Review Article:

S. Girvin Les Houches 1998

cond-mat/9907002

~120 pages

# Selected Topics in the Physics of Quantum Hall Systems

John Chalker, Oxford University

## Lecture One: Overview of the integer and factional quantum Hall effects

Plateau transitions as quantum critical points

The Laughlin wavefunction and fractionally charged quasiparticles

## Lecture Two: Broken symmetries in quantum Hall systems

Stripe and bubble phases

Quantum Hall ferromagnets and Skyrmions

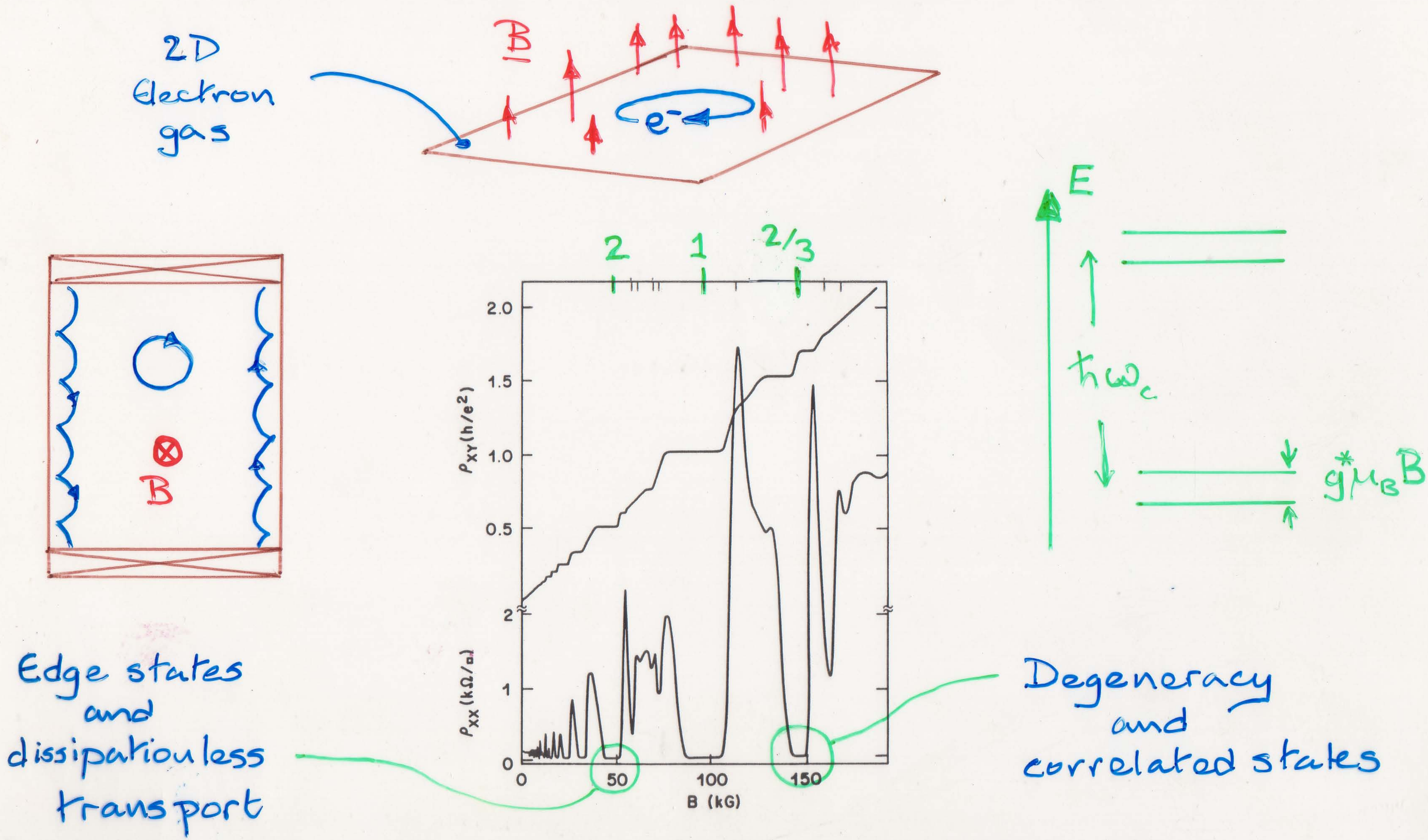
Bilayers

## Seminar: Transport between coupled quantum Hall edge states in multilayer samples

Multilayer samples and the Quantum Hall effect in 3D

Interaction and disorder effects in coupled edge states

# Aspects of the QHE



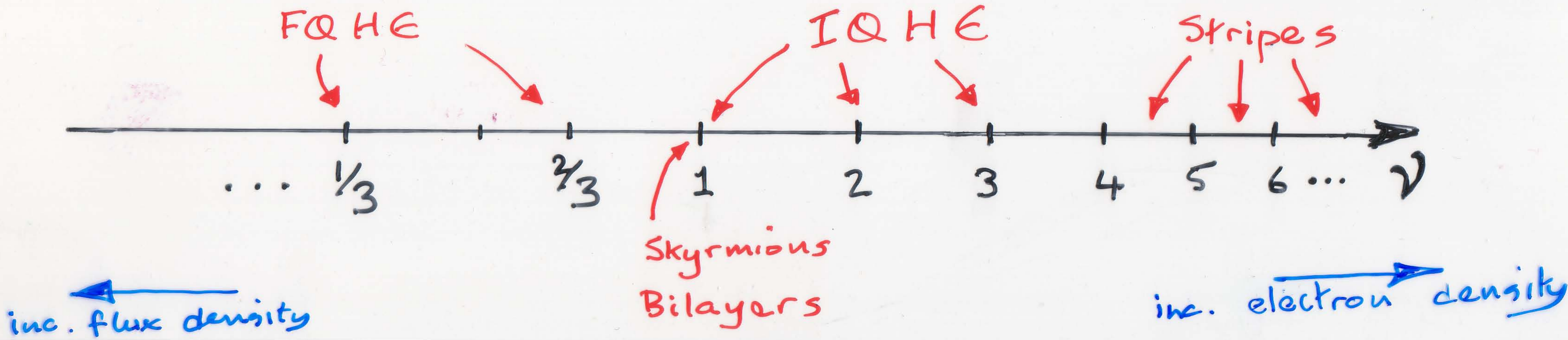
# Overview of Phenomena

## The control parameter

filling factor $\nu = \dfrac{\#\ \text{electrons}}{\#\ \text{flux quanta}}$

(# electrons $= n \times \text{Area}$; # flux quanta $= \dfrac{B \times \text{Area}}{h/e}$)

free electrons: $\sigma_{Hall} = \dfrac{ne}{B} = \dfrac{e^2}{h}\nu$

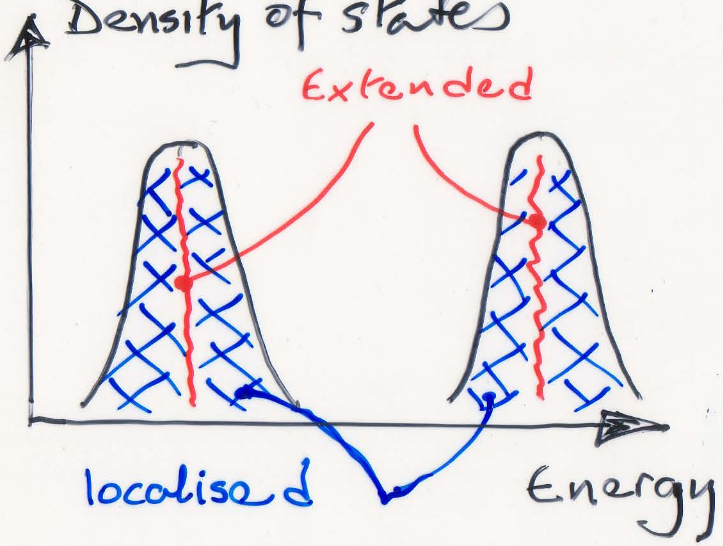


# Essentials of QHE

## IQHE

(Magnetic field → Energy gap)

Disorder → localisation




Electrons in localised states don't carry current

## FQHE

Interactions → Energy gap

(Disorder → localisation)

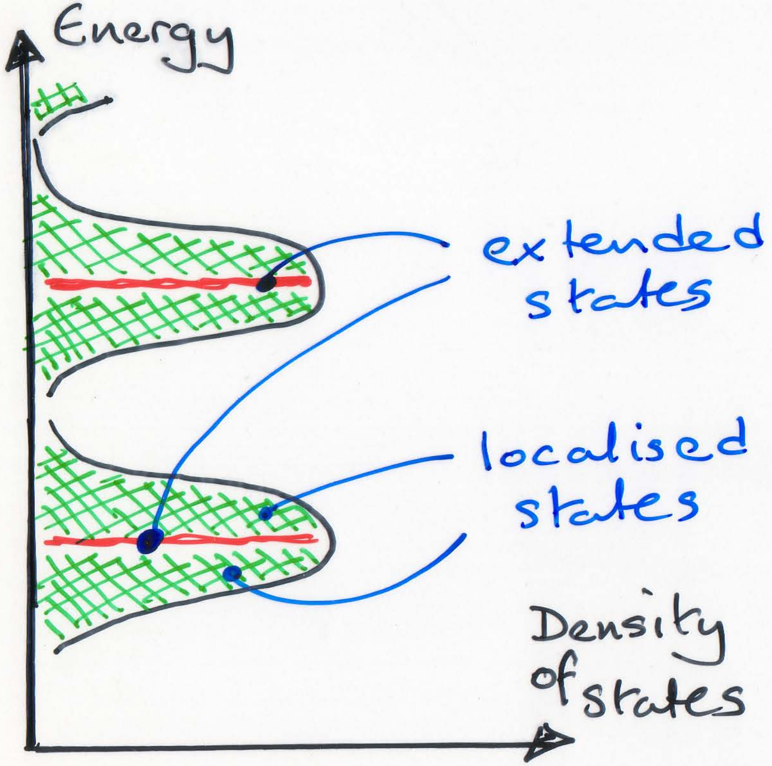
Laughlin states:

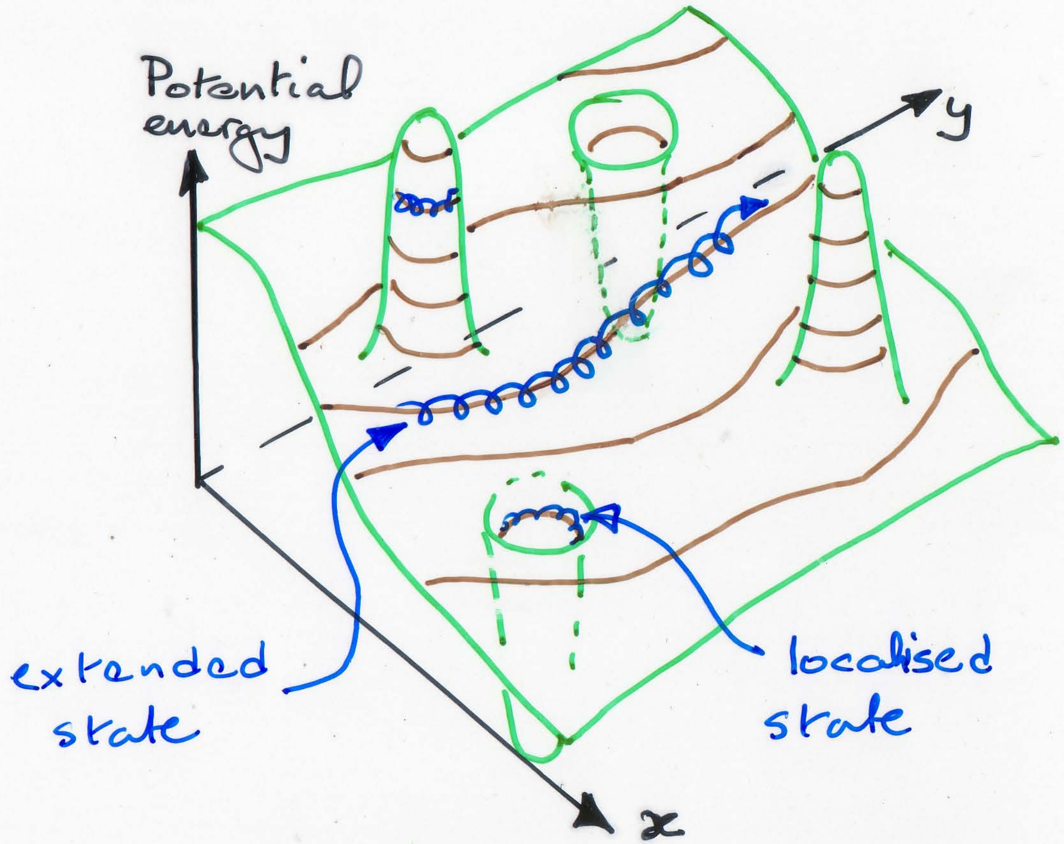
$$|\Psi(\underline{r}_1 \dots \underline{r}_N)|^2 \sim |\underline{r}_i - \underline{r}_j|^{2p} \quad p = 3, 5 \dots$$

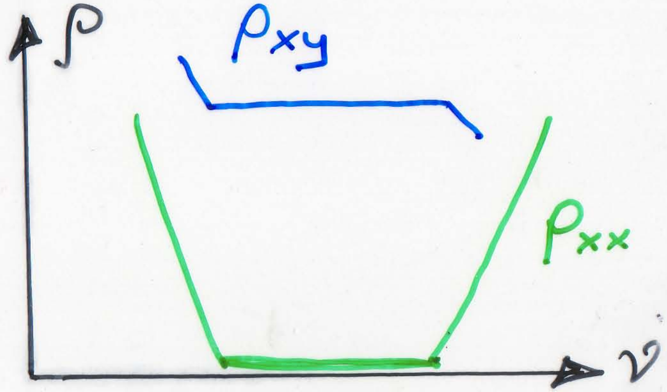
as $|\underline{r}_i - \underline{r}_j| \to 0$

