Seeing Inter-layer Coherence in Excitations of Quantum Hall Bilayers

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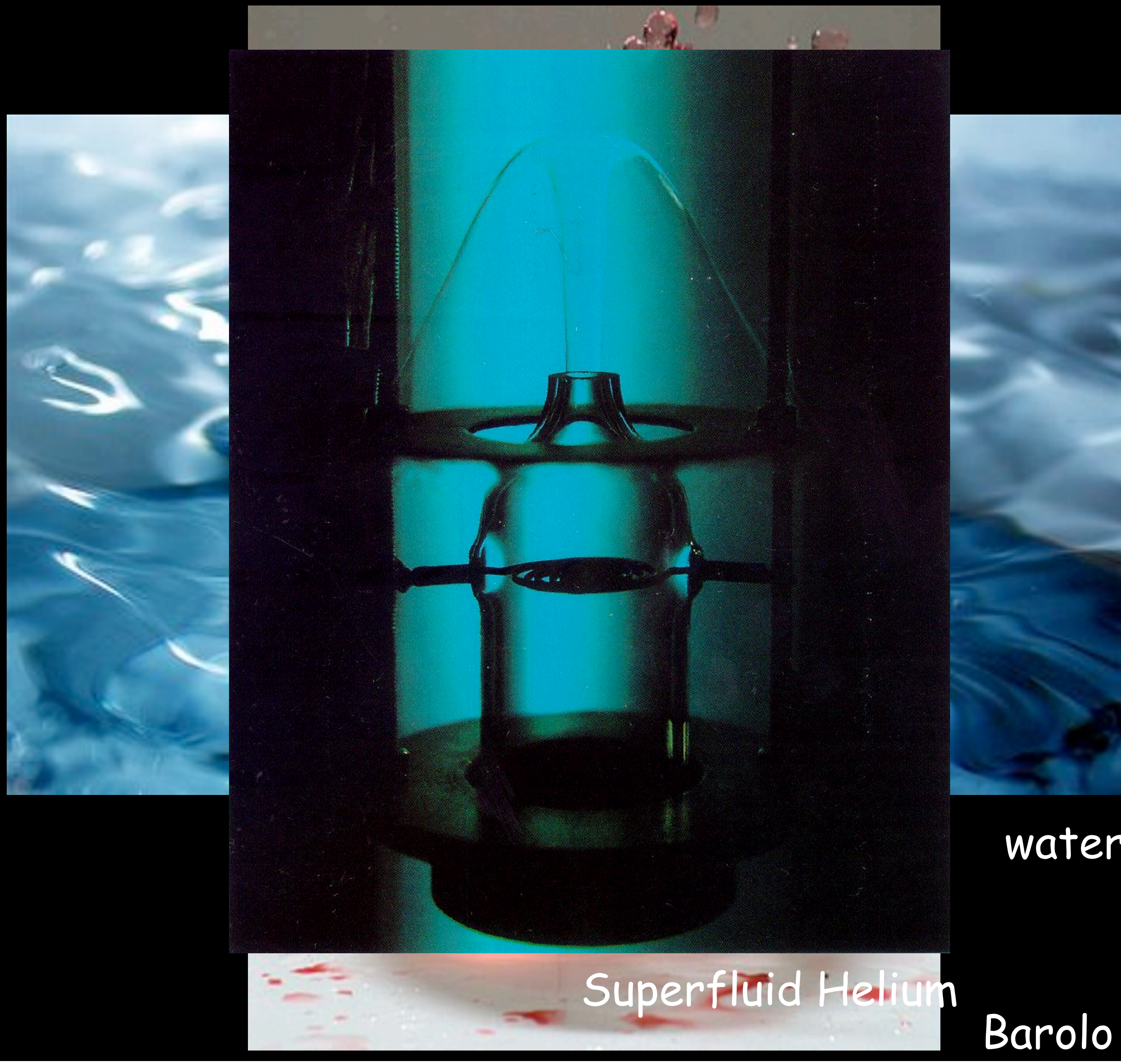
Excitations



water

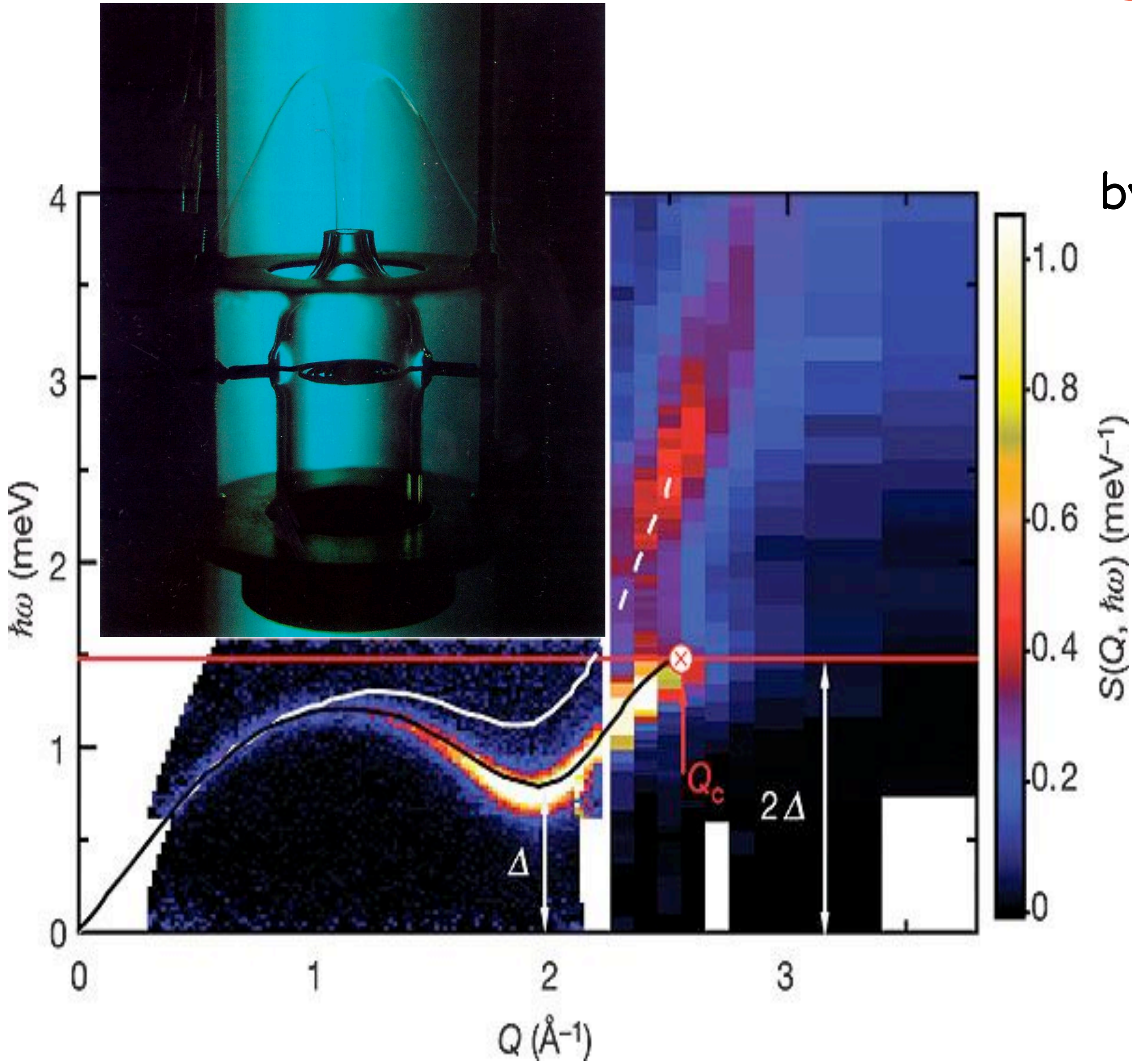
Barolo 1997

Quantum liquids

Superfluid ^{4}He

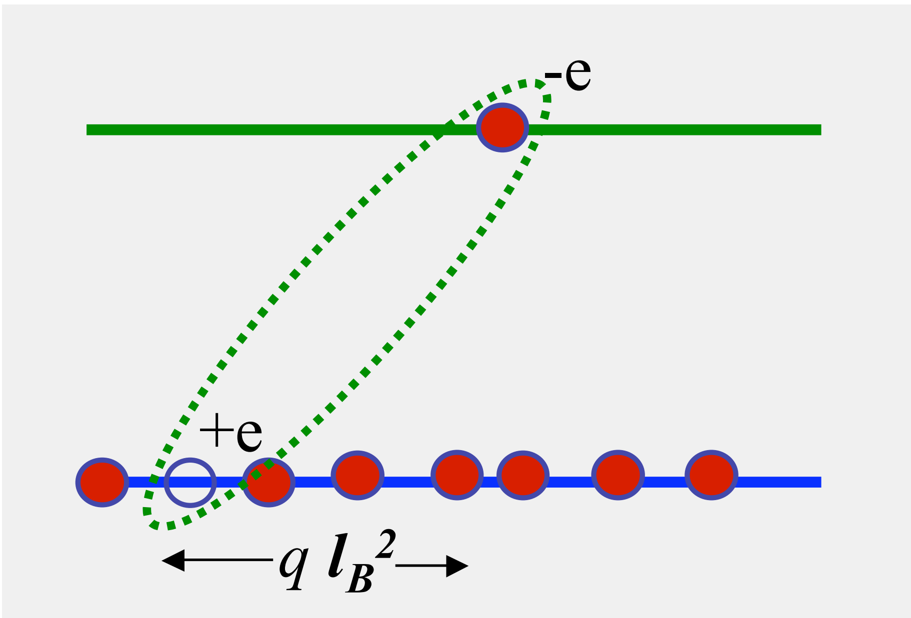
studied

by neutron scattering



M.B. Stone, et al., Nature **440**, 187 (2006)

Collective excitations

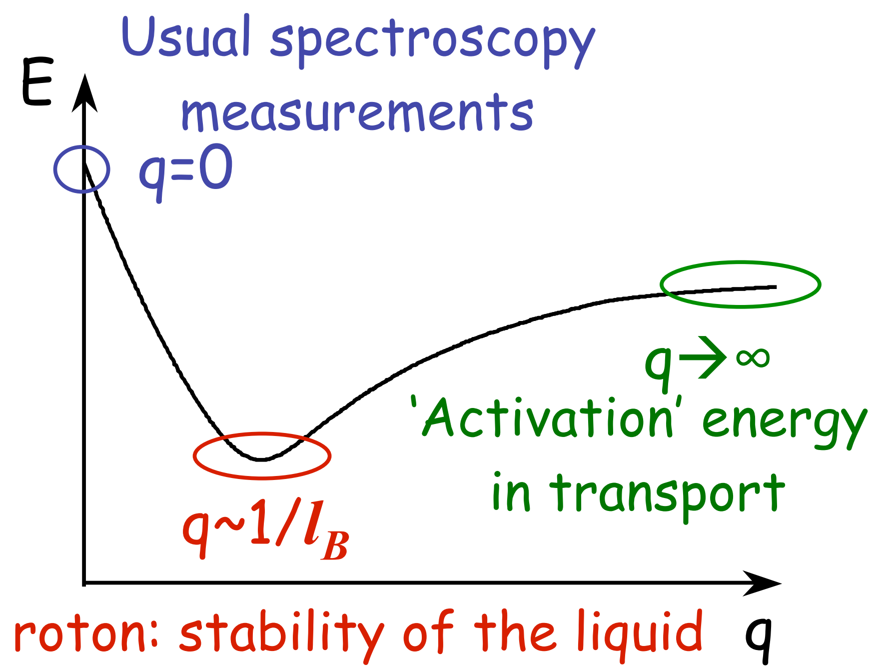


I.V. Lerner, Y. Lozovik, *Sov. Phys. JETP* (1980)
C. Kallin and B.I. Halperin, Phys. Rev. B (1984)

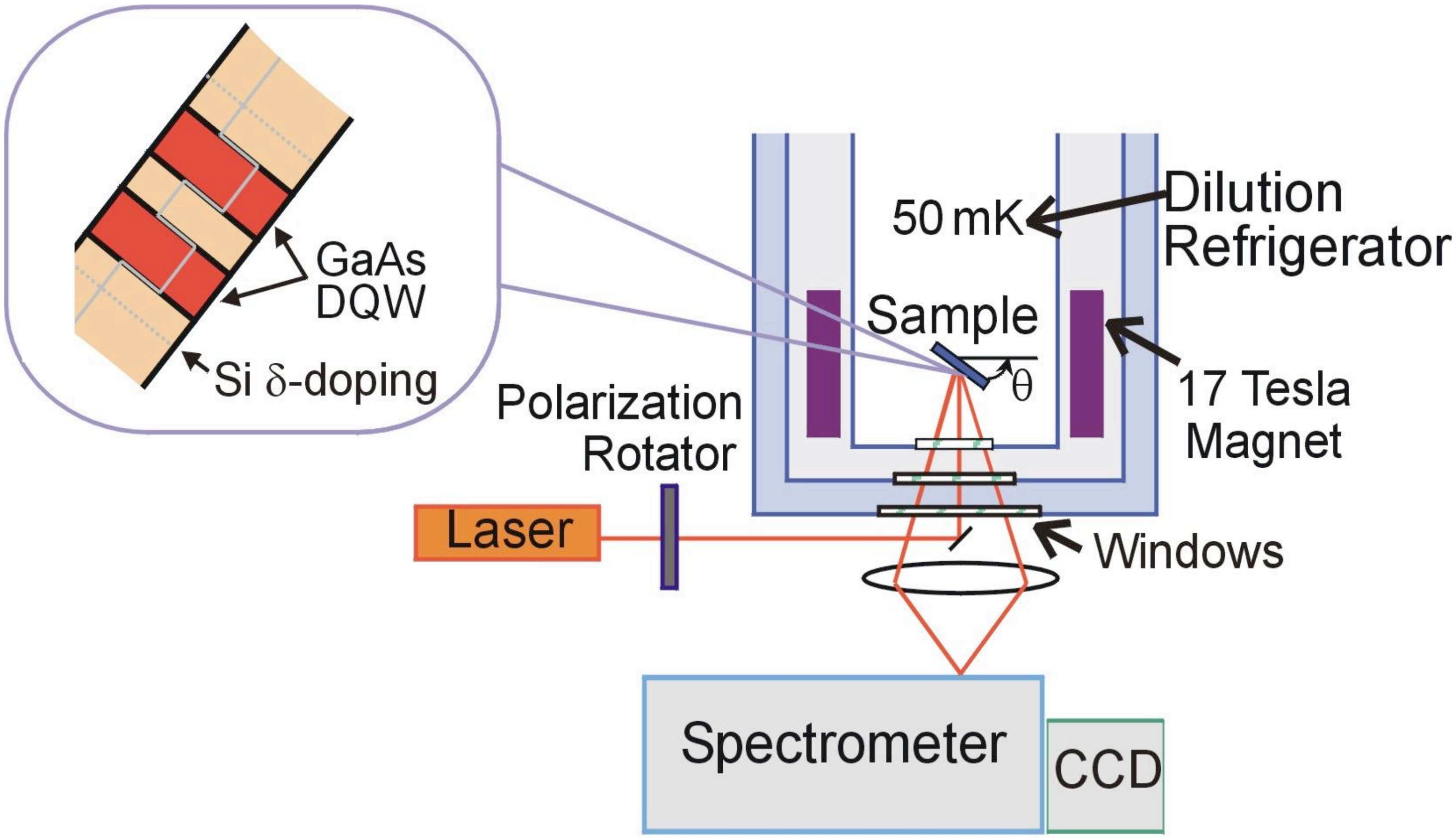
Excitonic binding + depolarization shift

