The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1957-21

Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

Antiparamagno-mediated superconductivity in CeCu2Si2 ?

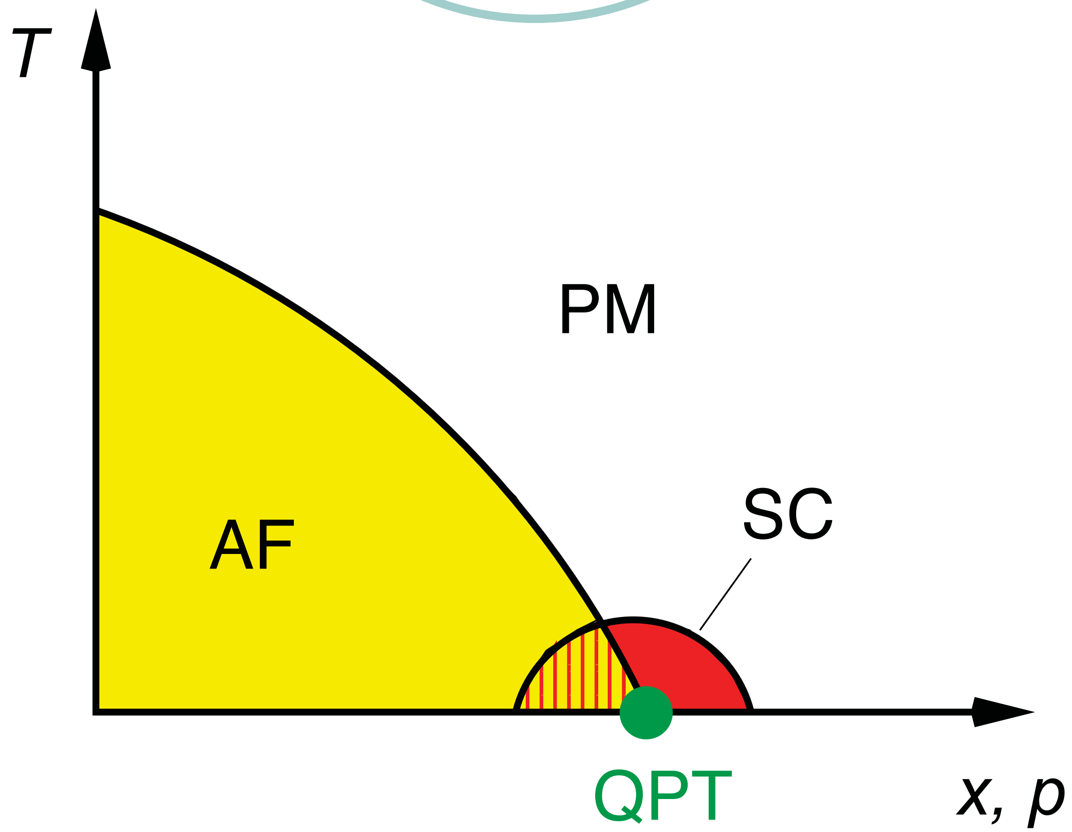
STOCKERT Oliver
Max Planck Institute
Dresden
GERMANY

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

ICTP, Trieste, 5.8.2008

Paramagnon-mediated superconductivity in the heavy-fermion compound $CeCu_2Si_2$?

O. Stockert
Max-Planck-Institut CPfS, Dresden, Germany



Outline

Quantum phase transitions

Neutrons as microscopic probe

$CeCu_2Si_2$:

- Ground state properties / antiferromagnetic order
- Interplay magnetism / superconductivity
- Spin dynamics in superconducting state

Conclusion

Collaborations

Thanks ...

J. Arndt, M. Deppe, H.S. Jeevan, C. Geibel, M. Nicklas, F. Steglich — Max-Planck-Institut CPfS Dresden

E. Faulhaber, A. Schneidewind*, M. Loewenhaupt — Institut für Festkörperphysik, TU Dresden

K. Prokes, N. Stüßer, K. Habicht, S. Gerischer, P. Smeibidl, M. Meißner — Hahn-Meitner-Institut Berlin

K. Schmalzl, W. Schmidt, F. Thomas, X. Tonon, S. Pujol — Institut Laue-Langevin Grenoble

A. Amato, D. Andreica** — Paul Scherrer Institut, Villigen

H. Schneider* — JCNS, Forschungszentrum Jülich

* FRM-II, TU München
** Babes-Bolyai Univ., Cluj-Napoca

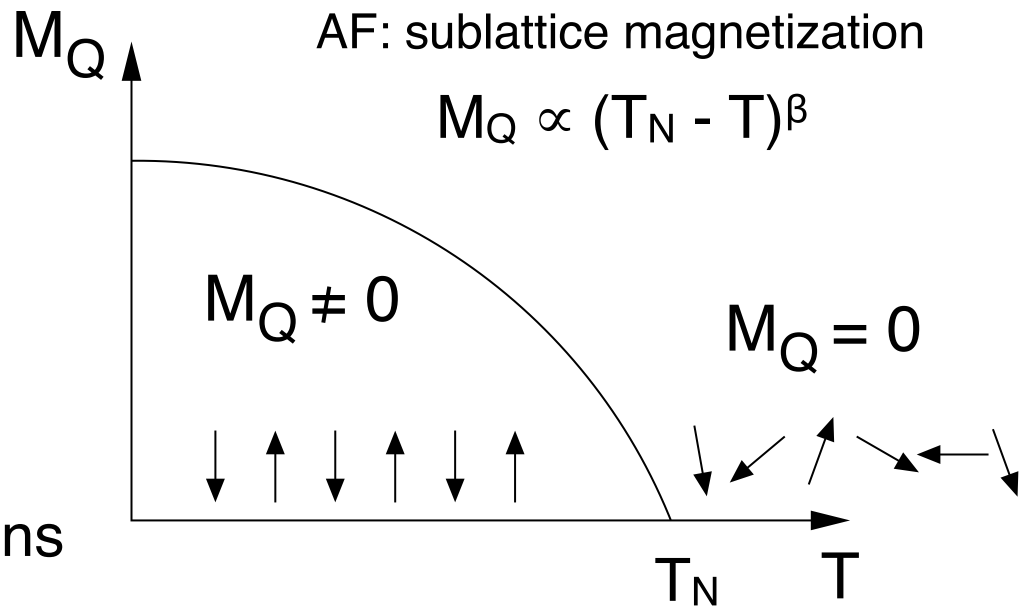
Work partially funded by SFB 463, DFG, and EU

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

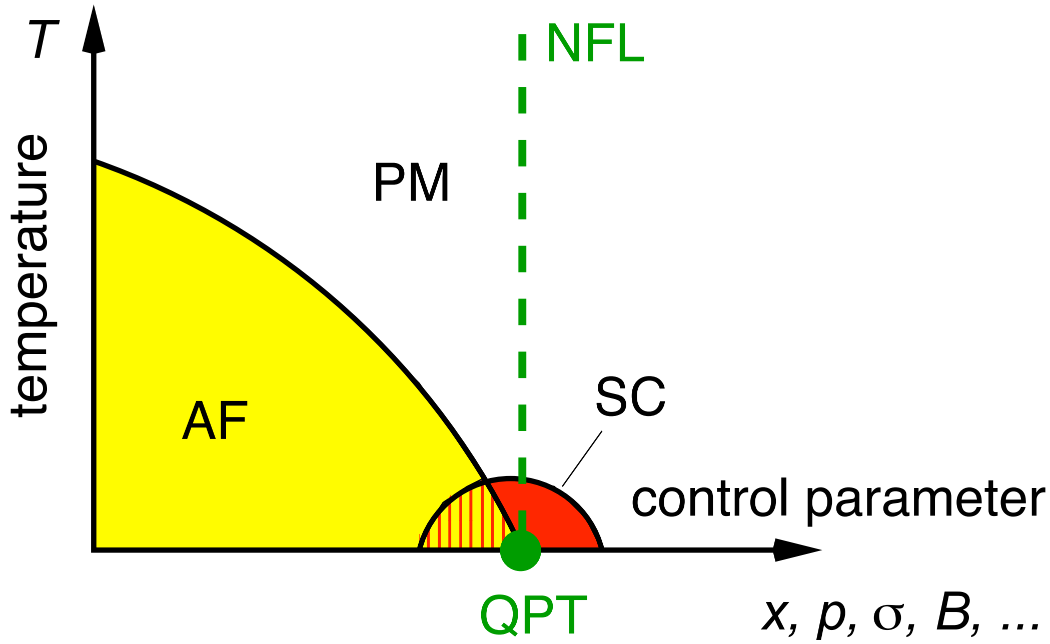
Continuous phase transition
for T ➞ 0

➞ Quantum phase transition (QPT)
with unusual low temperature
properties, e.g.:

- $C/T \propto -\ln T$;

  $\Delta\rho \propto T^{\alpha}$, $\alpha < 2$ (NFL)

- superconductivity



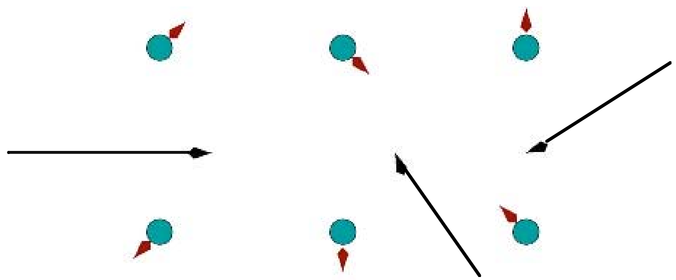
Origin?

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

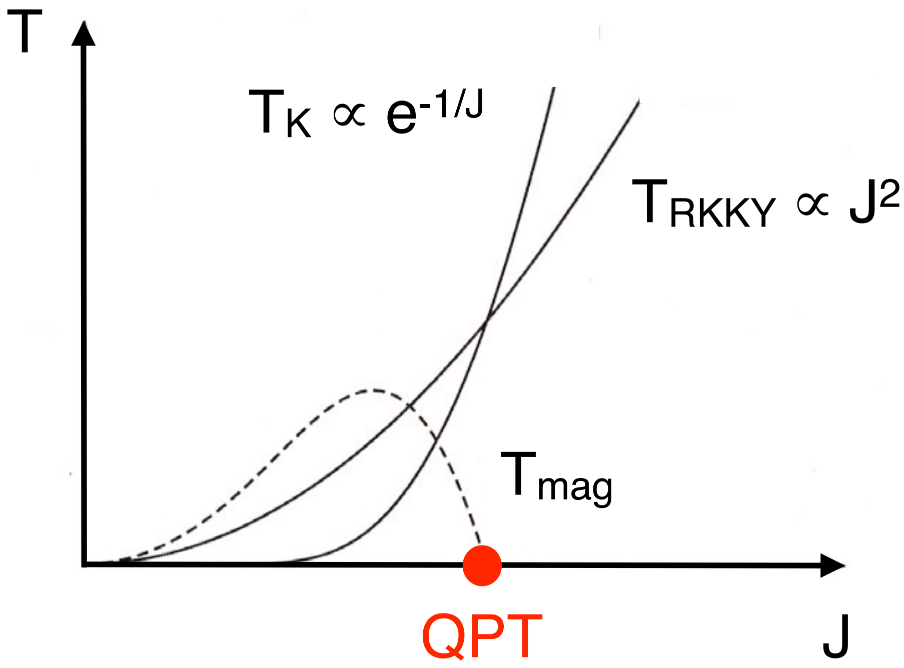
[recent review QPT:
H. v. Löhneysen, RMP '07]

Heavy fermions

$T \gg T_K$:



$T < T_K$: heavy electrons

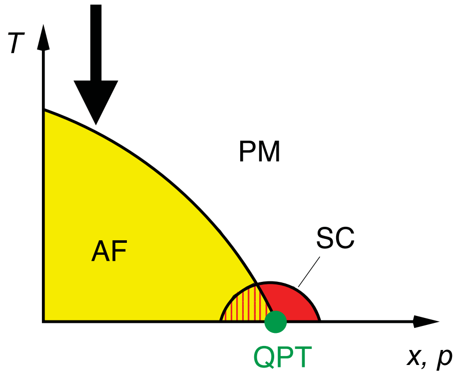


Kondo screening vs.
RKKY interaction:

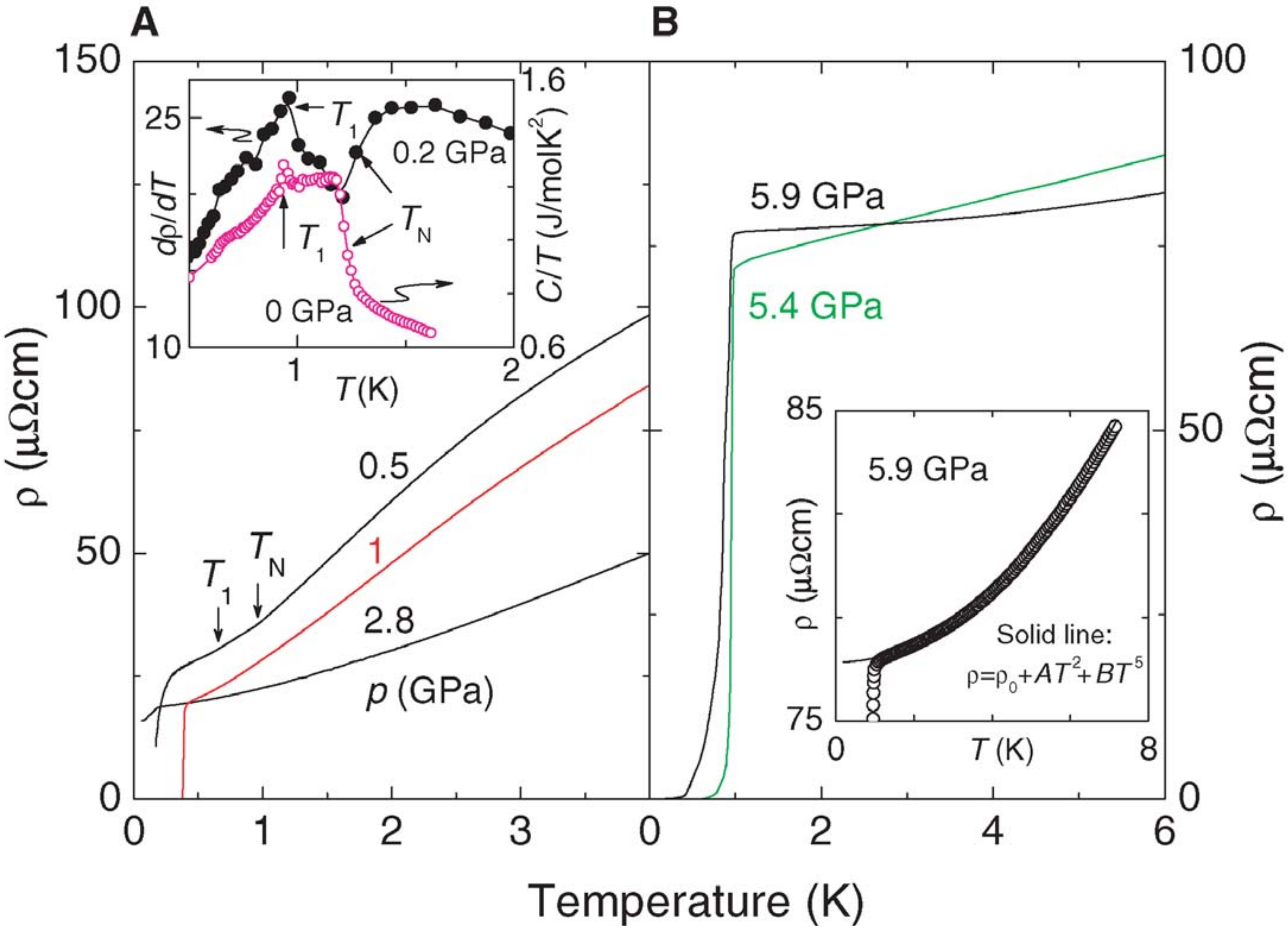
Kondo effect
→ nonmagnetic singlet

indirect RKKY interaction
→ magnetic order

Pressure tuning: electrical resistivity

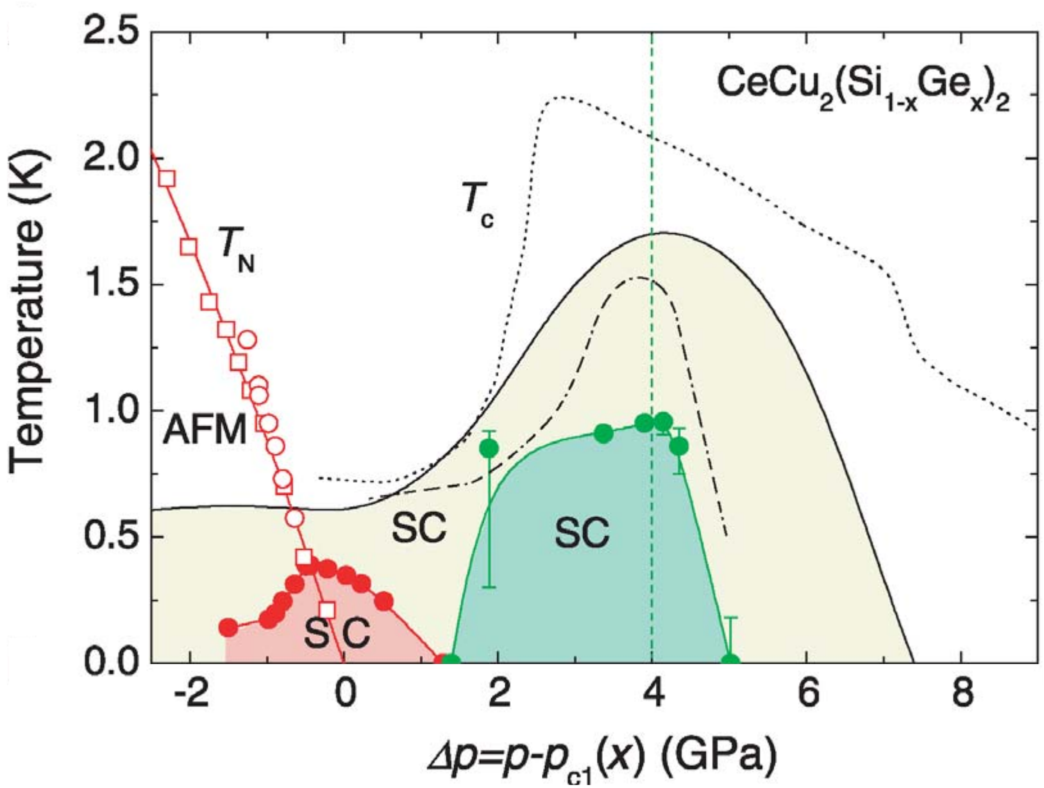


$CeCu_2(Si_{0.9}Ge_{0.1})_2$ single crystal:



[H.Q. Yuan, Science, ’03]

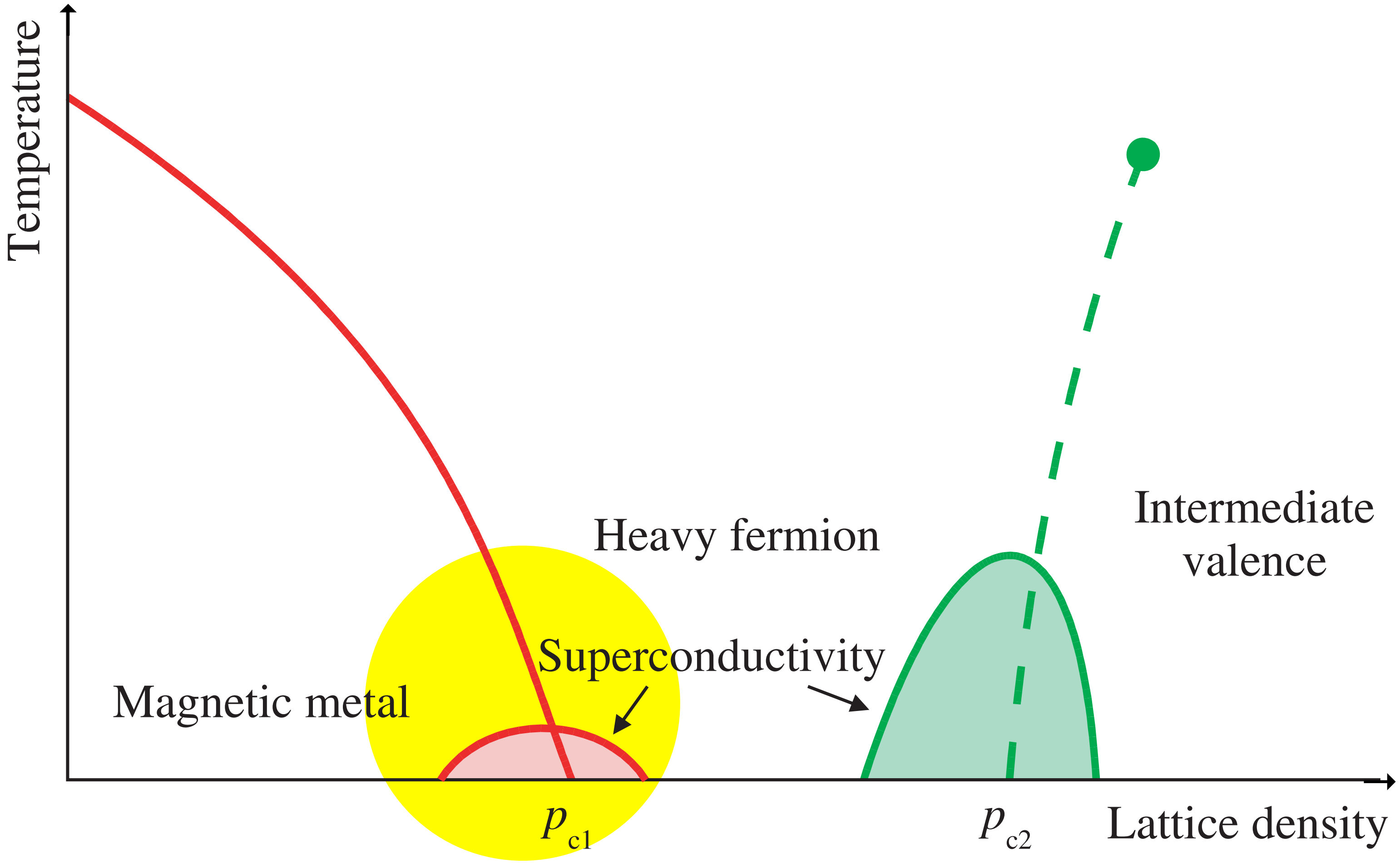
Pressure tuning: phase diagram



- T_N suppressed under pressure
- Occurrence of two superconducting regimes

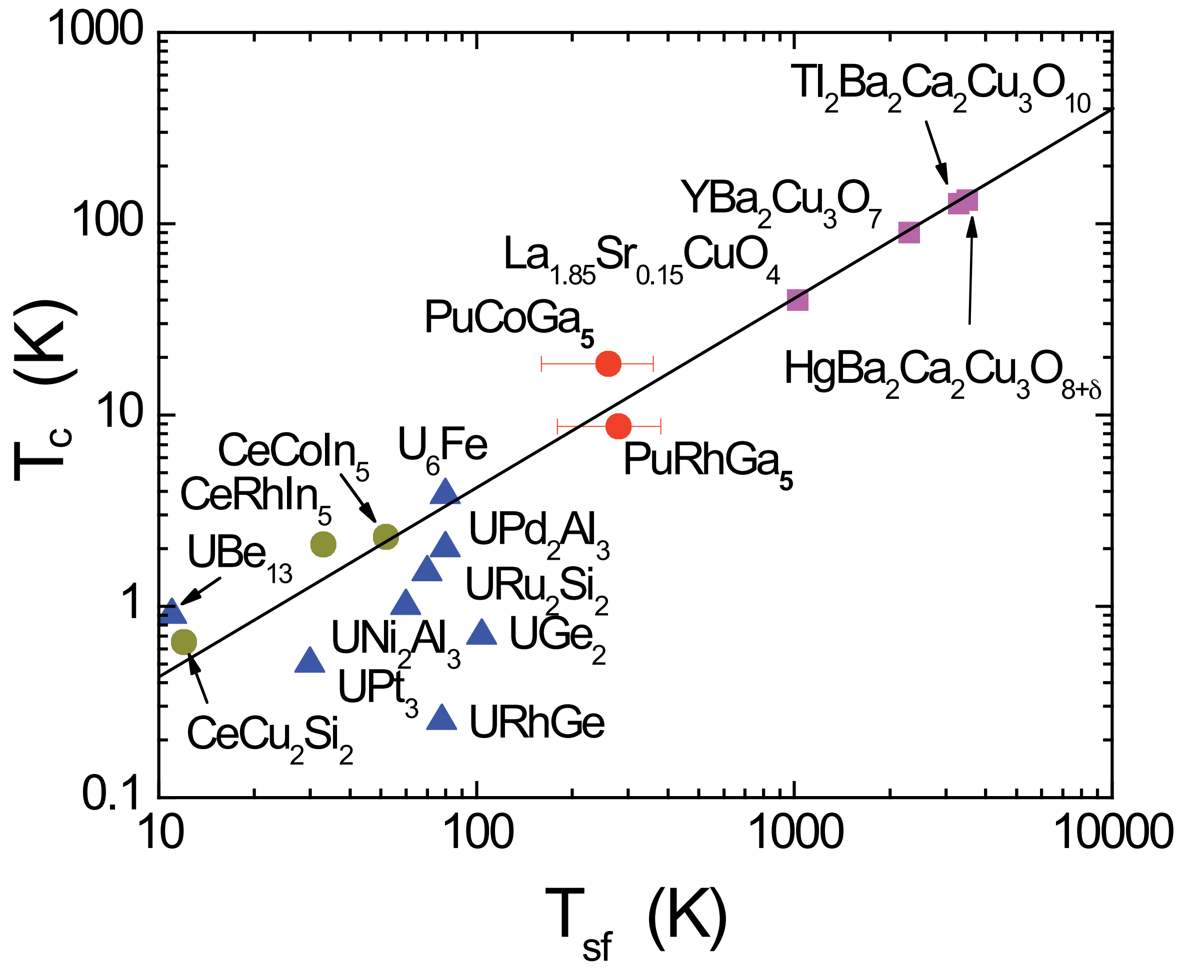
[H.Q. Yuan, Science, '03]

