

Simulating quantum Hall physics in ultracold atomic gases

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Bad Honnef physics school *Ultracold quantum matter*

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lecture notes at <https://comptes-rendus.academie-sciences.fr/physique/articles/10.5802/crphys.243/>

Outline

1. Topological bands and the integer quantum Hall effect

- 1.1. Landau levels
- 1.2. Quantization of the Hall conductance
- 1.3. Topological bands in lattice systems

2. Realizing quantum Hall systems with ultracold atoms

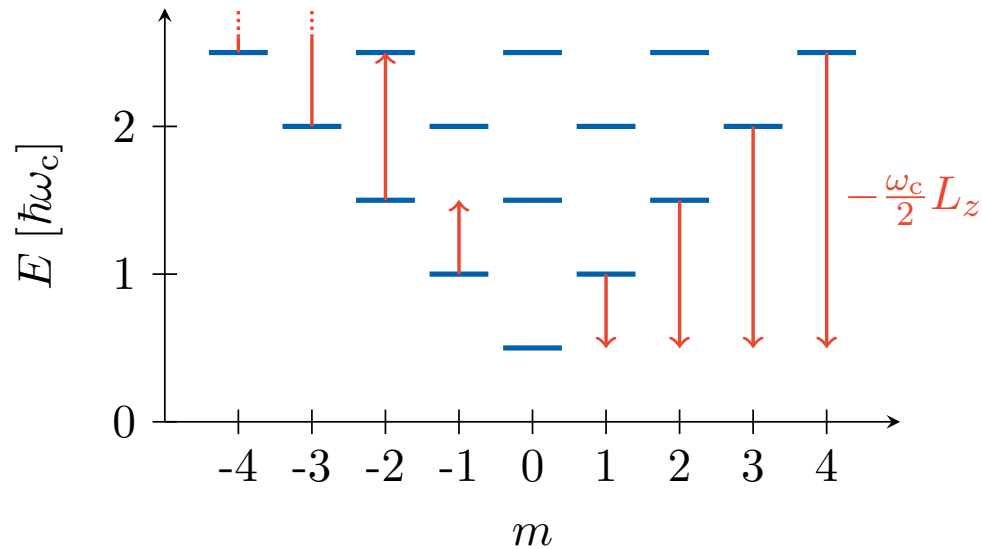
- 2.1. Rotating gases
- 2.2. Lattice systems
- 2.3. Synthetic dimensions

3. Towards fractional quantum Hall states

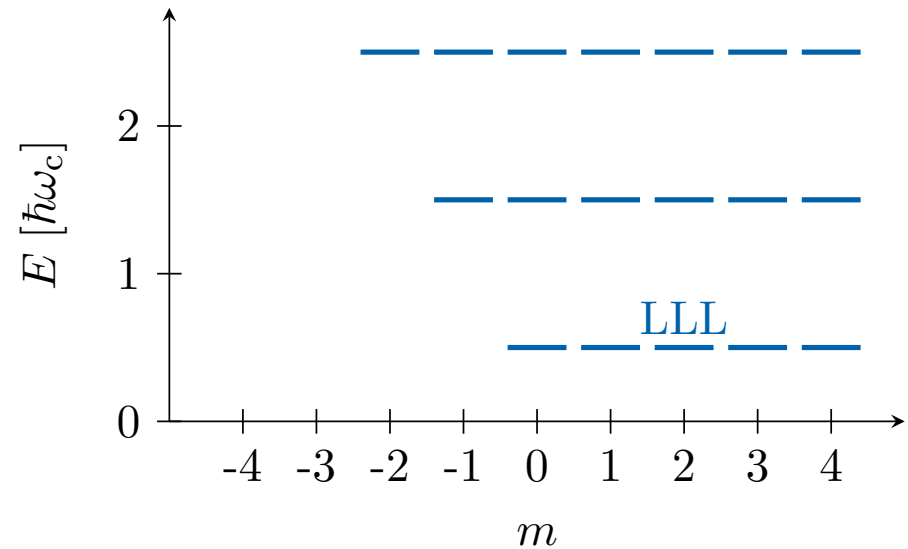
- 3.1. The bosonic Laughlin state
- 3.2. Current status of experiments
- 3.3. Perspectives

