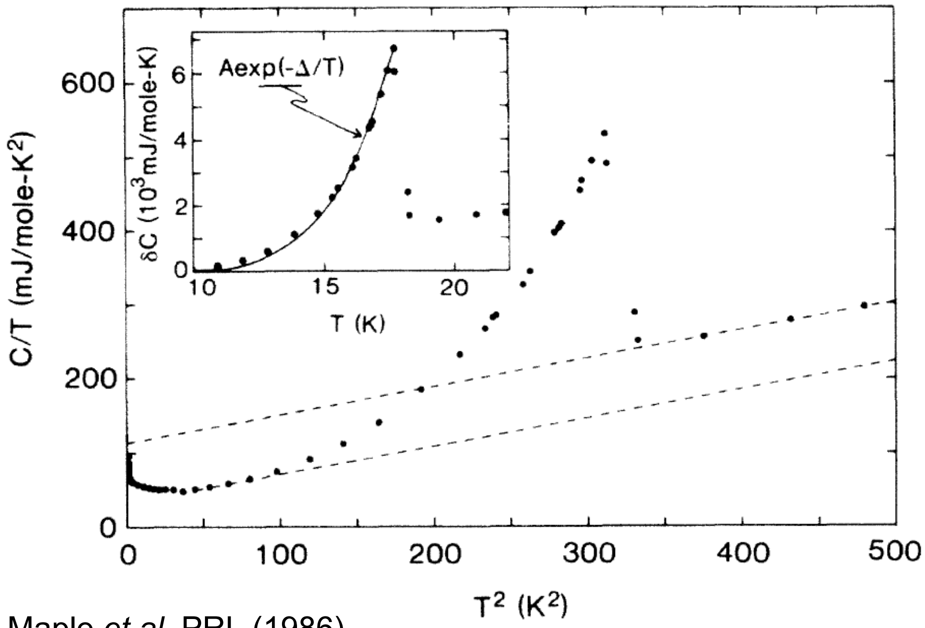
Hidden Order versus Antiferromagnetism in URu_2Si_2

Elena Hassinger

SPSMS, CEA Grenoble

INSTITUT NANOSCIENCES ET CRYOGÉNIE

Mystery of URu_2Si_2



Maple *et al.* PRL (1986)

huge entropy loss ~0.2Rln2

No ordered moment found with neutrons

Hidden Order

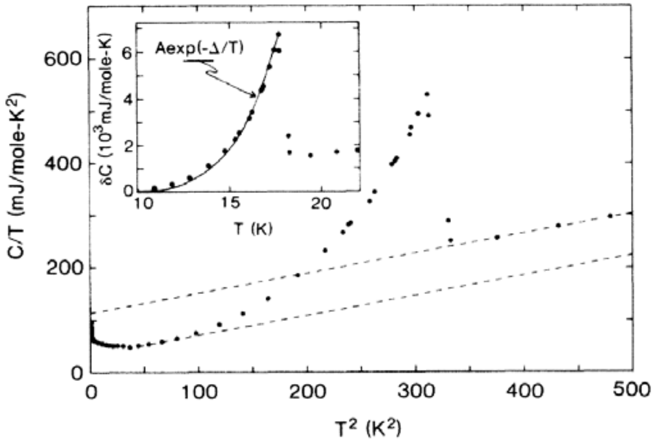
Outline

Dai Aoki samples
Frédéric Bourdarot neutrons
Georg Knebel
Tatsuma Matsuda
Stéphane Raymond
Louis-Pierre Regnault
Valentin Taufour
Alain Villaume
Jacques Flouquet

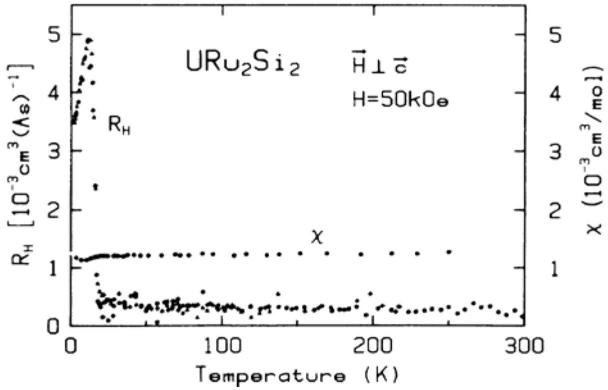
1. Introduction
2. Pressure measurements
3. New neutron results
4. Fermi surface study
5. Conclusion

URu_2Si_2 - macroscopic view

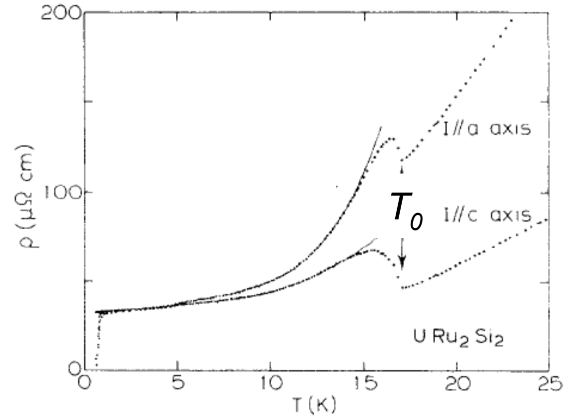
Heavy Fermion system



Maple *et al.* PRL (1986)

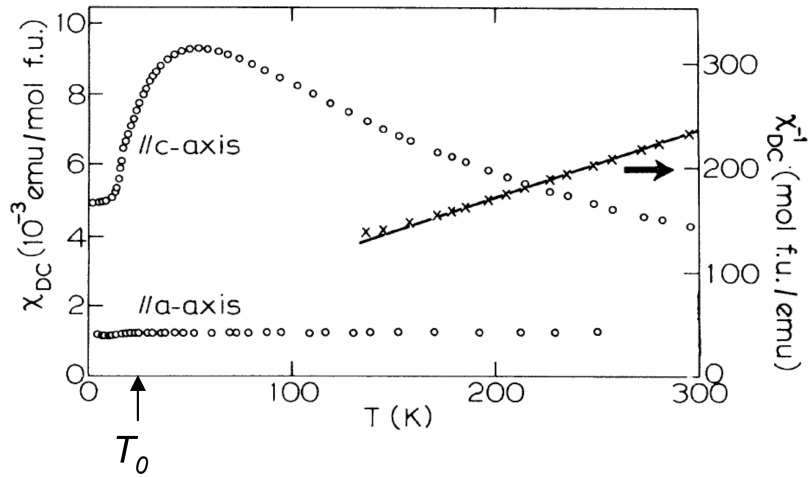


Schoenes *et al.* PRB (1987)



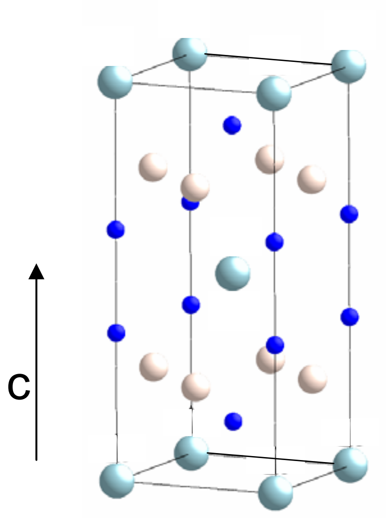
Palstra *et al.* PRB (1986)

- Large anomalies in macroscopic quantities at 17.5 K
- Sommerfeld coefficient γ changes from 180 mJ/molK² above T_0 to 60 mJ/molK² below T_0
- change in Hall constant (factor of 10)
- Strong anisotropy (Ising)
- Exponential behavior below T_0 => gap (110 K from specific heat)
- Anisotropic superconductivity at T_c = 1.2K
- compensated metal, low carrier density



Palstra *et al.* PRL (1985)

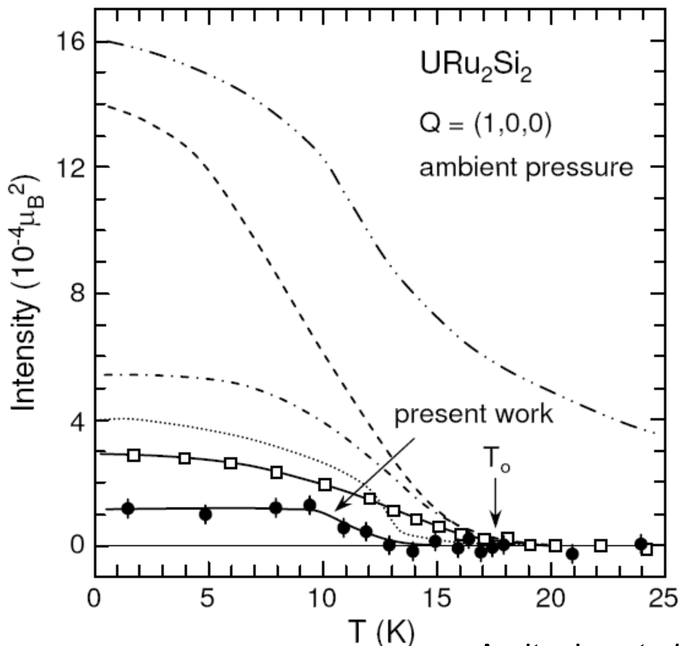
Neutron scattering - microscopic view



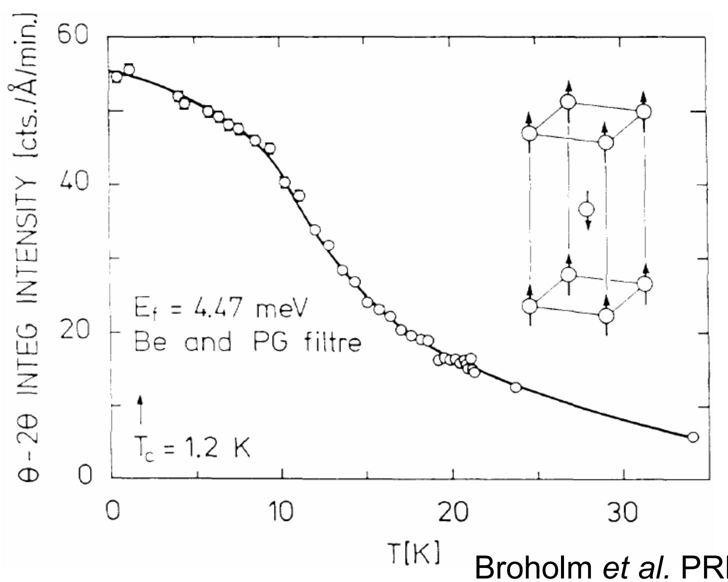
Body centered tetragonal
Space group: I4/mmm

- Very small ordered moment: $m \approx 0.04\ \mu_B$ /U
- Moment is too small to explain entropy loss

There must be a hidden order parameter!