Quantum phase transitions in $CeCu_2Si_2$



[H.Q. Yuan, Science '03]

Energy scales: superconductivity and spin fluctuations



[T. Moriya, '03]

superconducting T_c scales with spin fluctuation T_{sf}

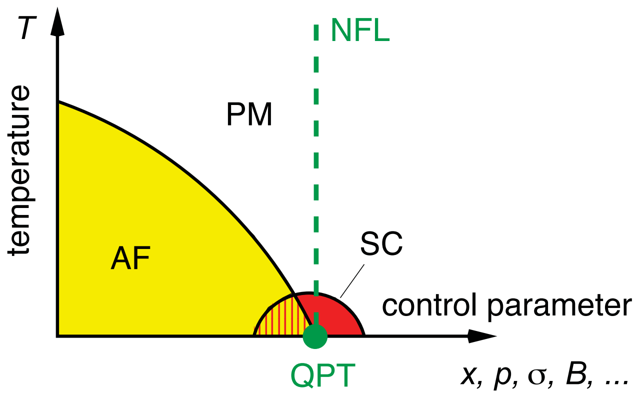
Neutrons as microscopic probe

Magnetic neutron scattering:

FT of spin-spin-correlation function

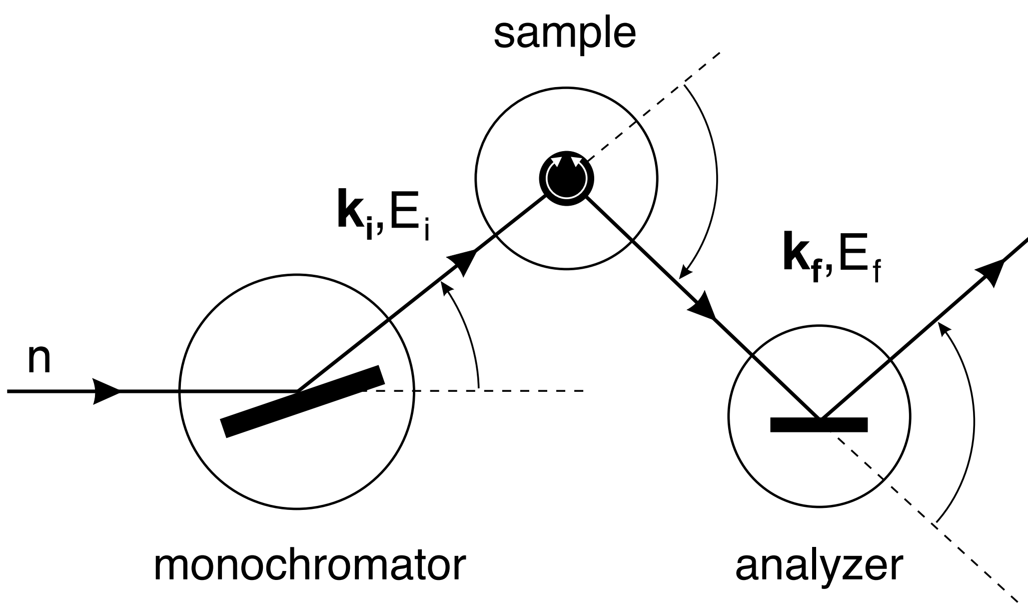
$$\mathrm{I} \propto \frac{d^2\sigma}{d\Omega d\omega} \propto S(\mathbf{q},\omega) = \mathrm{FT}\left\{ \sum_{i,j} e^{i\mathbf{q}(\mathbf{R}_i - \mathbf{R}_j)} \langle \hat{S}_i(0)\hat{S}_j(t)\rangle \right\}$$

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



Inelastic neutron scattering

- Instruments for different **q**-, ω-regions
- Three-axis spectrometer:



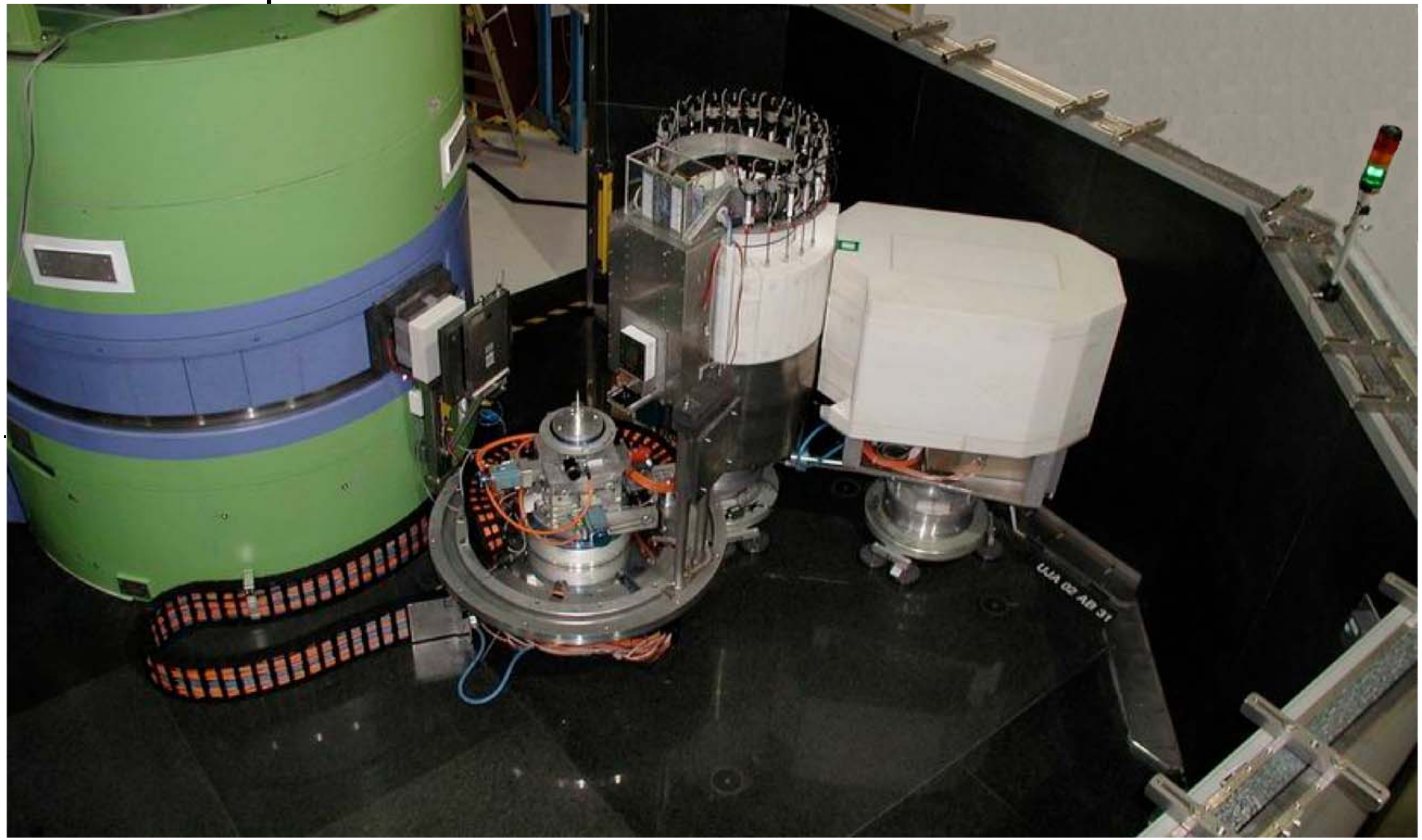
$$\hbar \mathbf{q} = \hbar(\mathbf{k}_i - \mathbf{k}_f)$$

$$\hbar\omega = \frac{\hbar^2}{2m}(\mathbf{k}_i^2 - \mathbf{k}_f^2)$$

Instruments: IN12, IN14 at ILL / Grenoble
V2 at HMI / Berlin
PANDA at FRM-II / Garching

Inelastic neutron scattering

- Instruments for different **q**-, ω-regions
- Three-axis spectrometer:



PANDA at FRM-II / Garching

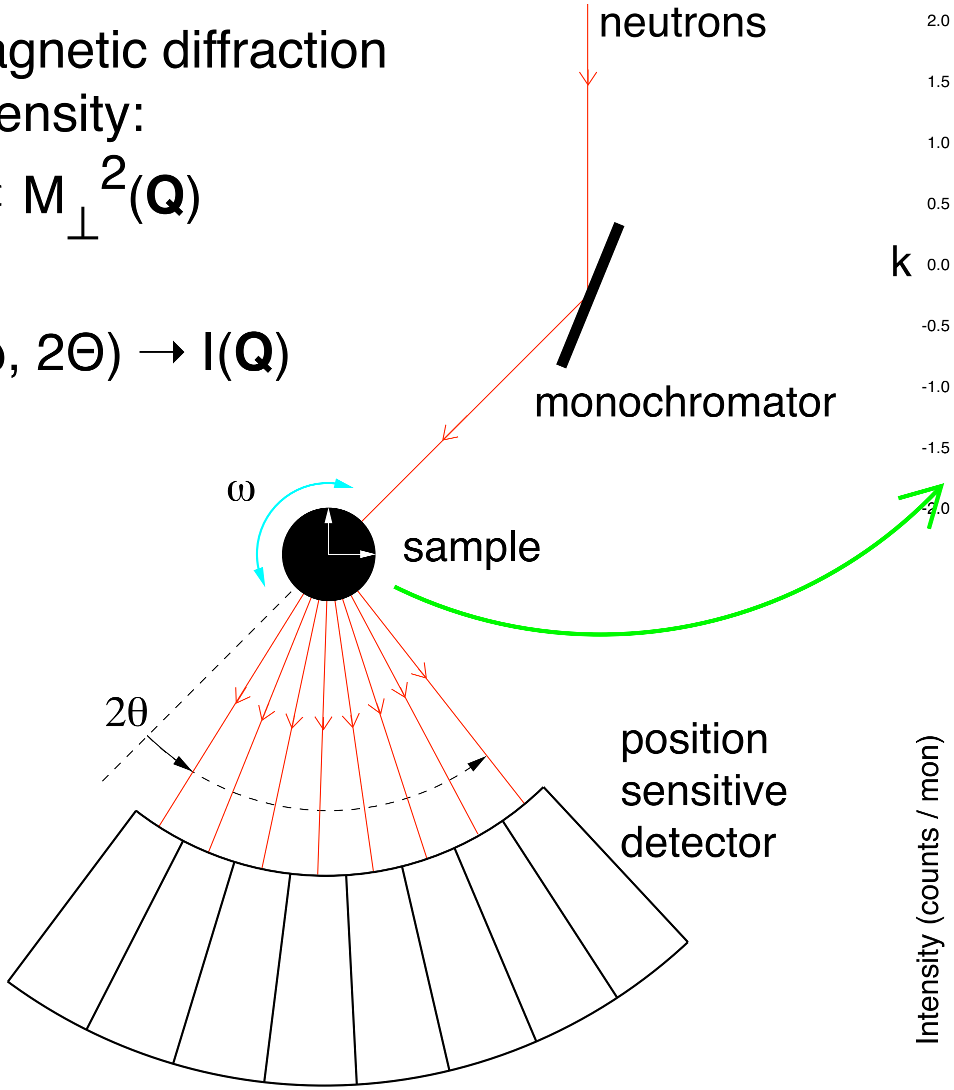
Neutron diffraction

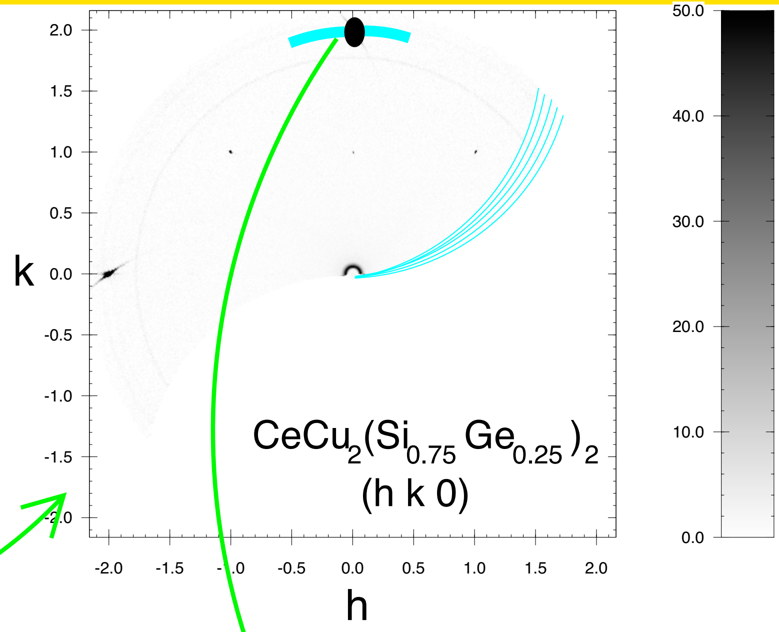
Magnetic diffraction

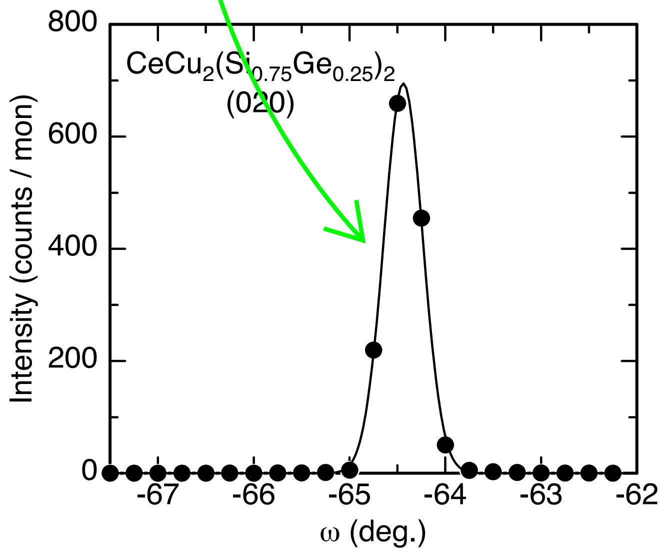
Intensity:

$I \propto M_{\perp}^{2}(\mathbf{Q})$

$I(\omega, 2\Theta) \rightarrow I(\mathbf{Q})$

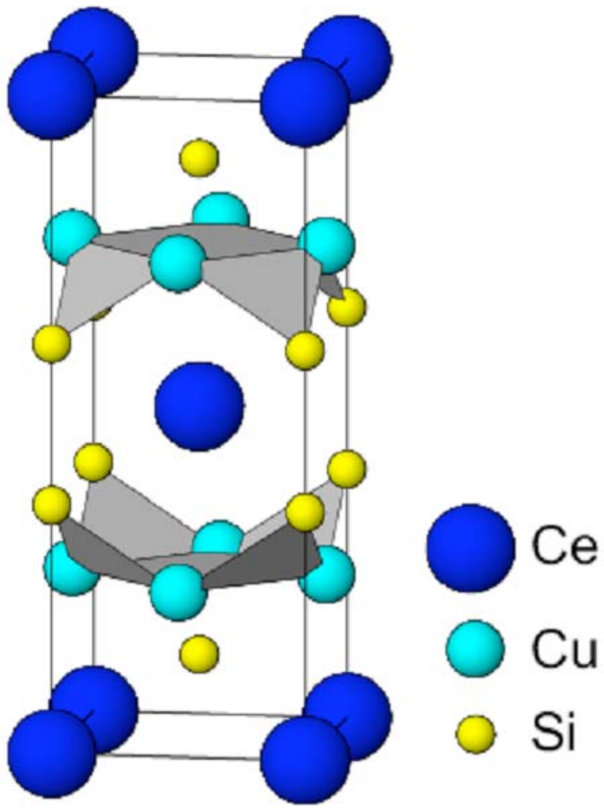


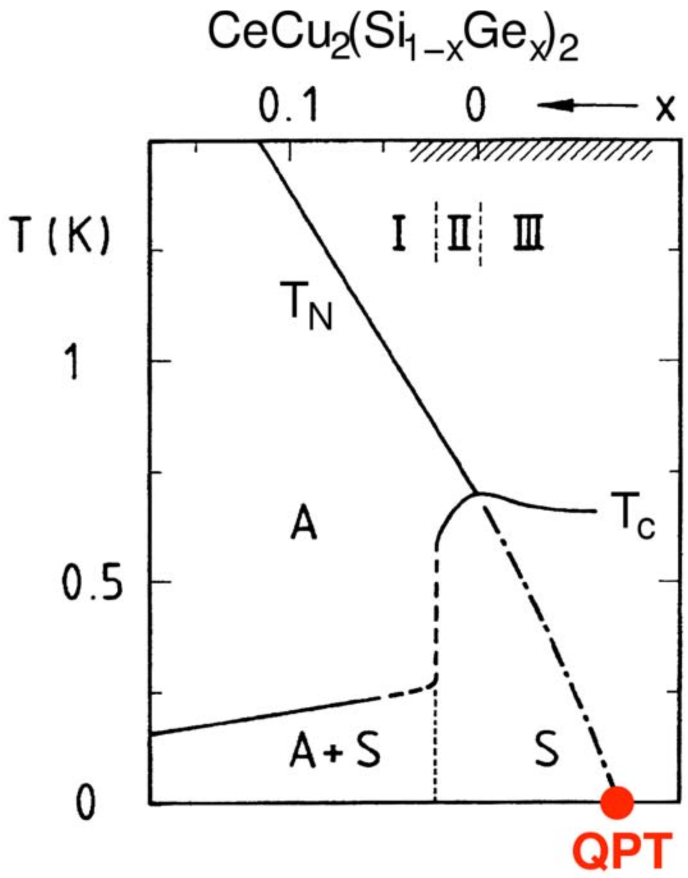




Instruments: E2, (E4), E6 at HMI / Berlin

Magnetism and superconductivity in $CeCu_2Si_2$

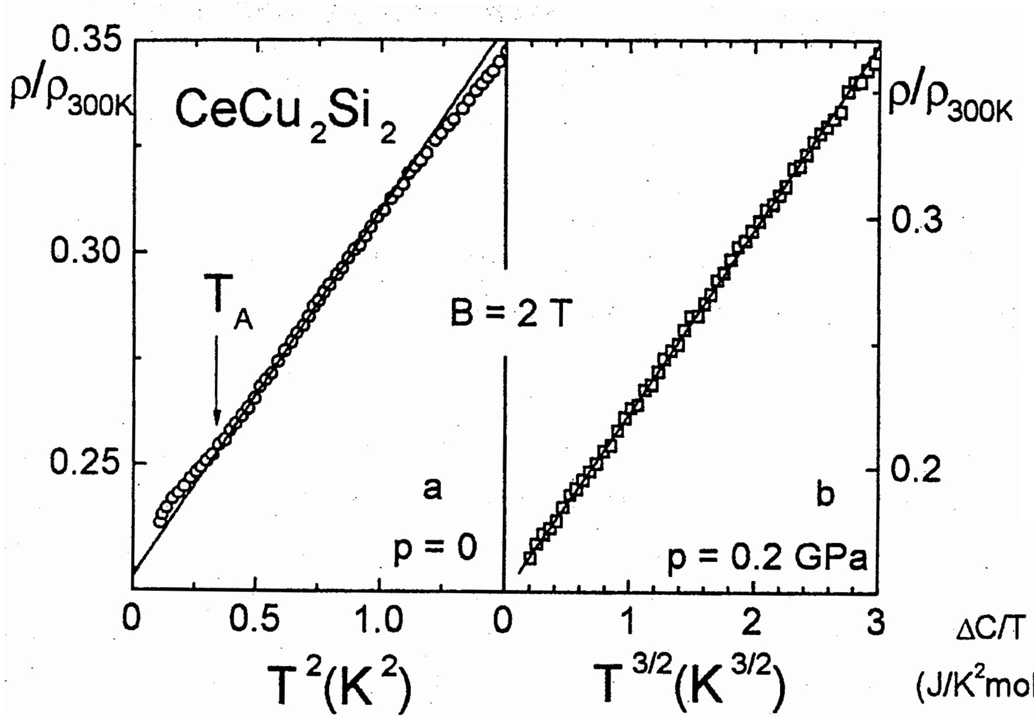




[P. Gegenwart, PRL ’98]

- Heavy-fermion superconductor [F. Steglich, PRL ’79]
- NMR and μSR: first indication of magnetic order (A-phase)
  [H. Nakamura, JMMM ’88; Y. J. Uemura, Physica C ’88, PRB ’89]
- Vicinity to quantum phase transition: $\Delta\rho \propto T^{1...1.5}$; $C/T = \gamma_0 - \alpha\sqrt{T}$
  (3D-AF instability)

QPT in A/S-$CeCu_2Si_2$: low T properties



$CeCu_2Si_2$ under pressure

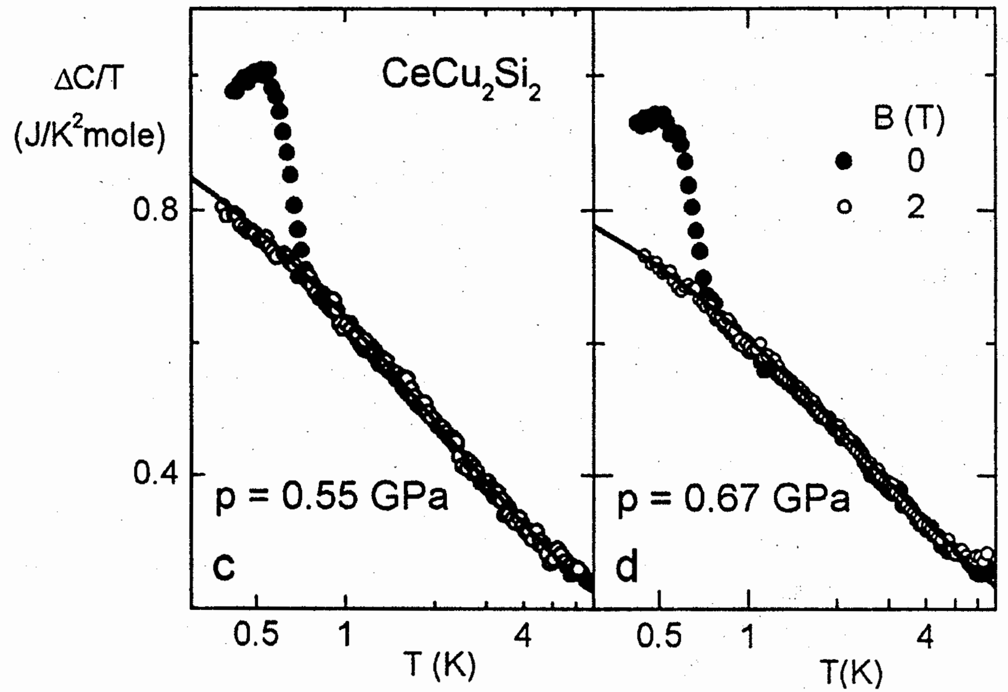
$(B > B_{c2})$:

[G. Sparn, Rev. High Press. Sci. Tech. '98]

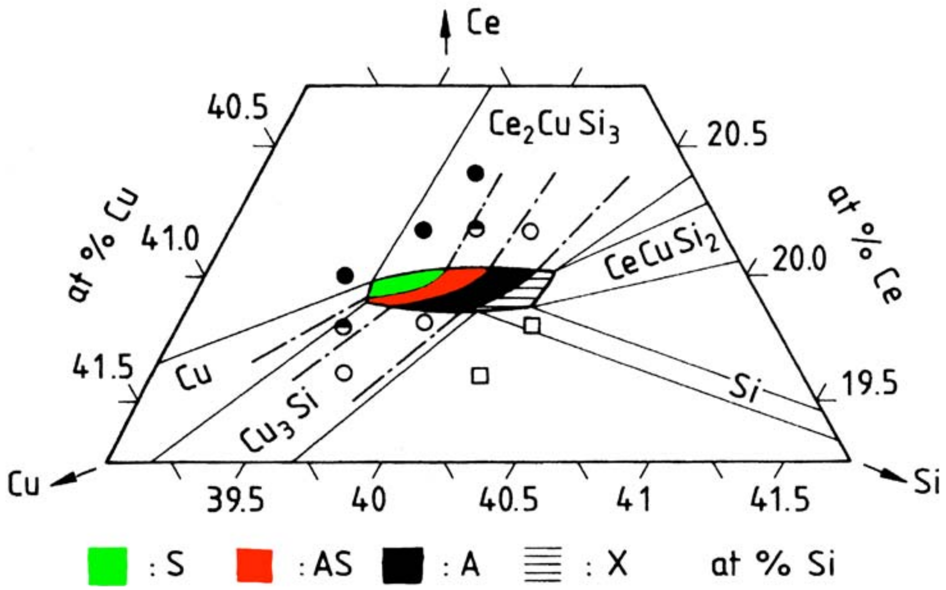
$\Delta\rho \propto T^{3/2}$

$\Delta C/T = \gamma_0 - \alpha\sqrt{T}$

3D-AF instability (SDW)