Landau levels

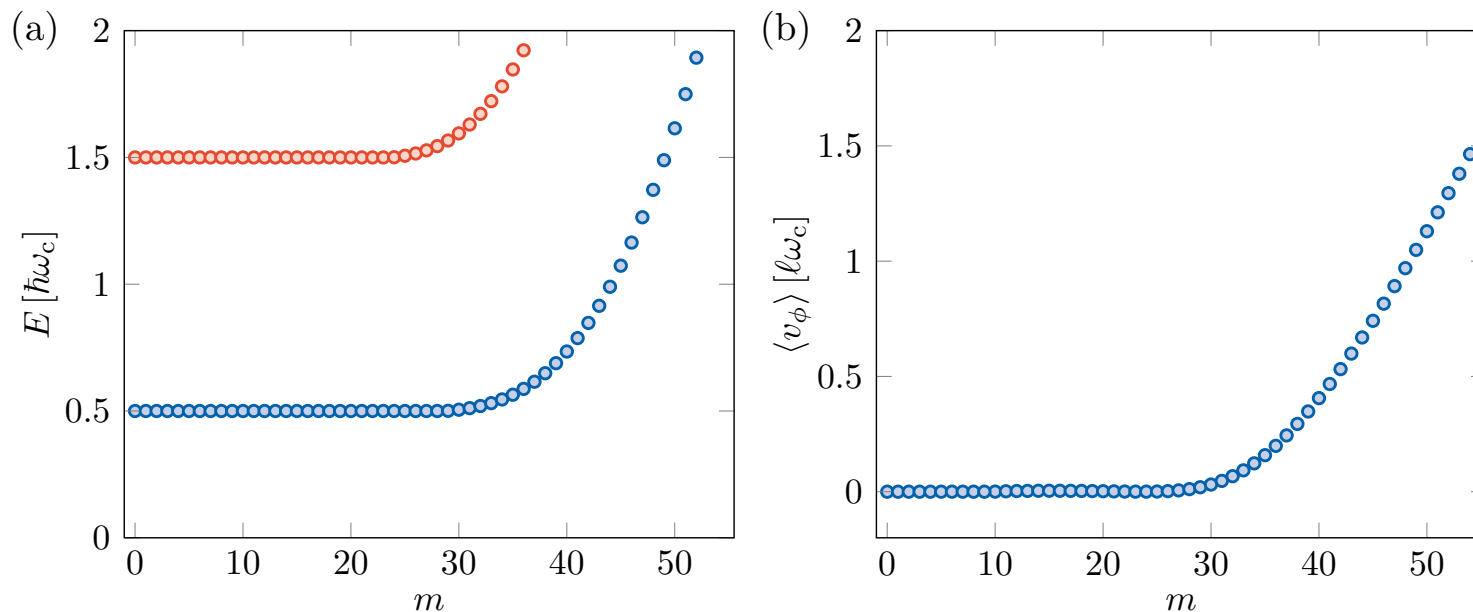
isotropic harmonic oscillator



Landau levels

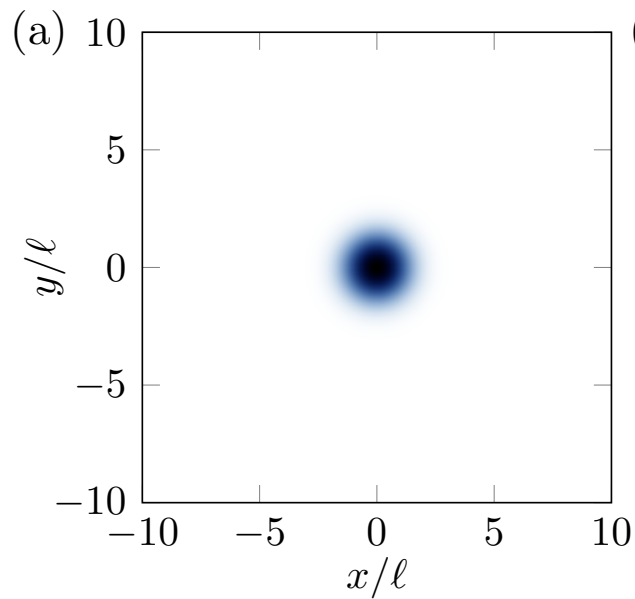


Edge states

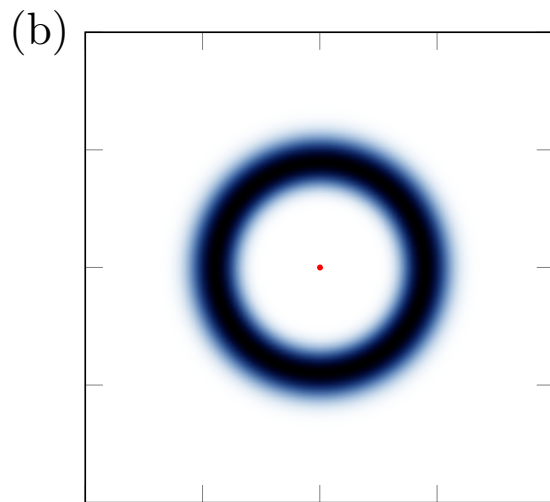


Spectrum of a quantum Hall system restricted to a disk of radius $R = 10\ell$.

