# Topological matter controlled by light

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Colloquium at the Department of Physics at Clemson University – 1/14/2019

# Topological Systems

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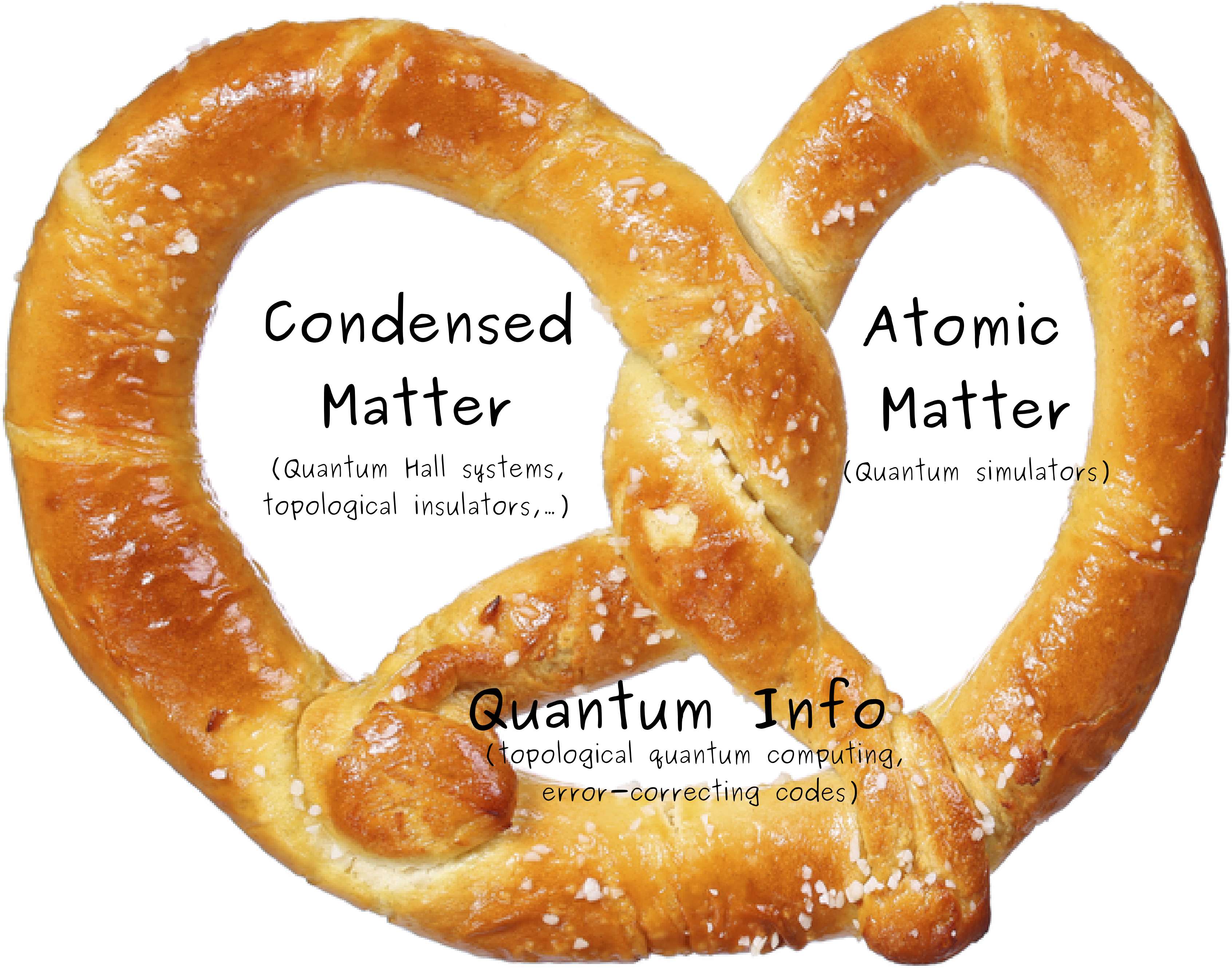


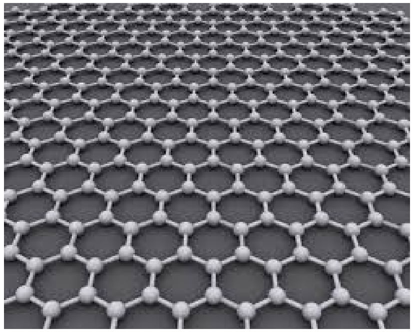
INTRODUCTION: Quantum Hall Effect – challenges and opportunities

## PART I: OPTICAL APPROACHES TO REAL MATTER SYSTEMS

### OPTICAL PROBING (EXPERIMENT):

Photocurrents in Quantum Hall Graphene

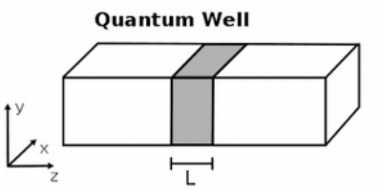
[Gazzano, Cao, Hu, Huber, Grass, Gullans, Newell, Hafezi, Solomon]



### OPTICAL STATE PREPARATION (PROPOSAL):

Anyon creation with light

[Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]

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Non–Abelian phases in optically driven system

[Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]

## PART II: SYNTHETIC SYSTEMS

### OPTICAL ENGINEERING OF INTERACTIONS IN ATOMIC GAS

Anyon crystal

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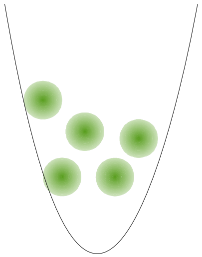

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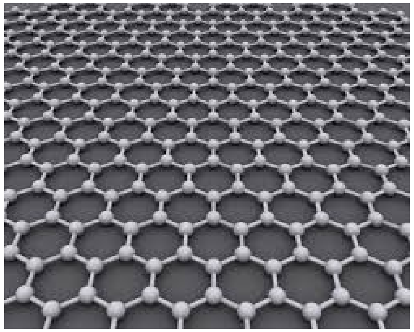

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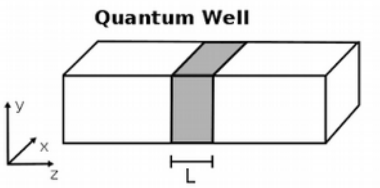


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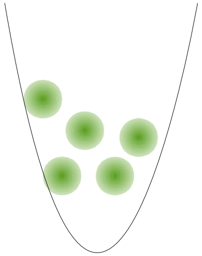
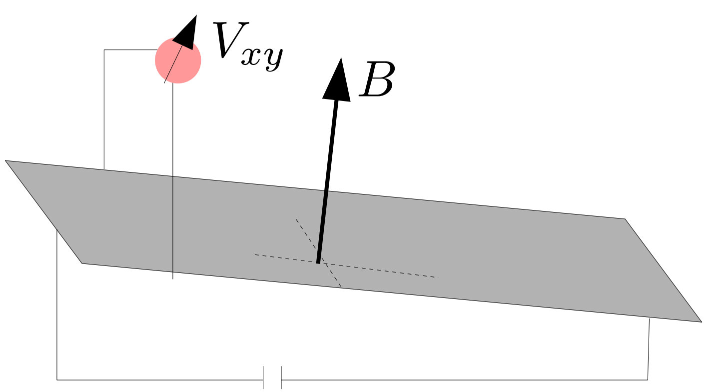


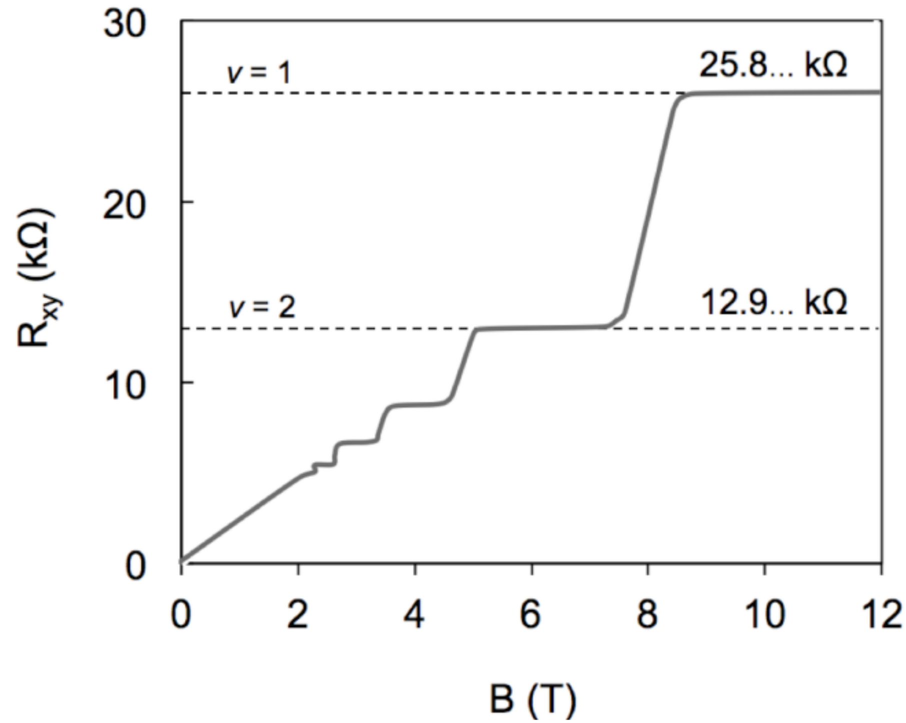
Anyon crystal

[Grass, Bienias, Gullans, Lundgren, Maciejko, Gorshkov, PRL (2018)]


In 2D and in the presence of a strong magnetic field, electronic transport features topological behavior.




