High-field study of the heavy-fermion material URu_2Si_2

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Colloquium: Hidden order, superconductivity, and magnetism: The unsolved case of URu_2Si_2

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This Colloquium reviews the 25 year quest to understand the continuous (second-order), mean-field-like phase transition occurring at 17.5 K in URu_2Si_2. About ten years ago, the term "hidden order" (HO) was coined and has since been utilized to describe the unknown ordered state, whose origin cannot be disclosed by conventional solid-state probes, such as x rays, neutrons, or muons. The HO is able to support superconductivity at lower temperatures ($T_c \approx 1.5$ K), and when magnetism is developed with increasing pressure both the HO and the superconductivity are destroyed. Other ways of probing the HO are via Rh doping and large magnetic fields. During the last few years a variety of advanced techniques have been tested to probe the HO state and these attempts will be summarized. A digest of recent theoretical developments is also included. It is the objective of this Colloquium to shed additional light on the HO state and its associated phases in other materials.

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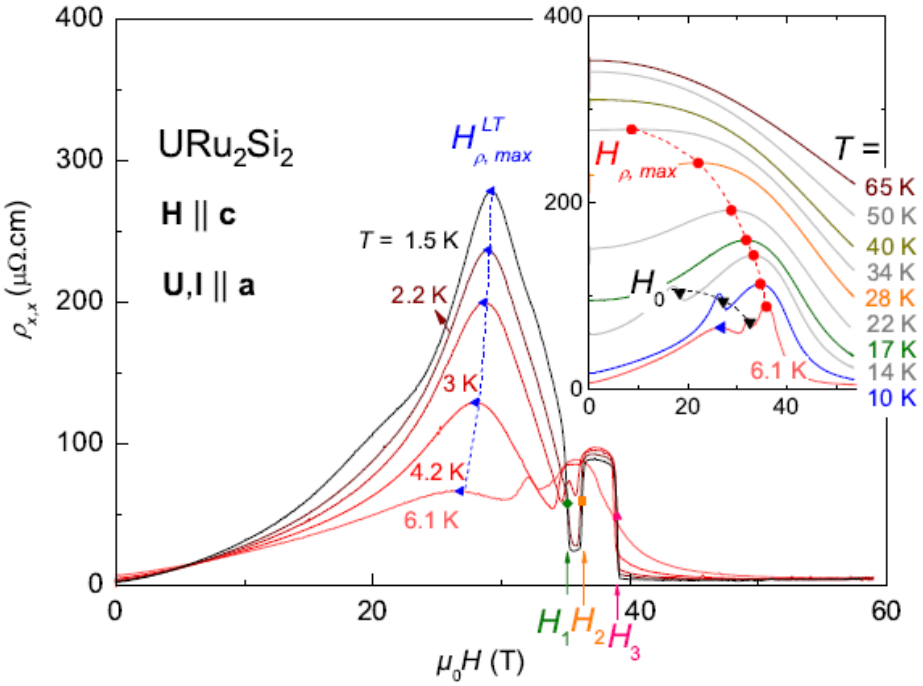
Outlook

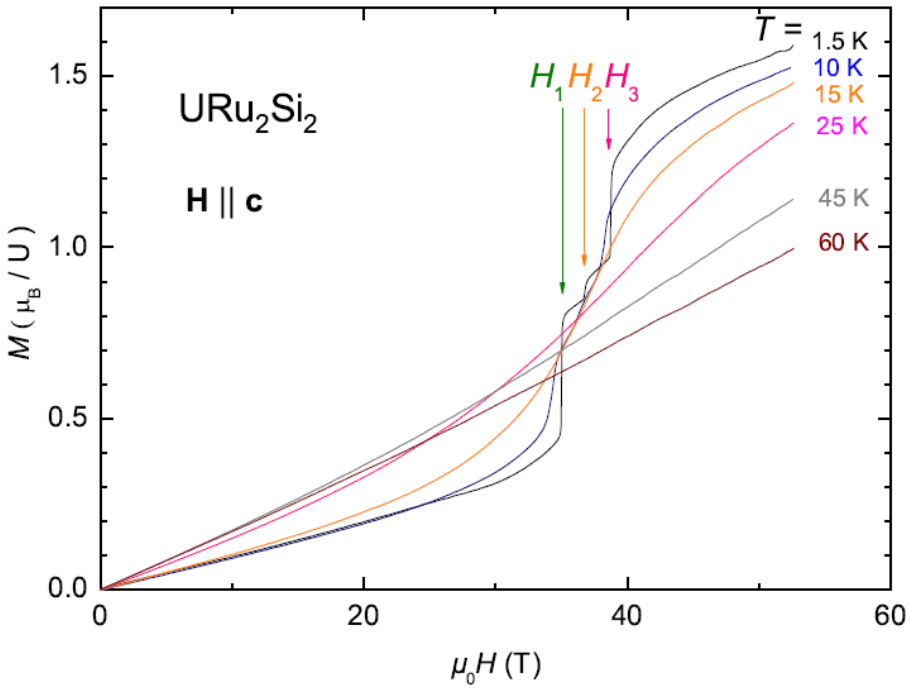
- High-Magnetic Field Properties: **H** || **c**
- (*H*,*T*)-phase diagram (**H** || **c**) of URu_2Si_2
- Angle dependence of the magnetoresistivity
- High-field quantum oscillations:

  H || **a**, up to 80 T

  H || **c**, FS modification inside the “hidden-order“

High-Magnetic Field Properties (**H** || **c**)





H_1, H_2, and H_3 : magnetic transitions

$H_{\rho,max}^{LT}$ = low-temperature crossover

H_0 = destruction of the “hidden-order” phase

$H_{\rho,max}$ = high-temperature crossover

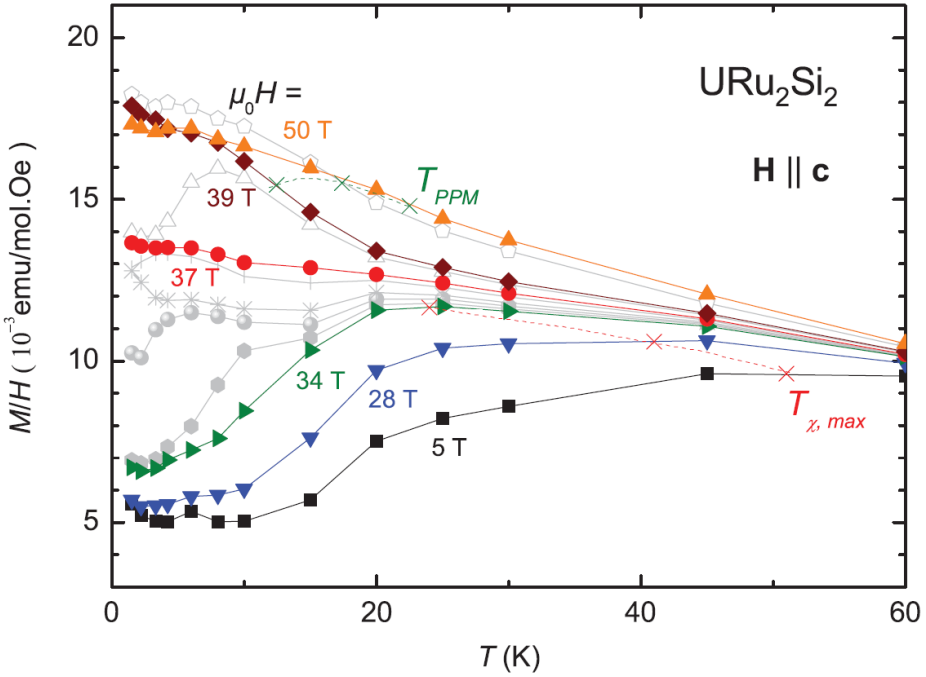
See also:

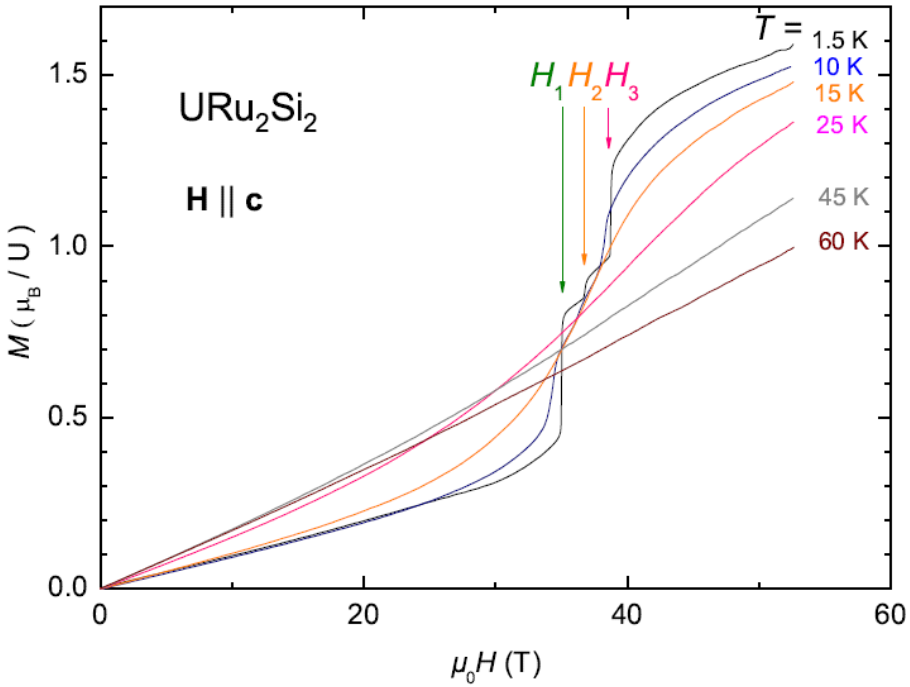
Jaime, et al., Phys. Rev. Lett. (2002)
Kim et al., Phys. Rev. Lett. (2003)
Kim et al., Phys. Rev. Lett. (2004)
Oh et al., Phys. Rev. Lett. (2007)
Jo et al., Phys. Rev. Lett. (2007)
Levallois et al., EPL (2009)

See also:

Sugiyama et al., J. Phys. Soc. Jpn. (1990)
Sugiyama et al., J. Phys. Soc. Jpn. (1999)

High-Magnetic Field Properties





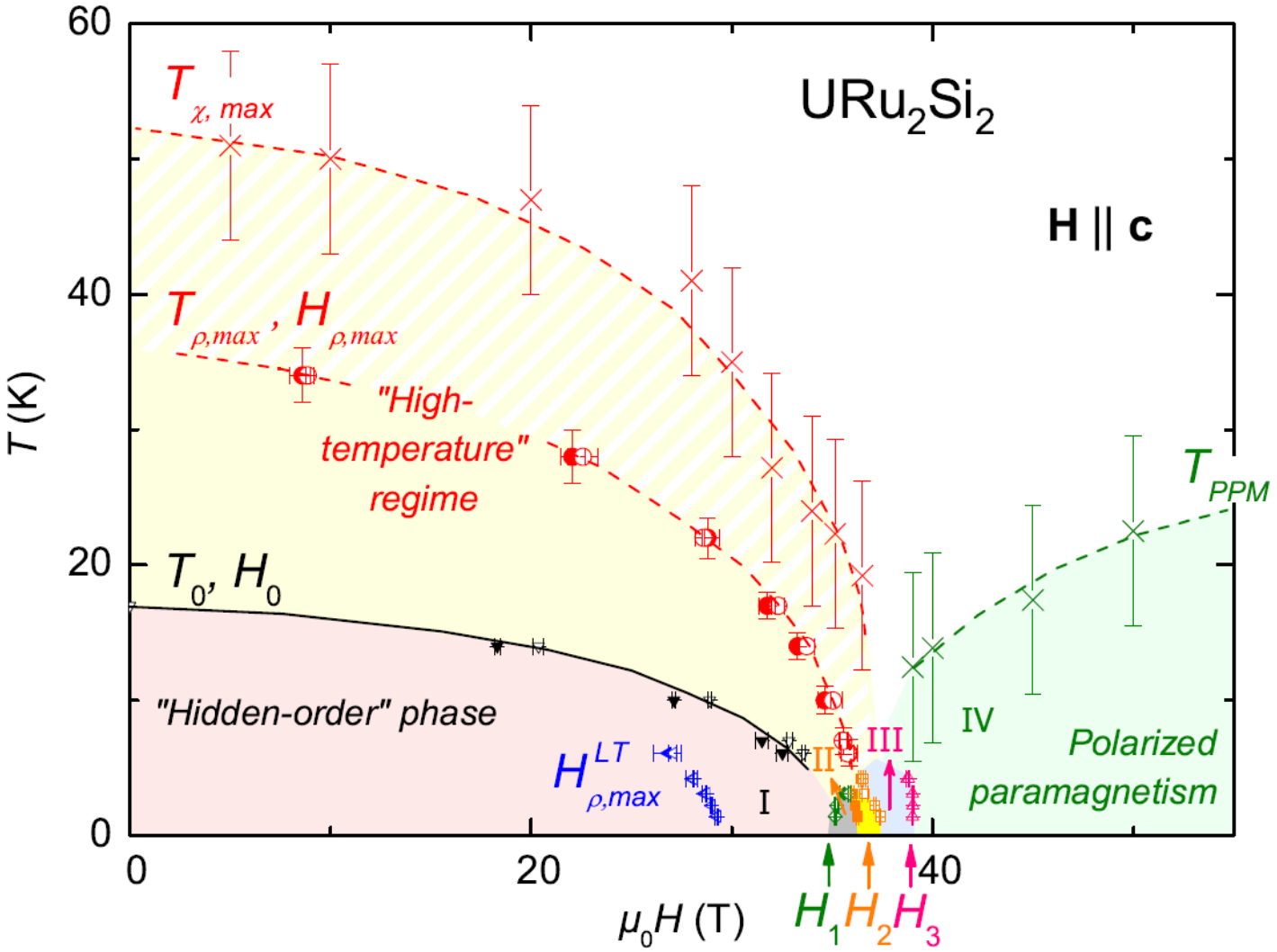
T_{PPM} = temperature scale of the polarized paramagnetic regime

