Field Induced Quantum Critical Point in YbAgGe

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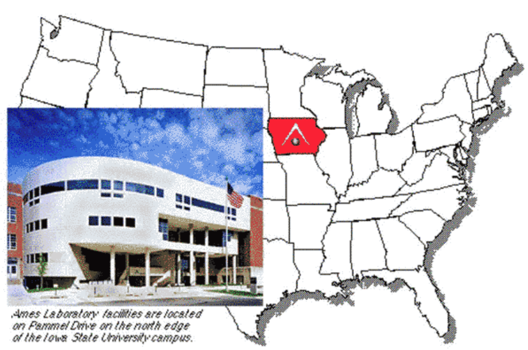
Ames Laboratory



Mid-sized DOE Laboratory with ~ 400 employees

Organized in 1947 as a part of Manhattan Project

Now:

Applied Mathematics and Computational Sciences

Chemical and Biological Sciences

Condensed Matter Physics

Environmental and Protection Sciences

Granular and Multiphase Systems

Materials Chemistry

Materials and Engineering Physics

Non-Destructive Evaluation

Also:

Biorenewable Resources Consortium

Materials Preparation Center

Iowa State University

Large Land Grant University

~25,000 Students

Known for Ag. (not Silver), Vet., and, in our circles, Physics and Chemistry associated with Ames Lab.

In collaboration with:

Emilia Morosan, Yuri Janssen, Yurij Mozharivskyj, Stephanie Law (ISU);

Björn Fåk (CEA/Grenoble), Desmond McMorrow (Univ. College /London); Philipp Niklowitz, Jacques Flouquet (CEA/Grenoble)

Discussions with:

Jörg Schmalian, Maxim Dzero (ISU) ***and I hope many of you here at the workshop.***

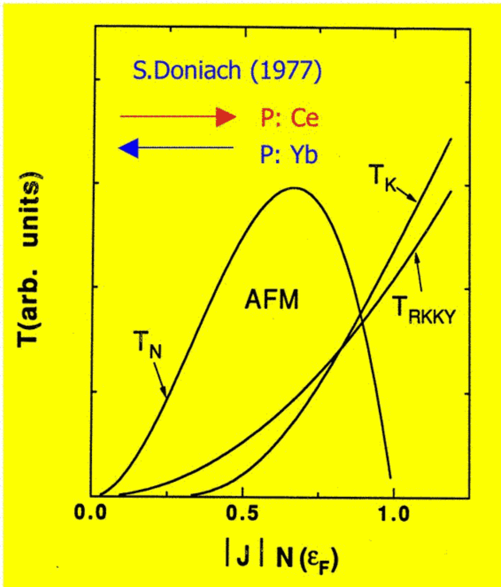
Also thanks to:

and A. Paul Ness, Marc D. McGinn (ISU)

Outline and salient papers

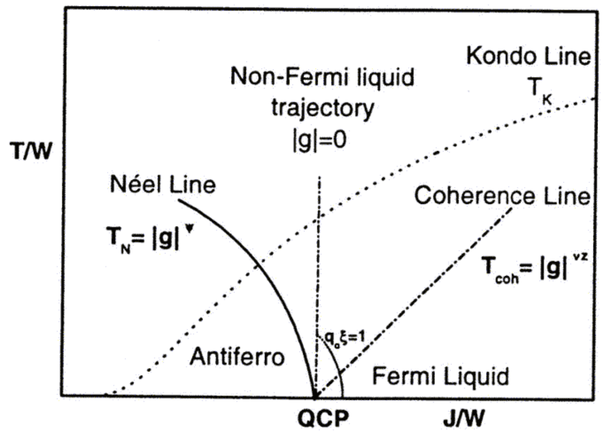
- Thermodynamic and Transport Properties of RAgGe (R = Tb – Lu) single crystals, E. Morosan et al., JMMM 277 (2004) 298. (cond-mat/0309327)
- Angular-dependent planar metamagnetism in the hexagonal compounds TbPtIn and TmAgGe, E. Morosan et al., PRB 71 (2005) xxxx. (cond-mat/0408121)
- Magnetic field induced non-Fermi-liquid behavior in YbAgGe single crystals, S. L. Bud'ko et al., PRB 69 (2004) 014415. (cond-mat./0308517)
- Hall effect in single crystal heavy Fermion YbAgGe, S. L. Bud'ko et al., PRB 71 (2005) xxxx. (cond-mat./0406435)
- Inelastic neutron scattering study of single crystal heavy fermion YbAgGe, B. Fak et al., J. Phys. Cond. Matter 17 (2005) 301
- Low temperature transport properties of YbAgGe near a quantum critical point, P. Niklowitz et al., unpublished.

Doniach's phase diagram and QCP



$T_K \propto E_F \exp(-1/|J|N(E_F))$

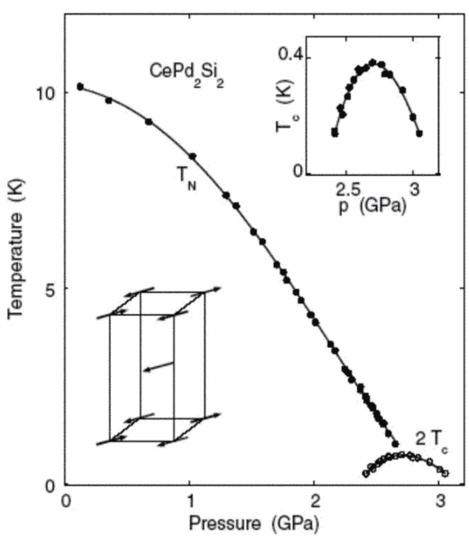
$T_{RKKY} \propto J^2[N(E_F)]$



Usually pressure or substitution

M.Continentino (1989) and many others before and mostly after…

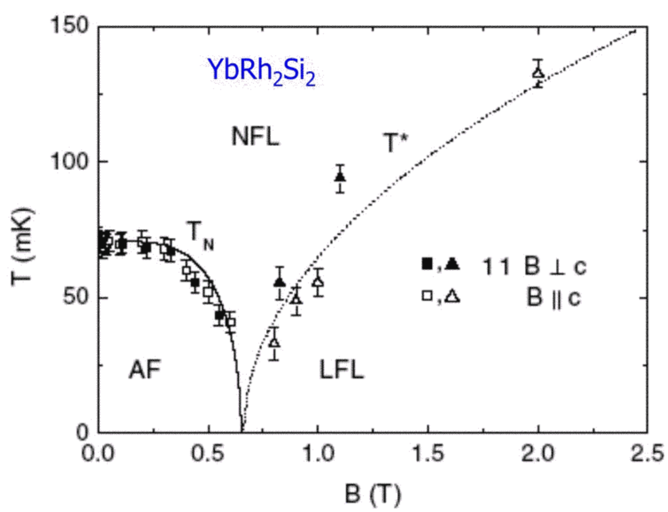
QCP – experimental examples (P, x, H)



Grosche et al., JPCM 13 (2001) 2845

(Similar results for $CeIn_3$)

pressure



Gegenwart et al., PRL 89 (2002) 056402.

applied field

QCP – experimental examples

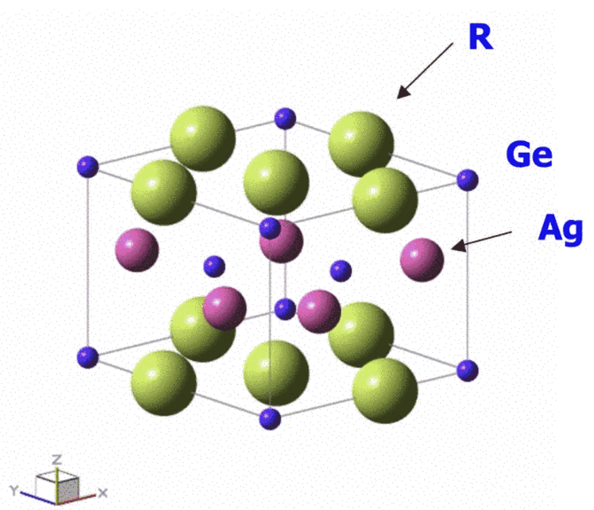
Problems: **substitution** ⇒ disorder
pressure: discontinuity, difficult

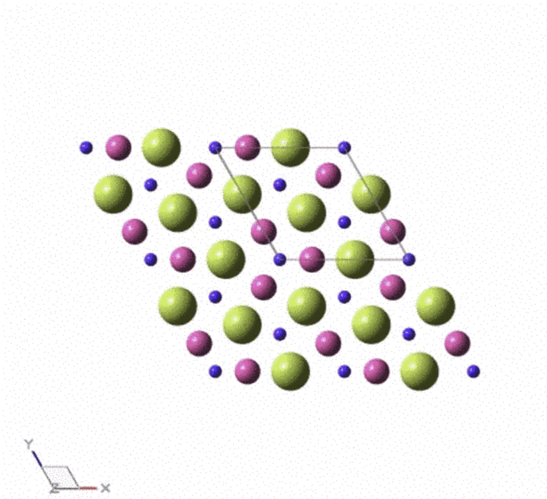
Magnetic field: continuous, more measurements are accessible.