Correlations keep electrons apart

# Why are there Hall plateaus?

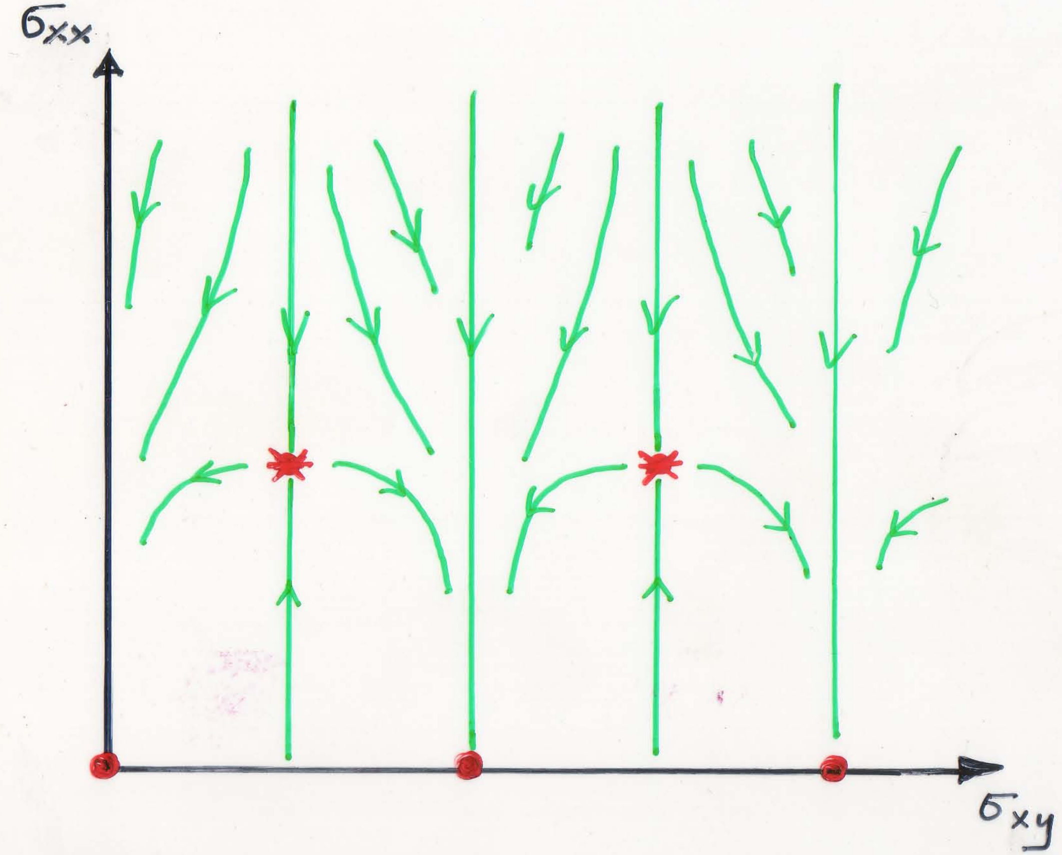


# IQHE Plateau Transition & Scaling

σ-model with $\sigma_{xx}$ & $\sigma_{xy}$ as coupling constants




Scaling near critical point

Correlation length: $\xi \sim |\Delta B|^{-\nu}$

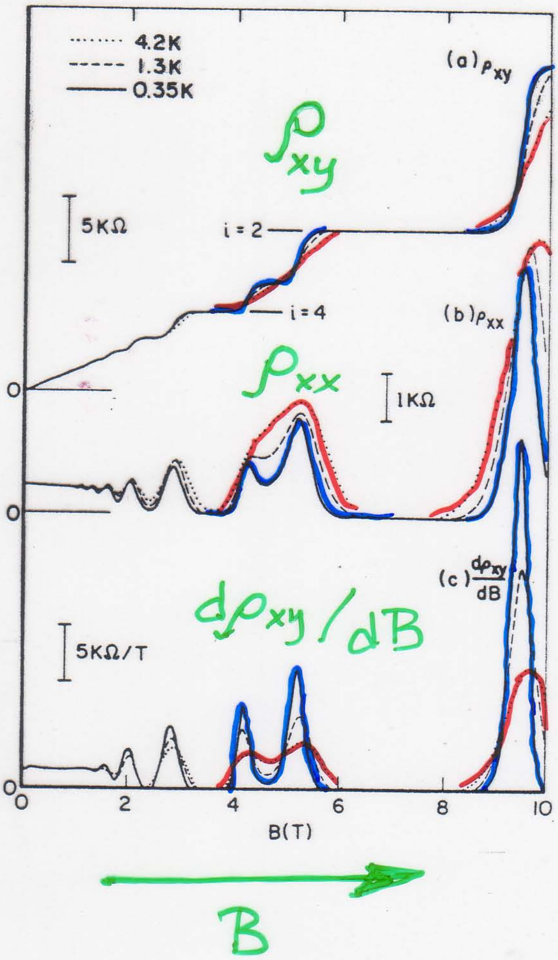
Correlation time: $\tau \sim \xi^{z}$

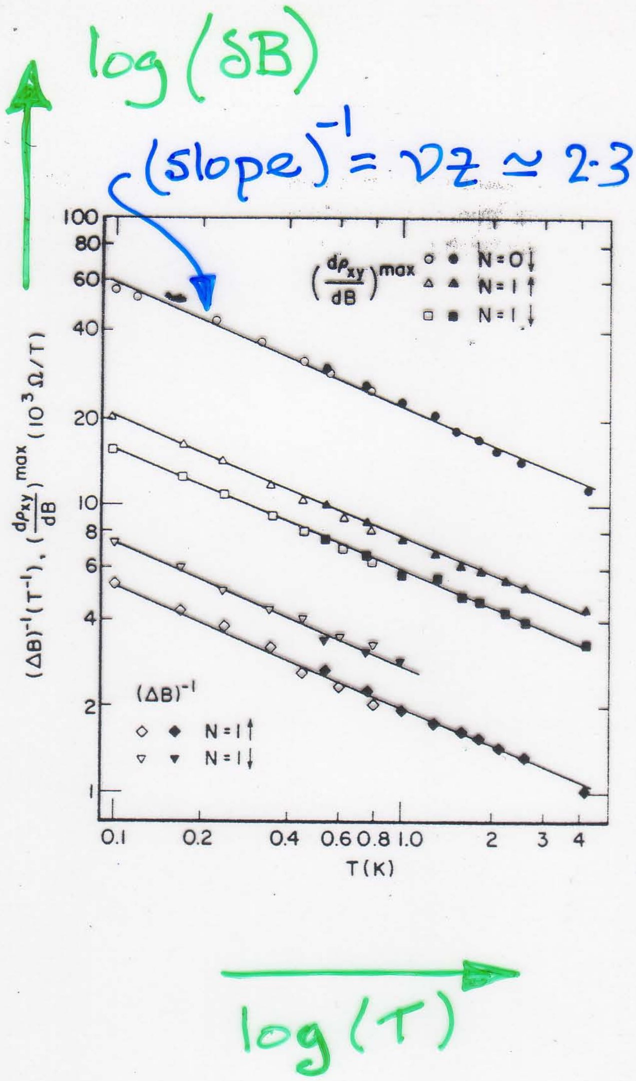
Energy scale: $\frac{\hbar}{\tau} \sim |\Delta B|^{\nu z}$

$$\sigma = F\left(\frac{|\Delta B|^{\nu z}}{T}, \frac{\omega}{T}, \dots\right)$$

# Experiments on Scaling

4·2 K
0·35 K




Wei et al PRL 61

Also scaling with
- frequency
- electric field
- sample size

See Haug et al for recent results

# Fractional Quantum Hall Effect

## Central ideas

At special $\nu$:

- Highly correlated ground state
- Energy gap for excitations
  → incompressibility
- Fractionally charged quasiparticles

— treat using trial wavefunctions

# Electrons in lowest Landau level

## Single particle wavefunctions

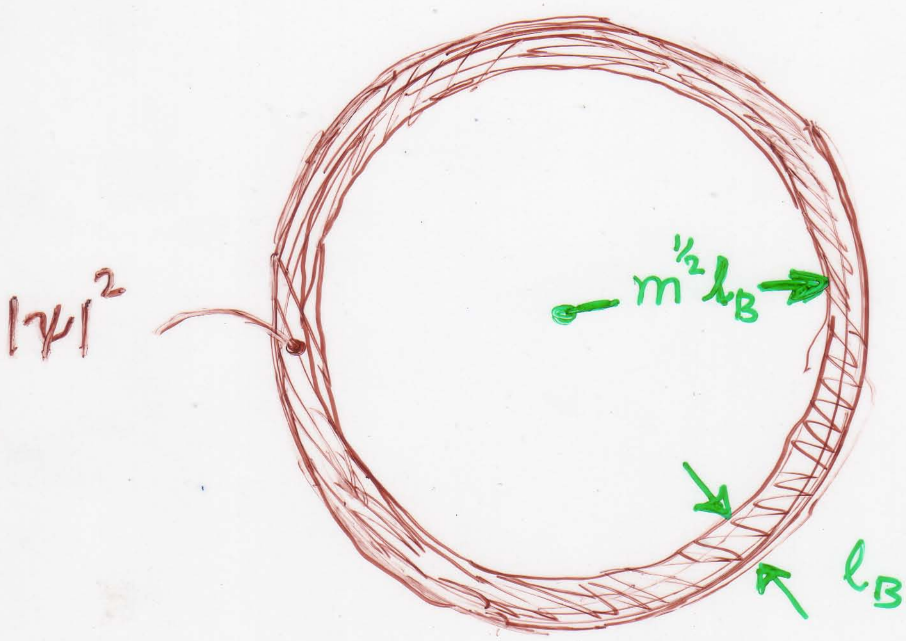
Circular gauge: $\vec{A} = \frac{B}{2}(y, -x, 0)$

with $l_B \equiv (\hbar/eB)^{1/2} = 1$

Complex coordinates: $z = x + iy$

$$\psi_m(x,y) \propto z^m \, e^{-|z|^2/4}$$

$m = 0, 1, 2 \ldots$



# Two particles in lowest Landau level

$$\psi(z_1, z_2) = f(z_1, z_2)\, e^{-\frac{1}{4}(|z_1|^2 + |z_2|^2)}$$

$f(z_1, z_2)$ ← polynomial in $z_1$ & $z_2$

Pauli ⇒ $f(z_1, z_2)$ antisymmetric

Forced to take:

$$f(z_1, z_2) = (z_1 - z_2)^l (z_1 + z_2)^m$$

integer $l, m \geq 0$

$(z_1 - z_2)^l$: relative motion

$(z_1 + z_2)^m$: centre of mass motion

- Relative motion fixed by confinement to lowest Landau level

'incompressible state'

Pauli: $l$ <u>odd</u> integer

# Many particles: Laughlin wavefunction

## Try variational form

$$\psi_L(z_1 \cdots z_N) = \prod_{i<j} f(z_i - z_j)\, e^{-\frac{1}{4}\sum_k |z_k|^2}$$

N electrons — correlated in pairs

Natural to pick $f(z_i - z_j)$ so as to minimise probability for electrons to get close together

## In fact, have no freedom

- Lowest Landau level $\Rightarrow$ $f(z_i - z_j)$ is polynomial
- Eigenstate of total angular momentum $\Rightarrow$ polynomial is homogeneous

$$\boxed{f(z_i - z_j) \propto (z_i - z_j)^q}$$

- Pauli $\longrightarrow$ $q$ is odd integer

## Making quasiparticles

Add hole at $\xi$

$$\psi(z_1 \cdots z_N) = \prod_l (z_l - \xi) \times \psi_L$$

$\prod_l (z_l - \xi)$: electrons avoid $\xi$

$\psi_L$: Laughlin wavefunction

# Understanding $\psi(z_1, z_2 \cdots z_N)$

## – the plasma analogy

Hard problem to find properties of state $\psi$

Use analogy with classical statistical mechanics

Suppose

$$|\psi(z_1 \cdots z_N)|^2 = \exp\left(-\beta H_{cl}(z_1 \cdots z_N)\right)$$

– defines $H_{cl}(z_1 \cdots z_N)$

Wavefunction

$$\psi(z_1 \cdots z_N) = \prod_\ell (z_\ell - \xi) \prod_{i<j} (z_i - z_j)^q \, e^{-\frac{1}{4}\sum_k |z_k|^2}$$

Equivalent classical system

$$H_{cl}(z_1 \cdots z_N) = -\frac{2q}{\beta} \sum_{i<j} \ln|z_i - z_j| + \frac{1}{2\beta} \sum_k |z_k|^2$$

$$- \frac{2}{\beta} \sum_\ell \ln|z_\ell - \xi|$$

## Compare with electrostatics in 2D

Point charge $Q$ at origin

Electric field $E(r) = \frac{Q}{2\pi\varepsilon_0 r}$

Electrostatic potential $V(r) = -\frac{Q}{2\pi\varepsilon_0} \ln(r)$

## Compare with $H_{cl}$

Set $\frac{1}{\beta} = \frac{q}{4\pi\varepsilon_0}$

$H_{cl}$ is energy of classical charges $q$:

- Interacting with each other:

$$-\frac{q^2}{2\pi\varepsilon_0} \sum_{i<j} \ln|z_i - z_j|$$

- Interacting with unit charge at $\xi$:

$$-\frac{q}{2\pi\varepsilon_0} \sum_{l} \ln|z_l - \xi|$$

- Interacting with potential from background charge of opposite sign

$$+\frac{q}{8\pi\varepsilon_0} \sum_{k} |z_k|^2$$

Background charge density? $\rho = \nabla^2 \left(\frac{|z|^2}{8\pi}\right) = \frac{1}{2\pi}$

# Screening in classical plasmas

and

# Properties of Laughlin wavefunction

## Principle

Charge fluctuations cost energy

- **Electron density matches background**

  Background charge density $\frac{1}{2\pi}$

  Electrons ≡ charges $q$

  So number density $\frac{1}{2\pi q}$

- **Depletion of electron density at quasiparti**

  "Hole" represented by unit classical charge

  Screened by $\frac{1}{q}$ of an electron

| Quasiparticles have fractional charge |
|---|

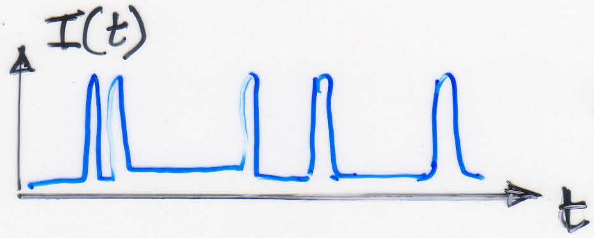
# Direct observation of a fractional charge

**R. de-Picciotto, M. Reznikov, M. Heiblum, V. Umansky, G. Bunin & D. Mahalu**

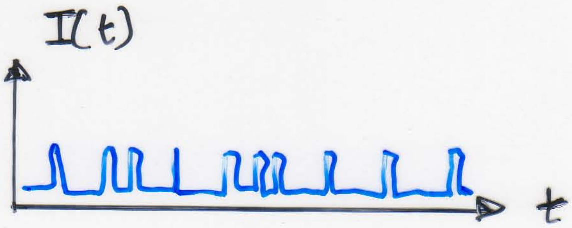
*Braun Center for Submicron Research, Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

Nature 1997

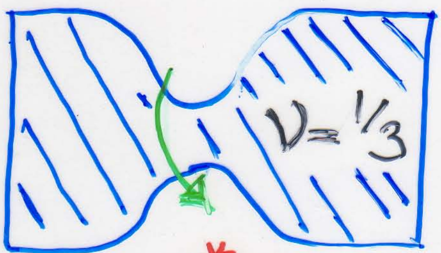
Measure shot noise power vs $\langle I \rangle$




large $e^*$




small $e^*$




$e^* = 1/3$

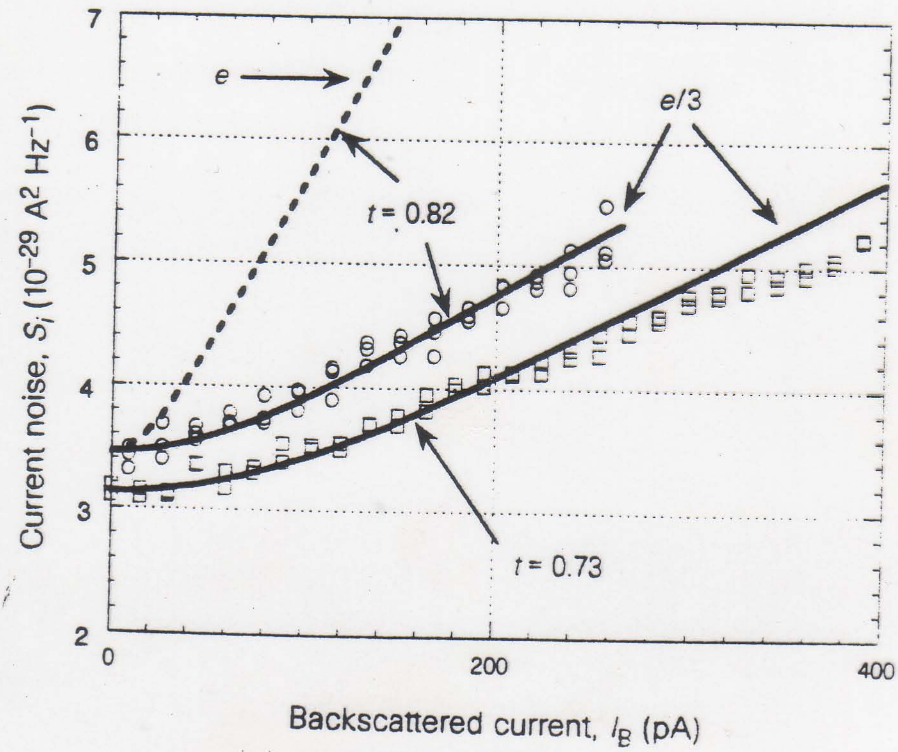
Expect

$\langle S \rangle = 2e^* \langle I \rangle$

noise power

– measure $e^*$

Noise Power




Mean current

# Lecture I: Summary

Integer quantum Hall effect

- plateau transition as quantum phase transition

Fractional quantum Hall effect:

- Laughlin wavefunction and fractionally-charged quasiparticles

Omissions:

Neutral excitations
Composite fermions
$\nu = 1/2$
Topological order
Fractional quantum Hall edge states ...

