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Quantum criticality in heavy-fermion compounds: effect of magnetic field

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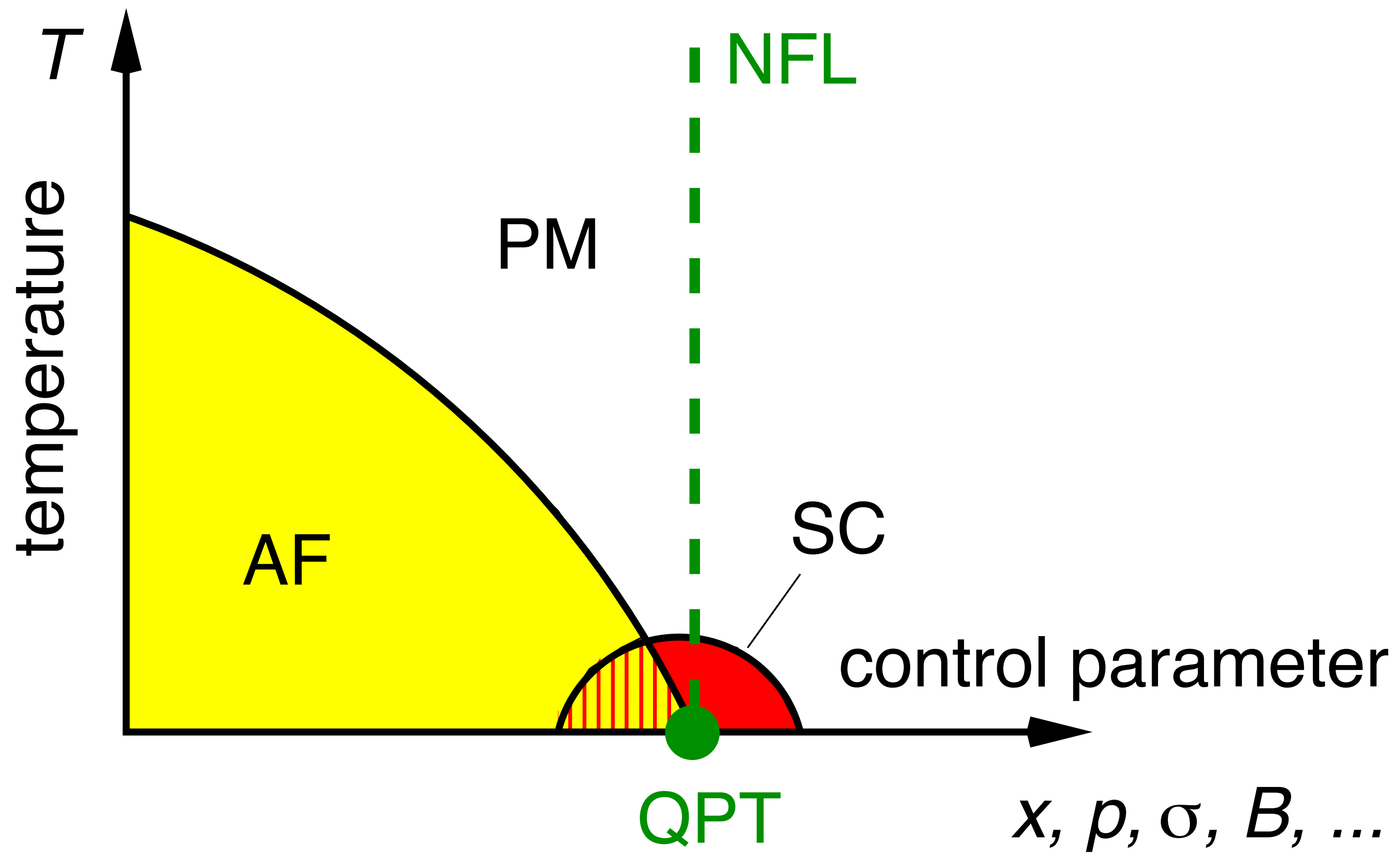
Outline

- Magnetic quantum phase transitions
- Effect of dimensionality: $CeCu_{6-x}Au_x$
- Magnetism versus superconductivity: Cd-dopded $CeCoIn_5$, $CeCu_2Si_2$
- Unconventional superconductivity in $CeCu_2Si_2$, magnetically driven sc
- Conclusions



Collaborations

Thanks ...

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K. Prokes, N. Stüßer, K. Habicht, S. Gerischer, P. Smeibidl, M. Meißner	*Helmholtz-Zentrum-Berlin
M. Enderle, K. Schmalzl, W. Schmidt, F. Thomas, X. Tonon, S. Pujol	Institut Laue-Langevin Grenoble
H. Schneider	JCNS at FRM-II, Forschungszentrum Jülich
S. Kirchner	Max-Planck-Institut PKS Dresden
Q. Si	Rice University Houston

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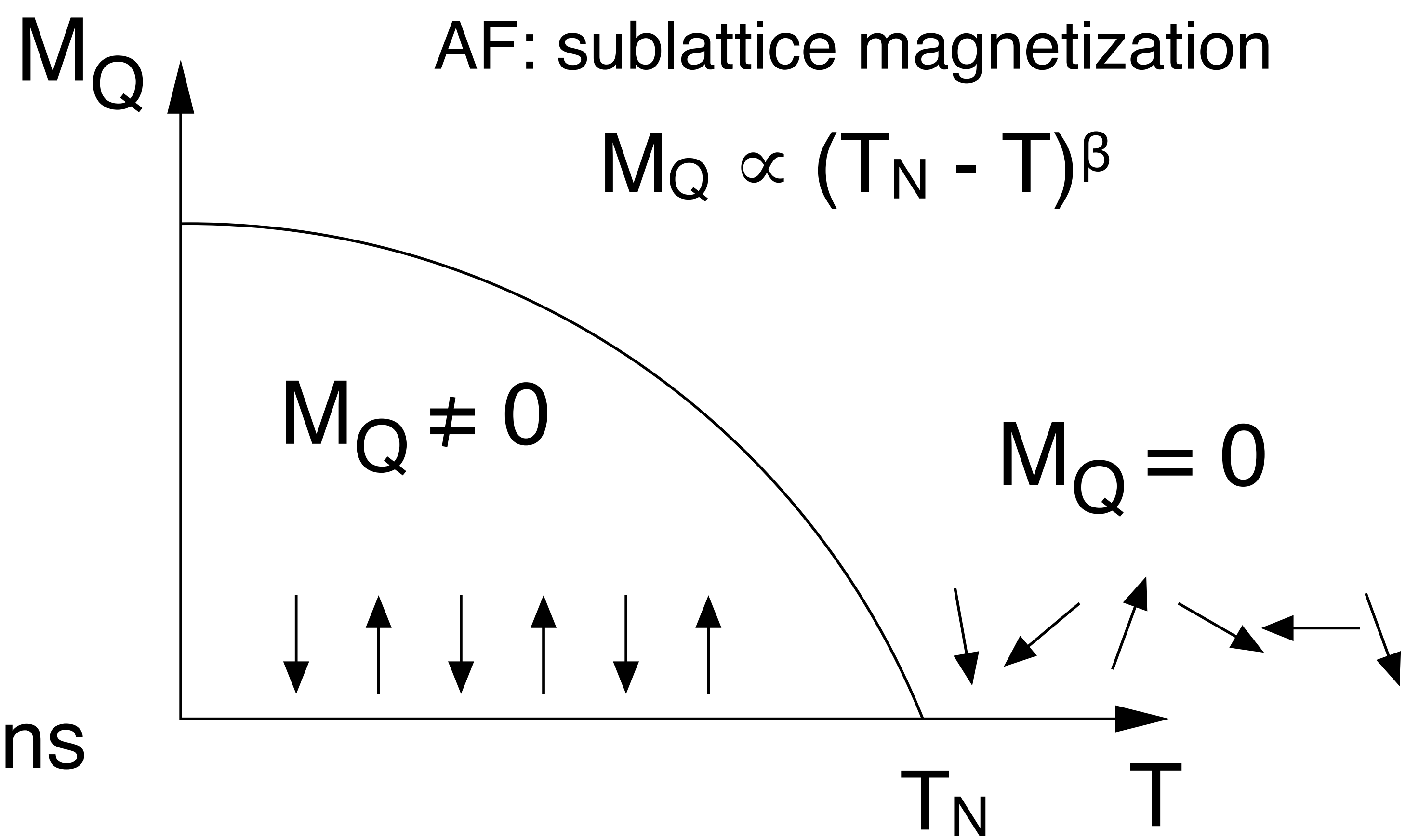
Continuous phase transitions

Continuous phase transitions:

- (critical) fluctuations of order parameter
- critical exponents in thermodynamic properties:
  α, β, γ, ... (scaling laws)



Critical behavior depends on

- dimensionality
- dimensionality/symmetry
  of order parameter
- range of interactions/fluctuations

classification → universality classes

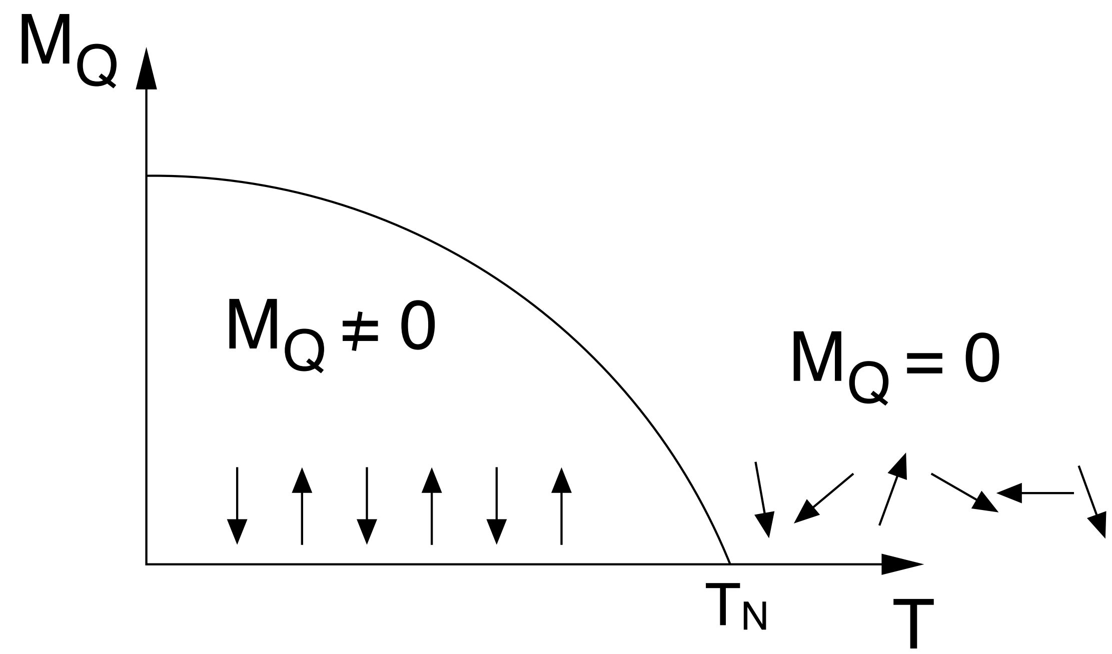
Can concept also be applied to QPTs?

Quantum phase transitions

Continuous phase transition
for T ⟶ 0

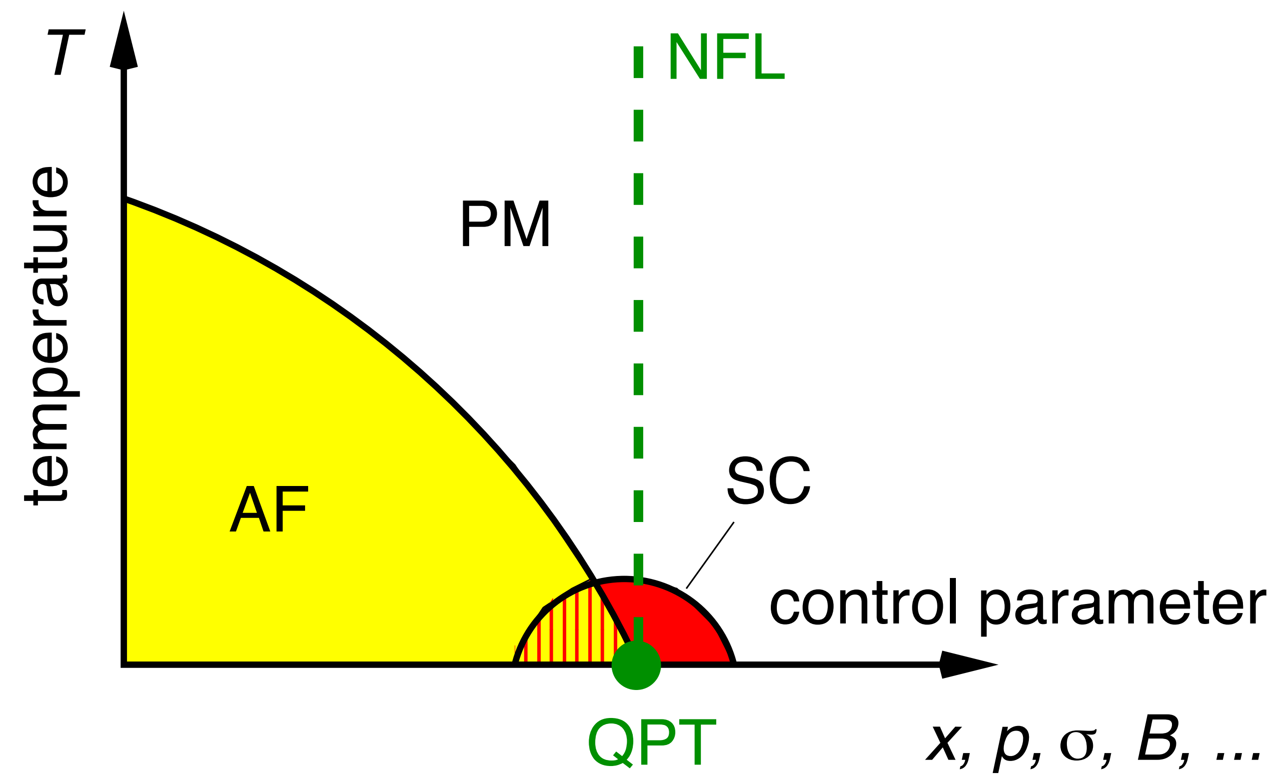
⟶ Quantum phase transition (QPT)
with unusual low temperature properties:

- C/T ∝ -ln T;
  $\Delta\rho \propto T^{\alpha}$, $\alpha \neq 2$ (NFL)
- superconductivity



Origin?

