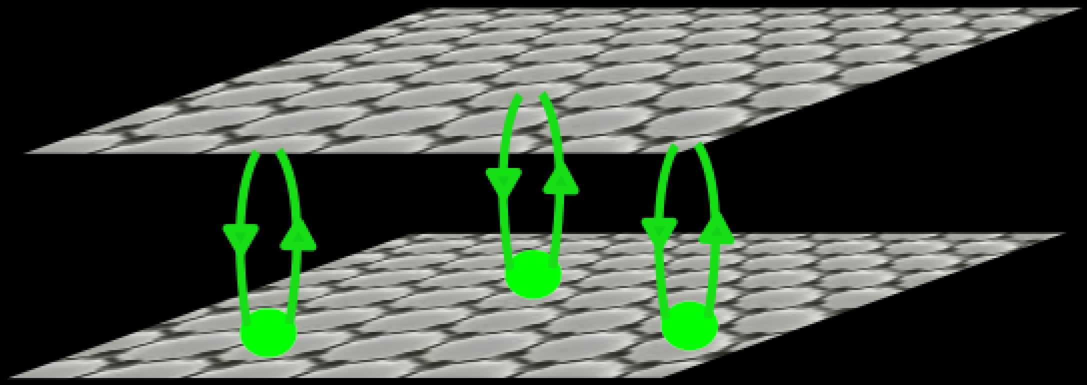
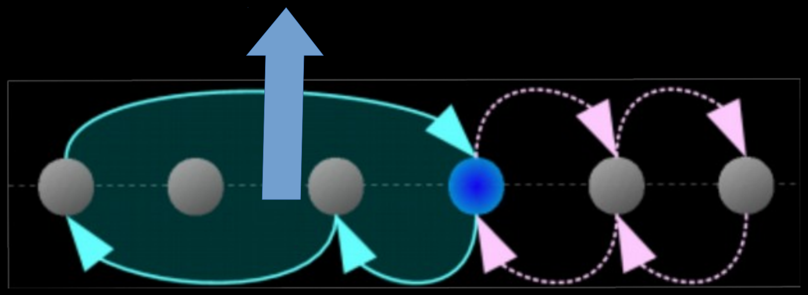
University of Oklahoma
Department of Physics and Astronomy
02/14/2019
Colloquium

Topological Quantum Simulators



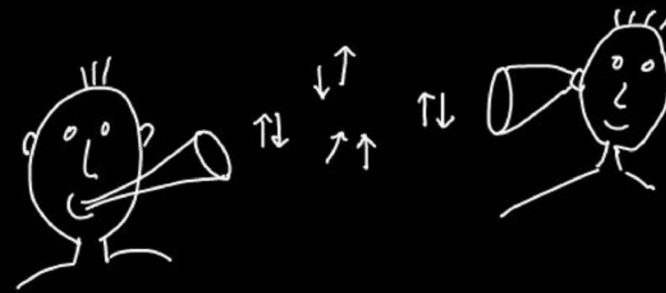


Tobias Grass

Joint Quantum Institute and University of Maryland

College Park, Maryland, USA

Quantum Sensing
(precision measurements, atomic clocks, quantum imaging, ...)

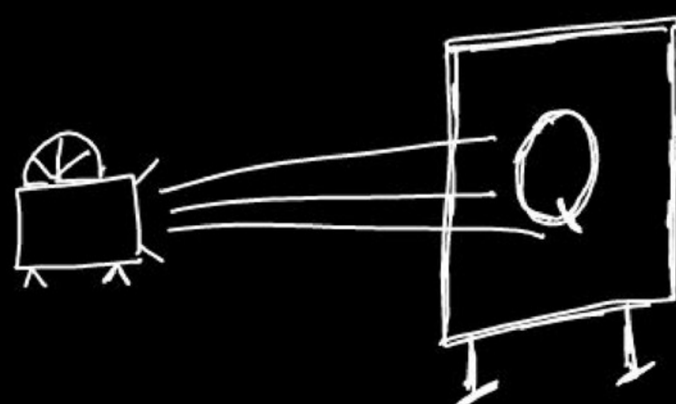


Quantum Communication
(Quantum cryptography, quantum networks,...)

Quantum Technologies

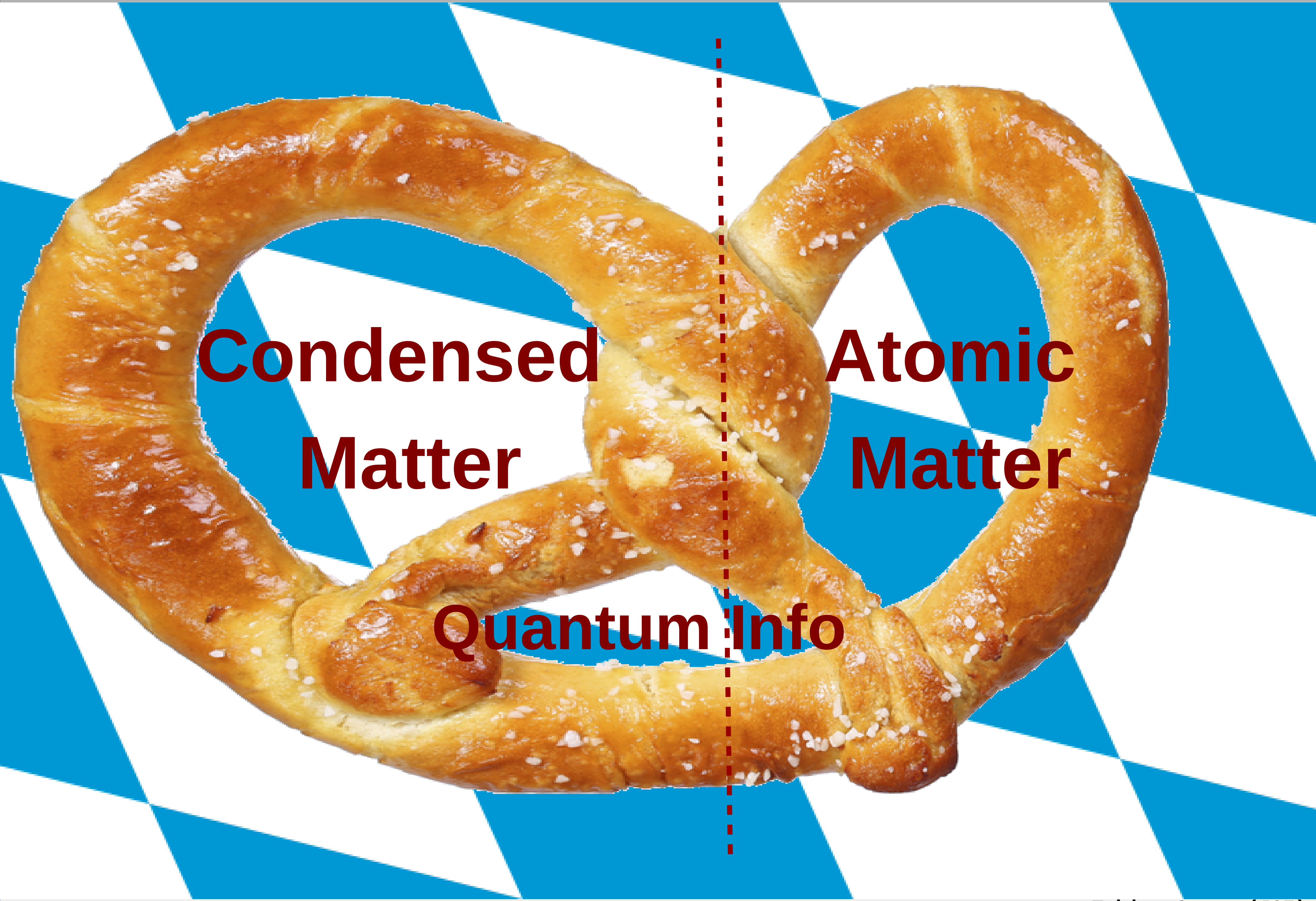
Quantum Computation
(Quantum processor, quantum algorithms, error-correction,...)

Quantum Simulation
(quantum many-body physics, model solver, quantum annealing...)

