRL 93(2004)

Phase diagram simplified on doping with Rh, yielding single field-induced phase (II) [without phase I (Hidden Order)] and clearer evidence for quantum critical point

Quantum criticality occurs in absence of hidden order: so hidden order not responsible for quantum criticality

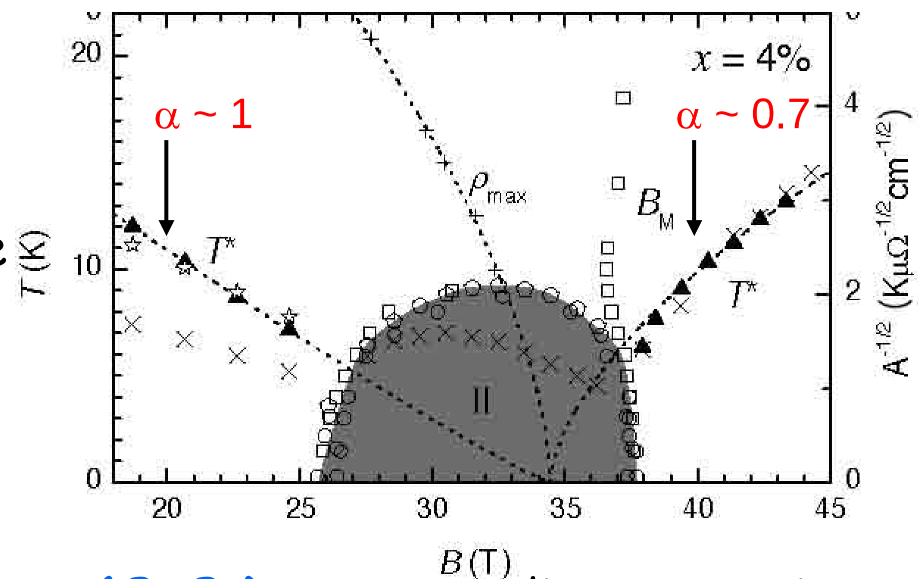
Nexus between quantum critical point, phase II and $B_M$ observed as a function of Rh, indicating causality link



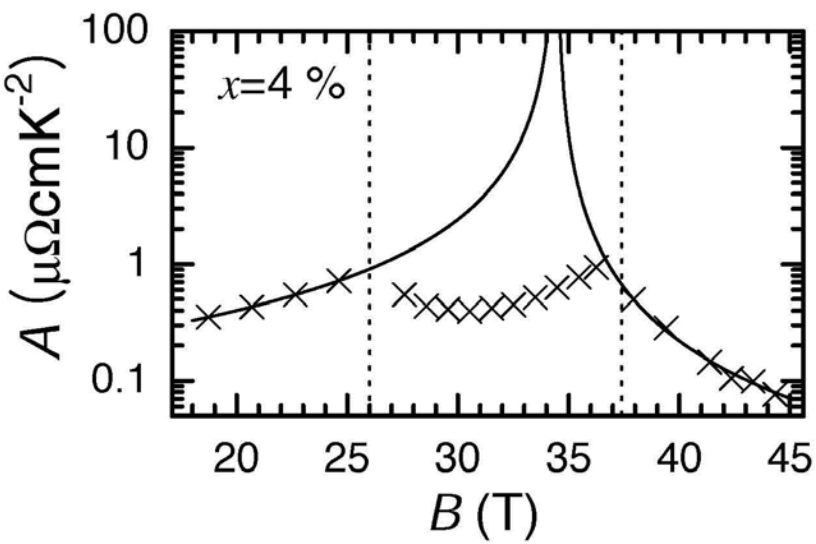




(magnetization in pulsed fields and transport in dc fields)