Are P, x, H "equivalent"? Is there any single, "universal" picture?

More, "clean" examples needed!

RAgGe - structure



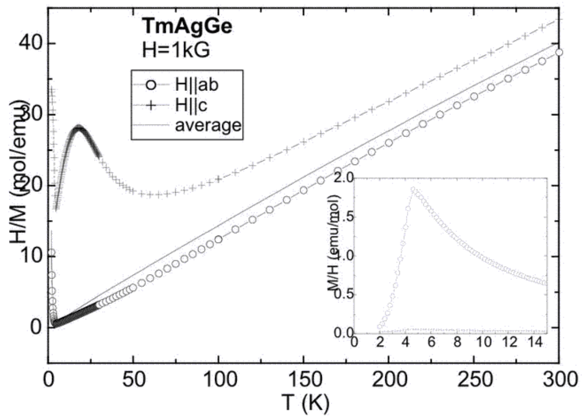


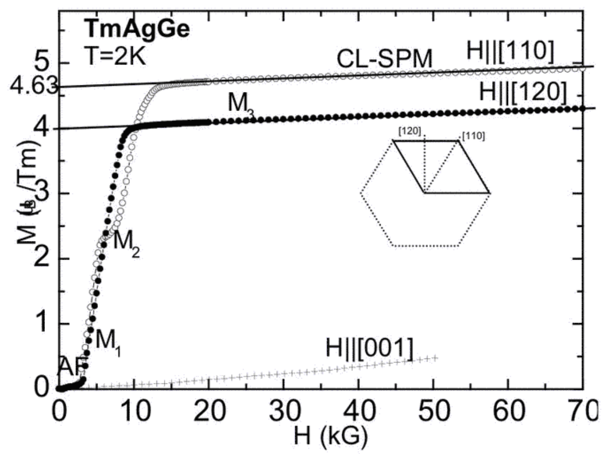
Hexagonal P-62m, R in orthorhombic point symmetry
For RAgGe overview see E.Morosan et al. JMMM 277 (2004) 298.
Lots of curious stuff: metamagnetism, "unconventional" resistivity, etc. for R = Tb-Tm.

• “**Thermodynamic and transport properties of RAgGe (R = Tb – Lu) single crystals**”, E. Morosan *et al.,* J. Magn. Magn. Mater. **277** (2004) 298 and **cond-mat/0309327**

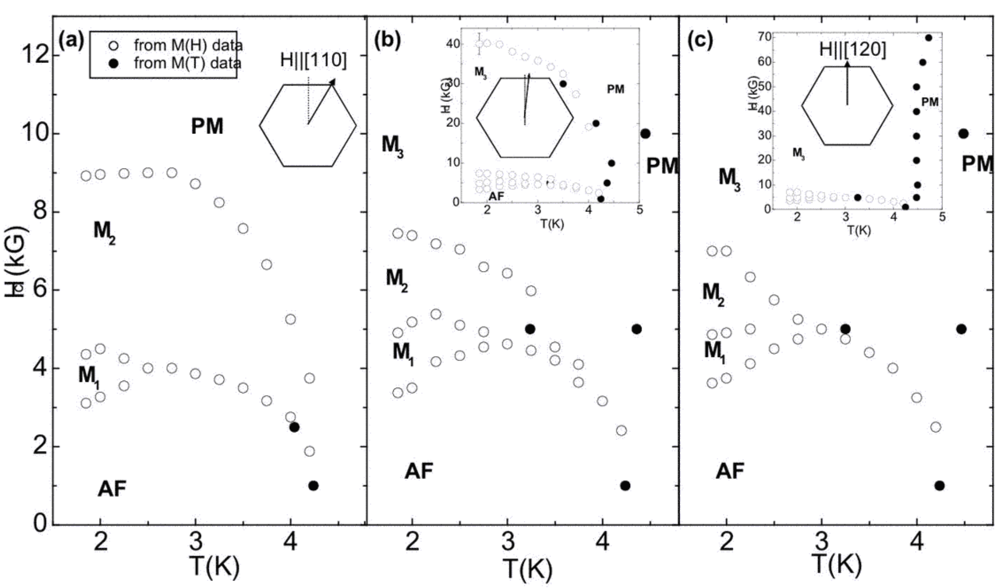
• **“Angular dependent planar metamagnetism in the hexagonal compounds TbPtIn and TmAgGe”,** E. Morosan *et al.,*Phys. Rev. B (in press) and **cond-mat/0408121**.

TmAgGe:

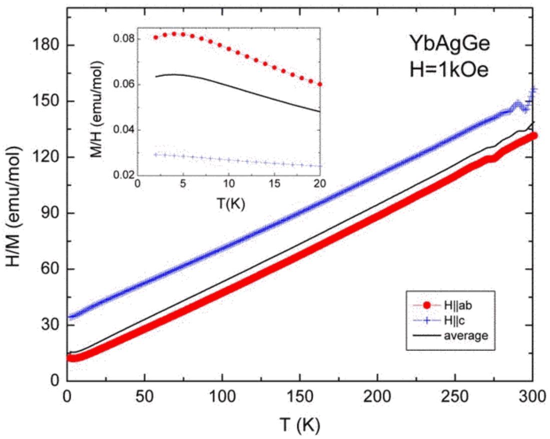


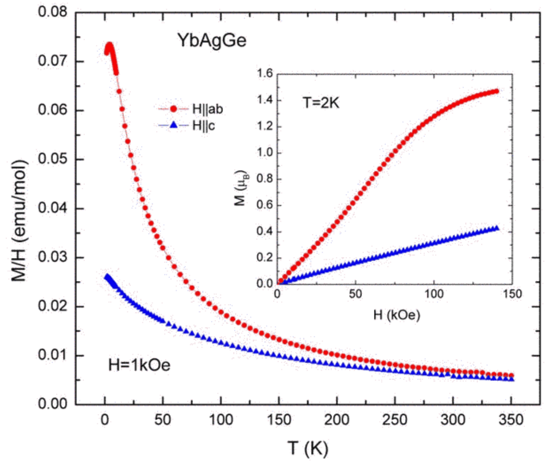


TmAgGe:



