Synthetic topological matter with quantum gases and light

Nathan Goldman

Lyon, May 17th 2021

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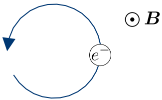
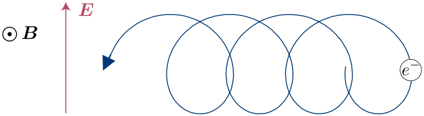
Materials immersed in a uniform magnetic field

- **An electron in a magnetic field : classical trajectories**



cyclotron orbit



net drift (transverse to applied **E** field)

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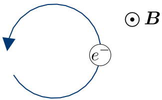

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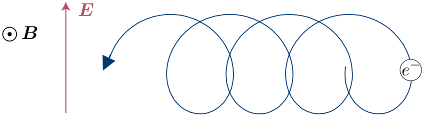

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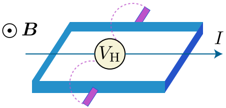
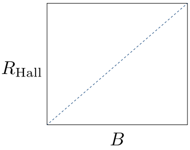


Hall resistance

$$R_{\mathrm{Hall}} = V_{\mathrm{H}}/I$$



Application : Hall effect sensors

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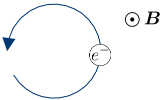

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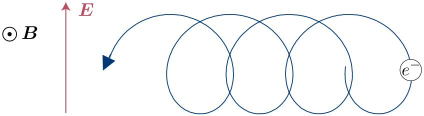

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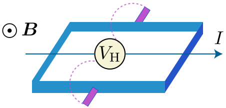

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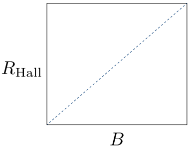
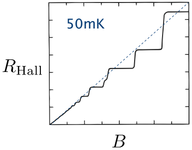


Application : Hall effect sensors

- **The quantized Hall effect (1980) : 2D systems, low temperature and strong magnetic field** 1985 1998



Quantized Hall plateaus

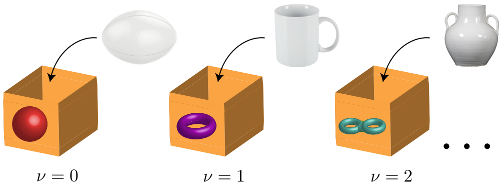
$$R_{\mathrm{Hall}} = (h/e^2) \times (1/\nu)$$

$$\nu \in \mathbb{Z}$$

- $R_{\mathrm{K}} = h/e^2$: "the Klitzing" (universal resistance : SI)
- The integers $\nu \in \mathbb{Z}$ are **topological** ! 2016

Topological matter

- **Topology ?**



A **topological invariant** : a **label** for each class

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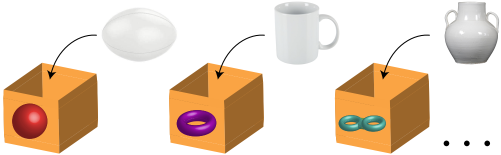
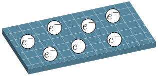


$\nu = 0$ $\nu = 1$ $\nu = 2$

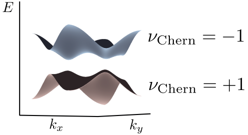
A **topological invariant** : a **label** for each class

- **Topology in solids ?**



Schrödinger's equation

$$\hat{H}|\Psi_\lambda\rangle = E_\lambda|\Psi_\lambda\rangle$$



The **Chern number** $\nu_{\text{Chern}} \in \mathbb{Z}$

is a **topological invariant**

for each **energy band**

Topological matter

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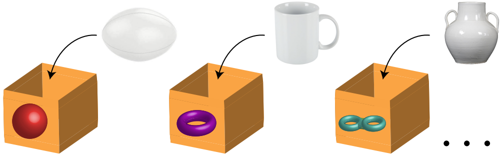

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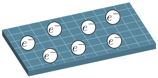

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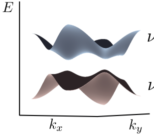