⇩

Dispersion



Resonant inelastic light scattering

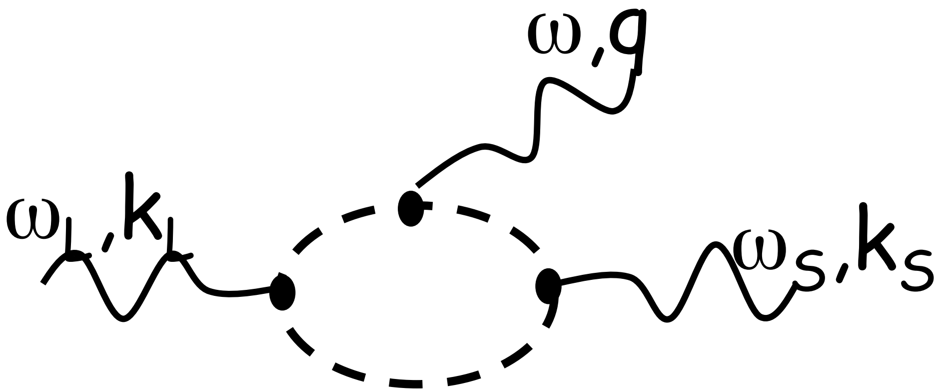


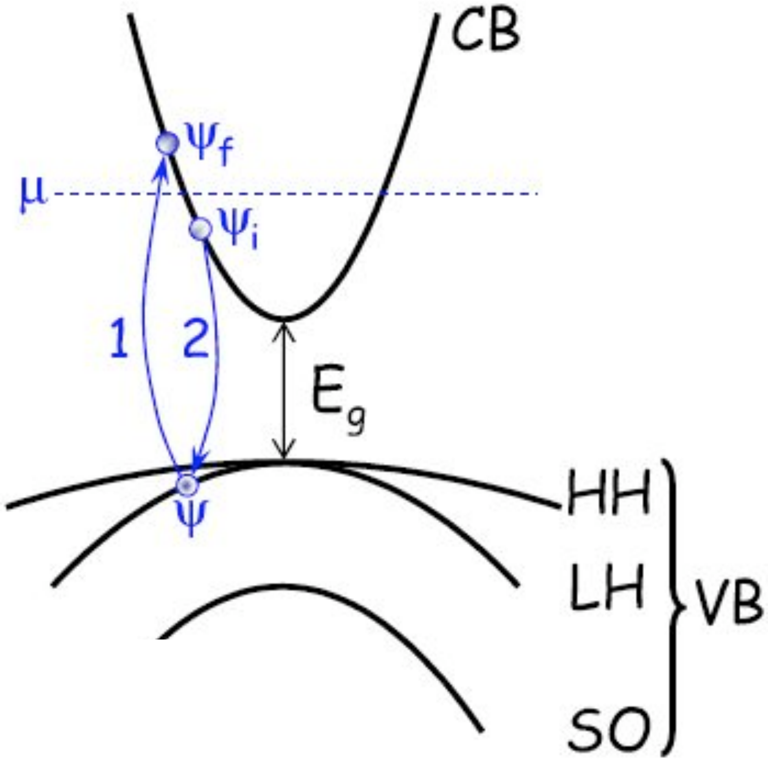
$$\omega_L - \omega_S = \pm\omega(q) \qquad q = |\mathbf{k}_{//}|$$

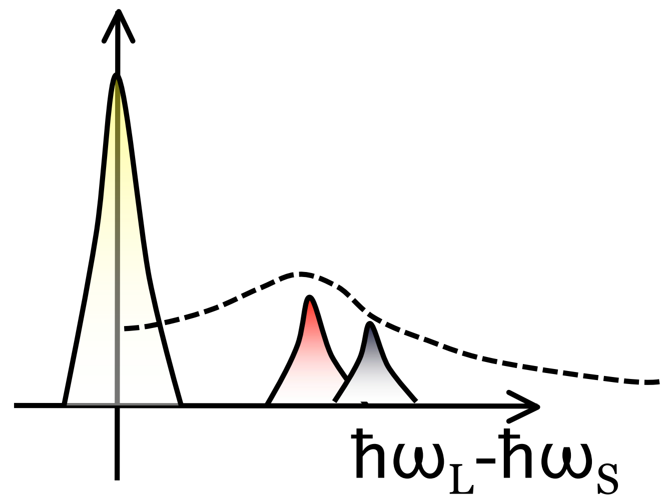
Translational invariance ⇨ $\mathbf{q} = \mathbf{k}_{L//} - \mathbf{k}_{S//} = (k_L - k_S)\sin\theta <\sim 10^5 \text{cm}^{-1}$

V. Pellegrini, A. Pinczuk Phys. Stat. Sol. (b) **243**, 3617 (2006)

Collective excitations probed by resonant inelastic light scattering





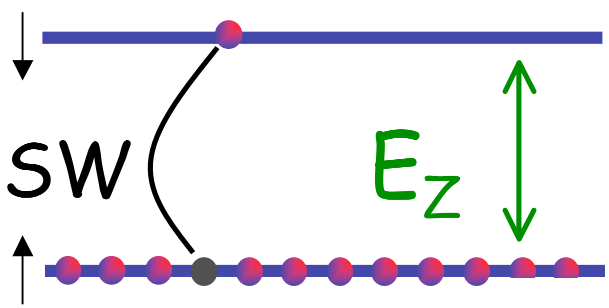


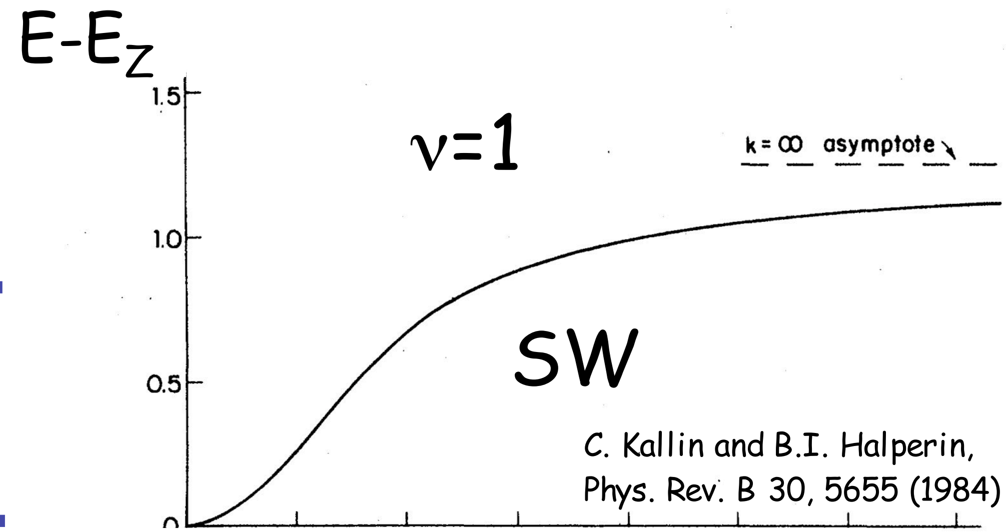
spin ($e_L \times e_S$)

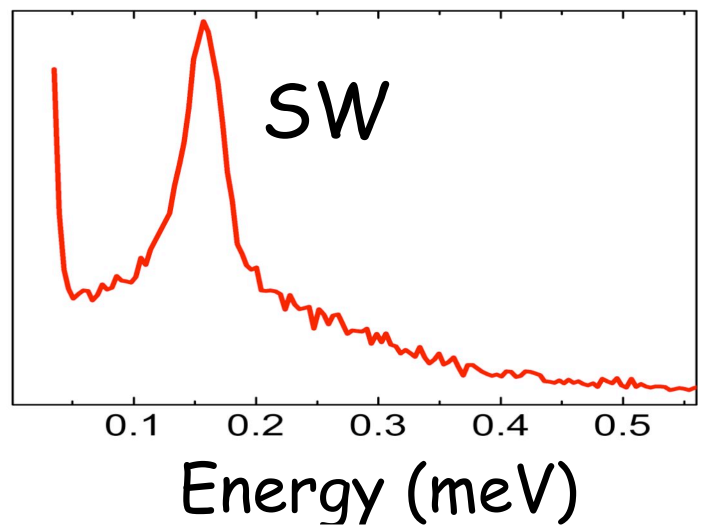
charge ($e_L \cdot e_S$)

