Experiments on a Quantum Hall Exciton Condensate

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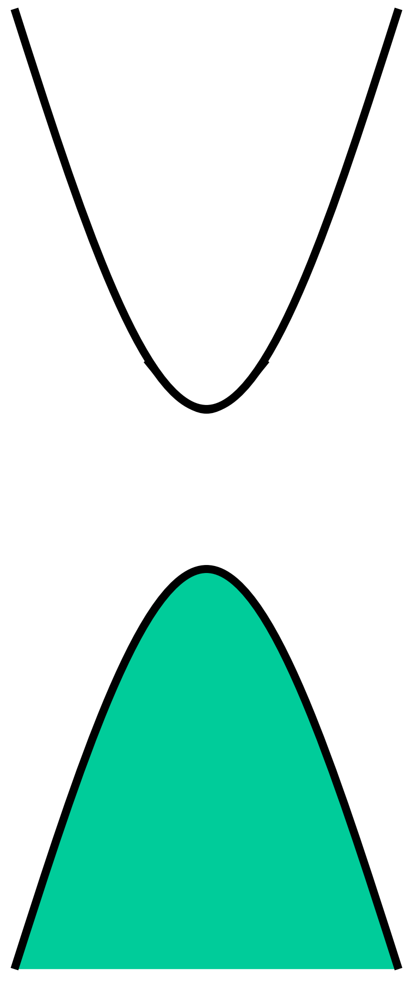
U.S. DEPARTMENT OF ENERGY: BASIC ENERGY SCIENCE