$\nu_{\text{Chern}} = -1$

$\nu_{\text{Chern}} = +1$

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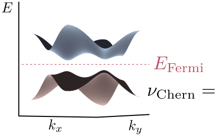
- **The quantized Hall effect and the notion of "Chern insulators"**



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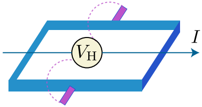


Quantized Hall resistance

$$R_{\text{H}} = (h/e^2) \times (1/\nu_{\text{Chern}})$$

$$\nu_{\text{Chern}} \in \mathbb{Z}$$

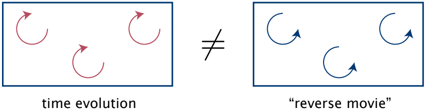
Thouless et al. '82

2016

How to generate a Chern insulator ?

- **Theorem: one has to break time reversal symmetry (Haldane, 1988)**

→ " impose a privileged orientation (chirality) in the system "



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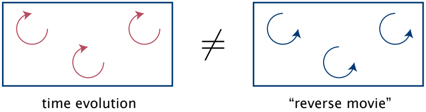

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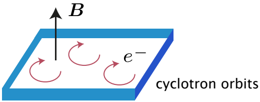

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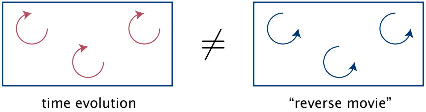

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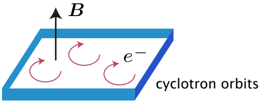

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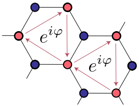

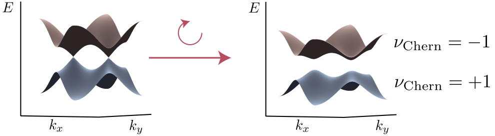

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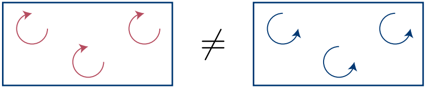
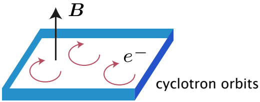


time evolution "reverse movie"

- **Immersion in a magnetic field**



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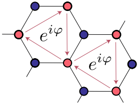
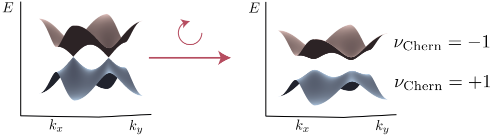
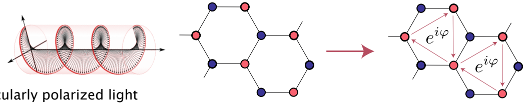




- **Light-induced methods :**



circularly polarized light

$\hat{H}_{e^-} \approx \hat{H}_{\text{Haldane}}$

th: Oka & Aoki PRB '08

exp: Cavalleri et al. '19

A zoo of topological insulators and superconductors

- **Are there other topological states of matter ? What are the relevant topological invariants ?**

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Mathematics (Altland & Zirnbauer '97, Kitaev '09, Ryu-Schnyder-Furusaki-Ludwig '08) : presence of **symmetries** !!

	symmetries			spatial dimensions							
classes	Θ	Ξ	Π	1	2	3	4	5	6	7	8
A	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	1	0	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	1	1	1	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	−1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
AII	−1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
CII	−1	−1	1	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	−1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	1	−1	1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

→ time reversal symmetry

- **Some concrete examples :**

: 2D Chern insulators → $\nu_{\mathrm{Chern}} \in \mathbb{Z}$ classe A = " Chern insulators " (even dimens.)

