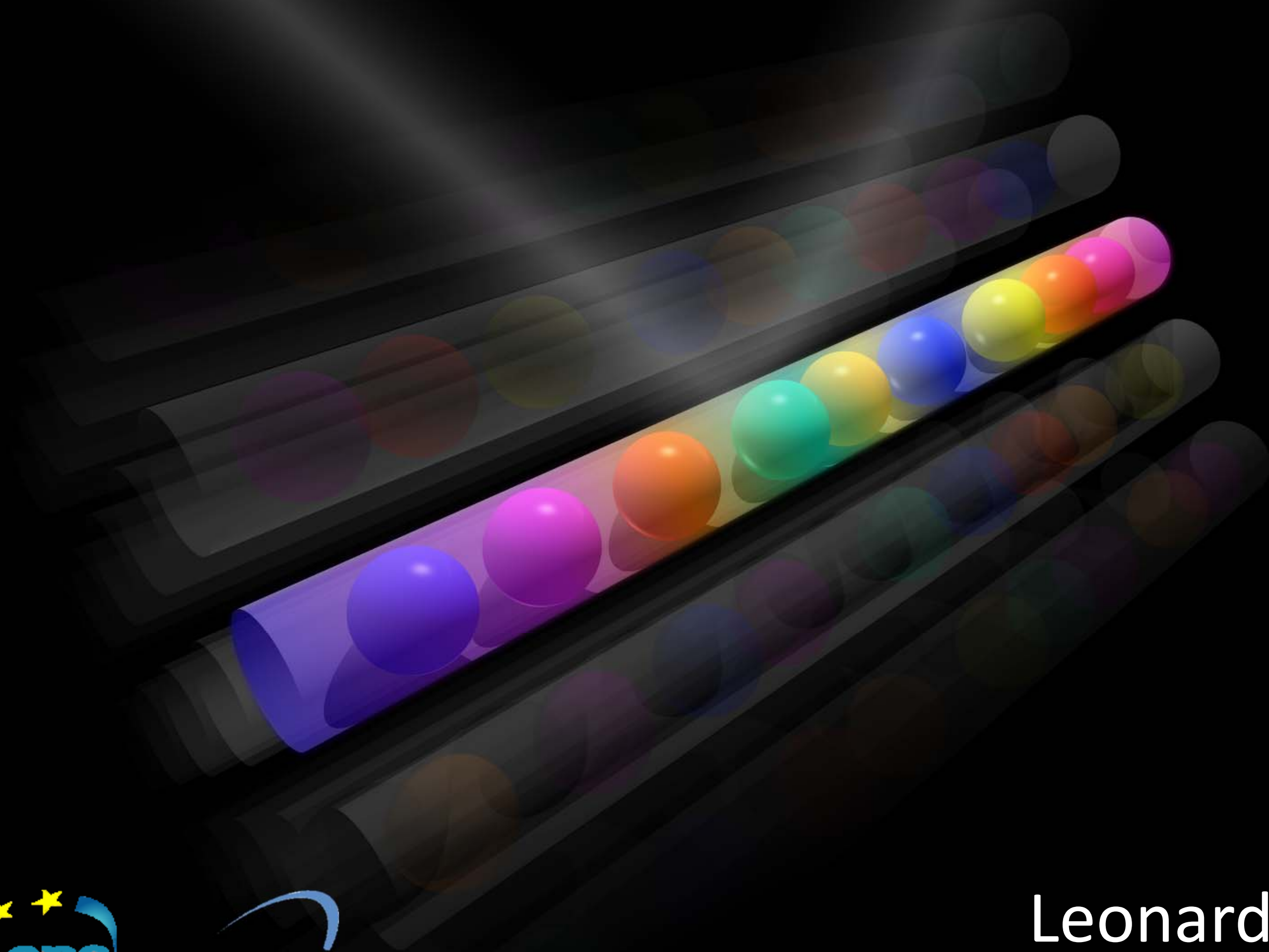
New quantum simulators with ultracold SU(N) fermions

INFN What Next – Fisica Fondamentale
Firenze, May 5th 2015



Leonardo Fallani

University of Florence, LENS & INFN

Introduction

Exploring quantum Hall physics

New directions: towards high-energy

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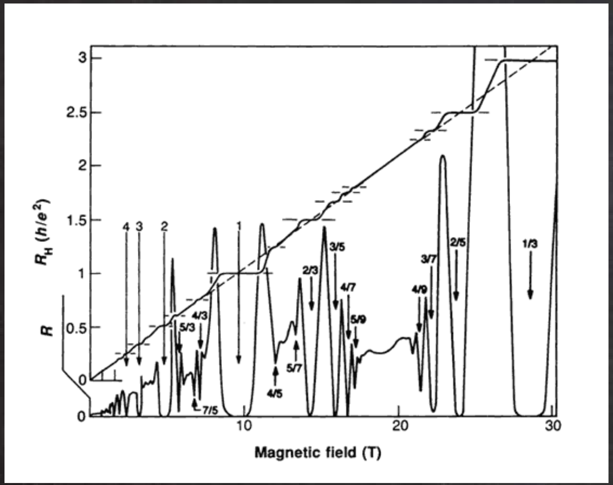
Exploring quantum Hall physics

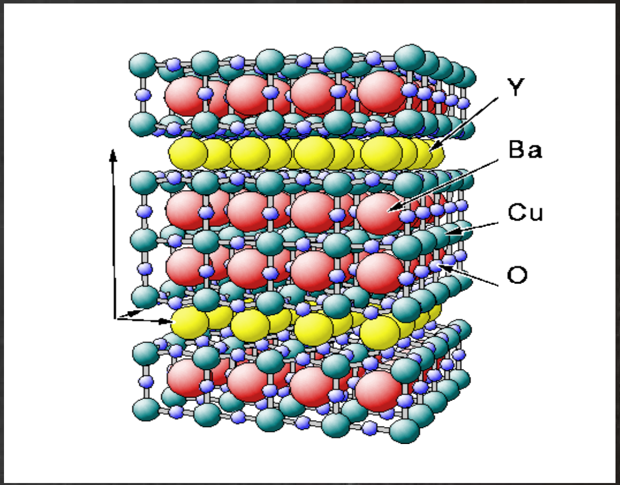
New directions: towards high-energy

Interacting fermionic systems

fractional Quantum Hall

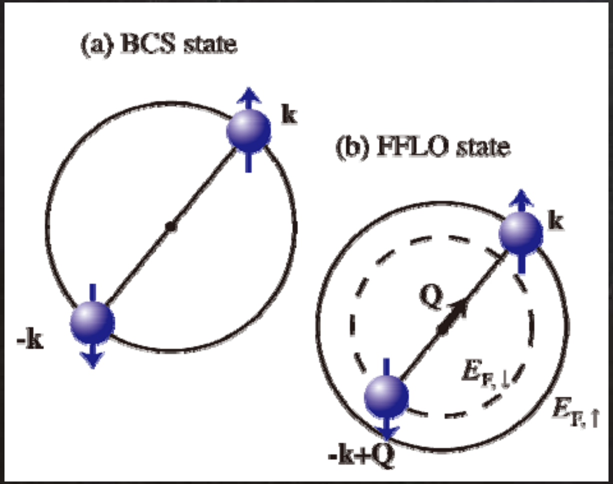


High-T_C superconductivity

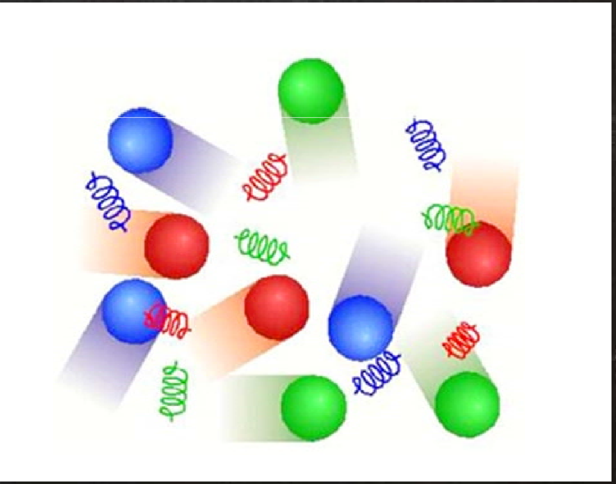


Fundamental physics…

Fermionic superfluidity



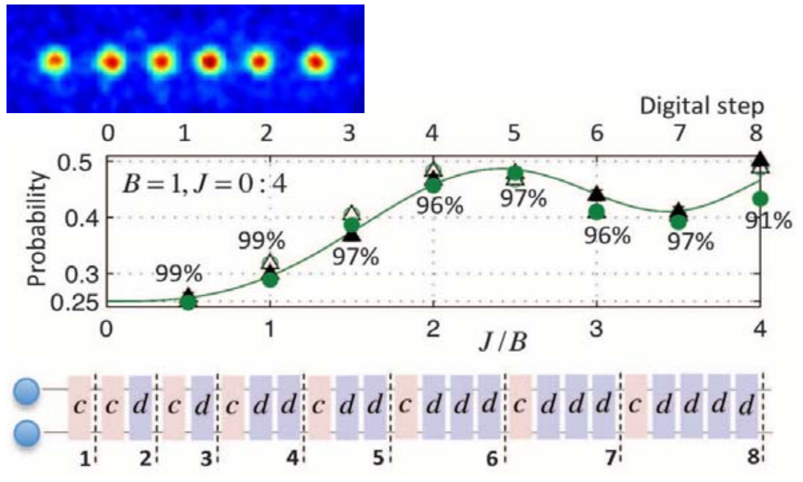
Strong interactions



Quantum simulators

Quantum simulators: quantum machines designed to solve physical problems untractable by a classical hardware

Digital quantum simulator

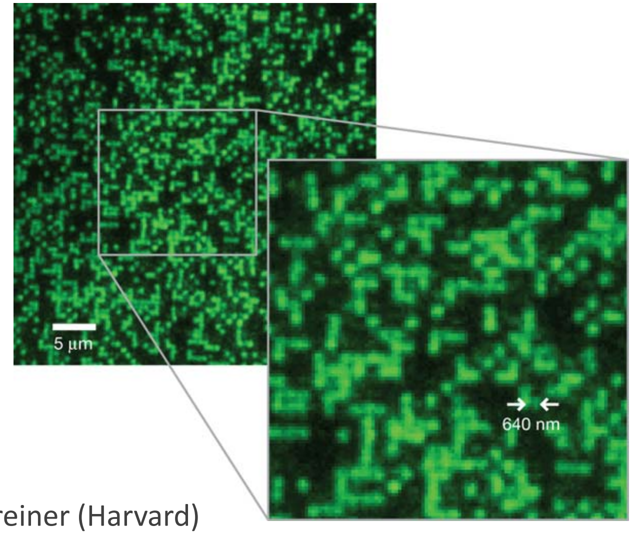


R. Blatt (Innsbruck)

Implementation of quantum gates and quantum algorithms (**<u>few qubits</u>**)