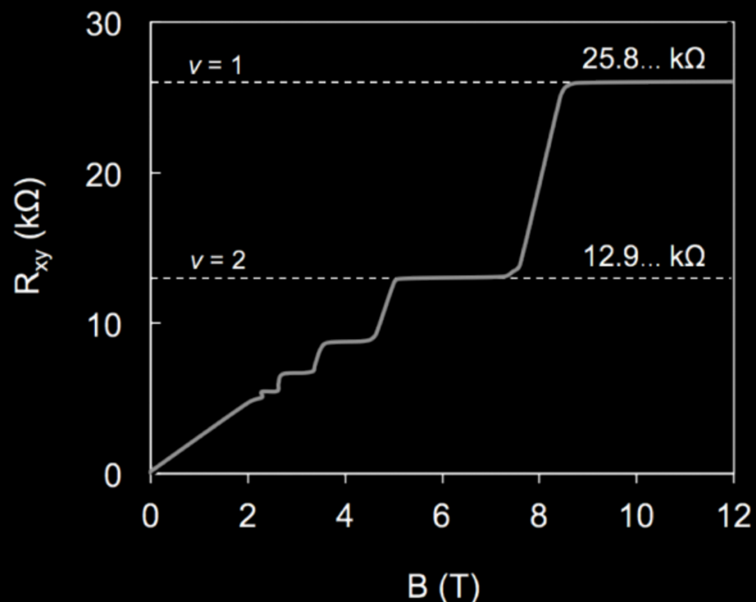


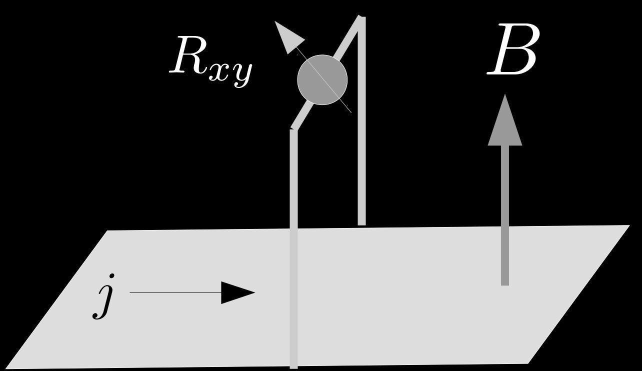
Topology and Symmetry

Topology and Symmetry


Condensed Matter
Atomic Matter
Quantum Info

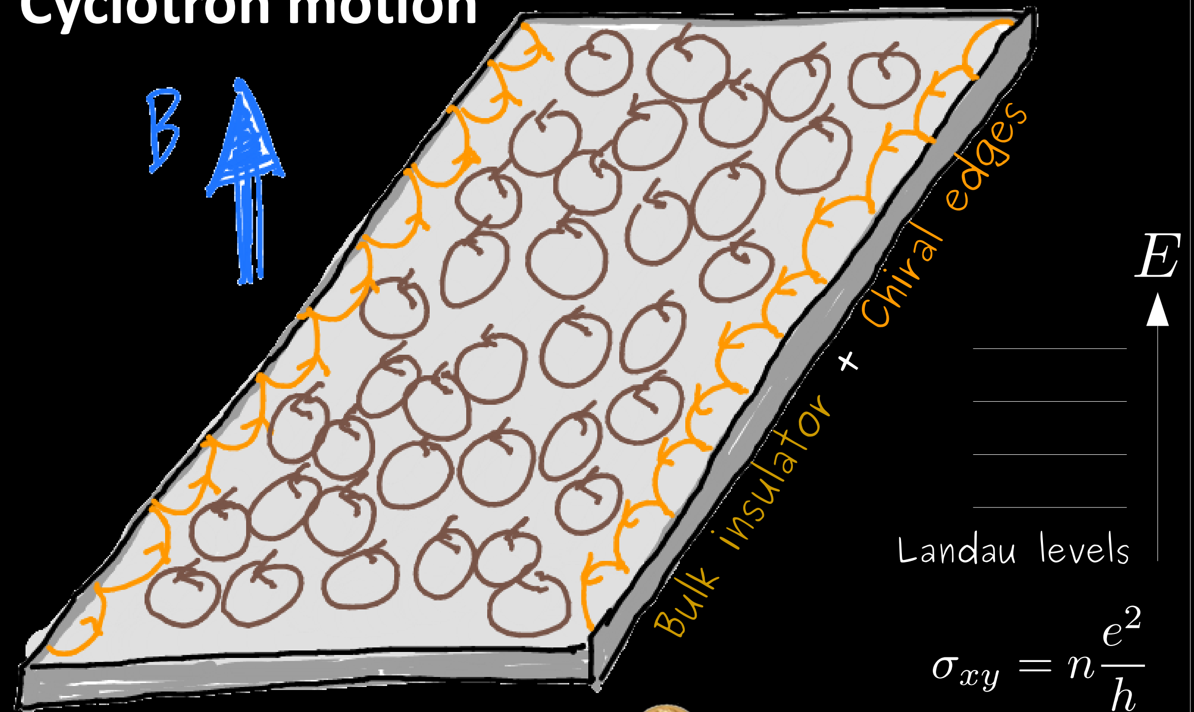
Experimental observation:
Quantized Hall resistance





[von Klitzing, Dorda, Pepper, PRL (1980)]

2d transport in magnetic field:
Cyclotron motion

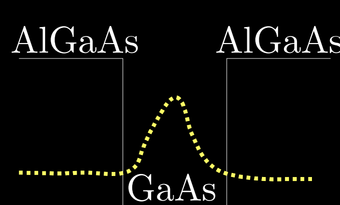


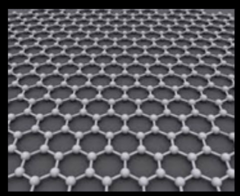
$$\sigma_{xy} = n\frac{e^2}{h}$$

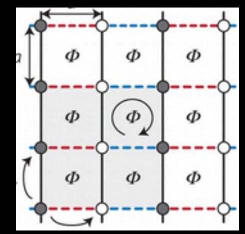
[Thouless, et al., PRL(1982)]

Experimental systems:

- Semiconductors Quantum Wells
- 2d materials (graphene)
- Quantum simulators



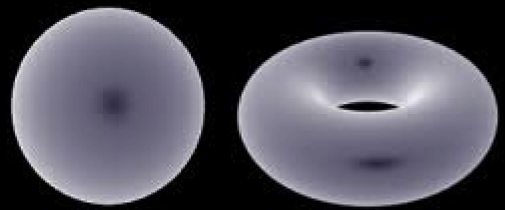


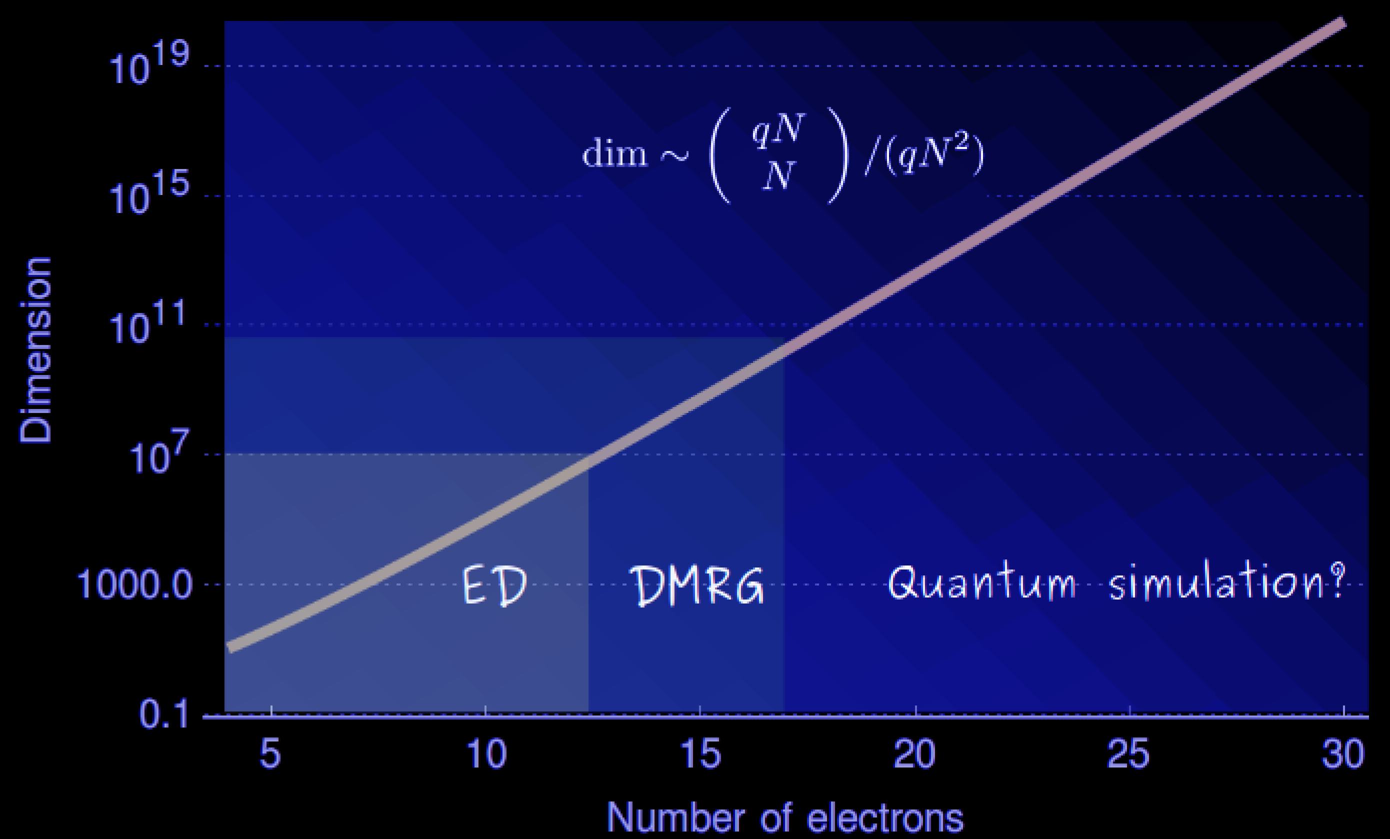


Remarkable observation: Robust Hall conductances also for fractionally filled Landau levels [Tsui, Stormer, Gossard, PRL (1982)]

Explanation: Gapped liquid due to interactions [Laughlin, PRL (1982)]

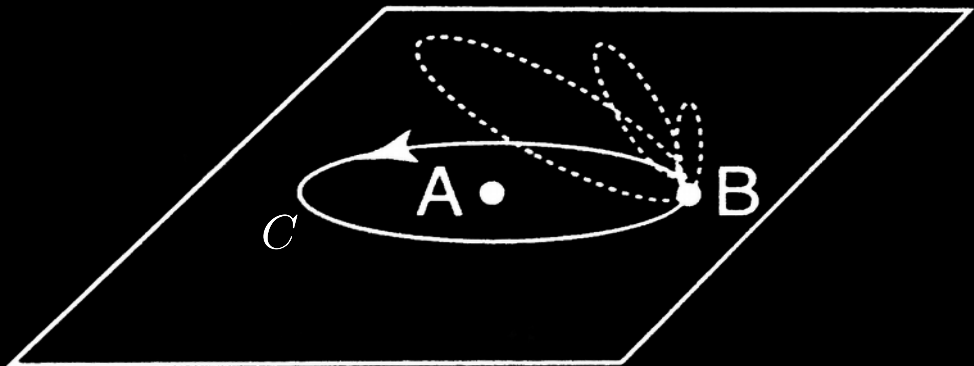
→ Non-perturbative many-body problem
→ Numerical methods: Exact diagonalization, DMRG





Spin-Statistics Theorem: bosons, fermions, anyons

Particle exchange in 3 dimensions:



$$\Psi_{AB} \to e^{i\gamma(C)} e^{i2\varphi_{\text{stat}}} \Psi_{AB}$$

Topological equivalence between double–exchange loop and no loop

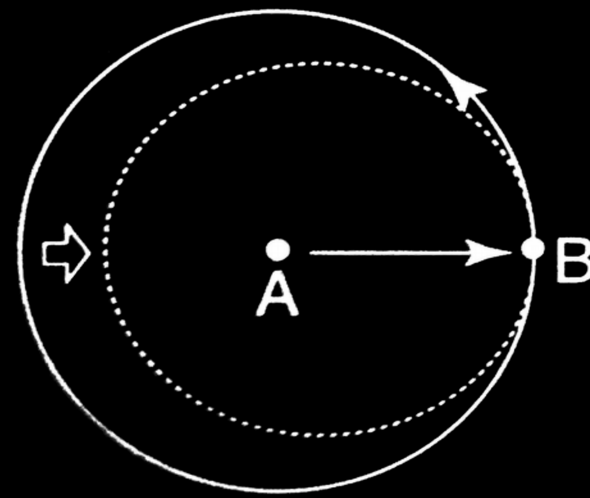
$$e^{i2\varphi_{\text{stat}}} = 1$$

→ Statistical phase restricted:

$$\varphi_{\text{stat}} = 0 : \quad \Psi_{AB} = +\Psi_{BA} \quad \to \quad \text{bosons}$$

$$\varphi_{\text{stat}} = \pi : \quad \Psi_{AB} = -\Psi_{BA} \quad \to \quad \text{fermions}$$

Particle exchange in 2 dimensions:



Double–exchange loop cannot be shrunk away

→ Particle exchange can produce an arbitrary phase

$$\Psi_{AB} = e^{i\varphi_{\text{stat}}} \Psi_{BA} \quad \to \quad \text{anyons}$$

Quasiparticle excitations in FQH systems exhibit anyon statistics!

[Leinaas & Myrheim, Il Nuovo Cimento B (1977)]

Non-Abelian Anyons

<u>Non-Abelian anyons:</u> degenerate states characterized by "fusion rules"

Example: Fibonacci anyons

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

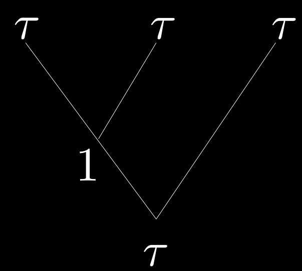
$$\Rightarrow$$

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

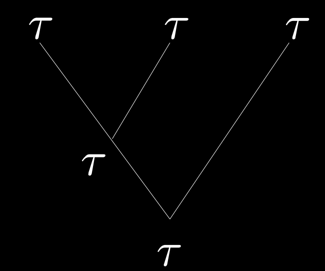
Number of states which fuse to τ follows Fibonacci series: 1,2,3,5,8...