- Magnetic order
- (Quantum-)critical spin fluctuation
- Interplay between AF(FM) and SC

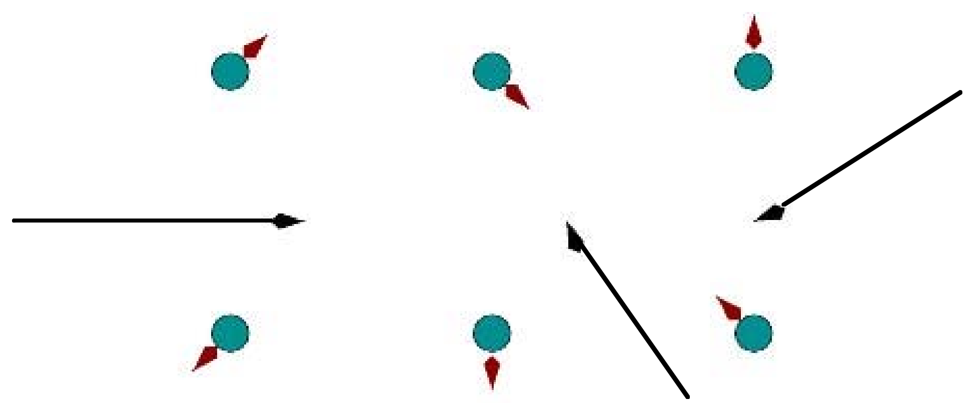


Neutrons ideal microscopic probe!
Magnetic field easy to tune, no change in disorder

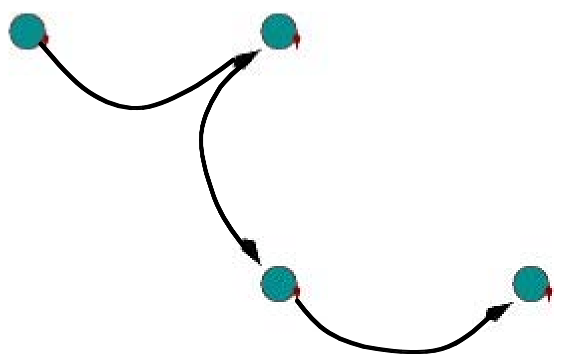
[reviews:
QPT: H. v. Löhneysen, RMP ´07
SC: C. Pfleiderer, RMP '09]

Heavy fermions

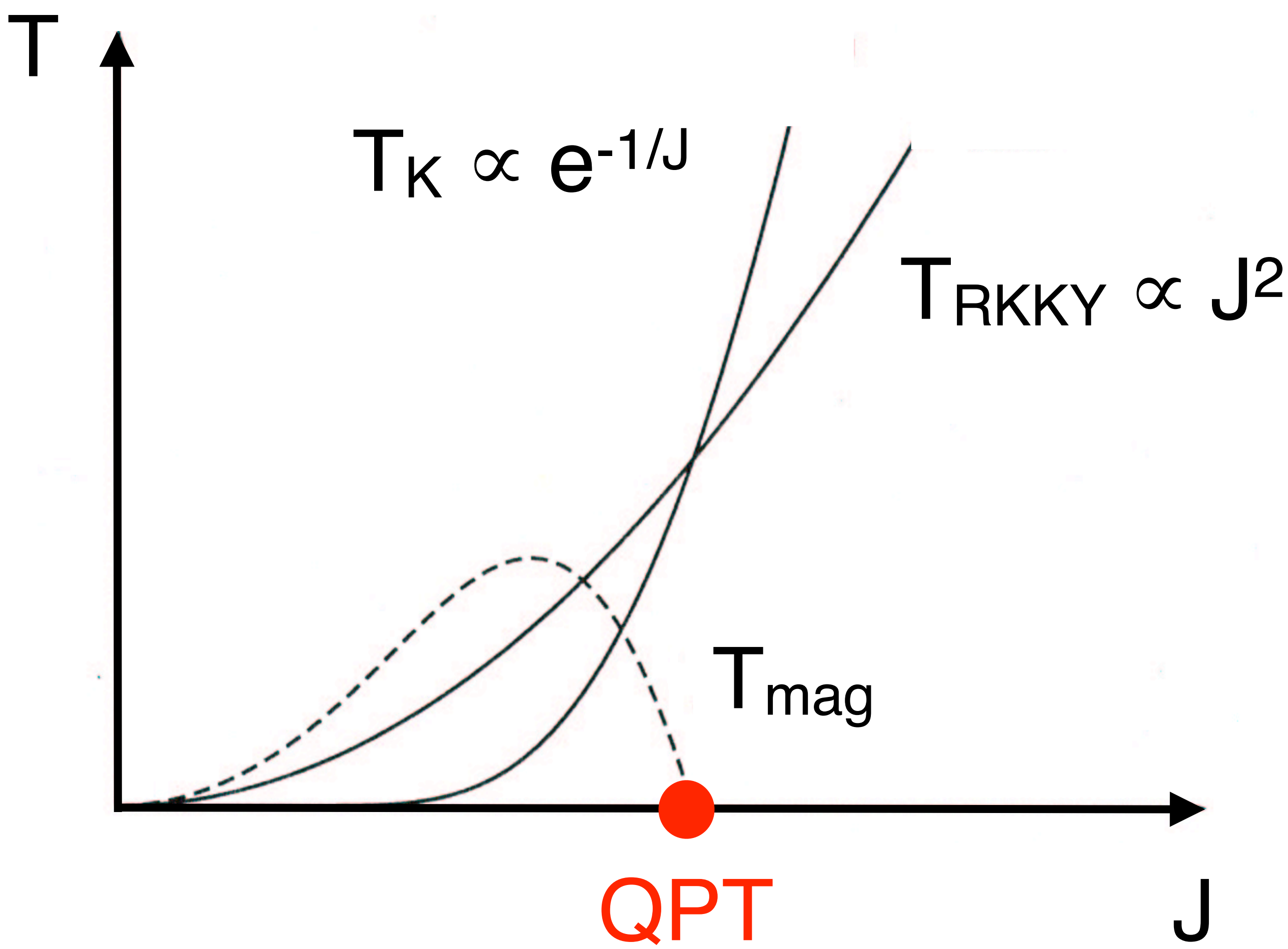
T >> T_K:



T < T_K: heavy electrons



$T_K \approx 5$ - 50 K

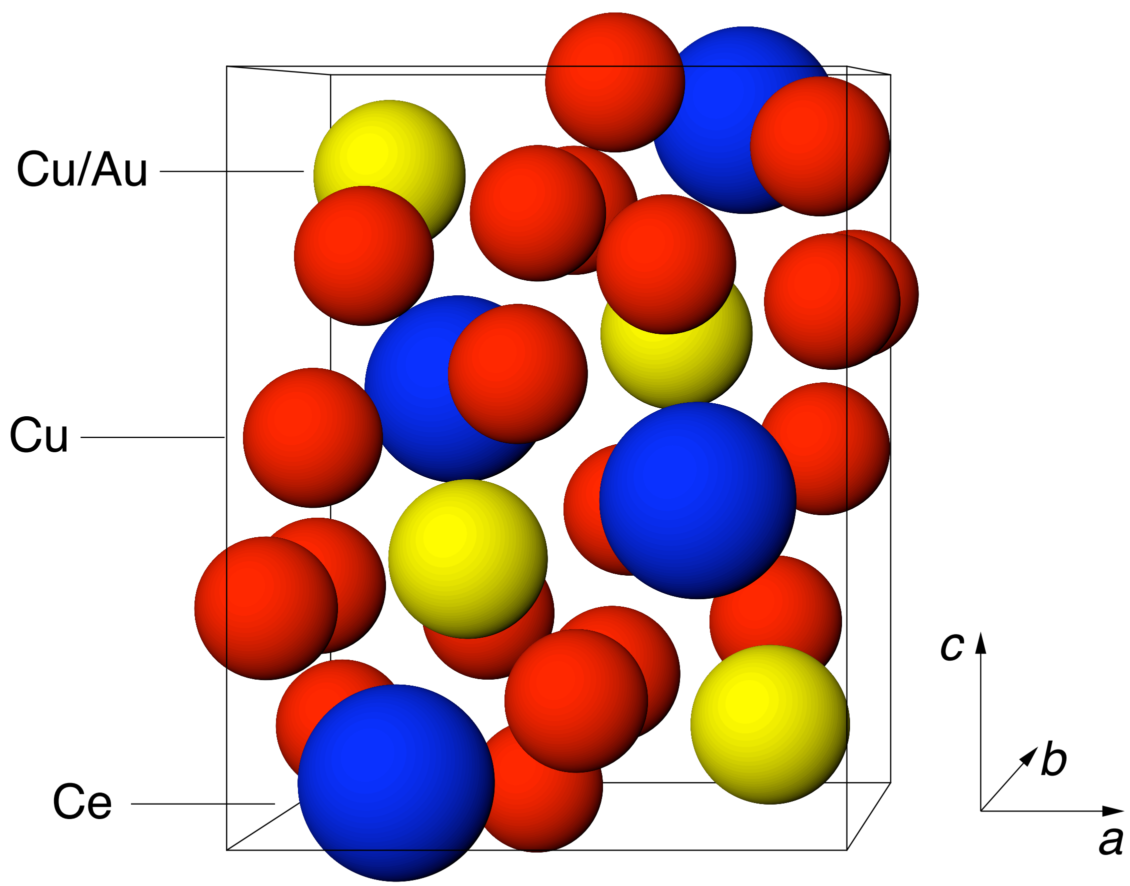


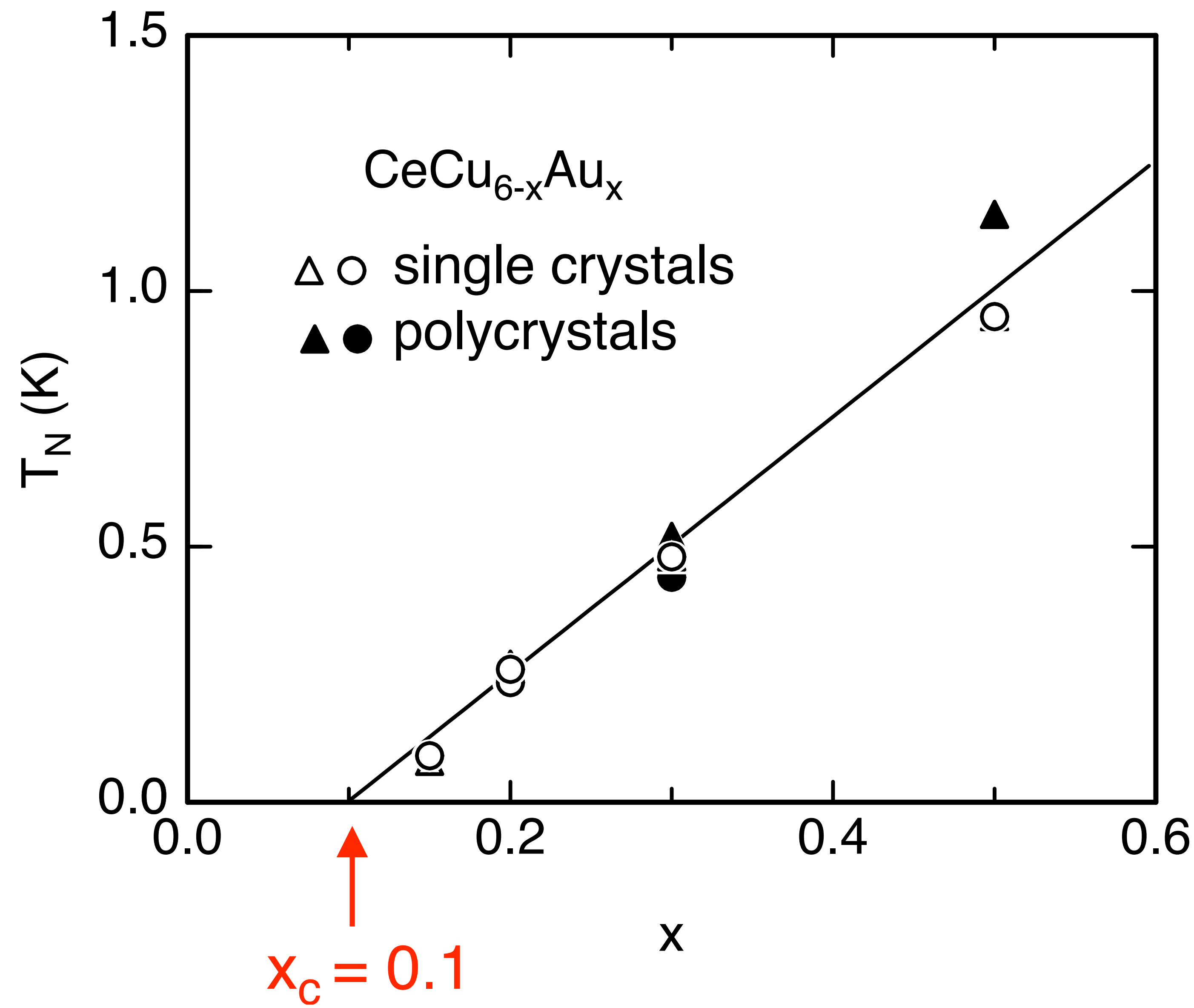
Kondo screening vs.
RKKY interaction:

Kondo effect
→ nonmagnetic singlet

indirect RKKY interaction
→ magnetic order

Magnetism in $CeCu_{6-x}Au_x$





- Incommensurate antiferromagnetic order for $x > x_c = 0.1$
- Magnetic instability, $x = x_c = 0.1$: $C/T \propto -\ln T$; $\Delta\rho \propto T$ (NFL)

  [$x = 0$: C/T = const.; $\Delta\rho \propto T^2$ (FL)]

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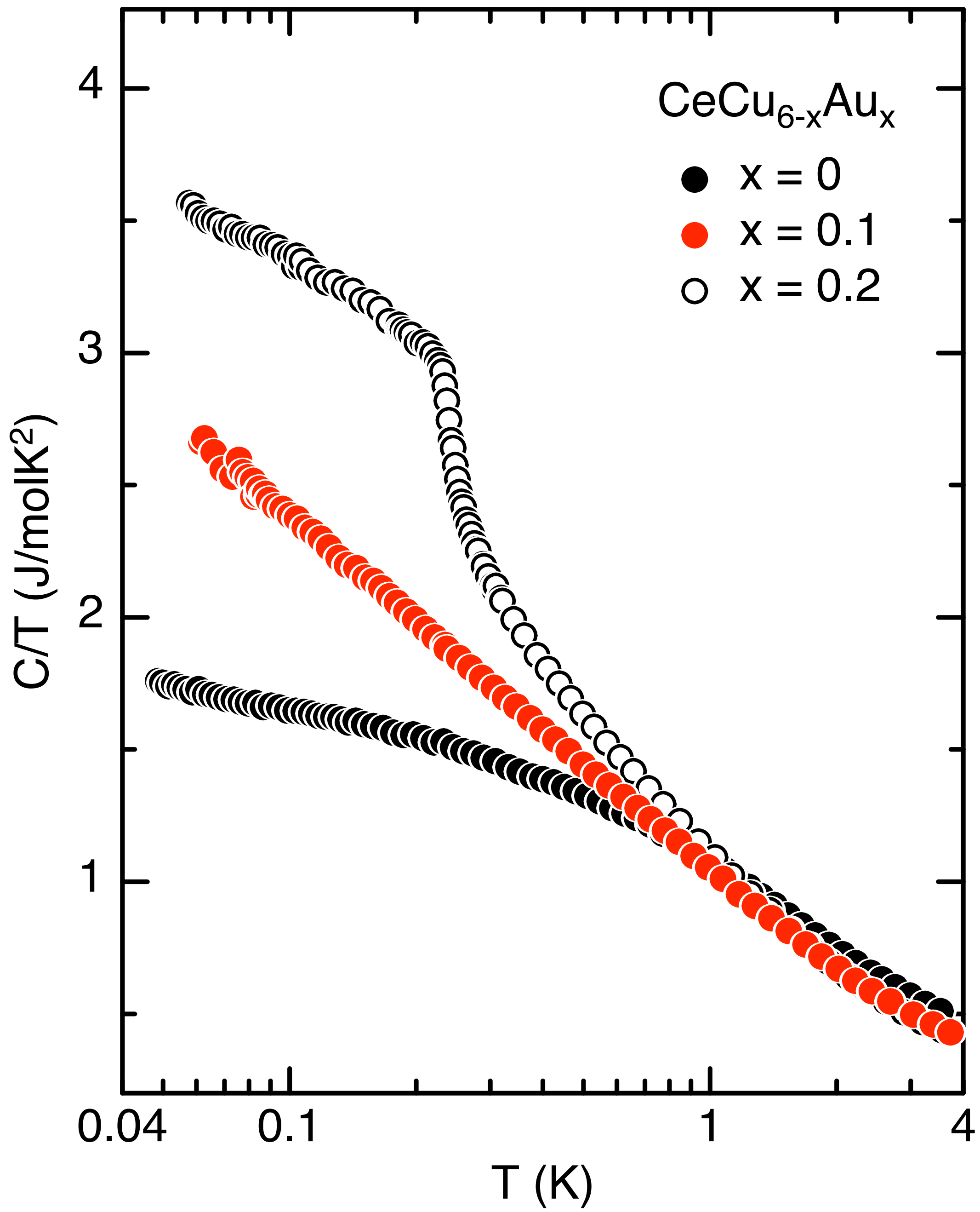