$T_{\chi,max}$ = low-field crossover scale controlled by intersite electronic correlations

See also:

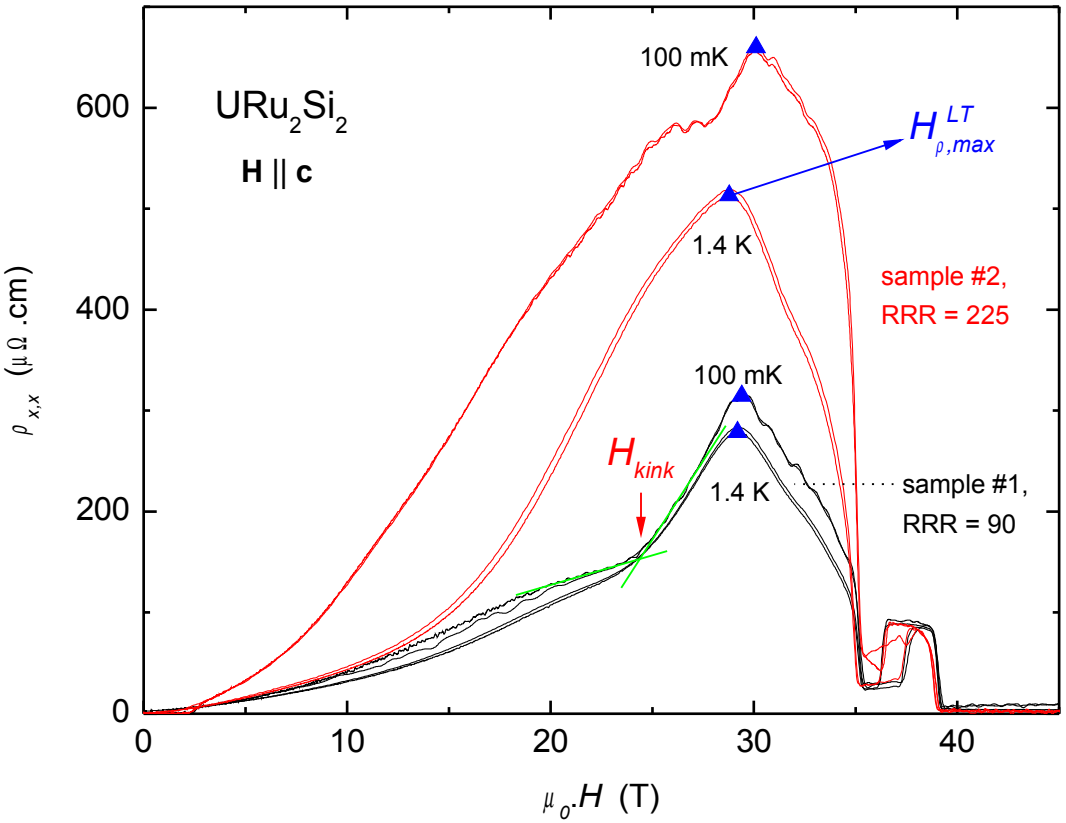
Sugiyama et al., J. Phys. Soc. Jpn. (1990)
Sugiyama et al., J. Phys. Soc. Jpn. (1999)

(*H*,*T*)-Phase Diagram



(*H*,*T*)-Phase Diagram

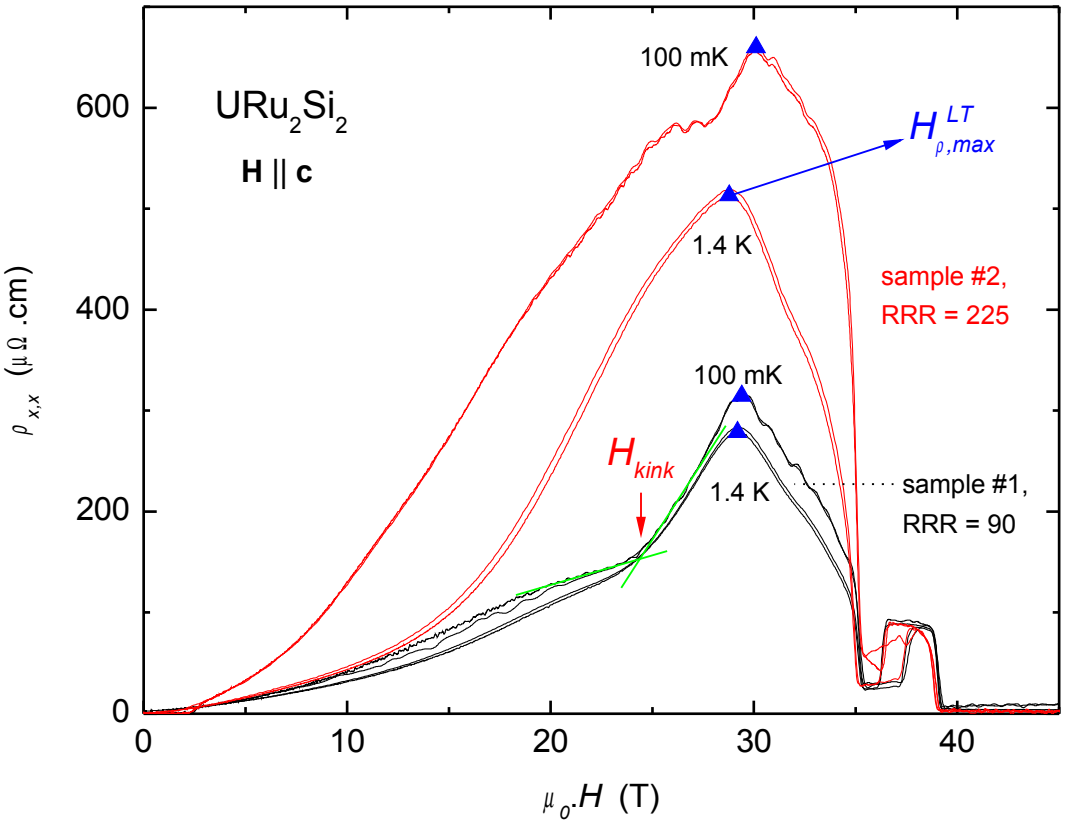
- Inside HO: magnetoresistivity governed by an orbital contribution



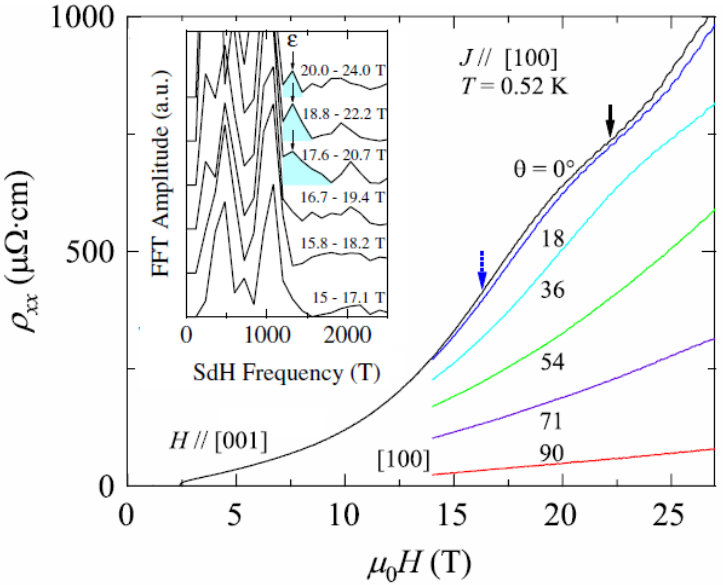
$$RRR = \left.\frac{\rho\,(300K)}{\rho\,(2K)}\right|_{0T}$$

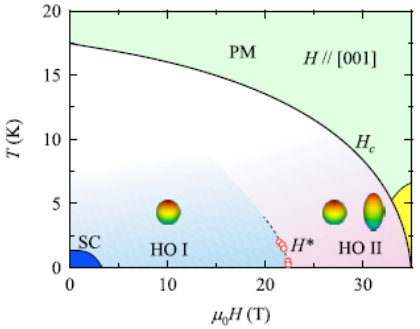
(*H*,*T*)-Phase Diagram

- Inside HO: magnetoresistivity governed by an orbital contribution
  - Anomaly at 23 T?



[Shishido et al., Phys. Rev. Let. (2009)]





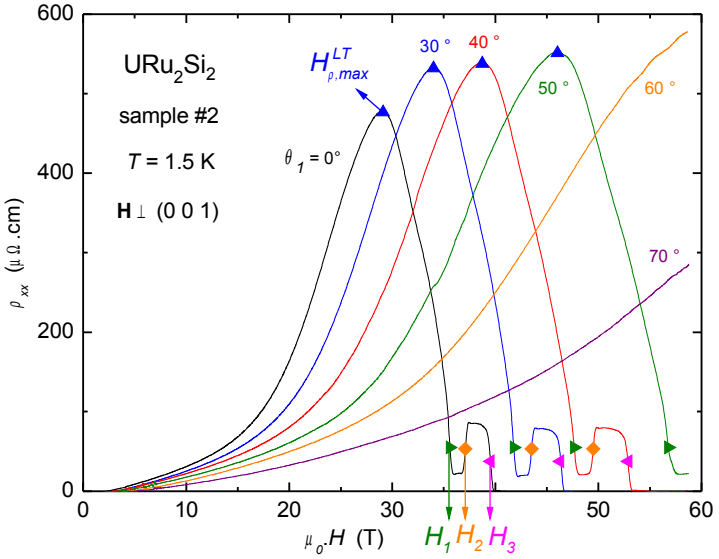
See also:

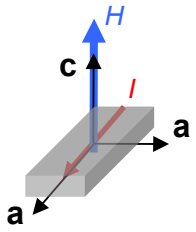
Malone et al., Phys. Rev. B (2011)

Angular dependence of the magnetoresistivity

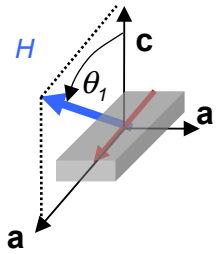
I) **H || c** → **H || a**

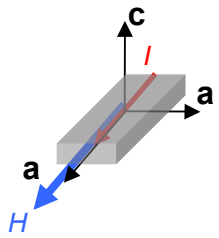
transverse → longitudinal





H ⊥ U,I





H || U,I

See also:
Sugiyama et al., J. Phys. Soc. Jpn. (1990)
Jo et al., Phys. Rev. Lett. (2007)

Angular dependence of the magnetoresistivity

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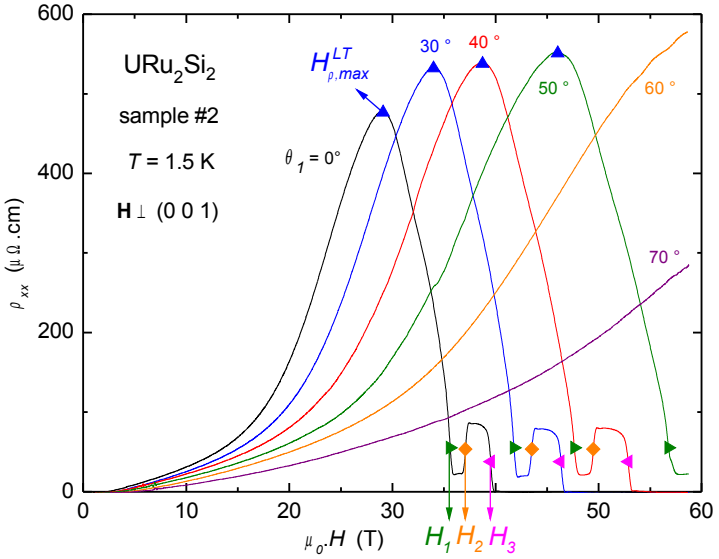
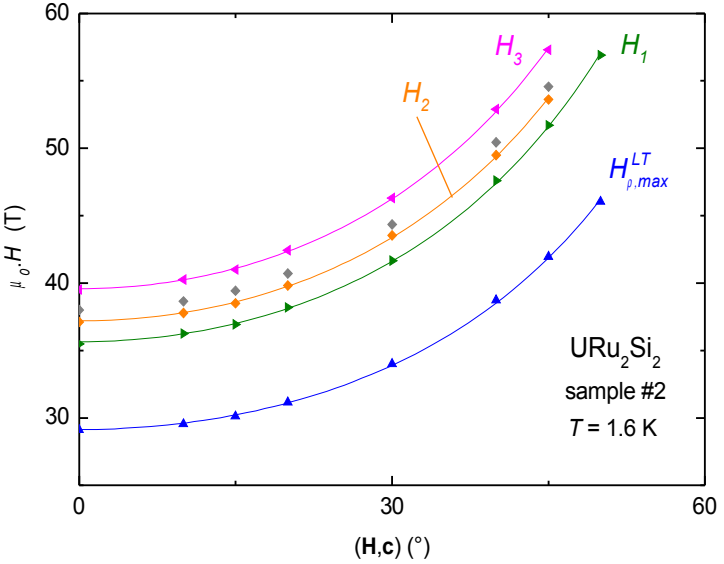




H_1, H_2, H_3, H_{max}^{LT} follow a

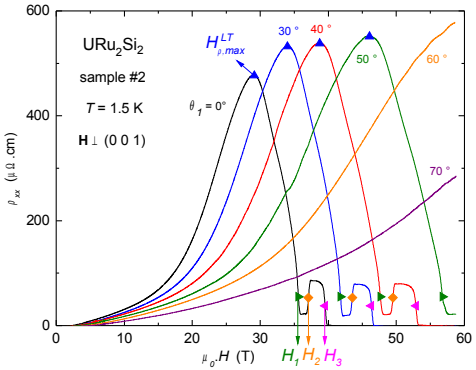
1 / cos θ law !