YbAgGe – basic properties



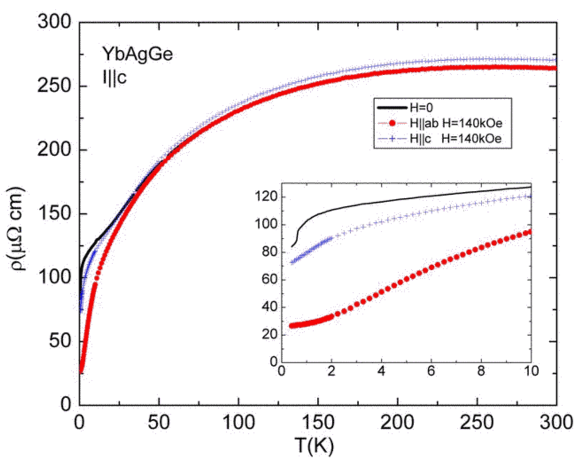


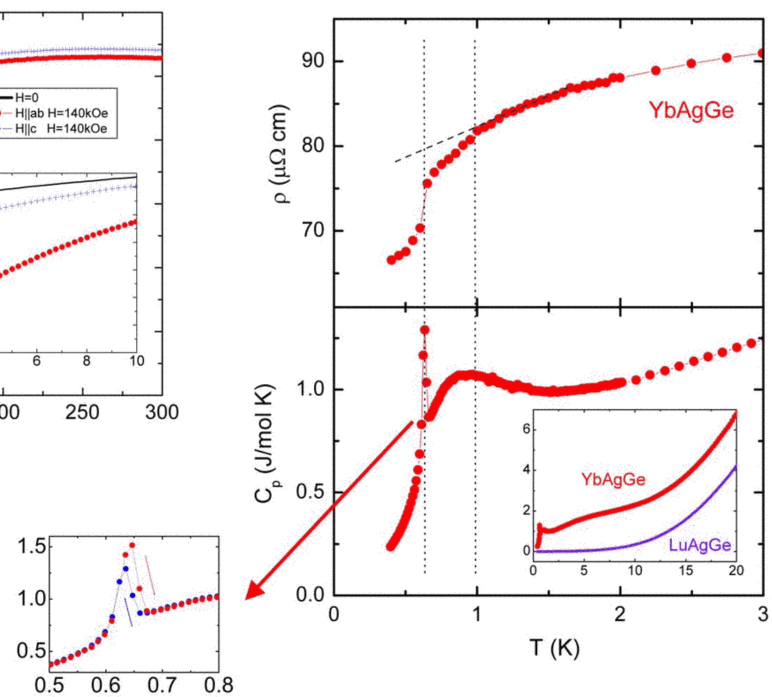
$\Theta_{ave} \approx -30$ K

Deviations from CW law in χ_{ave} below ~ 20 K

E.Morosan et al., JMMM 277 (2004) 298

YbAgGe – basic properties

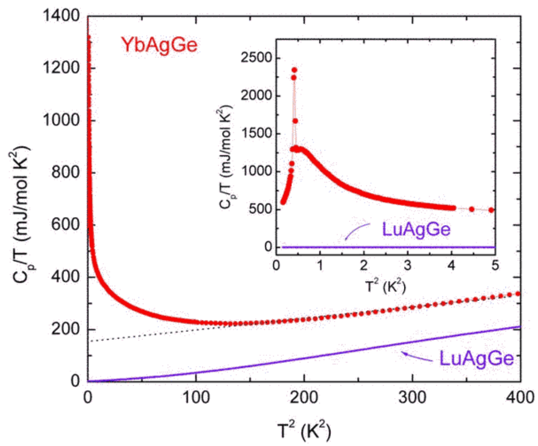


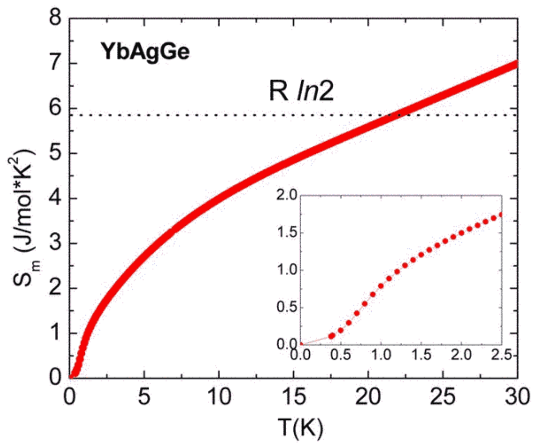


$T_M \approx 0.65$K, 1K

E.Morosan et al., JMMM 277 (2004) 298; SLB et al., PRB 69 (2004) 014415

YbAgGe – basic properties





$\gamma \approx$ 150 mJ/mol K^2 from 10K-20K range extrapolation. More realistic estimate: 150 mJ/mol K^2 $\leq \gamma \leq$ 1J/mol K^2

(i) YbAgGe is new Yb-based HF (or close to being HF)

(ii) LRO below 1K, probably small moment ordering

$\Rightarrow$ **good candidate for suppression of T_N to QCP**

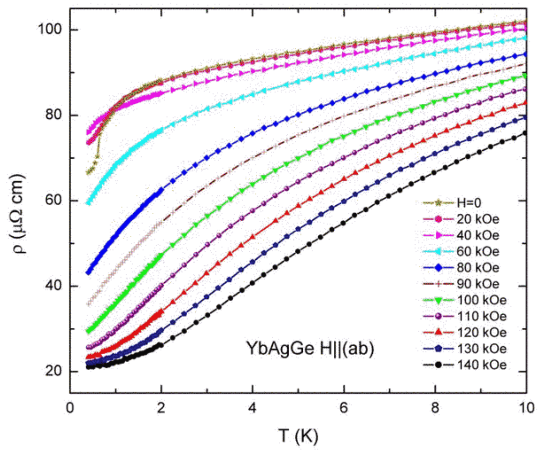
YbAgGe – estimate of some parameters

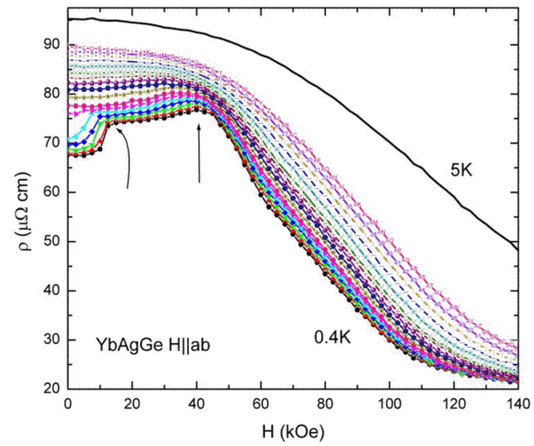
- **150 mJ/mol K^2 $\leq \gamma \leq$ 1J/mol K^2**
- $\Theta_{ave} \approx -30$ K, $\Theta/10 \leq T_K \leq \Theta \Rightarrow$ **3K $\leq T_K \leq$ 30 K**
- $T_K = w_N \pi^3 R/6\gamma$

  w_N=0.4107 (Wilson number), R – gas constant $\Rightarrow$ **15K $\leq T_K \leq$ 120 K**
- Wilson ratio: ***R*** $= 4\chi\pi^2 k_B^2/3\gamma\mu_{eff}^2 \approx$ **1.8**

  (***R*** = 1 for non-interacting electrons, ***R*** = 2 for heavy fermions)

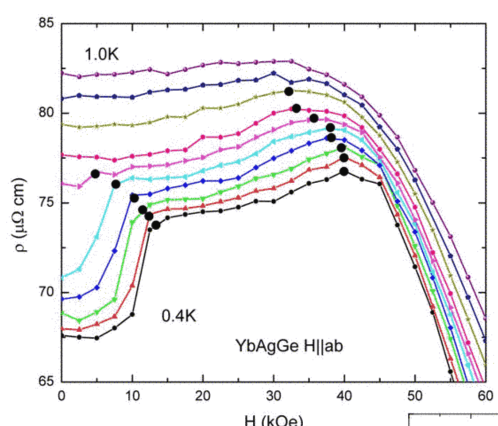
YbAgGe – resistivity in applied field

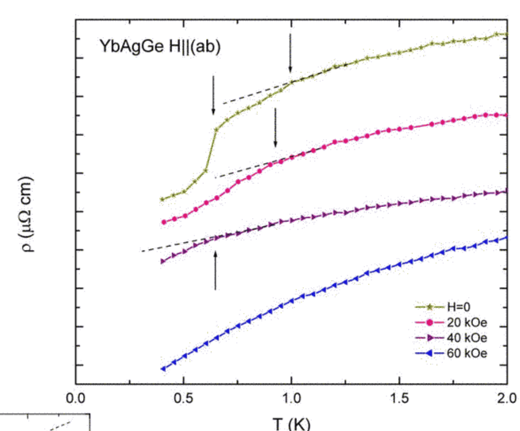


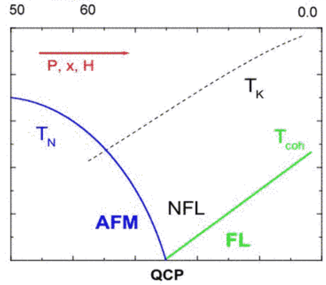


Let us look in more detail

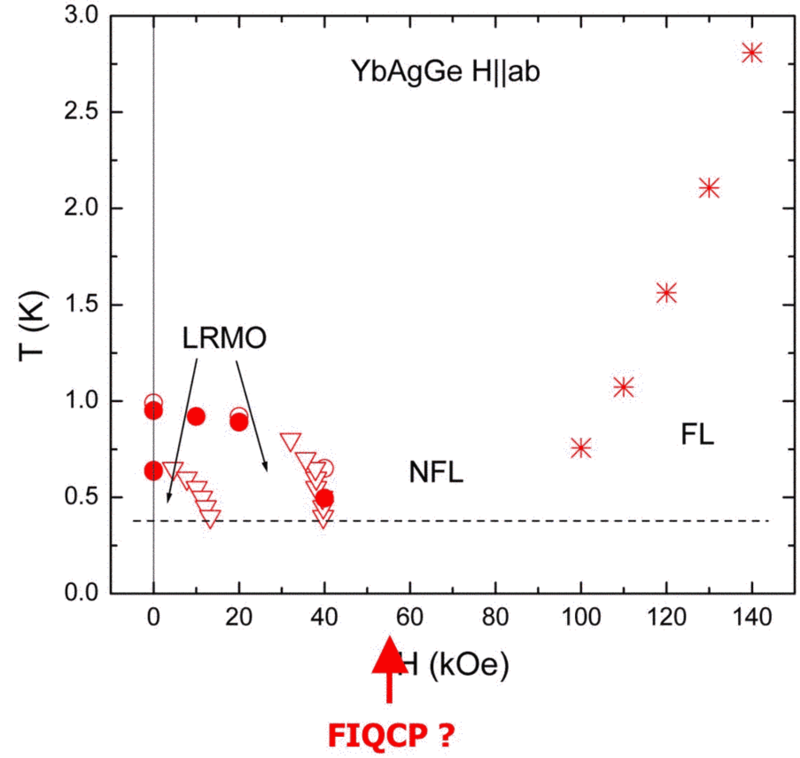
YbAgGe - ρ(T,H): shift of magnetic transitions in applied field