examples: ions, superconducting circuits

Analog quantum simulator



M. Greiner (Harvard)

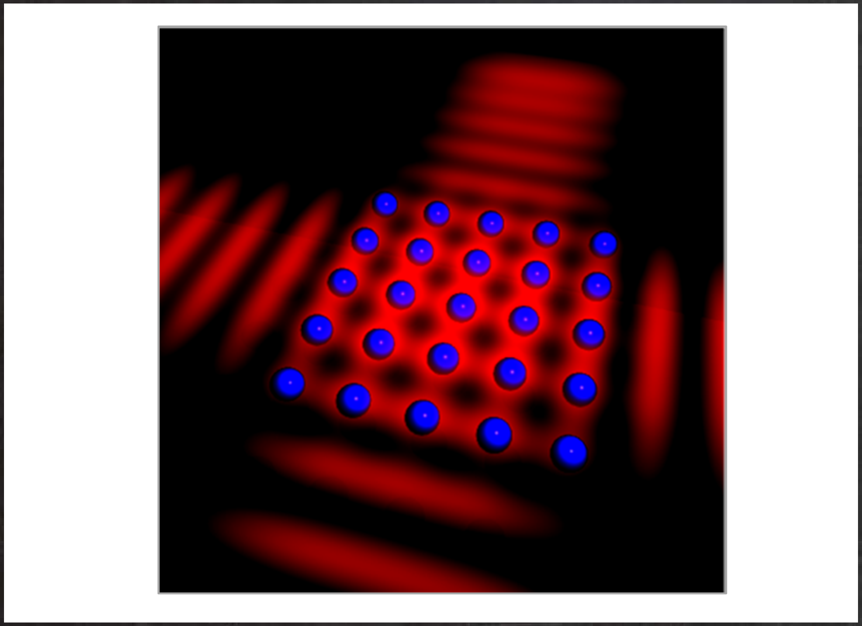
Engineering a system (**<u>many particles</u>**) to behave according to a target model

example: ultracold atoms

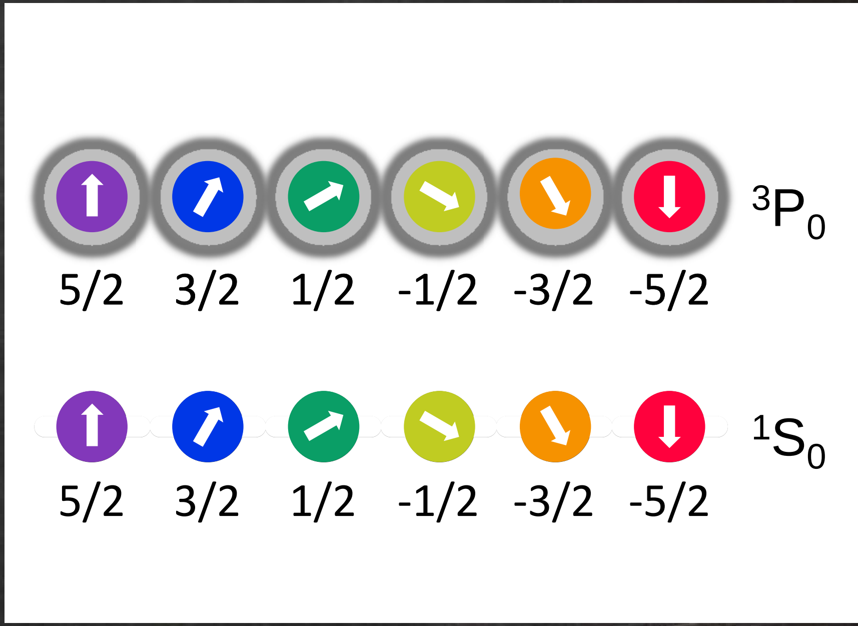
Ultracold atoms

Ultracold atoms: a physical system with extended possibilities of quantum control

External motion



Internal state



- cooling to quantum degeneracy
- optical trapping (lattices, …)
- tuning mobility and dispersion
- control of disorder and topology
- …

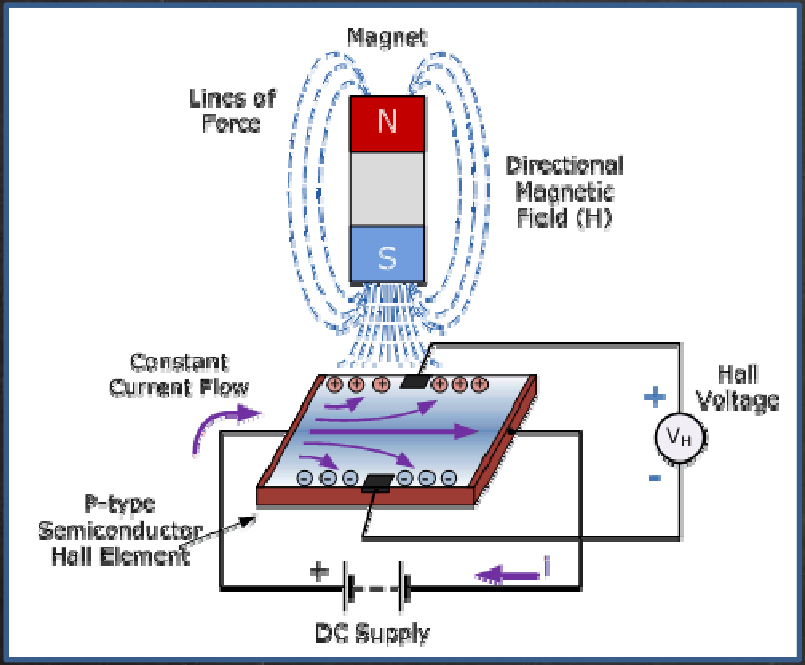
- electronic state
- spin state
- spectroscopy
- coherent control
- …

Introduction

Exploring quantum Hall physics

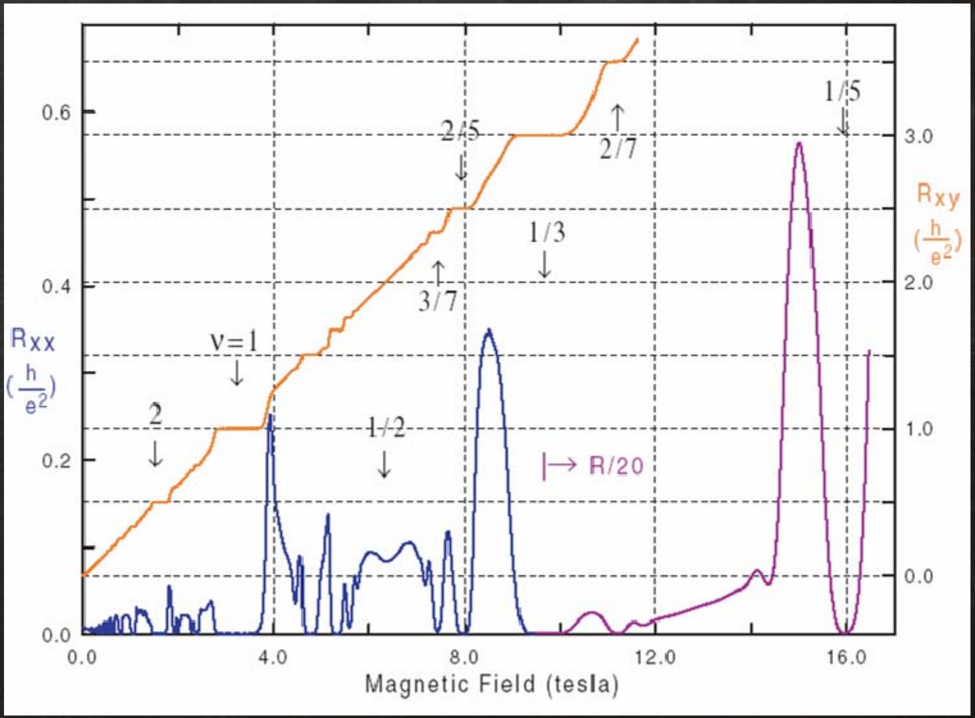
New directions: towards high-energy

Quantum Hall effect



Quantization of Hall conductance

$$\sigma_{xy} = \frac{i}{V_H} = \nu \frac{e^2}{h}$$



von Klitzing (1980)
Stoermer, Tsui (1982)
Laughlin (1983)

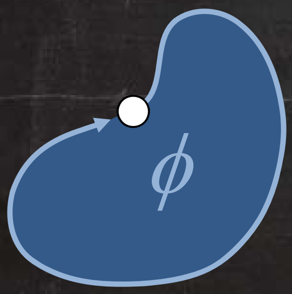
Magnetic fields

How to produce a Lorentz force for neutral atoms?

Magnetic field $\vec{B}$ $\longrightarrow$ Magnetic vector potential $\vec{A}$ $\quad \vec{B} = \nabla \times \vec{A}$

Gauge invariance: $\vec{A} \rightarrow \vec{A} + \nabla\chi$

Quantum mechanically… $$\widehat{H} = \frac{1}{2m}\left(\vec{p} - q\vec{A}\right)$$

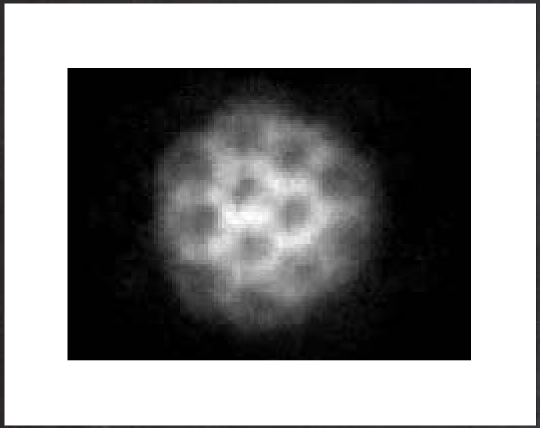


Aharonov-Bohm geometric phase for the closed loop of a charged particle in a magnetic field

$$\psi \rightarrow e^{i\phi}\psi \qquad \phi = 2\pi\frac{\Phi}{\Phi_0} \qquad \Phi_0 = \frac{h}{e}$$

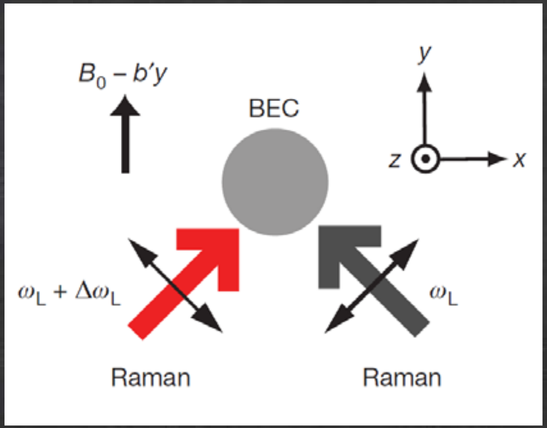
Artificial magnetic fields for ultracold atoms