# Lecture II: Broken symmetries in quantum Hall systems

## Stripe and bubble phases

What takes the place of the FQHE in high Landau levels?

## Quantum Hall ferromagnets and skyrmions

Electron spin as a degree of freedom

Charged quasiparticles with large spin

## Bilayers

Spontaneous interlayer phase coherence

Excitonic superfluidity

# Quantum Hall Systems at Weak field

## Energy Scales

Cyclotron energy $\hbar\omega_c = \frac{\hbar e B}{m^*}$

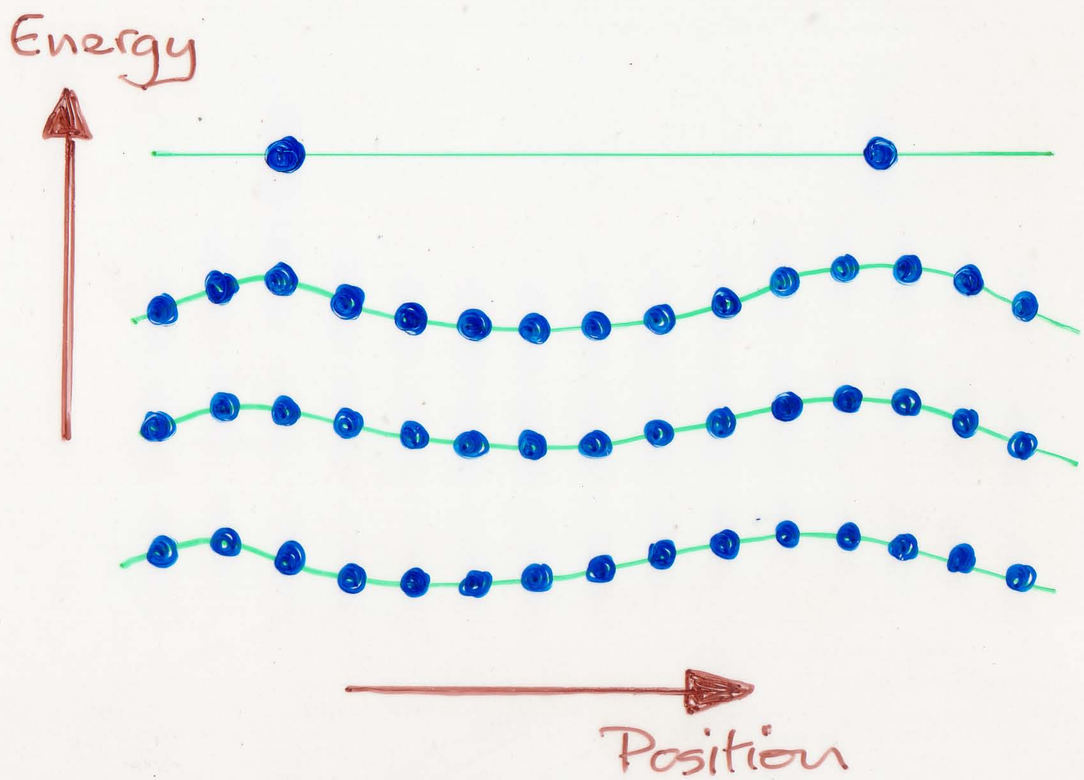
Coulomb energy $\frac{e^2}{4\pi\varepsilon\varepsilon_0 \ell_B} \propto B^{1/2}$

## Length Scales

Magnetic length $\ell_B = \left(\frac{\hbar}{eB}\right)^{1/2}$

Larmor radius $R_c = \sqrt{\nu} \cdot \ell_B$

## Screening by polarisatión of filled Landau levels



# Why is FQHE a strong-field phenomenon?

## Length scales

Magnetic length $\ell_B = \left(\frac{\hbar}{eB}\right)^{1/2}$

— electron-electron separation within Landau level

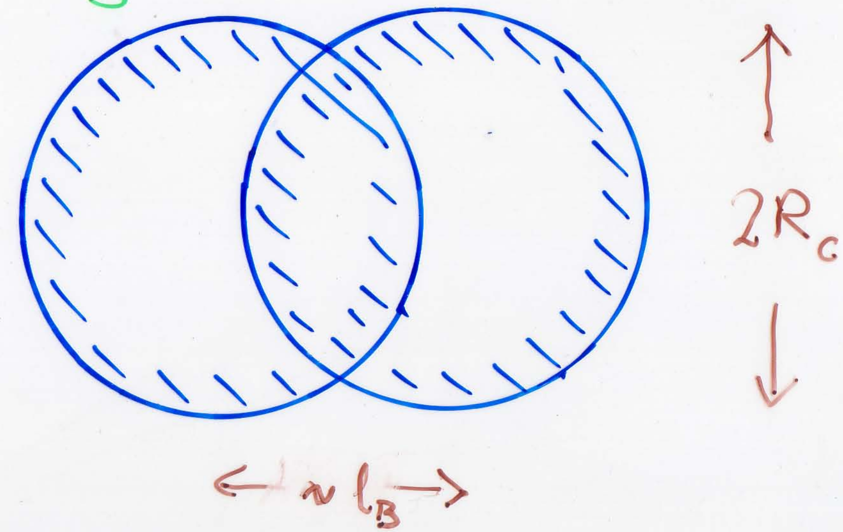
Larmor radius $R_c = \sqrt{\nu}\, \ell_B$

— radius of cyclotron orbit

## Two neighbouring electrons

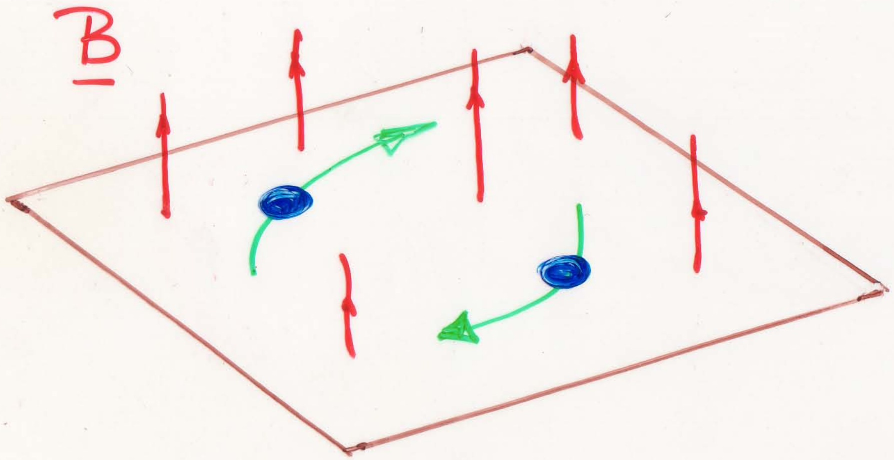
In lowest Landau level

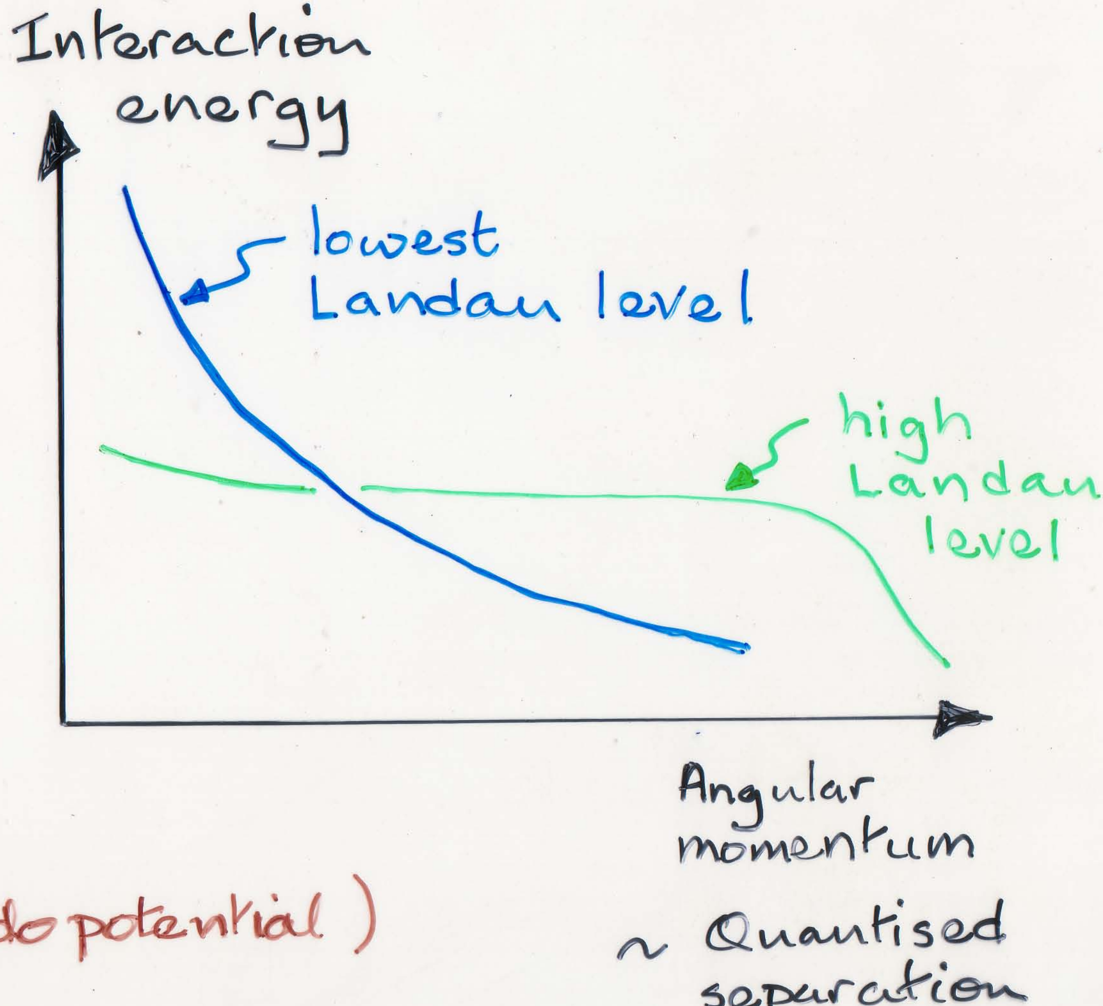

In higher Landau level



# Correlated States at Strong and Weak Field

## Two-particle states




(Haldane pseudopotential)

PHYSICAL REVIEW B VOLUME 19, NUMBER 10 15 MAY 1979

# Two-dimensional electron gas in a strong magnetic field

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*The Institute for Solid State Physics, The University of Tokyo, Tokyo, Japan*

P. M. Platzman and P. W. Anderson*
*Bell Laboratories, Murray Hill, New Jersey 07974*

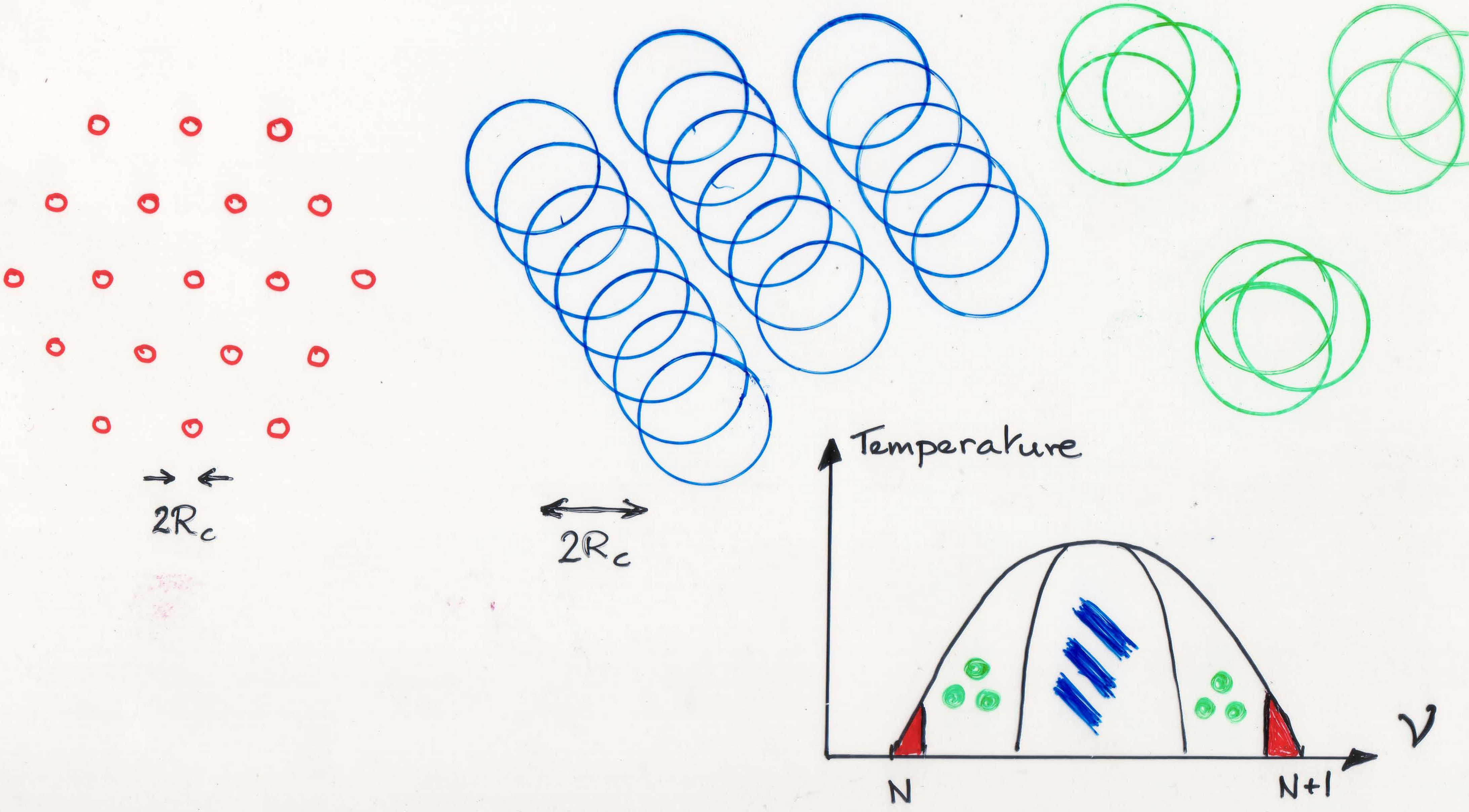
(Received 15 May 1978; revised manuscript received 29 December 1978)

Some interesting properties of the phase diagram of a two-dimensional electron gas are calculated within the framework of Hartree-Fock picture. We find that the system is unstable to the formation of a charge-density wave at temperatures well above the *classical* Wigner solid transition temperature.