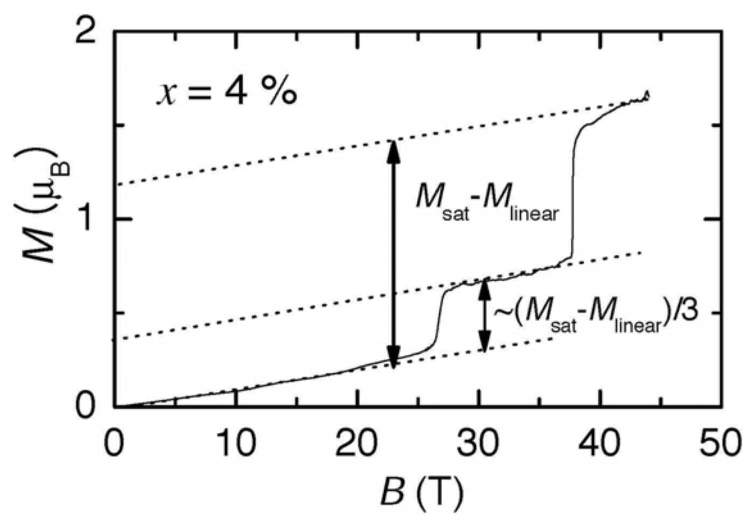
# Quantum criticality and Phase II



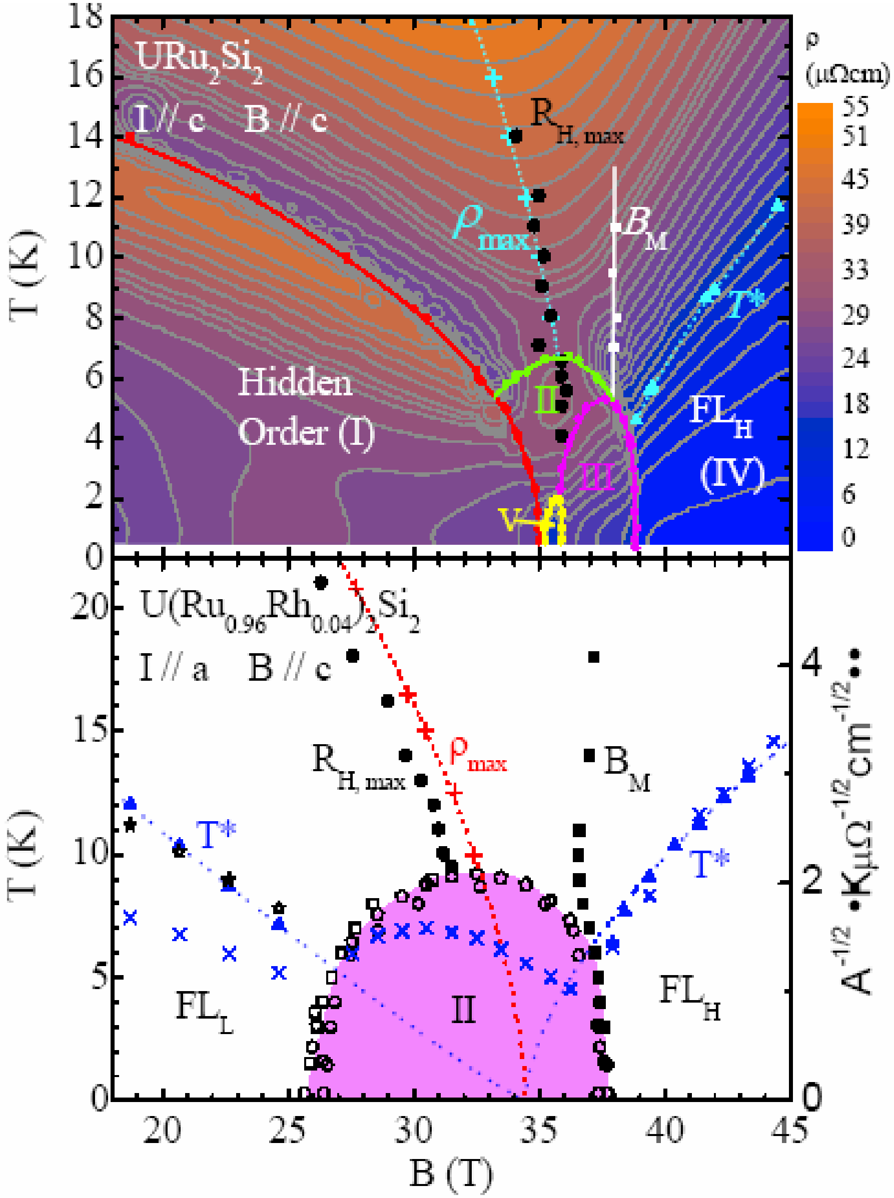

Evidence for quantum criticality occurs at at low and high magnetic fields, pointing to single quantum critical point concealed inside phase II, with scaling: $T^* \propto A^{-1/2} \propto \varepsilon_F$



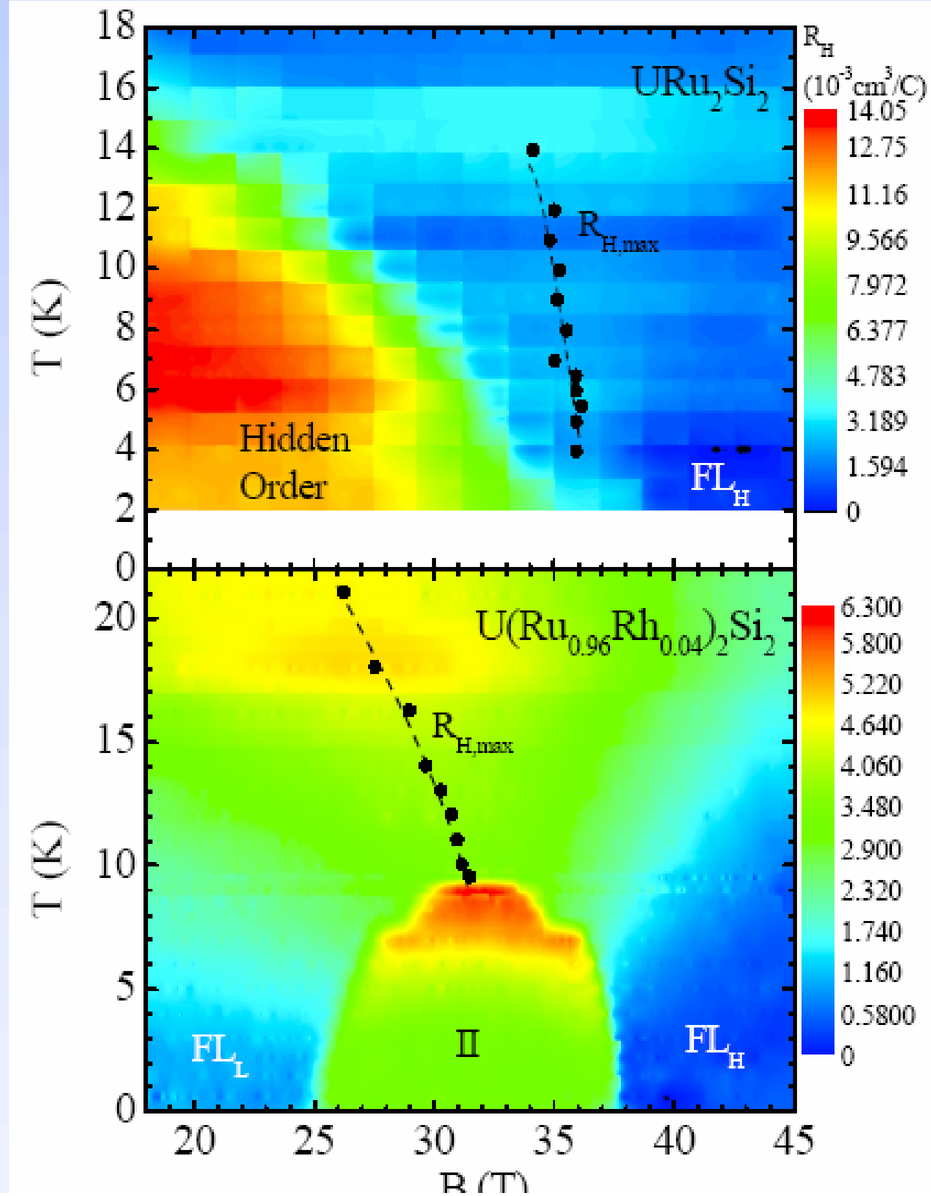

Fits of $A$ to $(B-B_M)^{\alpha}$ support divergence in $m^*$ at quantum critical point: formation of phase II leads to suppression of fluctuations