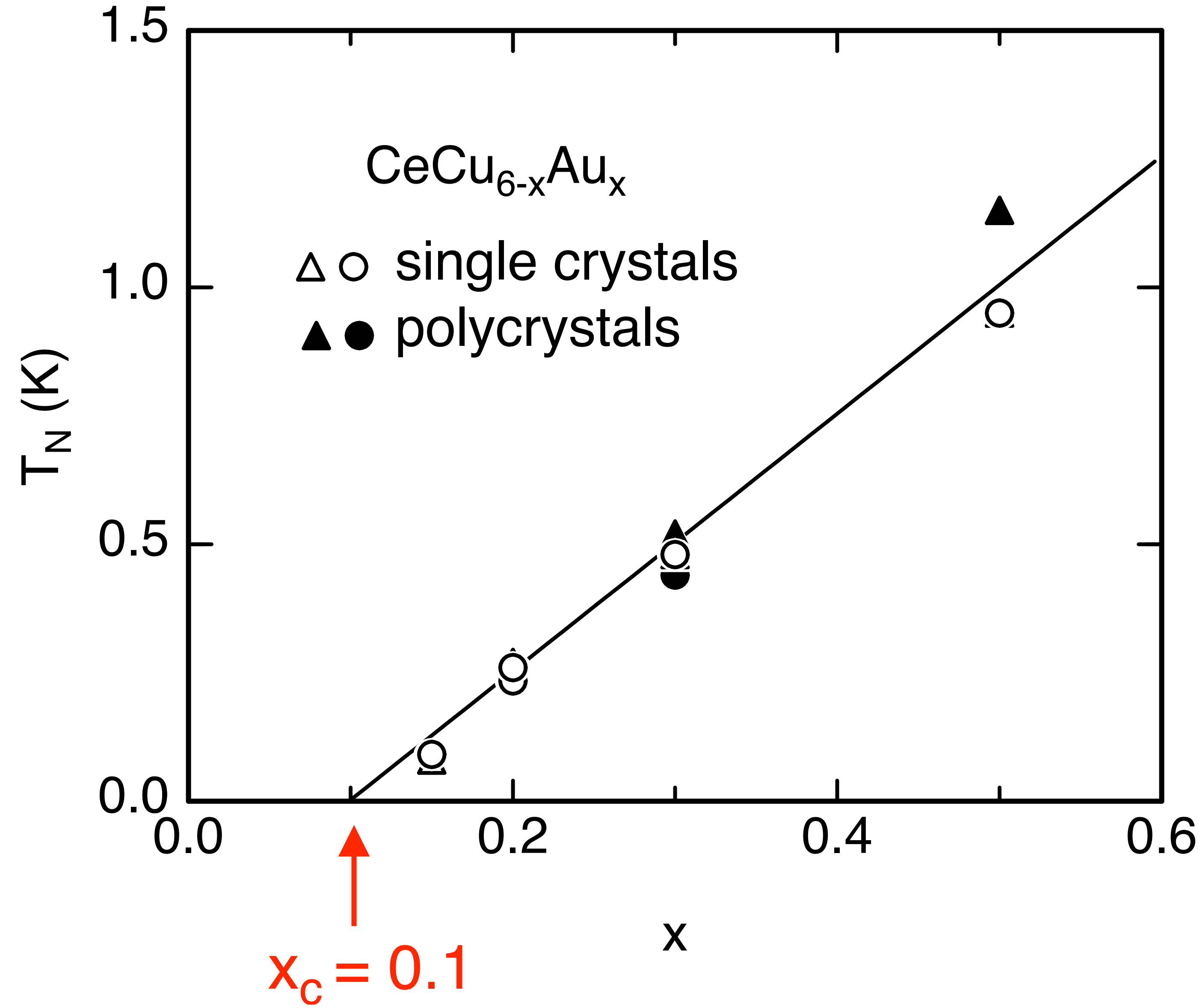

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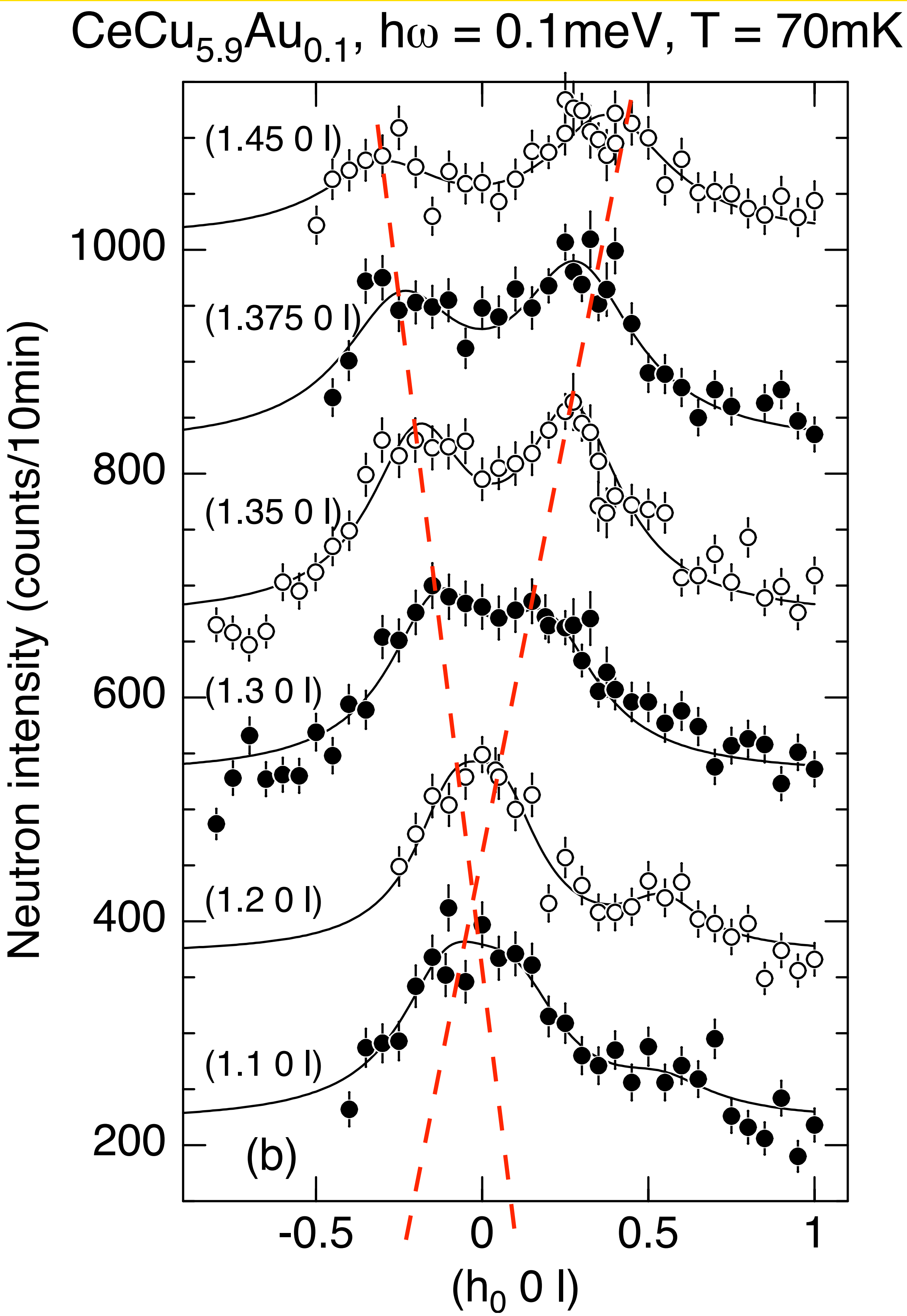
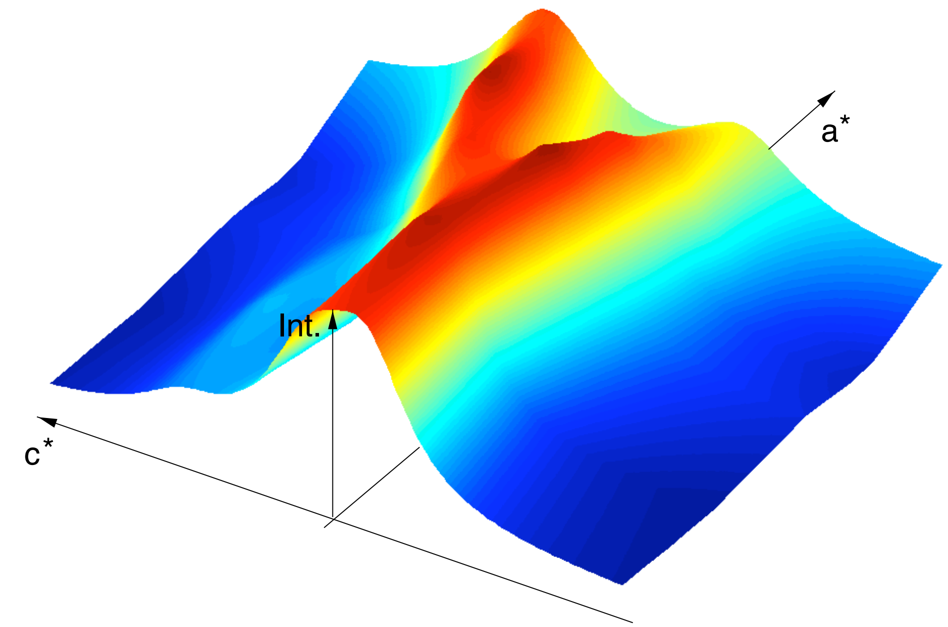
Dynamic correlations in critical $CeCu_{5.9}Au_{0.1}$



IN14 [OS, '98]



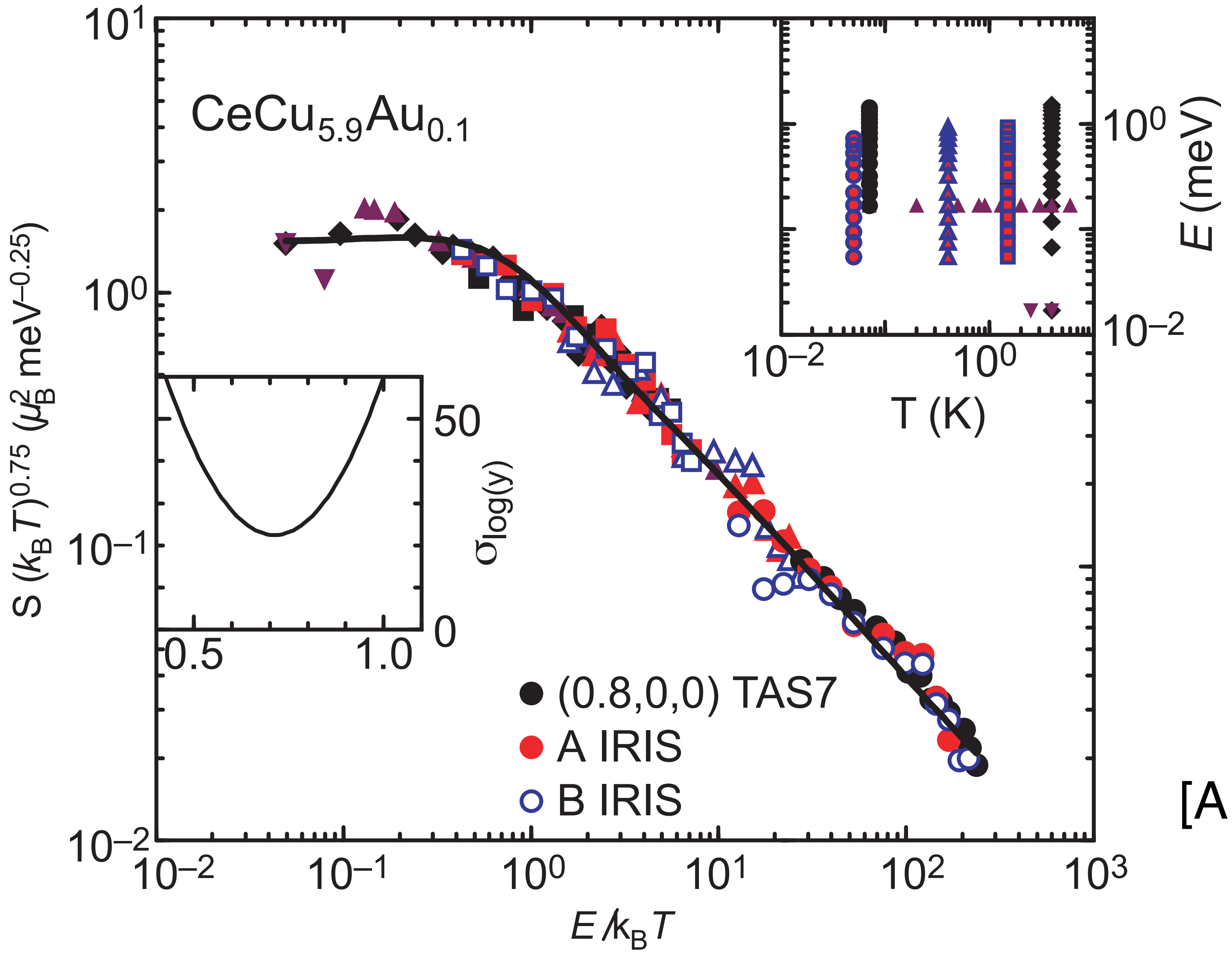
- rodlike dynamic correlations in a*c* plane
- correspond to 2D dynamic correlations in real space

Spin fluctuation theory for AF with 2D critical fluctuations

→ $C/T \propto -\ln T$, $\Delta\rho \propto T$, $T_N \propto x - x_c$

[Millis, '93; Rosch, OS, '97]

Scaling of dynamic susceptibility in $CeCu_{5.9}Au_{0.1}$



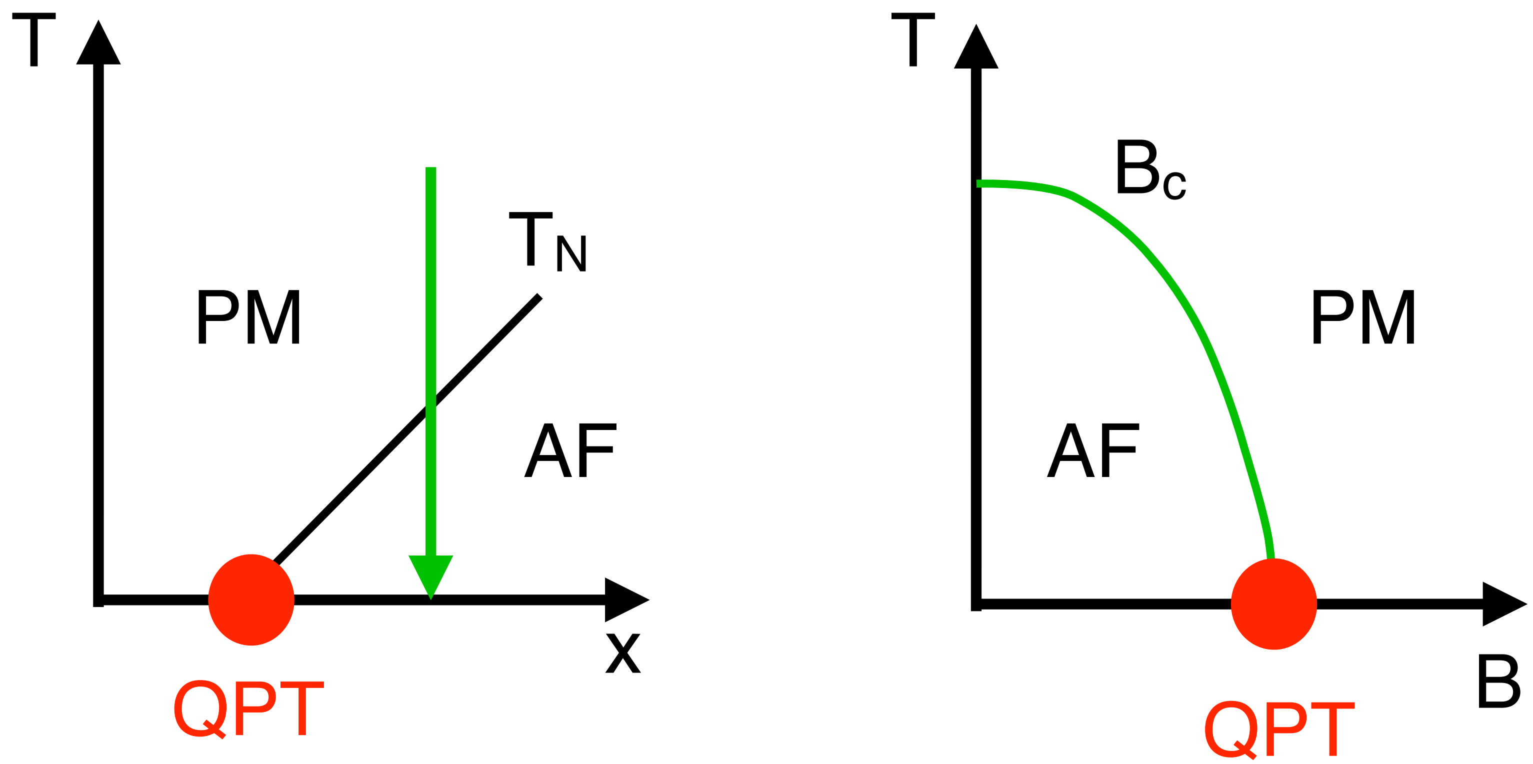
[A. Schröder, OS, '00]

E/T scaling with anomalous exponent $\alpha = 0.75$, $\chi'' = T^{-\alpha} g(E/T)$

→ local physics relevant

local scenario ↔ 2D criticality

Magnetic field tuning in $CeCu_{5.8}Au_{0.2}$



- $CeCu_{5.8}Au_{0.2}$: T_N = 220 mK, $B_c \approx 0.35$ T || c to suppress AF order