Collective spin excitations

Spin wave at ν=1







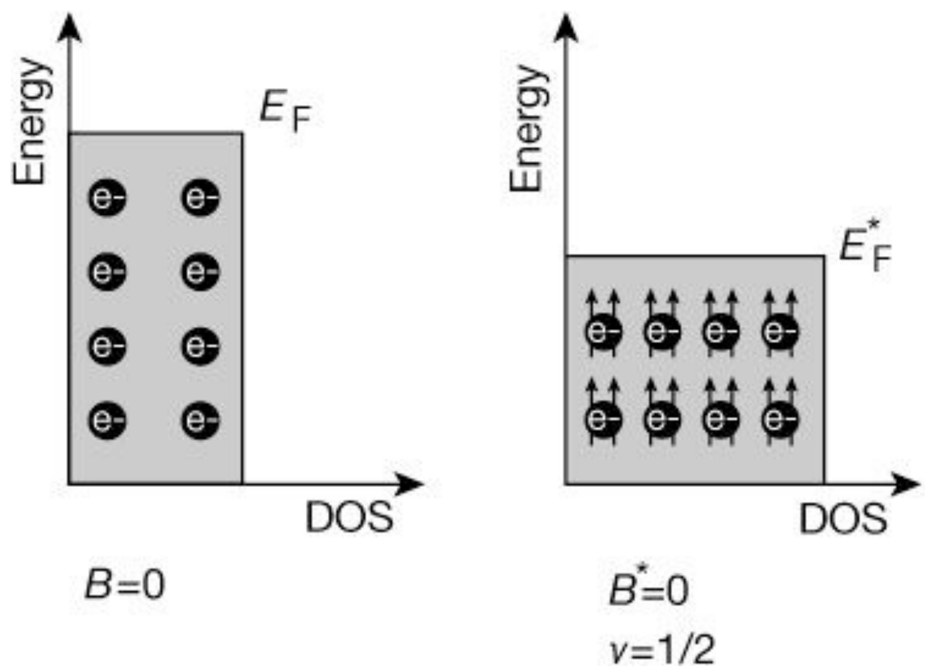
Composite fermion quasiparticles

$$\nu = \nu_{CF}/(2\nu_{CF} \pm 1)$$

CF's experience effective magnetic field

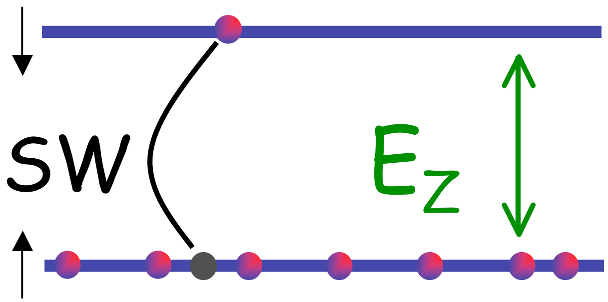
$$B^* = B - B_{1/2}$$

Electron Fermi sea   Composite fermion Fermi sea

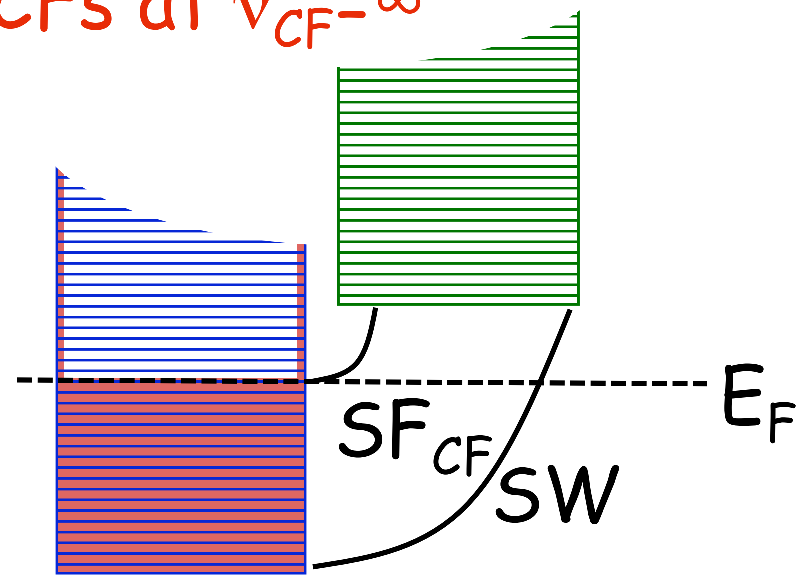


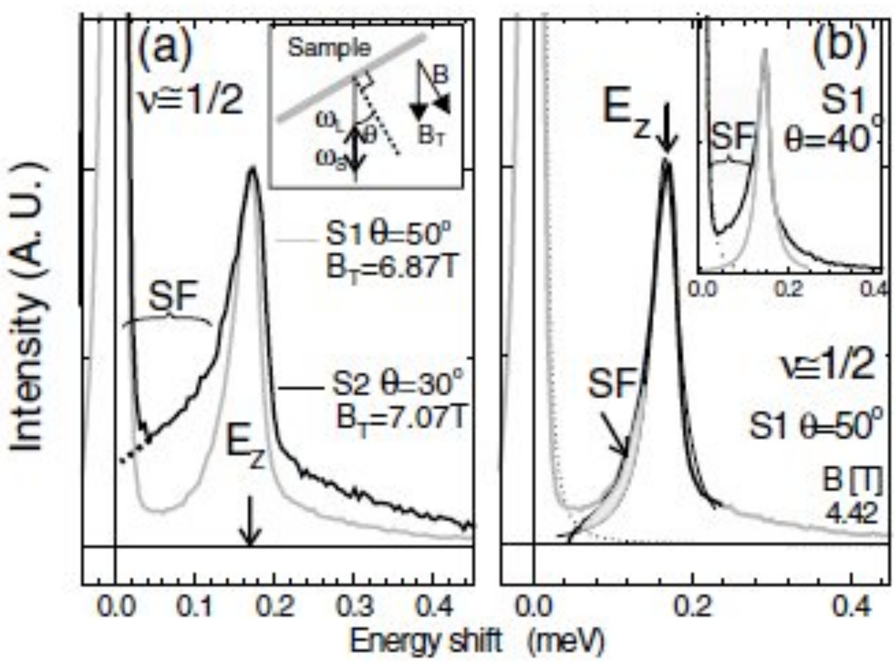
Composite fermion spin excitations

Electrons at $\nu=1/2$



CFs at $\nu_{CF}=\infty$



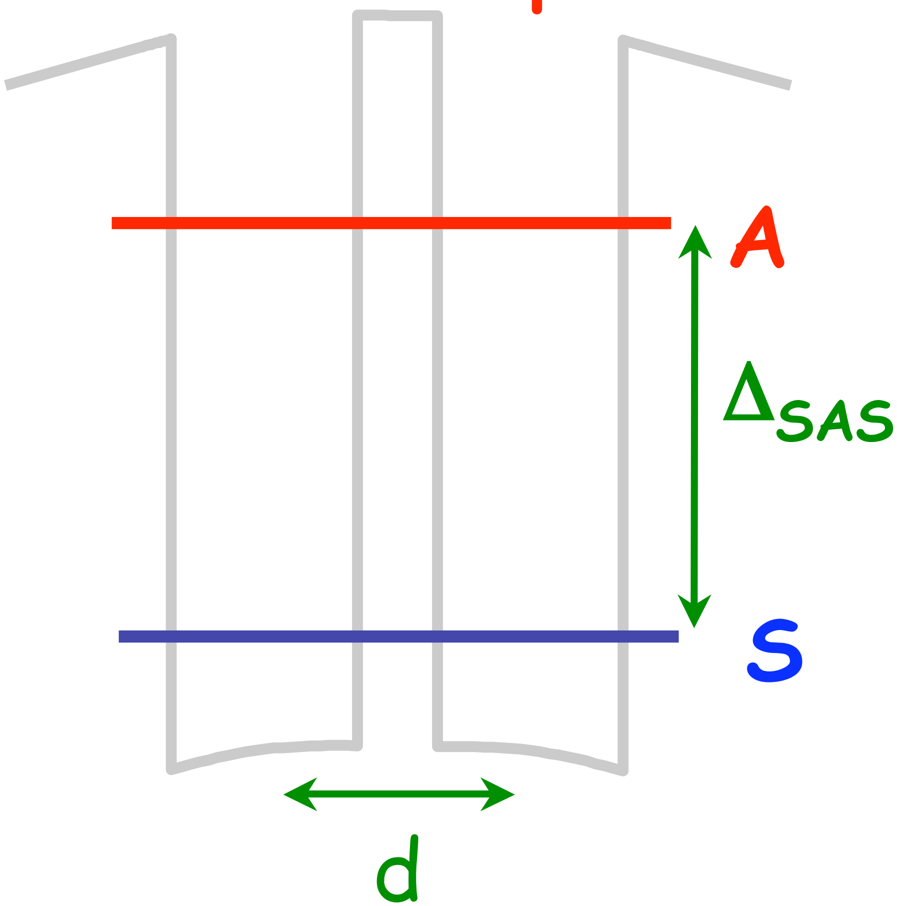


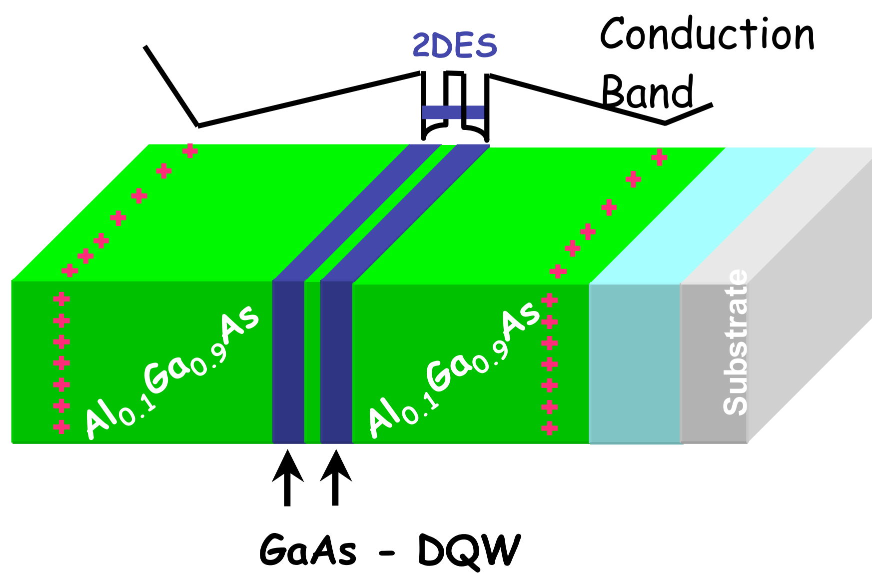
I. Dujovne et al. PRL **95**, 056808 (2005)

Quantum Hall fluids in bilayers at $\nu_T=1$

A multicomponent quantum Hall fluid

PseudoSpin or layer index



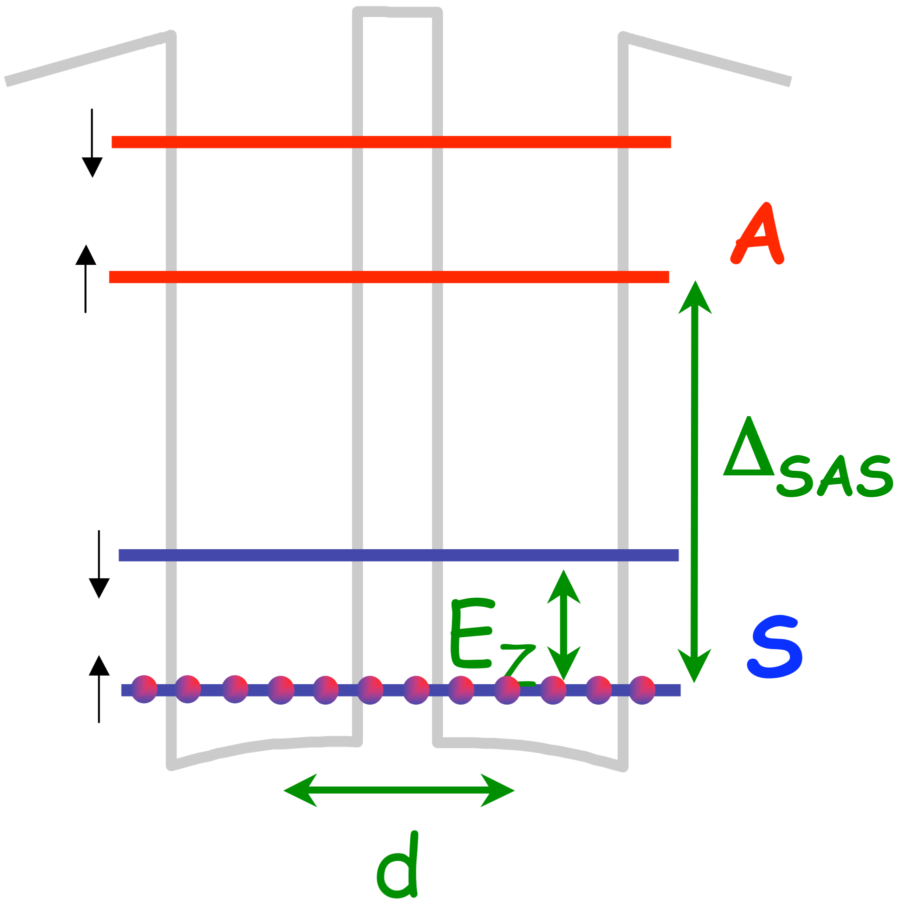


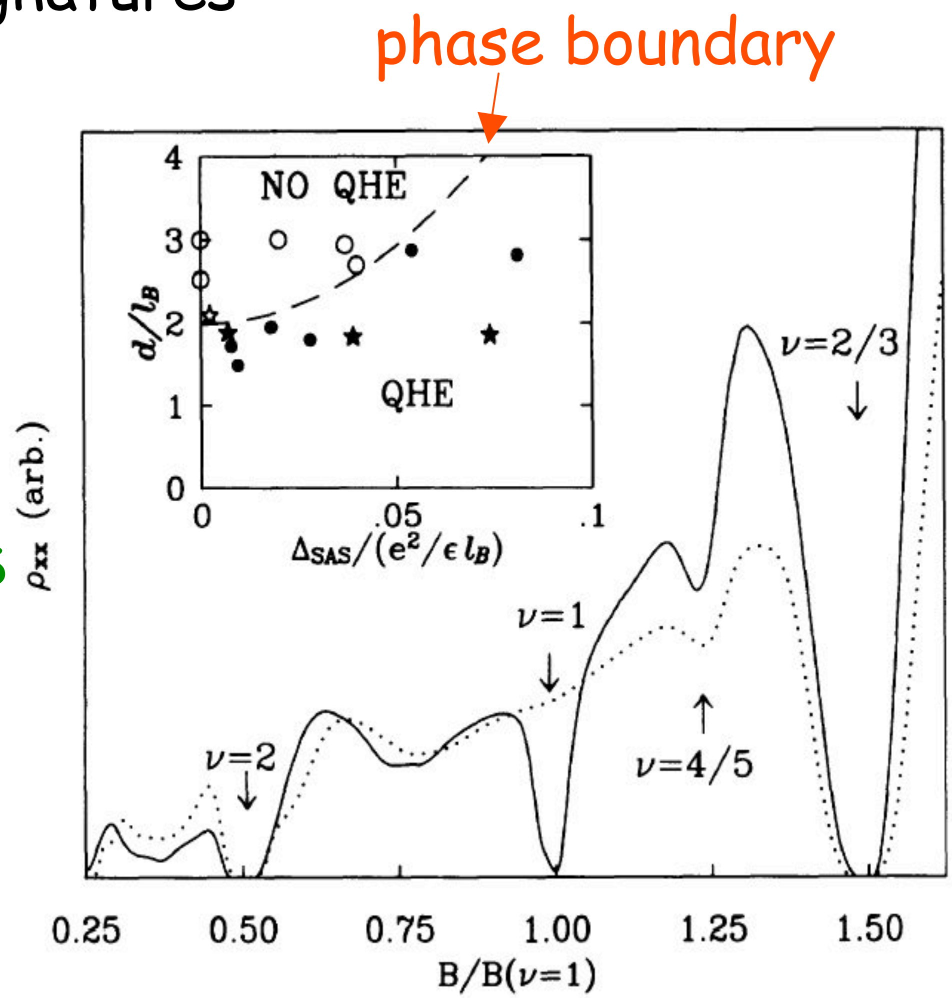
L_w = 18nm
L_b = 7.5nm; 6.23nm

$n \approx 1.2 \cdot 10^{11}$ cm^{-2}
$\mu > 10^{6}$ cm^2/Vs

Instabilities in quantum Hall ferromagnets

Seminal magneto-transport signatures





G. S. Boebinger *et al.*, Phys. Rev. Lett. **64**, 1793 (1990)

S. Q. Murphy, *et al.*, Phys. Rev. Lett. **72**, 728 (1994)

Interlayer-correlated excitonic phase and superfluid-like behavior in counterflow current

$\Delta_{SAS} = 0$

M. Kellogg et al., PRL (2004)

E. Tutuc et al., PRL (2004)

R.D. Wiersma et al., PRL (2004)

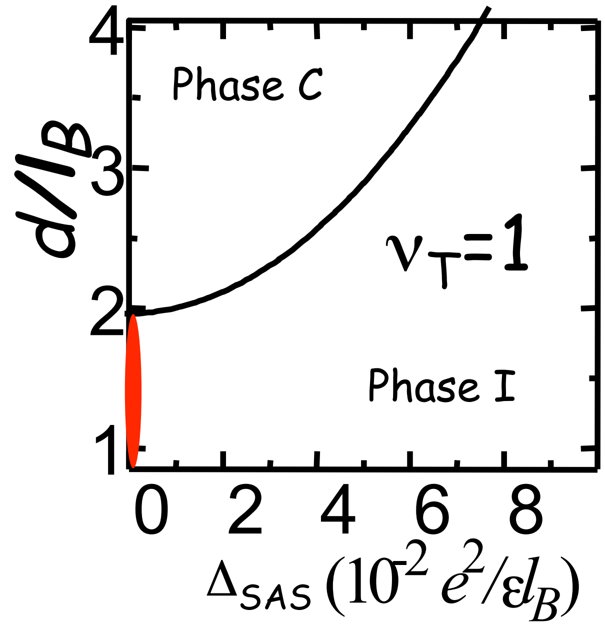
$\Delta_{SAS} > 0$

S. Luin et al., (2005)

P. Giudici, et al., Phys. Rev. Lett. (2008)

A.R. Champagne, et al., Phys. Rev. Lett. (2008)

B. Karmakar et al., Phys. Rev. Lett. (2009)



What is the nature of the incompressible and compressible phases at finite Δ_{SAS}?