Topological qubit:

$|0\rangle \equiv$



$|1\rangle \equiv$



Topological quantum computing:

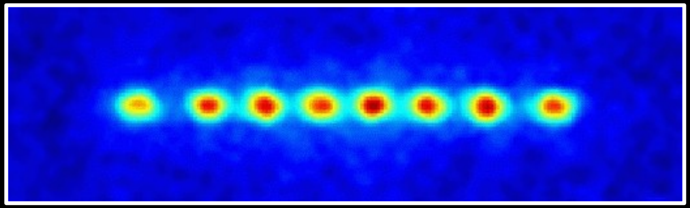
Process information by braiding

Microsoft

\- Technically involved

\+ Robust against local noise

THIS TALK: How to engineer Fibonacci phase in graphene!



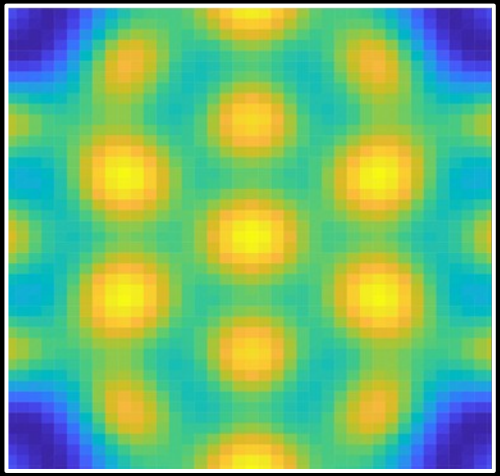
(1) QUANTUM SIMULATIONS WITH TRAPPED IONS:

Synthetic Hofstadter ladder (IQH system)

→ Microscopic System (individual control)

→ Naturally long-ranged interactions

→ 1-D

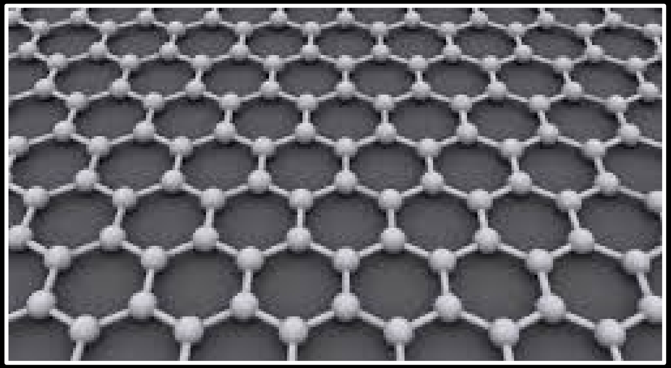


(2) QUANTUM SIMULATION WITH COLD ATOMS:

Fractional Wigner Crystal

→ Mesoscopic System

→ Long-range interactions through Rydberg dressing



(3) QUANTUM SIMULATION IN REAL MATTER

Non-Abelian Fibonacci phase

→ Macroscopic System

(1)
QUANTUM SIMULATION OF TOPOLOGICAL MATTER WITH TRAPPED IONS

Synthetic Hofstadter ladder
[Grass, Muschik, Celi, Chhajlany, Lewenstein PRA (2015)]

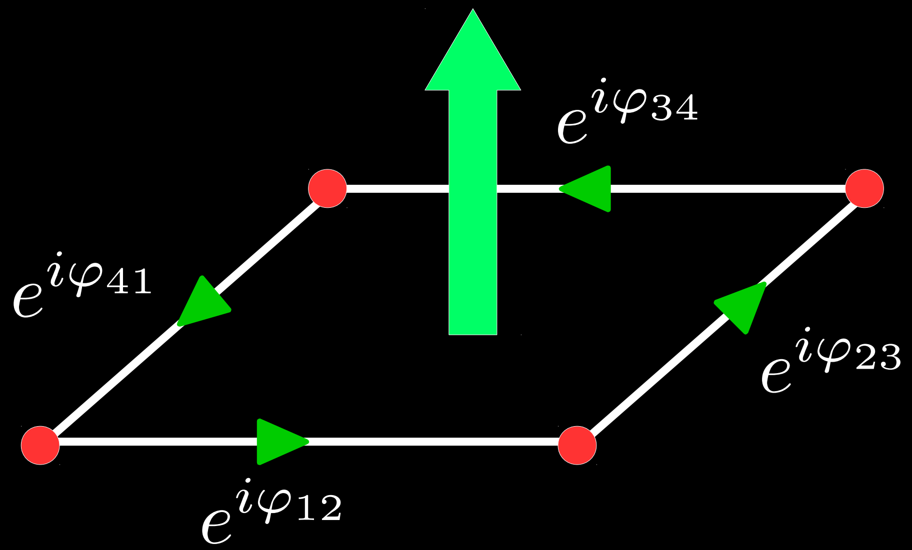
Triangle with flux

[Grass, Celi, Pagano, Lewenstein, PRA (Rapid) (2018)]

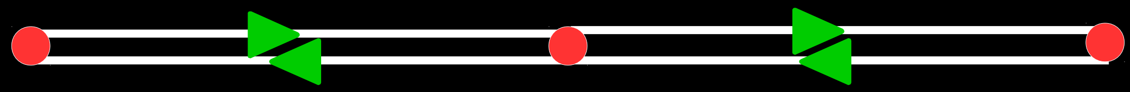
Magnetic Flux

Magnetic field → wave function picks up Berry phase
when moving along closed loop

$$\Phi = \varphi_{12} + \varphi_{23} + \varphi_{34} + \varphi_{41} \qquad \text{(= encircled flux)}$$

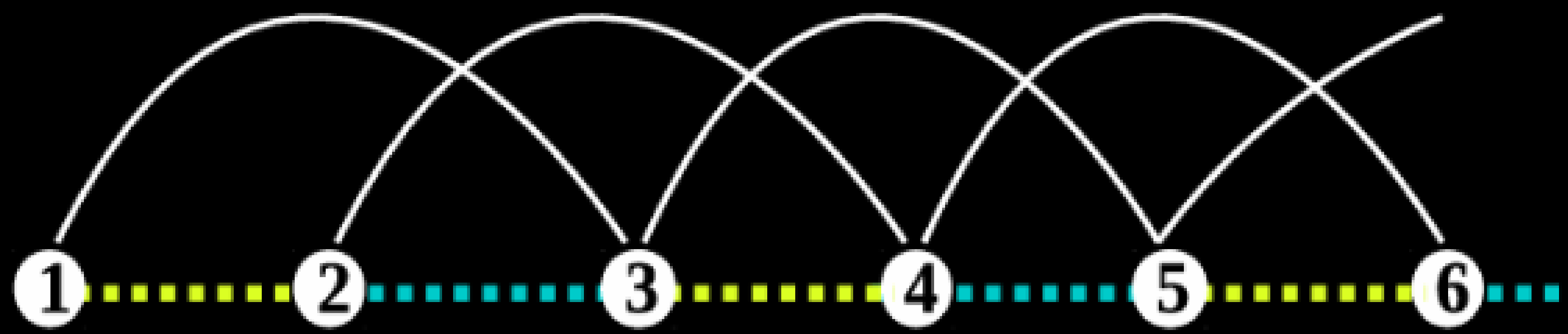


In 1D: Closed loops are along straight lines

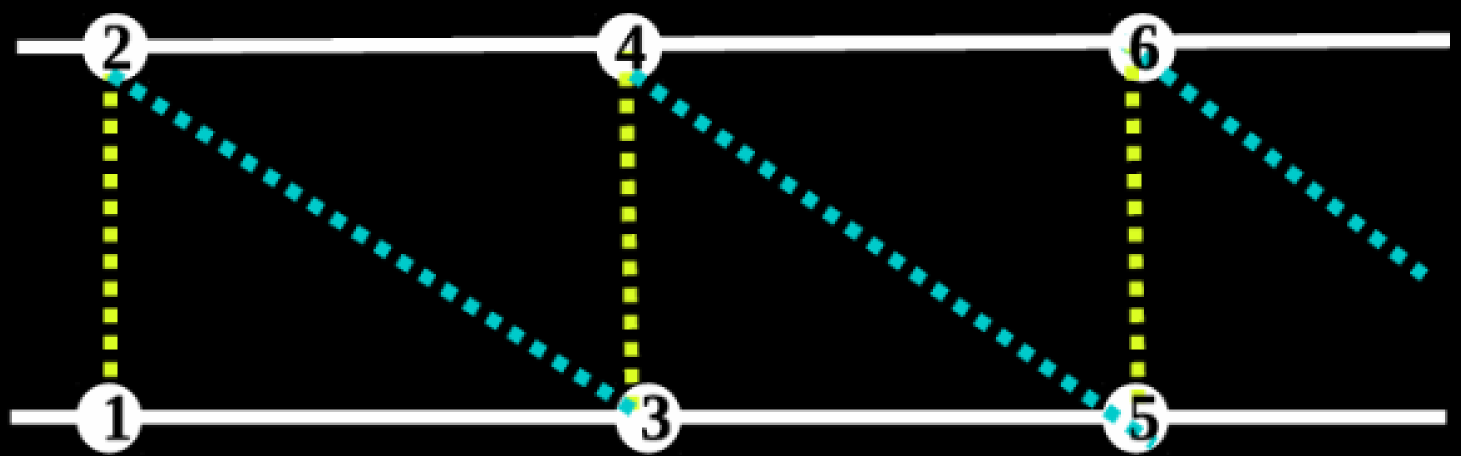


Can we still pick up a non-zero Berry phase?

Chain with nearest and next-nearest neighbor interactions:

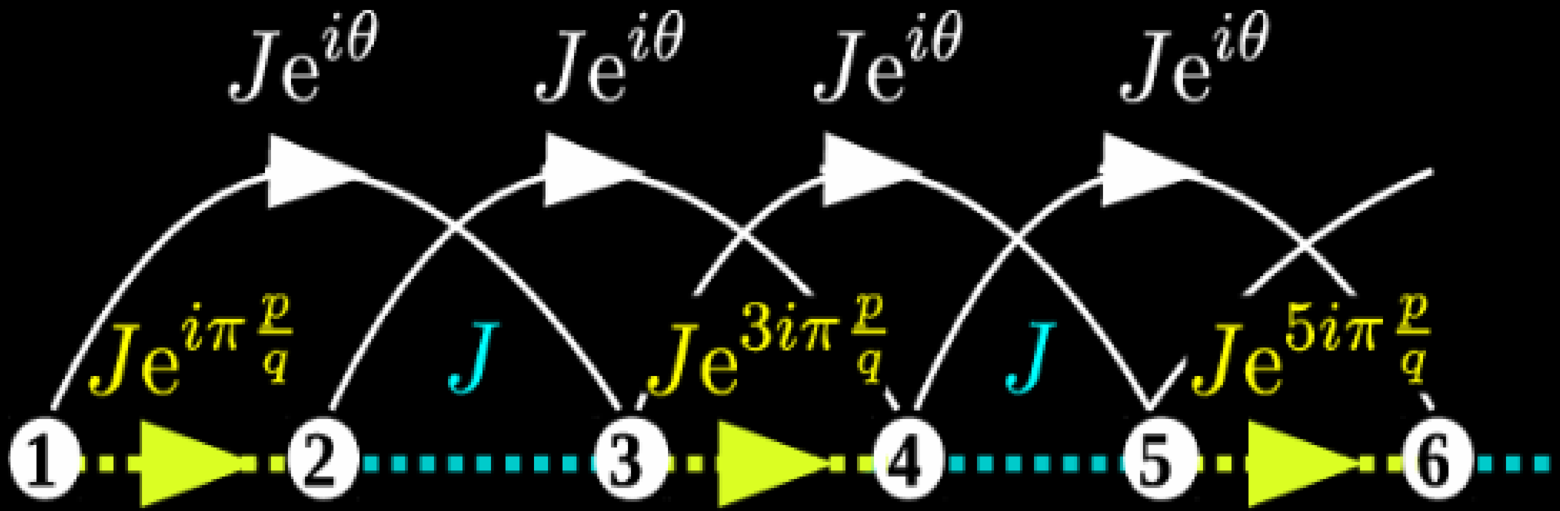


Mapping onto triangular ladder ("synthetic ladder"):