## I. INTRODUCTION

Recently there has been a great deal of interest in the properties of quasi-two-dimensional electron gases.

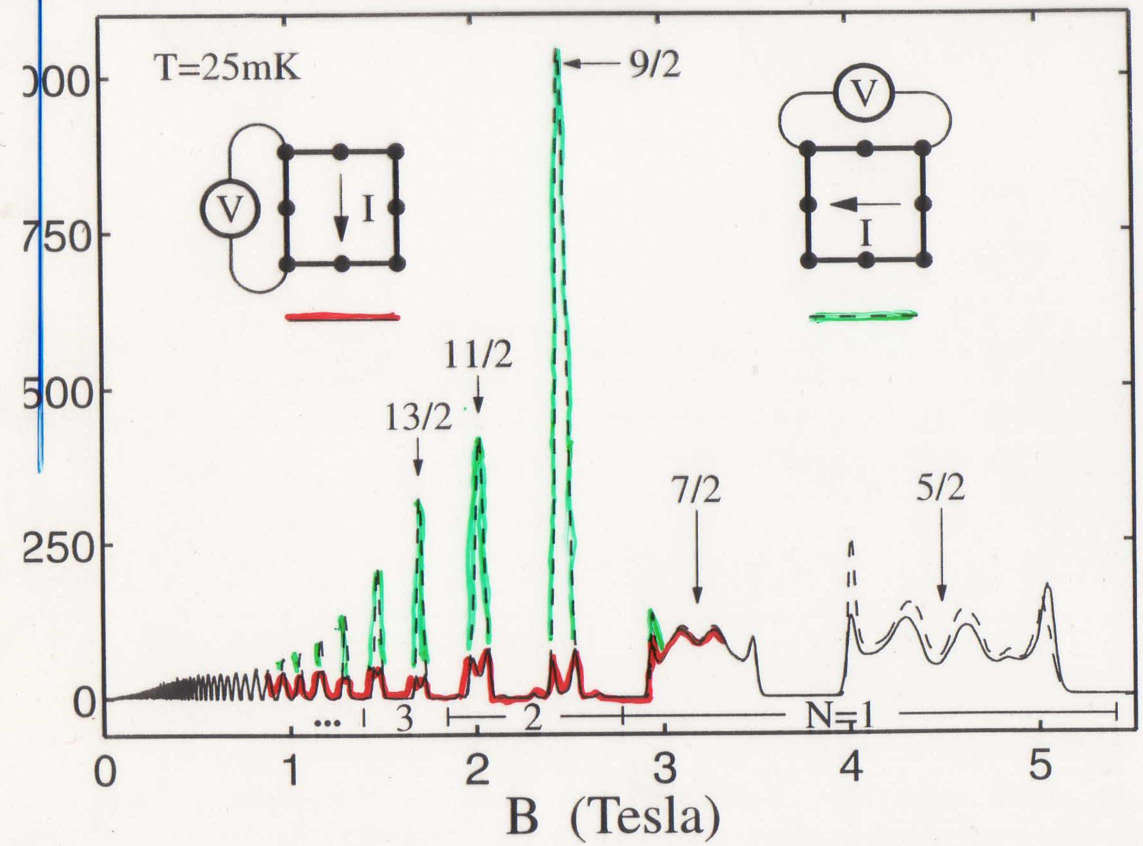
# Wigner Crystals, Stripes and Bubbles



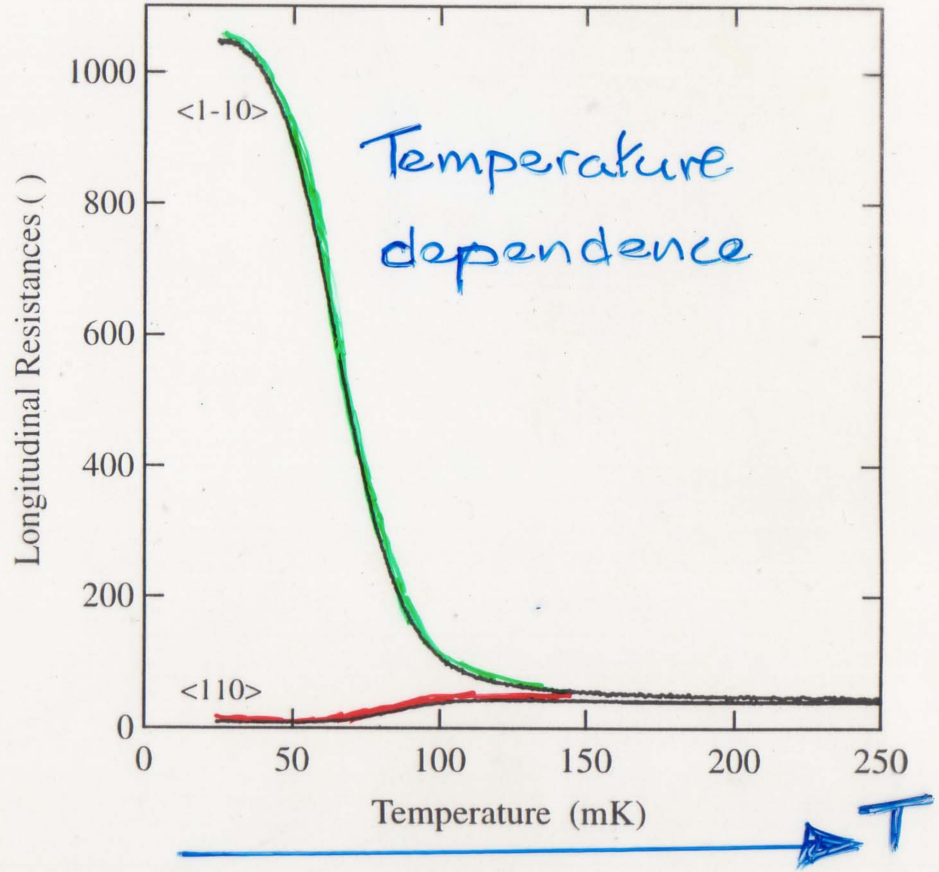
# Anisotropic Conduction at Low Temperature

Longitudinal resistance

in high Landau levels



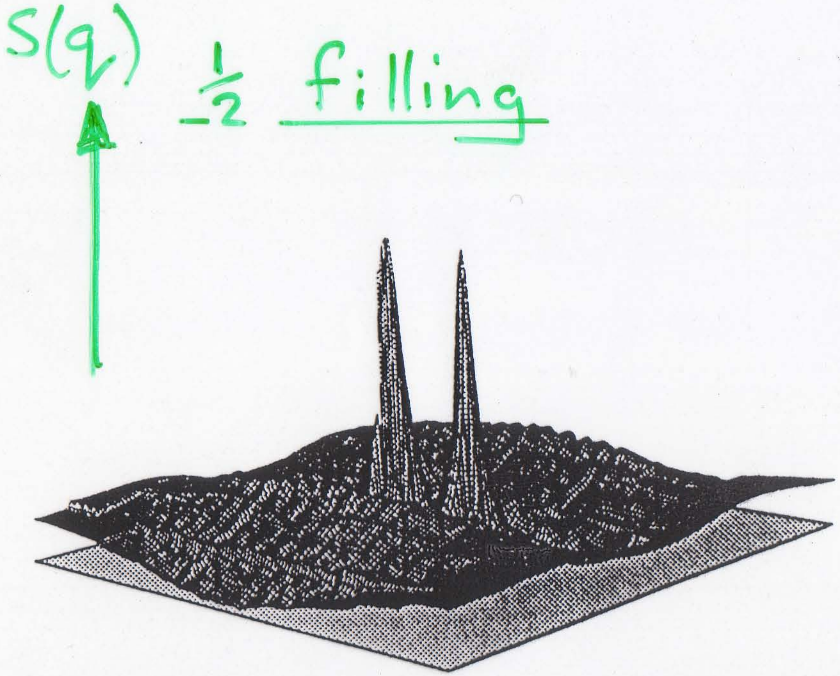

Lilly, Cooper, Eisenstein
Pfeiffer + West 1999

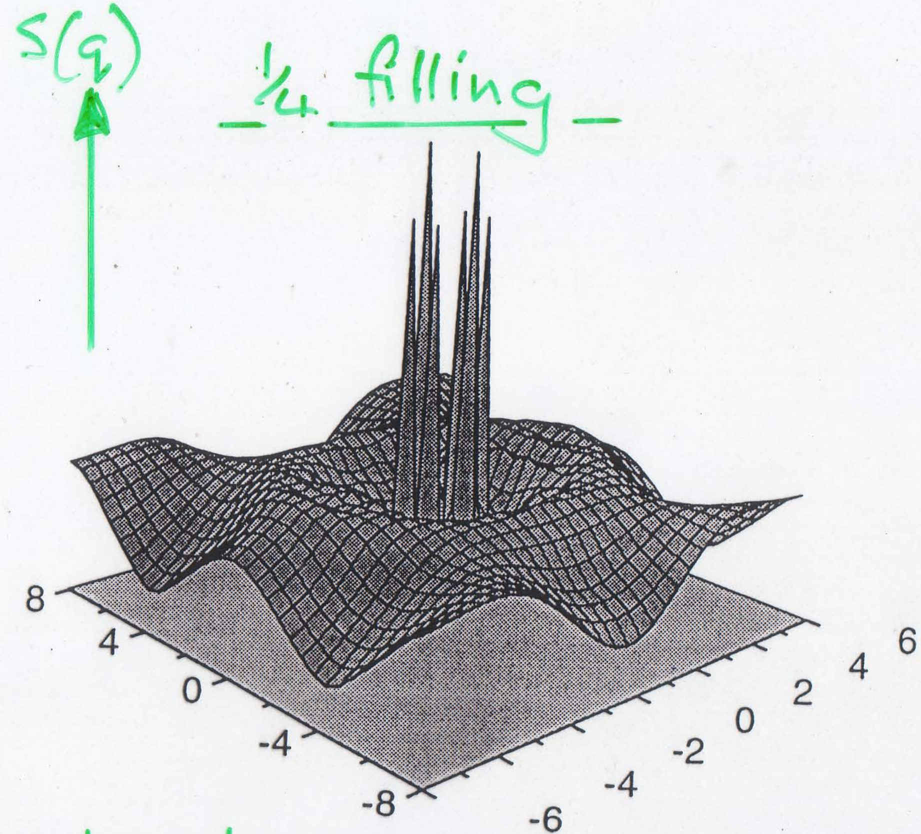


# Density Correlations by Exact Diagonalisation

8 electrons on torus

Rezai, Haldane and Yang 2000




$n=2$ Landau level

# Quantum Hall Ferromagnets

## Cyclotron, Zeeman & Exchange energies

Typically $g^* \mu_B B \sim \frac{1}{40} \times \hbar \omega_c$

At $\nu = 1$

Exchange $\Rightarrow$ Spin polarisation

even for $g^* = 0$

cf

$$\Psi = \prod_{i<j} (z_i - z_j)\, e^{-\frac{1}{4}\sum_k |z_k|^2}$$

## Spin waves

Landau gauge basis states

$$\psi_k(x,y) \sim e^{iky}\, e^{-\frac{1}{2}(x+k)^2}$$

Polarised ground state

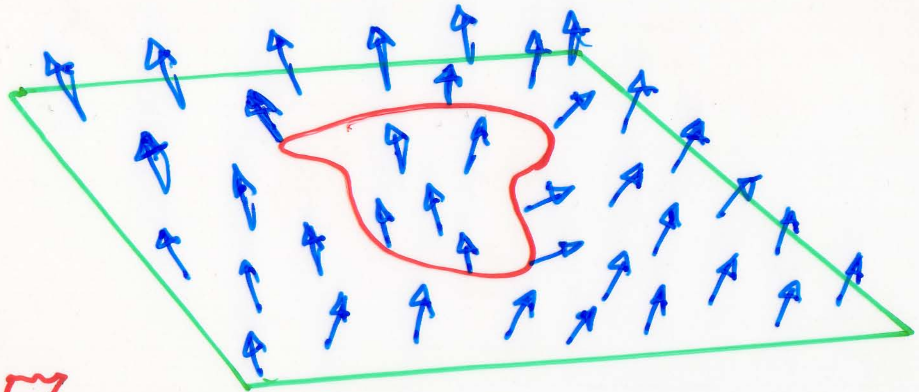
$$|\Psi_0\rangle = \prod_k c^\dagger_{k\uparrow} |0\rangle$$

Spin wave excitation

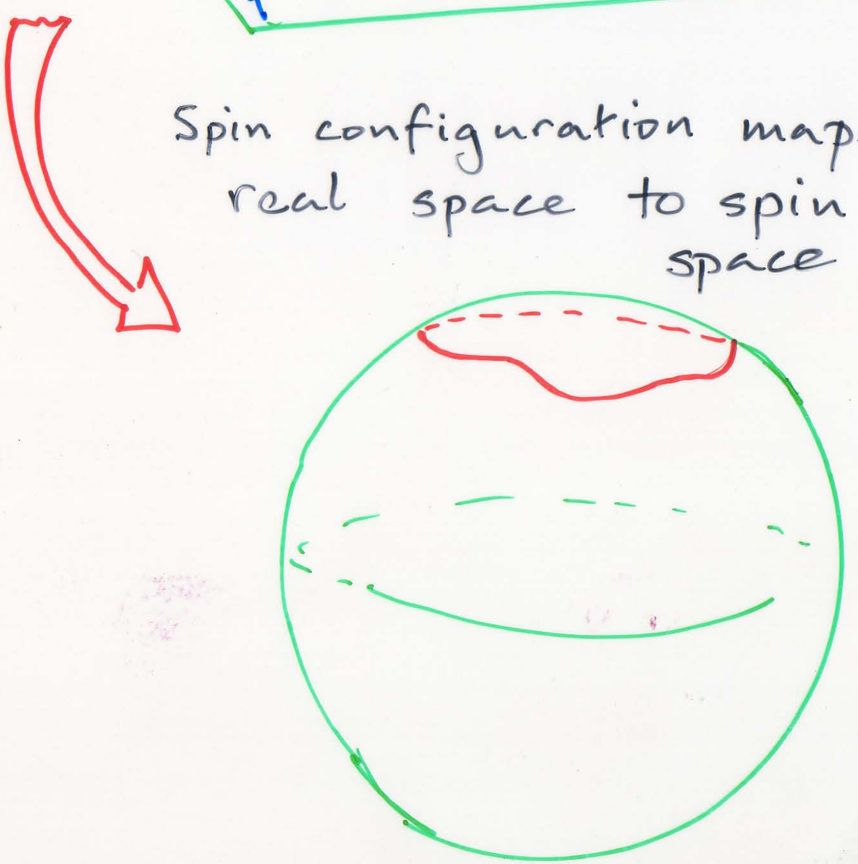
$$|q\rangle = \sum_k e^{ikq_x}\, c^\dagger_{k-q_y\downarrow} c_{k\uparrow} |\Psi_0\rangle$$

