Coexistence of Phases and Gapped Excitations in the Second LL: Fundamental Insights from Inelastic Light Scattering

Ursula Wurstbauer

Columbia University, New York

Walter Schottky Institut and Physik-Department, TU München

DMR-0803445,
CHE 0641523

Acknowledgement

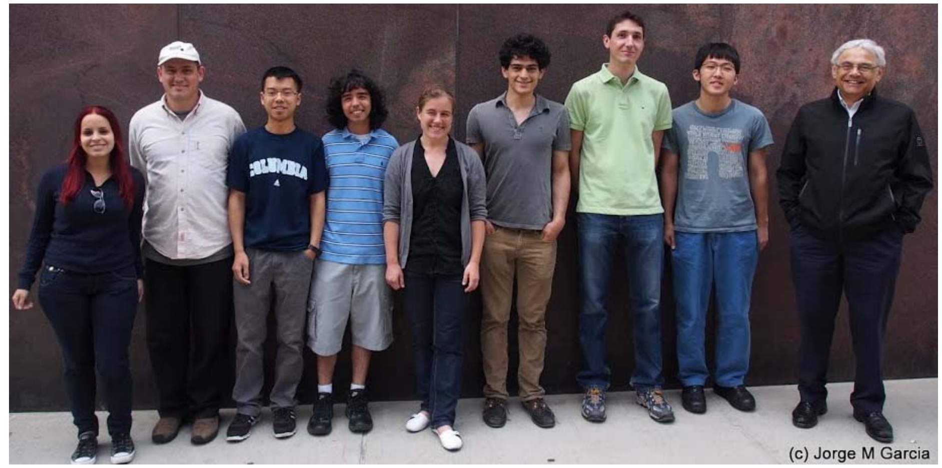
Columbia University:

Aron Pinczuk

Antonio Levy

Albert Rigosi

Dov Fields



Princeton University:

Loren Pfeiffer

Ken West

Purdue University:

Michael Manfra

John Waston

Sumit Mondal

WSI and TUM:

Alexander Holleitner and his group

Financial support:

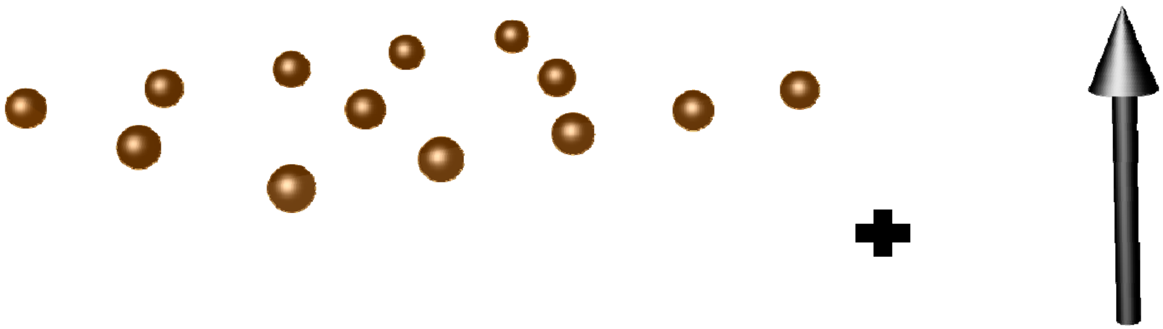
NSF (DMR-0803445,CHE 0641523)

Alexander von Humboldt Foundation

Alexander von Humboldt
Stiftung/Foundation

2DES with magnetic field

2D charge carrier system ✚ **strong perpendicular magnetic field**

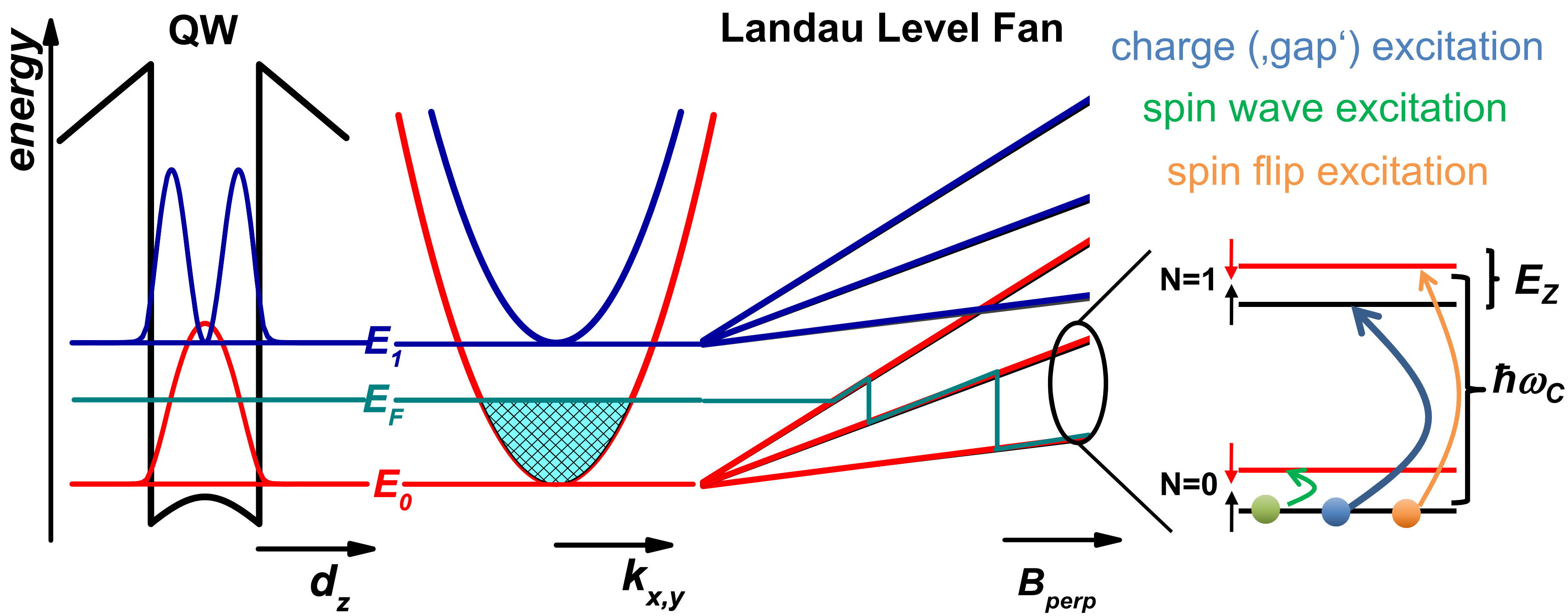


Cyclotron gap:

$\hbar\omega_C = eB_{perp}/m^*$

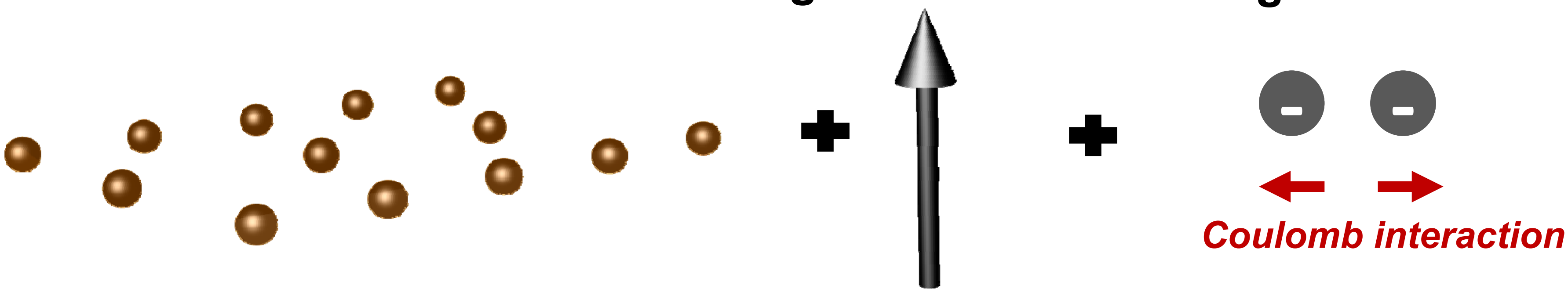
Spin gap:

$E_Z = g\,\mu B_{tot}$



2DES with strong magnetic field

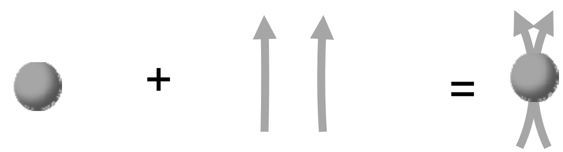
2D charge carrier system | strong perpendicular magnetic field | strong e-e interaction



→ **Fractional Quantum Hall Effect (FQHE) States**

→ **Formation of new quasiparticles: Composite Fermions**

(J. K. Jain, PRL 1989)

