Quantum Criticality in the Itinerant Antiferromagnet Cr-V

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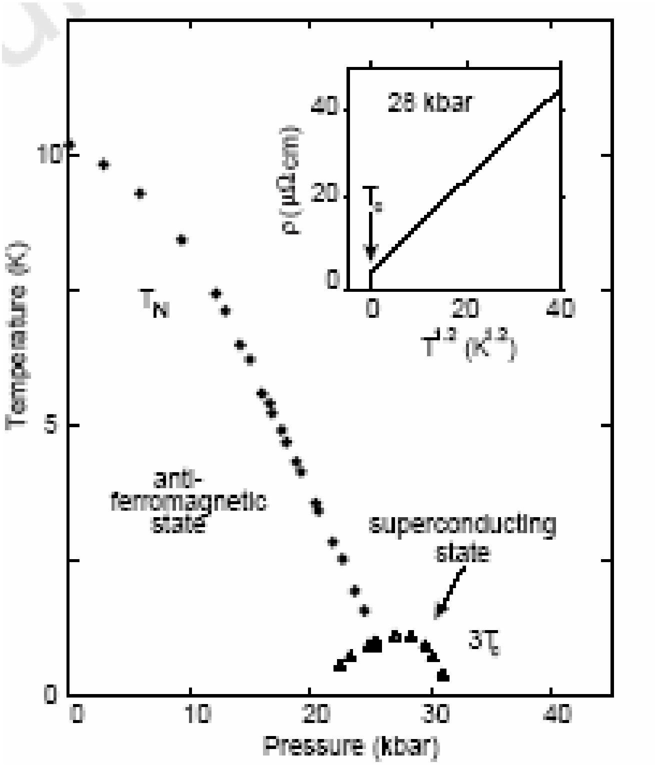
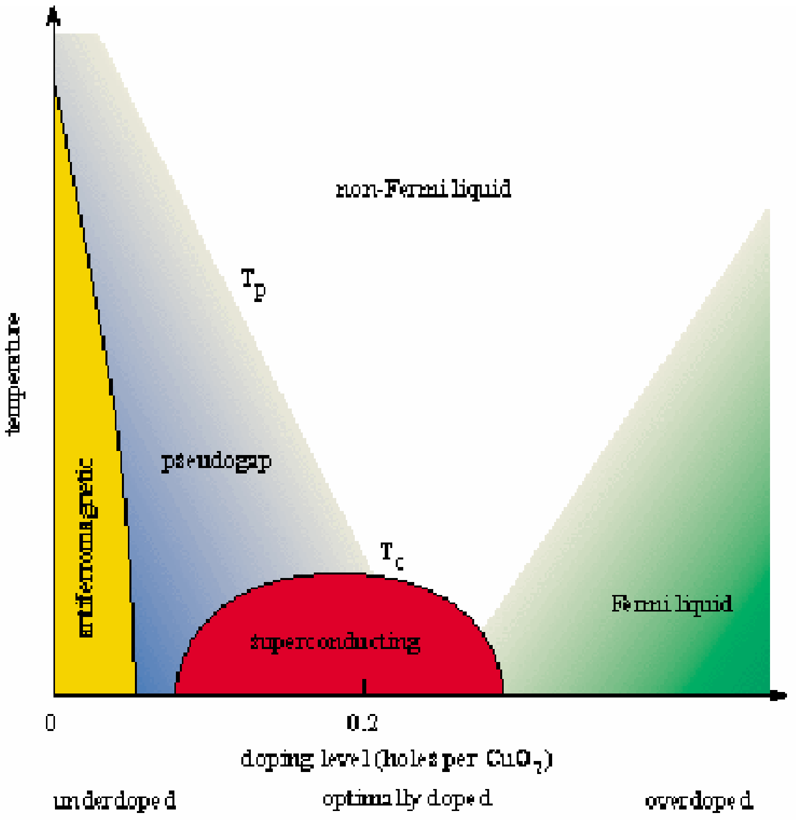
Quantum Critical Points

Heavy Fermion Intermetallics



$CePd_2Si_2$ (Mathur 1998)

Complex Oxides



Need for simpler model systems: itinerant magnets

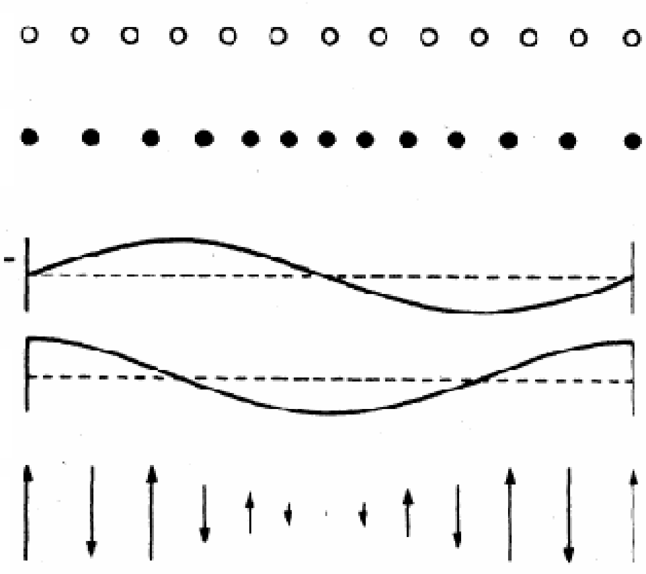
Spin Density Wave in Chromium

$T>T_N$

$T<T_N$

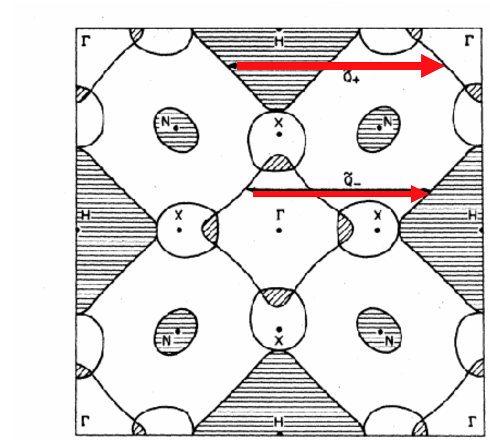
Lattice displacement

Spin Density Wave (SDW)



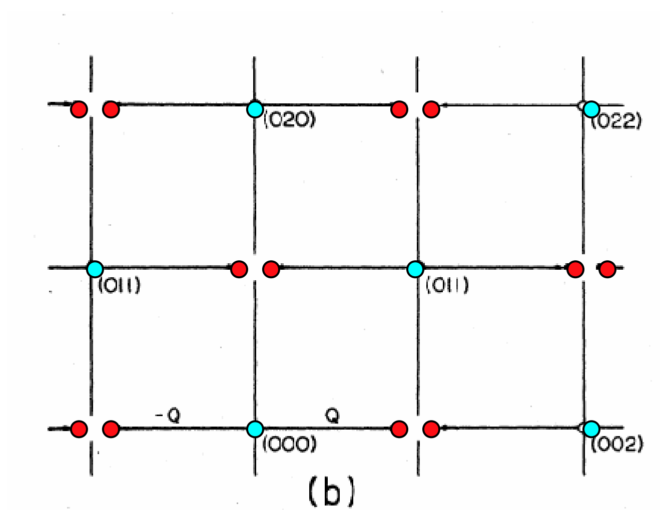
Cr Fermi surface

Laurent 1981



Q_{SDW} = (0,0,1+/-δ) a*
δ=0.0485 (2 K)