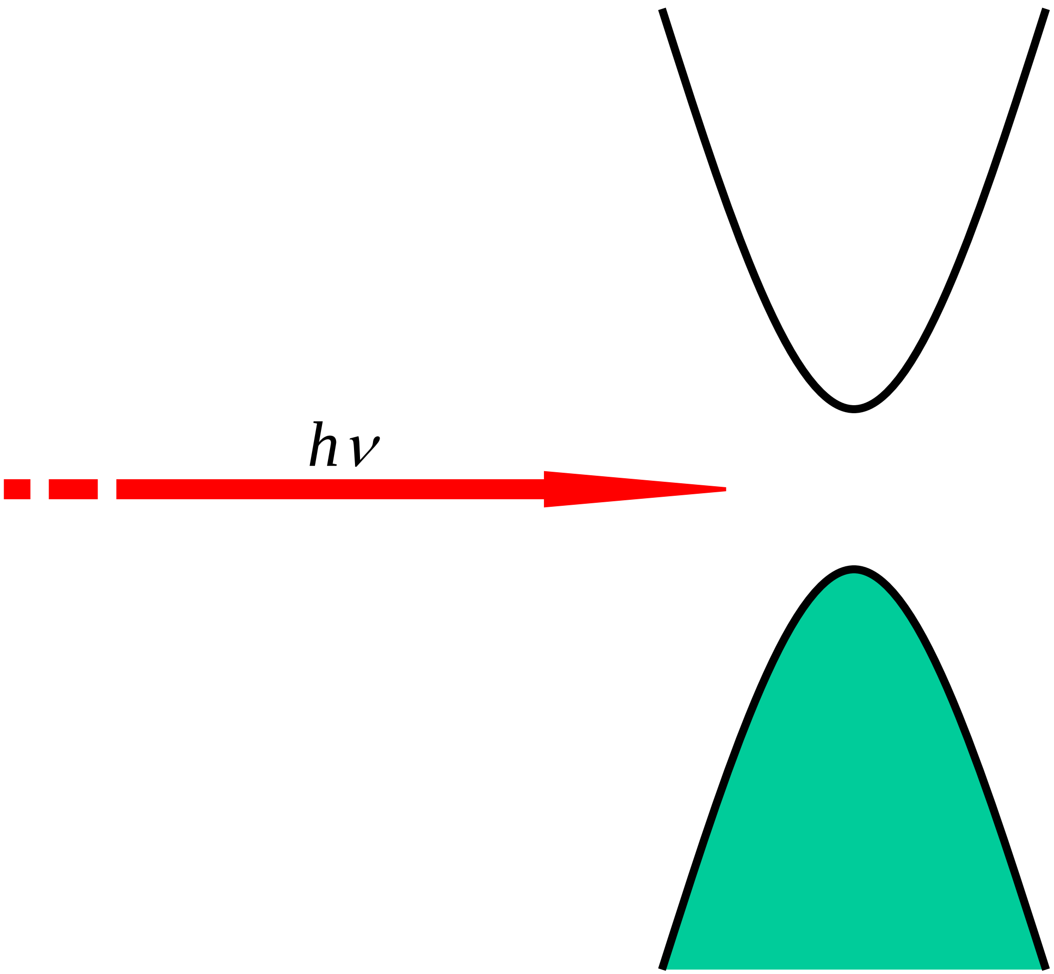
Division of Materials Sciences

KITP Exotic Order and Criticality in Quantum Matter Conference, June 7-11, 2004

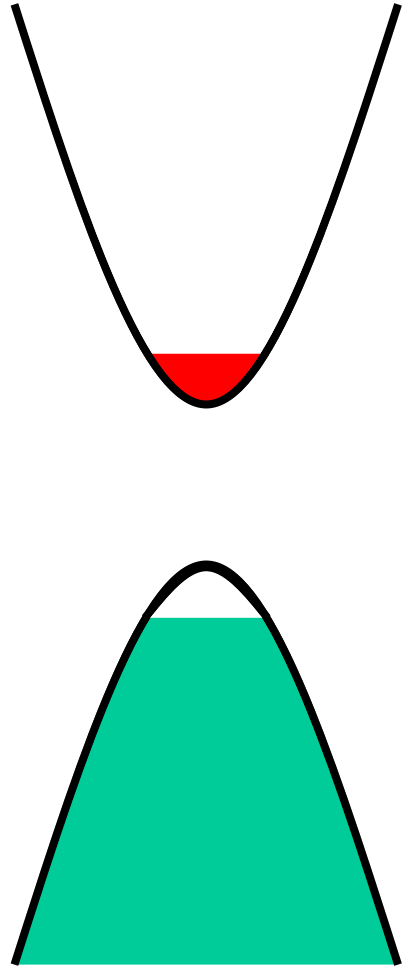
Intrinsic semiconductor at $T = 0$



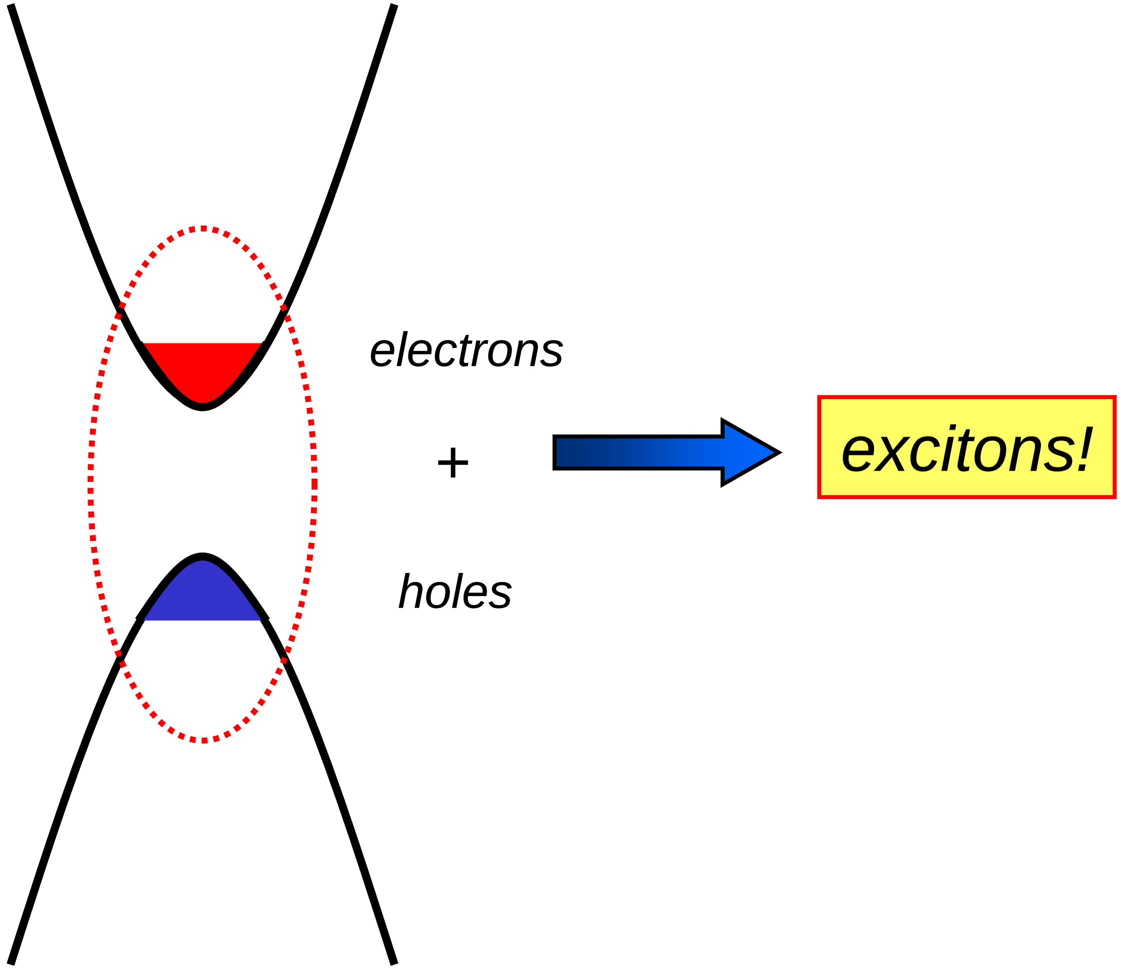
Add light

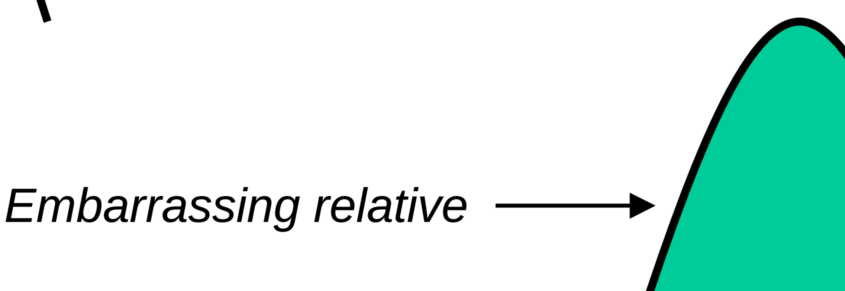


Only electrons

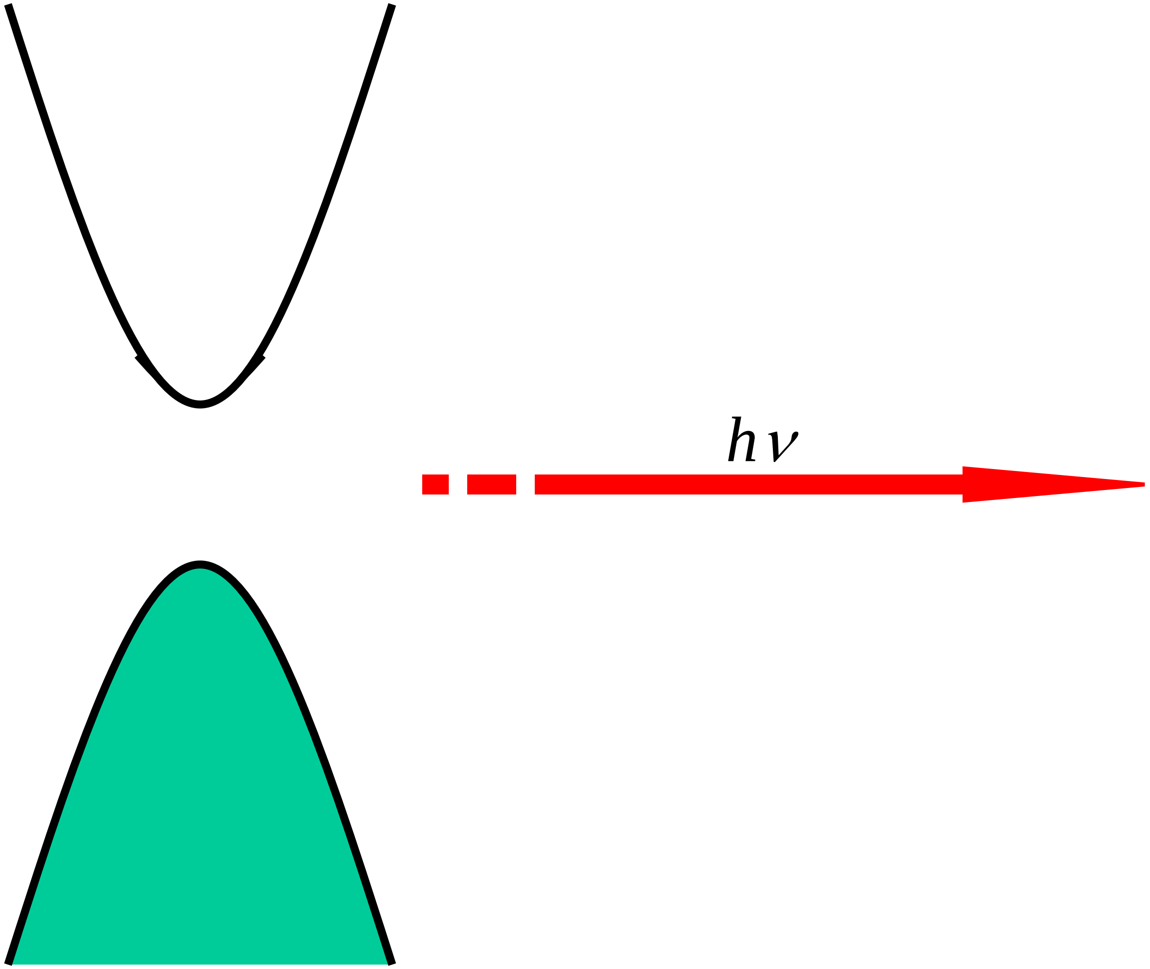


Particle-hole transformation on valence band

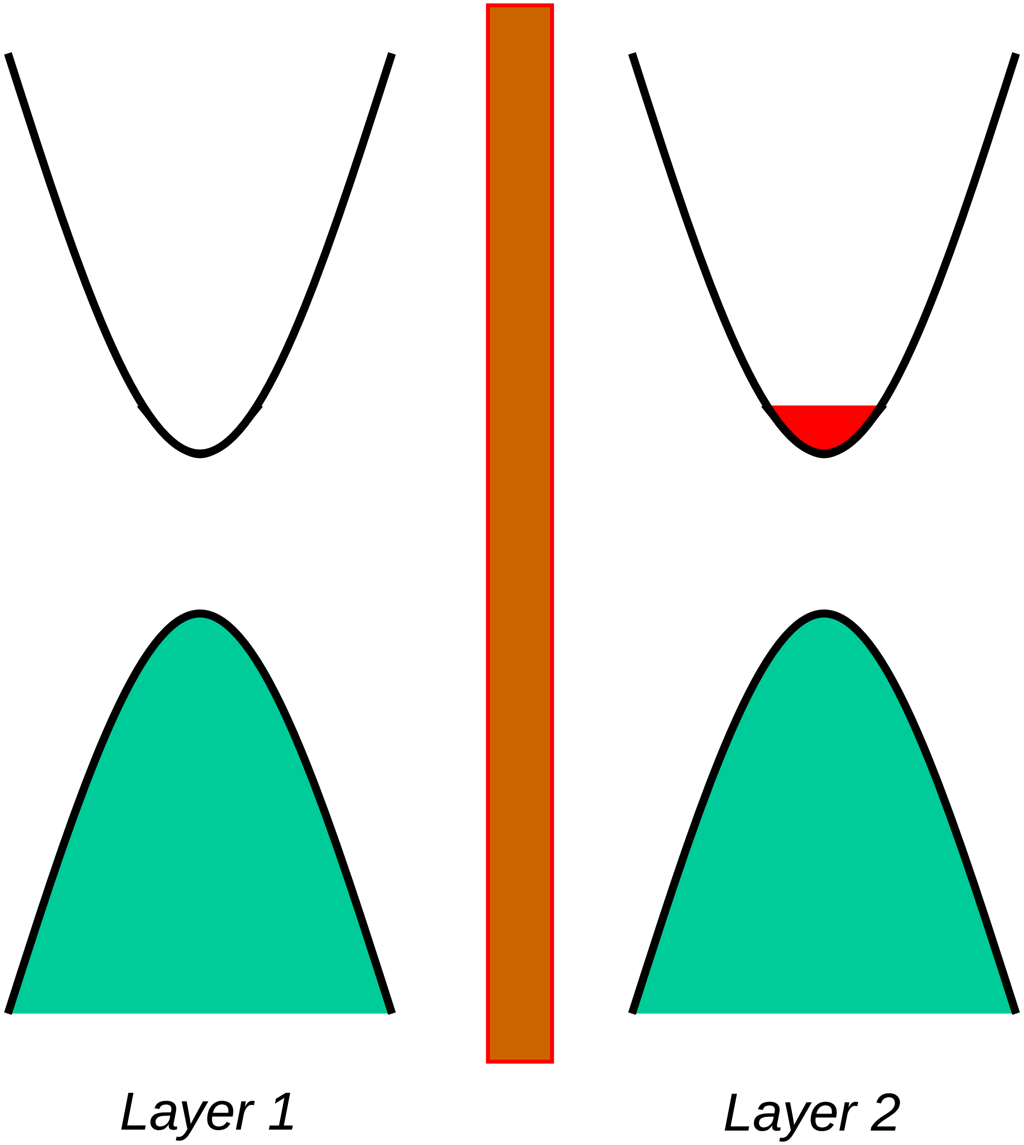




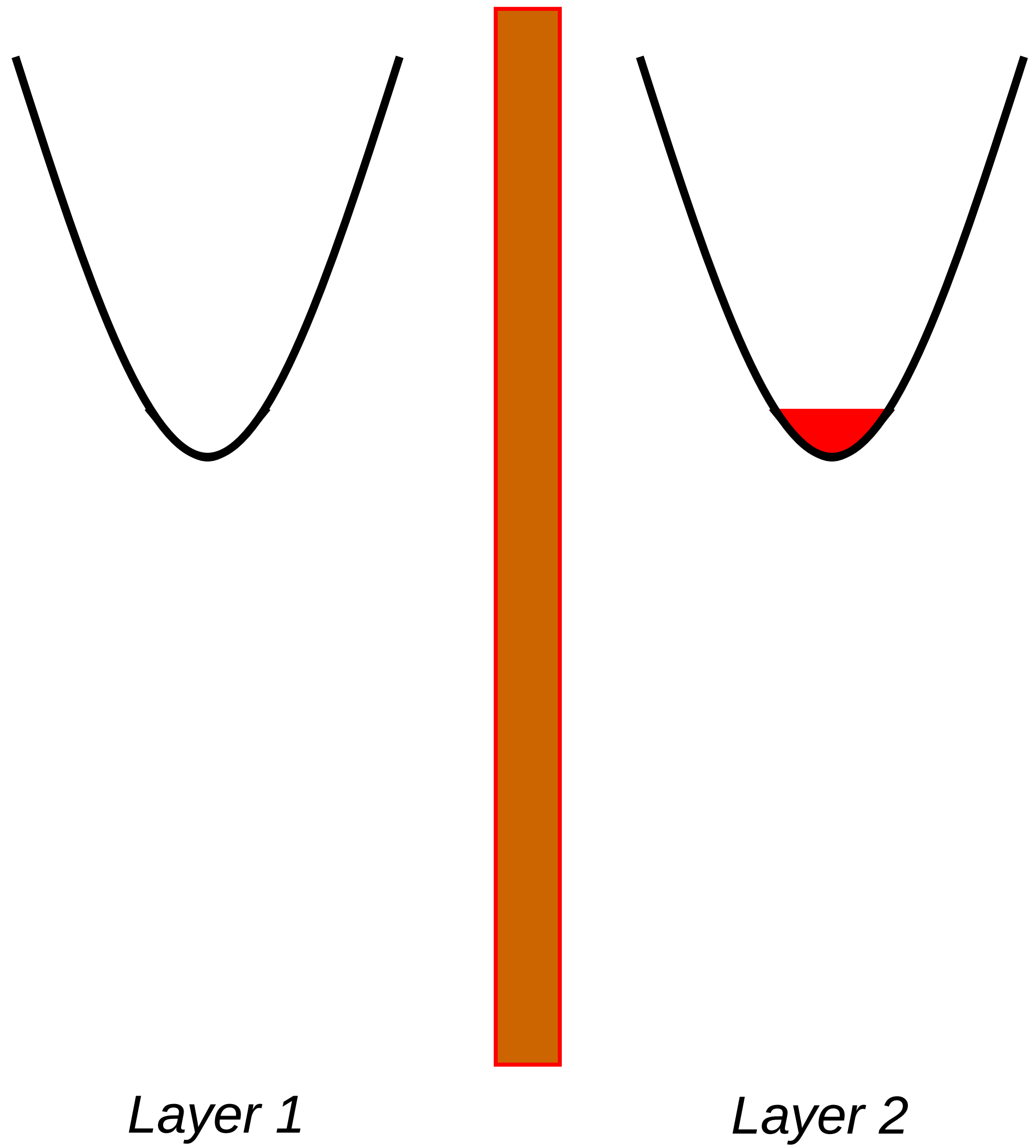
Recombination



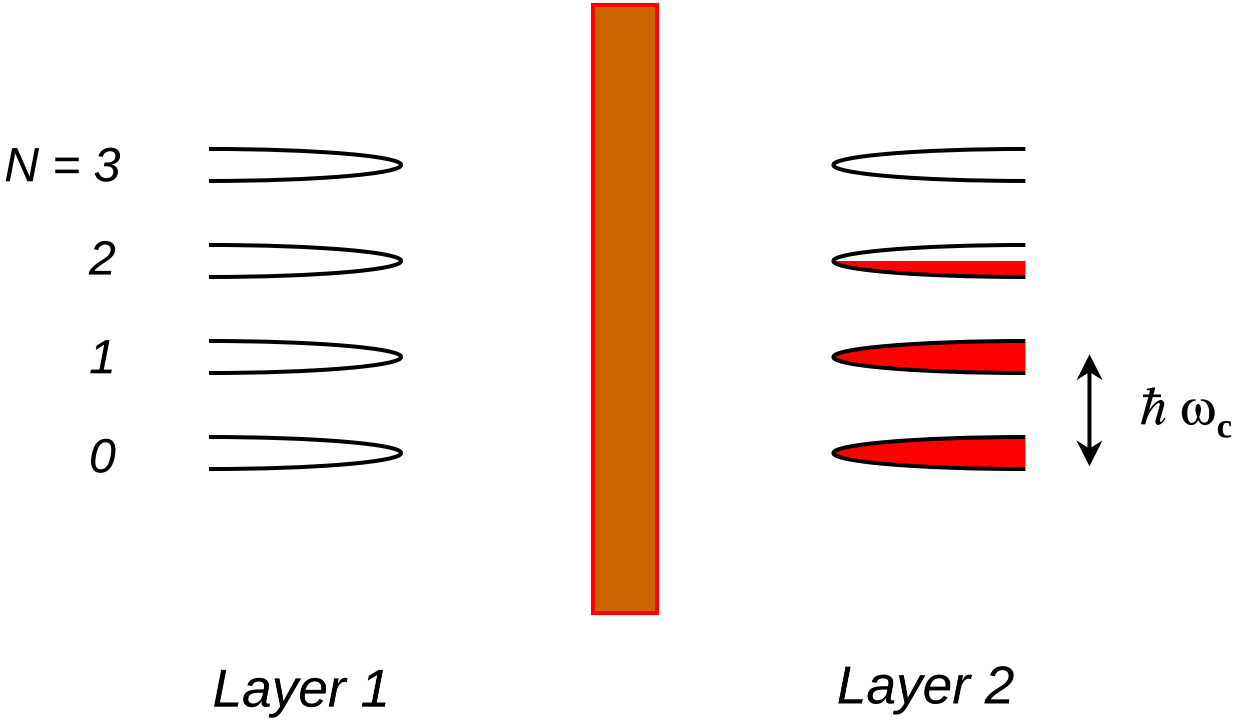
A different way: Doped bilayer semiconductor



Discard the valence band

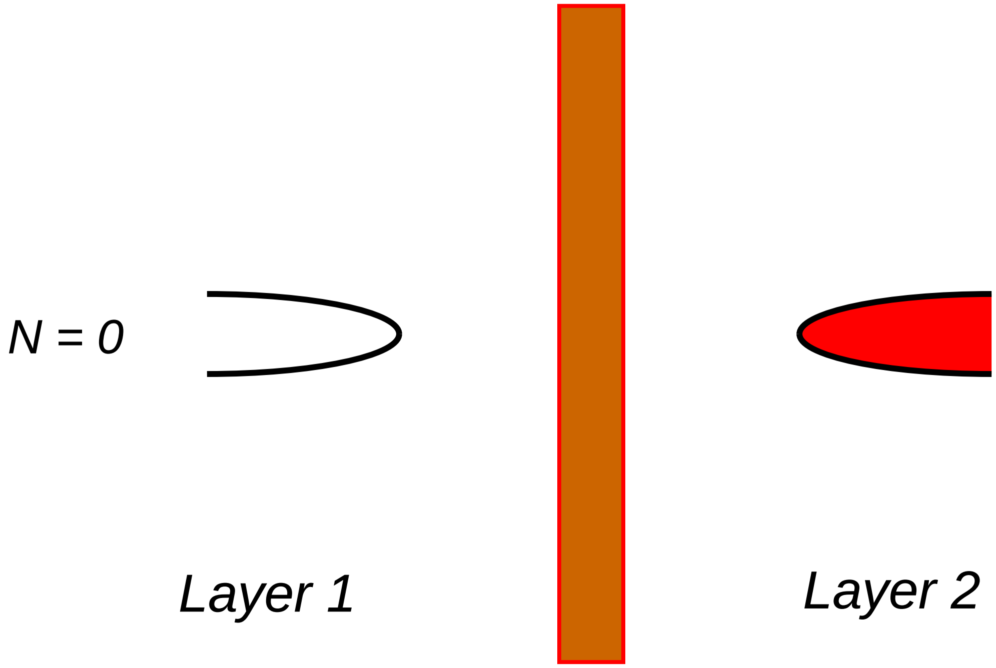


Add a magnetic field



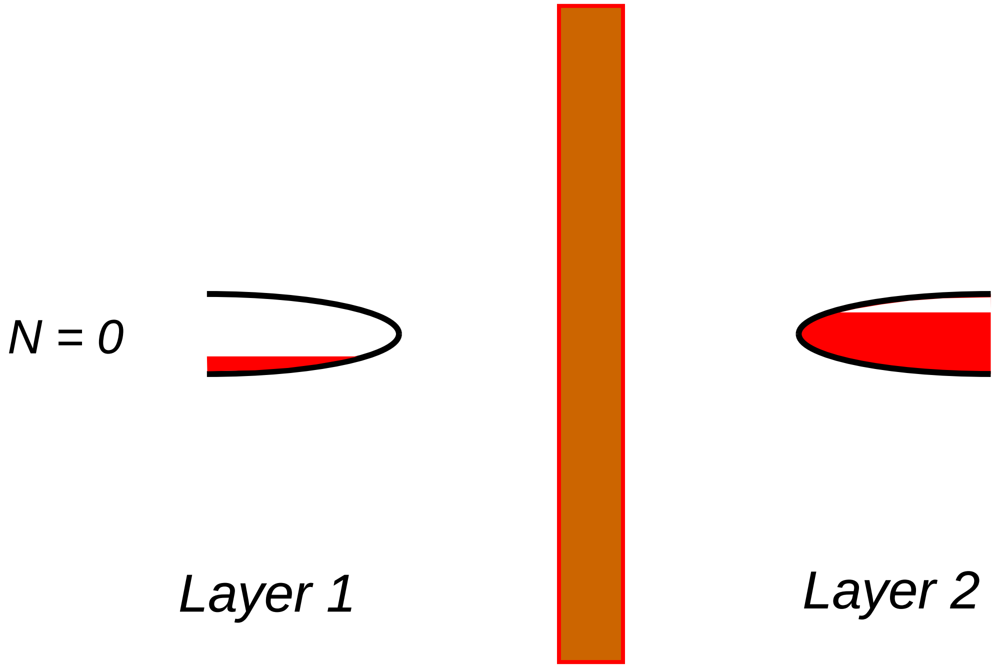
conduction band Landau levels

A bigger magnetic field: One filled Landau level



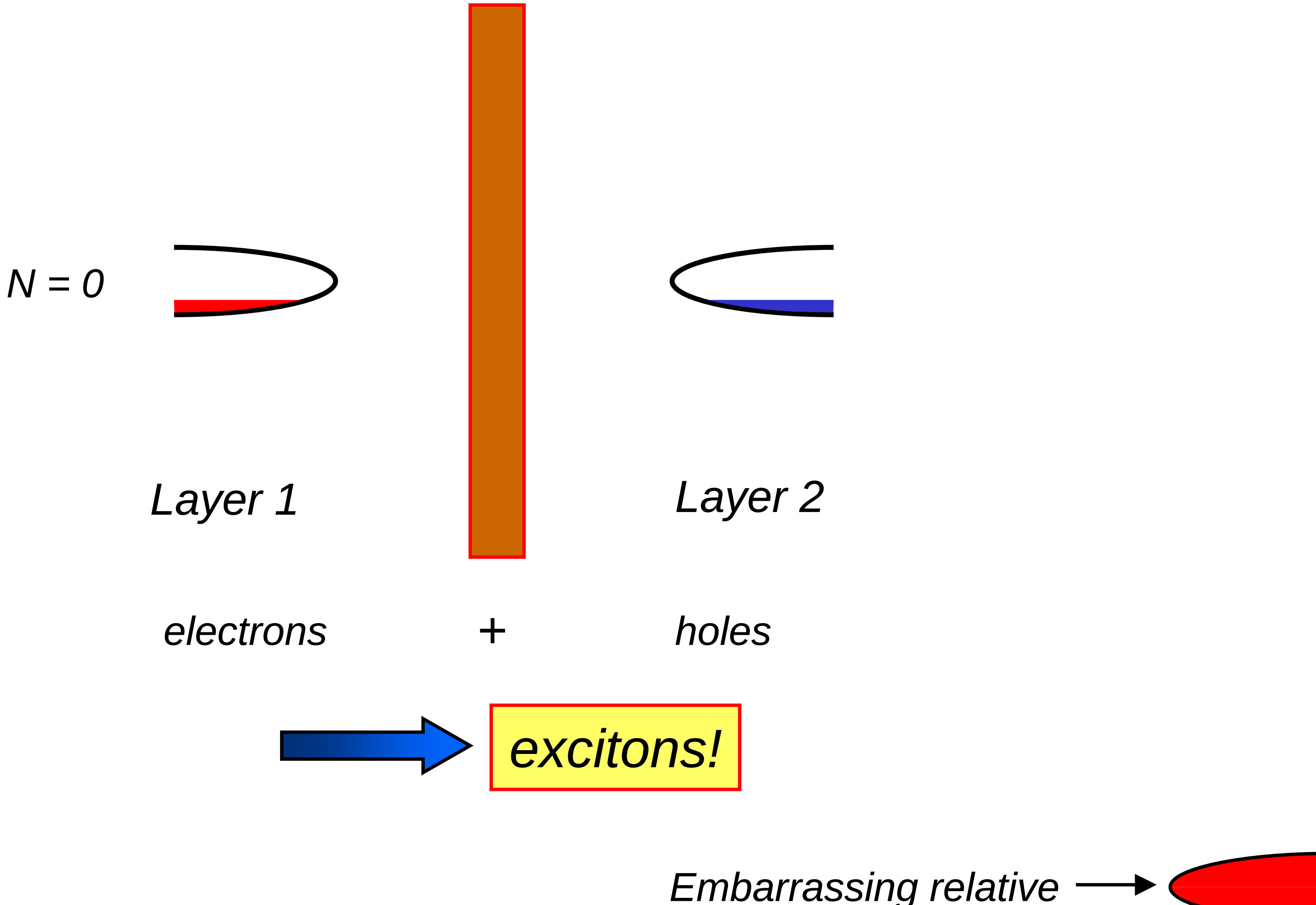
Analogous to intrinsic semiconductor at T = 0, but no gap!