Transverse (Hall) resistance forms flat plateaux:




Bands are Landau levels with topologically robust Hall conductances

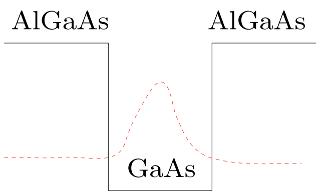
$$\sigma_{xy} = n\frac{e^2}{h}$$

[von Klitzing, Dorda, Pepper, PRL (1980)]
[Thouless, Kohmoto, Nightingale, den Nijs, PRL (1982)]

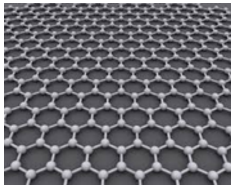
Ingredients:

- 2d system

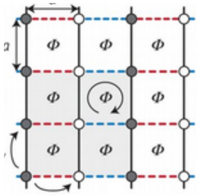
Semiconductors Quantum Wells




2d materials (graphene)



Quantum simulators

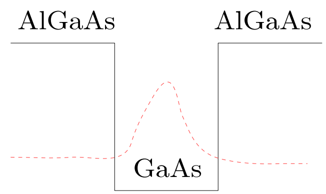


# Integer Quantum Hall Effect

## Ingredients:

- 2d system

**Semiconductors** Quantum Wells

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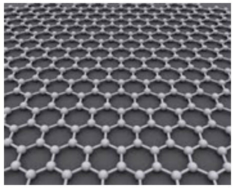
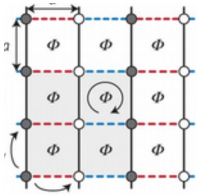
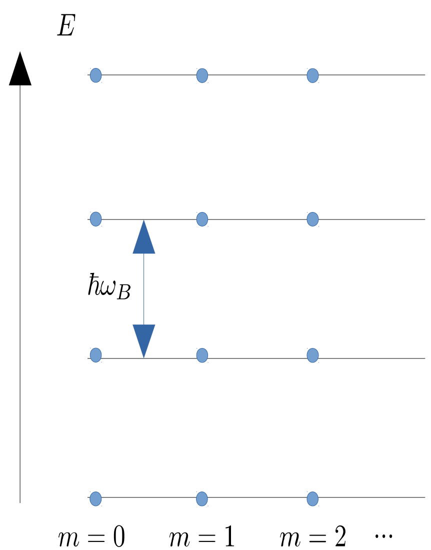


**Quantum simulators**



- Strong magnetic field (or synthetic gauge field)

Landau levels: Flat energy bands




2D Hamiltonian

$$H = \frac{1}{2m}\left[\mathbf{p} + e\mathbf{A}(\mathbf{r})\right]^2$$

Ladder operators:

$$a \sim P_x + iP_y$$
$$a^\dagger \sim P_x - iP_y$$

Dynamical momenta:

$$P_i = p_i - eA_i$$

$$H = \hbar\omega_B\left(a^\dagger a + \frac{1}{2}\right)$$

takes the form of a 1D harmonic oscillator

Where are the other degrees of freedom?
→ highly degenerate single-particle spectrum

Remarkable observation: Robust Hall conductances also for fractionally filled Landau levels [Tsui, Stormer, Gossard, (1982)]

Explanation: Gapped liquid due to interactions

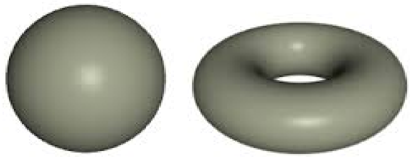
Most famous trial wave function: $$\Psi = \mathcal{N} \prod_{i<j} (z_i - z_j)^q \exp\left( - \sum_i |z_i|^2/4 \right) \quad \text{at} \quad \nu = \frac{1}{q}$$
[Laughlin, (1982)]

$$(z \equiv x + iy)$$

**Theoretical Methods to study FQH physics:**

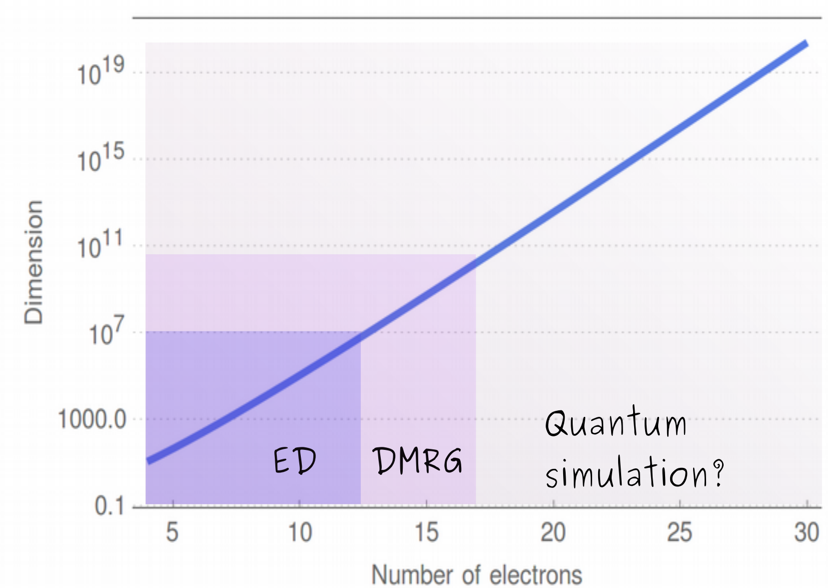
Whether a FQH liquid is formed, and which wave function describes such liquid, must be studied by means of exact or quasi-exact numerical methods (exact diagonalization, DMRG).

- Compact 2d surfaces:

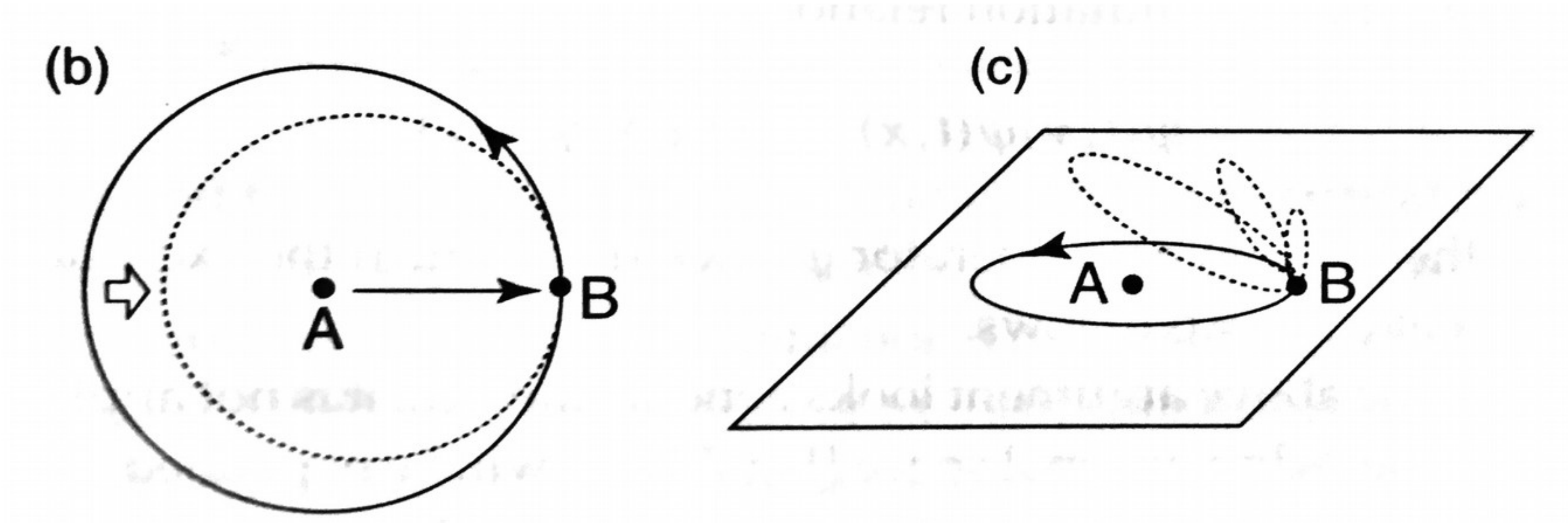


Finite number of states per Landau level
- Neglect Landau level mixing
- Exploiting all symmetries

$$\dim \sim \binom{qN}{N} / (qN^2)$$



Exchanging two identical particles twice:




In 3d:

- must return to same wave function
- exchange may produce nothing but a sign: $\Psi_{AB} = +\Psi_{BA} \quad \rightarrow \quad$ bosons

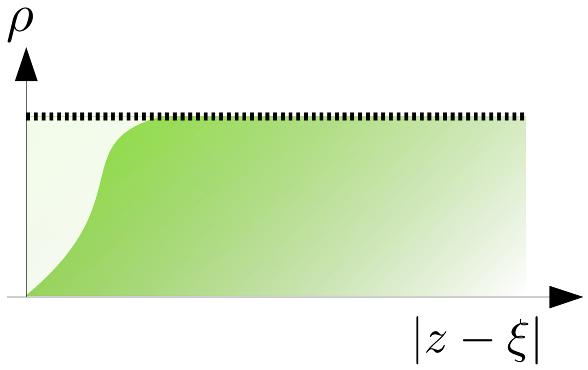
  $\Psi_{AB} = -\Psi_{BA} \quad \rightarrow \quad$ fermions

In 2d:

- any complex phase is possible: $\Psi_{AB} = -e^{i\theta}\Psi_{BA} \quad \rightarrow \quad$ anyons

Theory answer: **YES!**

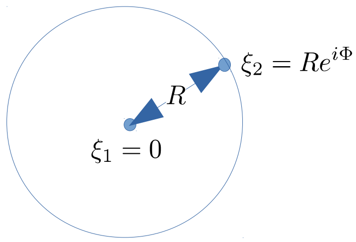
Vortices in Laughlin liquid:

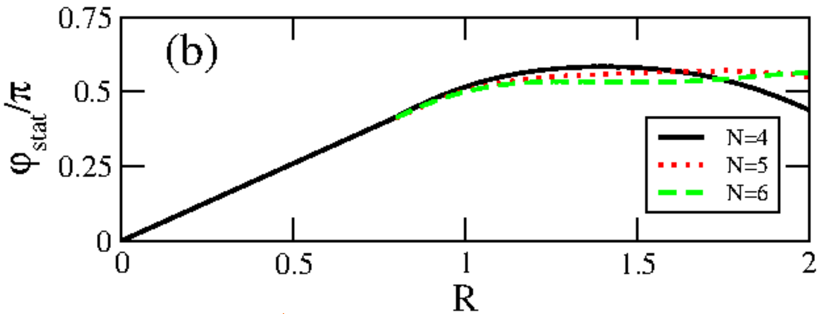



$$\Psi^{\mathrm{qh}}(\xi) \sim \prod_i (\xi - z_i)\Psi$$

$$\Psi^{2\mathrm{qh}}(\xi_1, \xi_2) \sim \prod_i (\xi_1 - z_i) \prod_i (\xi_2 - z_i)\Psi$$