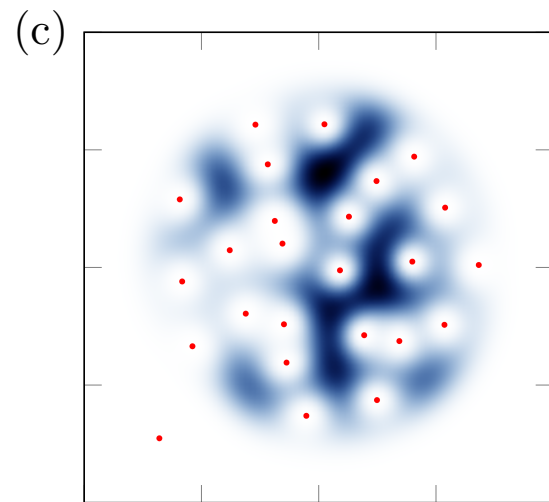
Density of several LLL states



$\psi_{m=0}$



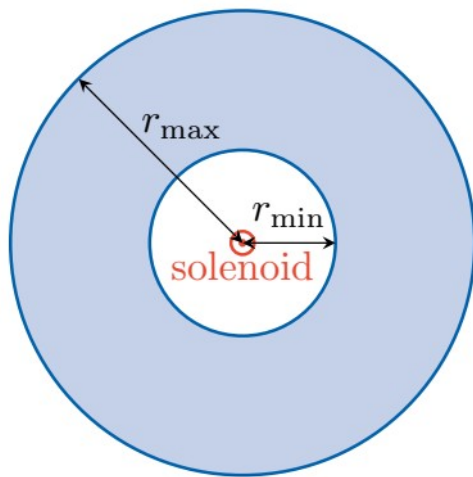
$\psi_{m=10}$



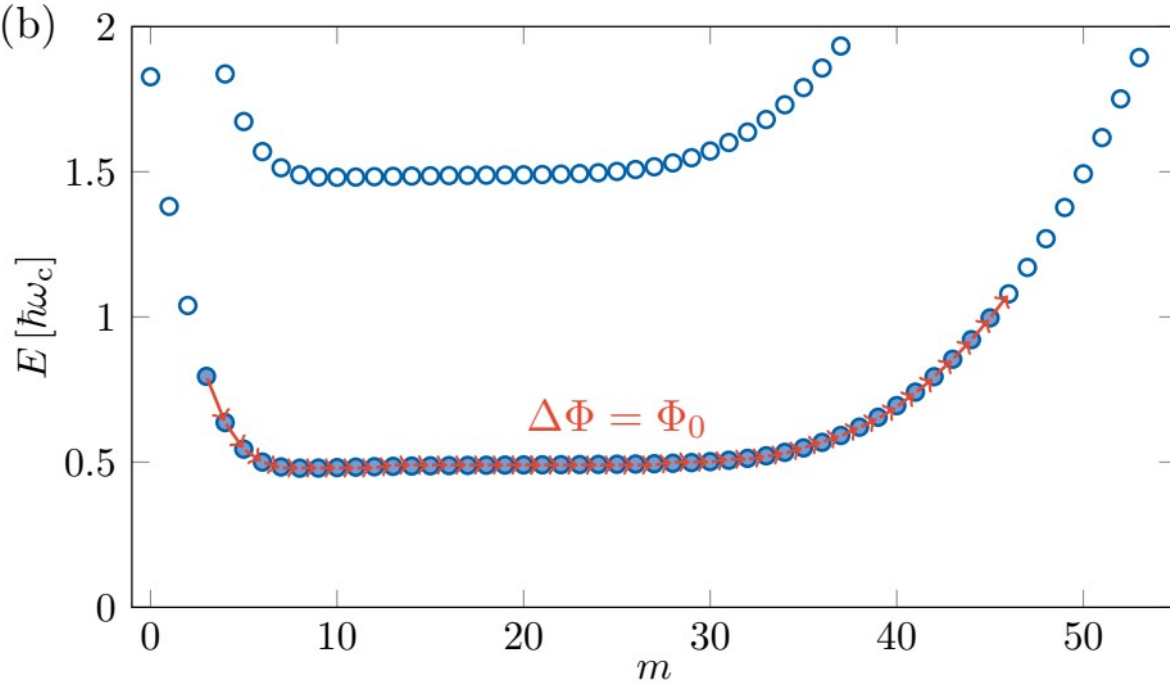
random complex polynomial
of order 25

Quantized Laughlin pump (Corbino geometry)

(a)

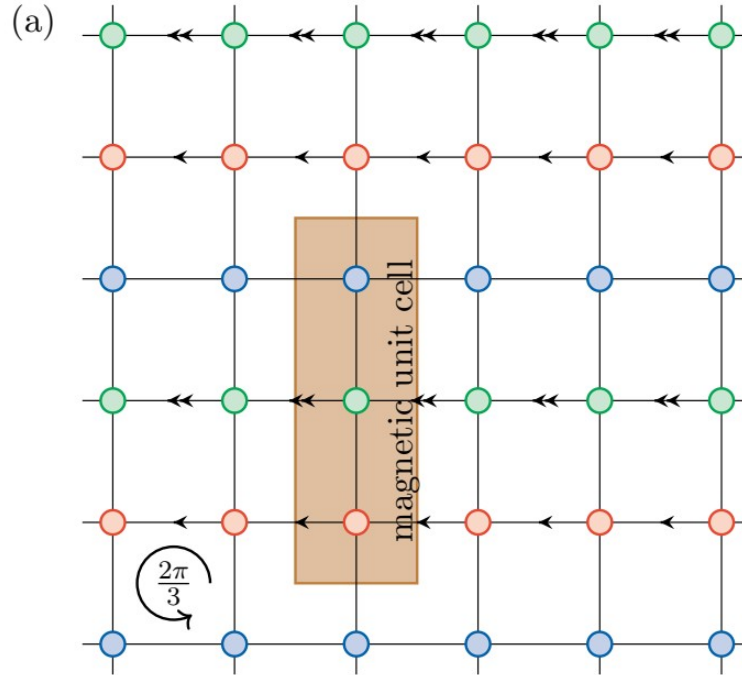


(b)

