Magnetically driven superconductivity at quantum phase transitions: a neutron scattering study

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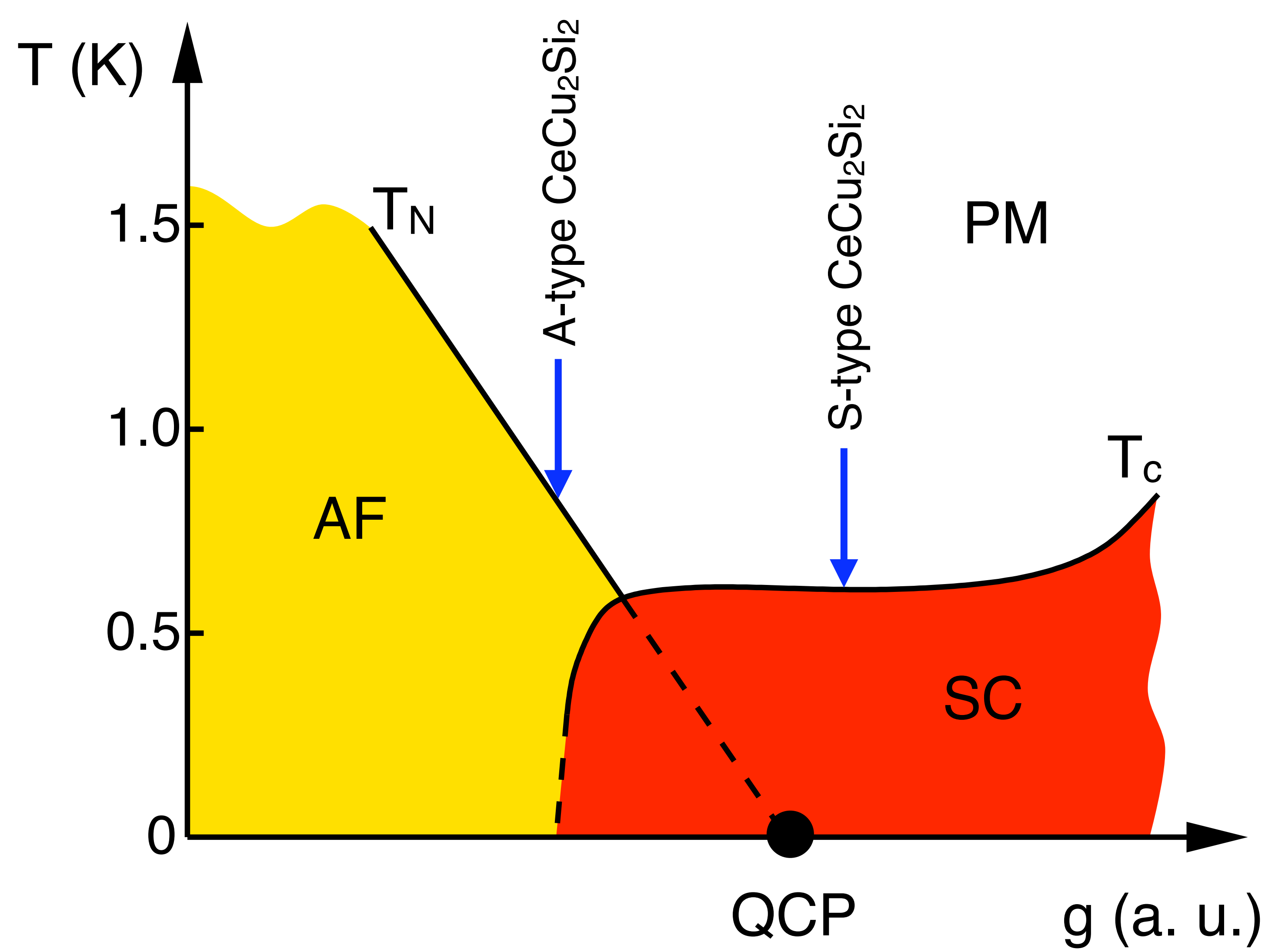
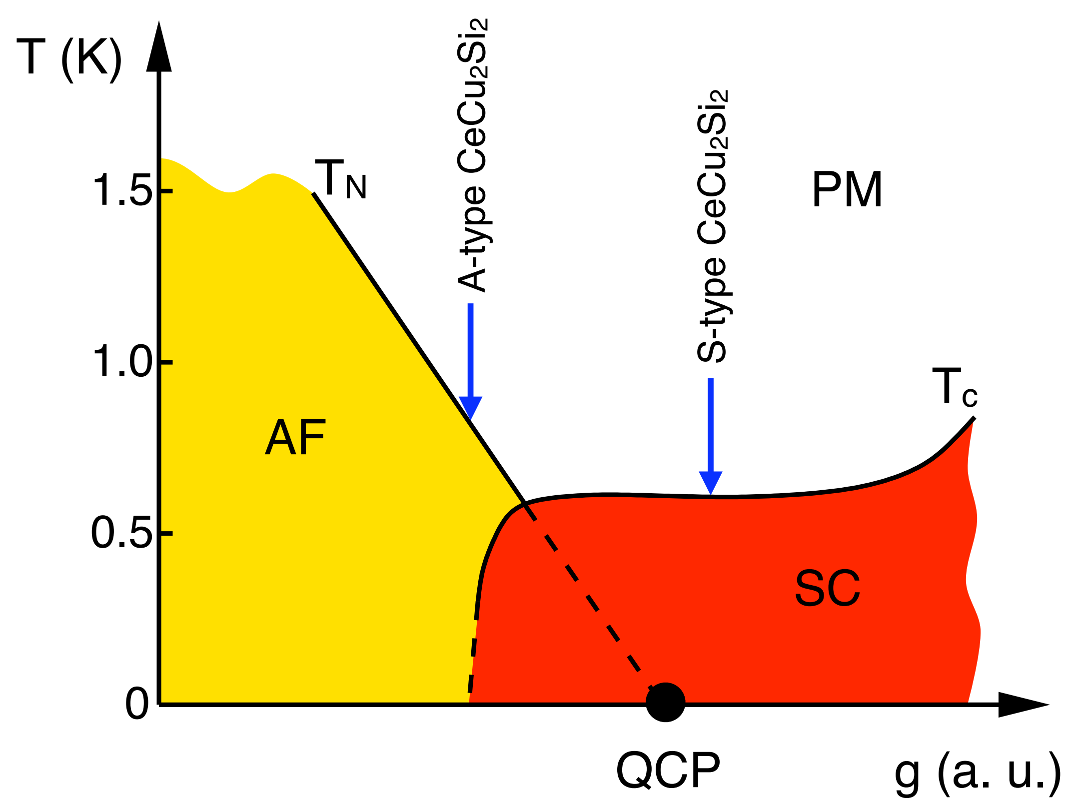


Outline

- Magnetic quantum phase transitions
- Cd-doped $CeCoIn_5$, pure and Ge-doped $CeCu_2Si_2$:
  - coexistence and competition of SC and AF
- Spin dynamics in $CeCu_2Si_2$:
  - Normal state: vicinity to quantum critical point
  - Superconducting state and energetics
- Perspectives, Outlook



more information:

- Proc. Natl. Acad. Sci. USA **107**, 9537 (2010)
- Nature Physics **7**, 119 (2011)
- Phys. Rev. Lett. **106**, 246401 (2011)

Collaborations

Thanks ...

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Q. Si — Rice University Houston

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Quantum phase transitions

Continuous phase transition
for T ⟶ 0

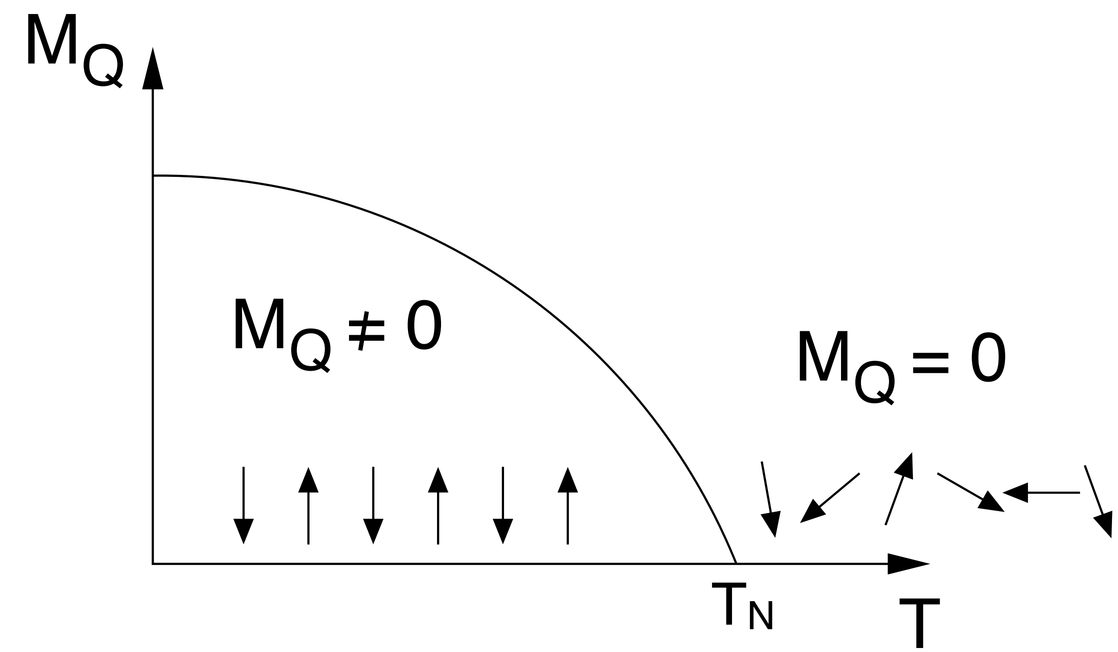
⟶ Quantum phase transition (QPT)
with unusual low temperature
properties:

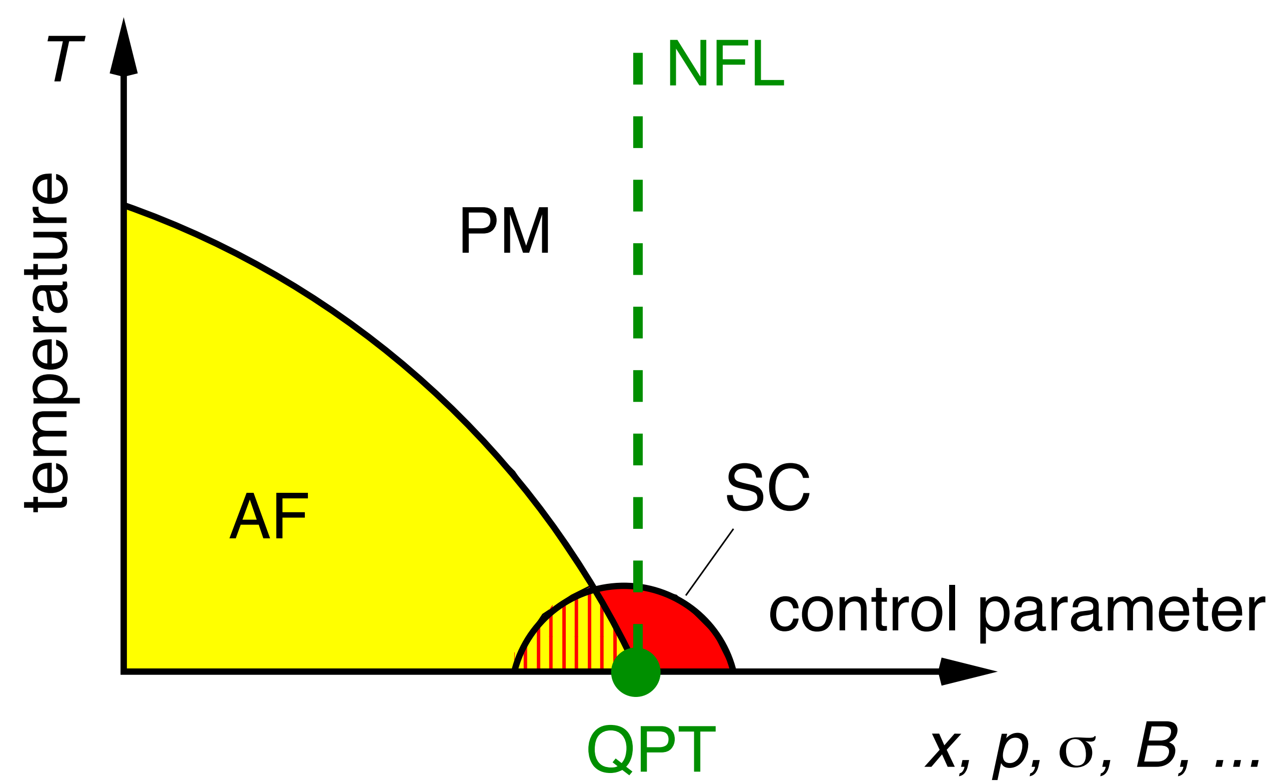
- $C/T \propto -\ln T$;
  $\Delta\rho \propto T^{\alpha}$, $\alpha \neq 2$ (NFL)
- superconductivity

Origin?

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

Neutrons ideal microscopic probe!





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

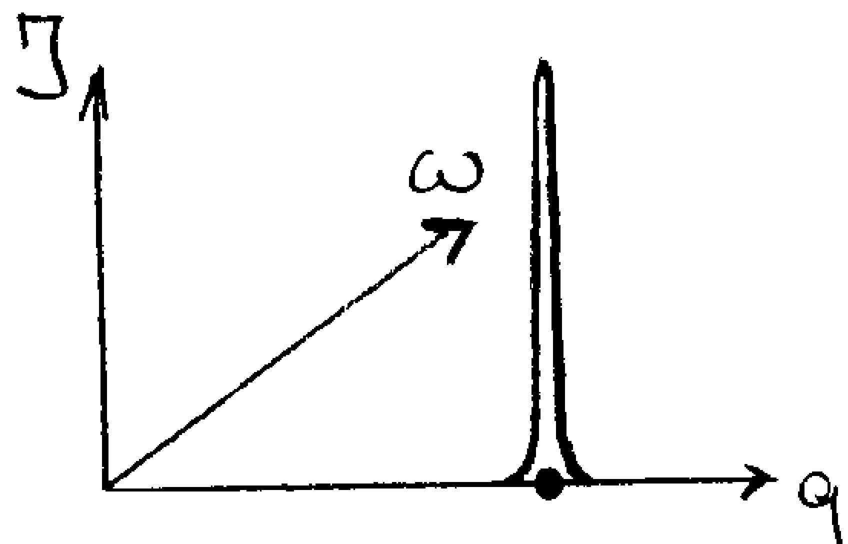
Neutrons as microscopic probe

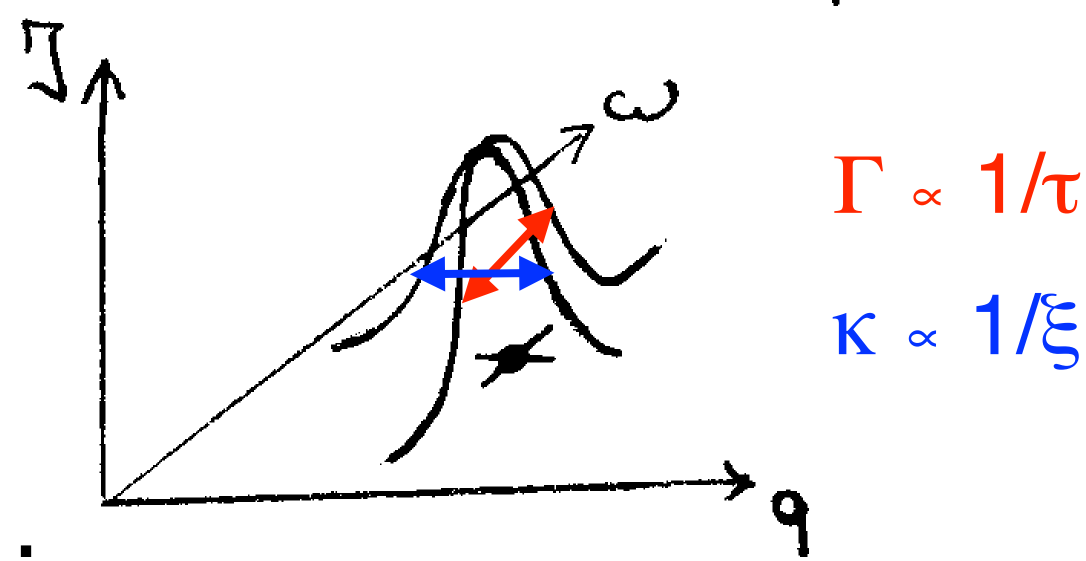
Magnetic neutron scattering:

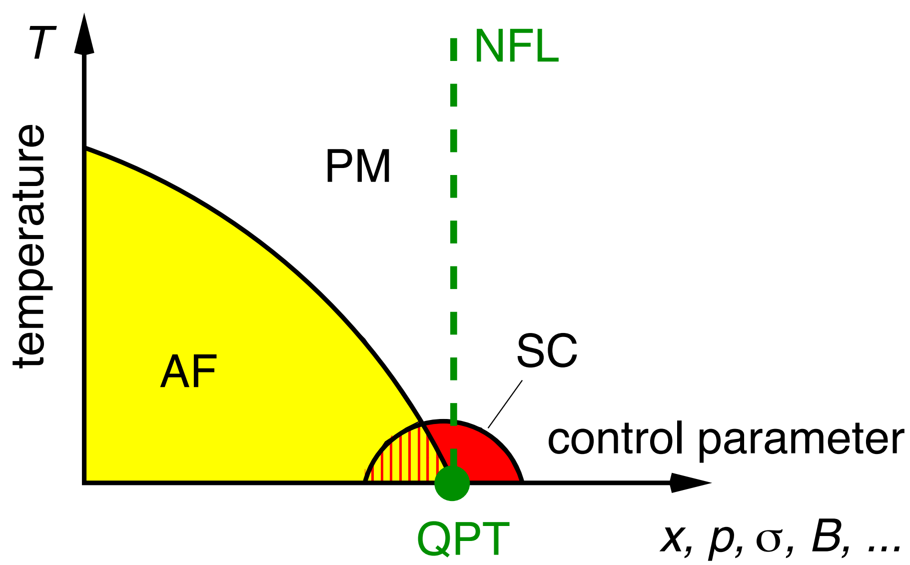
FT of spin-spin-correlation function

$$\mathrm{I} \;\propto\; \frac{d^2\sigma}{d\Omega d\omega} \;\propto\; S(\mathbf{q},\omega) \;=\; \mathrm{FT}\left\{ \sum_{i,j} e^{i\mathbf{q}(\mathbf{R}_i - \mathbf{R}_j)} \;\langle \hat{S}_i(0)\hat{S}_j(t)\rangle \right\}$$

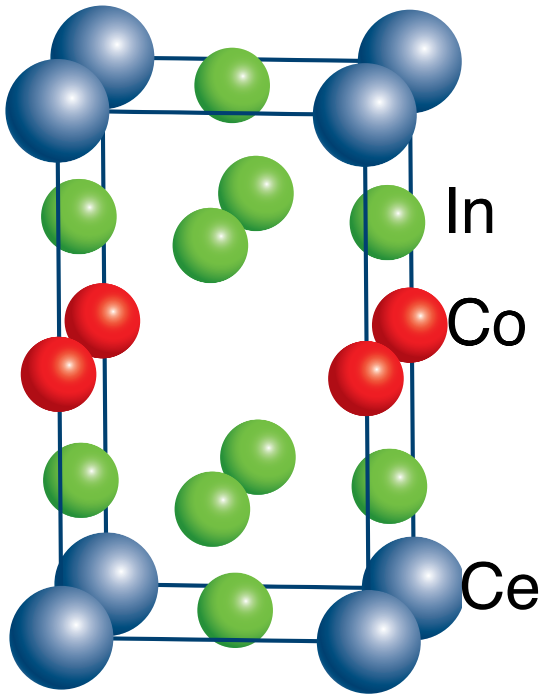
- Magnetic order
- Spin wave
- Spin fluctuations: resolved in energy and momentum transfer

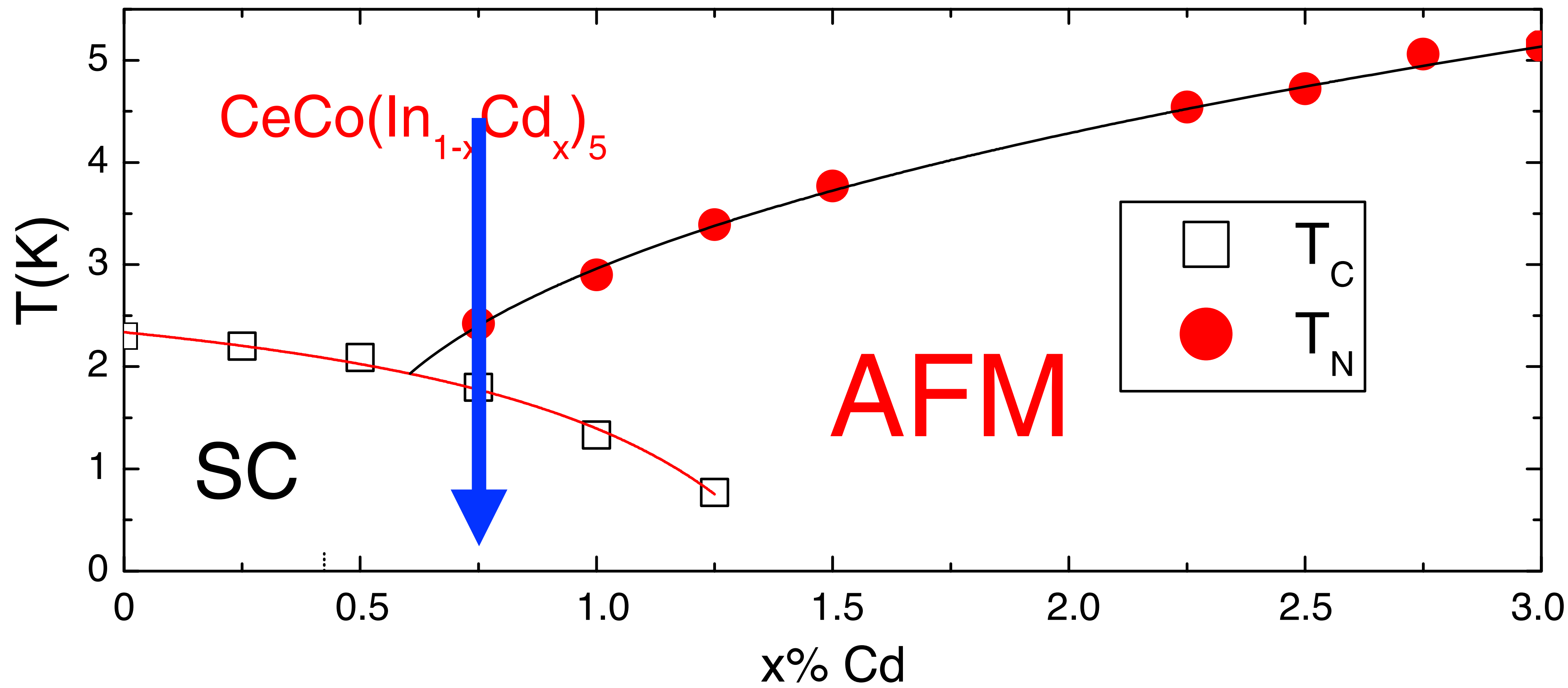






Cd-doped $CeCoIn_5$





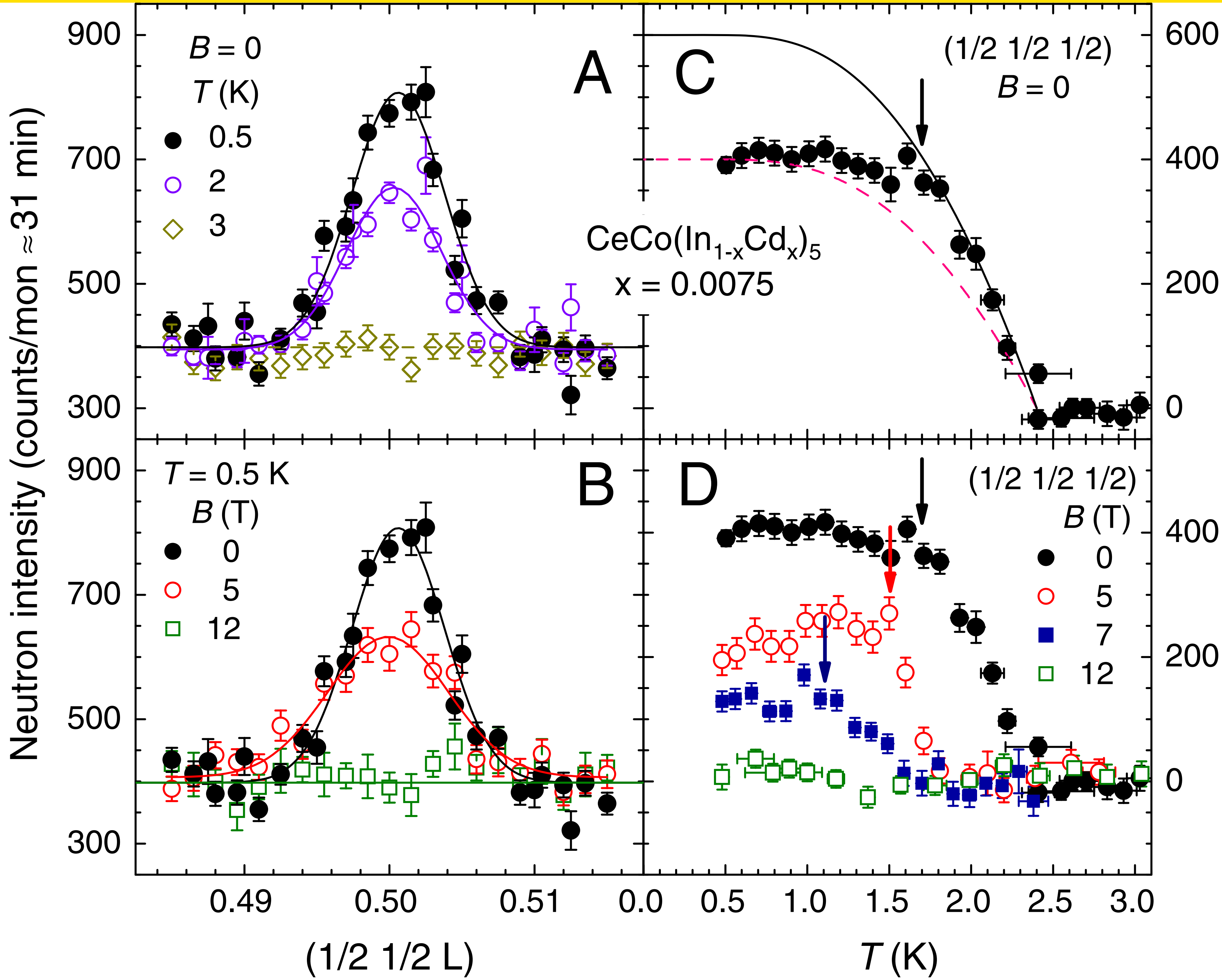
[L. Pham, '06]

$CeCoIn_5$:

- $\Delta\rho \propto T$, $\Delta C/T \propto \ln T$ [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

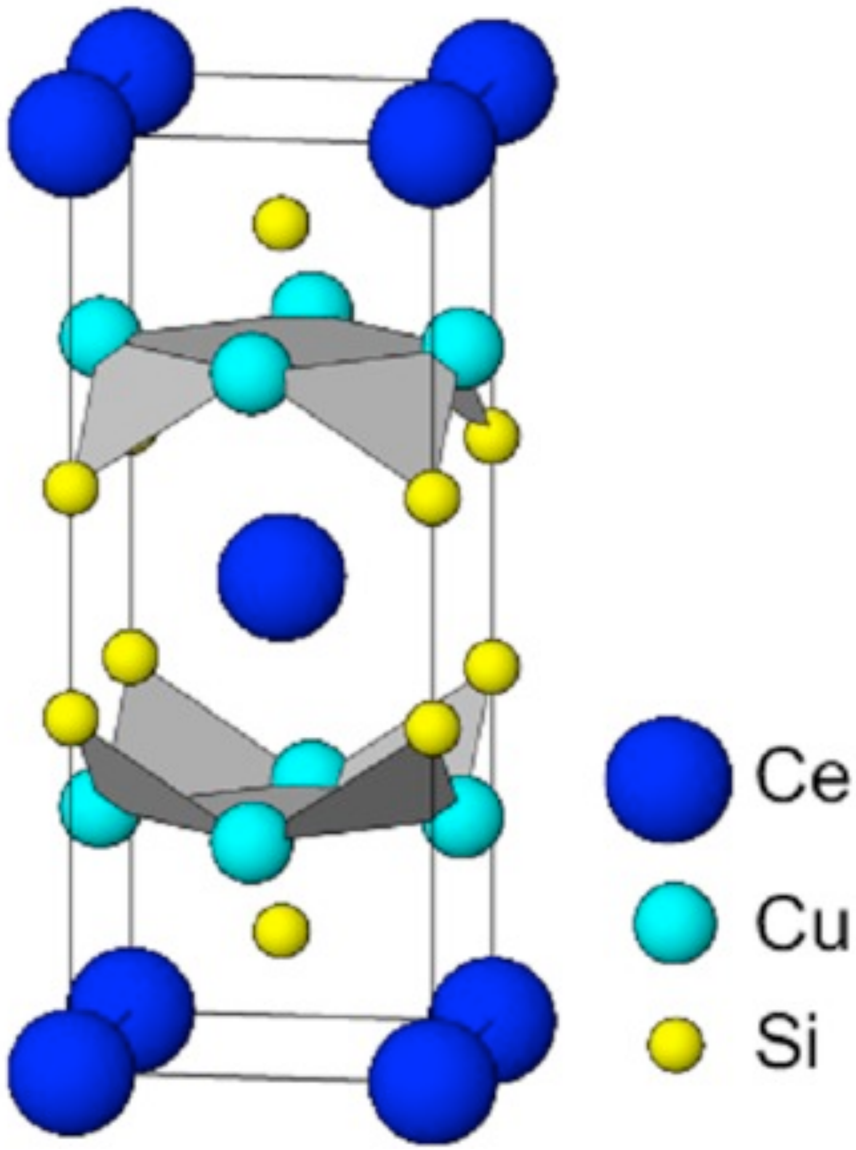
m ≈ 12 mg,
E1/HMI

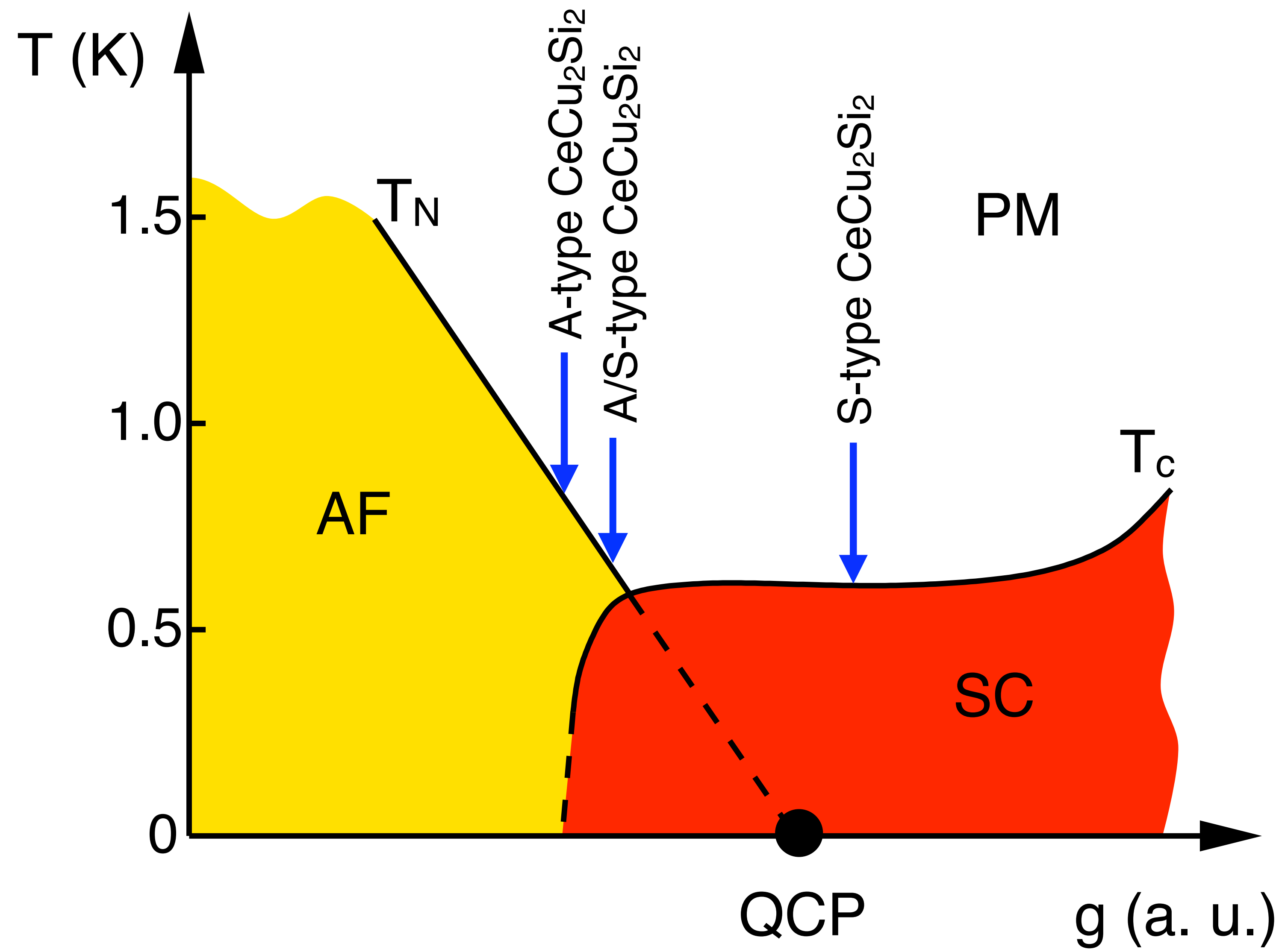
[S. Nair, OS, '10]