- Fractional Charge
- Fractional Statistics



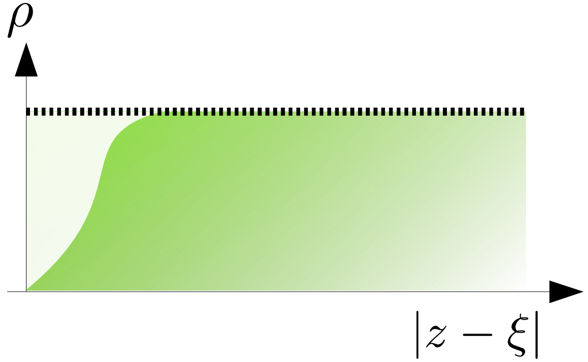




[Julia-Diaz, Grass, Barberan, Lewenstein, NJP (2012)]

# Anyon there?

## Theory answer: YES!

Vortices in Laughlin liquid:




$$\Psi_q^{\mathrm{qh}}(\xi) \sim \prod_i (\xi - z_i)\Psi_q$$

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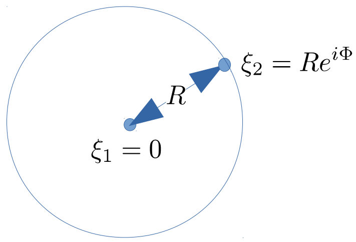
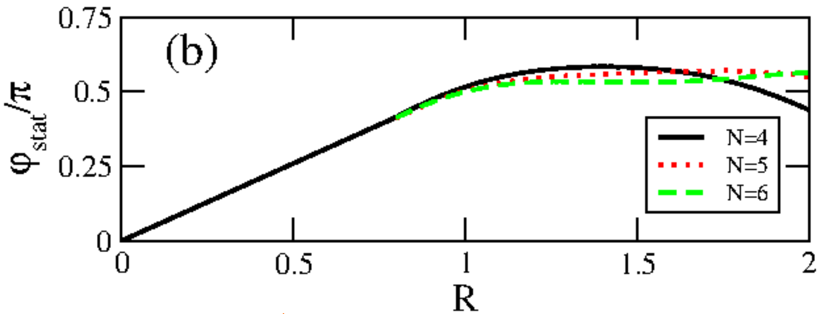


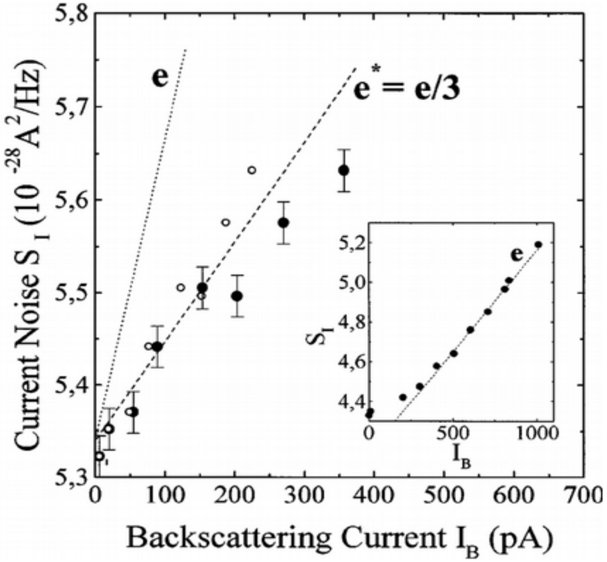

[Julia-Diaz, Grass, Barberan, Lewenstein, NJP (2012)]

## Experiment answer: NOT YET!

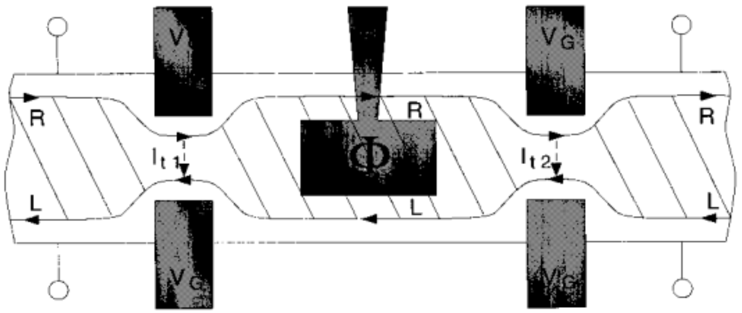
Detection of fractional charge via shot noise

$$S_I = 2q_{\mathrm{eff}} I_B$$

[Saminadayar, Glattli, Jin, Etienne, PRL (1997)]




Interferometric detection of statistical phase?




Proposal:
[Chamon, Freed, Kivelson, Sondhi, Wen, PRB (1997)]
Experimental attempt:
[Camino, Zhou, Goldman, PRB (2005)]

# Non-Abelian Anyons and topological quantum computing

**Non-Abelian anyons:**

degenerate quantum states, characterized by "fusion rules":

Example: Fibonacci anyons

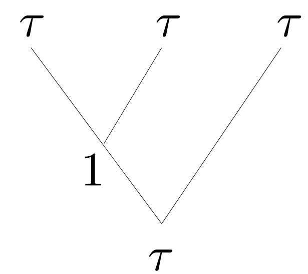
$$1 \otimes \tau = \tau$$
$$1 \otimes 1 = 1$$
$$\tau \otimes \tau = 1 \oplus \tau$$

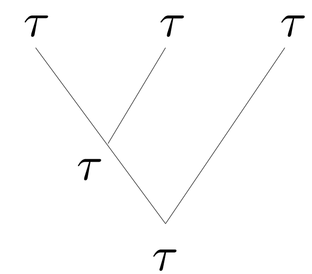
$$\Rightarrow$$

$$\tau \otimes \tau \otimes \tau = 1 \oplus 2 \cdot \tau$$
$$\tau \otimes \tau \otimes \tau \otimes \tau = 2 \cdot 1 \oplus 3 \cdot \tau$$
$$\tau \otimes \tau \otimes \tau \otimes \tau \otimes \tau = 3 \cdot 1 \oplus 5 \cdot \tau$$
$$\vdots$$

Number of states which fuse to $\tau$ follows Fibonacci series: 1,2,3,5,8…

- possibility of storing quantum information:

$|0\rangle \equiv$ 


$|1\rangle \equiv$ 


- braiding of anyons changes quantum state → processes quantum information

(+) Robust against local noise

(-) Technically involved

- Occurrence of non-Abelian anyons:
  - certain FQH states (e.g. at filling 5/2)
    [Moore & Read, Nucl. Phys. B (1991), R. H. Morf PRL (1998)]
  - Majorana wires (e.g. super-semi interfaces)
    [Fu & Kane, PRL (2008), Sau, Lutchyn, Tewari & Das Sarma, PRL (2009)]

"Short-term" motivation: Fundamental interest

Experimental demonstration of anyonic behavior

"Long-term" motivation: Technological application

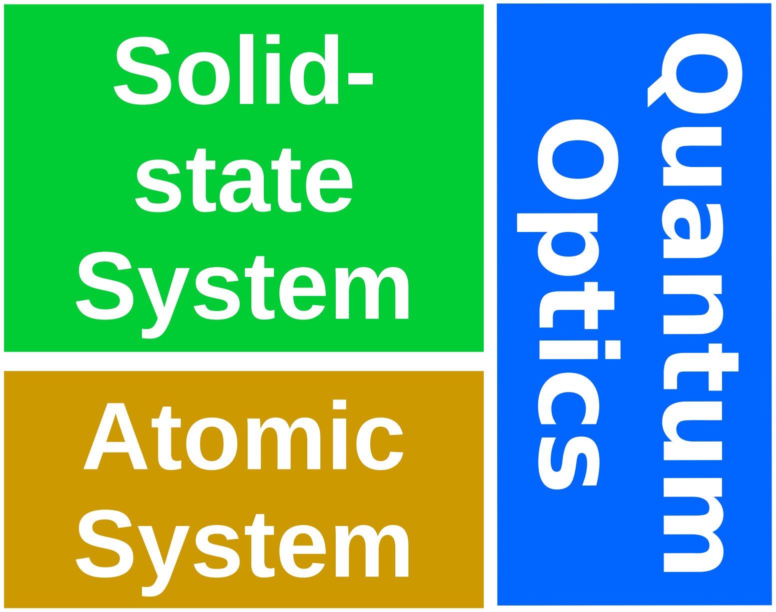
Use anyons for quantum-information purposes

Strategies:

Use quantum optics to generate

(1) semi-synthetic solid matter
(intrinsic+synthetic features)

(2) synthetic atomic matter
(intrinsically featureless)



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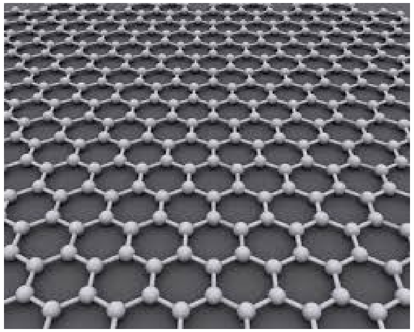

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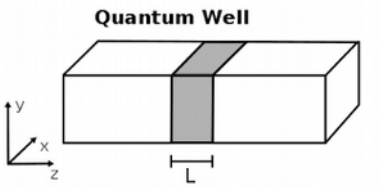