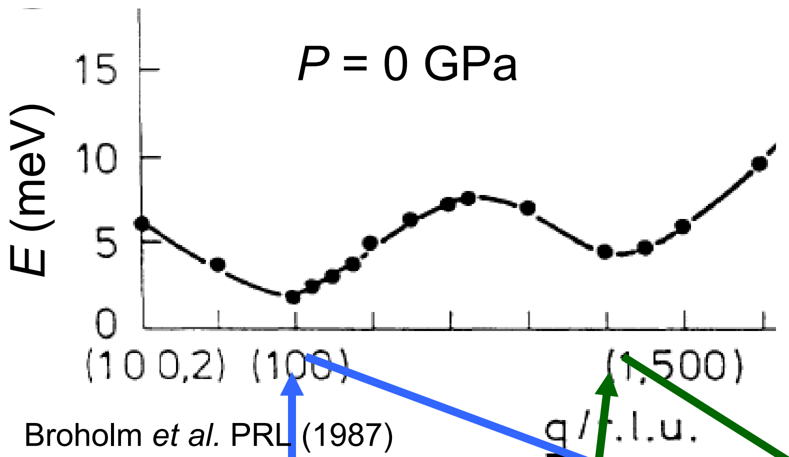
Amitsuka *et al.* JMMM (2006)



Broholm *et al.* PRL (1987)

Ordered moment sample dependent:
extrinsic, due to defects
But independent of sample two strong
excitations

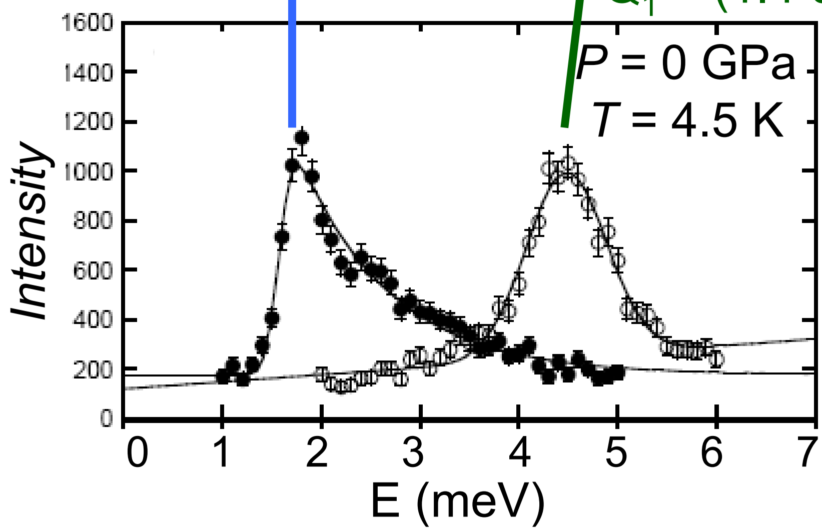
Dispersion Relation and Excitations



Broholm *et al.* PRL (1987)

Q_0 = (1 0 0)

Q_1 = (1.4 0 0)



Bourdarot *et al.* arXiv:cond-mat/0312206 (2003)

2 well-defined sharp peaks (robust)

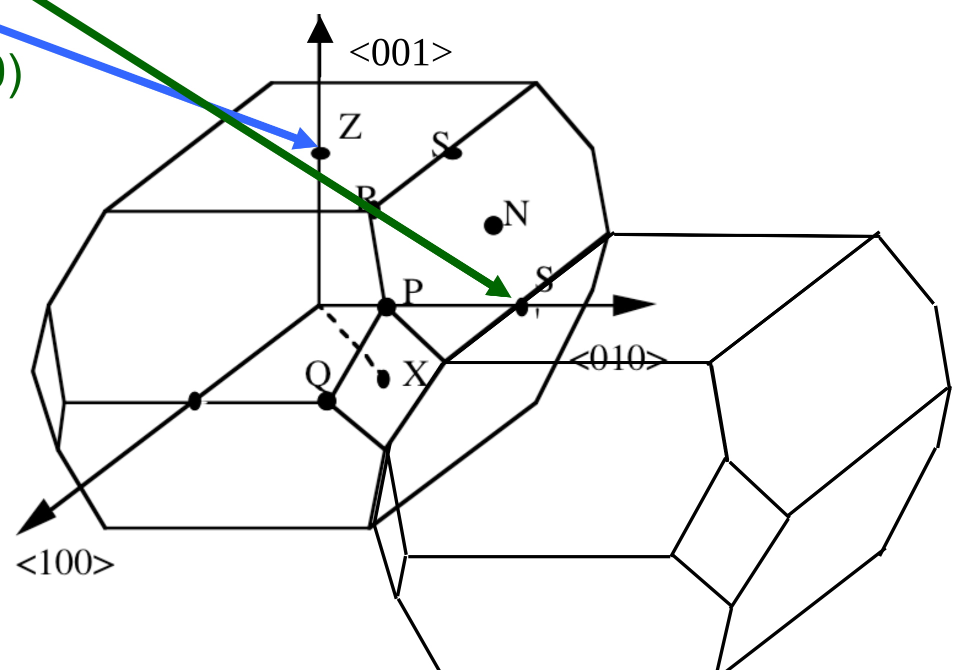
Q_0= (1 0 0) $E_0 \approx$ 1.6 meV

Commensurate Q_0 equivalent to Q_{AF}= (0 0 1)

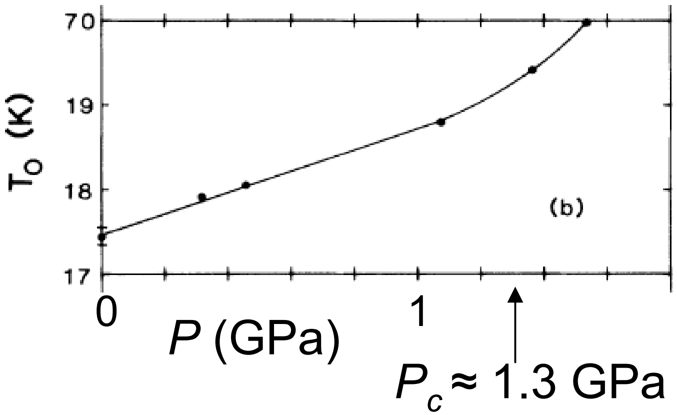
Q_1= (1.4 0 0) $E_1 \approx$ 4.8 meV

Incommensurate

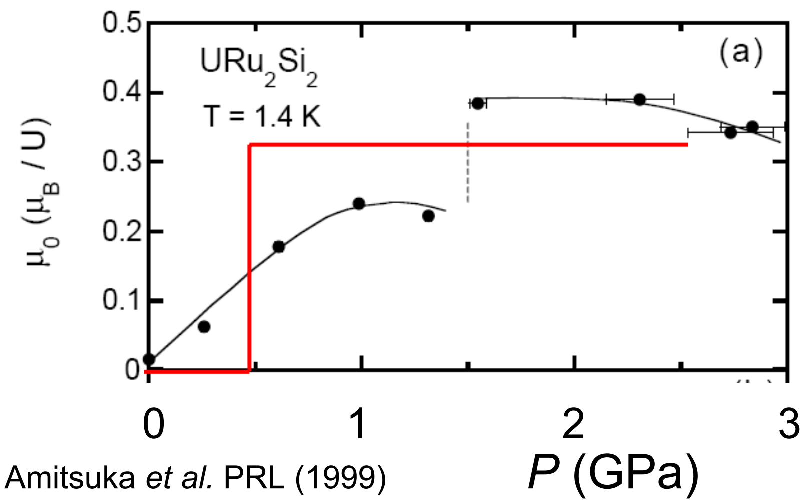
- longitudinal excitations:
  no magnons
- only low E microscopic signature of HO



URu_2Si_2 under Pressure

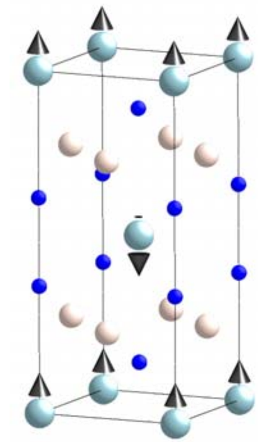


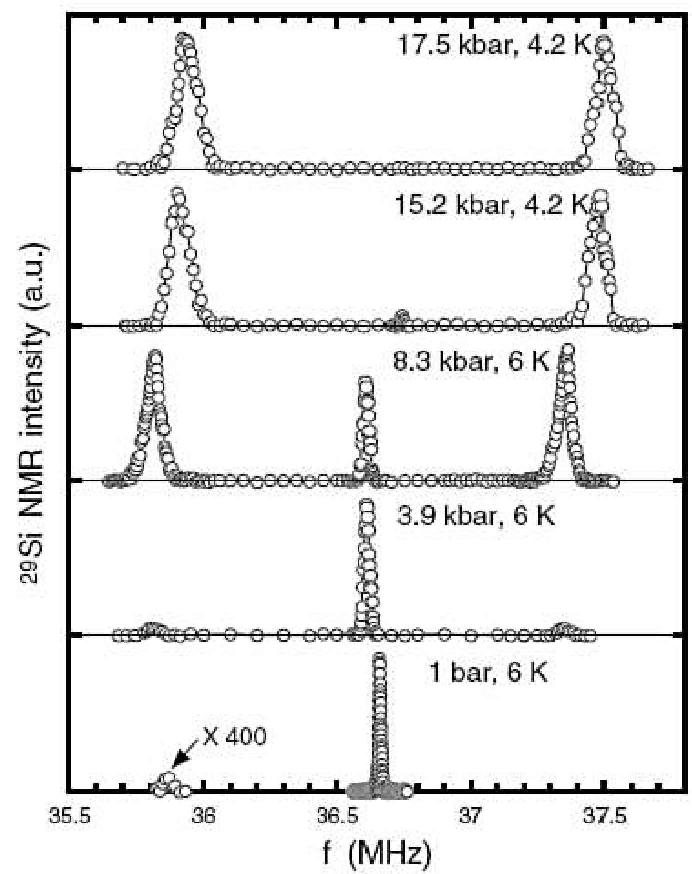
McElfresh *et al.* PRB (1987)



Amitsuka *et al.* PRL (1999)

NMR: not moment but volume increases
In HO locally AF droplets near defects

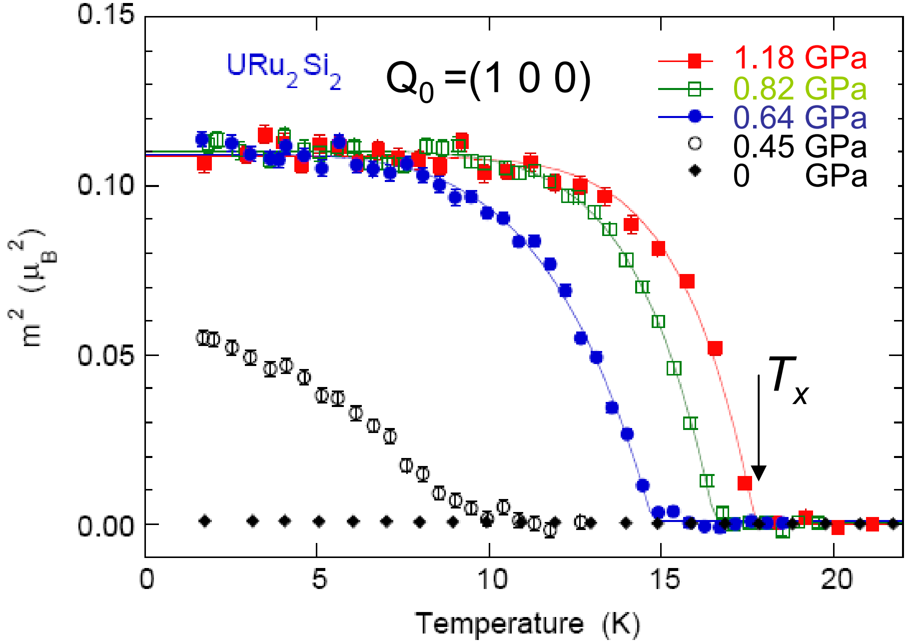


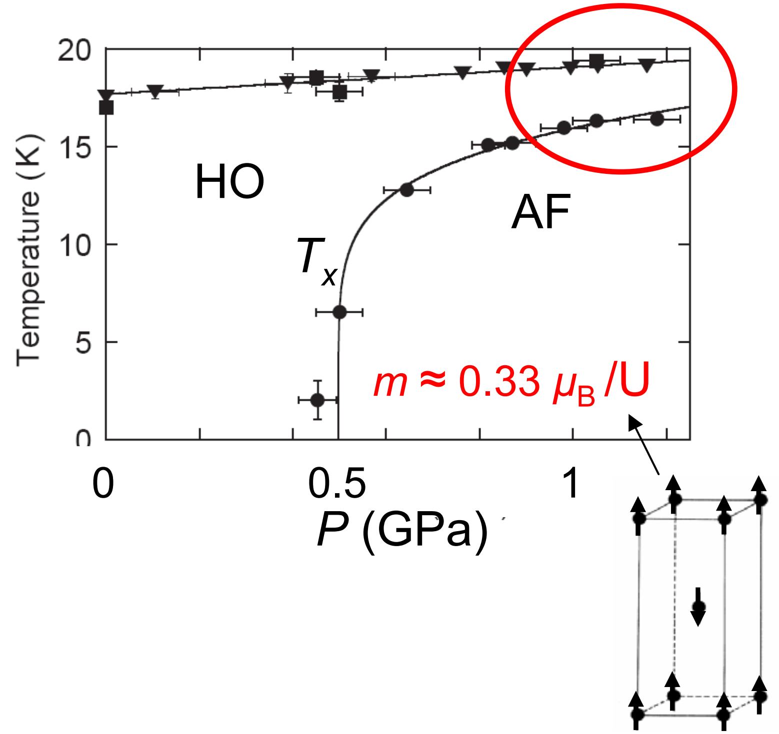


Matsuda *et al.* JPCondMat (2003)