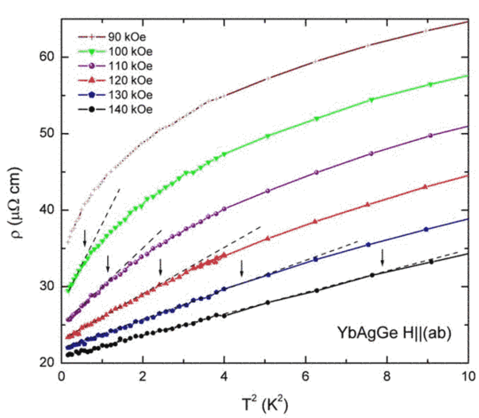


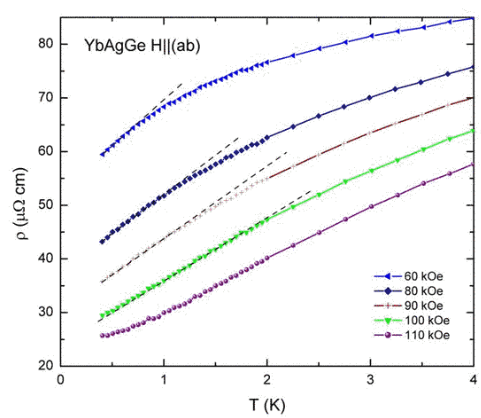


YbAgGe – phase diagrams

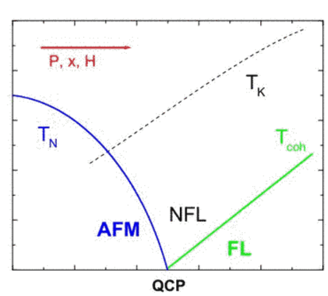


YbAgGe - ρ(T,H): Fermi-liquid vs. non-Fermi-liquid



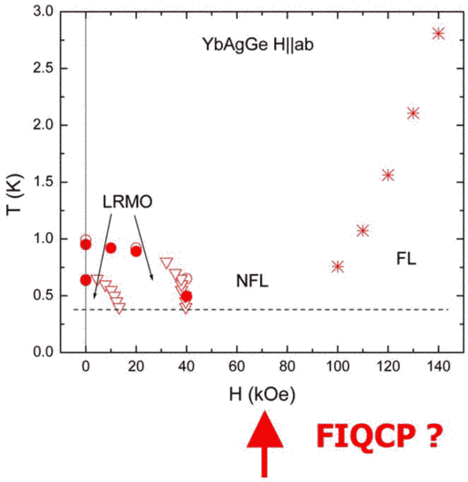


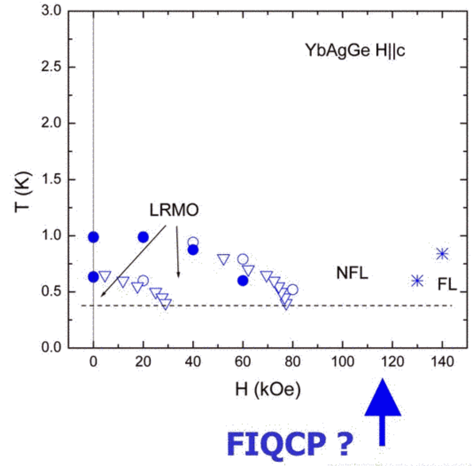
High fields:
$\rho = \rho_0 + AT^2$:
FL - like



Intermediate fields:
$\rho = \rho_0 + BT$: **NFL**

YbAgGe – phase diagrams

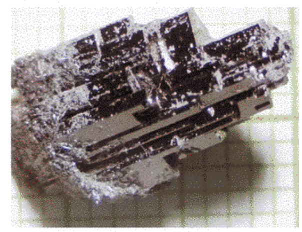




(i) Tuning via simple and clean knob – H (not P or x)

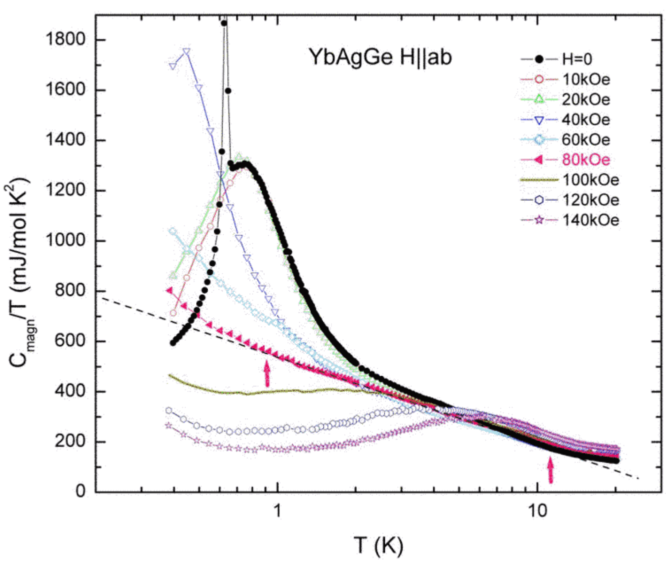
(ii) Only second stoichiometric Yb- compound to show this

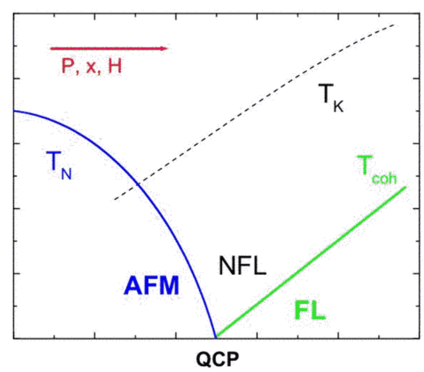
(iii) Unlike $YbRh_2Si_2$ crystals can be BIG



2 gram single crystal for scattering from Yuri Janssen

YbAgGe – heat capacity in applied field





H = 80 kOe: $C_{magn}/T \propto -ln\, T$ for over a decade in temperature

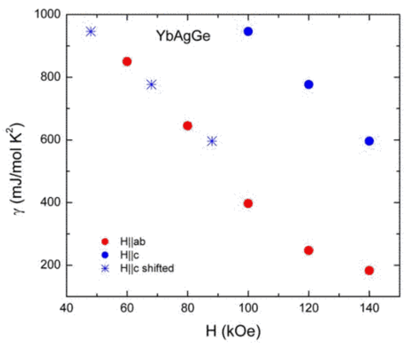
$C_{magn}/T = \gamma'_0 \ln(T_0/T)$: $\gamma'_0 \approx 144$ mJ/mol K^2; $T_0 \approx 41$ K

Also: scaling of the specific heat:

$[C(H)-C(H=0)]$ vs. H/T^{β}, $\beta = 1.15$

(observed in a number of materials with NFL properties)

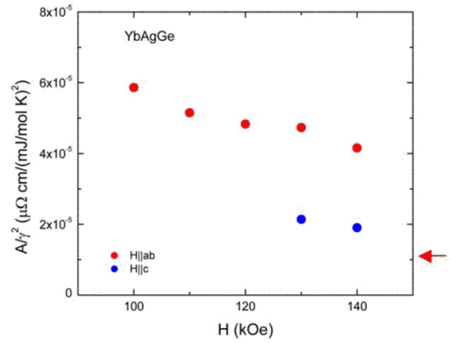
YbAgGe: resistivity and heat capacity coefficients

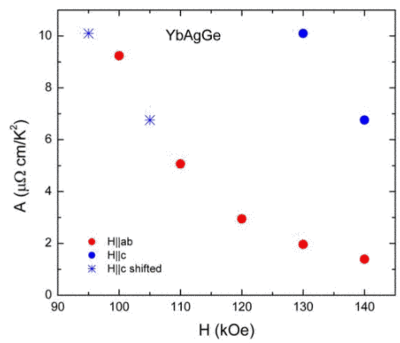


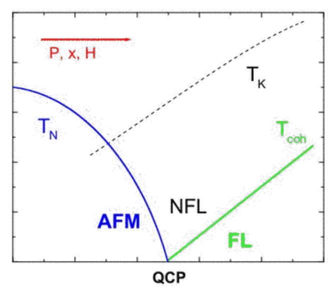
$C/T = \gamma + \beta T^2$

$\rho = \rho_0 + AT^2$

Kadowaki – Woods ratio: A/γ^2







Higher KW ratio close to magnetic instability – Takimoto & Moriya, SSC 99 (1996) 457