A zoo of topological insulators and superconductors

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: topological superconductors (**th**: '00 et **exp**: '14)

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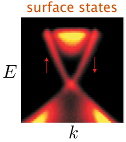
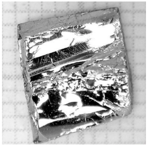


: topological superconductors (**th**: '00 et **exp**: '14)

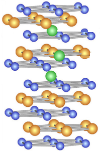
: topological insulators (**th**: '05 et **exp**: '07)

Creating synthetic topological matter

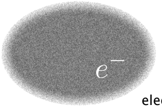
- **Topological matter :**



a material (ex. topological insulator)



atomic structure



electron gas

⟶ topological properties (conductivity, ...)

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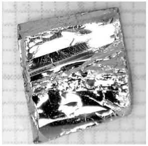

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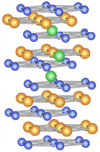

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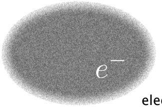
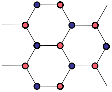
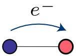


electron gas

→ topological properties (conductivity, ...)

- **Theoretical description : design a simple model**

Schrödinger's equation : $\hat{H}^{\text{topo}}_{e^-} \, |\psi\rangle_{e^-} = E \, |\psi\rangle_{e^-}$ E : energy spectrum (band structure)

Hamiltonian operator : $\hat{H}^{\text{topo}}_{e^-} =$  $+$ 

$+$ 

lattice

motion (kinetics)

interactions

$+$ 

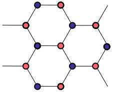
additional effects (couplings)

- coupling to an external field : ex. magnetic field (Hall effect)
- intrinsic coupling : ex. spin-orbit coupling (topological insulators)

Synthetic realizations

- **Can one create synthetic topological matter in the lab ?**

$\hat{H}^{\mathrm{topo}}_{e^-} =$



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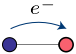

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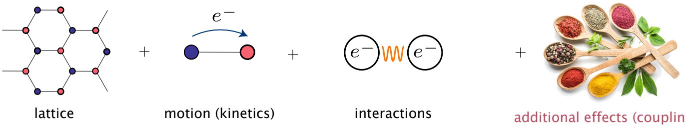
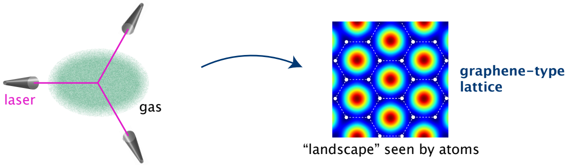
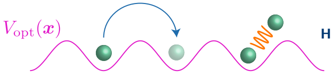


- **Quantum simulation with ultracold atomic gases:**  **(neutral atoms)**

  - lattice: **optical lattice**



  - hopping and interactions

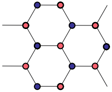
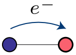


Hubbard models

Bloch, Dalibard, Zwerger, RMP '08

Synthetic realizations

- **Can one create synthetic topological matter in the lab ?**

$\hat{H}^{\text{topo}}_{e^-} =$  $+$  $+$  $+$ 

lattice | motion (kinetics) | interactions | additional effects (couplings)

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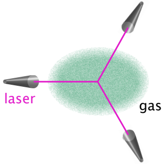
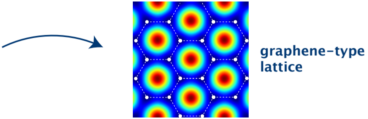
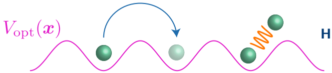




"landscape" seen by atoms

  - hopping and interactions



Hubbard models

Bloch, Dalibard, Zwerger, RMP '08

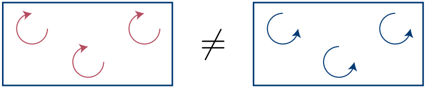
-  → **synthetic topological matter ? ? ?**

additional effects (couplings)

A synthetic Chern insulator ?

