Discussion on Quantum Criticality of Heavy-Fermion Systems

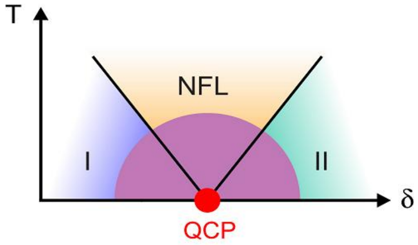
Hilbert v. Löhneysen

Karlsruhe Institute of Technology (KIT)

KITP Program
Intertwined Order and Fluctuations in Quantum Materials

Santa Barbara, September 28, 2017

1. Introduction
2. Quantum criticality of $CeCu_{6-x}Au_x$
3. Entropy landscape near quantum criticality



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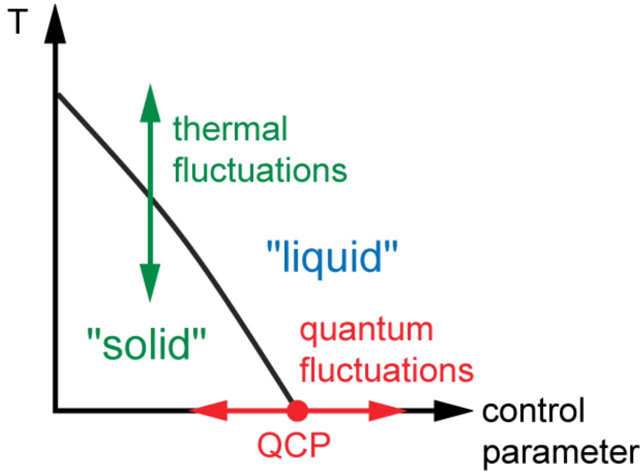
The Standard Model of phase transitions: Ginzburg-Landau-Wilson theory

V. Ginzburg

Universality:

critical behavior (exponents α, β, γ, ν, ...) depend on spatial dimension and symmetry of the order parameter only because correlation length diverges at T_c, $\xi \sim |T - T_c|^{-\nu}$

correlation time: $\tau \sim \xi^z$ ("critical slowing down")



G. K. Wilson

J. A. Hertz

$T_c \to 0$: energy of fluctuations $\hbar/\tau$ important: temperature sets the system size in the time direction: $d \to d + z$

Problem: low-energy fermions

The Standard Model of Metals: Landau Fermi-liquid theory

L. D. Landau

1:1 correspondence between excitations of interacting and noninteracting systems:

"Fermi liquid"

Electron-electron interactions parametrized by a few parameters: m^*, F_0^a, F_0^s, ...

$$C = \gamma T = \frac{m^*}{m_0}\gamma_0 T; \quad \chi = \frac{m^*}{m_0}\frac{1}{1+F_0^a}\chi_0$$

$$\Delta\rho \sim T^2$$

Even "heavy fermions" with $m^* \sim 100\, m_0$, can be decribed as Fermi liquids

Since ~ 1990: many systems show deviations:
"non-Fermi liquids"

Distinctly different physical origins of NFL behavior

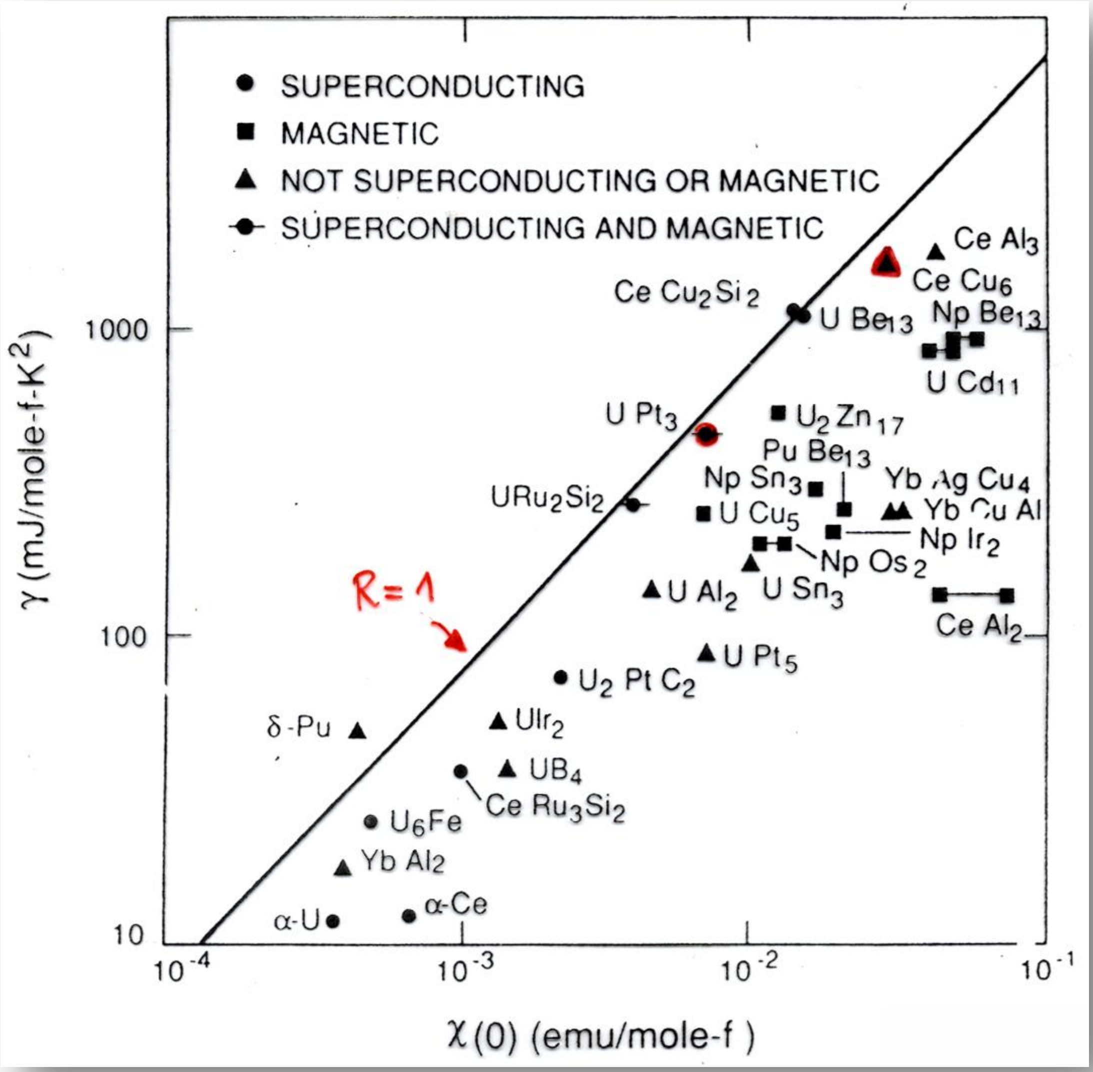
Multichannel Kondo effect
Distribution of Kondo temperatures
Quantum phase transitions

Wilson relation between the specific-heat coefficient γ and the Pauli susceptibility χ

Z. Fisk et al.

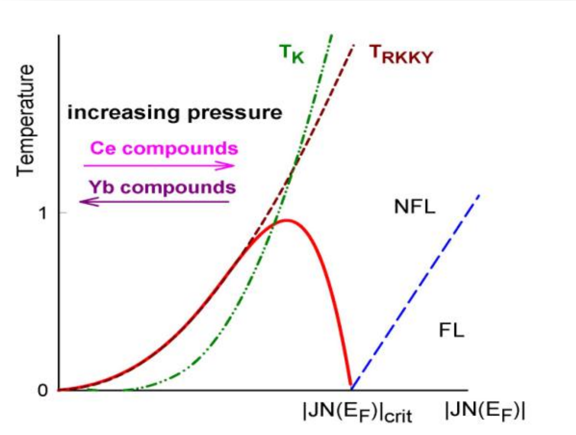
Heavy-fermion systems:

$F_0^a \sim -0.5$



Competing interactions with the possibility of quantum phase transitions

Heavy-fermion metals: Kondo vs. RKKY interaction



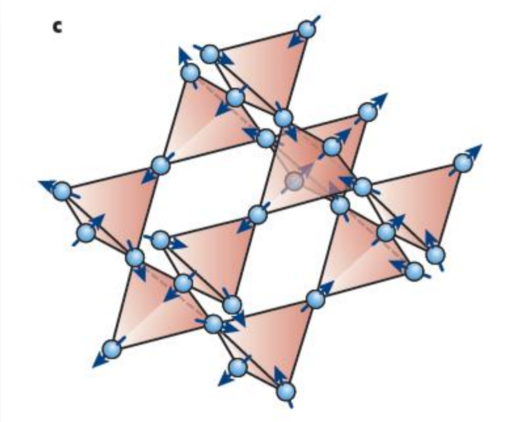
onsite – intersite competition

Doniach “phase diagram“

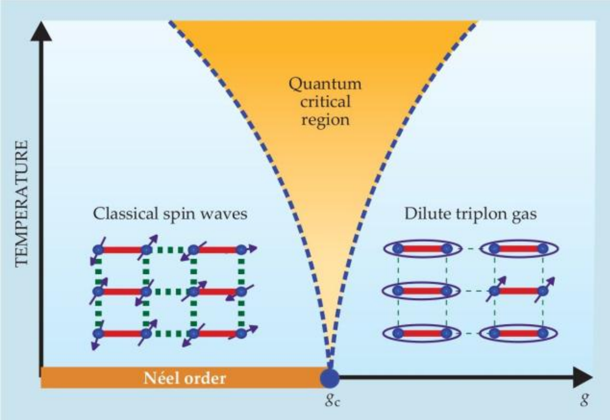
S. Doniach, Physica ***91B,*** *231 (1977)*

Competing nn or nn/nnn interactions in insulating magnets

Geometric frustration of nn interactions



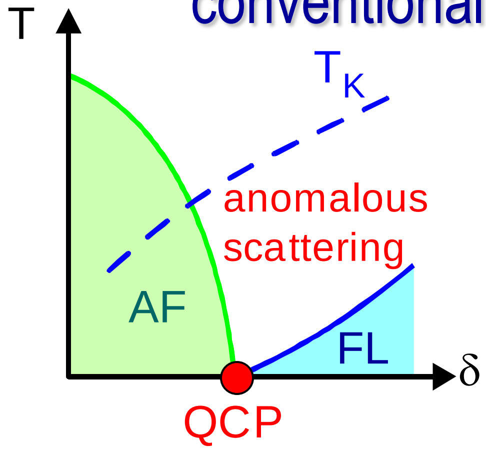
Competing nn and nn interactions



S. Sachdev, B. Keimer, Physics Today ***64*** *(2), 29 (2011)*

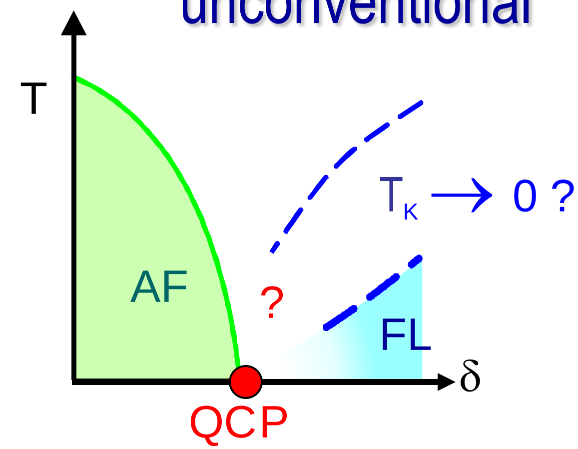
Scenarios for quantum criticality in heavy-fermion systems

"conventional"



Scattering of heavy quasiparticles
by spin fluctuations:
diverging m^* for 3D FM and 2D AF

"unconventional"



Unbinding of composite
heavy quasiparticles;
local quantum criticality

$CeCu_2Si_2$ | $Ce_{1-x}La_xRu_2Si_2$ | $CePd_2Si_2$ | $UCu_{5-x}Pd_x$ | $CeCu_{6-x}Au_x$ | $YbRh_2Si_2$

$CeNi_2Ge_2$

Critical quasiparticles

Abrahams, Wölfle, Schmalian

Fractionalized Fermi liquids

Senthil, Sachdev, Vojta

Change of Fermi volume ?
Dimensionality ?
Disorder effects ?

Hertz, Millis, Moriya, Rosch et al.

Coleman, Si, Pepin et al.

Kondo effect and magnetic order in $CeCu_{6-x}Au_x$

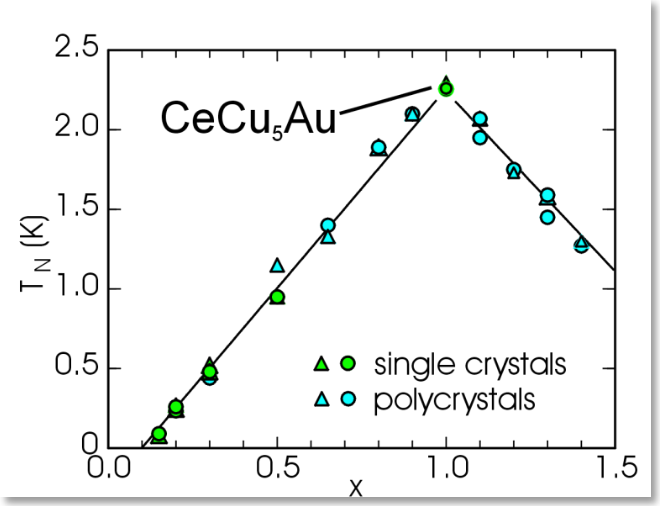
$CeCu_6$: heavy fermions with $\gamma = 1.6$ J/molK^2

non-magnetic groundstate

Ōnuki et al., Amato et al.

short lived AF correlations

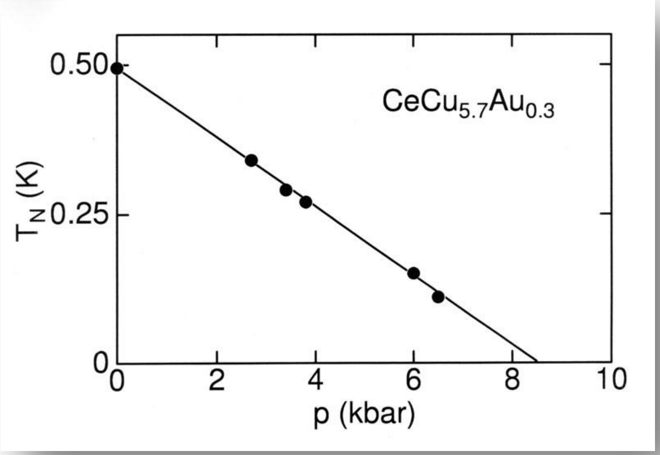
Aeppli et al., Rossat-Mignod et al.



