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Incommensurate Correlations & Mesoscopic Spin Resonance in YbRh2Si2

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INSTITUTE FOR QUANTUM MATTER

A collaboration between
JOHNS HOPKINS UNIVERSITY
and PRINCETON UNIVERSITY

Incommensurate correlations & mesoscopic spin resonance in $YbRh_2Si_2$*

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Overview

❖Introduction

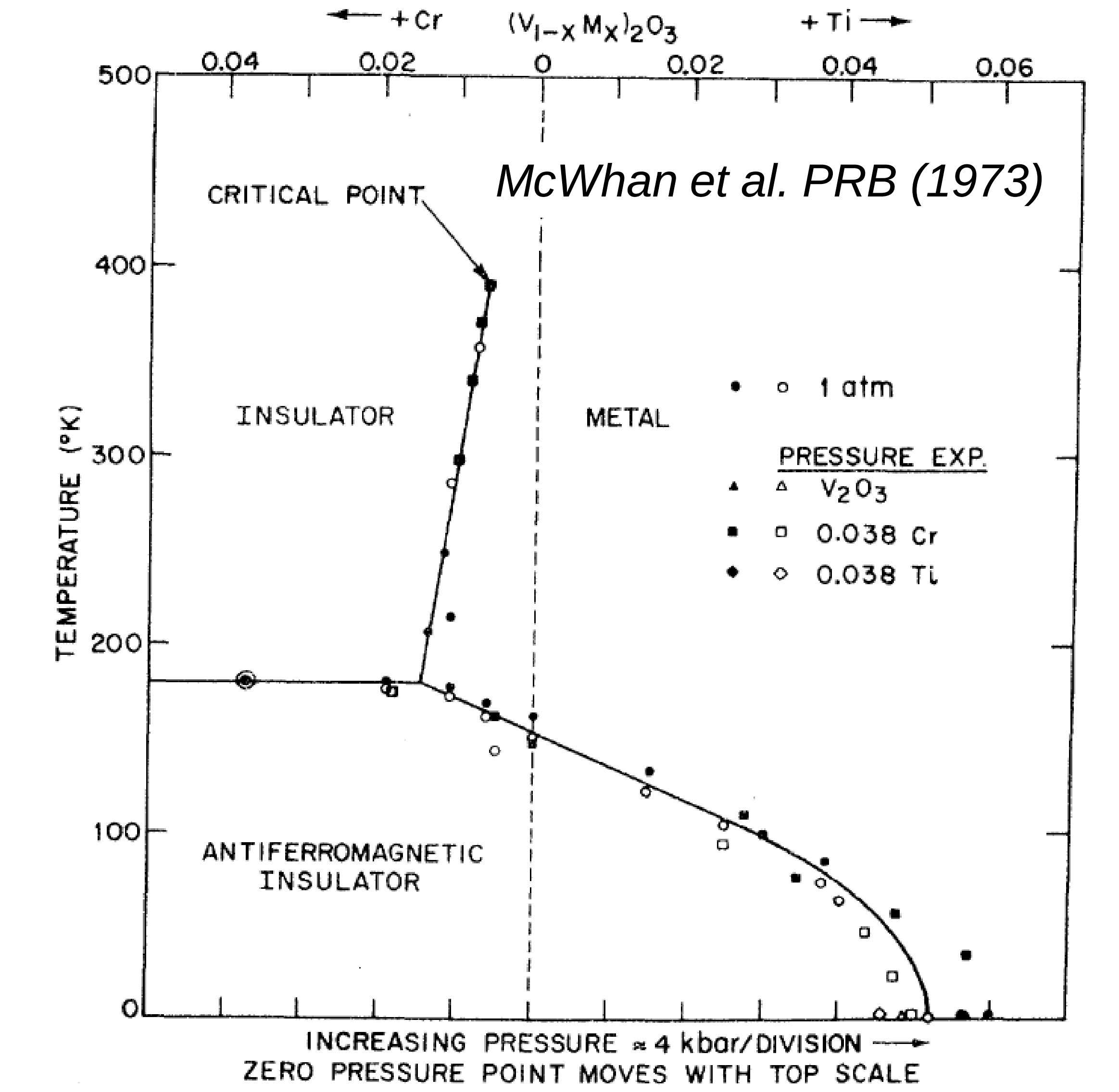
- SDW Quantum Criticality in metals
- The case of $YbRh_2Si_2$

❖Results & Discussion

- Incommensurate spin correlations
- Quasi-FM Quantum Critical Scaling
- Unconventional spin resonance

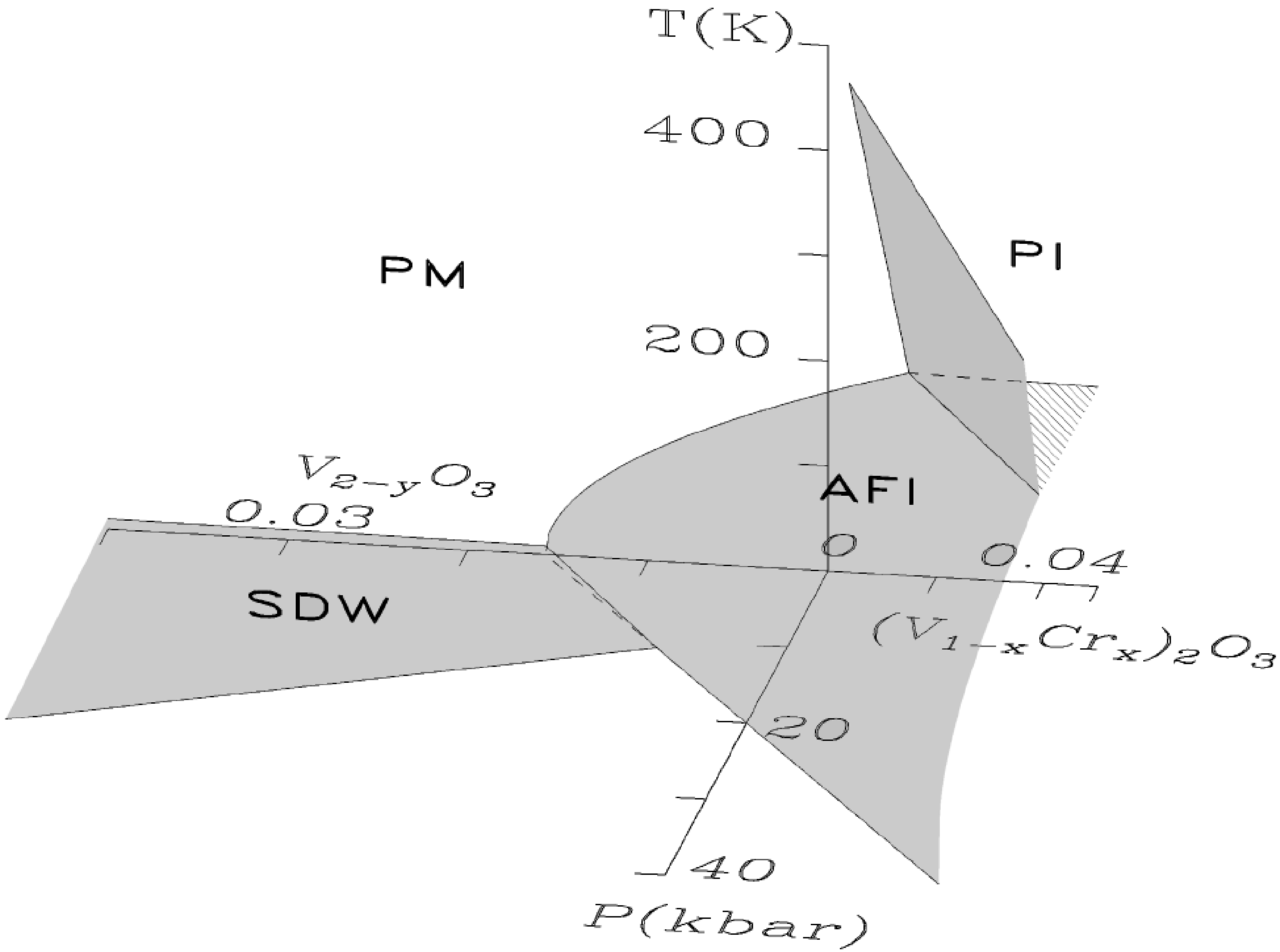
❖Conclusions

Phases of a correlated metal



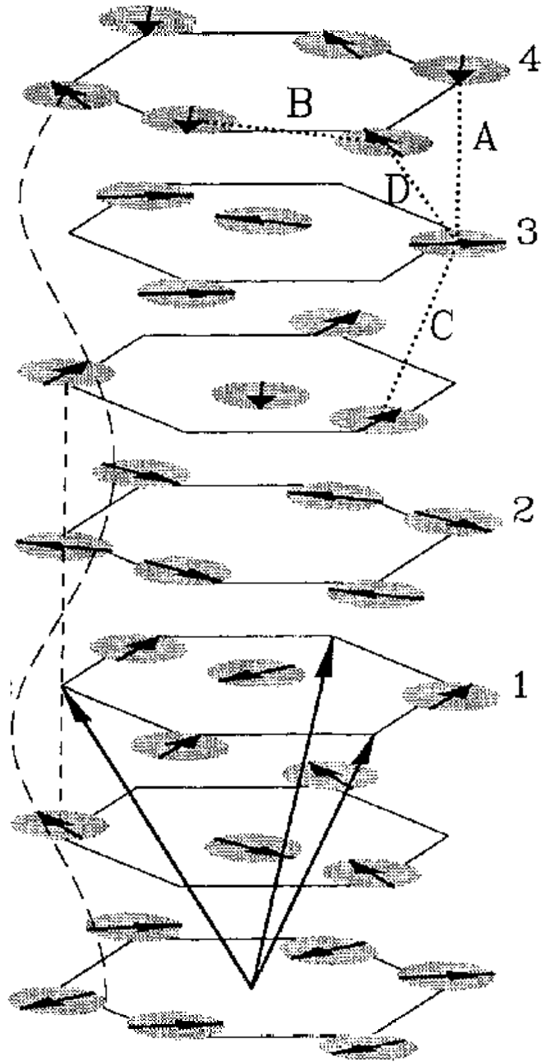
Phases of a correlated metal

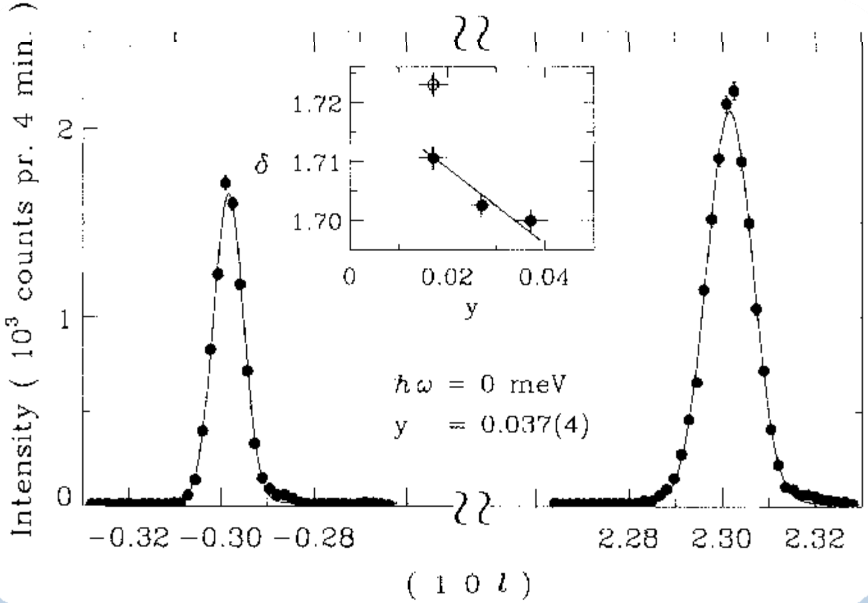
McWhan et al. PRB (1973)

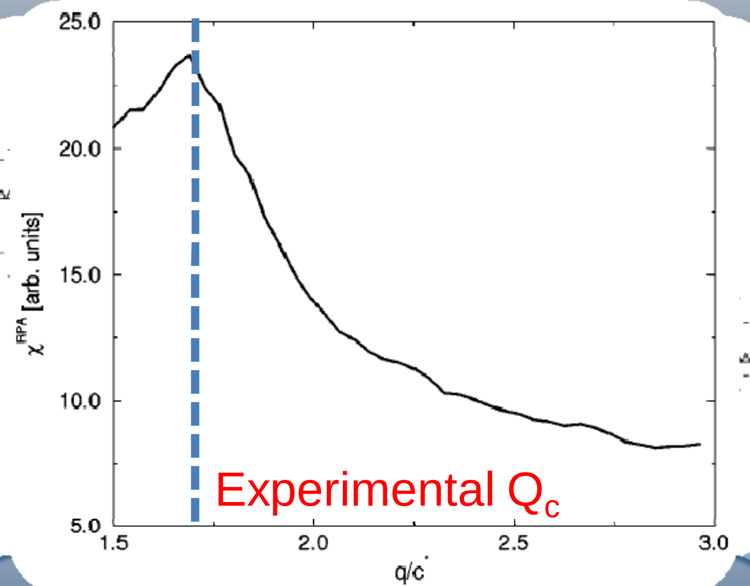


Spin Density Wave Order

Bao et al. PRL (1993)



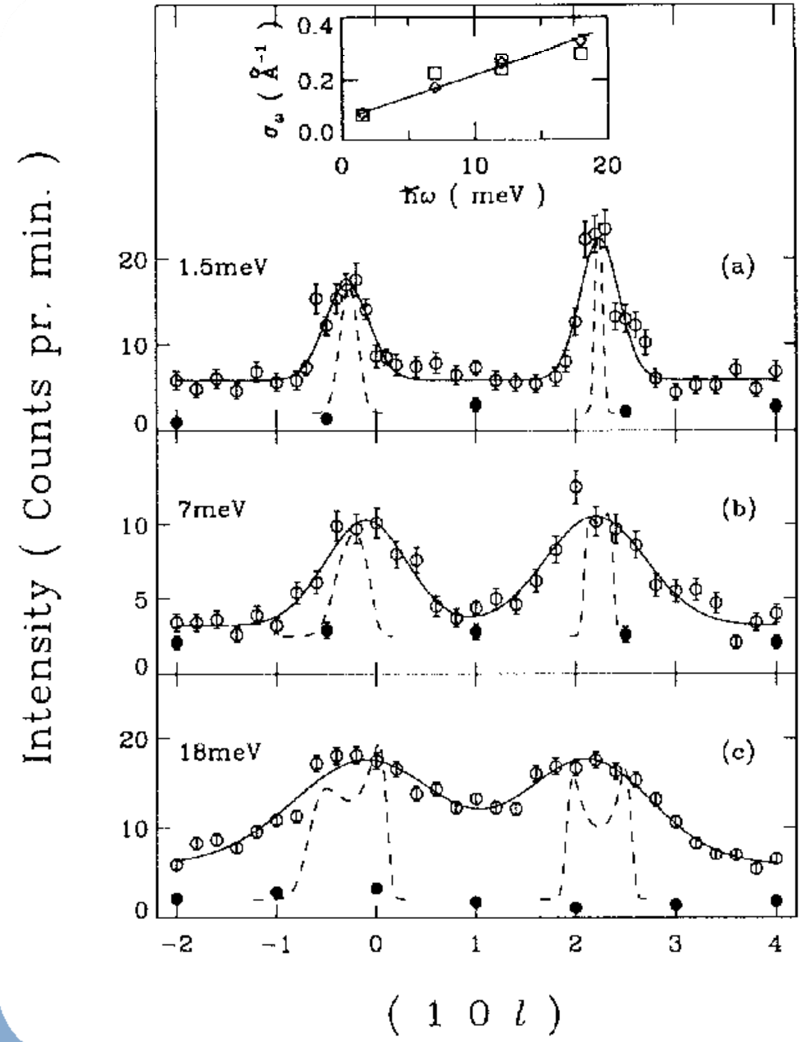




Wolenski et al., PRB (1998)