- **Haldane (1988) : one has to break time reversal symmetry**

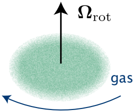
→ “ impose a privileged orientation (chirality) in the system ”



time evolution

“ reverse movie ”

- **In ultracold atomic gases**
  - **Rotation**



$\hat{H}_{\rm atom} \approx \hat{H}_{\rm Hall}$

$\boldsymbol{\Omega}_{\rm rot} \approx \boldsymbol{B}$: artificial magnetic field

exp: Dalibard ‘00, Ketterle ’01, Cornell ’04

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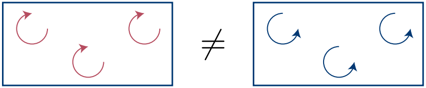

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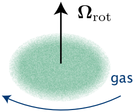

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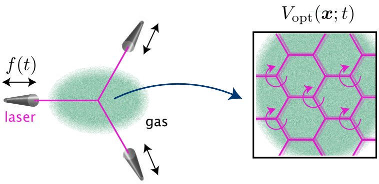
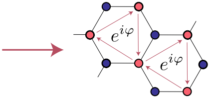
  - **Shaken optical lattices**





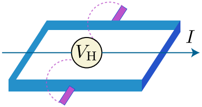
$\hat{H}_{\rm atom} \approx \hat{H}_{\rm Haldane}$

→ topological bands with $\nu_{\rm Chern} \neq 0$

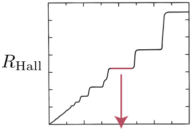
exp: Arimondo '07, Sengstock '11, Bloch '12, Ketterle '13, Esslinger '14, ...

Probing synthetic topological matter

- **Standard probes in solid states :**
  - **Transport (conductivity)**

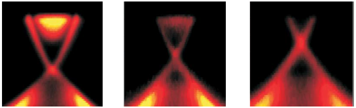


$R_{\rm Hall} = V_{\rm H}\,/I$: Hall resistance



$(R_{\rm Hall})^{-1} \sim \nu_{\rm Chern}$

  - **Spectroscopy (ARPES)**



exp: Hasan et al. ‘09

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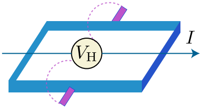

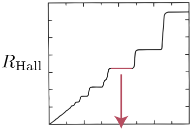

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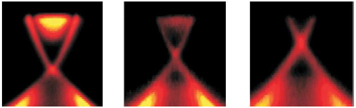

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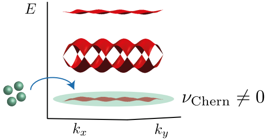
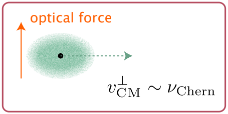
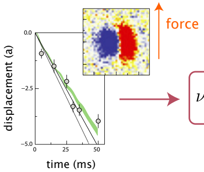
- **Examples of probes in ultracold topological matter :**
  - **Transport (centre of mass) :** Munich experiment (Aidelsburger et al. ‘15)





th: Dauphin & Goldman ‘13



$\nu_{\rm Chern}^{\rm exp} = 0.99(5)$

Probing synthetic topological matter

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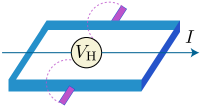

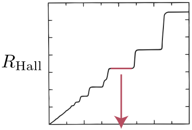

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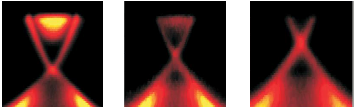

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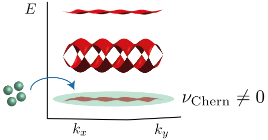
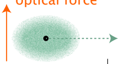
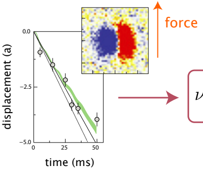


optical force



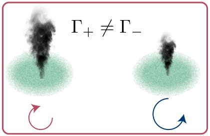
$v_{\rm CM}^{\perp} \sim \nu_{\rm Chern}$

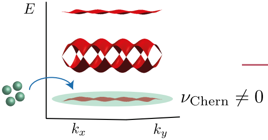
th: Dauphin & Goldman '13



$\nu_{\rm Chern}^{\rm exp} = 0.99(5)$

  - **Circular dichroism :** Hambourg experiment (Asteria et al. '19)