- 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

Magnetism and superconductivity in $CeCu_2Si_2$

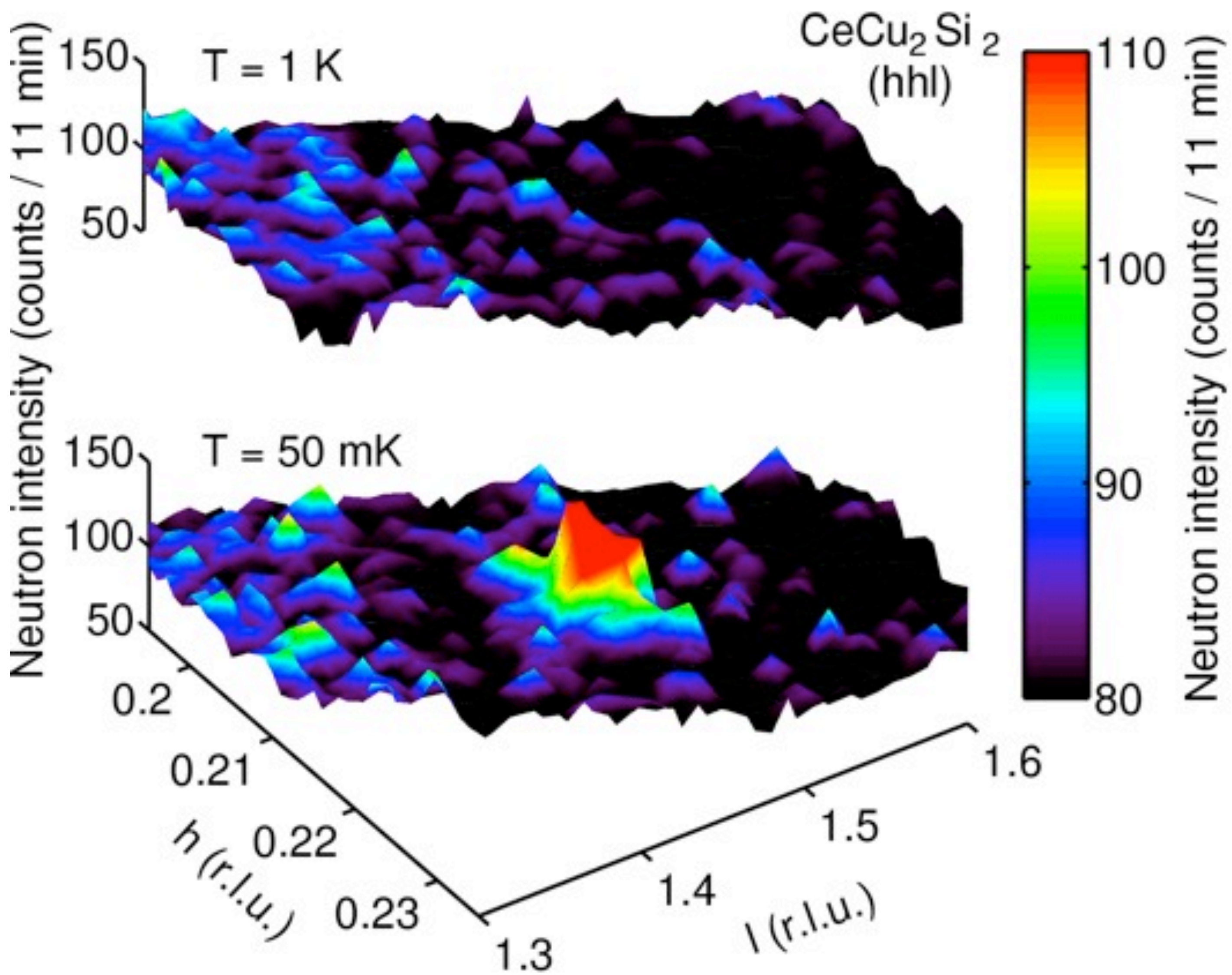




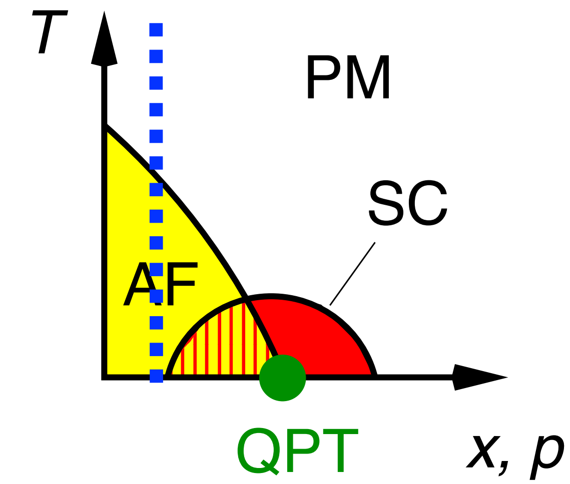
- Vicinity to quantum critical point at disappearance of antiferromagnetism:
  - $\Delta\rho \propto T^{1...1.5}$
  - $C/T = \gamma_0 - \alpha\sqrt{T}$ (3D-AF instability)

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

Antiferromagnetism in $CeCu_2Si_2$

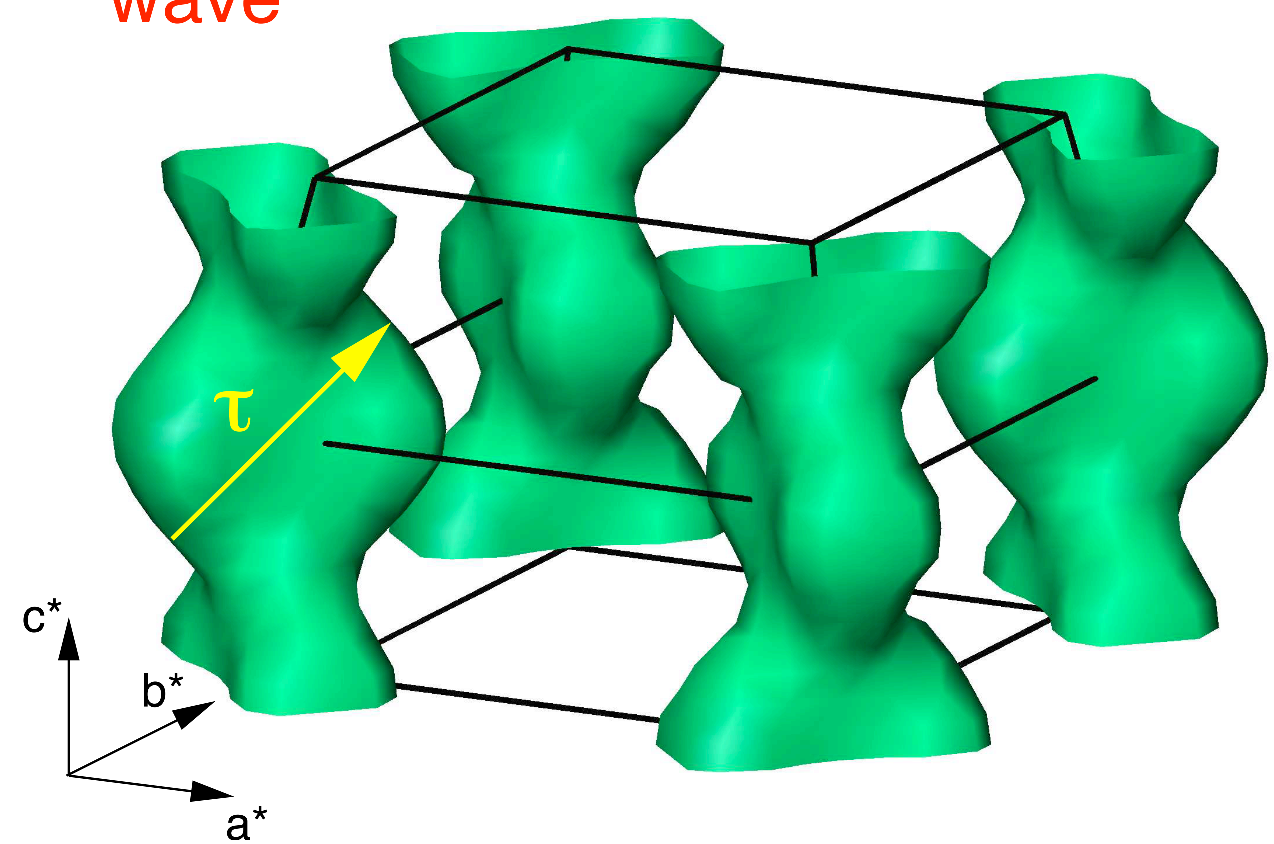


E6/HMI



Fermi surface: nesting for wave vector q ≈ (0.21 0.21 0.55)

→ Fermi surface unstable with respect to formation of spin-density wave



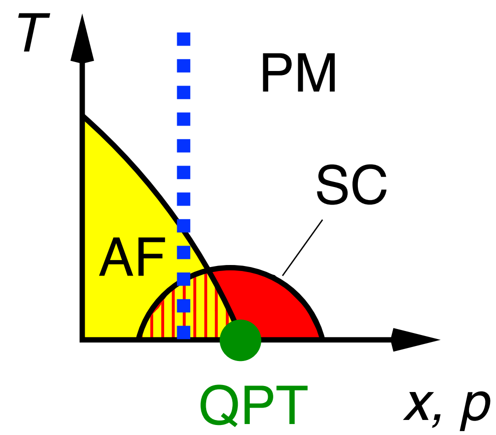
- Observation of incomm. AF order
- Propagation vector

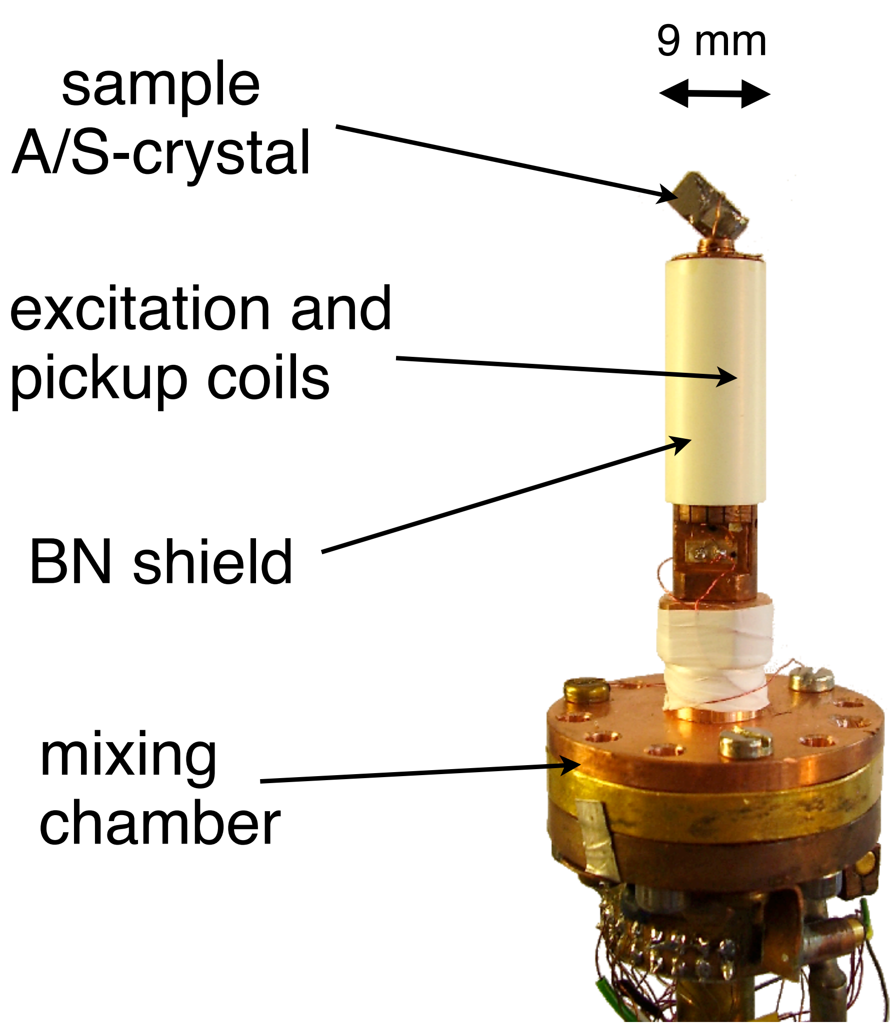
  τ = (0.215 0.215 0.530) at T = 50 mK
- $T_N \approx 0.8$ K, $m_0 \approx 0.1\ \mu_B$

  [OS, PRL ’04]

Magnetism and superconductivity in A/S-$CeCu_2Si_2$

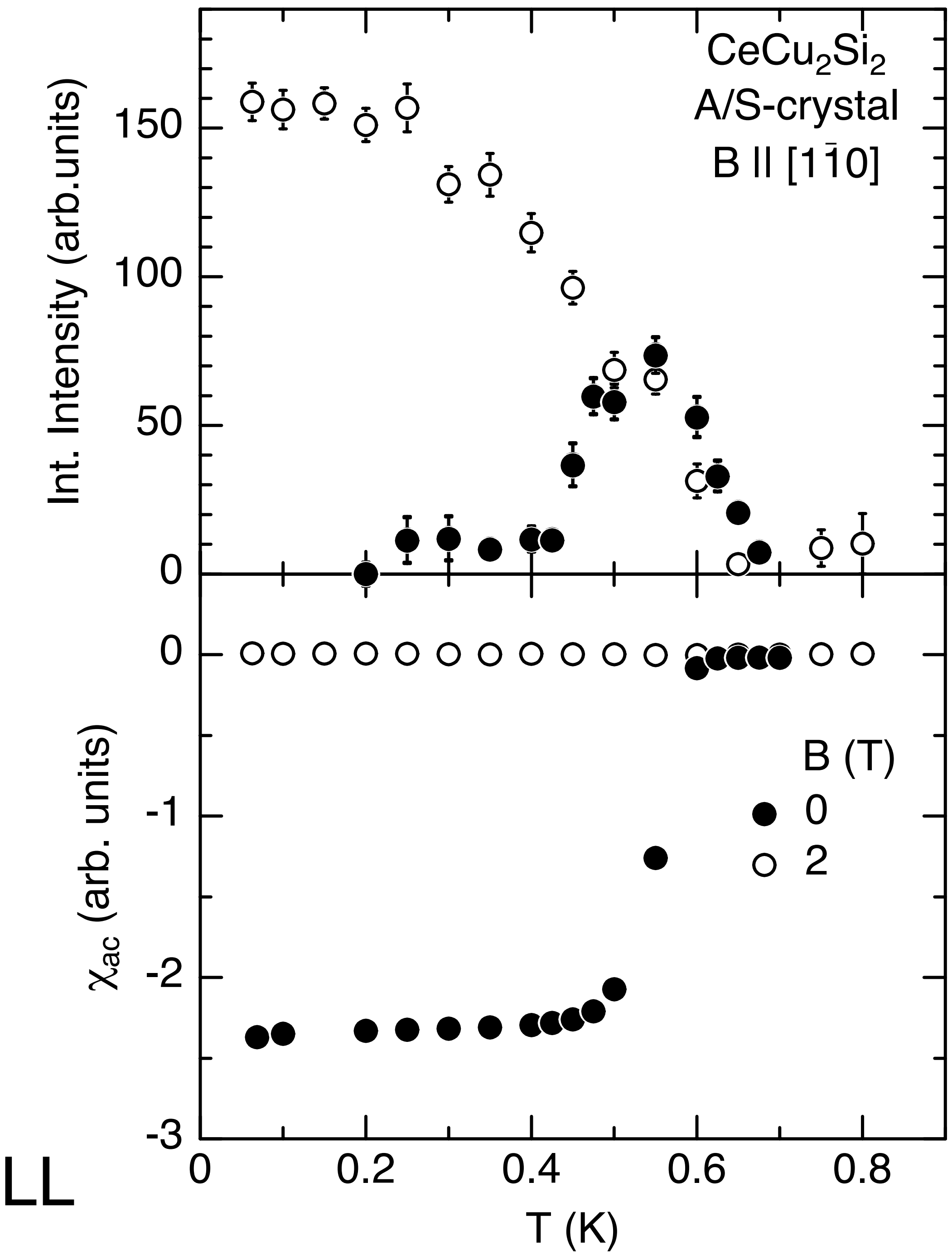
$T_N \approx 700$ mK
$T_c \approx 550$ mK
$B_{c2} \approx 1$ T