Spin Fluctuations & Neutrons Scattering

Bao et al. PRL (1993)



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{k'}{k}(\gamma r_0)^2 \left|\frac{g}{2}F(\mathbf{q})\right|^2 e^{-2W(\vec{\kappa})}$$

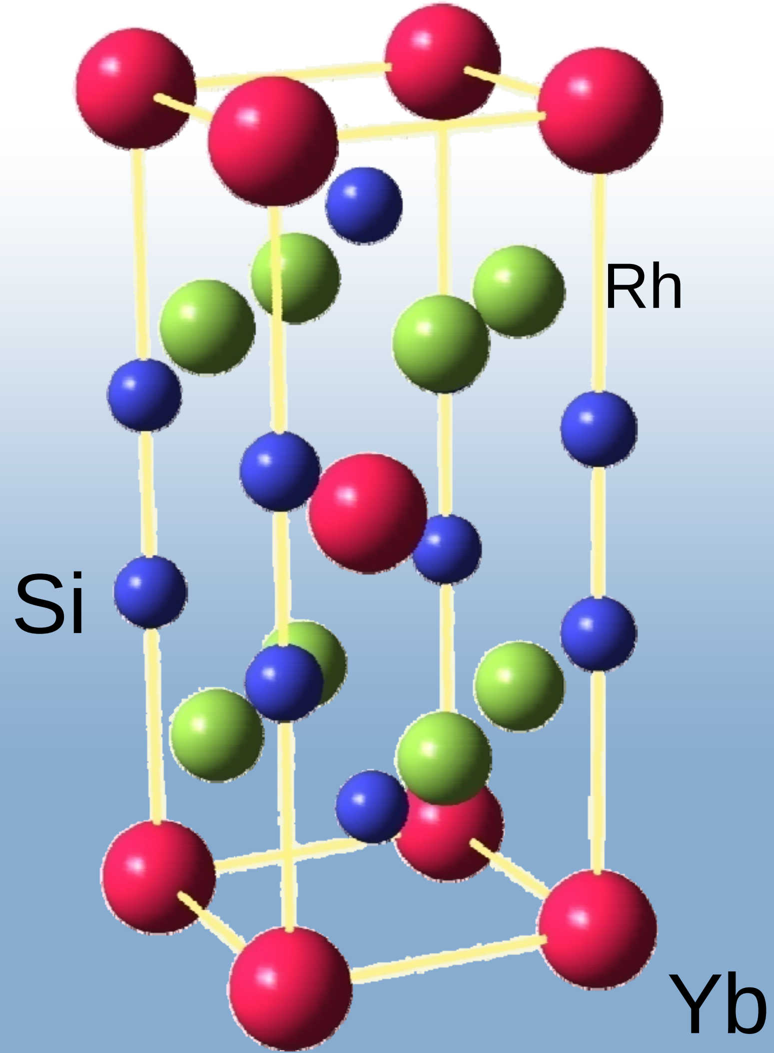
$$\times \sum_{\alpha\beta}\left(\delta_{\alpha\beta} - \hat{\mathbf{q}}_\alpha \hat{\mathbf{q}}_\beta\right)\mathcal{S}^{\alpha\beta}(\mathbf{q}\omega)$$

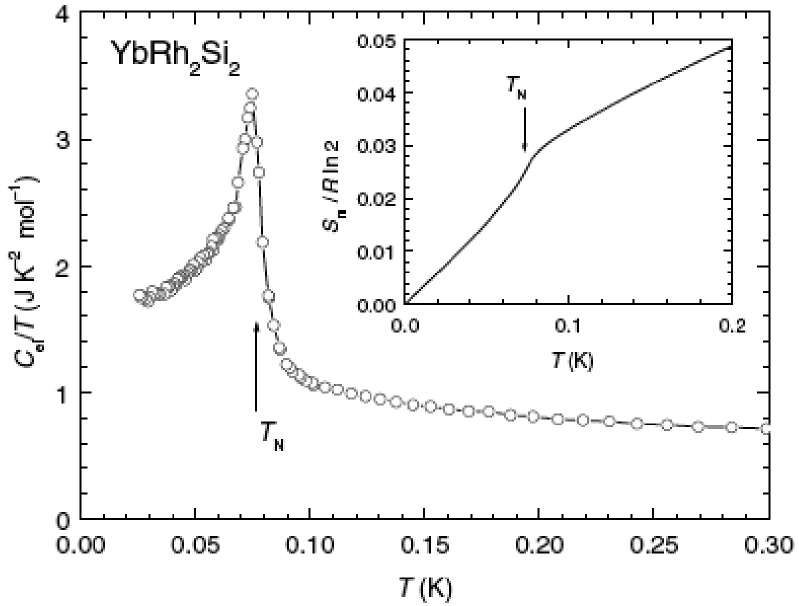
$$\mathcal{S}^{\alpha\beta}(\mathbf{q}\omega) = \frac{1}{1-e^{-\beta\hbar\omega}} \frac{\chi''_{\alpha\beta}(\mathbf{q}\omega)}{(g\mu_B)^2\pi}$$

$$\chi(\mathbf{q}\omega) = \frac{\chi_0(\mathbf{q}\omega)}{1-\mathcal{J}(\mathbf{q})\chi_0(\mathbf{q}\omega)}$$

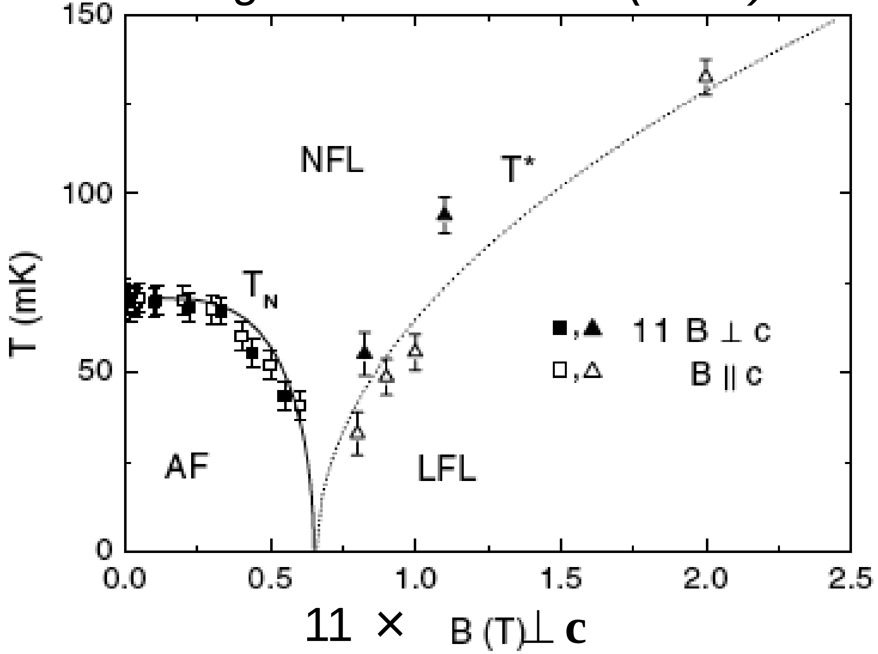
$$\chi_0(\mathbf{q}) = \sum_{\mathbf{k}} \frac{f(\epsilon_{\mathbf{k}+\mathbf{q}}) - f(\epsilon_{\mathbf{k}})}{\epsilon_{\mathbf{k}+\mathbf{q}} - \epsilon_{\mathbf{k}}}$$

Field Driven QCP in $YbRh_2Si_2$





Gegenwart et al PRL (2002)



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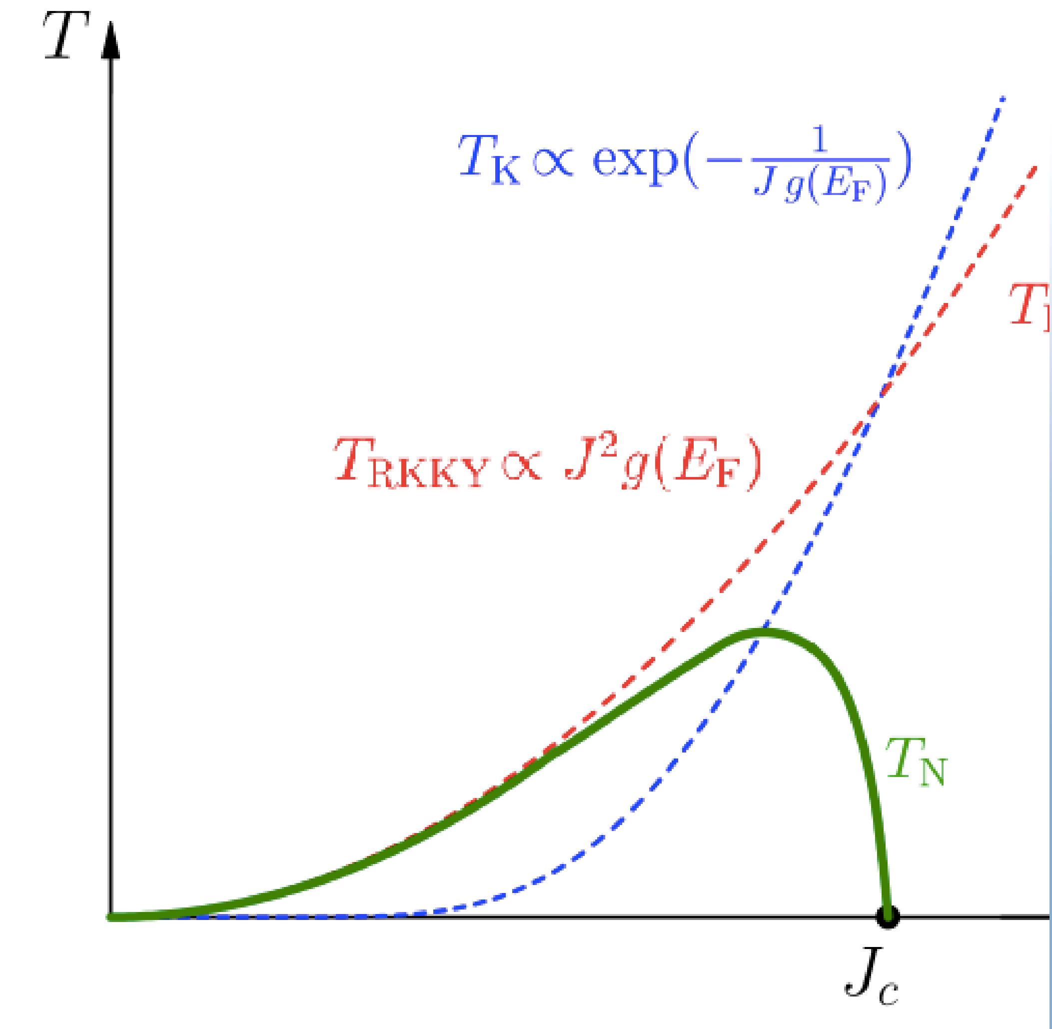
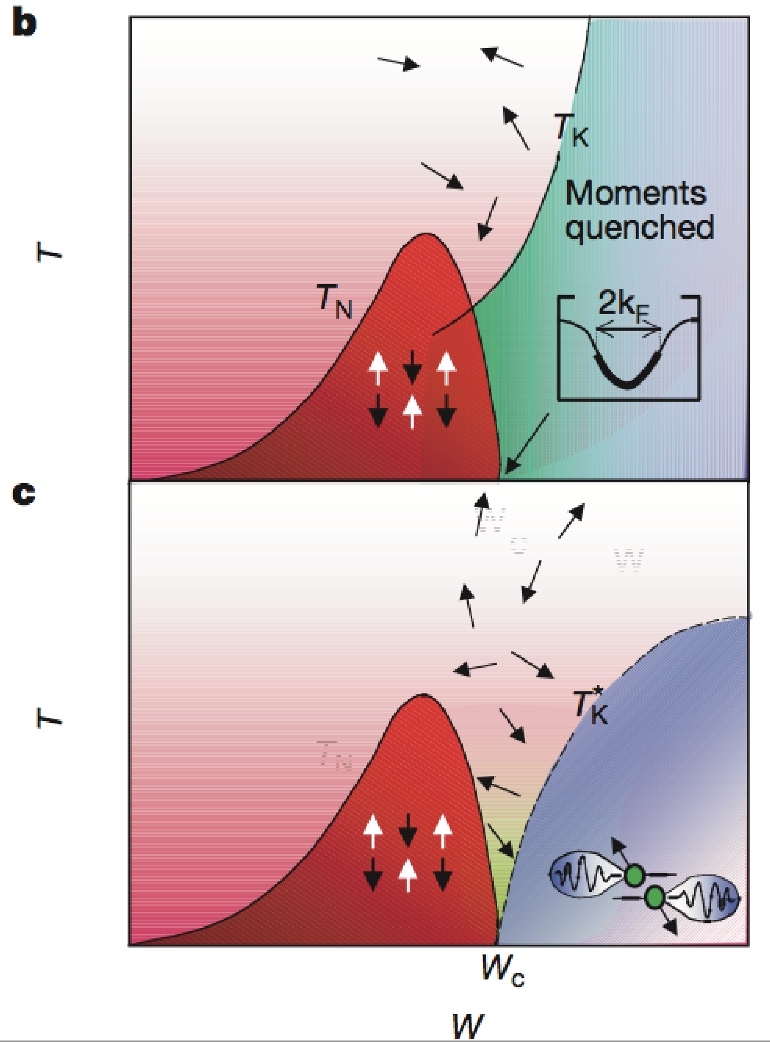
Kondo Lattice quantum criticality