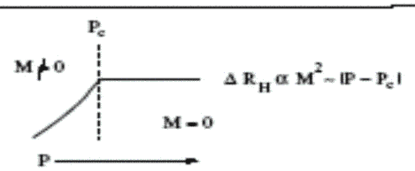
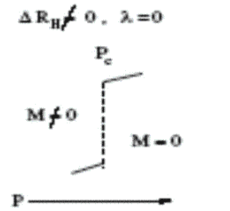
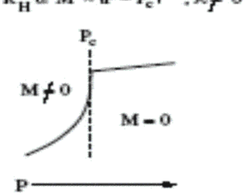
Constant – in local critical regime

Hall effect at QCP

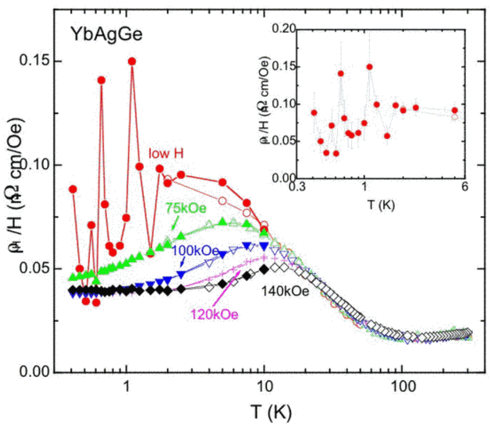
P.Coleman et al., JPCM 13 (2001) R723

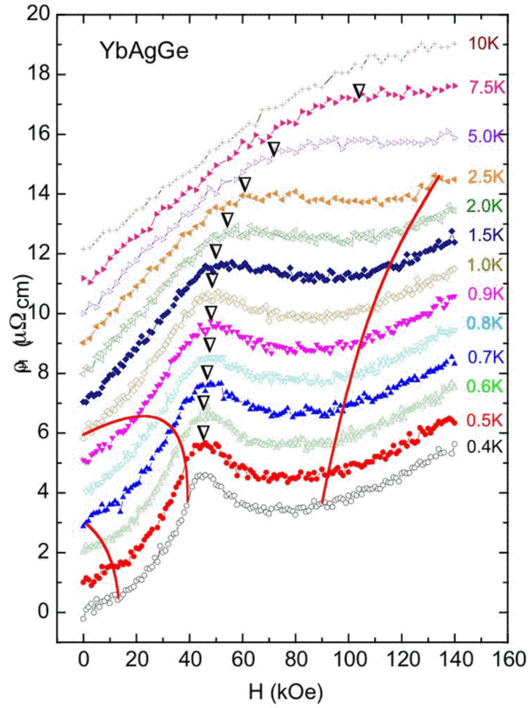
Two scenarios of quantum critical behavior:
- **SDW**
- **breakdown of composite HF**

Hall effect as a test:

Mechanism	R_H	
S. D. W.		
Breakdown of composite Fermions	$\Delta R_H \neq 0$, $\lambda = 0$ 	$\Delta R_H \propto M \sim \lvert P - P_c \rvert^{1/2}$, $\lambda \neq 0$ 

YbAgGe – Hall effect (H||ab)

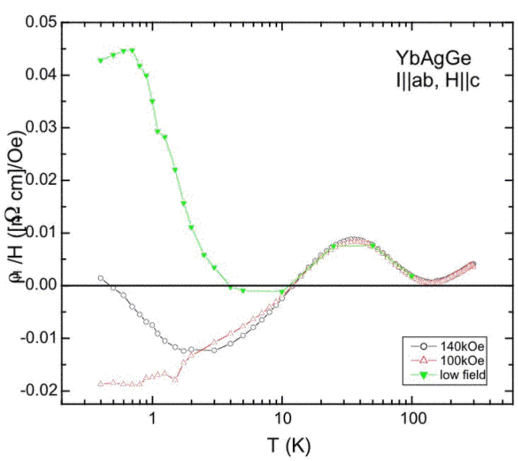


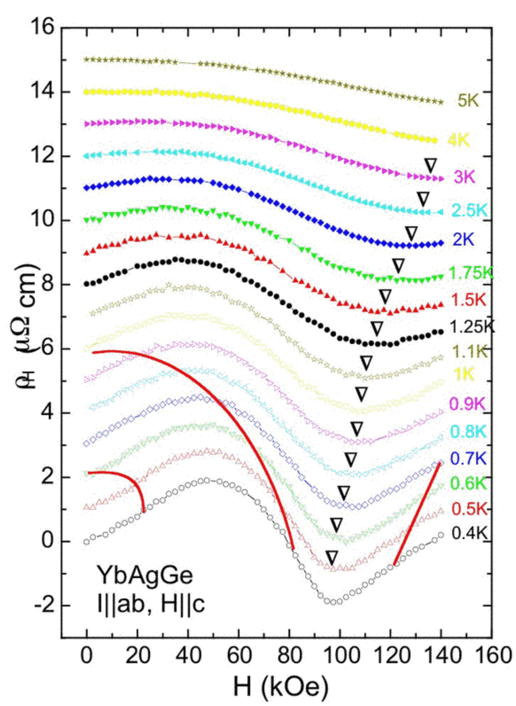


New line on the phase diagram?

SLB et al, cond-mat/0406435

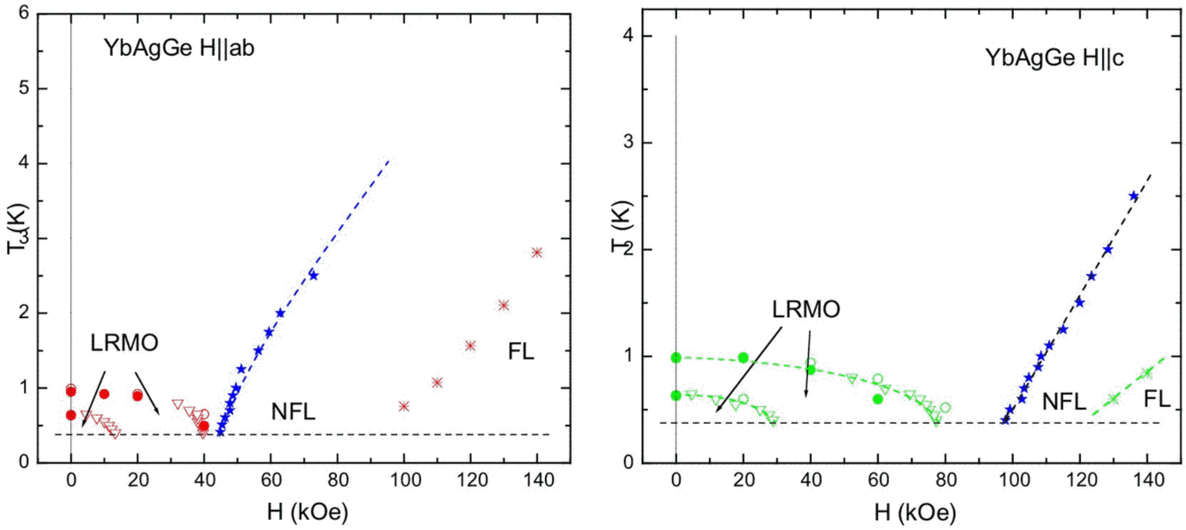
YbAgGe – Hall effect (H||c)





Similar to H||ab

YbAgGe – "revised" phase diagrams

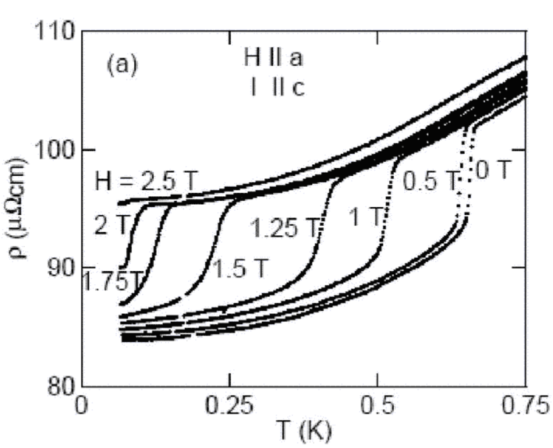


For both field orientations $\rho_H(H)$ define a new line.