- T_0 increases slowly then faster
- under pressure AF phase with large moment $m \approx 0.33\ \mu_B$ /U
- Ordering vector Q_{AF} = (0 0 1) Brillouin zone changes

URu_2Si_2 under Pressure





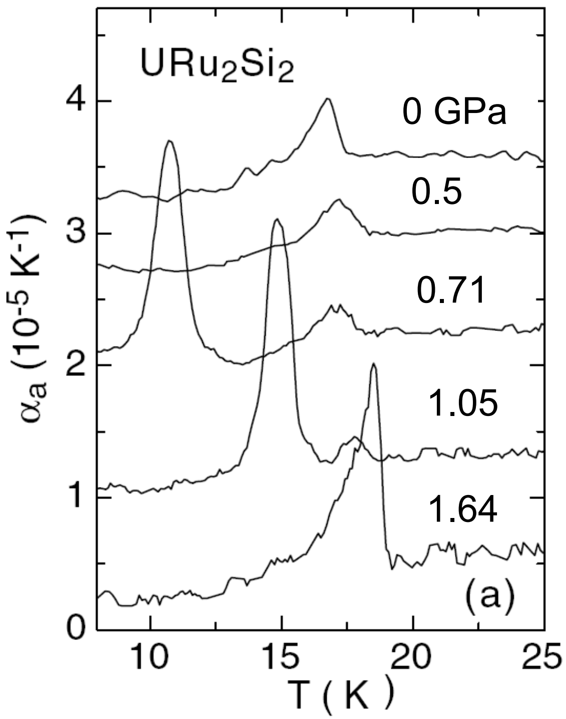
Moment increases abruptly for

$P > P_x \approx 0.5$ GPa

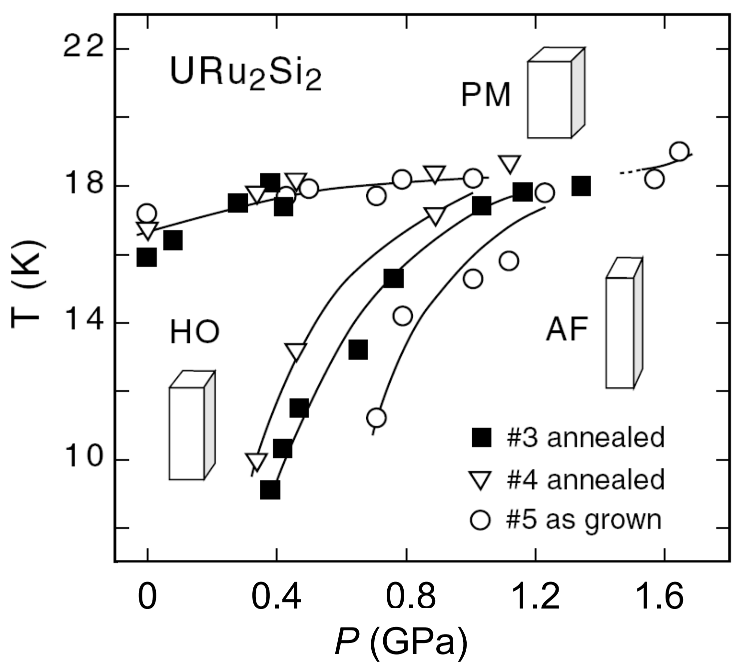
Do these lines touch?

Bourdarot *et al.* arXiv:cond-mat/0312206 (2003)

Thermal expansion



Phase diagram



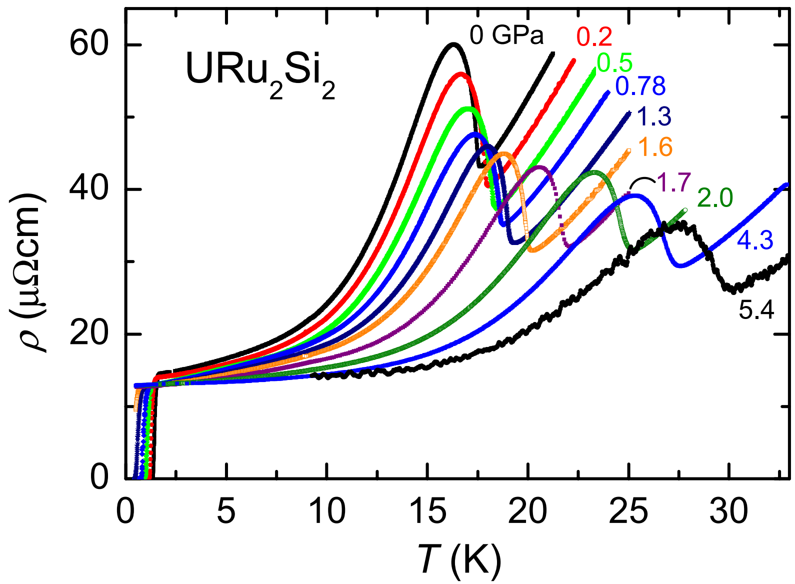
Motoyama *et al.* PRL (2003)

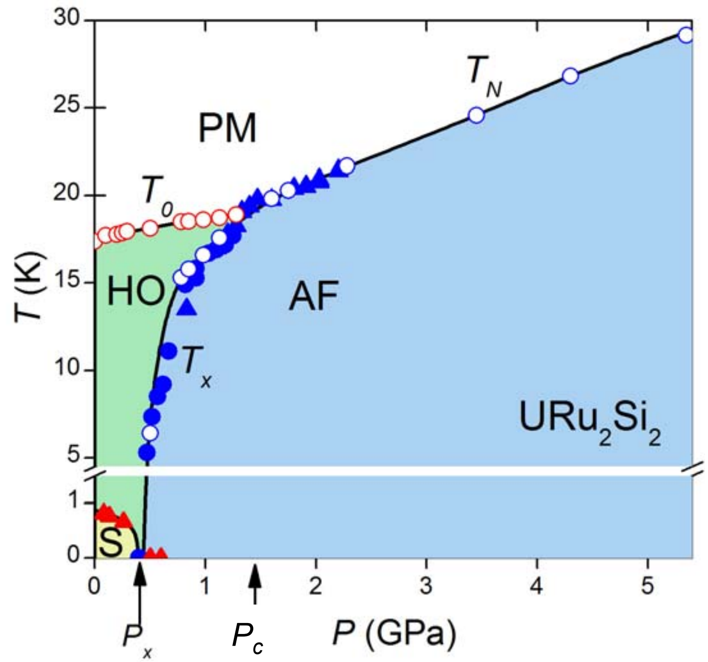
- Strong signal at T_x
- Phase diagram depends on sample and pressure conditions

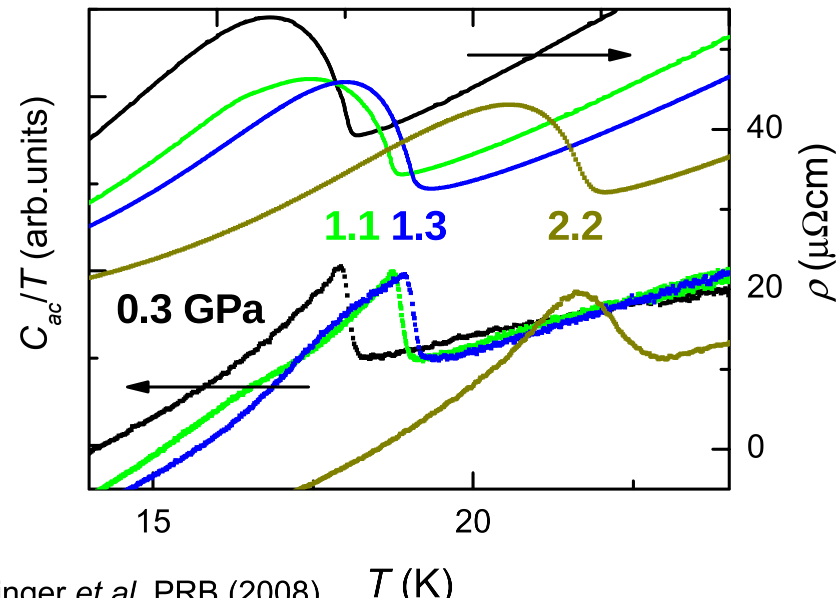
Questions:
Change of entropy at T_x and T_N
Change of signature of transition

Approach:
Comparison of AF phase with HO phase to learn more about the HO state itself

Resistivity and Specific Heat under Pressure



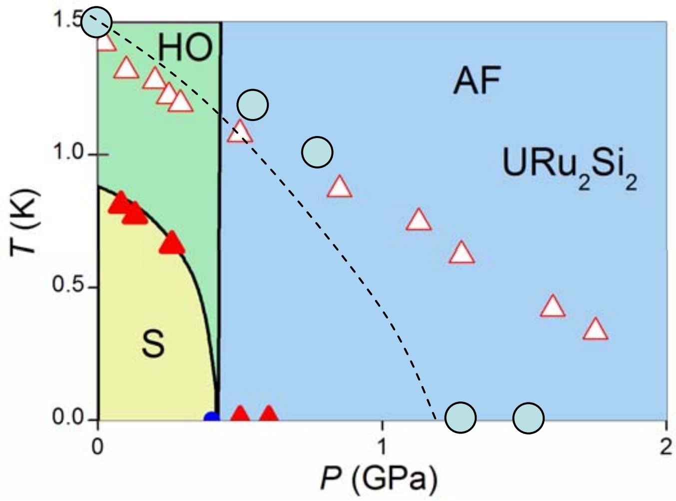


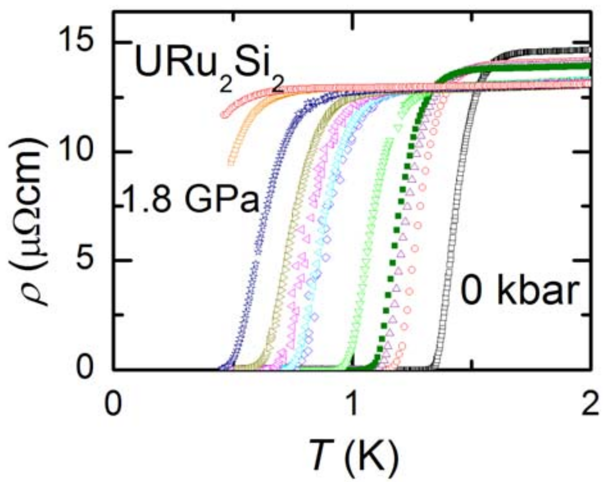


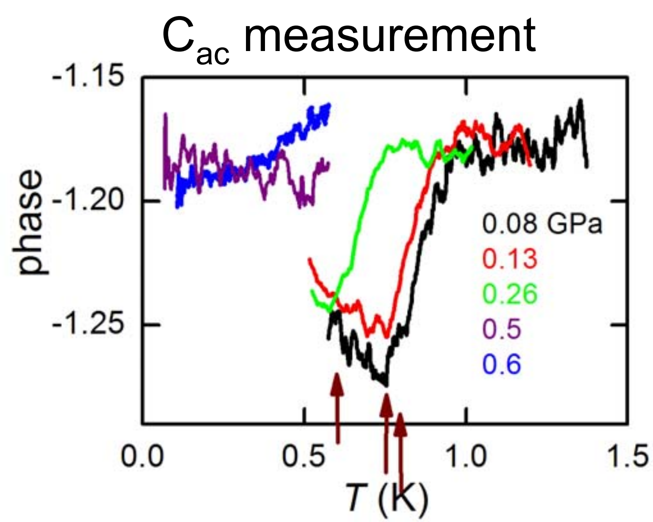
Hassinger *et al.* PRB (2008)

- Resistivity anomaly basically does not change with P
- clear reconstruction of Fermi surface similar in HO and AF state maybe due to bandfolding when BZ is changed, same BZ in HO and AF
- broad anomaly in resistivity and specific heat at T_x
- Transition lines seem to touch