What is the nature of the QPT?

What about the thermal and filling factor stabilities of the coherent phase?

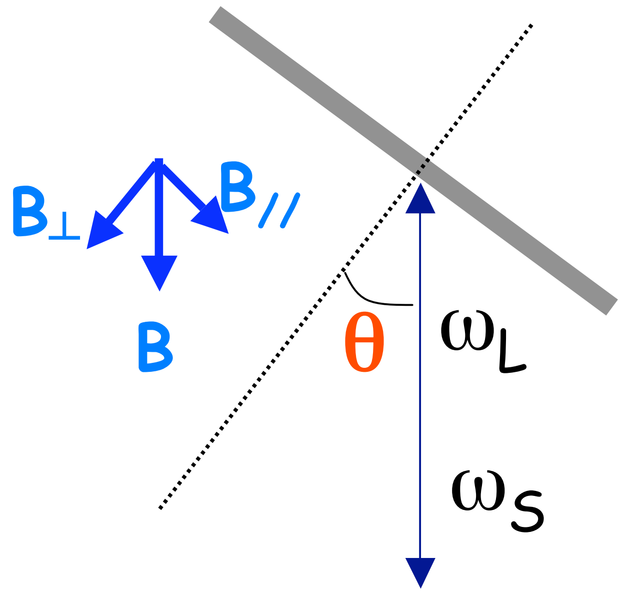
What is the high temperature phase?

What is the role of composite fermions (if any)?

What is the role of spin?

Is there co-existence of phases ?

In-plane magnetic fields to tune the total magnetic field (i.e. Zeeman gap) and the tunneling gap



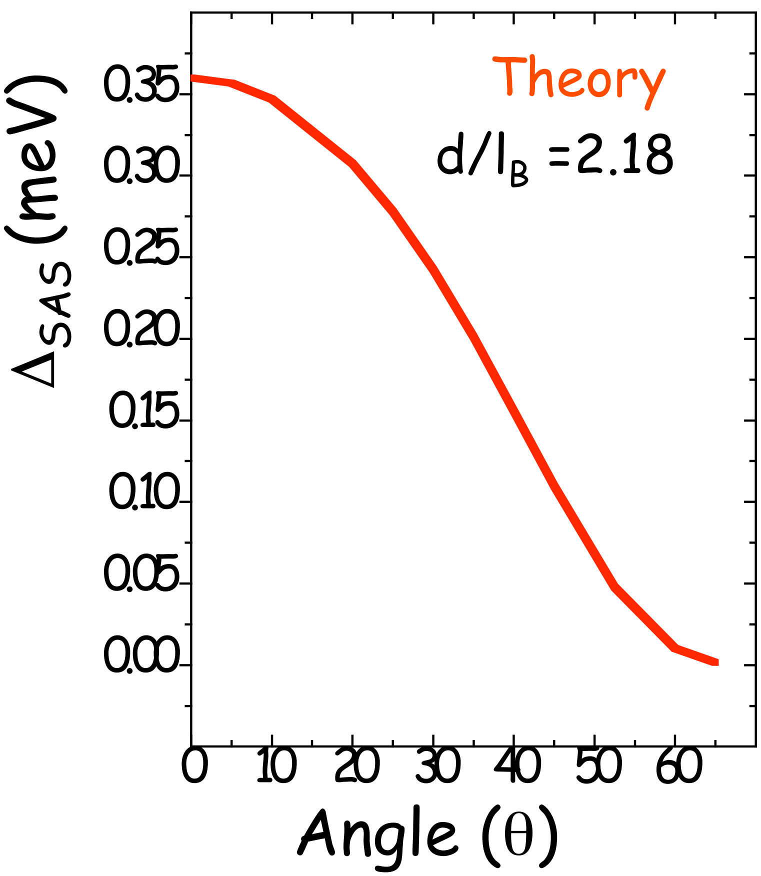
$$\tan(\theta) = \frac{B_{//}}{B_{\perp}}$$