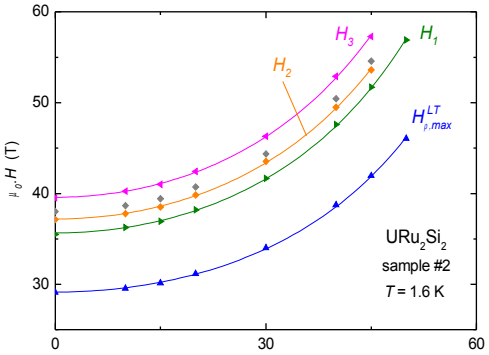
See also:
Sugiyama et al., J. Phys. Soc. Jpn. (1990)
Jo et al., Phys. Rev. Lett. (2007)

Angular dependence of the magnetoresistivity

I) **H || c → H || a**

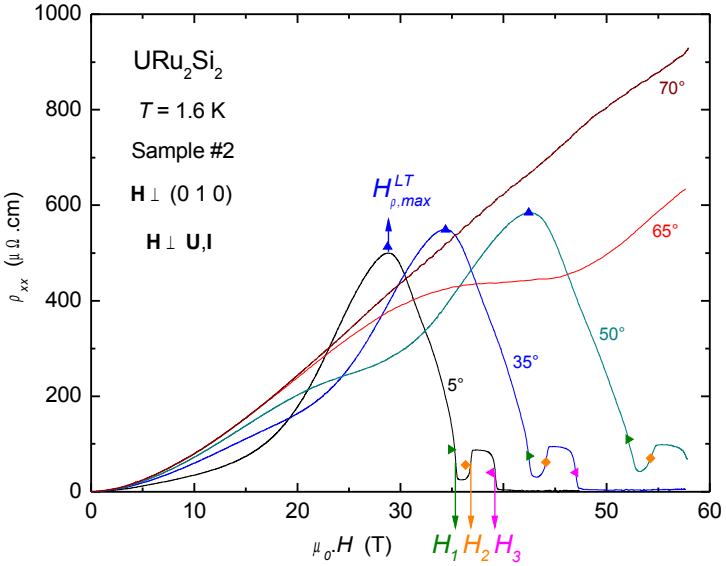
transverse → longitudinal

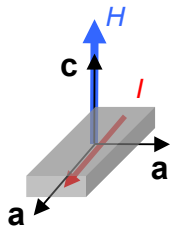




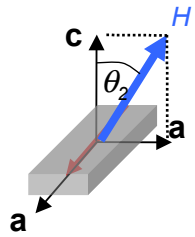
II) **H || c → H || a**

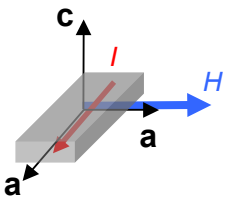
transverse → transverse





H ⊥ U,I





H ⊥ U,I

Angular dependence of the magnetoresistivity

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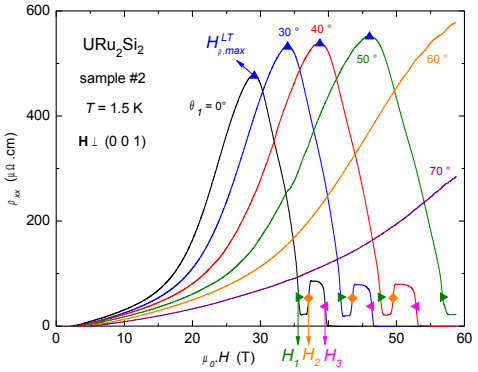
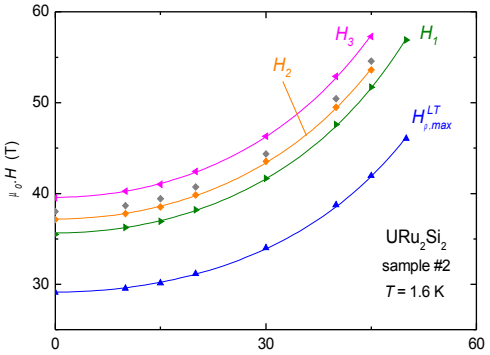
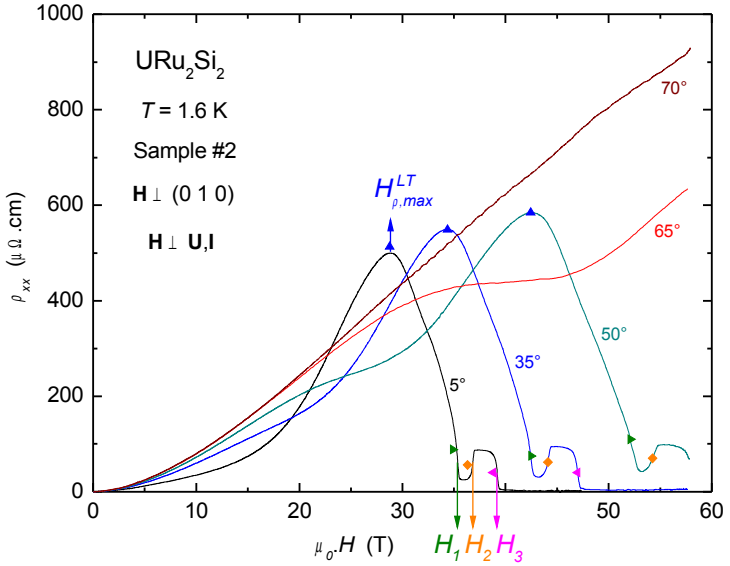
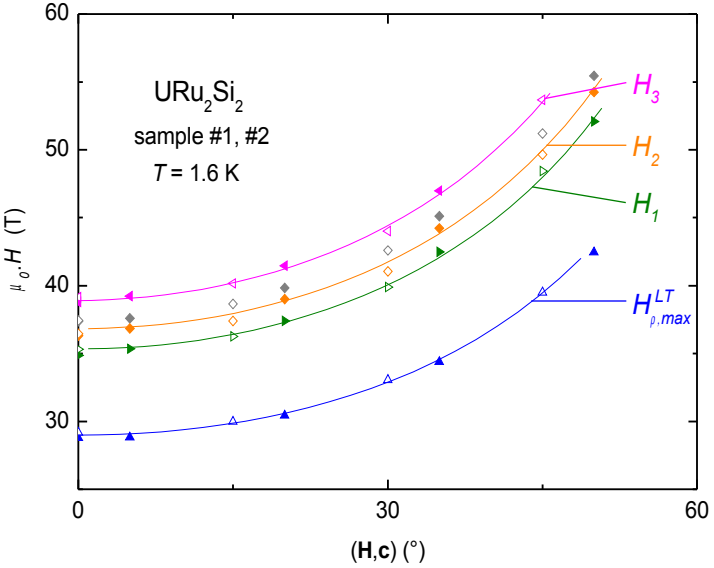




II) **H || c → H || a**

transverse → transverse





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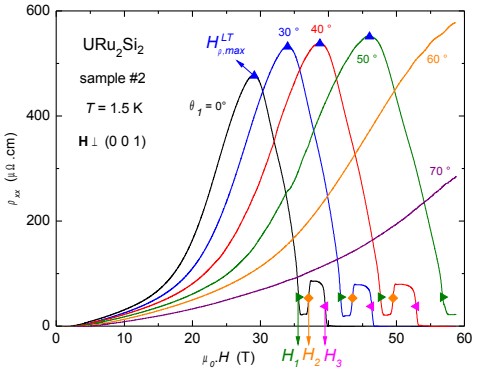
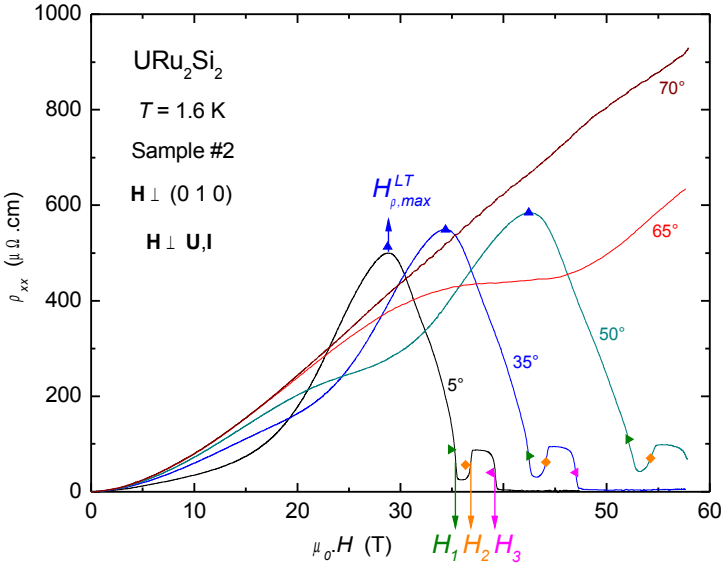
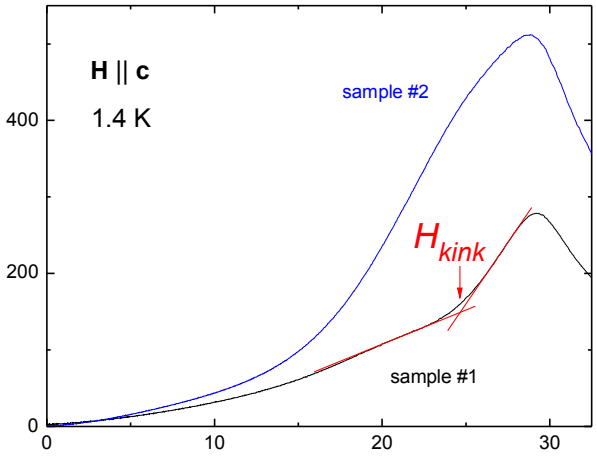


II) **H || c** → **H || a**

transverse → transverse





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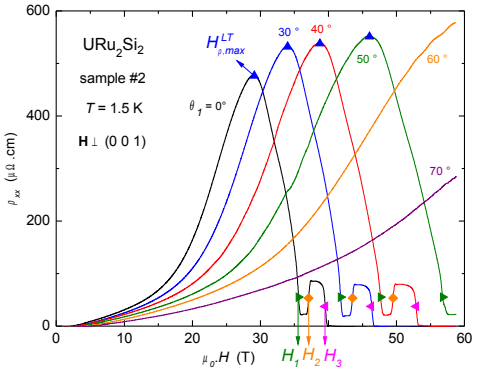
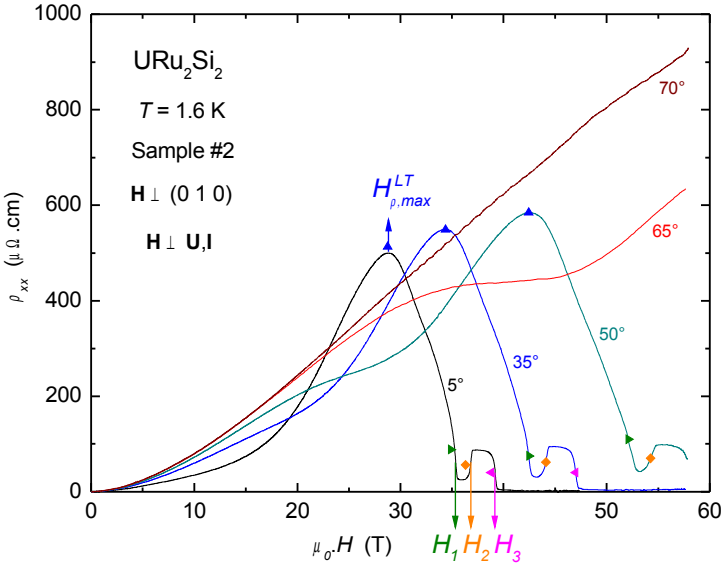
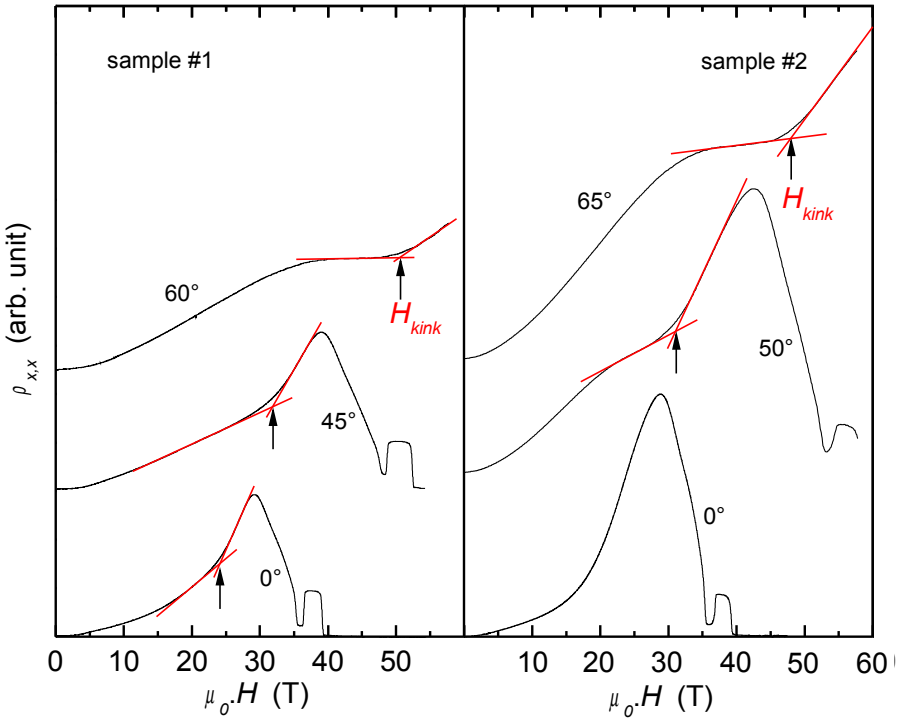