Transfer charge by doping or gating

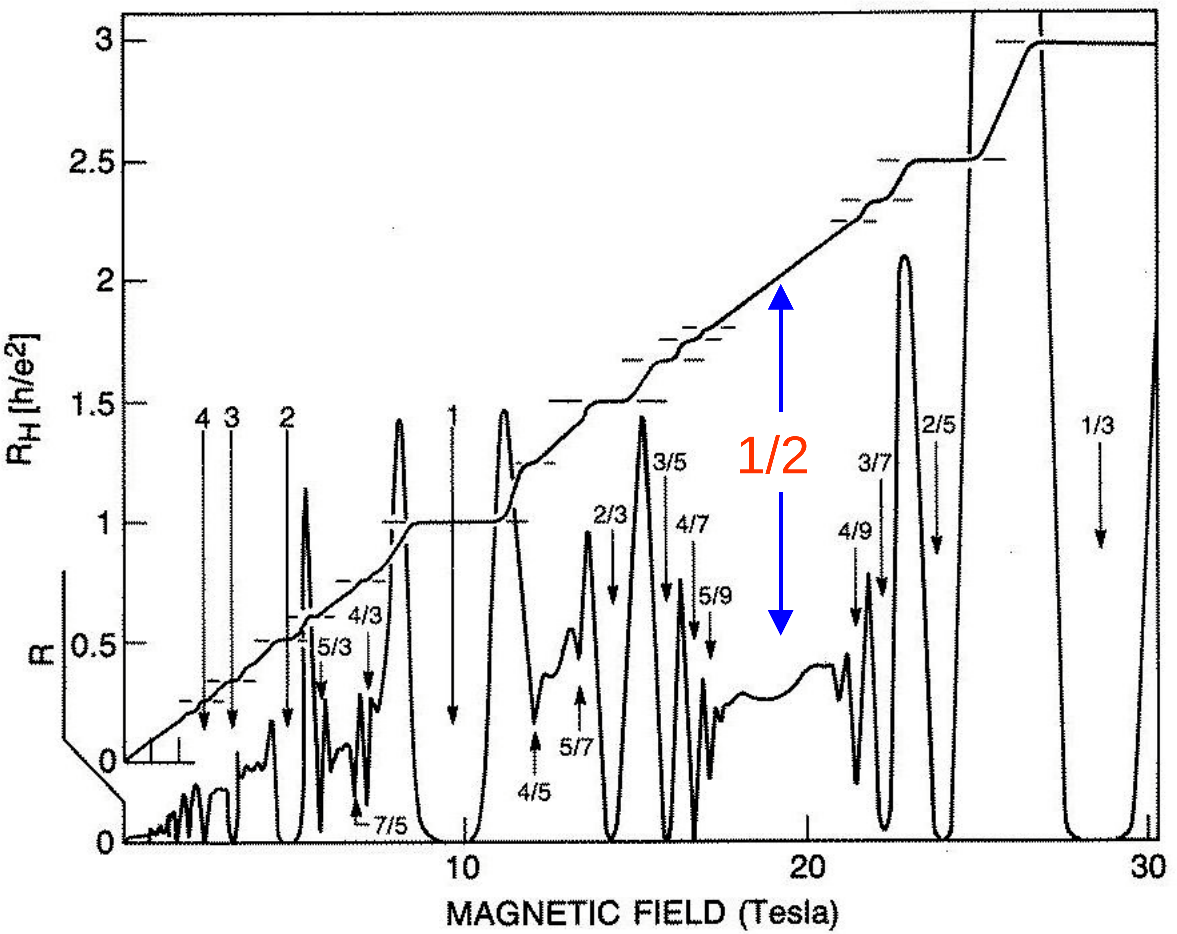


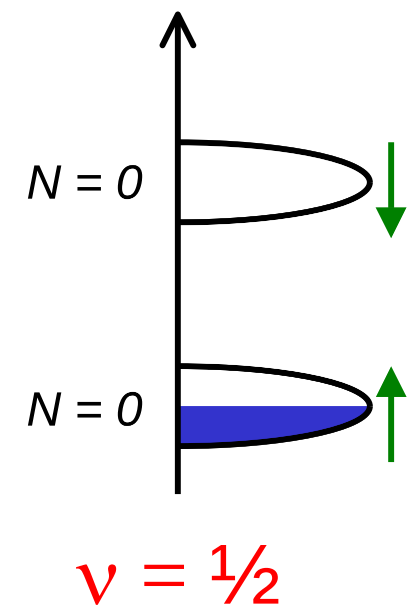
Total number of electrons unchanged

Particle-hole transformation on lowest Landau level in layer 2



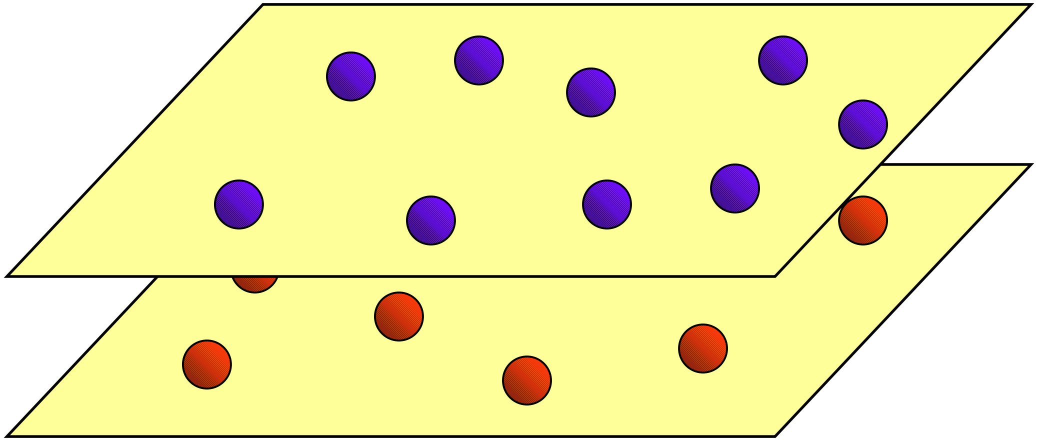
QHE Single Layer 2D System



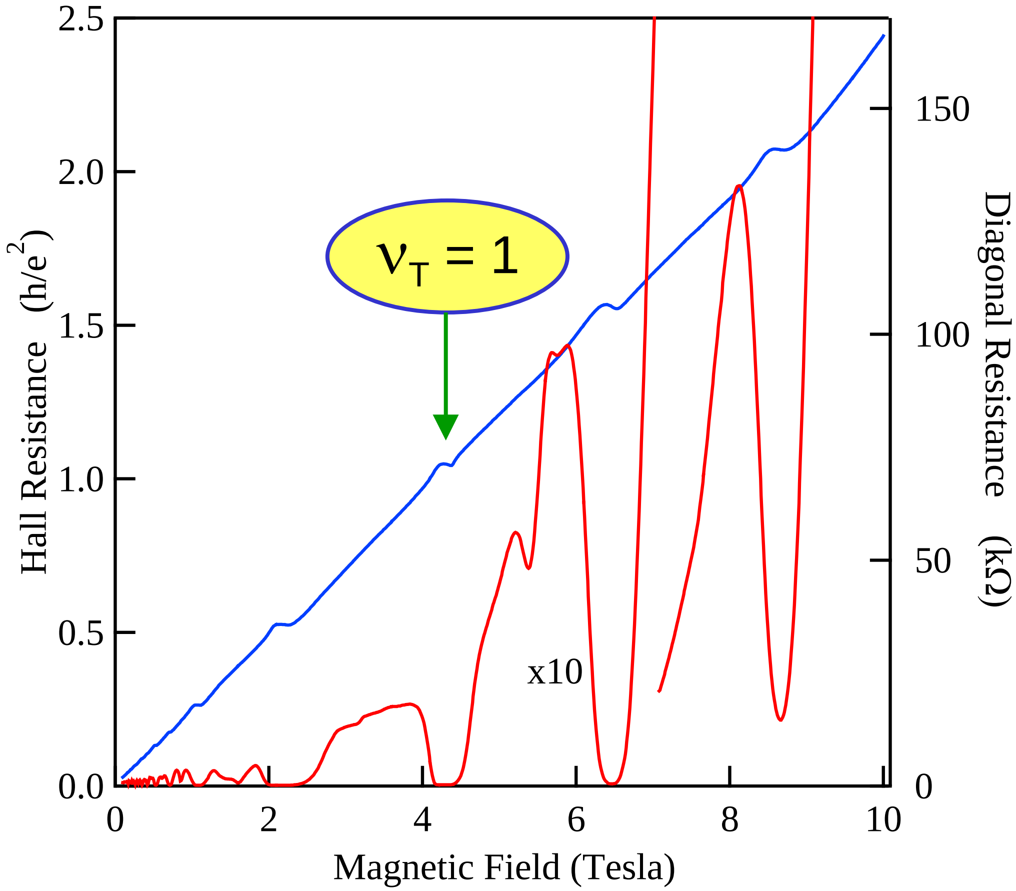


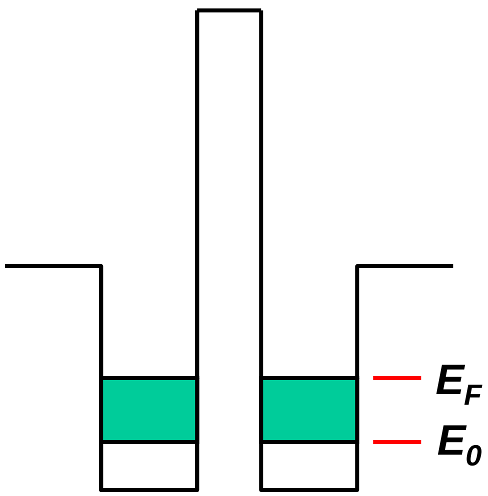
No QHE at half-filling of the lowest Landau level

Double Layer Two-Dimensional Electron Gas



QHE in Double Layer 2D System

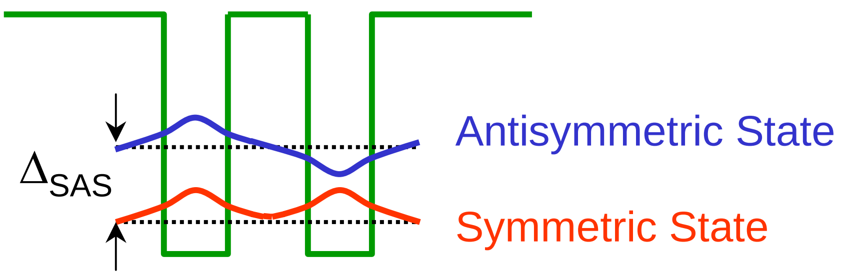


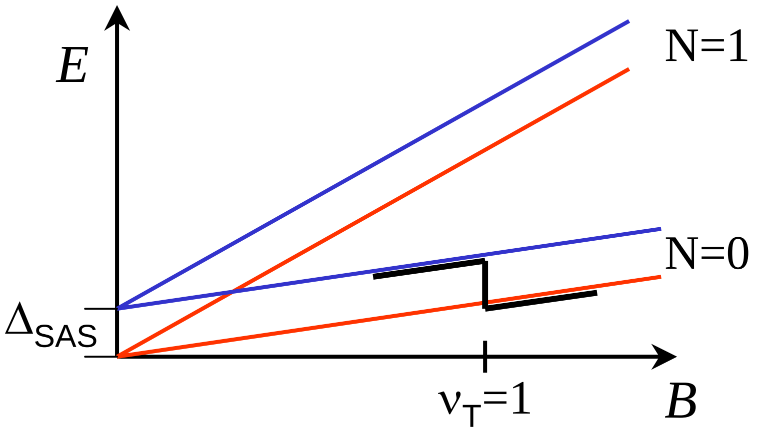


$\nu_T = 1 = ½ + ½$

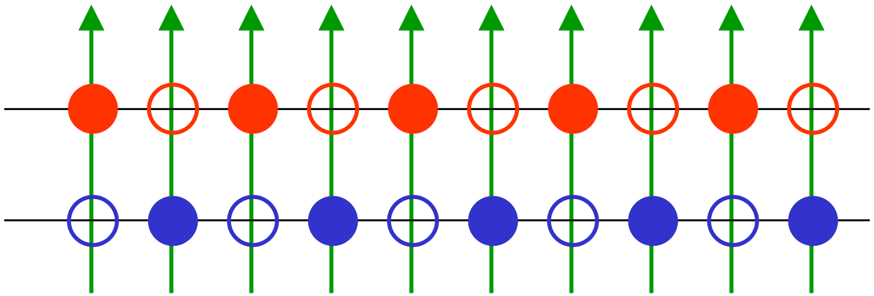
Single Particle and Many-body Origins for ν_T =1 QHE

1. Single Particle Tunneling



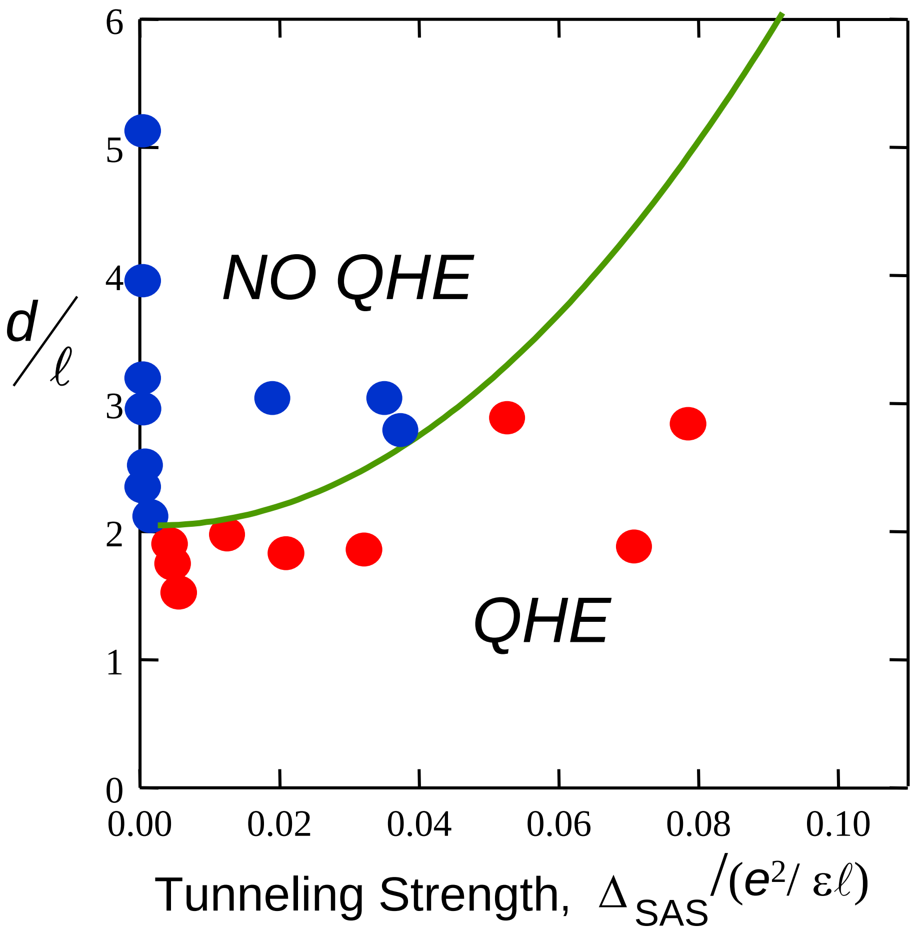


2. Pure Many-body Effect



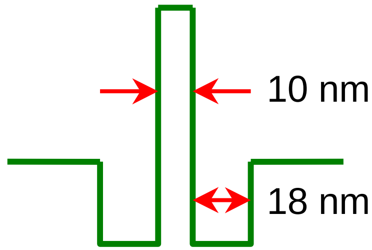
$$\Psi \sim \prod_{i,..,n} (z_i - z_j)\ (w_k - w_l)\ (z_m - w_n)$$

Phase Diagram

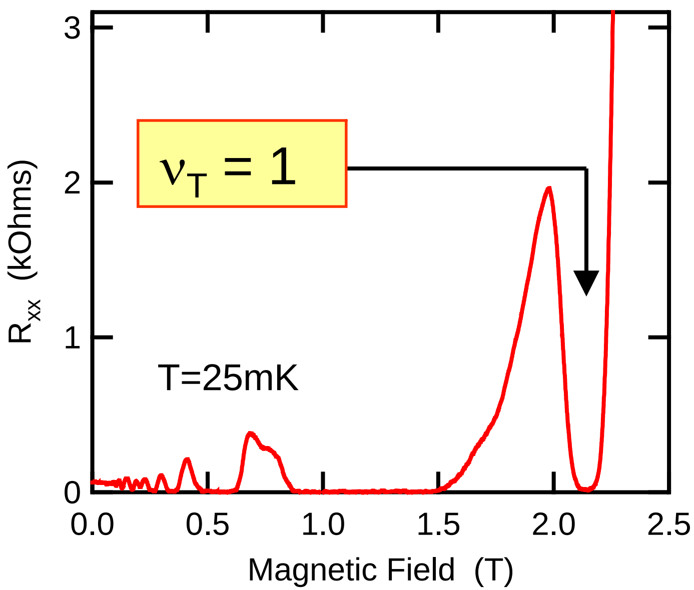


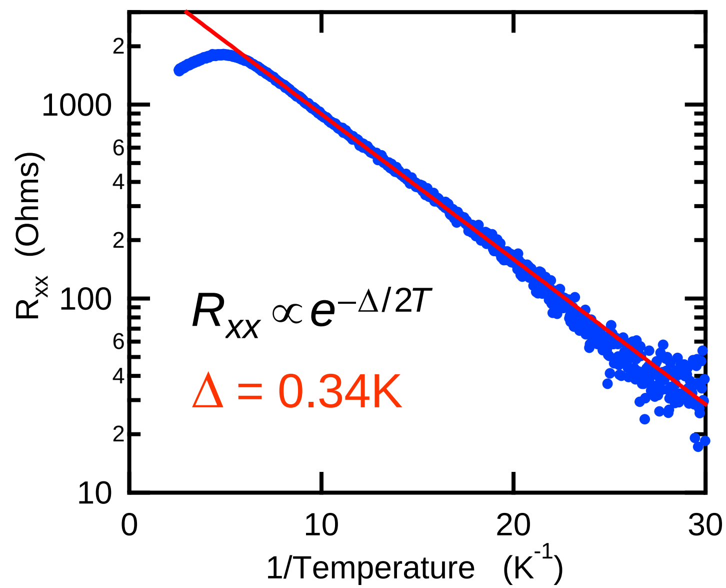
QHE persists in zero tunneling limit

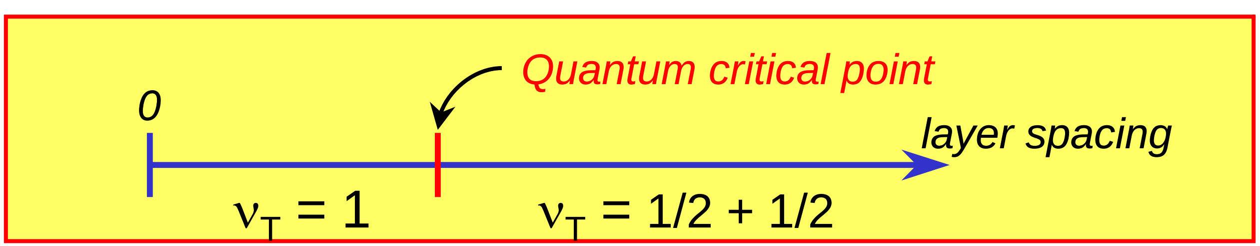
Bilayer ν_T = 1 QHE with Nearly Zero Tunneling



$$\Delta_{SAS} \approx 90\mu K \approx 1.2\times10^{-6}\left(\frac{e^2}{\varepsilon\ell}\right)$$

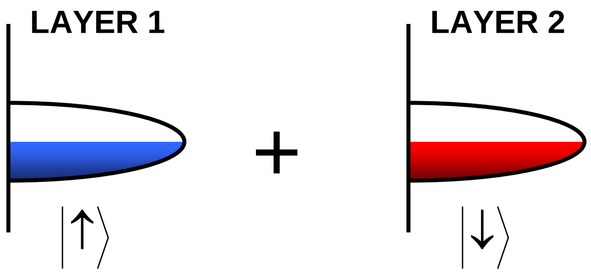


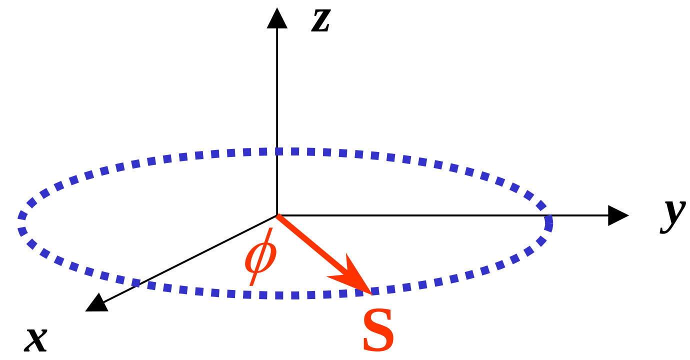




Easy-Plane Ferromagnet

layer index $\rightarrow$ *pseudospin*





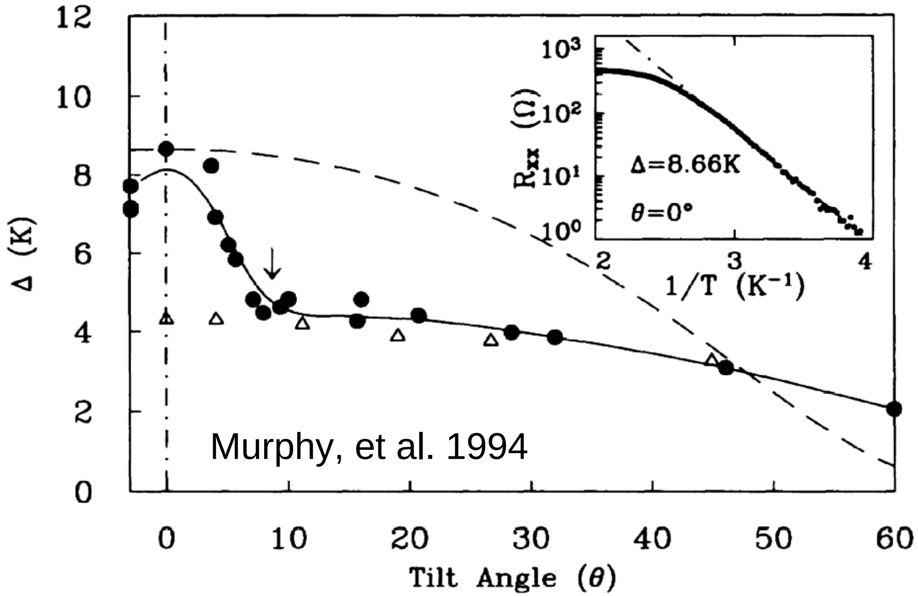
$$|\Psi\rangle = \prod_k |k\rangle \otimes \frac{1}{\sqrt{2}}\left[\,|\uparrow\rangle + e^{i\phi}\,|\downarrow\rangle\,\right]$$

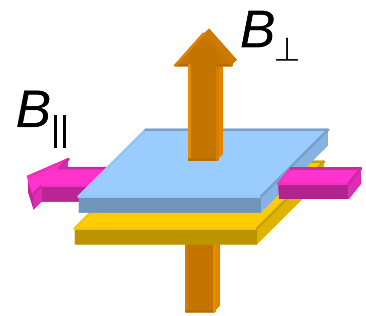
Spontaneous interlayer phase coherence and “which layer” uncertainty.

pseudo-spin waves, charged vortices, etc.