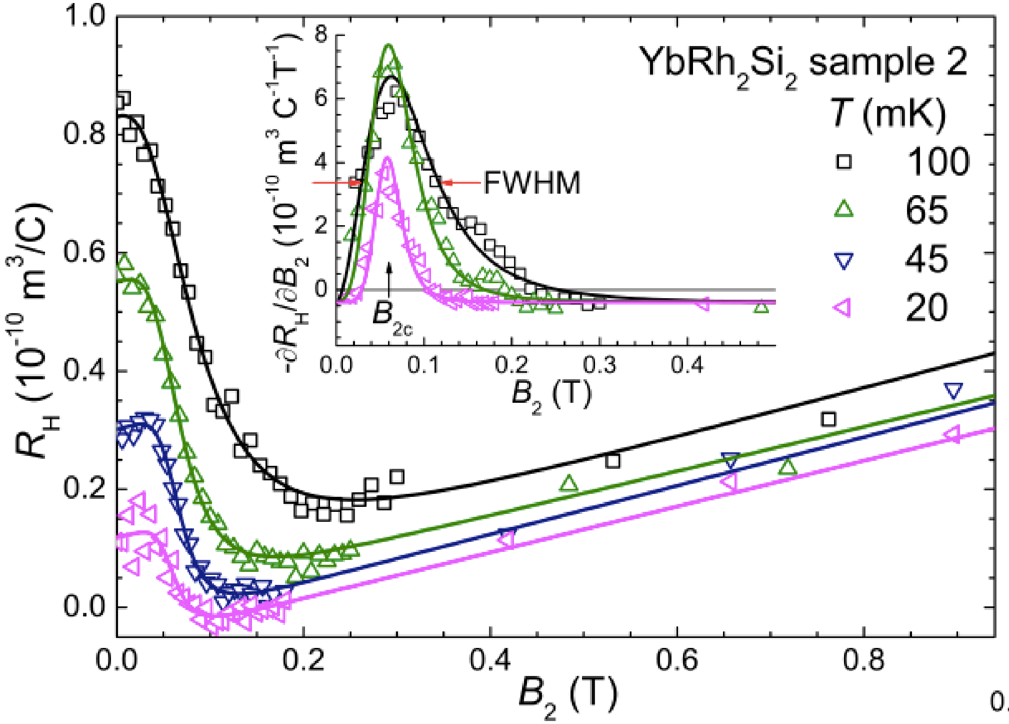
Steglich et al J. Phys. Cond. Matter (2012)

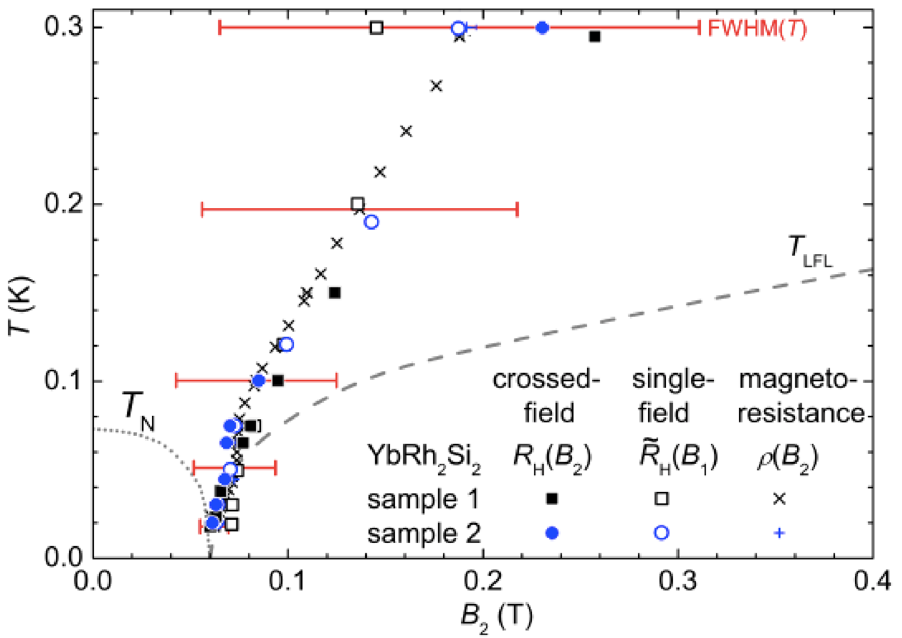


Schroeder et al Nature (2003)



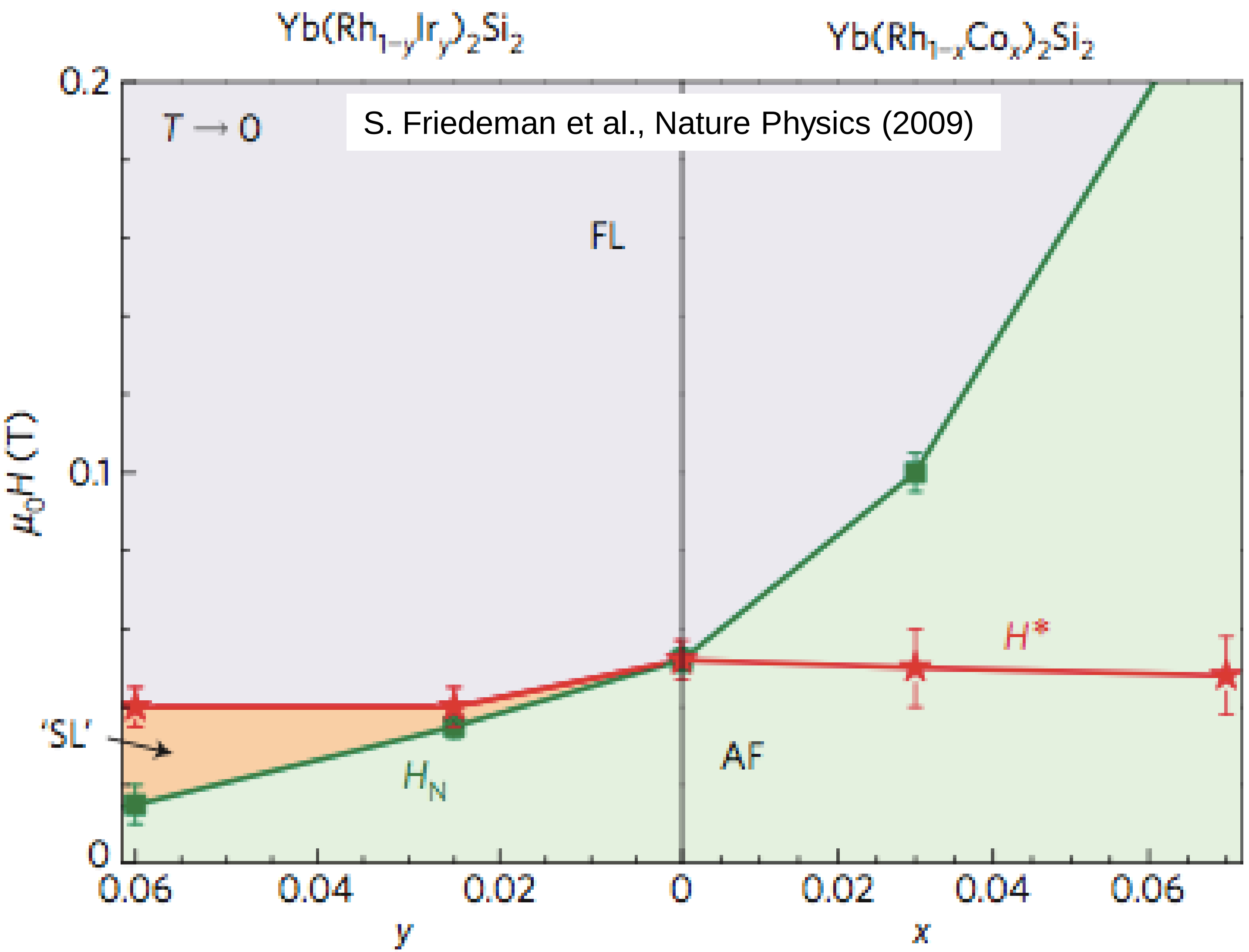
Fermi-surface reconstruction at T_N?



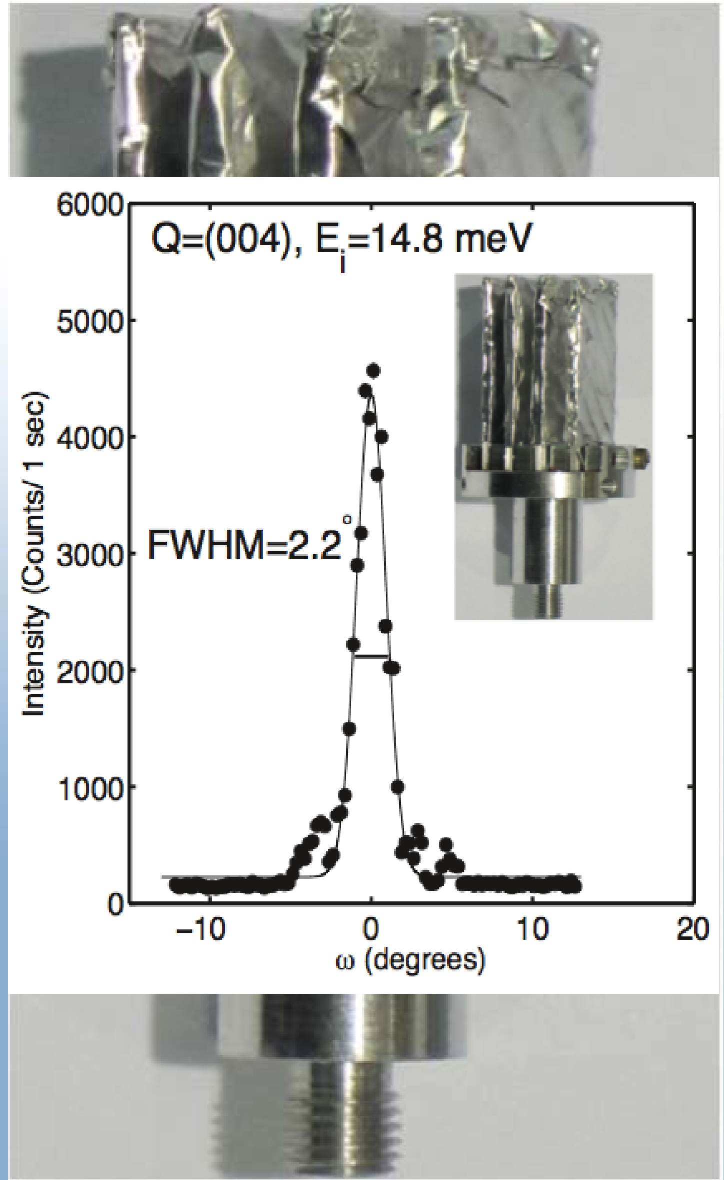


Friedemann et al PNAS (2010)

Can Kondo & SDW transition be “detached”?

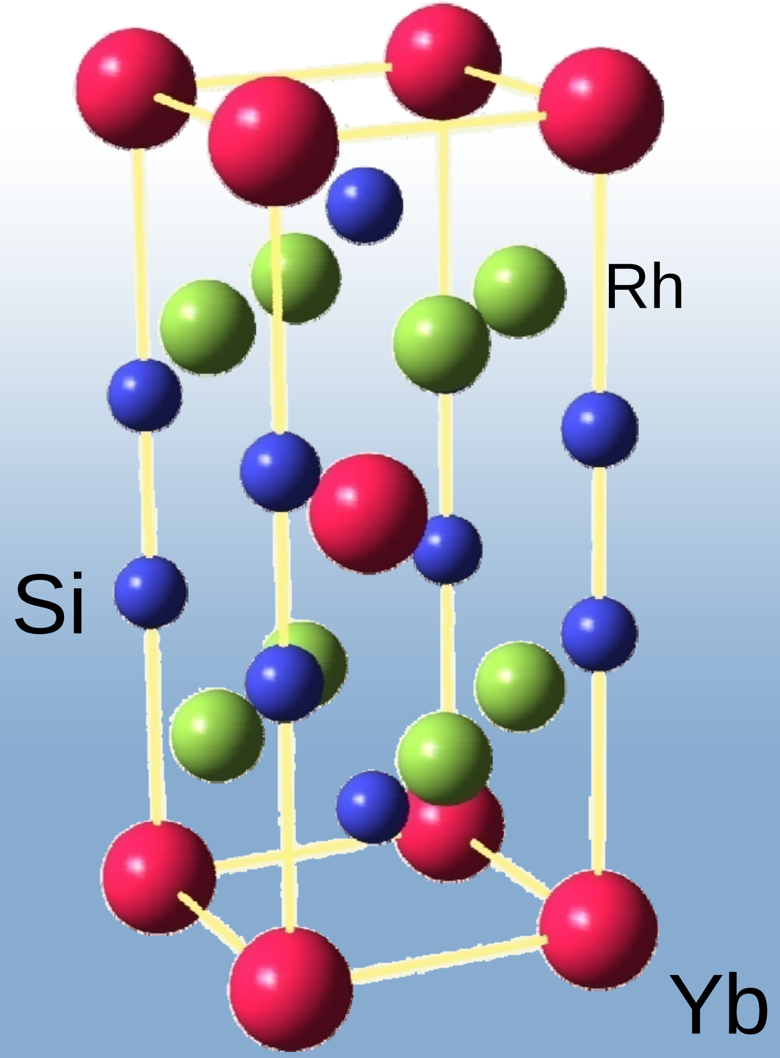


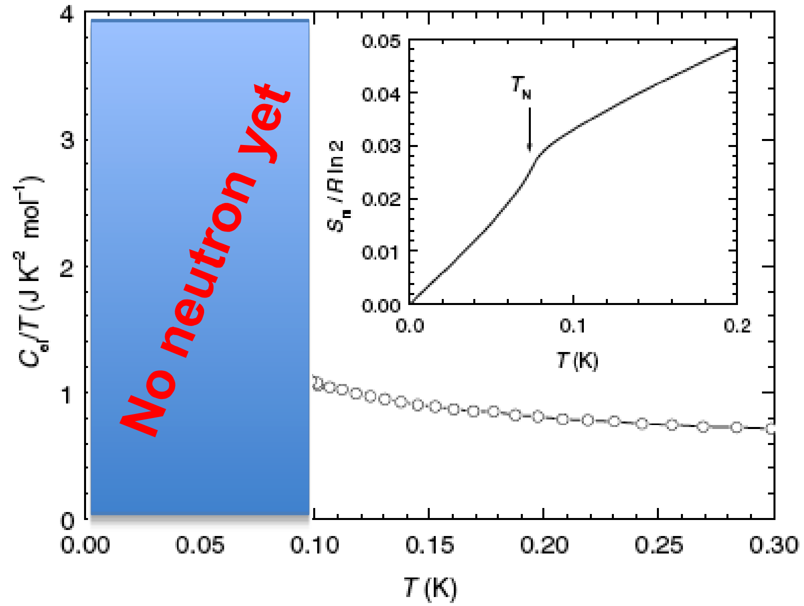
$YbRh_2Si_2$: neutrons come lately



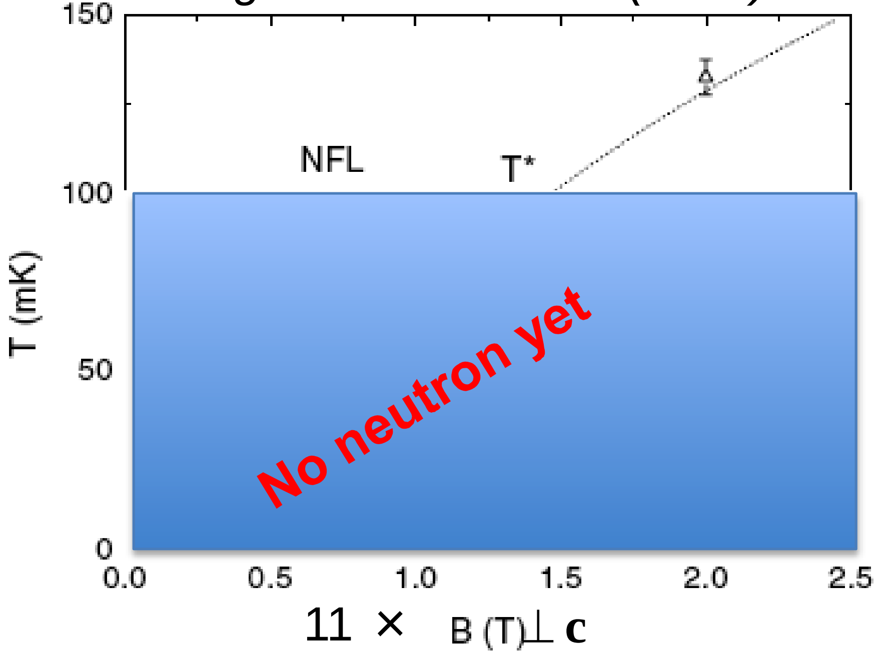
- 200 x 5 × 5 mm^2 crystals
- Mounted with H-free oil
- Total mass 3 g
- Mosaic FWHM 2°
- Penetration depth ≈2 mm