  $B = B_c$: $C/T = \gamma_0 - a\sqrt{T}$; $\Delta\rho \propto T^{3/2}$ [v. Löhneysen, OS, '01]

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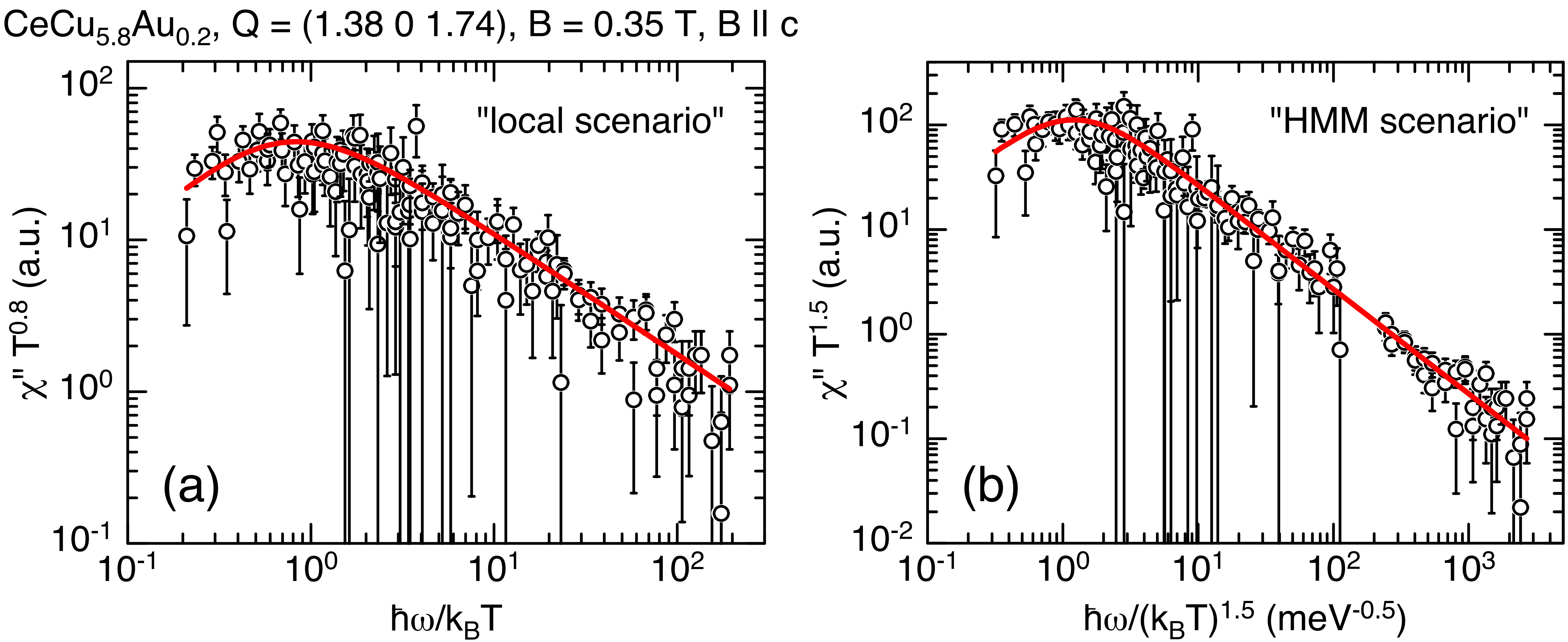


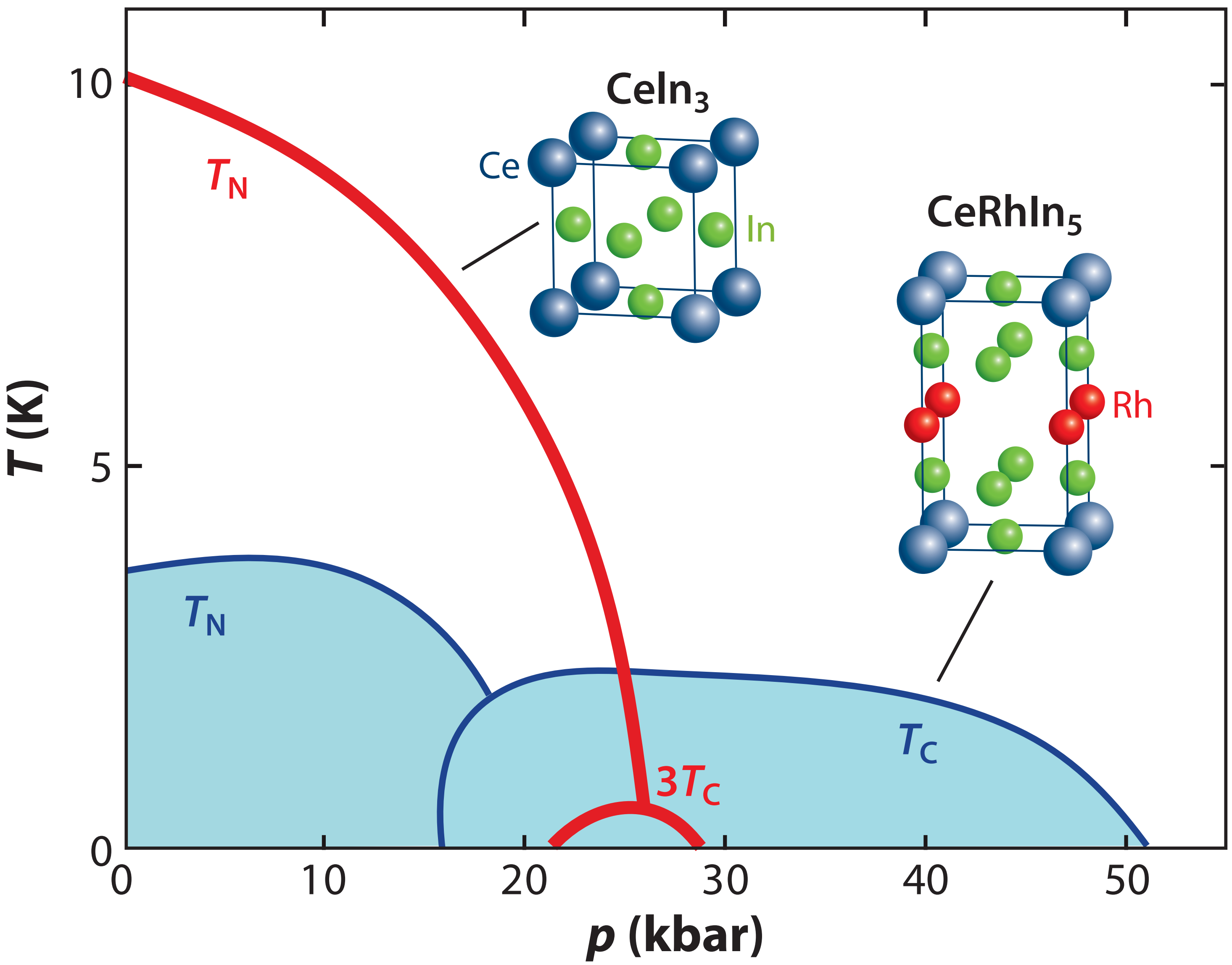
[OS, '07]

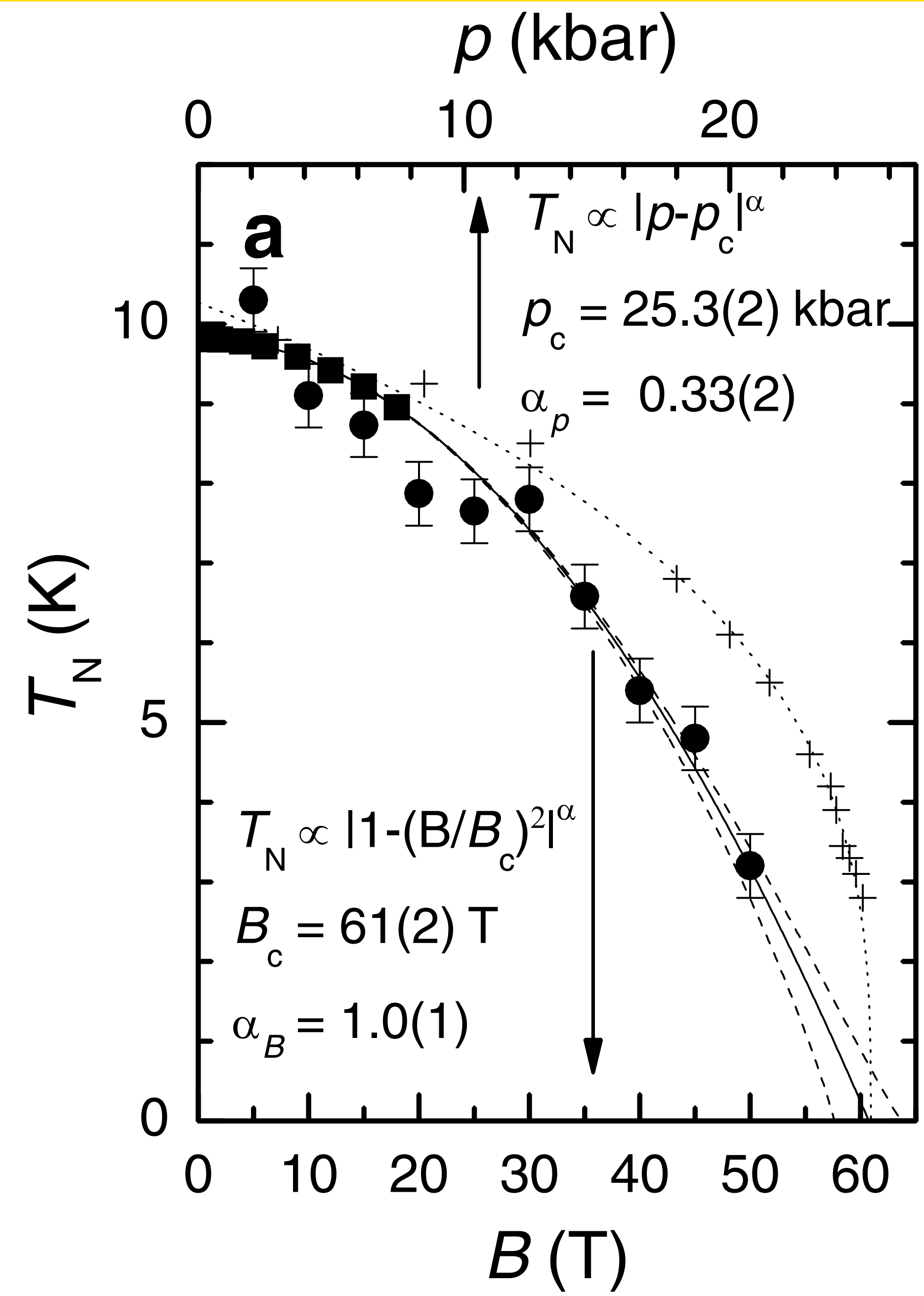
- $CeCu_{5.8}Au_{0.2}$: T_N = 220 mK, $B_c \approx$ 0.35 T ll c to suppress AF order

  $B = B_c$: $C/T = \gamma_0 - a\sqrt{T}$; $\Delta\rho \propto T^{3/2}$ [v. Löhneysen, OS, '01]
- $E/T^{3/2}$ scaling → 3D critical behavior (SDW-, HMM-scenario)

field tuning distinctly different from concentration tuning of the QPT in $CeCu_{6-x}Au_x$

Quantum criticality in $CeIn_3$

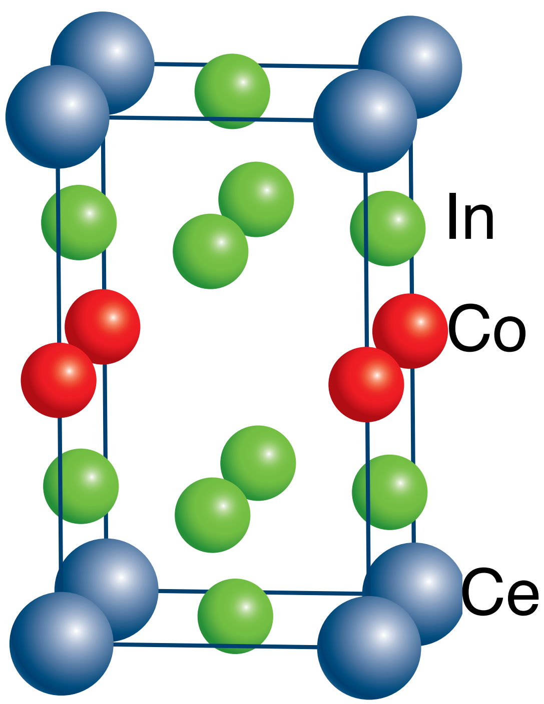


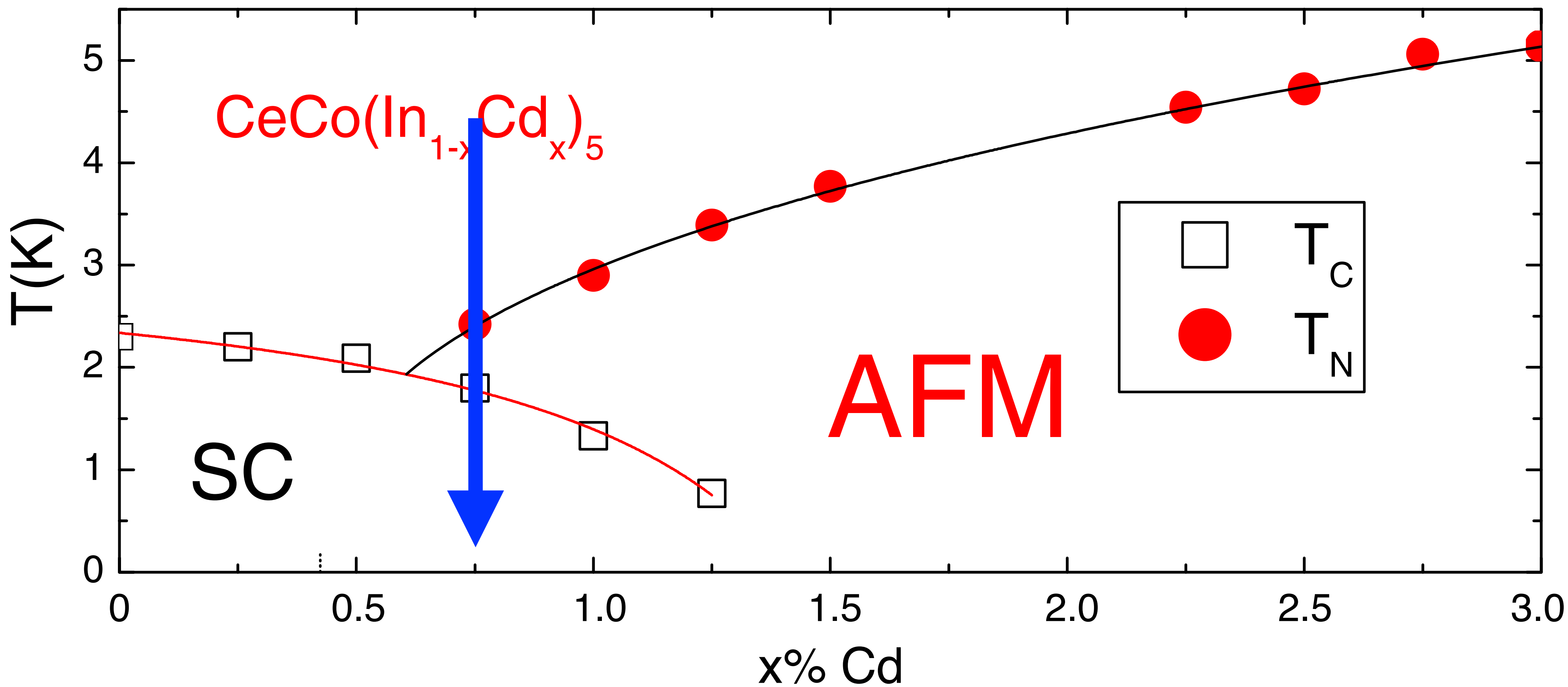


[Monthoux, Nature '07; Ebihara, PRL '04]

- high pressures/magnetic fields needed to drive $CeIn_3$ quantum critical
  $CeIn_3$ → Ce(Rh,Co,Ir)In_5 easier tunable