II) **H || c → H || a**

transverse → transverse





Angular dependence of the magnetoresistivity

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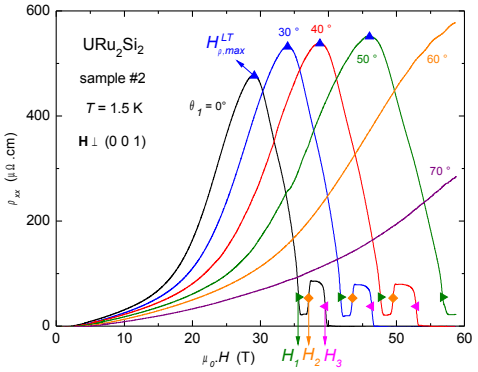
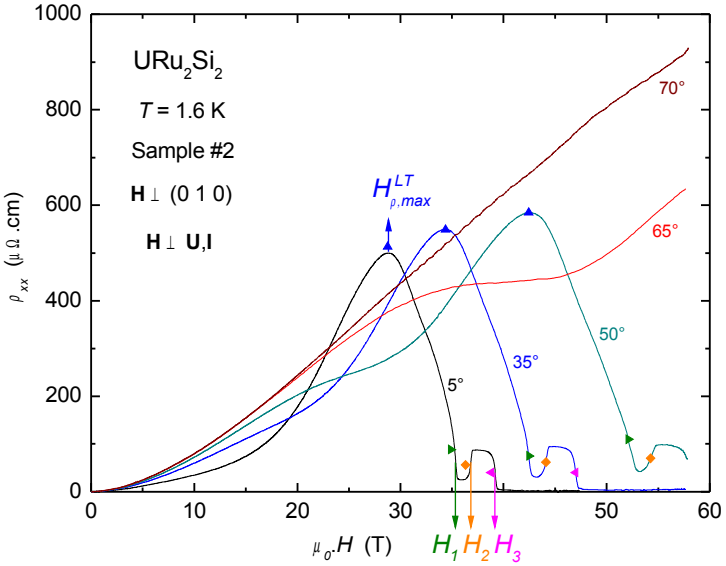
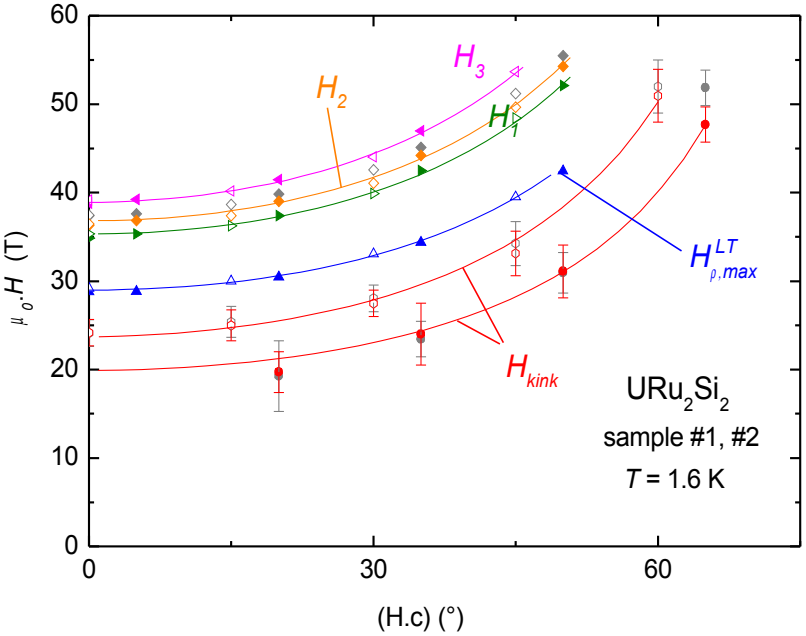