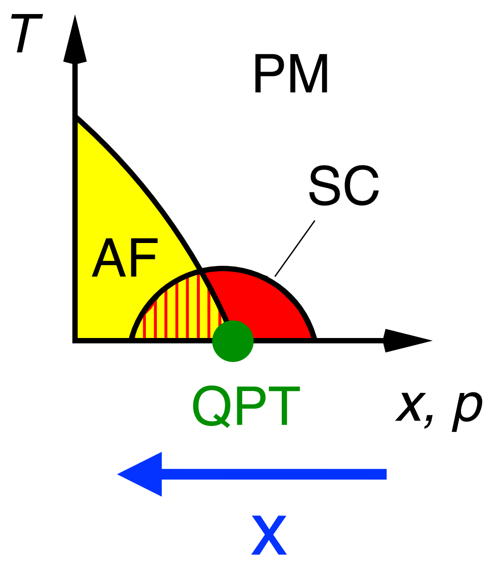
IN12/ILL

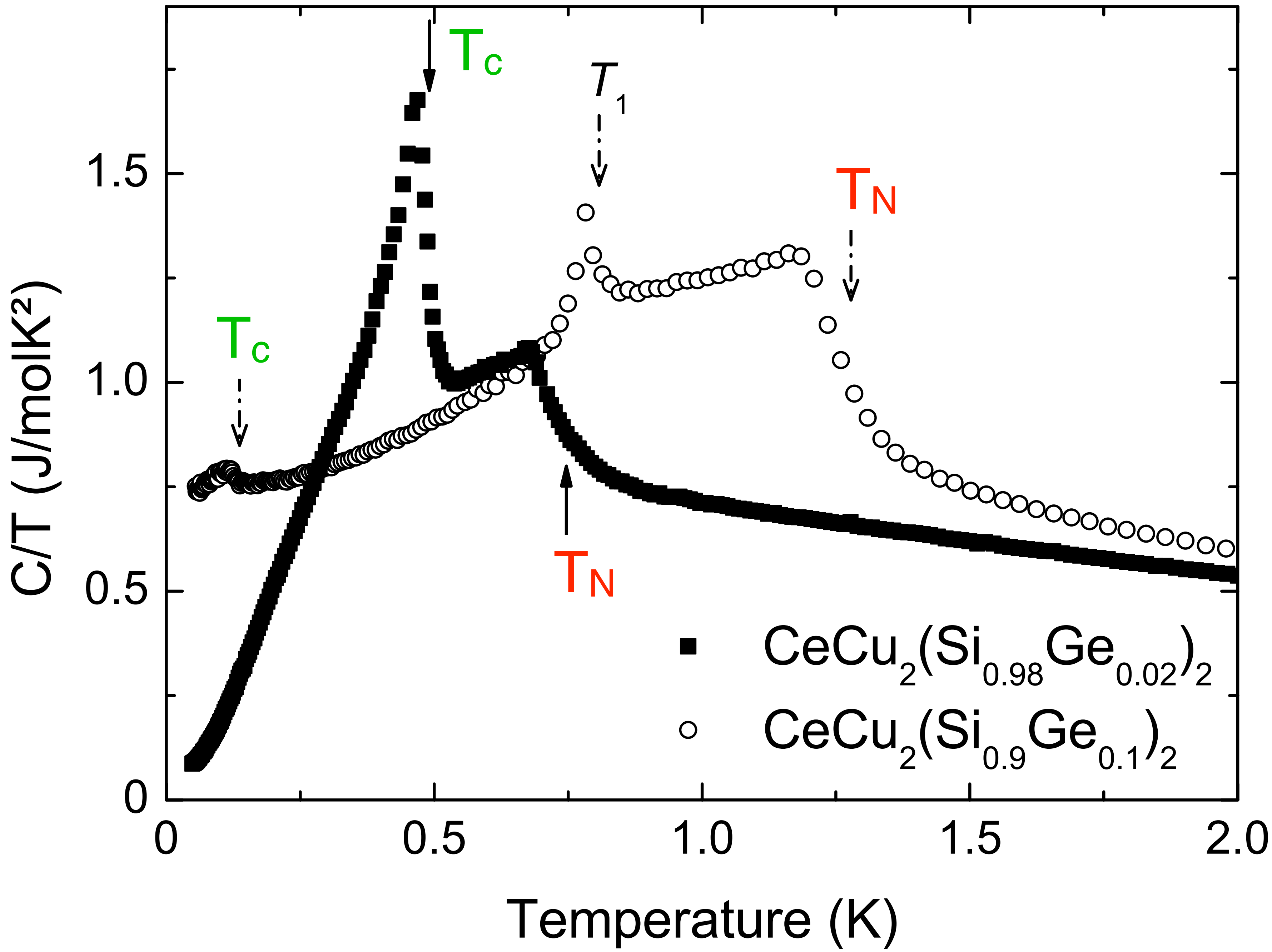
Q ≈ (0.22 0.22 1.47)



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

Heat capacity in Ge-doped $CeCu_2Si_2$



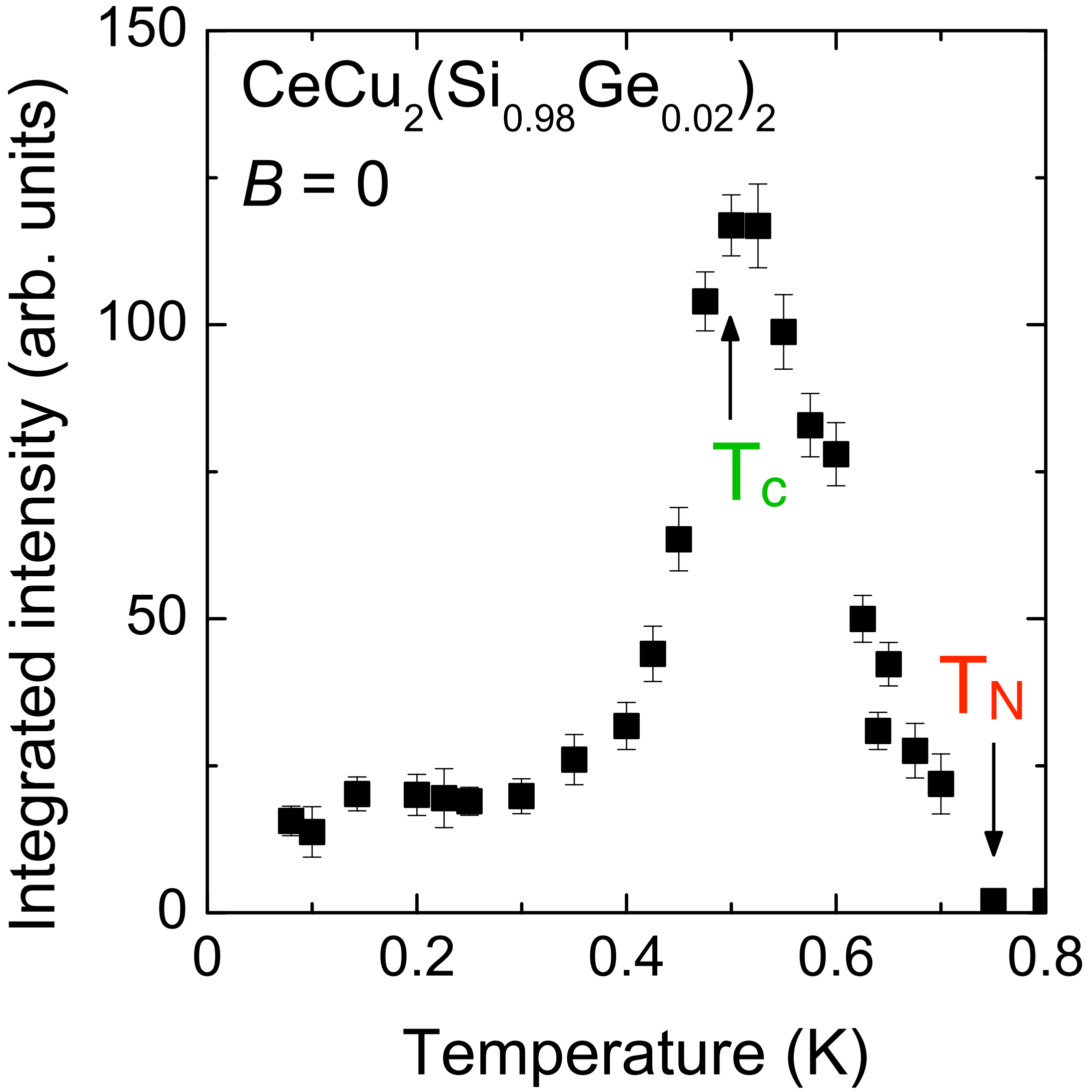


upon Ge doping:
- stabilization of magnetic order (T_N ↗)
- depression of superconductivity (T_c ↘)

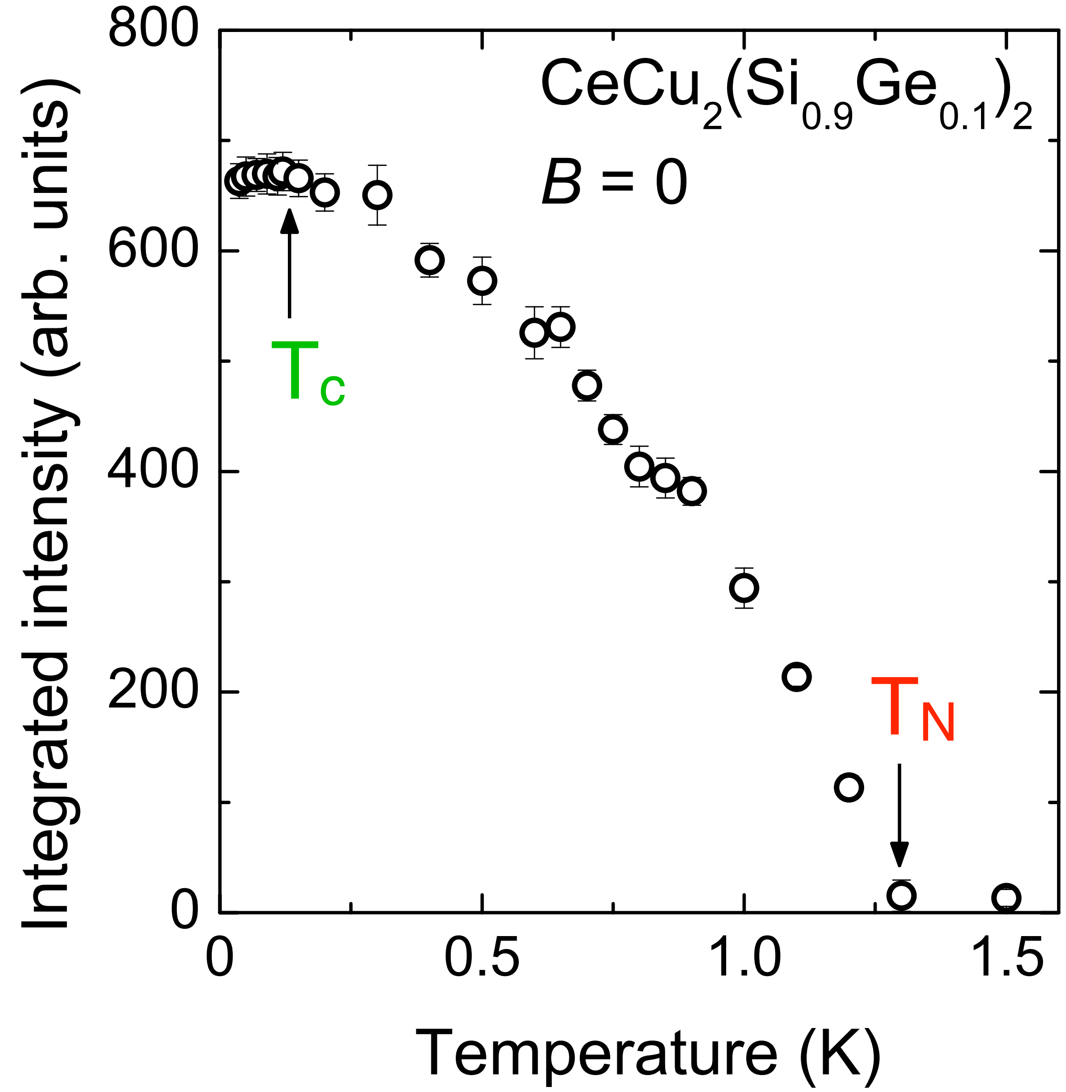
[J. Arndt, OS, J.Phys.: Conf. Series, '09]

Magnetism and superconductivity in Ge-doped $CeCu_2Si_2$

2% Ge-doped



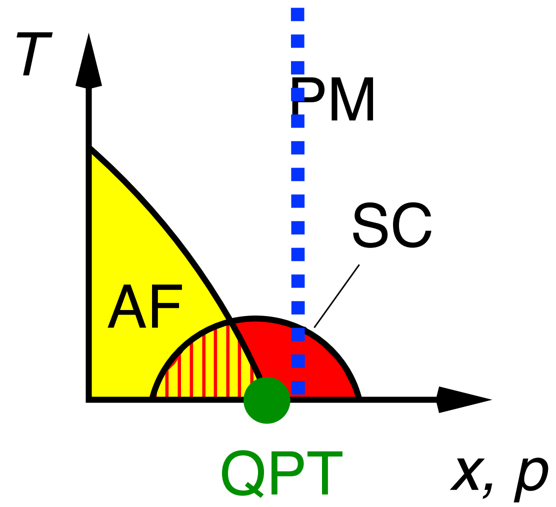
10% Ge-doped $CeCu_2Si_2$

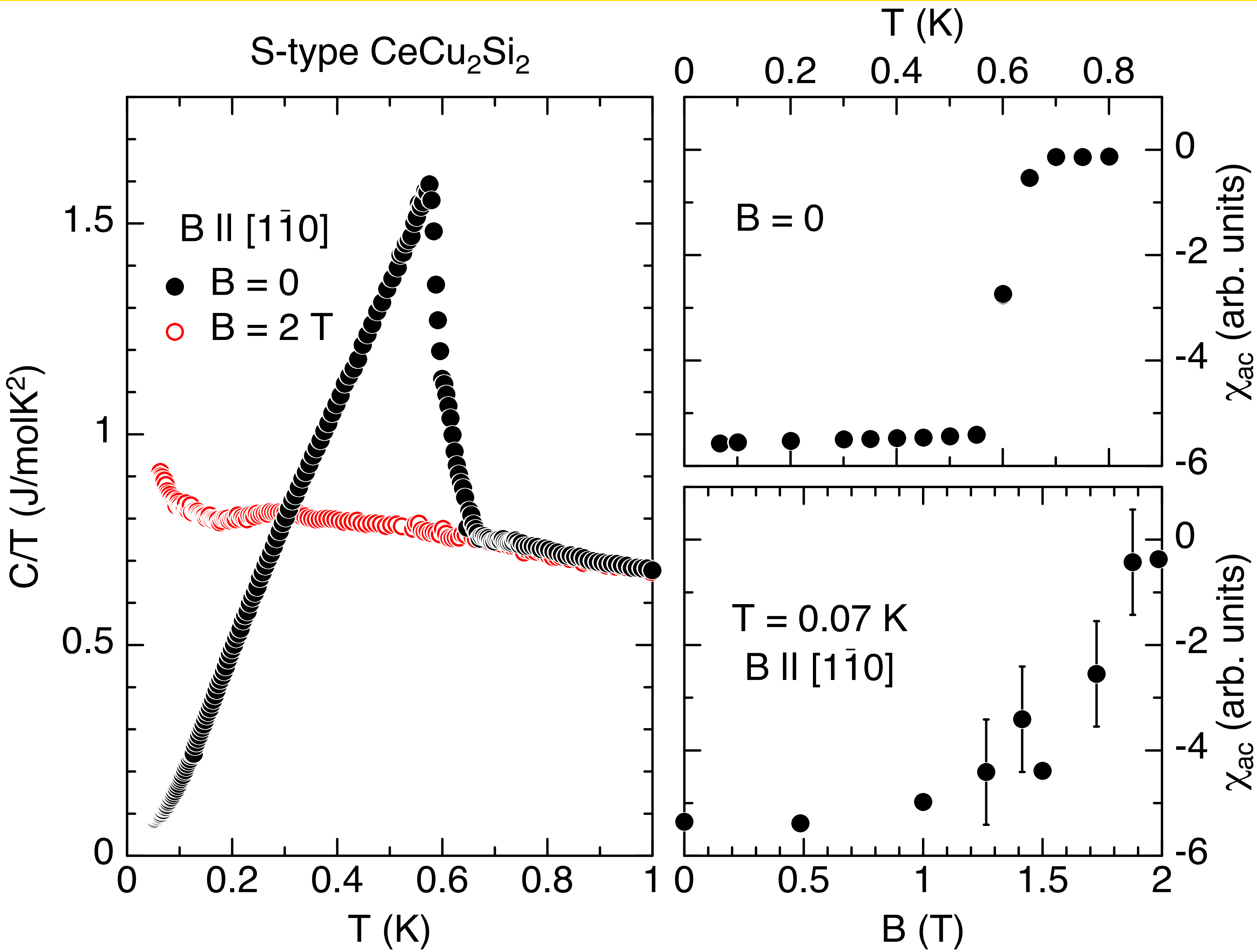


- for higher Ge concentrations less influence of SC on AF
- from competition to coexistence (expected theoretically [Kato, PRB ’88])

[J. Arndt, OS, J.Phys.: Conf. Series, '09]