Superconducting Transition under Pressure





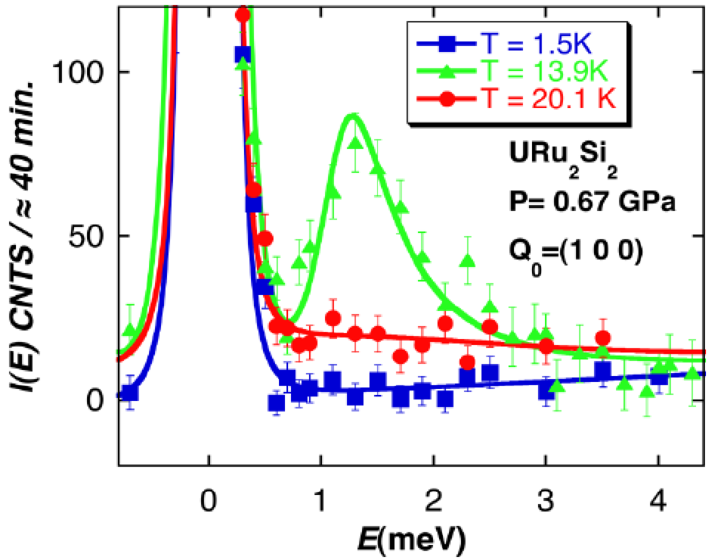


- $P = 0$: Transition temperature different in resistivity and specific heat
- In resistivity transition is observed above P_x
- above P_x SC is not bulk (surviving HO component in AF phase)

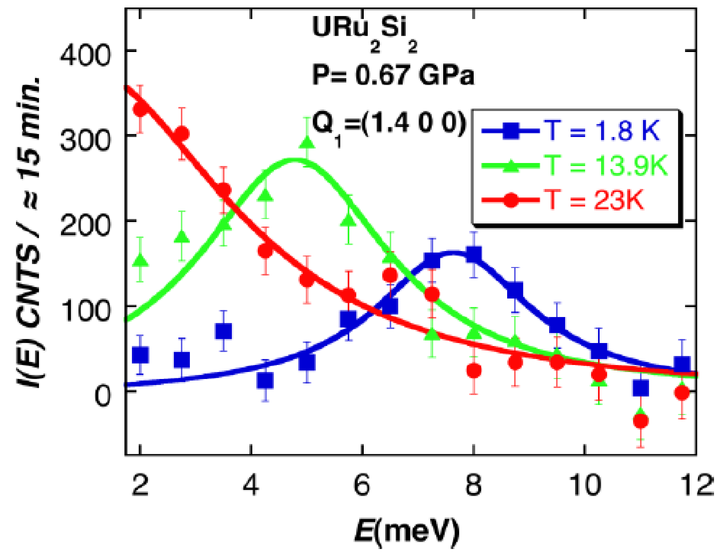
Hassinger *et al.* PRB (2008)

Excitations in different phases

Q_0 = (1 0 0)



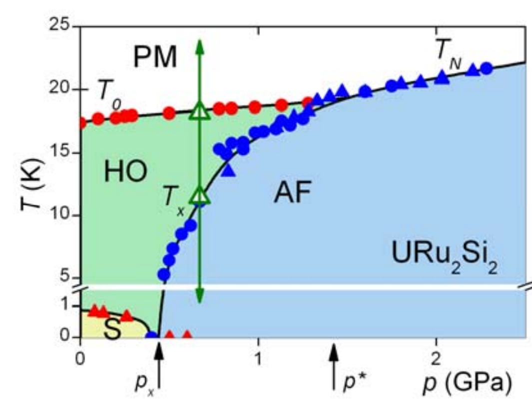
Q_1 = (1.4 0 0)



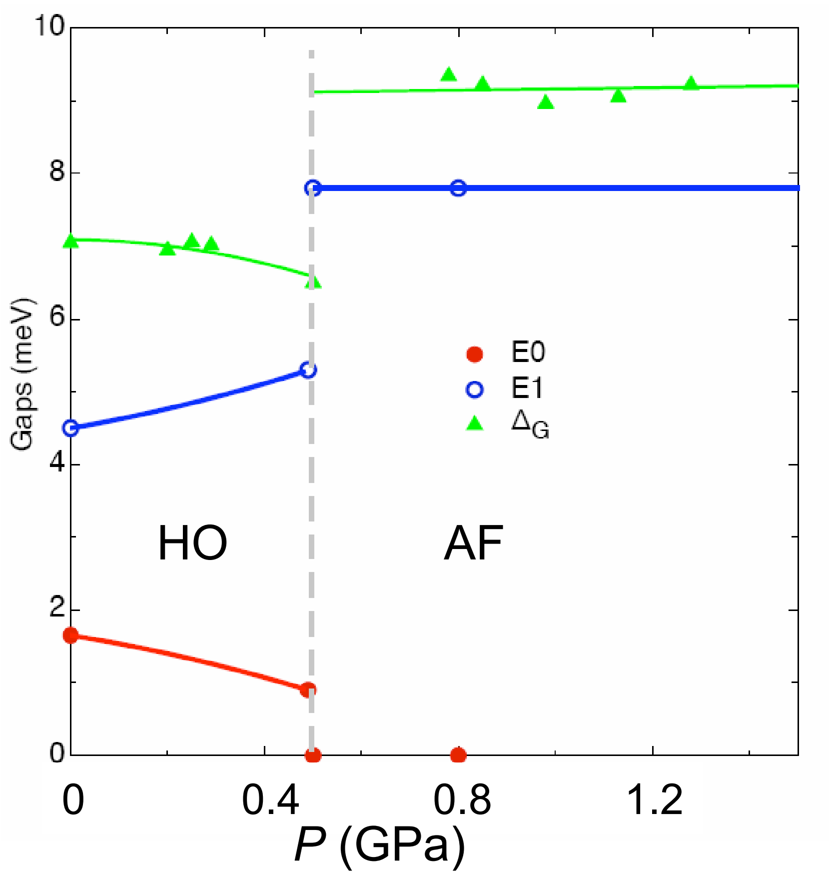
Villaume *et al.* PRB (2008)

- Excitation at Q_0 exists only in the HO phase
- Peak at Q_1 persists in the AF phase

 i.e. at high pressure and gap shifts
- We conclude that Q_0 is also the significant wave vector of the HO, excitation is « smoking gun » of the order parameter
- confirms the assumption that same BZ in HO as in AF



Excitations in different phases

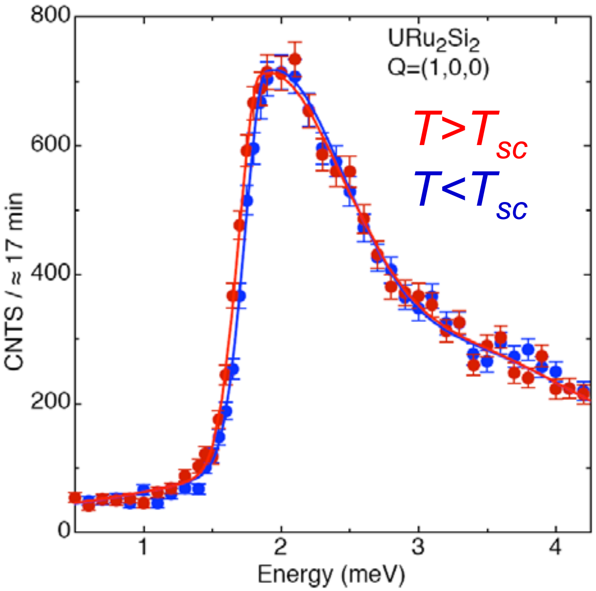


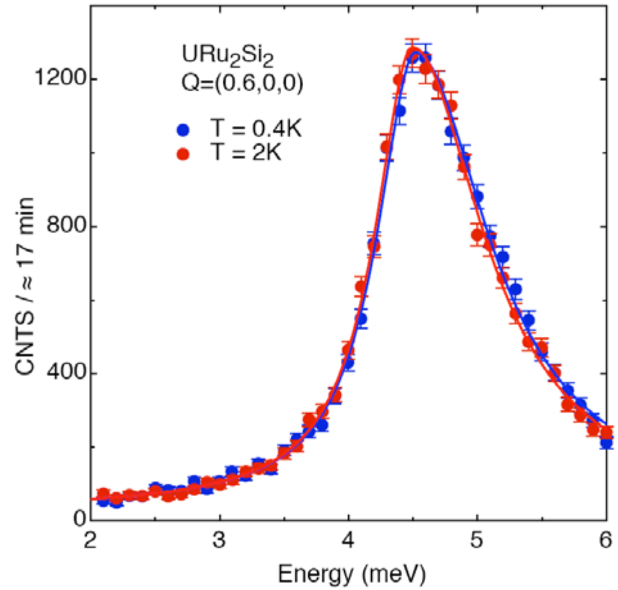
Δ_G from resistivity below T_0

$$\rho = \rho_0 + AT^2 + Bexp(-\frac{\Delta_G}{T})$$

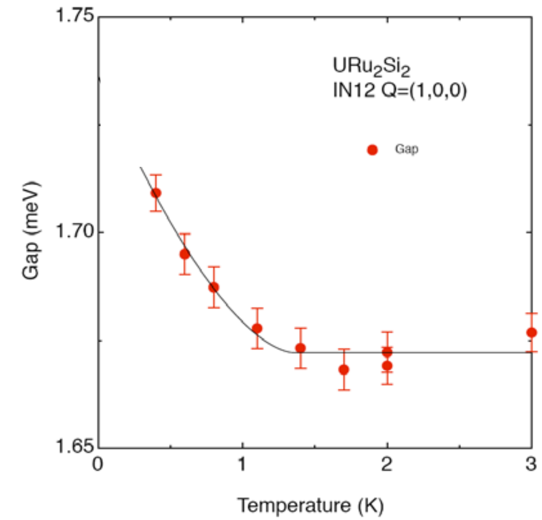
- Q_0 = (1 0 0) significant wave vector in both phases: excitation in HO phase, elastic signal in AF phase
- Superconductivity disappears also in AF phase: possible link to excitation at Q_0?

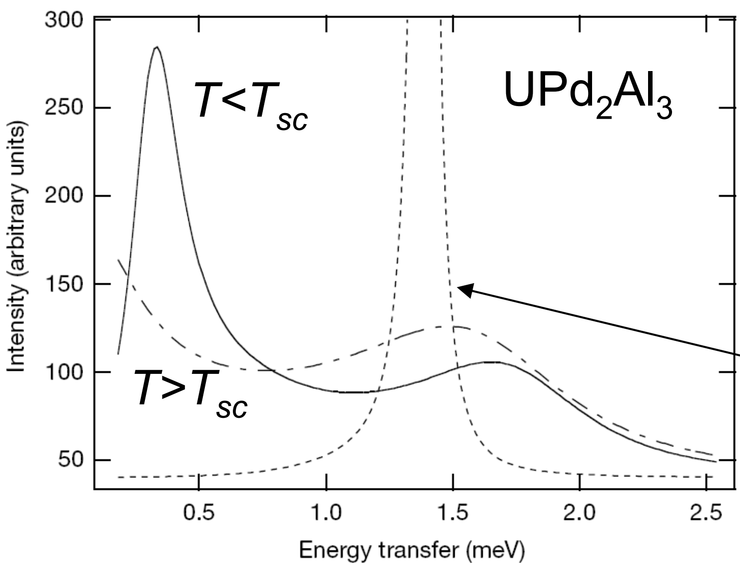
Excitations in superconducting phase





Small shift of excitation at Q_0 in superconducting phase





Comparison to UPd_2Al_3 (**strong coupling** between local and itinerant electrons)
In URu_2Si_2 no quasielastic signal =>
no peak appears
but shift of magnetic excitation

weak coupling

Sato *et al.* Nature (2001)

New theories

Band structure calculations (Elgazzar *et al.* Nature Materials 2009):

- symmetry breaking from AF fluctuations
- can lead to nesting at Q_1
- T dependence of intensity of Q_0 should be order parameter-like

DMFT (Haule and Kotliar):

- Hexadecapole

Group symmetry (Harima *et al.* to be published):