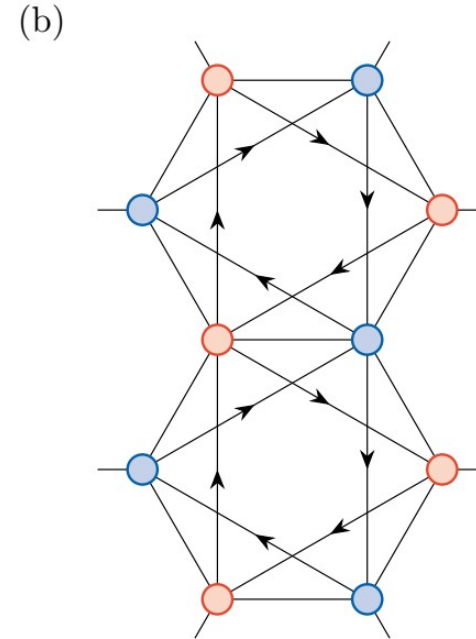


$$r_{\min} = 2\ell \text{ and } r_{\max} = 10\ell.$$

Hofstadter and Haldane lattice models

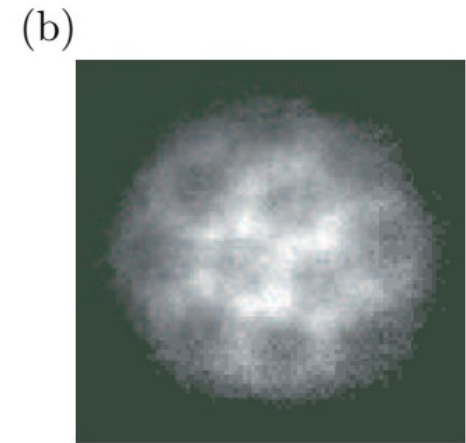
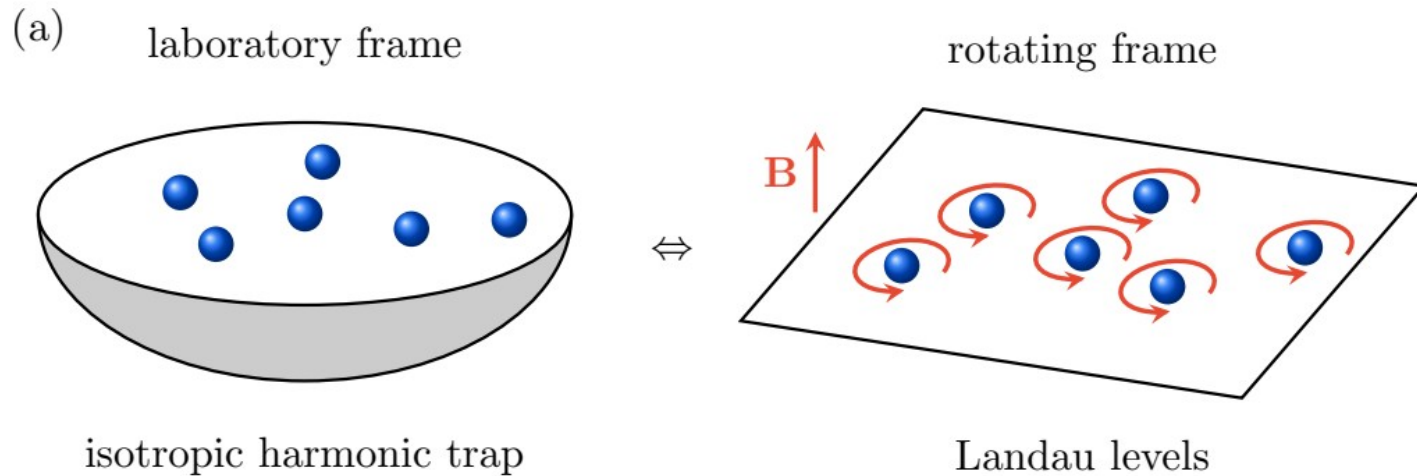


link			
Peierls phase	0	$-2\pi/3$	$-4\pi/3$



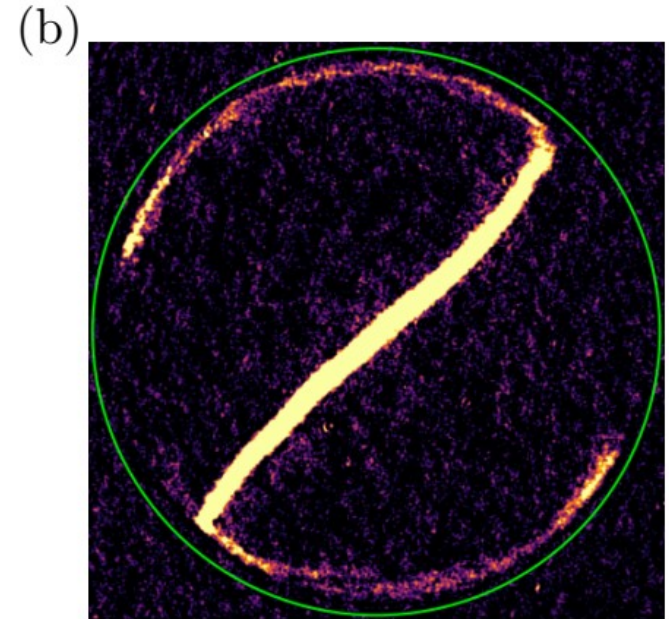
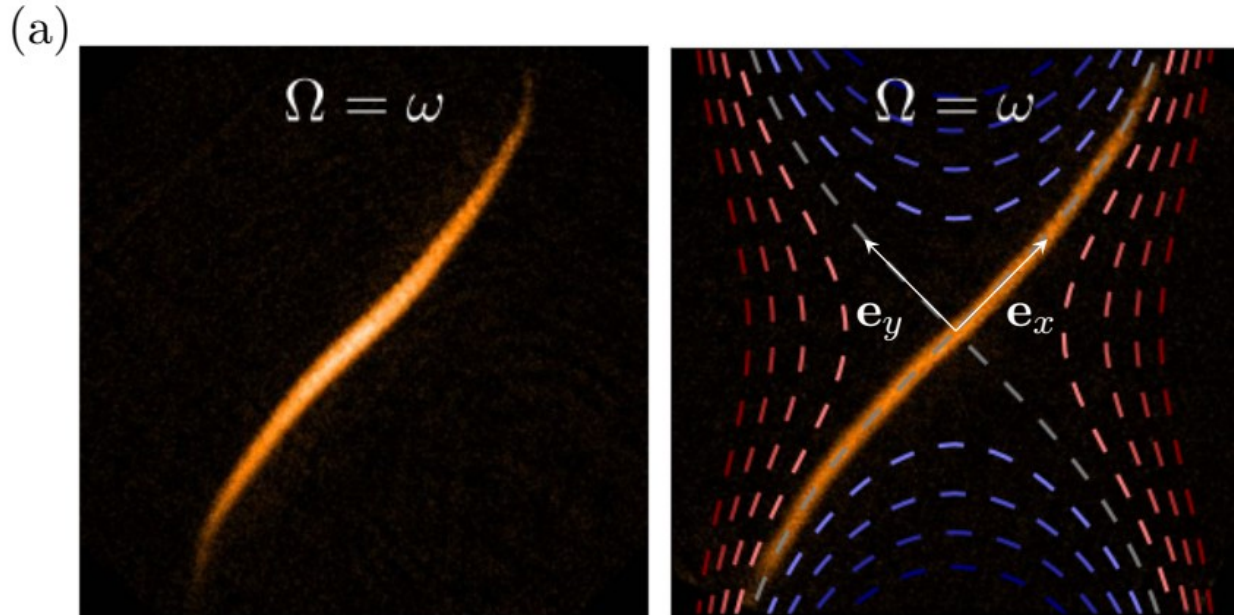
link		
Peierls phase	0	$\neq 0$