Thermodynamic properties in S-$CeCu_2Si_2$

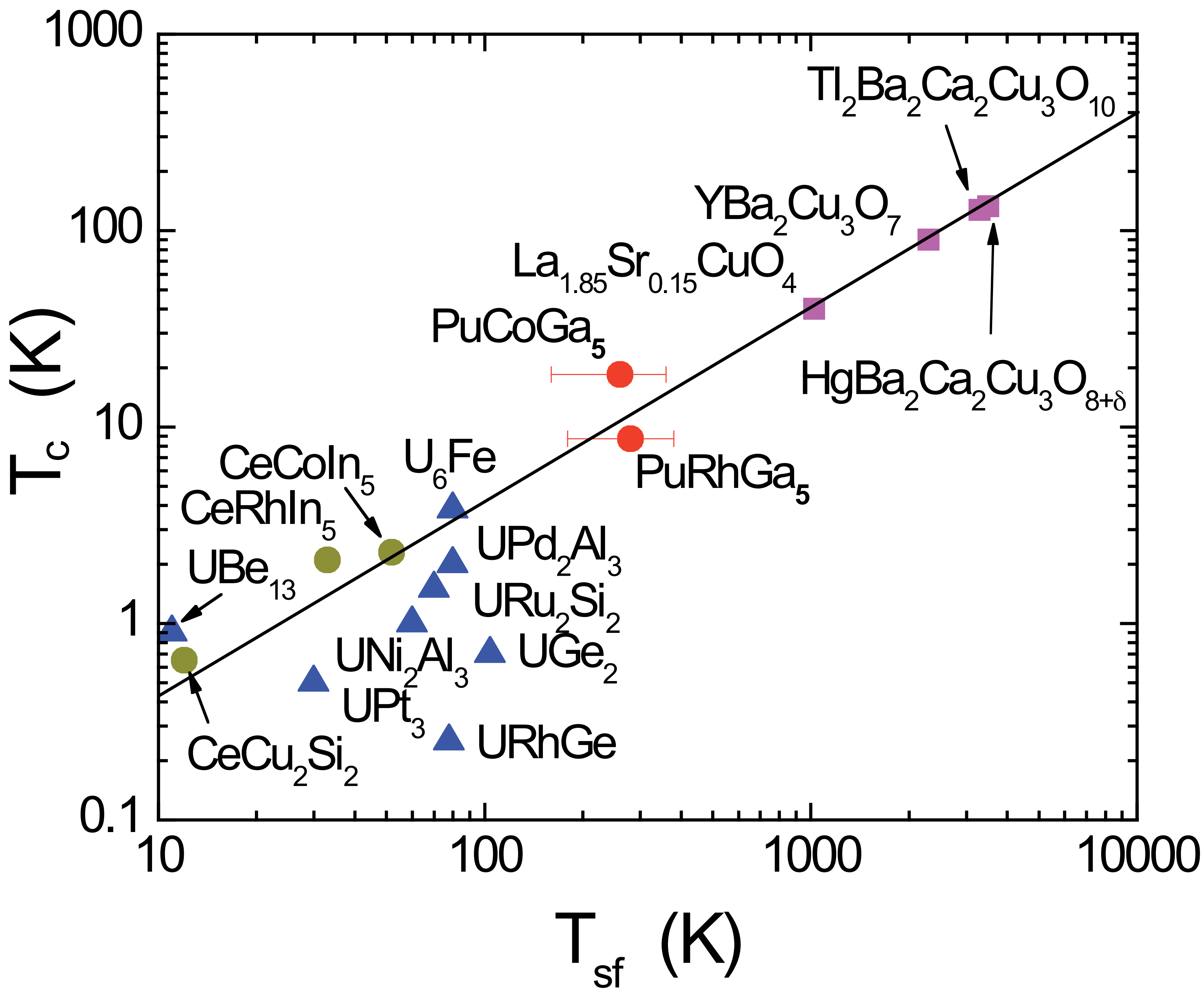




heavy-fermion superconductivity with

T_c = 600 mK and $B_{c2} \approx 1.7$ T

Energy scales: superconductivity and spin fluctuations

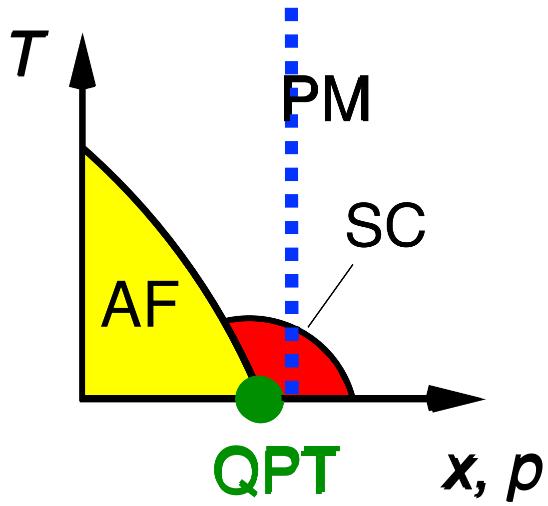


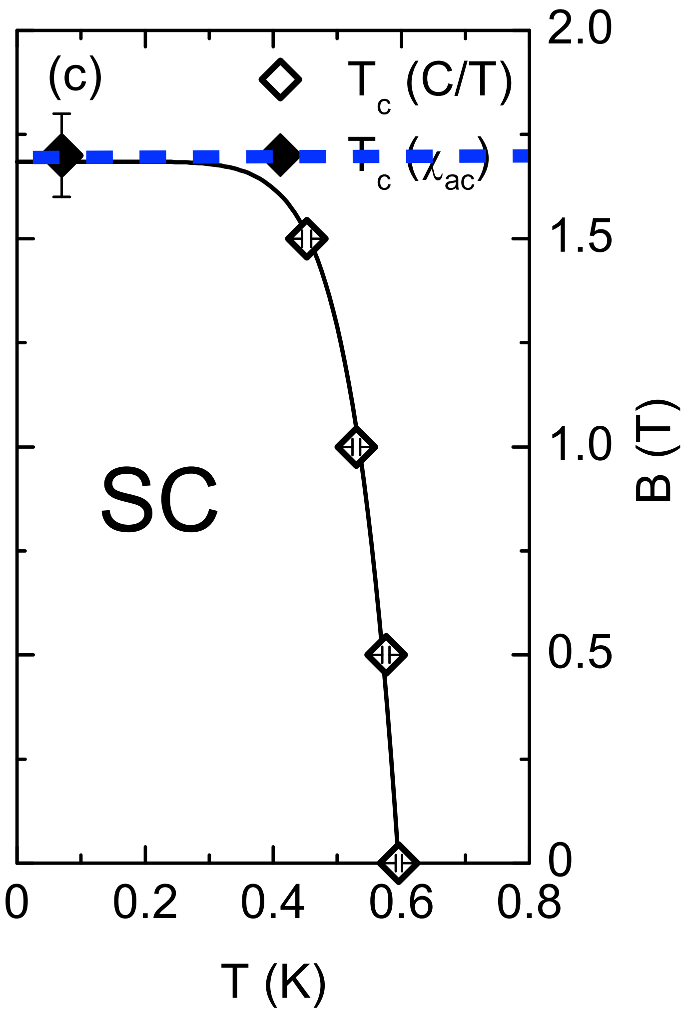
[T. Moriya, '03]

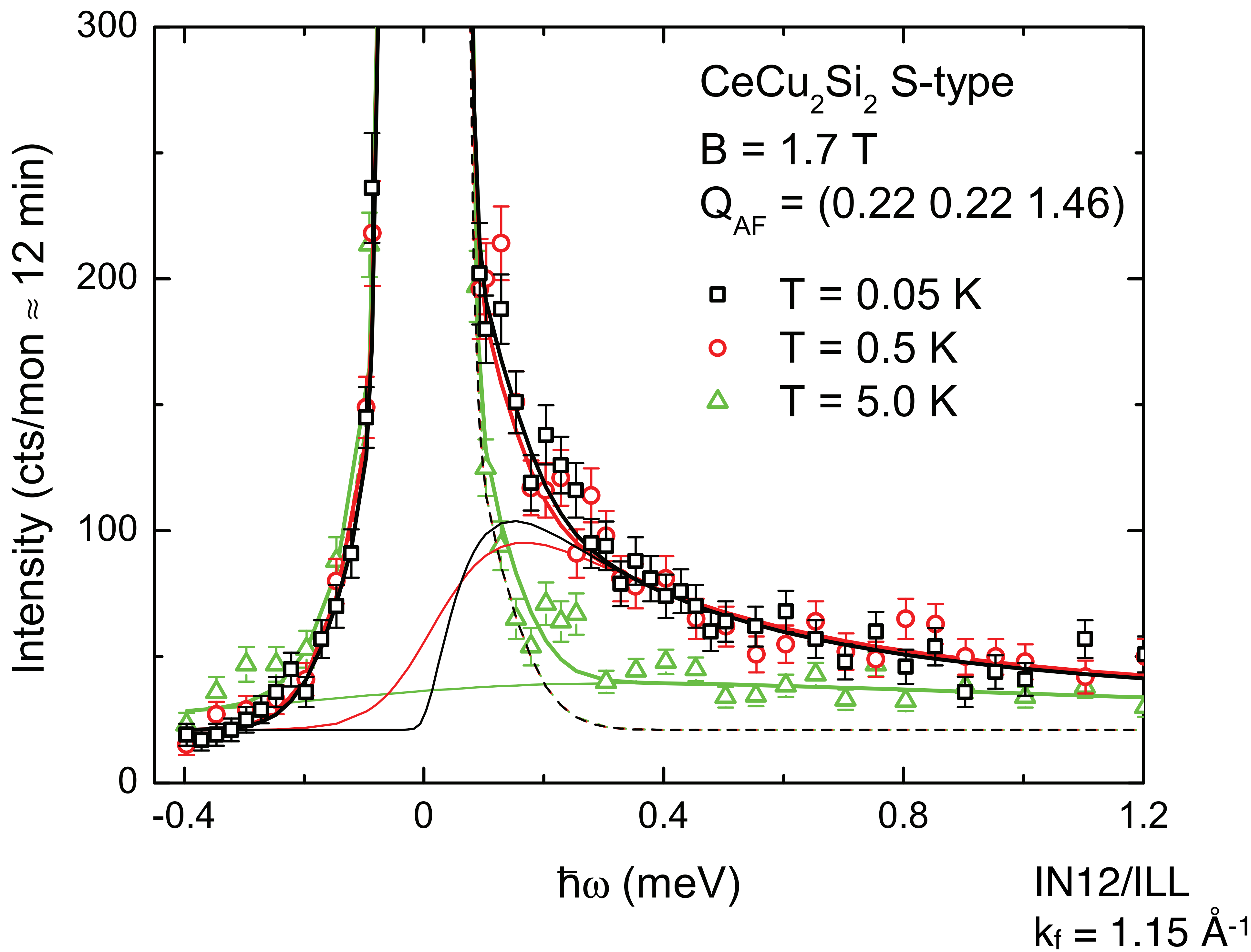
superconducting T_c scales with spin fluctuation T_{sf}

heavy-fermions: $T_K \approx 5$ - 50 K

Normal state spin dynamics in S-$CeCu_2Si_2$



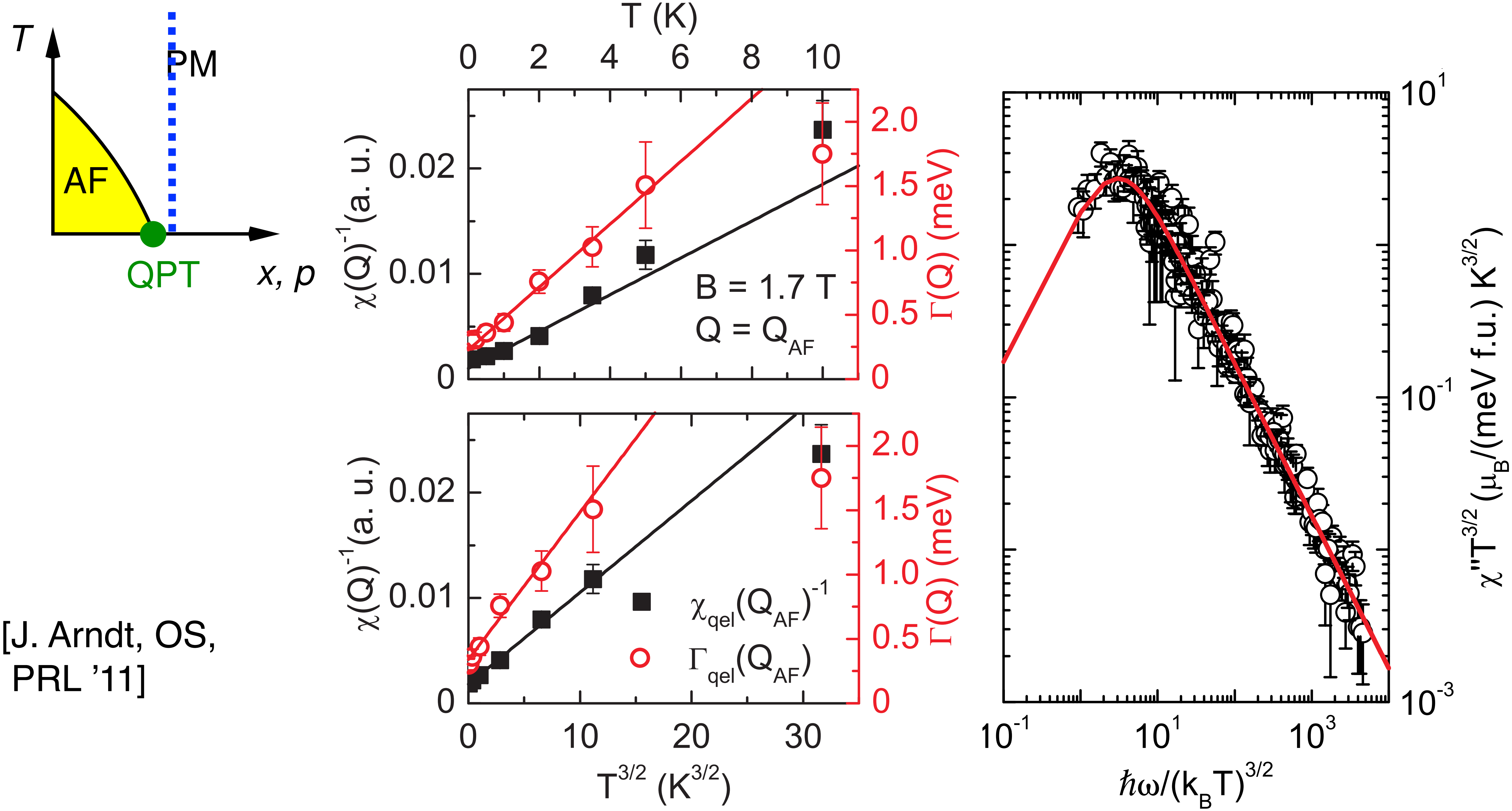




- Quasielastic Lorentzian response
- Decrease in intensity and broadening with T

[J. Arndt, OS, PRL ’11]

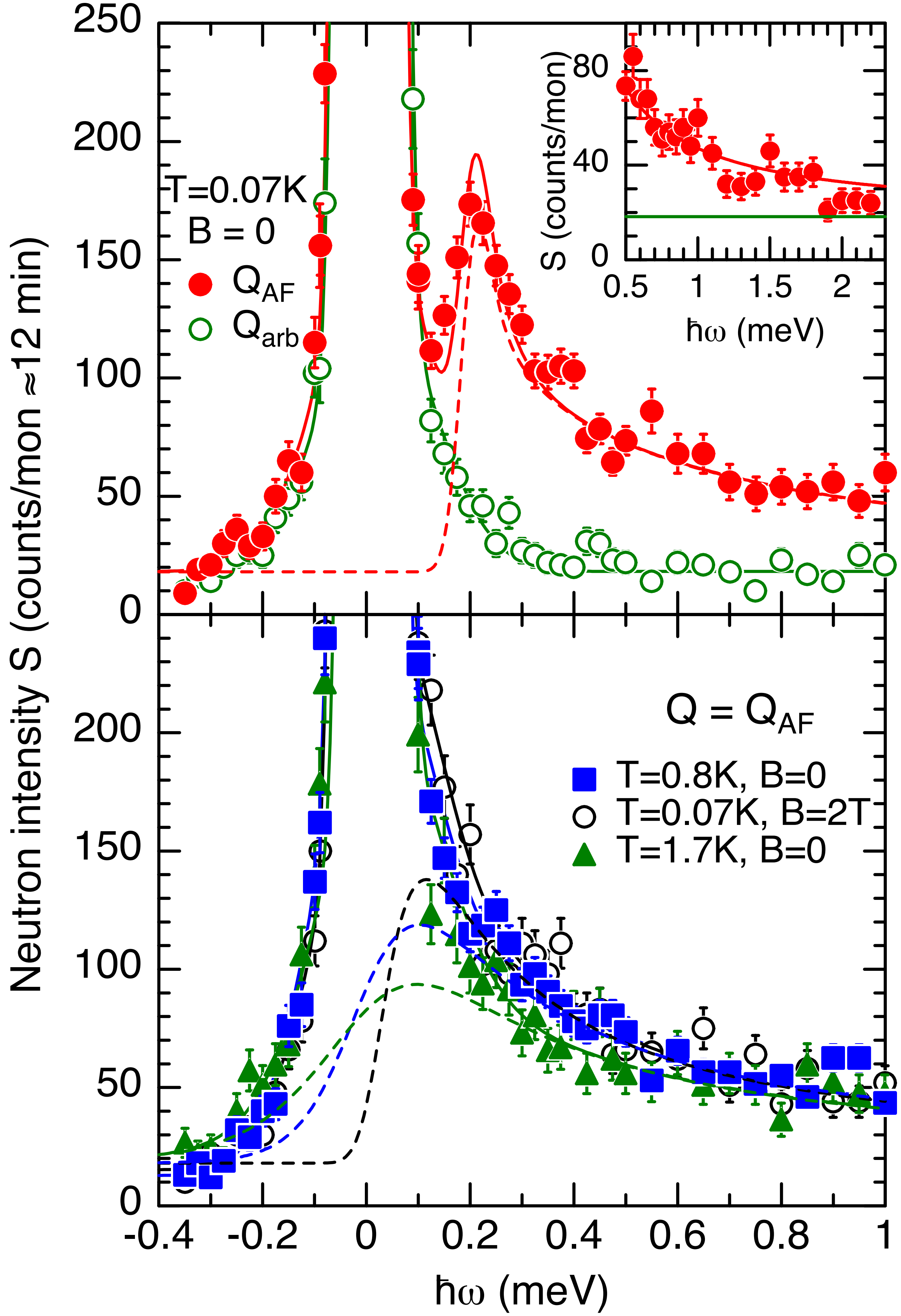
Normal state spin dynamics in S-$CeCu_2Si_2$

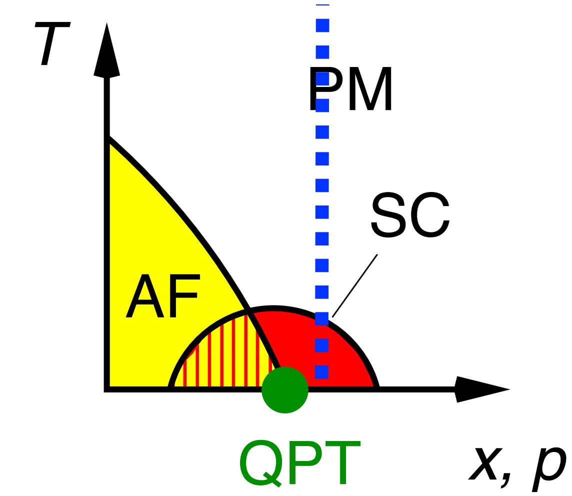


[J. Arndt, OS, PRL '11]