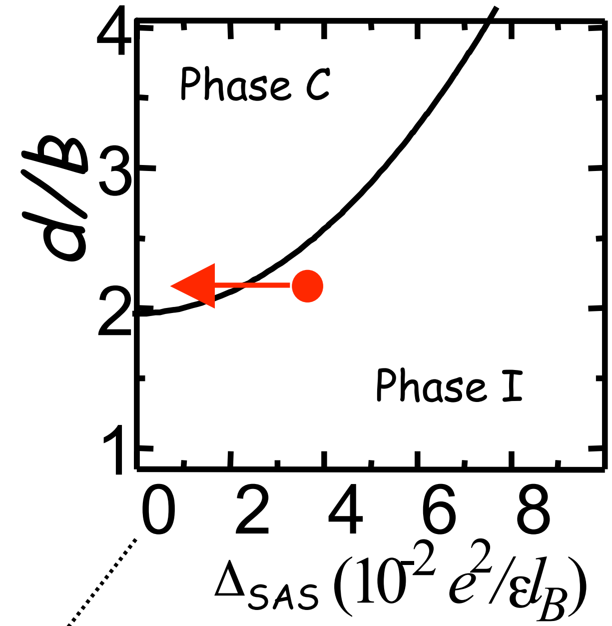
$$\Delta_{SAS} > 0$$

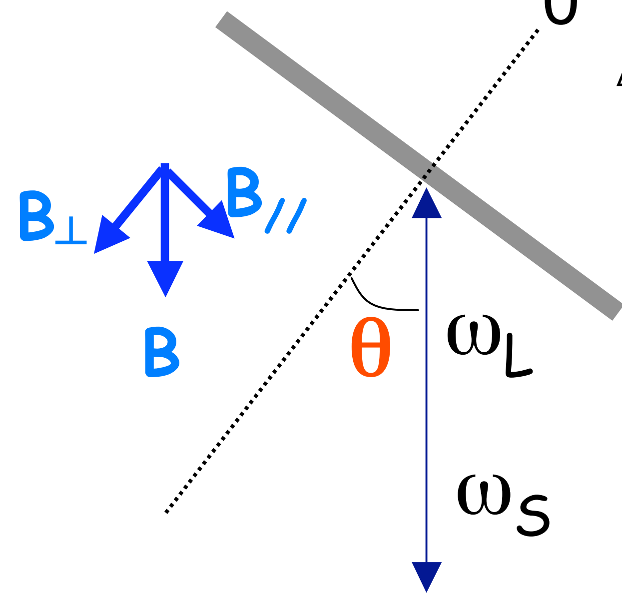
In-plane magnetic fields reduce Δ_{SAS}

$$\Delta_{SAS}(\theta) = \Delta_{SAS}\, e^{-[d/2l_B \tan(\theta)]^2}$$

J. Hu, A.H. MacDonald, Phys. Rev. B **46**, 12554 (1992)

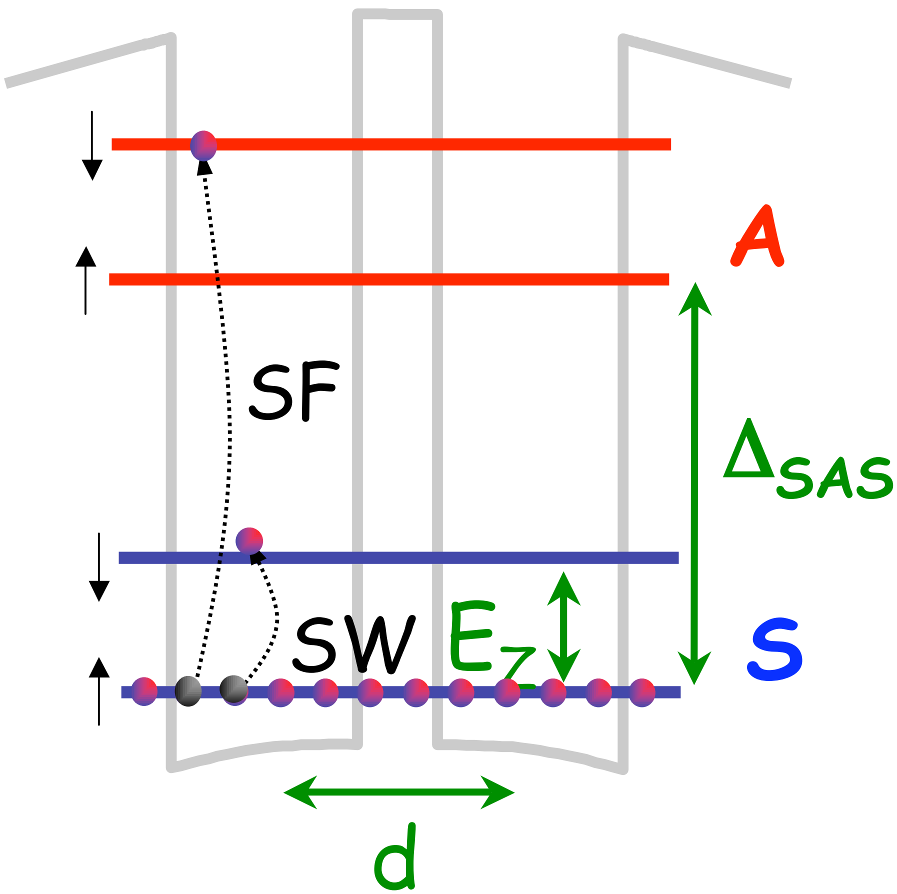


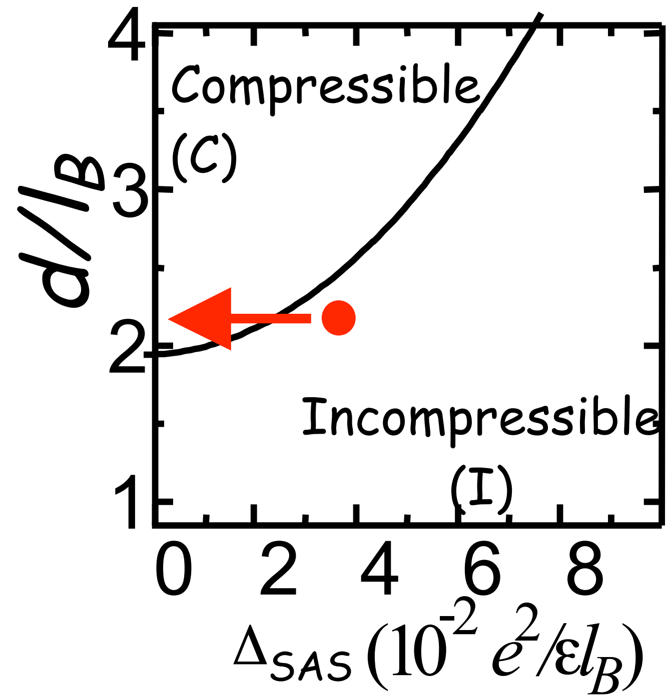




$$\tan(\theta) = \frac{B_{//}}{B_{\perp}}$$

Quantum Hall ν_T=1 bilayers at finite tunneling

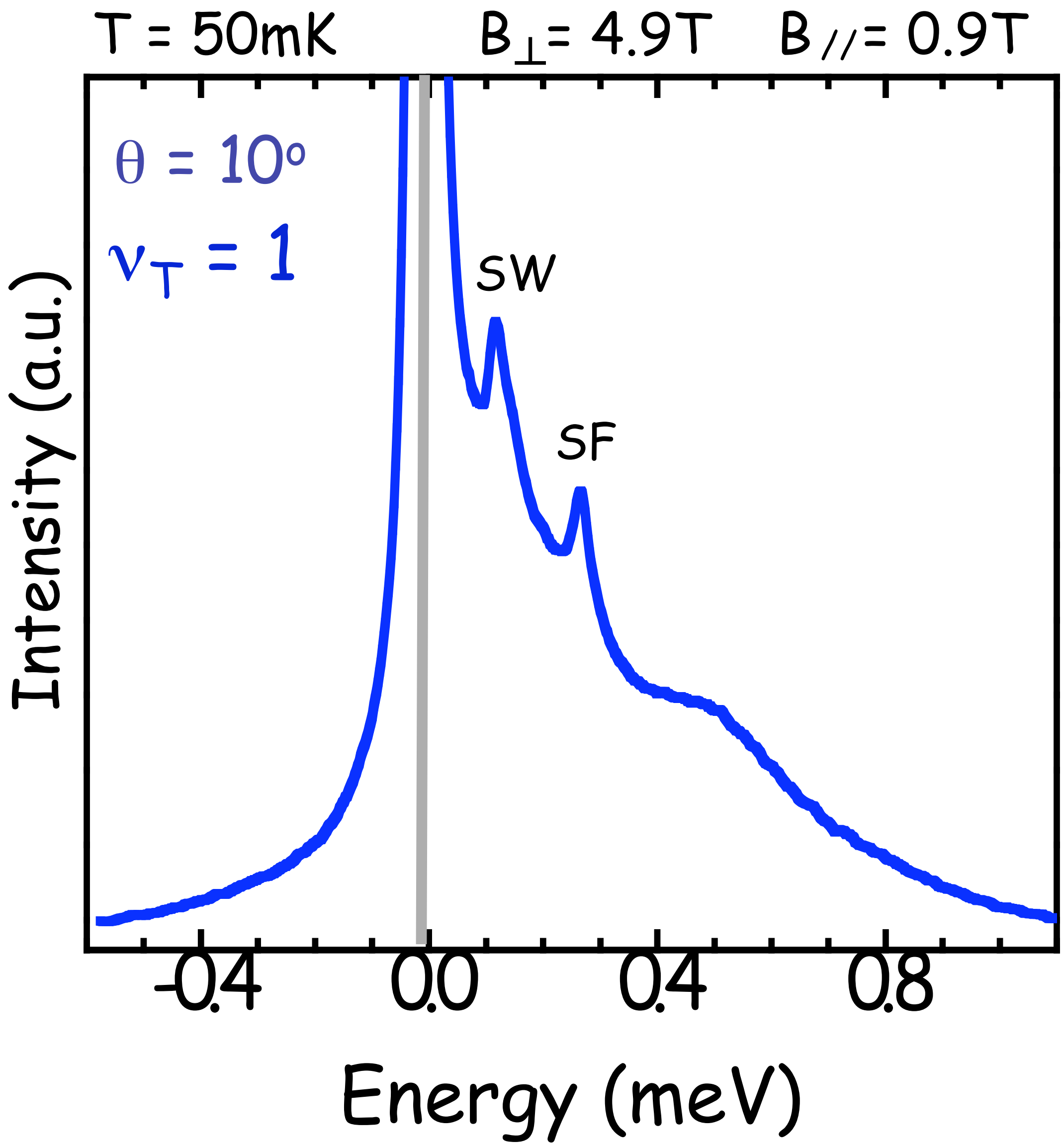




We probe emergent phases and phase transition

by measurements of Rayleigh scattering

Resonant light scattering in phase I



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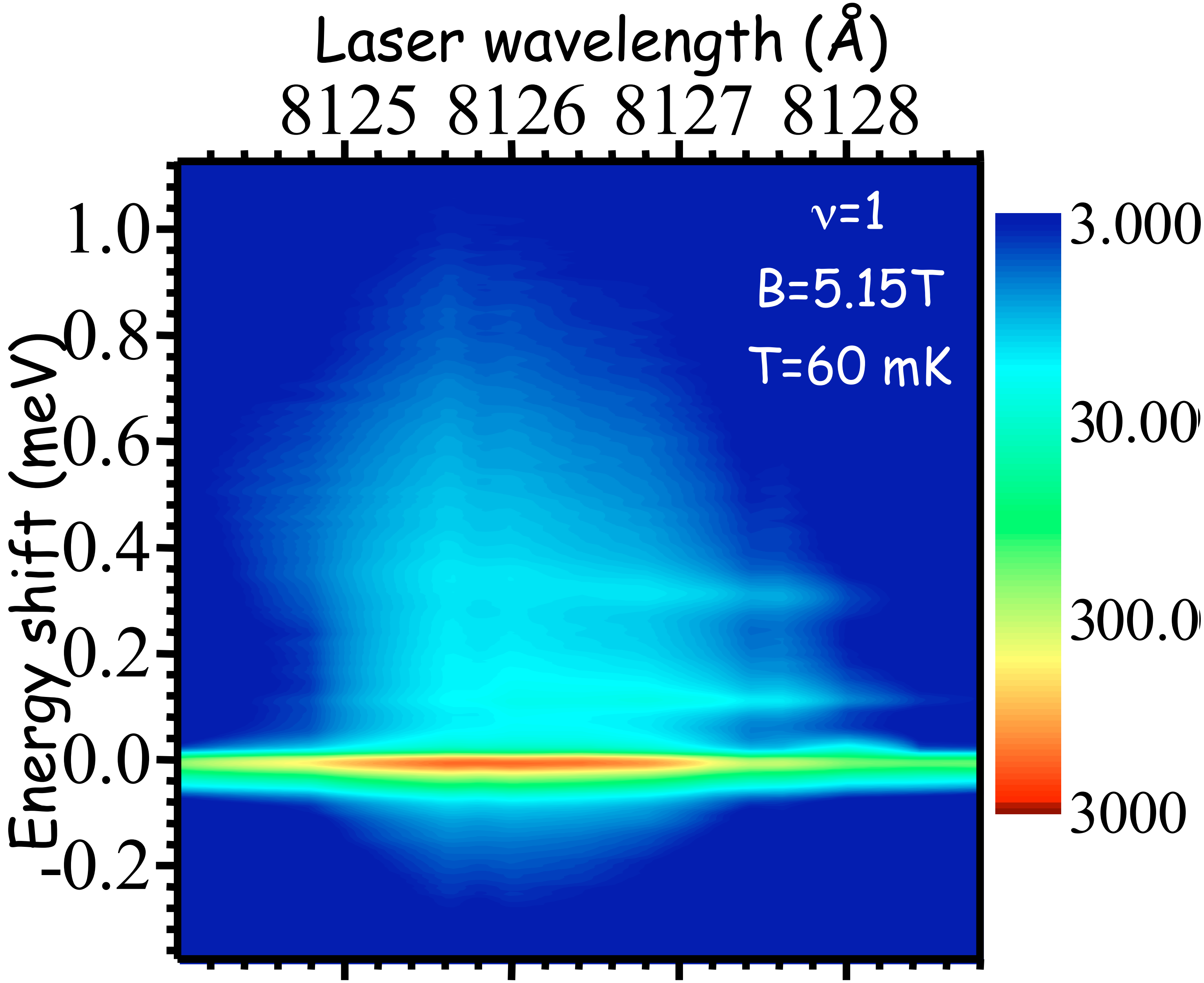
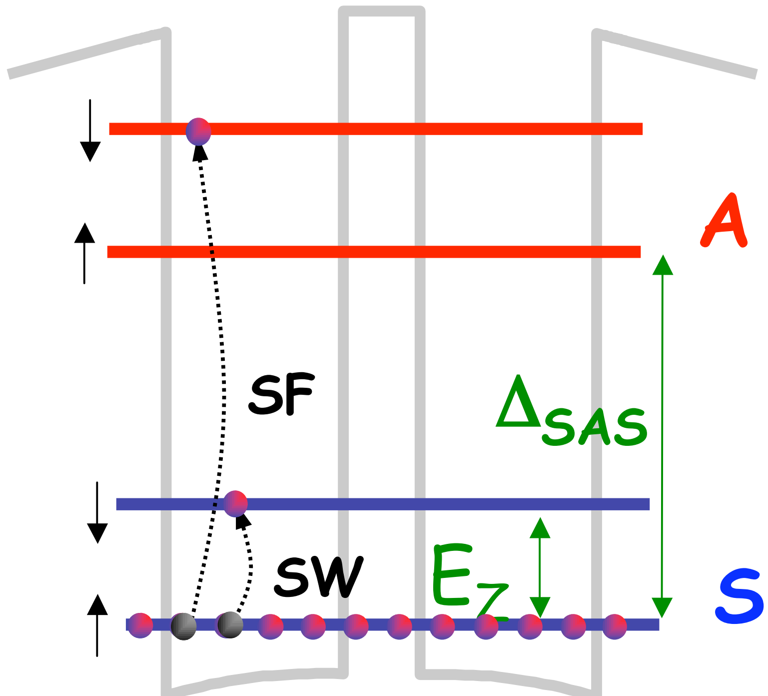
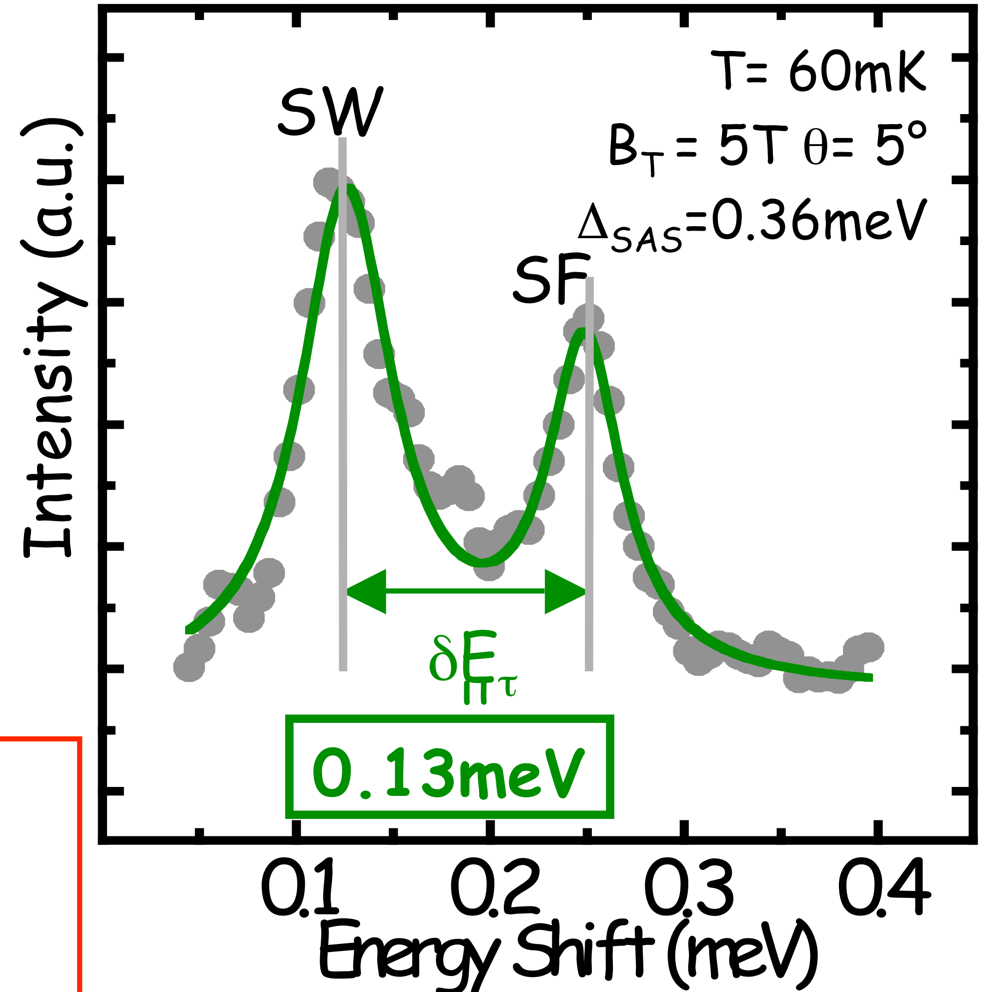
Resonant light scattering in phase I



Excitons in phase I at finite Δ_{SAS}



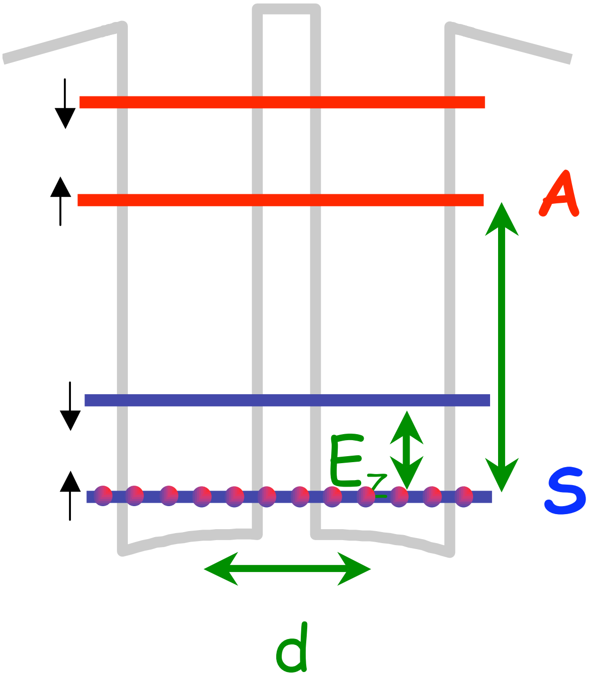


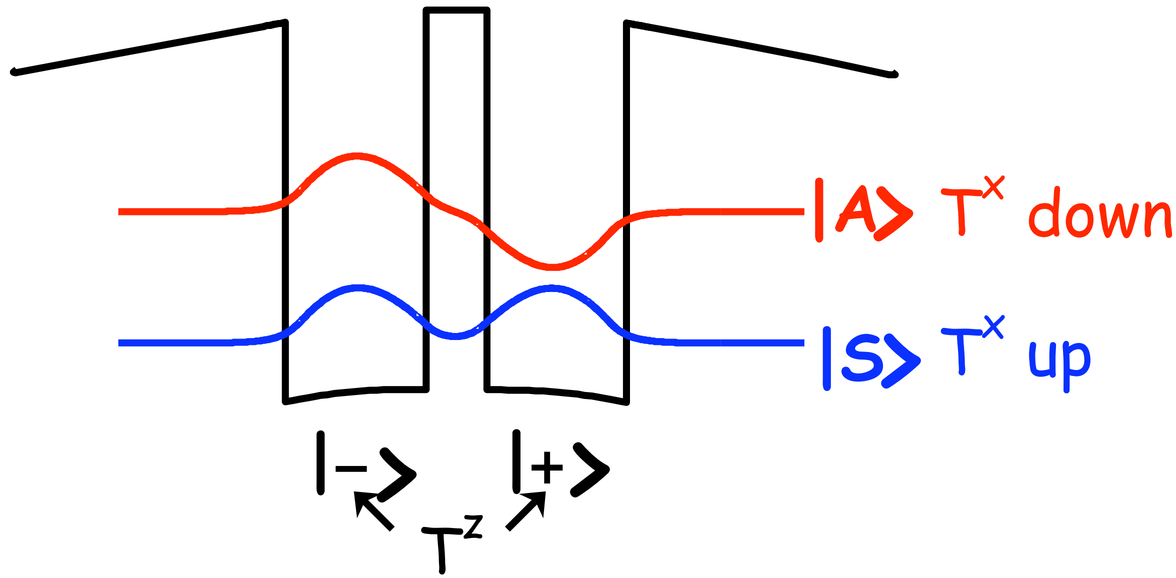
$$E_{SW} = E_Z$$

$$E_{SF} = E_Z + \Delta_{SAS} \cdot \langle \tau^x \rangle$$

$$(E_{SF} - E_{SW}) / \Delta_{SAS} = \langle \tau^x \rangle$$

Order parameter





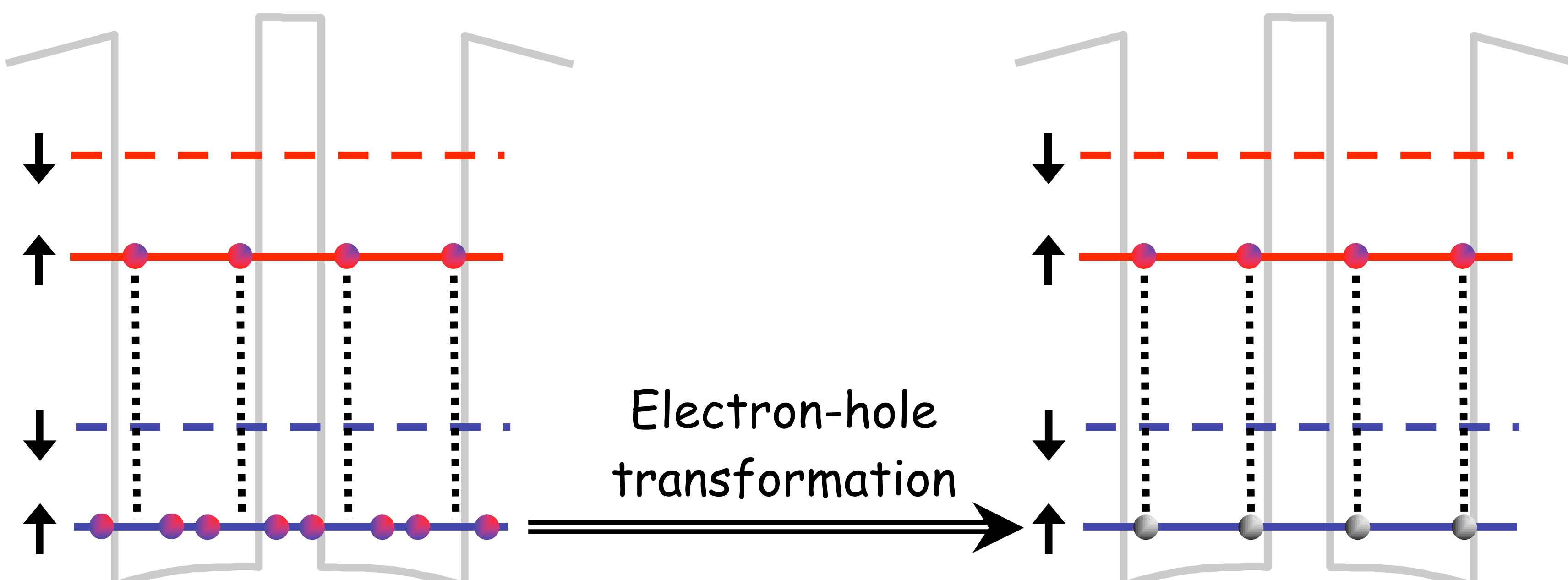
Order parameter: $\langle\tau^x\rangle = (n_S - n_{AS})/(n_S + n_{AS})$ $[\tau^x = 2T^x]$