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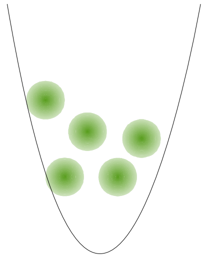
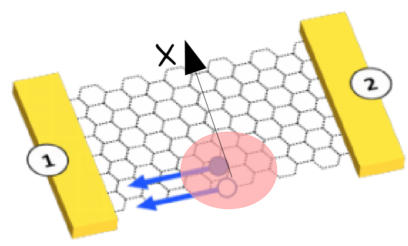
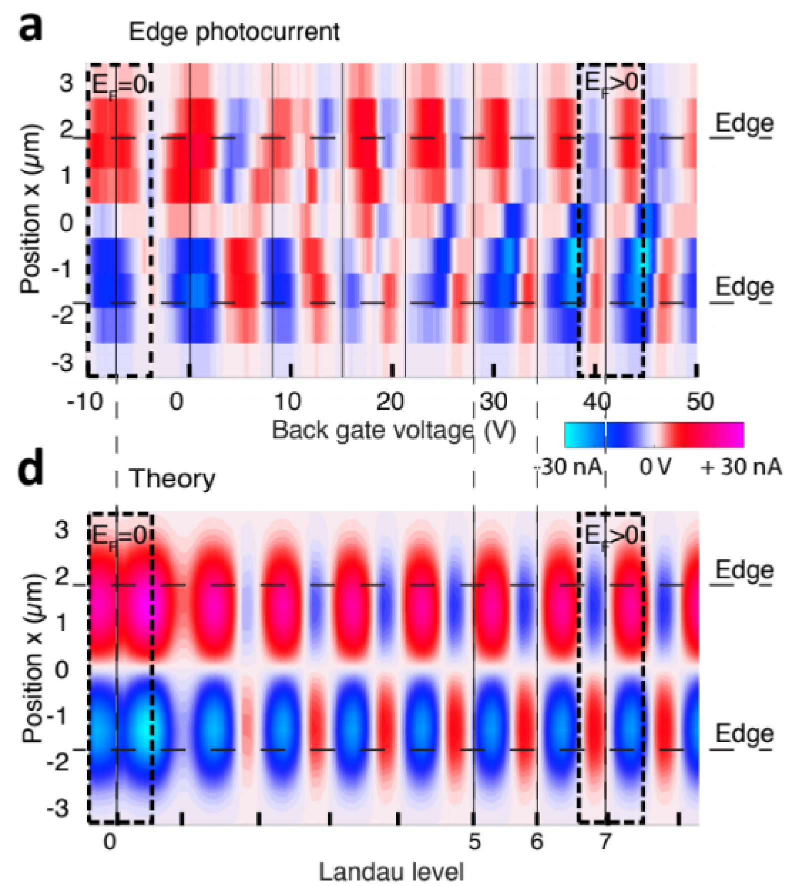


## Experimental setup:

- Graphene sample in magnetic field:
  → exhibits integer QH effect
- Laser field exciting carriers in the sample




- Detection of photocurrents through the sample




## Opportunities:

- Local probing: focus laser beam on a finite spot → Chirality of edge channels
  [see also: Nazin, Zhang, Zhang, Sutter, Sutter, Nat. Phys. (2010)]
- Photocurrents as a function of backgate voltage → Sensitive probe of Landau quantization

[ Gazzano, Cao, Hu, Huber, Grass, Gullans, Newell, Hafezi, Solomon (unpublished)]

# OPTICAL STATE PREPARATION: Creation of quasiholes with light

Given a quantum Hall state – can we optically create a (quasi)hole on top of it?

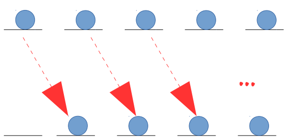
Initial state

$$\Psi$$

Final state

$$\Psi_{\mathrm{qh}} \sim \left( \prod_i z_i \right) \Psi$$

Coherent transfer by optically coupling different orbitals?

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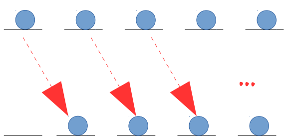
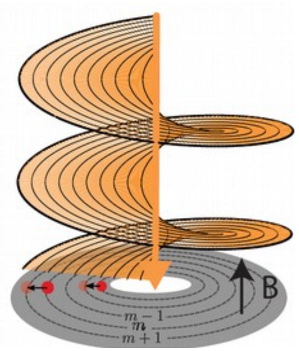


Selection rules:

- Dipole transitions: Orbital quantum number is conserved $m \leftrightarrow m$
- Light with orbital angular momentum ("twisted light"): $m \leftrightarrow m + \ell$

[Gullans, Taylor, Imamoglu, Ghaemi, Hafezi, PRB (2017)]




Available empty levels:

- Coupling into empty Landau level: $n, m \leftrightarrow n+1, m+1$ → short lifetimes!
- Coupling into (metastable) spin manifold: $n, m, s \leftrightarrow n, m+1, s+1$ → HOW?

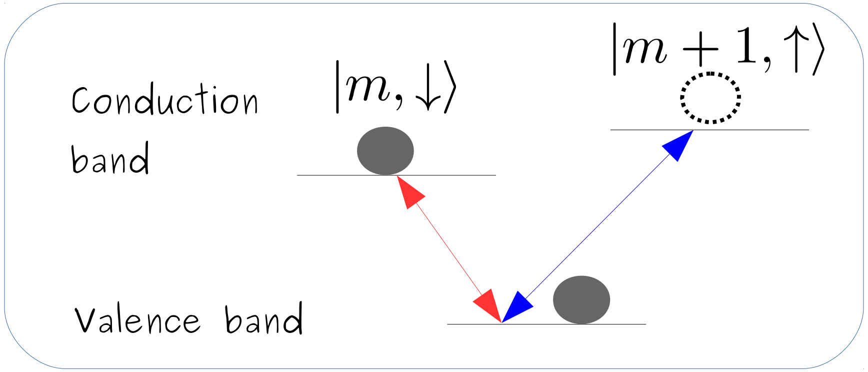
[Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]

Optical coupling between two spin manifold:

→ direct coupling microwave coupling (slow)

→ indirect optical coupling via a third level:

in GaAs: spin-orbit coupled valence band

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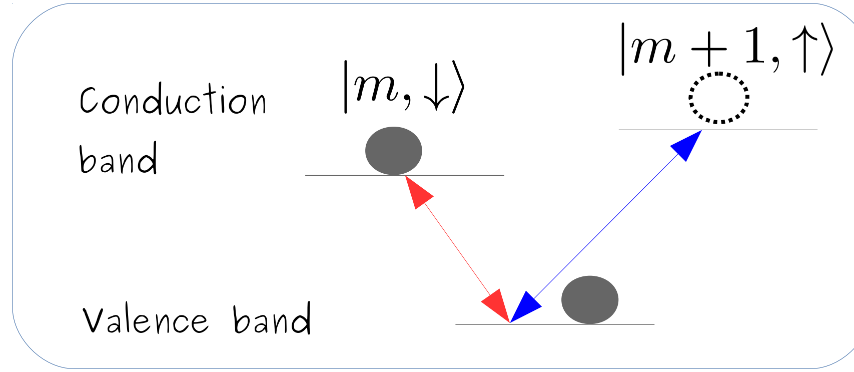
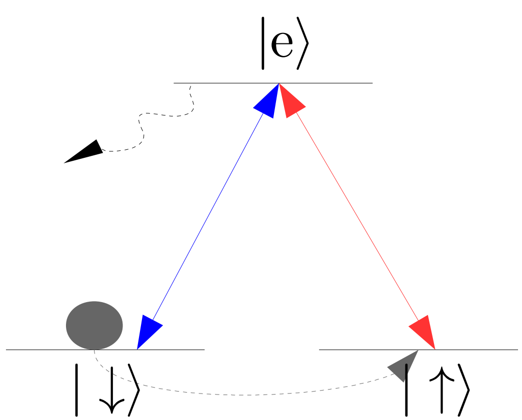
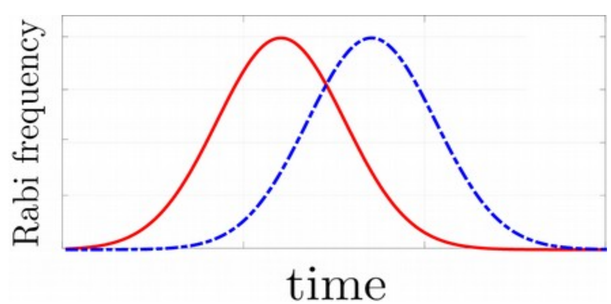



## STIRAP

Appropriate timing of the pulses avoids excitations from the third level:




"Red" field: create dark state of $|e\rangle$ and $|\uparrow\rangle$

"Blue" field: couple $|\downarrow\rangle$ to this dark state

[Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]

# OPTICAL STATE PREPARATION: STImulated Raman Adiabatic Passage

Optical coupling between two spin manifold:

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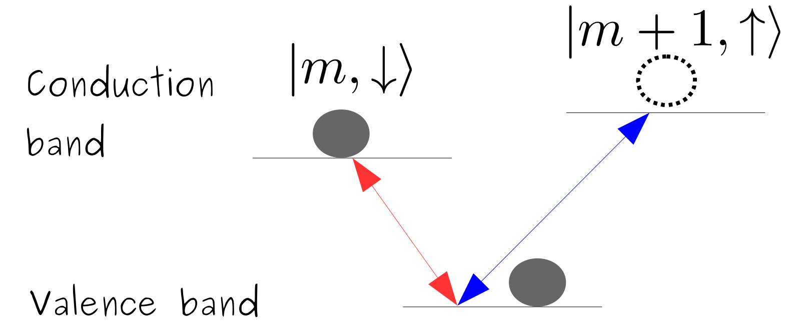


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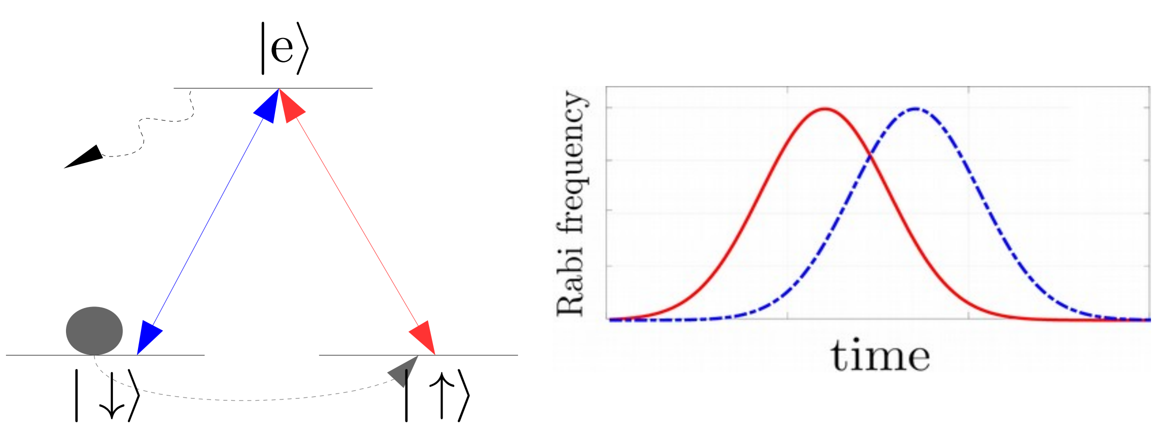