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

Spin dynamics in superconducting $CeCu_2Si_2$



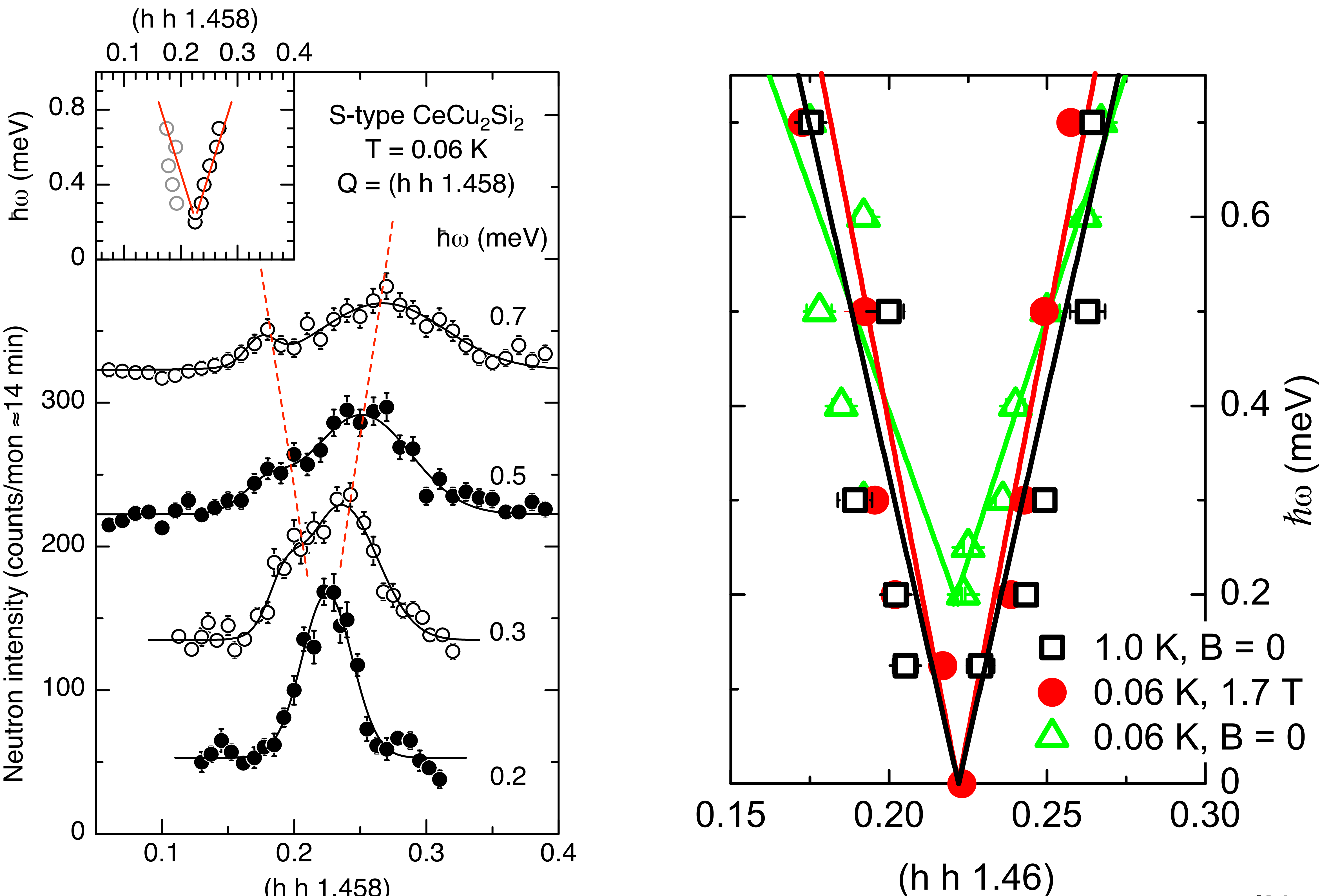


- broad quasielastic Lorentzian response at Q_{AF}
- gapped in the sc state, $\hbar\omega_{gap} \approx 0.2$ meV ($\approx 3.9\, k_B T_c$)
- $\hbar\omega_{gap}$ follows roughly BCS order parameter (in contrast to high-T_c sc)

IN12/ILL
$k_f = 1.15$ Å^{-1}
$\Delta E = 57$ µeV

[OS, Nat. Phys., 2011]

Q-dependence of gap mode in S-$CeCu_2Si_2$



- "dispersive" excitation, v ≈ 4.44 meVÅ (v_F ≈ 57 meVÅ)
- extends up to 3-4 times $\hbar\omega_{gap}$

IN12/ILL
k_f = 1.15 Å^{-1}

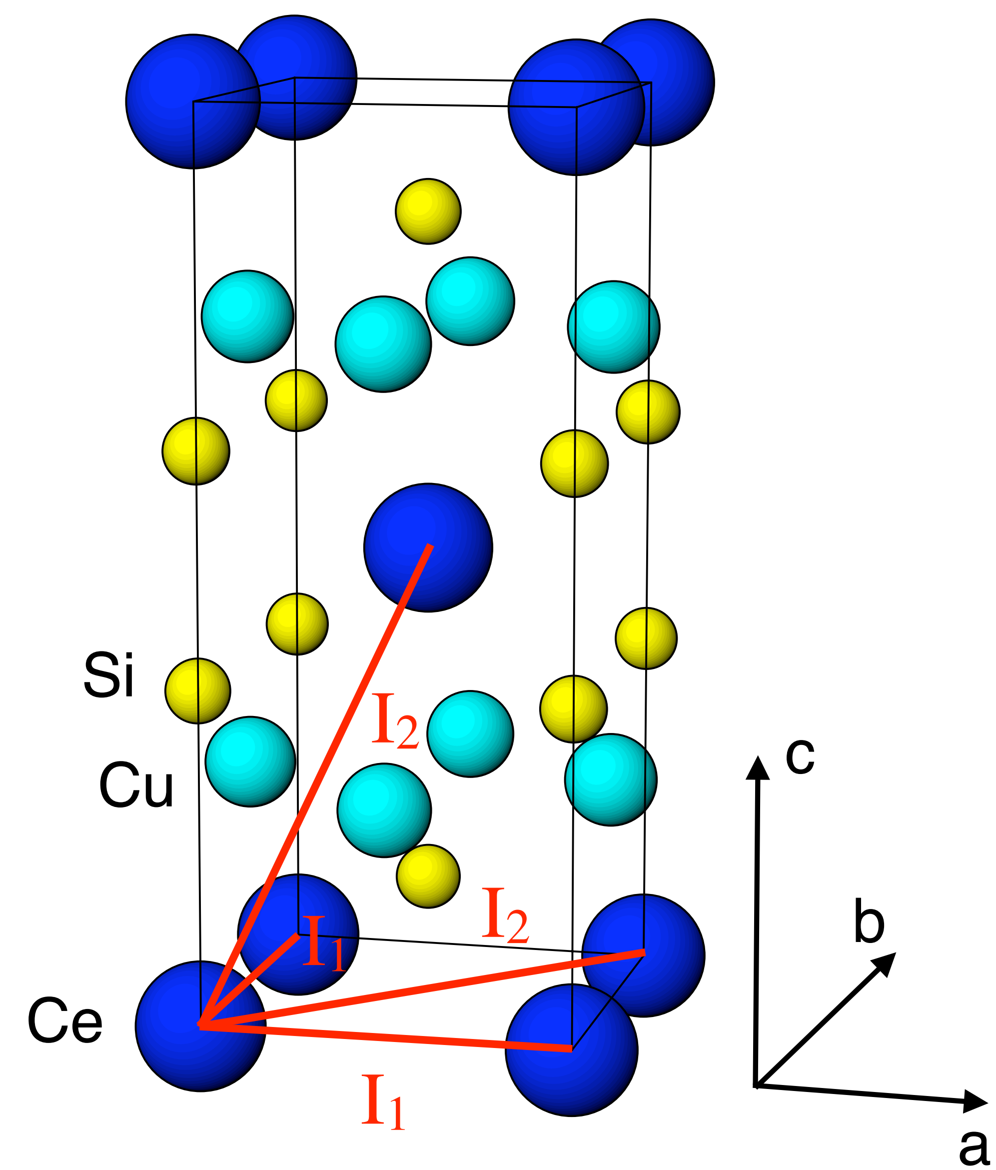
[OS, Nat. Phys., '11; J. Arndt, PRL, '11]

Magnetic exchange energies in S-$CeCu_2Si_2$

Magnetic exchange energy gain ΔE_x:

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

$I(\mathbf{q})$: exchange interaction between nearest neighbor (I_1) and next-nearest neighbor (I_2) Ce moments



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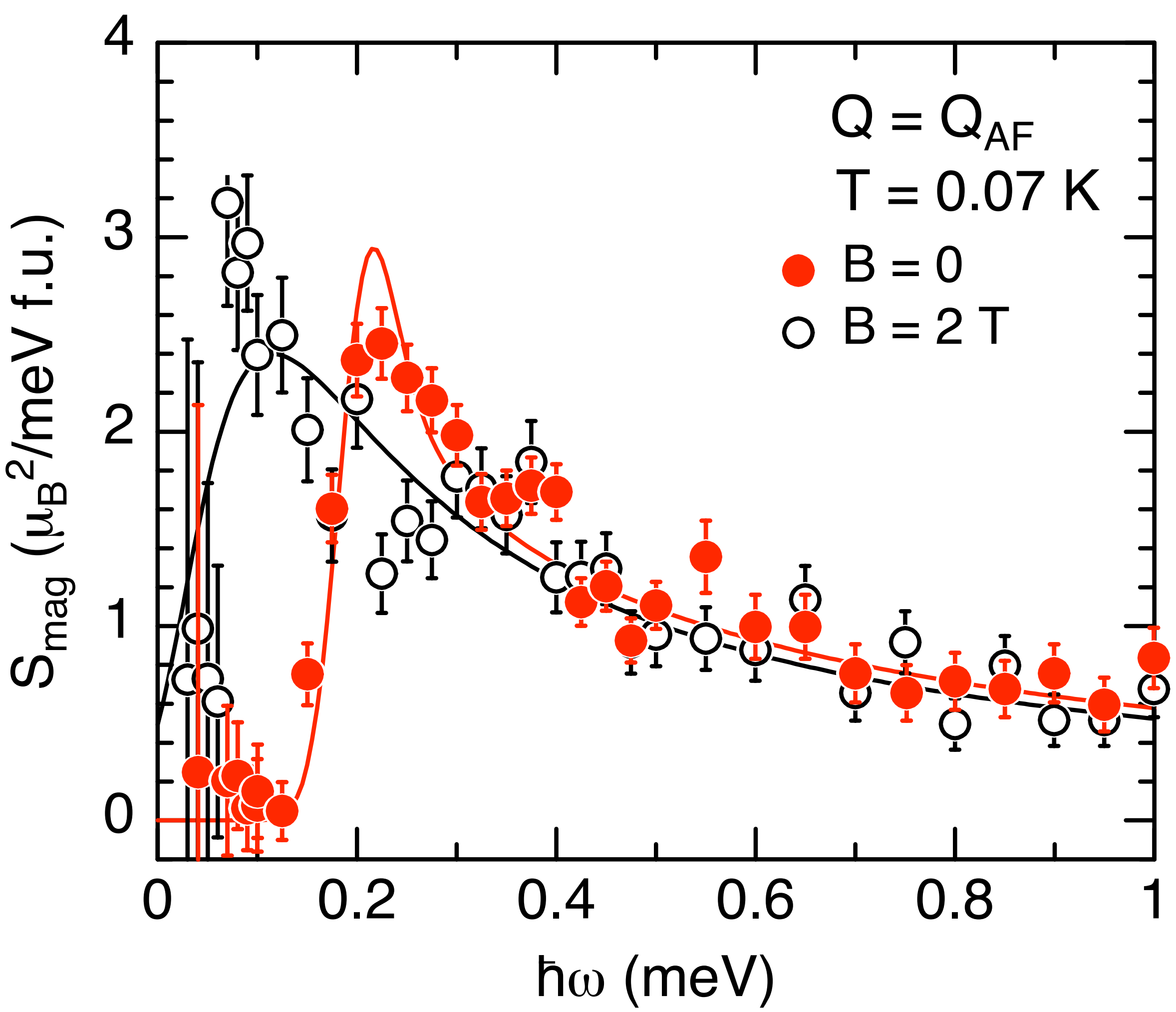
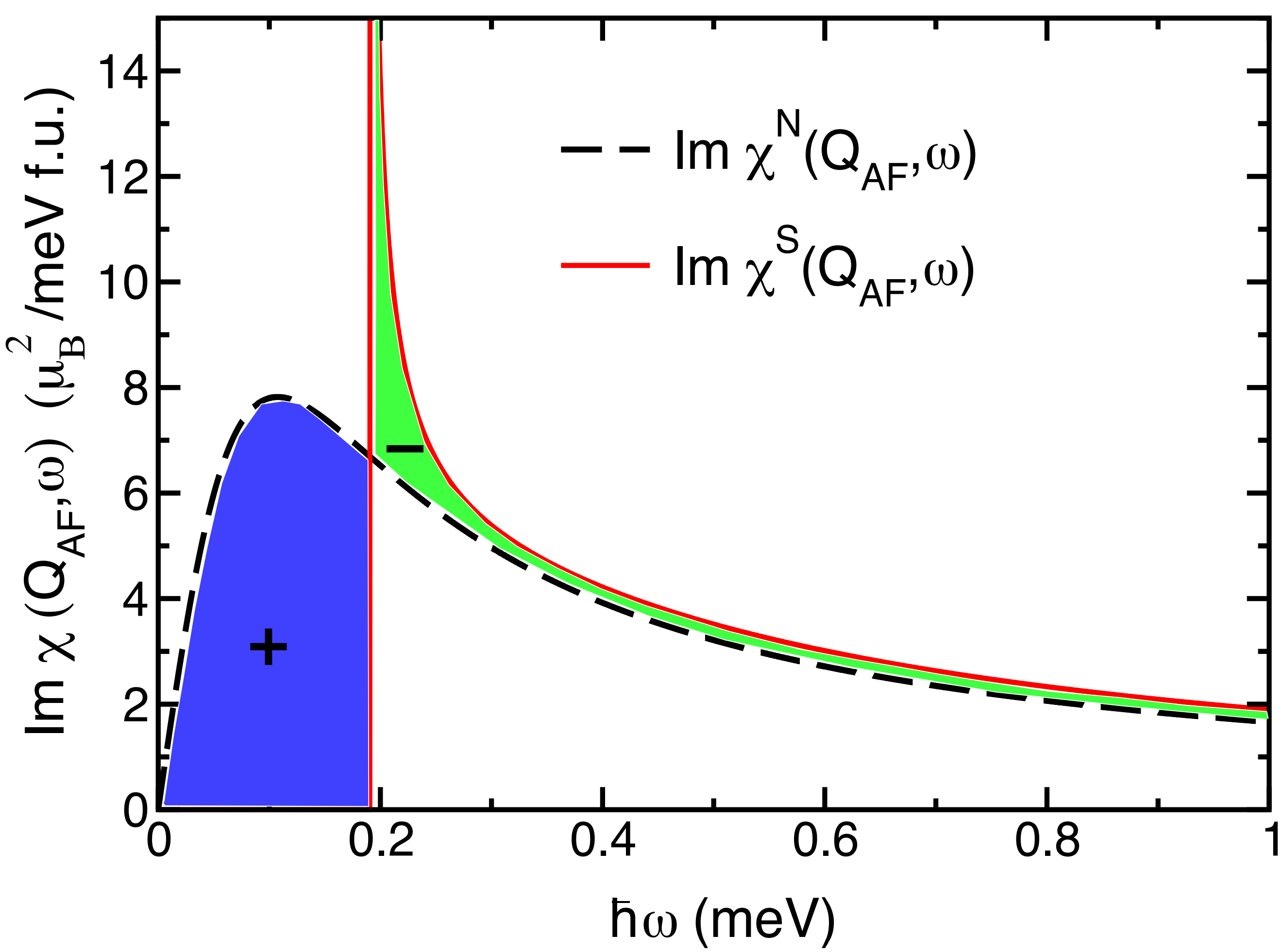