Alloying with Au: long-range AF order

"negative lattice pressure" explains $T_N(x)$ for $x < 1$

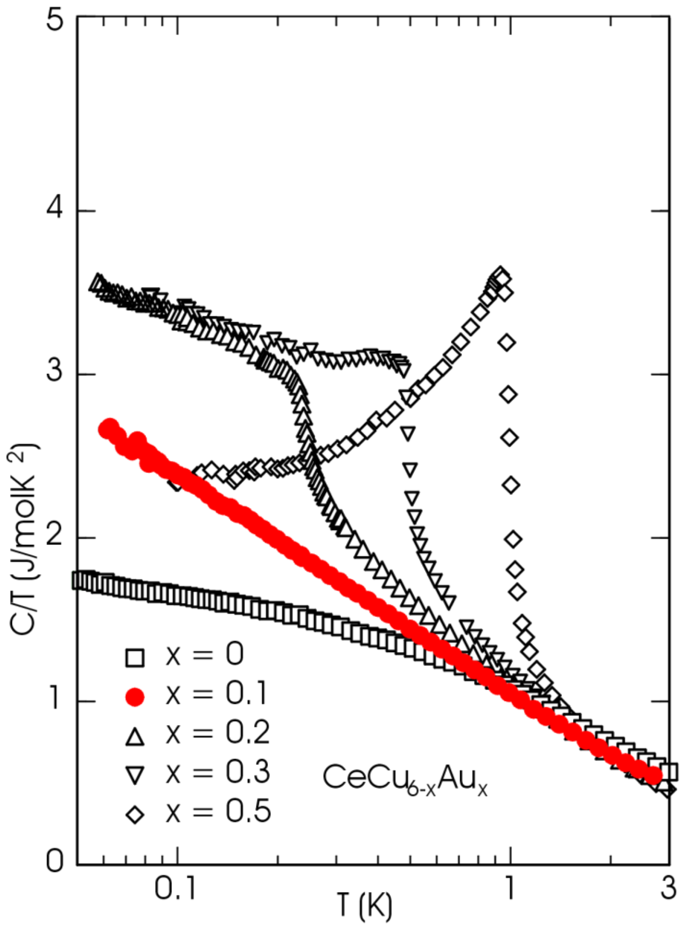
Direct proof: Néel temperature T_N vanishes under hydrostatic pressure



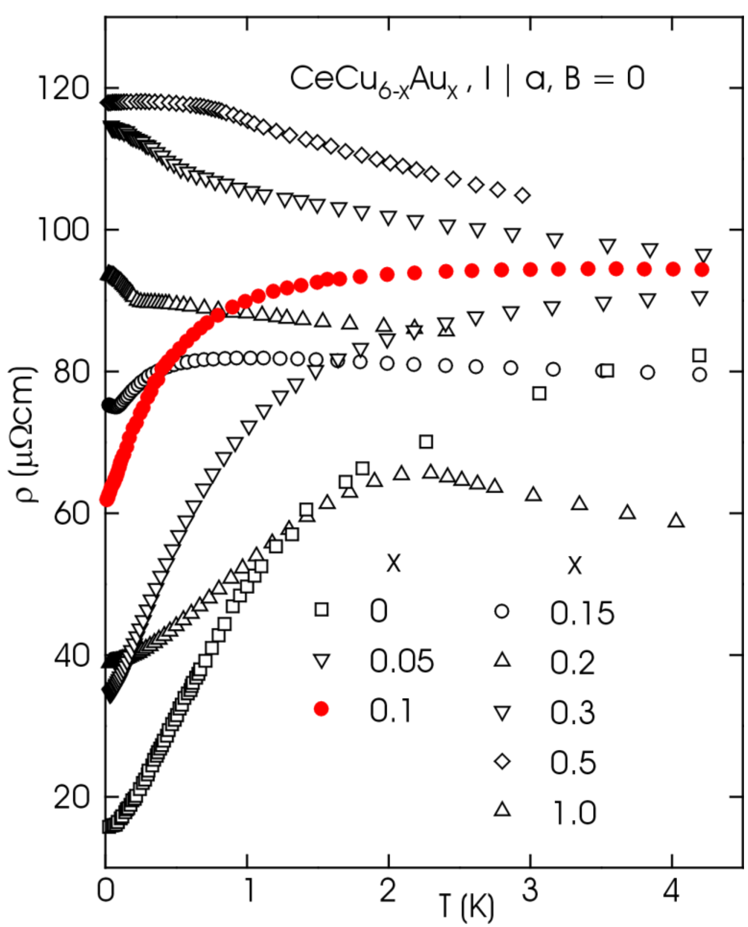
x = 0.1: Quantum critical point with "non-Fermi liquid" behavior

Non-Fermi-liquid effects at the concentration-tuned quantum critical point in $CeCu_{6-x}Au_x$