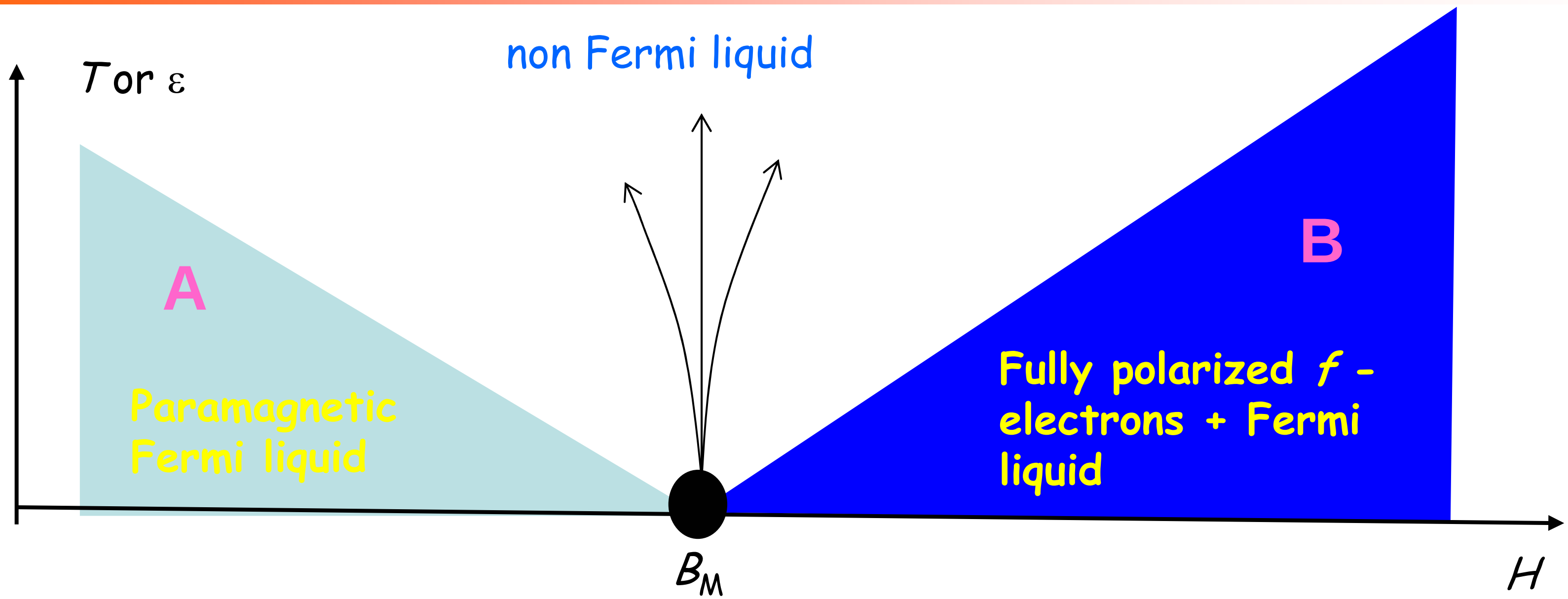

Phase II likely holds key to understanding magnetism, because it has 1/3rd of full saturated moment (neutrons should be able to detect large moment that is absent in Hidden Order phase): Ising moments imply broken translational symmetry likely




phase diagram determined from longitudinal resistance (R_xx)



# Metamagnetism and Quantum Criticality




"Transition" from Fermi surface A to Fermi surface B

Metamagnetism expected to be first order (no symmetry change?)

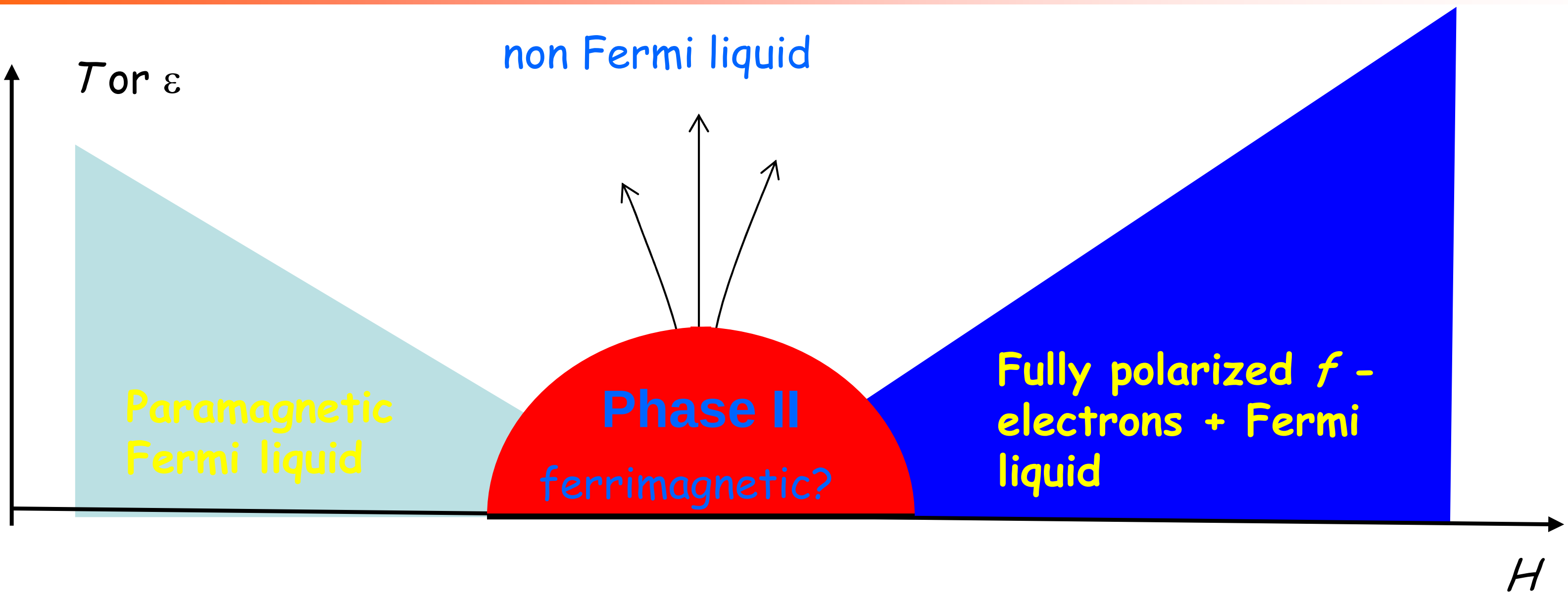
Experimentally first order transition **not** seen in itinerant electron metamagnets $CeRu_2Si_2$ or $UPt_3$ [Sakakibara et al. PRB 51,12030(1995)].

Existence of Fermi liquid at $B_M$ nevertheless quite unthinkable ?

Understanding Fermi surface topology holds the key to everything

Issue of Fermi surface change at antiferromagnetic QCP in antiferromagnetic heavy fermion systems

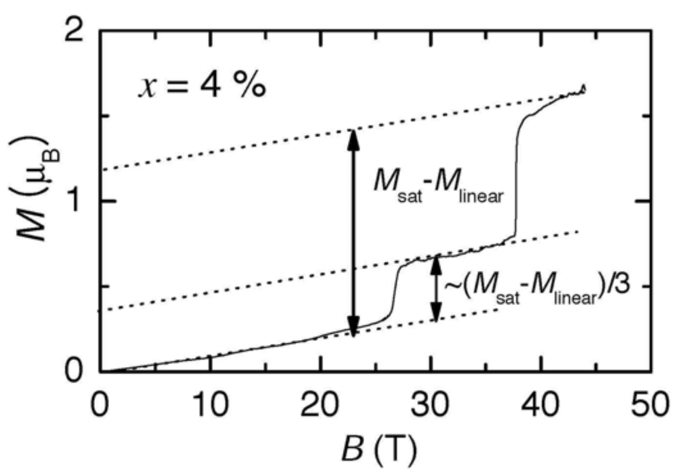
# Fermi Liquids and Quantum Criticality




Quantum critical point between two Fermi liquids: one with polarized *f*-electrons

New phase forms so as to avoid quantum critical point

Phase with 1/3rd saturated moment possibly analogous to to **Q** = 2/3**c*** ferrimagnetic phase in $UPd_2Si_2$? [Honma et al.,J.Phys.Soc.Japan 67,1017(1998)]