Gases under rotation



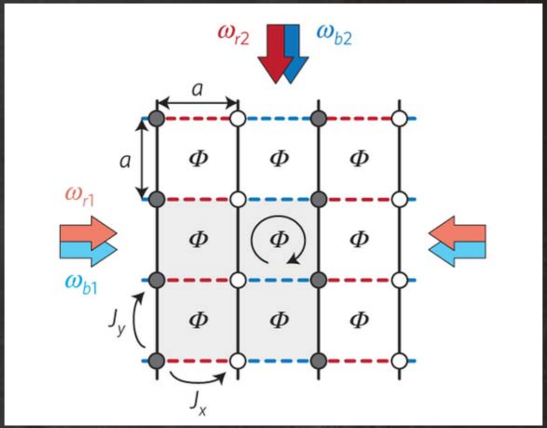
ENS, JILA, …

Raman transitions



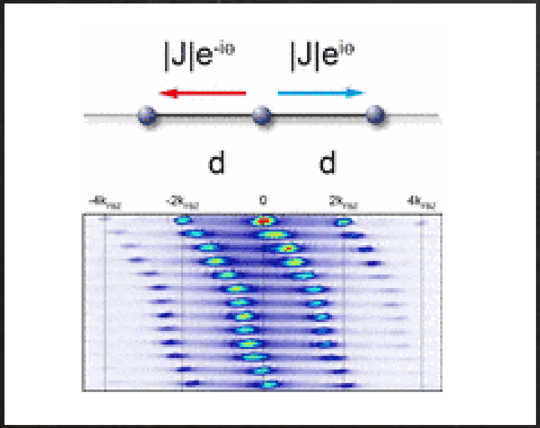
NIST

Laser-assisted tunnelling



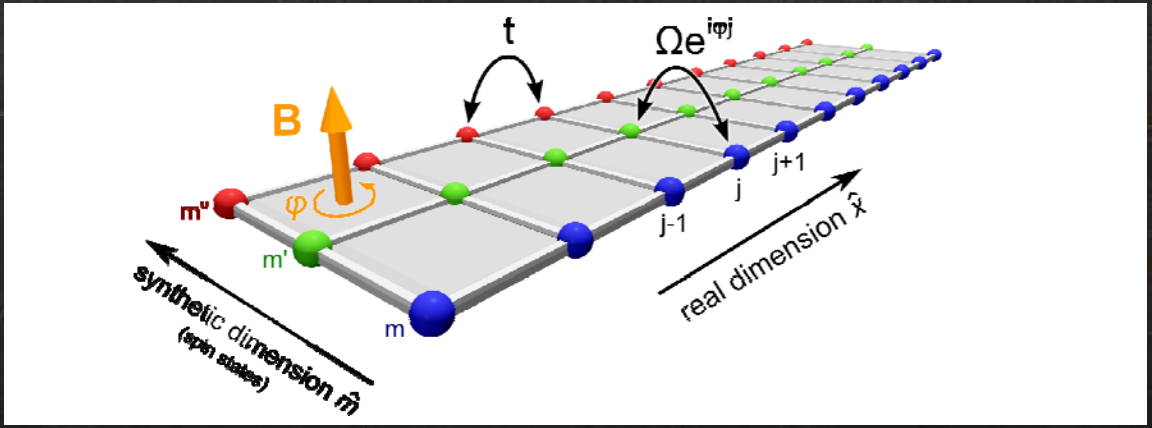
Munich, MIT

Lattice shaking



Hamburg, …

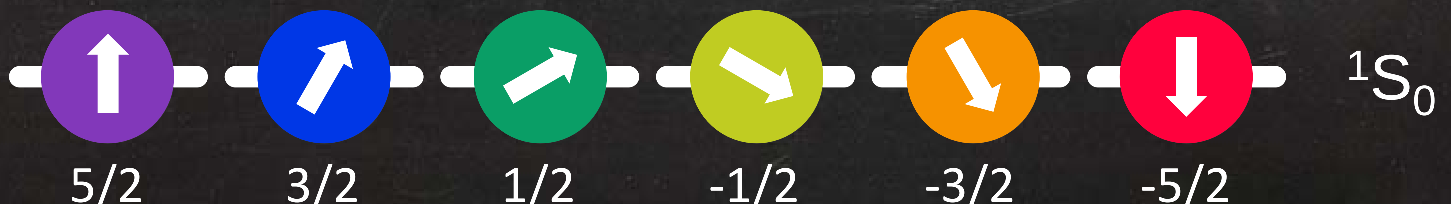
Synthetic dimensions



LENS, NIST

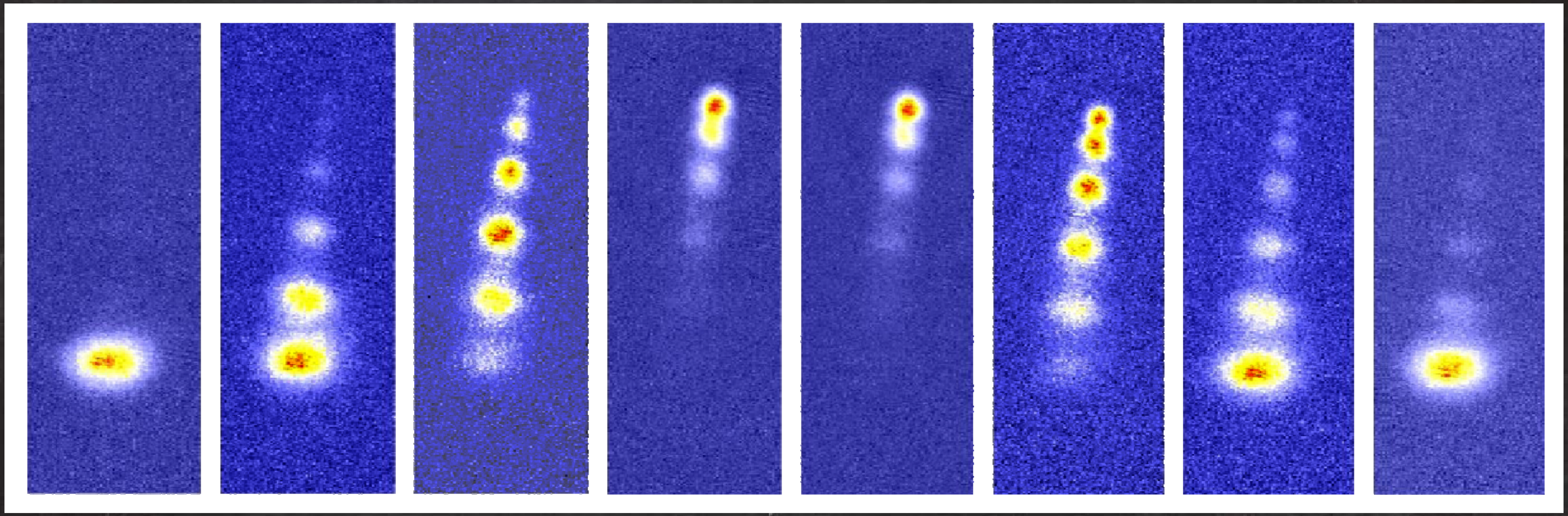
Simulating an "extra dimension"

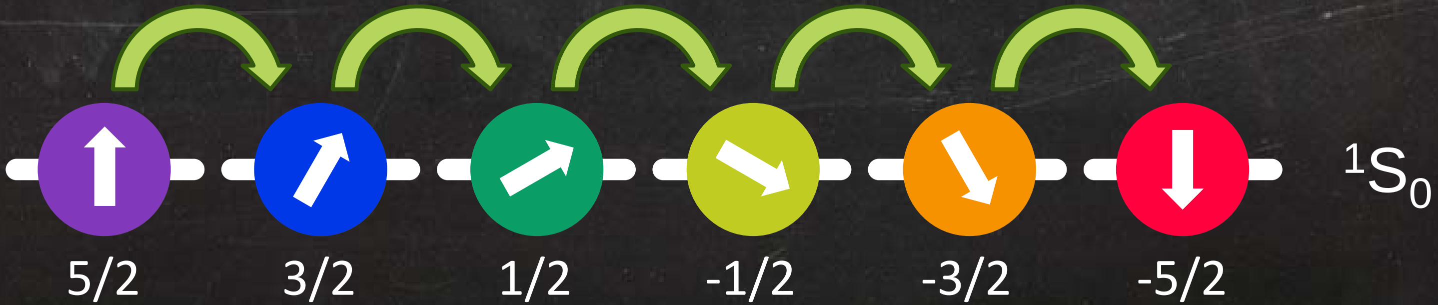
Multicomponent ^{173}Yb fermions (nuclear spin 5/2):



Simulating an "extra dimension"

Raman transitions coupling coherently different nuclear spin states:

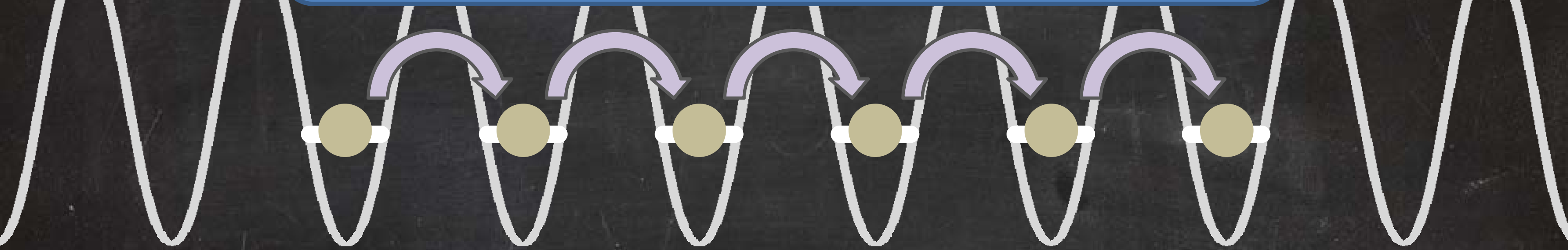




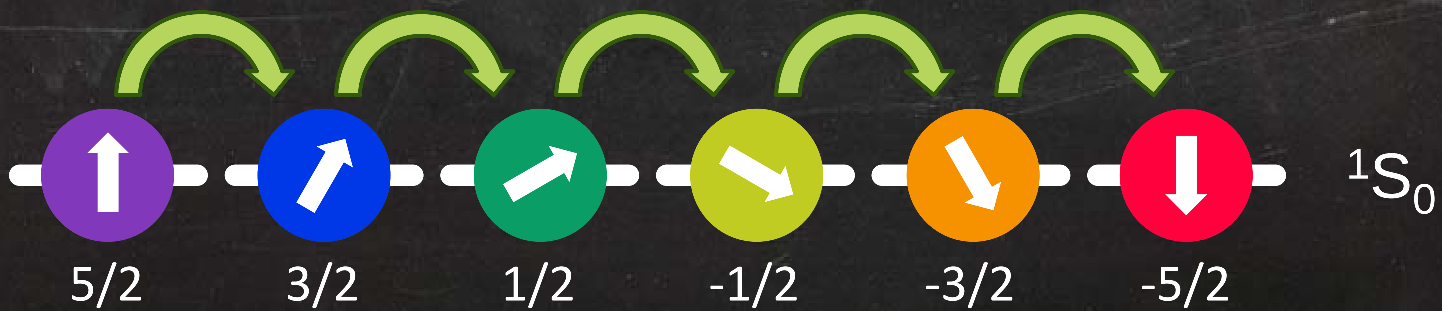
Simulating an "extra dimension"

Analogous to coherent tunnelling in a lattice:

$$H = -t \sum_j \left(c_j^\dagger c_{j+1} + h.c. \right)$$



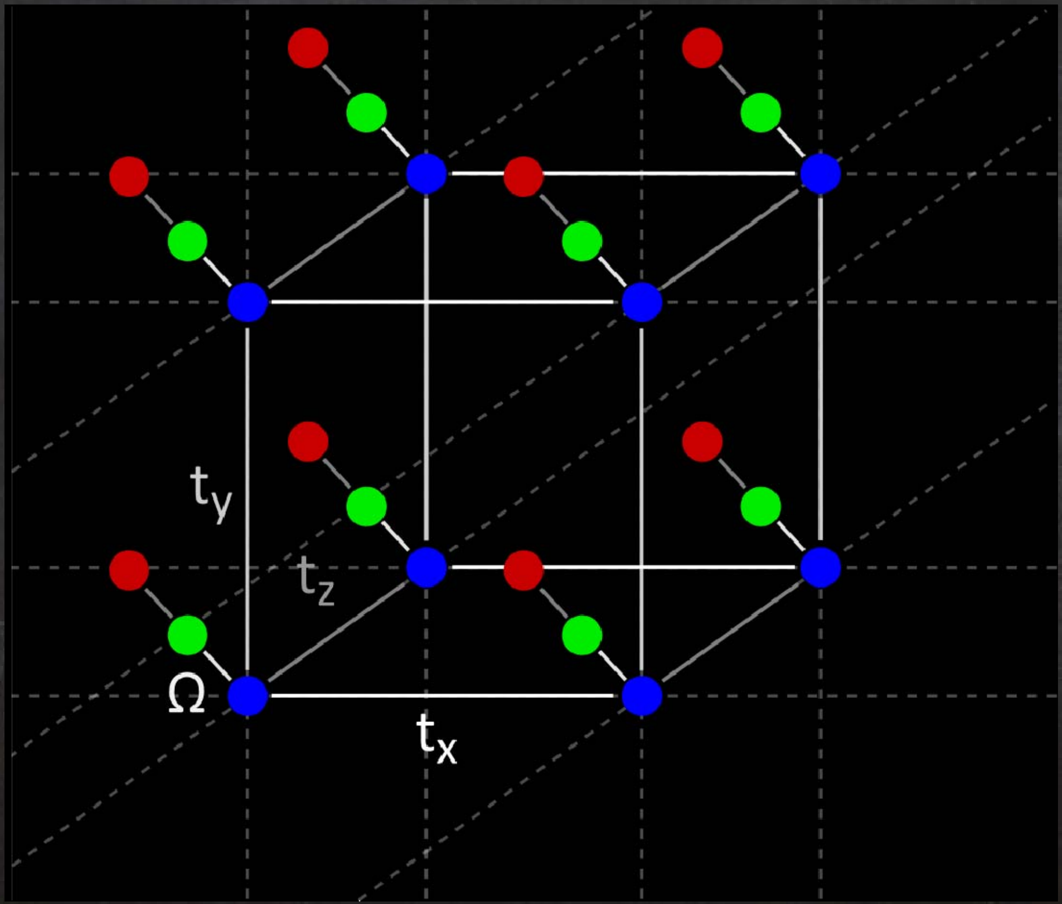
$$H = -\Omega \sum_m \left(c_m^\dagger c_{m+1} + h.c. \right)$$