Quantum Hall effect in rotating gases



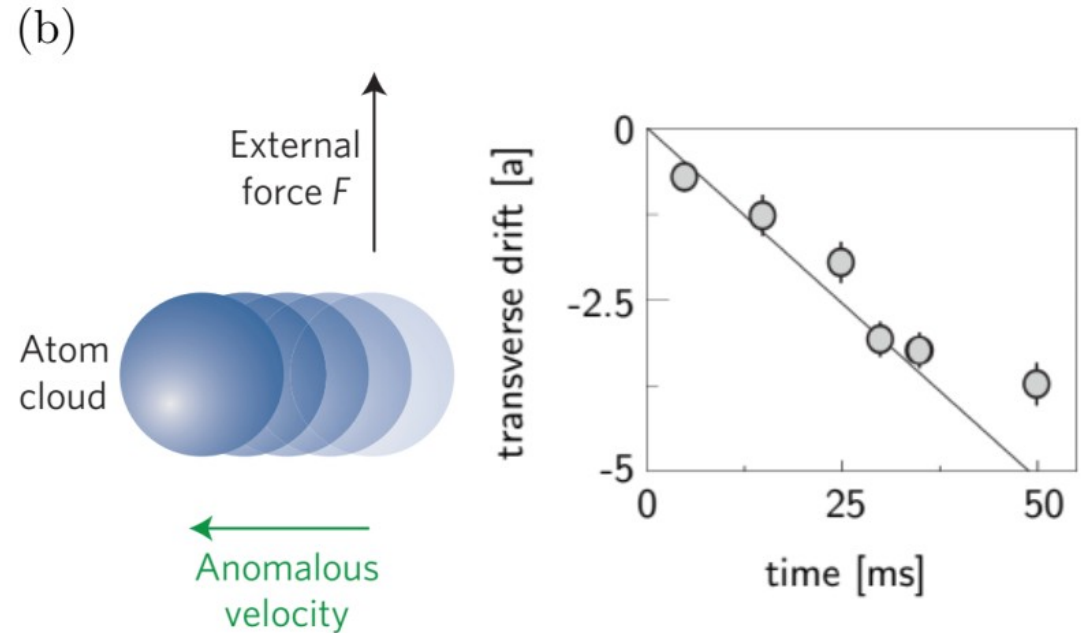
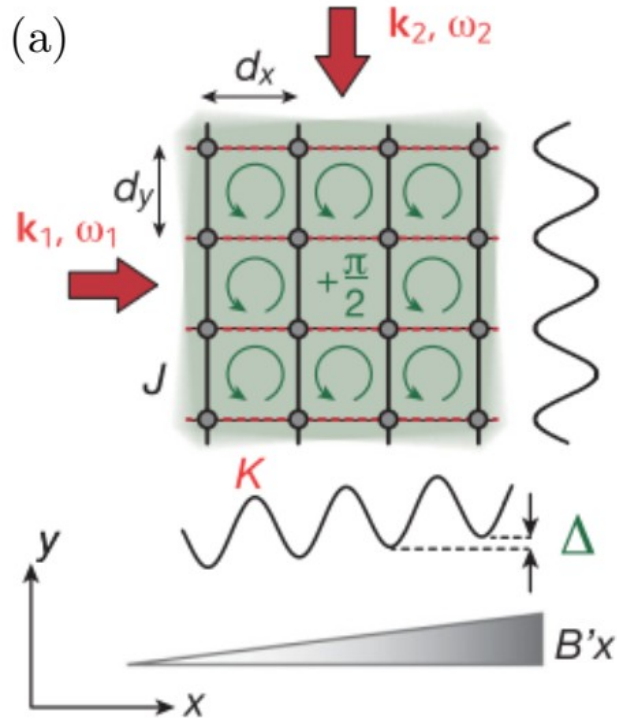
J. Dalibard group (2000),
see also E. Cornell
and W. Ketterle groups

LLL states in a box



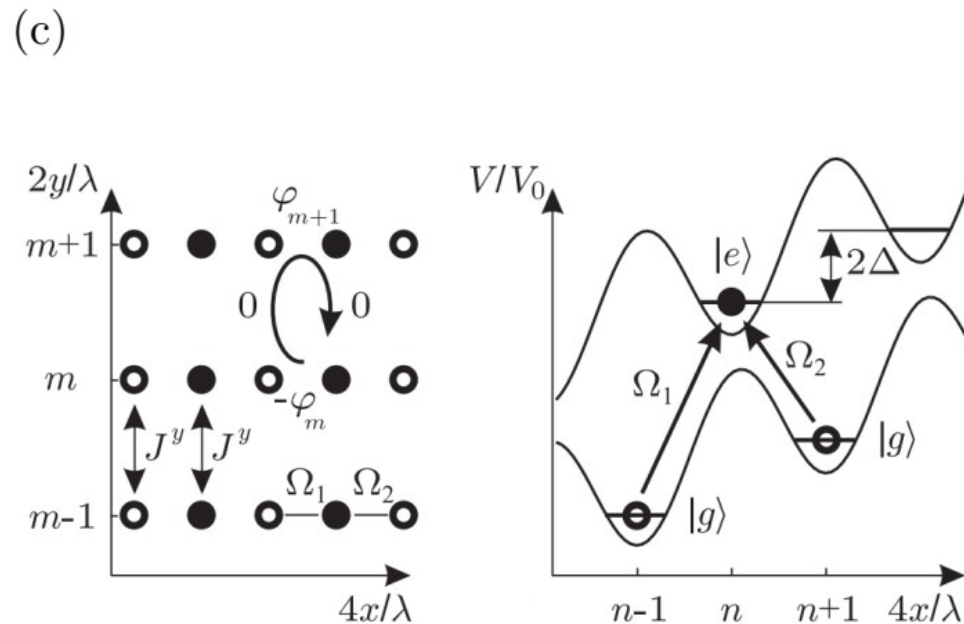
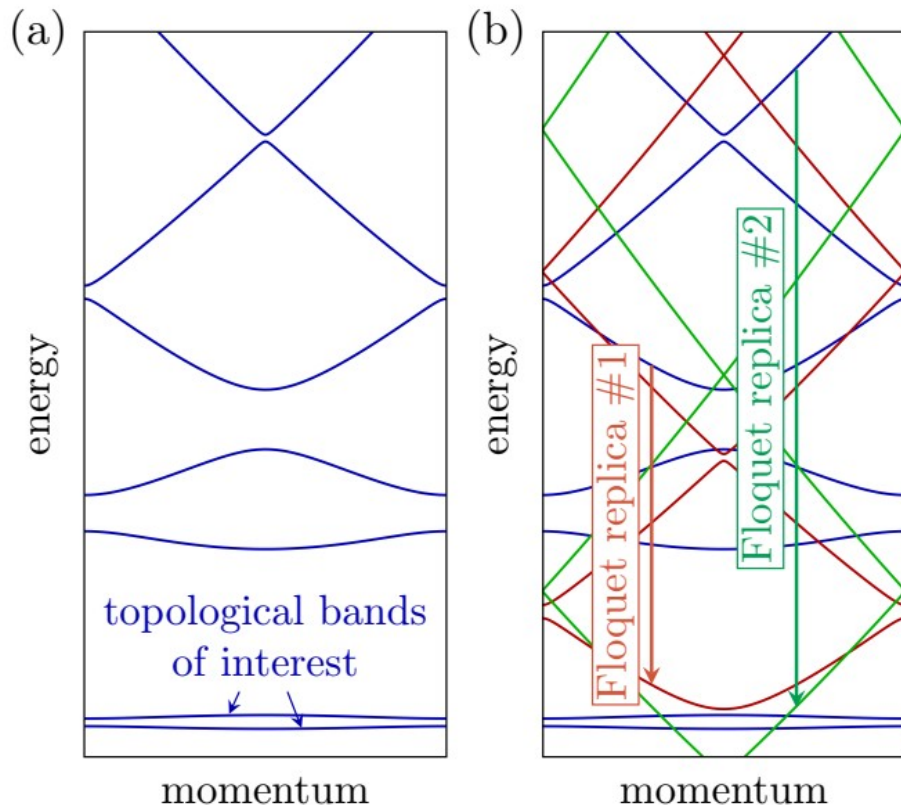
Zwierlein group (2021 & 2023)