Cd-doped $CeCoIn_5$





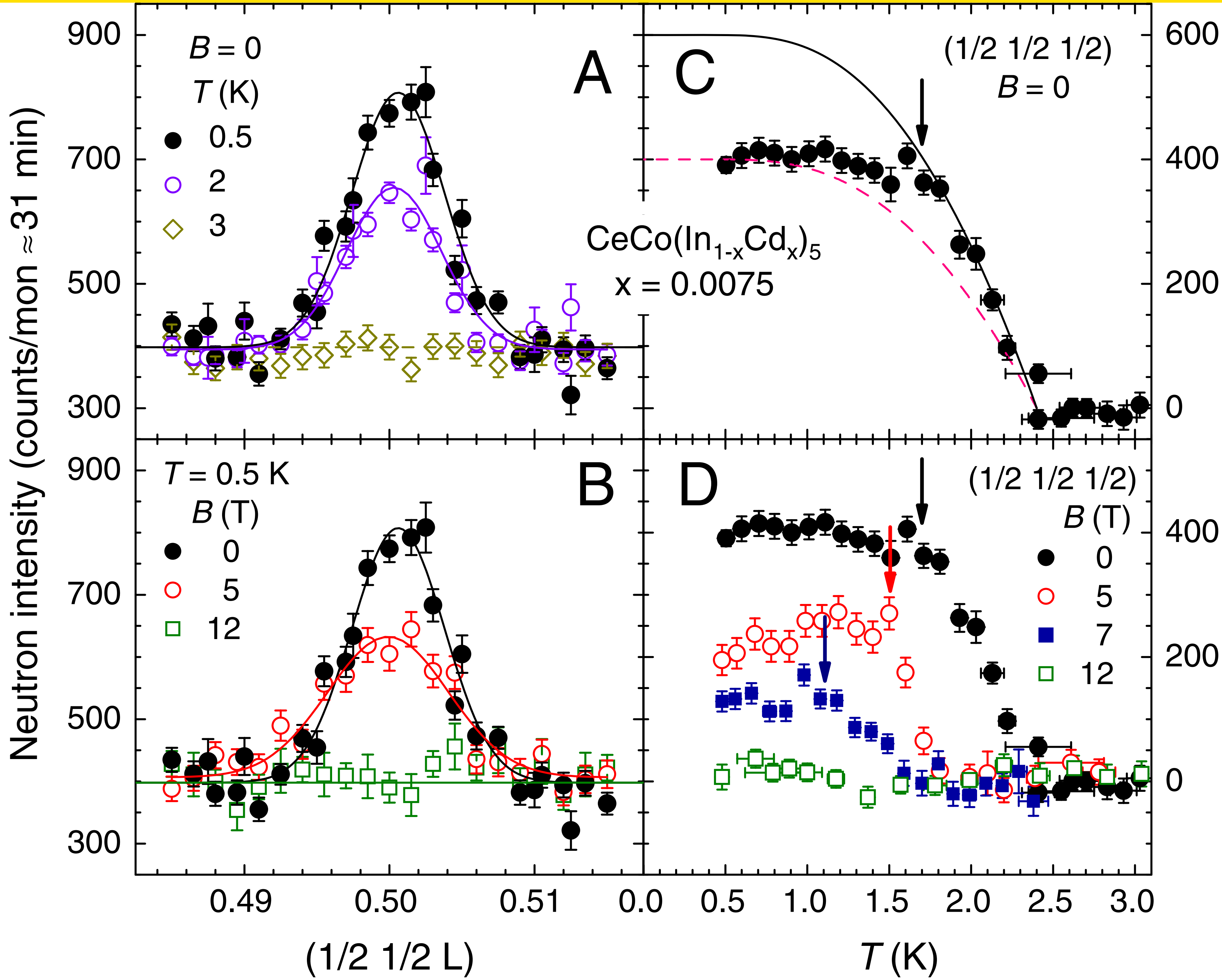
[L. Pham, ’06]

$CeCoIn_5$:

- $\Delta\rho \propto T$, $\Delta C/T \propto \ln T$ [C. Petrovic, ’01]
- strong AF spin fluctuations, e.g. NMR/NQR [Y. Kohori, ’01]
- Cd doping → AF order

⇒ proximity to a QPT

Neutron scattering on Cd-doped $CeCoIn_5$



small crystals,
low temperatures,
high magnetic fields

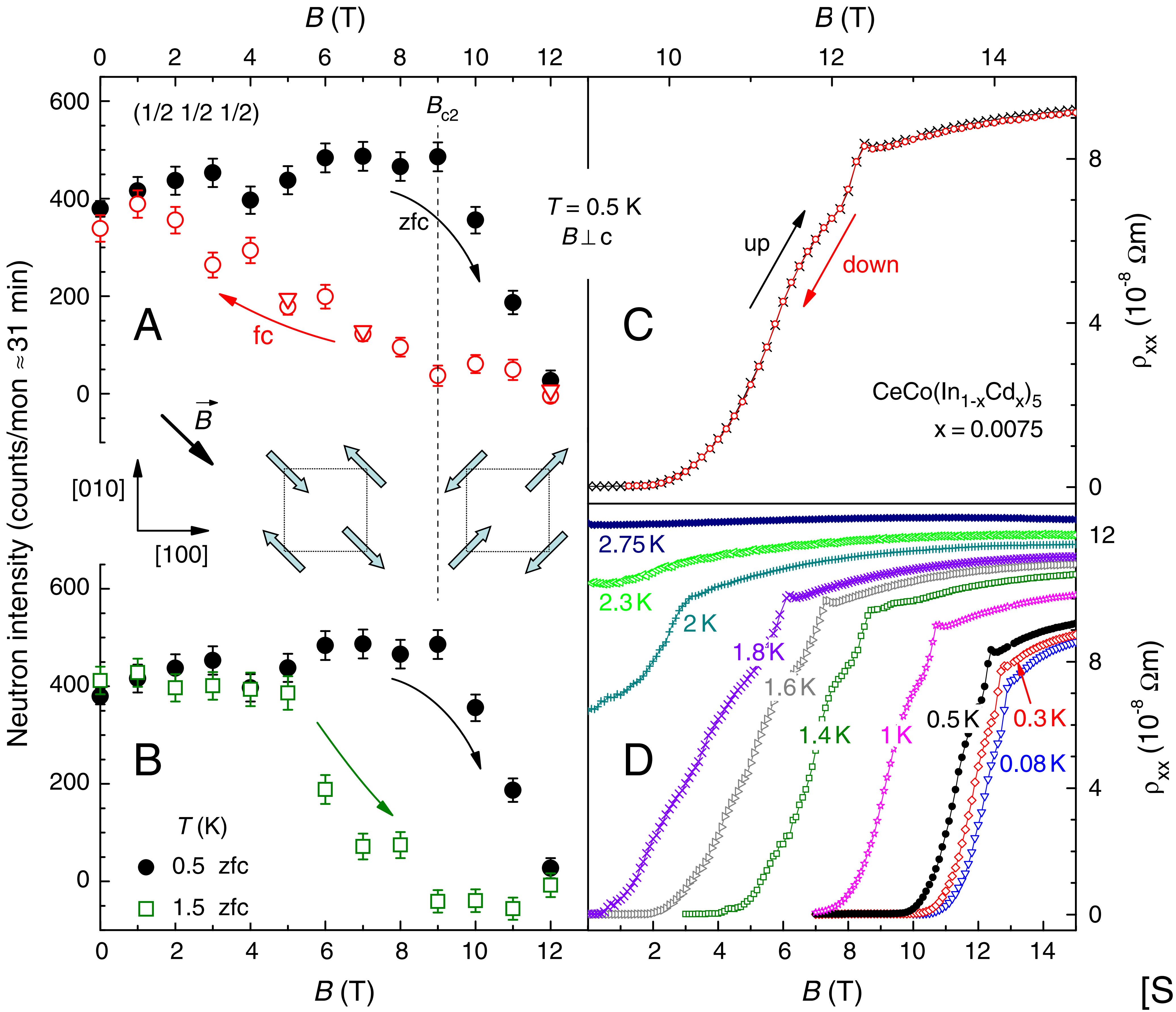
m ≈ 12 mg,
E1/HMI

[S. Nair, OS, '10]

- commensurate AF order with τ = (1/2 1/2 1/2) below $T_N \approx 2.5$ K
- magnetic intensity: kink at $T_c \approx 1.7$ K (B = 0)

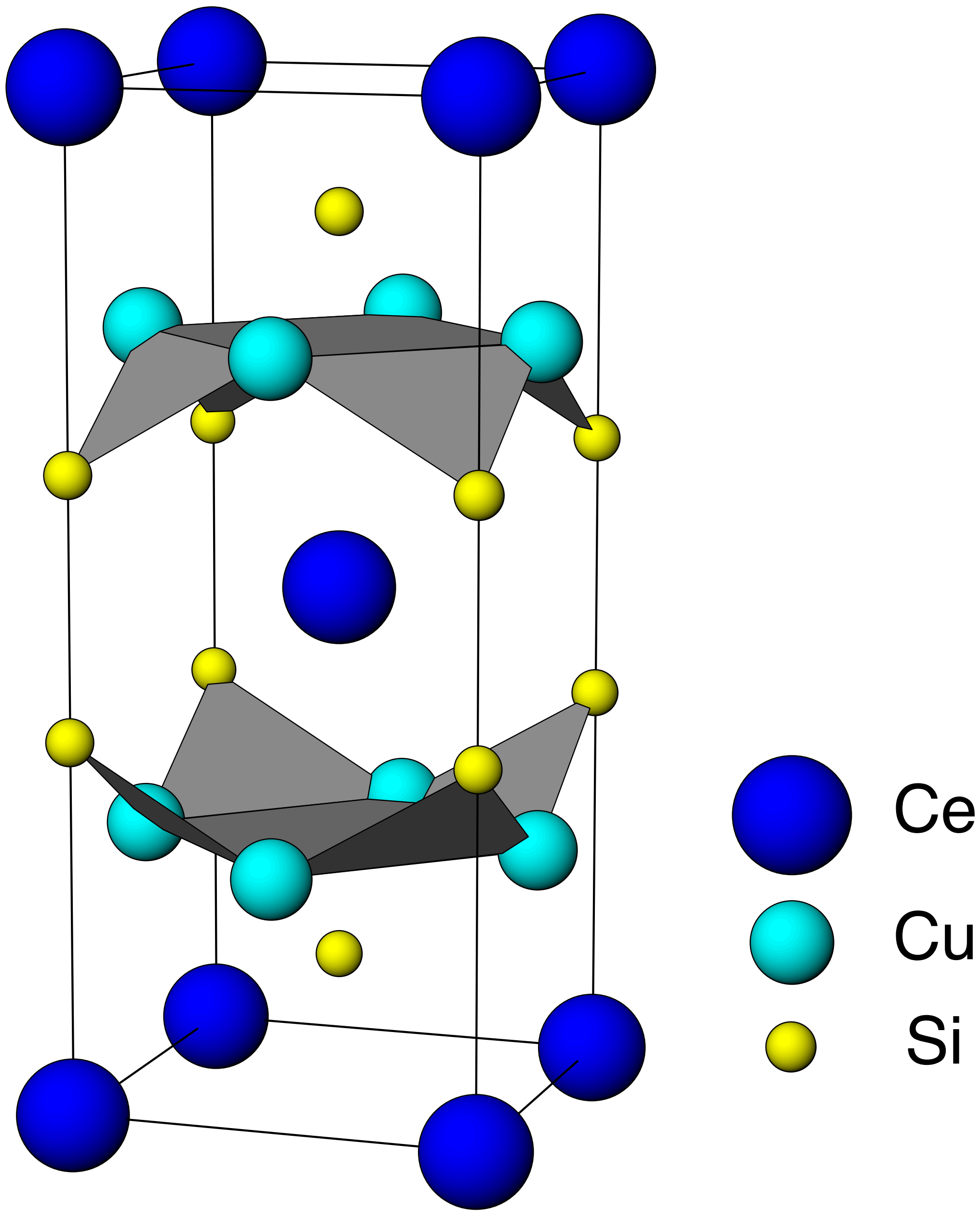
coexistence of antiferromagnetism and superconductivity

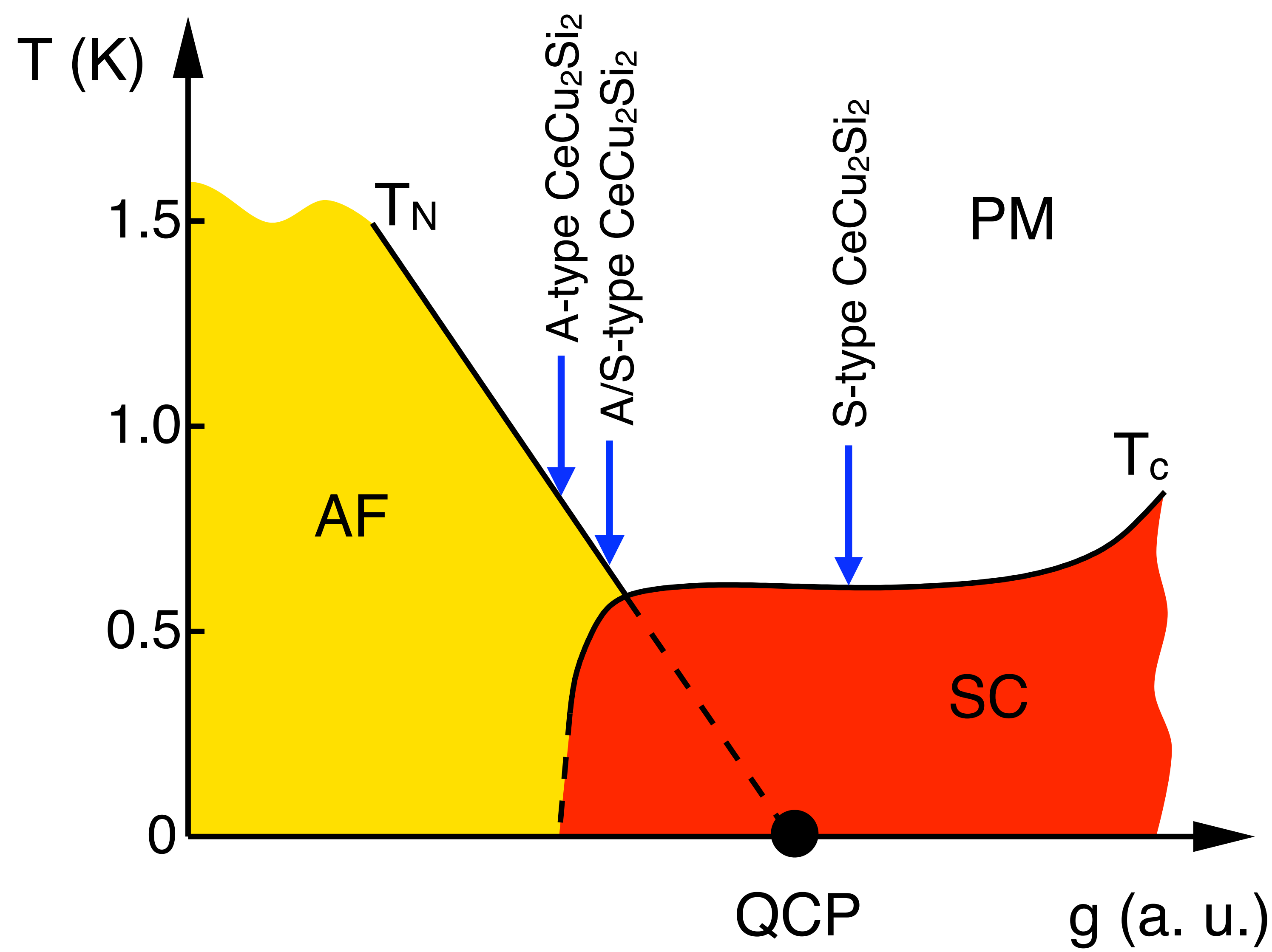
Neutron scattering on Cd-doped $CeCoIn_5$



[S. Nair, OS, '10]

Magnetism and superconductivity in $CeCu_2Si_2$





- Vicinity to quantum critical point at disappearance of antiferromagnetism:
  - $\Delta\rho \propto T^{1...1.5}$
  - $C/T = \gamma_0 - \alpha\sqrt{T}$ (3D-AF instability)

[Gegenwart, PRL ’98; Yuan, Science ’03]