Specific heat

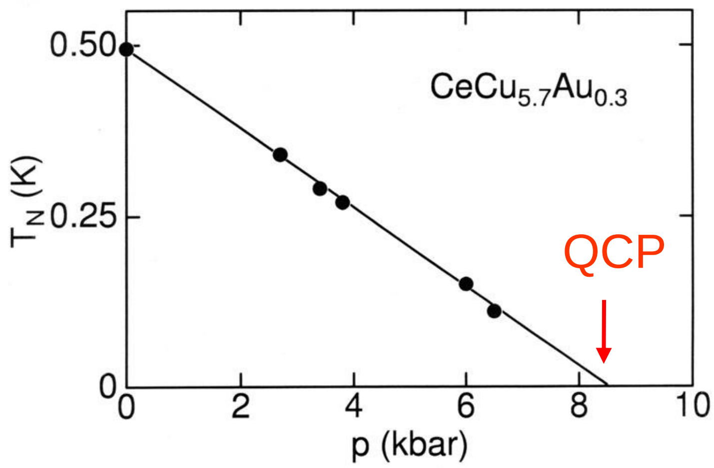


Electrical resistivity



Interplay of concentration and pressure tuning in $CeCu_{6-x}Au_x$

Pressure dependence of T_N

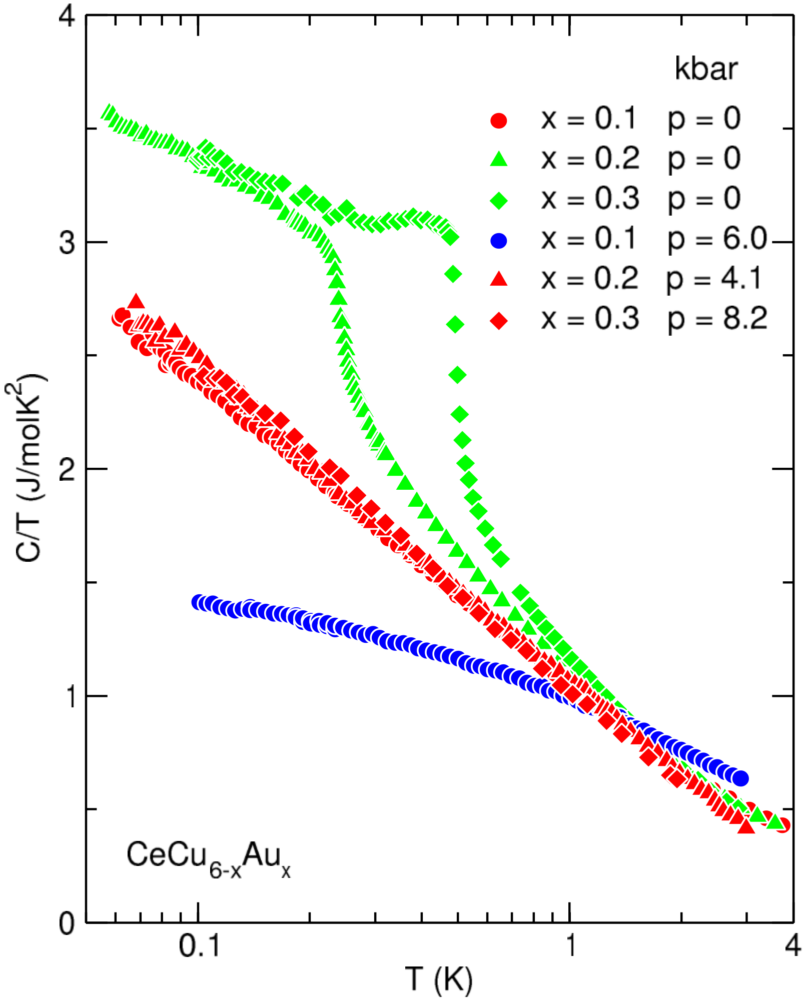


Surprising universality of C/T at quantum critical points

$x = 0.1$	$p = 0$
x = 0.2	$p = 4.1$ kbar
$x = 0.3$	$p = 8.2$ kbar

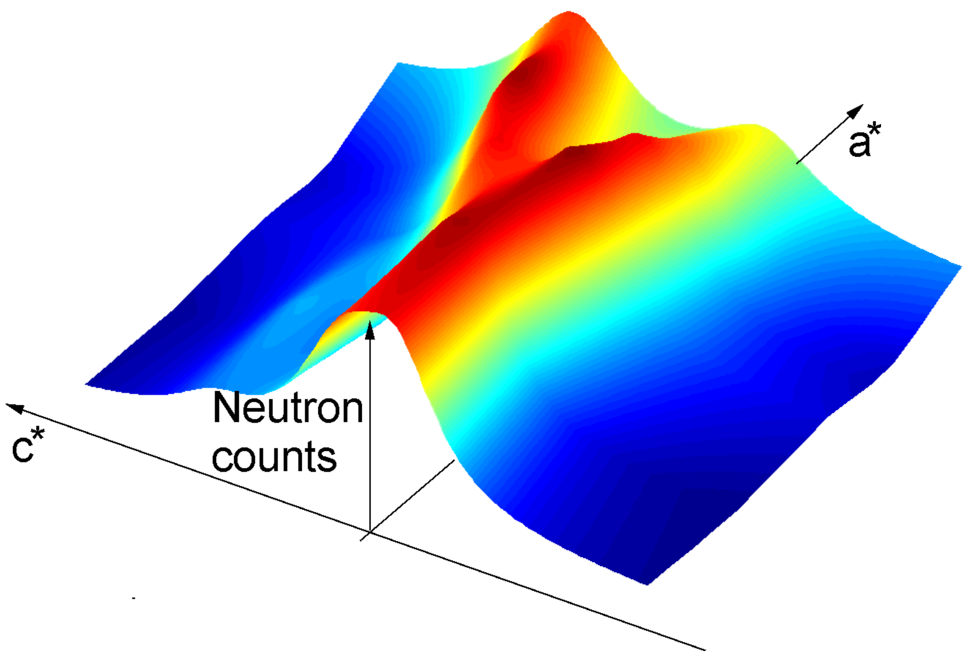
Suggestive of 2D fluctuations under pressure

Specific heat



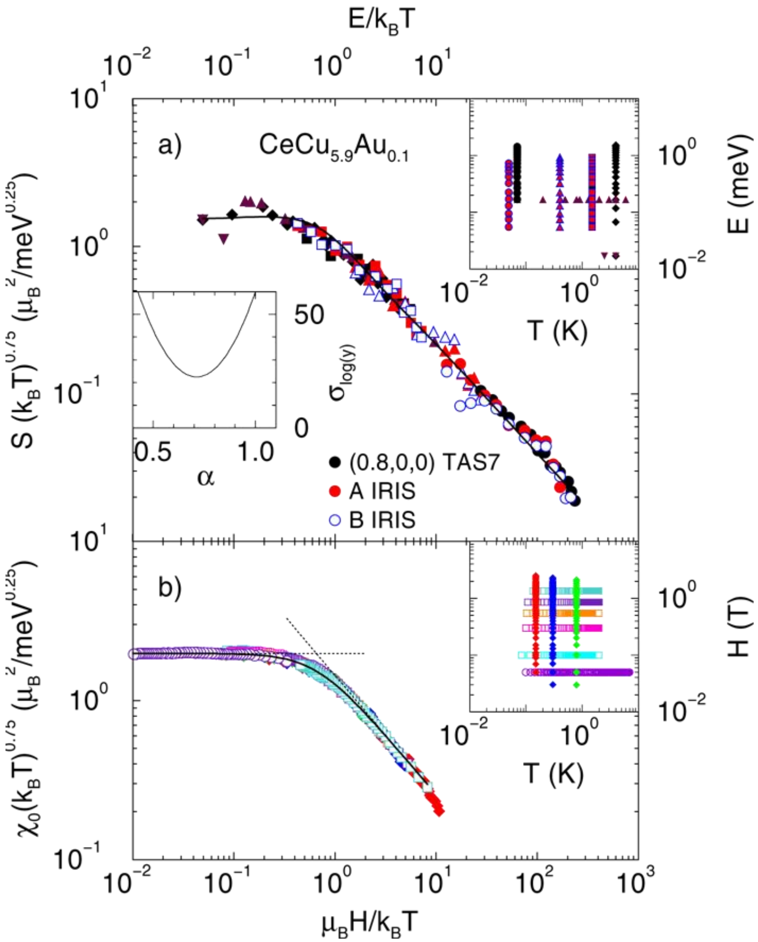
What's so special about $CeCu_{6-x}Au_x$?

Anomalous *q* dependence of critical fluctuations in a wide range, indicative of quasi two-dimensional fluctuations in real space



O. Stockert et al., PRL **80**, 5627 (1998)

ω/*T* scaling of critical fluctuations for *x* = 0.1, independent of *q*, with anomalous scaling exponent α = 0.75



A. Schröder et al., PRL **80**, 5623 (1998); Nature **407**. 351 (2000)

Anomalous quantum criticality in $CeCu_{6-x}Au_x$ described in terms of critical quasiparticles: specific heat

*Wölfle, Abrahams, PRB **84**, 041101 (2011)*
*Abrahams, Wölfle, PNAS **109**, 3218 (2012)*
*Abrahams, Schmalian, Wölfle, PRB **90**, 045105 (2014)*

Quasiparticle weight factor Z at E_F given by

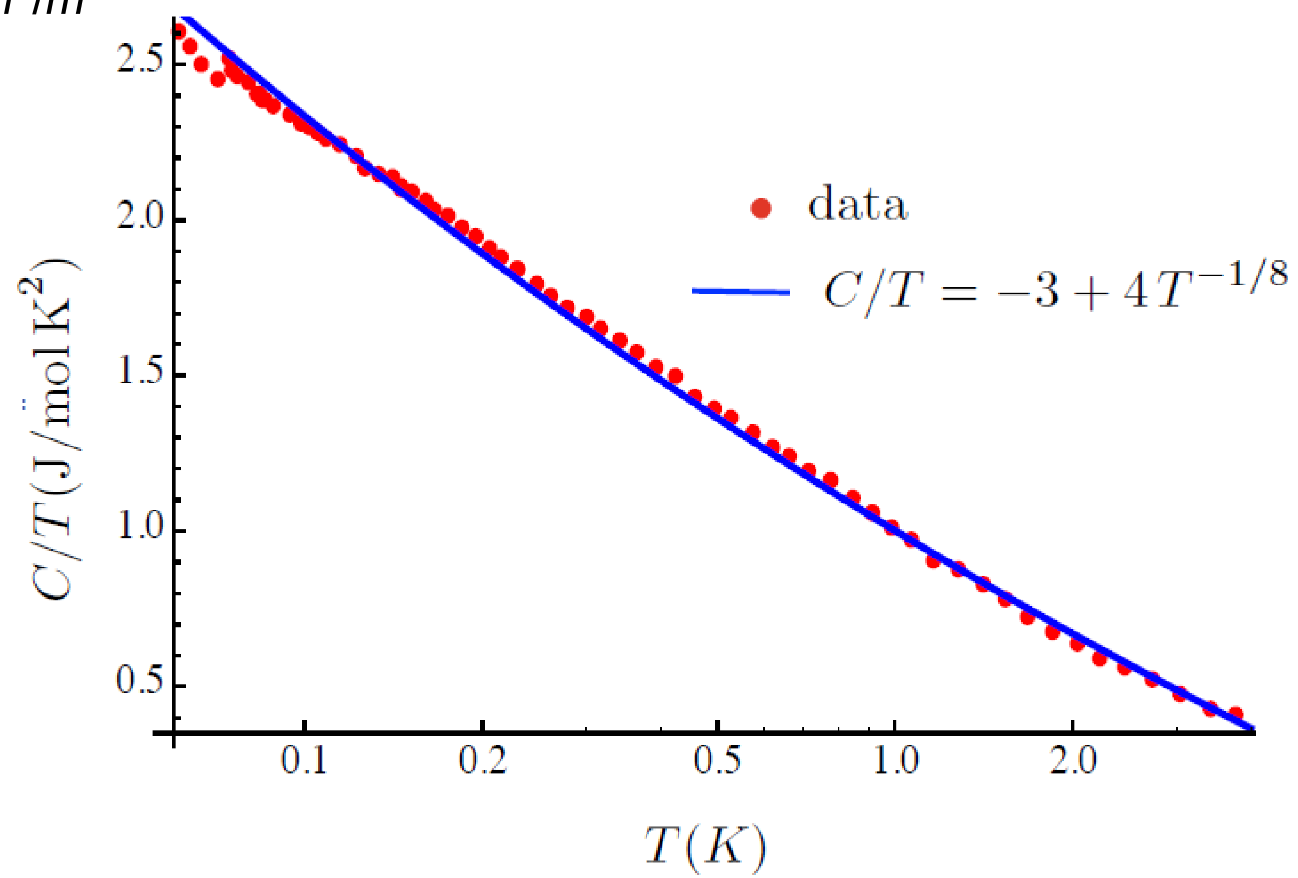
$Z^{-1} = 1 - \partial \mathrm{Re}\Sigma(\omega)/\partial\omega = m^*/m$

Non-Fermi liquid: $Z = 0$.