T_N=311 K

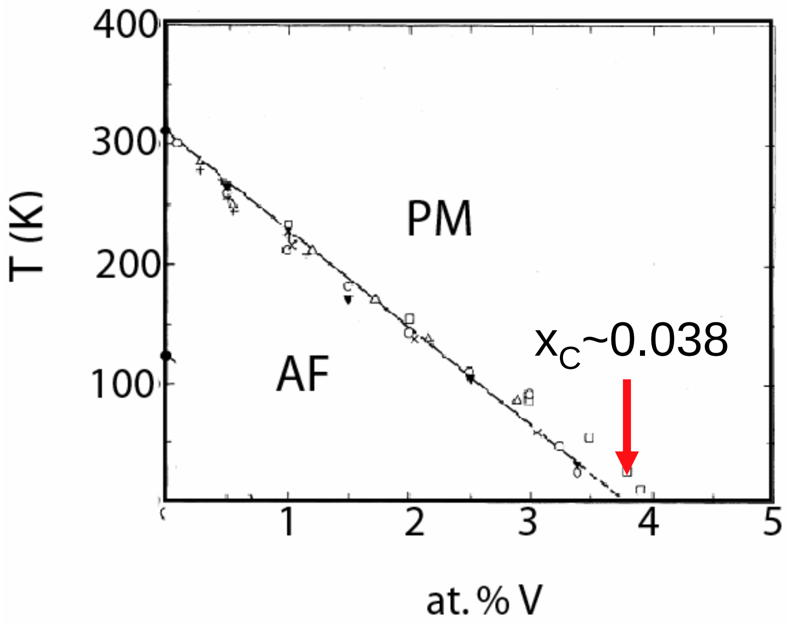


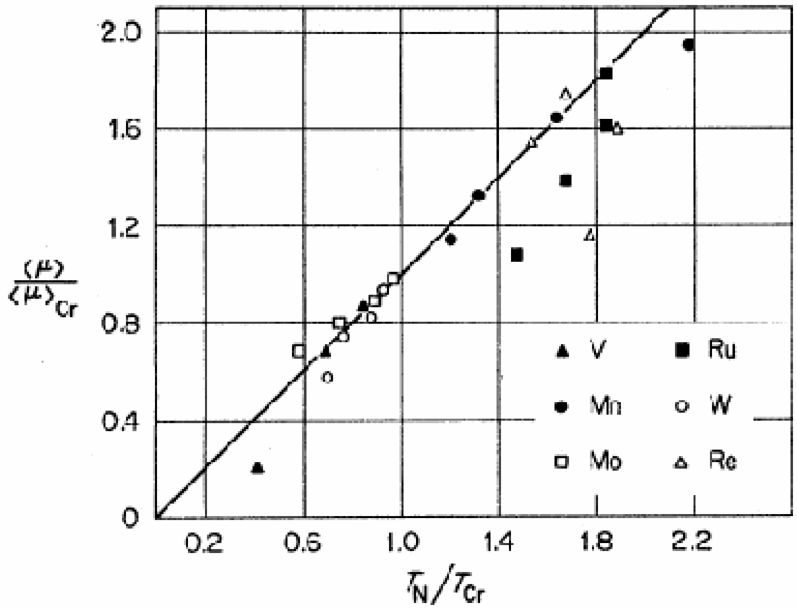
Quantum critical point in $Cr_{1-x}V_x$ ($x=x_C=0.035$)

- $x \rightarrow x_C$: simultaneous suppression of T_N and staggered moment μ

Koehler 1966

Fawcett 1994

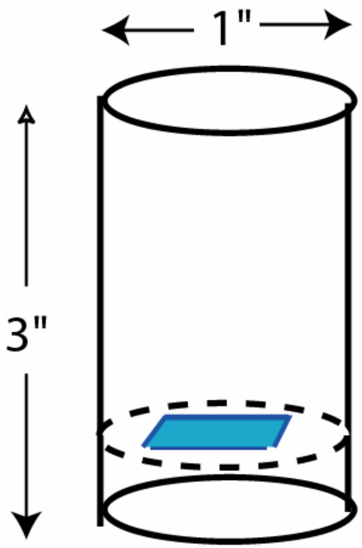


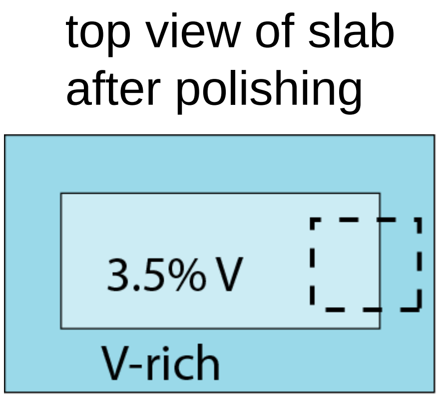


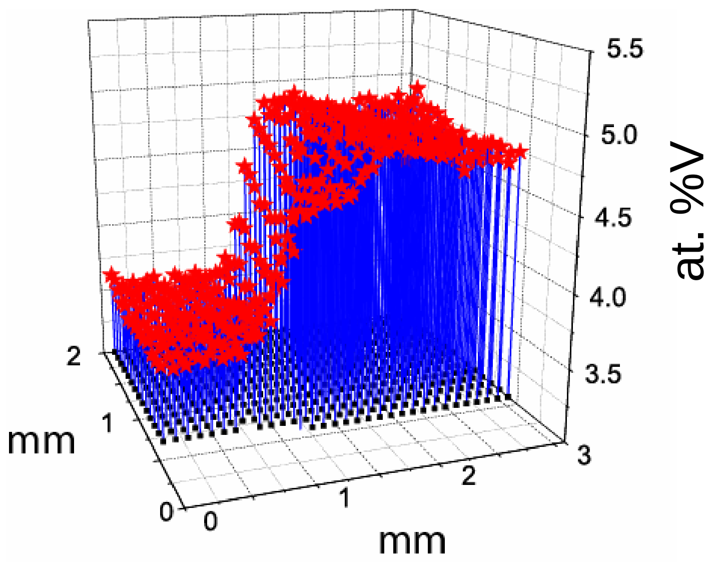
Cr: [Ar]$3d^5 4s^1$
V: [Ar]$3d^3 4s^2$

Electron Microprobe

- 45 g single crystal grown by arc-zone melting (Ames Laboratory)







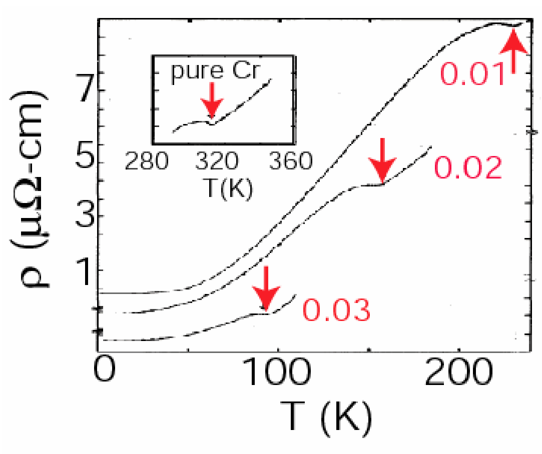
1. rectangular slab spark-cut from interior of crystal