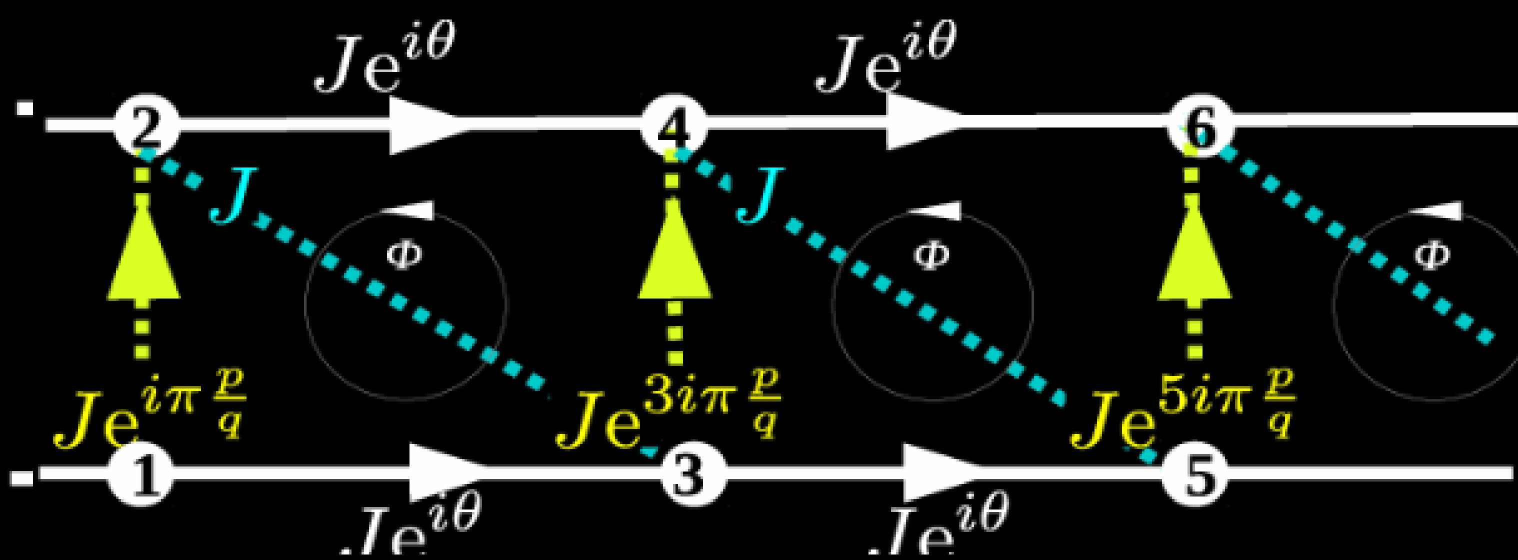
[Grass, Muschik, Celi, Chhajlany, Lewenstein, PRA (2015)]

Chain with nearest and next-nearest neighbor interactions:



Mapping onto triangular ladder ("synthetic ladder"):

$$\Phi = 2\pi\frac{p}{q}$$

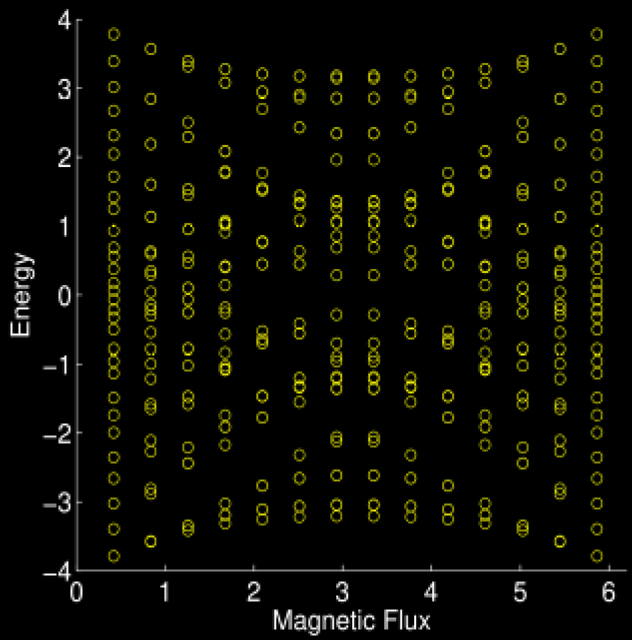


[Grass, Muschik, Celi, Chhajlany, Lewenstein, PRA (2015)]

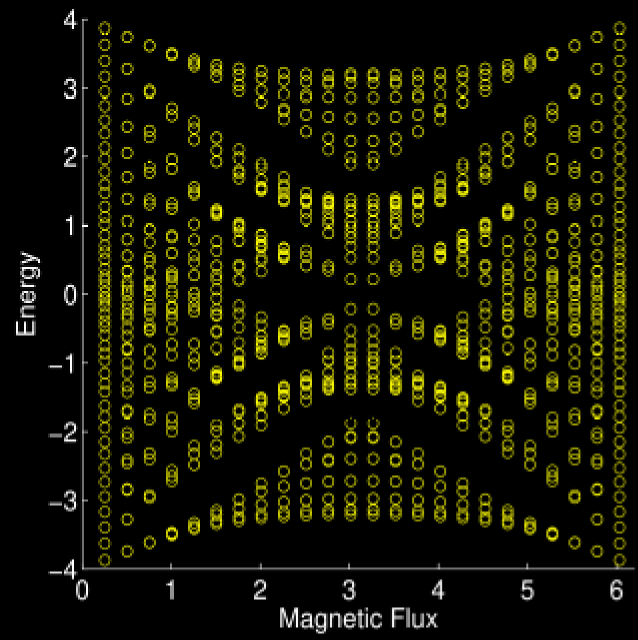
Hofstadter model: Lattice model for integer quantum Hall effect

Famous feature: Fractal energy spectrum → "Hofstadter butterfly"

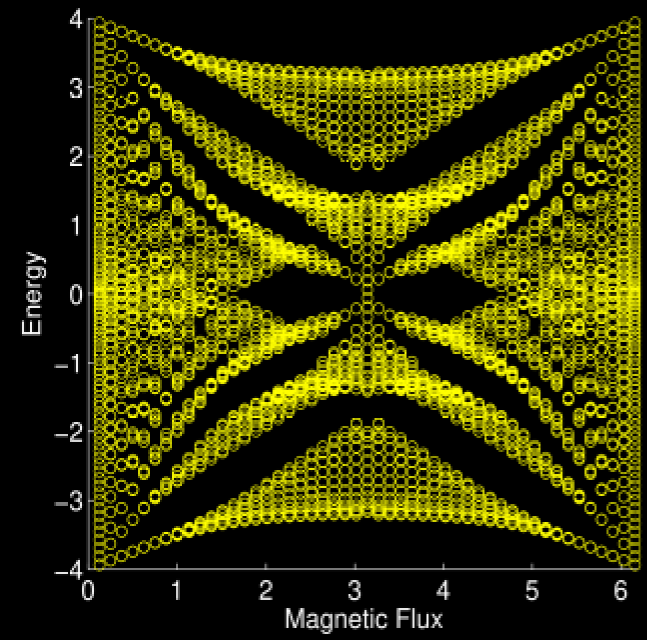
Energy vs. flux per plaquette



N=30



N=50



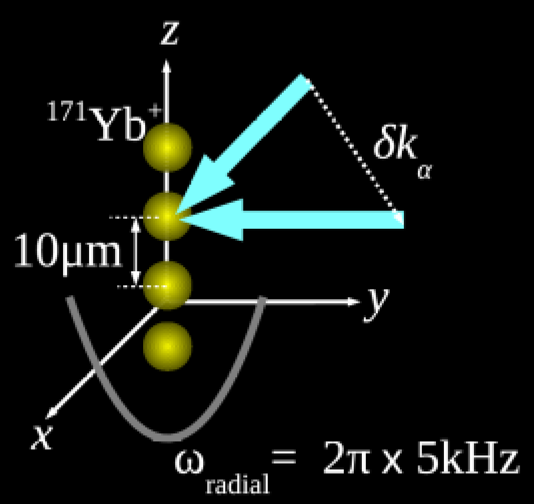
N=100

Also: Localized edge states, non-zero Chern numbers, ...

[Grass, Muschik, Celi, Chhajlany, Lewenstein, PRA (2015)]

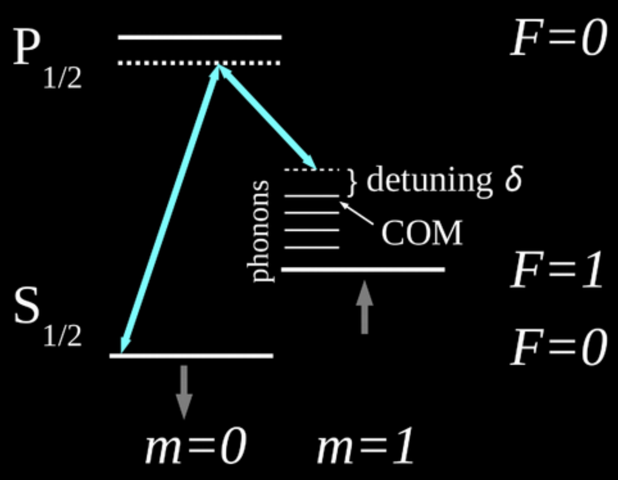
Engineering spin-spin interactions

[Porras, Cirac, PRL (2004)]



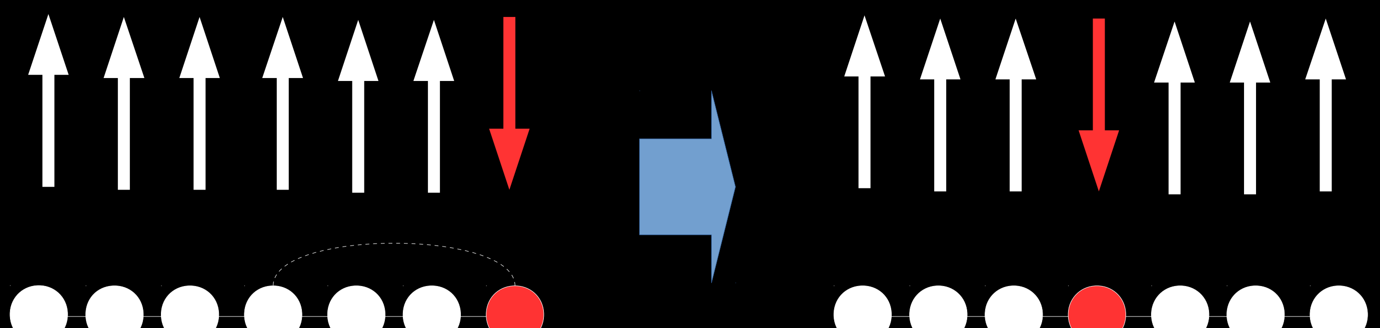
$$H_{\rm eff} = \sum J_{ij} \sigma_j^x \sigma_i^x$$

2^{nd} order perturbation theory for spin-phonon model (i.e. virtual phonons)