Modulated optical lattice simulating the Hofstadter model



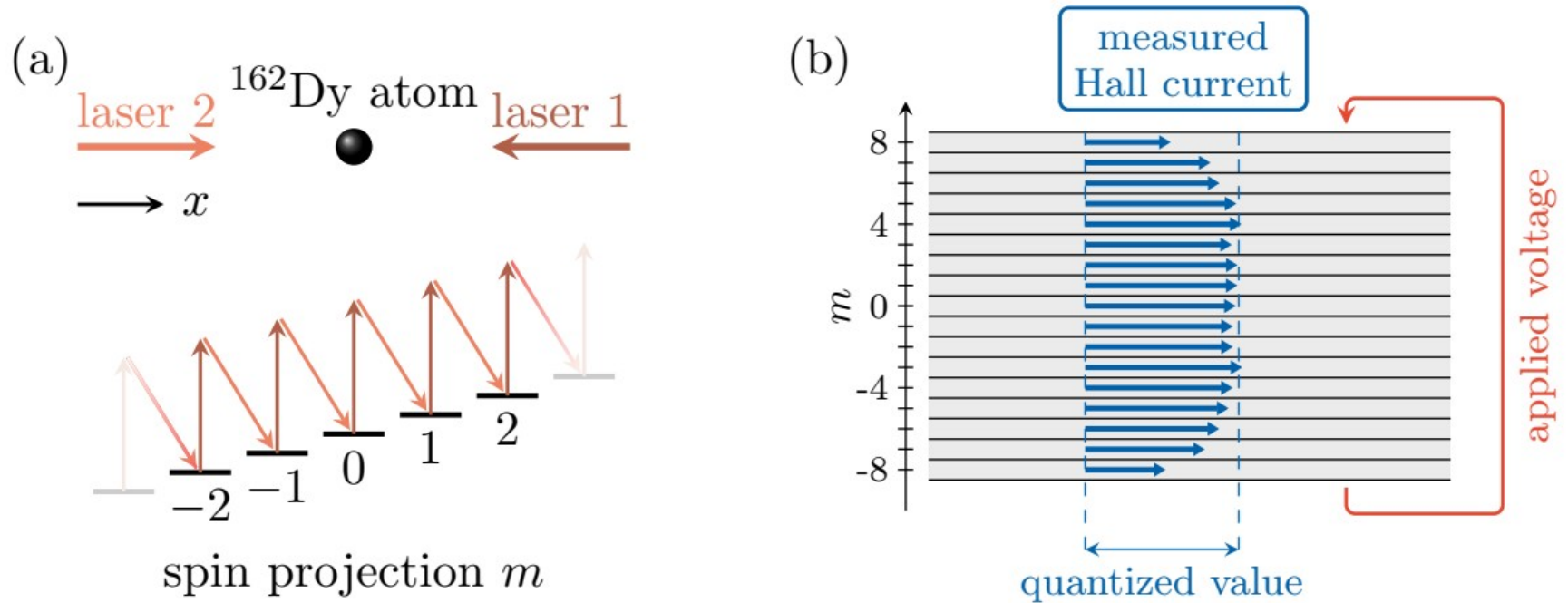
Bloch group (2013 & 2015), see also W. Ketterle, T. Esslinger groups

The issue of Floquet heating (and possible solution)