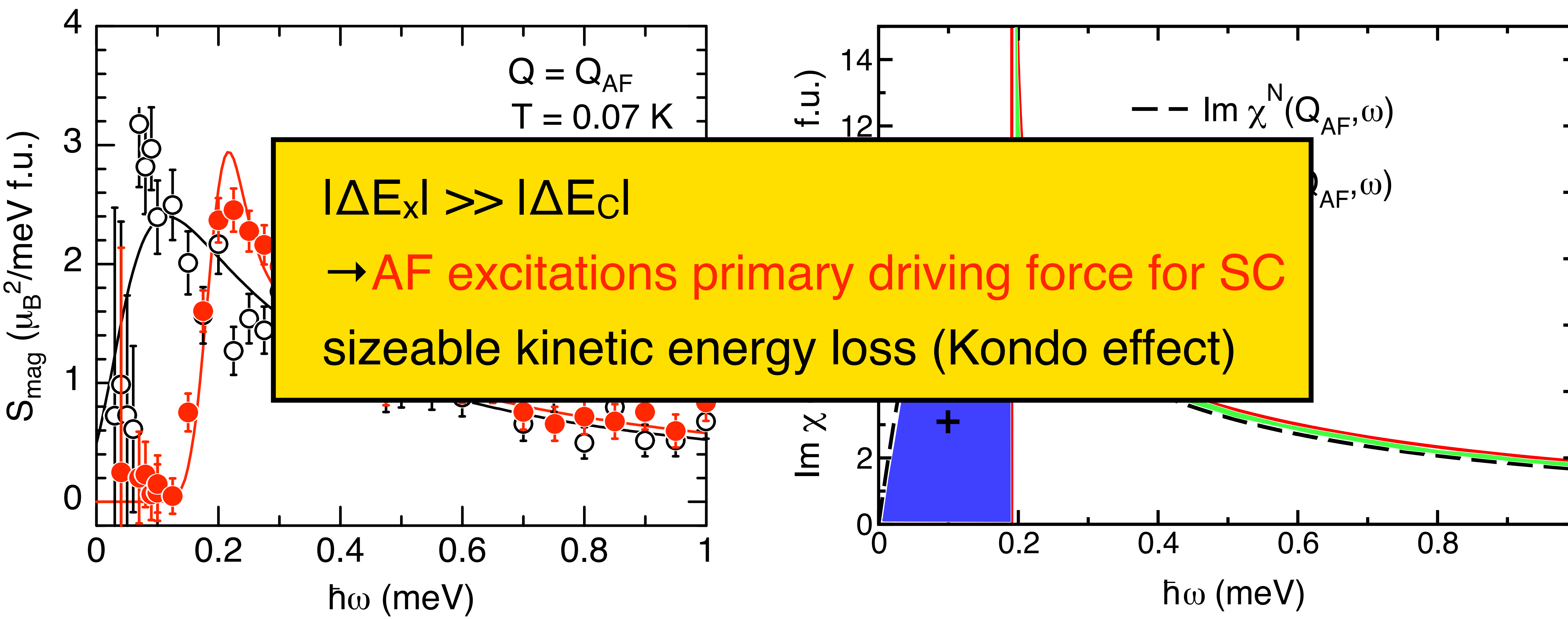
$|\Delta E_x| = 5.36 \cdot 10^{-3}$ meV/Ce >> $|\Delta E_C| = 2.27 \cdot 10^{-4}$ meV/Ce

[OS, Nat. Phys., 2011]

Magnetic exchange energies in S-$CeCu_2Si_2$

Magnetic exchange energy gain ΔE_x:

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



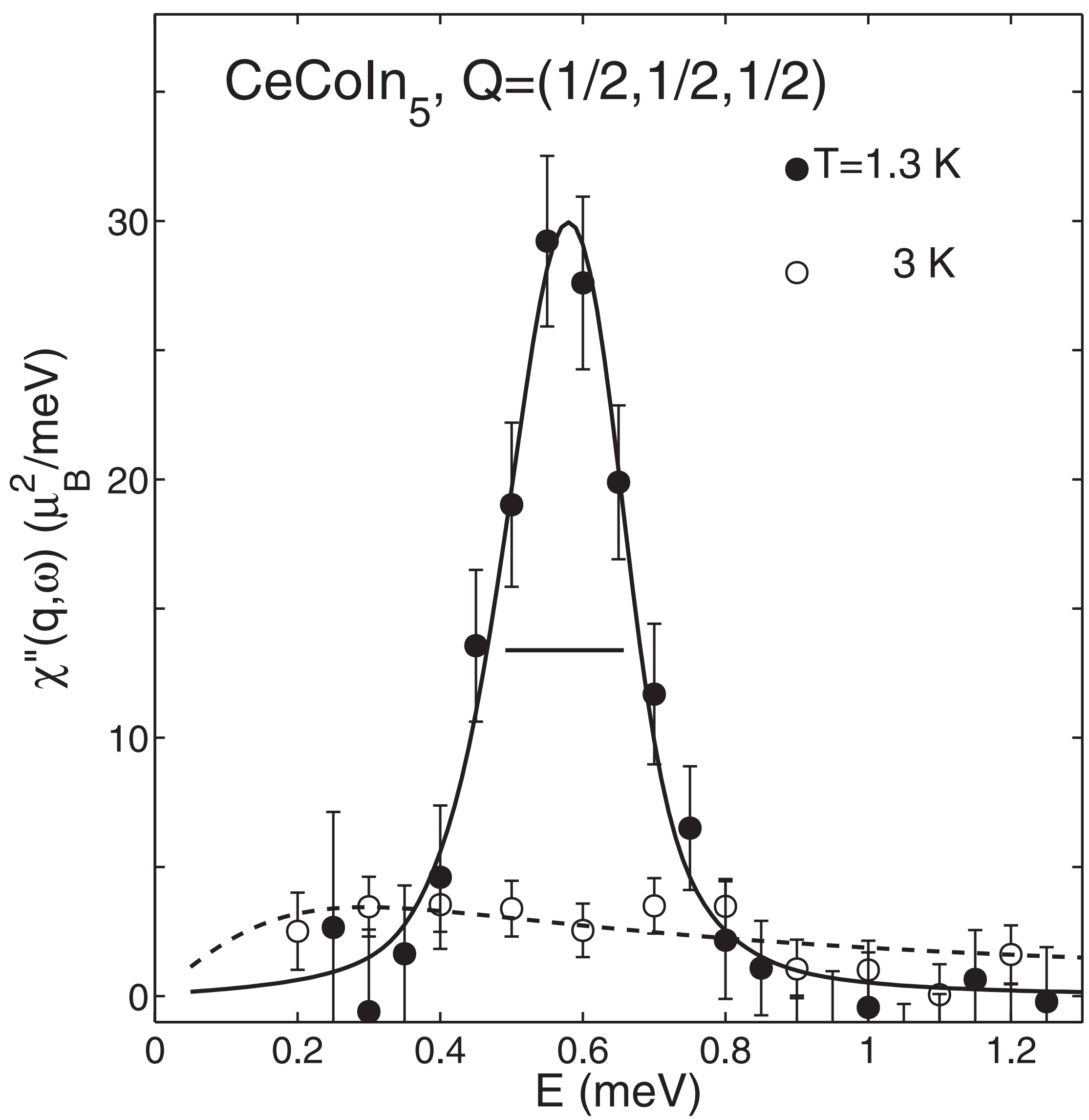
$|\Delta E_x| \gg |\Delta E_C|$

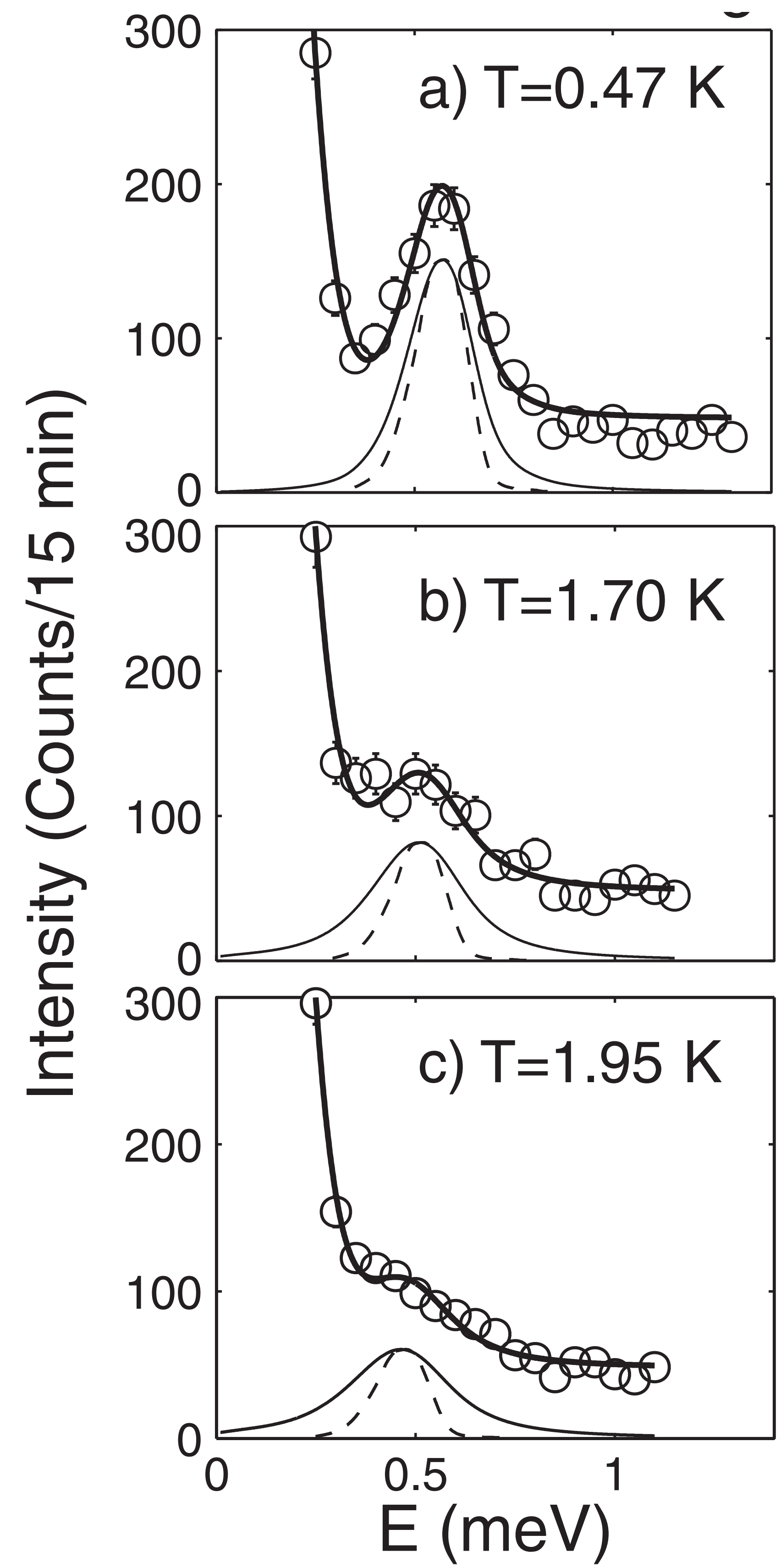
→ AF excitations primary driving force for SC

sizeable kinetic energy loss (Kondo effect)

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

Spin resonance in $CeCoIn_5$

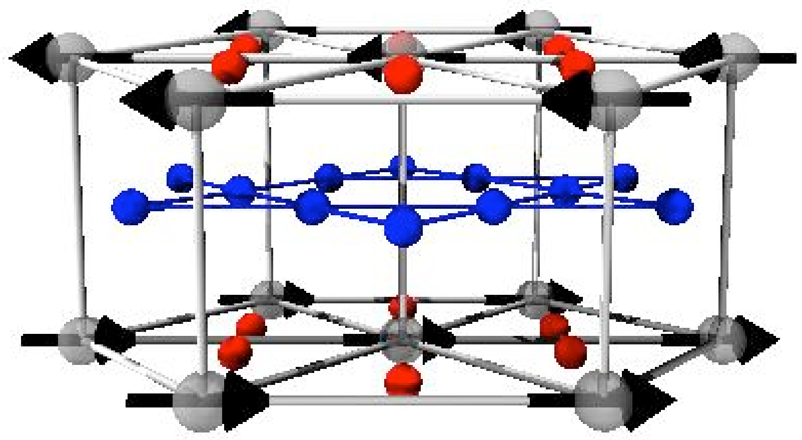




- Superconductivity below T_c = 2.3 K
- Commensurate AF spin fluctuations at Q_{AF} = (1/2 1/2 1/2)
- Sharp spin resonance in superconducting state

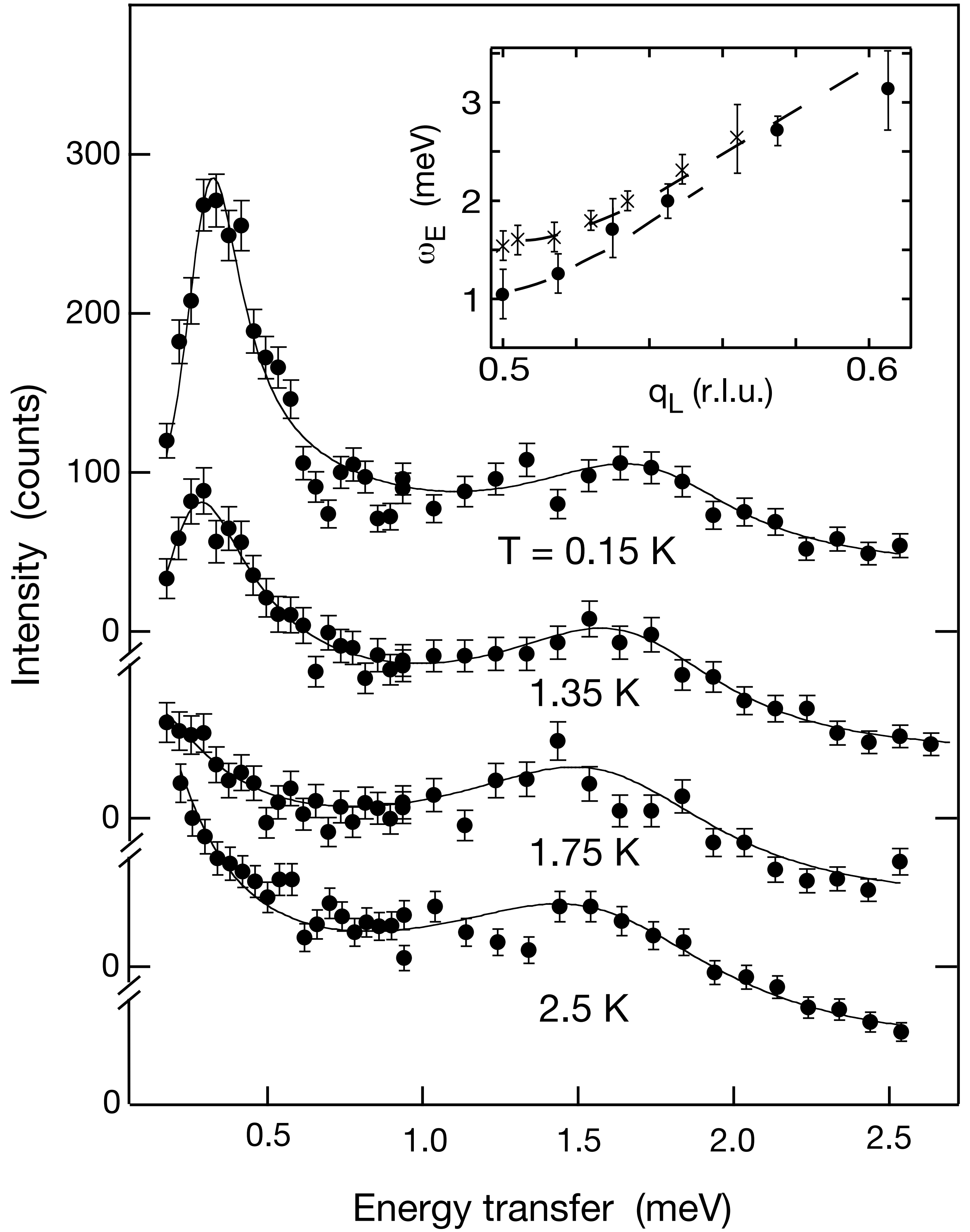
[C. Stock, PRL '08]

Magnetic response in UPd_2Al_3



- Coexistence of antiferromagnetism T_N = 14 K, $\mu = 0.85\ \mu_B$, τ = (0 0 1/2) and superconductivity (T_c = 1.9 K)

- Inelastic neutron scattering: spin wave (E = 1.5 meV) and „resonance“ (E = 0.3 meV) in superconducting state