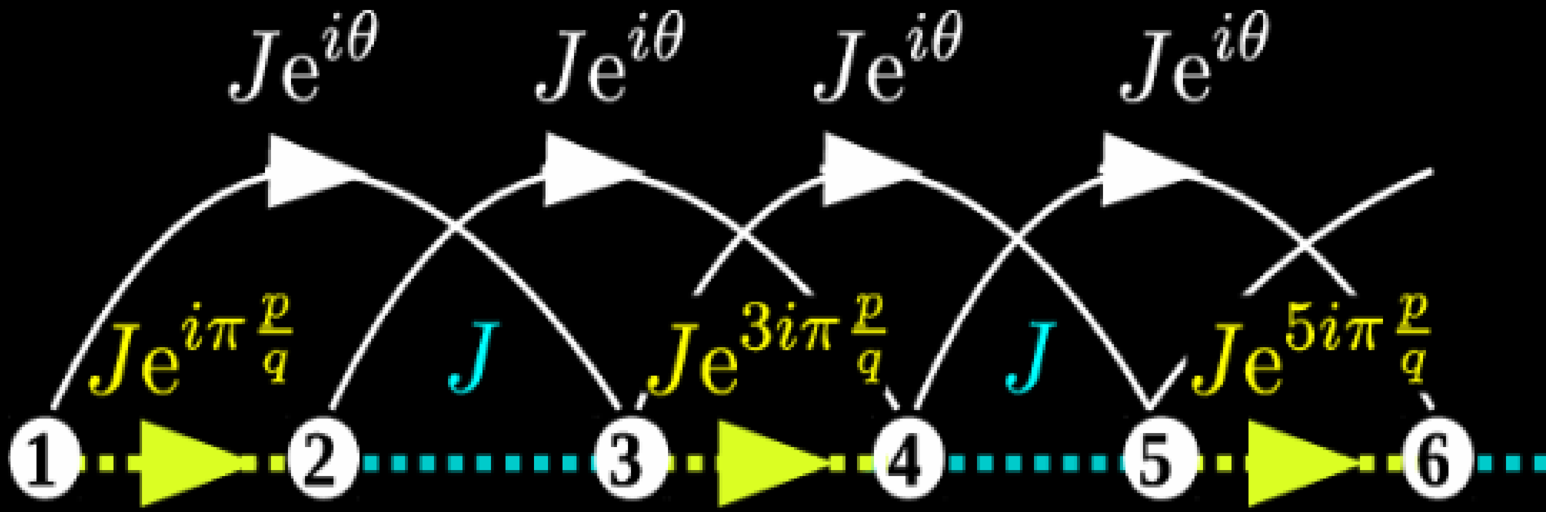
Early experiments:
[Friedenauer, Schmitz, Glueckert, Porras, Schaetz, Nat. Phys (2008)] [Kim, Chang, Islam, Korenblit, Duan, Monroe, PRL (2009)]

Equivalence spin flip ↔ hopping:



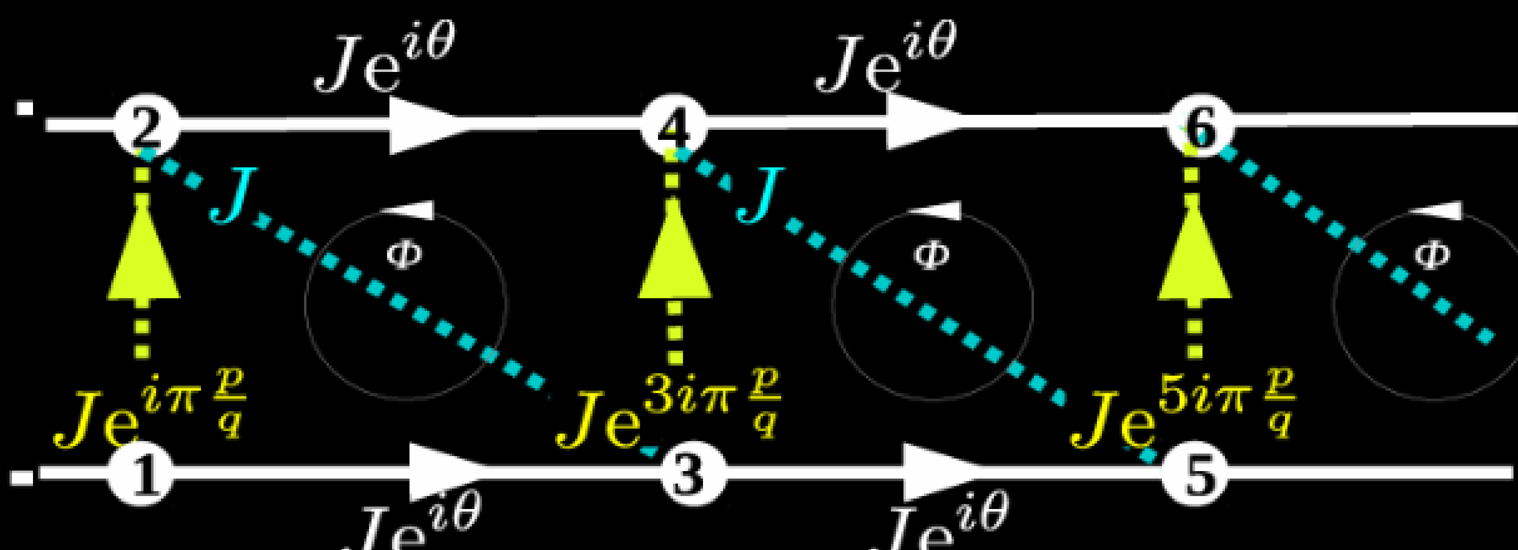
From Chain to Synthetic Ladder

Chain with nearest and next-nearest neighbor interactions:



Mapping onto triangular ladder ("synthetic ladder"):

$$\Phi = 2\pi \frac{p}{q}$$



[Grass, Muschik, Celi, Chhajlany, Lewenstein, PRA (2015)]

Periodic driving to engineer gauge potentials

[Cold atom experiments: Pisa (Arimondo), Hamburg (Sengstock), MIT (Ketterle), Munich (Bloch), Zurich (Esslinger)...]

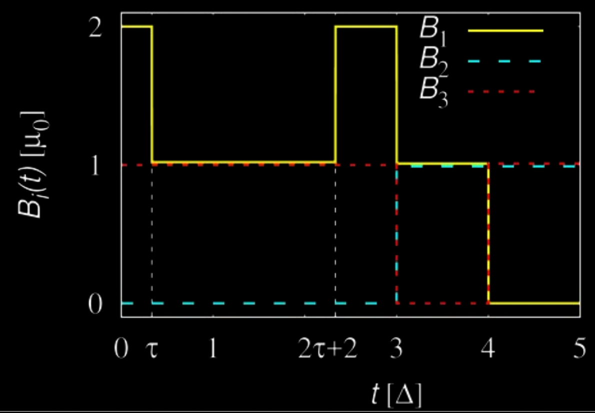
Recipe for spin chain (XY model):

Add “shaken” field: $H(t) = H_{\rm XY} + \sum_i B_i(t)\sigma_i^z$ with $H_{\rm XY} = \sum_{i<j} J_{ij}(\sigma_i^+\sigma_j^- + \text{h.c.})$

Gauge transform (Floquet basis): $U(t) = e^{-i\sum_i \chi_i(t)\sigma_i^z}$ with $\chi_i(t) = \int_0^t dt' B_i(t')$

In new basis, average over shaking period: $H_{\rm eff} = \sum_{i<j} J_{ij}^{\rm eff}(\sigma_i^+\sigma_j^- + \text{h.c.})$ where $J_{ij}^{\rm eff} = \frac{\bar{J}_{ij}}{T}\int_0^T {\rm d}t e^{2i[\chi_i(t)-\chi_j(t)]}$

Effective Hamiltonian is again XY model, with renormalized interaction parameters



[Grass, Muschik, Celi, Chhajlany, Lewenstein, PRA (2015)]
[Grass, Celi, Pagano, Lewenstein, PRA Rapid (2018)]

Spin-phonon model + driving

↓

Effective spin chain + driving

↓

Effective spin chain w/ flux

First approximation:
Problematic for strong driving

Second approximation:
Problematic for weak driving

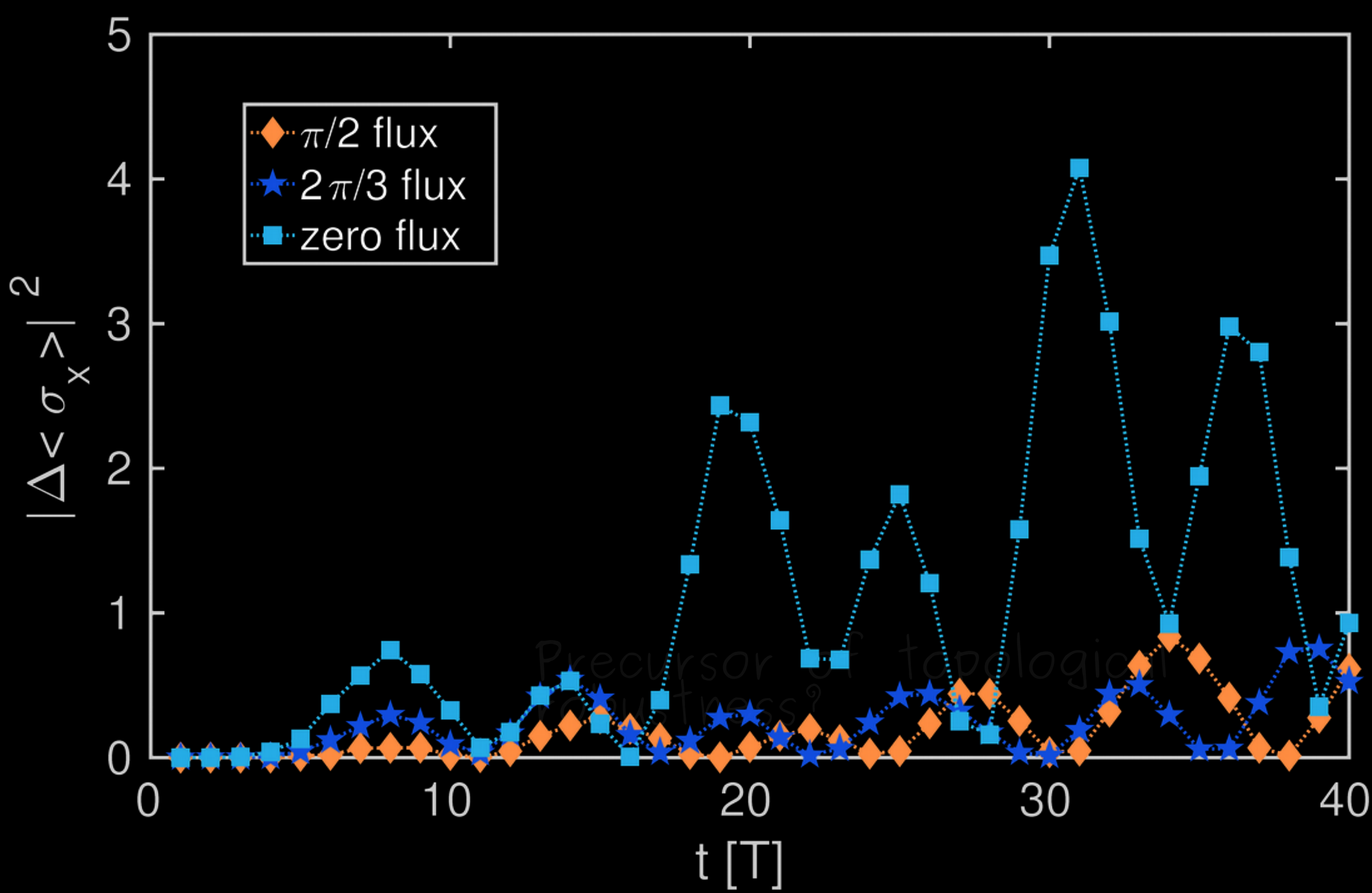
$\Phi = \pi/2$

Good fidelity

$\Phi = 0$

Low fidelity

Onset of topological robustness?