Field Driven QCP in $YbRh_2Si_2$





Gegenwart et al PRL (2002)



Collaborators

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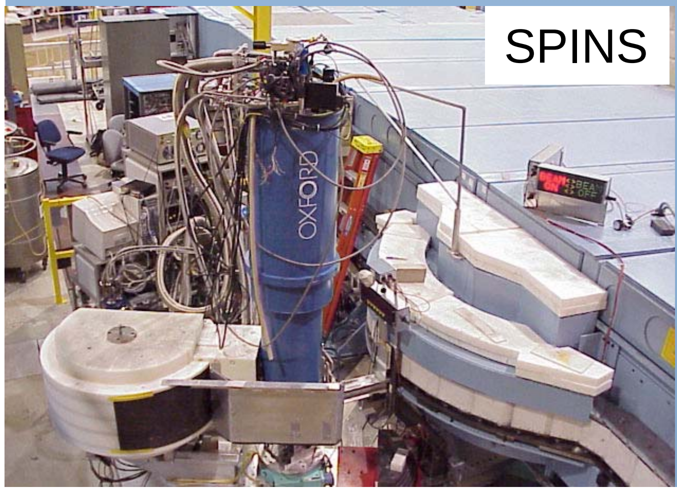
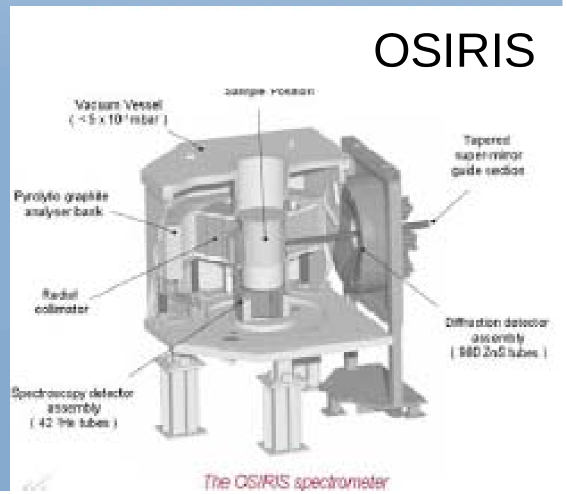
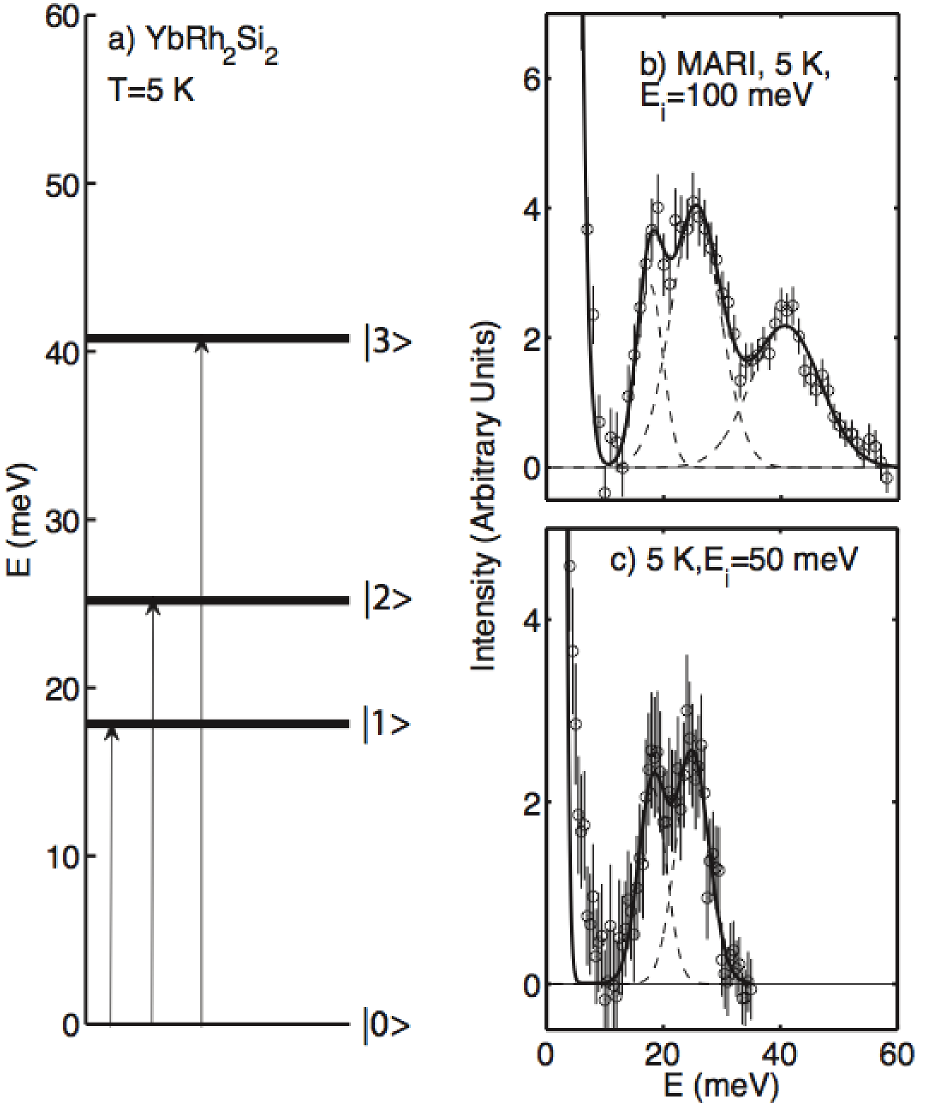
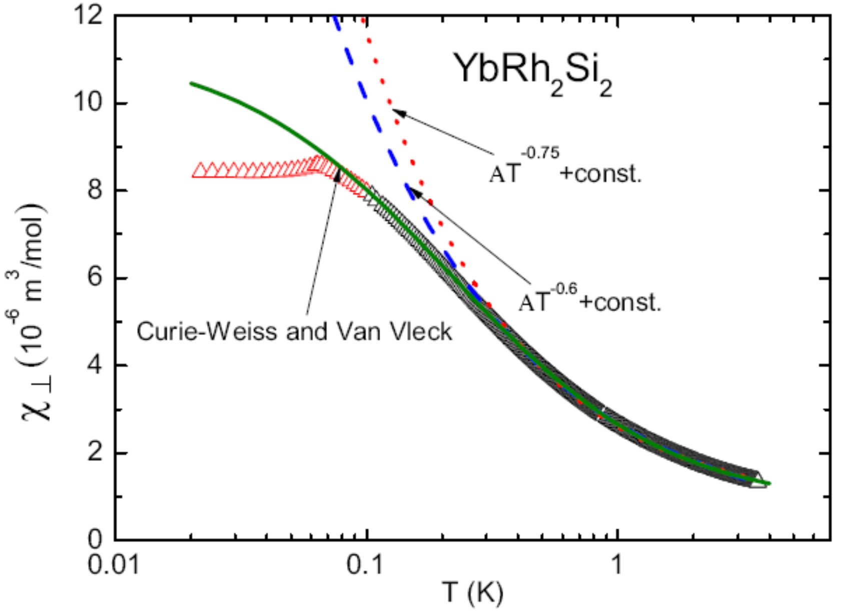
NIST Center for Neutron Research





Four CF Kramer's Doublets in $YbRh_2Si_2$

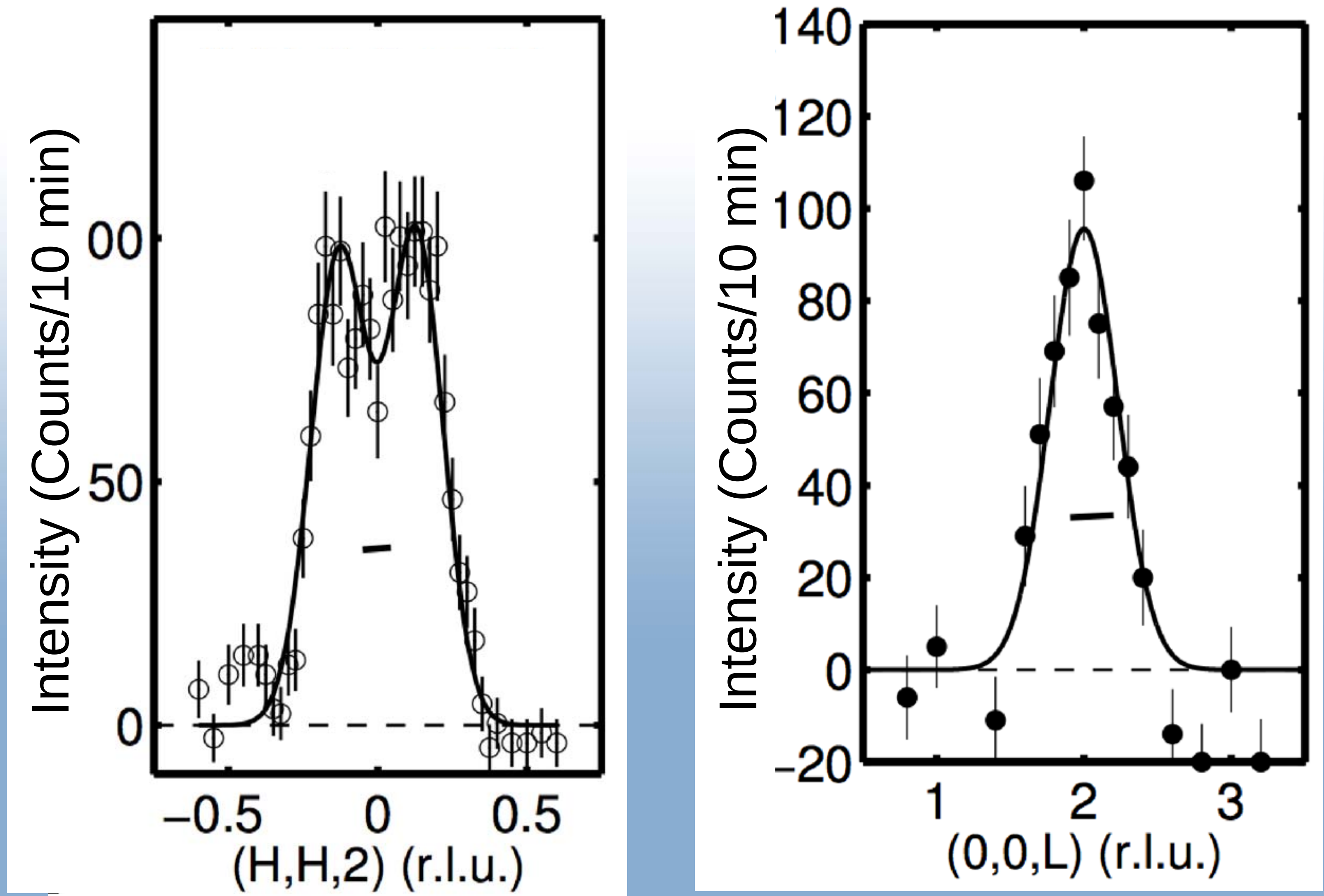




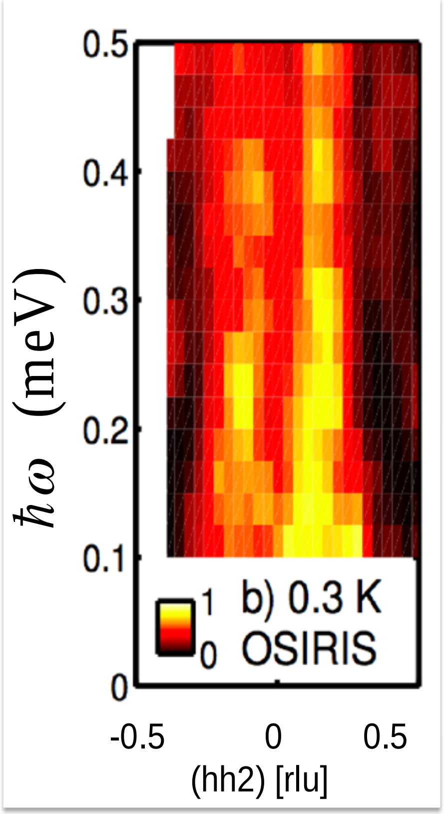
$$|0_+\rangle = (-0.77 \pm 0.05)|\frac{3}{2}\rangle + (-0.63 \pm 0.05)| - \frac{5}{2}\rangle,$$
$$|0_-\rangle = (0.63 \pm 0.05)|\frac{5}{2}\rangle + (0.77 \pm 0.05)| - \frac{3}{2}\rangle,$$