II) **H || c → H || a**

transverse → transverse

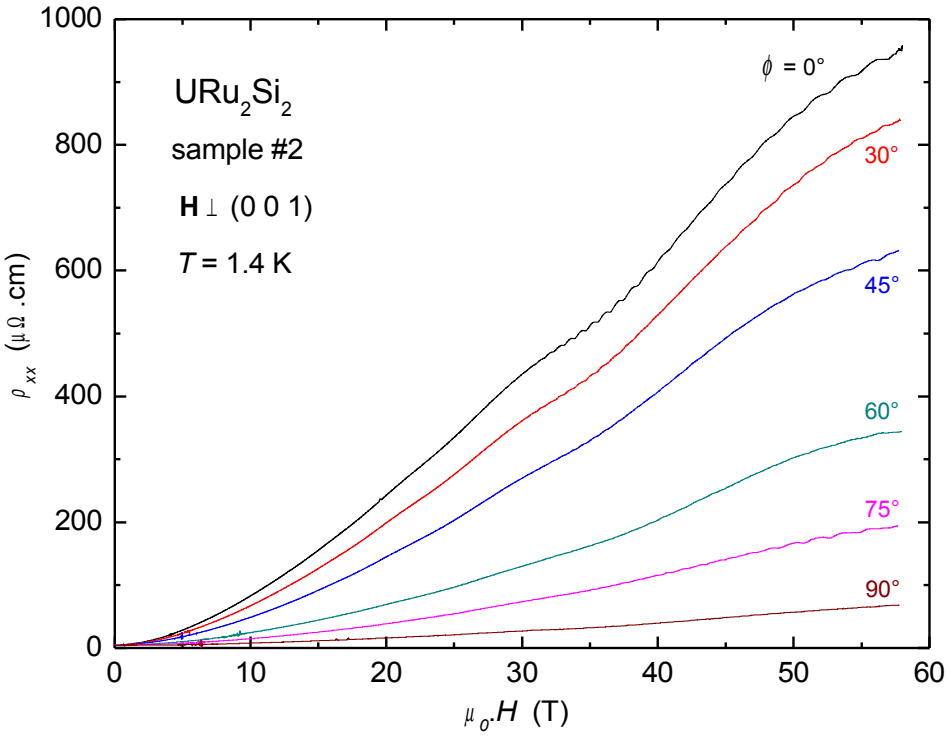


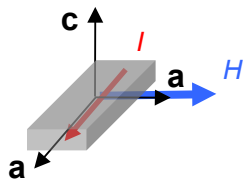


Angular dependence of the magnetoresistivity

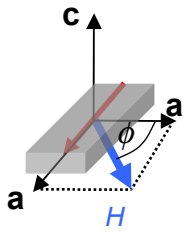
III) **H || a** → **H || a**

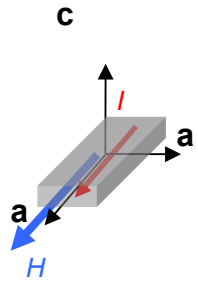
transverse → longitudinal





H ⊥ U,I



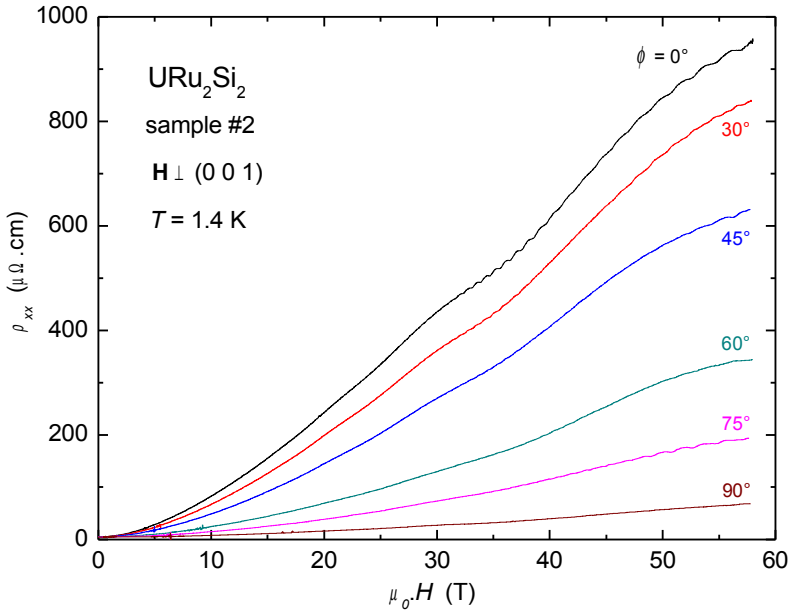


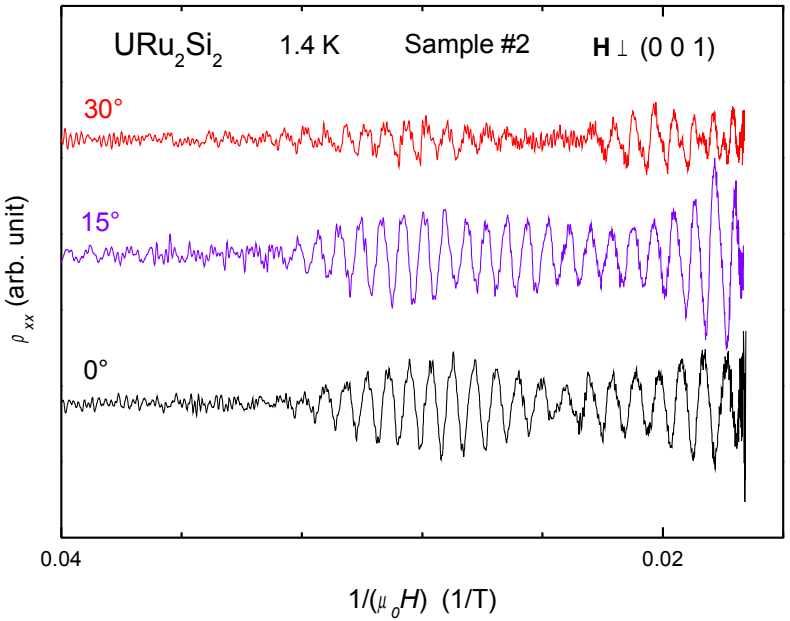
H || U,I

Angular dependence of the magnetoresistivity

III) **H** || **a** → **H** || **a**

transverse → longitudinal





Angular dependence of the magnetoresistivity

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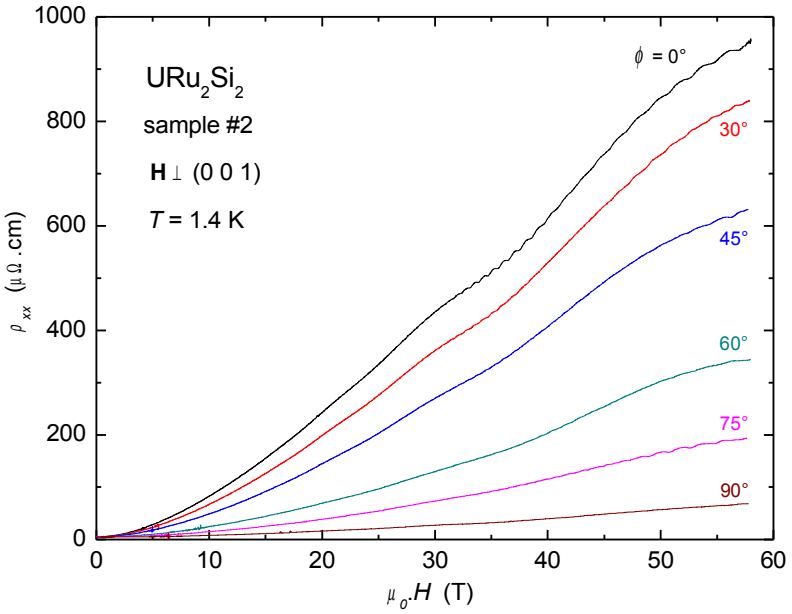
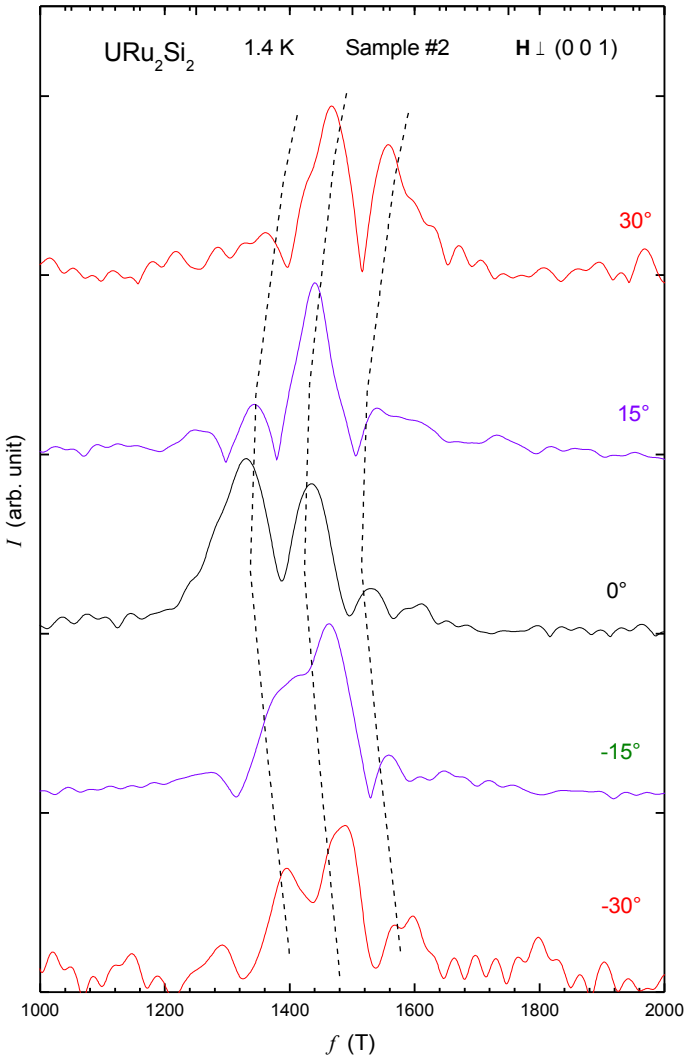
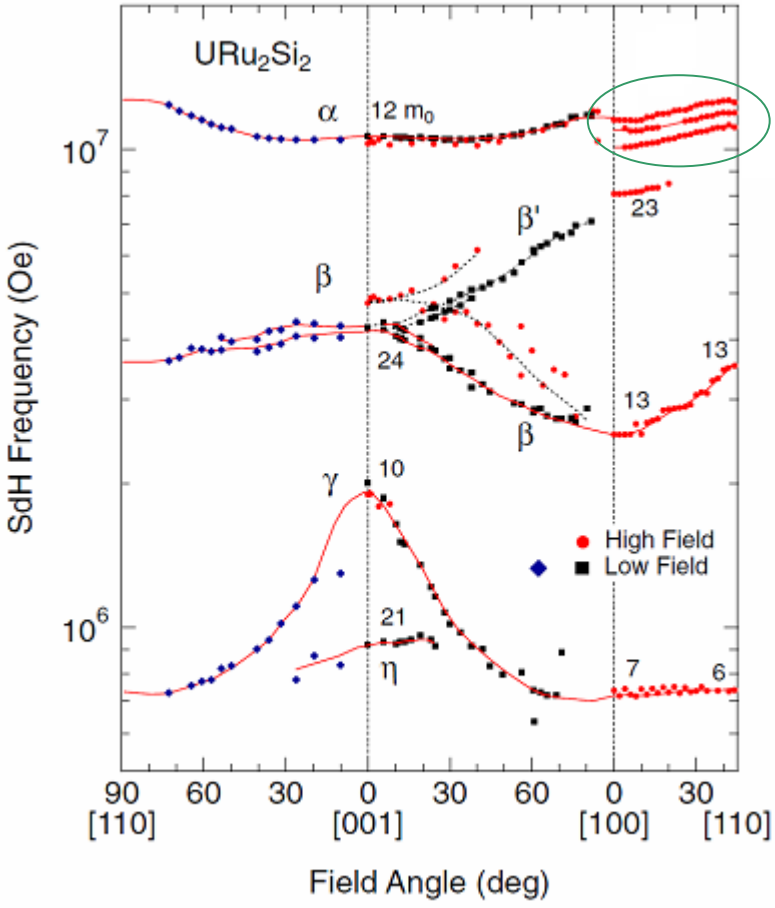
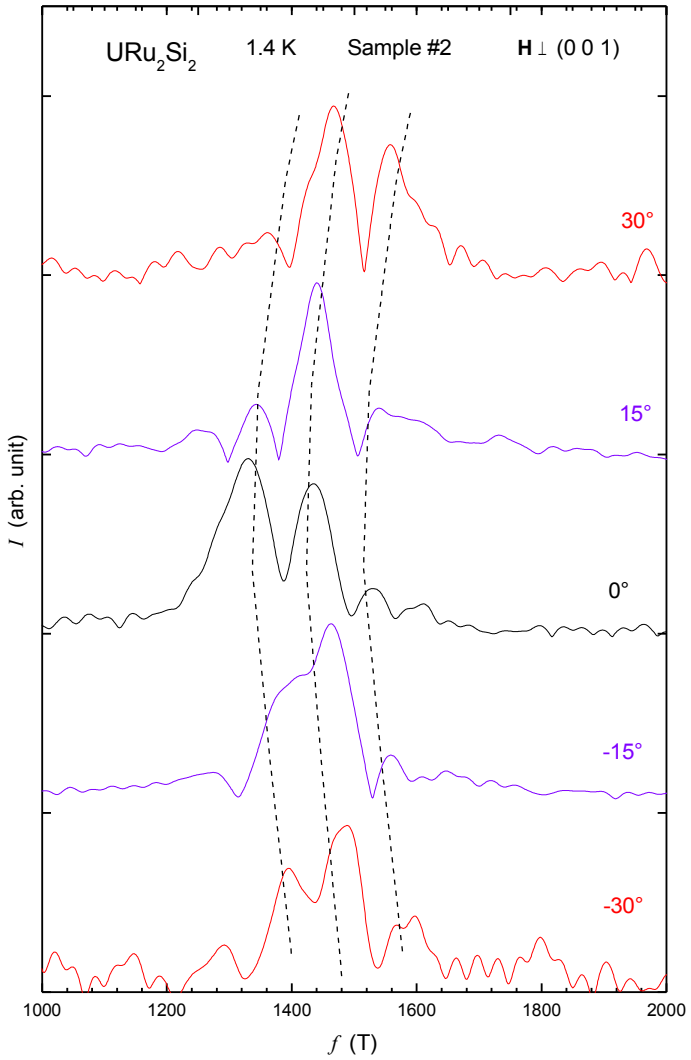




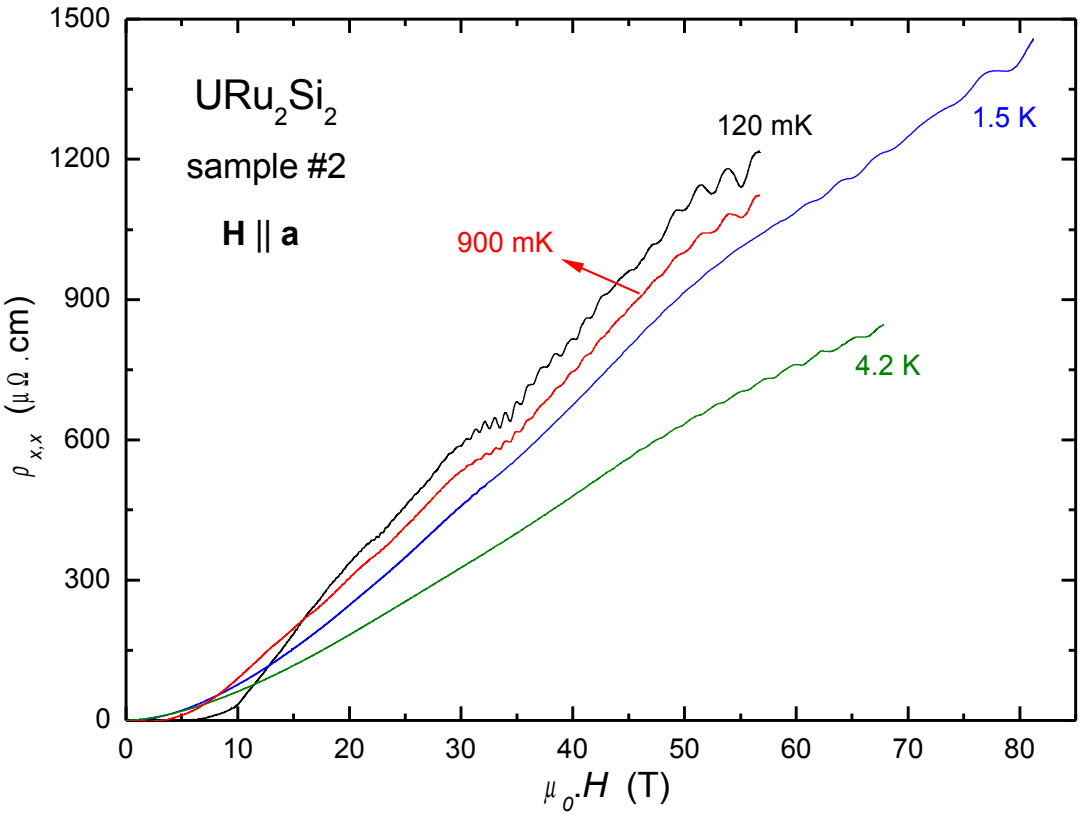
Angular dependence of the magnetoresistivity



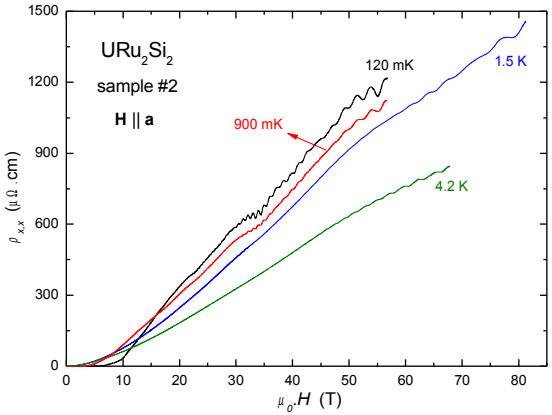
[Aoki et al., J. Phy. Soc. Jpn. (2012)]