Simulating an "extra dimension"

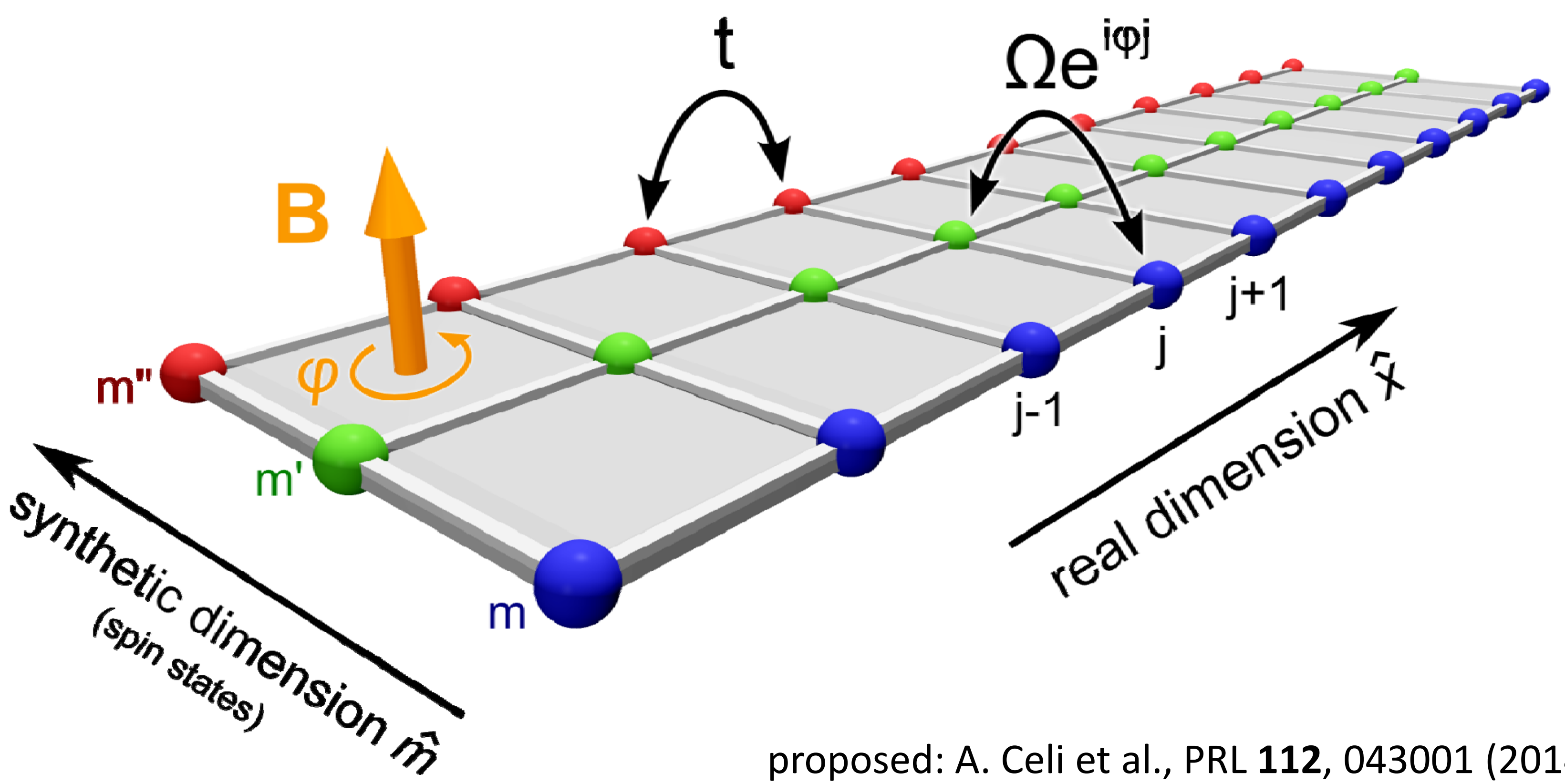
Raman transitions coupling coherently different nuclear spin states:

Realization of a synthetic lattice dimension O. Boada et al., PRL **108**, 133001 (2012)



An atomic Hall ribbon

Investigating topological states of matter in a **hybrid lattice**



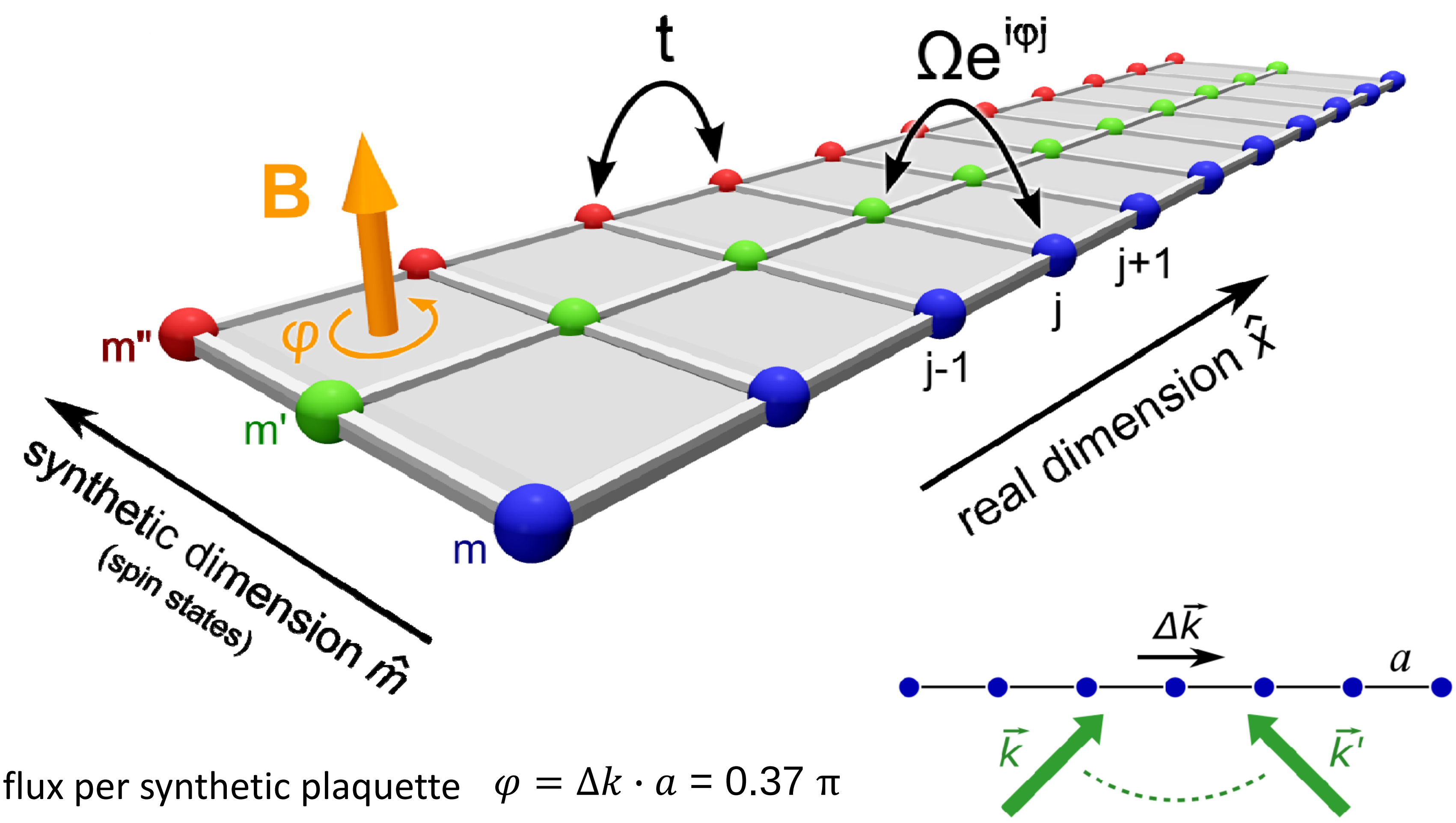
proposed: A. Celi et al., PRL **112**, 043001 (2014)

realized: M. Mancini et al., arXiv:1502.02495 (2015)
B. K. Stuhl et al., arXiv:1502.02496 (2015)

An atomic Hall ribbon

Feature #1

Complex laser-assisted tunneling →
Synthetic gauge fields with minimal requirements



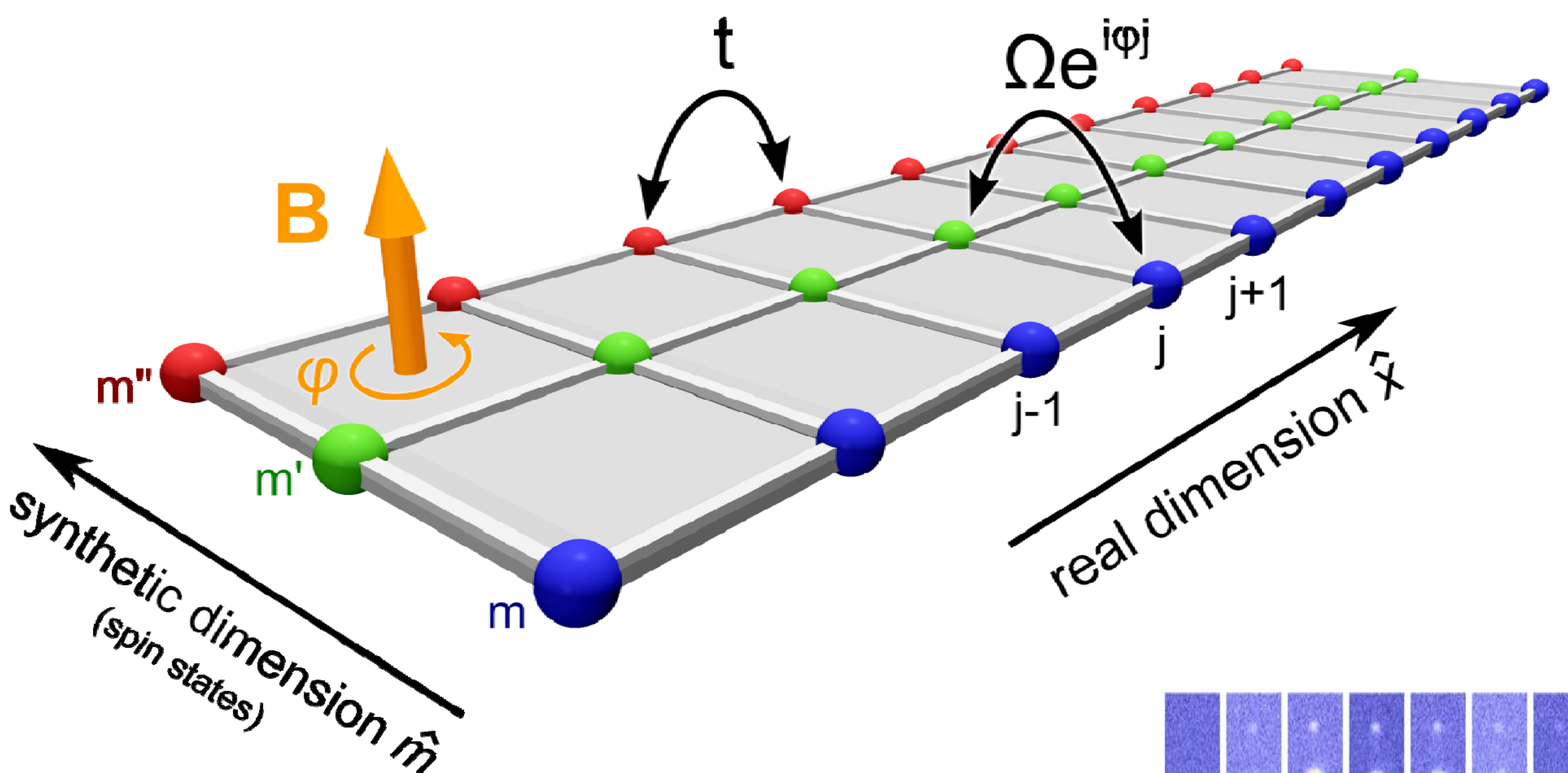
flux per synthetic plaquette $\varphi = \Delta k \cdot a = 0.37\,\pi$