[Grass, Celi, Pagano, Lewenstein, PRA Rapid (2018)]

(2)
QUANTUM SIMULATION OF TOPOLOGICAL MATTER WITH COLD ATOMS

Synthetic gauge fields through laser dressing
[Julia-Diaz, Dagnino, Guenther, Grass, Barberan, Lewenstein, Dalibard, PRA (2011)]

Non-Abelian spin singlet phases in bosonic FQH system
[Grass, Julia-Diaz, Barberan, Lewenstein, PRA (Rapid) (2012)]

Engineering fermionic Laughlin state through confinement-induced resonance
[Julia-Diaz, Grass, Dutta, Lewenstein, Nat. Commun. (2013)]

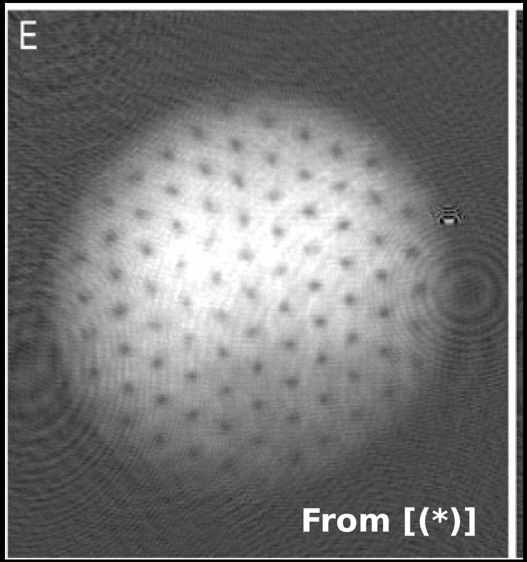
Integer quantum Hall phase of bosons
[Grass, Raventos, Lewenstein, Julia-Diaz, PRB (2014)]

Fractional Wigner crystal through Rydberg dressing
[Grass, Bienias, Gullans, Lundgren, Maciejko, Gorshkov, PRL (2018)]

Atoms: Electro-neutrality = insensitivity to magnetic fields

Synthesize the effect of a magnetic field:

- rotation (Coriolis force ↔ Lorentz force)
- laser-dressing (imprinted Berry phase)
- laser-assisted tunneling (in optical lattices)
- Floquet engineering (complex hopping term)



From [(*)]

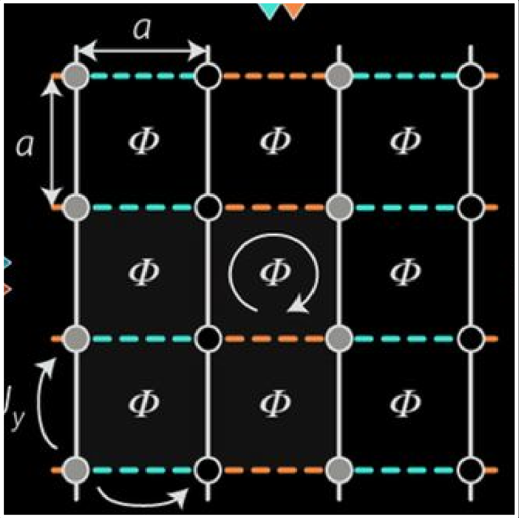
Experimentally achieved phases:

- 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)]
...



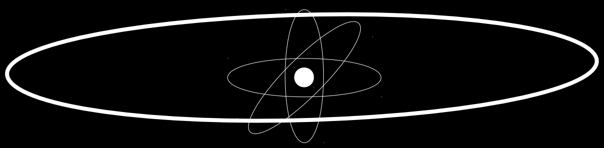
From [(**)]

Still outstanding: Synthesis of fractional quantum Hall phase

GOAL: Engineer long-ranged atom-atom interactions

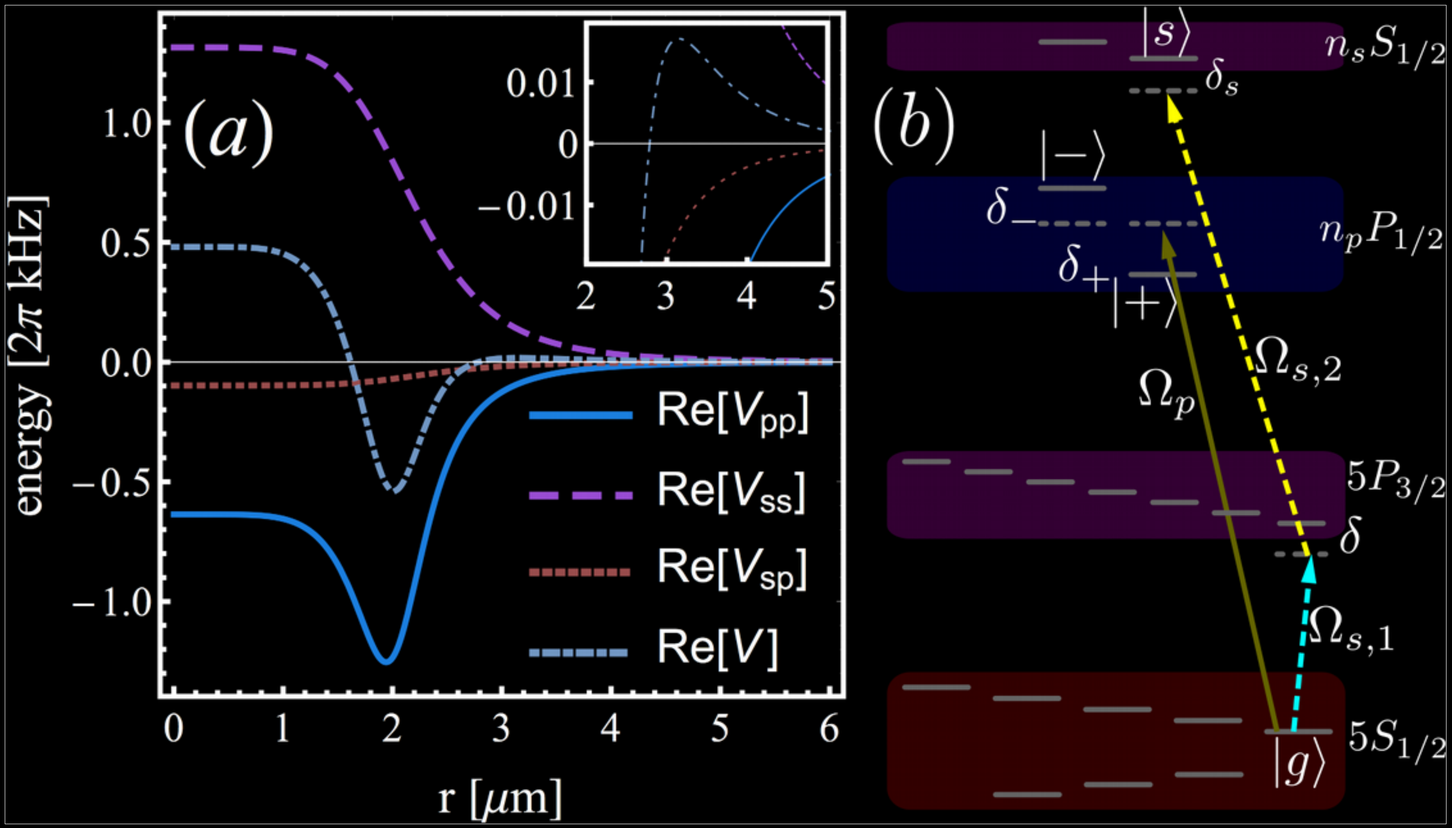
HOW: Using Rydberg states (van der Wals interactions)

Short-lived => only Rydberg dressing



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

APPLICATION: Atomic quantum Hall system with tunable pseudopotentials



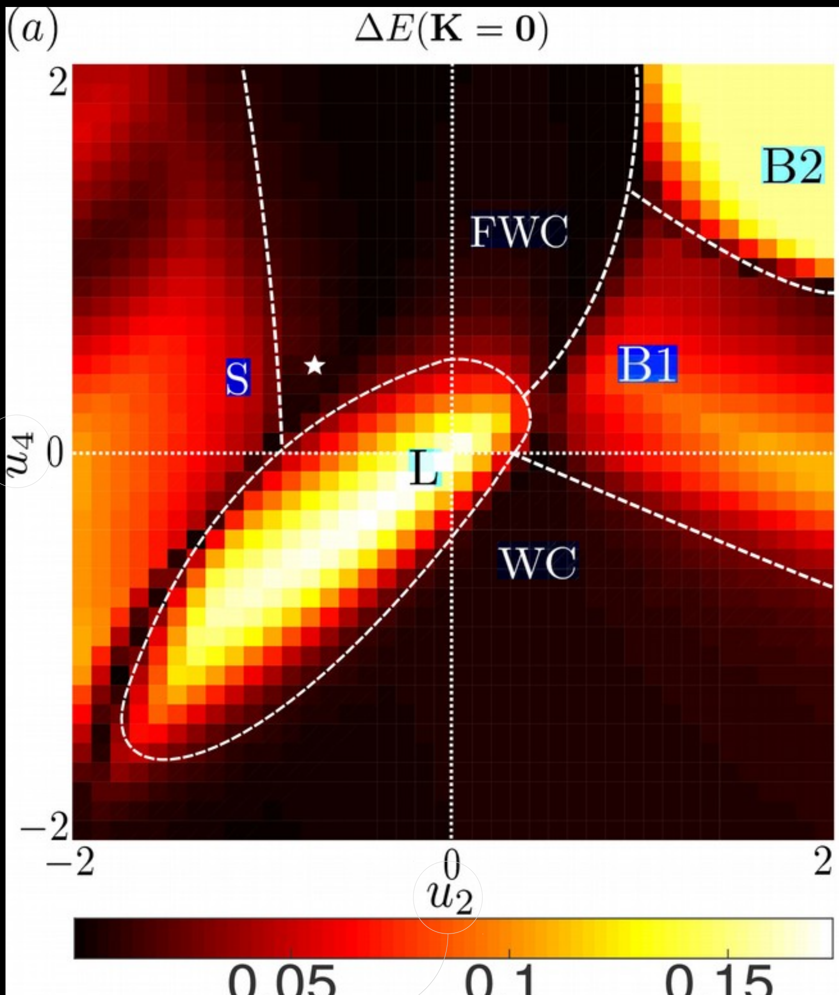
Combined s- and p- state dressing for enhanced flexibility