2. Surface damaged by spark cutting, removed by polishing.

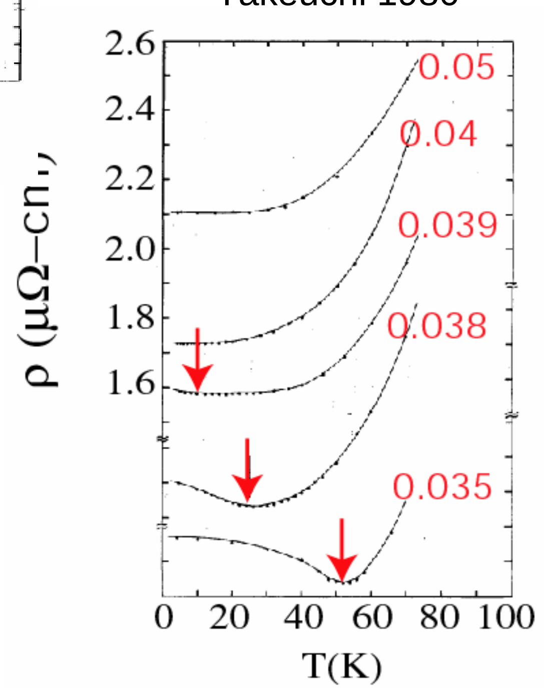
3. Microprobe performed on indicated area.

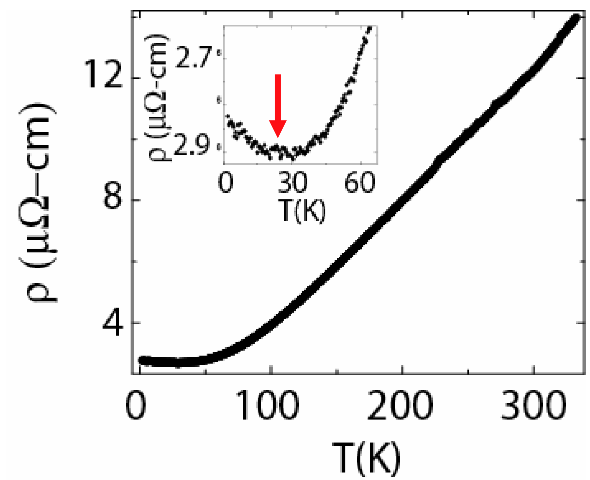
- Composition of crystal interior is nominal 3.5 +/- 0.2 at. % V.

Electrical Resistivity of $Cr_{0.965}V_{0.035}$



Takeuchi 1980



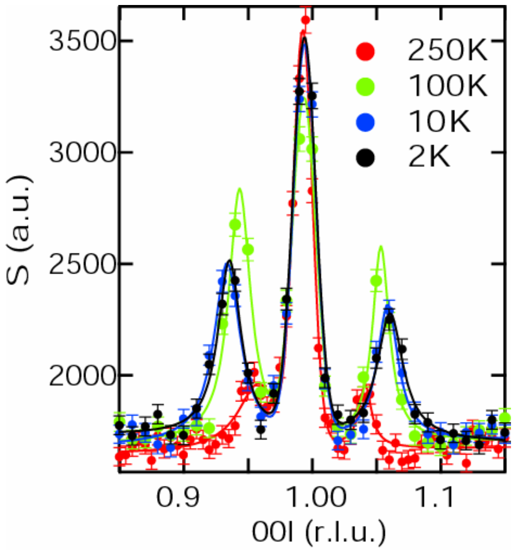


V concentration 3.5%<x<3.8%

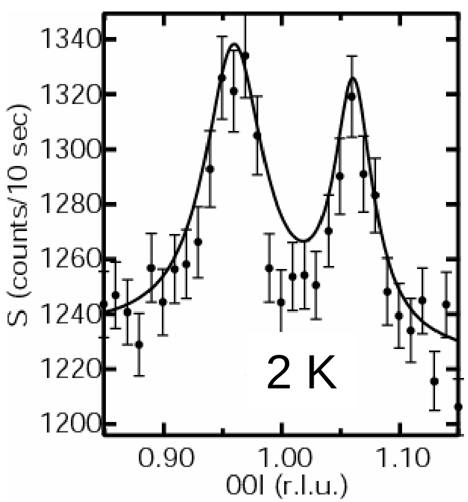
Elastic Scattering: Magnetic Modulation

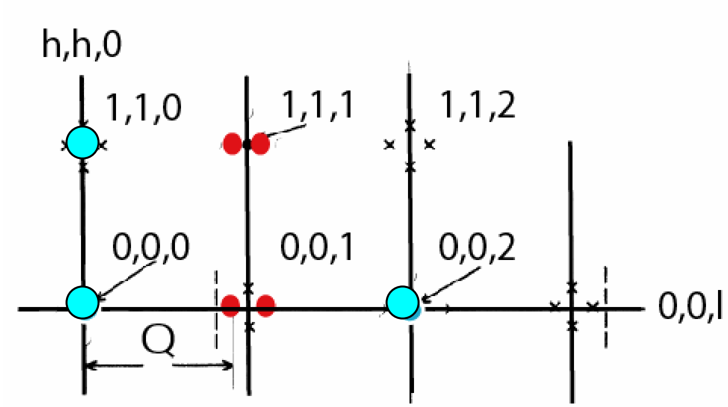
- Triple axis spectroscopy: HB-3 at High Flux Isotope Reactor
  Collimation: 48’-40’-80’-120’

no filter



with λ/2 filter



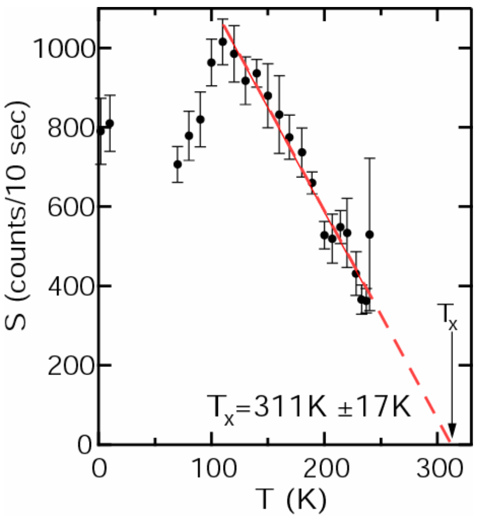


- Elastic scattering:

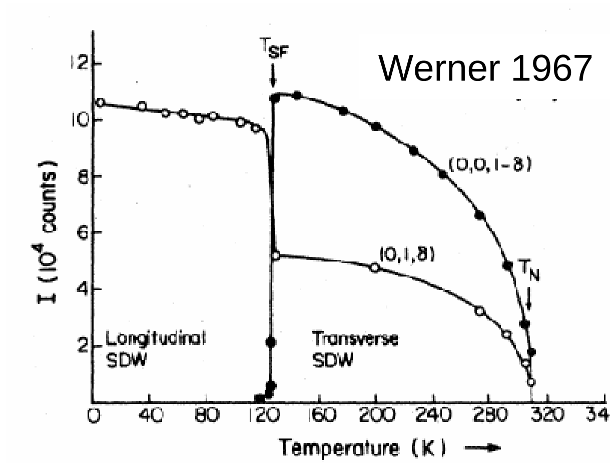
h+k+l =2n+1	magnetic satellites	red dot	SDW
h+k+l =2n	bcc structure factor	cyan dot	