Allow for $Z = Z(\omega) \sim \omega^\eta$, with $Z = 0$ at E_F

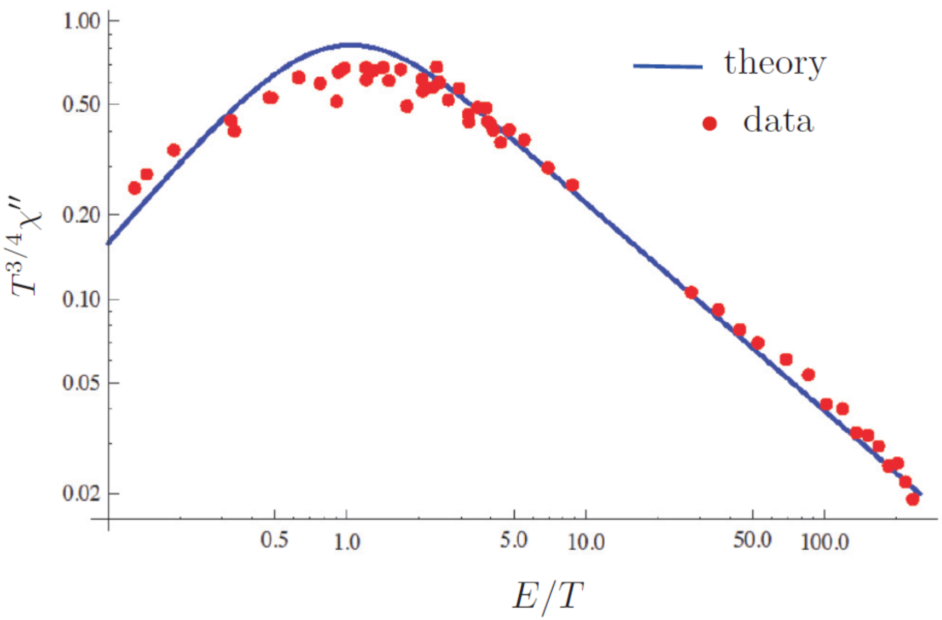
Predictions for
2D quantum fluctuations

Specific heat
$C/T \sim T^{-1/8}$

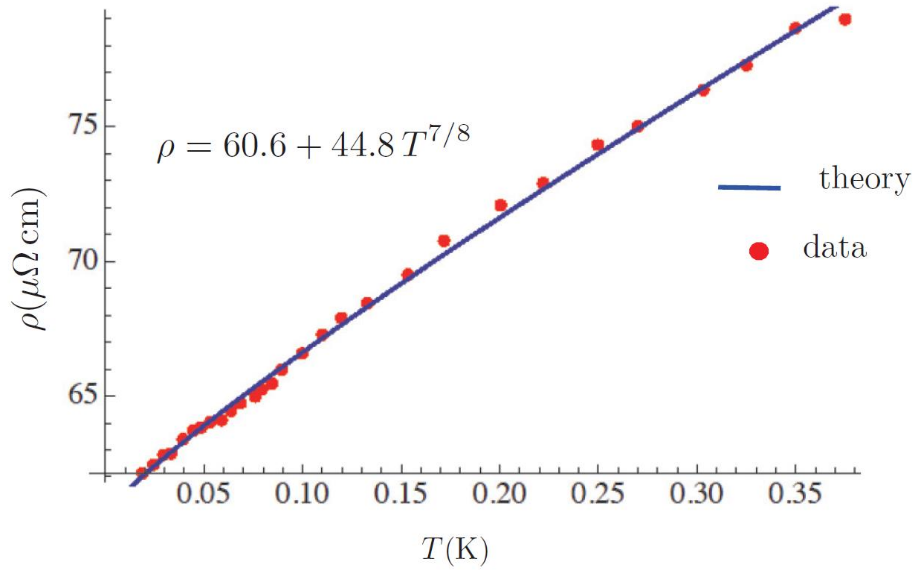


Anomalous quantum criticality in $CeCu_{6-x}Au_x$ described in terms of critical quasiparticles: $\chi''(\omega,T)$ and $\rho(T)$

ω/T scaling of the dynamical susceptibility



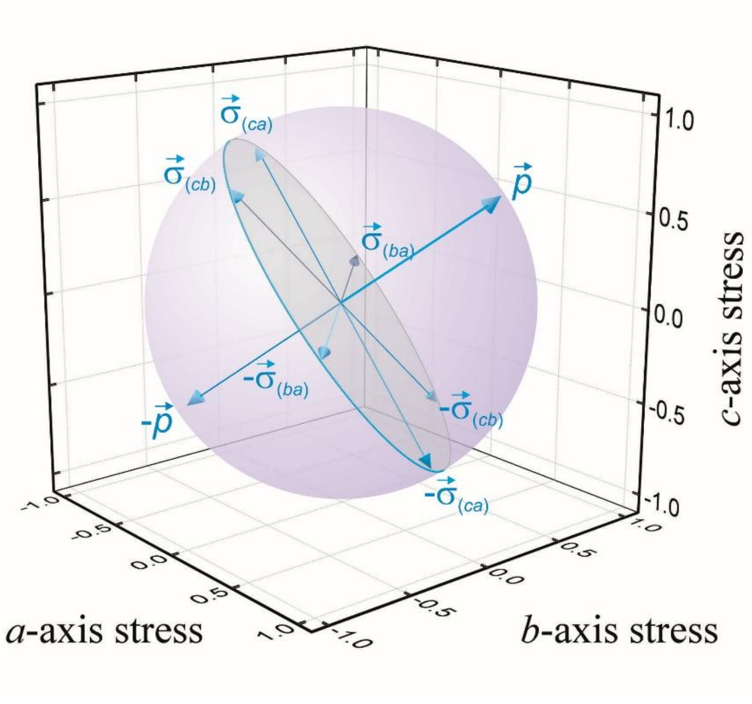
Roughly *T*-linear electrical resistivity



Dependence of entropy on arbitrary stress direction

$$\alpha_{ij} = \frac{1}{V}\frac{\partial^2 G}{\partial T \partial \sigma_{ij}} = -\frac{1}{V}\frac{\partial S}{\partial \sigma_{ij}}.$$

$$\frac{\partial S}{\partial \sigma_u} = \vec{\nabla} S \hat{u} = \sum_{i=1}^{3} \frac{\partial S}{\partial \sigma_i}\hat{u}_i = -V \sum_{i=1}^{3} \alpha_i \hat{u}_i.$$



Specific stress combinations:

hydrostatic pressure $\vec{p} = p \times (1, 1, 1).$

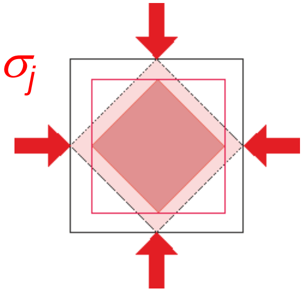
stress $\perp$ $\vec{p}$ “pure shear stress“

$$\vec{\sigma}_{(lm)} = \vec{\sigma}_l - \vec{\sigma}_m \text{ with } \vec{\sigma}_l \cdot \vec{\sigma}_m = 0$$