An atomic Hall ribbon

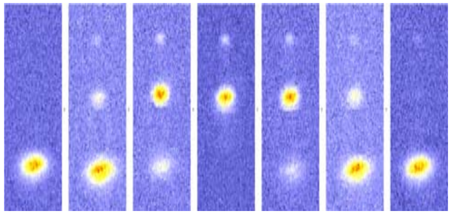
Feature #2

<u>Sharp and addressable edges</u>

Single-site imaging along synthetic dimension



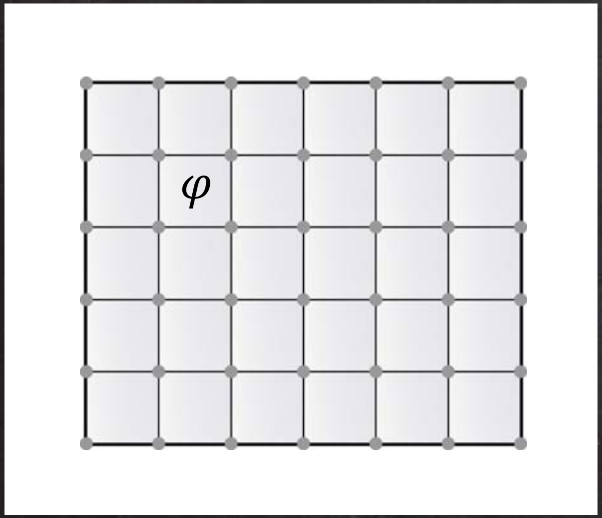
optical Stern-Gerlach
Spin-selective imaging

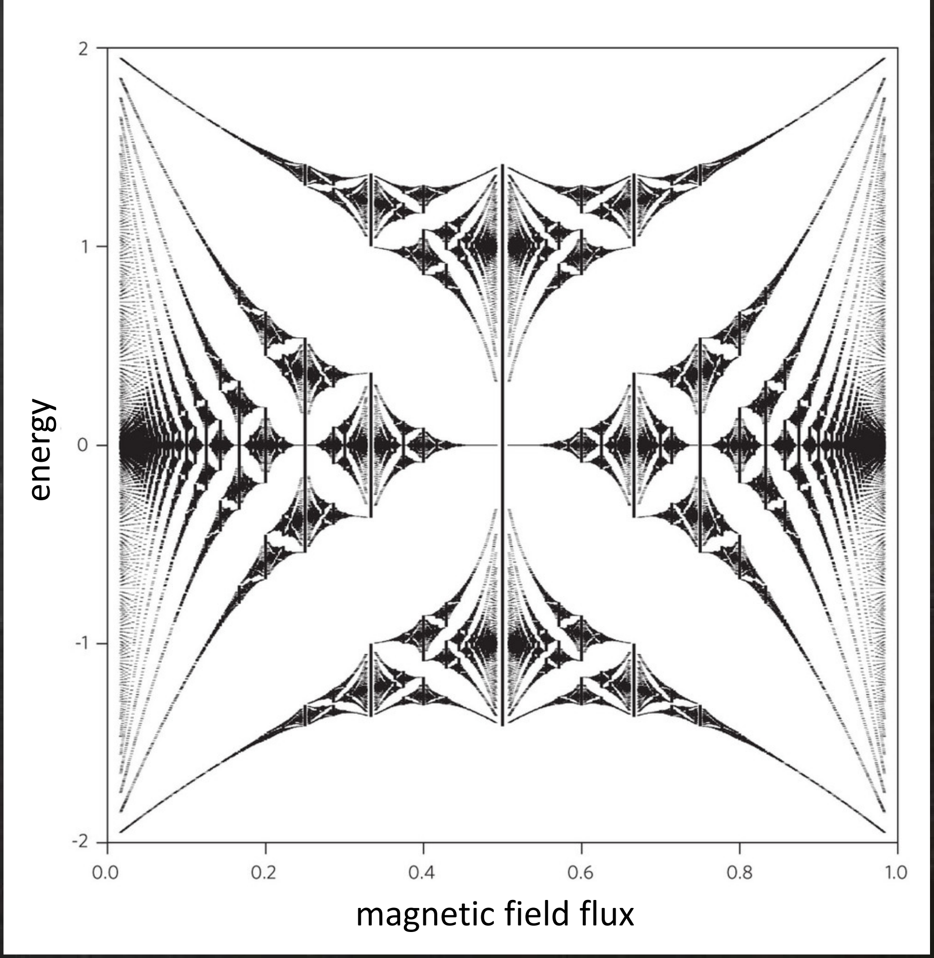


Harper-Hofstadter model

$$H = -t \sum_{j,m} \left(c^{\dagger}_{j,m} c_{j+1,m} + h.c.\right) - \Omega \sum_{j,m} \left(e^{i\varphi j} c^{\dagger}_{j,m} c_{j,m+1} + h.c.\right)$$

Harper, Proc. Phys. Soc. A **68**, 874 (1955)
Hofstadter, PRB **14**, 2239 (1976)





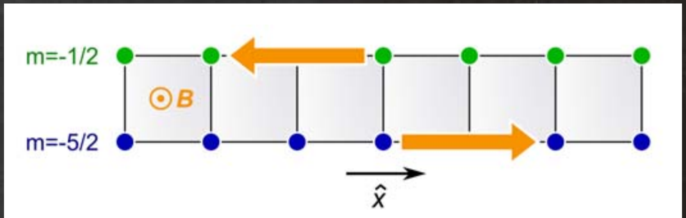
The Hofstadter butterfly

Spectrum of a charged particle
in a 2d lattice + magnetic field (bulk states)

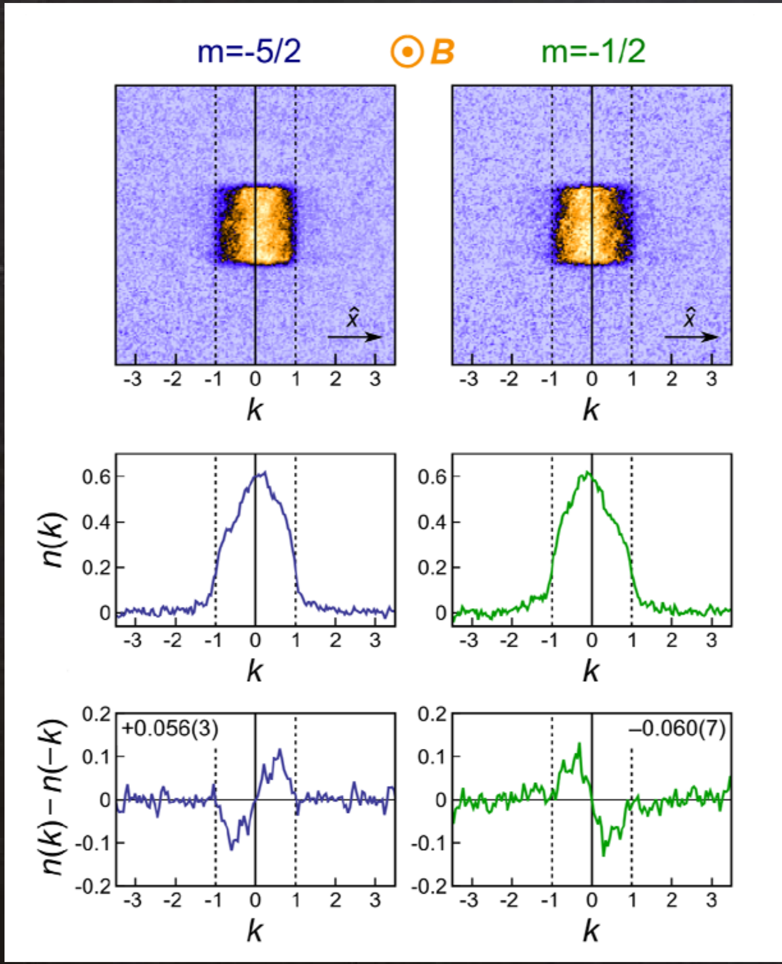
2-leg fermionic ladders

M. Mancini et al., arXiv:1502.02495 (2015)

Adiabatic loading of a 2-leg ladder (edges only)



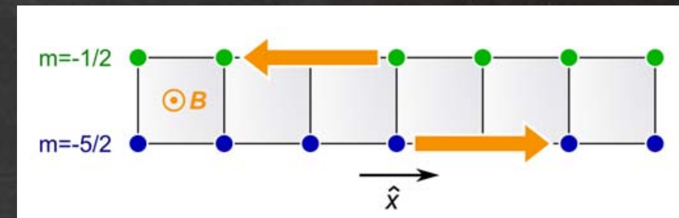
Lattice momentum distribution:



Chiral edge currents circulating along the edges

M. Mancini et al., arXiv:1502.02495 (2015)

2-leg fermionic ladders



Adiabatic loading of a 2-leg ladder (edges only)