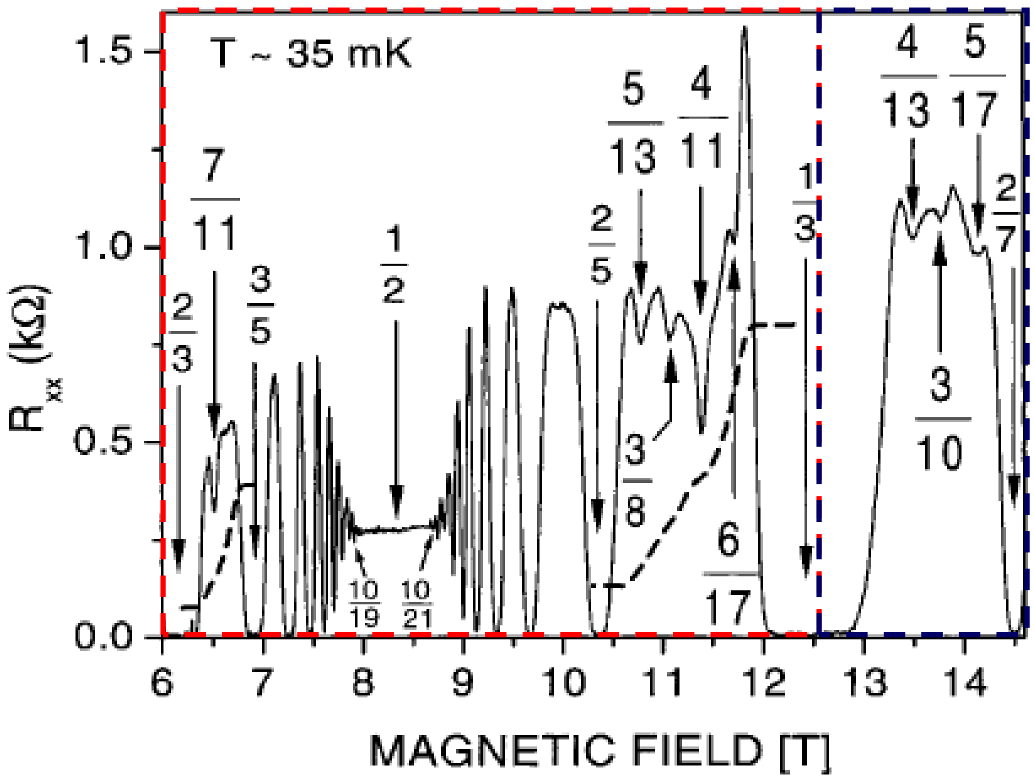


electron + 2n flux quanta = ^{2n}CF

$$B_{eff} = B_{\nu} - B_{1/2} \qquad \nu = \frac{p}{(2p \pm 1)}$$

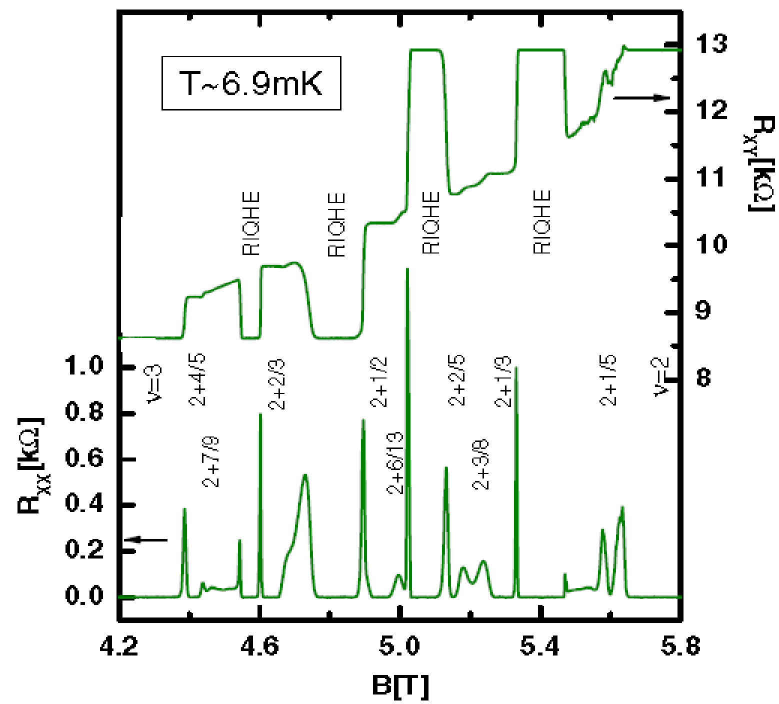
Transport signatures of FQHE States

Lowest Landau Level



W. Pan *et al.* PRL 90.016801 (2003)

Second Landau Level

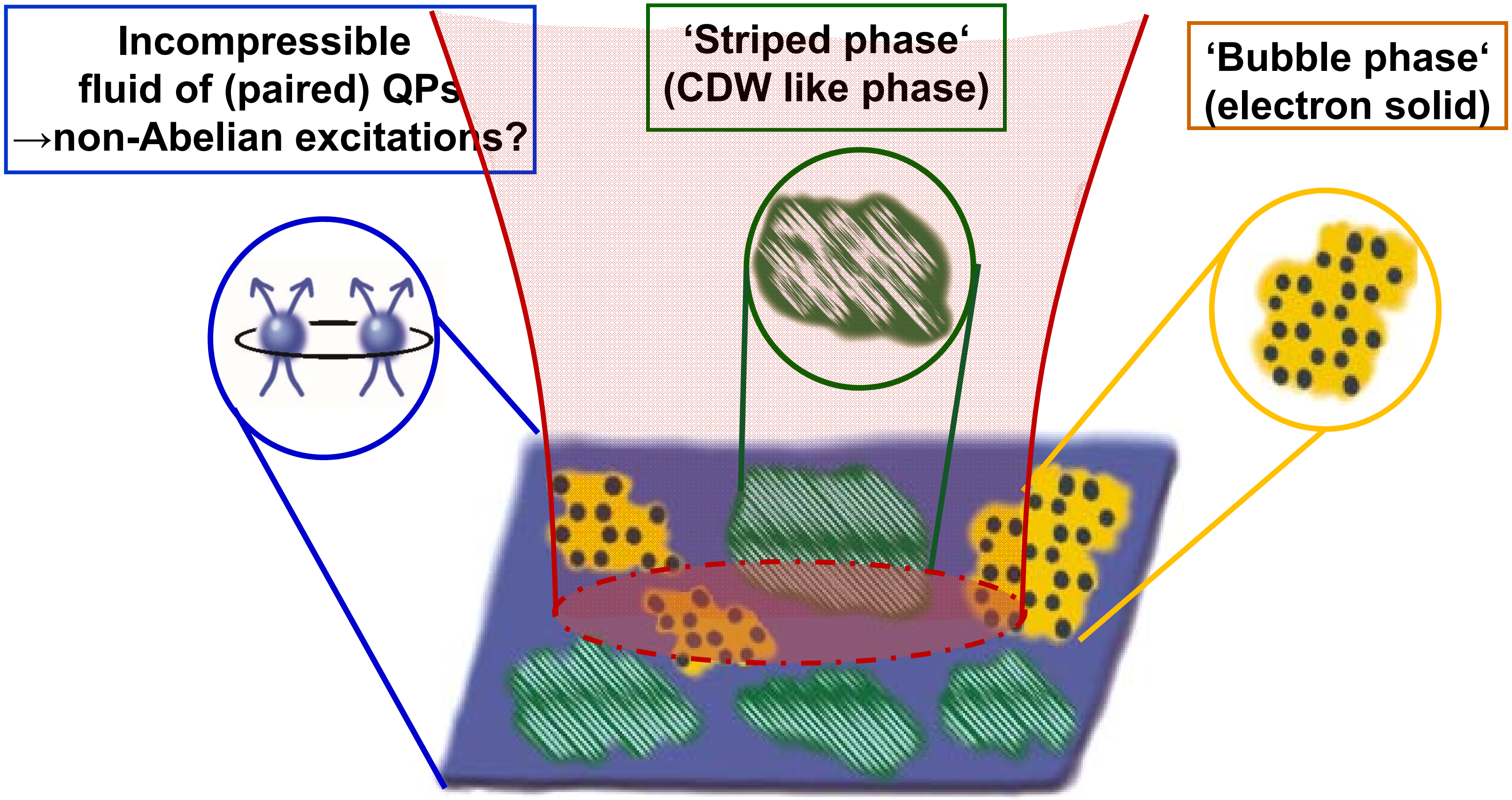


A. Kumar, *et al.* PRL 105, 246808 (2010)

- More than 70 odd-denominator states explored → most of them in the LLL
- Even-denominator states only in SLL (5/2 & 7/2)

  → supposed to obey non-Abelian excitations
- Competing phases in SLL: RIQHE states, FQHE states, anisotropies, …

Competing phases in the second LL



Exploring collective low-energy excitation of the 'bulk'

by Resonant Inelastic Light Scattering (RILS)

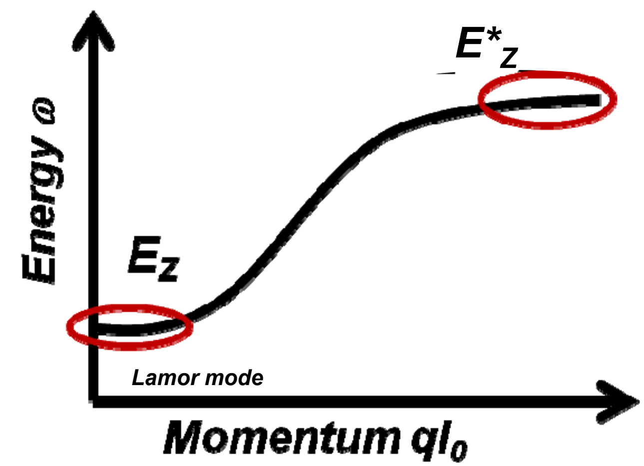
Outline

- Resonant Inelastic Light Scattering (RILS)
- Collective Excitation Spectrum for ν=5/2
- Collective Excitations at ν=2+1/3
- Conclusion