$\nabla\phi$ → *dissipationless pseudo-spin currents*

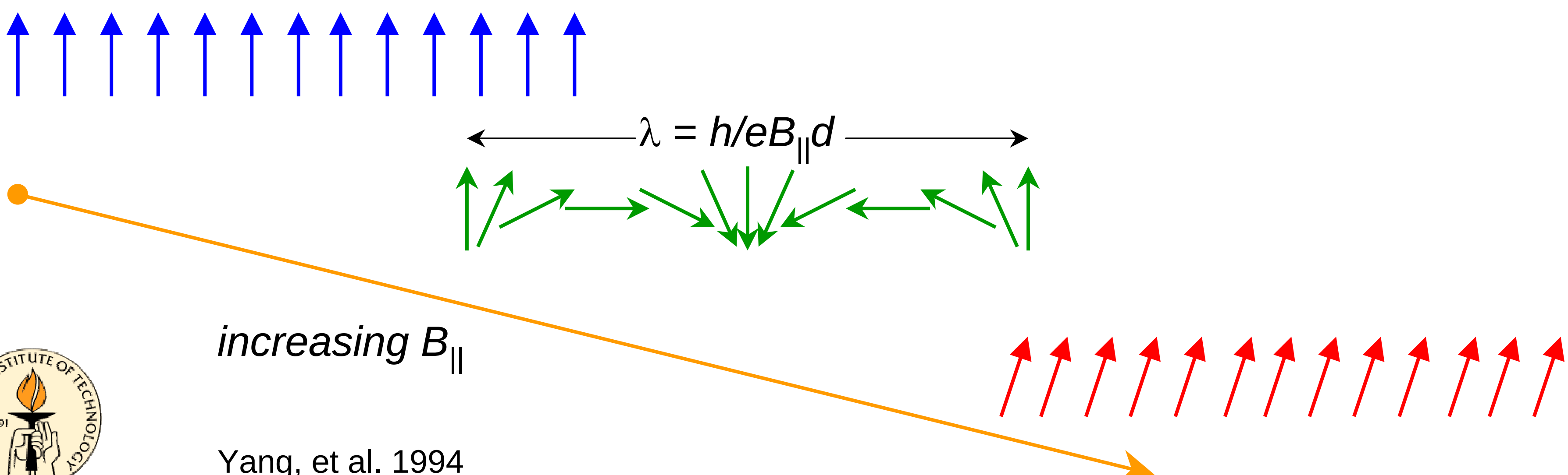
Pseudospin Textural Phase Transition



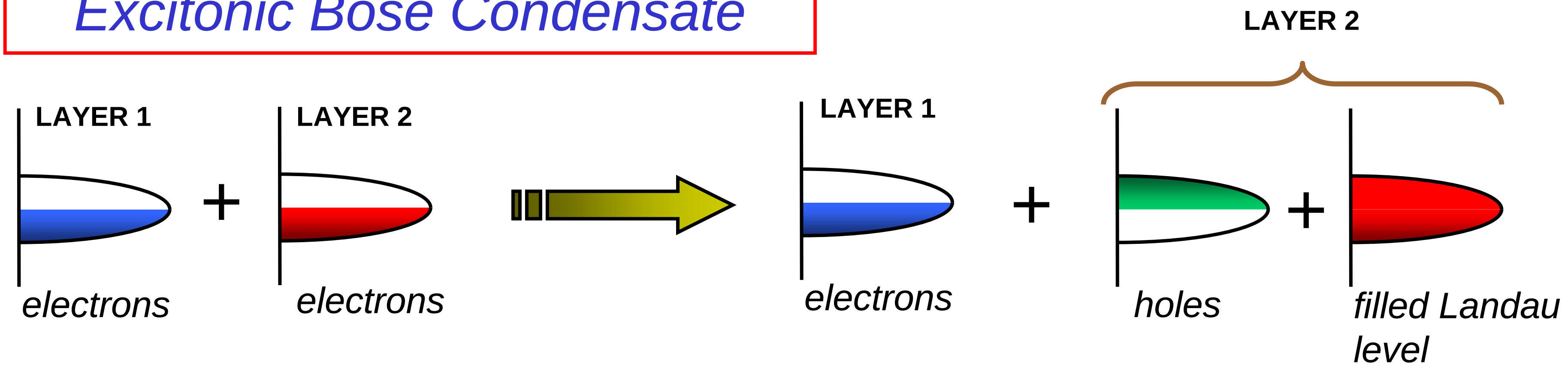


$$H = \frac{\rho_s}{2}\left|\nabla\varphi\right|^2 - \frac{\Delta_{SAS}}{4\pi\ell^2}\cos\left(\varphi - Qx\right)$$

$$Q = eB_{||}d/\hbar$$

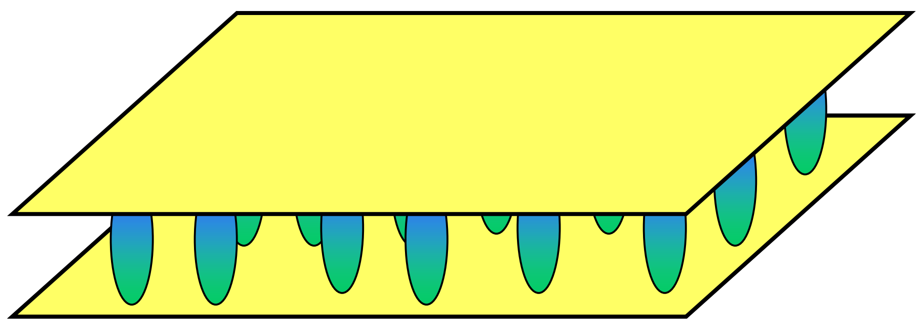


Excitonic Bose Condensate



$$|\Psi\rangle = \prod_k \frac{1}{\sqrt{2}}\left[1 + e^{i\phi} c^\dagger_{k,1}\, c_{k,2}\right]|vac'\rangle$$

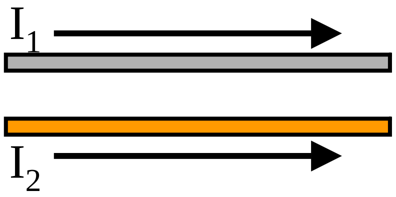
exciton creation operator



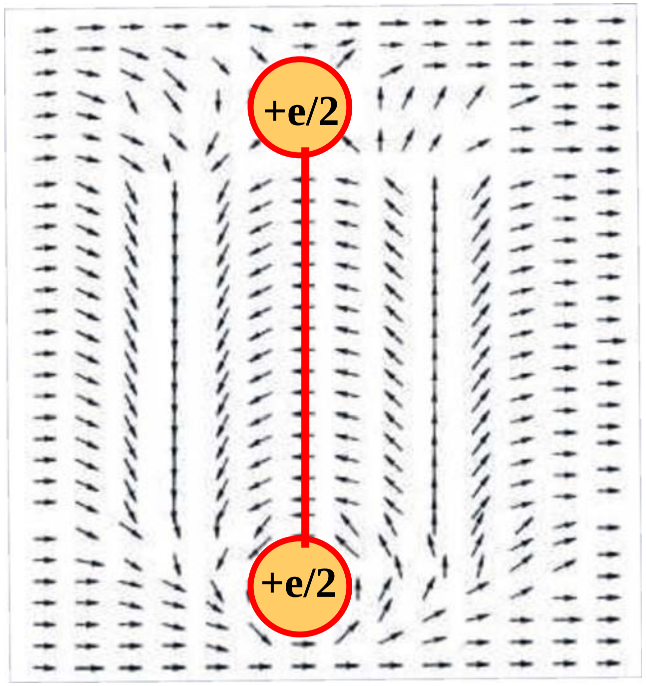
$\nabla \phi$ → *excitonic supercurrents*

Two Transport Channels

1. Parallel Transport



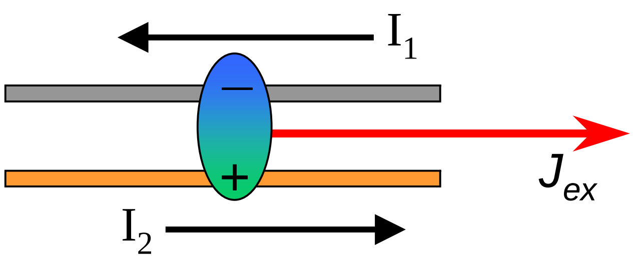
meron / anti-meron pair



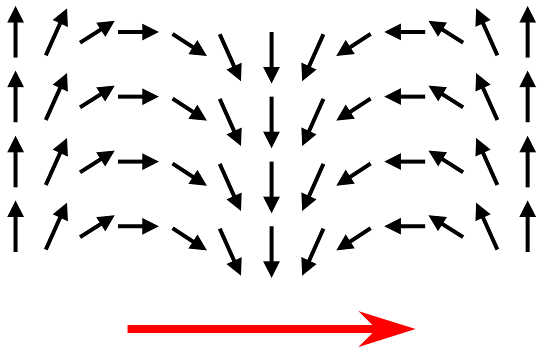
- *vortex charged excitations above gap*
- *edge states*
- *quantized Hall effect*
- *dissipation ~ exp* $(-\Delta/T)$

Two Transport Channels

2. Counterflow Transport



$\nabla \phi$ = constant

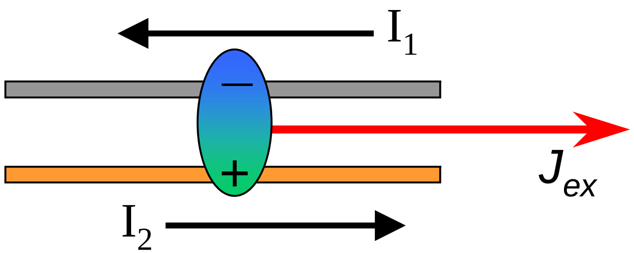


$J_{ex} = \rho_s \nabla \phi$

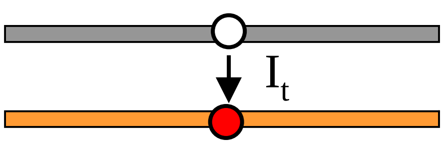
- *collective exciton transport in condensate*
- *bulk flow*
- *zero dissipation for $T < T_{KT}$*

The really cool physics is in the antisymmetric channel!

counter-flow transport



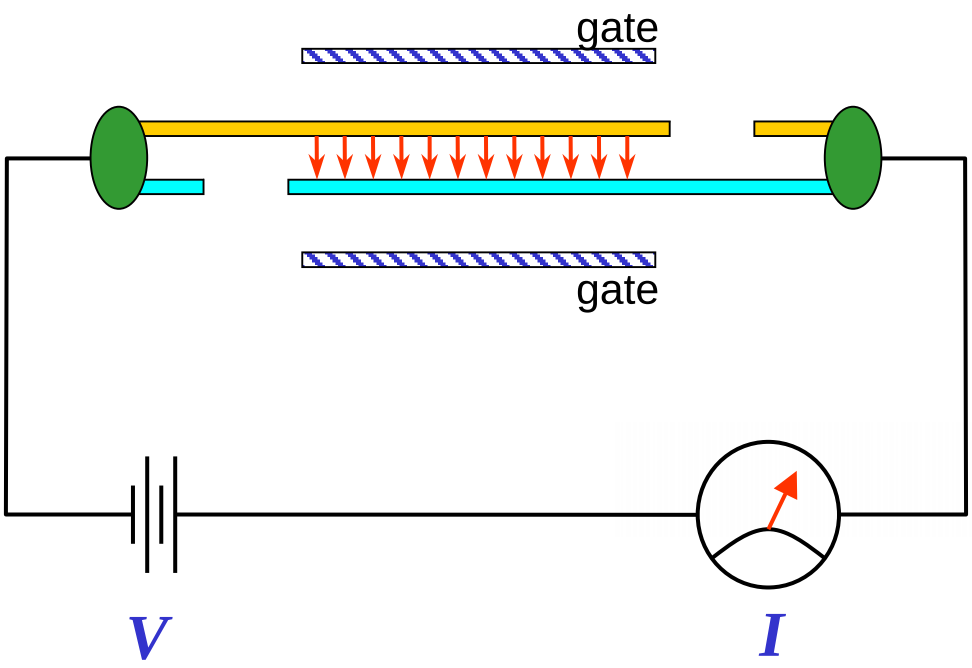
interlayer tunneling



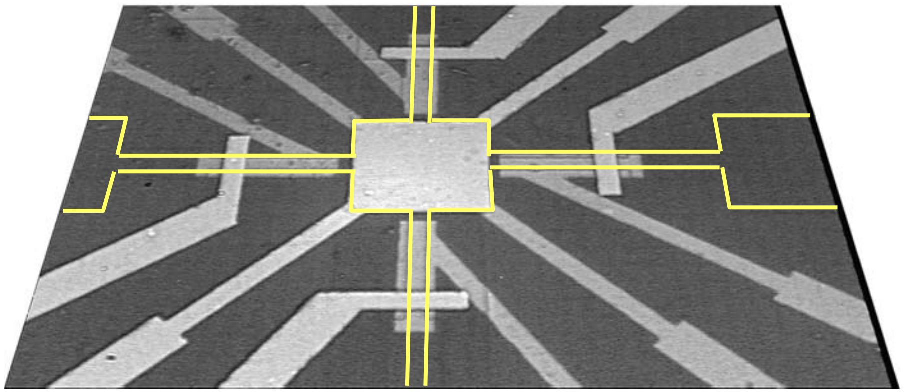
separate layer contacts are essential

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

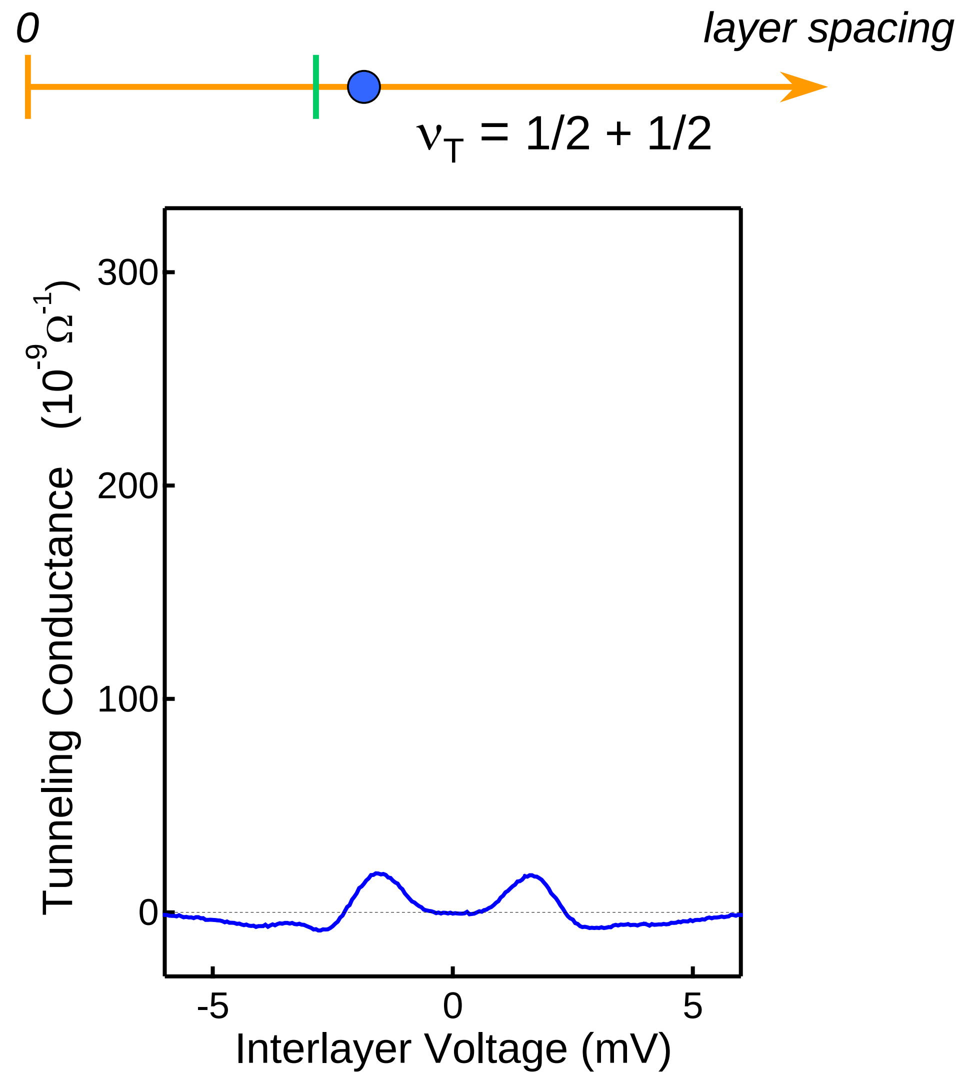
Tunneling Experiment



Symmetric gating allows continuous tuning of effective layer spacing in a single sample.

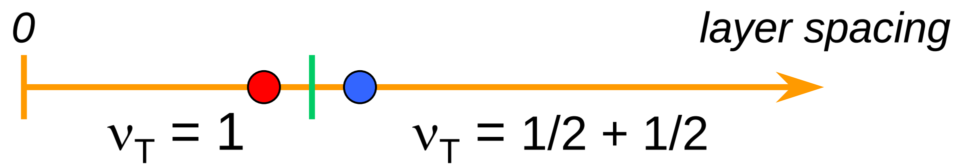


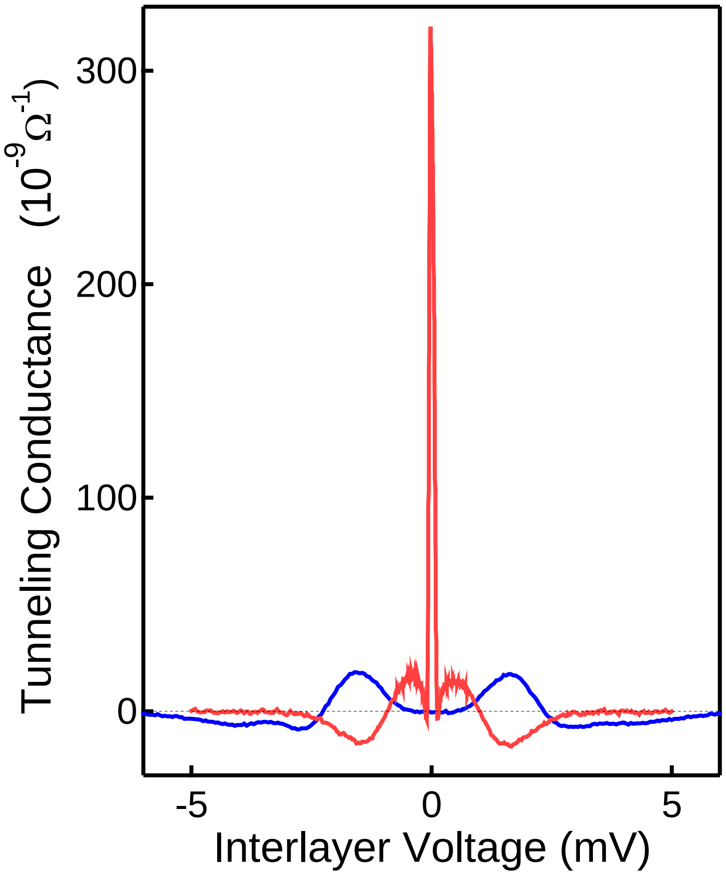
Crossing the phase boundary



Zero bias tunneling heavily suppressed by intra-layer correlations.