Real space picture

# Topological Excitations



Spin configuration maps real space to spin space



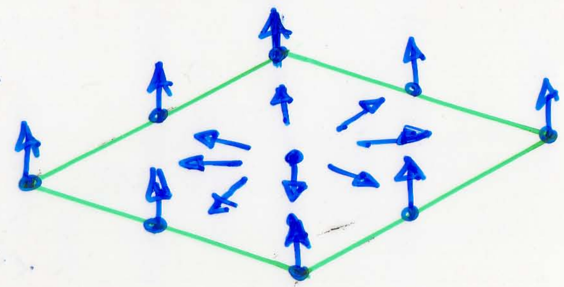
**Berry phase modulates charge density**

$$\delta\rho = \frac{e}{4\pi} \vec{S}\cdot(\partial_x \vec{S} \times \partial_y \vec{S})$$

**Skyrmion**

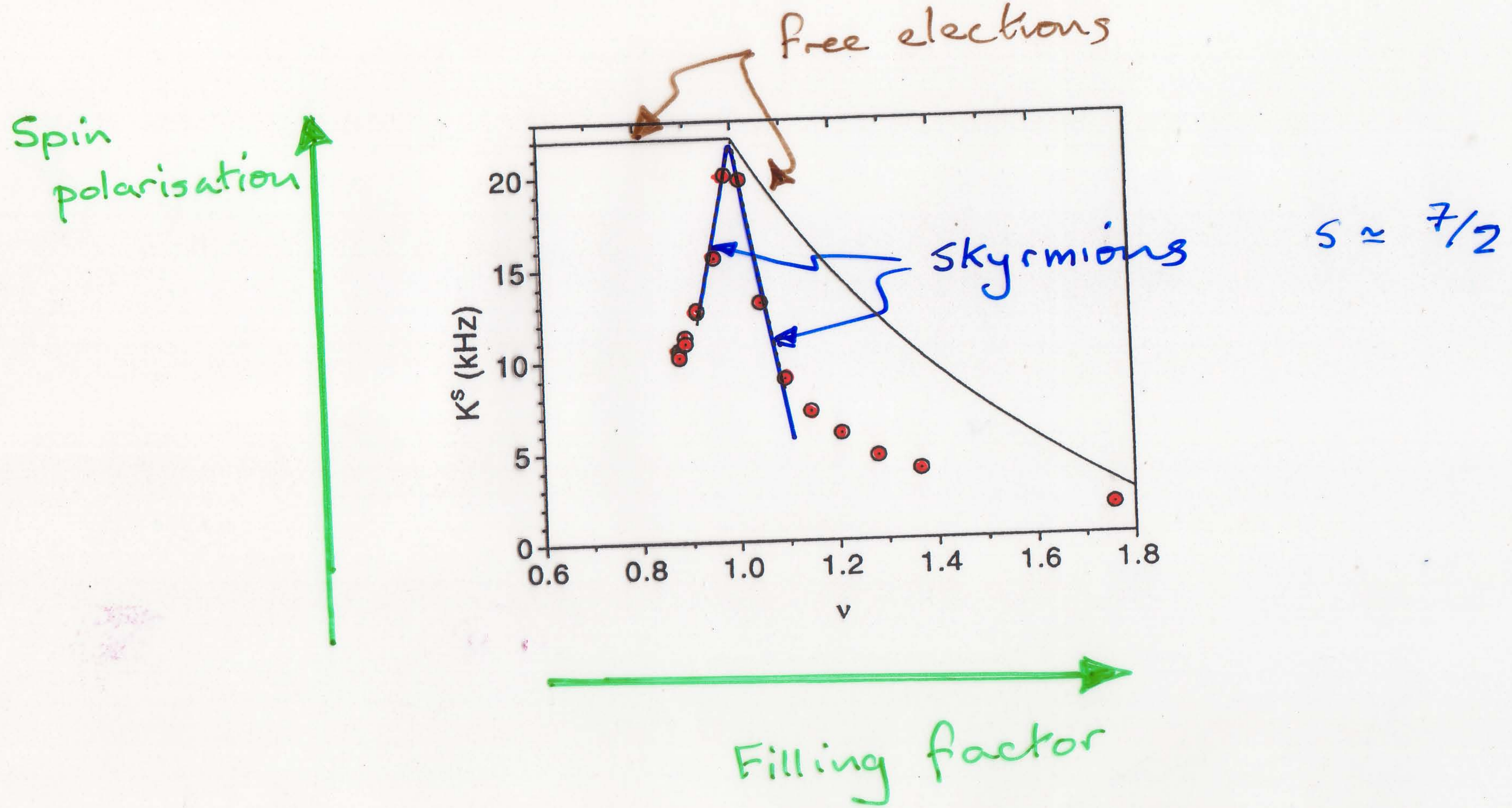
$$\begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix} = \frac{1}{r^2+a^2}\begin{pmatrix} 2ar\cos\phi \\ 2ar\sin\phi \\ r^2-a^2 \end{pmatrix}$$

$$\delta\rho = -\frac{e}{\pi}\frac{a^2}{(a^2+r^2)^2}$$

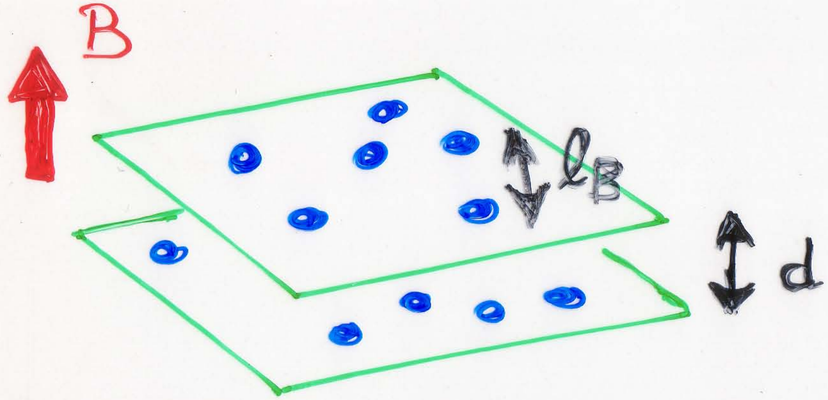


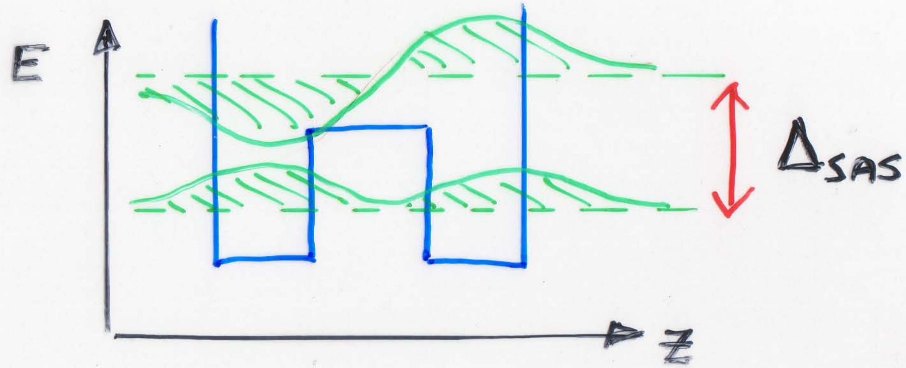
# Optically Pumped NMR Evidence for Finite-Size Skyrmions in GaAs Quantum Wells near Landau Level Filling $\nu = 1$

S. E. Barrett,* G. Dabbagh, L. N. Pfeiffer, K. W. West, and R. Tycko†
*AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974*
(Received 19 December 1994)



# Quantum Hall Bilayers at $\nu_{Total} \simeq 1$



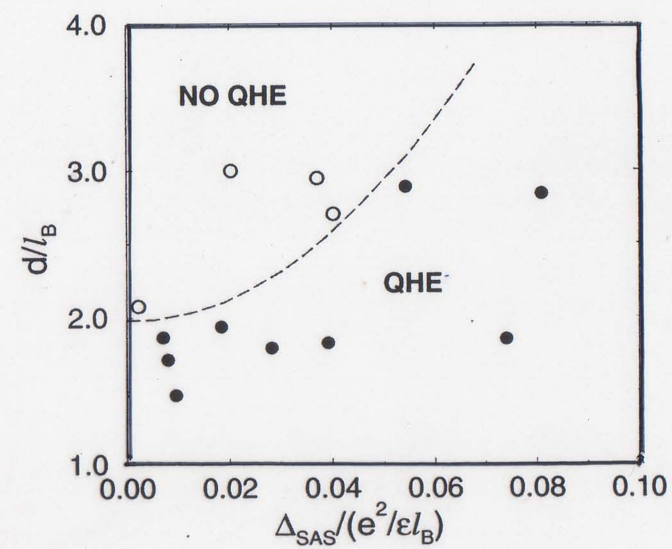




## Parameters

$\frac{d}{\ell_B}$ : inter- vs intra-layer correlations

$\frac{\Delta_{SAS}}{e^2/\varepsilon \ell_B}$ : single particle vs correlation energies

## Phase diagram



# Descriptions of interlayer coherence

## Easy plane ferromagnet

Pseudospins $\Uparrow \sim$ layer # a

$\Downarrow \sim$ layer # b

Correlated state:

$$|\psi\rangle = \prod_k \left(\cos\frac{\theta}{2}\, a_k^\dagger + \sin\frac{\theta}{2}\, e^{i\phi}\, b_k^\dagger\right)|0\rangle$$

Cost of smooth changes in pseudo spin orientation

$$E \sim \int d^2\underline{r} \left\{ \frac{J}{2} |\underline{\nabla}\vec{S}|^2 + D(S^z)^2 - t\, S^x \right\}$$

$|\vec{S}| = 1$

exchange ($J$), charging ($D$), tunneling ($t$)

## Excitonic condensate

$$|vac\rangle = \prod_k a_k^\dagger\, |0\rangle$$

Particle hole transformation in one layer: $d_k^\dagger = a_{-k}$

Condensate:

$$|\psi\rangle = \prod_k \left(u + v\, d_k^\dagger b_k^\dagger\right)|0\rangle$$

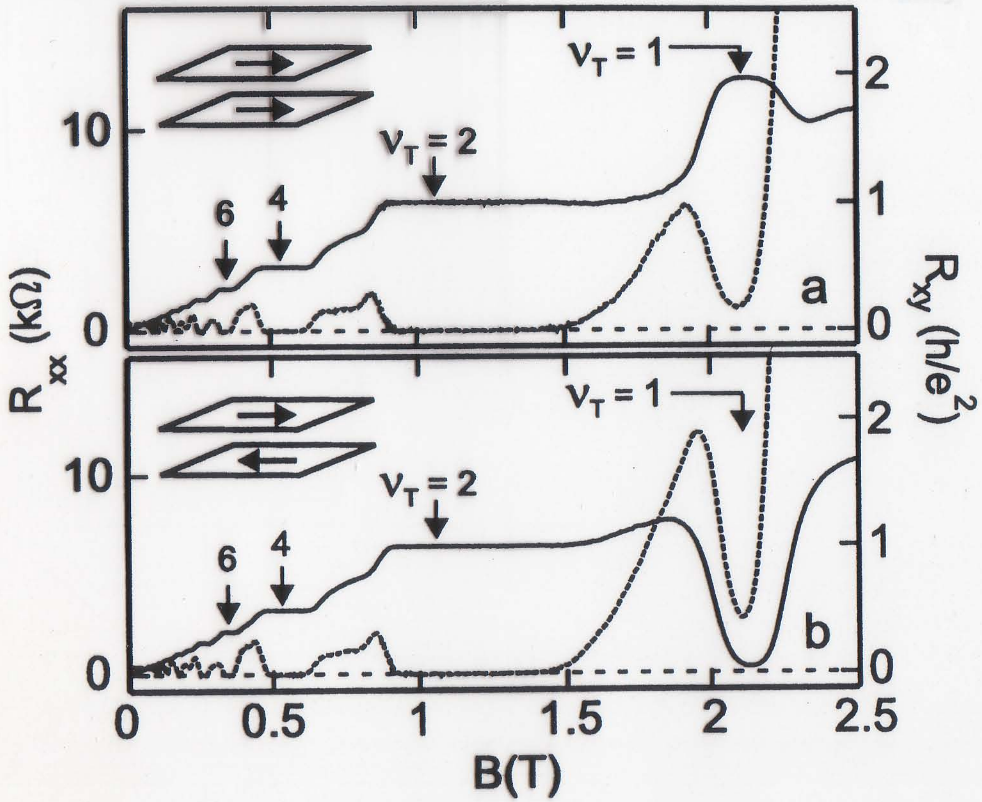
Charge balance

$|u| = |v|$

# Observation of Excitonic Superflow

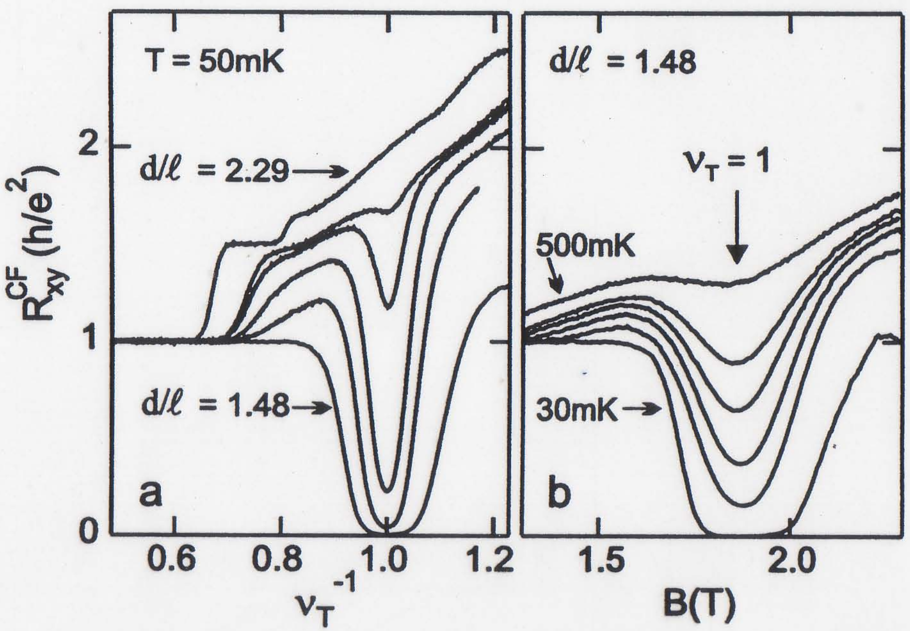
Kellogg, Eisenstein et al
PRL (2004)

## Counterflow vs Parallel flow




**All** components of $\rho$ vanish for counterflow

## Dependence on T & d/ℓ



# Lecture II: Summary

## Ordering in high Landau levels

Crystallisation vs Laughlin states

## Exchange energy and spin ordering

Spin textures and charge density

Topological excitations

## Bilayers

Pseudospin order/exciton condensation

# Seminar: Interactions and Transport Between Coupled Quantum Hall Edge States

Joe Tomlinson (Oxford)
J-S Caux (Amsterdam)
John Chalker (Oxford)

Outline:

Edge states in multilayer quantum Hall systems

Overview of experiments

Theory for coupled edge states in multilayer systems

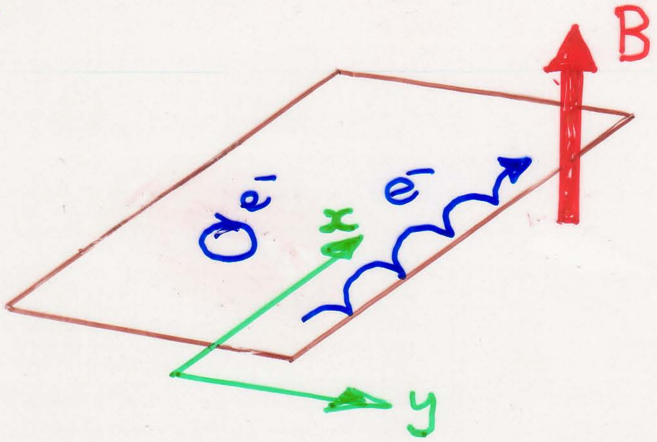
Past work on multilayer quantum Hall systems and chiral metal:

JTC + Dohmen, PRL (1995)
Balents and Fisher, PRL (1996)
Cho, Balents and Fisher, PRB (1997)
Betouras + JTC, PRB (2000)

Experiments: Gwinn et al, UCSB

# Edge States in Multilayer QH Systems

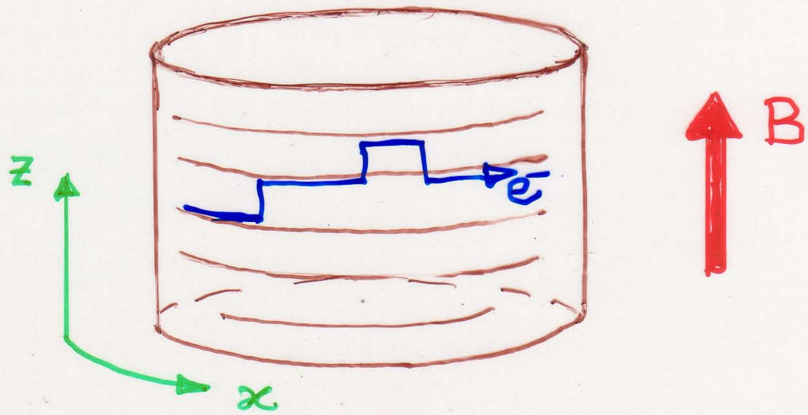
## Single layer




2D → 1D

$H = v p_x$

## Multilayer




$$H = H_{\text{edge}} + H_{\text{imp}} + H_{\text{int}} + H_{\text{hopping}}$$

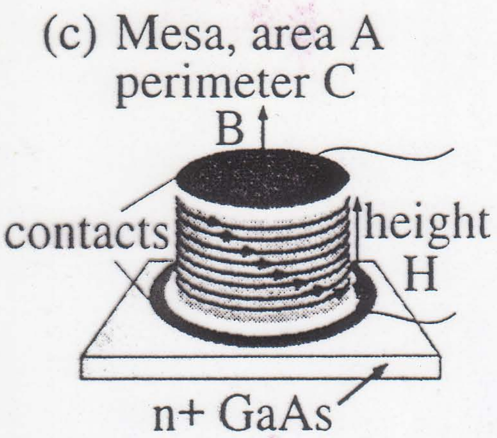
$$H_{\text{edge}} + H_{\text{imp}} = \sum_n \int dx \psi_n^\dagger(x)[-iv\partial_x + V_n(x)]\psi_n(x)$$

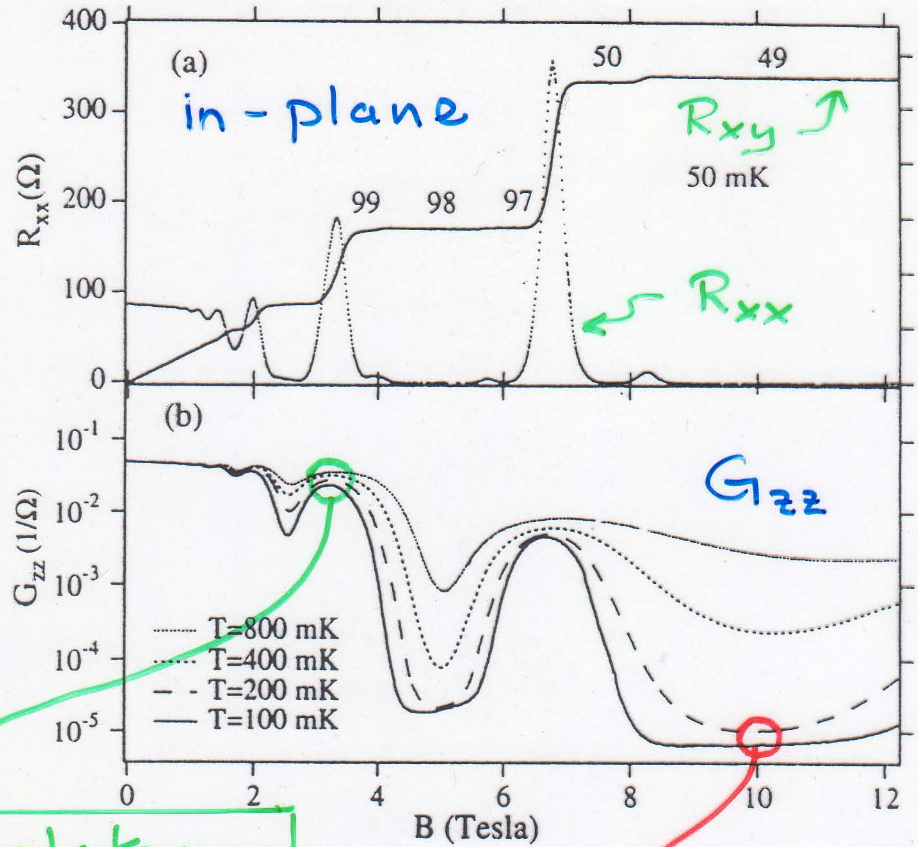
$$H_{\text{int}} = \sum_{n,m} \int dx \int dx' \rho_n(x) U_{n-m}(x - x')\rho_m(x')$$

$$\rho_n(x) = \psi^\dagger(x)\psi(x)$$

$$H_{\text{hopping}} = t_\perp \sum_n \int dx [\psi_{n+1}^\dagger(x)\psi_n(x) + \text{h.c.}]$$