Collective excitations

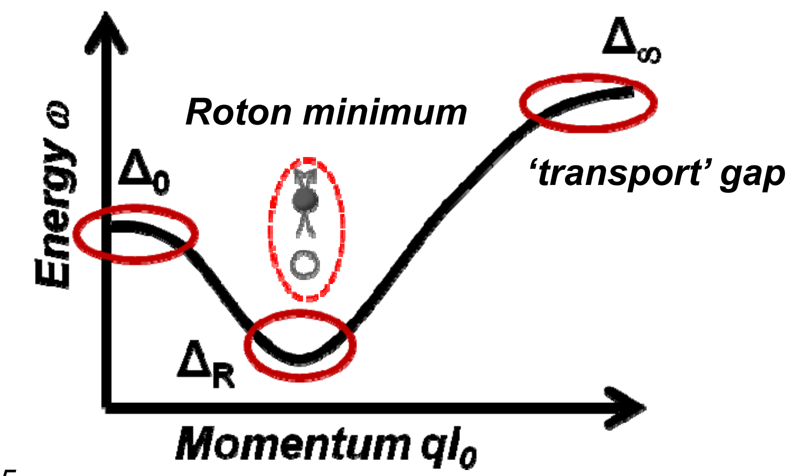
1. **Collective Spin Excitations**

   - ***Spin wave (SW) at the bare E_Z***
   - *Spin flip excitations (change of spin and orbital quantum number)*



2. **Collective Charge Excitation**

Modes at critical points in E(q), e.g. at Δ_R , Δ_∞



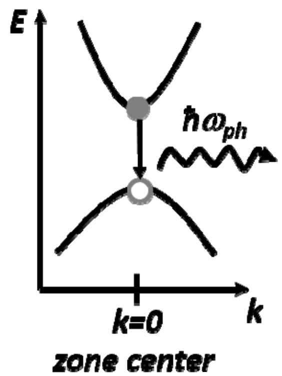
C. Kallin and B. Halperin, 1984
D. Haldane and E. Rezayi, 1985
S. Girvin, A. MacDonald, P. Platzman, 1985

Observation of excitations

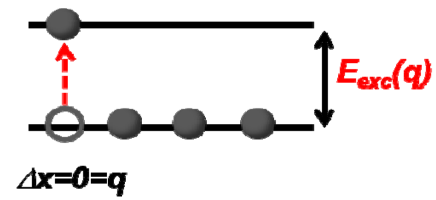
Momentum - space $E(q)$ | Real-space

- **<u>Emission</u>**

  photoluminescence

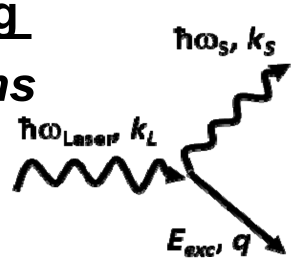


$q = 0$

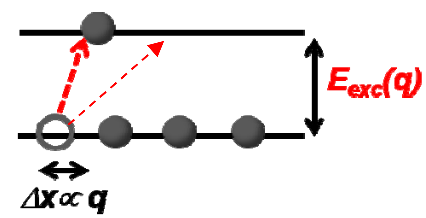


- **<u>Inelastic Light Scattering</u>**

  by collective excitations

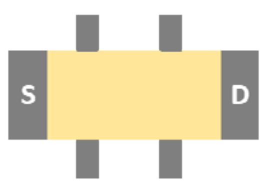


small q

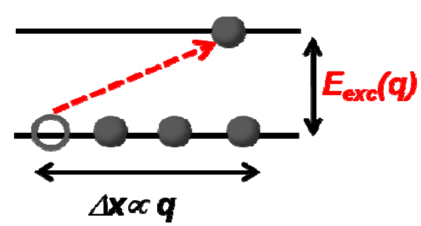


- **<u>(Magneto)transport</u>**

  current induced

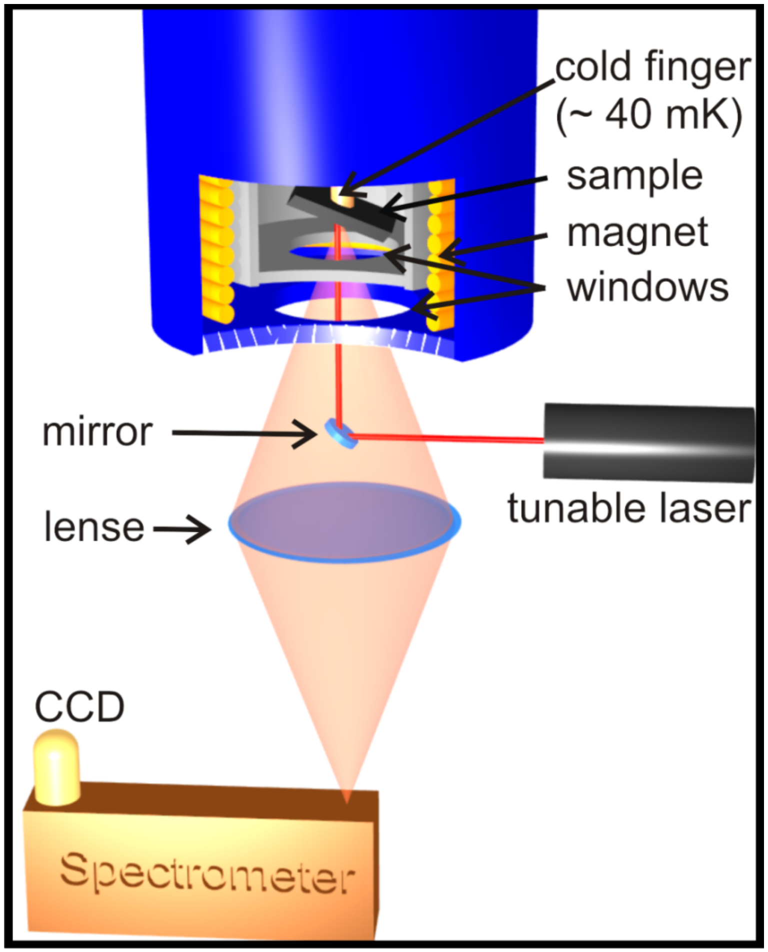


large q

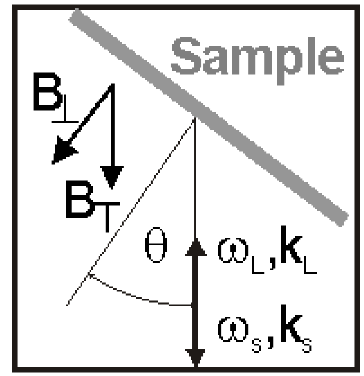


Inelastic light scattering at mK

Dil-fridge with windows and B ≤ 16T



Back scattering geometry with tilt θ



Conservation of energy:

$$\omega = \omega_L - \omega_S$$

Conservation of wavevector:

$$q = k_L - k_S$$

Tilt angle θ modifies:

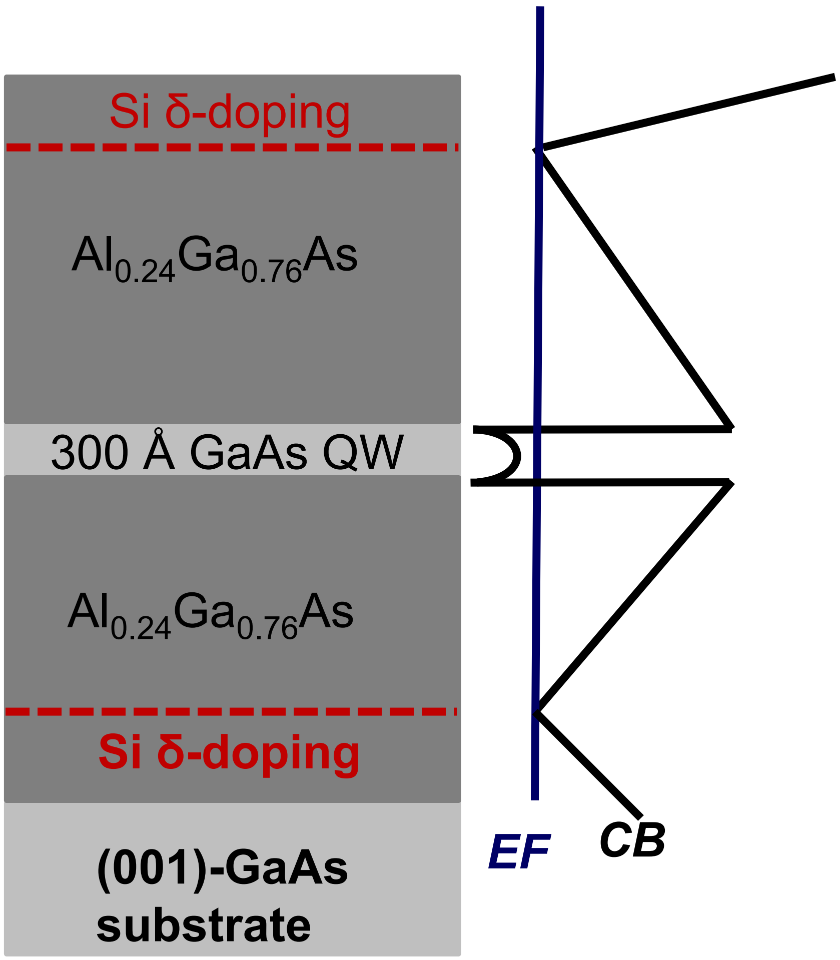
- Transferred momentum:

  $$q_0 = k_L - k_S = (2\omega_L/c)\sin\theta$$

- $E_Z = g\mu_B B_T$ independent from $B_\perp$

Sample for studies in the SLL

dsd QW structure:



From transport at 300 mK:

ensity range:

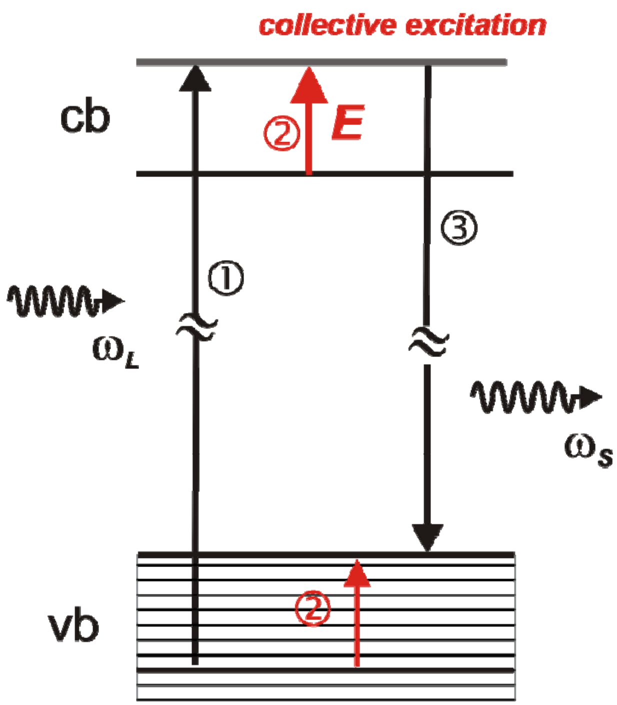
n: ~$3\cdot10^{11}$ cm^{-2}

mobility:

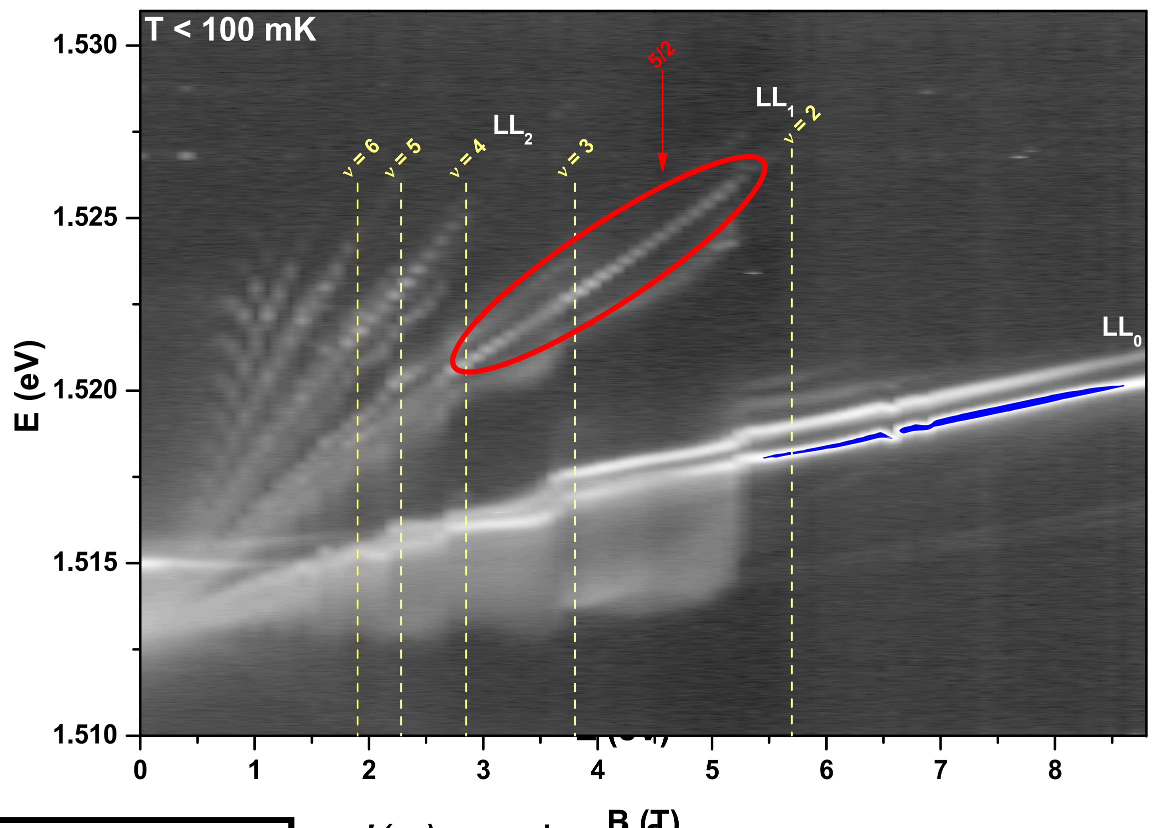
μ: $23.9\cdot10^{6}$ cm^2/Vs

Resonant inelastic light scattering

RILS by collective excitations: n –step process (n≥3)



Emission spectrum



Scattering intensity:

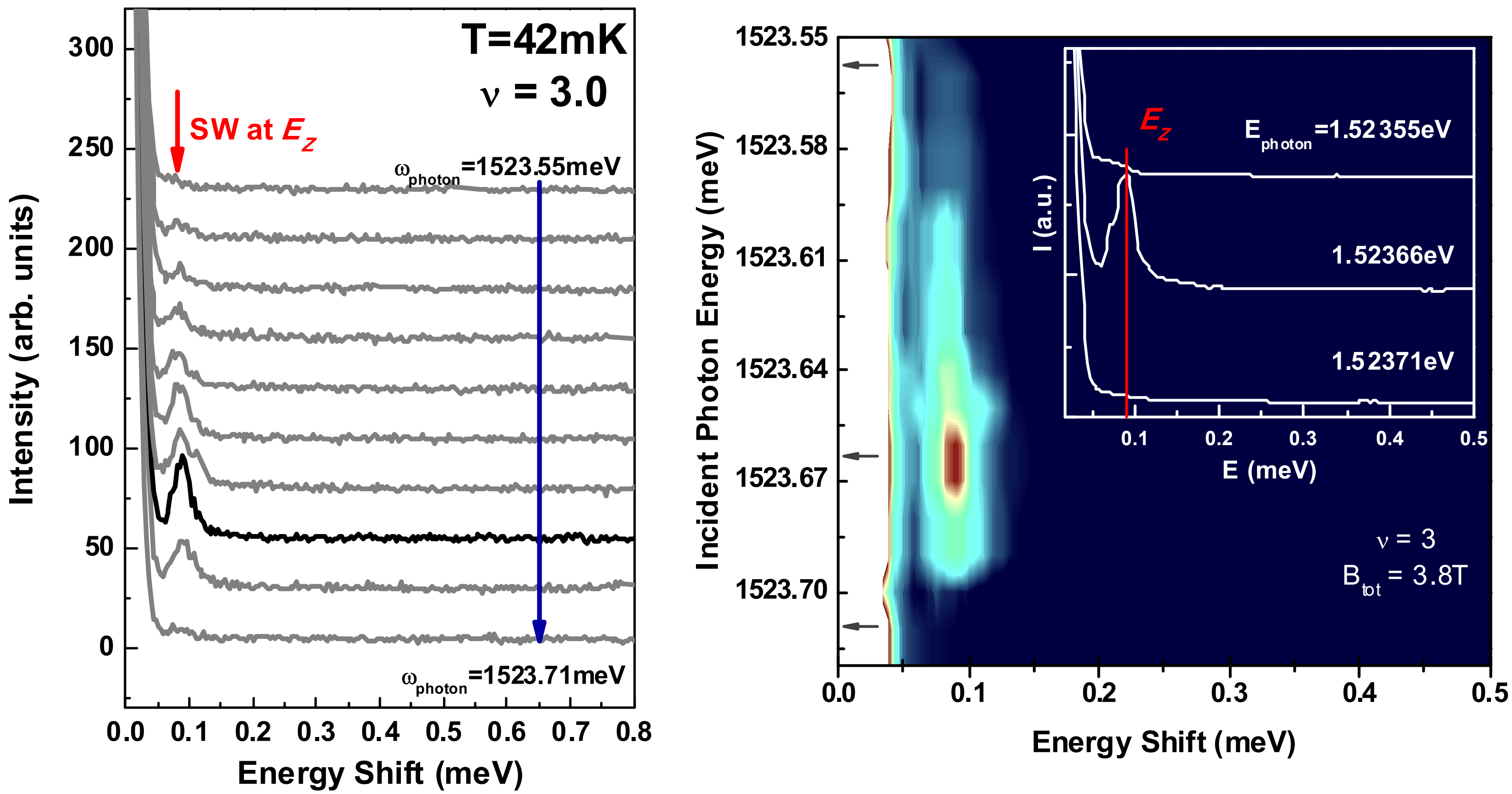
$$I(\omega) \propto \left| \sum_{k_1 k_2} \frac{\langle F \mid H_{\text{int}}^{'} \mid k_2 \rangle \langle k_2 \mid H_{ee} \mid k_1 \rangle \langle k_1 \mid H_{\text{int}}^{'} \mid I \rangle}{(\omega_I - \omega_{k_2})(\omega_I - \omega_{k_1})} \right|^2$$