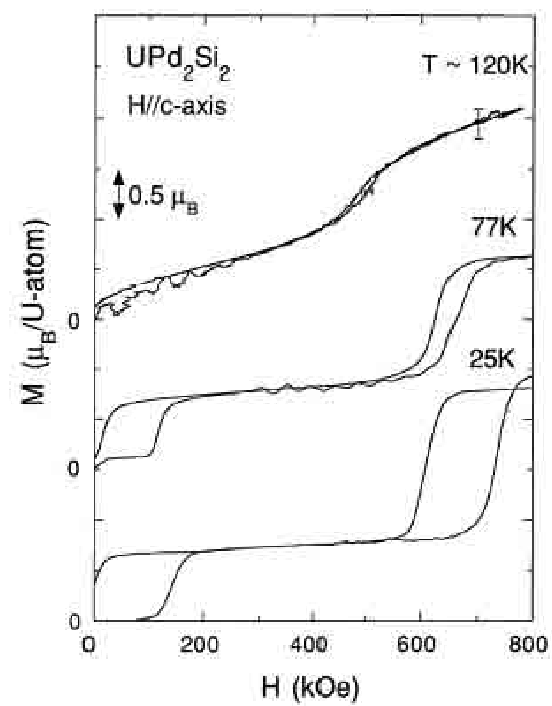
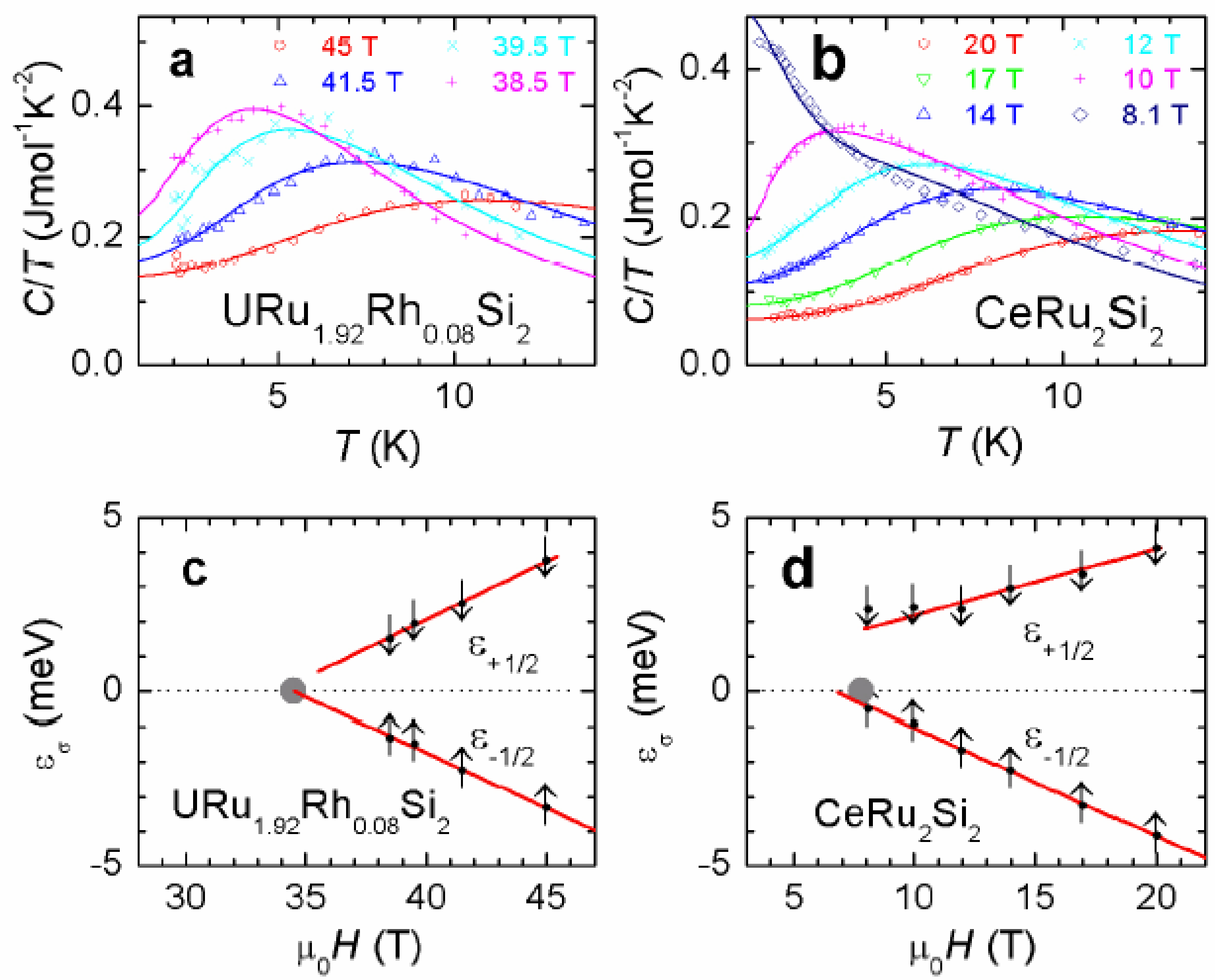



Fig. 2 of Silhanek et al




A.V.Silhanek, N.Harrison, C.D.Batista, M.Jaime, A.Lacerda, H.Amitsuka and JAM, PRL 95(2005)