"Red" field: create dark state of |e> and |↑>

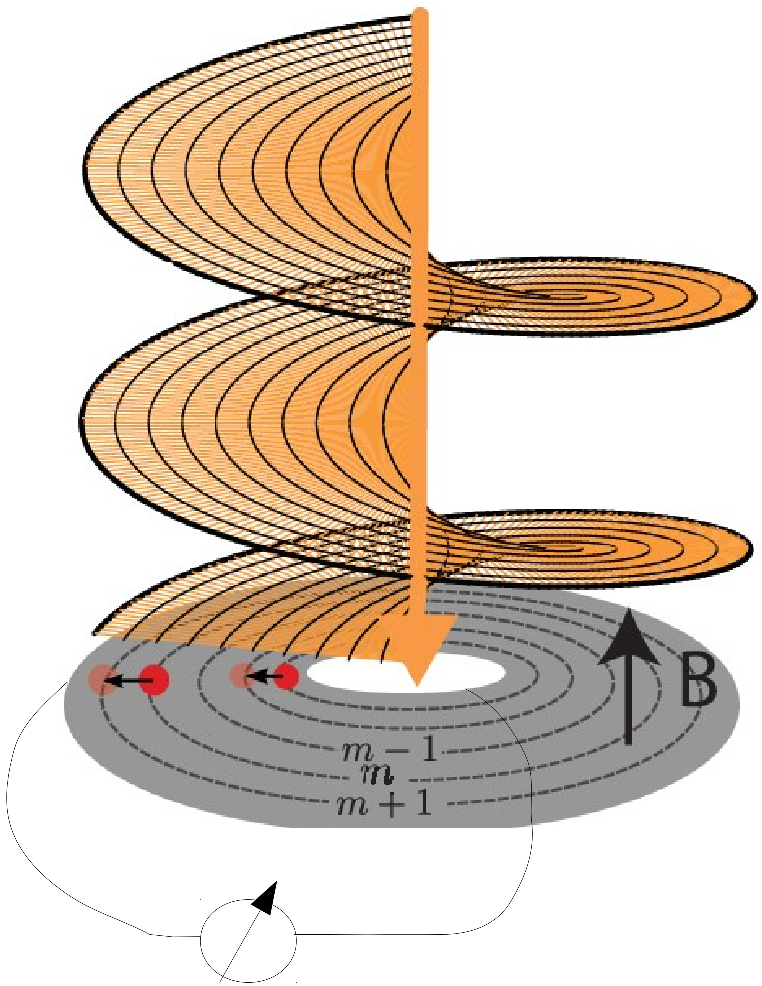
"Blue" field: couple |↓> to this dark state

## Our scheme

- Particle-hole transformation: Consider STIRAP pulse acting on the empty state ('hole') in the conduction band
- Coulomb interactions: Numeric simulation shows that transfer fidelity remains large if detuning and Rabi frequency are strong

[Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]

Detection of fractional charge via flux pumping in Corbino geometry




STIRAP pulse create fractional quasiparticles/quasiholes and inner and outer edge (fraction 1/q).

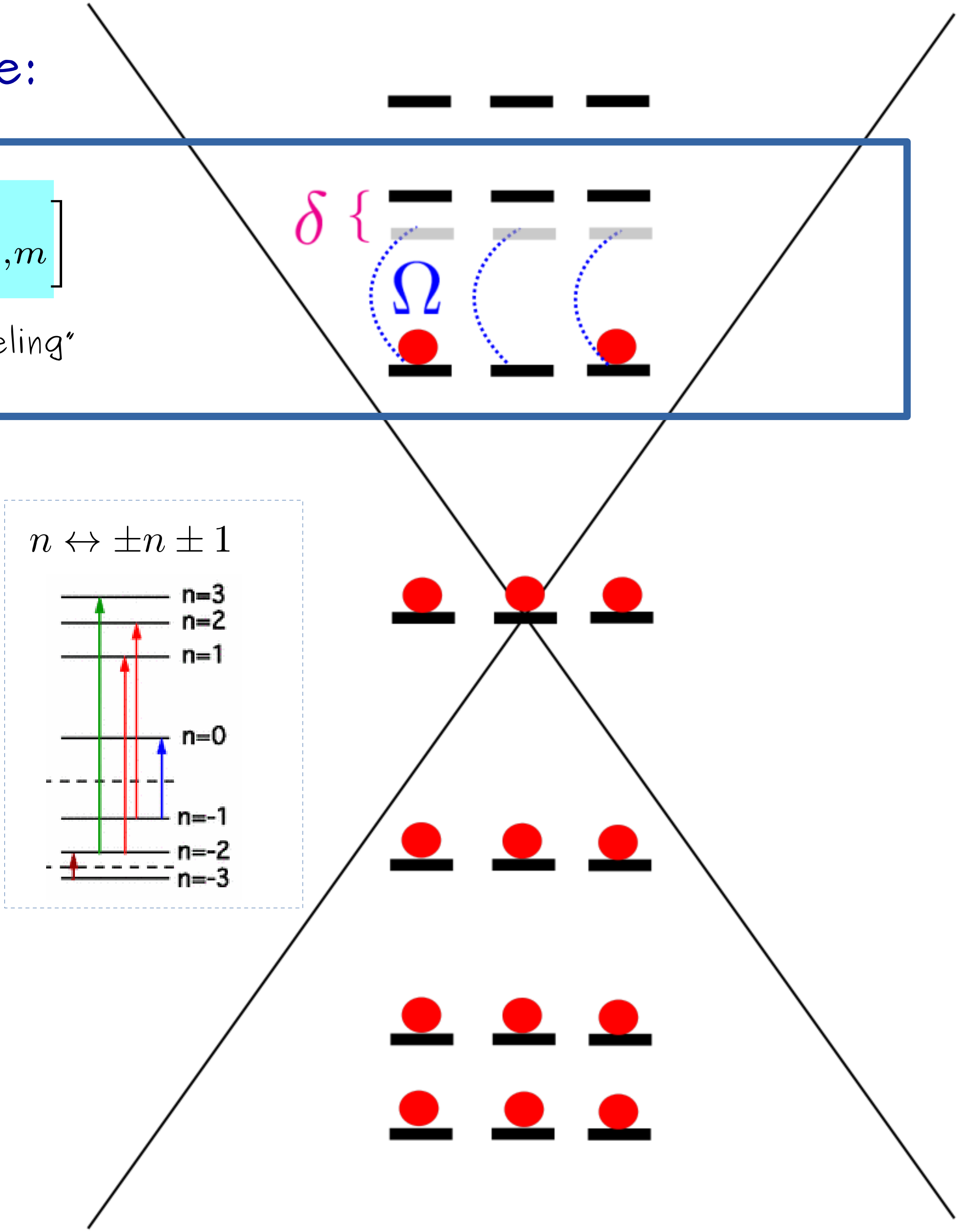
After q STIRAP pulses, an electronic charge can flow through wire connecting the edges.

[Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]

## Landau level coupling in graphene:

$$H_0 = \sum_m \left[ \hbar\delta c^\dagger_{n+1,m} c_{n+1,m} + \hbar\Omega c^\dagger_{n+1,m} c_{n,m} \right]$$

"chemical potential" "interlayer tunneling"




TAKE: monolayer graphene in FQH phase

ADD: optical coupling to empty Landau Level with circularly polarized IR field [Jiang, …, Kim, Stormer, PRL (2007)]

GET: synthetic bilayer



[Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]

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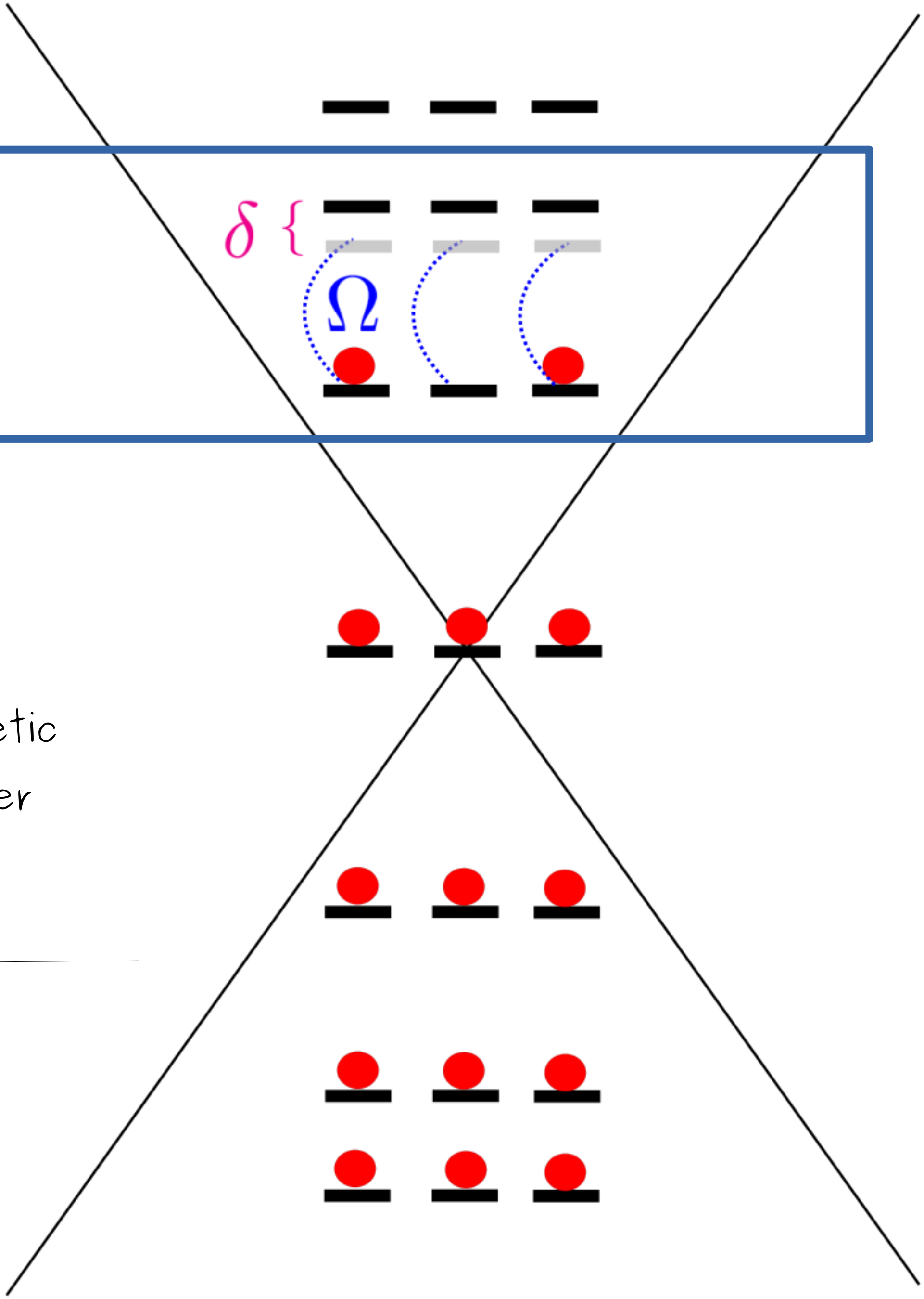