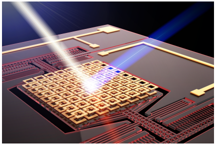


$\int \Gamma_+ - \Gamma_- \sim \nu_{\rm Chern}$ **quantized**

th: Tran et al. '17

Replacing matter by light : topological photonics

- **Band structures for light : photonic crystals**

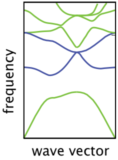


Zhang lab (Boston)

Maxwell' equations as an eigenproblem

$$\hat{\Theta}|\boldsymbol{E}\rangle = \omega^2|\boldsymbol{E}\rangle$$

ω : modes frequency



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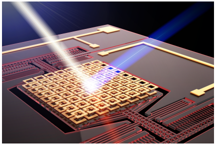

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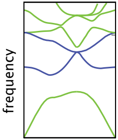
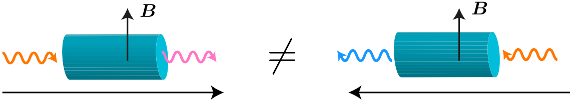


- **Create Chern bands ?** The idea of Haldane and Raghu ('05-'08) : **break time reversal symmetry**
  - Basic ingredient : magneto-optic materials [**nonreciprocal** medium (Faraday effect)]



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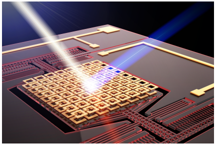

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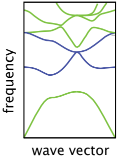

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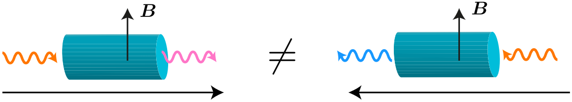
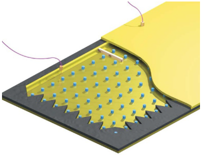
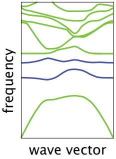
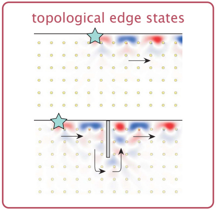


  - Periodic setting : photonic crystal (experiment at MIT, Wang et al. '09)





$\nu_{\text{Chern}} \neq 0$



Explore the zoo of topological states with synthetic systems

- **The periodic table is rich and broad:**

examples discussed today

classes	symmetries Θ	Ξ	Π	spatial dimensions 1	2	3	4	5	6	7	8
A	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	1	0	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	1	1	1	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	−1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
AII	−1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
CII	−1	−1	1	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	−1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	1	−1	1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

Reviews : • Cold atoms : Cooper-Dalibard-Spielman RMP '19 • Photonics : Ozawa et al. RMP '19

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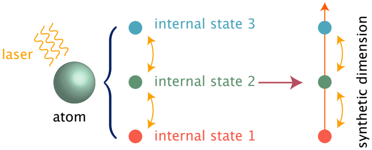
- **Synthetic matter allows for synthetic dimensions !** → **D > 3 ?** (4D quantized Hall effect, Zhang & Hu ‘01)



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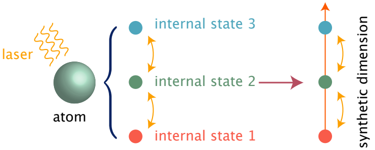
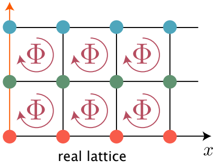
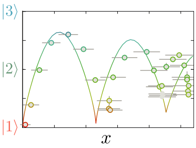






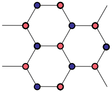
exp: Florence (Fallani) '15, NIST (Spielman) '15, ... Collège de France (Dalibard) '20: **17 internal states (dysprosium)**

th: Price et al. '15 (**4D QHE with cold atoms**), Ozawa et al. '16 (**4D photonics**), ...