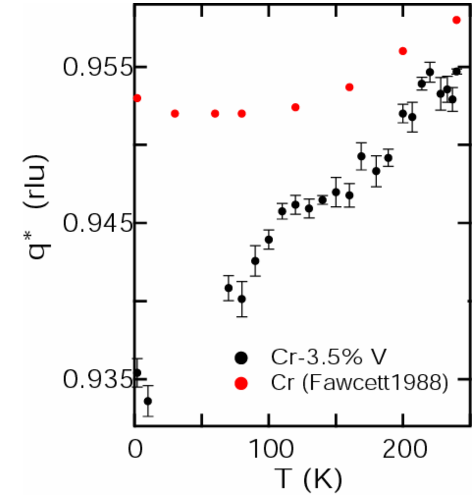
Incommensurate Elastic Scattering

Cr – 3.5%V

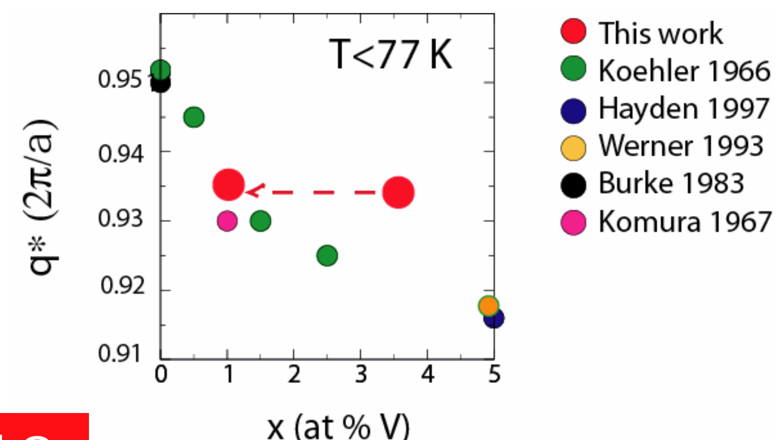


Pure Cr: T_N=311 K





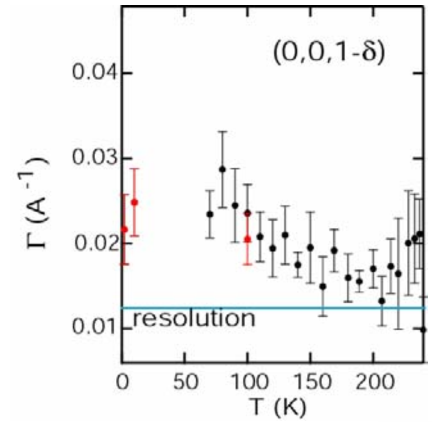
- Elastic scattering: critical SDW fluctuations, T_N~311 K
- Commensurability δ: x~1 %

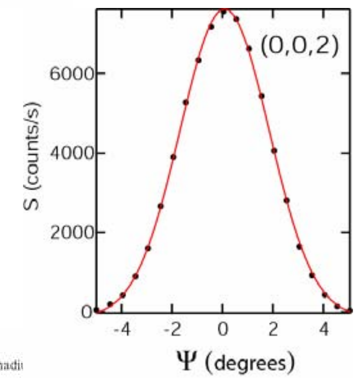


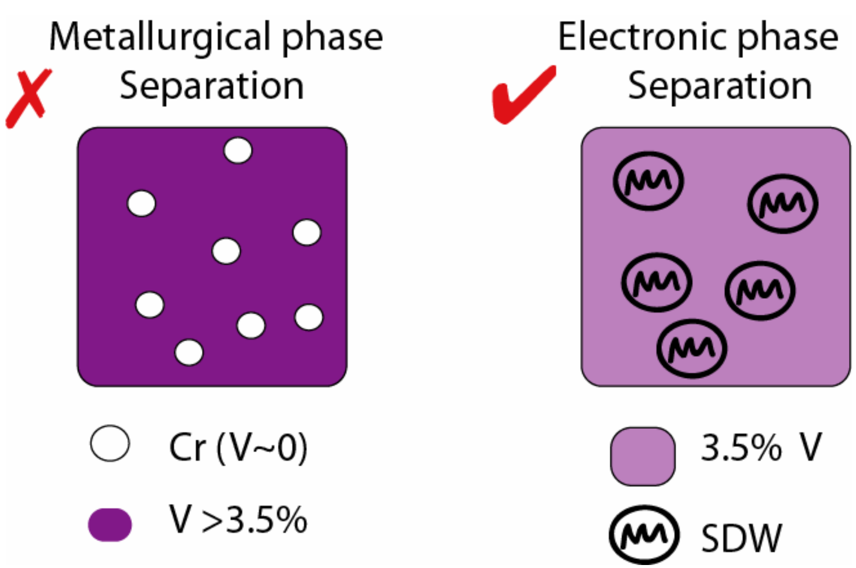
Part of crystal is electronically like lightly doped Cr

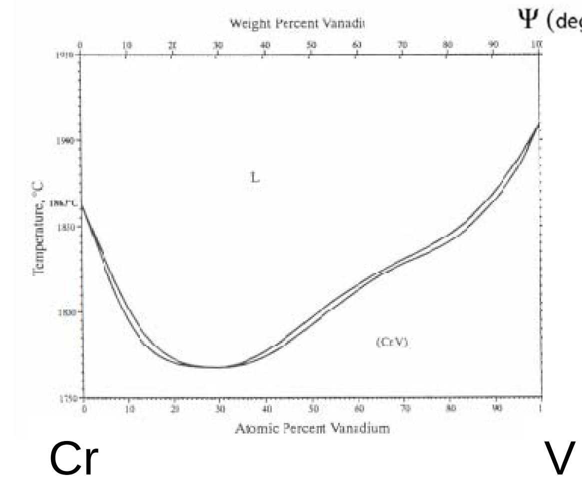
Evidence for Phase Separation

- Elastic scattering from regions which are at least 500 A in size
- Sample is large single crystal, no appreciable twinning (Laue, rocking curve)
- Averaging over length scales larger than ~1 μm, our crystal: 3.5 at. % V (microprobe, resistivity)
- Phase diagram: continuous V solubility in Cr