Mean field theories: at $\nu=1$ $\langle\tau^x\rangle = 1$

Correlations --> antisymmetric electrons

$$\langle \tau^x \rangle = (n_S - n_{AS})/(n_S + n_{AS}) = (n_S - n_{AS})/n_T$$

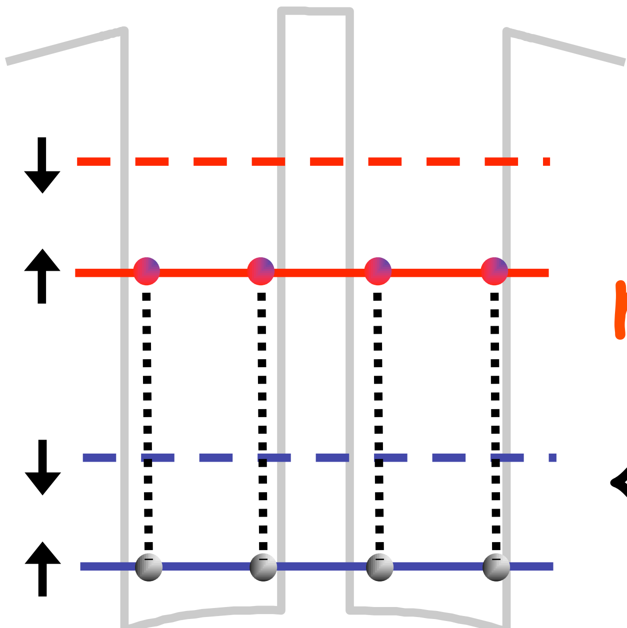
$$\langle \tau^x \rangle < 1 \Rightarrow n_{AS} > 0$$



The persistence of the QH state suggests that electrons and holes are bound

Phase I is an excitonic insulator (QH state)

Correlations --> inter-layer excitons



$n_{AS} = n_{ex}$

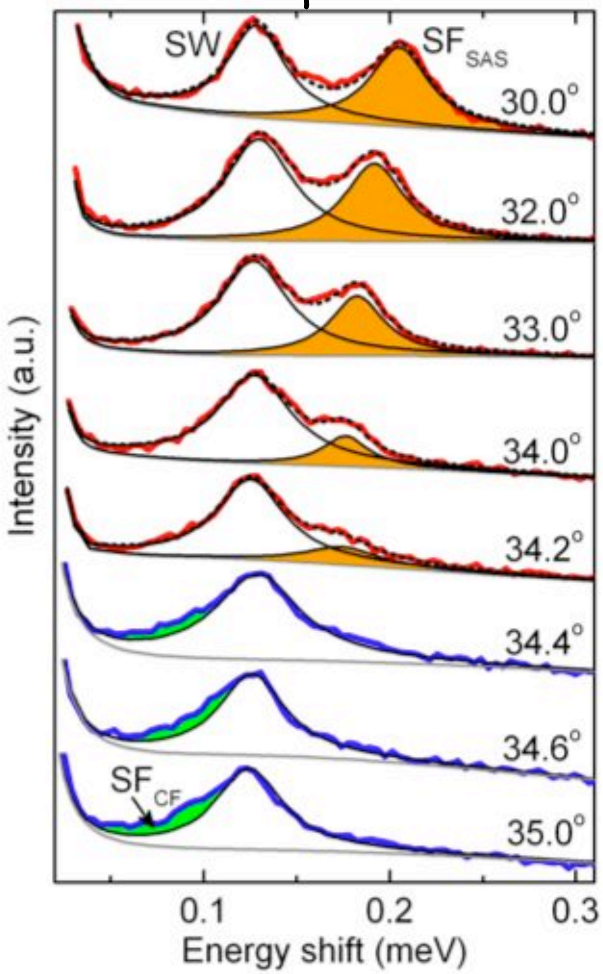
$\langle \tau^x \rangle = (n_S - n_{AS})/(n_S + n_{AS})$

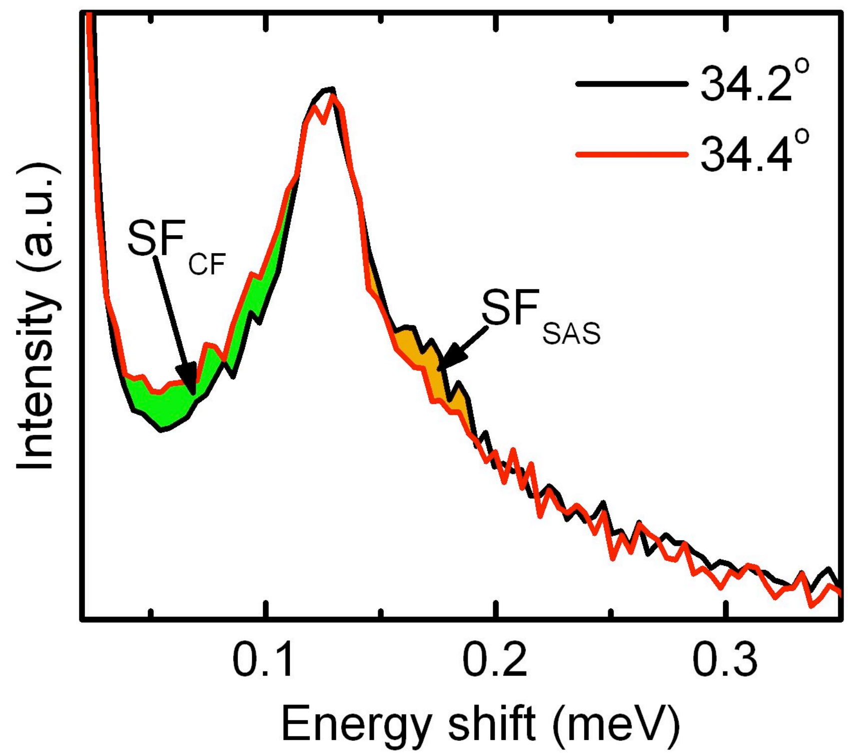
$= 1 - 2n_{ex}/n_T$

Phase I is an excitonic insulator (QH state)

First-order quantum phase transition between an excitonic and a CF-metal correlated phases

$\nu_T = 1$

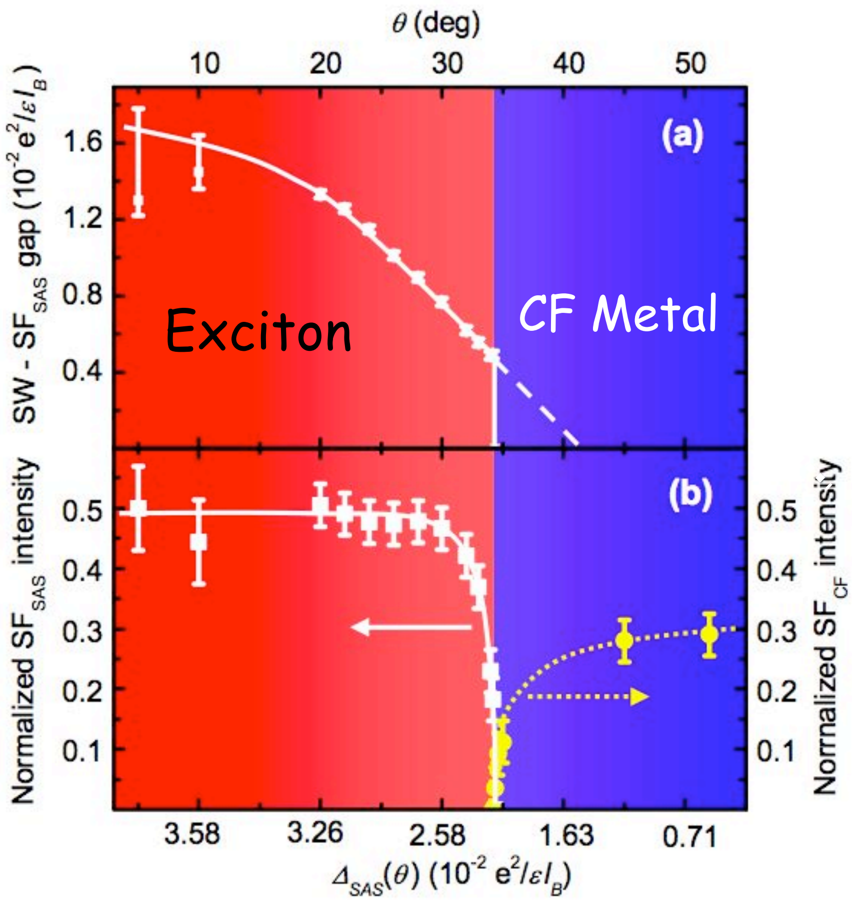


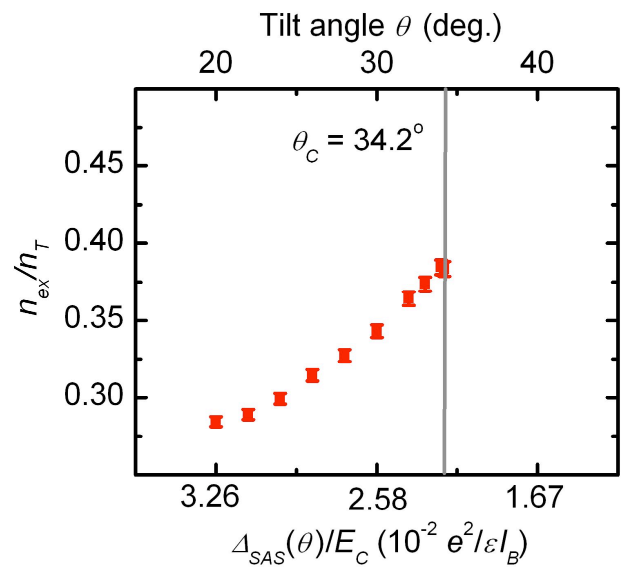


$$\Delta^c_{SAS}/E_c = 2.21 \times 10^{-2} \pm 10^{-4}$$

B. Karmakar et al., PRL (2009)

First-order quantum phase transition between an excitonic and a CF-metal correlated phases