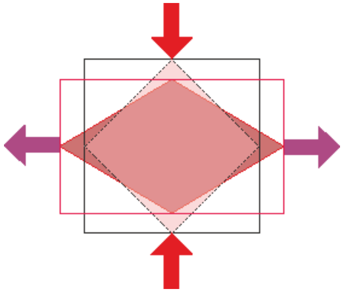
hydrostatic pressure:
volume change
without distortion
(if bulk modulus isotropic)

pure shear stress:
distortion
without volume change

$\sigma_i = \sigma_j$

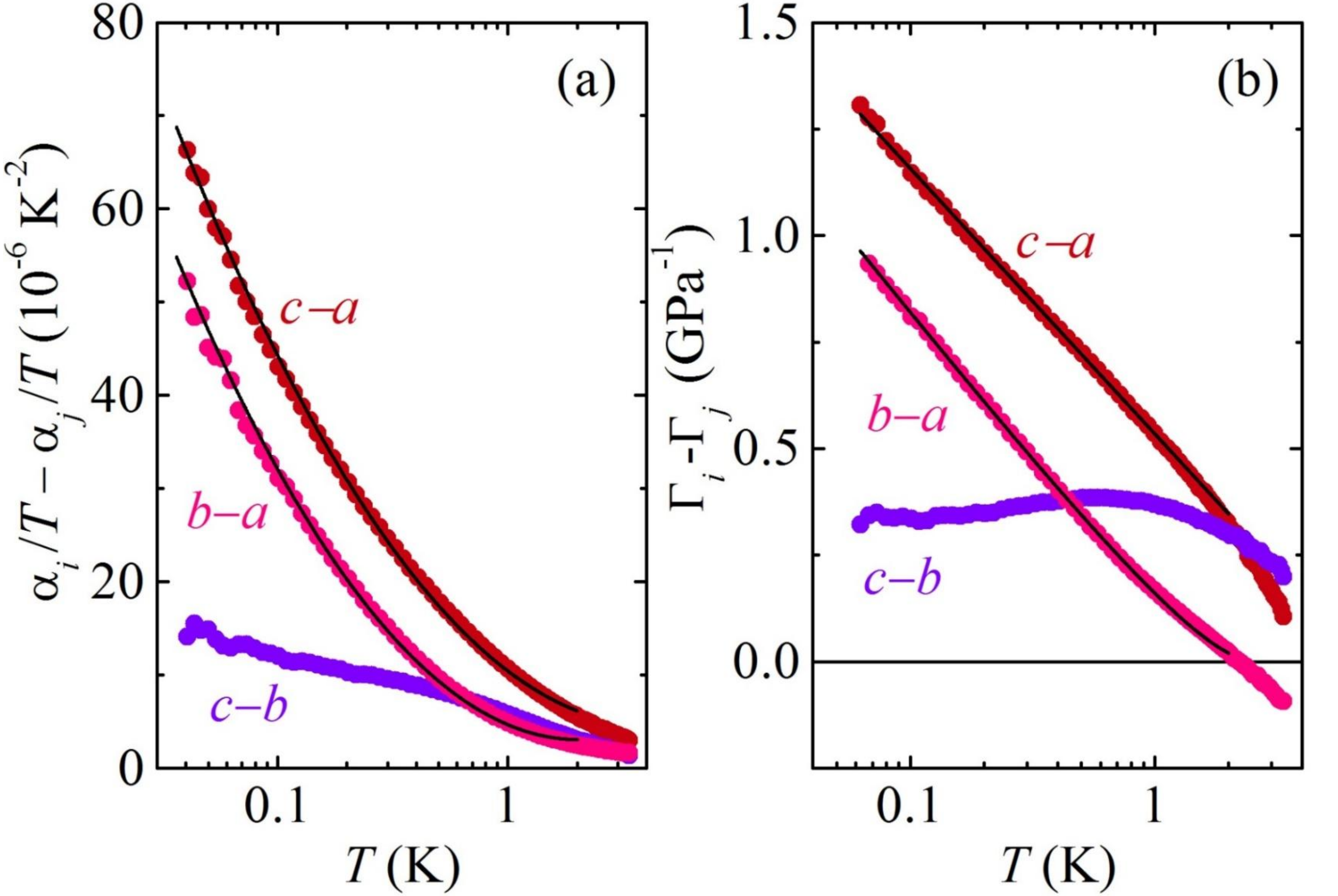


$\sigma_i = - \sigma_j$



$\sigma_{(lm)}$ picks up the anisotropy:
$\sigma_{(lm)} = 0$ for isotropic systems

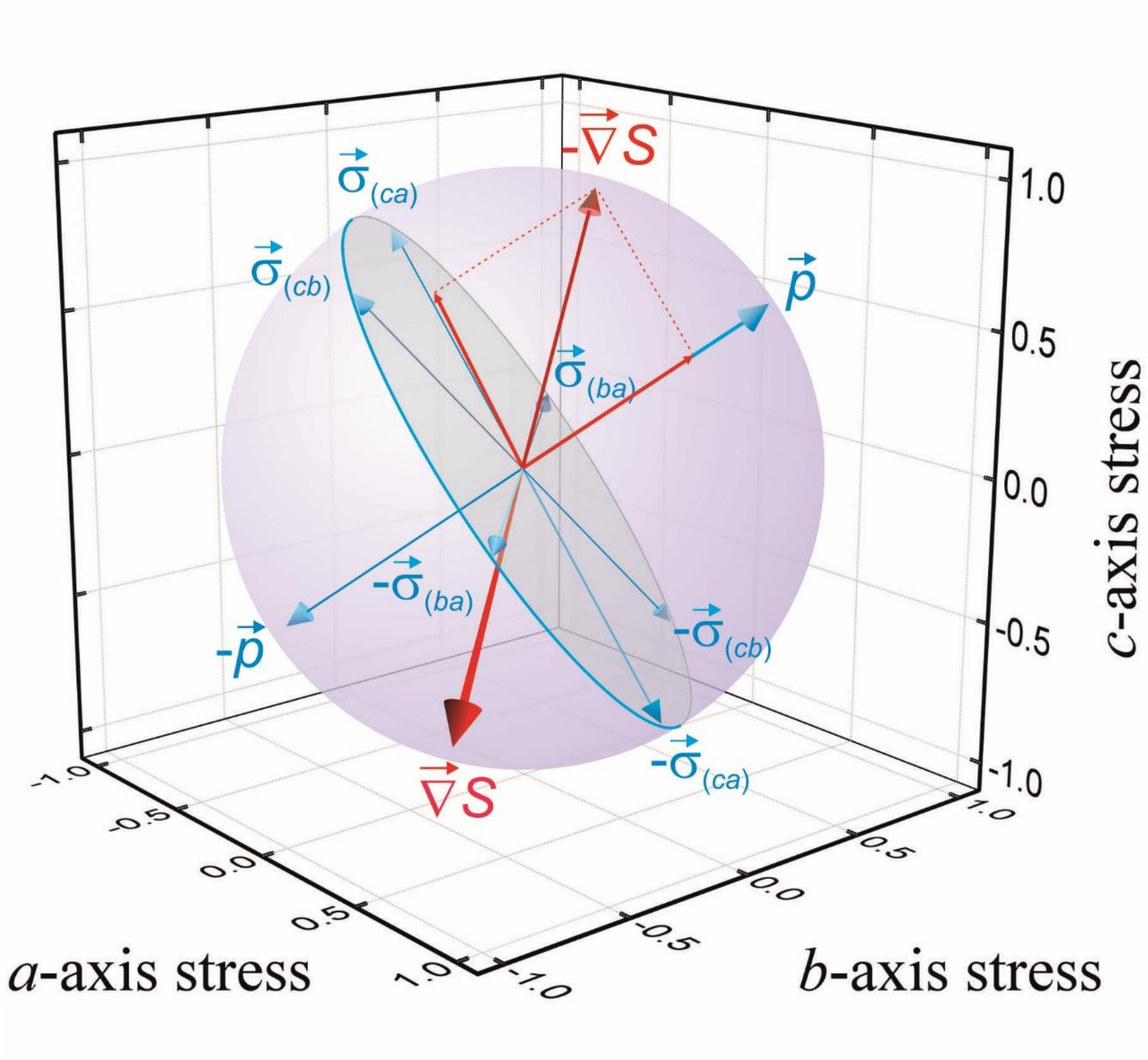
Shear stresses in $CeCu_{5.9}Au_{0.1}$



K. Grube et al., Nature Phys. ***13****, 742 (2017)*

Measuring the stress dependence of the entropy

$$\vec{\nabla} S = (\partial S/\partial \sigma_a, \partial/\partial S \sigma_b, \partial S/\partial \sigma_c)$$