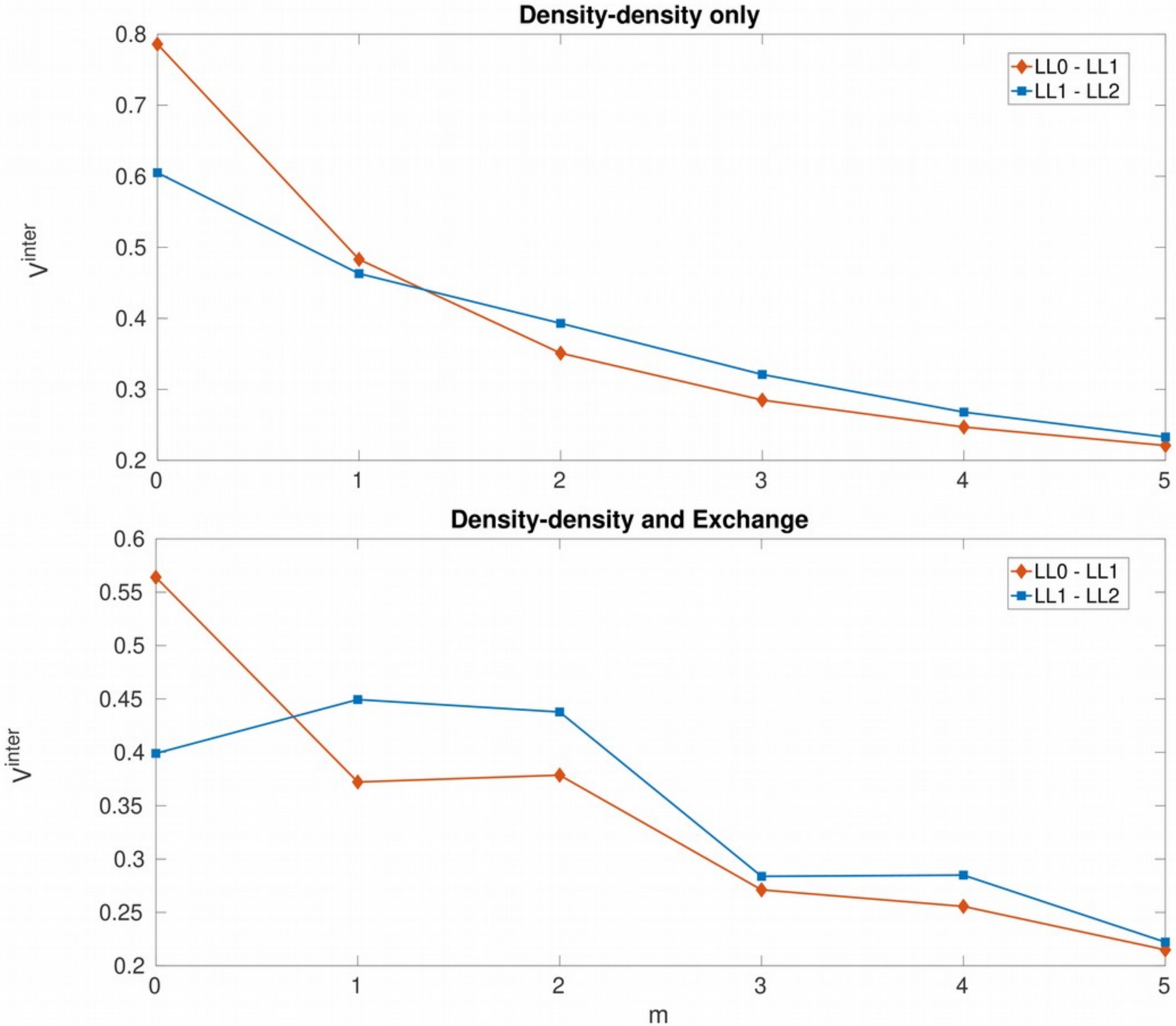

DIFFERENCE TO REAL BILAYER:

- Tunability
- Interlayer interactions:

| | Real bilayer | Synthetic bilayer |
|---|---|---|
| Density-density $\Psi_i^\dagger(z_1)\Psi_j^\dagger(z_2)\Psi_j(z_2)\Psi_i(z_1)$ | YES | YES |
| Exchange $\Psi_i^\dagger(z_1)\Psi_j^\dagger(z_2)\Psi_i(z_2)\Psi_j(z_1)$ | NO | YES |

[Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]

Haldane pseudopotentials: Expand interaction in terms of their strength for fixed relative angular momentum m




Monotonic decay with m

For LL1 – LL2: Non-monotonic behavior favoring singlets at m=0

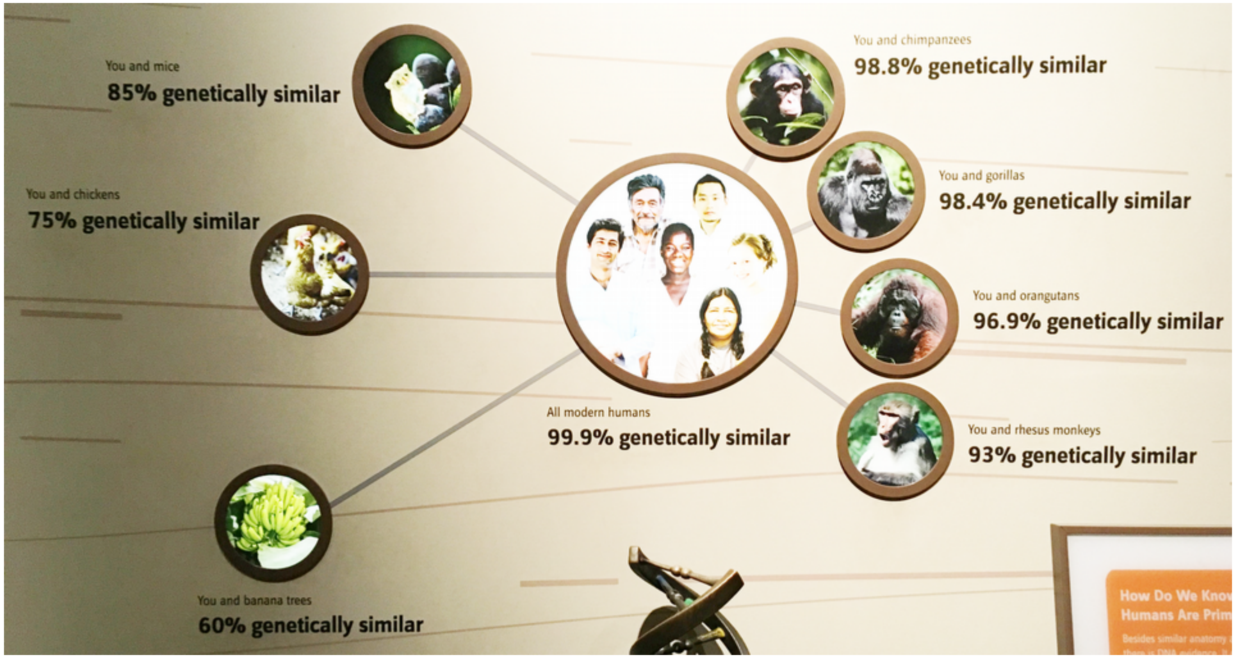
[Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]

- Ground state overlaps:

$\nu = 2/3$

"No" overlap with:
- Halperin states (113, 330)
- Composite Fermions
- Intra-layer Pfaffian