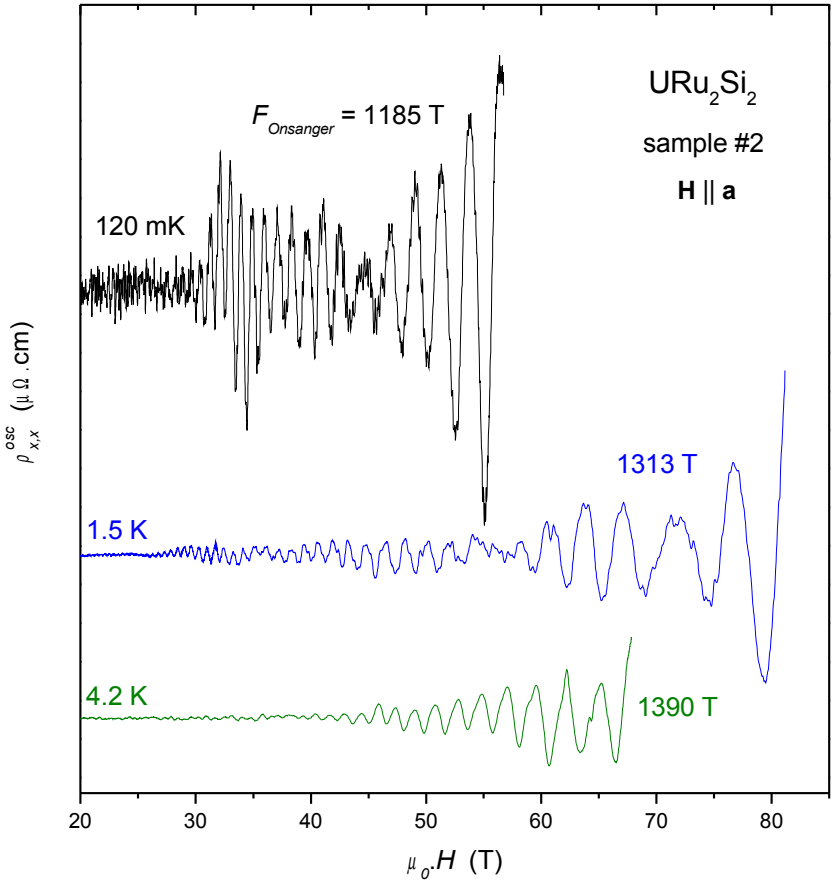


Quantum Oscillations: **H** || **a**

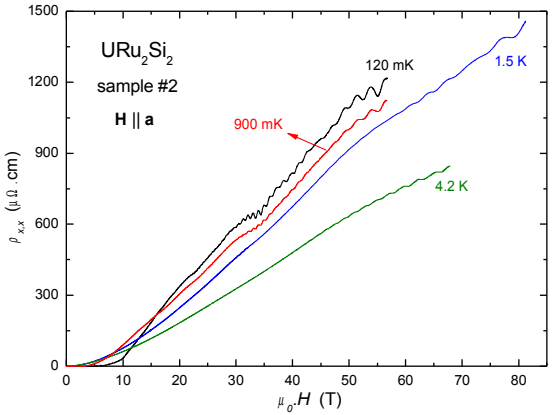


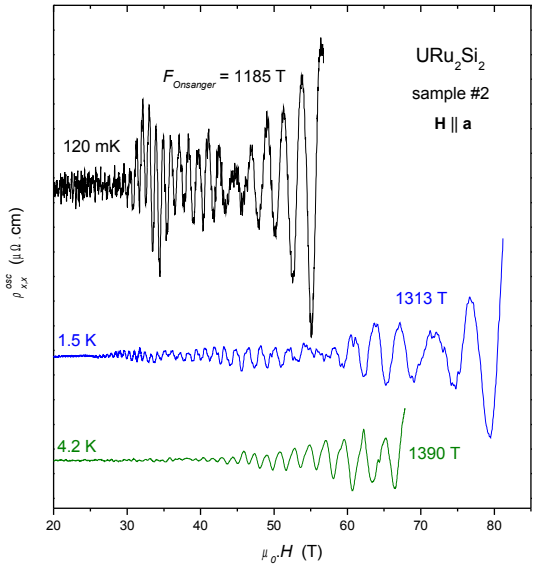
Quantum Oscillations: **H** || **a**

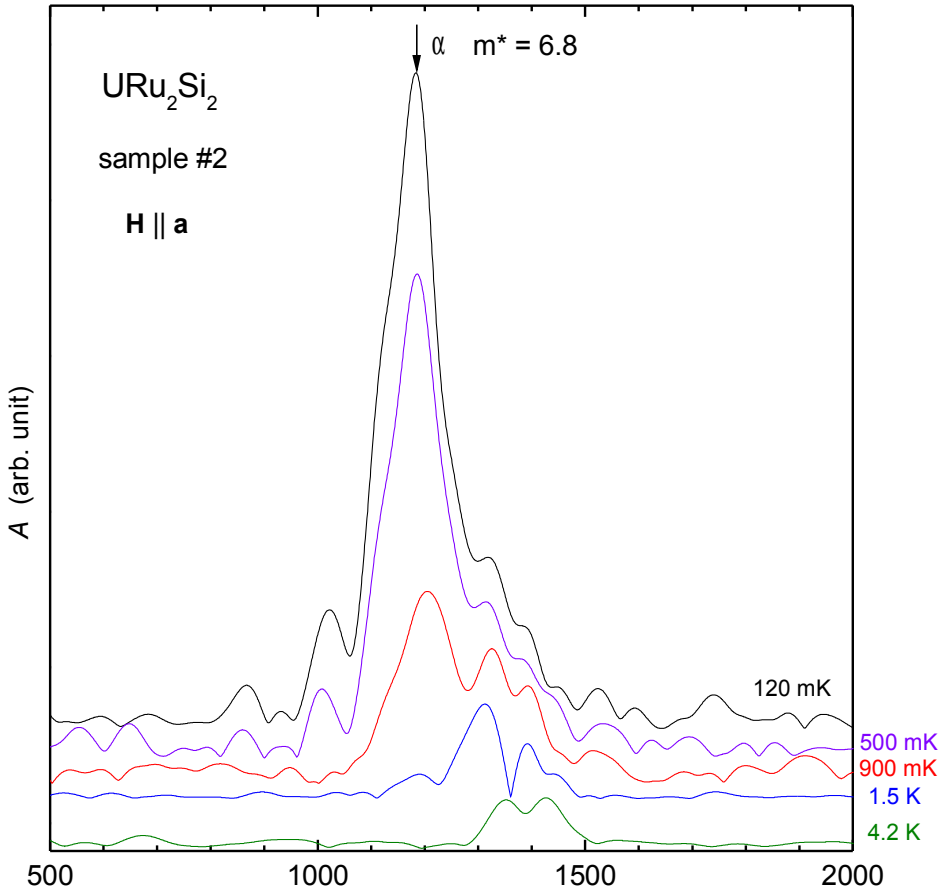




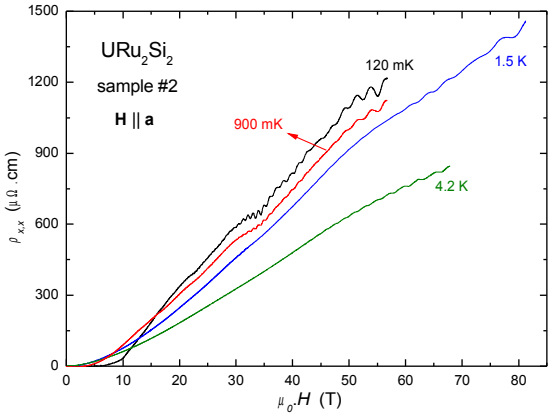
Quantum Oscillations: **H || a**

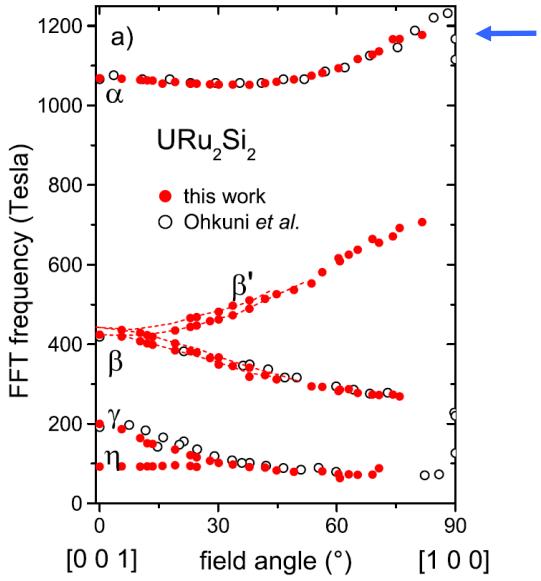




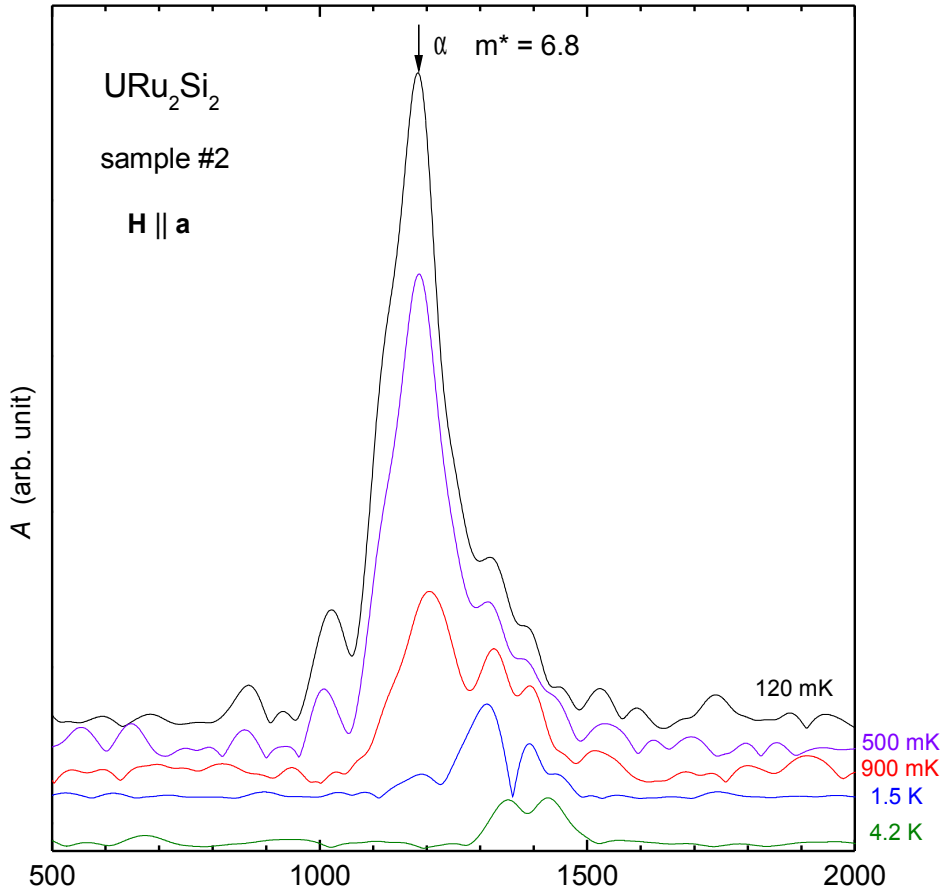


Quantum Oscillations: **H || a**

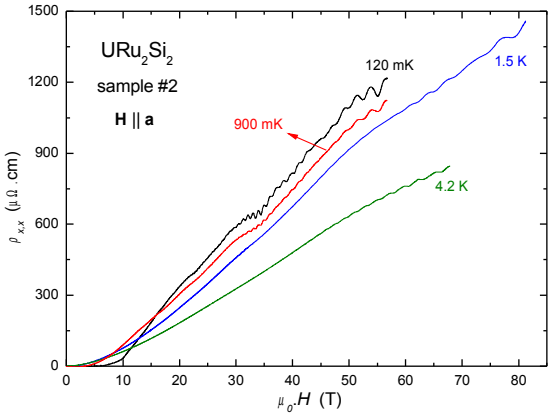


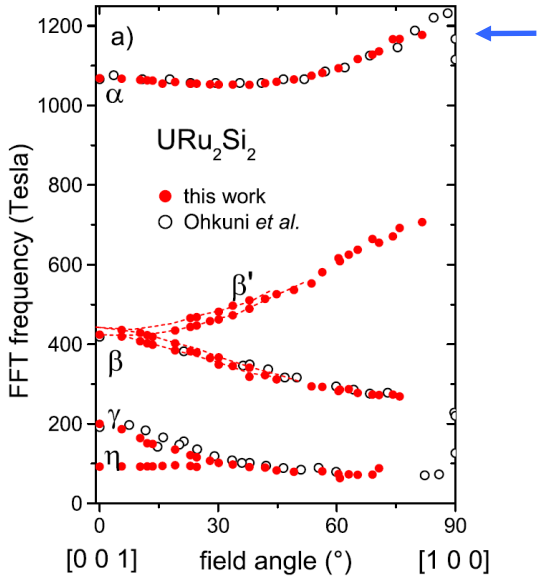


[Hassinger et al., PRL (2010)]

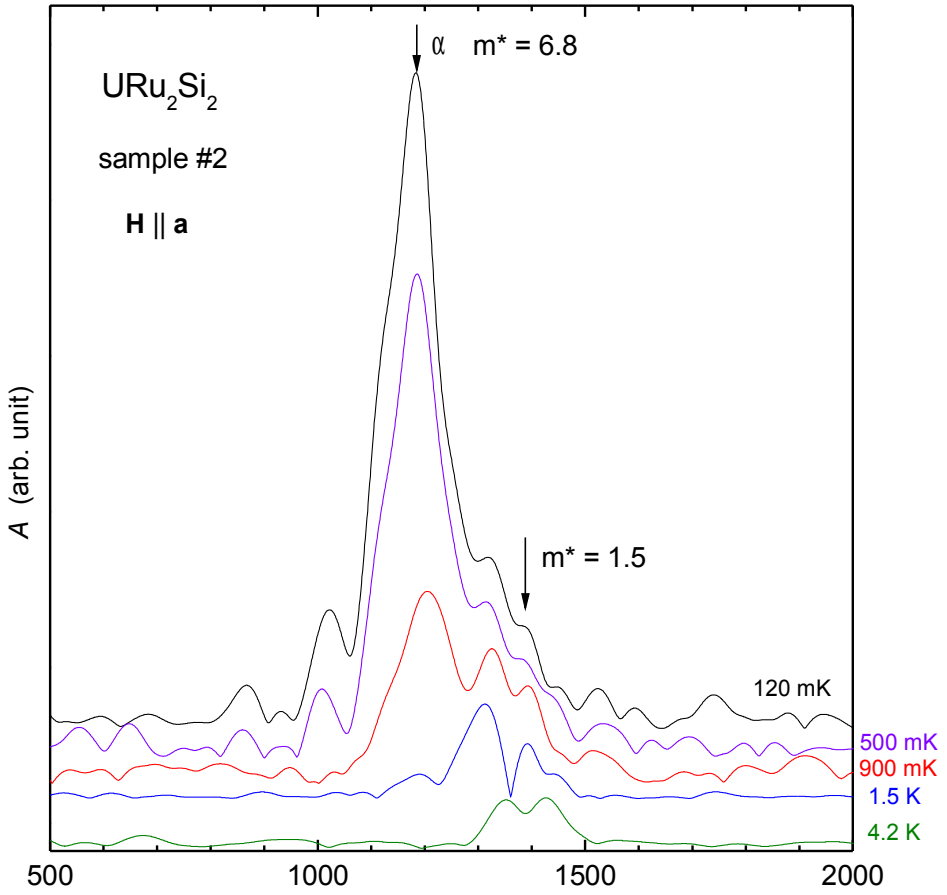


Quantum Oscillations: **H || a**

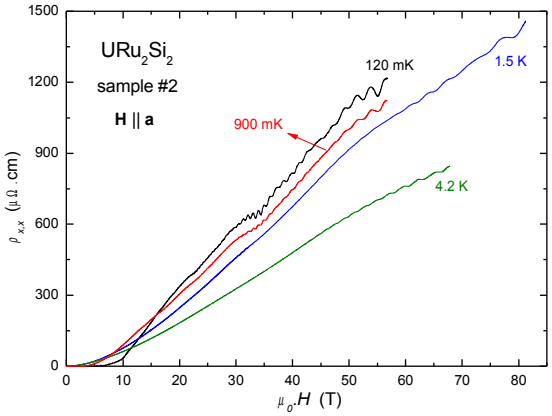


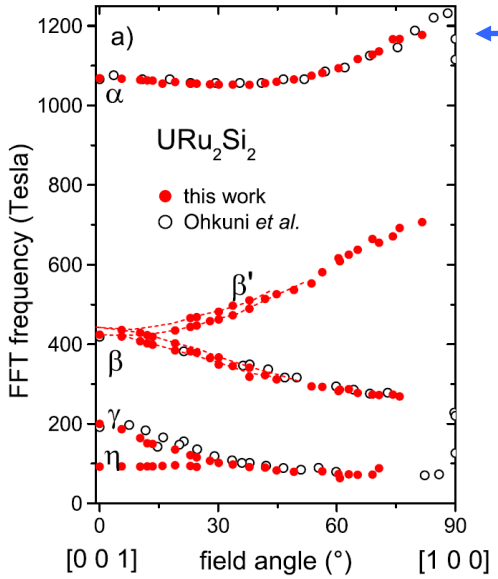


[Hassinger et al., PRL (2010)]