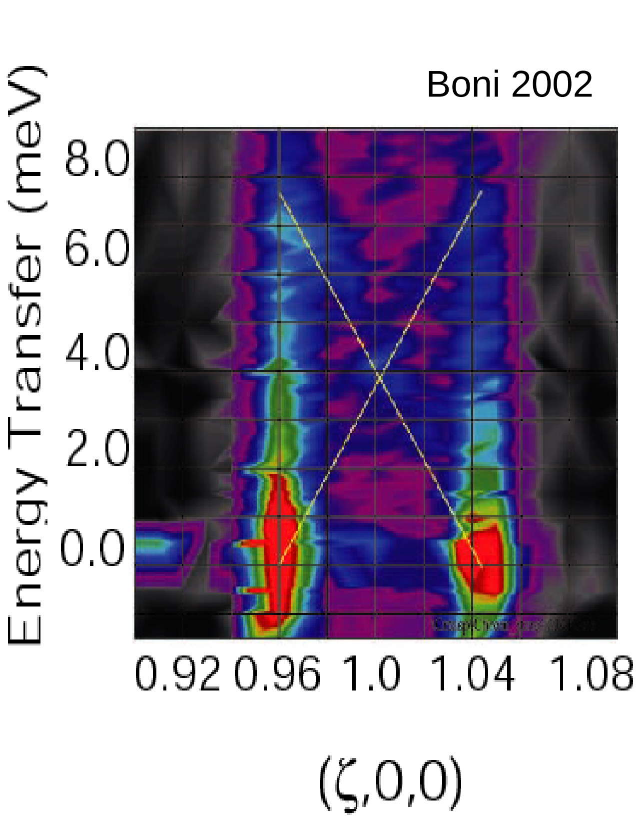


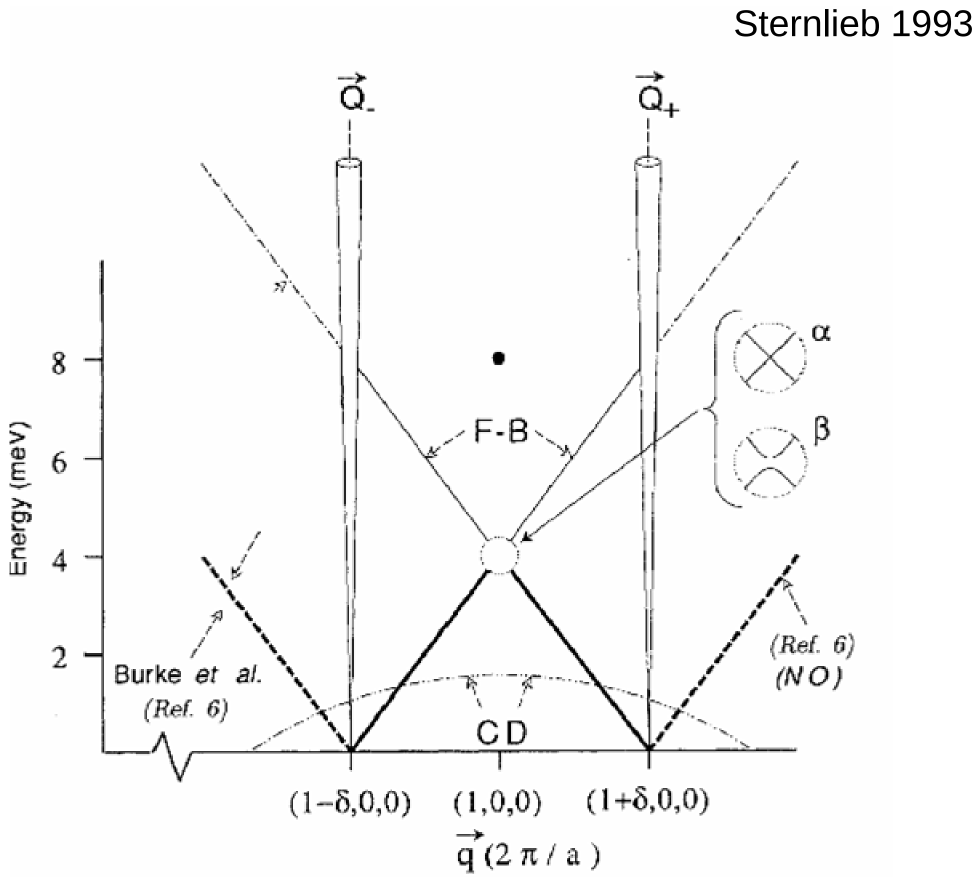






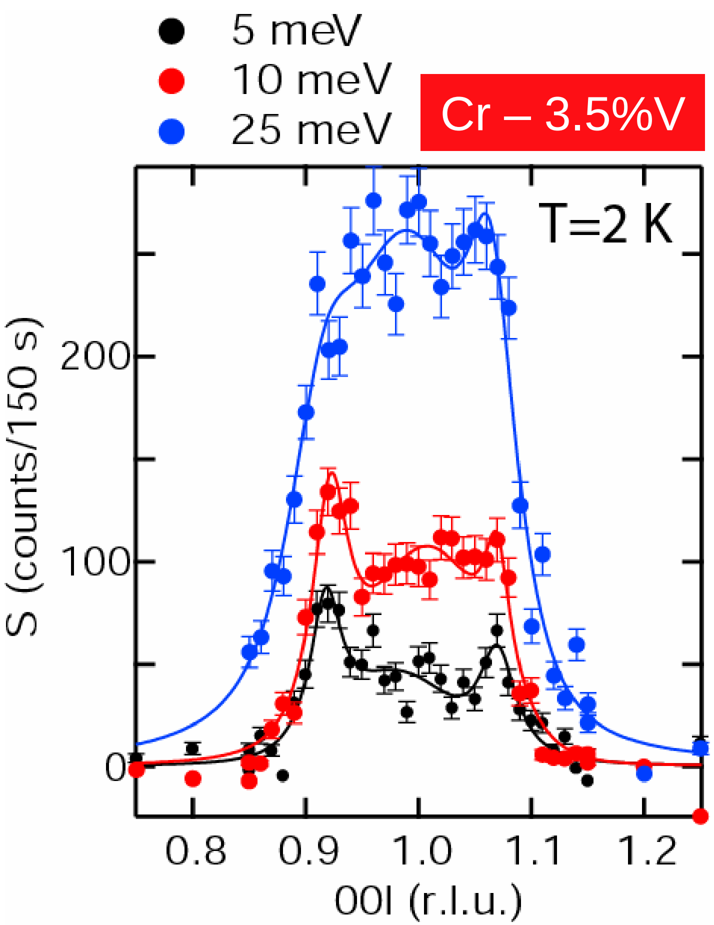
Inelastic Scattering in Chromium

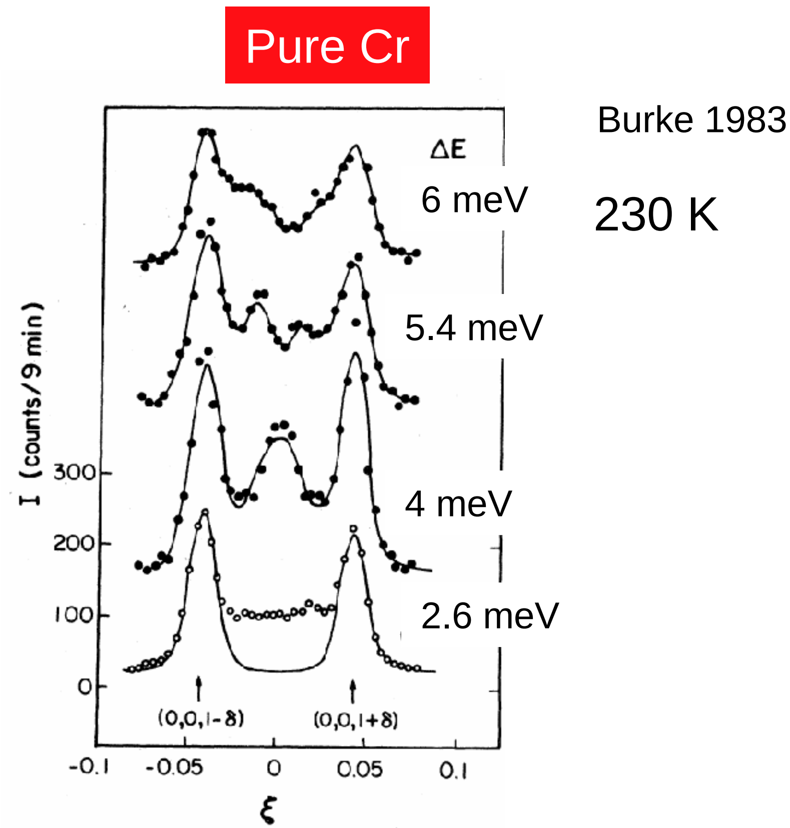




- Nearly dispersionless spin waves emanating from SDW satellites at (1+/-δ,0,0).
- Fincher-Burke excitations near (1,0,0).

Inelastic Scattering in $Cr_{0.965}V_{0.035}$

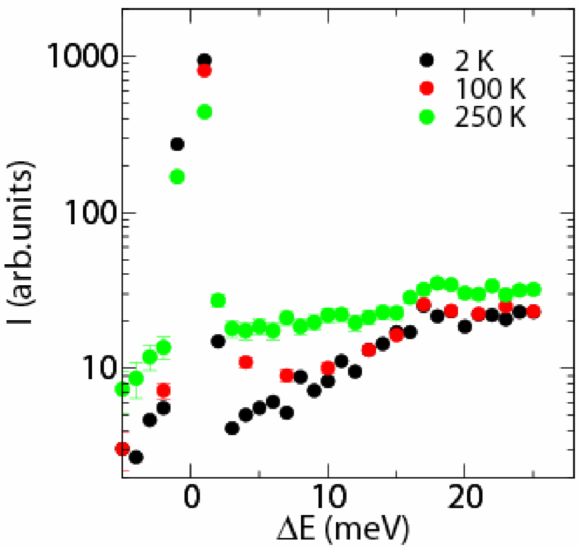




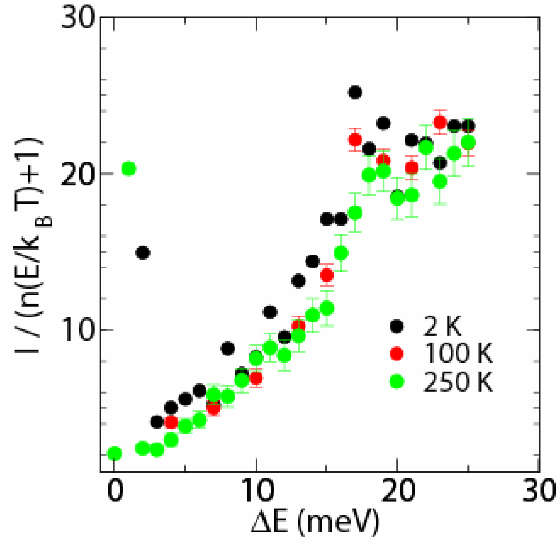