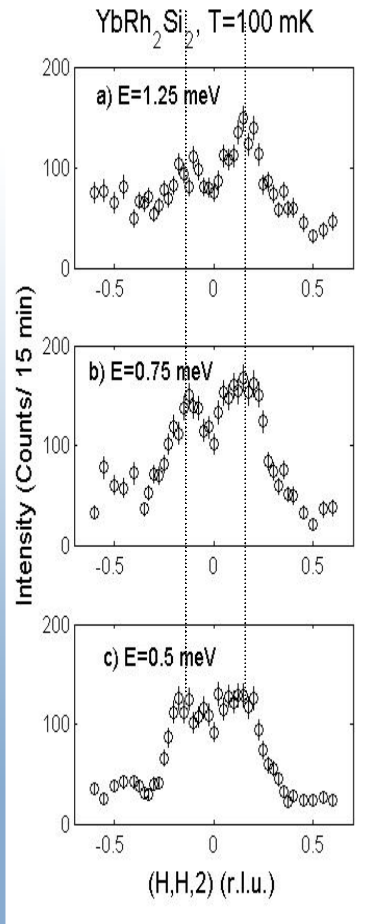
Incommensurate critical fluctuations

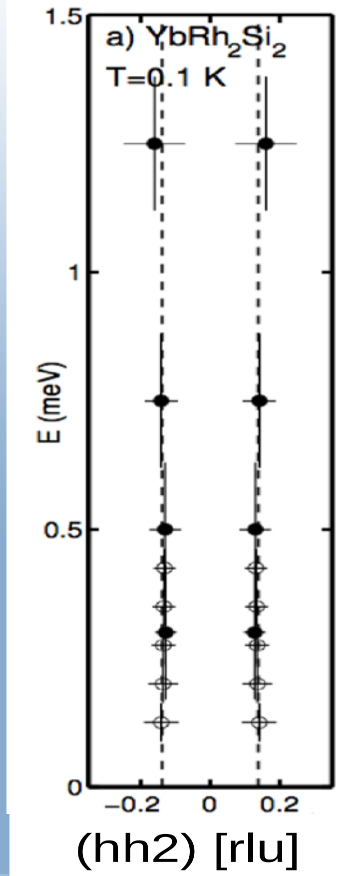
$$T = 0.1\ \mathrm{K} \qquad \hbar\omega = 0.5\ \mathrm{meV}$$



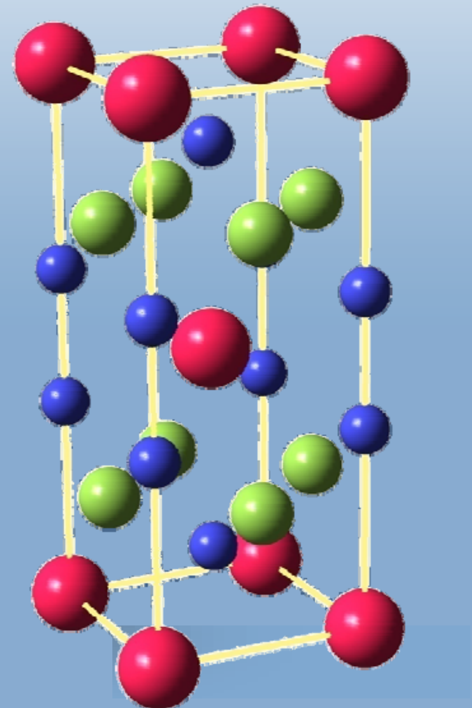
Incommensurate correlations





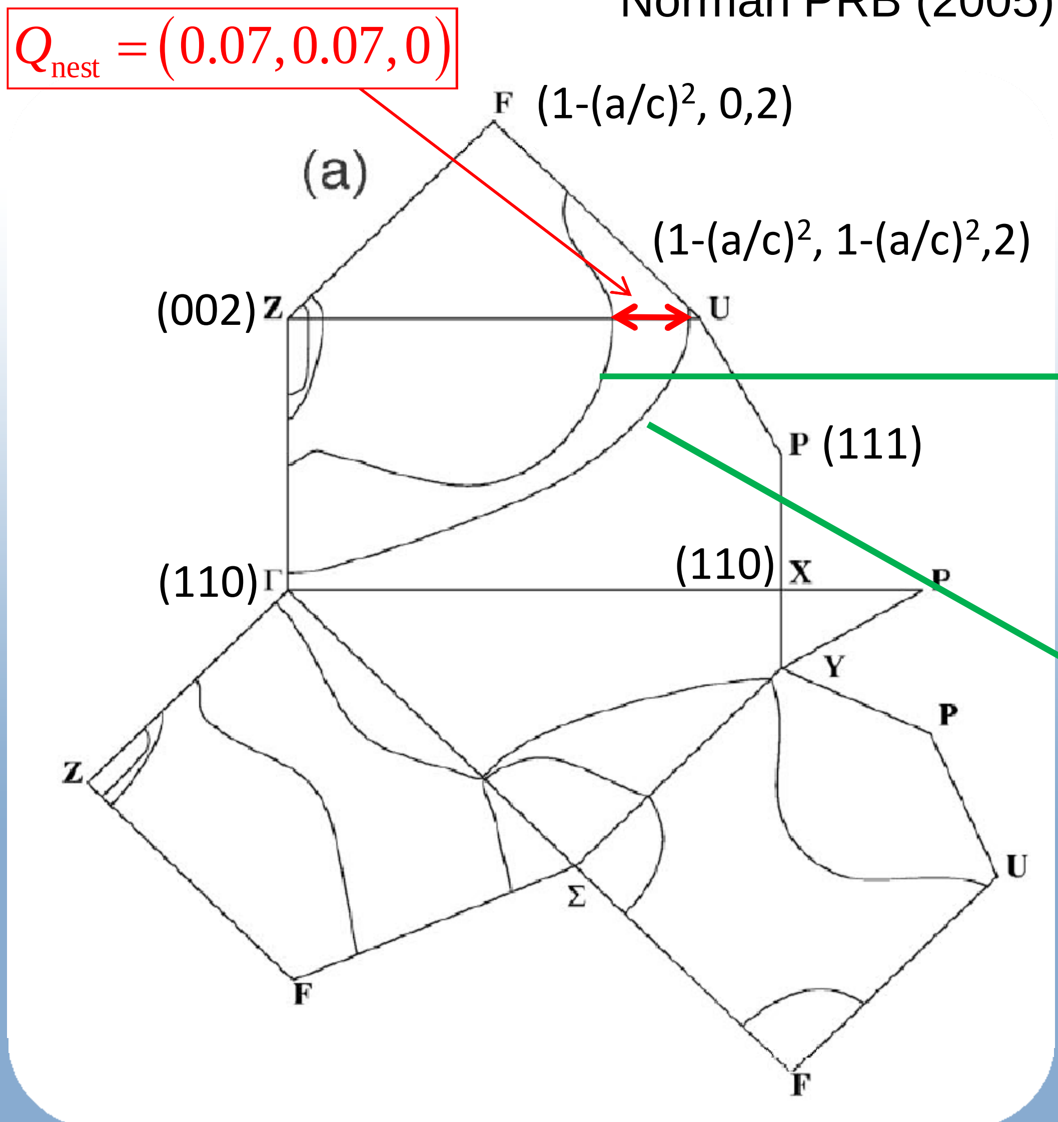


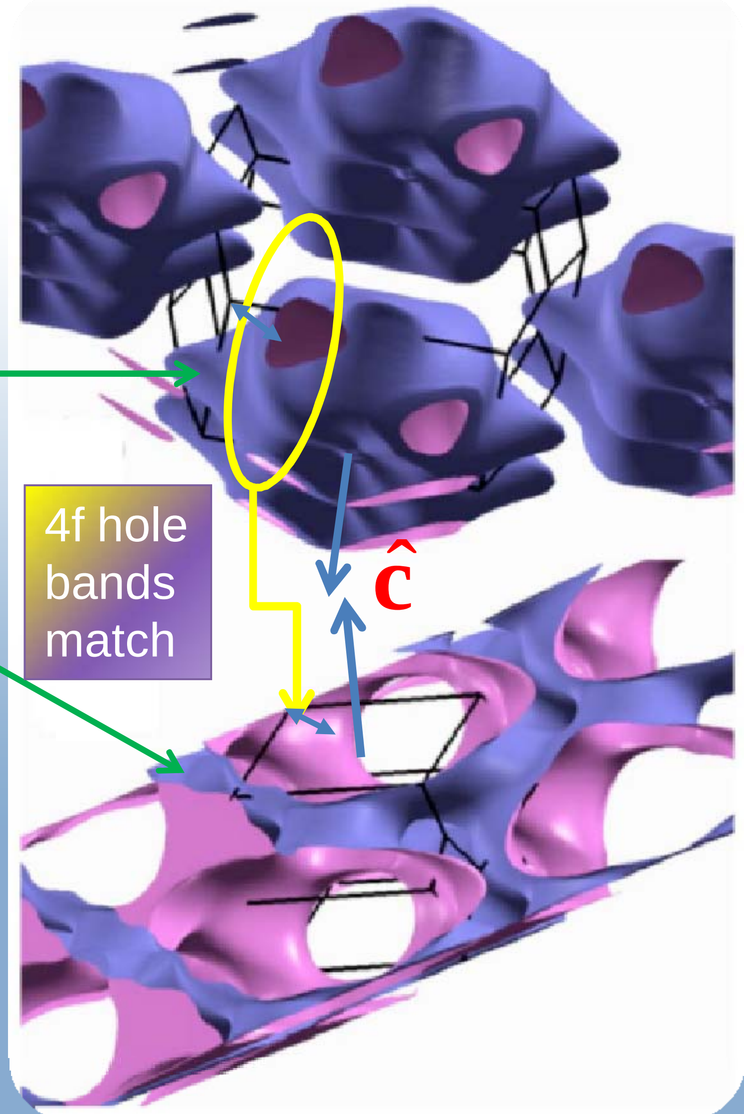
$$\vec{Q}_m = (\delta\delta 0)$$
$$\delta = 0.14(4)$$
$$\ell \sim 3.6\left(\vec{a}+\vec{b}\right)$$
$$\hbar\Omega \geq 1 \text{ meV}$$



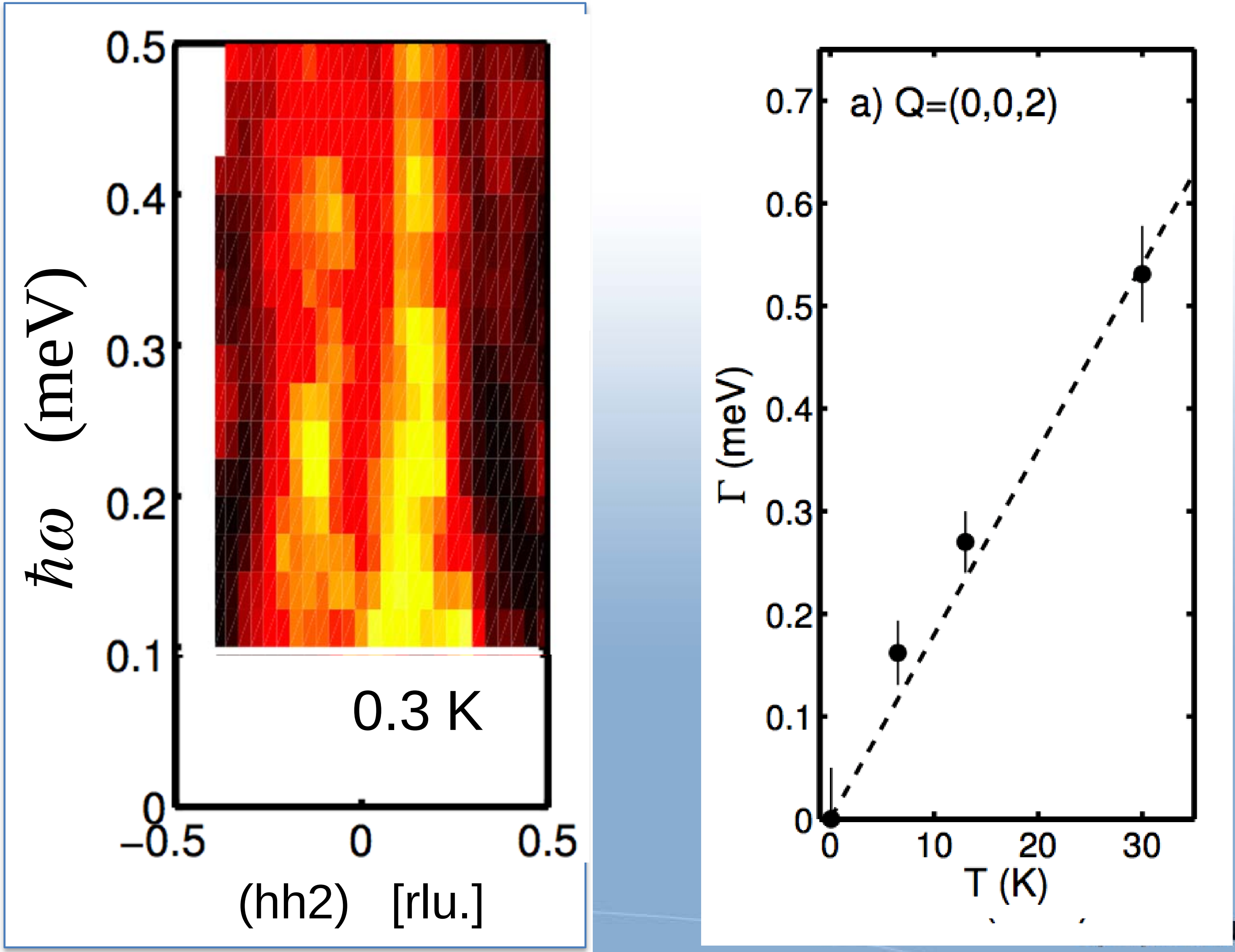
SDW from nesting instability?