From $\rho_H(H)$ no unambiguous choice between the two QCP models.

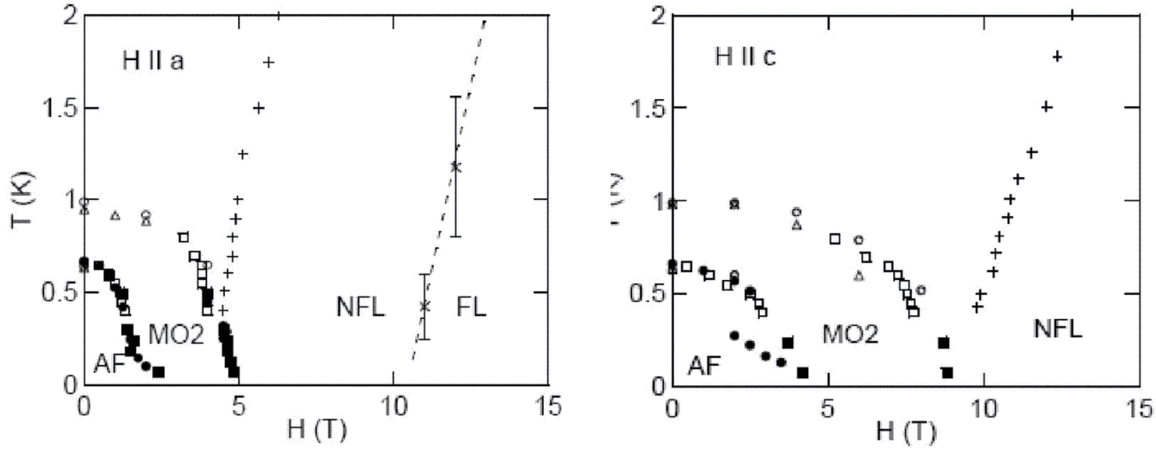
Possible FIQCP in YbAgGe – next steps

- Lower temperatures
- Neutron scattering measurements



Philipp Niklowitz, Jacques Flouquet
(CEA/Grenoble)

YbAgGe H-T Phase diagrams



Extended temperature range data from Philipp Nicklowitz et al., CEA Grenoble. These data further support identification of field induced QCP.

Possible FIQCP in YbAgGe – next steps

Other techniques:

NEUTRON SCATTERING:

(i) Find and confirm ordering (partially done) and fully determine ordered structure (ongoing).

(ii) Look at inelastic scattering near QCP (ongoing with several runs scheduled for the first quarter of '05)

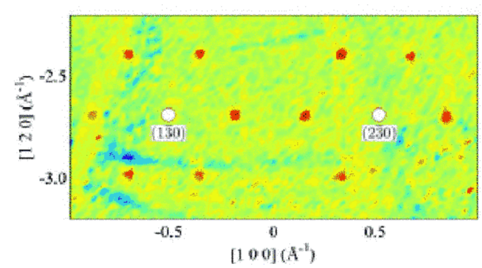


Figure 2. Color map of the low-T magnetic scattering in YbAgGe, taken as the difference between data at $T = 0.32$ and 2.0 K, in the (hk) scattering plane for $l = 1/3$. The six-fold symmetry of the magnetic satellites characterized by a propagation vector of k=(1/3,0,1/3) is easily seen.

Below 0.6 K a (1/3,0,1/3) wave vector evolves.

Björn Fåk, Desmond McMorrow, et al.

JPCM 17 (2005) 301

YbAgGe – Stiochiometric FIQCP compound

- Resistivity: decrease of $T_{magn} \Rightarrow$ linear LT resistivity $\Rightarrow$ recovery of T^2 (FL) behavior
- Heat capacity: decrease of $T_{magn} \Rightarrow C_{magn}/T \propto -\ln T \Rightarrow$ recovery of FL behavior. Scaling of [C(H)-C(H=0)] vs. H/T^{β}
- Anomaly in Hall resistivity data very clear and apparently associated with FIQCP
- FIQCP in accessible fields ($\leq$ 11T) associated with a H = 0 T_N that is also very accessible.
- One of the few stoichiometric compounds possibly showing FIQCP
- Effects are anisotropic

Conclusions:

- Yb-based heavy fermions offer fertile ground for QCP research
- They allow to address "key" question of how can correlated electron state evolve out of local moment. One can be a voyeur and watch how it happens.
- Few properties are curious and entertaining (for some).
- Potentially can shed light on few open questions in HF physics (if samples and "knobs" are under control).
- Can we find a few more so as to identify unifying trends?

Group: Novel Materials and Ground States

Two permanent members: http://cmp.ameslab.gov/personnel/canfield/

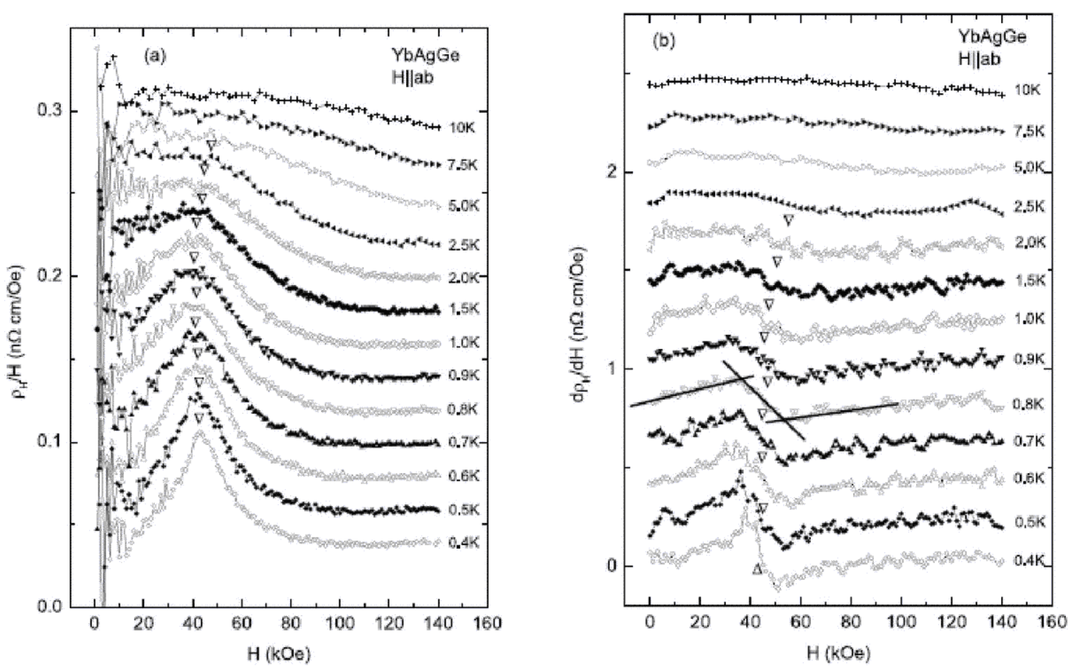
Paul C. Canfield and Sergey L. Bud'ko

in a steady state:
- 2-3 post-docs / visiting scientists
- 2-4 graduate students
- 1-3 (hourly) undergraduates

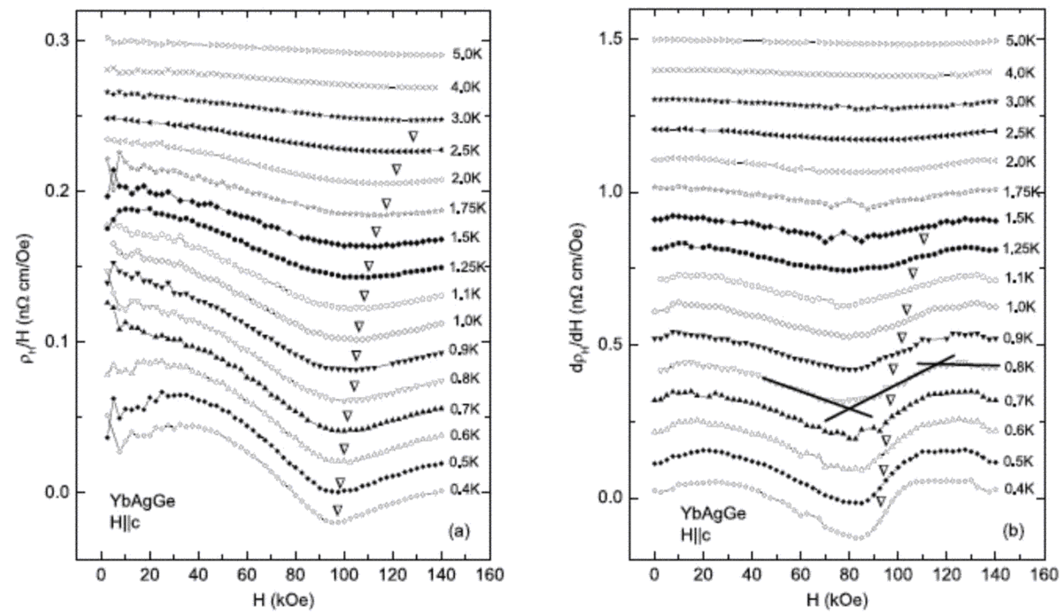
Toys:

Furnaces, arc-melter
Powder diffractometer
2_ QD MPMS magnetometers
1_ QD PPMS systems (with a few widgets and gadgets)
Polishers, wire & diamond saws, press, etc.