"Larger" overlap with:
- Inter-layer Pfaffian
- Fibonacci phase



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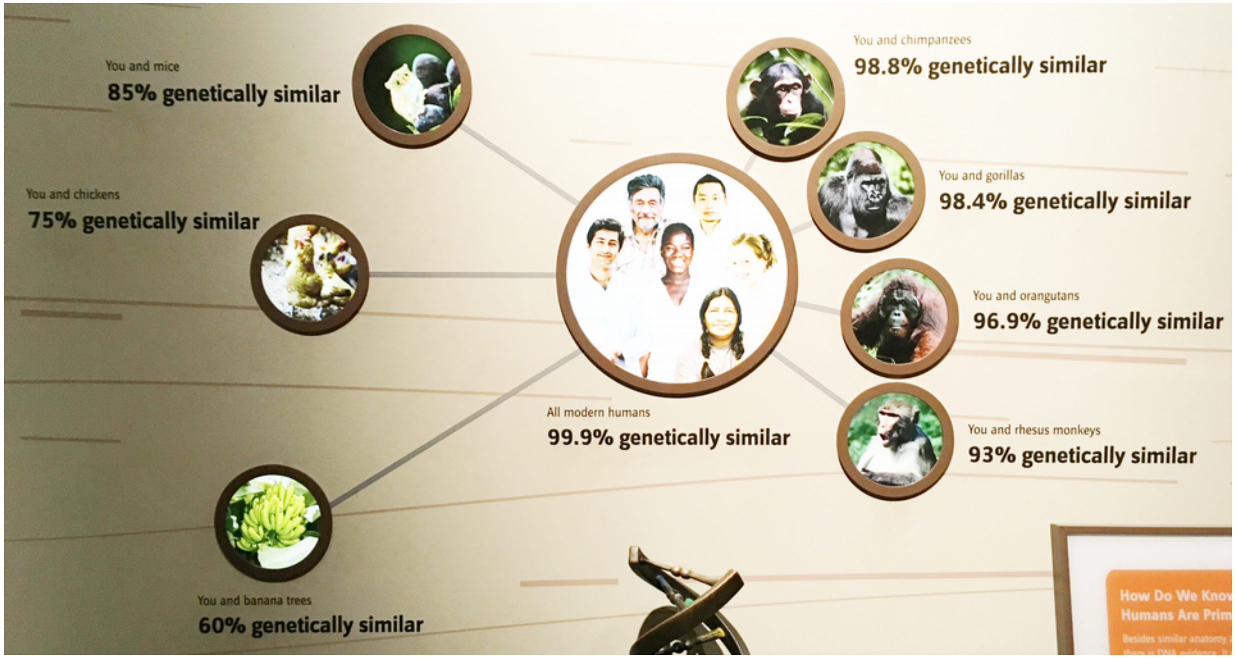
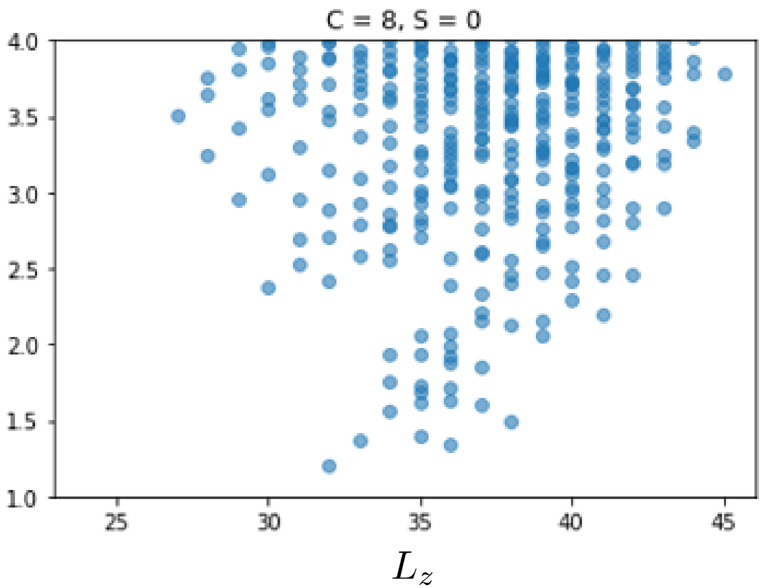



- Topological "quantum numbers":
  - Ground state degeneracies on the torus (ν=2/3: becomes 6-fold when squeezed)
  - Edge state counting ν=2/3: 1,1,3,6,… which is characteristic for Fibonacci phase




Entanglement spectrum for 16 electrons on sphere (DMRG result by Ze-Pei Cian)

Optical driving might be a for engineering of Fibonacci anyons.

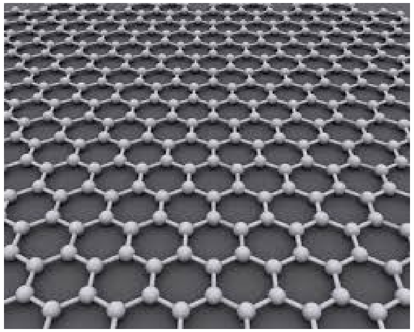
INTRODUCTION: Quantum Hall Effect – challenges and opportunities

## PART I: OPTICAL APPROACHES TO REAL MATTER SYSTEMS

### OPTICAL PROBING (EXPERIMENT):

Photocurrents in Quantum Hall Graphene

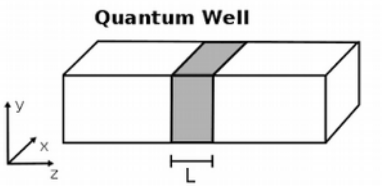
[Gazzano, Cao, Hu, Huber, Grass, Gullans, Newell, Hafezi, Solomon]



### OPTICAL STATE PREPARATION (PROPOSAL):

Anyon creation with light

[Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]




### OPTICAL PHASE ENGINEERING (PROPOSAL)

Non-Abelian phases in optically driven system

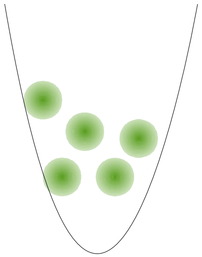
[Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]

## PART II: SYNTHETIC SYSTEMS

### OPTICAL ENGINEERING OF INTERACTIONS IN ATOMIC GAS

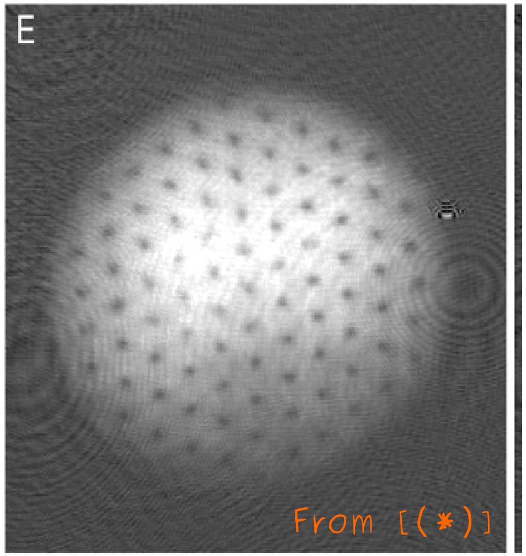
Anyon crystal

[Grass, Bienias, Gullans, Lundgren, Maciejko, Gorshkov, PRL (2018)]



Neutral atoms are insensitive to real magnetic fields, but various techniques exist to synthesize the effect of a magnetic field:

- rotation (Coriolis force equivalent to Lorentz force)
- imprinted Berry phase by laser-dressing of atoms
- laser-assisted tunneling in optical lattices
- Floquet engineering of complex hopping term



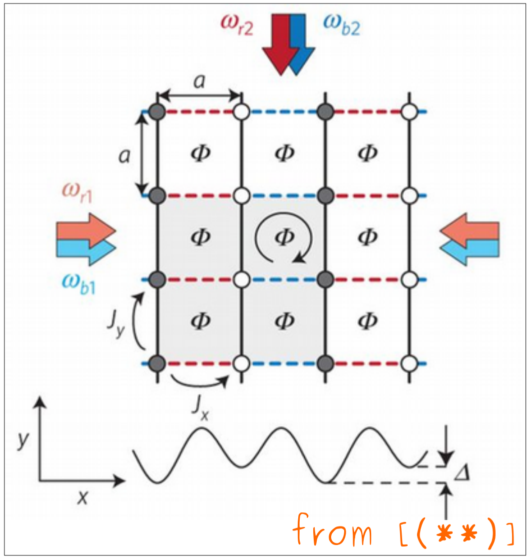

Experimentally achieved phases:

- vortices and vortex lattices

[Matthews, Anderson, Haljan, Hall, Wieman, and Cornell, PRL (1999)]
[(*) Abo-Shaeer, Raman, Vogels, Ketterle, Science (2001)]

- integer quantum Hall phases (Hofstadter model)

[(**) Aidelsburger, ..., Bloch & Goldman, Nat. Phys. (2015)]
[Stuhl, ..., Spielman, Science (2015)]
[Mancini, ..., Fallani, Science (2015)]




Still outstanding: Synthesis of fractional quantum Hall phase

# Engineering interactions by Rydberg dressing

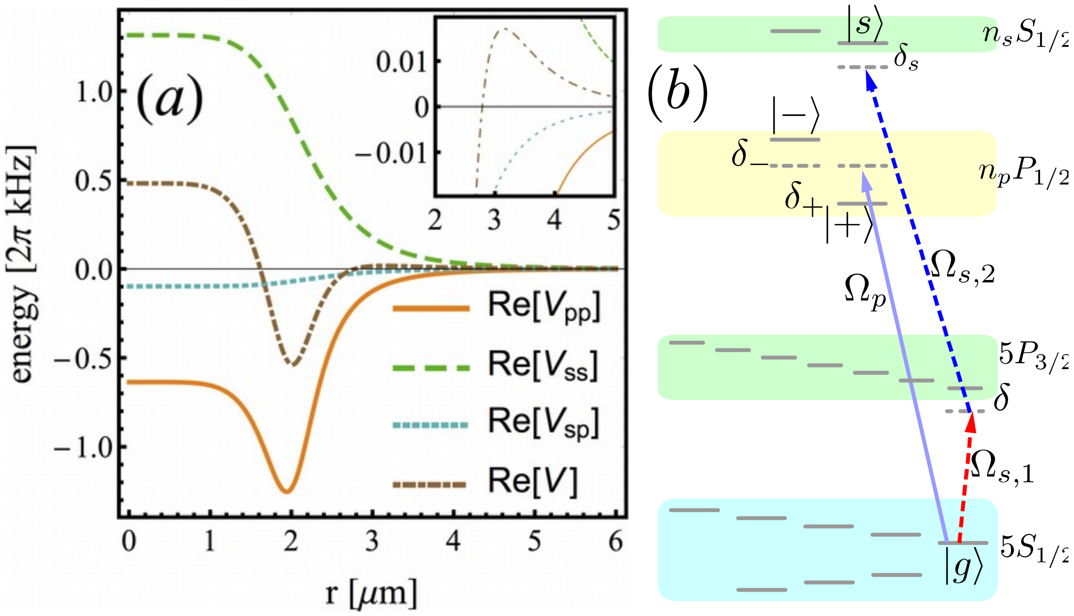
WANTED: Long-ranged atom-atom interactions, e.g. van der Wals interactions between Rydberg states

BUT: fast decay of Rydberg states $\Gamma$

SOLUTION: Rydberg dressing (small Rydberg admixture $P_{\rm Ryd} = \left(\frac{\Omega}{2\Delta}\right)^2 \Rightarrow \Gamma_{\rm dressed} = P_{\rm Ryd}\Gamma$ )