Challenge: strongly-correlated synthetic topological matter

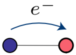
- **Our model Hamiltonian :**

$\hat{H}^{\text{topo}}_{e^-} =$



lattice

$+$



motion

$+$

interactions

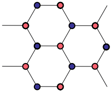
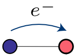
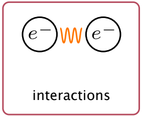
$+$

additional effects (couplings)

→ **strongly-correlated states** (ex. **fractional quantum Hall liquids**)

Challenge: strongly-correlated synthetic topological matter

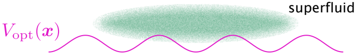
- **Our model Hamiltonian :**

$\hat{H}^{\text{topo}}_{e^-} =$  +  +  + 

additional effects (couplings)

→ **strongly-correlated states** (ex. **fractional quantum Hall liquids**)

- **Cold atoms :**
  - **Strongly-correlated states (non topological) :**



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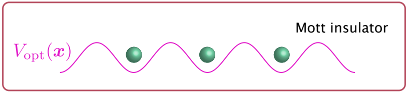
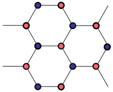


exp: Greiner et al. ‘02

Challenge: strongly-correlated synthetic topological matter

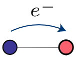
- **Our model Hamiltonian :**

$\hat{H}_{e^-}^{\mathrm{topo}} =$



lattice

$+$



motion

$+$

interactions

$+$

additional effects (couplings)

→ **strongly-correlated states** (ex. **fractional quantum Hall liquids**)

- **Cold atoms :**

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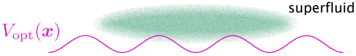

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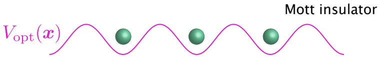
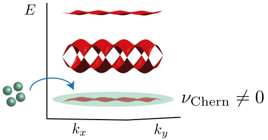


exp: Greiner et al. '02

  - **Strongly-correlated topological states :**



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interactions

→

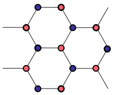
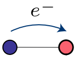
theory: FQH states predicted (anyons, ...)

experiments: still a challenge !

Review : Cooper-Dalibard-Spielman RMP '19

Challenge: strongly-correlated synthetic topological matter

- **Our model Hamiltonian :**

$\hat{H}^{\text{topo}}_{e^-} =$  $+$  $+$  $+$ 

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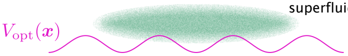
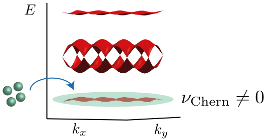


→

exp: Greiner et al. '02

  - **Strongly-correlated topological states :**



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→ **theory**: FQH states predicted (anyons, ...)

experiments: still a challenge !

Review : Cooper-Dalibard-Spielman RMP '19

- **Photonics :**
  - Create strong photon-photon interactions **Reviews** : Carusotto & Cuiti RMP '13, Ozawa et al. RMP '19
  - Stabilize many-photon states despite losses (out-of-equilibrium systems)

Some reading …

- **Ultracold atoms and topological matter :**
  - Topological quantum matter with ultracold gases in optical lattices,
    N. Goldman, J. C. Budich and P. Zoller,
    Nature Physics 12, 639 (2016)
  - Topological bands for ultracold atoms,
    N. R. Cooper, J. Dalibard, and I. B. Spielman,
    Rev. Mod. Phys. 91, 015005 (2019)
- **Topological photonics :**
  - Topological photonics,
    T. Ozawa, H. M. Price, A. Amo, N. Goldman, M. Hafezi, L. Lu, M. C. Rechtsman,
    D. Schuster, J. Simon, O. Zilberberg, and I. Carusotto,
    Rev. Mod. Phys. 91, 015006 (2019)
- **Artificial gauge fields:**
  - Artificial gauge fields in materials and engineered systems,
    M. Aidelsburger, S. Nascimbene and N. Goldman,
    Comptes Rendus Physique, 19, 394 (2018)