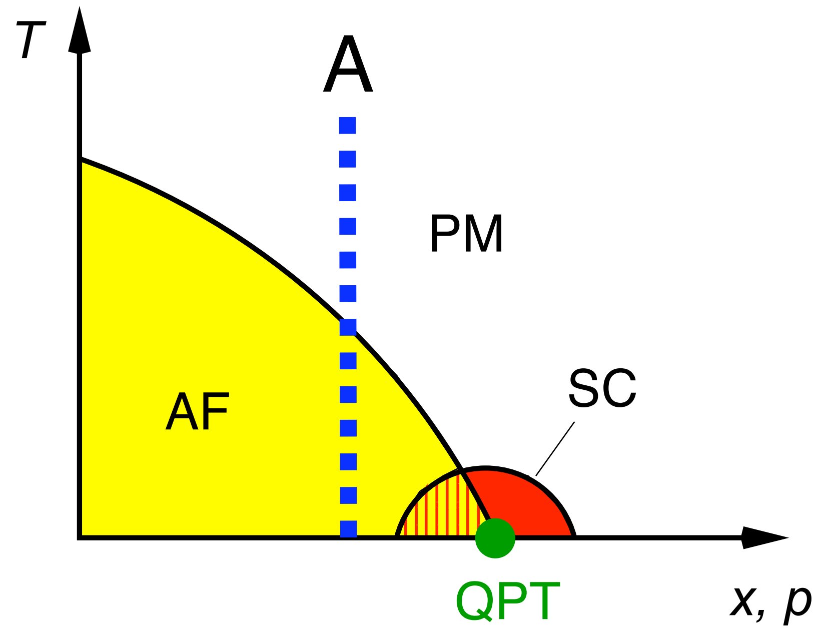
Ground states in $CeCu_2Si_2$



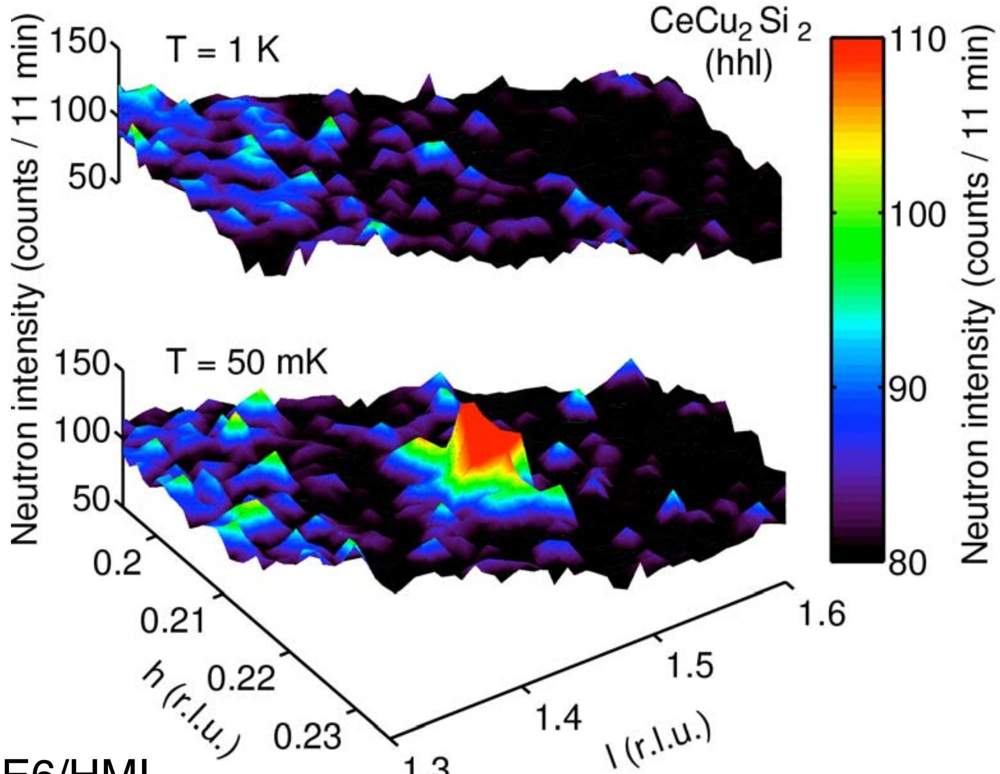
Ground state dependent on stoichiometry:
A, Superconducting, A/S

[C. Geibel, '95]

Vicinity to quantum phase transition at disappearance of magnetic order



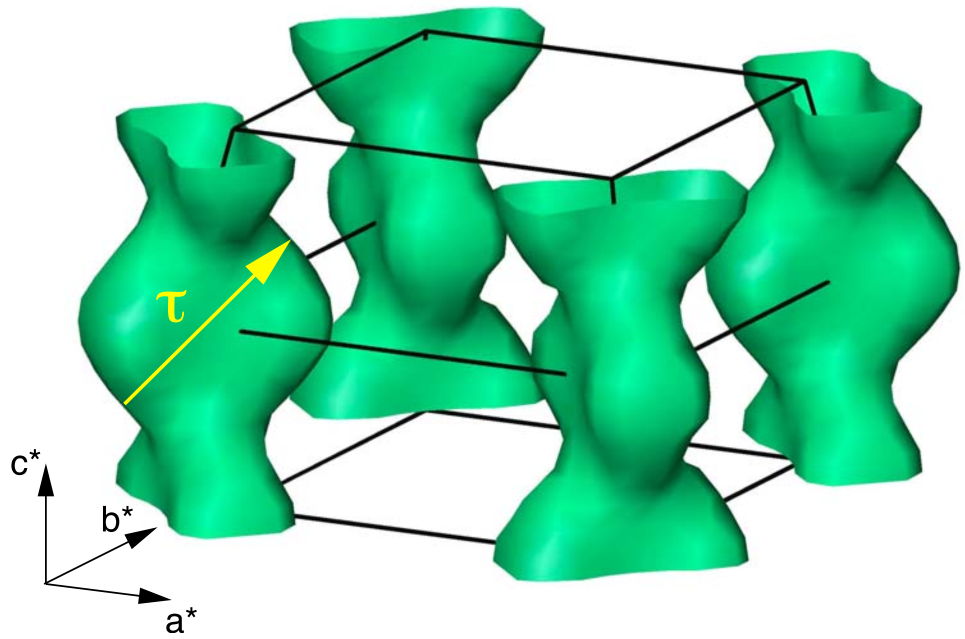
Nature of the magnetic A-phase in $CeCu_2Si_2$



E6/HMI

Fermi surface: nesting for wave vector $q \approx (0.21\ 0.21\ 0.55)$

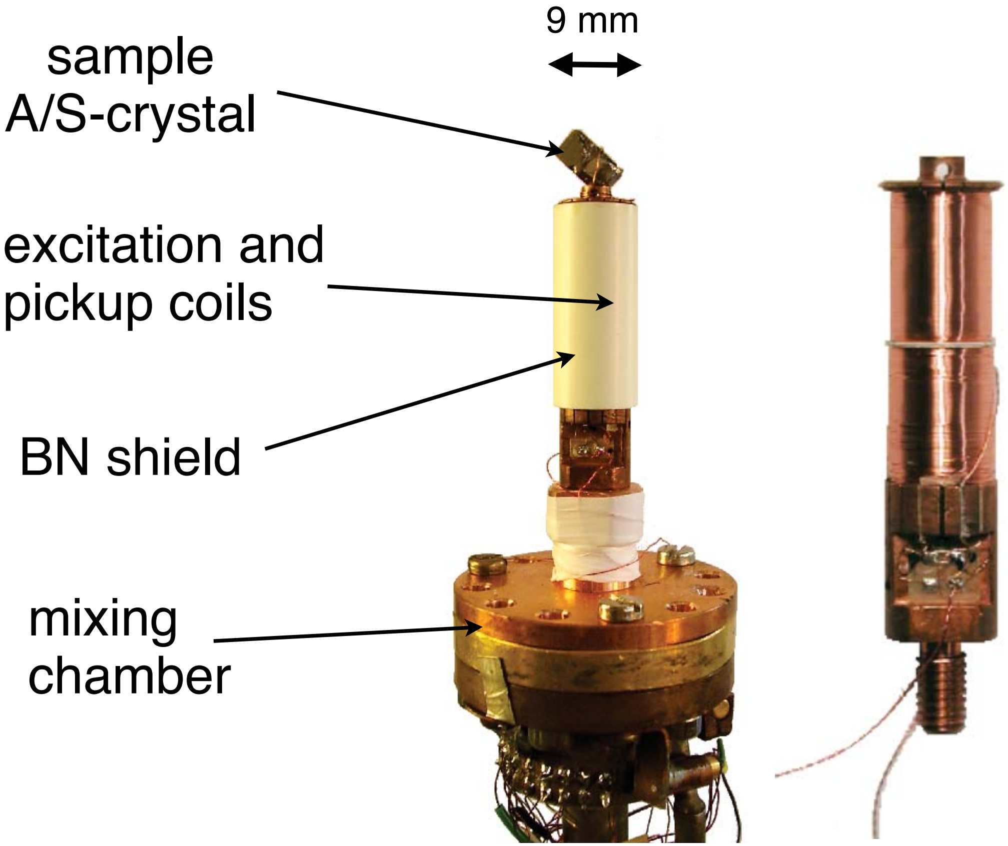
→ Fermi surface unstable with respect to formation of spin-density wave

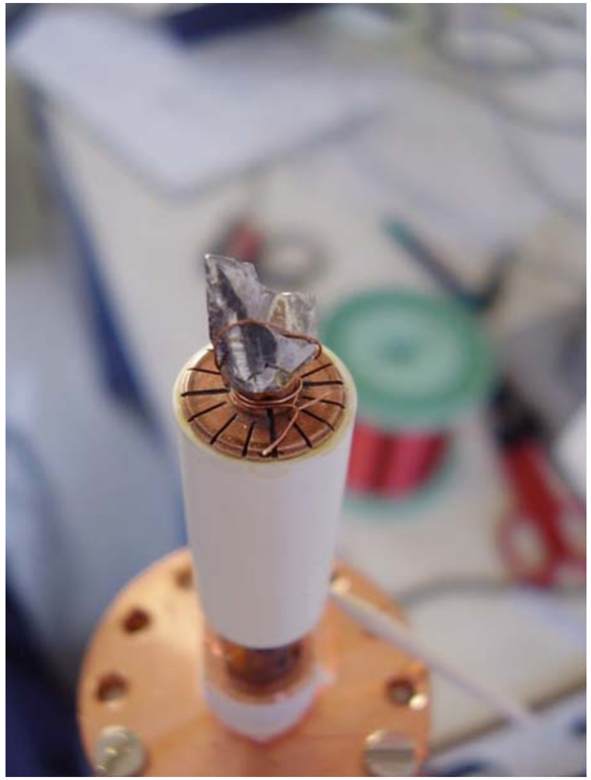


- Observation of incomm. AF order
- Propagation vector
  $\tau = (0.215\ 0.215\ 0.530)$ at T = 50 mK
- $T_N \approx 0.8$ K, $m_0 \approx 0.1\ \mu_B$

[OS, PRL '04]