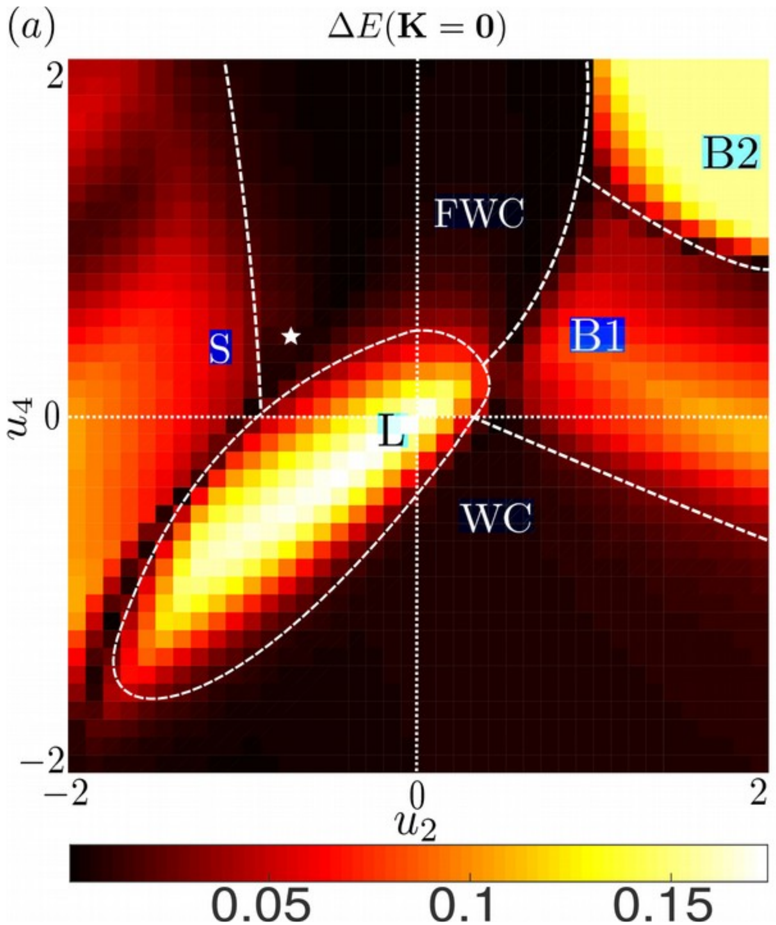
[Jau, Hankin, Keating, Deutsch, Biedermann, Nat. Phys. (2016); Zeiher,..., Bloch, Gross, Nat. Phys. (2016)]

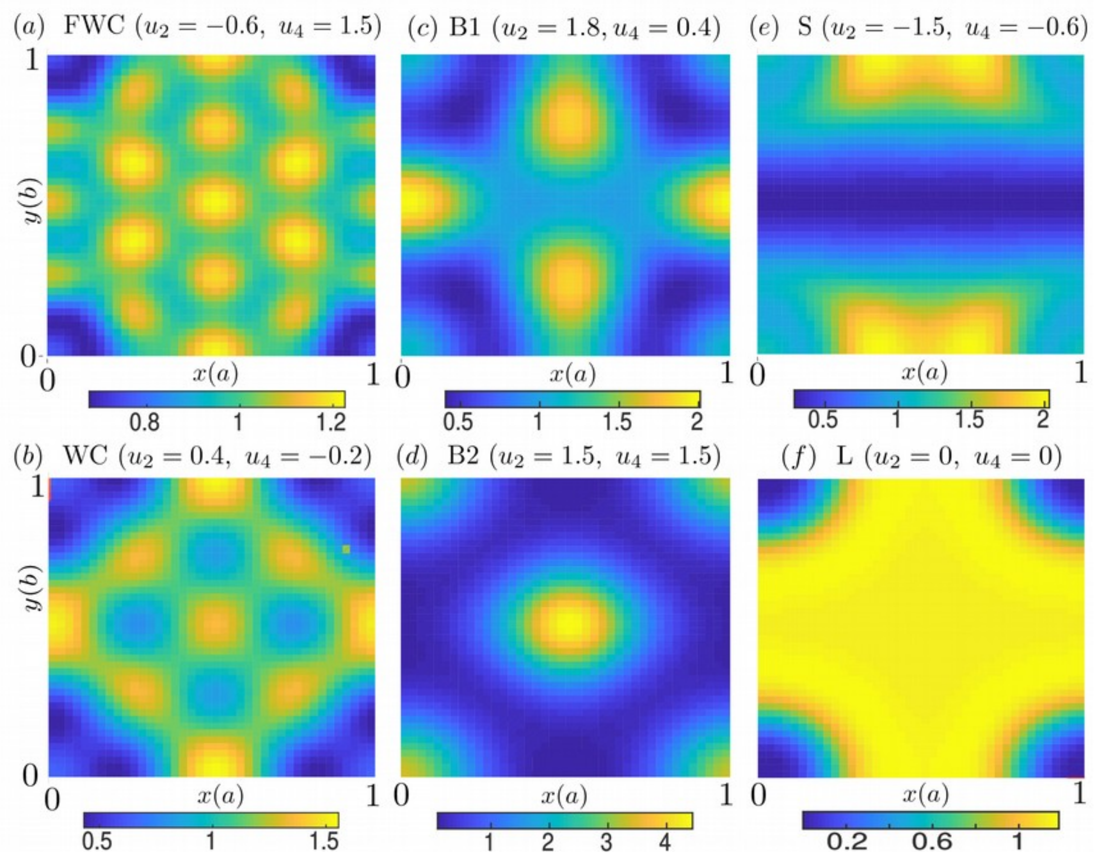
Tune several Haldane pseudopotential through combination of s- and p- state dressing:




[Grass, Bienias, Gullans, Lundgren, Maciejko, Gorshkov, PRL (2018)]

## What happens if we tune interactions?



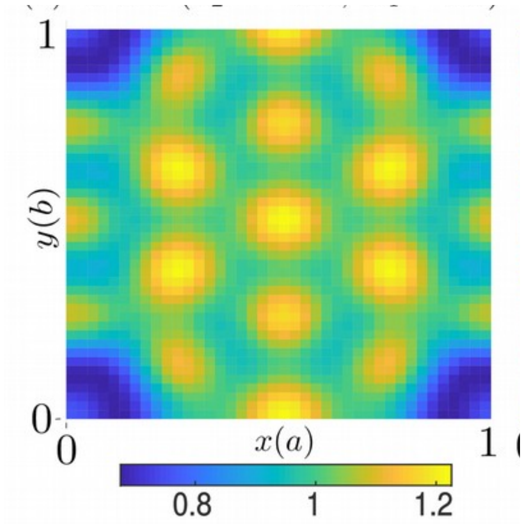

Bosonic phases at Landau level filling ν=1/2 as a function of Haldane pseudopotentials

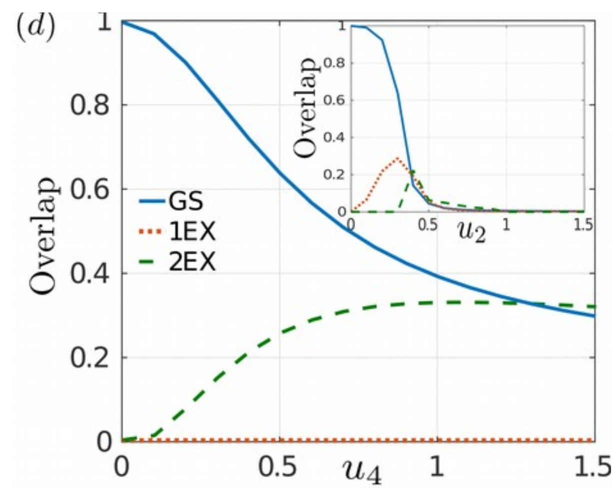
Two-body correlation functions (periodic boundary): symmetry-broken phases vs. Laughlin liquid

[Grass, Bienias, Gullans, Lundgren, Maciejko, Gorshkov, PRL (2018)]

# Fractional Wigner Crystal

Symmetry-broken (crystal) phase with 2N peaks emerges from "deforming" the Laughlin liquid and has finite overlap with the Laughlin state:

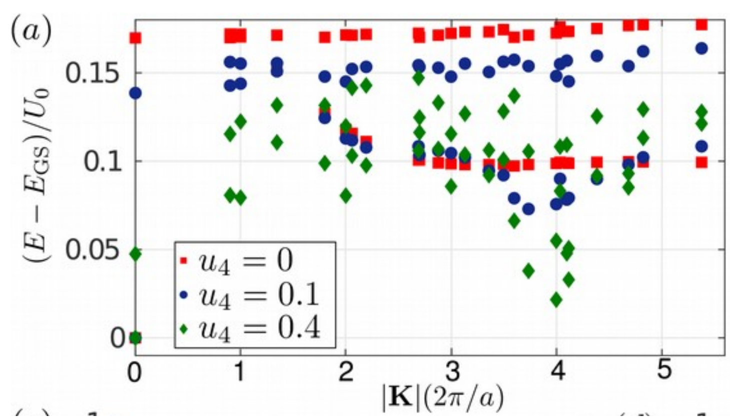



Coexistence of topological order and symmetry-broken order?

Cf. recent experiments: Nematic FQH phase
[Xia, Eisenstein, Pfeiffer, West, Nat. Phys. (2011)]
[Samkharadze, Schreiber, Gardner, Manfra, Fradkin, Csáthy, Nat. Phys (2016)]

Symmetry-breaking through softening of the magnetoroton mode?
[Maciejko, Hsu, Kivelson, Park, Sondhi, PRB (2013)]
[You, Cho, Fradkin, PRX, (2014)]




[Grass, Bienias, Gullans, Lundgren, Maciejko, Gorshkov, PRL (2018)]

## Topological systems:

- Exotic excitations (Abelian and non-Abelian anyons), but detection is challenging!
- Great opportunities for quantum technology applications!

## → Develop optical control strategies:

- OPTICAL PROBING: Detection of edge states via photocurrents
  [Gazzano, Cao, Hu, Huber, Grass, Gullans, Newell, Hafezi, Solomon (2018)]
- OPTICAL STATE PREPARATION: Anyon creation using light with orbital angular momentum
  [Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]
- OPTICAL PHASE ENGINEERING : Synthetic bilayer with non-Abelian FQH phases
  [Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]
- SYNTHETIC MATTER: Designer interactions for FQH systems via Rydberg dressing: anyon crystal?
  [Grass, Bienias, Gullans, Lundgren, Maciejko, Gorshkov, PRL (2018)]

# Thank you!

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