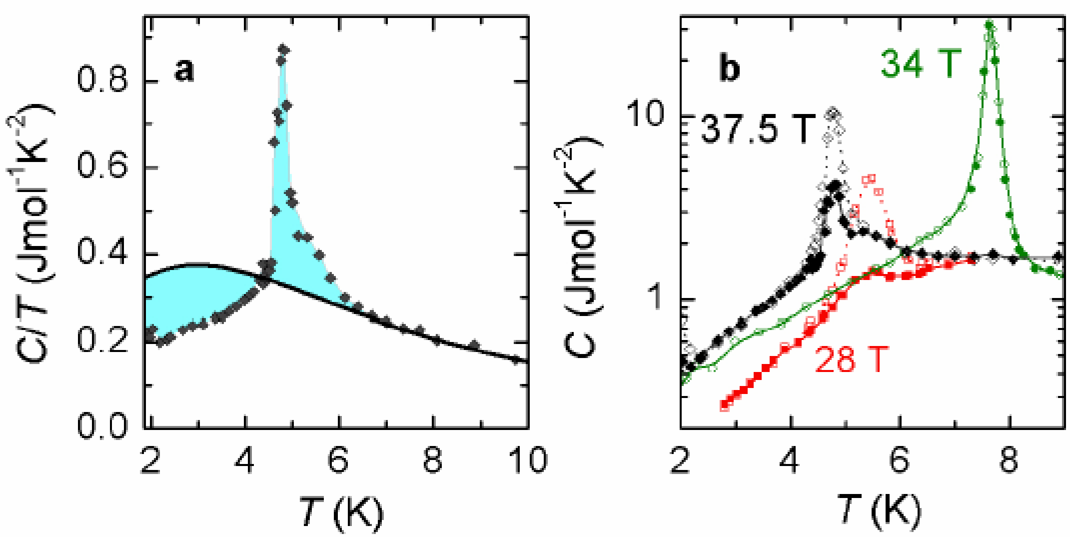
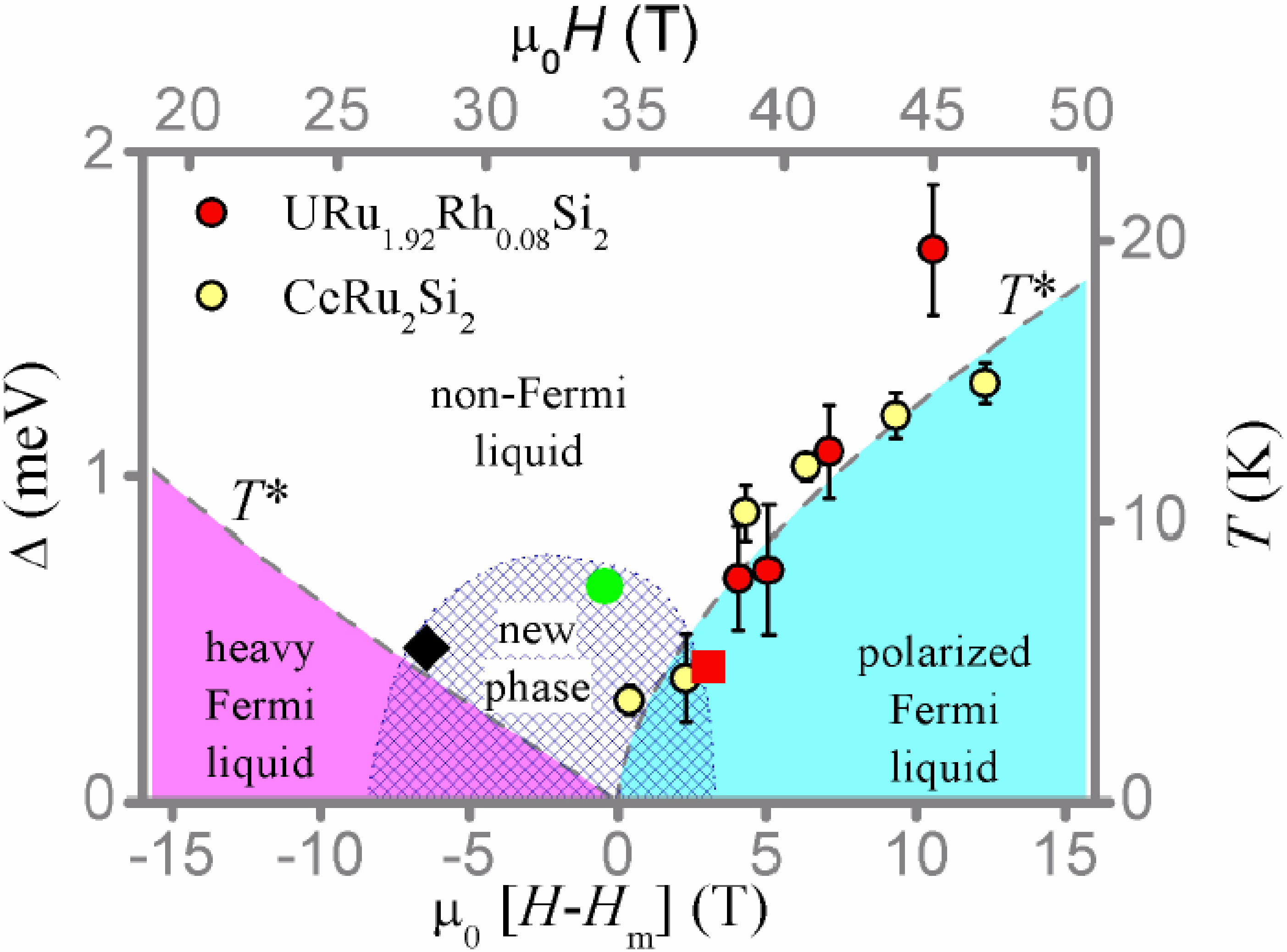
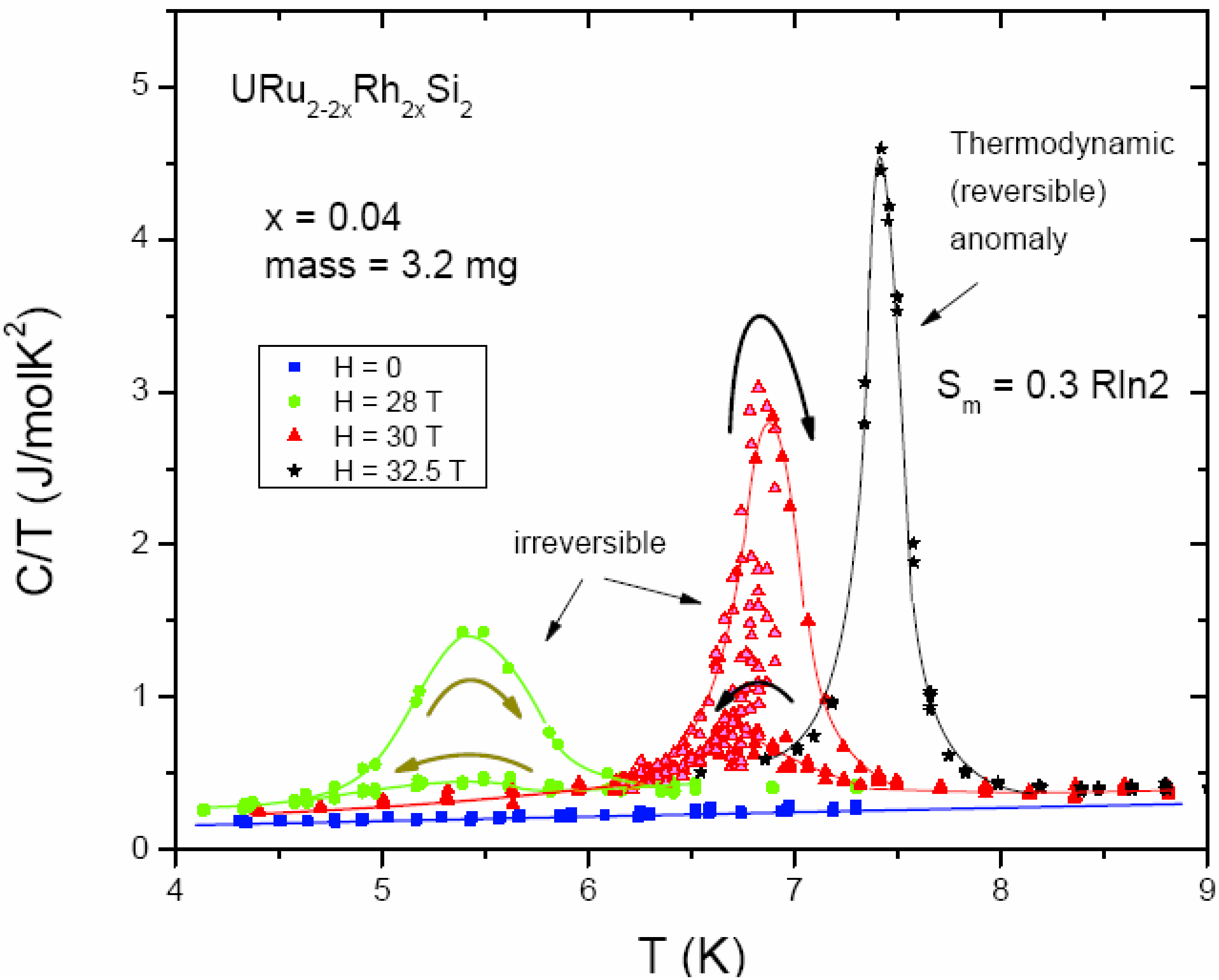