- staggered quadrupolar order Q_{xy}
- group 136, leaves Ru unchanged for NMR

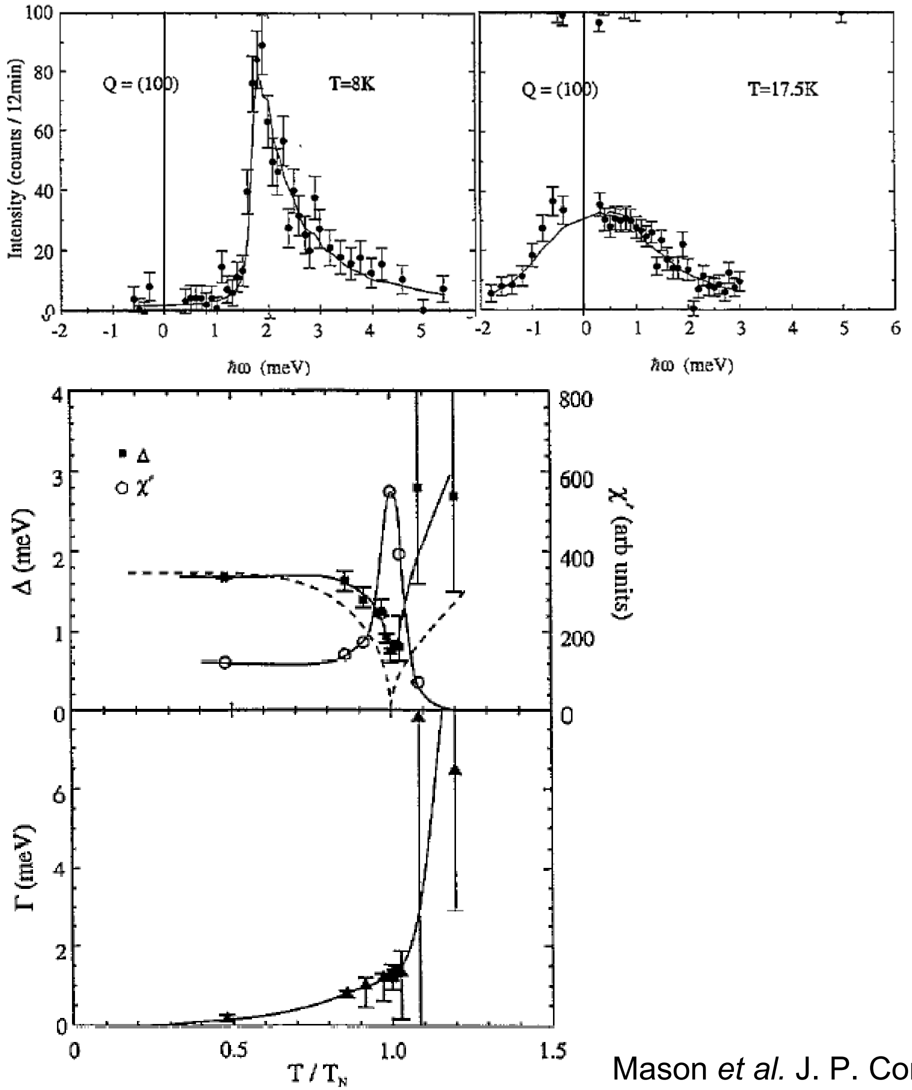
Both multipole of even order: no time reversal symmetry breaking in HO

Incommensurate CDW (Balatsky)

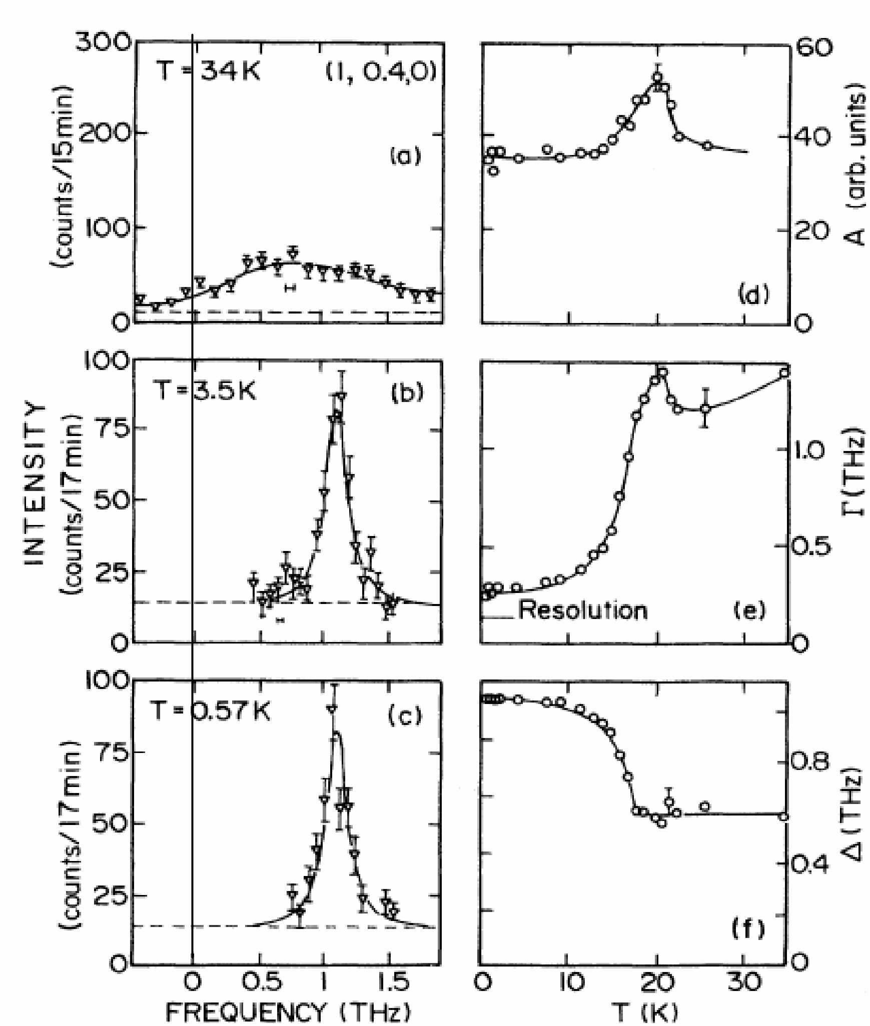
Temperature Dependence of Excitations

Q_0= (1 0 0)
for $T > T_0$ quasielastic

Q_1= (1.4 0 0) $E_1 \approx$ 4.8 meV
for $T > T_0$ inelastic but strongly damped



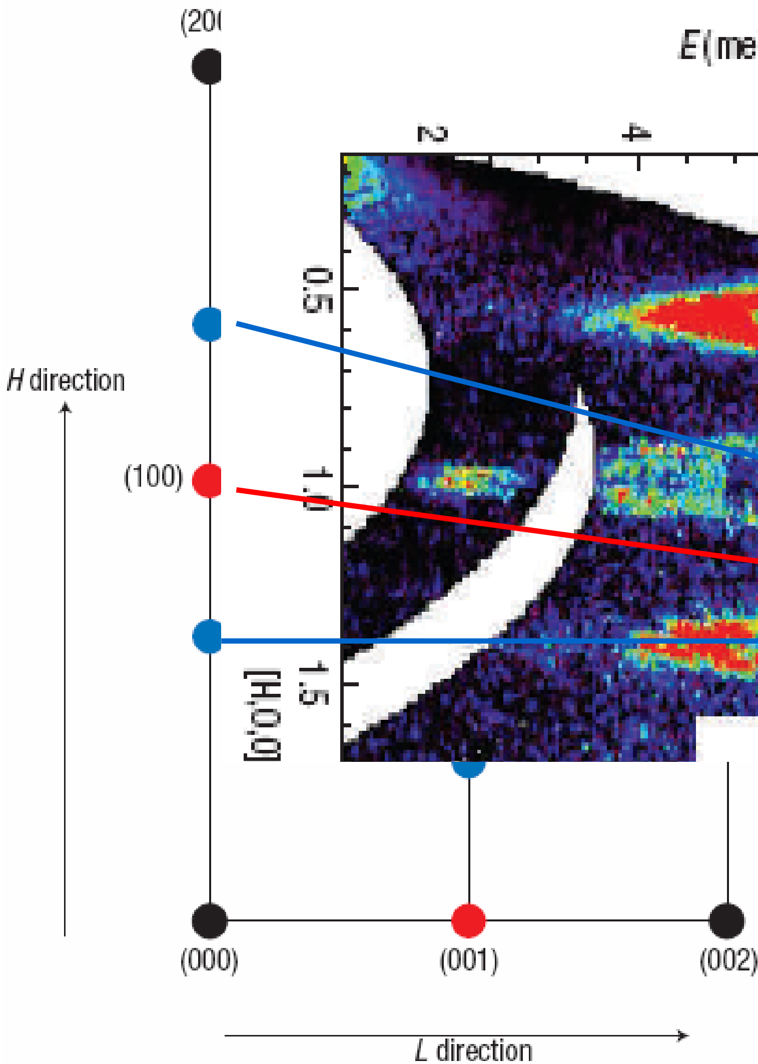
Mason *et al.* J. P. Cond Mat (1995)



Broholm *et al.* PRL (1987)

Excitations

Reciprocal space



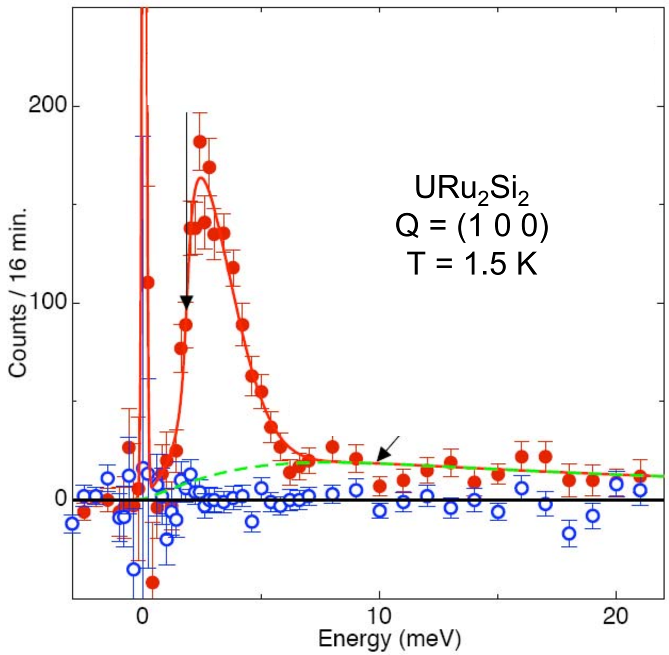
Wiebe *et al.* Nature Physics (2007)

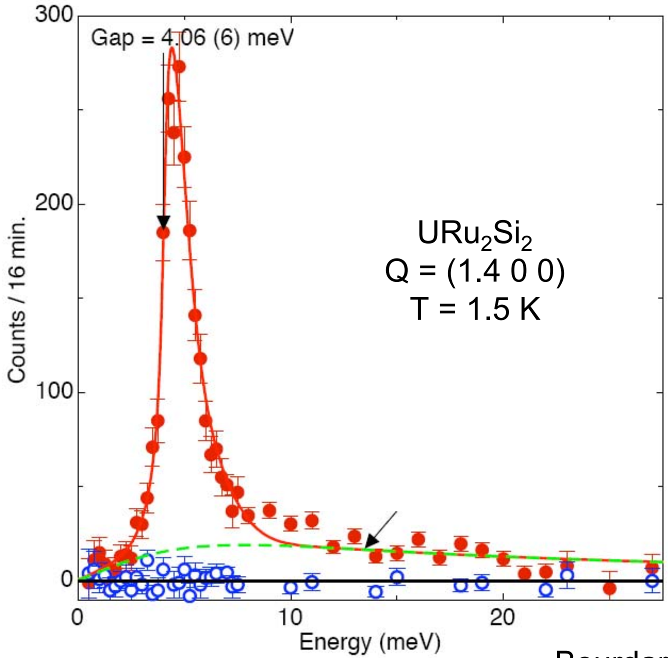
T = 1.5 K

Higher intensity for excitation at Q_1 = (1.4 0 0)