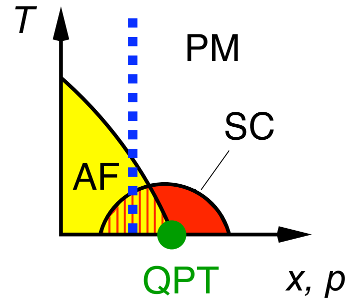
In situ ac susceptibility

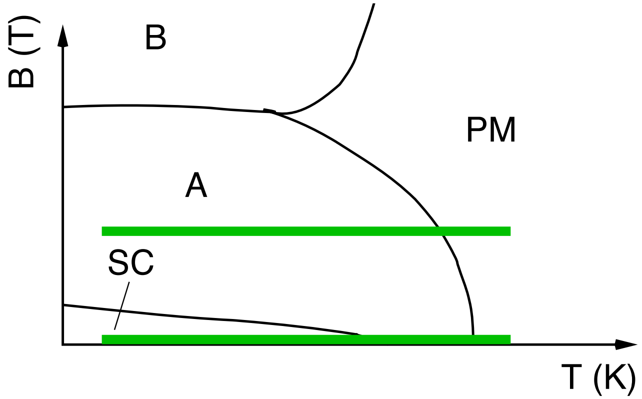




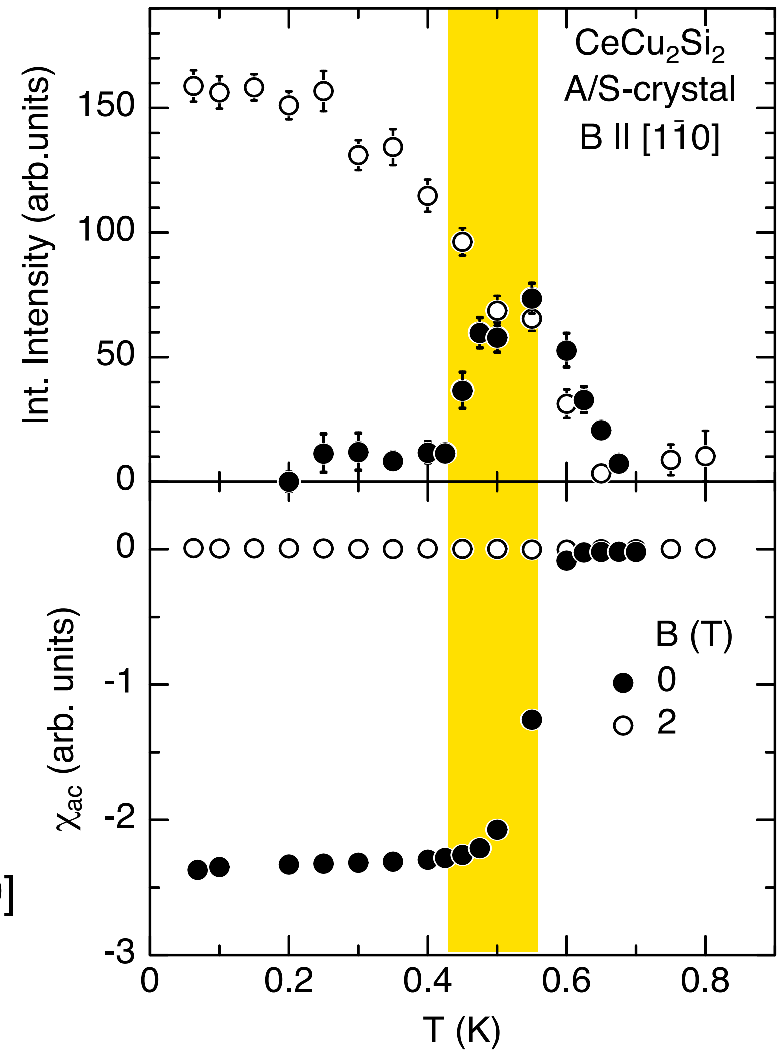
Magnetism and superconductivity in A/S-$CeCu_2Si_2$

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





$Q \approx (0.22\ 0.22\ 1.47)$



- No coexistence of AF and SC on microscopic scale
- Confirmation of μSR and NQR

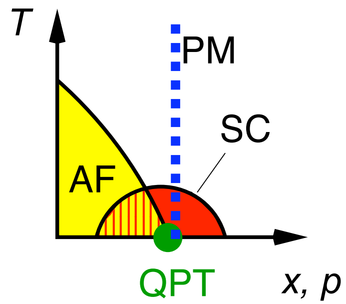
[R. Feyerherm, PRB '97; K. Ishida, PRL '99]

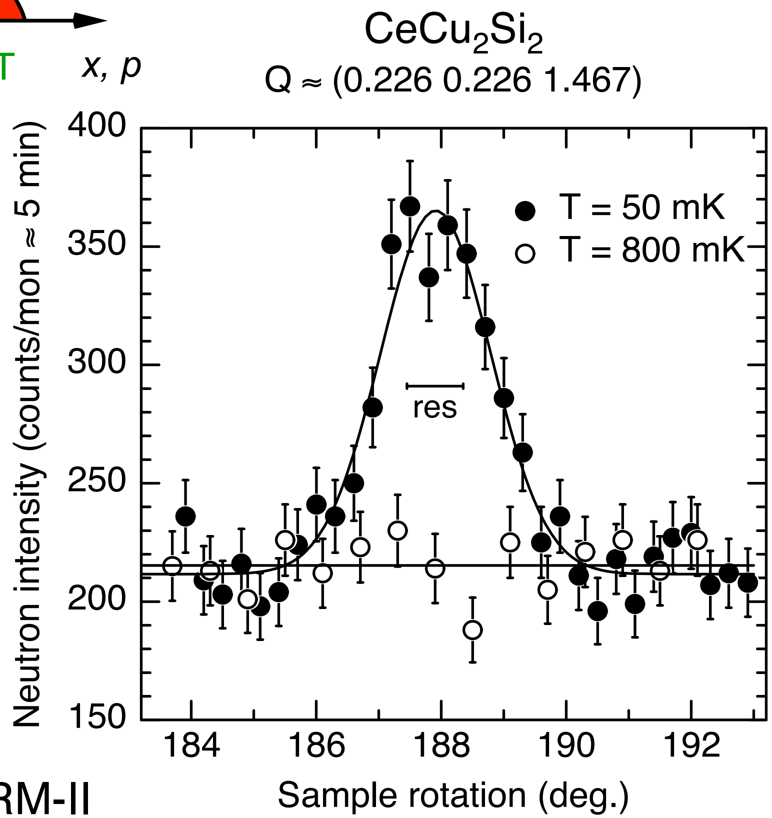
- Magnetic intensity just below T_c
- μSR: phase separation! Different AF and SC volumes

[OS, '06]

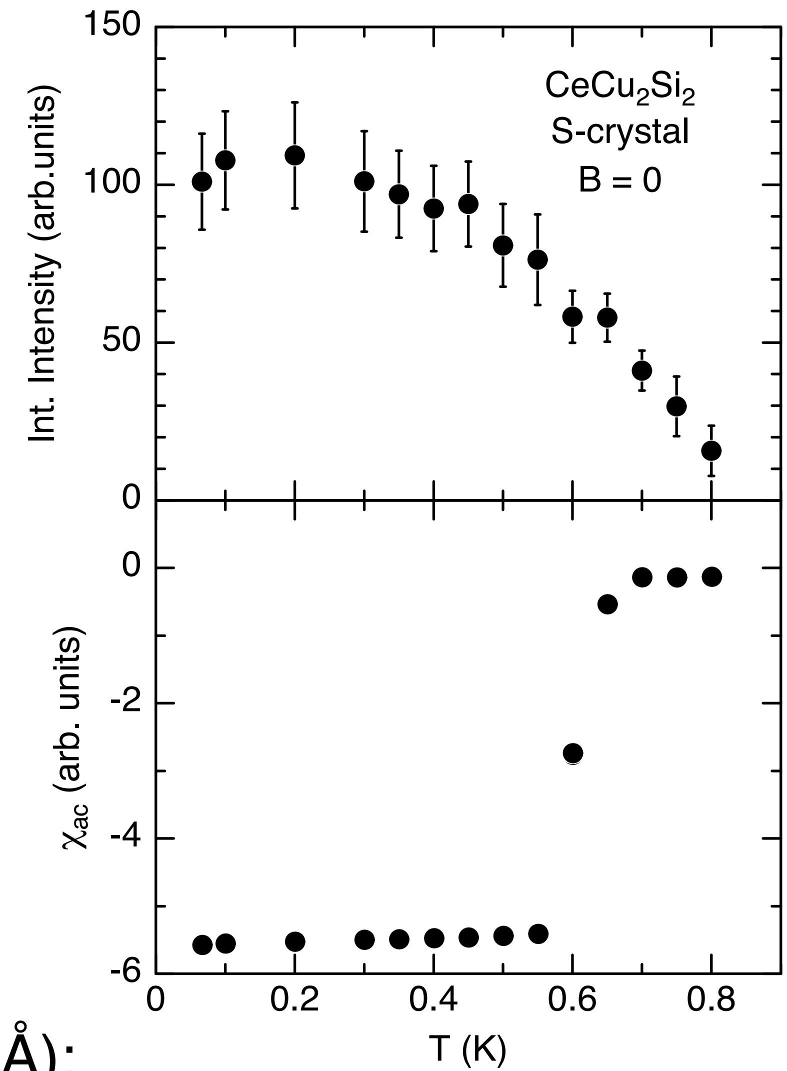
IN12/ILL

Magnetic correlations in S-$CeCu_2Si_2$





PANDA/FRM-II

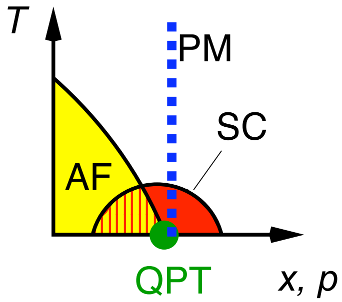


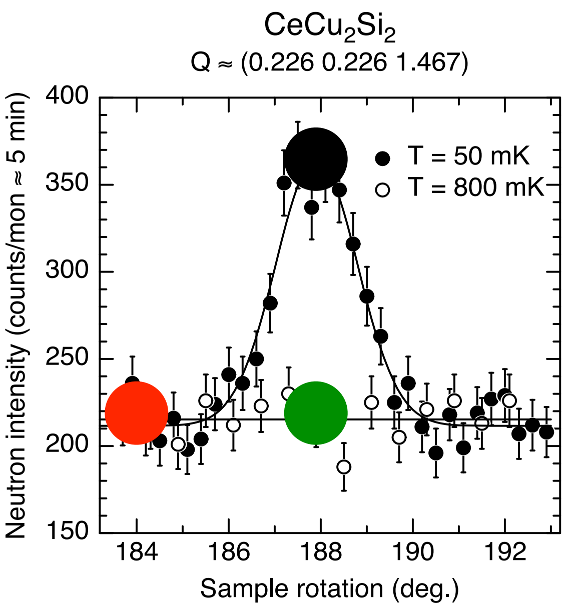
- Short-range correlations (ξ ≈ 50–60 Å):

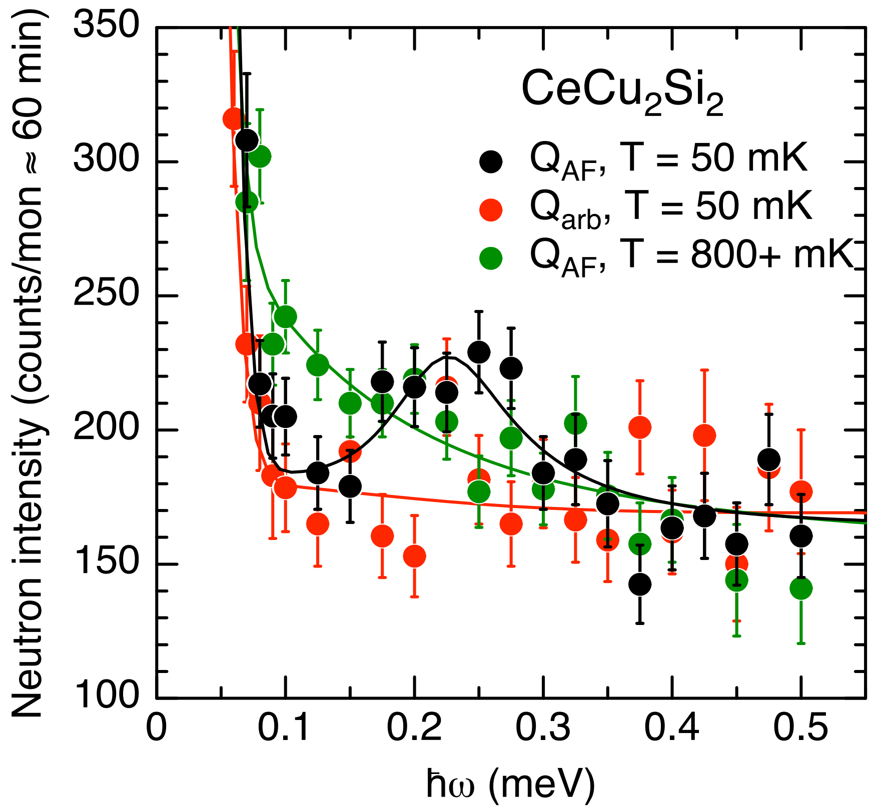
  Relation to superconductivity?