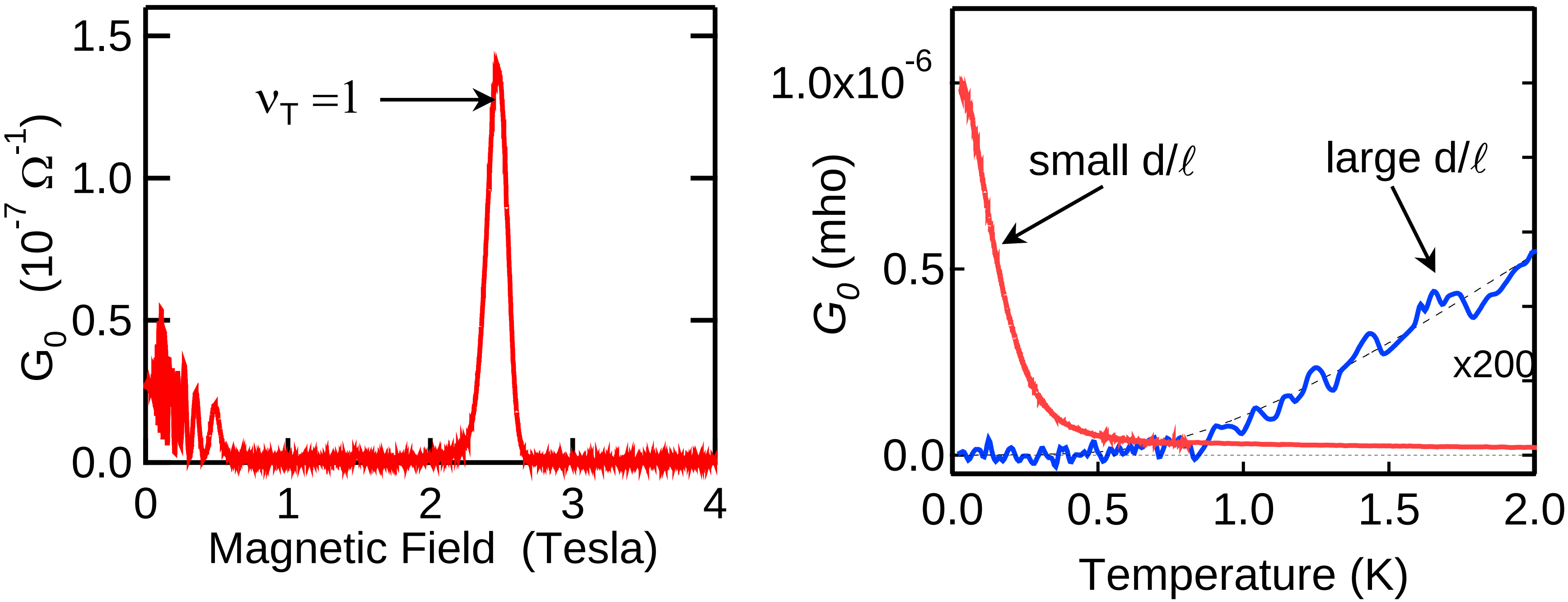
Crossing the phase boundary



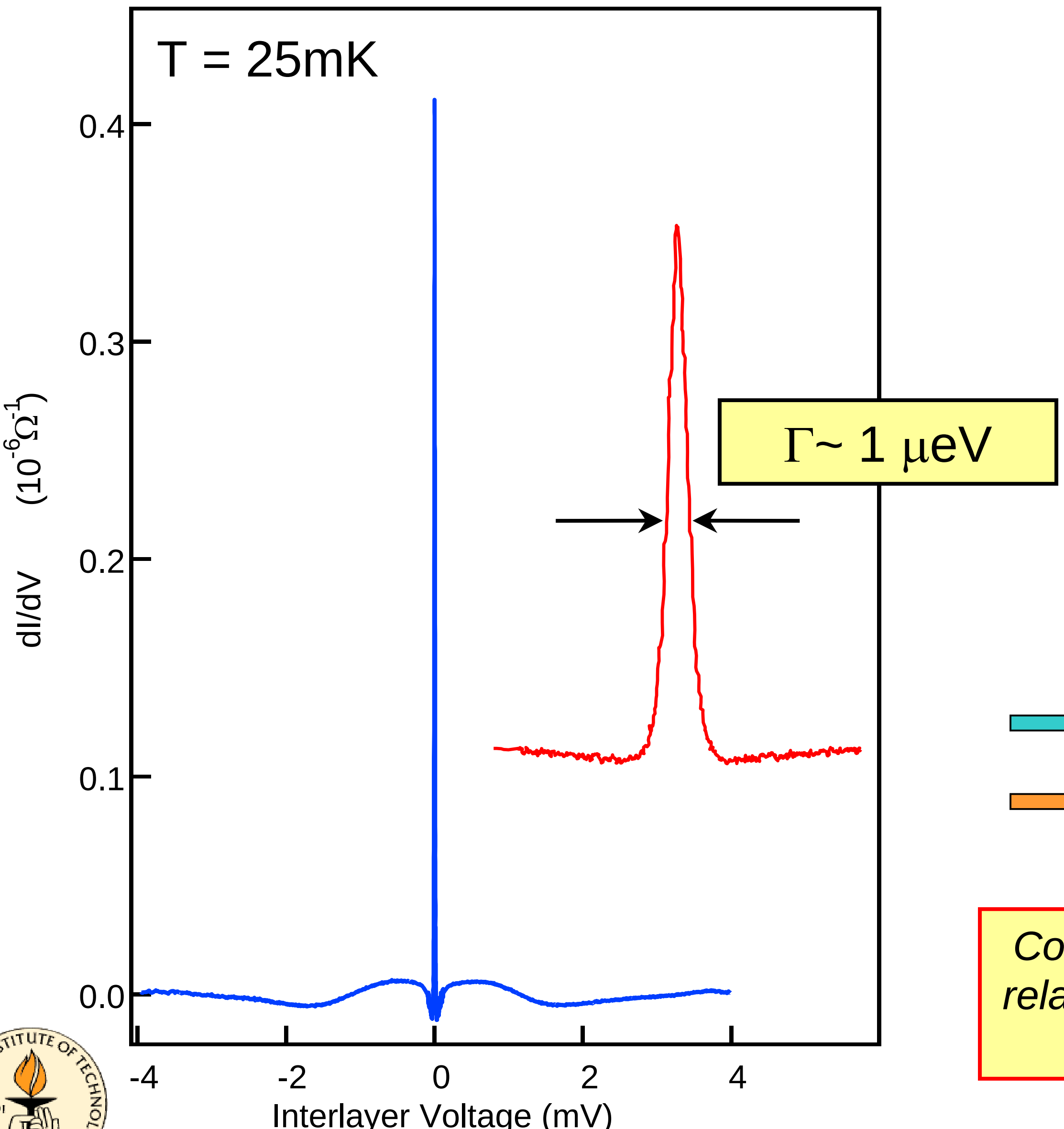


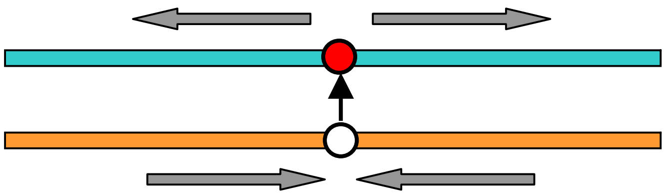
Coulomb gap replaced by resonant enhancement.

Magnetic Field and Temperature Dependences



Extremely Narrow Resonance





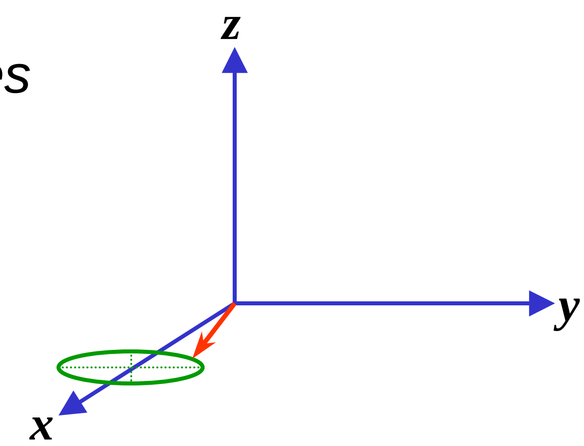
Counter-flow superfluidity rapidly relaxes charge defects created by tunneling.

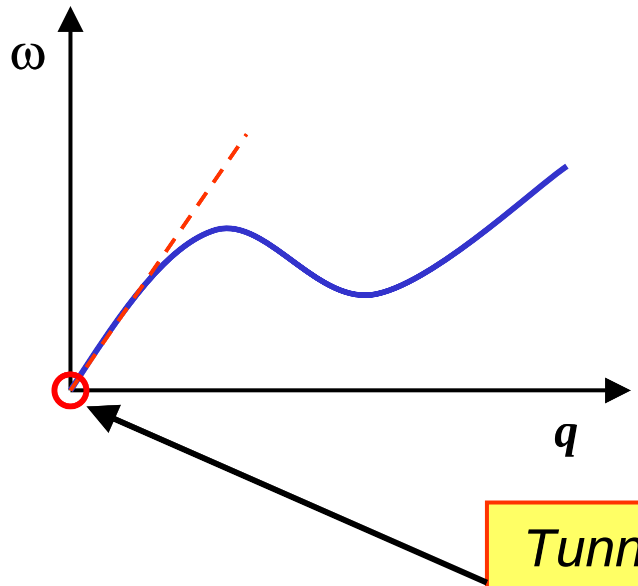
Collective Modes

Fertig '89

Wen & Zee '92

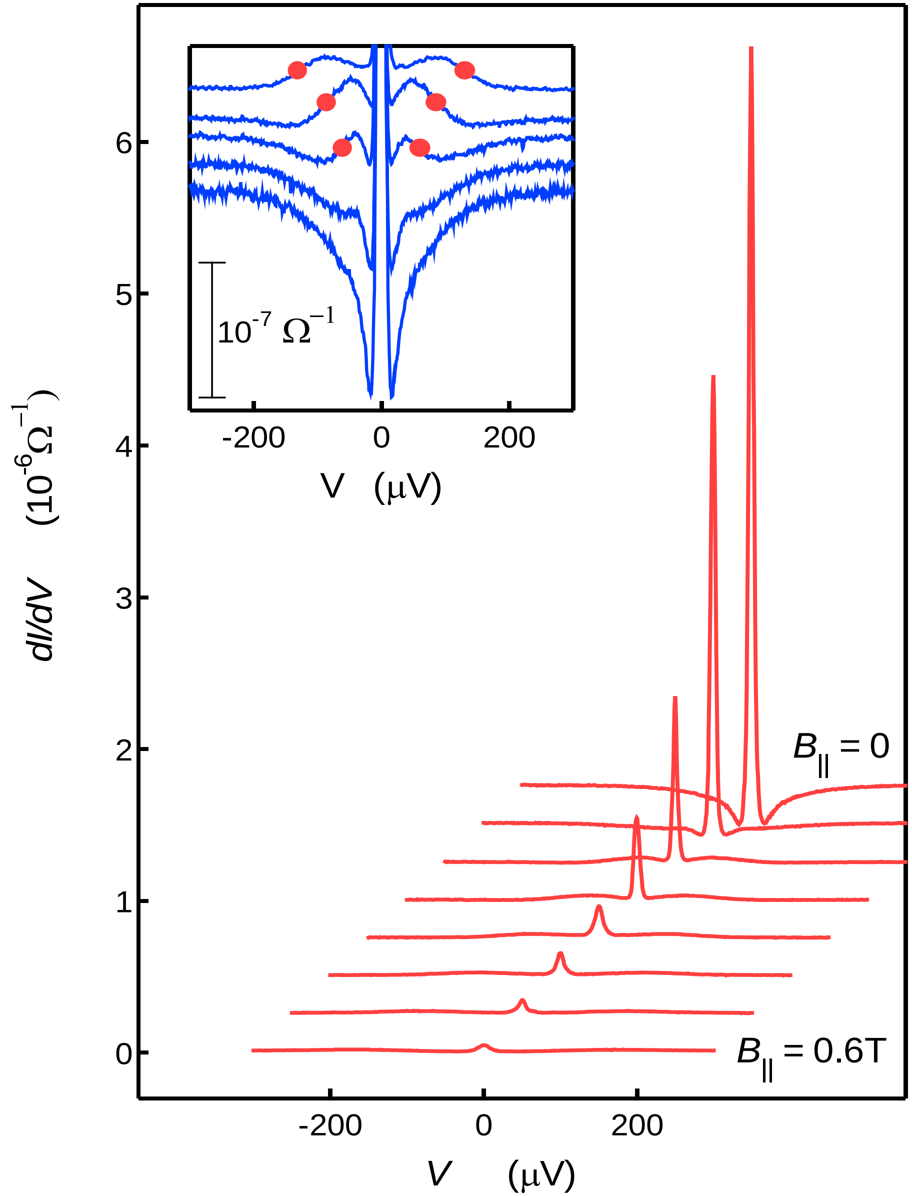
pseudo-spin waves

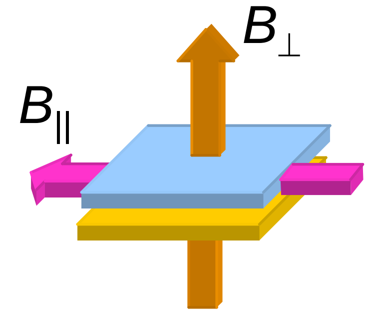




Tunneling detects the Goldstone mode of the broken symmetry ground state.

Parallel Field Spectroscopy

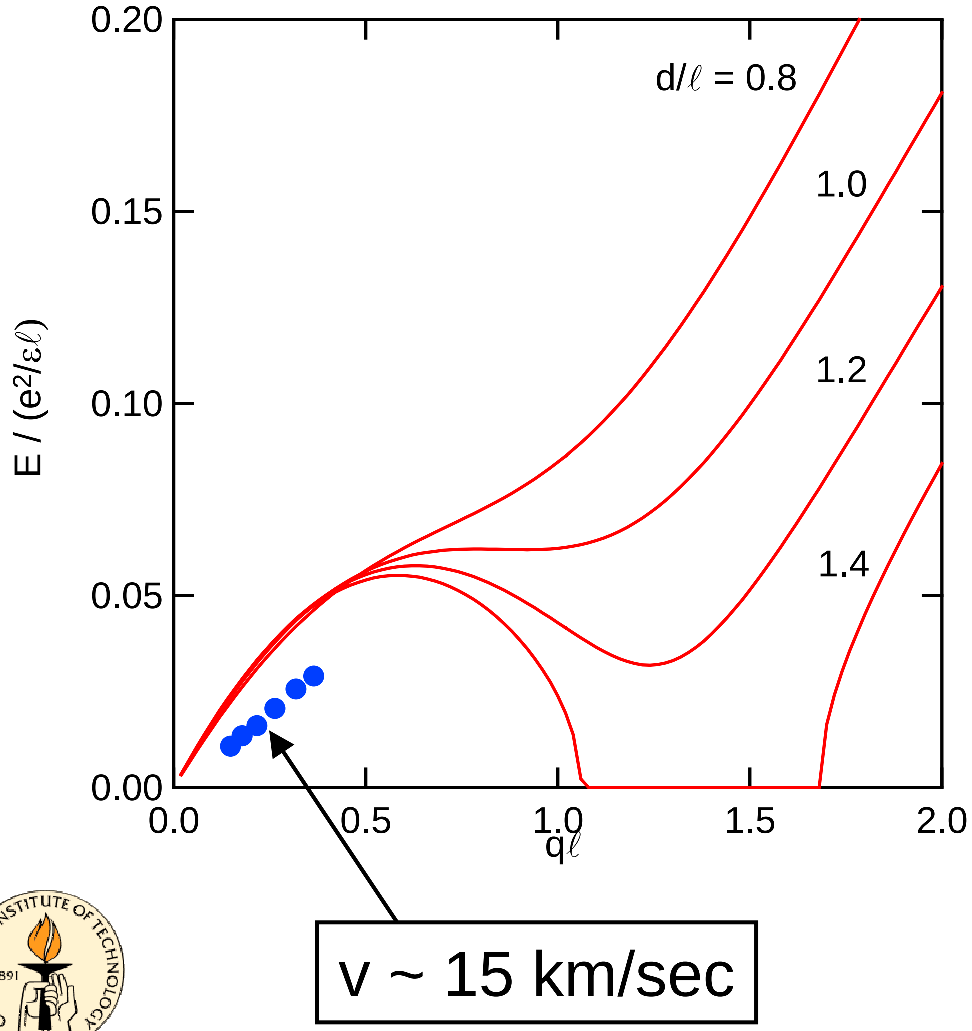




$$q = eB_{||}\, d / \hbar$$

Peak is suppressed and satellites appear.

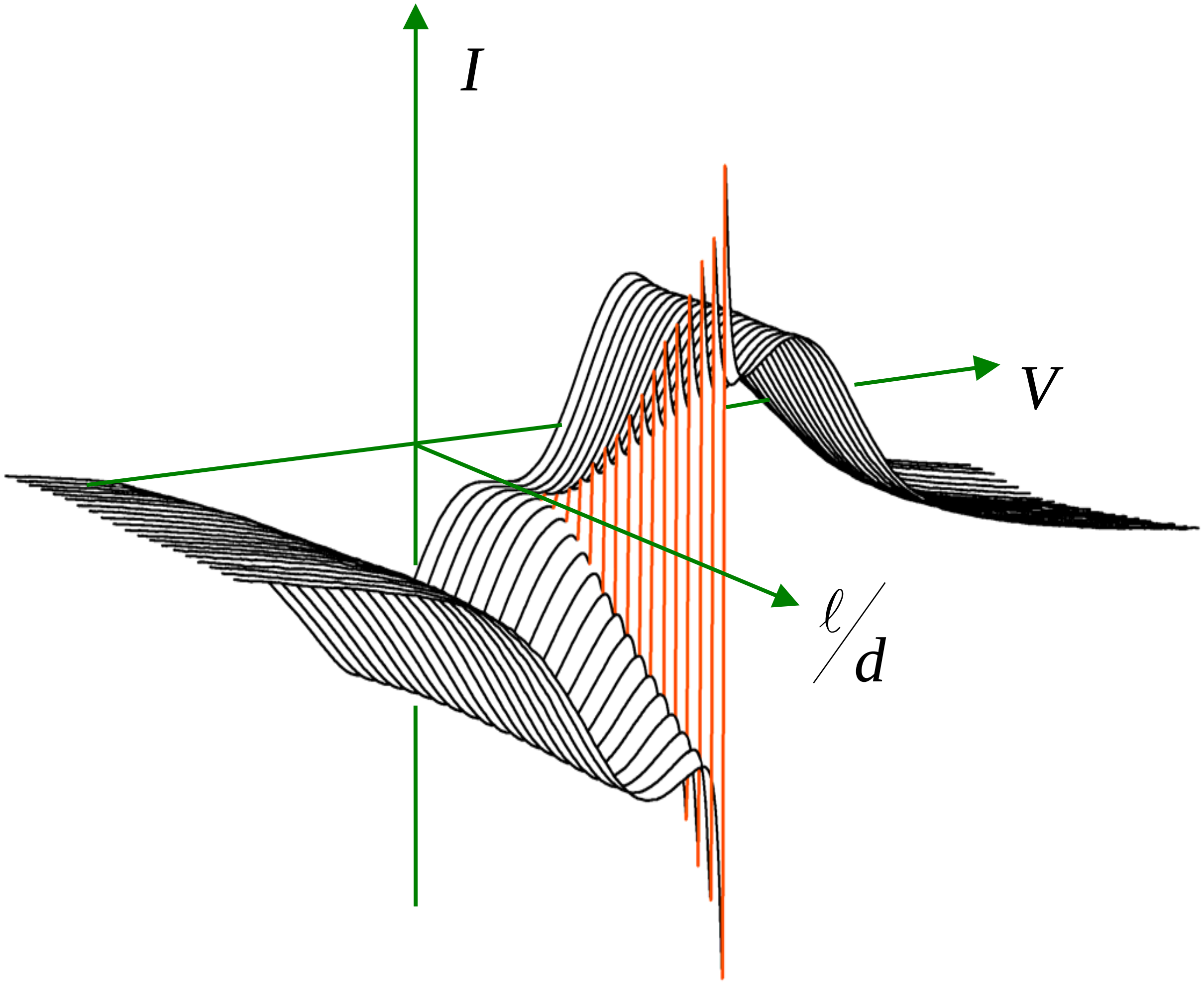
Measured Collective Mode Dispersion



Direct observation of linearly dispersing Goldstone mode.

- red curves: A.H. MacDonald

A quantum phase transition



Demonstration of spontaneous interlayer phase coherence.