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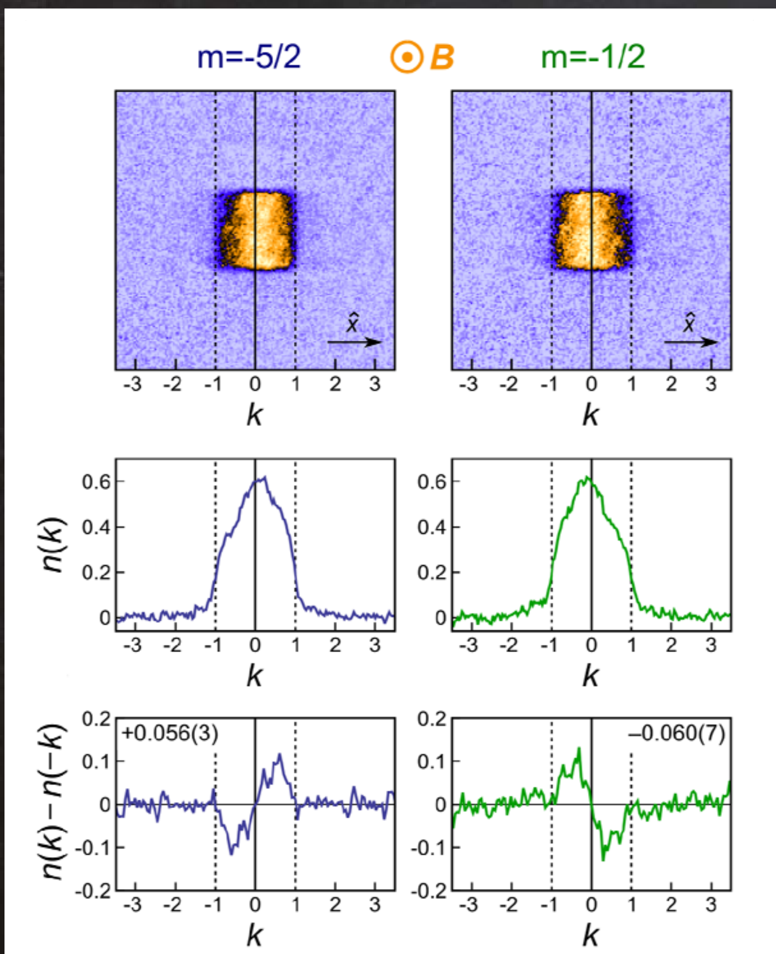
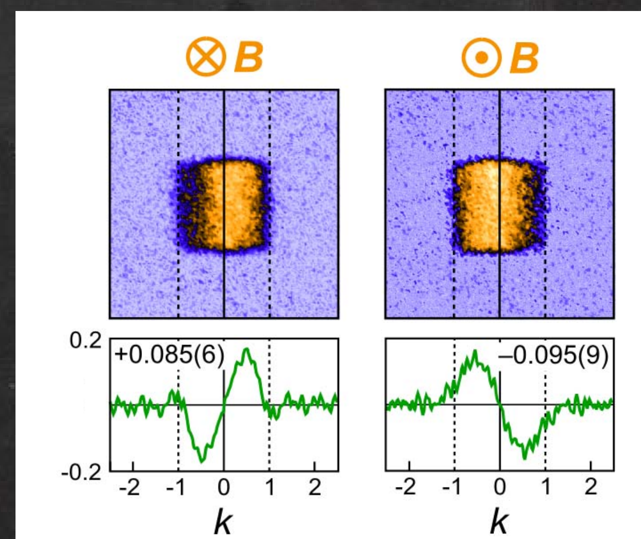


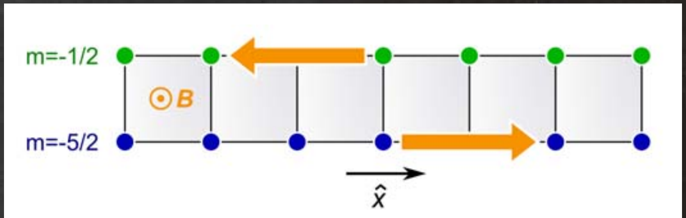
Chirality depends on the flux sign!



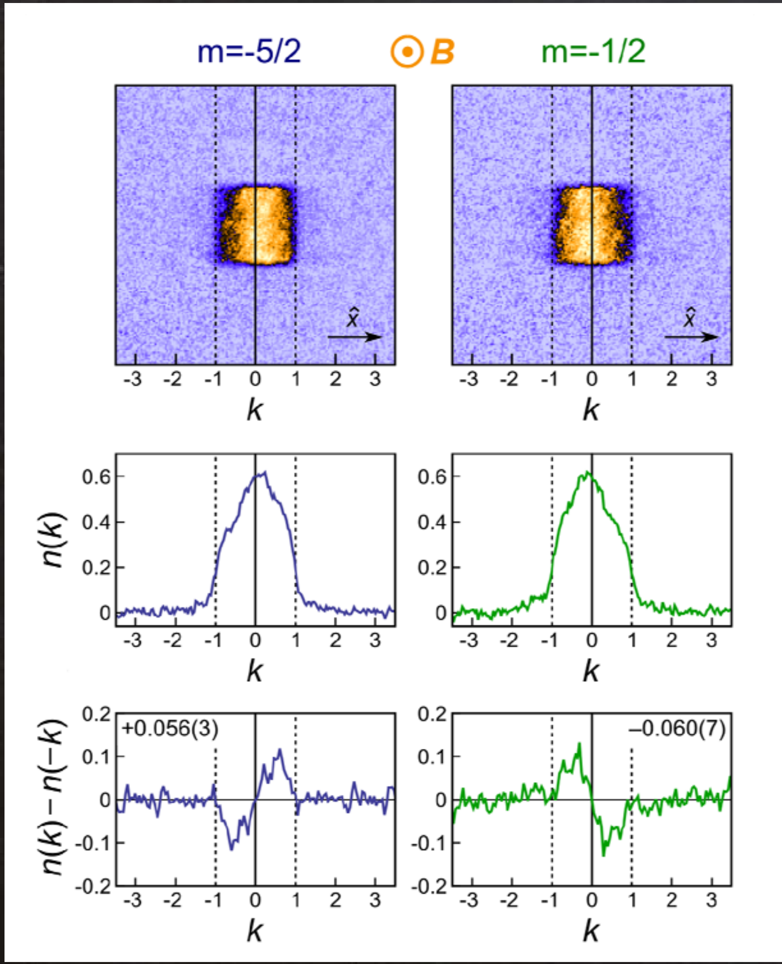
M. Mancini et al., arXiv:1502.02495 (2015)

2-leg fermionic ladders

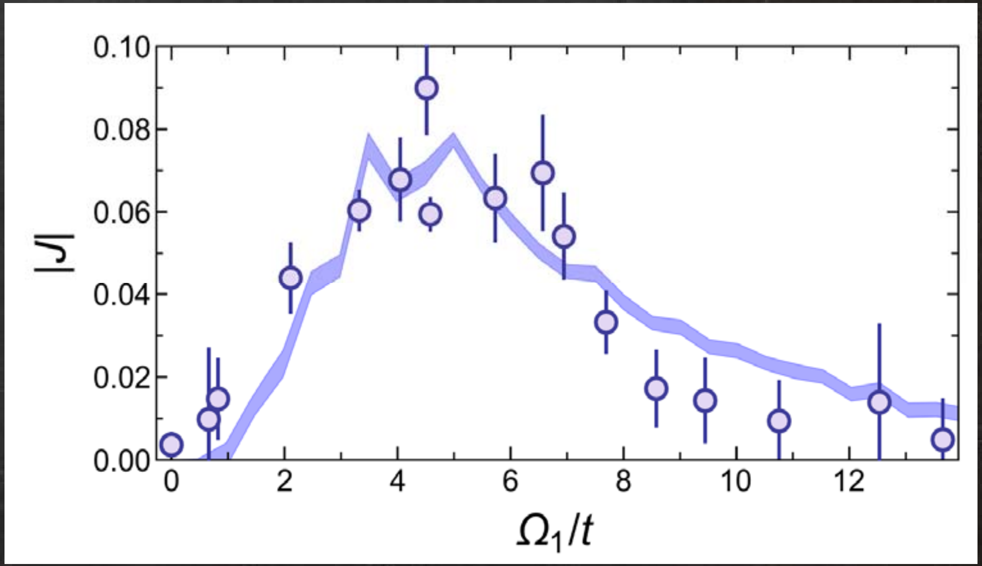
Adiabatic loading of a 2-leg ladder (edges only)



Lattice momentum distribution:



Chiral phase transition vs. lattice anisotropy
(theory by M. Rider, P. Zoller, M. Dalmonte)



see related work on bosonic ladders:

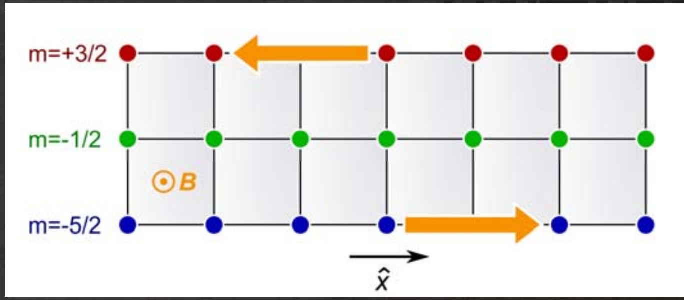
experiment: M. Atala et al., Nature Phys. **10**, 588 (2014)

theory: E. Orignac, T. Giamarchi, PRB **64**, 144515 (2001)
M. Piraud et al., arXiv:1409.7016 (2014) ….

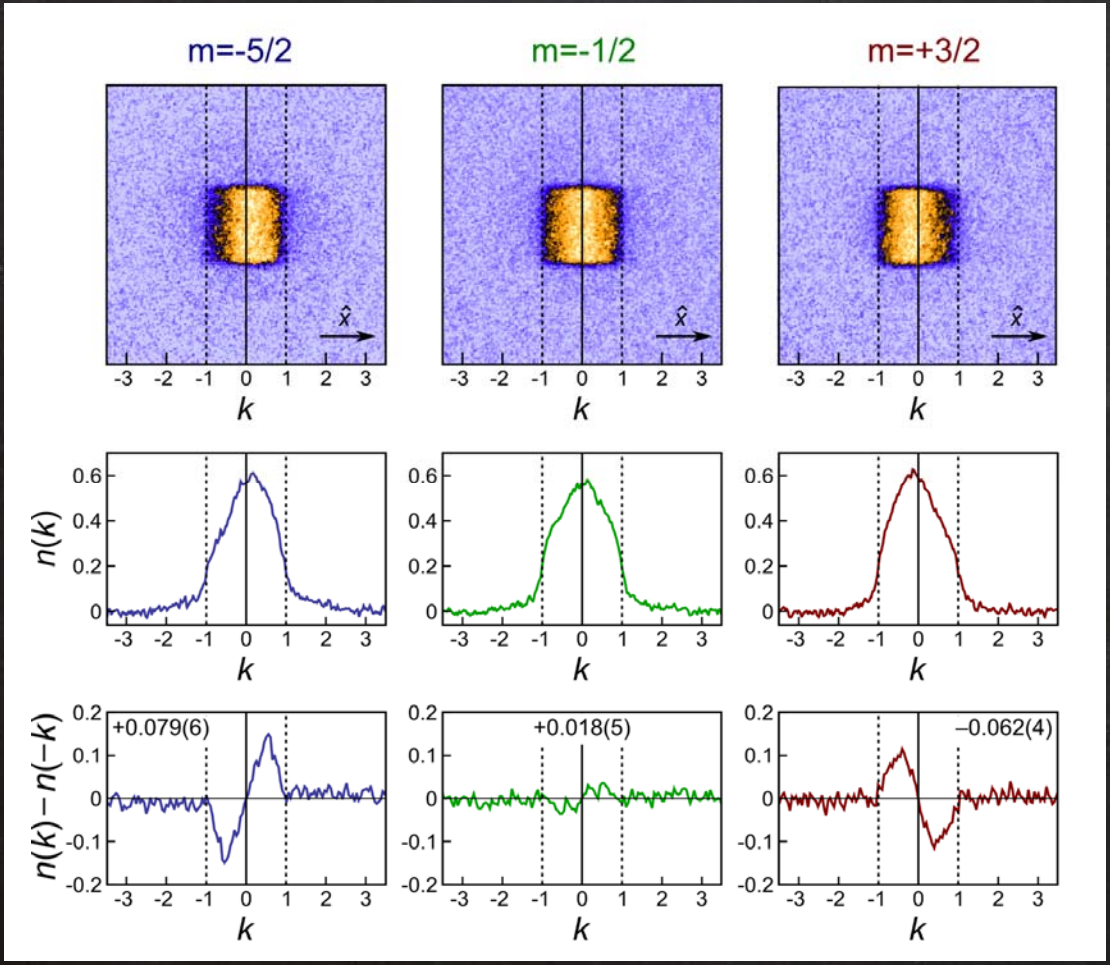
M. Mancini et al., arXiv:1502.02495 (2015)

3-leg fermionic ladders

Adiabatic loading of a 3-leg ladder (edges + bulk)