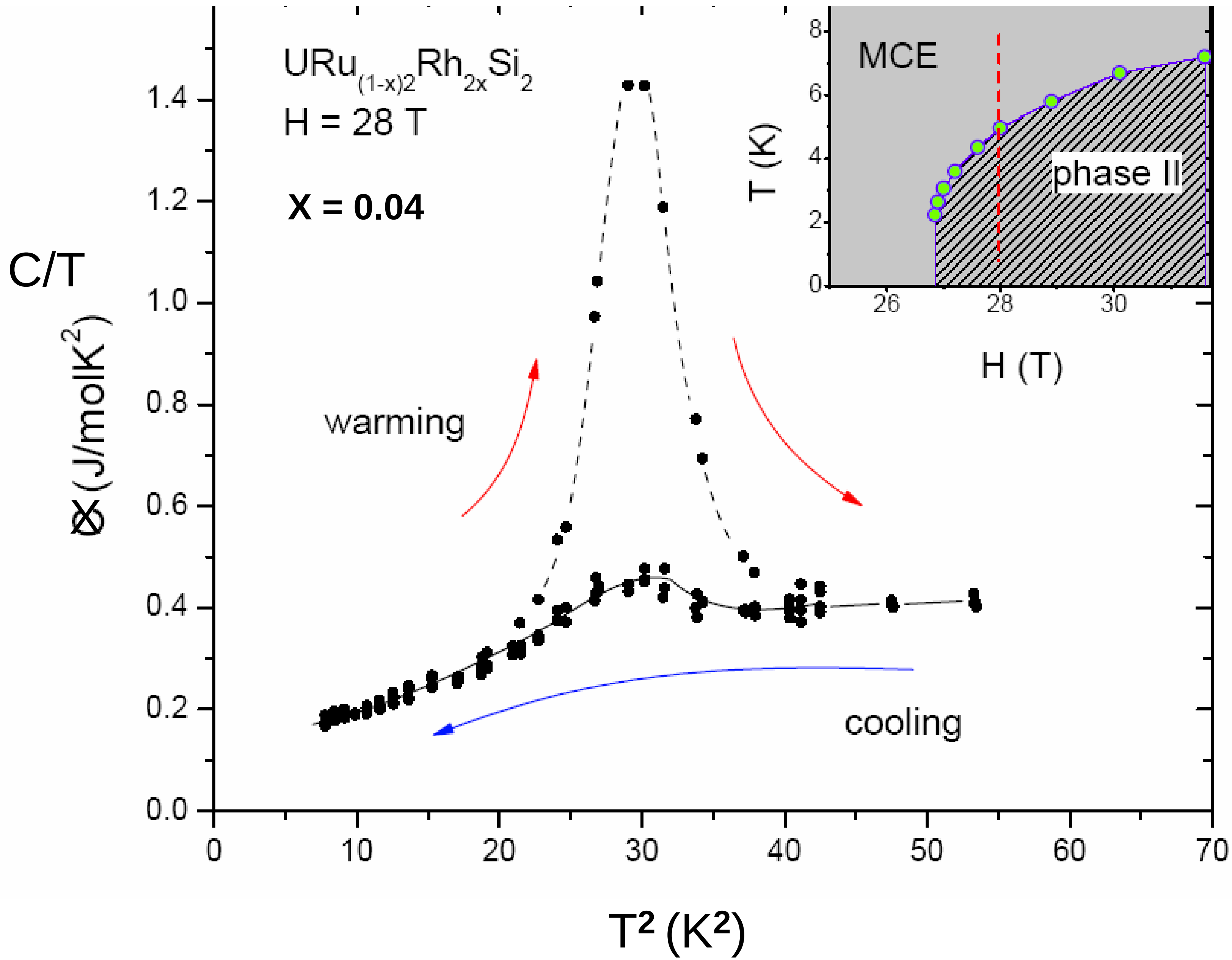

Fig. 4 of Sihanek et al.



μ0H (T)
20 25 30 35 40 45 50
2 1 0
Δ (meV)
20 10 0
T (K)
URu1.92Rh0.08Si2
CeRu2Si2
T*
T*
non-Fermi liquid
new phase
heavy Fermi liquid
polarized Fermi liquid
-15 -10 -5 0 5 10 15
μ0 [H-Hm] (T)