$I(\omega)$ maximal for

- $\omega_I - \omega_{k1} = \omega_L - (E_{gap} + E) = \omega_s - E_{gap} = 0$
- $\omega_I - \omega_{k2} = \omega_L - (E_{k2} + E) = \omega_s - E_{k2} = 0$

A. Pinczuk, G. Abstreiter in Light Scattering of Solids, Topics in Applied Physics Vol. 66 (1988)

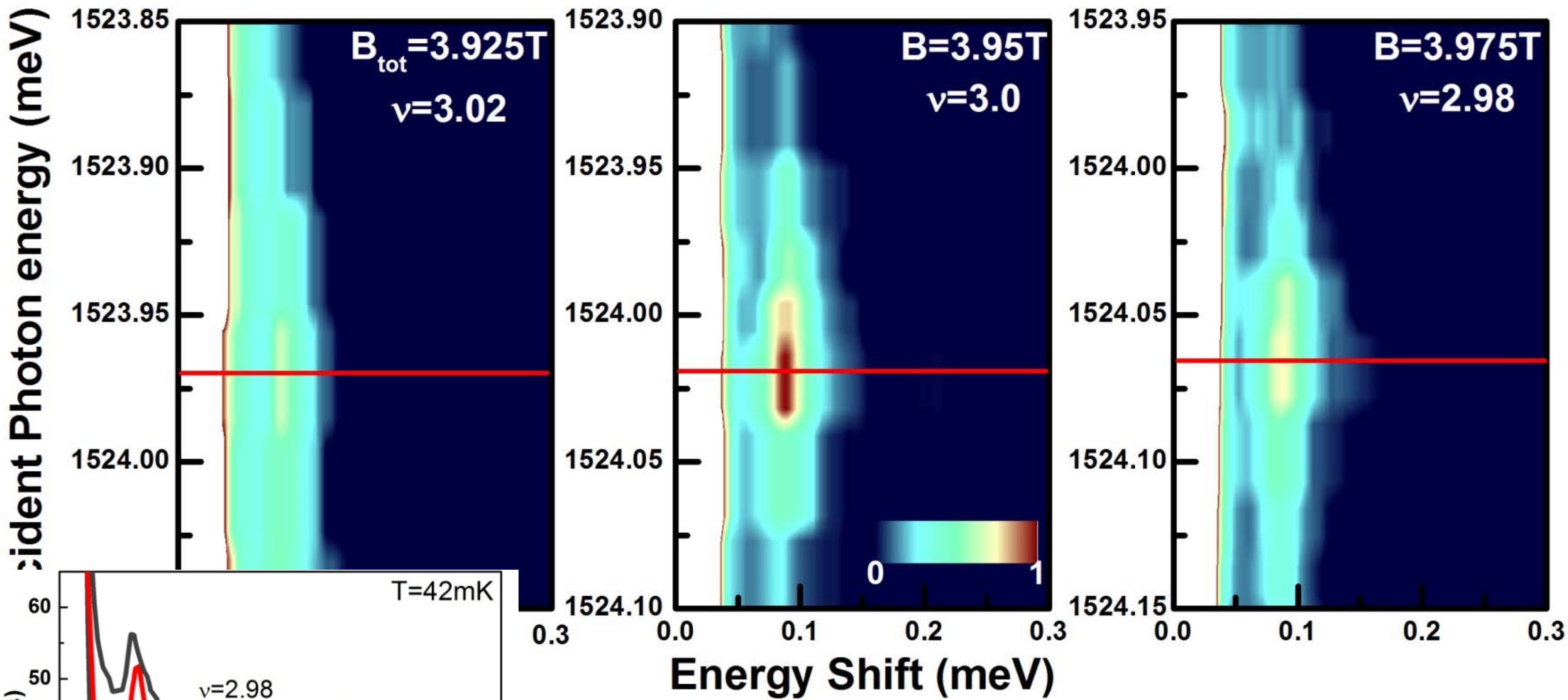
Excitation spectrum at ν=3

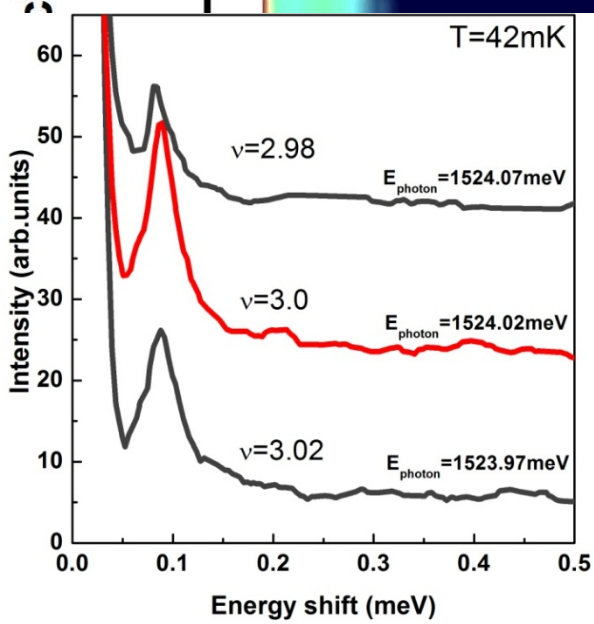


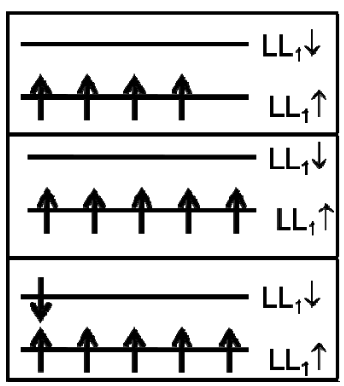
RILS mode only observable under resonance conditions

(SW vanishes by changing the photon energy by only **50 μeV**)