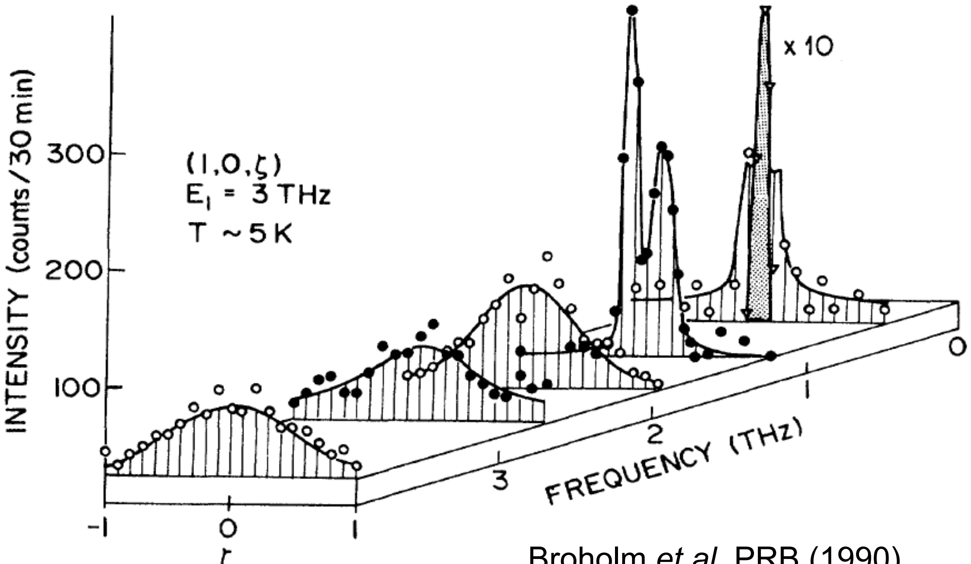
Gapping of excitations at Q_1 and equivalent points can account for entropy jump

Polarized neutron scattering in HO





Bourdarot *et al.* to be published (2010)

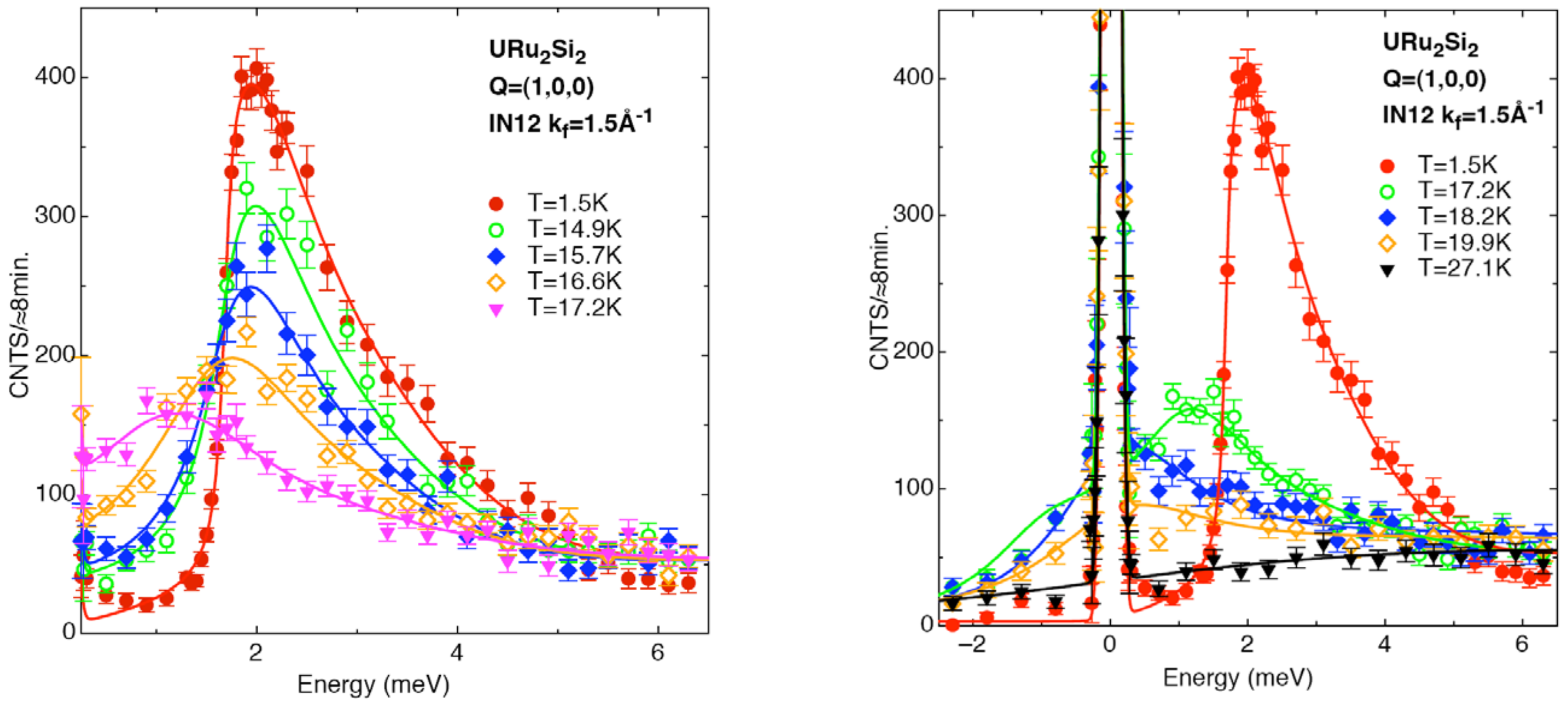


Broholm *et al.* PRB (1990)

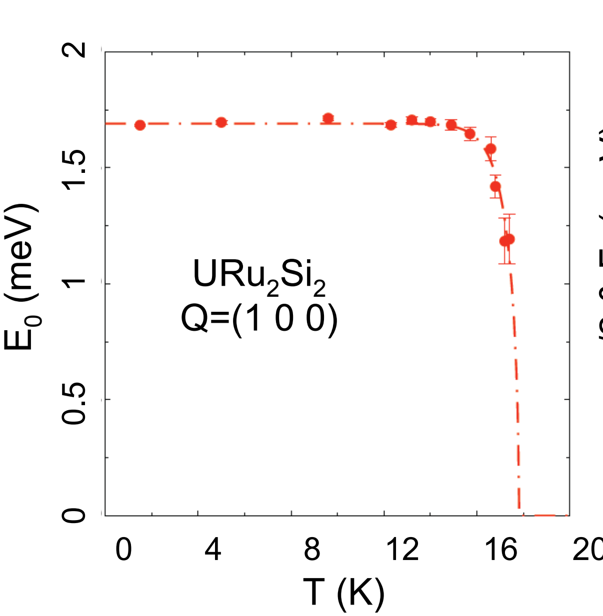
- Broad purely magnetic high energy signal (continuum)
- Both excitations and broad signal purely longitudinal
- Continuum quasielastic with characteristic energy Γ=7.8 meV much higher than k_BT_0
- Sommerfeld term γ=96 mJ/(molK$^{2)}$

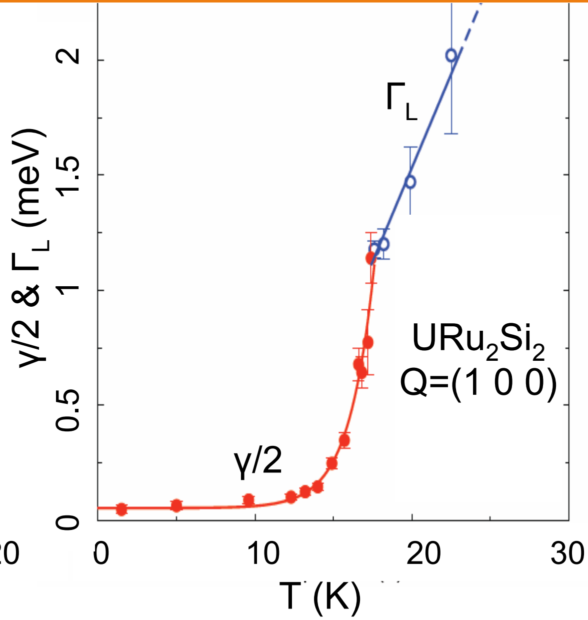
Temperature dependence of excitation at Q_0

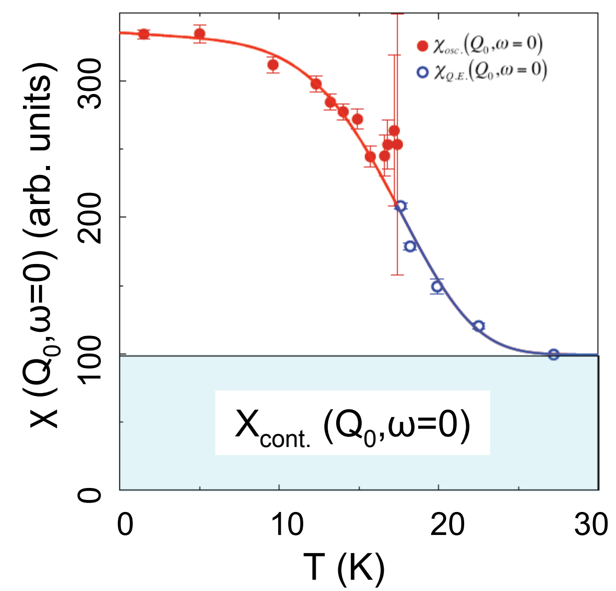
Signal far above T_0 is the same as from polarized neutrons at 1.5 K
$\Rightarrow$ High energy continuum assumed temperature independent
new analysis of spectra at different temperatures:
Below T_0 oscillator (taking into account resolution)
above T_0 quasielastic signal

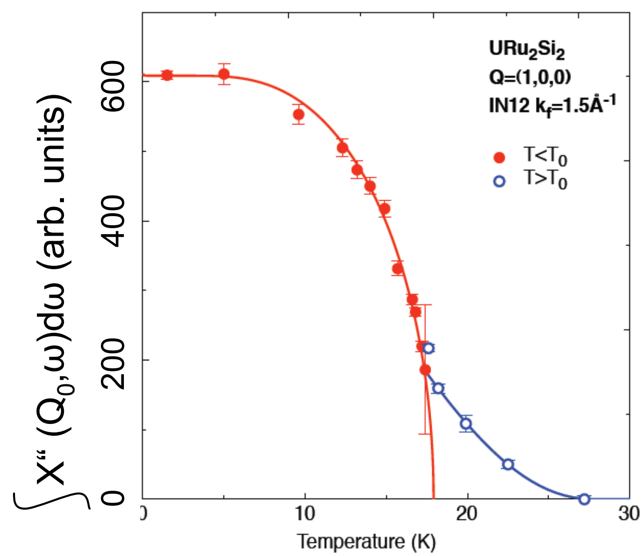


Temperature dependence









- Gap E_0 has very strong *T* dependence

At low *T*: very sharp $E_0/\gamma/2 \sim 35$

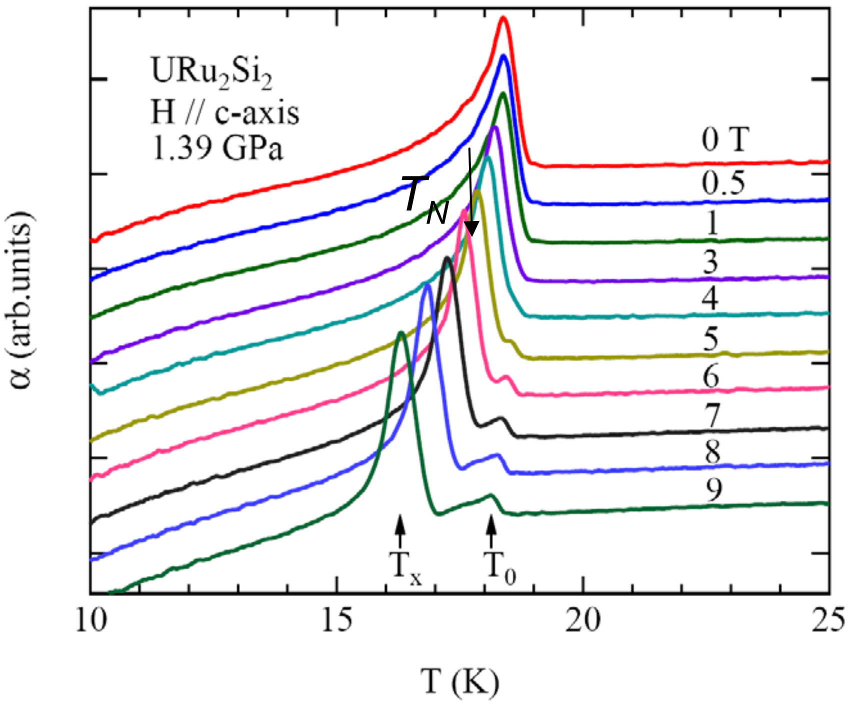
At T_0 strong damping (width becomes rapidly larger than E_0)