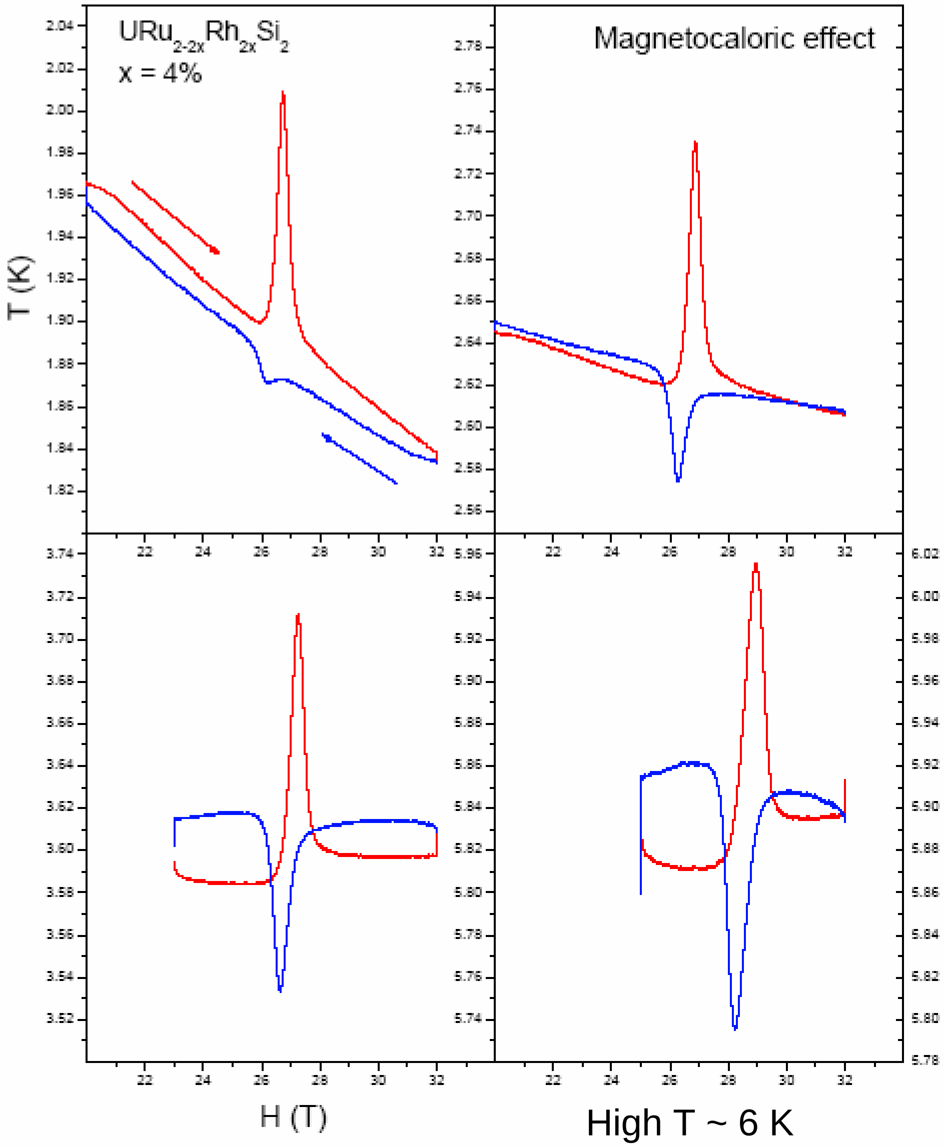


URu2-2xRh2xSi2
x = 0.04
mass = 3.2 mg
H = 0
H = 28 T
H = 30 T
H = 32.5 T
Thermodynamic
(reversible)
anomaly
Sm = 0.3 Rln2
irreversible
C/T (J/molK2)
T (K)
0
1
2
3
4
5
4
5
6
7
8
9

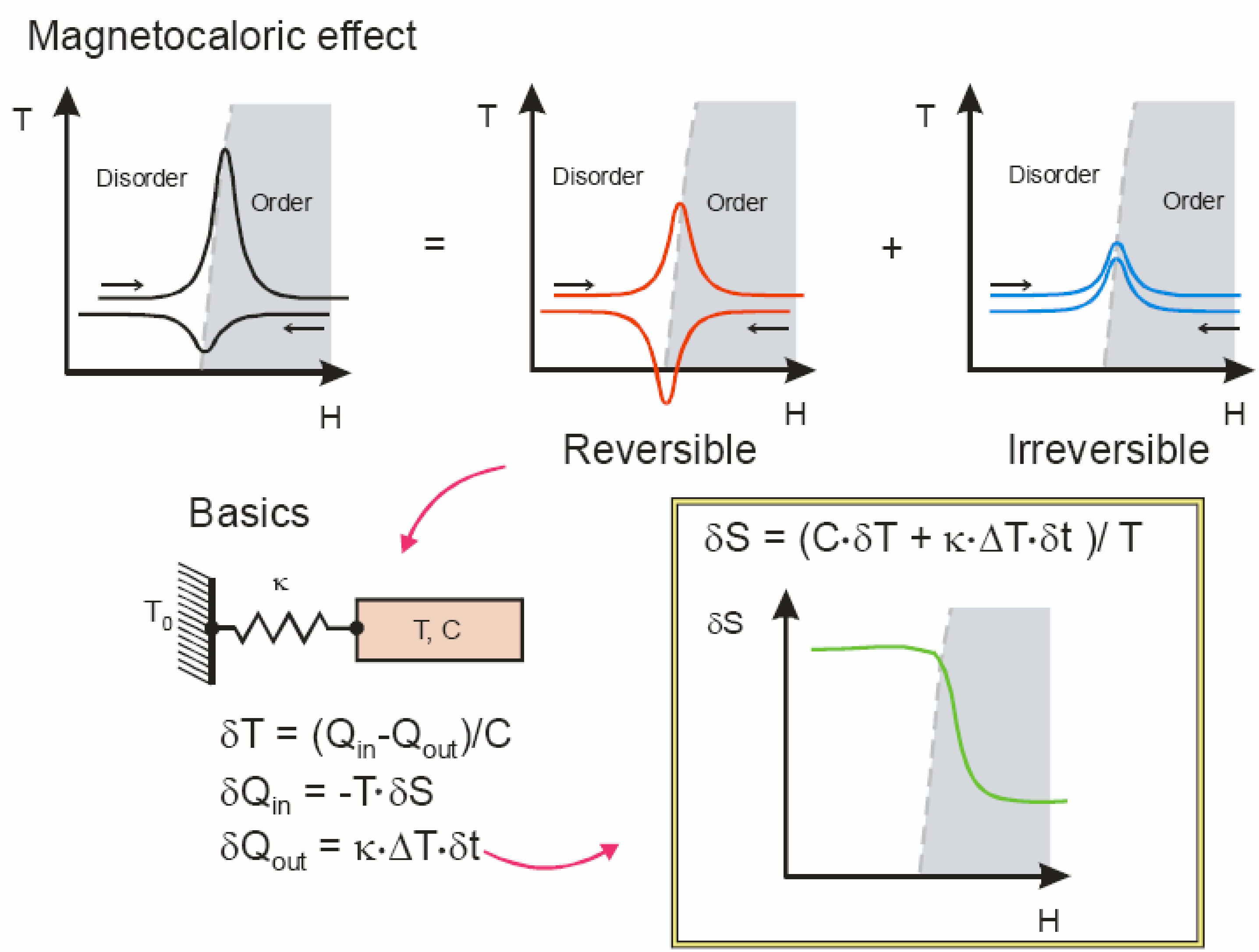


URu(1-x)2Rh2xSi2
H = 28 T
X = 0.04
C/T
(J/molK2)
warming
cooling
T2 (K2)
MCE
phase II
T (K)
H (T)