Josephson Effect in a Non-Superconductor?

dc Josephson effect in a superconductor:

$$J_T = J_c \sin \Delta\varphi$$

Interlayer tunneling in $\nu_T = 1$ bilayer QHE:

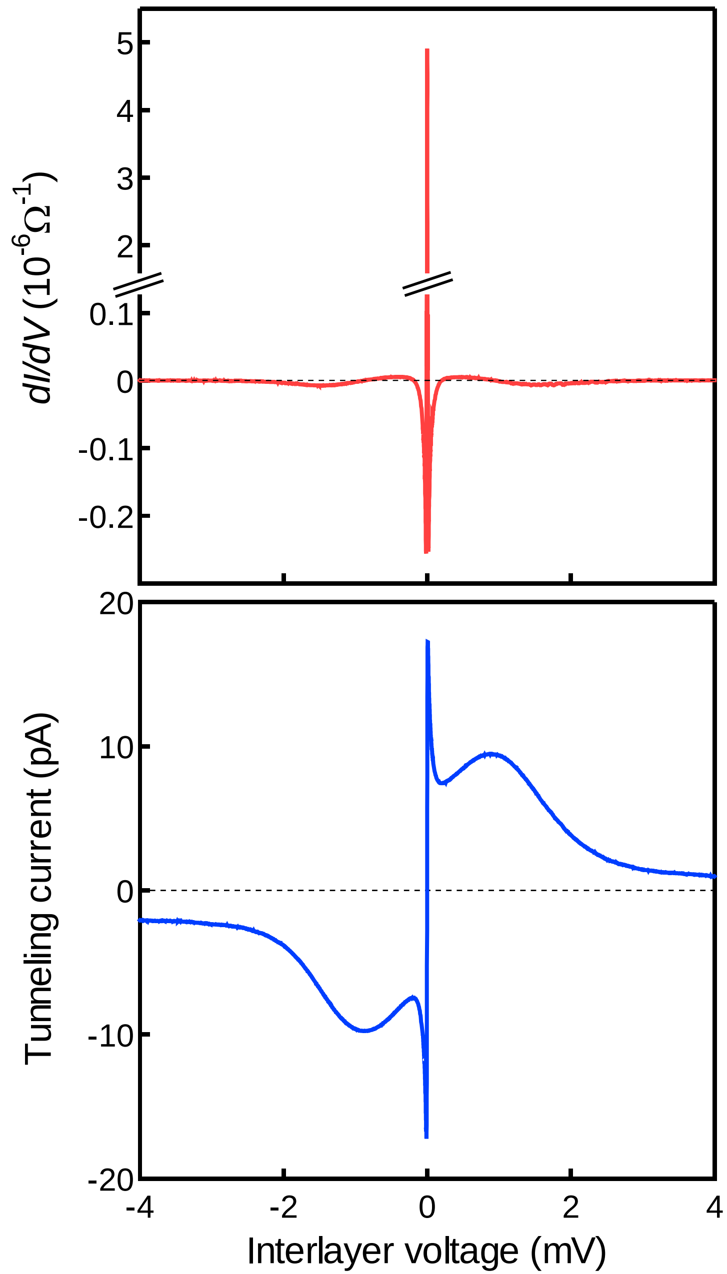
$$J_T = \frac{e}{4\pi \ell^2 \hbar} \Delta_{SAS} \sin \varphi$$

QHE critical current:

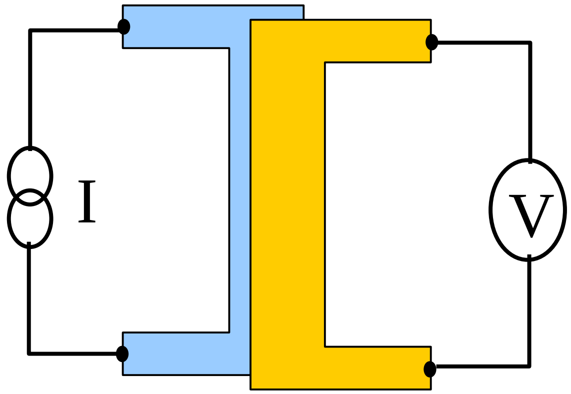
$$I_c = \frac{eA}{4\pi \ell^2 \hbar} \Delta_{SAS} \approx 50\,\mu A$$

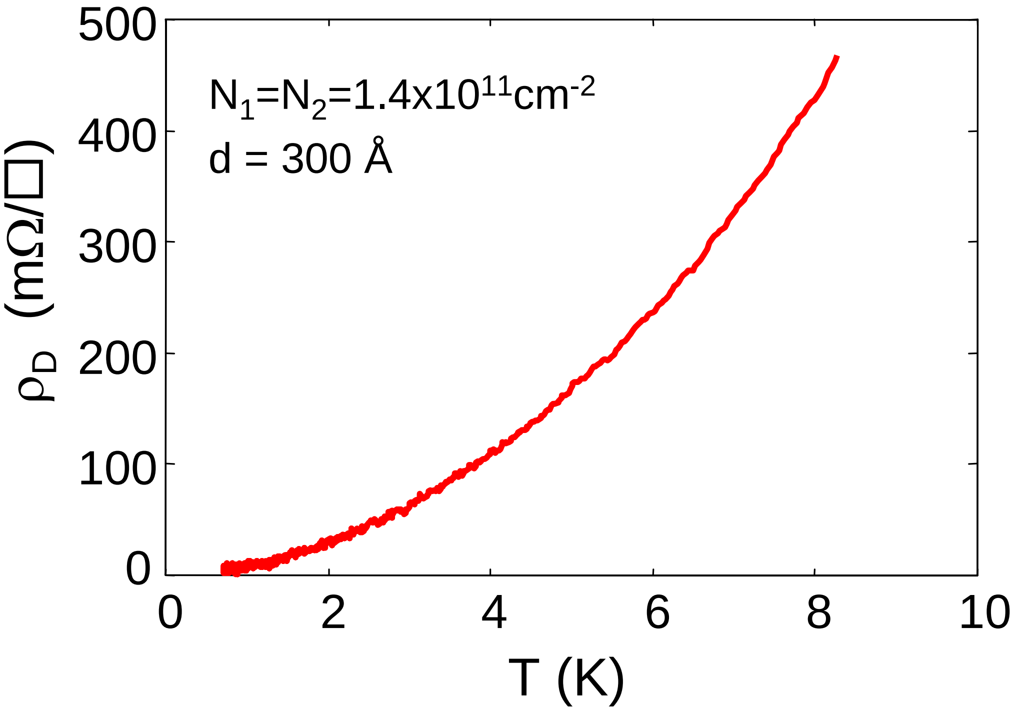
Suggests that pseudospin field is heavily disordered on macroscopic scales

cf. Fertig and Straley, cond-mat/0301128

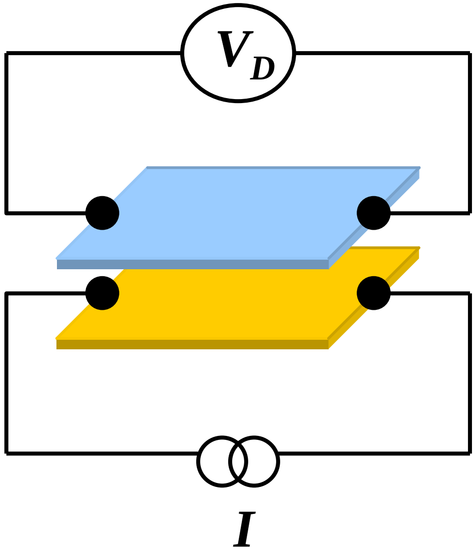


Coulomb Drag at B=0



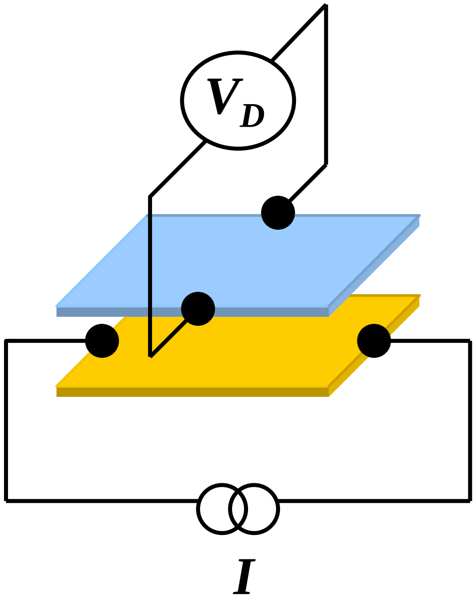


Two Kinds of Coulomb Drag in a Magnetic Field

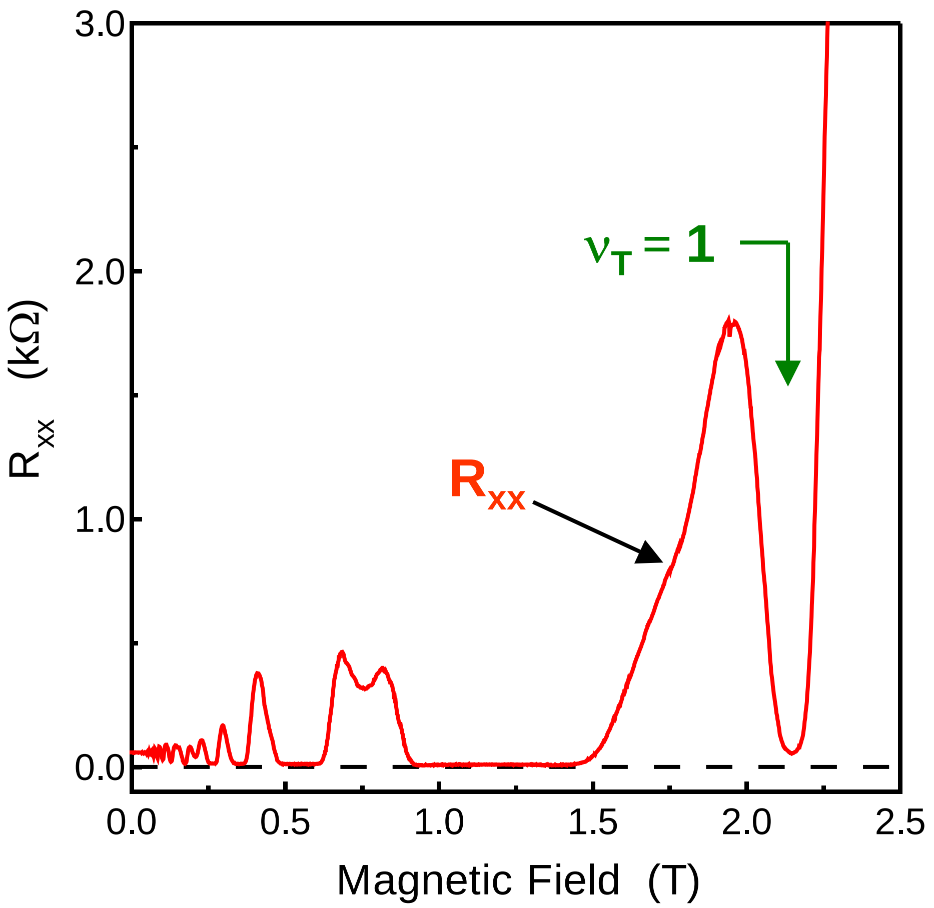


Longitudinal drag

"Hall" drag



Transport coefficients



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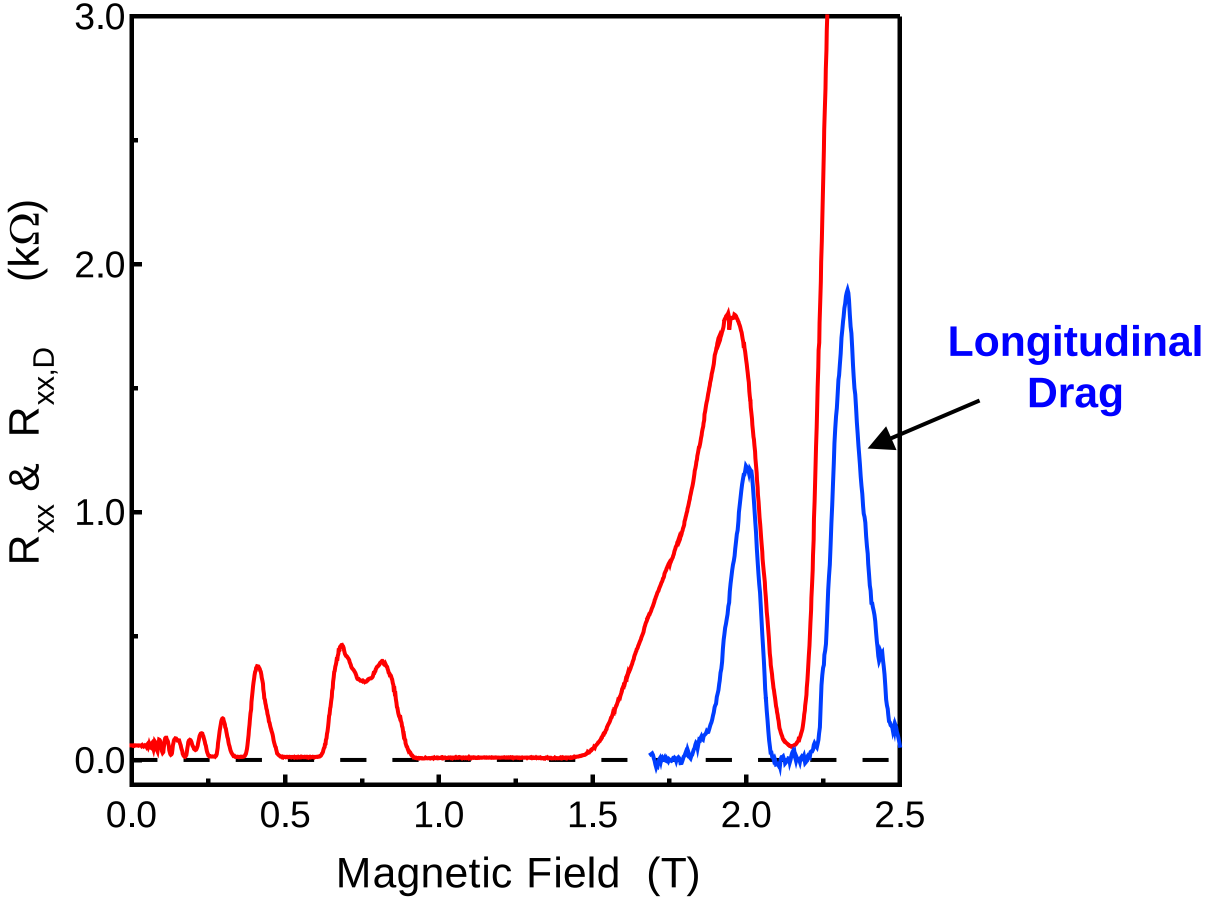

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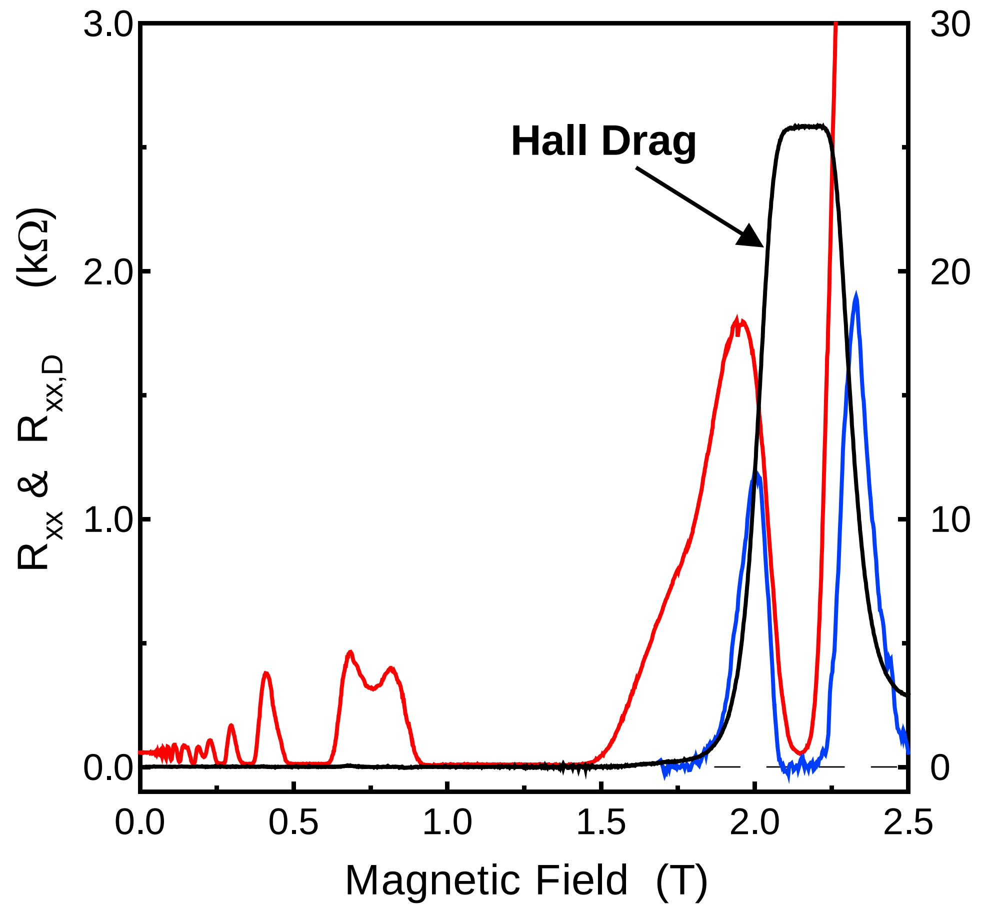

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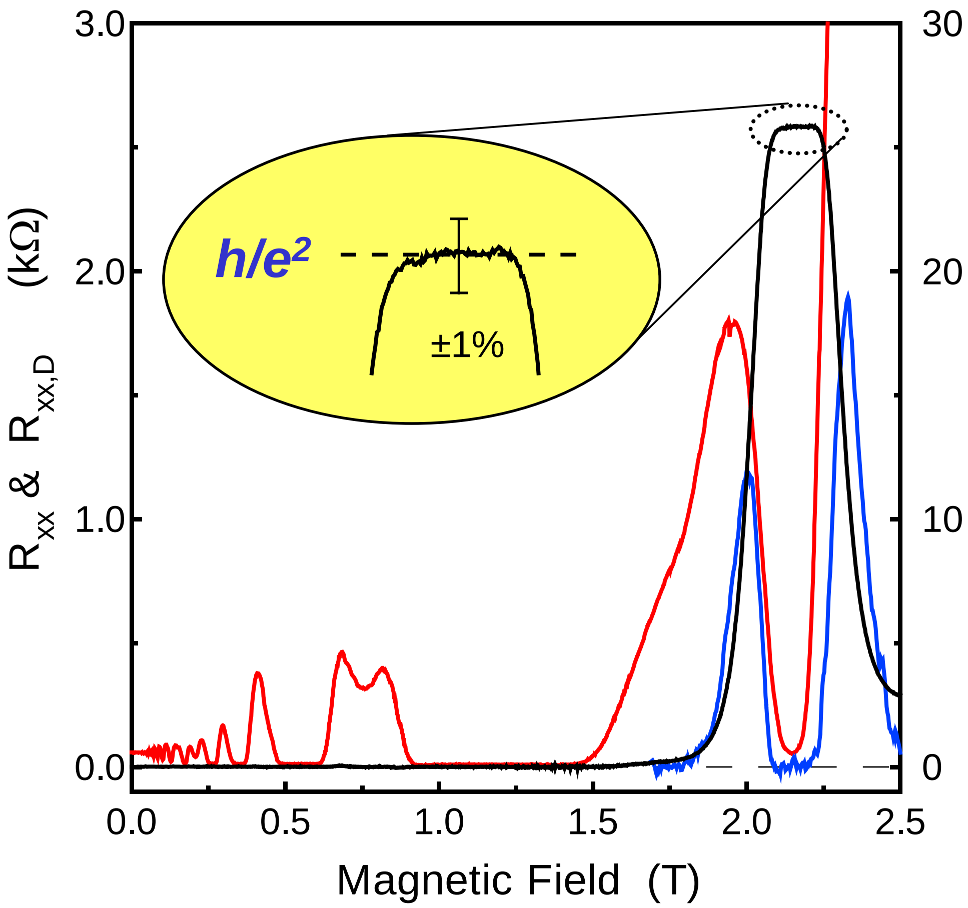
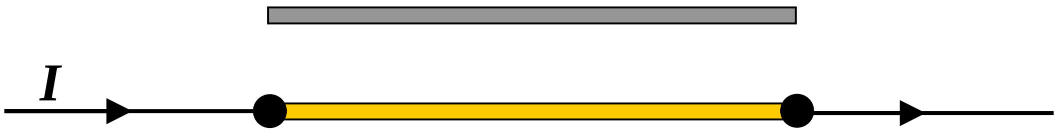


Exact quantization of Hall drag.

Two Transport Channels

In a drag measurement, current flows only in one layer:



The $\nu = 1$ excitonic state supports two kinds of transport: charged quasiparticle currents and neutral excitonic superflow.