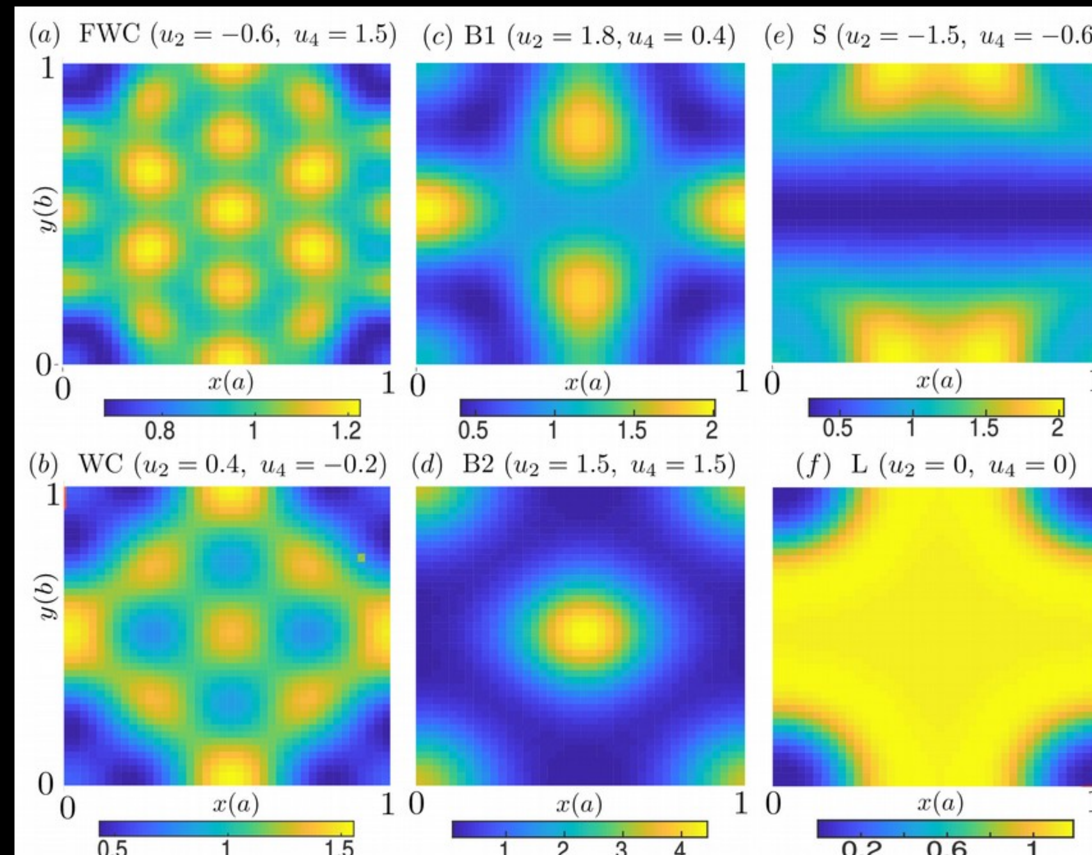
Tunable via principal quantum numbers, detuning, Rabi frequencies

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

Phase diagram of bosonic atoms

Landau level filling v=1/2: Laughlin liquid and what else?



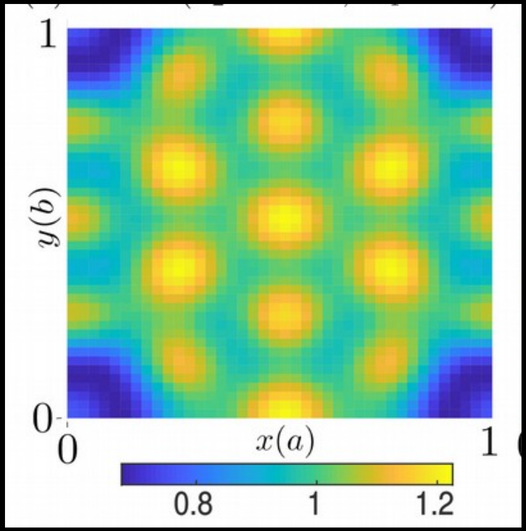


2-body correlation functions (on torus): Symmetry-broken phases

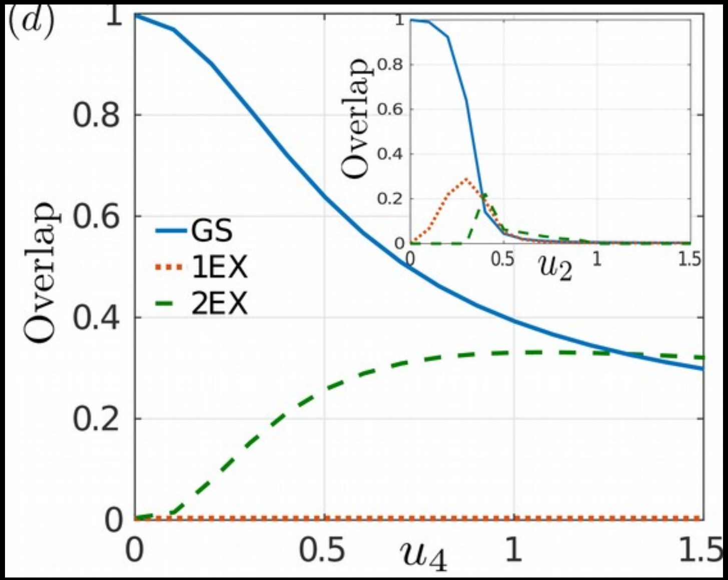
u_2 and u_4 are pseudopotentials: interaction strength at fixed relative angular momentum $2\hbar$ and $4\hbar$

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

Crystal structure with 2N peaks: formed by fractionalized bosons?



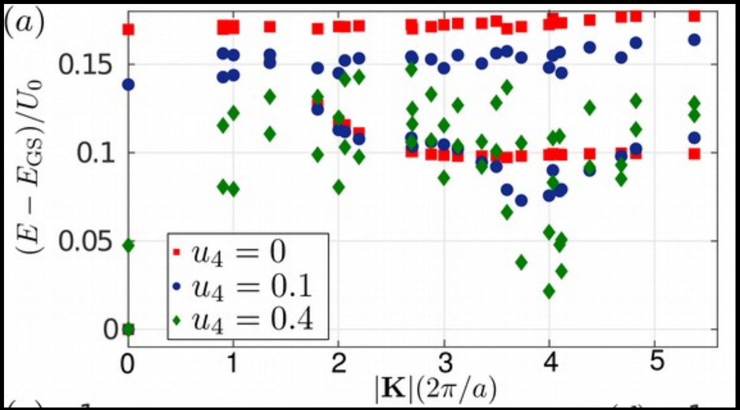
Wave-function overlap with Laughlin state



Coexistence of topological order and symmetry-broken order?

Nematic FQH – Experiments:

[Xia, Eisenstein, Pfeiffer, West, Nat. Phys. (2011)]
[Samkharadze, Schreiber, Gardner, Manfra, Fradkin, Csáthy, Nat. Phys (2016)]



Explanation through softening of a collective mode (magnetoroton)?

[Maciejko, Hsu, Kivelson, Park, Sondhi, PRB (2013)]
[You, Cho, Fradkin, PRX, (2014)]

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

(3)
QUANTUM SIMULATION OF TOPOLOGICAL MATTER WITH SOLID-STATE SYSTEMS

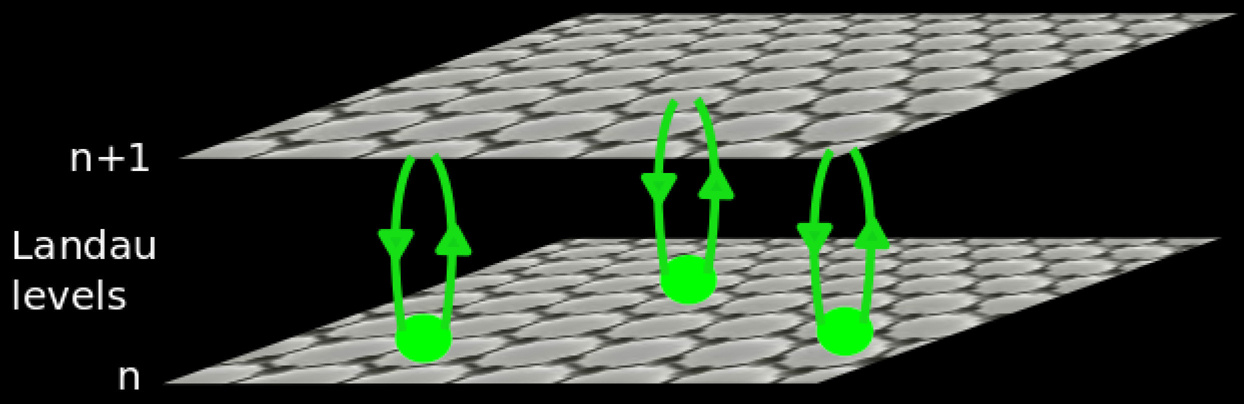
Engineering of non-Abelian phase in synthetic bilayer graphene

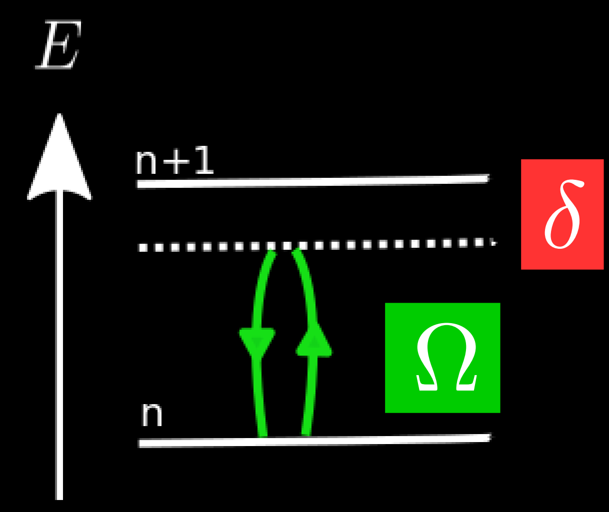
[Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]

Creation of anyons by light-matter interactions:
[Grass, Gullans, Bienias, Zhu, Ghazaryan, Ghaemi, Hafezi, PRB (2018)]

Synthetic graphene bilayer

Optically coupled Landau levels:

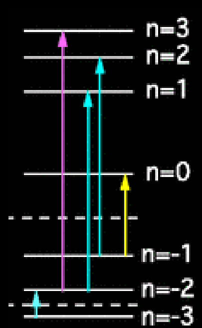




$$H_0 = \sum_m \left[\hbar\delta c^\dagger_{n+1,m} c_{n+1,m} + \hbar\Omega c^\dagger_{n+1,m} c_{n,m} \right] + \text{h.c.}$$

"chemical potential" "interlayer tunneling"