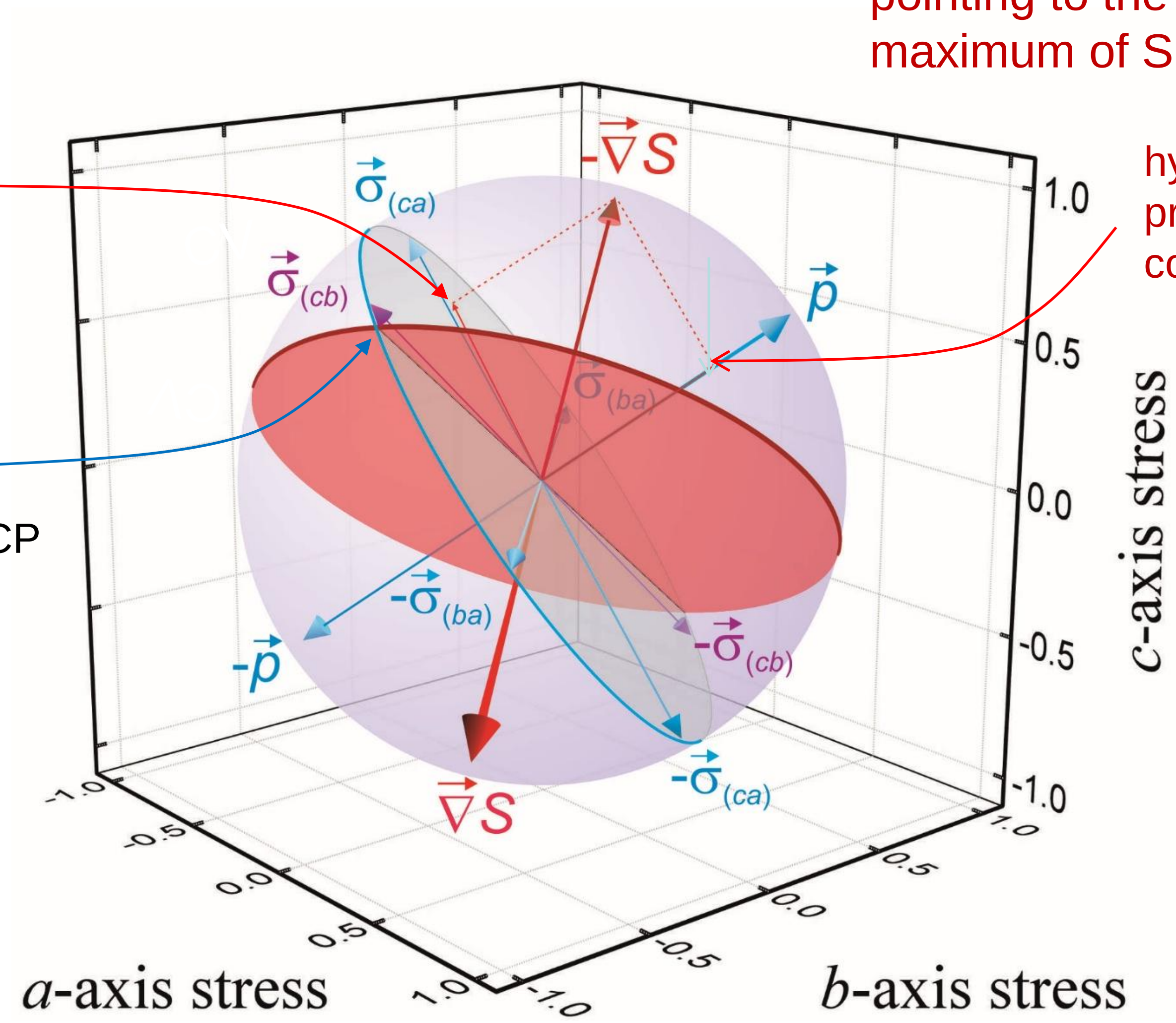
Anisotropic stress dependence of the entropy in $CeCu_{5.9}Au_{0.1}$

steepest slope of S, pointing to the closest maximum of S, i.e. a QCP

pure shear stress contribution

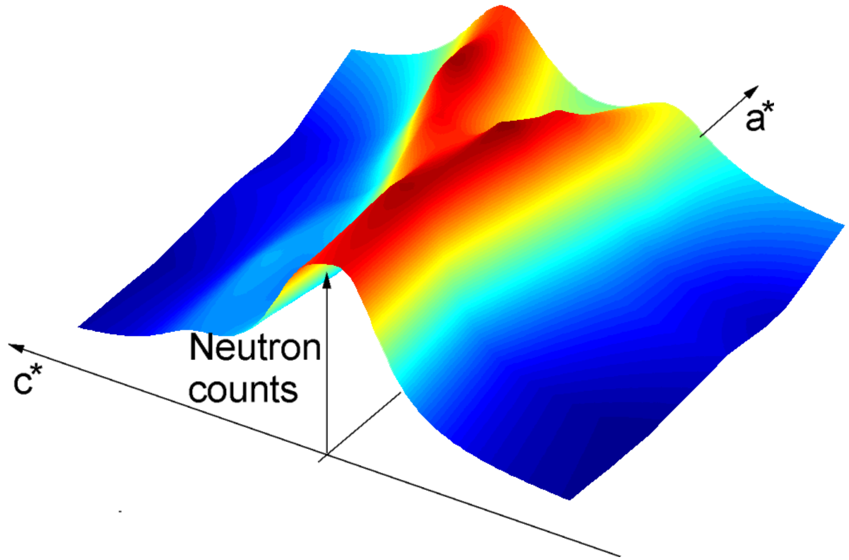
hydrostatic pressure contribution

$\vec{\sigma}_{(cb)}$ nearly $\perp \vec{\nabla} S$.
does not change distance to the QCP

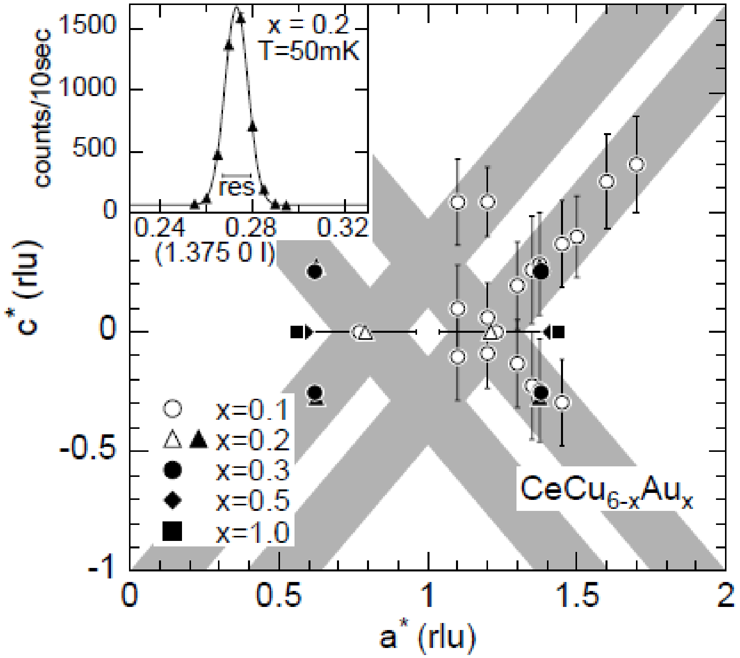


Relation of stress anisotropies to quantum critical fluctuations?