IN12/ILL

Spin dynamics in S-$CeCu_2Si_2$







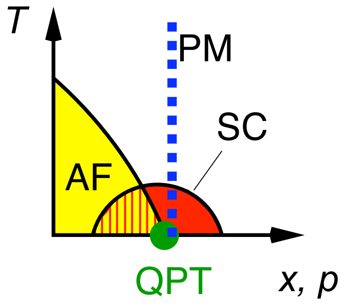
PANDA/FRM-II
[O. Stockert, '08]

T_c = 600 mK

$Q = Q_{AF/nesting}$:

Spin excitation gap below T_c

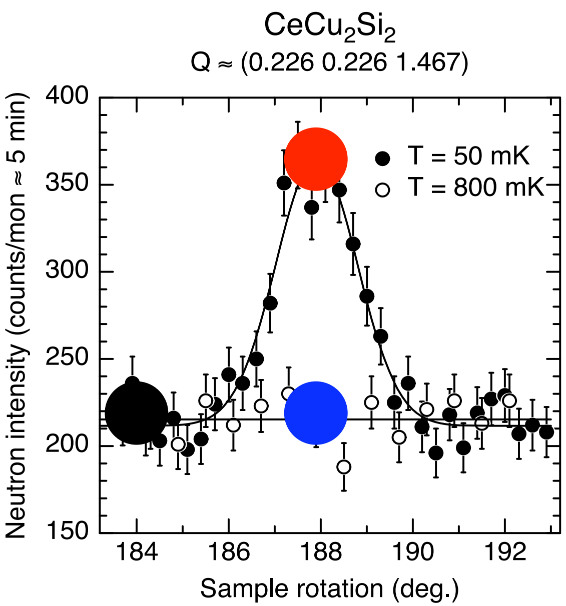
Spin dynamics in S-$CeCu_2Si_2$



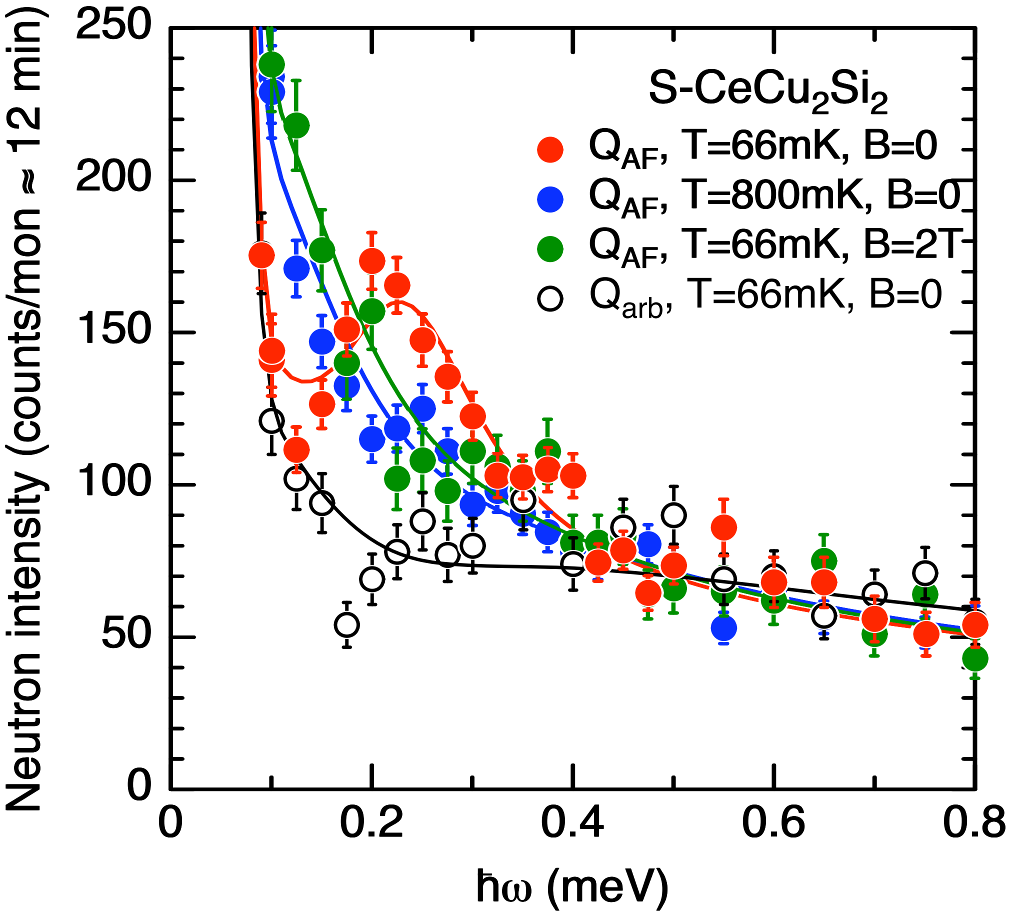
IN12/ILL

$k_f = 1.15$ Å^{-1}

$\Delta E = 57$ µeV (FWHM)



T_c = 600 mK

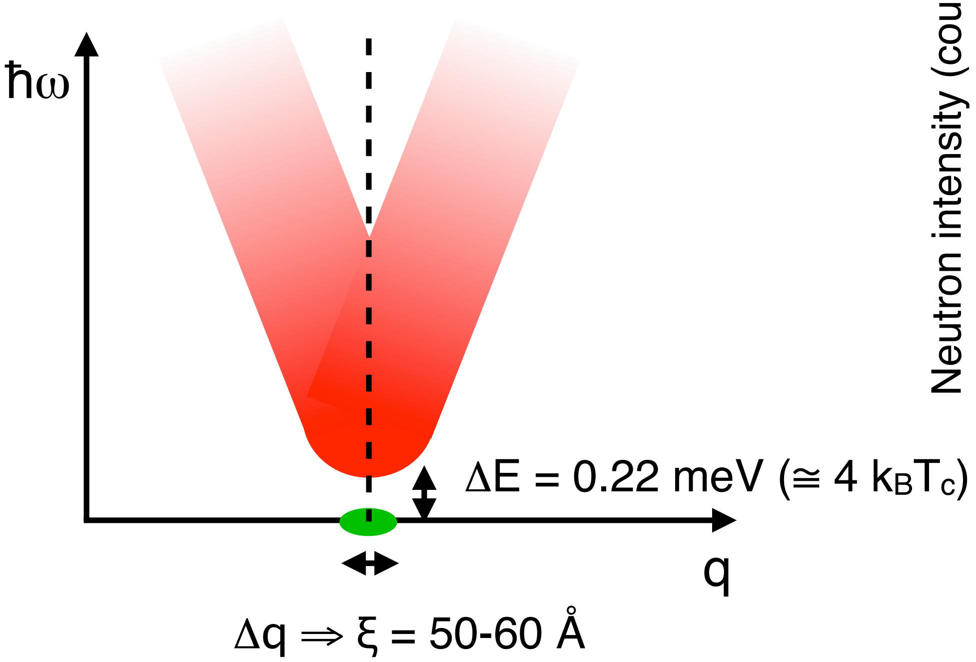


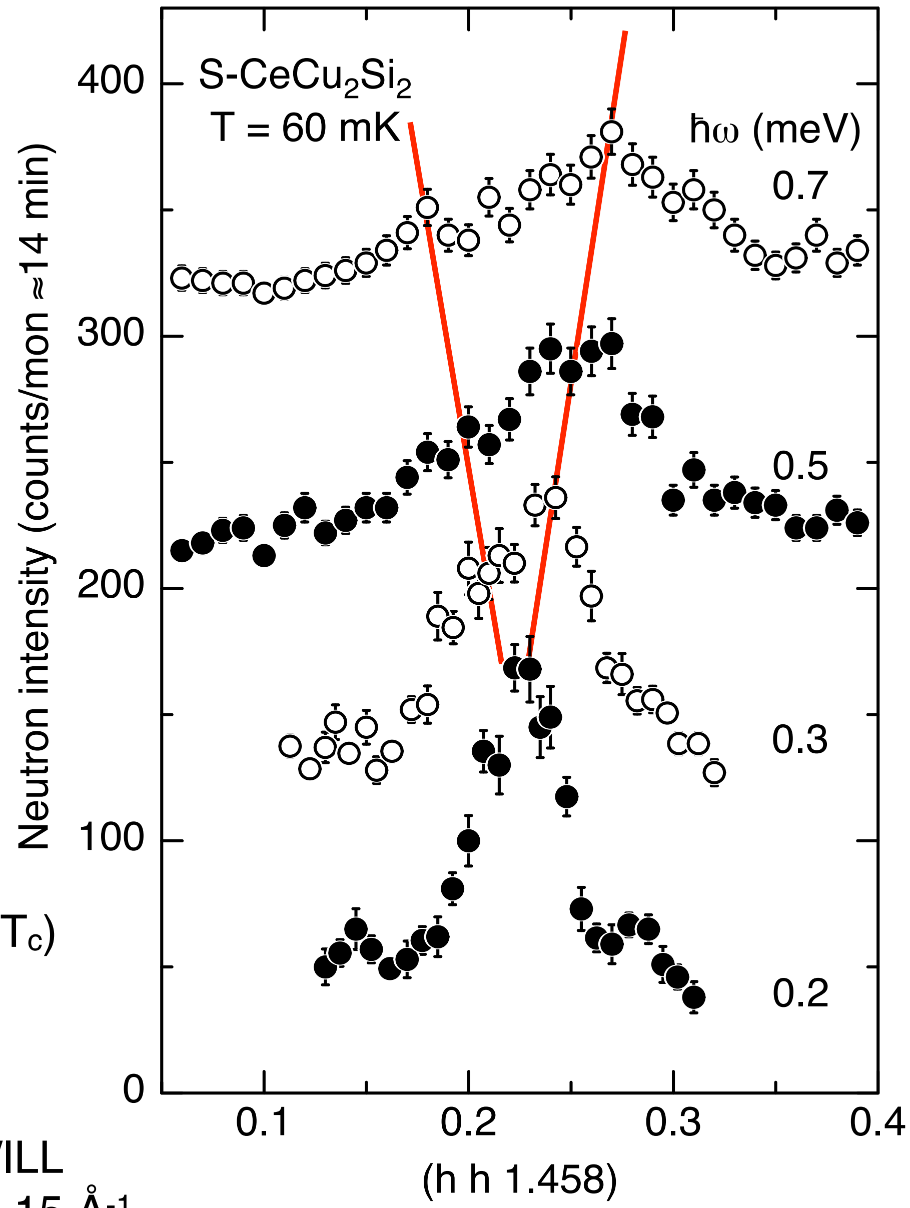
$Q = Q_{AF/nesting}$:

Spin excitation gap below T_c with $\Delta E \approx 0.2$ meV

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

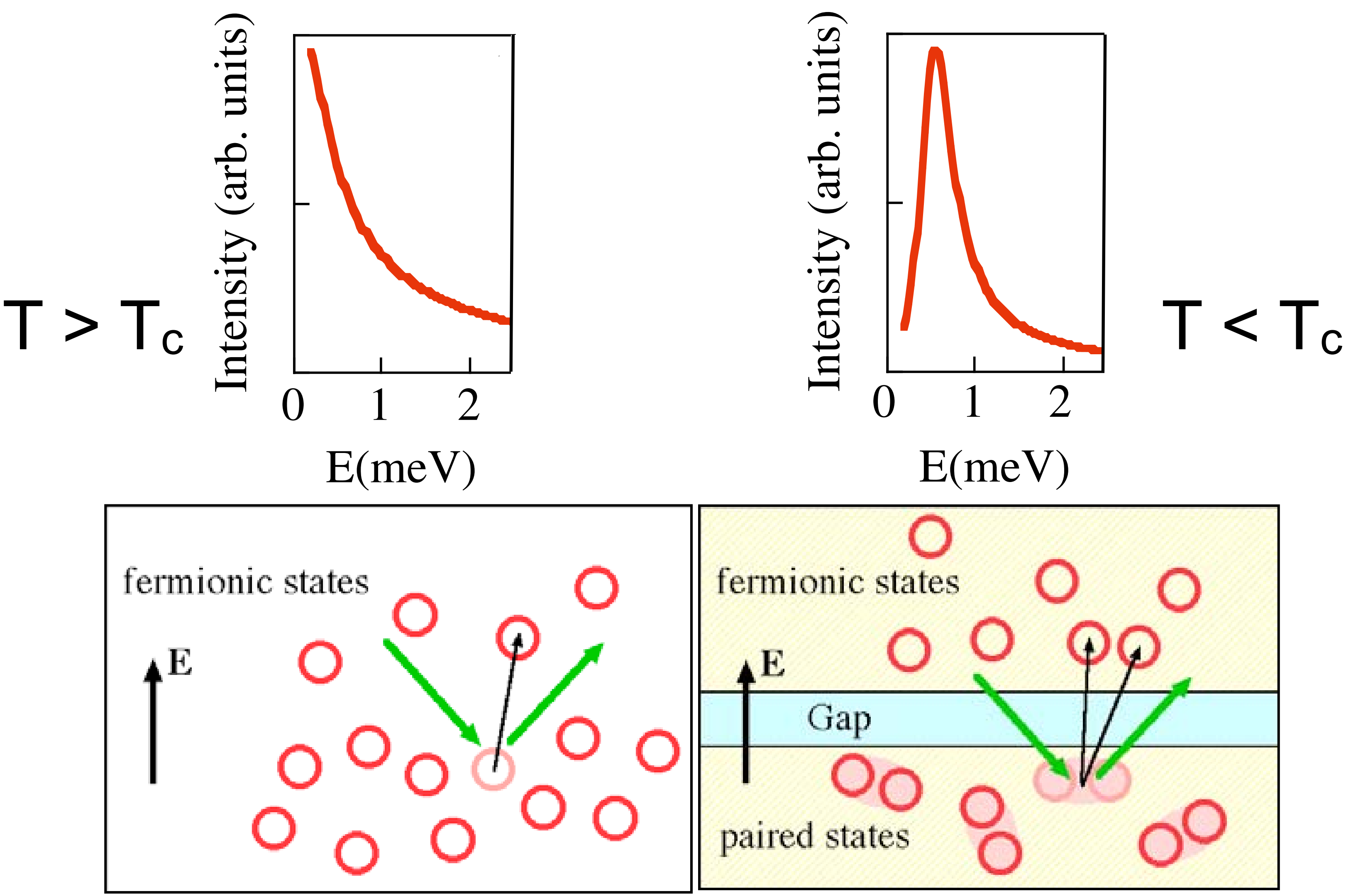
„Resonance“ peak
origin of dispersive mode