# Focussing on Surface States

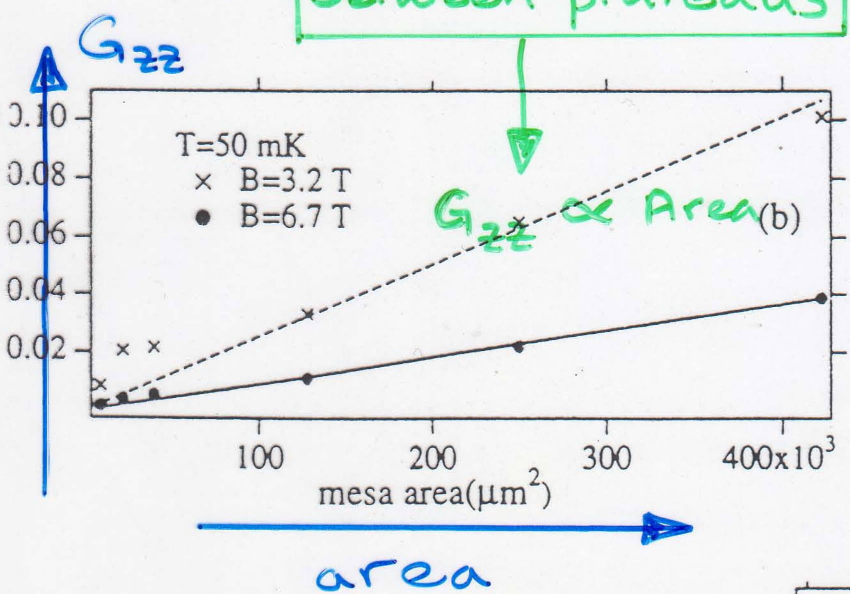


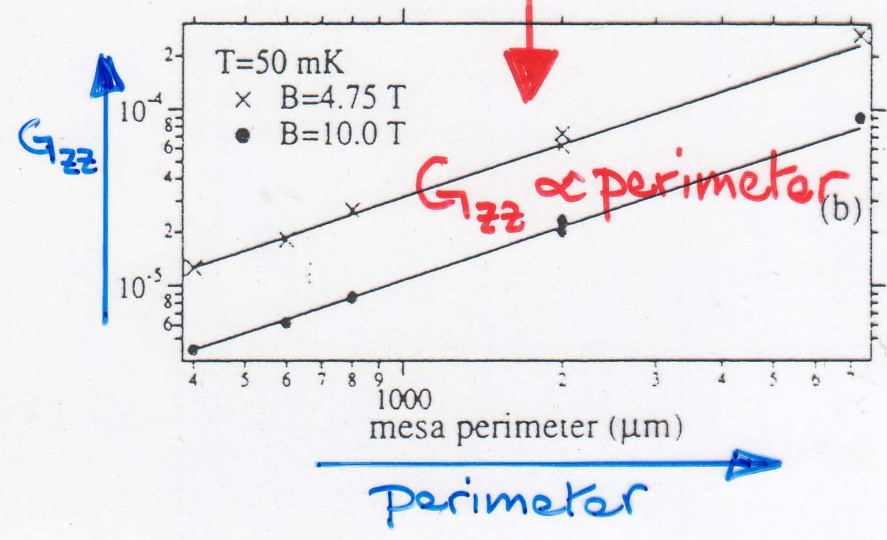




Vertical transport: $G_{zz}$

between plateaus

In plateaus

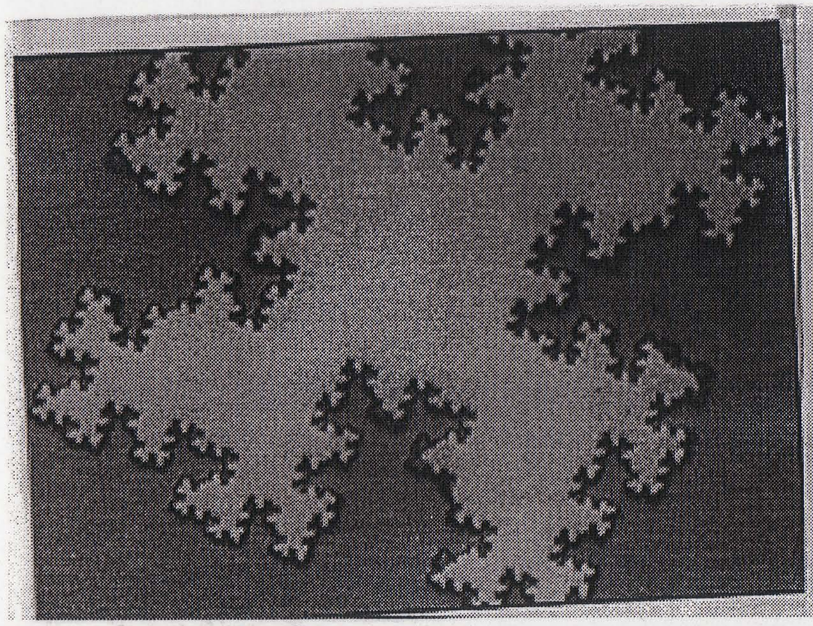


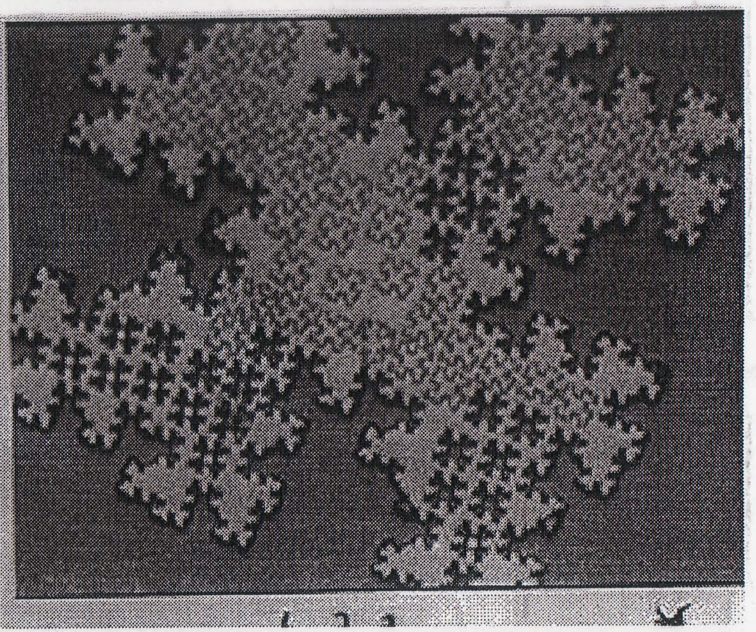

Druist et al 1998

UCSB

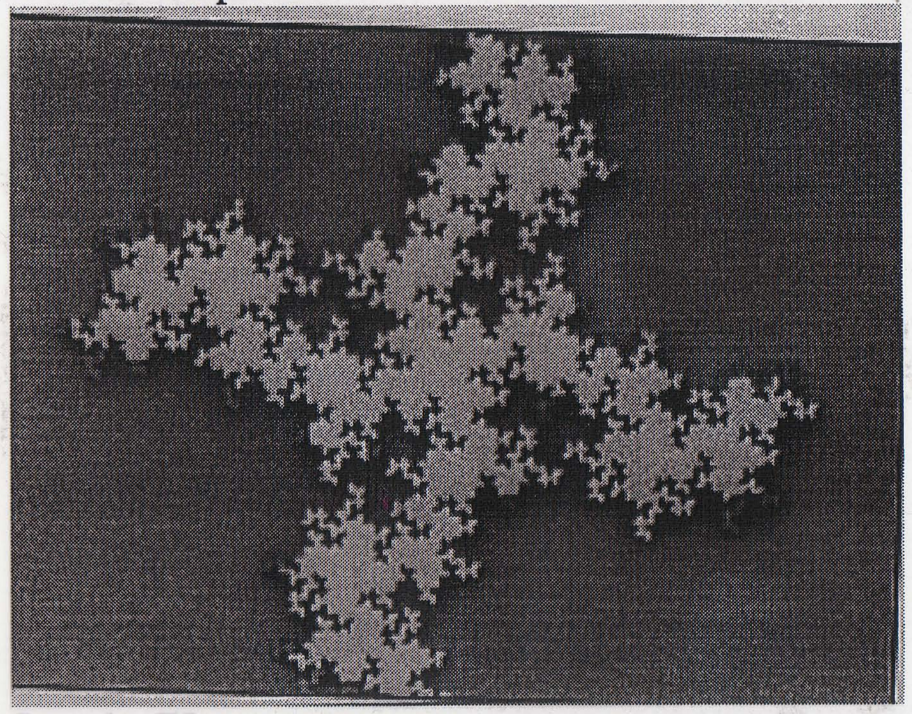
Samples for studying surface states



Sample F1



Sample F3

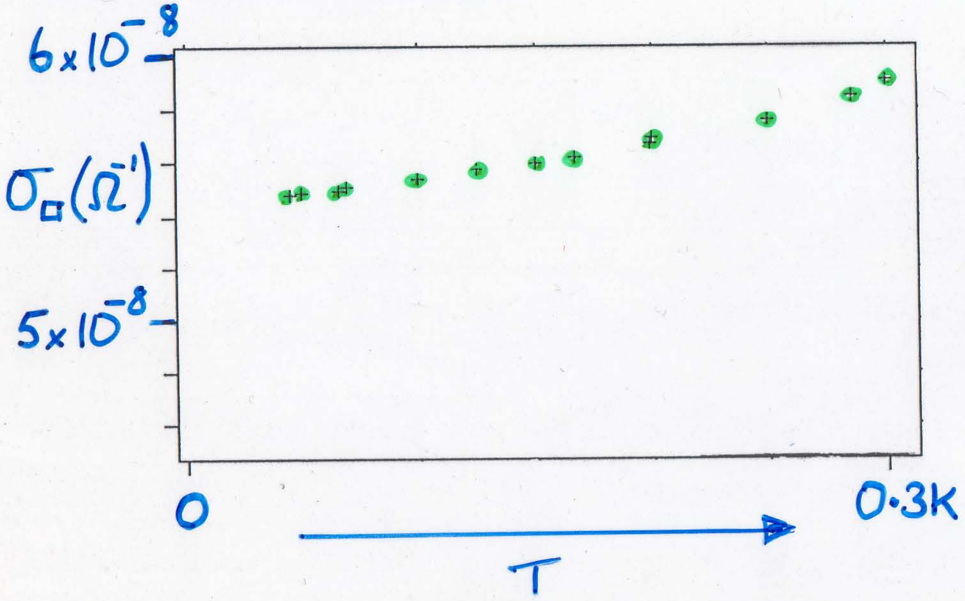


Sample F5

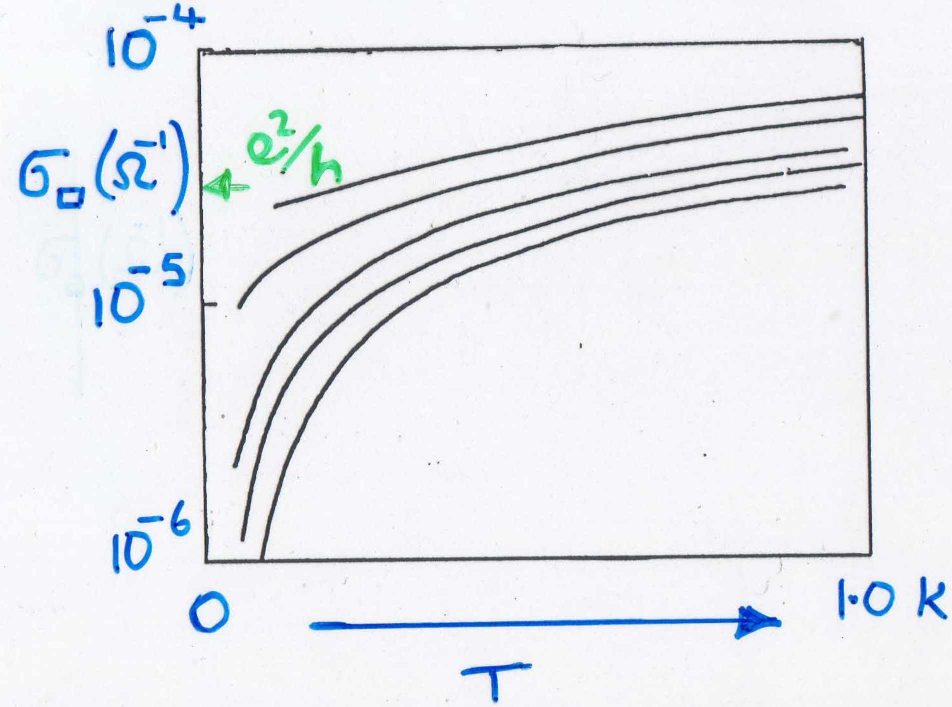
E. Gwinn et al
UCSB

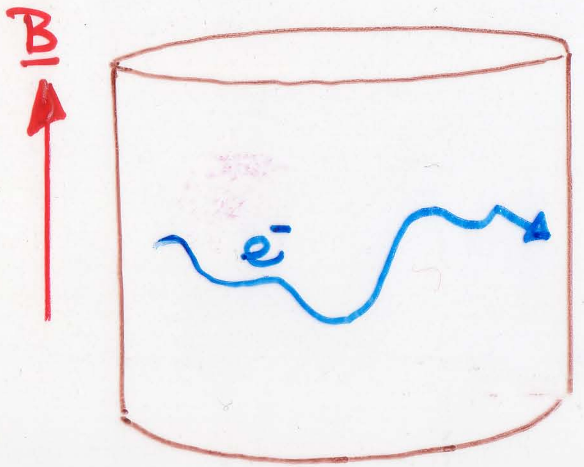
# Special Features of Chiral Metal

## Chiral Metal



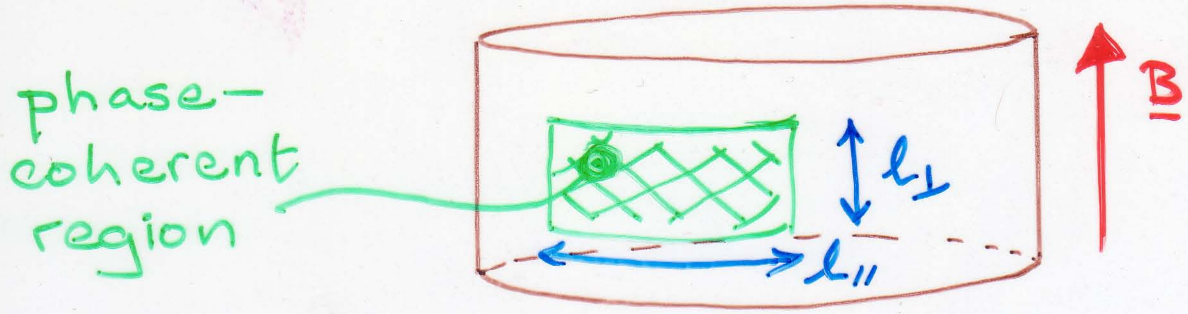

## Conventional 2D MOSFET



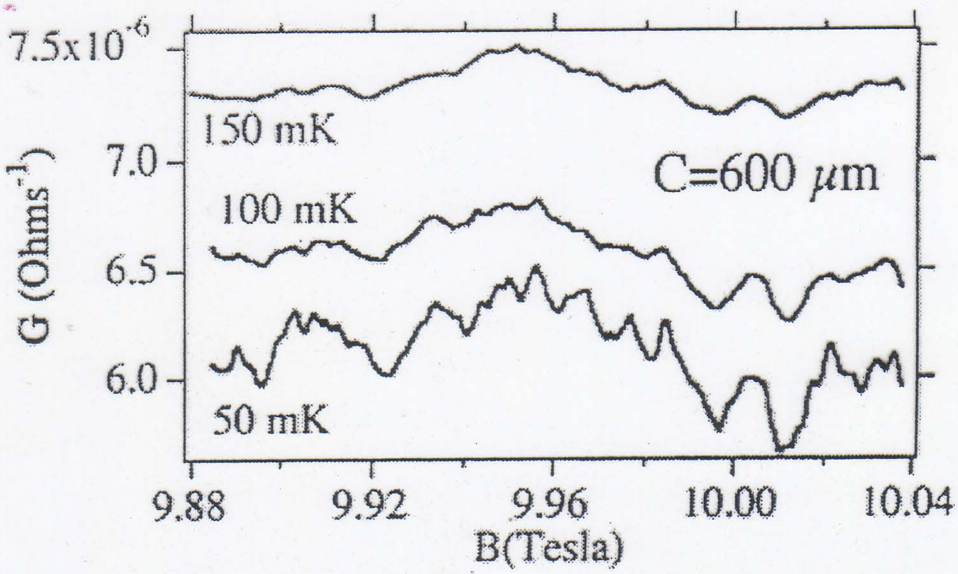




- No backscattering by disorder
  - no localisation

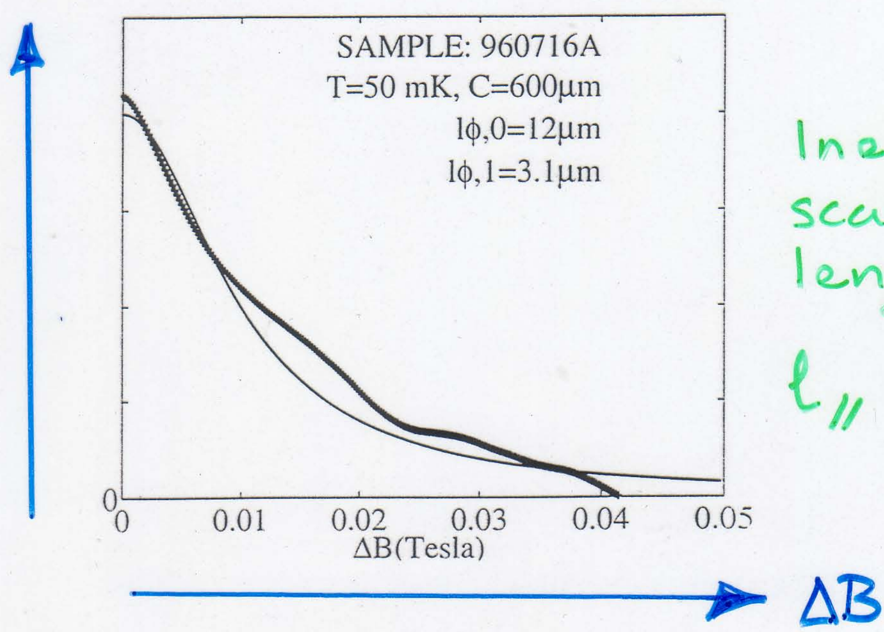
# Conductance fluctuations as a Probe




## Mescoscopic fluctuations




$\langle \delta G(B)\, \delta G(B+\Delta B) \rangle$



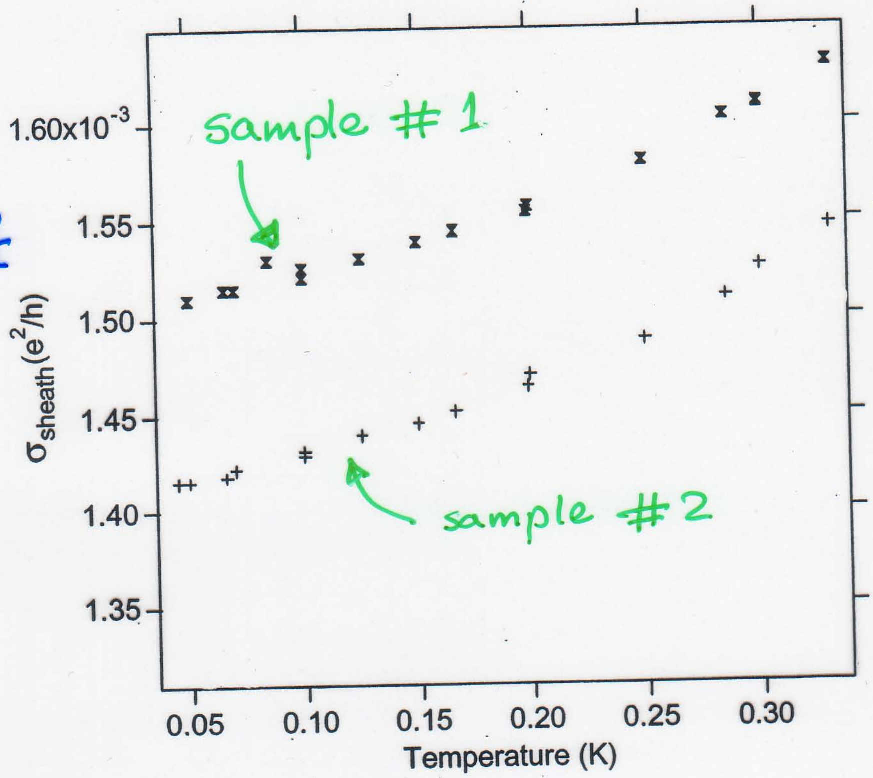

Inelastic scattering length

$l_{//} \approx 3.\mu m$

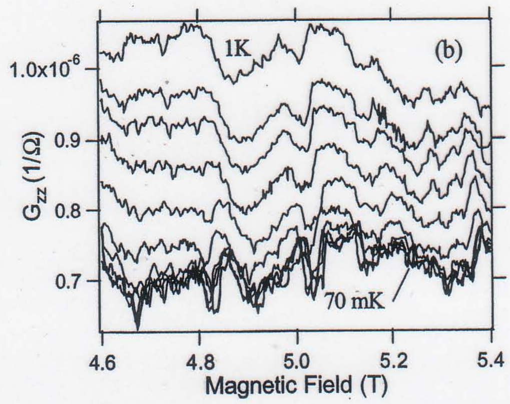
# Recent Experiments

Walling et al
UCSB (2004)

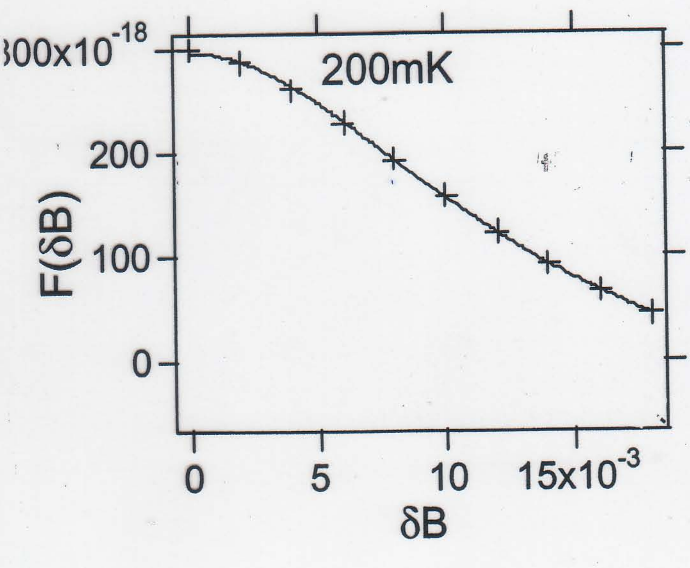
## Temperature dependence of conductance