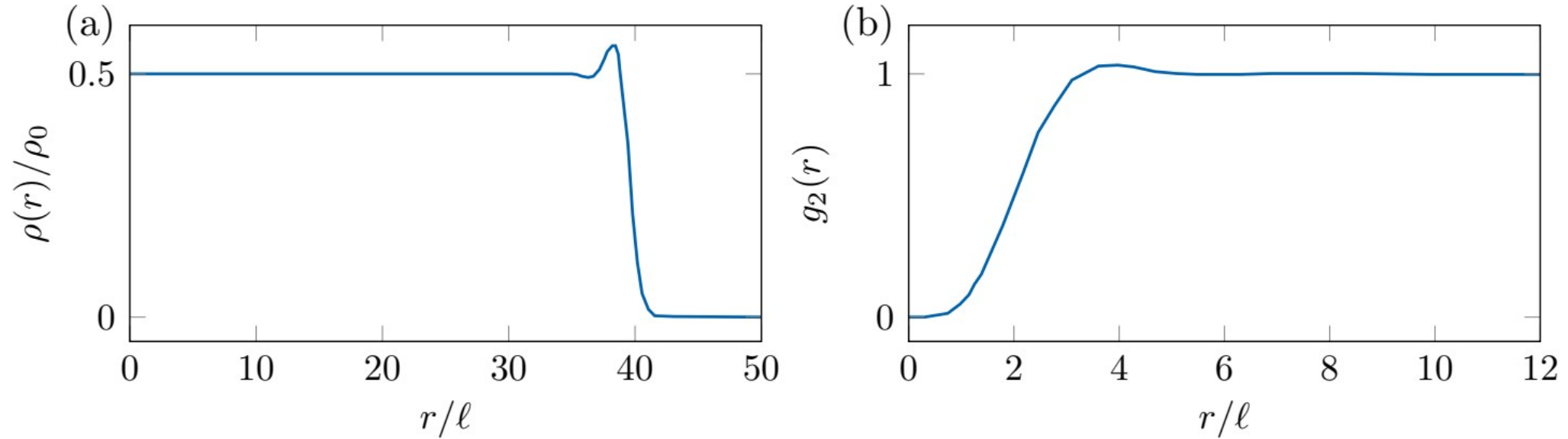
Jaksch and Zoller (2003)

Quantum Hall system using a synthetic dimension



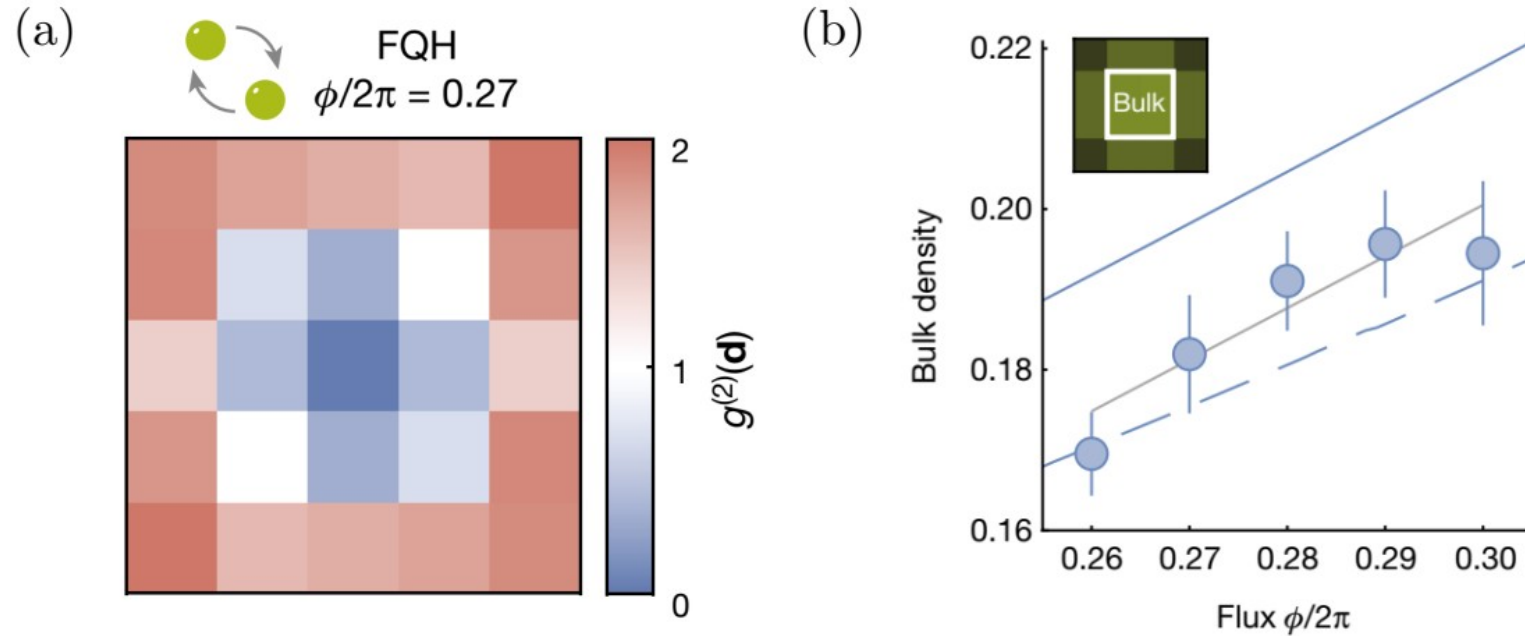
SN group (2020), see also I. Spielman and L. Fallani groups