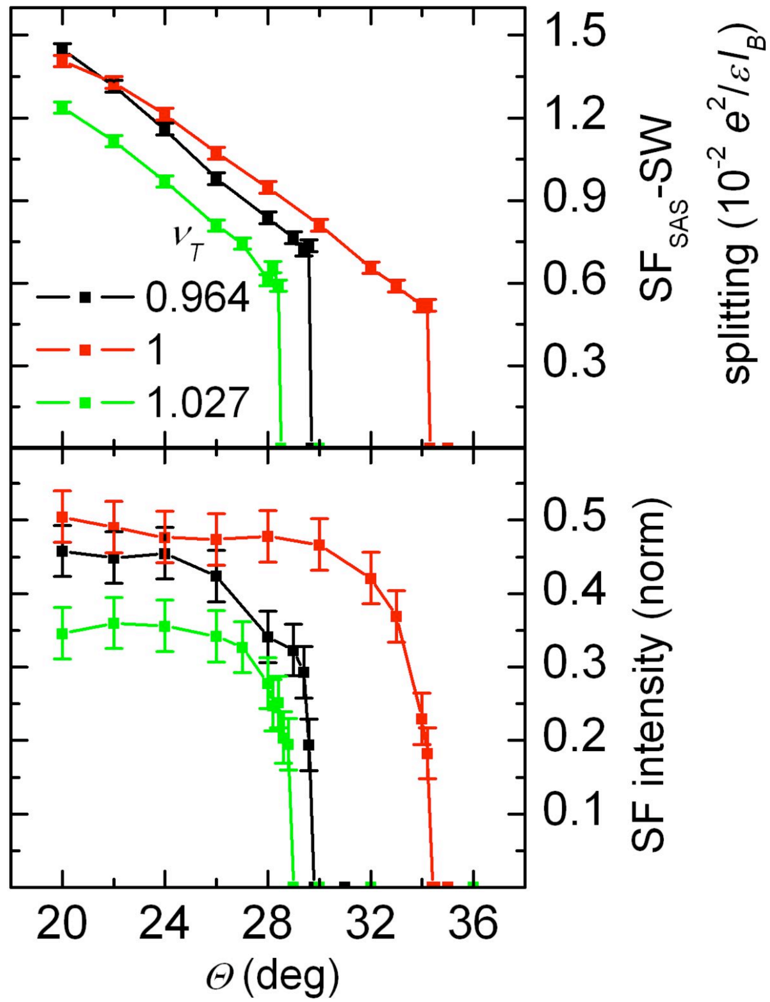


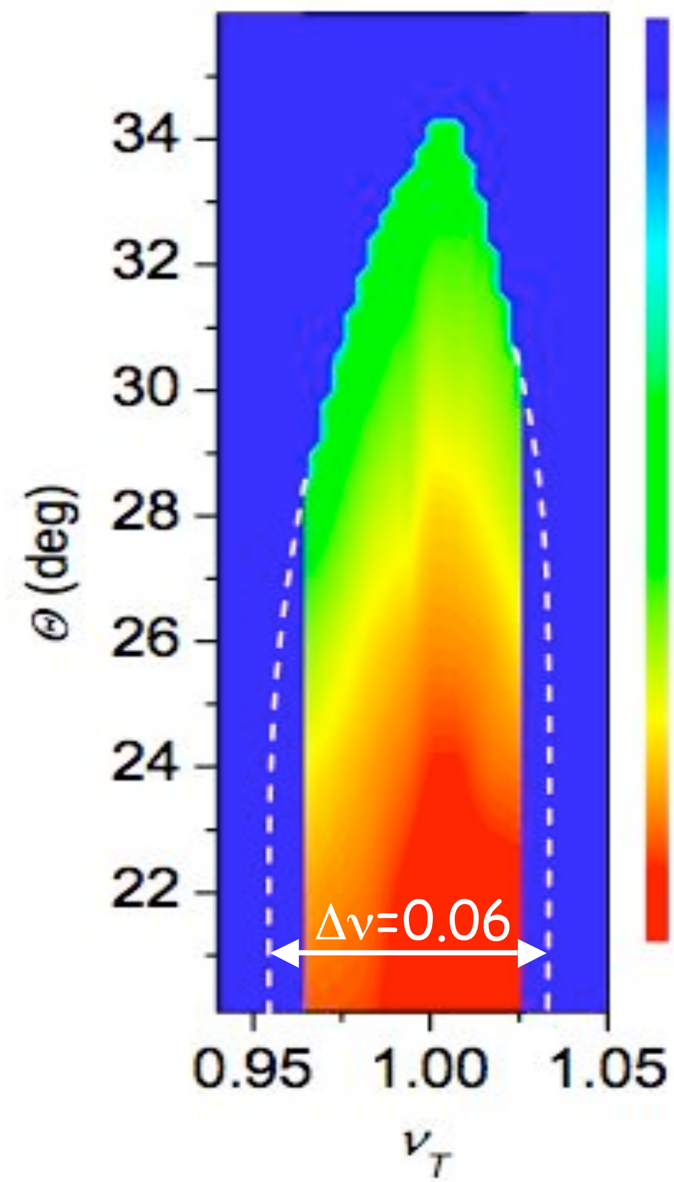


$\nu_T = 1$

B. Karmakar et al., PRL (2009)

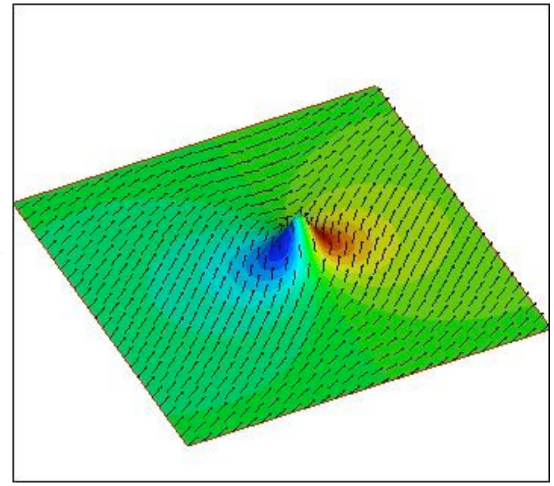
Phase diagram vs filling factor

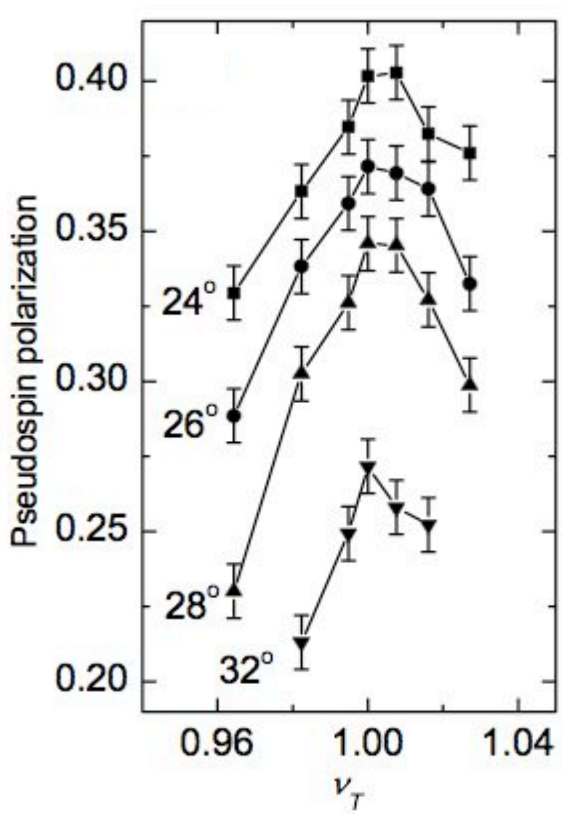




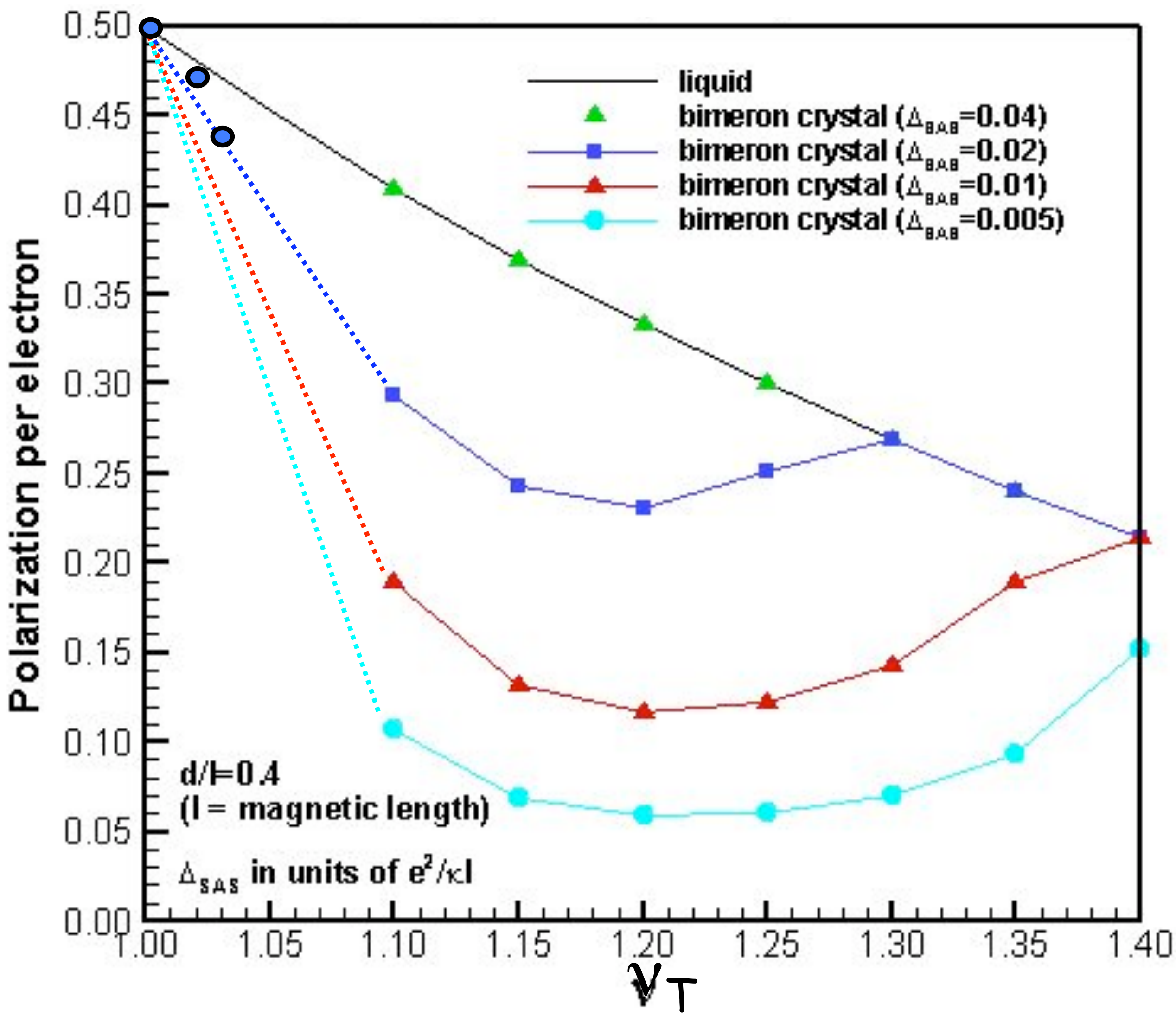
Reduction of pseudospin polarization with deviation from ν_T=1

$$(E_{SF}-E_{SW})/\Delta_{SAS}= \langle\tau^x\rangle$$





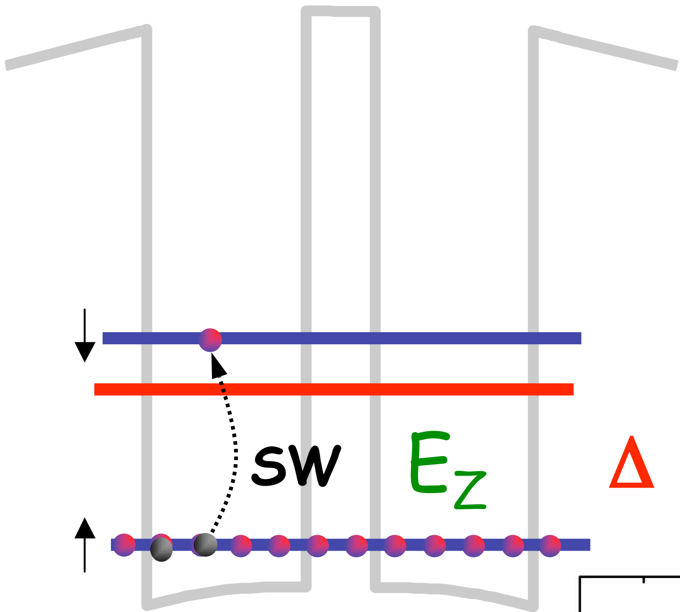
Reduction of pseudospin polarization with deviation from ν_T=1



In collaboration with R. Cotè, H. Fertig

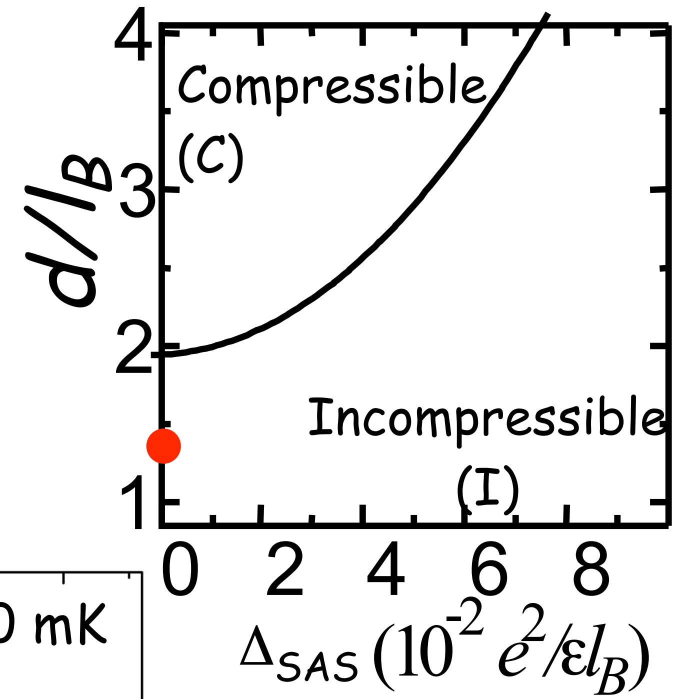
$$\Delta_{SAS} = 0$$

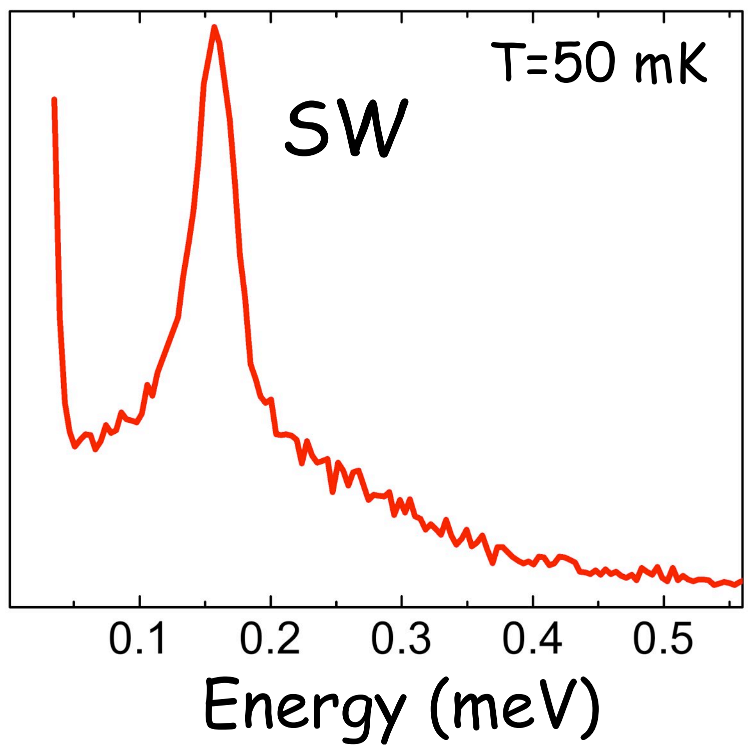
Quantum Hall ν_T=1 bilayers at zero tunneling