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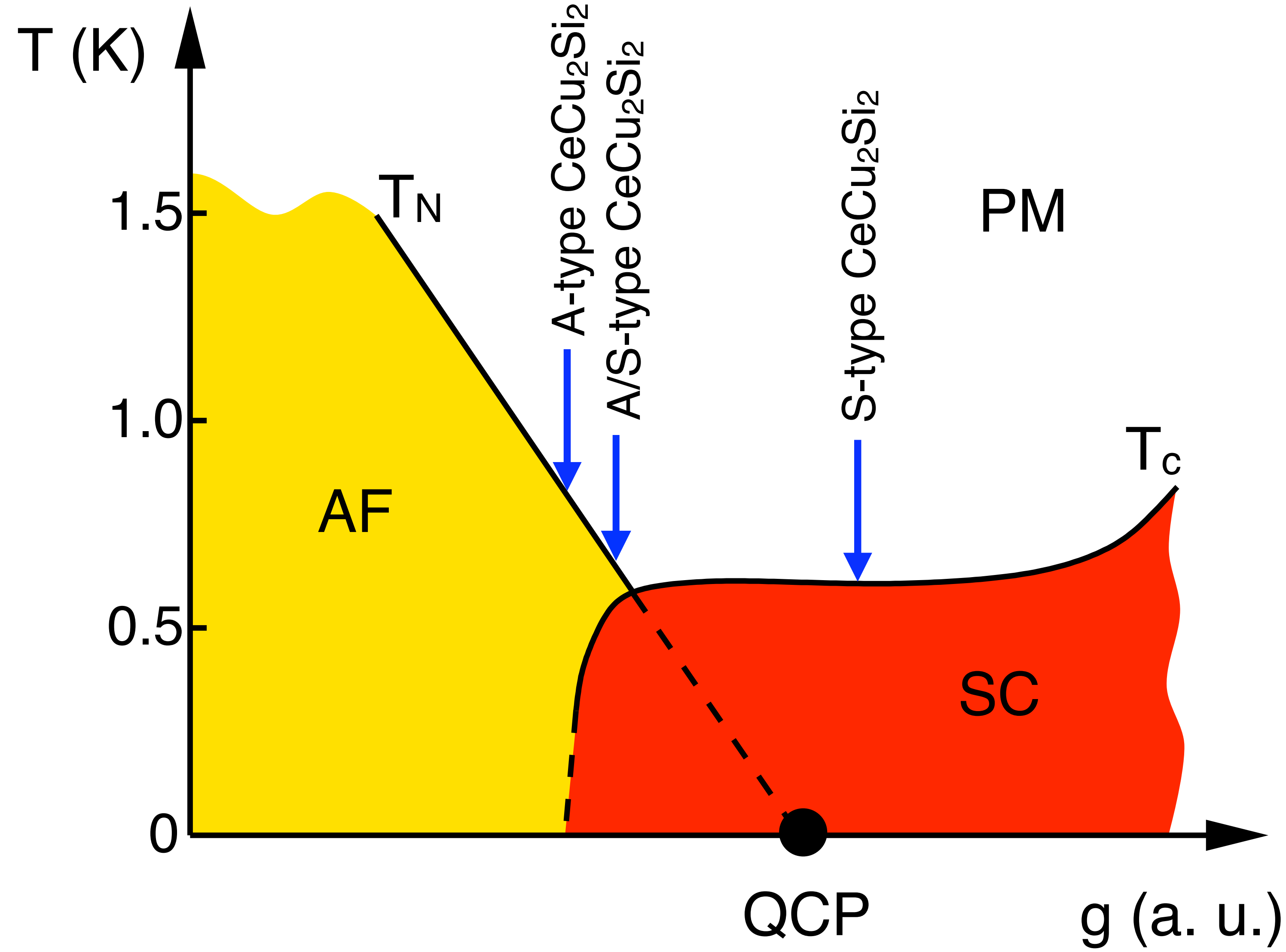

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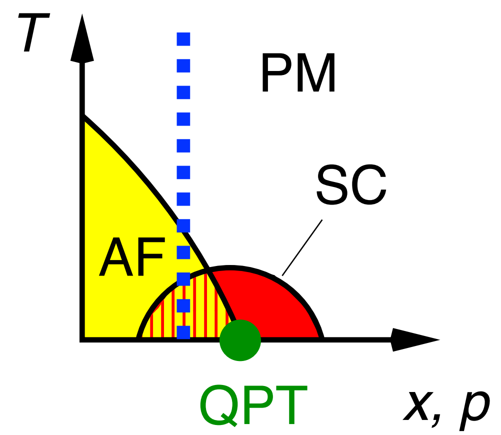
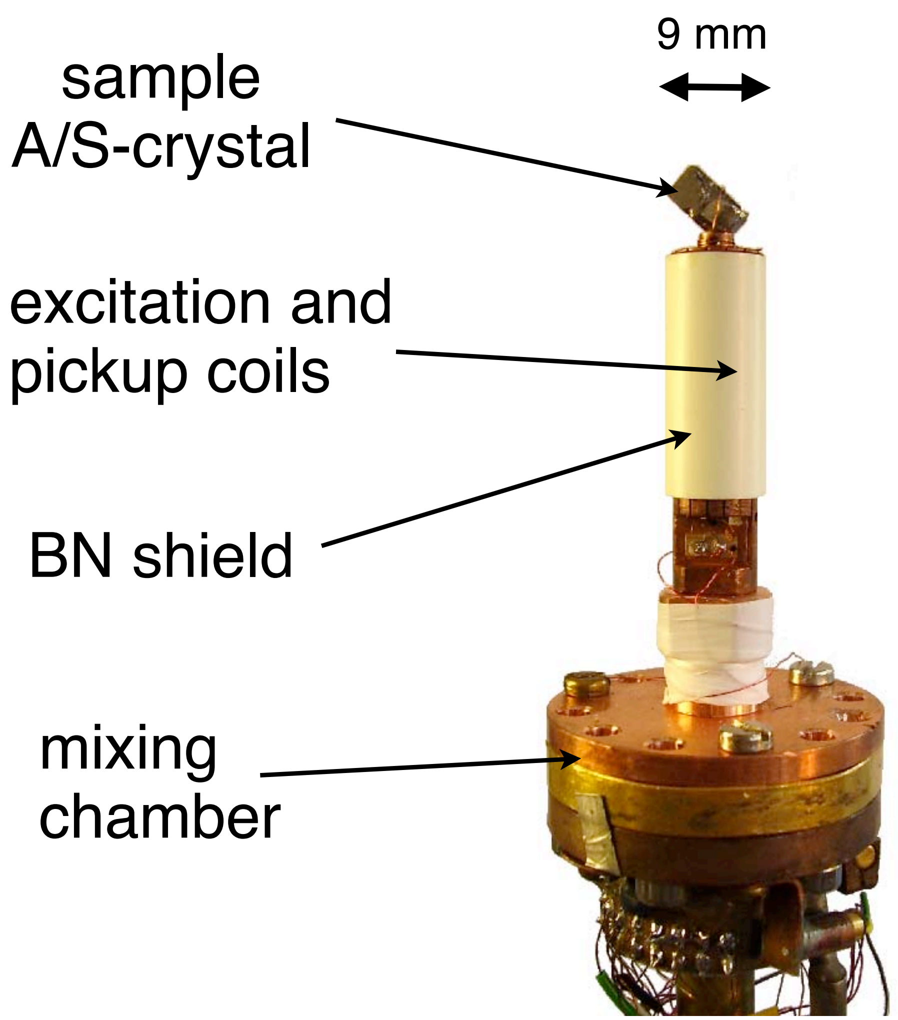
[Gegenwart, PRL '98; Yuan, Science '03]

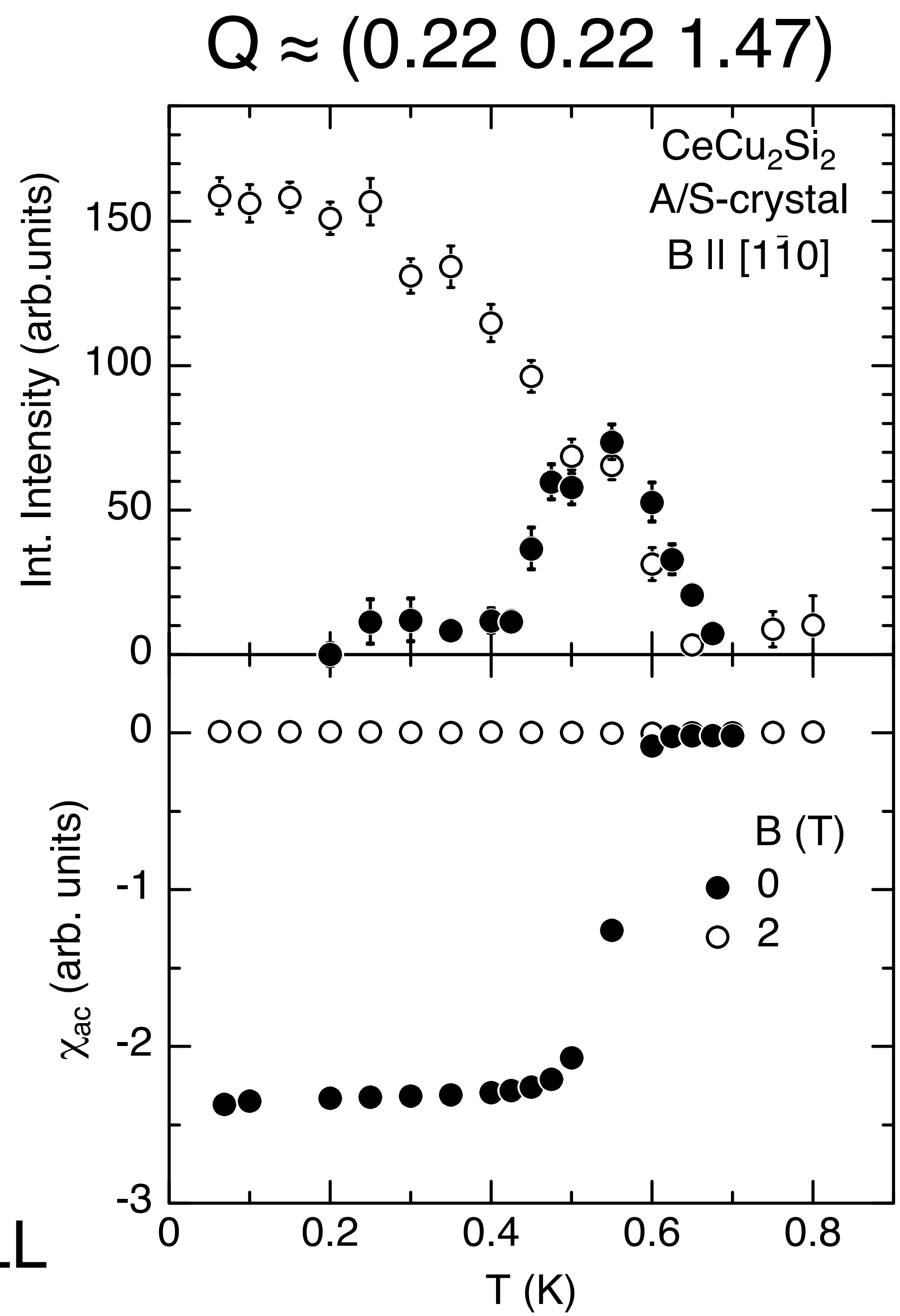
Magnetism and superconductivity in A/S-$CeCu_2Si_2$

$T_N \approx 700$ mK
$T_c \approx 550$ mK
$B_{c2} \approx 1$ T



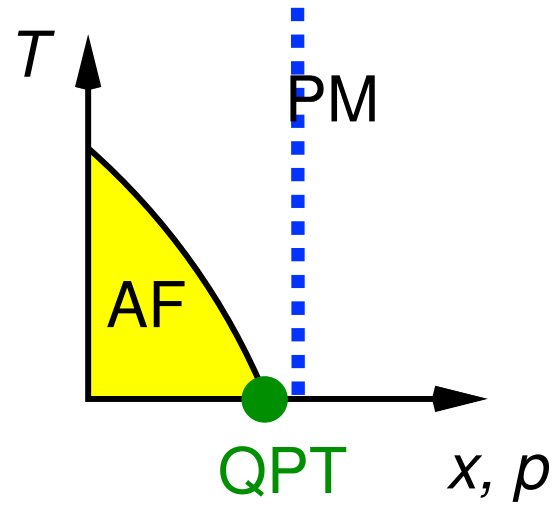


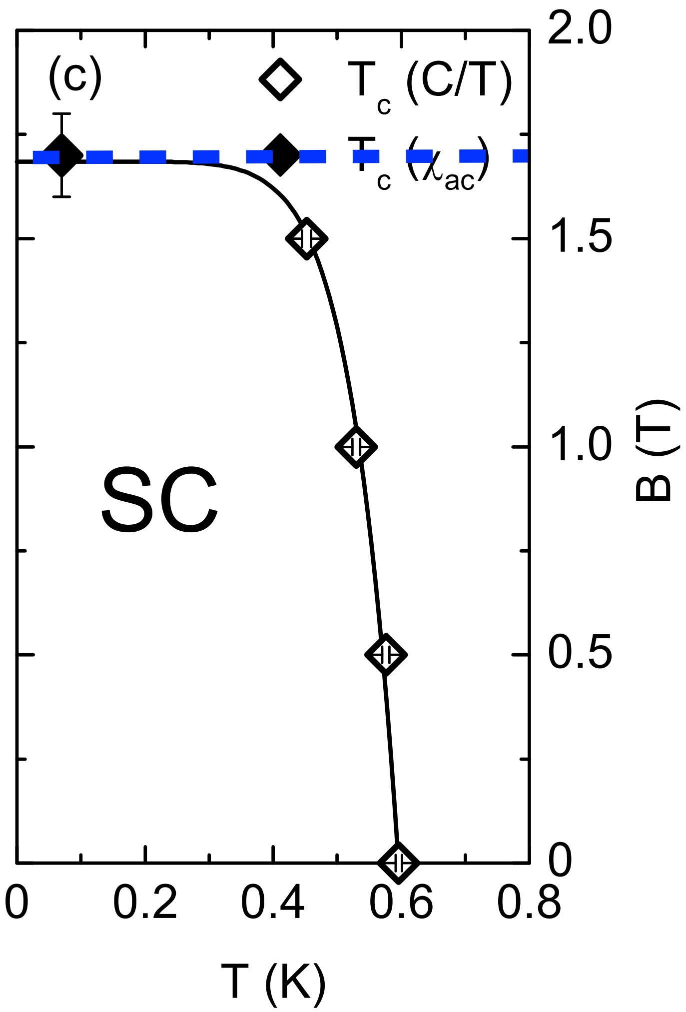
IN12/ILL

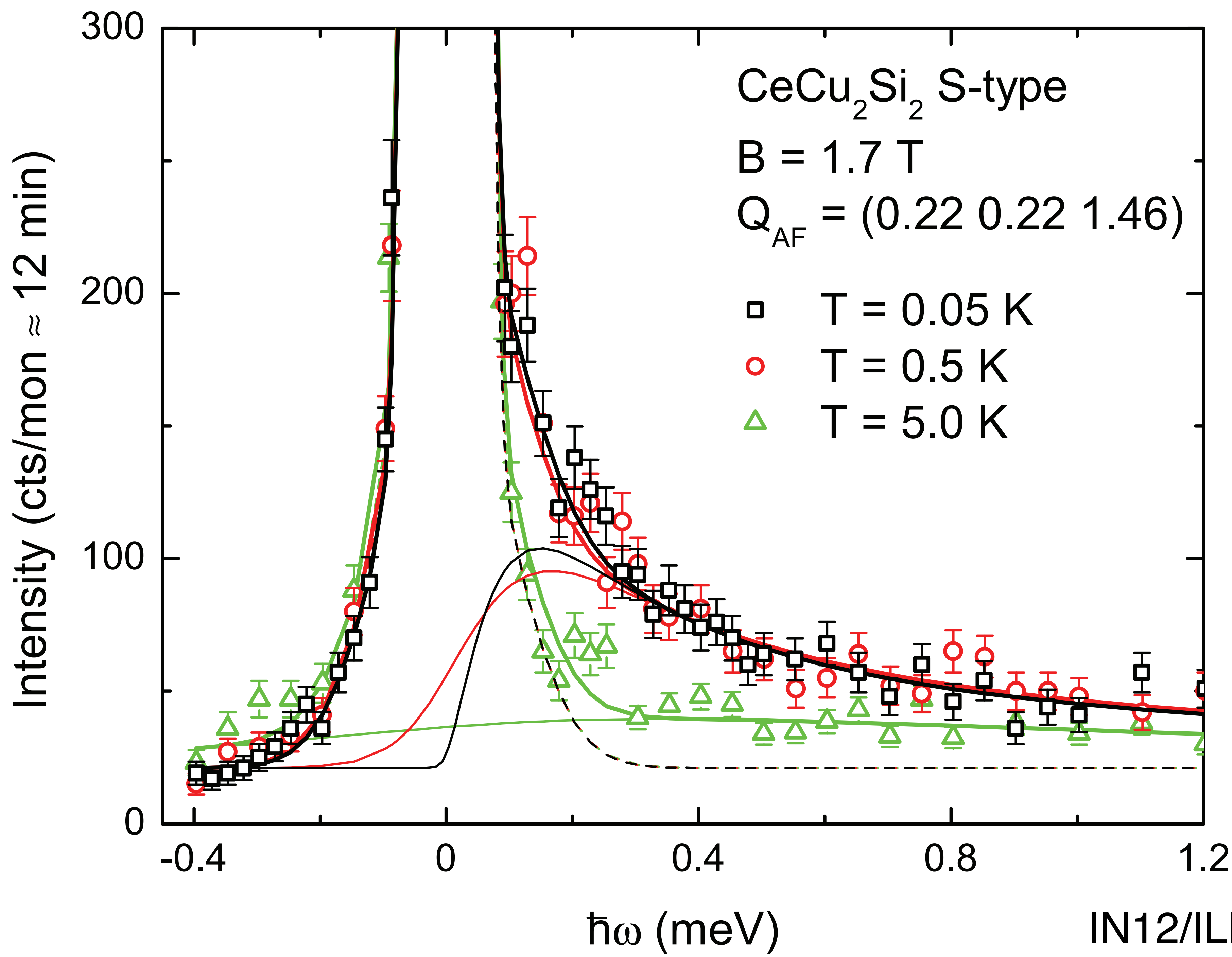


- No coexistence of AF and SC on microscopic scale
- Confirmation of μSR and NQR [R. Feyerherm, ’97; K. Ishida, ’99; OS, ’06]