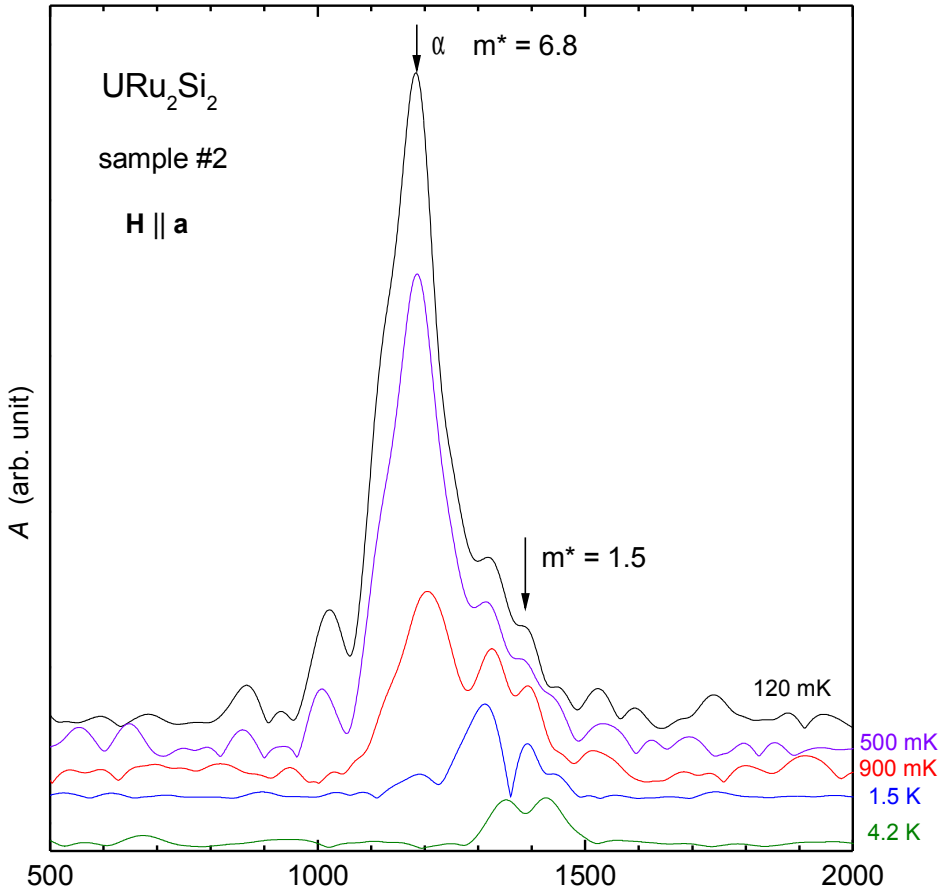


Quantum Oscillations: **H || a**



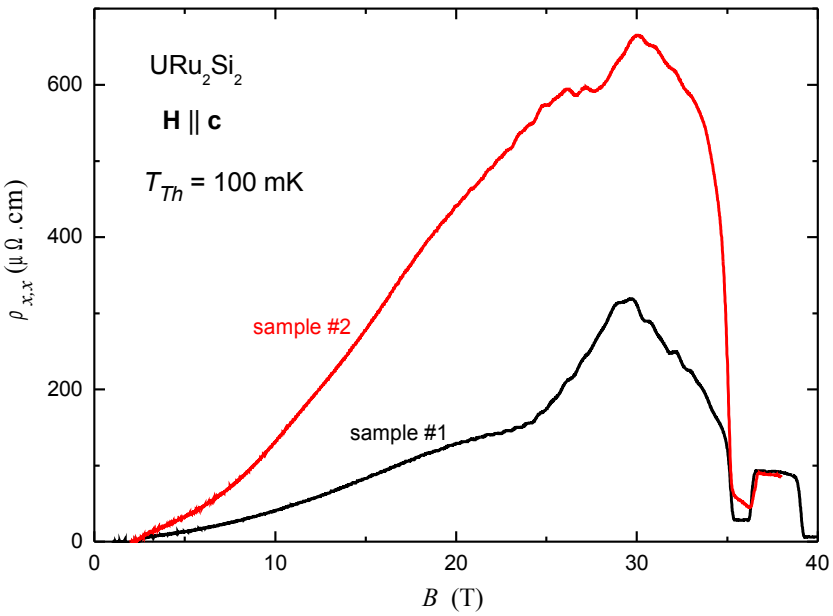


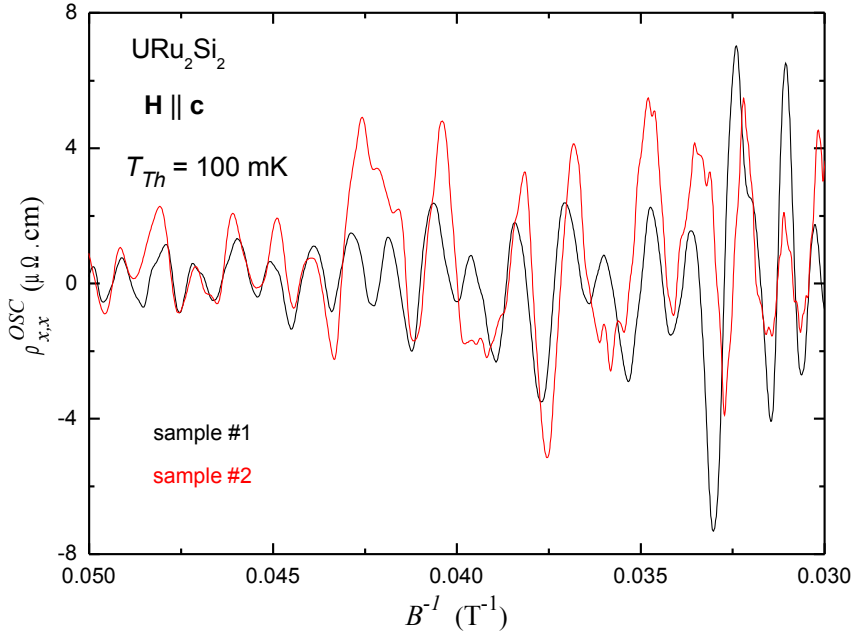
[Hassinger et al., PRL (2010)]



→ Light mass branch ($m^* = 1.5 * m_e$) survives up to 4.2 K

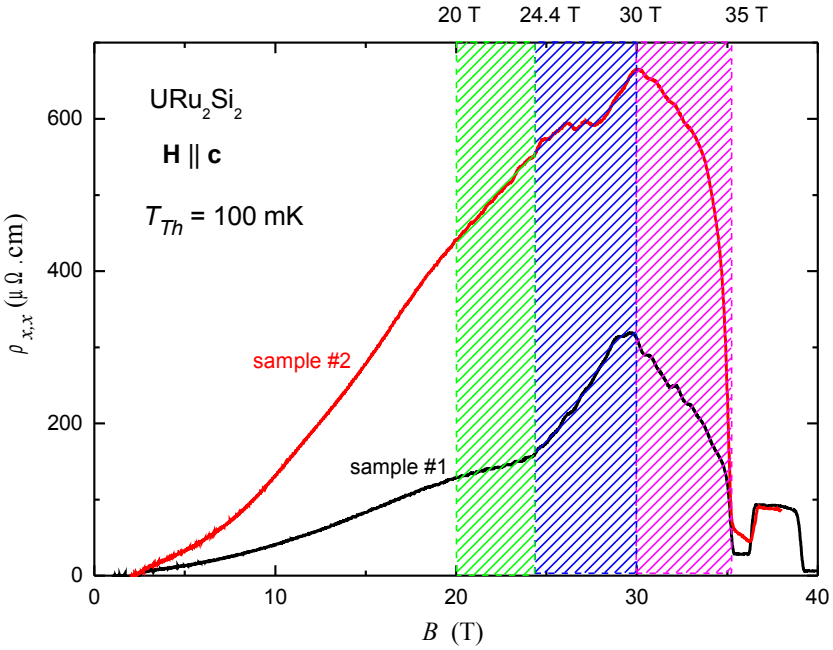
Quantum Oscillations: **H** || **c**

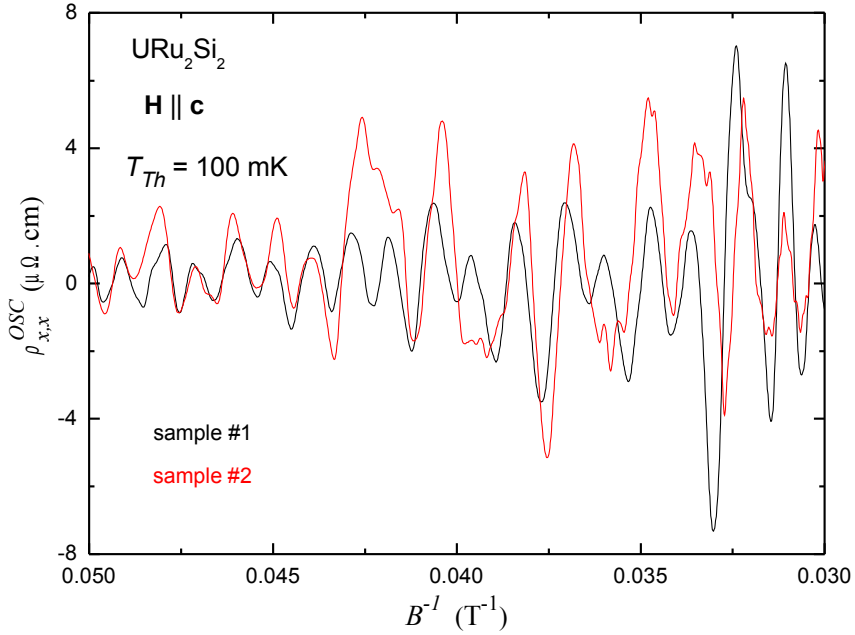




"hidden order" : 0 – 35 T

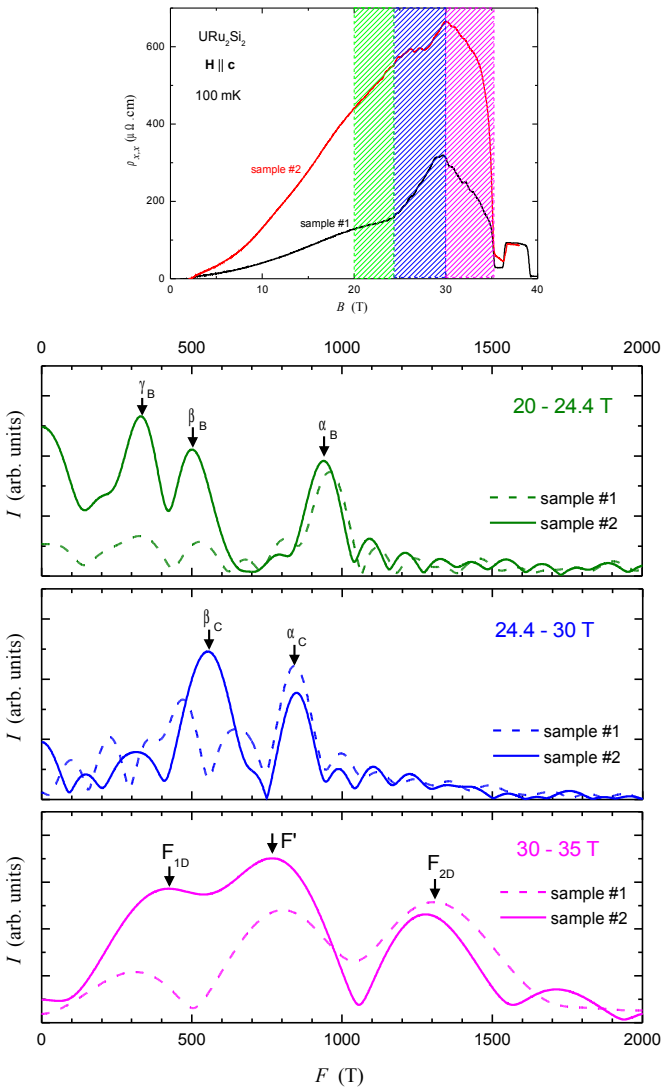
Quantum Oscillations: **H** || **c**





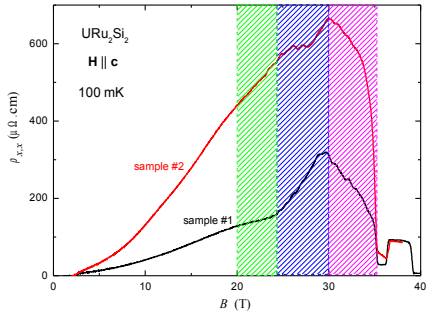
"hidden order" : 0 – 35 T

Quantum Oscillations: **H** || **c**

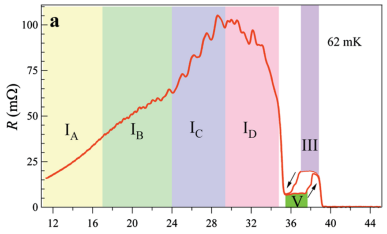


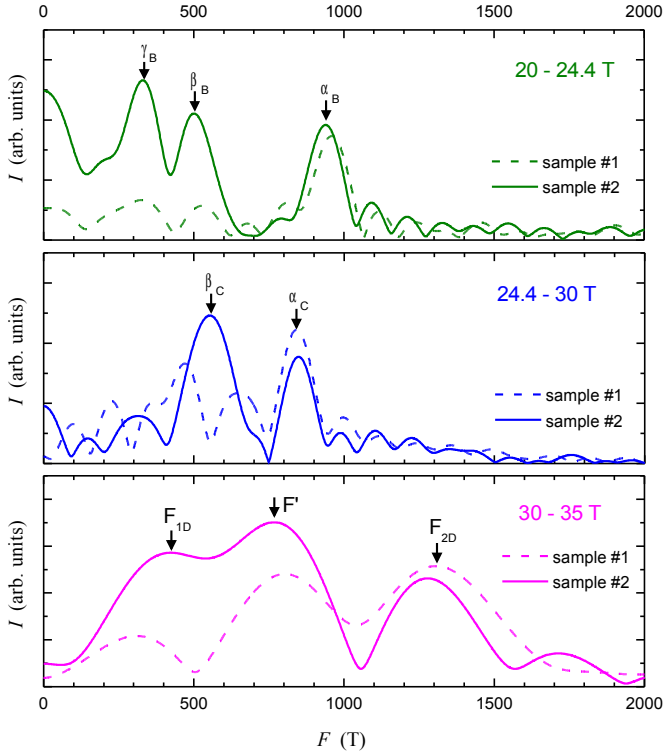
Fermi surface modification inside the „hidden order“