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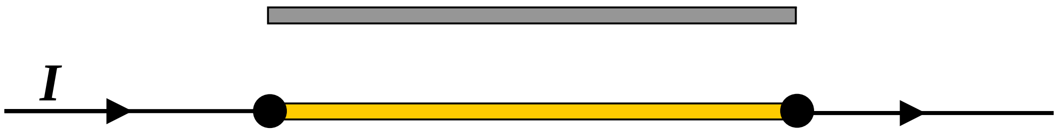

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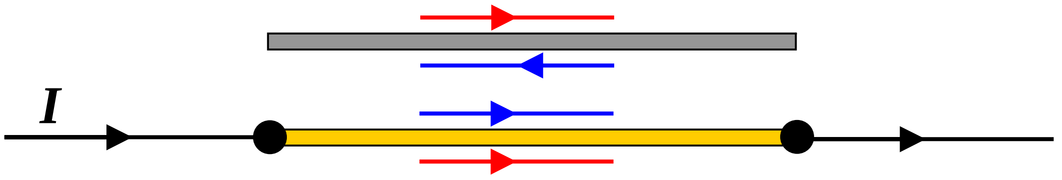
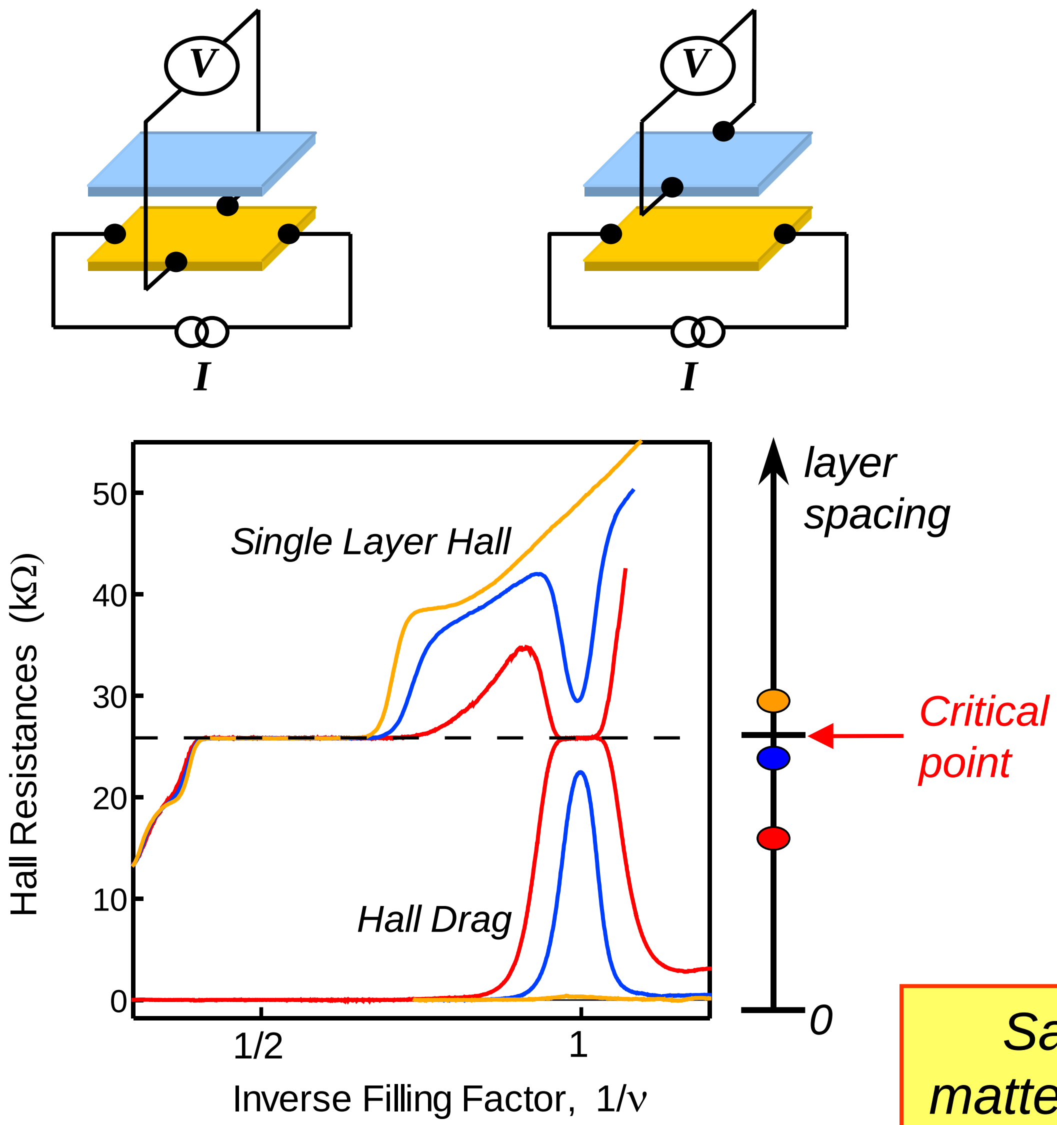


$$I_1 = I_{qp} + I_{ex} = I$$

$$I_2 = I_{qp} - I_{ex} = 0$$

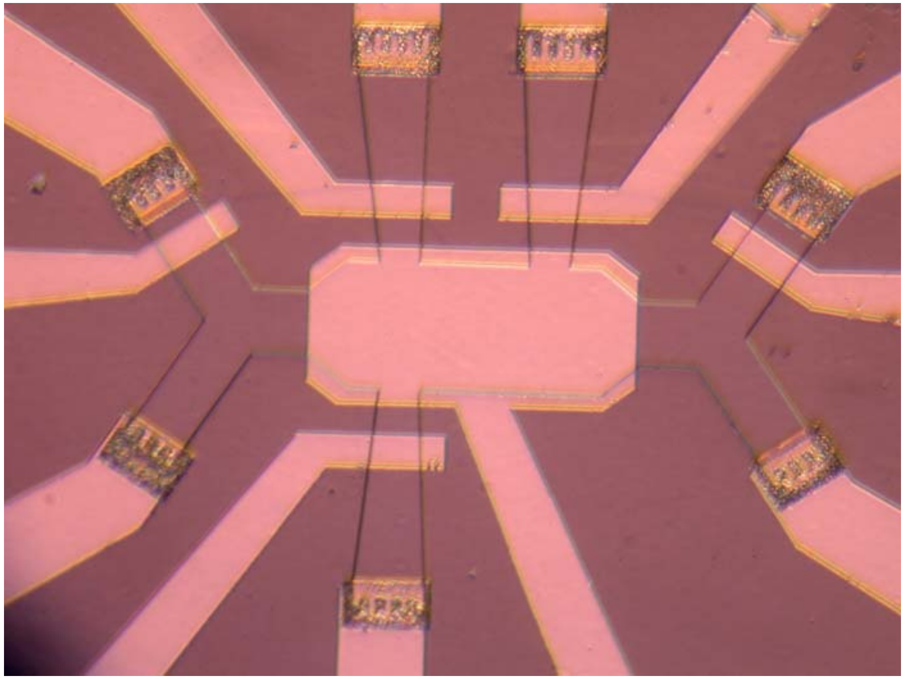
"Explains" quantization of Hall drag, and...

It's stranger still...

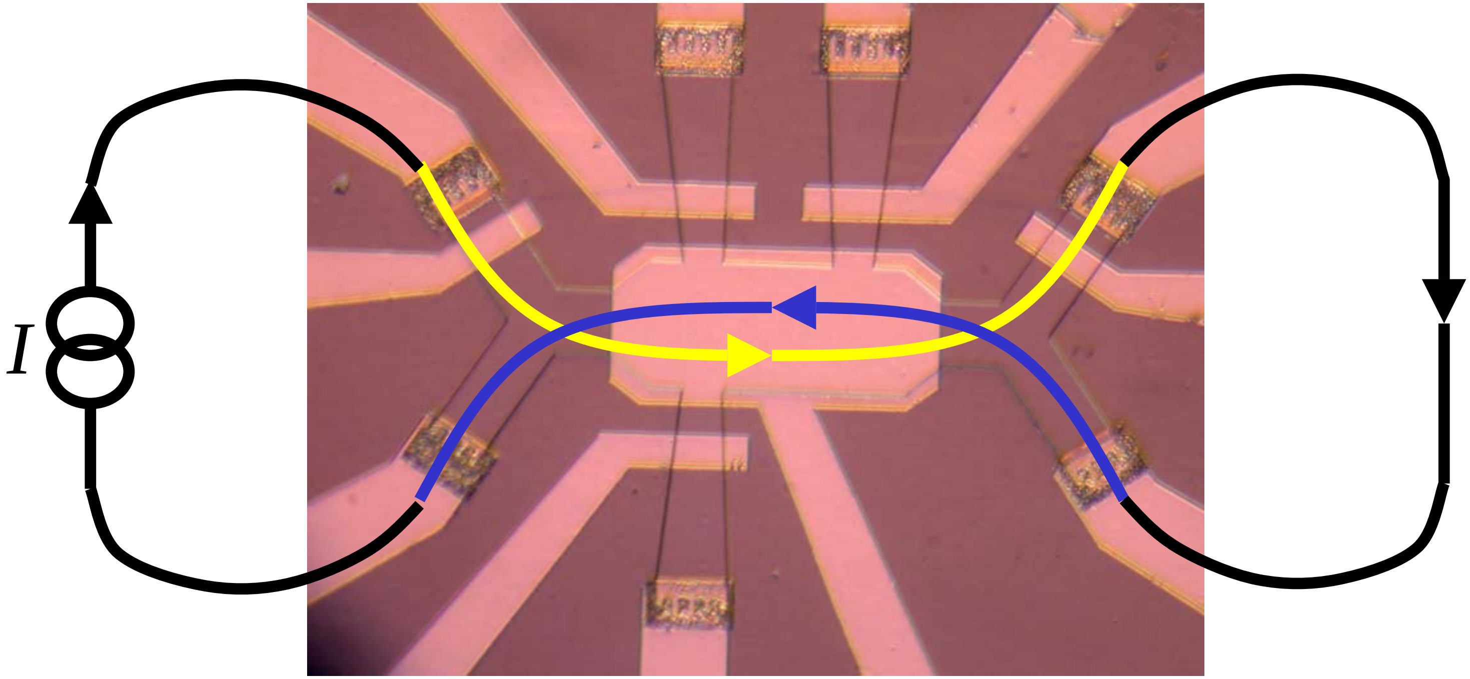


Same Hall voltages no matter how current is divided between the layers!