- $q^*=(0,0,1\pm\delta)$ $S(q)=S_o/(1+4((q\pm q^*/\Gamma)^2) + S_g\exp(-0.5q^2/\Gamma^2)$
- Resolution corrections with RESLIB

Commensurate Scattering in $Cr_{0.965}V_{0.035}$

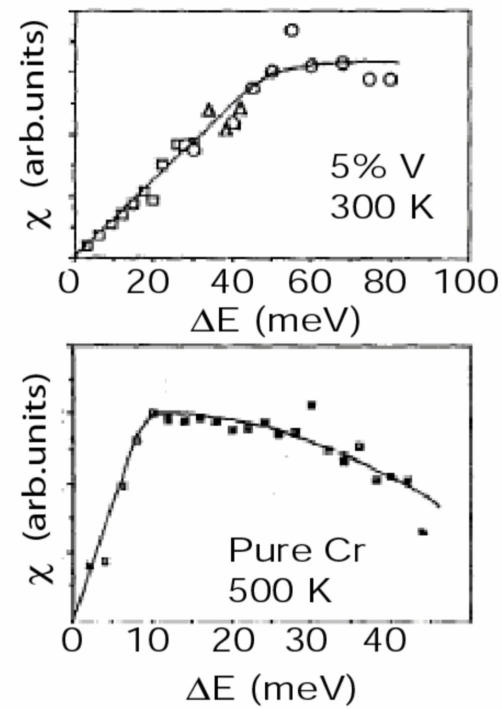
q=(0,0,1) 2π/a



q=(0,0,1) 2π/a



Werner 1993

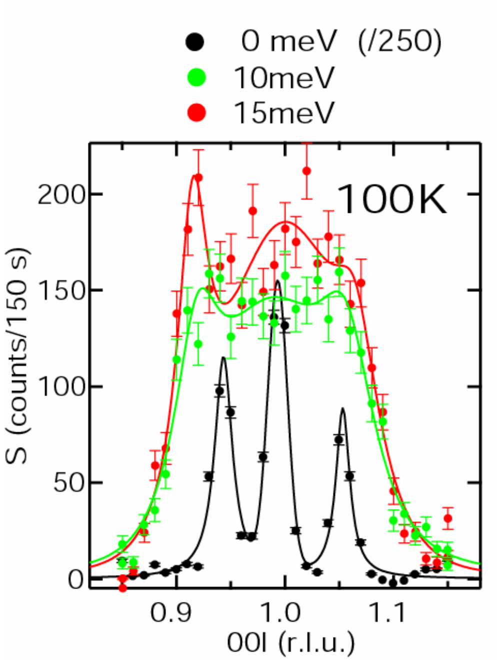


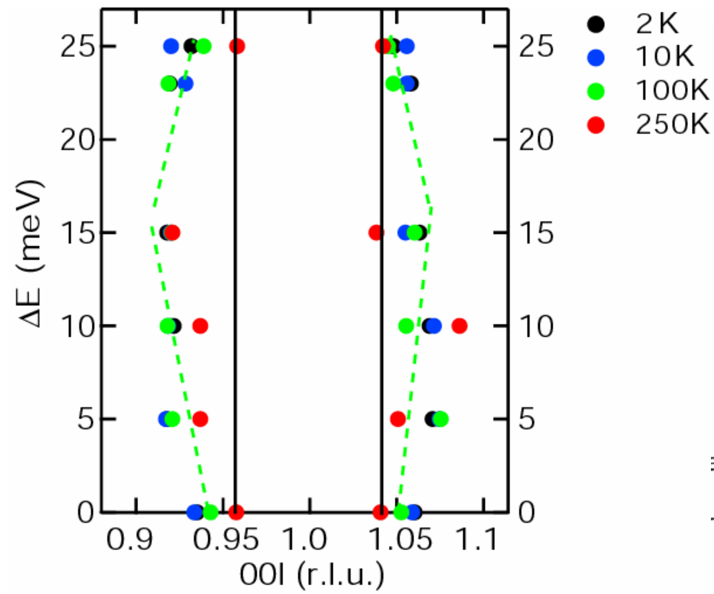
- Detailed balance corrected intensity: constant energy scale for T<100 K, q=0,0,1 (2π/a).