Identifying filling factor $\nu=3$

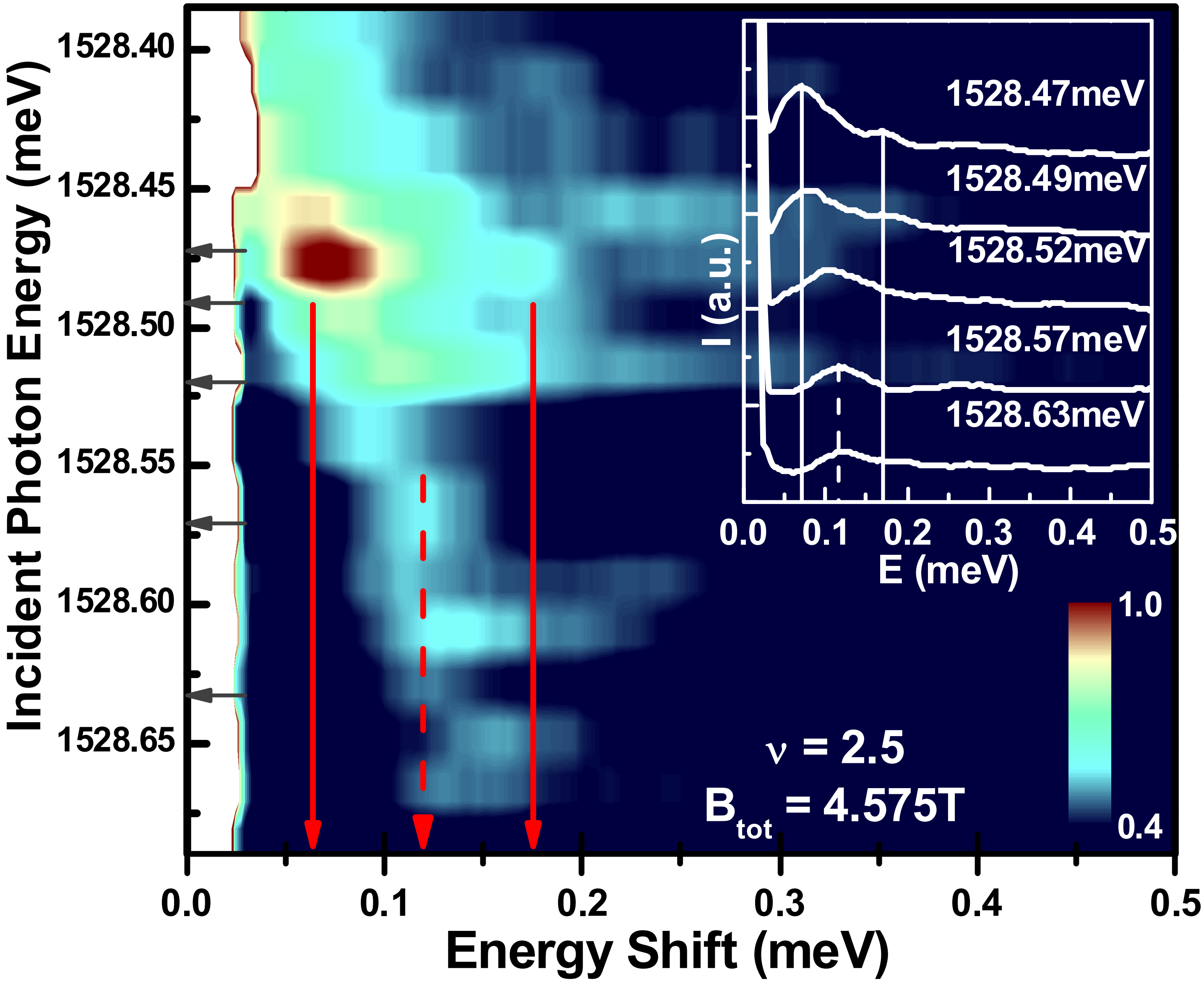






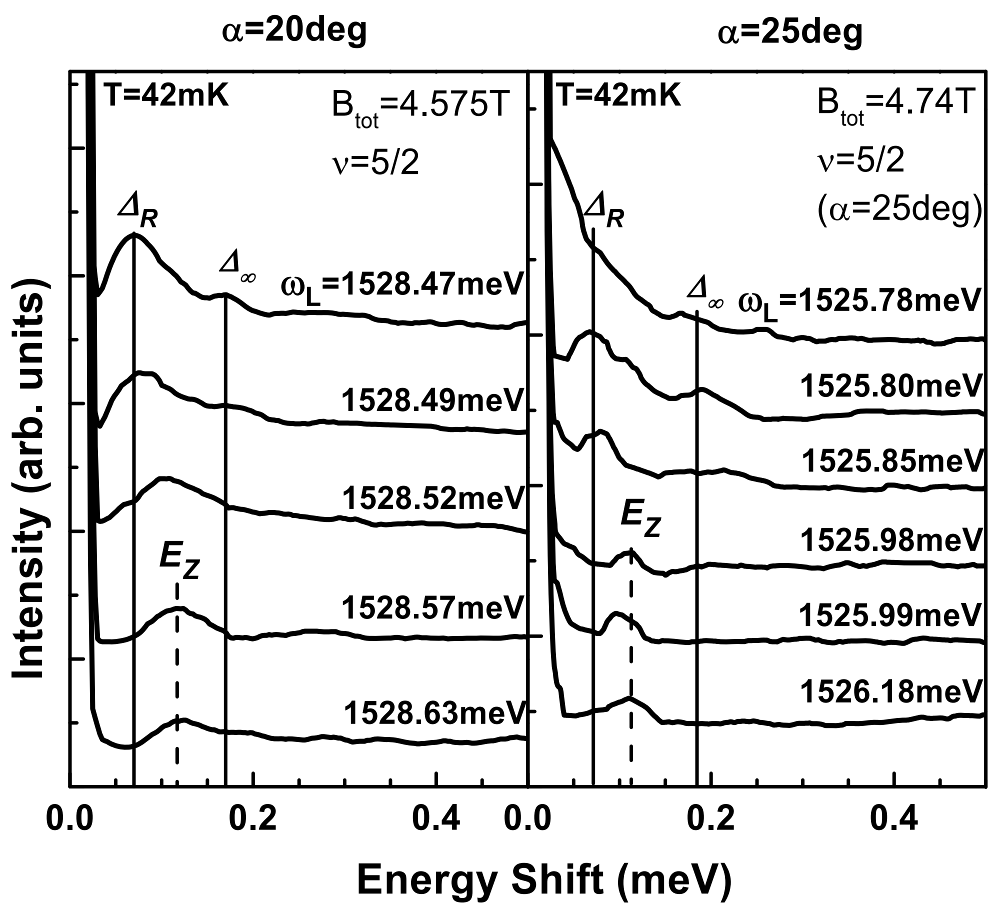
Spin-wave most intense at ν = 3

Gapped collective excitations at 5/2

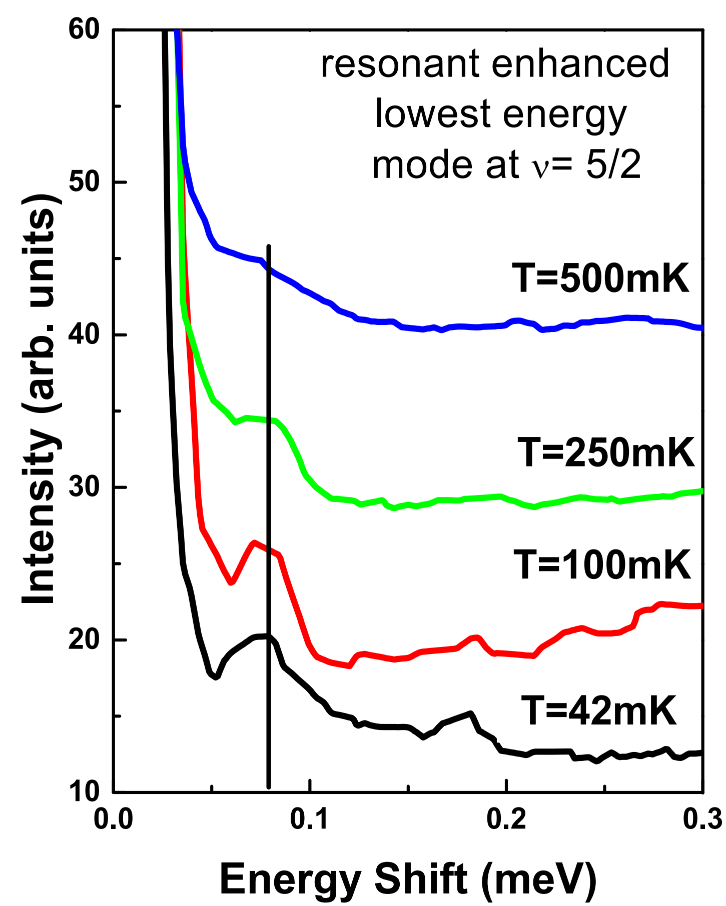


Gapped collective excitations at 5/2

Reproducibility

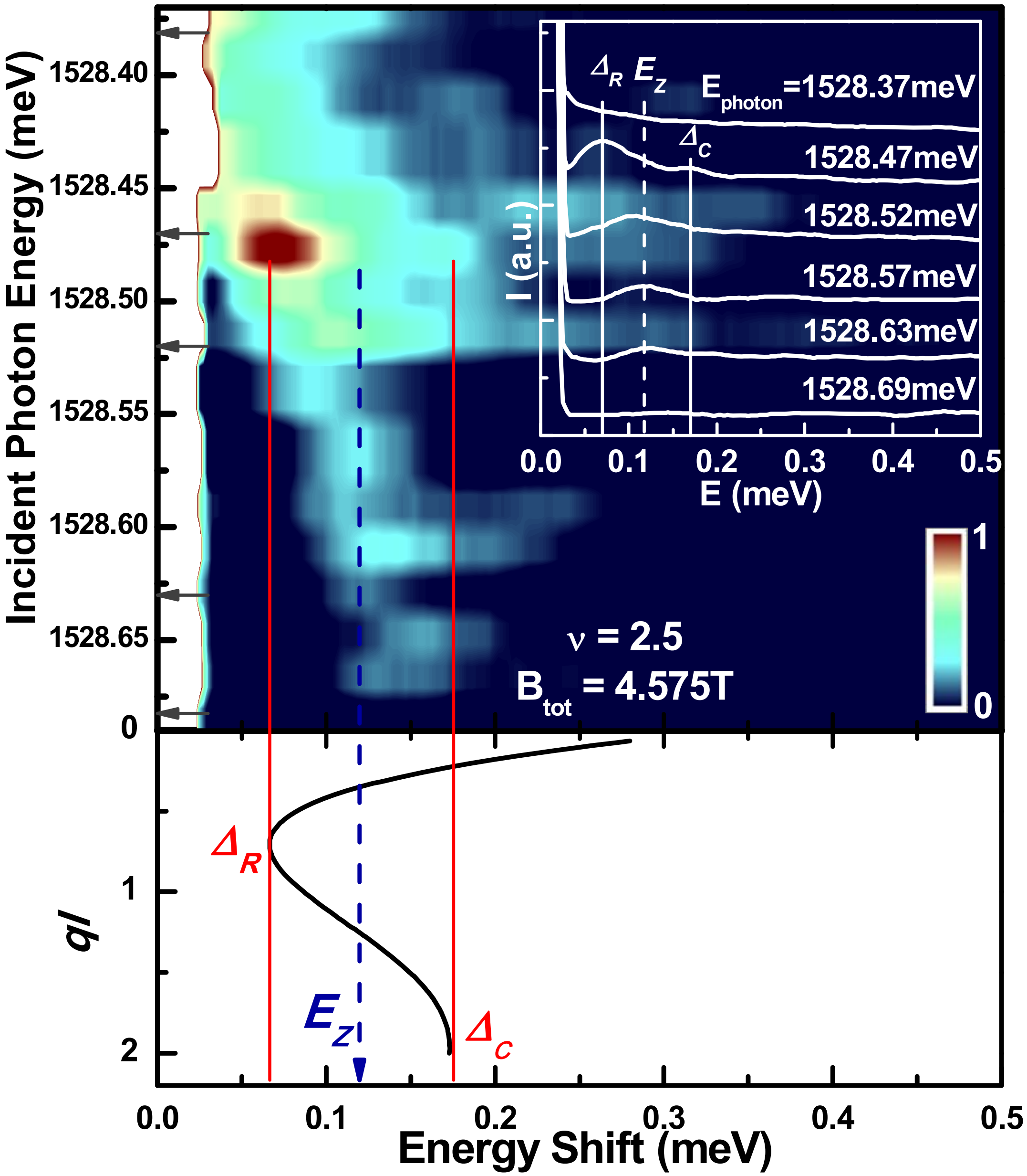


Temperature dependency



- Modes are reproducible and unchanged for small variations in tilt angles (momentum and in-plane field)
- Gapped mode vanishes for T>250 mK, (Δ_R=70μeV=0.81K)