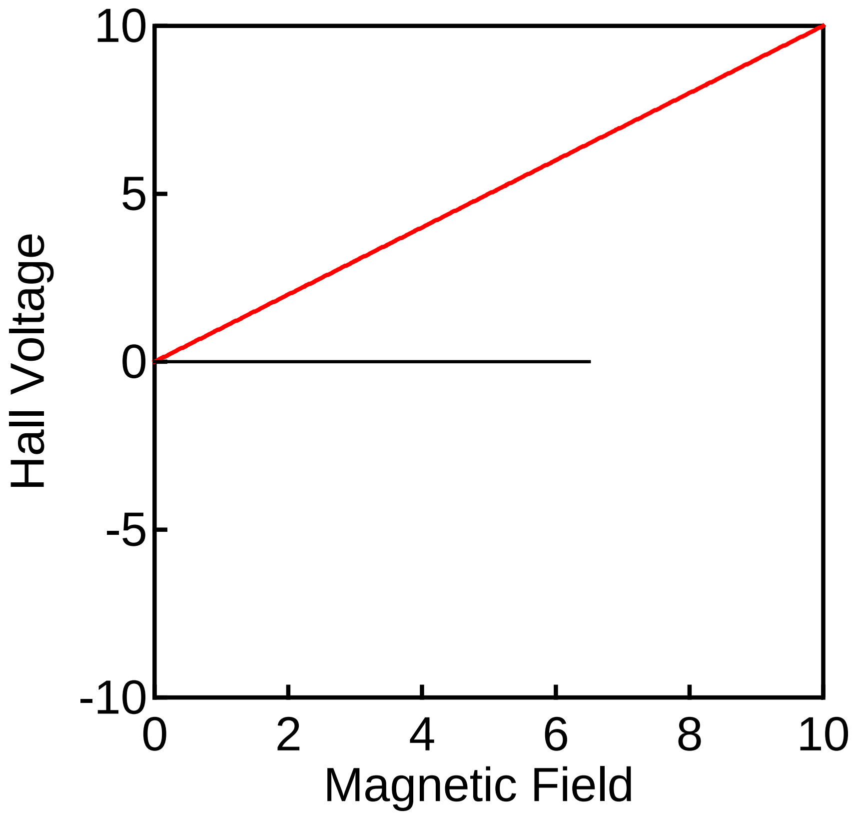
Counterflow Experiment

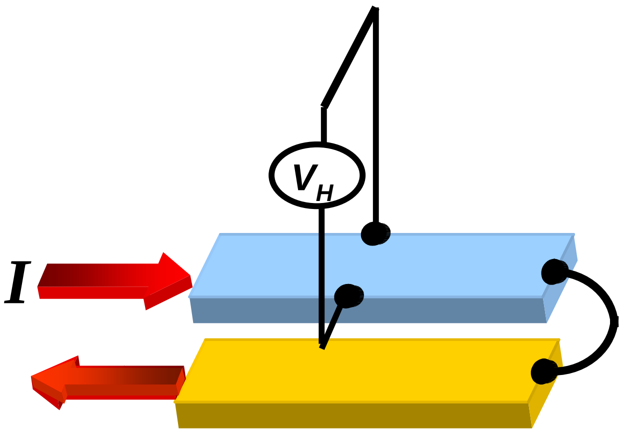


Counterflow Experiment

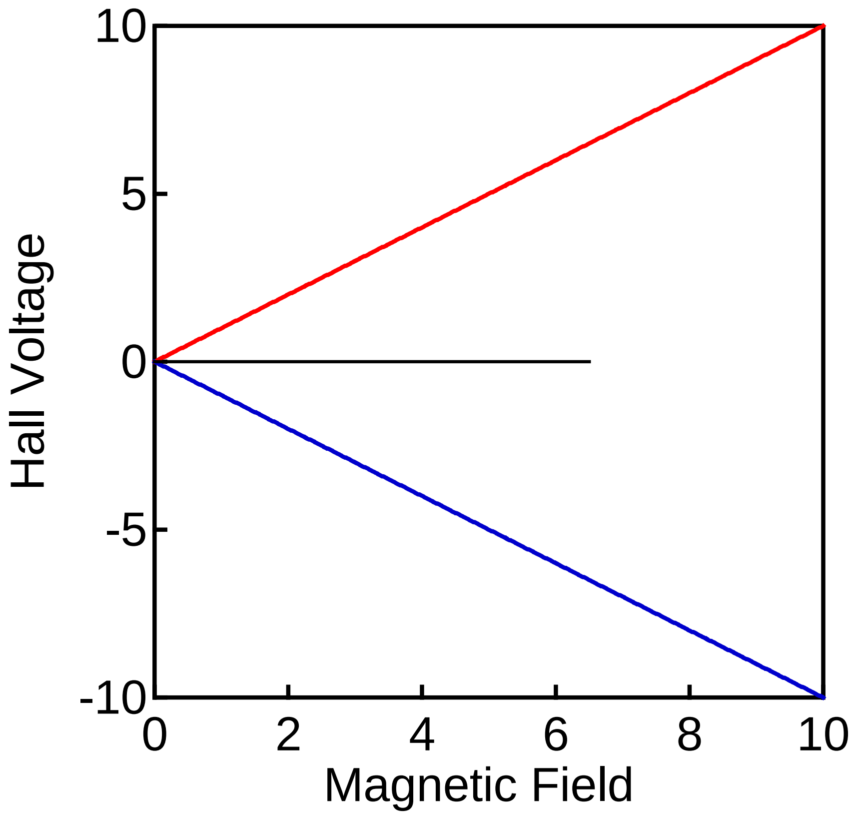


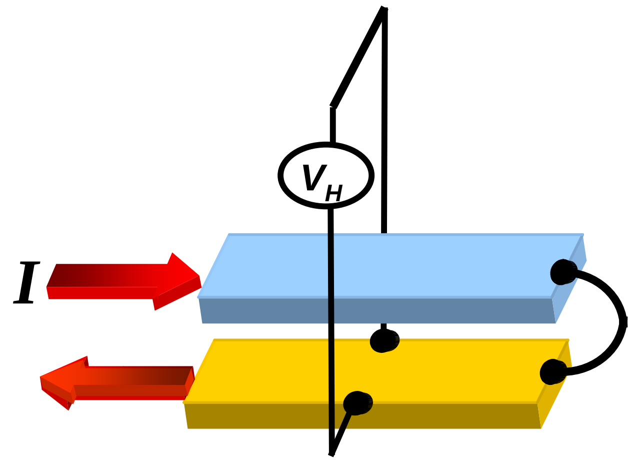
Counterflow Experiment - cartoon



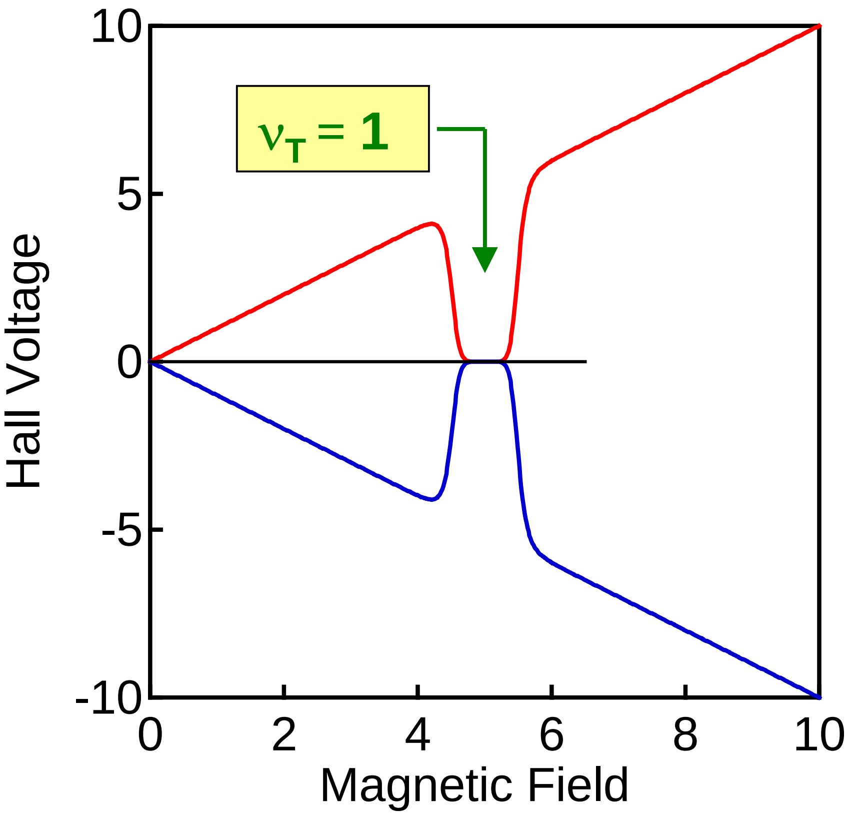


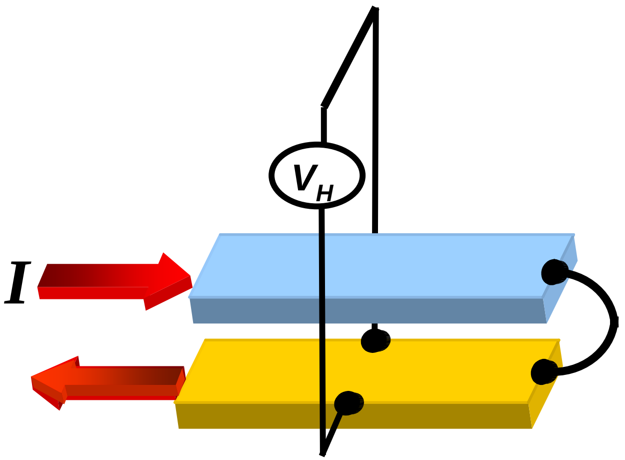
Counterflow Experiment - cartoon





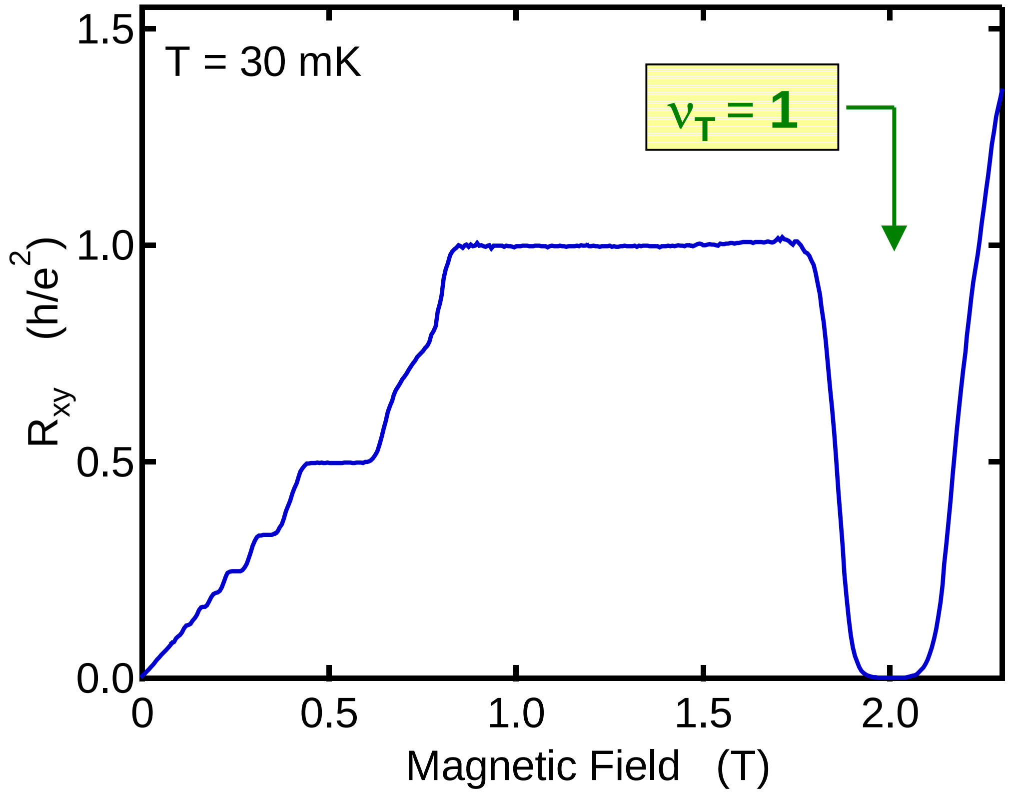
Counterflow Experiment - cartoon

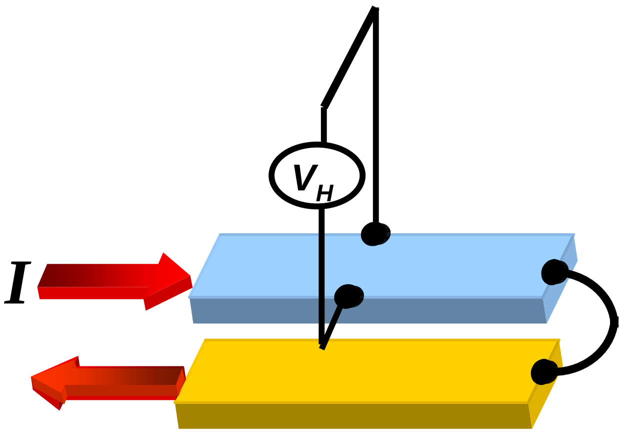




Charge neutral excitons should feel no Lorentz force!

Counterflow Experiment - reality

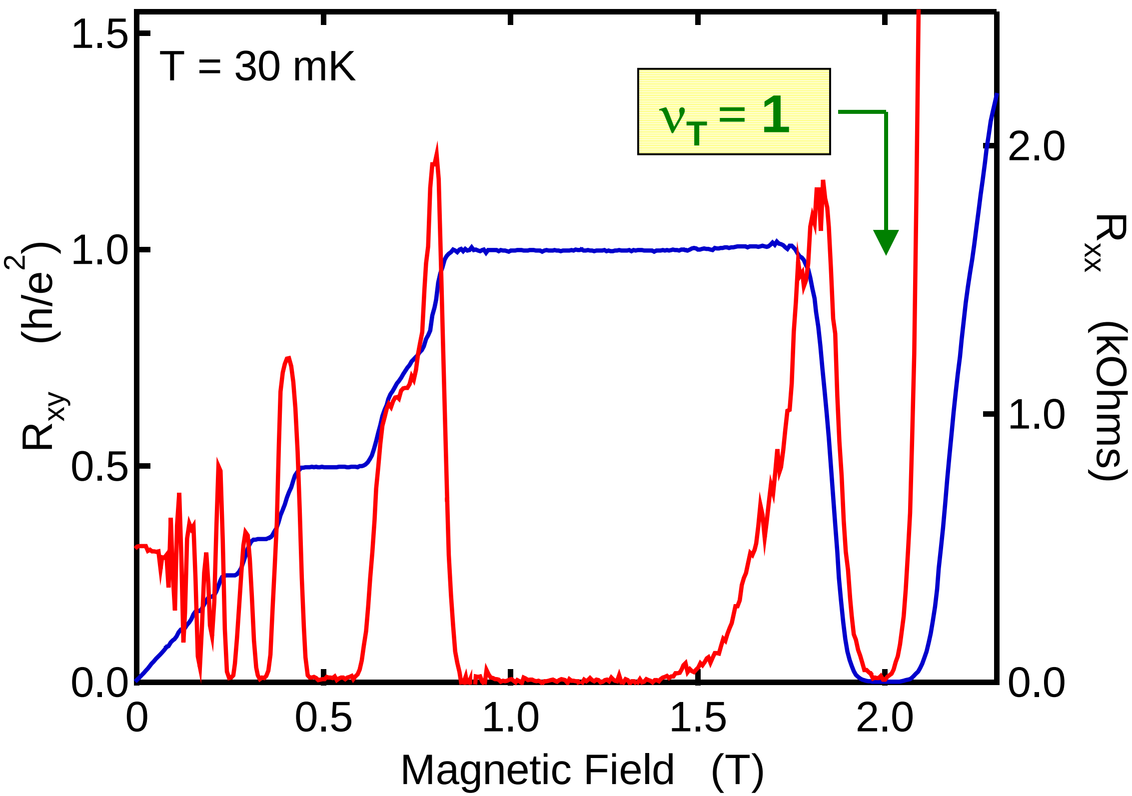


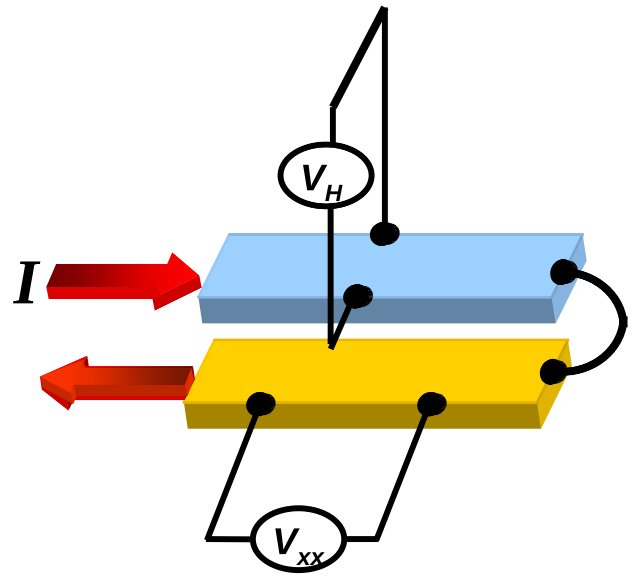


At $\nu_T = 1$ $R_{xy}^{CF} \to 0$ *as* $T \to 0$

exciton transport dominates counterflow

Counterflow Experiment - reality

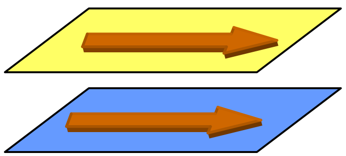




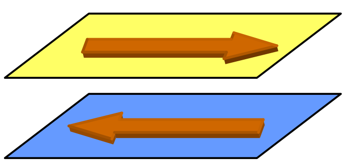
At $\nu_T = 1$: $R_{xy}^{CF} \to 0$ and $R_{xx}^{CF} \to 0$

Parallel vs. Counterflow Transport

$$\sigma_{xx} = \frac{R_{xx}}{R_{xx}^2 + R_{xy}^2}$$



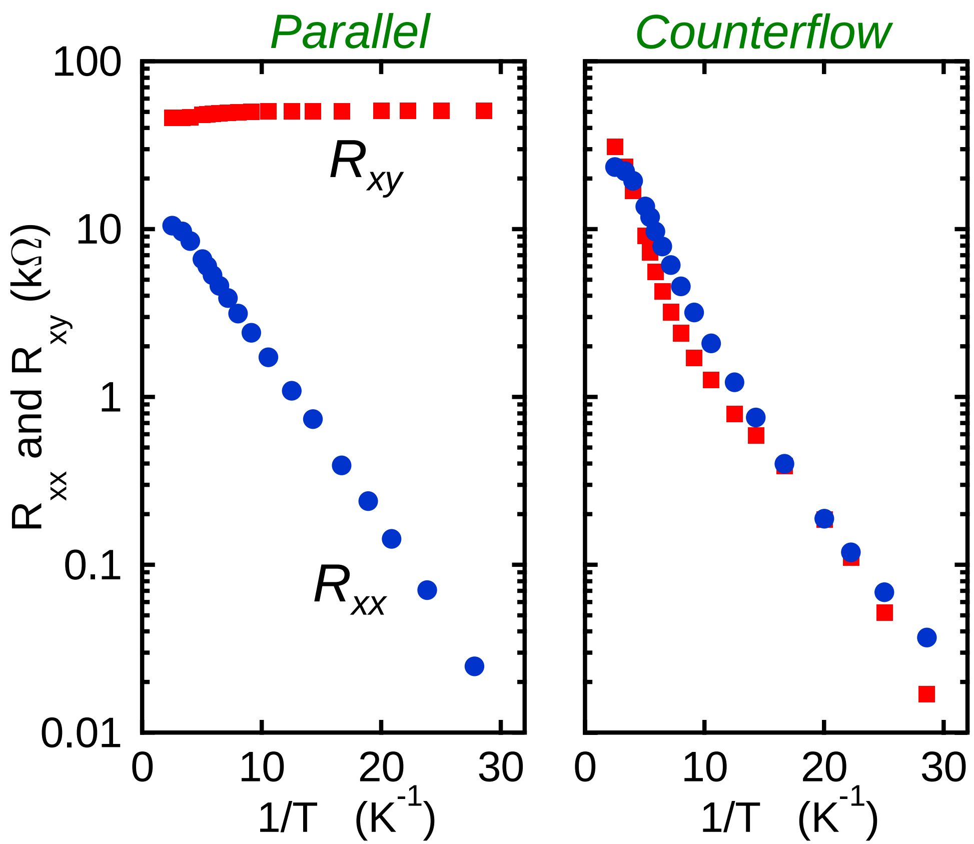
$$R_{xx}^{||} \rightarrow 0 \quad \text{and} \quad R_{xy}^{||} \rightarrow h/e^2 \quad \Longrightarrow \quad \sigma_{xx}^{||} \rightarrow 0$$



$$R_{xx}^{CF} \rightarrow 0 \quad \text{and} \quad R_{xy}^{CF} \rightarrow 0 \quad \Longrightarrow \quad \sigma_{xx}^{CF} \rightarrow ?$$

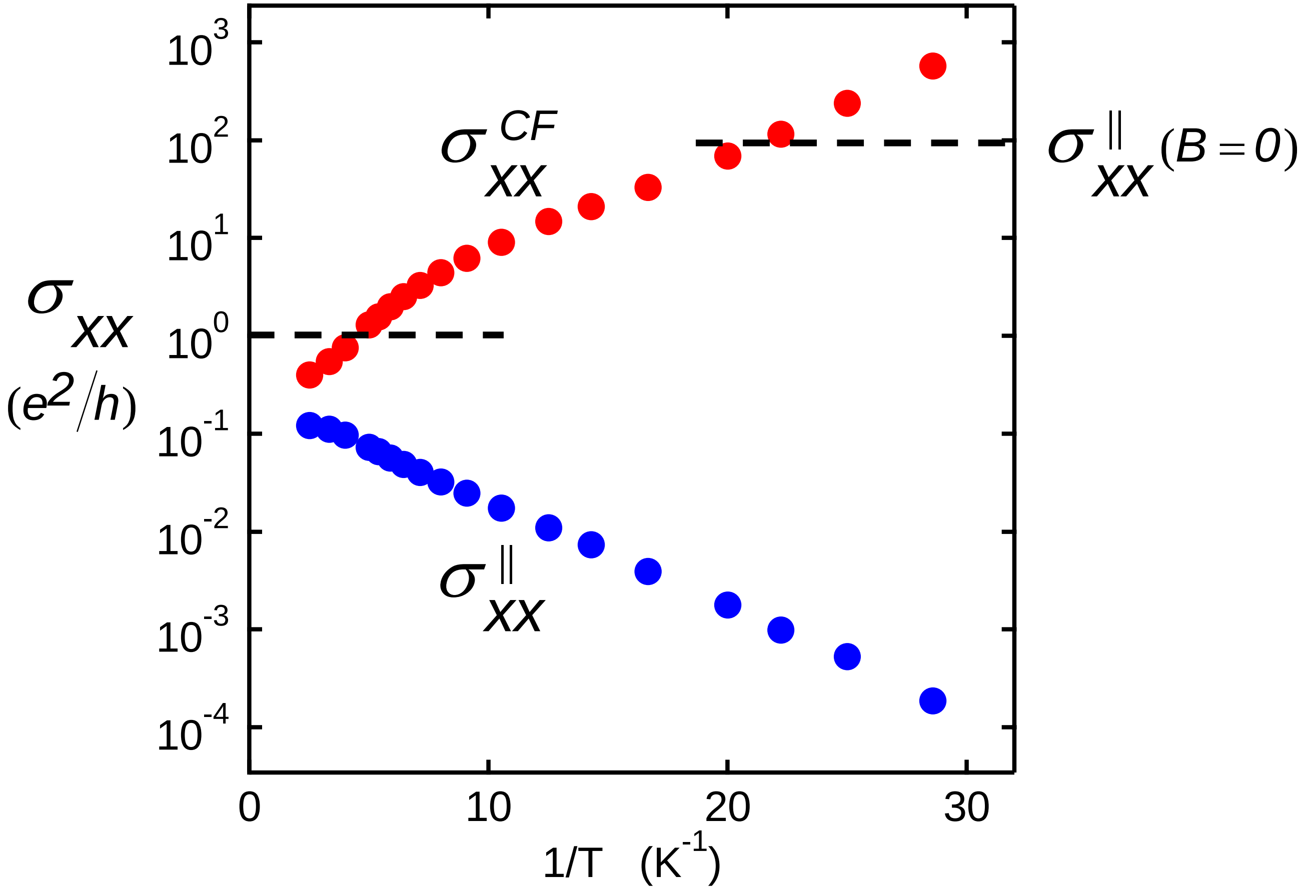
Temperature Dependences

$d/\ell = 1.5$



Conductivities

$d/\ell = 1.5$



Counterflow dissipation small but non-zero at all finite T.

Results

In closely-spaced bilayer 2D electron systems at $\nu_T = 1$:

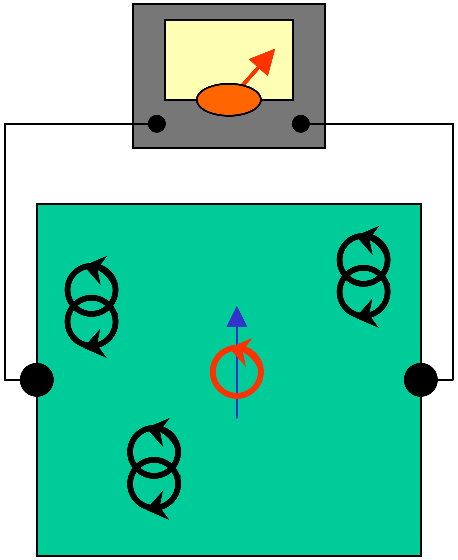
Tunneling reveals a phase transition to an interlayer phase coherent state and unveils the Goldstone mode.

Counterflow and Coulomb drag reveal collective transport of excitons. Dissipationless as $T \rightarrow 0$.

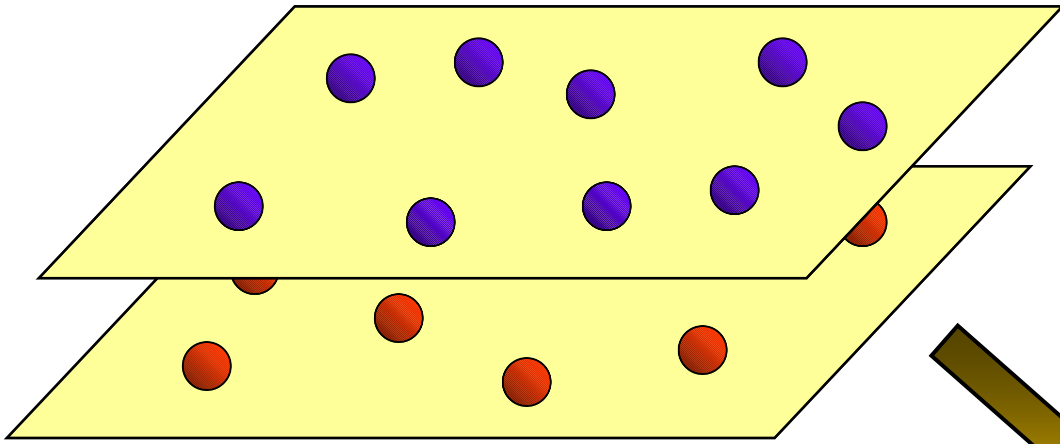
Puzzles

- *tunneling conductance peak too small*
- *$B_{||}$-dependence of tunneling not understood*
- *no non-linearity observed in counterflow transport*
- *thermally-activated dissipation suggests $T>T_{KT}$*

Disorder induced free vortices present at all temperatures.

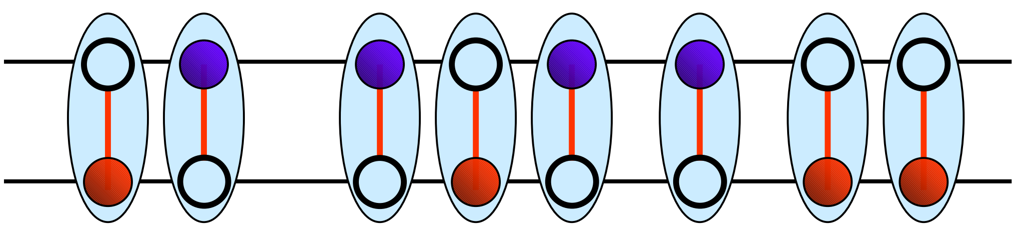


Quantum Hall Excitonic Bose Condensate



Start with a double layer 2D electron gas

Add a magnetic field



Presto! A BCS-like superfluid comprised of interlayer excitons.

Keldysh and Kopaev 1964; Lozovik and Yudson; Shevchenko 1976