Normal state spin dynamics in S-$CeCu_2Si_2$





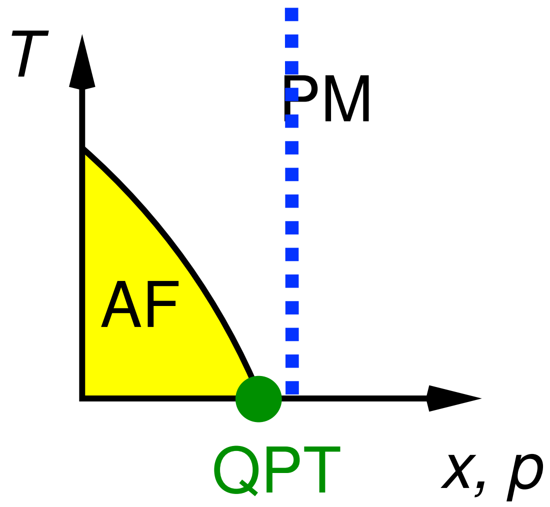


IN12/ILL
$k_f = 1.15$ Å^{-1}

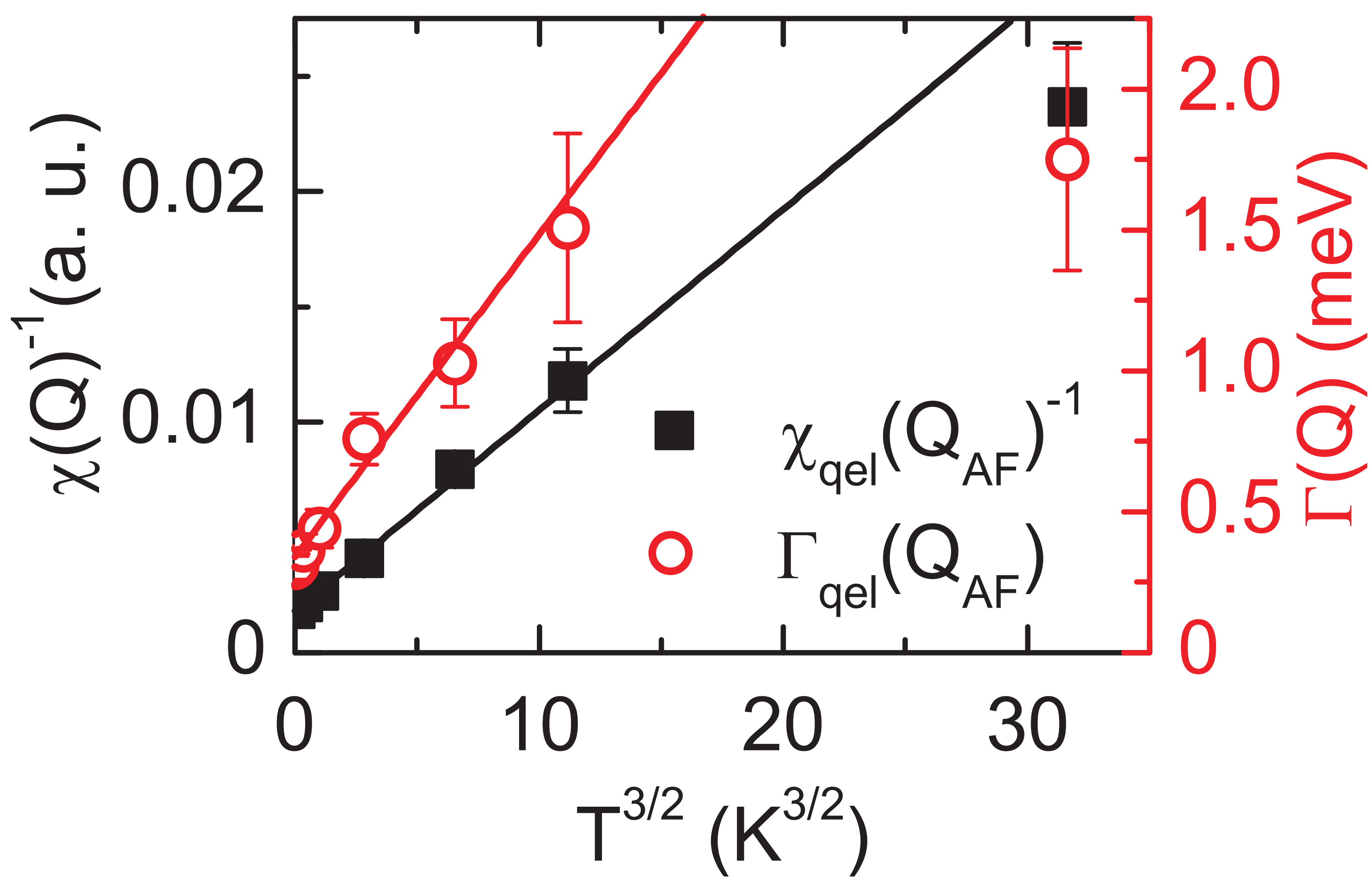
- Quasielastic Lorentzian response
- Decrease in intensity and broadening with T

[J. Arndt, OS, PRL '11]

Normal state spin dynamics in S-$CeCu_2Si_2$

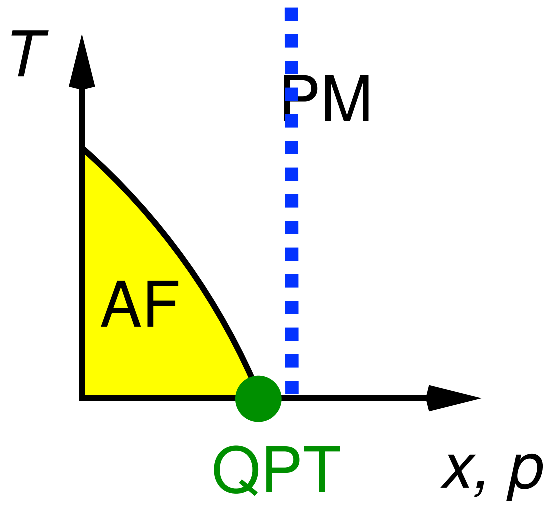


[J. Arndt, OS, PRL '11]

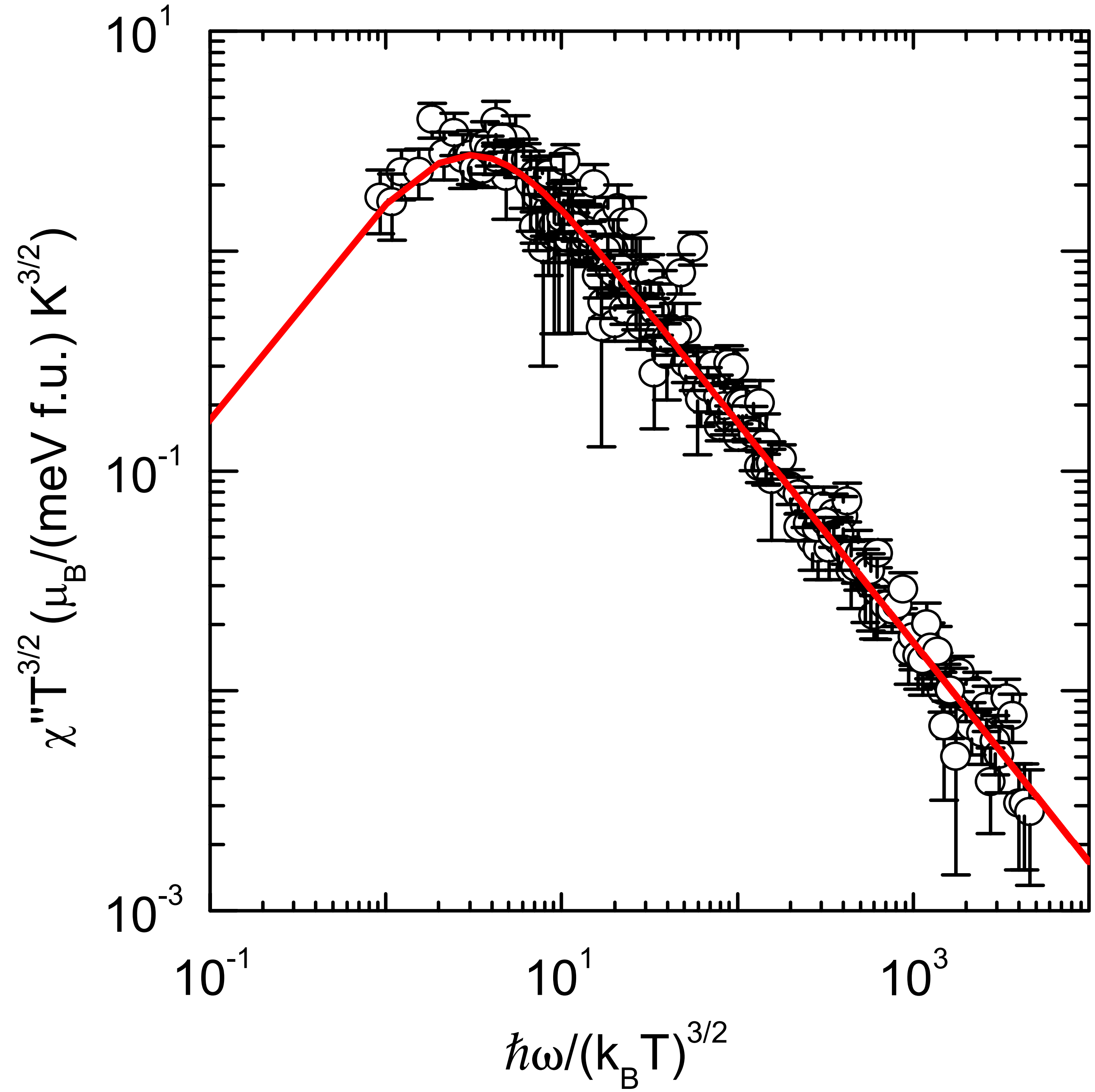


- Considerable slowing down of normal state spin dynamics
  → close vicinity to QPT
- $\omega/T^{3/2}$ scaling of magnetic response (3D critical behavior)

Normal state spin dynamics in S-$CeCu_2Si_2$



[J. Arndt, OS, PRL ’11]



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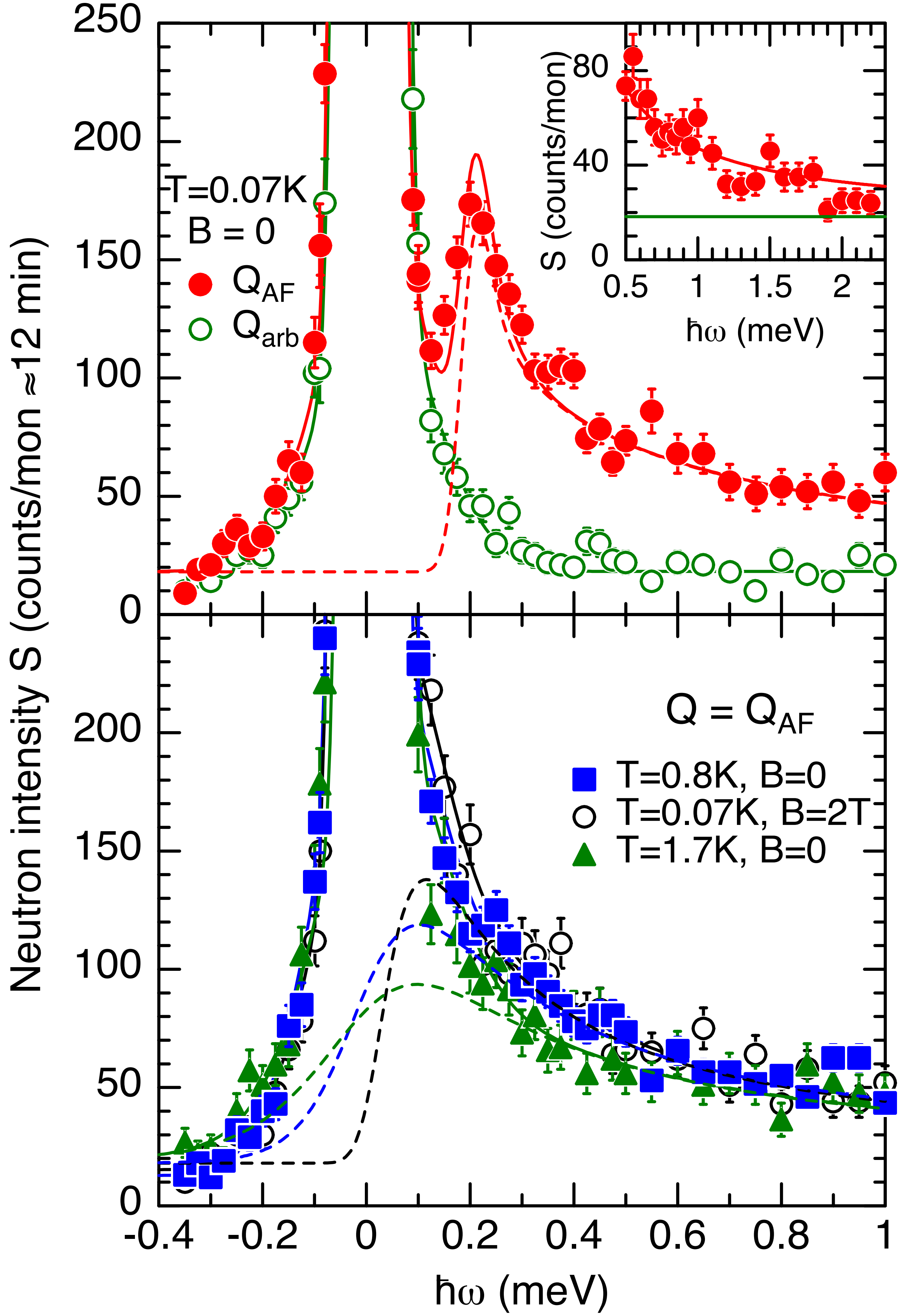
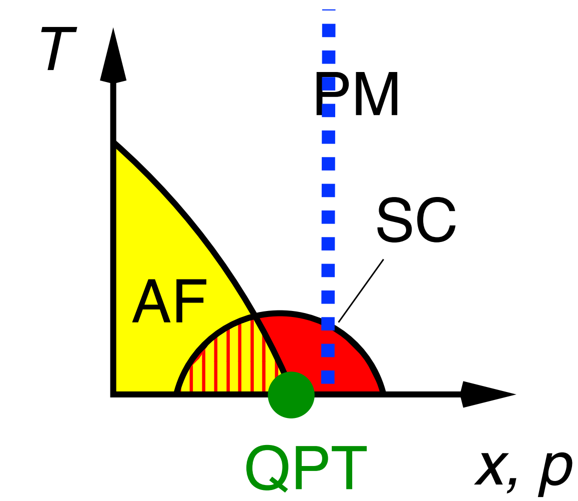
Spin dynamics in superconducting $CeCu_2Si_2$





- broad quasielastic Lorentzian response at Q_{AF}
- gapped in the sc state, $\hbar\omega_{gap} \approx 0.2$ meV ($\approx 3.9\ k_B T_c$)
- $\hbar\omega_{gap}$ follows roughly BCS order parameter (in contrast to high-T_c sc)