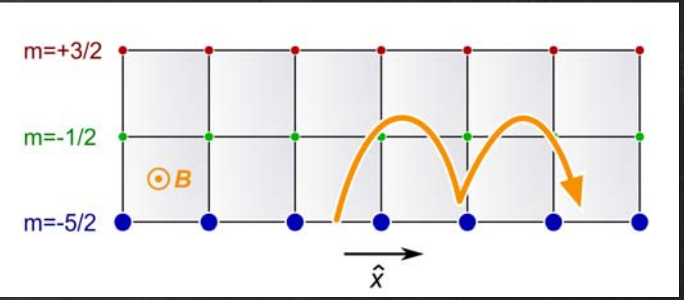
Lattice momentum distribution:



Observation of insulating bulk and chiral edge currents

M. Mancini et al., arXiv:1502.02495 (2015)

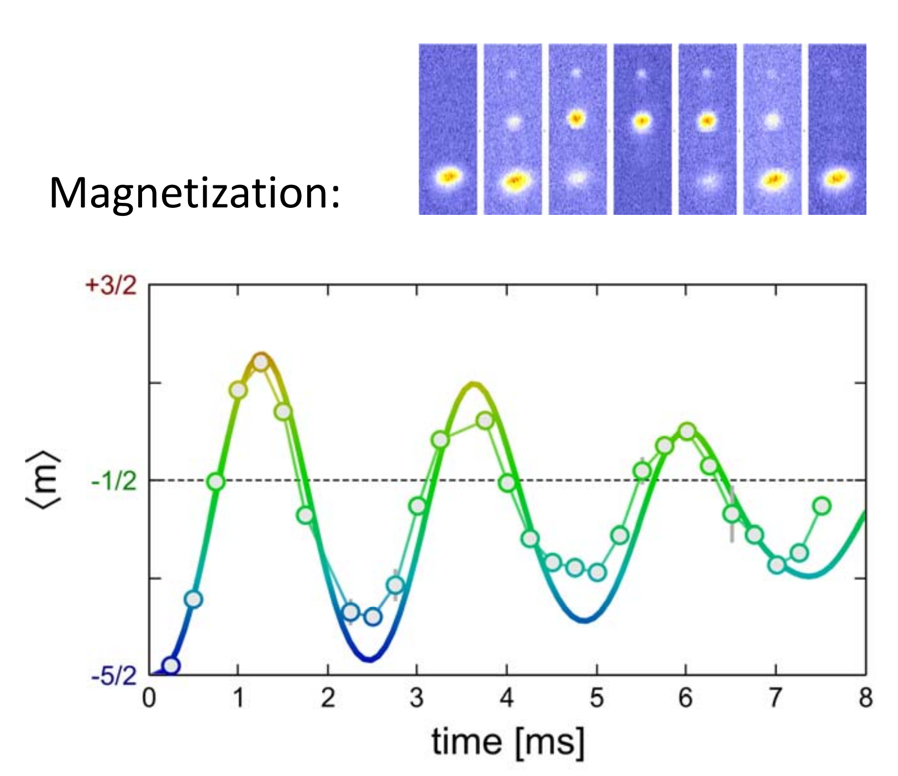
Edge-cyclotron orbits



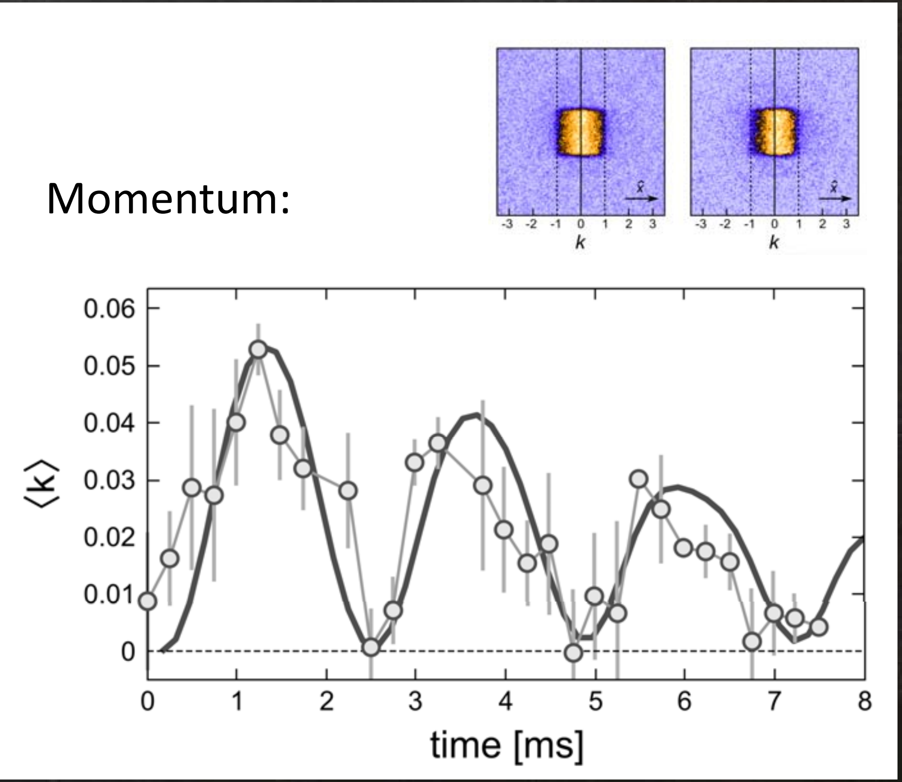
Initial state with <k>=0 on the m=-5/2 leg

Quenched dynamics after activation of synthetic tunneling

Magnetization:

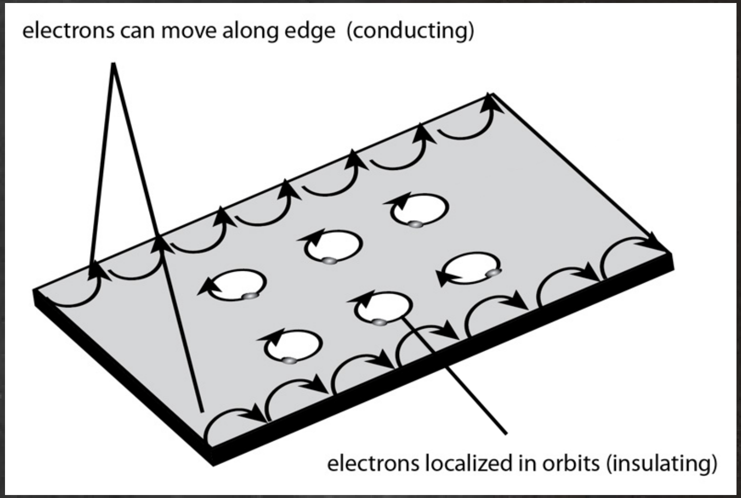


Momentum:



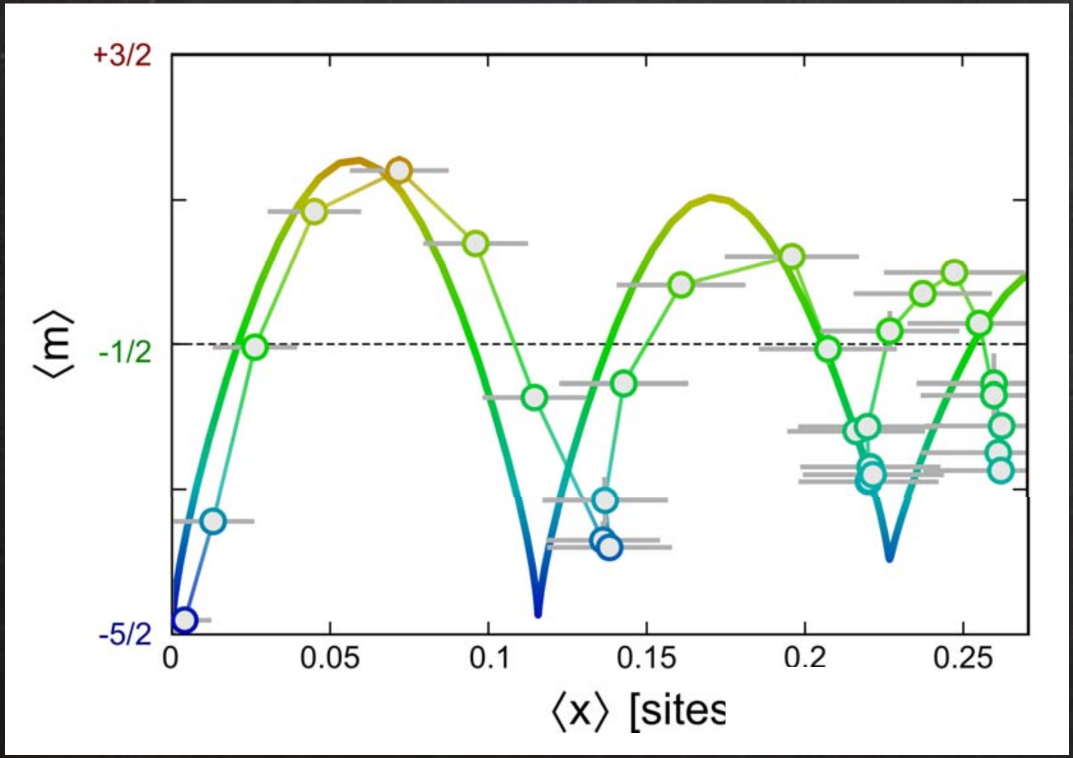
M. Mancini et al., arXiv:1502.02495 (2015)

Edge-cyclotron orbits



A hallmark of quantum Hall physics:

Visualization of edge-cyclotron orbits



Theory by M. Dalmonte,
P. Zoller, M. Rider (Innsbruck)

Related work at NIST:
B. K. Stuhl et al., arXiv:1502.02496 (2015)

Outlook: synthetic dimensions

Synthetic dimensions: a brand new concept for atomic physics experiments

New manipulation/detection possibilities

Measurement of topological invariants — L. Wang et al., PRL **110**, 166802 (2013)

Topological charge pumping — N. Cooper & A. M. Rey, arXiv:1503.05498 (2015)

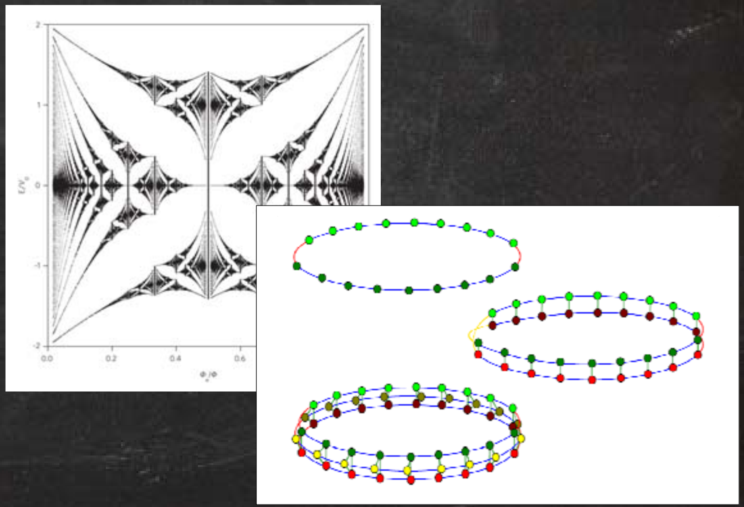
Engineering topology

Periodic boundary conditions

Rings, cylinders, tori, Moebius strips…

O. Boada et al., arXiv:1409.4770 (2014)

4-dimensional systems



Interactions + gauge fields

Fractional quantum Hall effect

New interaction-induced quantum phases — S. Barbarino et al., arXiv:1504.00164 (2015)