Norman PRB (2005)



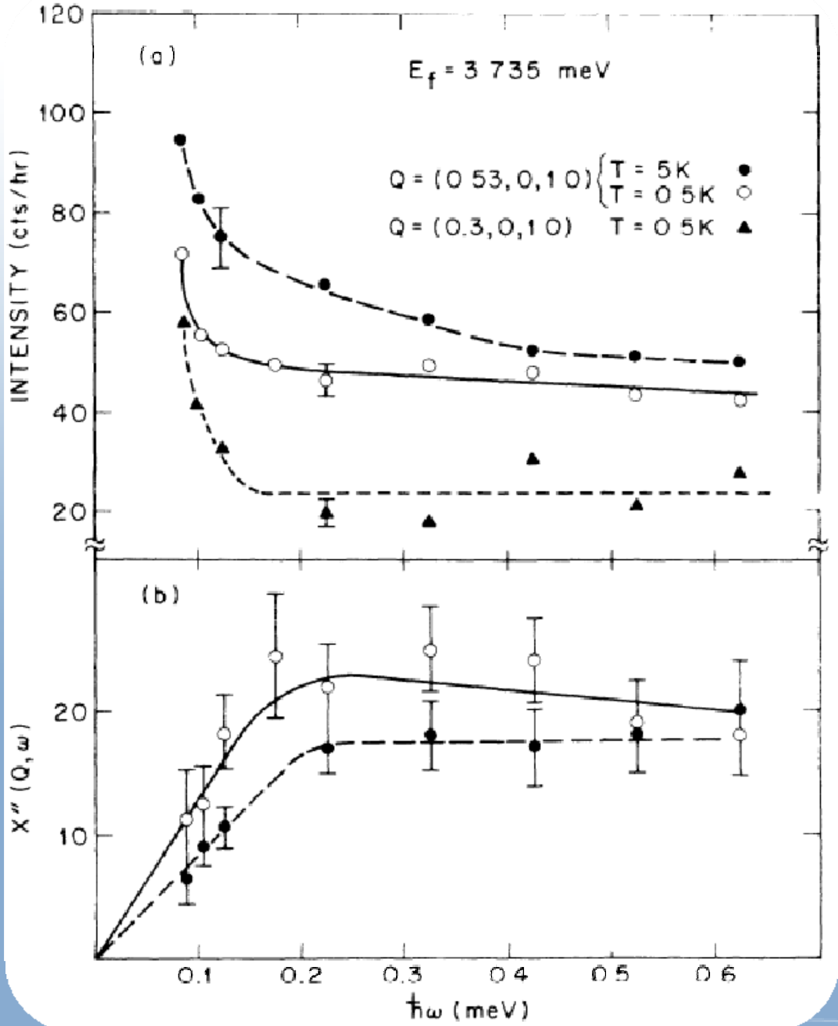


Apparent FM correlations upon heating

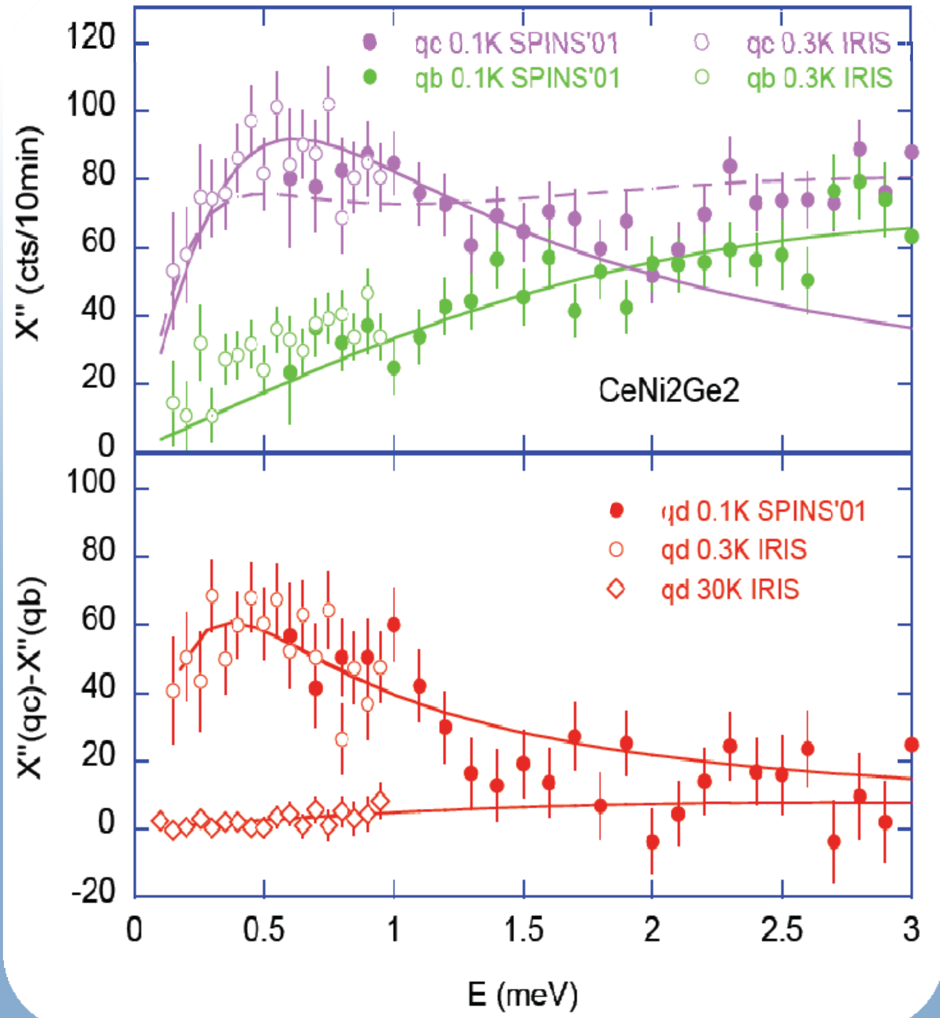


Finite $\Gamma(T \to 0)$ in non-critical HF systems

UPt_3



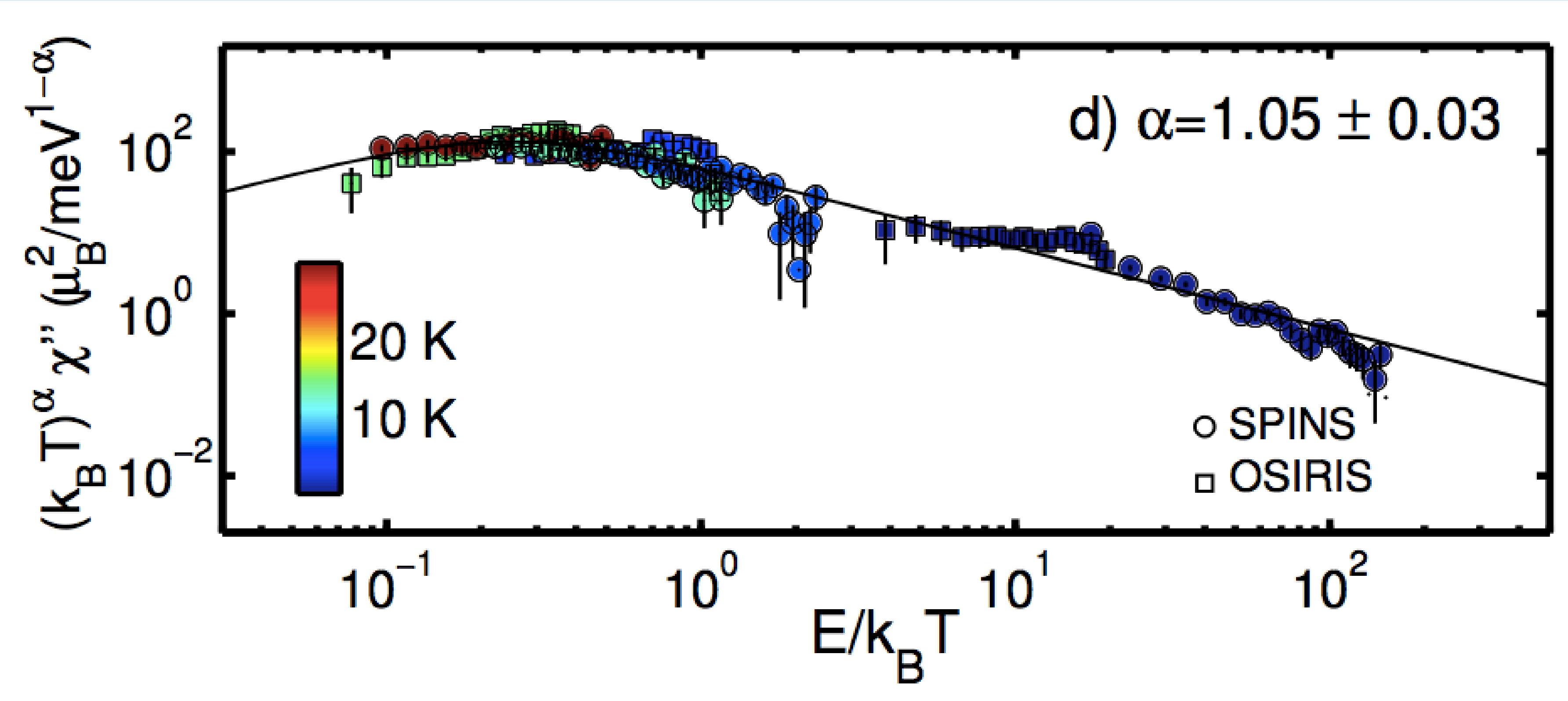
$CeNi_2Ge_2$



Quantum critical scaling for Q≈0

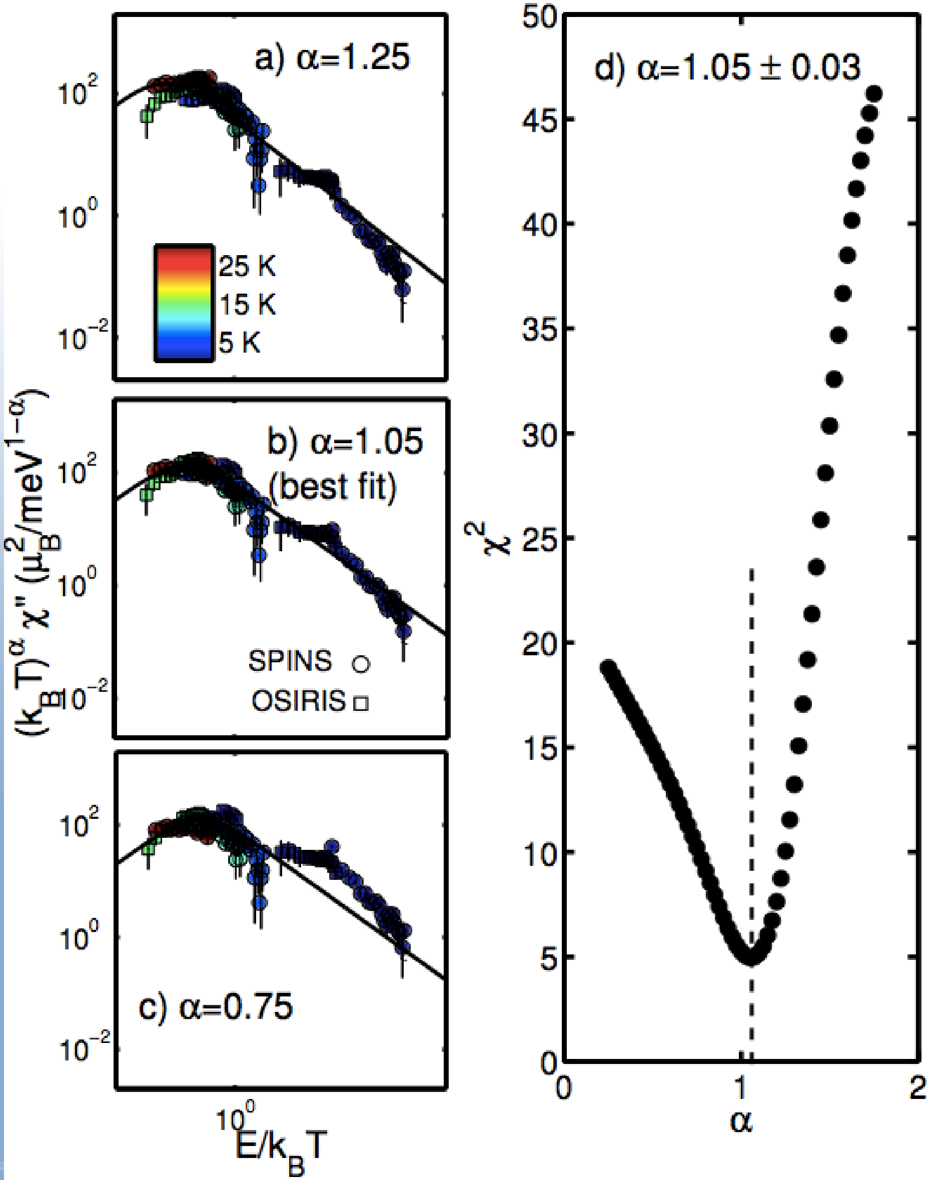
$$\chi''(\omega) = \frac{\chi_0 \Gamma \omega}{\Gamma^2 + \omega^2} \qquad \Gamma = \mathcal{C}_0 k_B T \qquad \chi_0 = \mu_{eff}^2 / k_B T$$

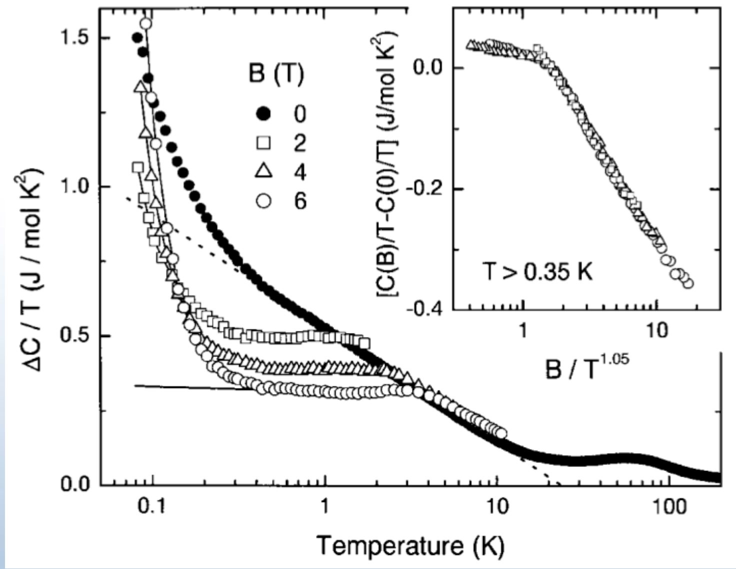
$$k_B T \cdot \chi''(\omega) = \mu_{eff}^2 \frac{\hbar \mathcal{C}_0 x}{(\hbar \mathcal{C}_0)^2 + x^2} = \mu_{eff}^2 f(x) \qquad x \equiv (\hbar\omega / k_B T)$$

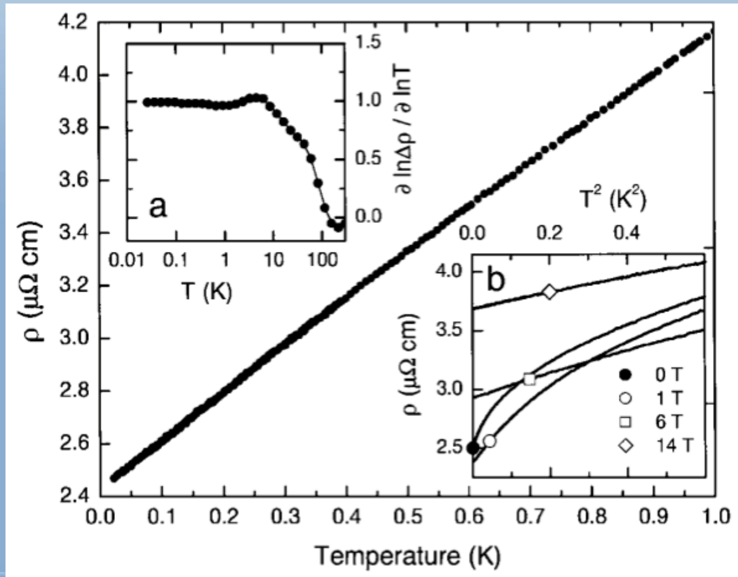


Critical Exponent $\alpha = 1.05(3)$

Trovarelli et al PRL (2010)