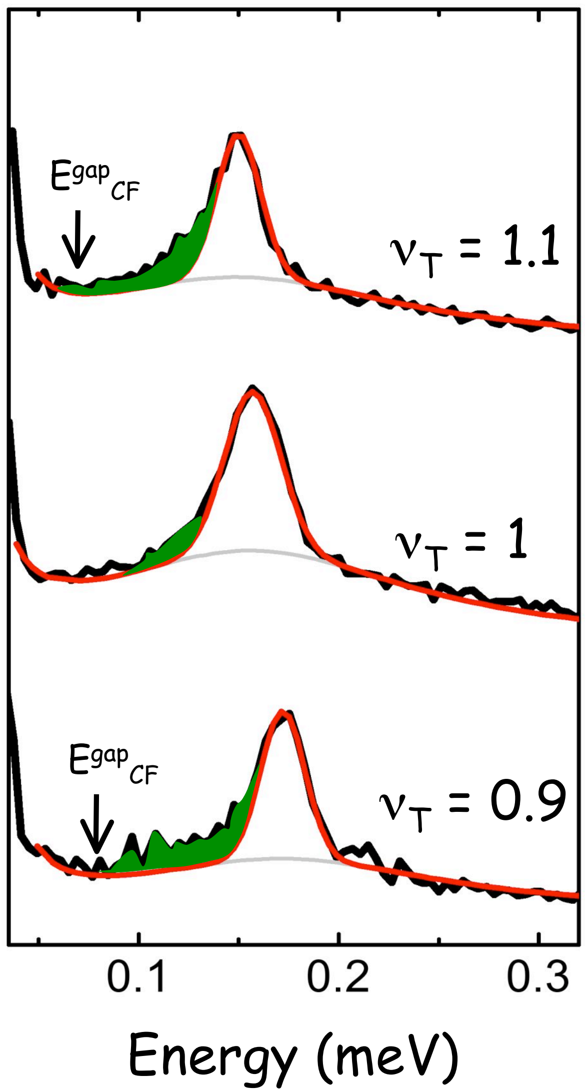
ν_T=1

n_T = 6.9x10^{10}/cm^2



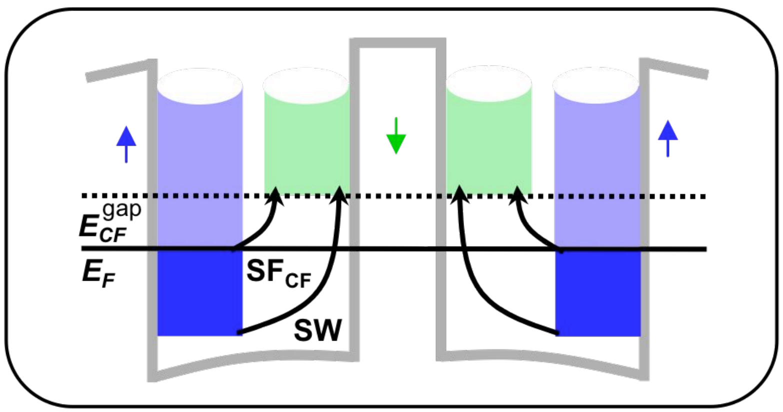


Spin-flip CF excitations appear as ν_T deviates from 1



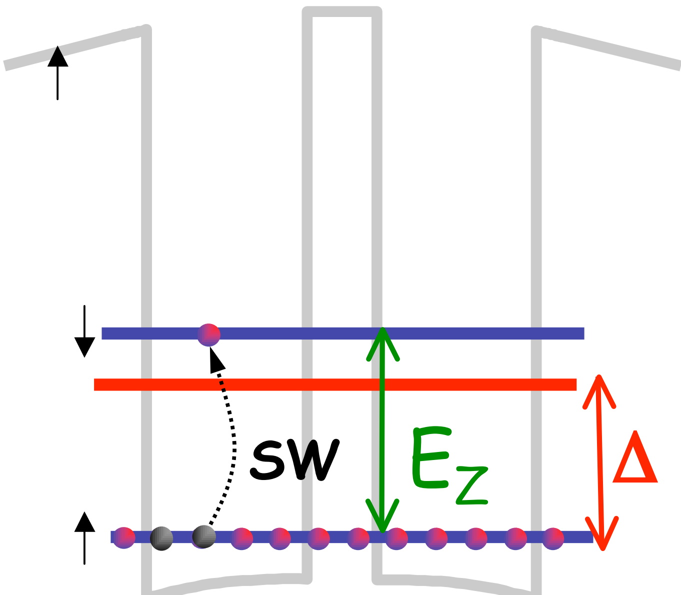
$\theta = 67.5^o$

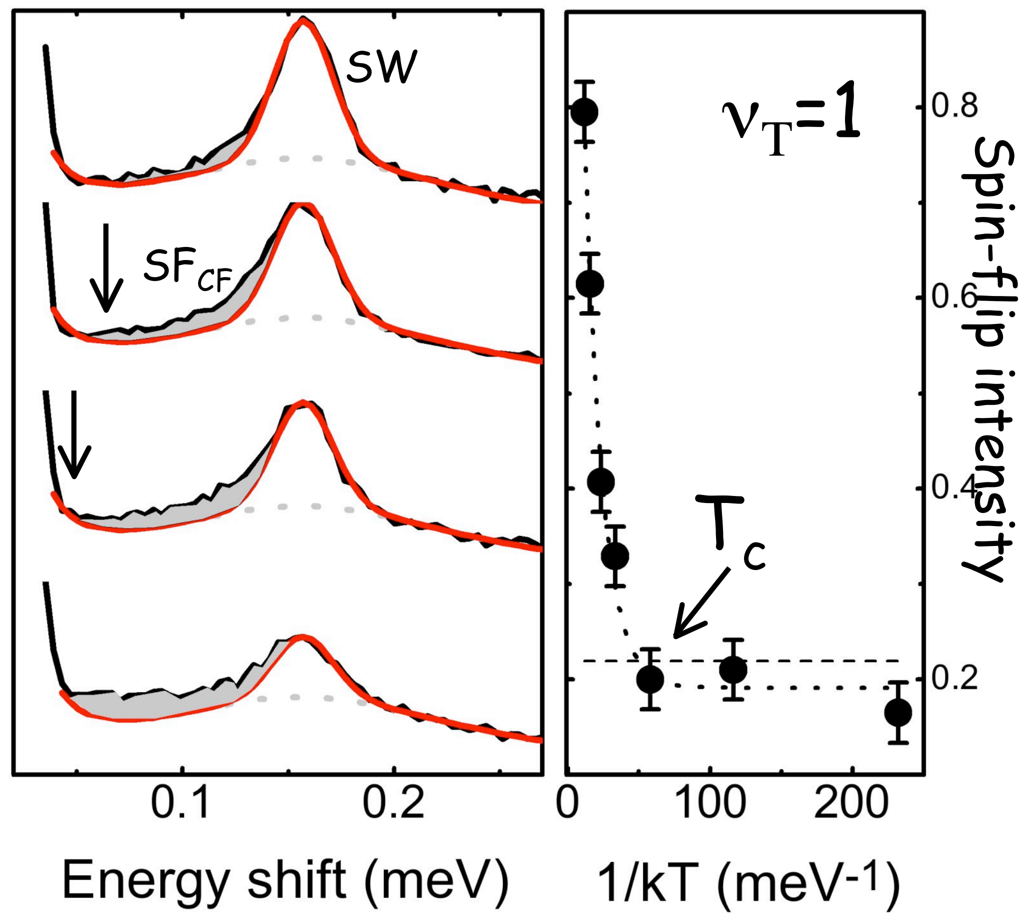
Composite fermions spin-flip excitations across the Fermi energy



Inter-layer coherence → absence of CF modes

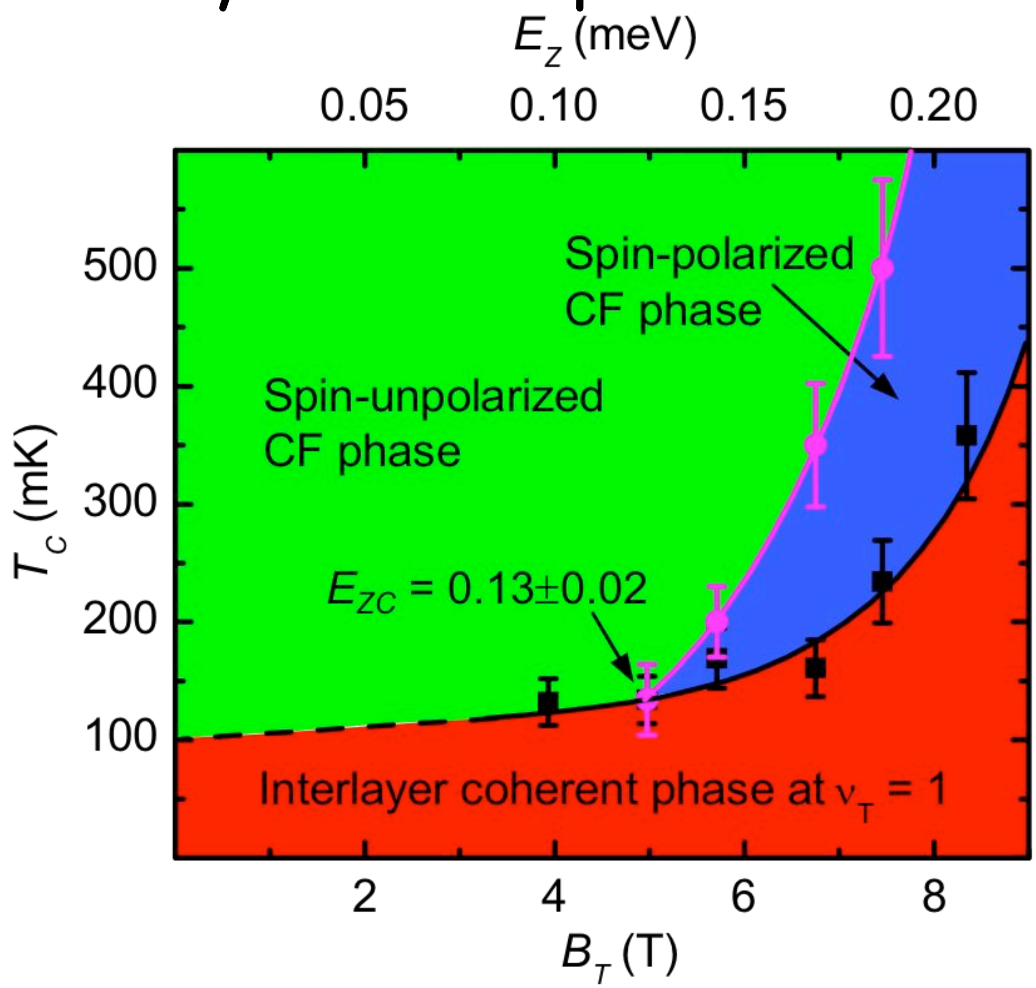
Inter-layer coherent state is replaced by a CF state at T_c





We see a spin transition at 5T ($E_Z \approx 0.125$ meV).

The transition is signaled by the collapse of the CF spin gap.



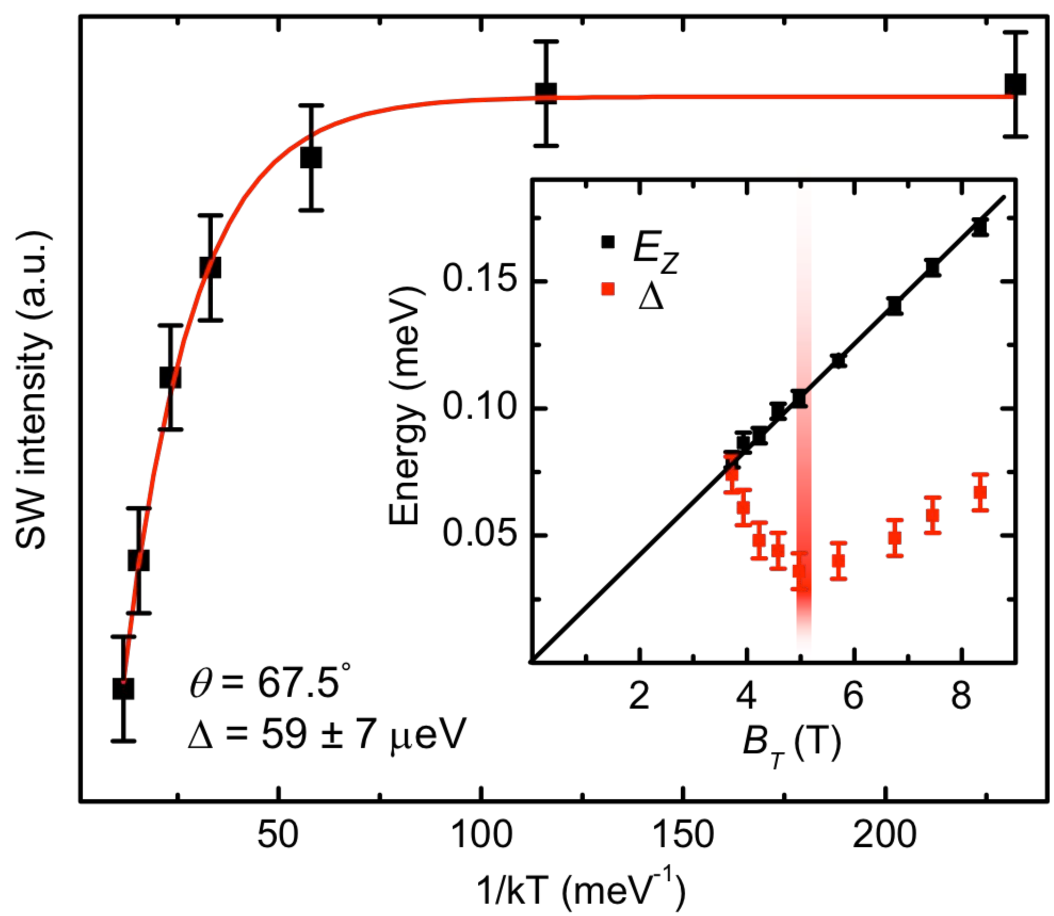
$\xi_c = E_Z/E_C \approx 0.019$

↓

CF in single layers at ½

I. Dujovne et al. PRL (2005)

Further evidence of a spin transition in the T-dependent behavior of the spin wave



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