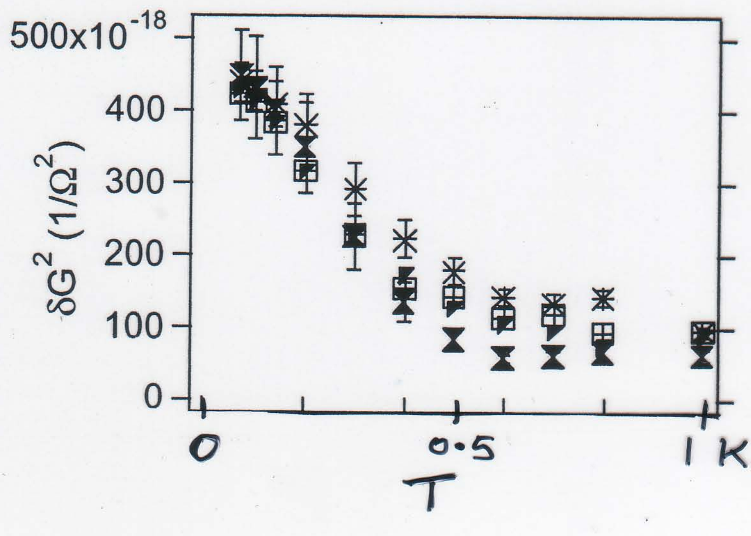

## Conductance fluctuations




## Correlator




## T-dependance



# Scales in experimental system

Sample

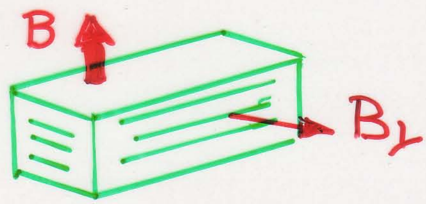
Layer spacing $a = 30\mathrm{nm}$

Number of layers: 50 - 100

Disorder

From transverse magnetoresistance

$l_{\mathrm{elastic}} \sim 40\mathrm{nm}$




Interactions

From amplitude of conductance fluctuations

$l_{\mathrm{inelastic}} \sim 0.5 - 3\mu\mathrm{m}$

depending on sample and temperature

Temperature

Thermal length

$L_{\mathrm{T}} = \hbar v / k_{\mathrm{B}} T = 10\mu\mathrm{m}$

at 100 mK for *sharp* confining potential

Tunneling

Tunneling length $l_{\perp} \sim 40\mu\mathrm{m}$

From conductivity

$$\sigma = ne^2 D \qquad \rightarrow \qquad \sigma = (e^2/h) \cdot (a/l_{\perp})$$

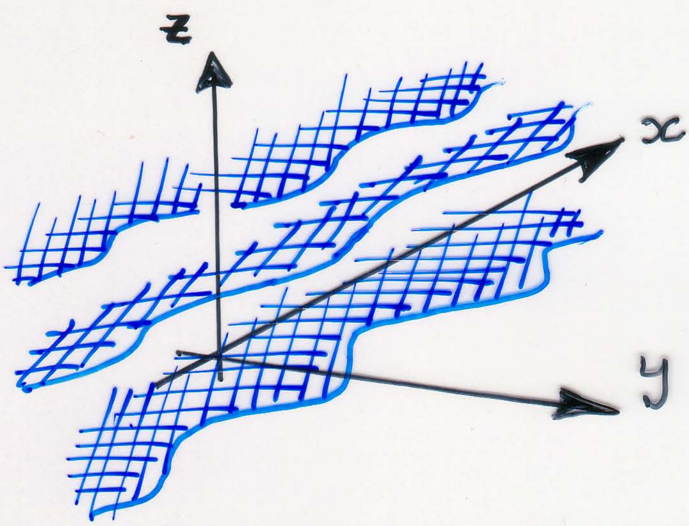
$$n = (ahv)^{-1} \quad \& \quad D = a^2/\tau_{\perp} \quad \& \quad l_{\perp} = v\tau_{\perp}$$

# Classical treatment of surface modes without tunneling

## Current

$$j_x(\vec{r},t) = v\rho(\vec{r},t)$$

$$j_z(\vec{r},t) = 0$$




## Continuity

$$\partial_t \rho(\vec{r},t) = -\vec{\nabla}\cdot\vec{j}(\vec{r},t) + \frac{\sigma_{xy}}{a}\mathcal{E}_x$$

electric field from $\rho(\vec{r},t)$

Hall current to/from bulk

Surface magnetoplasmon dispersion

$$\omega(q_x,q_z) = vq_x\left[1 + \frac{\kappa}{(q_x^2+q_z^2)^{1/2}}\right]$$

inverse screening length: $\kappa = \frac{ne^2}{2\epsilon\epsilon_0} = \frac{e^2}{2\epsilon\epsilon_0 ahv}$

experiment: $\kappa a \sim 2$ if confining potential sharp

# Essentials of calculations

## Disorder and gauge transformations

Single edge

$H = \int dx \psi^\dagger(x)[-i\hbar v \partial_x + V(x)]\psi(x)$

Remove $V(x)$ by $\psi \to e^{-i\theta(x)}\psi$

with $\theta(x) = (\hbar v)^{-1} \int^x V(x')dx'$

Phases appear in tunneling:

$$t_\perp \psi^\dagger_{n+1}(x)\psi_n(x) \quad \to \quad \underbrace{t_\perp e^{i[\theta_{n+1}(x)-\theta_n(x)]}}_{t_\perp(n,x)} \psi^\dagger_{n+1}(x)\psi_n(x)$$

## Kubo formula for conductivity

disorder avge

$$\sigma(\omega) \propto \int dx \langle t^*_\perp(n,x) t_\perp(n,0)\rangle \frac{1}{\omega} \int dt (e^{i\omega t} - e^{-i\omega t})$$
$$\times \langle \psi^\dagger_n(x,t)\psi_{n+1}(x,t)\psi^\dagger_{n+1}(0,0)\psi_n(0,0)\rangle$$

quantum avge

- Get $\sigma$ at leading order in $t_\perp$ from $\langle \psi^\dagger\psi\psi^\dagger\psi\rangle$ calculated in system without tunneling

# Bosonization

Get average conductance and mesoscopic fluctuations from

$$\langle \psi_n^\dagger(x,t)\psi_{n+1}(x,t)\psi_{n+1}^\dagger(0,0)\psi_n(0,0)\rangle$$

Only excitations are collective

- quantised surface magnetoplasmons

## Transformation:

boson operator $\quad b^\dagger_{qx,n} = i(\frac{2\pi}{Lqx})^{1/2}\sum_{kx}\psi^\dagger_{kx+qx,n}\psi_{kx,n}$

fermion operator $\quad \psi_n^\dagger(x) = e^{i\phi n(x)}$

with $\quad \phi n(x) = -(\frac{2\pi}{L})^{1/2}\sum_q(e^{-iqx}b_{qn} + e^{iqx}b^\dagger_{qn})$

## Hamiltonian:

$$H_{\rm edge} + H_{\rm int} = \sum_{\vec{q}}\hbar\omega(q_x,q_z)b^\dagger_{\vec{q}}b_{\vec{q}}$$

Boson dispersion:

$$\omega(q_x,q_z) = vq_x[1 + \frac{\kappa}{(q_x^2+q_z^2)^{1/2}}]$$

# Results (1)

$$\langle \psi_n^{+}(x,t)\, \psi_{n+1}(x,t)\, \psi_{n+1}^{+}(0,0)\, \psi_n(0,0) \rangle = (2\pi)^{-2} e^{S}$$

with

$$S = -\frac{1}{\pi} \int_{-\pi}^{\pi} dq_z \int_0^{\infty} dq_x \, \frac{1-\cos q_z}{q_x} \left\{ \coth\left(\frac{\beta\hbar\omega_q}{2}\right) \left[1 - \cos(q_x x - \omega_q t)\right] + i \sin(q_x x - \omega_q t) \right\}$$

# Results

Dependence of $\sigma(T)$ on $T$

Non-interacting system:

$$\sigma = \frac{e^2}{h}\frac{2t_\perp^2 a l_{\mathrm{elastic}}}{\hbar^2 v^2}$$

Interactions $\rightarrow$ Dispersion

$$v \rightarrow v(q_x, q_z) \equiv \frac{\partial\omega(q_x,q_z)}{\partial q_x}$$

Coulomb Interactions:

$$\omega(q_x, q_z) = vq_x[1 + \frac{\kappa}{(q_x^2+q_z^2)^{1/2}}]$$

For wide edge states

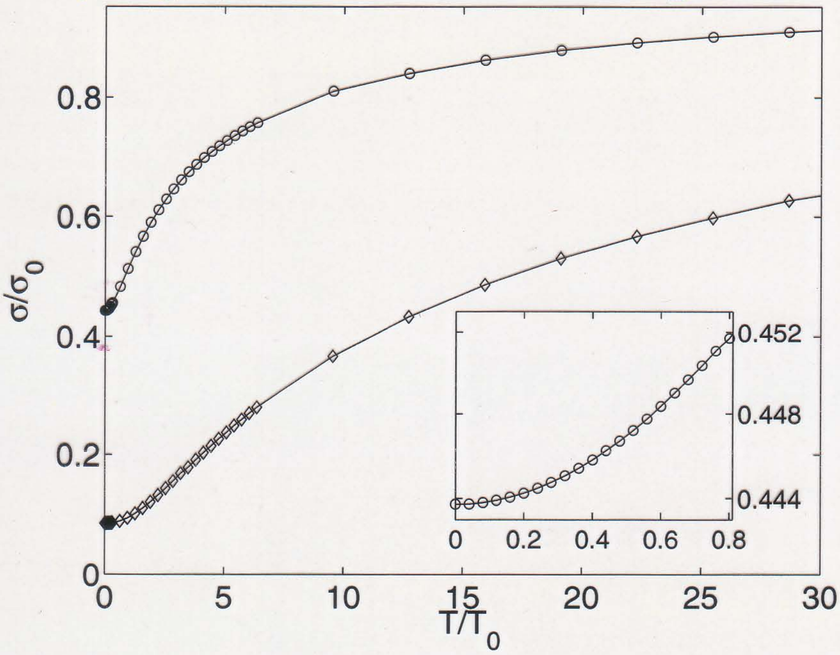
$$U_{m-n}(x-x') = \frac{e^2}{4\pi\epsilon\epsilon_0\sqrt{a^2(m-n)^2+(x-x')^2+w^2}}$$

and

$$\omega(q_x, q_z) = vq_x[1 + \frac{\kappa e^{-w|q|}}{(q_x^2+q_z^2)^{1/2}}]$$

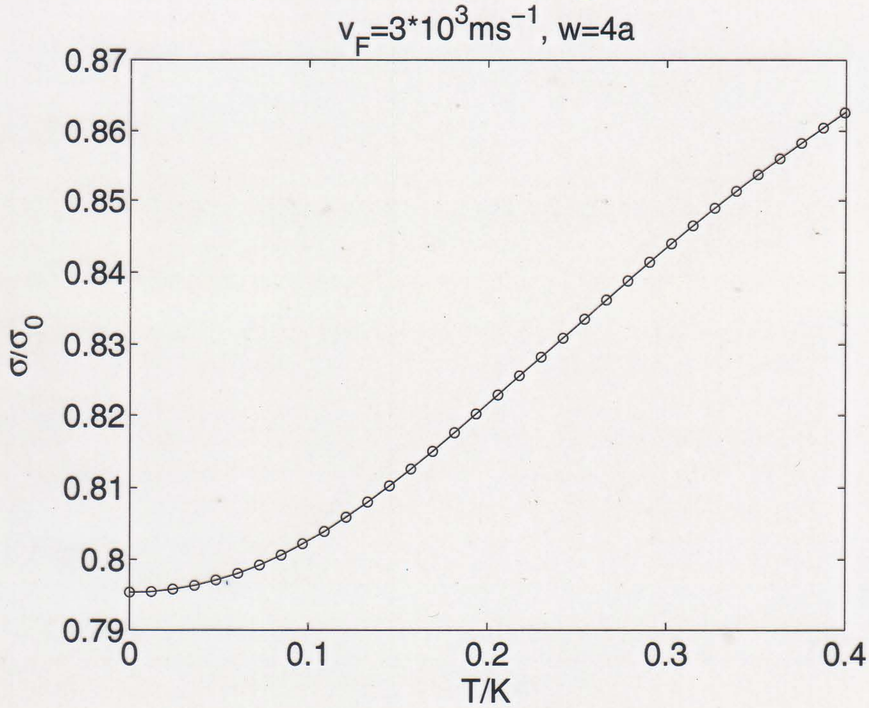
# Dependence of $\sigma(T)$ on $T$

Steep edge potential $\longrightarrow$ Narrow edges




Soft confining potential $\longrightarrow$ Wide edges

Match to experiment with edge width 120 nm



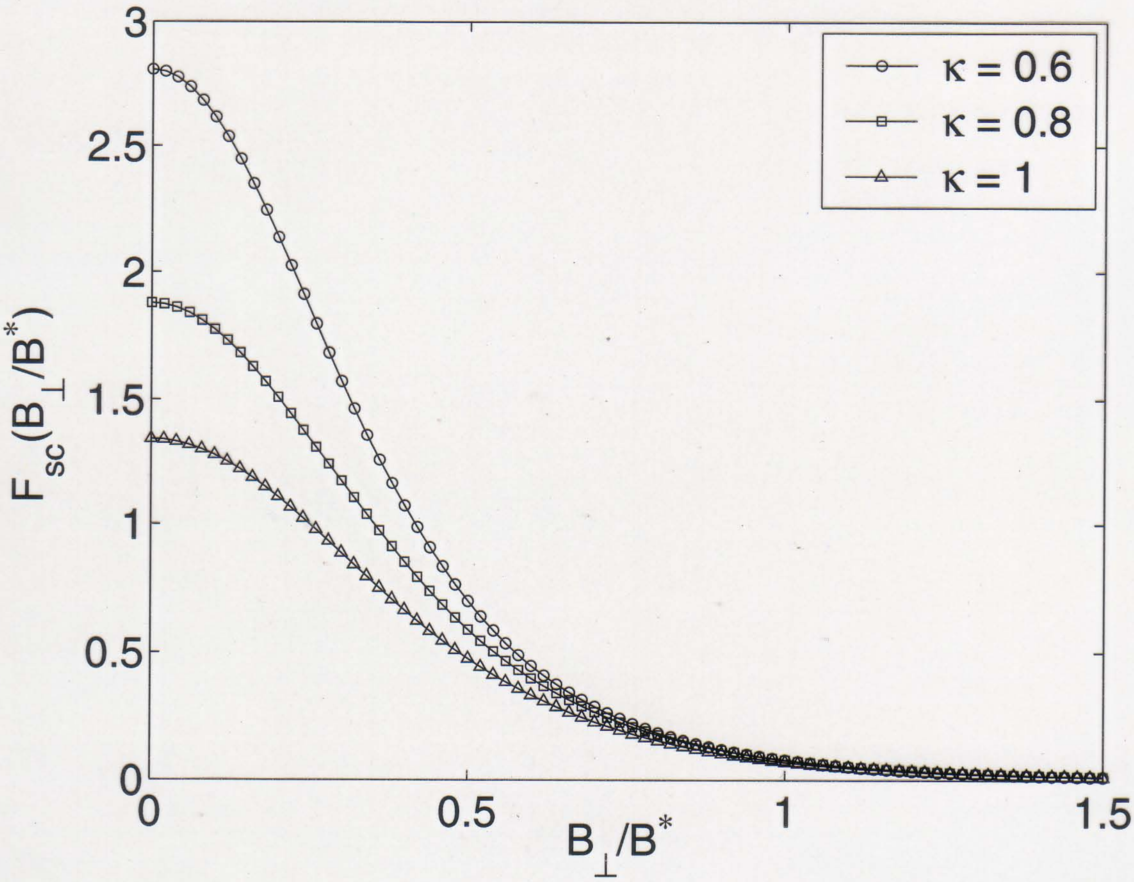
# Conductance Fluctuations

At low $T$: scaling form

Function of $\Delta B$ and $L_\mathrm{T} = \hbar v / k_\mathrm{B} T$

$$\langle \delta g(B) \delta g(B + \Delta B) \rangle = \frac{g_0^2 L_\mathrm{T}}{NL} F_\kappa(\Delta B / B^*)$$

$$B^* = \Phi_0 / a L_\mathrm{T}$$



# Summary

- Weakly coupled quantum Hall edges: can treat Coulomb interactions and disorder exactly using bosonization.

- Dependence of $\sigma(T)$ on $T$ reflects full $\vec{r}$-dependence of Coulomb interactions.

- Conductance fluctuations suppressed with increasing $T$ - despite coherence of bosonic excitations.