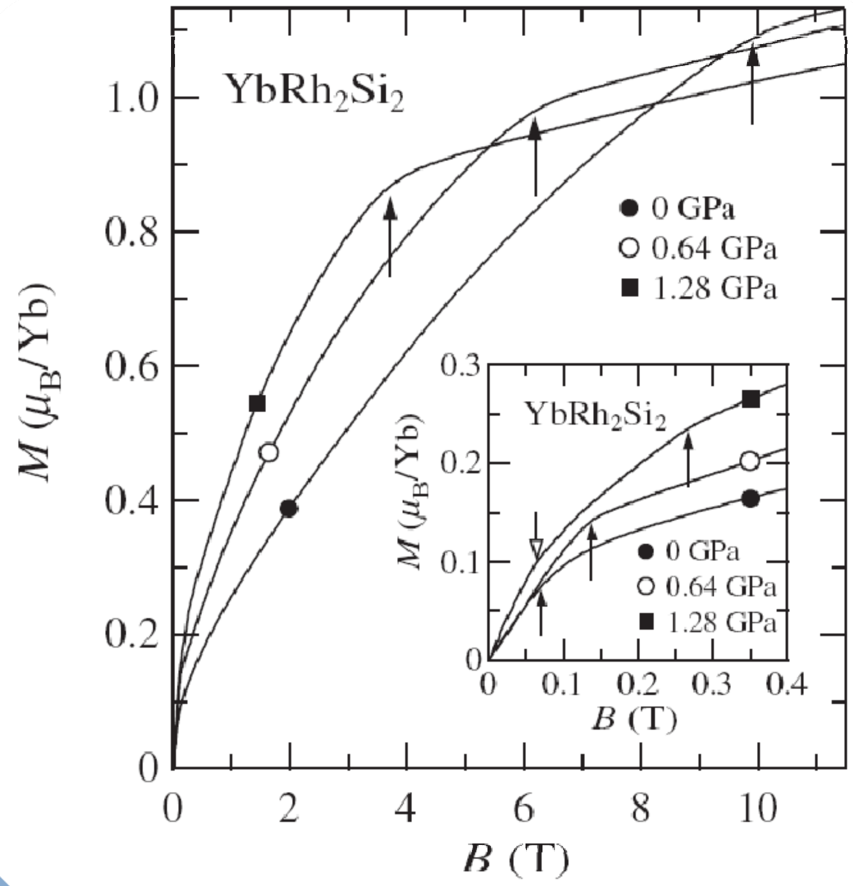




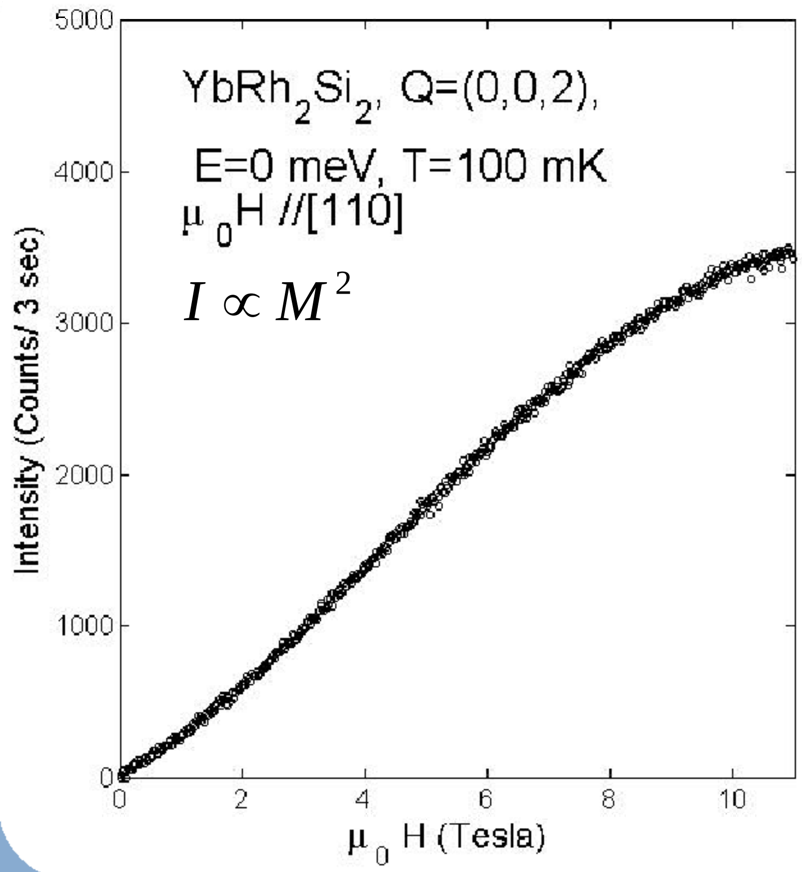


Magnetization SQUID & neutrons

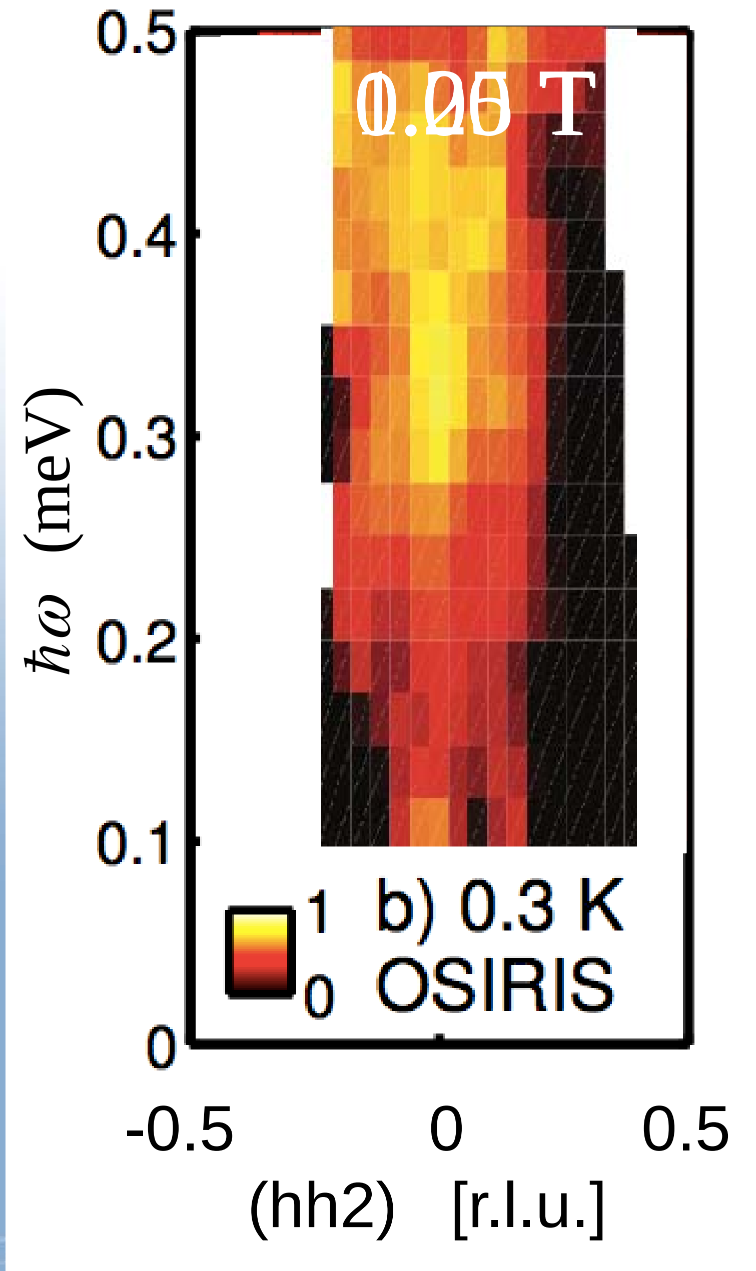
Gegenwart et al., NJP (2006)

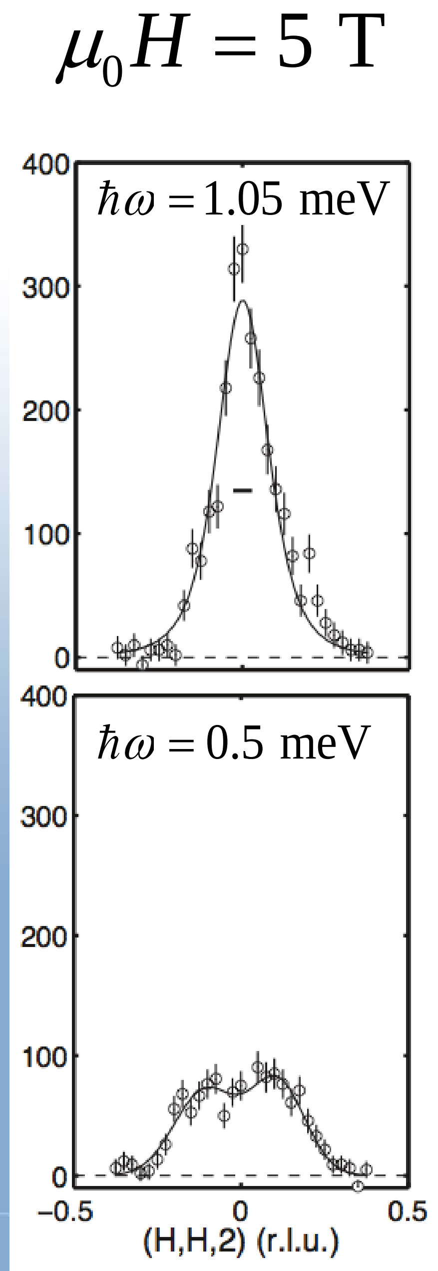


C. Stock et. al., (2009)



From SDW to FM correlations with field

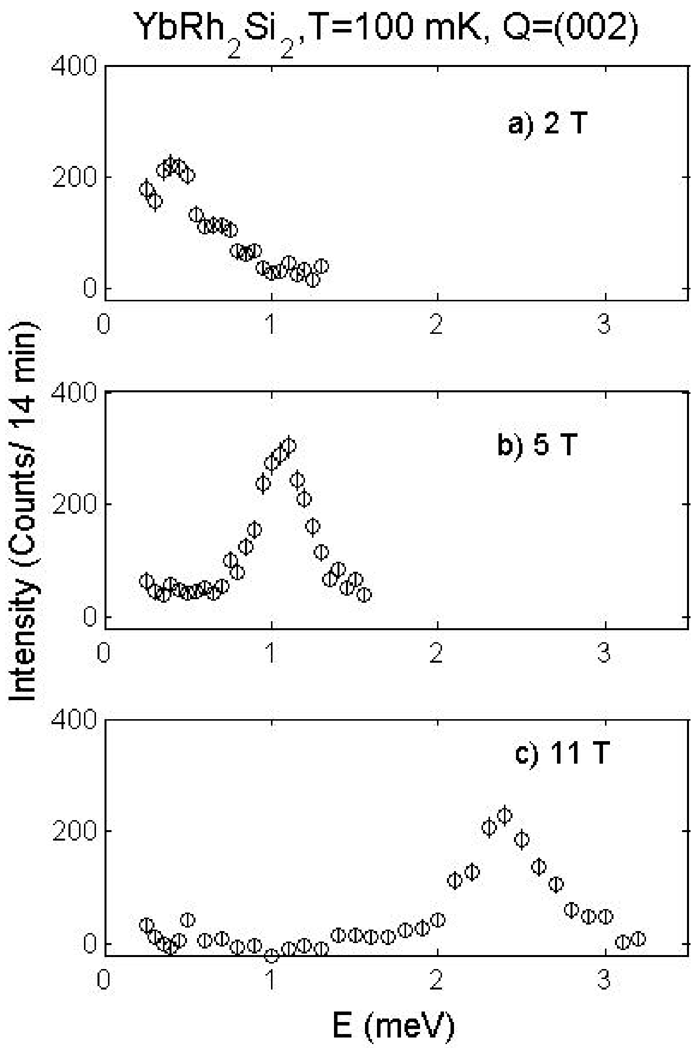




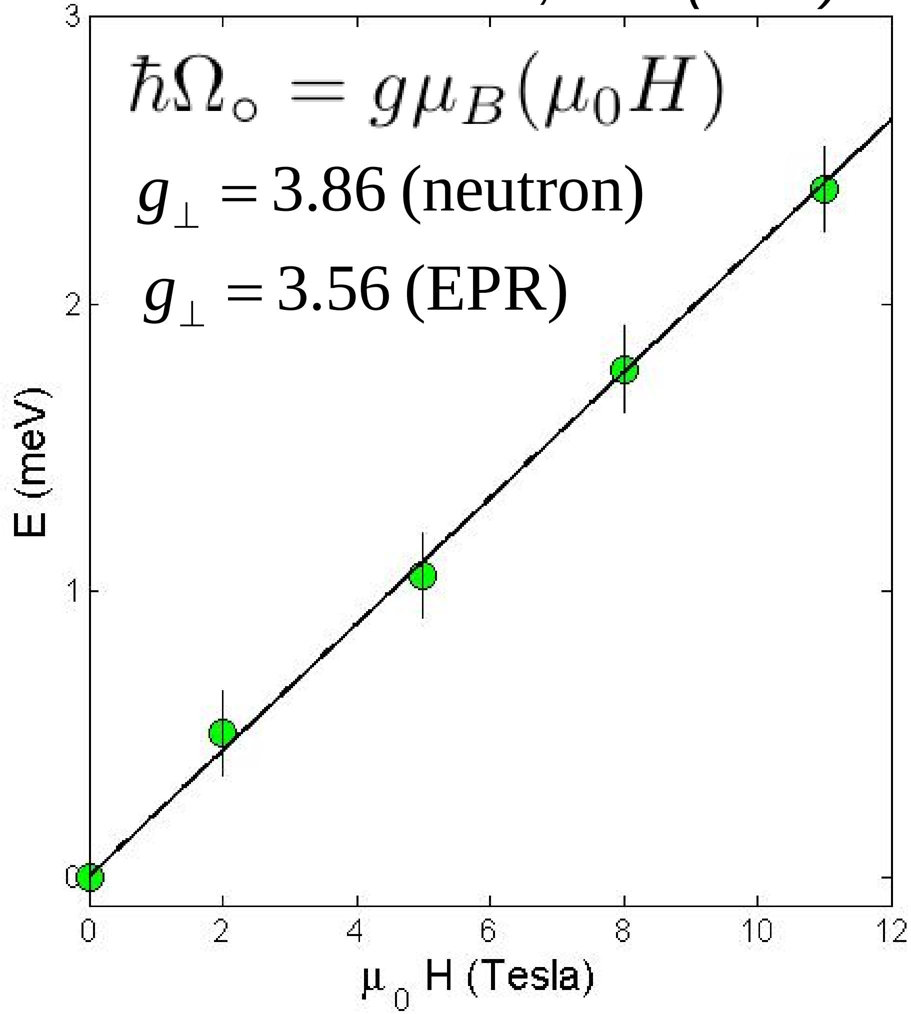
Effects of field:

- ❖ Upward shift of spectral weight
- ❖ Sharp peak at FM position
- ❖ Field induced resonance