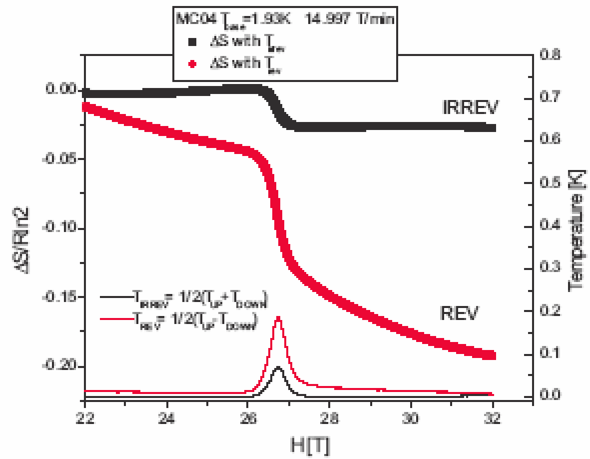
Low T ~ 2 K

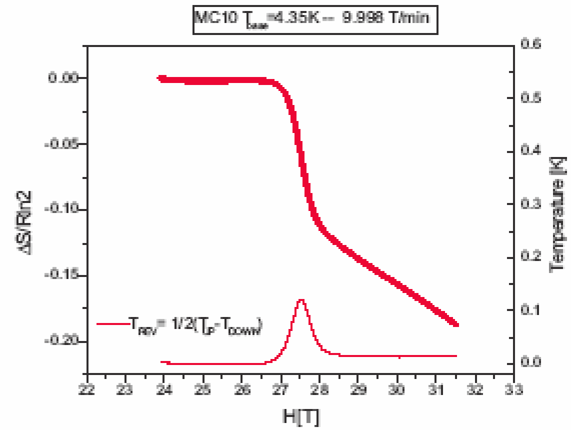


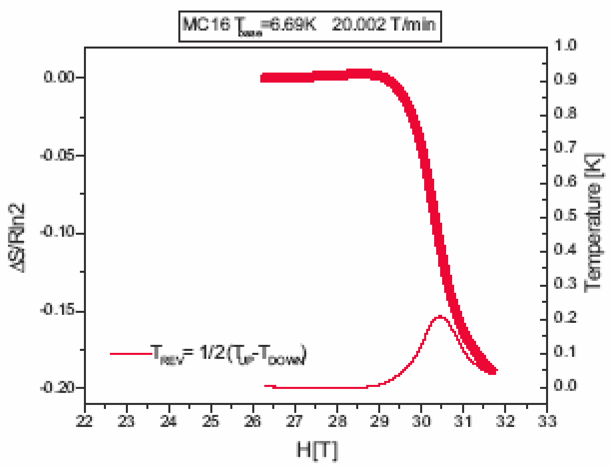

High T ~ 6 K

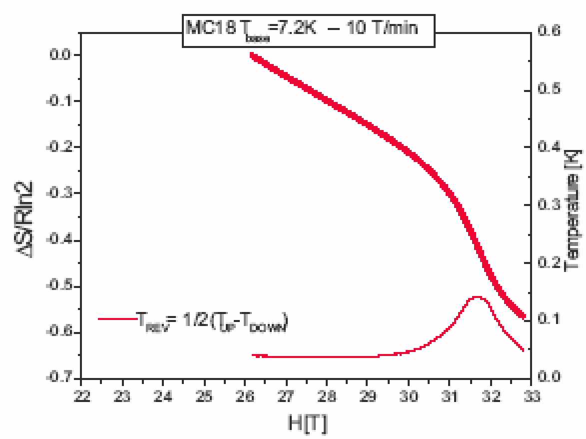


Magnetocaloric effect
T
Disorder
Order
H
=
T
Disorder
Order
H
Reversible
+
T
Disorder
Order
H
Irreversible
Basics
T0
κ
T, C
δT = (Qin-Qout)/C
δQin = -T·δS
δQout = κ·ΔT·δt
δS = (C·δT + κ·ΔT·δt )/ T
δS
H

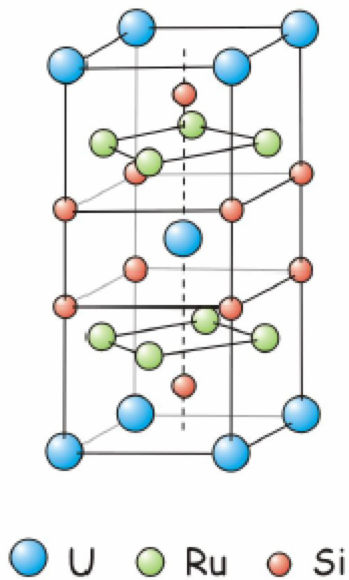

MC04 T=1.93K 14.997 T/min
ΔS with T
ΔS with T
IRREV
REV
T= 1/2(T+T)
T= 1/2(T-T)
ΔS/Rln2
Temperature [K]
H[T]


MC10 T=4.35K -- 9.998 T/min
T= 1/2(T-T)
ΔS/Rln2
Temperature [K]
H[T]

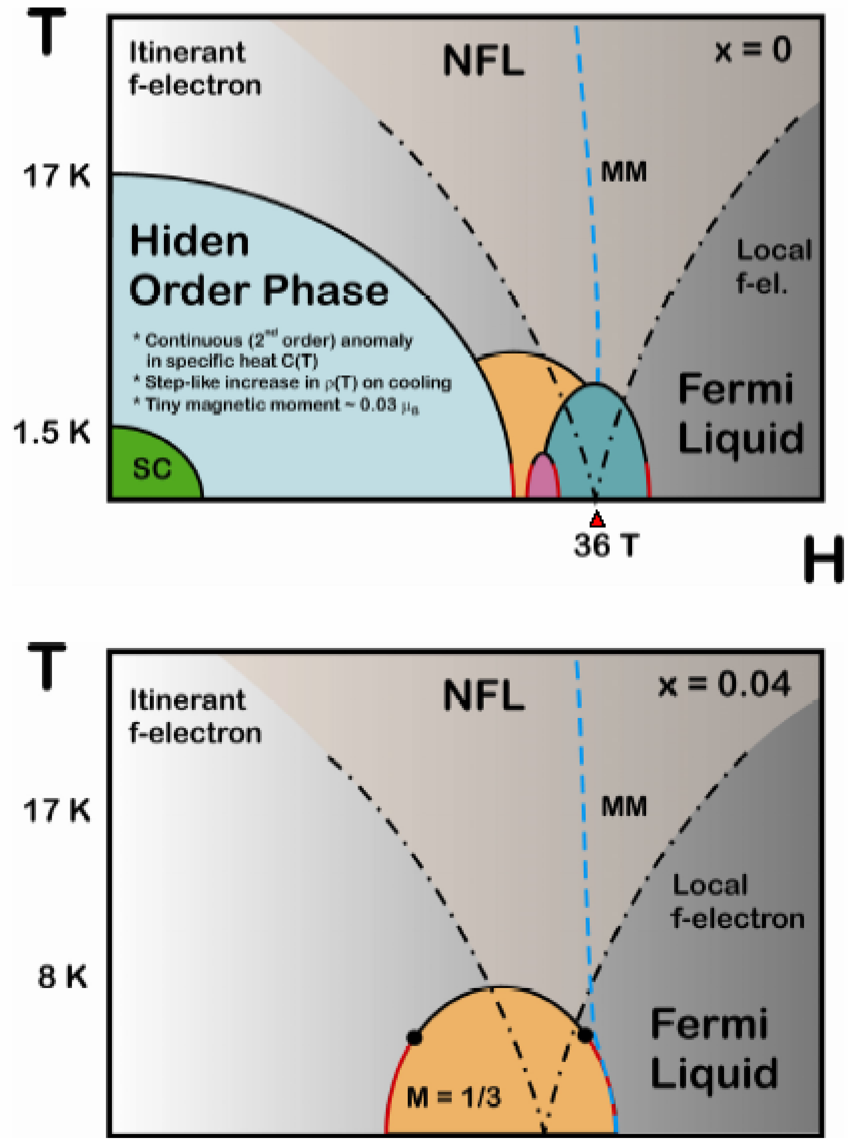

MC16 T=6.69K 20.002 T/min
T= 1/2(T-T)
ΔS/Rln2
Temperature [K]
H[T]


MC18 T=7.2K -- 10 T/min
T= 1/2(T-T)
ΔS/Rln2
Temperature [K]
H[T]

## $U(Ru_{1-x}Rh_x)_2Si_2$




Body Centered Tetragonal
a = 4.124 Å, c = 9.582 Å (4.2 K)



# Summary of Progress

1) $URu_2Si_2$ exhibits quantum critical behaviour associated with itinerant electron metamagnetism

2) Quantum criticality is involved in creation of new phase(s) at high magnetic fields

3) New phases may also help us to understand Hidden Order parameter

4) Rh doping greatly simplifies the phase diagram with a single phase II surrounded by two low temperature Fermi liquid phases

5) Phase II exhibits an enormous specific heat discontinuity indicative of a first order phase transition – tricritical points