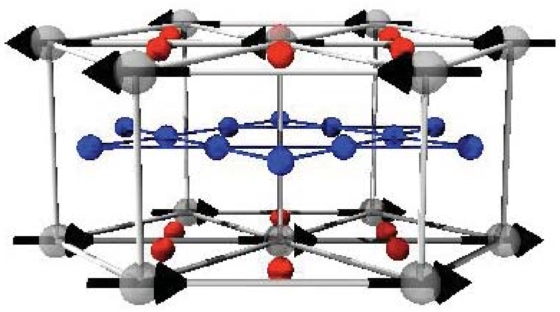
IN12/ILL
k_f = 1.15 Å^{-1}

Magnetic excitations in HF-superconductors

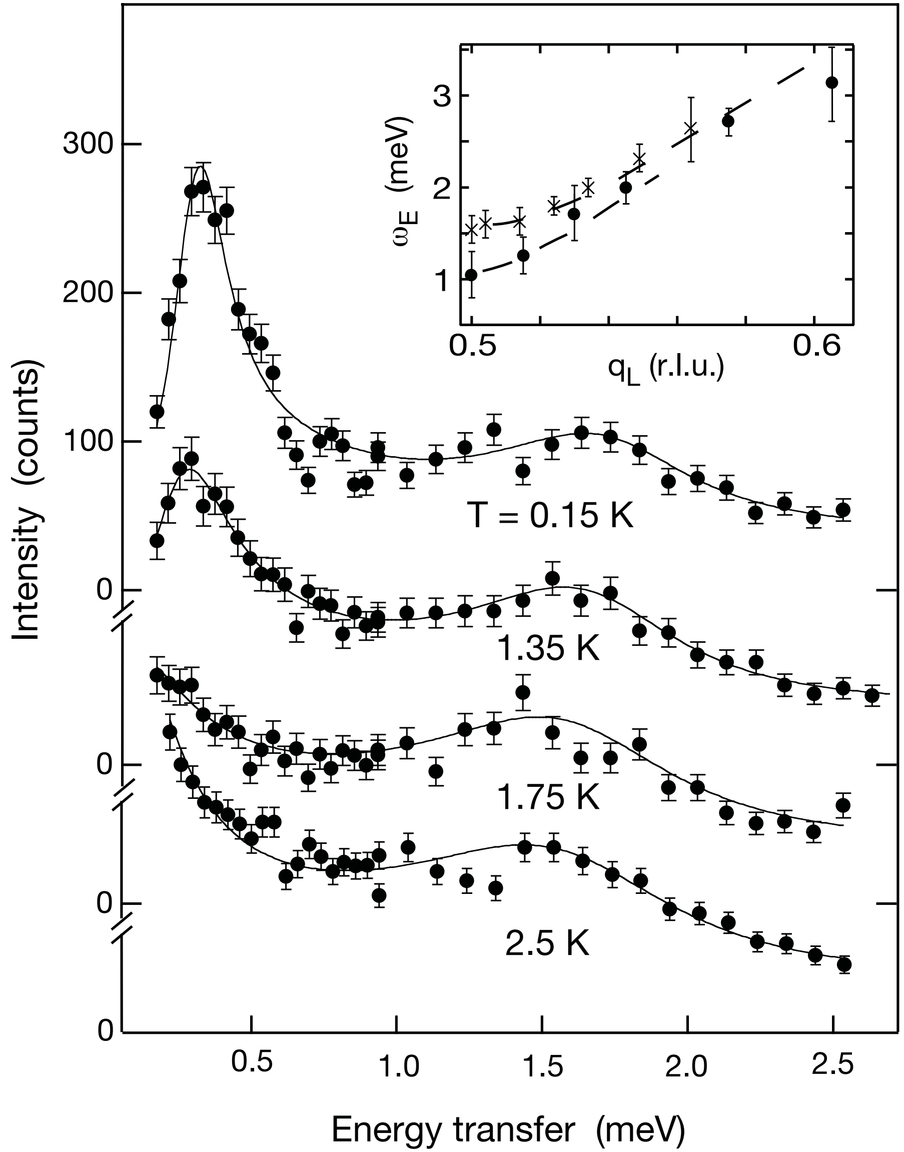


[N. Bernhoeft, '06]

Magnetic response in UPd_2Al_3

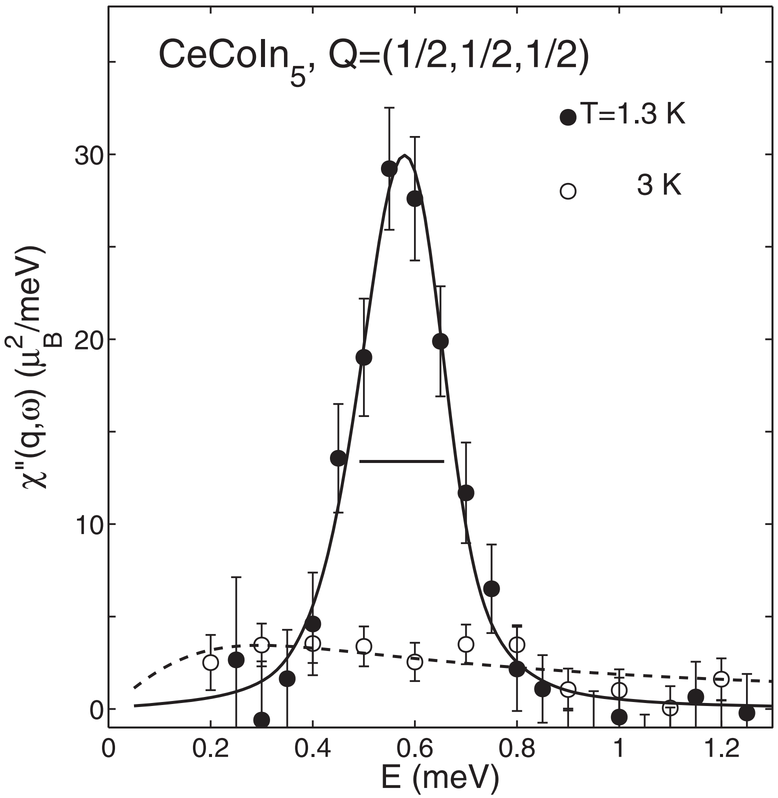


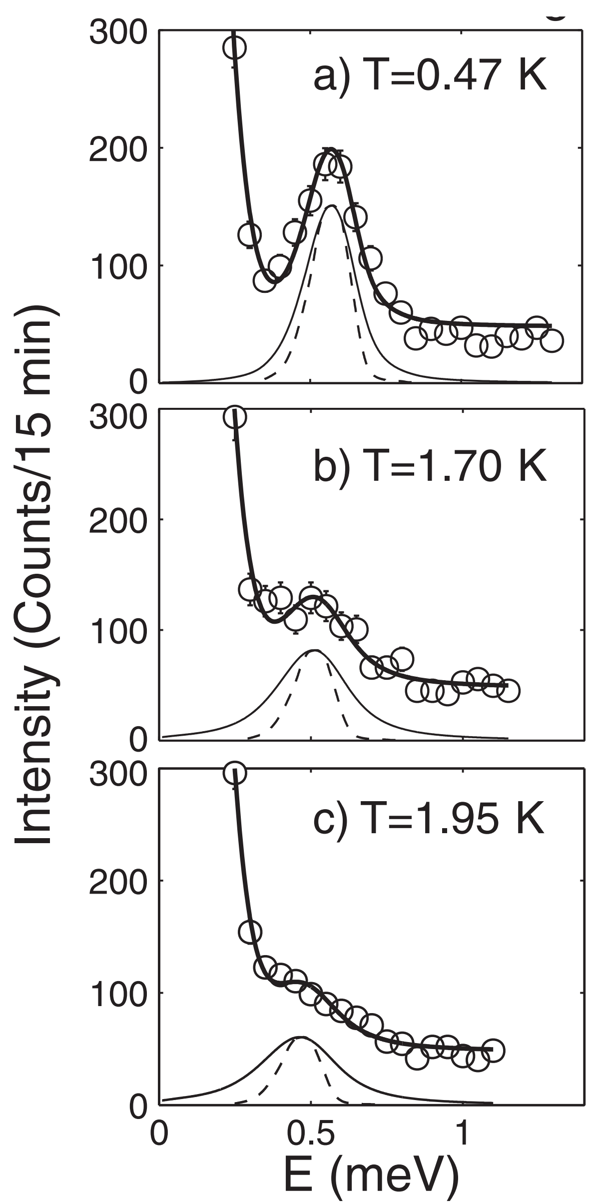
- Coexistence of antiferromagnetism T_N = 14 K, μ = 0.85 μ_B, τ = (0 0 1/2) and superconductivity (T_c = 1.9 K)
- Inelastic neutron scattering: spin wave (E = 1.5 meV) and „resonance“ (E = 0.3 meV) in superconducting state



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

Spin resonance in $CeCoIn_5$

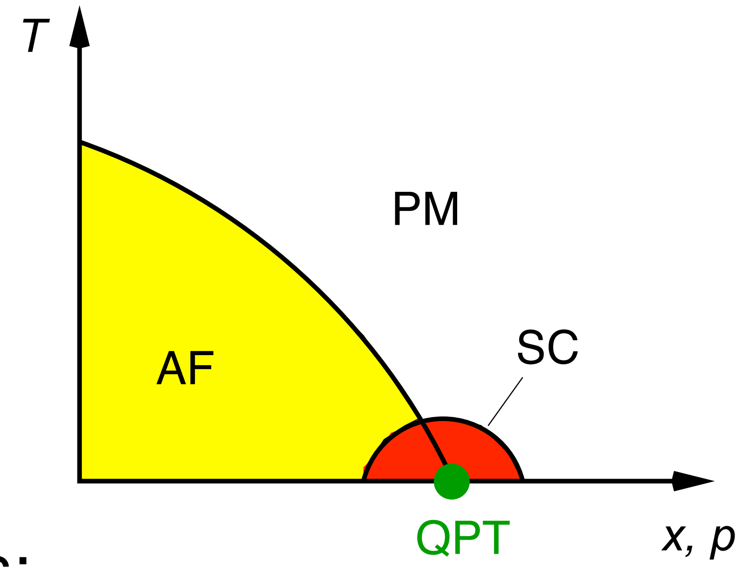




- Superconductivity below T_c = 2.3 K
- Commensurate AF spin fluctuations at Q_{AF} = (1/2 1/2 1/2)
- Spin resonance in superconducting state

[C. Stock, PRL '08]

Conclusions



- Quantum phase transitions

Heavy-fermion superconductors:

- Coexistence of magnetism and superconductivity only for commensurate order (?)
- Spin dynamics strongly affected in superconducting state

Conclusions

$CeCu_2Si_2$:

- Antiferromagnetic order due to Fermi surface nesting
- No coexistence of magnetism and superconductivity
- Observation of spin excitation gap with dispersive mode in superconducting state