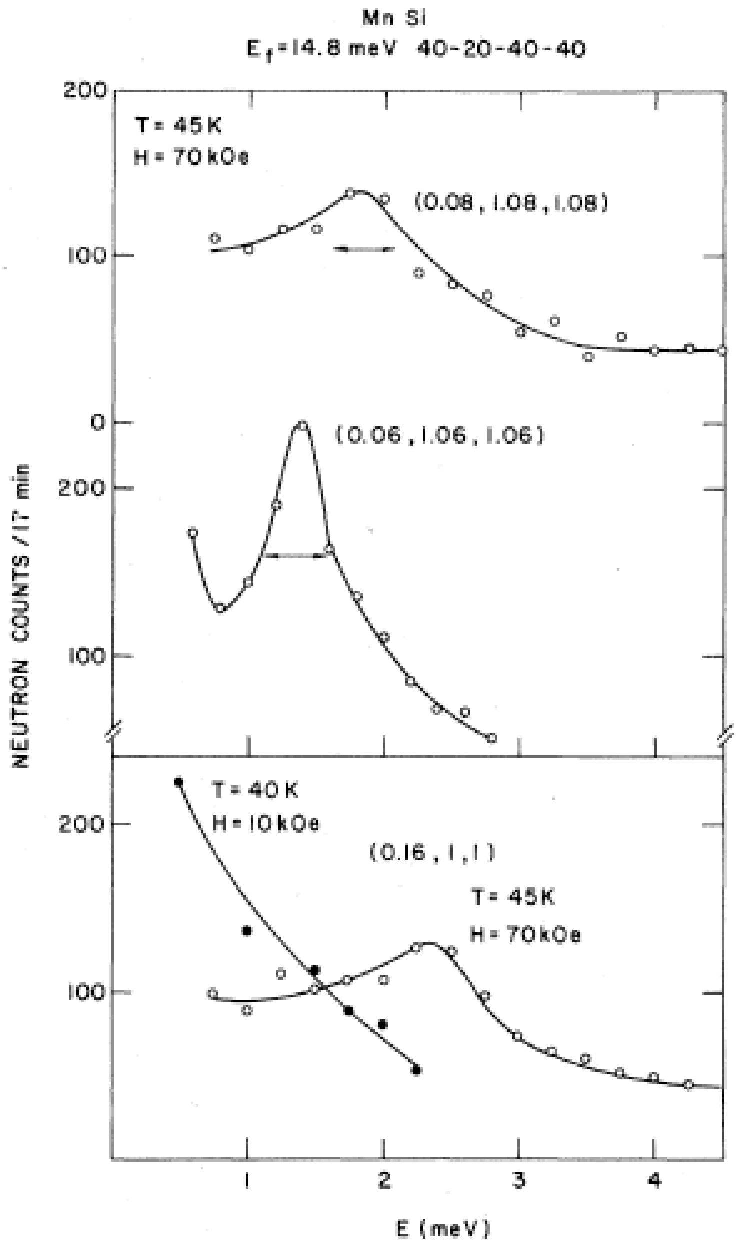
Field Induced Resonance



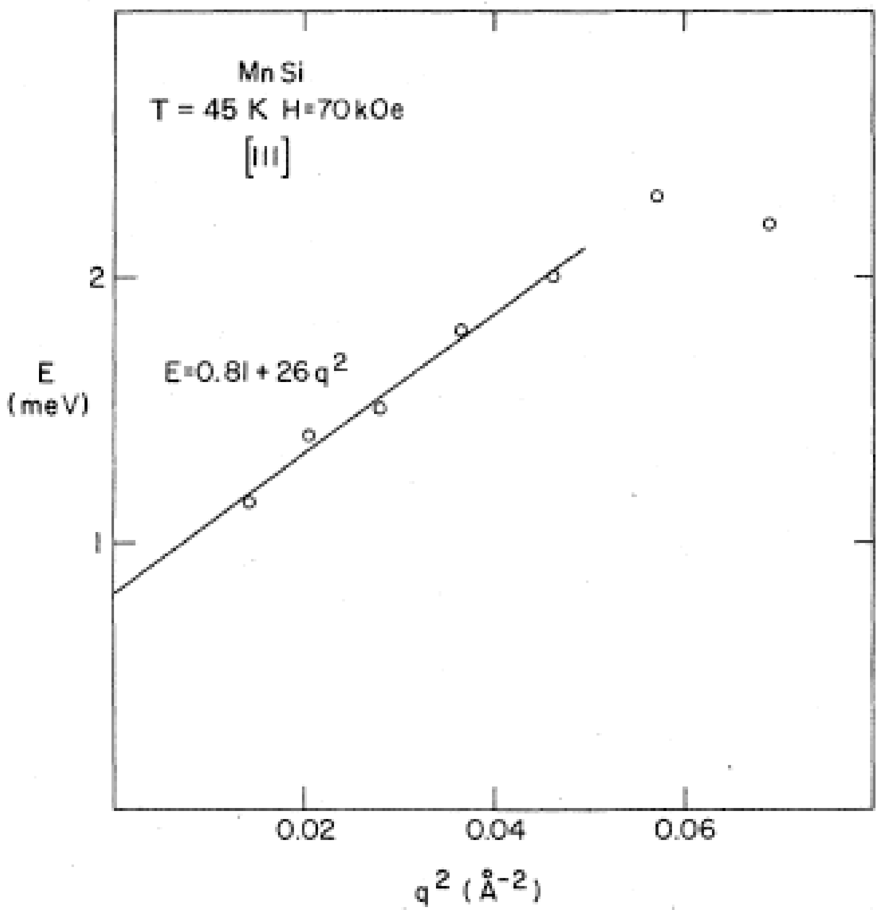
C. Stock et. al., PRL (2012)



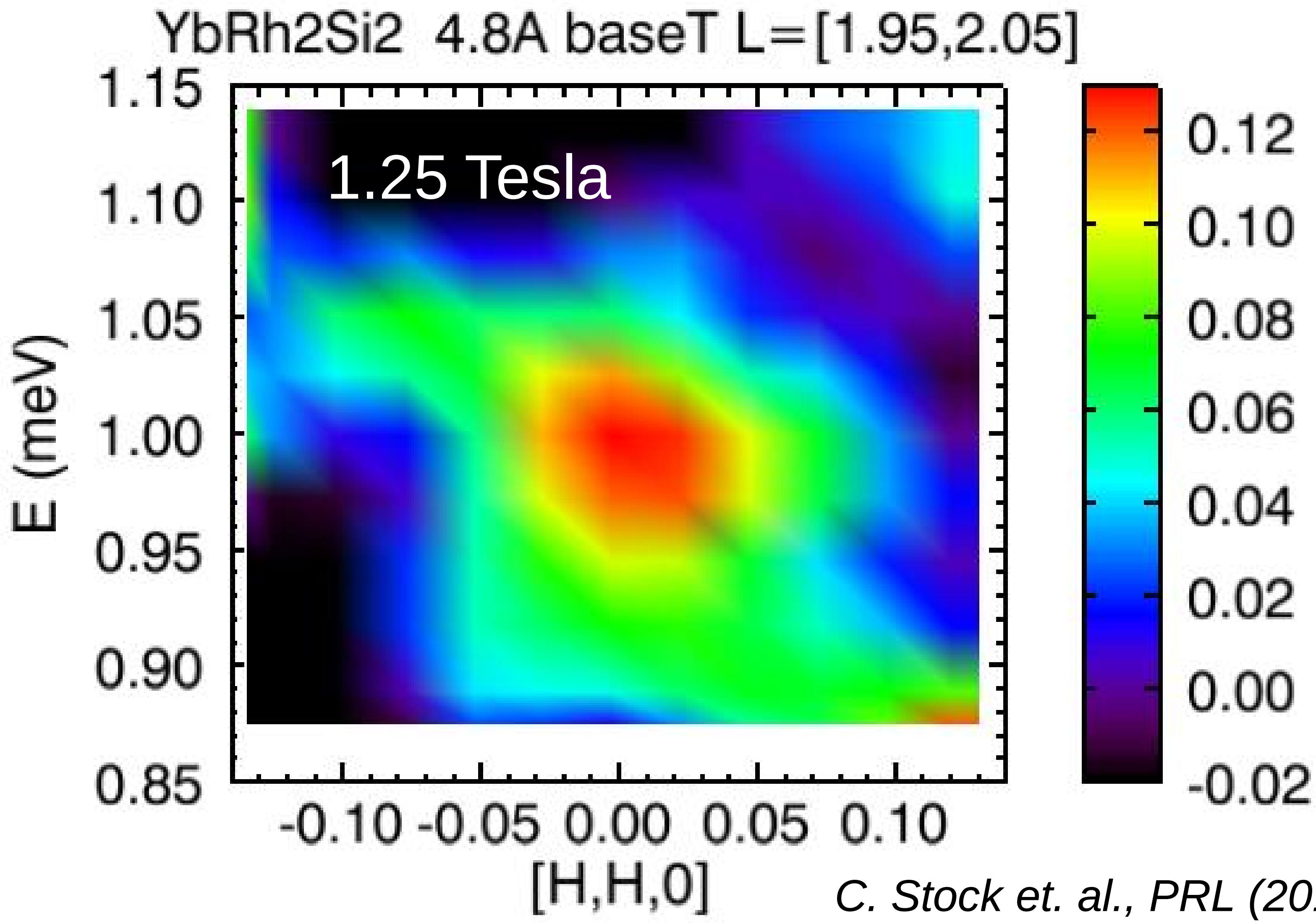
MnSi: Field induced "ferromagnons"



Tarvin et al., Phys. Rev. (1978).

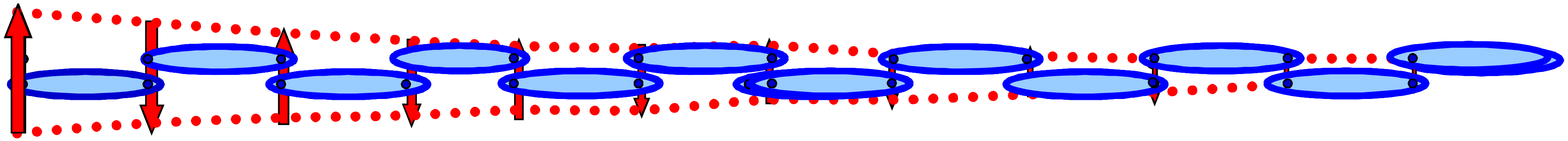


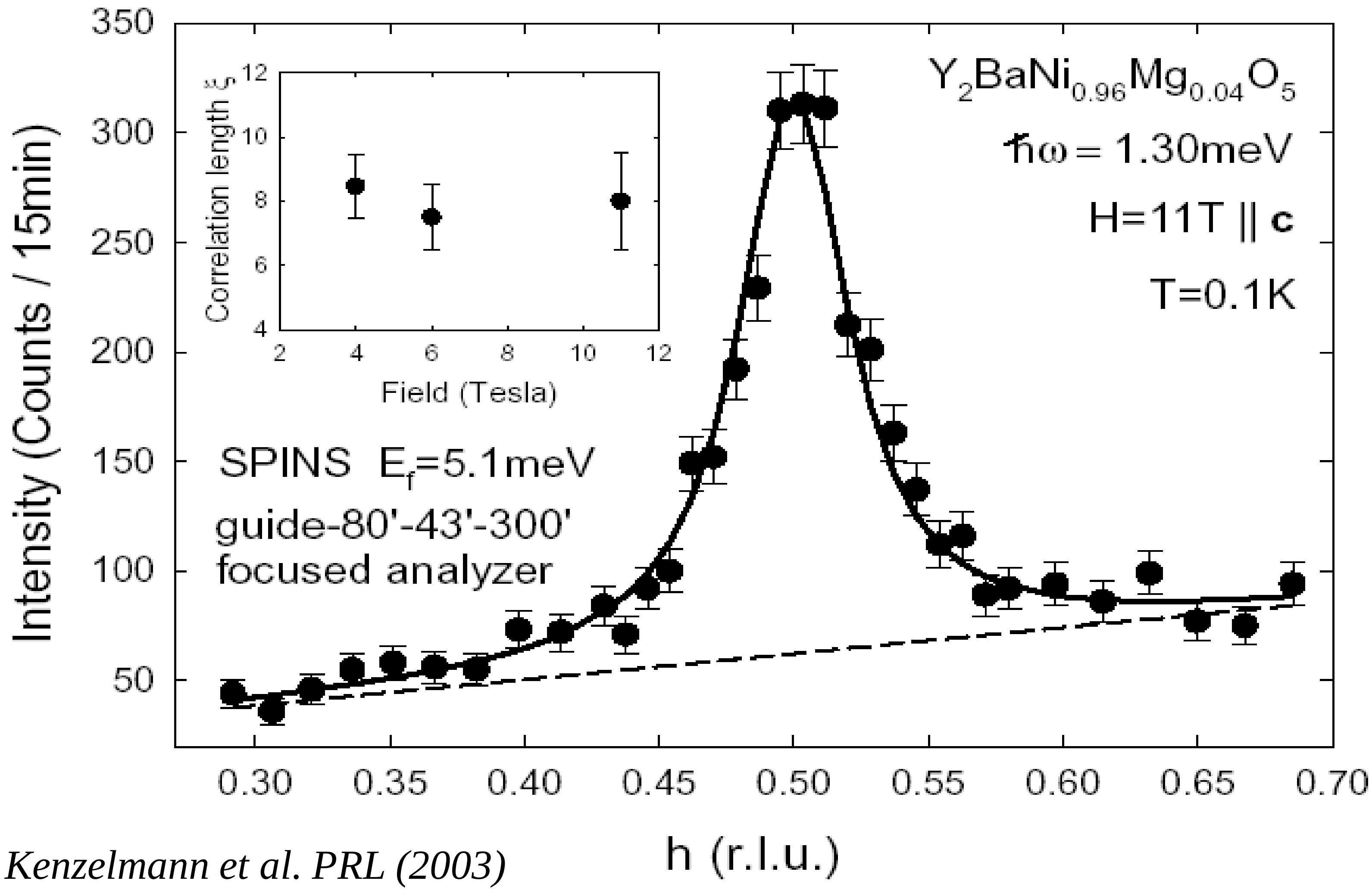
$YbRh_2Si_2$: A spot in Q-space



C. Stock et. al., PRL (2012)

Form factor for chain-end spin





Kenzelmann et al. PRL (2003)

Interpretation of the spin resonance

- Coincident g-factors indicate this is Electron Spin Resonance
- Coherent precession of spin density

$$\xi = 6(2)\overset{o}{A}$$

- Similar to a Kondo length scale

$$\xi_K \sim \hbar v_f / k_B T_K \sim 15\,\overset{o}{A}$$

- Kondo Screened spins for $B > B_c$

Conclusions

- **Effective FM critical regime for T>1 K**

$$\left(k_B T\right)^{\alpha} \cdot \chi''(\omega) = \mu_{eff}^2 f\left(\hbar\omega / k_B T\right) \qquad \alpha = 1.05(3)$$

- **Lower T: Incommensurate critical fluctuations**

$$Q_m = \left(0.14(4), 0.14(4), 0\right)$$

- **SDW instability may arise from nesting of hole fermi-surfaces**
- **B suppresses SDW favoring FM polarized metal**
- **Meso-scopic spin precession indicates Kondo screened 4f spin degree of freedom**
- **SDW correlations persist at lower energies in magnetized kondo lattice state**

Stock et al to appear in PRL (2012)

Outlook

- **SDW phase**
  - Can band-theory account for incommensurate $\mathbf{Q}_c$
  - Detect SDW Bragg peak and measure critical exponents
  - Pressure or doping driven changes in $\mathbf{Q}_c$
- **QCP**
  - Inelastic scattering at lower T and $\hbar\omega$
  - Identify field driven QC metal with higher critical temperatures and/or less neutron absorption