Density profile and g_2 function of a Laughlin state



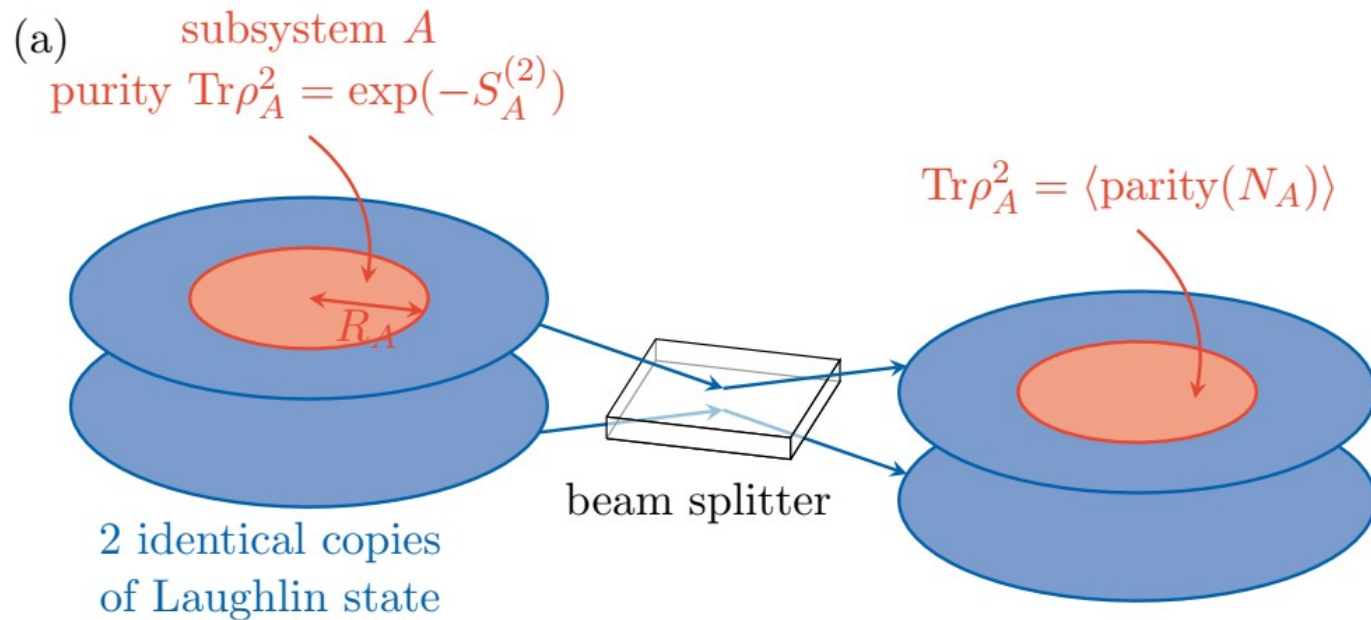
Laughlin state with 400 particles (Monte-Carlo simulation from O. Ciftja, 2006)

Laughlin state with 2 atoms on a lattice

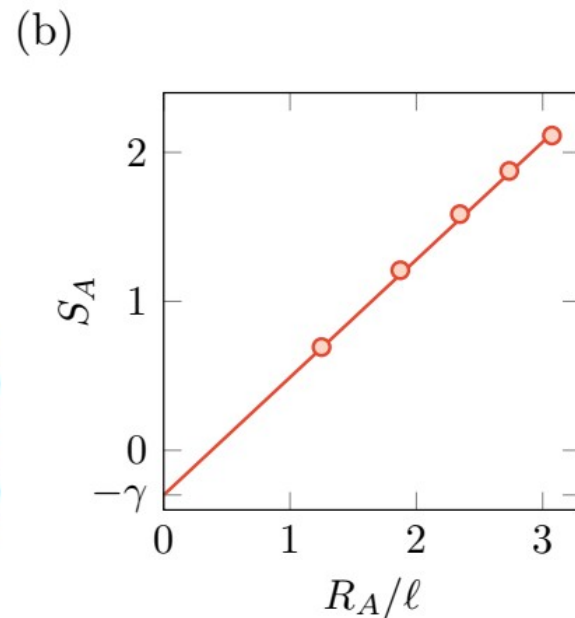


M. Greiner group (2023), see also S. Jochim group

Measuring the entanglement entropy



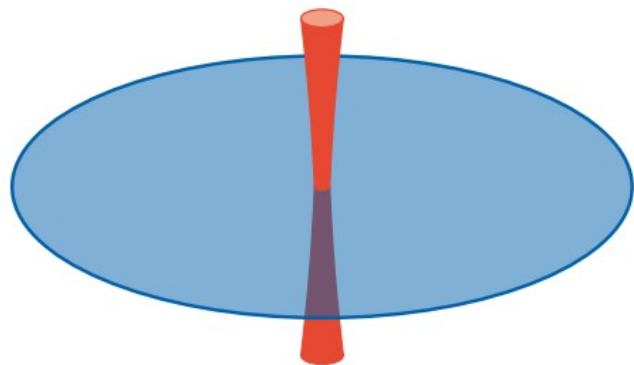
M. Greiner group (2015)



A. G. Morris,
D. L. Feder (2009)

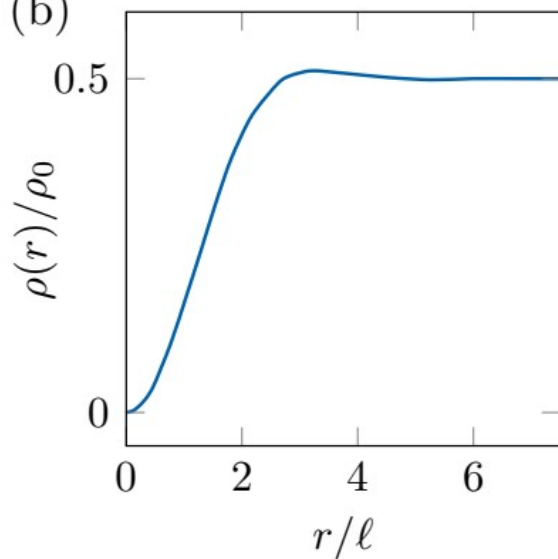
Quasi-hole excitation, fractional charge and statistics

(a)



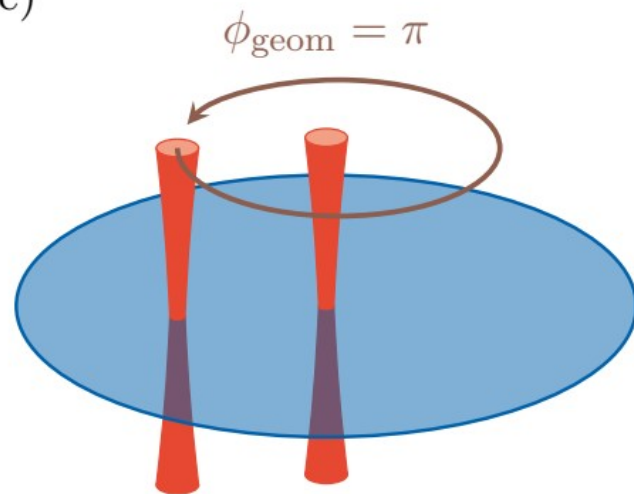
repulsive potential
nucleating a quasi-hole

(b)



quasi-hole density dip
→ charge $1/2$, spin $1/4$

(c)



braiding operation
→ fractional statistics