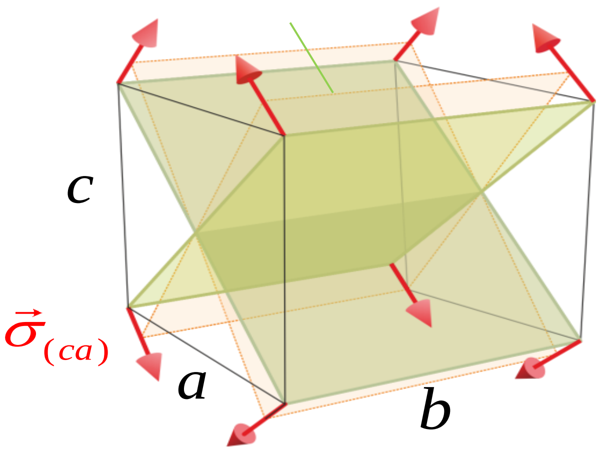
Inelastic fluctuations (ħω = 0.1 meV) in the *a*c** plane



*O. Stockert et al., PRL **80**, 5627 (1998)*

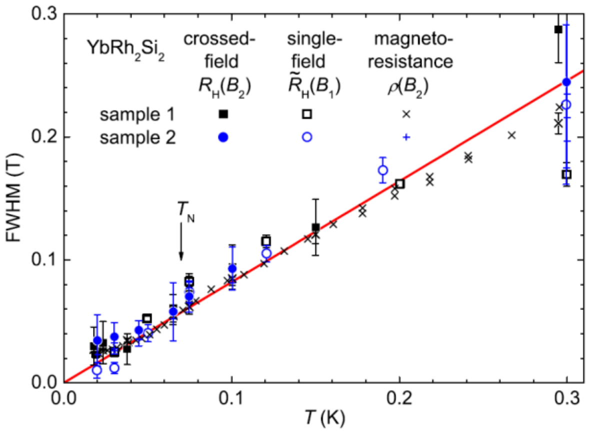


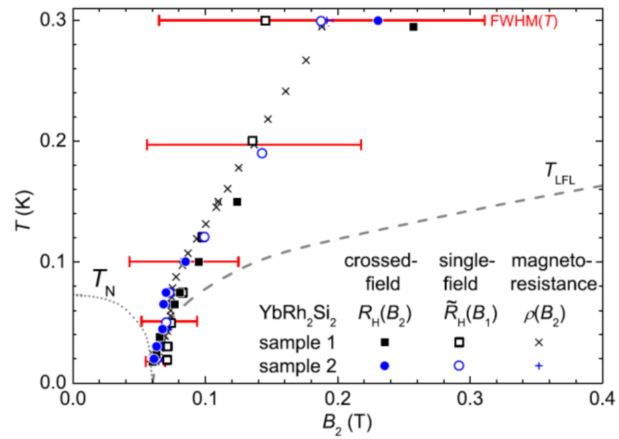
Pure shear stress $\sigma_{(ca)}$ tilts the planes of quantum-critical AF fluctuations



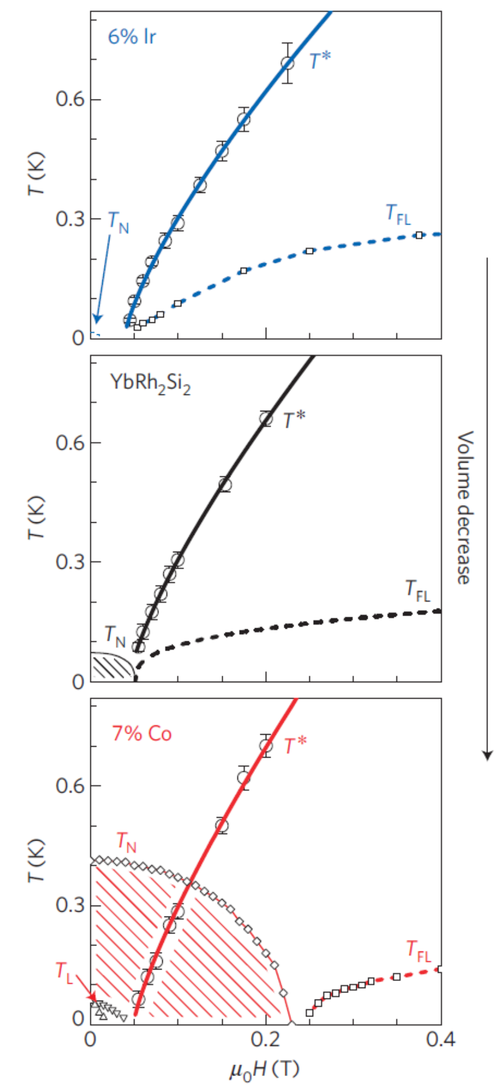
Is the "*T** line" a universal feature of unconventional quantum criticality?

*T** line is interpreted as a discontinuous change of Fermi volume in $YbRu_2Si_2$





S. Paschen et al., Nature ***432****, 881 (2004)*
S. Friedemann et al., PNAS ***107****, 14547 (2010)*



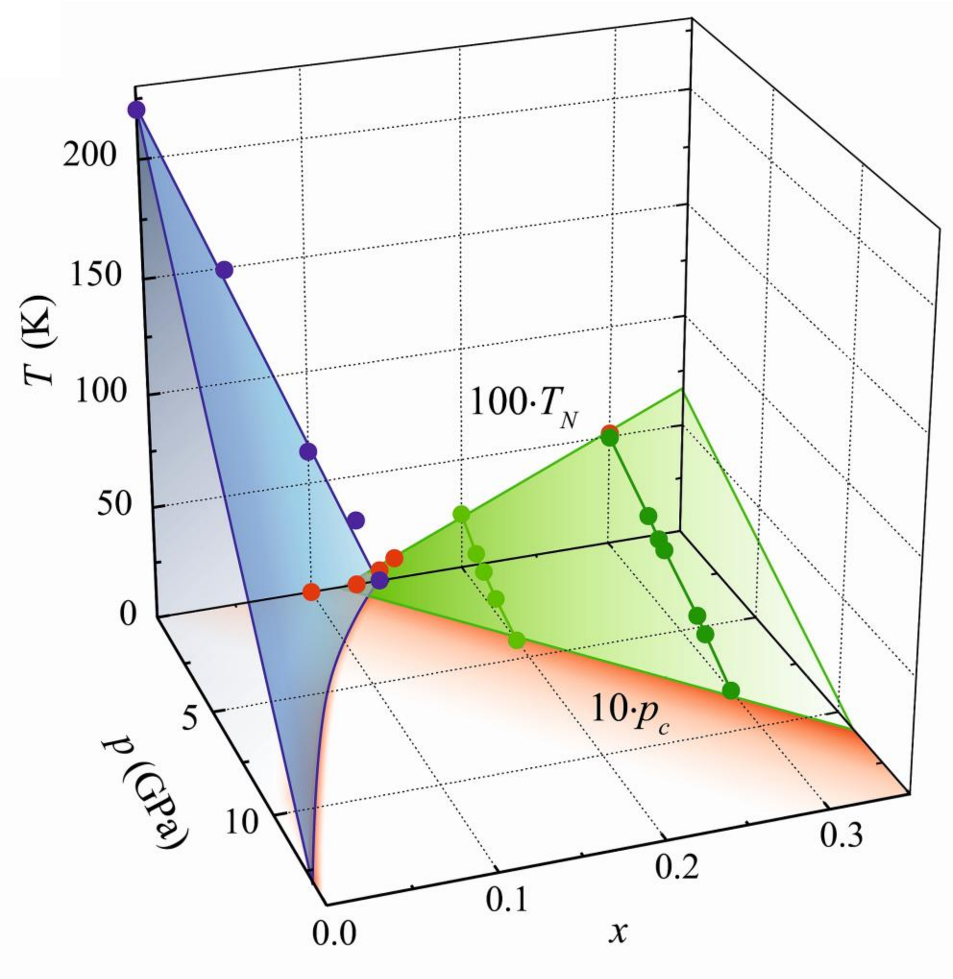
*T** line can be attached from magnetic QCP by alloying $YbRu_2Si_2$ with Ir or Co

S. Friedemann et al., Nature Phys. ***5****, 465 (2009)*

No evidence so far for *T** line in $CeCu_{6-x}Au_x$

Multicritical QCP in $CeCu_{6-x}Au_x$
intertwined magnetic and structural transition?

Orthorhombic-monoclinic transition



Antiferro-magnetic transition