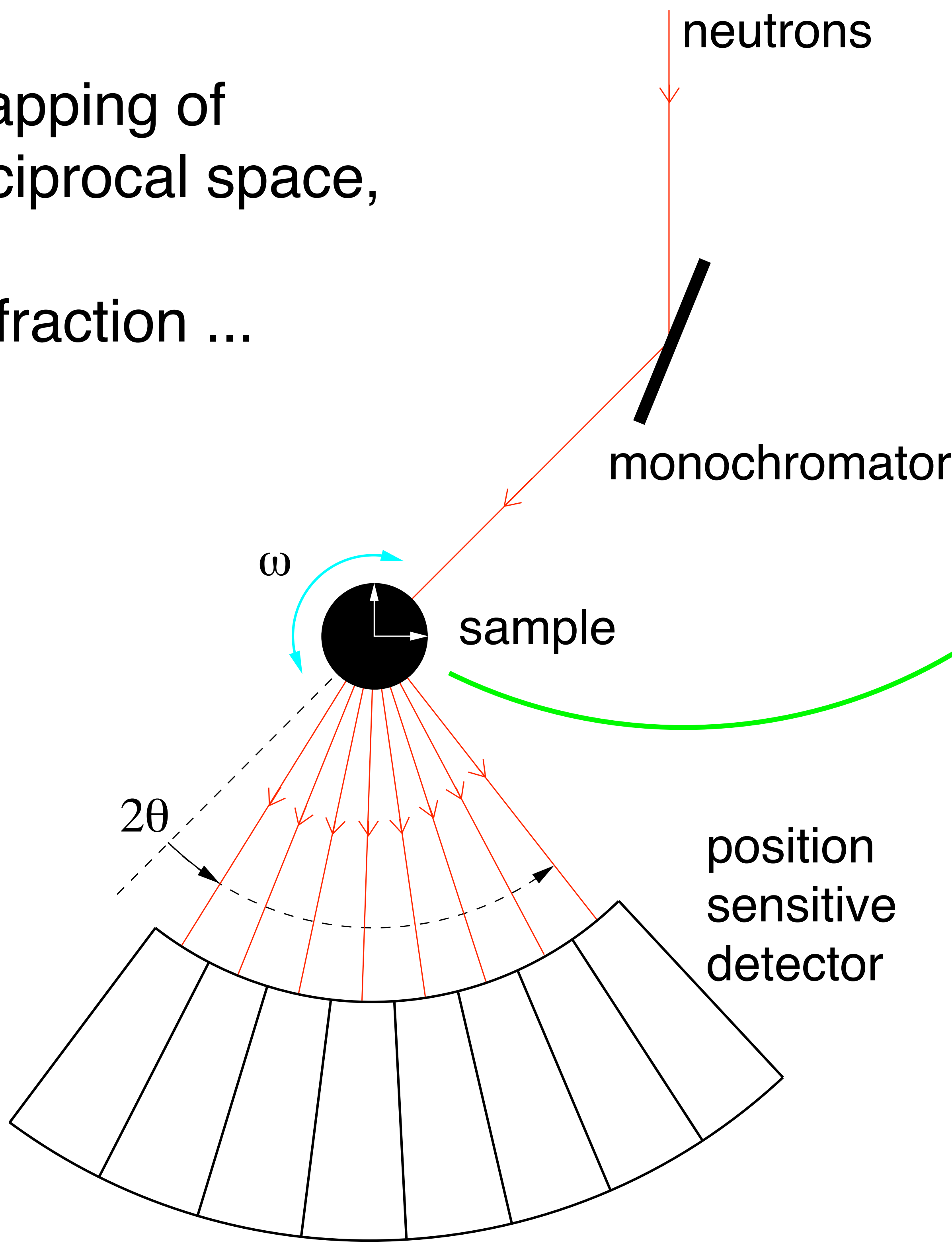


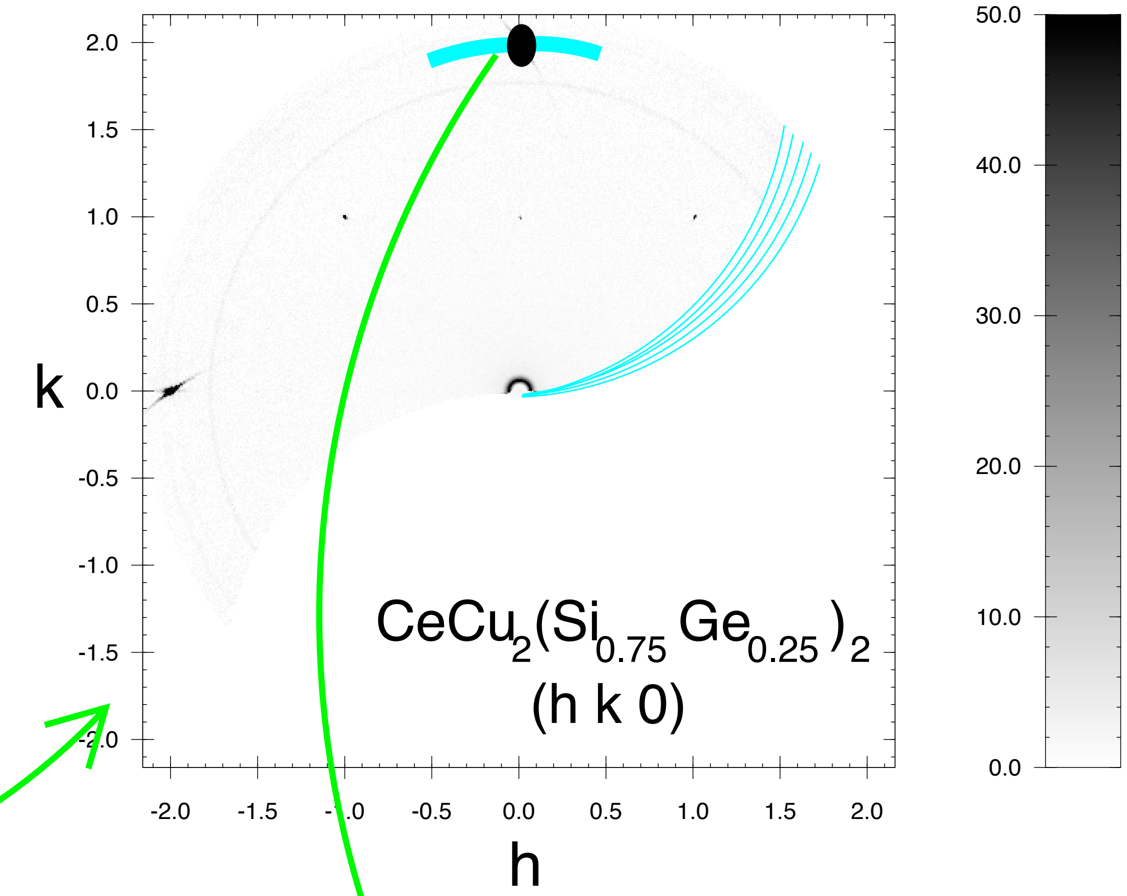
[N. Bernhoeft, ’98, N. K. Sato, ’01, A. Hiess, ’06]

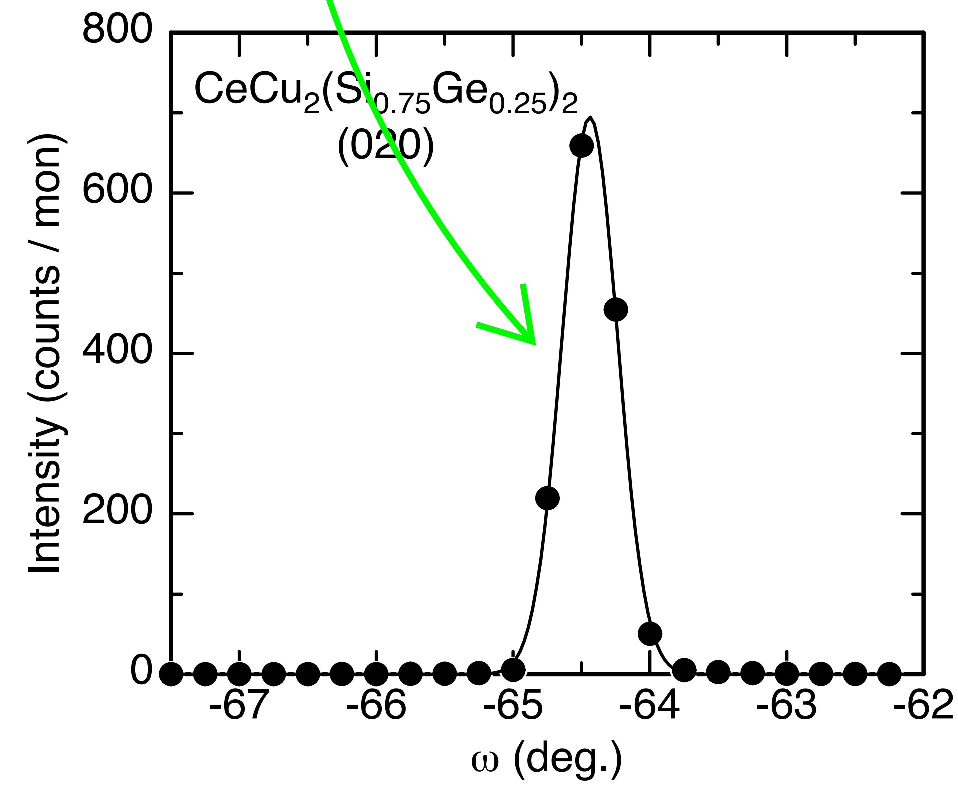
Where to go?

Mapping of reciprocal space,

diffraction ...





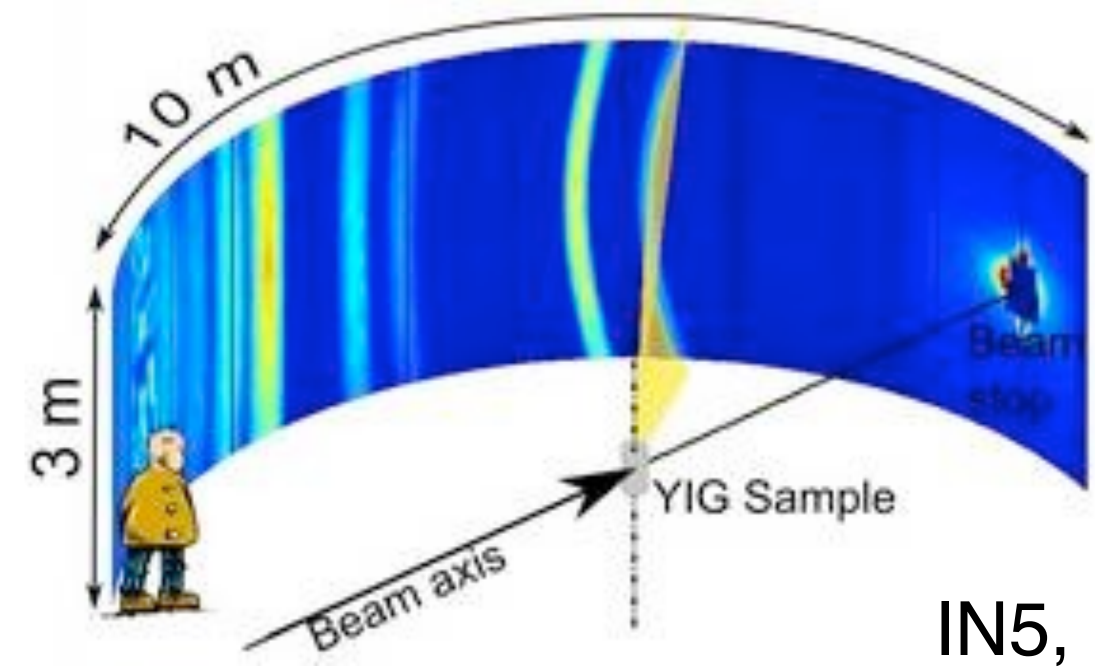


(useful for unknown magnetic structures)

Where to go?

... and energy analysis:

- Flatcone technique, measure spin dynamics in whole Brillouin zone
- TOF spectroscopy on single crystals



IN5, ILL

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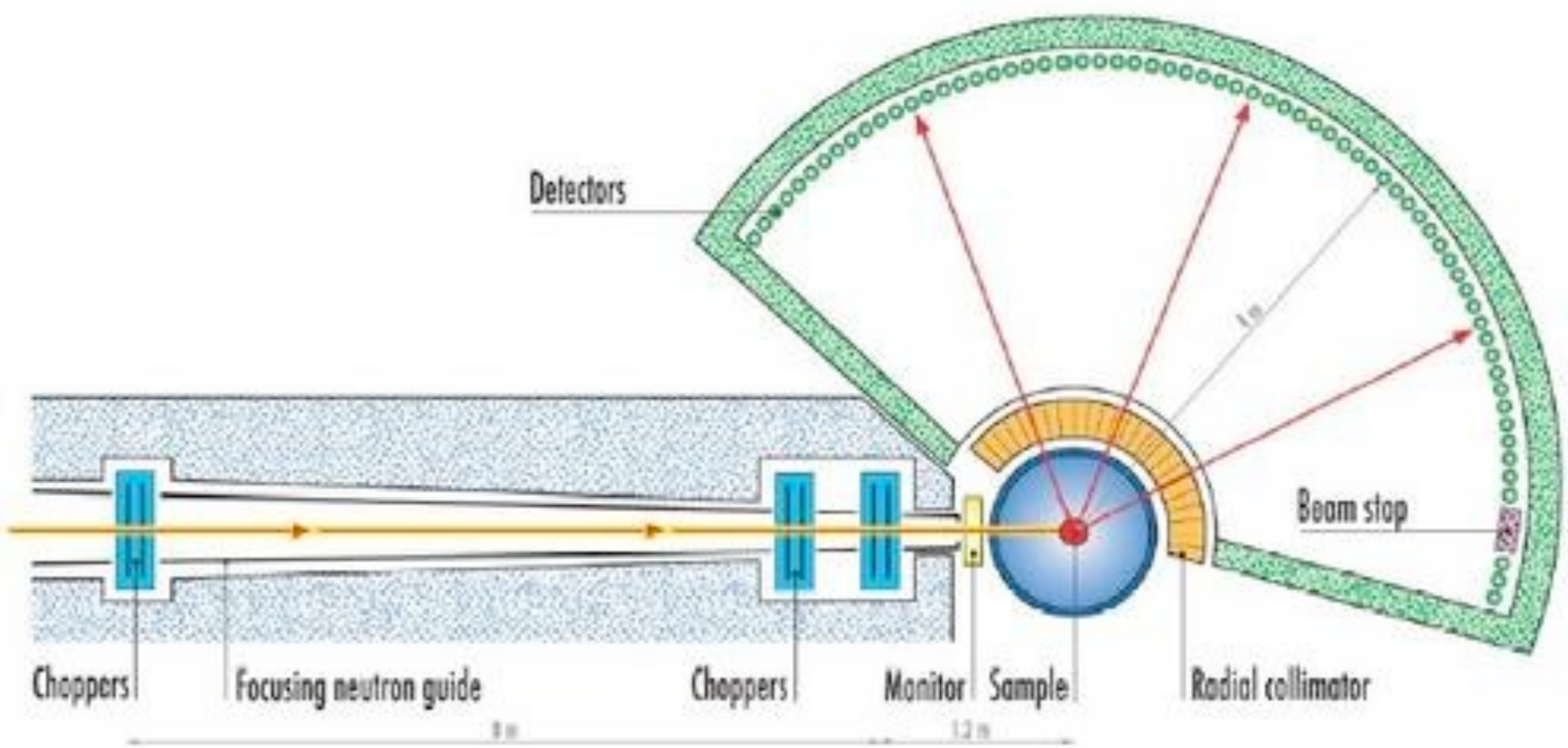
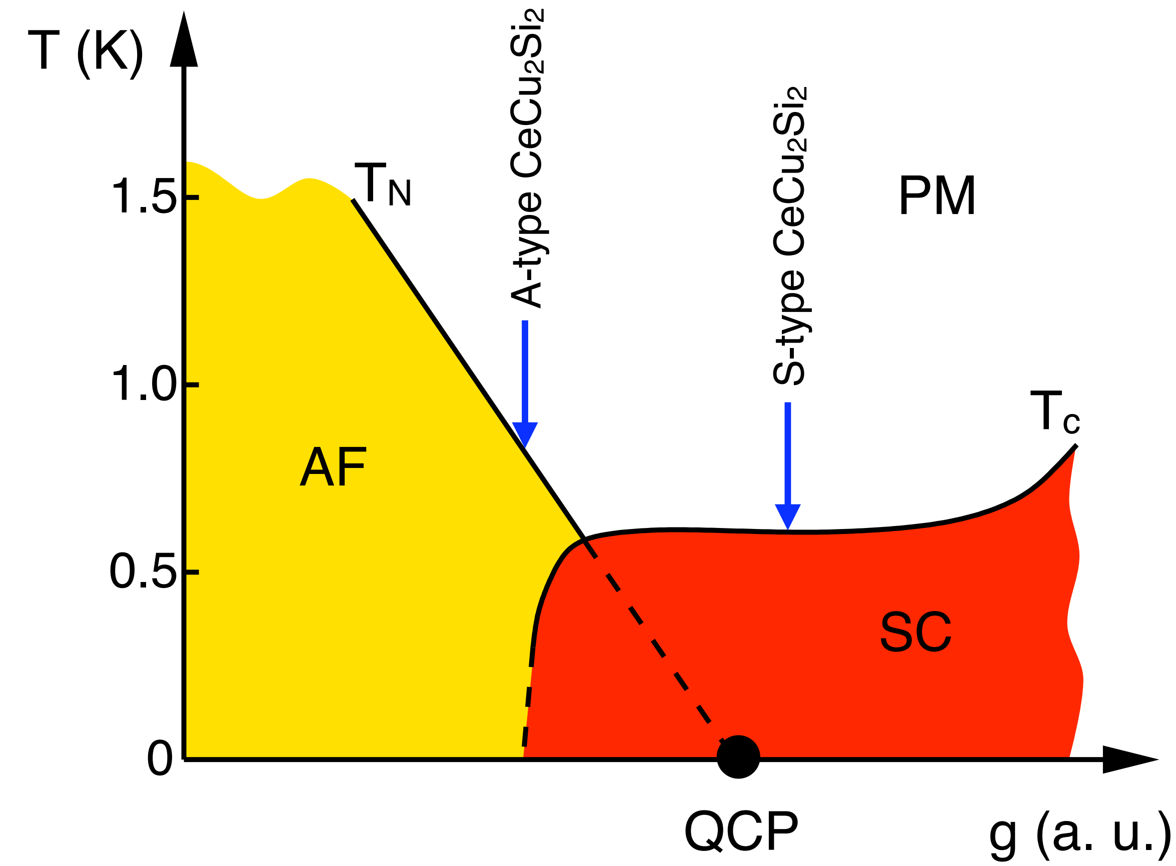


Conclusions



Cd-doped $CeCoIn_5$:

• Coexistence of AF and SC

Pure and Ge-doped $CeCu_2Si_2$:

• From competition to coexistence of AF and SC

Superconducting $CeCu_2Si_2$:

• Almost critical slowing down of normal state magnetic response, vicinity to QPT: $\omega/T^{3/2}$ scaling, $\Gamma \propto \chi^{-1} \propto T^{3/2}$ → 3D critical behavior

• Observation of dispersive spin excitations (paramagnons)

• Spin excitation gap in superconducting state

• Magnetic exchange energy saving in superconducting state

→ Evidence for magnetically driven superconductivity