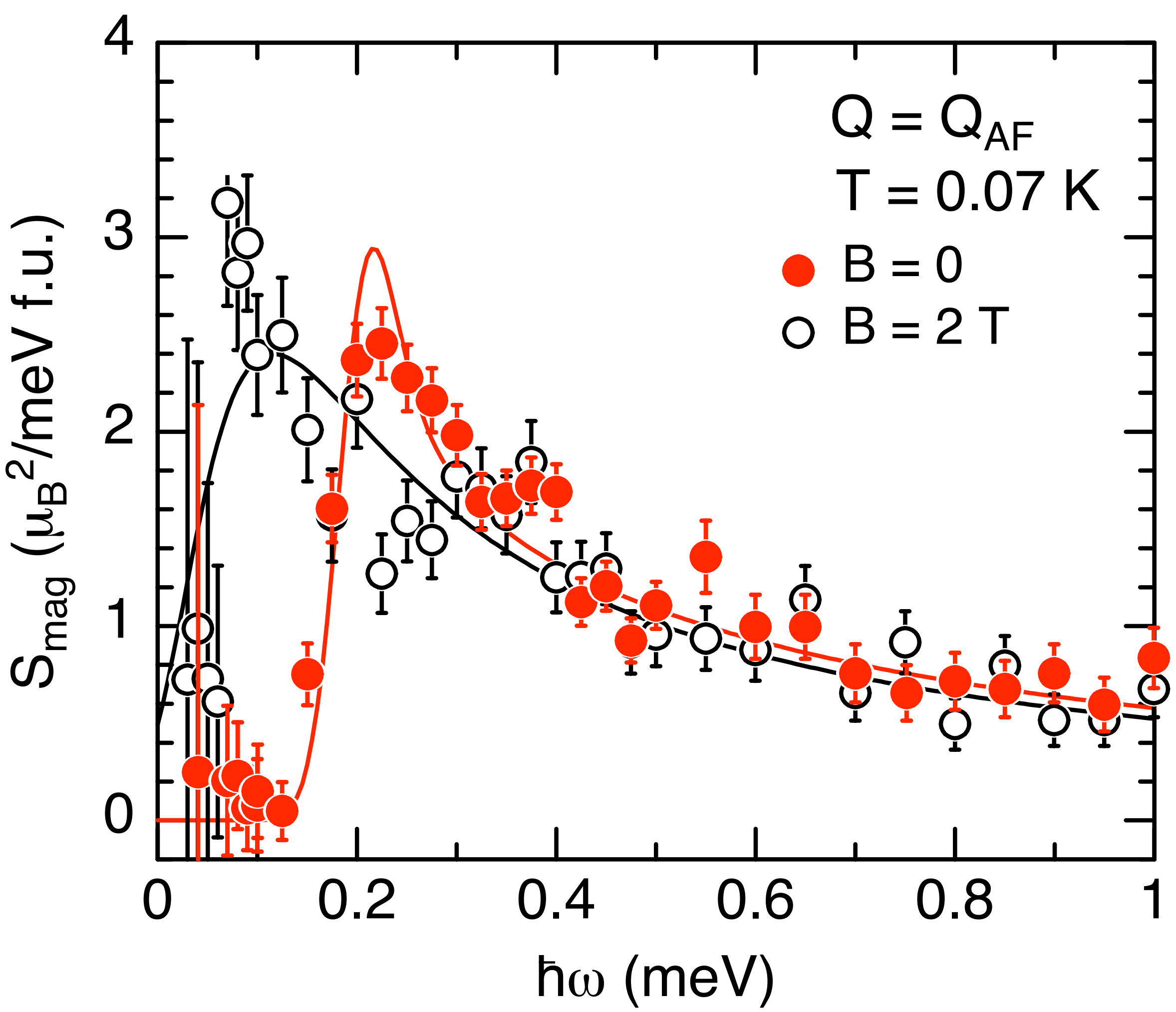
IN12/ILL
k_f = 1.15 Å^{-1}
ΔE = 57 μeV

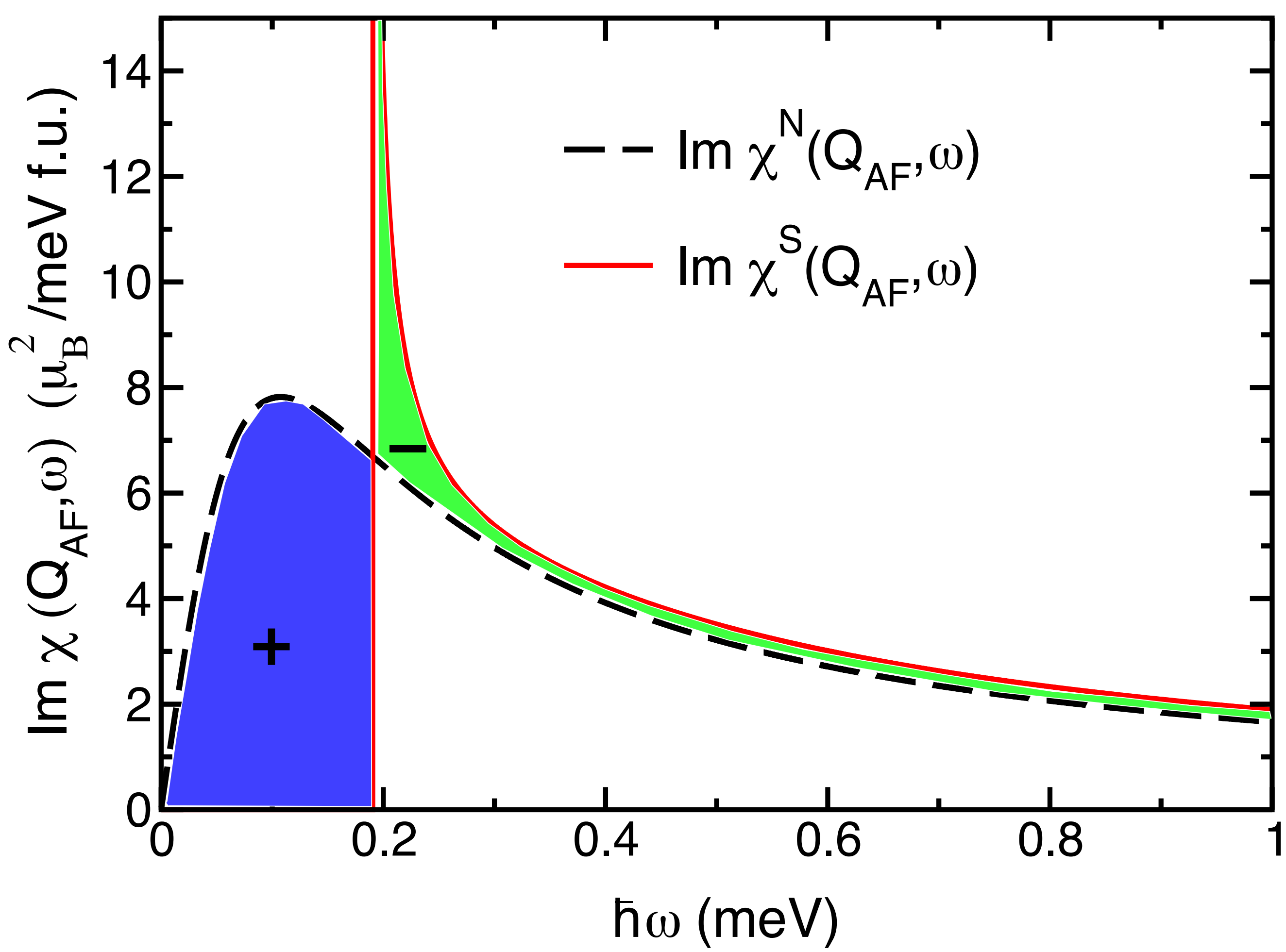
[OS, Nat. Phys., 2011]

Magnetic exchange energies in S-$CeCu_2Si_2$

Magnetic exchange energy gain ΔE_x:

$$\Delta E_x \equiv E_x^S - E_x^N = \frac{1}{g^2\mu_B^2}\int_0^\infty \frac{d(\hbar\omega)}{\pi}[n(\hbar\omega)+1] \times \left\langle I(\mathbf{q})\left[\mathrm{Im}\chi^S(q_x,q_y,q_z,\hbar\omega) - \mathrm{Im}\chi^N(q_x,q_y,q_z,\hbar\omega)\right]\right\rangle,$$





$|\Delta E_x| = 5.36 \cdot 10^{-3}$ meV/Ce >> $|\Delta E_C| = 2.27 \cdot 10^{-4}$ meV/Ce

Magnetic exchange energies in S-$CeCu_2Si_2$

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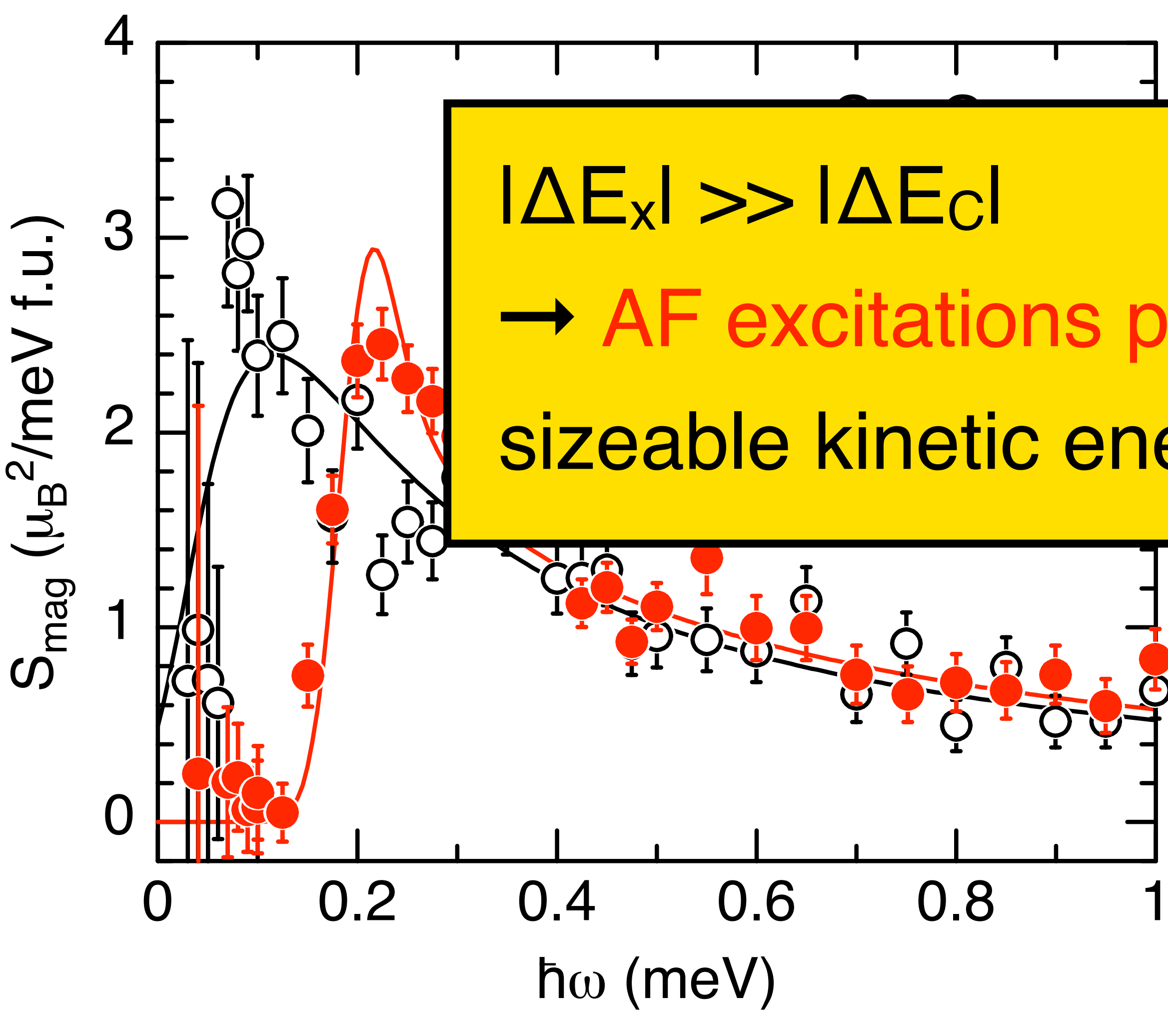

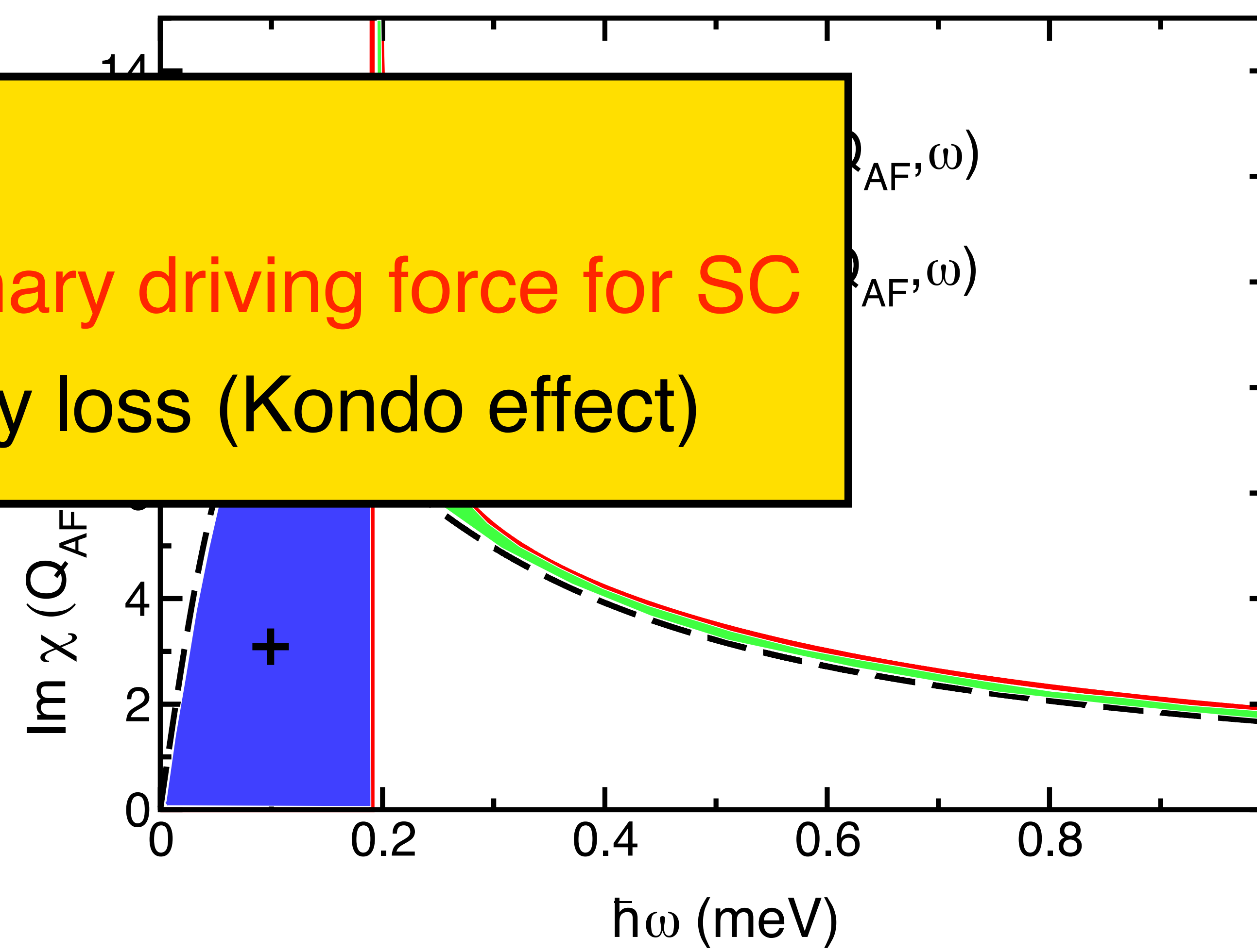

|ΔE_x| >> |ΔE_C|

→ AF excitations primary driving force for SC

sizeable kinetic energy loss (Kondo effect)

|ΔE_x| = $5.36 \cdot 10^{-3}$ meV/Ce >> |ΔE_C| = $2.27 \cdot 10^{-4}$ meV/Ce

Conclusions

$CeCu_{6-x}Au_x$:

• Importance of dimensionality for QCP behavior

Cd-doped $CeCoIn_5$, $CeCu_2Si_2$:

• Coexistence/Competition of AF and SC

$CeCu_2Si_2$:

• Almost critical slowing down of normal state magnetic response,
→ vicinity to QCP

• Spin excitation gap in sc state

• Analysis of magnetic exchange energy:
→ evidence for magnetically driven sc