Generic mode dispersion at 5/2



Δ_R=70μeV ('roton minimum')
(vanishes for T>250mK)

Δ_C=170μeV ('gap energy')
→ in agreement with
transport and calculations

*N. Samkharadze et al. PRB **84**, R121305 (2011)*

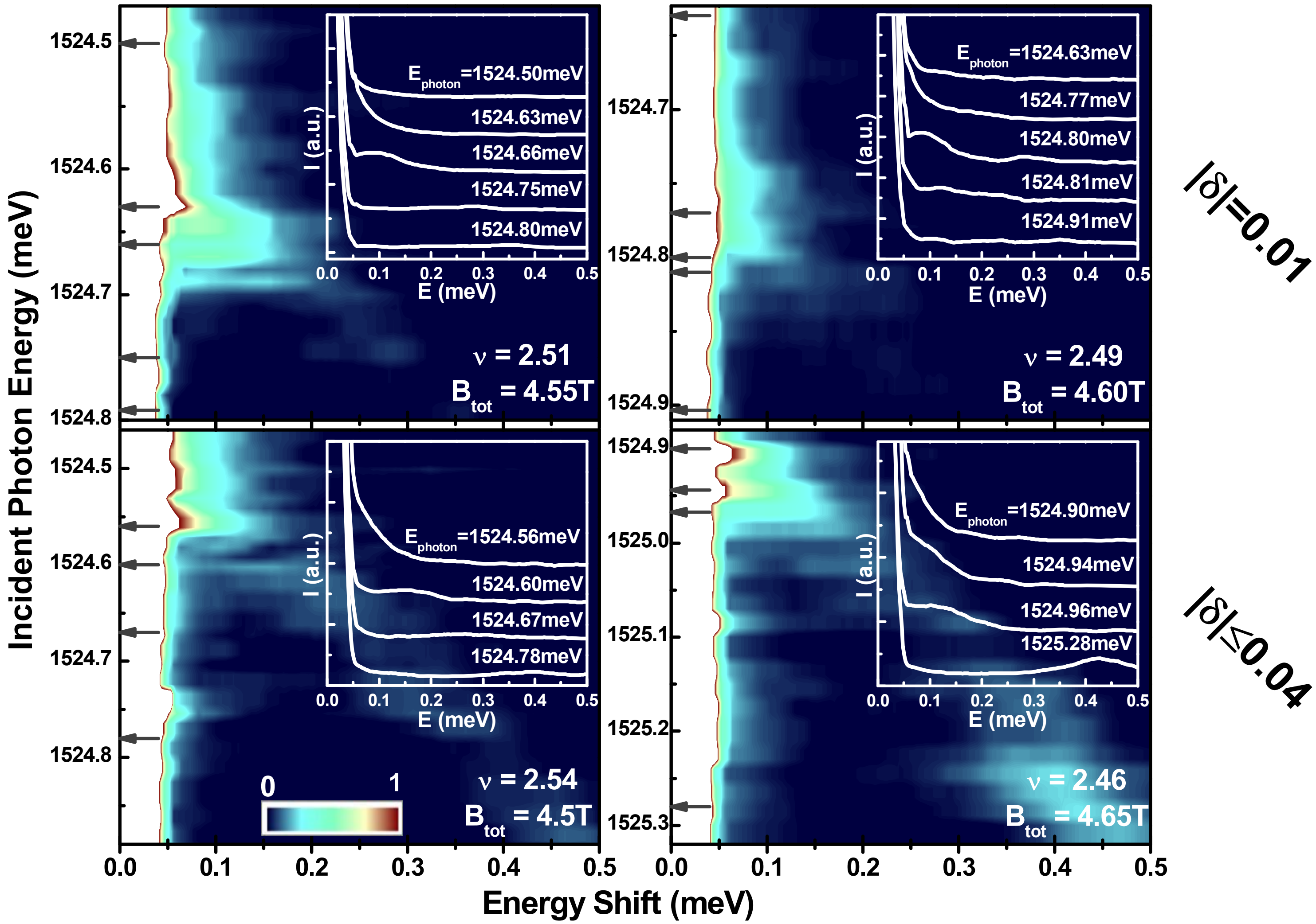
*R. Morf et al. PRB **68**, 113309 (2003)*

Broad mode at E_Z indicating (partial) spin-polarization

Generic wave-vector dispersion exhibit at least one **magnetoroton**

UW, *et al*. PRL **110**, 026801 (2013)

Collective excitation spectrum at 5/2±δ



Gapped modes merge into a continuum of low-lying excitations indicating a transition from a incompressible quantum fluid to a compressible phase.

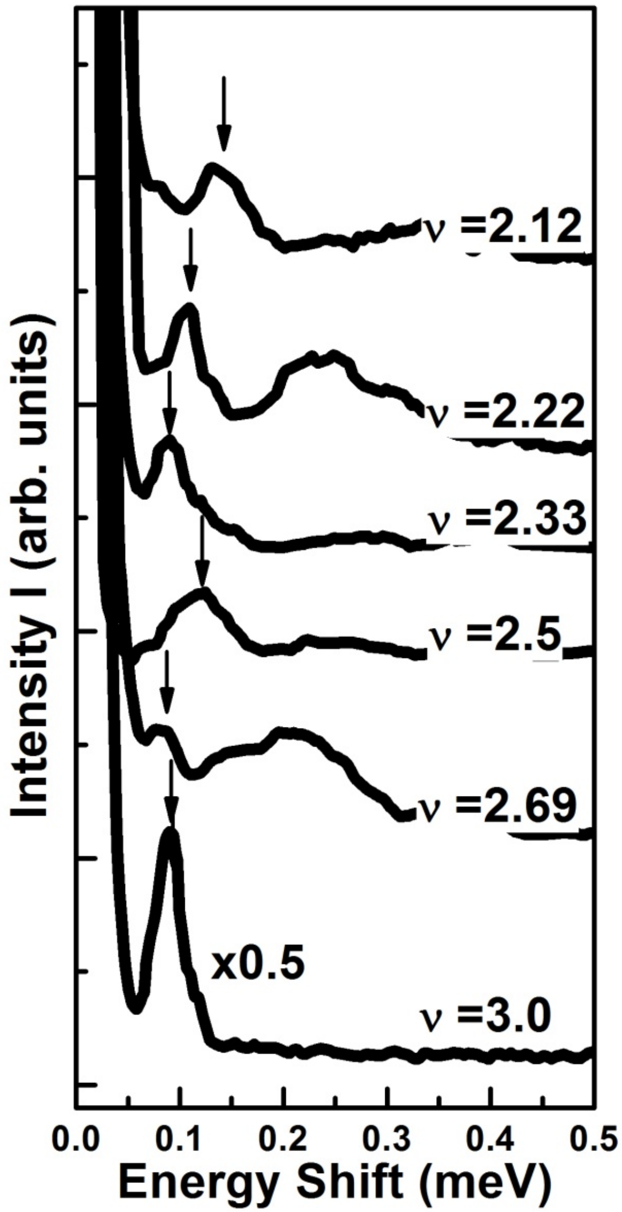
Open questions

- Can we determine the amount of spin-polarization at 5/2?

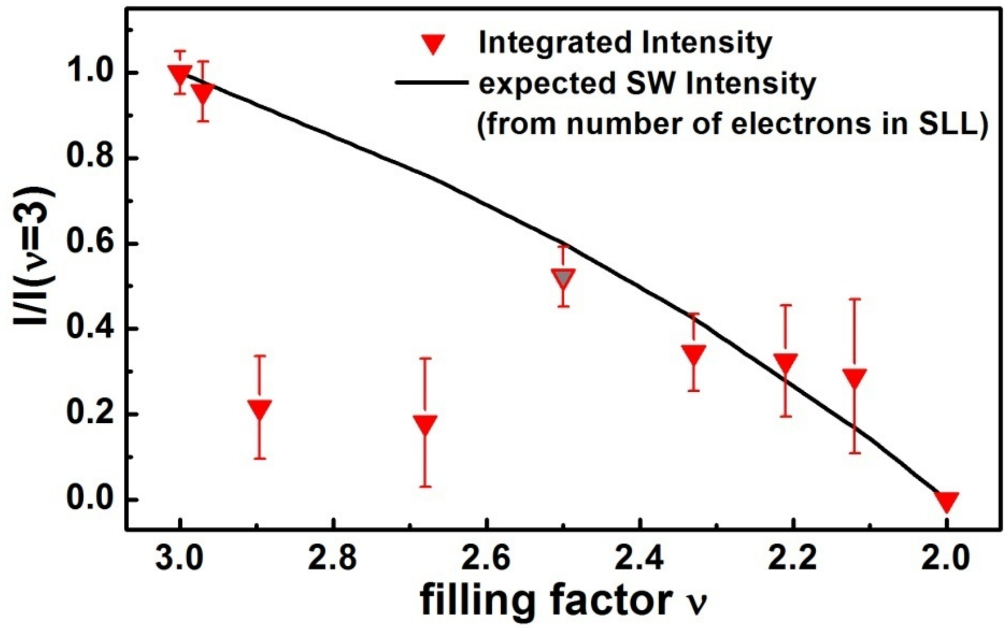
- Excitation spectra of other exotic phases and FQHE states in the SLL?