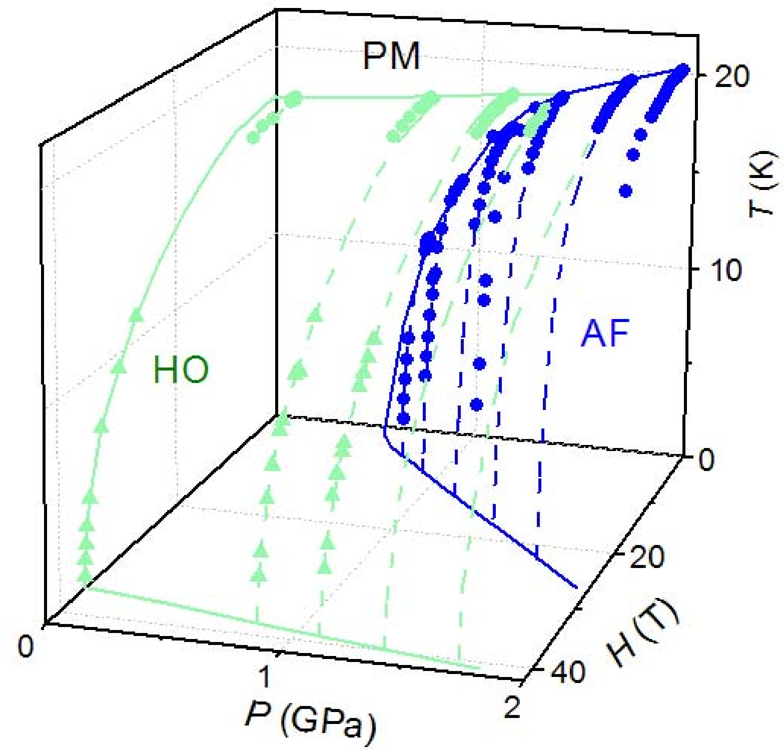
- Temperature dependence of width follows exponential behavior with characteristic energy of 7.7 meV close to Δ_G
- no divergence of χ at T_0 confirms HO is not AF
- intensity follows OP-like (BCS-like behavior)

Determination of phase diagram (*T,P,H*)

Thermal expansion measurement with strain gauge along a
For each fixed pressure, behavior of T_0, T_N or T_x in field is determined

- Transition HO-AF at T_x clearly visible
- near P_c transition splits in field

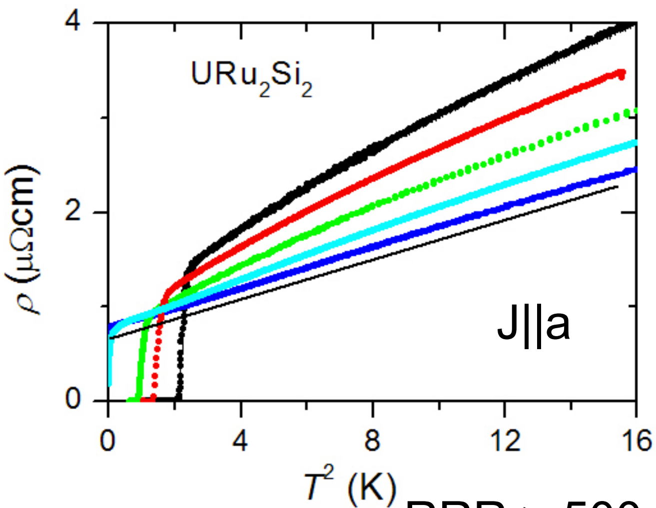




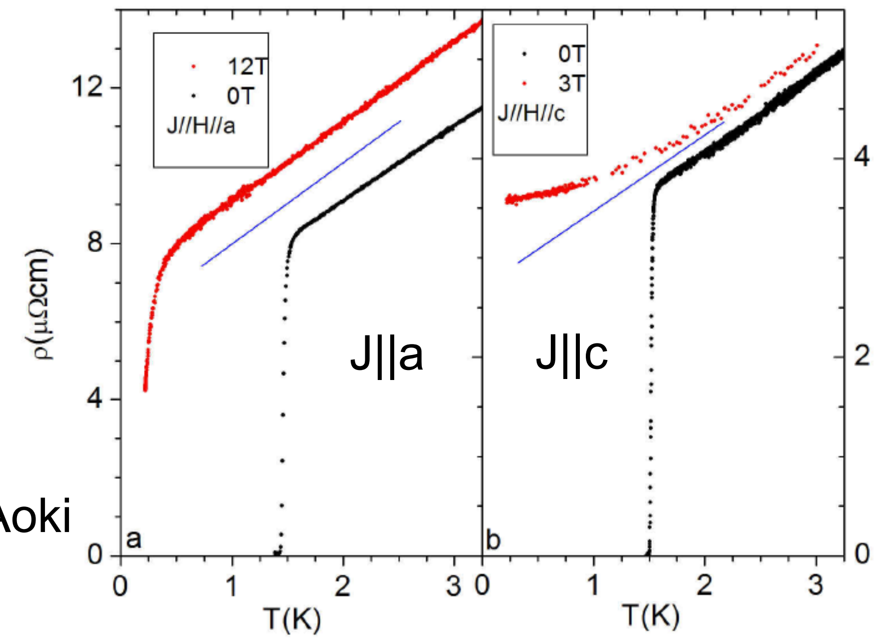
- At high pressure entrance into HO phase in field
- suppression of magnetic moment
- significant resonance at Q_0 = (1 0 0) reappears

Aoki *et al.* JPSJ 053701 (2009)

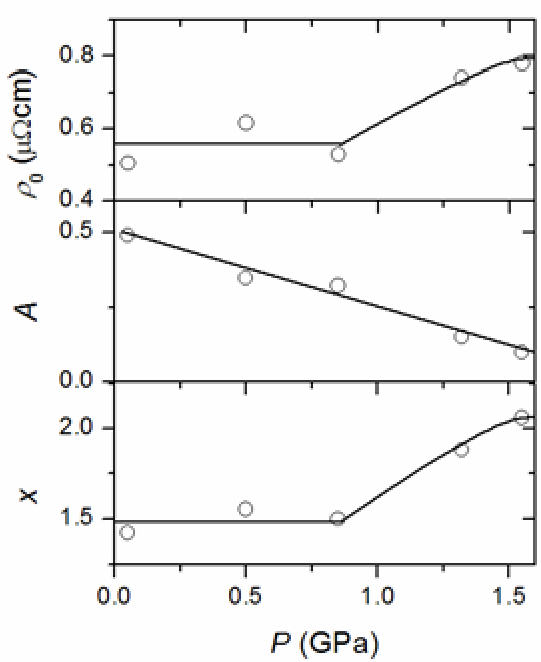
T^2 resistivity?

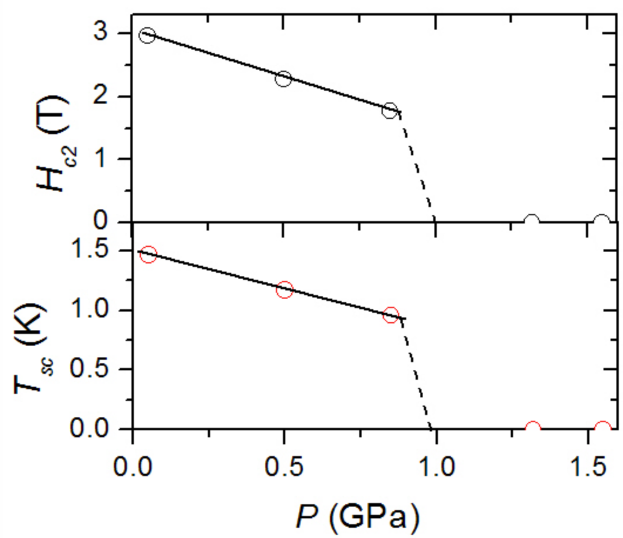


RRR > 500 made by Dai Aoki



Zhu *et al.* PRB (2009)



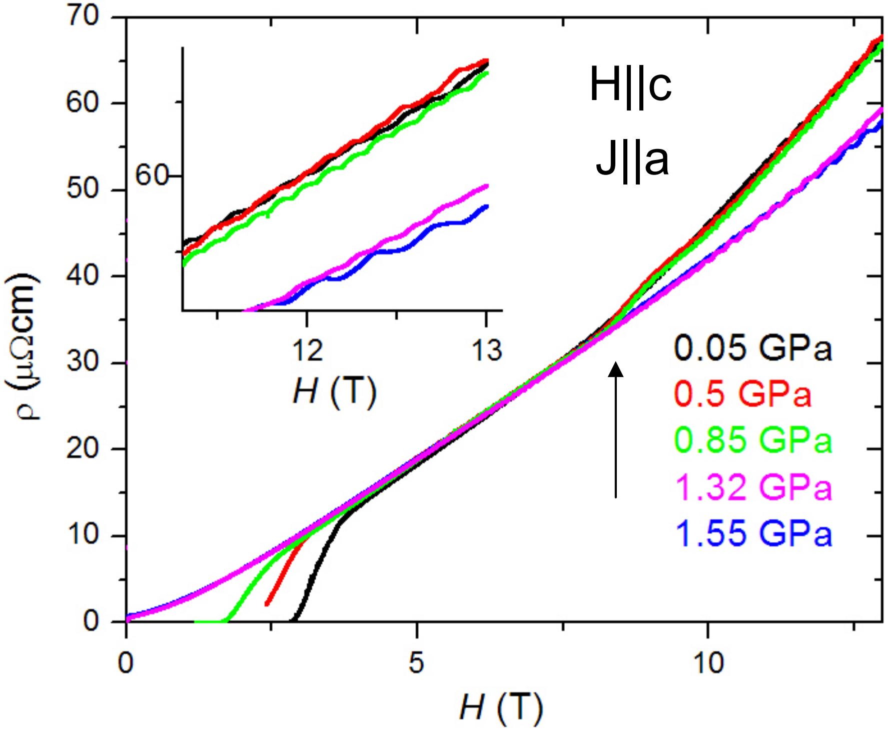


In this measurement P_x seems to be between 0.85 GPa and 1.32 GPa

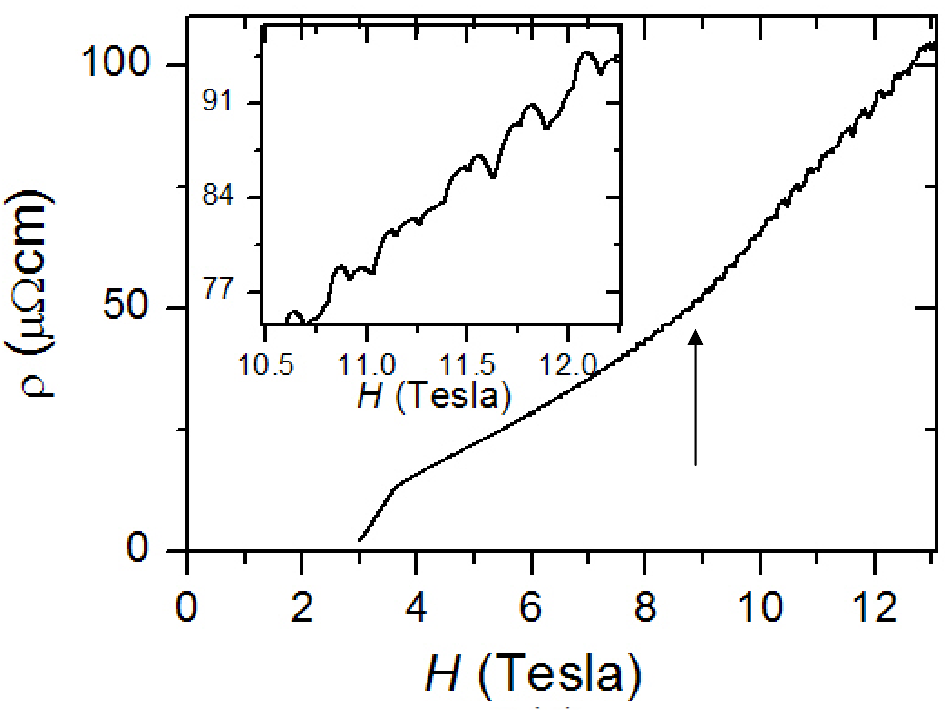
T^2 behavior only in AF phase => Extra scattering due to HO parameter