Easy access to Ames Lab resources



➢S. L. Bud'ko et al., PRB 71 (2005) xxxx. (cond-mat./0406435)



- S. L. Bud'ko et al., PRB 71 (2005) xxxx. (cond-mat./0406435)

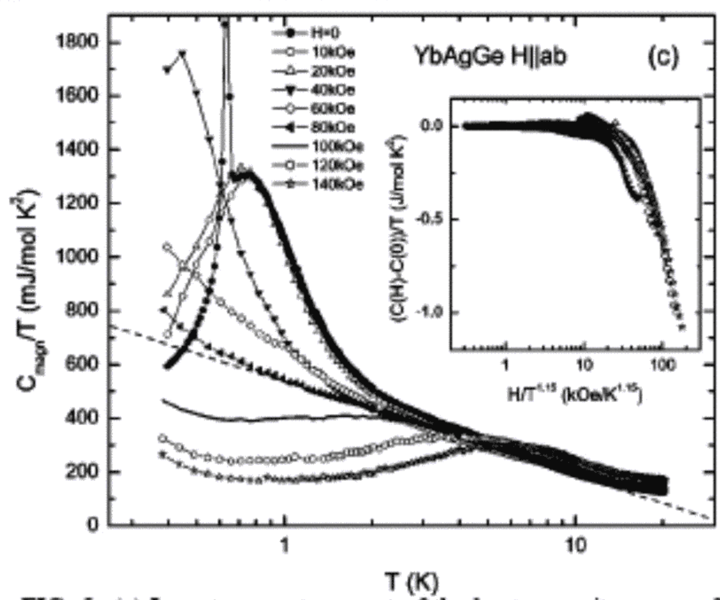


FIG. 5. (a) Low-temperature part of the heat-capacity curves for YbAgGe taken at different applied fields $H \| ab$, arrows indicate peaks associated with magnetic ordering; (b) low-temperature part of C_p vs T^2 curves; (c) *semi-log* plot of the magnetic part [$C_{magn} = C_p(\text{YbAgGe}) - C_p(\text{LuAgGe})$] of the heat capacity, C_{magn}/T vs T, for different applied magnetic fields, dashed line is a guide to the eye, it delineates linear region of the $H = 80$ kOe curve; inset: *semi-log* plot of $[C(H) - C(H=0)]/T$ vs $H/T^{1.15}$ ($T \geqslant 0.8$ K), note approximate scaling of the data for $H \geqslant 60$ kOe.

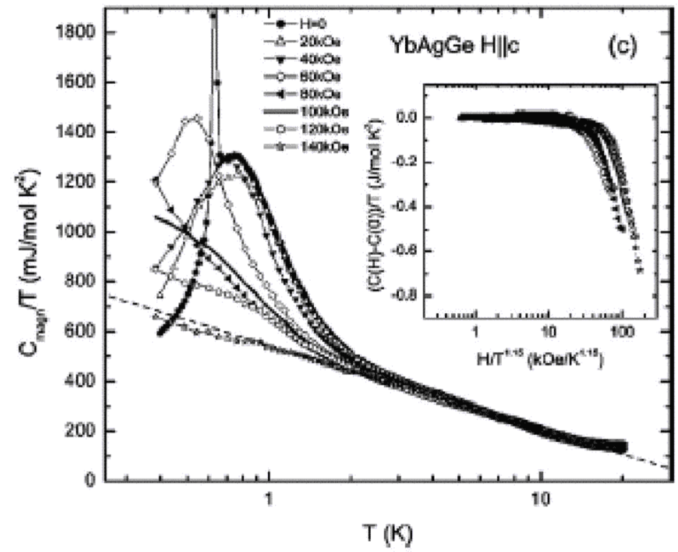


FIG. 8. (a) Low-temperature part of the heat-capacity curves for YbAgGe taken at different applied fields $H \| c$, arrows indicate peaks associated with magnetic ordering; (b) low-temperature part of C_p vs T^2 curves; (c) *semi-log* plot of the magnetic part $[C_{magn} = C_p(\mathrm{YbAgGe}) - C_p(\mathrm{LuAgGe})]$ of the heat capacity, C_{magn}/T vs T, for different applied magnetic fields, dashed line is a guide to the eye, it delineates linear region of the $H = 140$ kOe curve; inset: *semi-log* plot of $[C(H) - C(H=0)]/T$ vs $H/T^{1.15}$ $(T \geqslant 0.8$ K$)$, note approximate scaling of the data for $H \geqslant 100$ kOe.

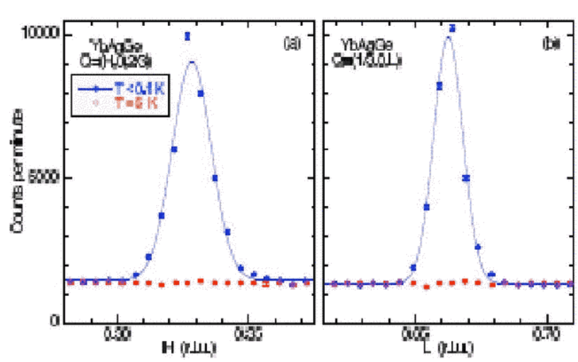


Figure 3. Scans at zero energy transfer along the (a) h and (b) l direction of the Q=(1/3,0,2/3) magnetic Bragg peak of YbAgGe measured on IN14 using $k_f = 1.3$ Å^{-1}. Closed and open circles correspond to temperatures of 0.1 and 5.0 K, respectively. The lines are Gaussian fits.

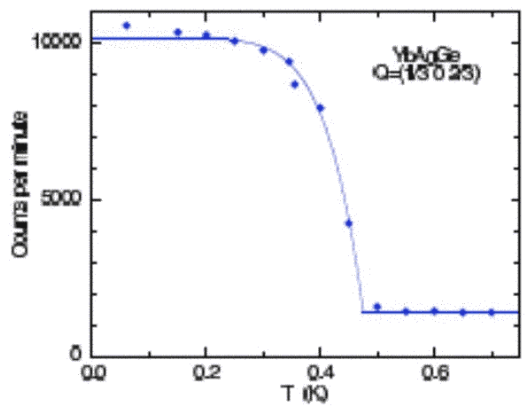


Figure 4. Temperature dependence of the magnetic Bragg peak intensity at Q= $(1/3, 0, 2/3)$ of YbAgGe measured on IN14 using $k_f = 1.3$ Å^{-1}. The line is a guide to the eye.

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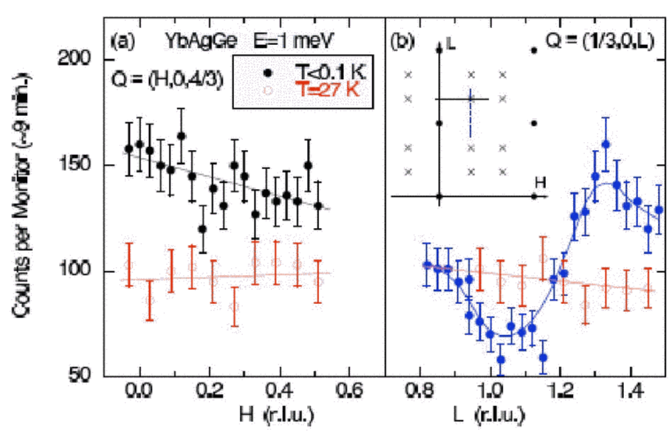

Figure 6. Scans in wave vector Q along the (a) h and (b) l direction of the spin-fluctuation scattering at an energy transfer of $E = 1$ meV, measured on IN14 using $k_f = 1.30$ Å^{-1}. Closed and open circles correspond to $T < 0.1$ and $T = 27$ K, respectively. The lines are guides to the eye. The inset shows the scan directions in the $(h0l)$ plane.