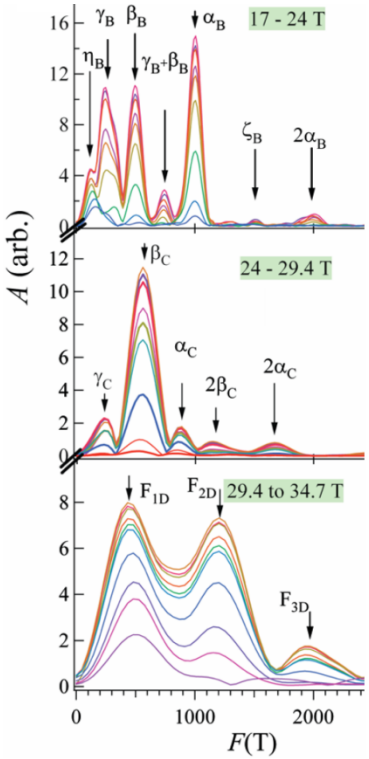
Quantum Oscillations: **H** || **c**



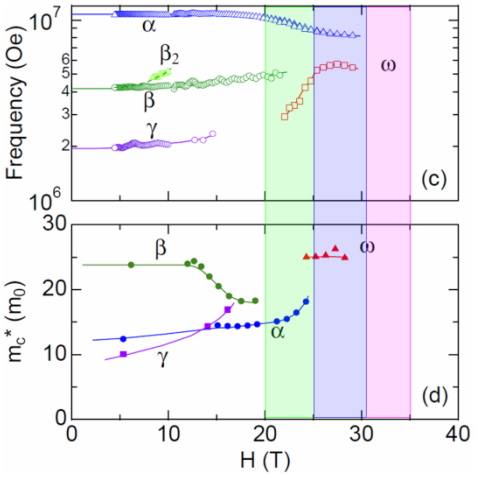
[Altarawneh et al., Phys. Rev. Lett. (2011)]







[Aoki et al., J. Phys. Soc Jpn. (2012)]



Conclusion

- (H,T)-phase diagram (**H** || **c**) of URu_2Si_2
- Angle dependence of $\rho_{x,x}$: transition fields follow 1/cos(θ)-law,
  observation of H_{kink} in magnetoresistivity
- High-field quantum oscillations:
  H || **a**: new light mass frequency above α
  H || **c**: Fermi surface modifications inside the “hidden-order“

Thank you!

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This work was supported by the French ANR DELICE, by Euromagnet II via the EU under Contract No. RII3-CT-2004-506239.

Scheerer et al., Phys. Rev. B 85, 094402 (2012)

Scheerer et al., J. Phys. Soc. Jpn. 81, SB005 (2012).


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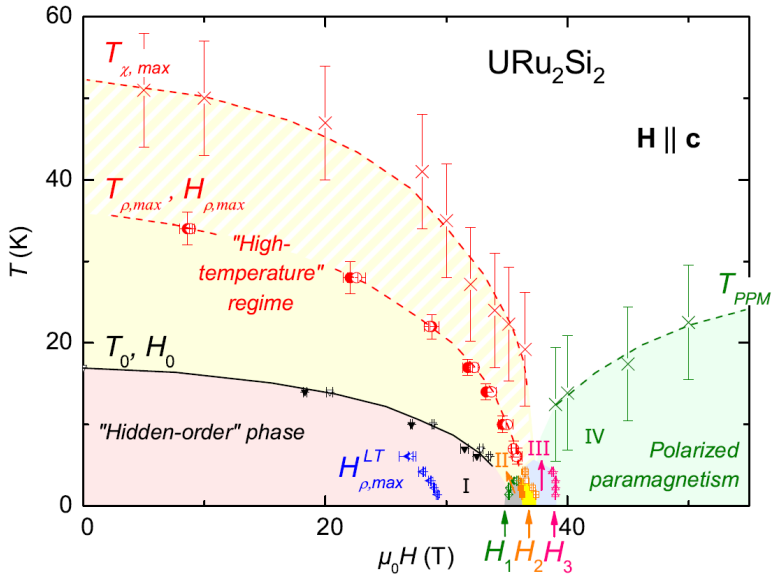
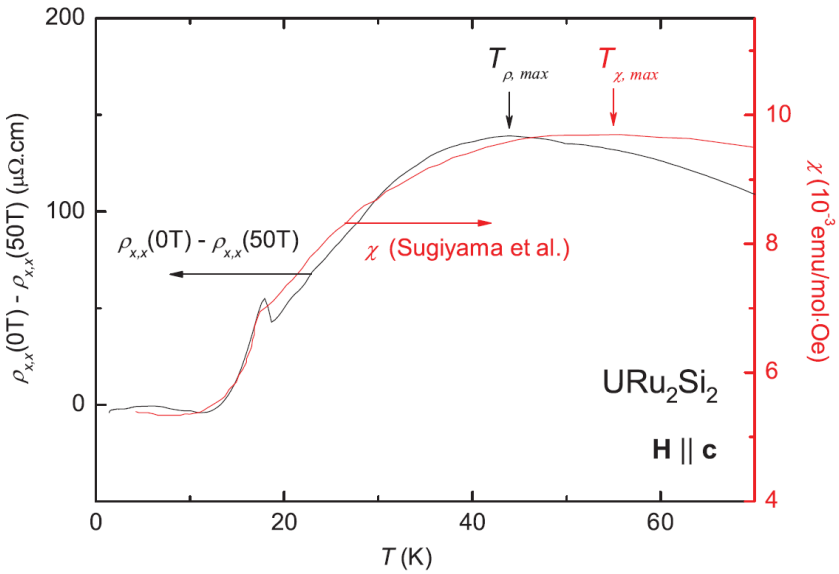
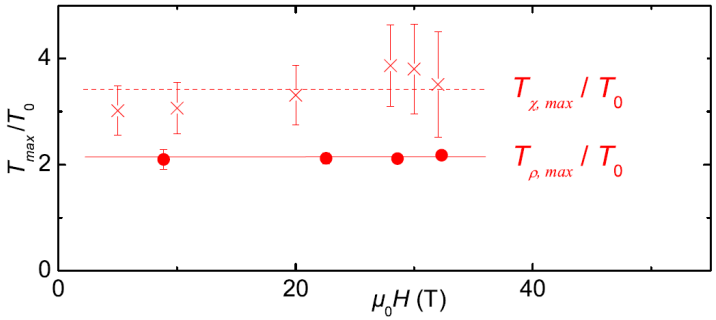
(*H,T*) Phase Diagram: Conclusions



[Sugiyama et al., J. Phys. Soc. Jpn. (1999)]



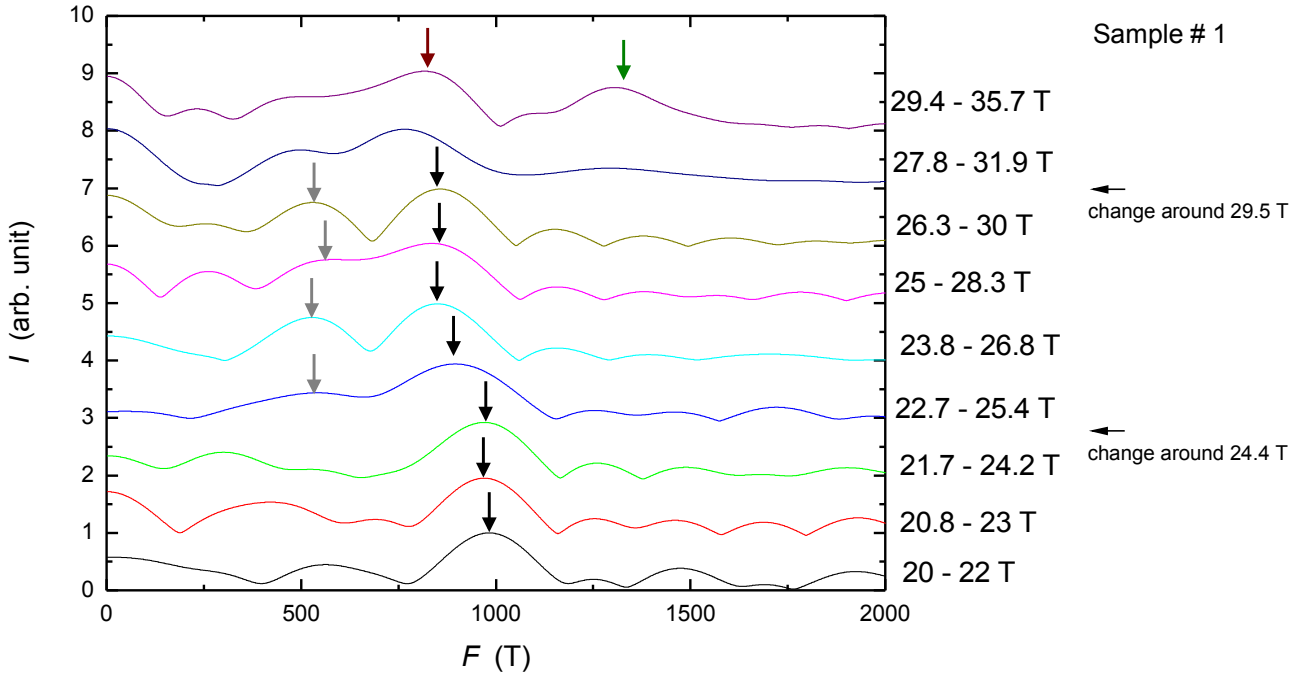


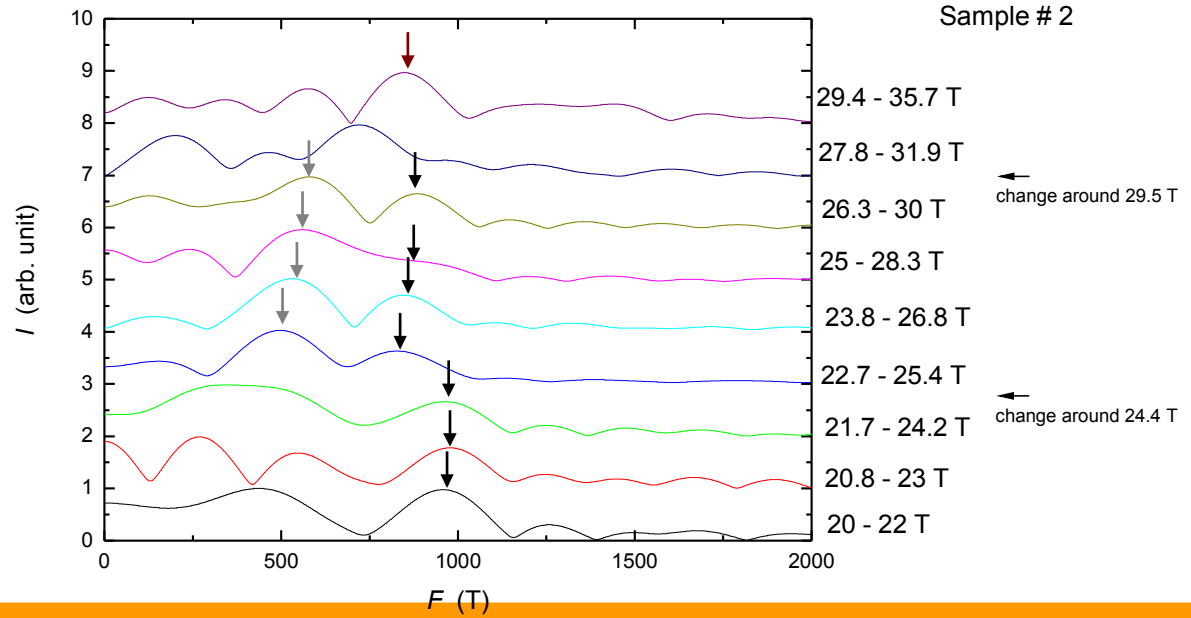
High-temperature scales $T_{\chi,max}$ and $T_{\rho,max}$ controled by same phenomenon:

Onset of antiferromagnetic correlations

- Lead to the critical area (H_1, H_2, and H_3)

- Precursor of the "hidden-order" phase.


Sample # 1
29.4 - 35.7 T
27.8 - 31.9 T
26.3 - 30 T
25 - 28.3 T
23.8 - 26.8 T
22.7 - 25.4 T
21.7 - 24.2 T
20.8 - 23 T
20 - 22 T
change around 29.5 T
change around 24.4 T
I (arb. unit)
F (T)
0
500
1000
1500
2000
0
1
2
3
4
5
6
7
8
9
10


Sample # 2
29.4 - 35.7 T
27.8 - 31.9 T
26.3 - 30 T
25 - 28.3 T
23.8 - 26.8 T
22.7 - 25.4 T
21.7 - 24.2 T
20.8 - 23 T
20 - 22 T
change around 29.5 T
change around 24.4 T
I (arb. unit)
F (T)
0
500
1000
1500
2000
0
1
2
3
4
5
6
7
8
9
10