Magnetoresistance under pressure

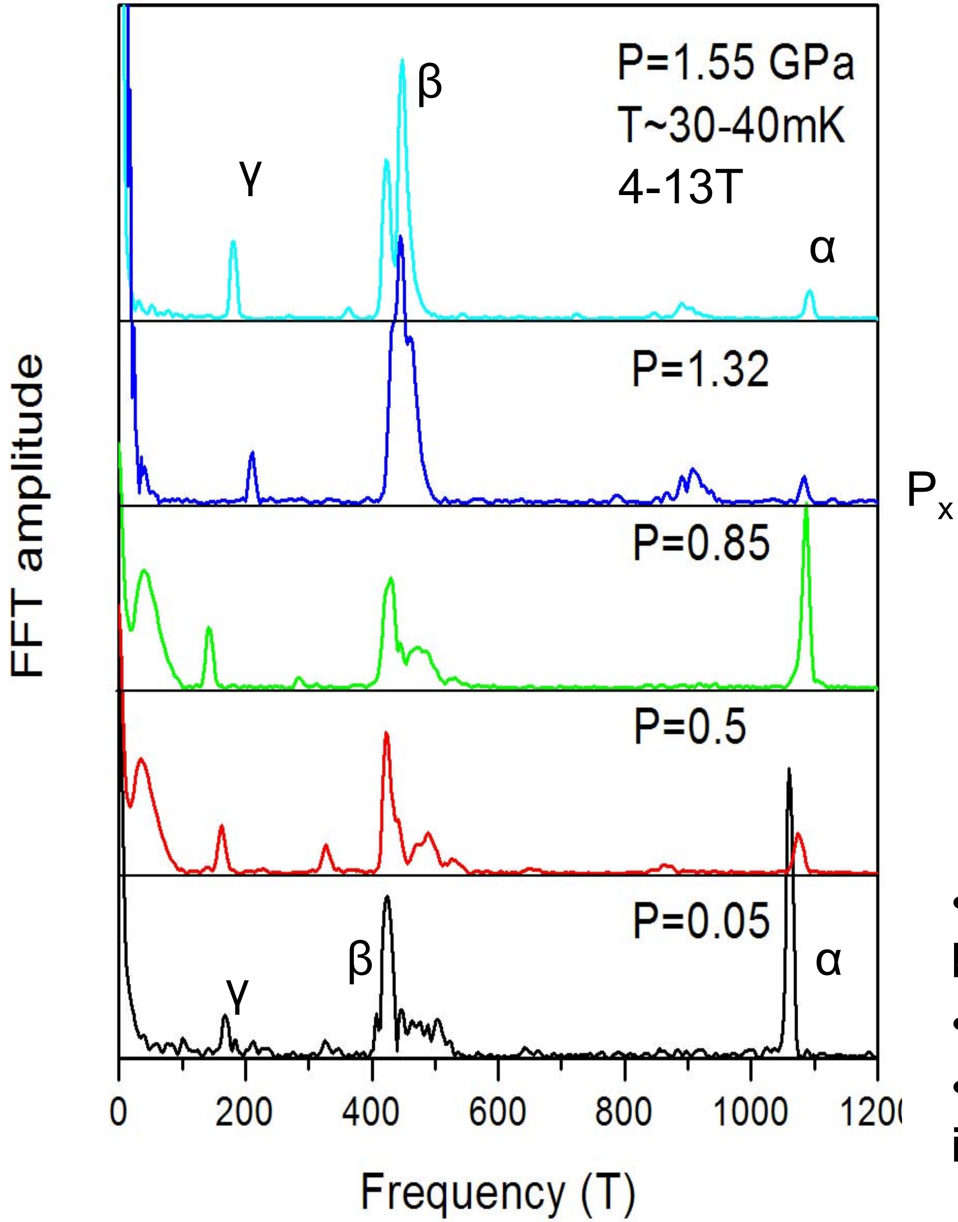
Clear Shubnikov-de Haas oscillations
At low pressures in HO kink in magnetoresistance at ~ 9 Tesla
Confirms P_x between 0.85 and 1.32 GPa

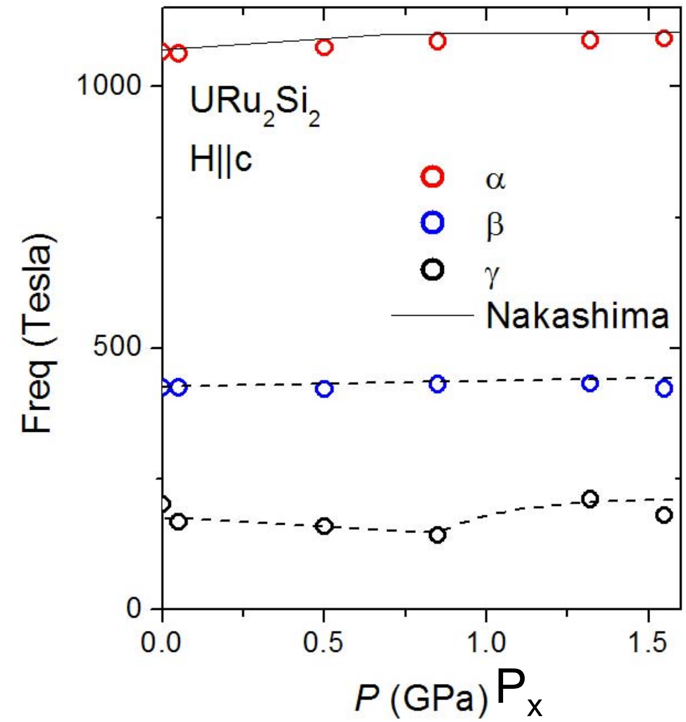


Best crystal ambient pressure



FFT spectra

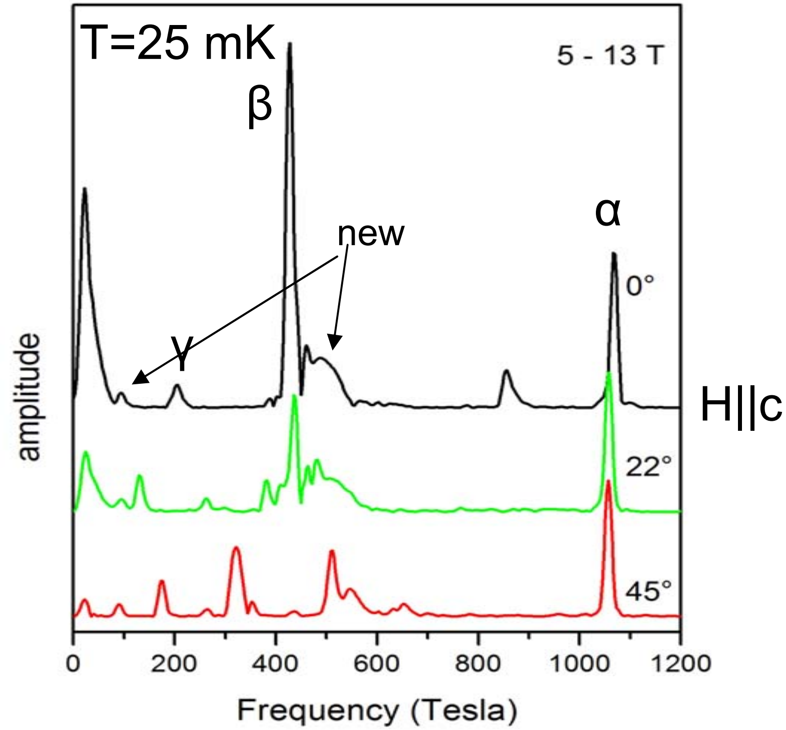


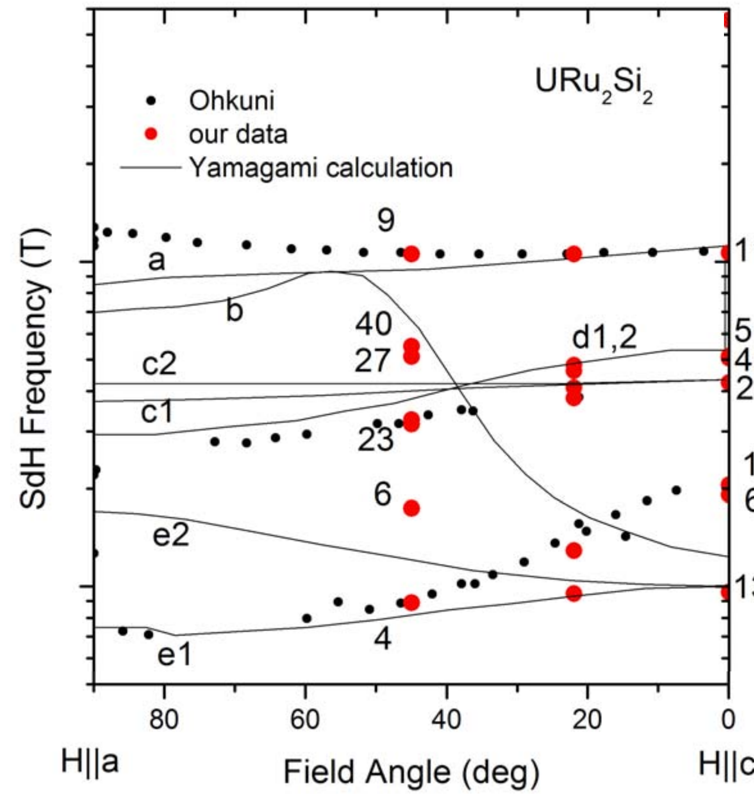


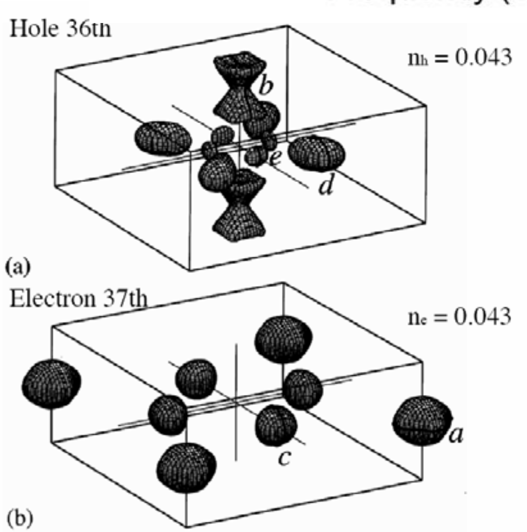
Nakashima *et al.* JPCondMat (2003)

- No big change in SdH frequencies between HO and AF for H||c
- splitting for β branch in AF
- large signal just above β branch with most important change under pressure

Angular dependence of high quality sample



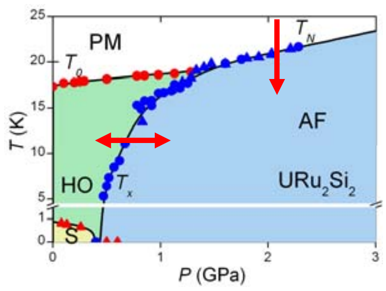




Yamagami *et al.* Physica B 2000
Ohkuni *et al.* Phil. Mag. B 1999

RRR=175= R(300K)/R(2K)
New frequencies with heavy mass
New γ of 30 mJ/molK^2 (50% of specific heat)
Test for theory

Conclusion



Indirect experimental evidence for order with Q = (001) in HO

- reconstruction of the Fermi surface at T_0 and T_N as seen in resistivity anomaly independent of pressure

- significant wave vector the same: Q_0 = (1 0 0) (in HO significant excitation, in AF static ordering vector)

- intensity of this excitation has OP-like temperature dependence

- no big changes in the FS in quantum oscillations with pressure

- new heavy bands observed