Spin wave intensities in the second LL

SW modes



Relative mode intensities



Relative mode intensities suggest:

→ ***full spin polarization for ν=3, ν=5/2 and 2.33≤ν<2***

In agreement with RD-NMR measurements by:

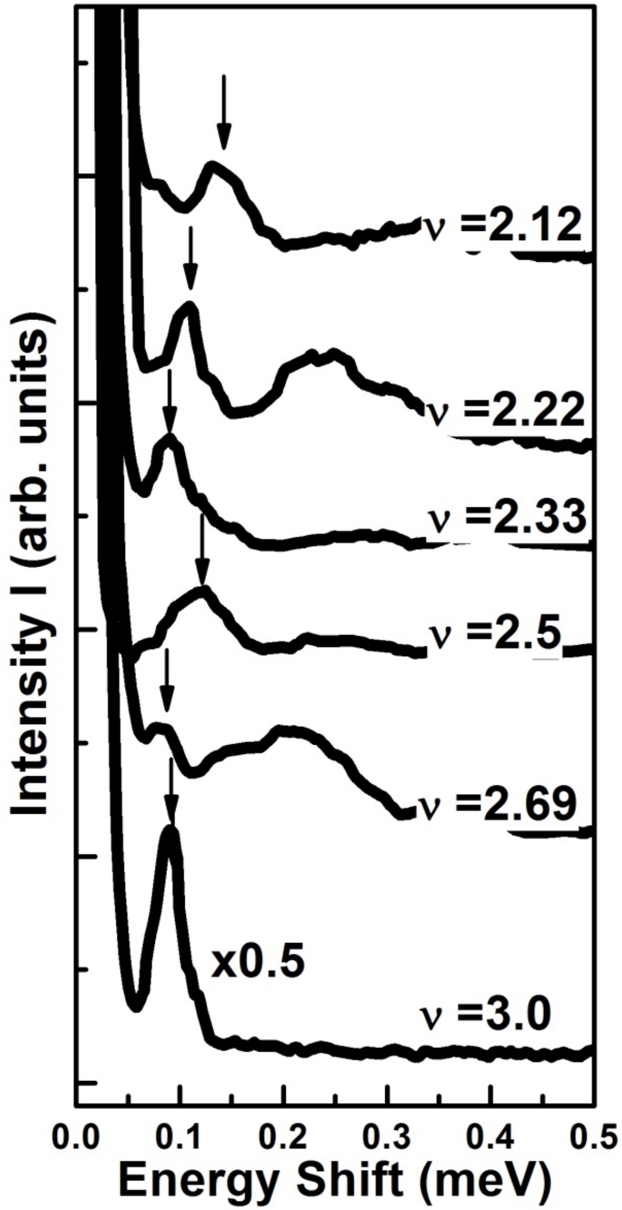
L. Tiemann *et al. Science* **335,** 828 (2012)

M. Stern *et al. PRL* **108,** 066810 (2012)

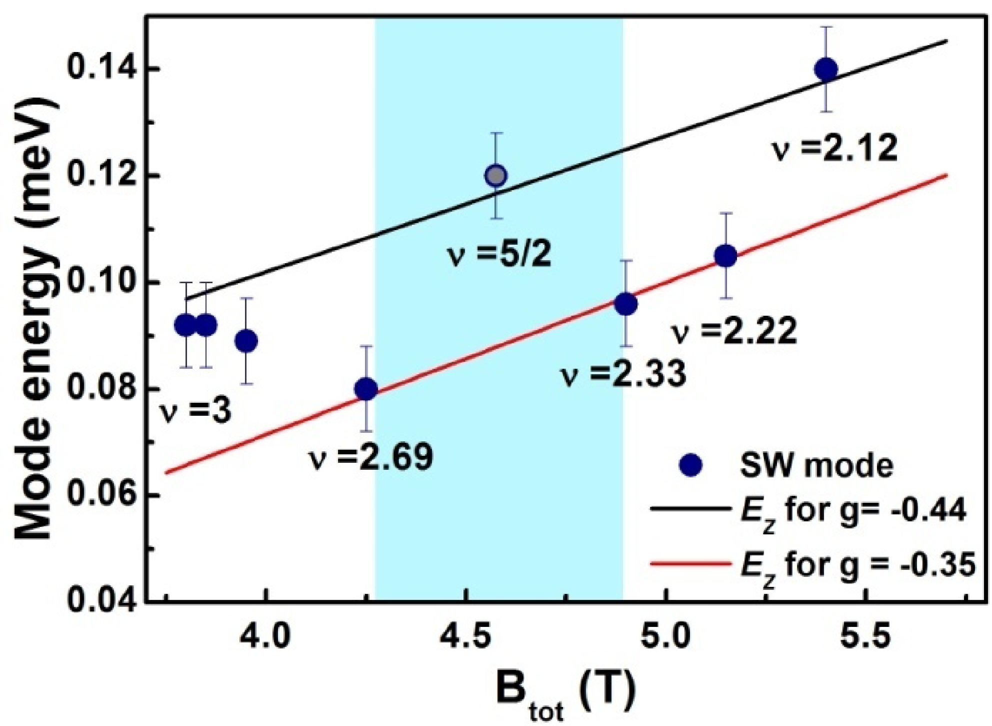
UW, *et al*. PRL **110**, 026801 (2013)

Spin wave energies in the second LL

SW modes



Mode energies



Electron g-factor from E_Z:

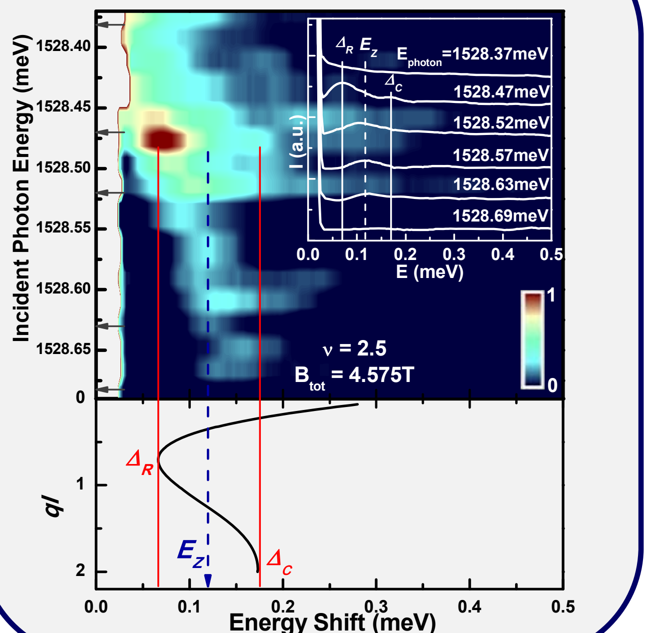
|g| ≈ 0.44 for ν=3, ν = 2.12 & ν = 5/2

? |*g*| ≈ *0.35 for ν = 2+1/3, 2+1/4, 2+2/3 and 2+4/5* ?

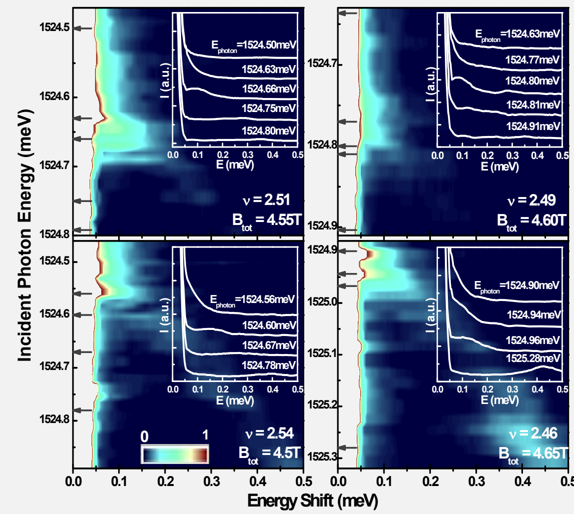
UW, *et al*. PRL **110**, 026801 (2013)

Conclusion

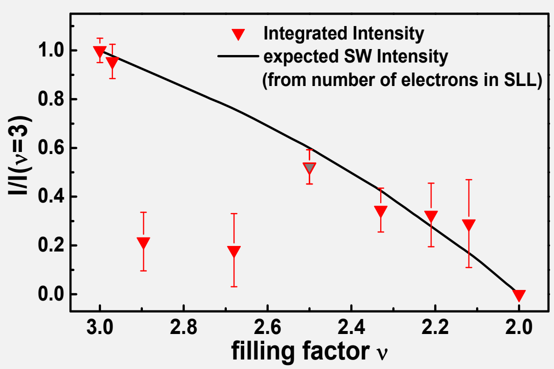
Gapped Excitations at 5/2



Gapless excitations at ν=5/2±δ



Spin polarization at 5/2



RILS spectra at ν=2+1/3: Evidence for coexcitence of phases