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

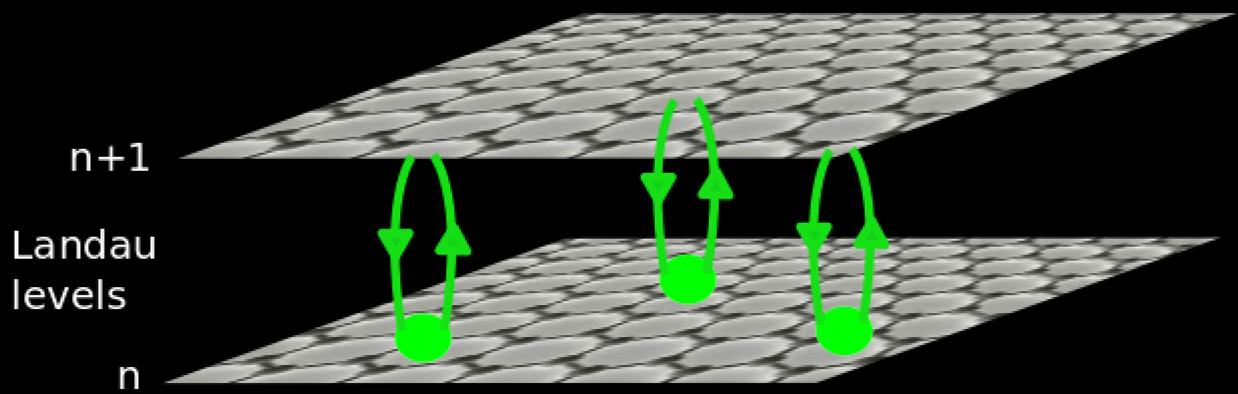


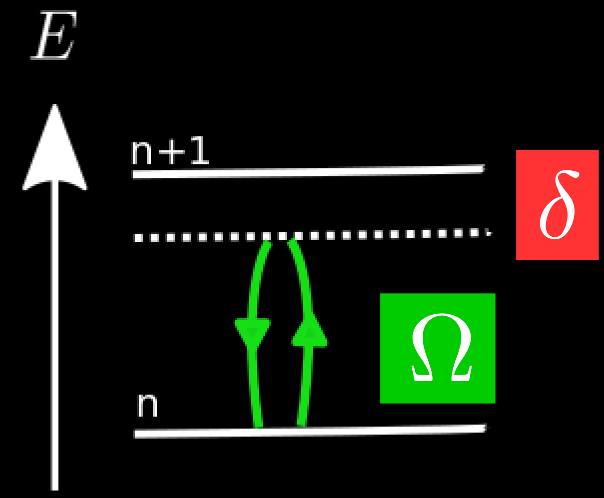
Selection rule for Landau level coupling in graphene:

$n \leftrightarrow \pm n \pm 1$ (B=10 Tesla → near-IR transitions)

[Jiang, ..., Kim, Stormer, PRL (2007)]

Optically coupled Landau levels:





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

"chemical potential" "interlayer tunneling"

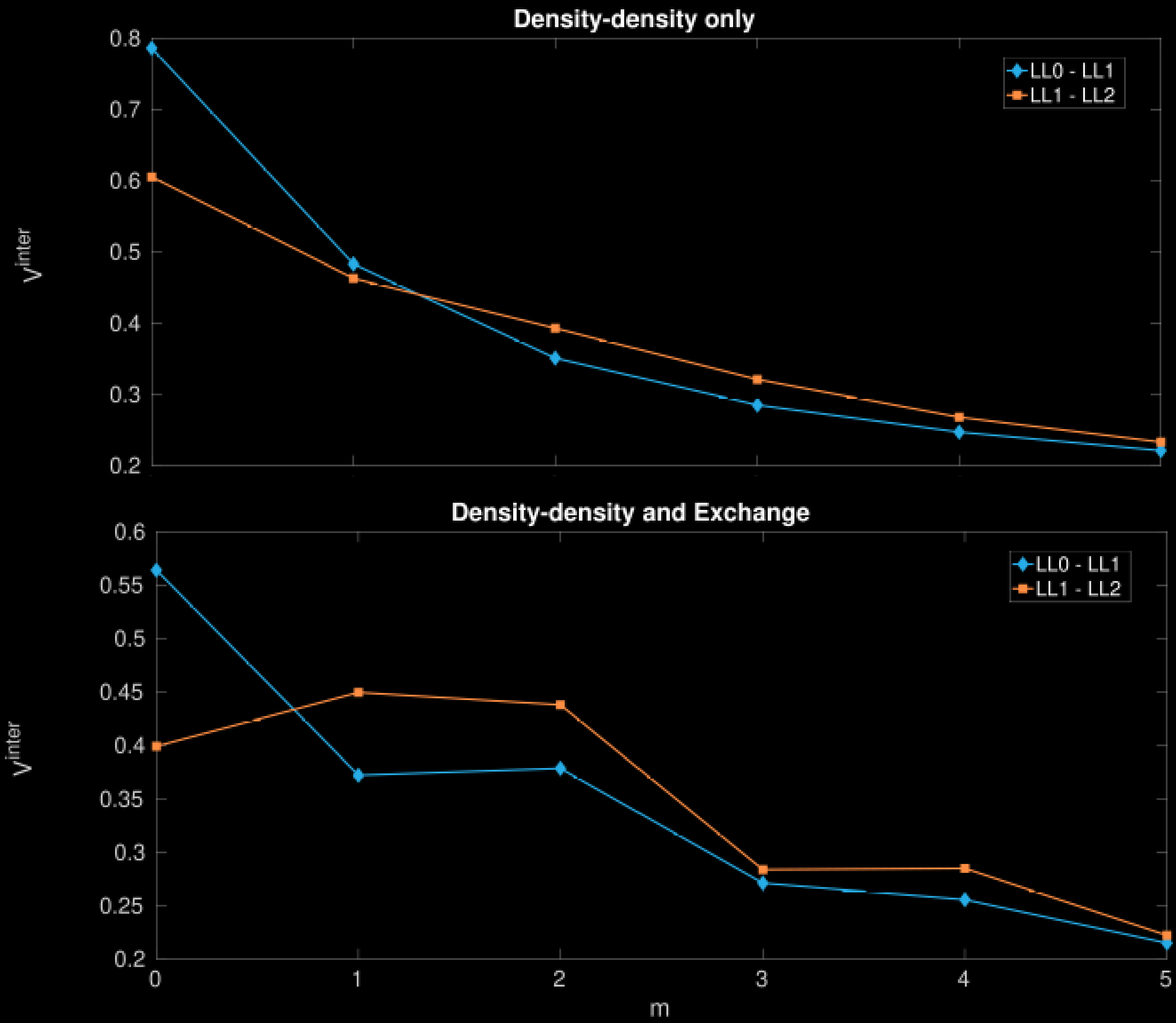
[Ghazaryan, Grass, Gullans, Ghaemi, Hafezi, PRL (2017)]

Real vs. synthetic

- Tunable parameters
- Exotic 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

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



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

Generic behavior: Monotonic decay with *m*

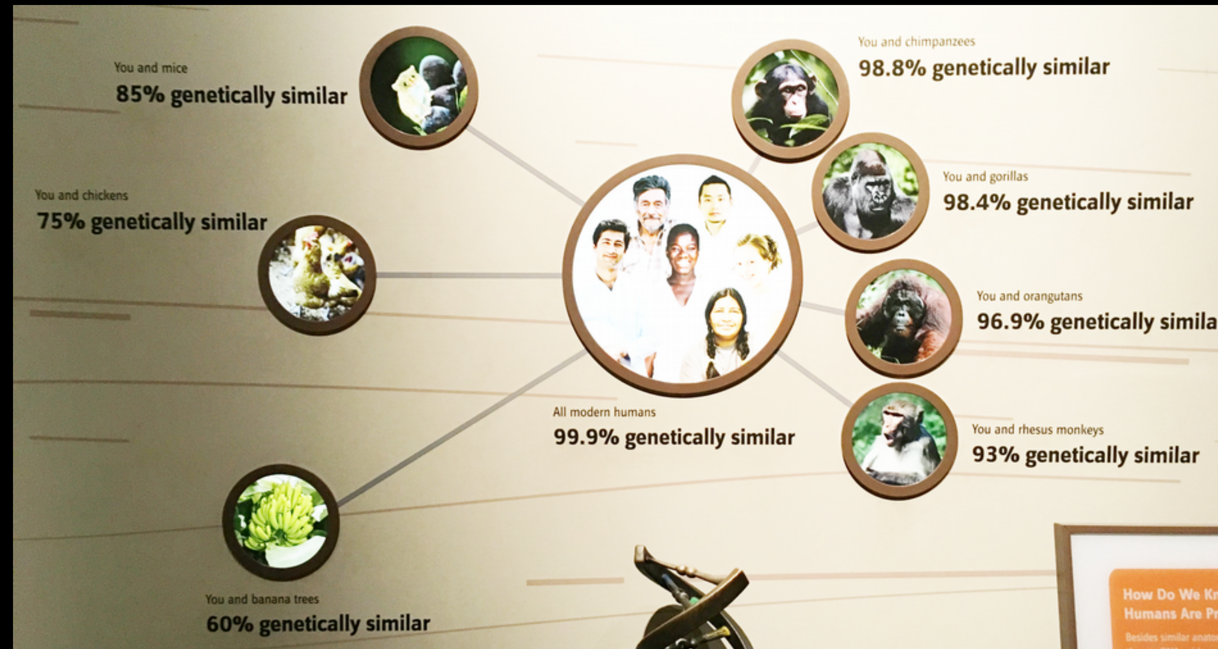
Synthetic bilayer interactions: Non-monotonic behavior → favoring singlets at *m*=0

Identification of the phase: Fibonacci?

Ground state overlaps:
(at filling 2/3)

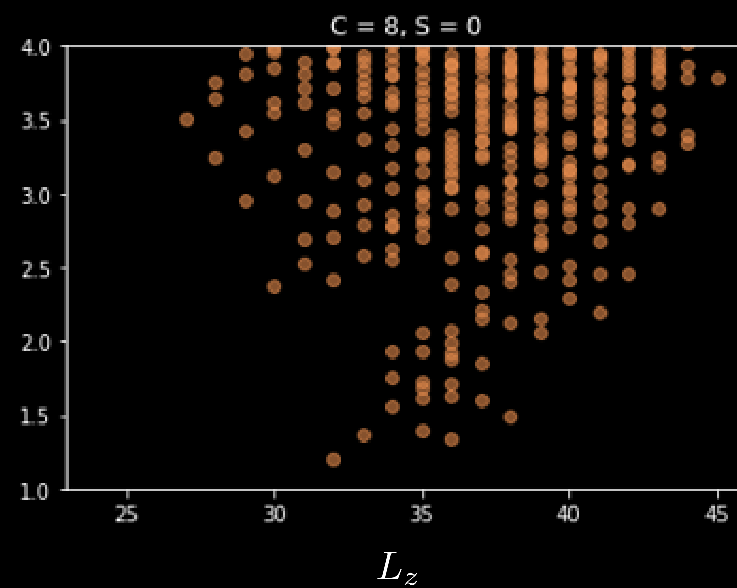
"No" overlap with:
- Halperin states (113, 330)
- Composite Fermions
- Intra-layer Pfaffian

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



Topological "quantum numbers":
- Ground state degeneracies on torus
- Edge state counting: 1,1,3,6,...

Conclusion:
Synthetic bilayer likely to host Fibonacci anyons



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

Summary

Quantum Simulation:

- Use light-matter interaction to synthesize features of interest
- Matter can be solid (with some intrinsic features) or atomic (featureless)

Ions: Synthetic Hofstadter ladder

→ Floquet-engineered fluxes in 1D geometry

→ Microscopic onset of topological protection

Atoms: Fractional Quantum Hall system

→ tunable pseudopotentials through Rydberg dressing

→ Fractional Wigner Crystal

Graphene: Fibonacci anyon phase

→ synthetic bilayer through light-matter interactions

→ exotic interlayer interactions

Collaborators

Theory:

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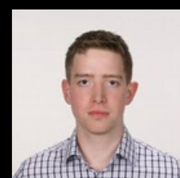


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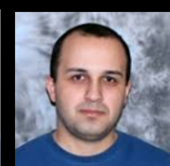

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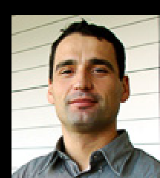
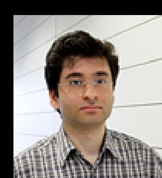


Experiments::

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Thank you!