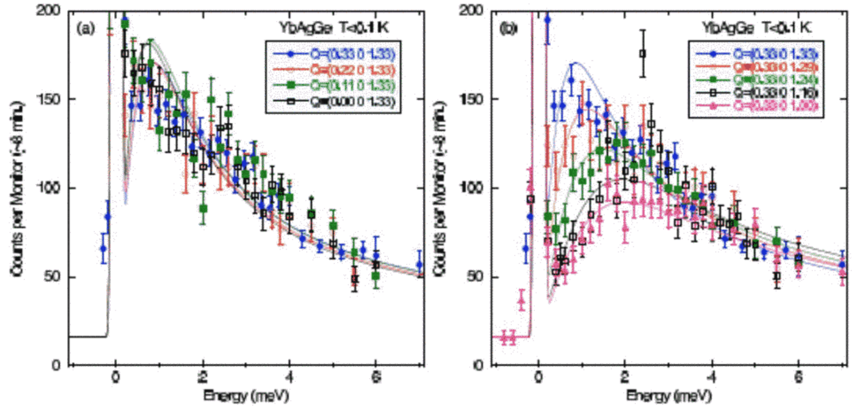

Figure 7. Energy scans of the quasielastic magnetic scattering at low temperatures, $T < 0.1$ K, for different $\mathbf{q}$ values along the (a) h and (b) l direction, measured on IN14 using $k_f = 1.30$ Å^{-1}. The lines are fits to a quasielastic Lorentzian, Eqs. (1-2), plus a Gaussian describing the elastic scattering.

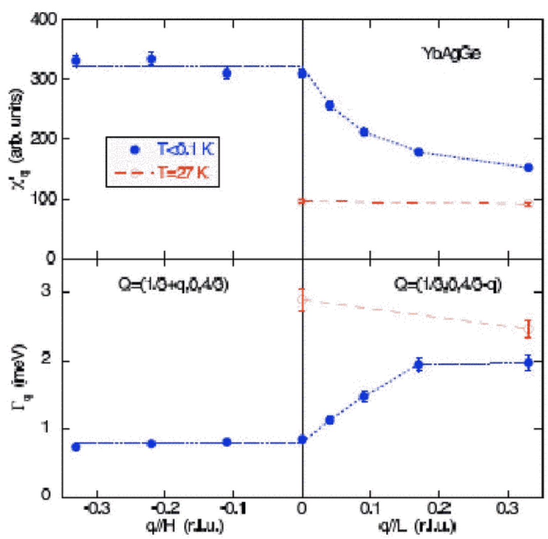

Figure 8. Wave vector dependence of the static susceptibility $\chi'_{\rm q}$ and the characteristic energy $\Gamma_{\rm q}$ of the quasielastic magnetic scattering along the h (left part) and l (right part) direction at $T < 0.1$ K (closed circles) and $T = 27$ K (open circles). The lines are guides to the eye.

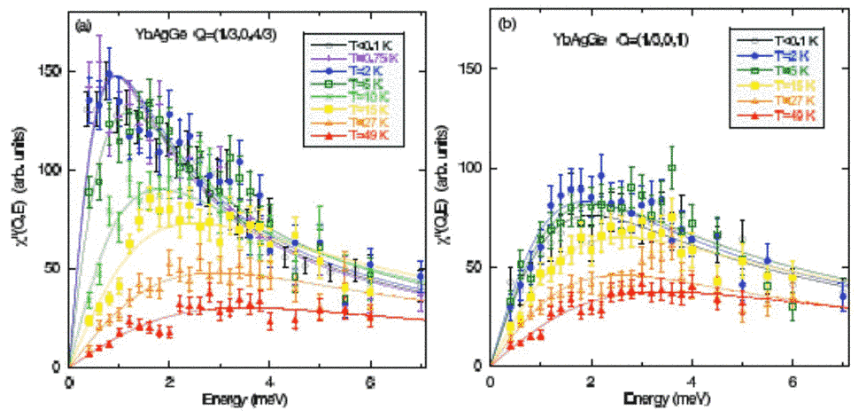

Figure 9. Dynamic magnetic susceptibility for different temperatures at (a) the AFM zone center **Q**=(1/3,0,4/3) and (b) the AFM zone boundary **Q**=(1/3,0,1), measured on IN14 using $k_f = 1.30$ Å^{-1}. The lines are fits to a quasielastic Lorentzian, Eq. (2).

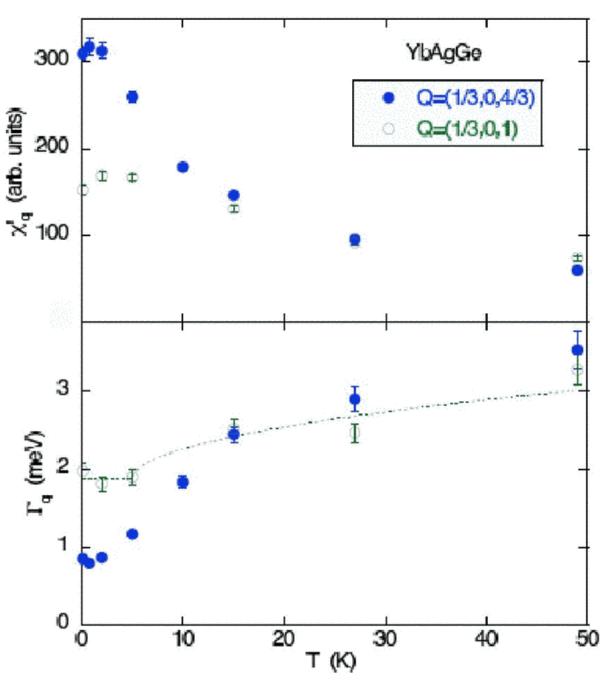

Figure 10. Temperature dependence of the static susceptibility $\chi'_{\mathbf{q}}(T)$ and the characteristic energy $\Gamma_{\mathbf{q}}(T)$ of the quasielastic magnetic scattering at the AFM zone center **Q**=(1/3,0,4/3) (solid circles) and at the AFM zone boundary **Q**=(1/3,0,1) (open circles). The dashed line shows a fit of Eq. (3) to the zone boundary energy Γ_0.

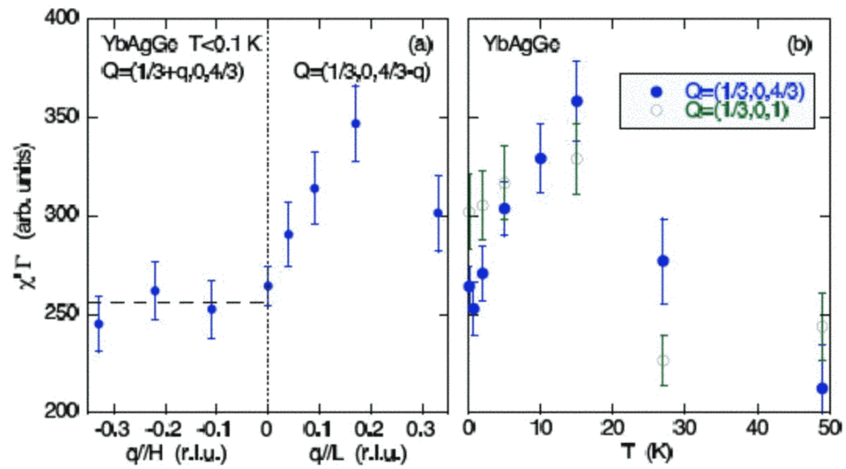

Figure 11. The product $\chi'\Gamma$ of the static susceptibility $\chi'_{\mathbf{q}}(T)$ and the characteristic energy $\Gamma_{\mathbf{q}}(T)$ of the quasielastic magnetic scattering. (a) $\chi'\Gamma$ as a function of **q** along h (left part) and l (right part). (b) $\chi'\Gamma$ as a function of temperature for **q** at the antiferromagnetic zone center and at the zone boundary.

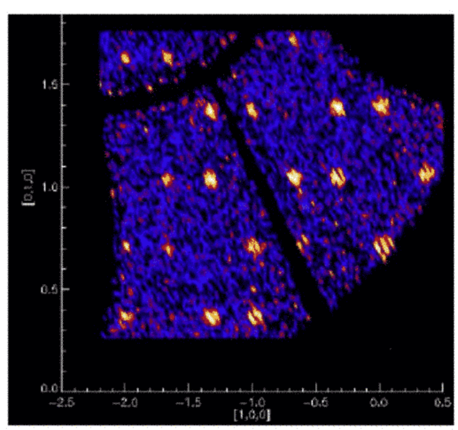

Figure 1: (hk) scattering plane of YbAgGe. Shown is the difference in intensity between $T = 0.32$ and 2.0 K.