- Characteristic energy scales:

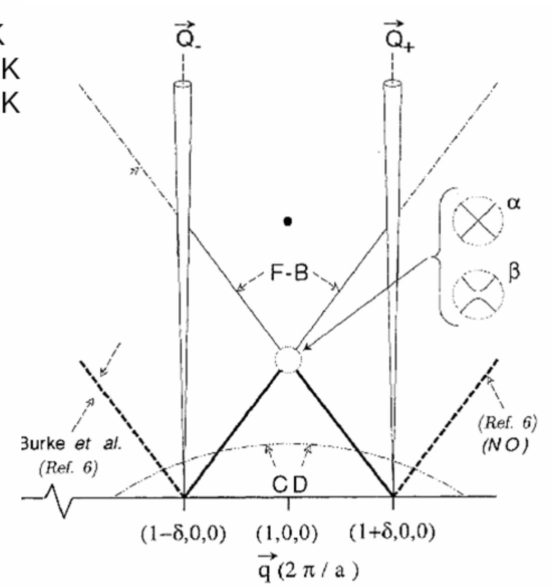
pure Cr: 10 meV $Cr_{0.0965}V_{0.035}$: 18 meV $Cr_{0.095}V_{0.05}$: 50 meV

Dispersion of the Incommensurate Excitations



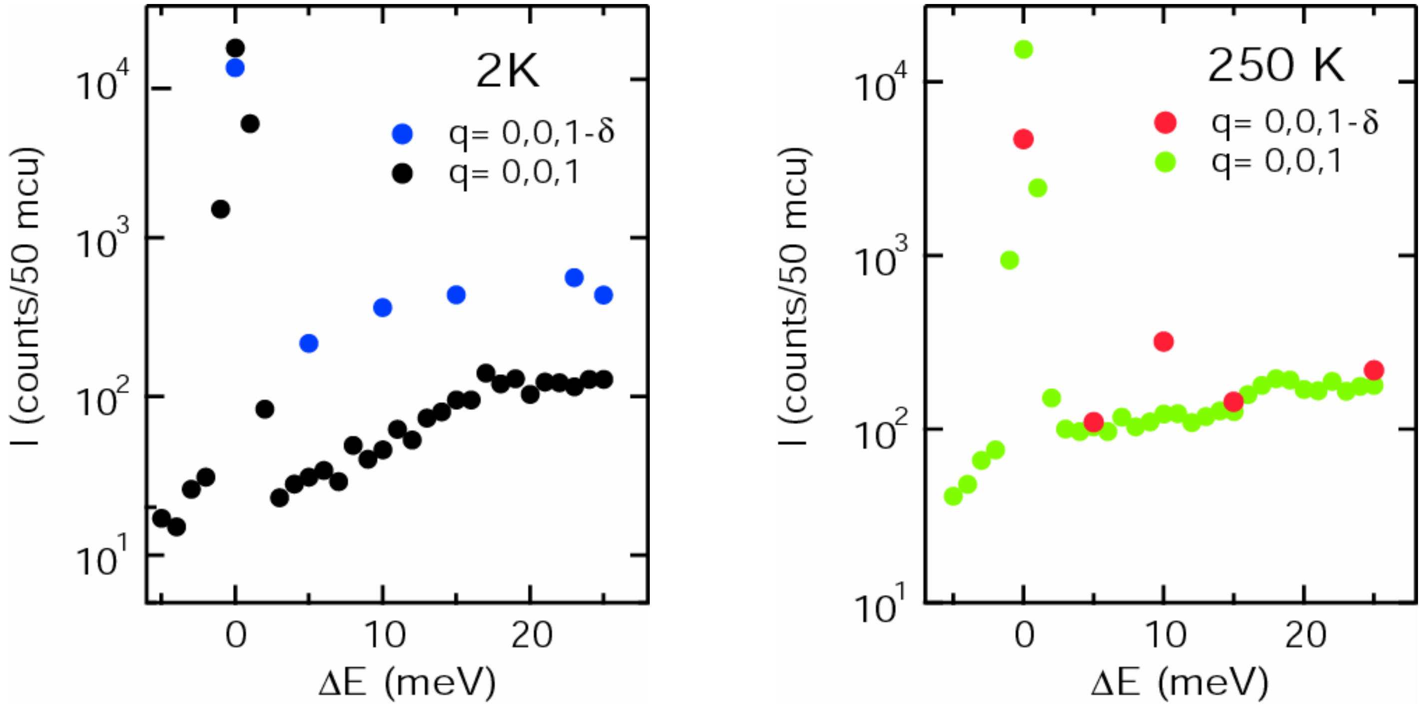


Sternlieb 1993



- Cr-3.5%V: Spin wave velocity greatly reduced relative to pure Cr
- New branch of excitations , perhaps observed by Burke (1983)

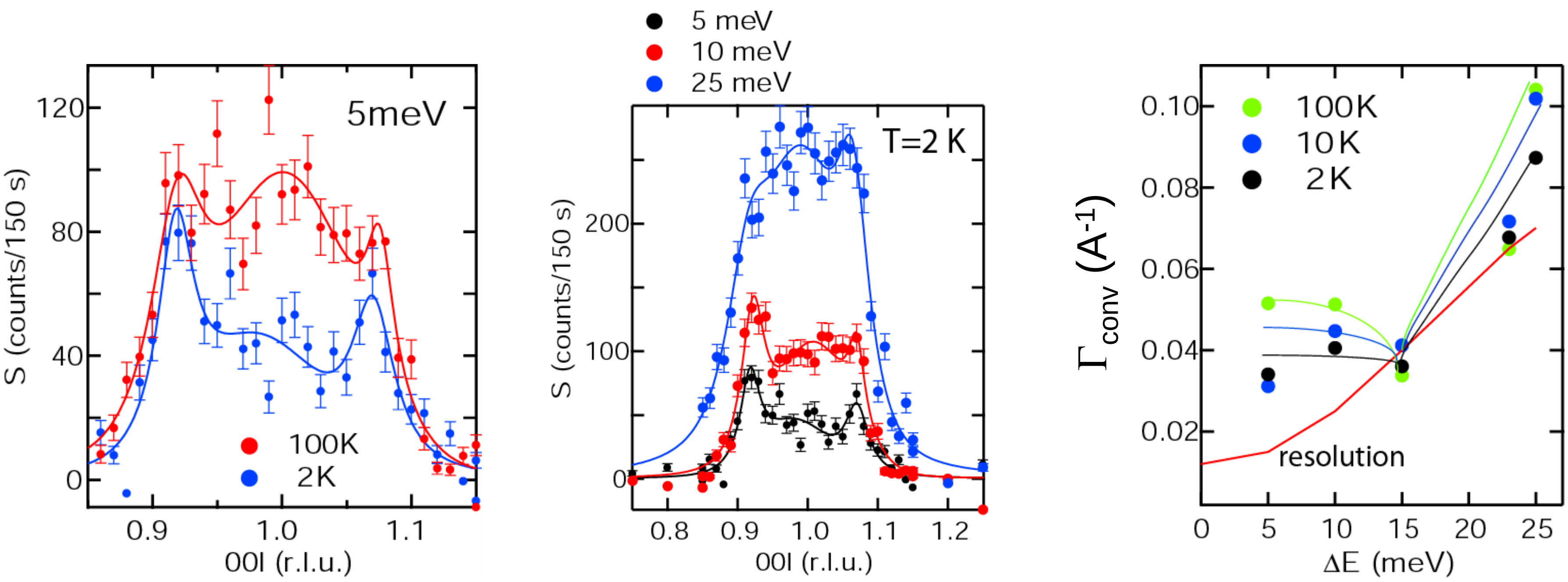
Incommensurate vs Commensurate Scattering



- Response most enhanced at $q^*=(0,0,1-\delta)2\pi/a$ and as $T \rightarrow 0$.
- Consistent with $\chi^{-1} \sim [\, a(T-T_N)^{\gamma} + \theta(q-q^*) + f(E)\,]$ where $\theta \rightarrow 0$ when $q \rightarrow q^*$

Critical scattering ($T>T_N$) for $q=q^*=(0,0,1+/-\delta)2\pi/a$

Critical Incommensurate Correlations

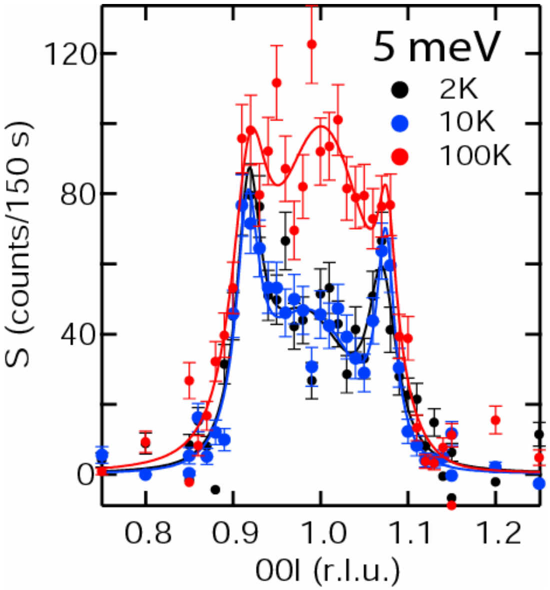


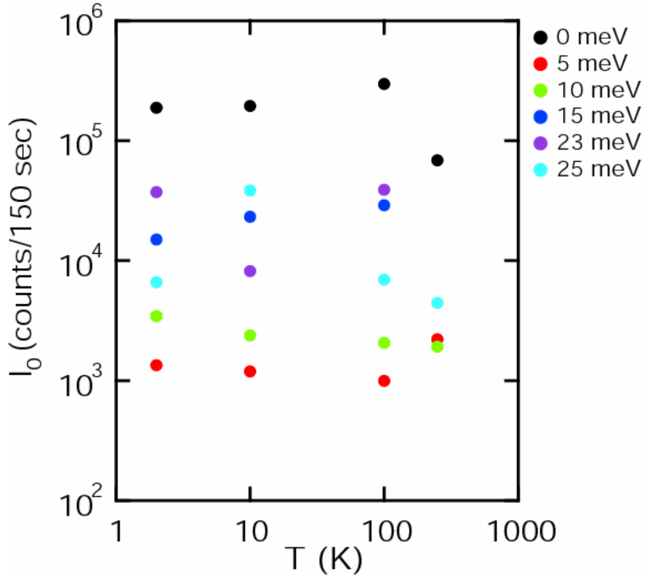
- Spatial correlations for q=(0,0,1+/-δ)2π/a diminished by

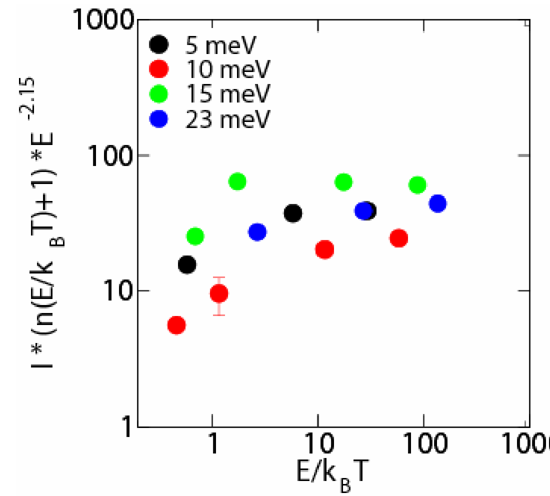
  increased temperature T>T_N and increased energy transfer E

- Critical susceptibility $\chi_q^{-1} \sim [\ \Gamma(E,T) + \theta(q\text{-}q^*)\ ]$ $\Gamma \sim a(T-T_N)^{\gamma} + f(E)$

Incommensurate Scattering







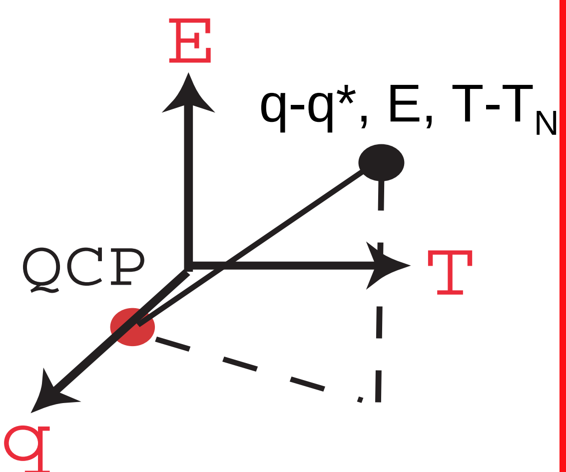
- q*=(0,0,1+/-δ)2π/a: temperature independent scattering T<100 K, all ΔE>0.
- $S(q,E,T) = [n(E/k_BT)+1]\ \chi''(q,E,T)$

$E/ k_BT \ll 1$	$n(E/k_BT)+1 \sim k_BT/E$	$\chi'' \sim E/k_BT\ \ G(E)$
$E/ k_BT \gg 1$	$n(E/k_BT)+1 \sim 1$	$\chi'' \sim G(E)$

Quantum Criticality: Scale Invariant Excitations

Neutron Scattering Study of $Cr_{0.0965}V_{0.035}$

- Elastic scattering: similar to pure Cr. Electronic phase separation?
- Commensurate scattering: Fermi – liquid like, E_F ~ 18 meV
- Incommensurate scattering: critical, divergence in the susceptibility controlled by distance from (quantum) critical point



$T \rightarrow T_N$ (=30 K?) $E \rightarrow 0$ $q \rightarrow q^*=2\pi/a(0,0,1+/-\delta)$

Generalized Critical Susceptibility:

$\chi^{-1} \sim [\,(T-T_N)^{\gamma} + iE + \theta(q-q^*)]$

$\chi^{-1} \sim [(aT-iE)^{\alpha} + \theta(q-q^*)^{\alpha}]$ $CeCu_{6-xc}Au_{xc}$ (Schroder2001)

$\chi^{-1} \sim [aT-iE + \theta(q-q^*)]^{\alpha}$ $Ce(Ru_{1-xc}Fe_{xc}]_2Ge_2$ (Montfrooij2003)