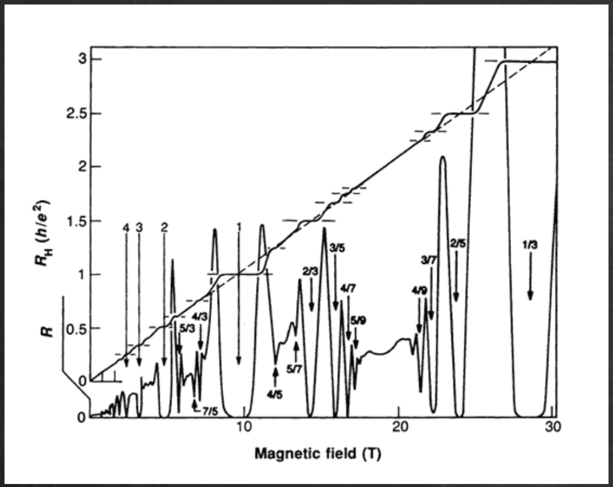
Introduction

Exploring quantum Hall physics

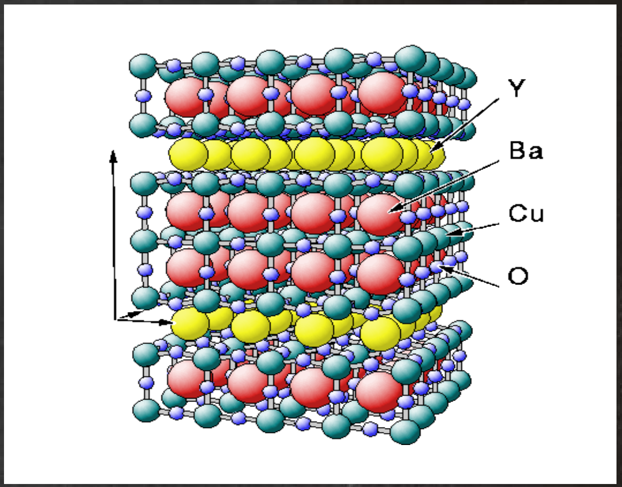
New directions: towards high-energy

What next?

fractional Quantum Hall

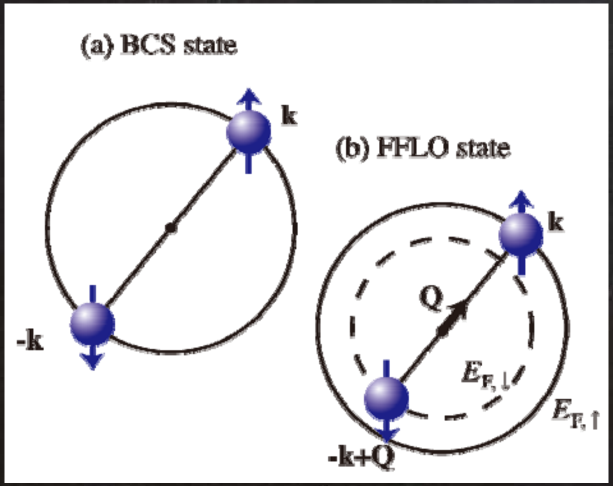


High-T_C superconductivity

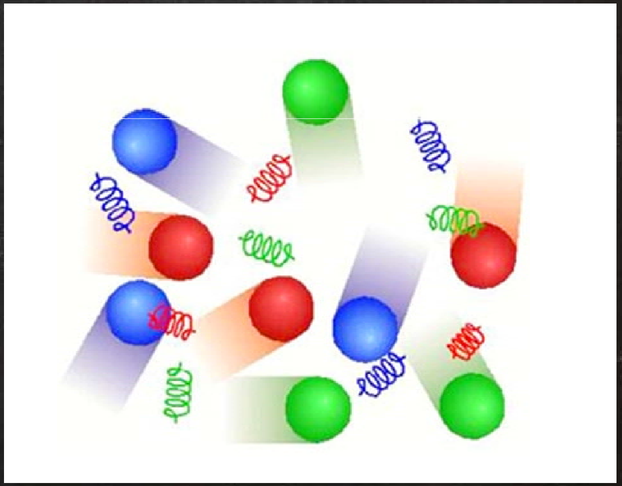


Fundamental physics…

Fermionic superfluidity

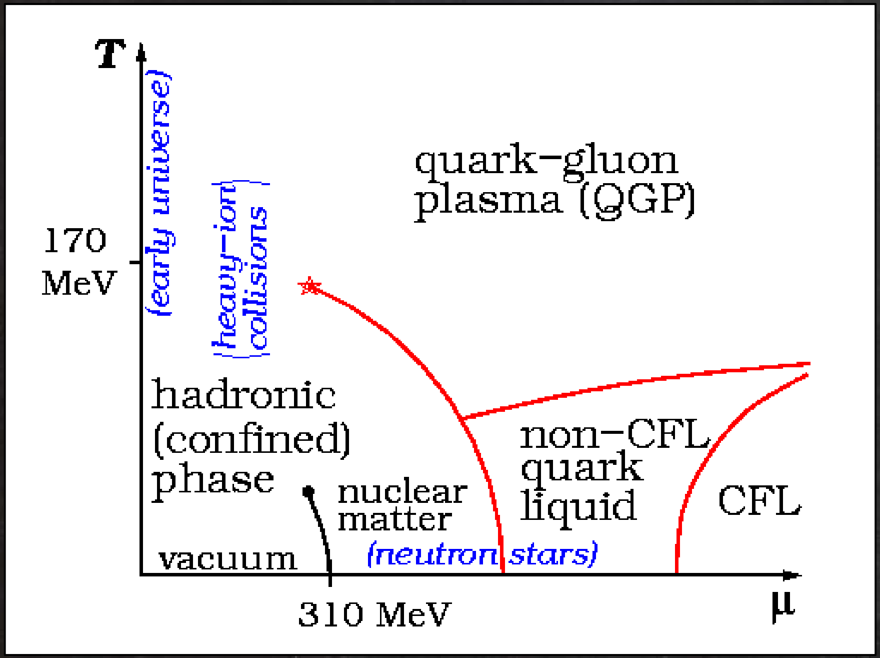


Strong interactions



An example: strong interactions

The Standard Model has received a huge number of experimental proofs.
However, fundamental problems are still open…



The QCD phase diagram is largely unknown

Exotic (color) fermionic superfluidity?
Dynamics of deconfined quarks?

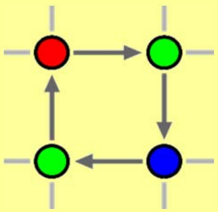
Can quantum simulators help us with these problems?

Ultracold simulation of high-energy physics

FISh
INFN
Fundamental Interactions Simulations
with quantum gases

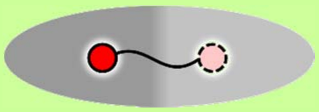
Realizzare dei simulatori quantistici di alcuni aspetti di fisica delle alte energie attraverso il controllo delle interazioni in gas atomici ultrafreddi

Firenze



Multi-component **fermions**
with SU(N)-symmetric interactions

Trento

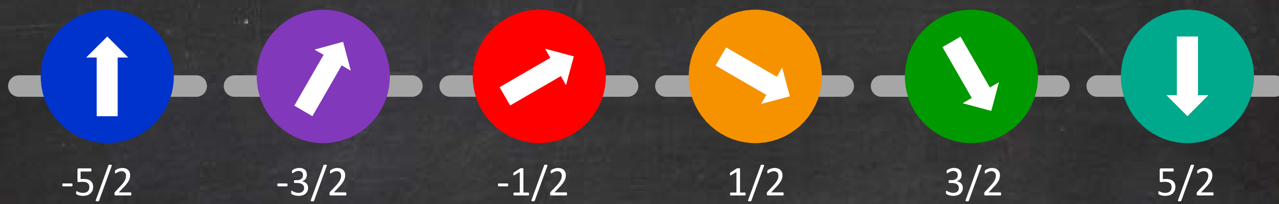


Topological defects in **BECs**
Simulation of quark confinement

Ultracold fermions with SU(N) interactions

A unique system: large-spin fermions with SU(N) interaction symmetry

^{173}Yb

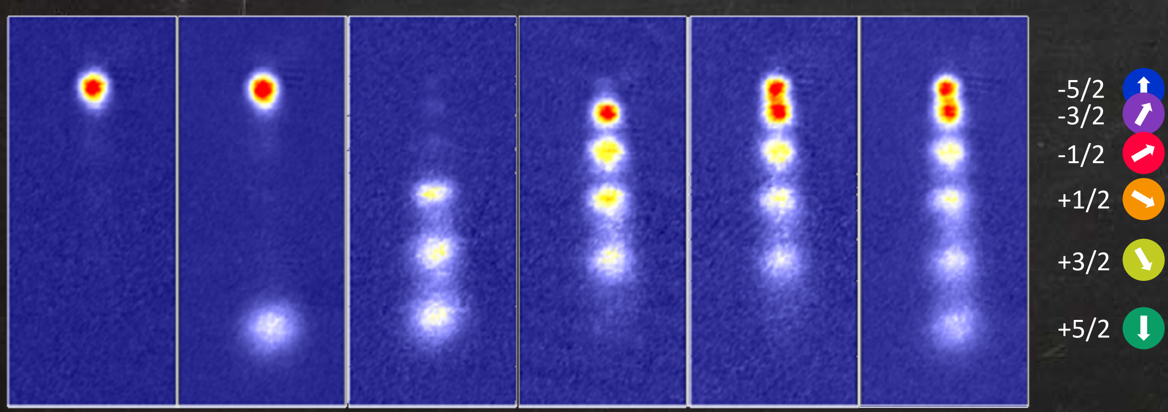


I=5/2

Same interactions between different nuclear spin states = "**colors**"

Investigation of strongly-interacting fermions with tunable interaction symmetry up to SU(6)

A. Gorshkov *al.*, Nat. Phys. **6**, 289 (2010)

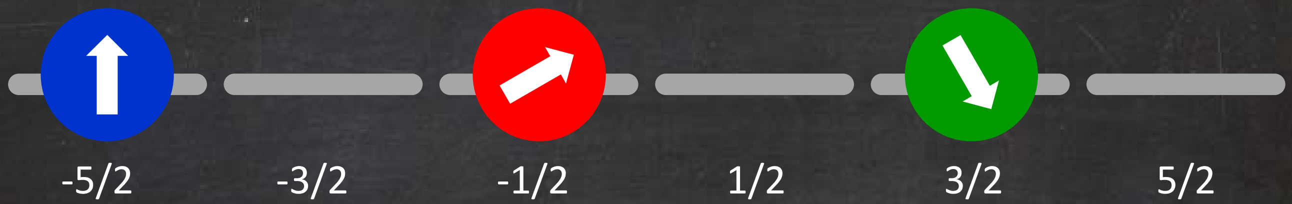


A novel quantum simulation tool!

Ultracold fermions with SU(N) interactions

A unique system: large-spin fermions with SU(N) interaction symmetry

^{173}Yb



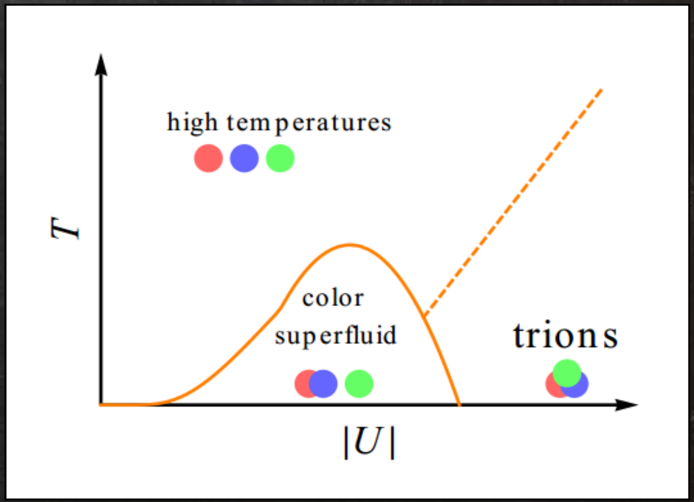
I=5/2

Same interactions between different nuclear spin states = "**colors**"

Strongly-interacting SU(3) fermions

Phase diagram of SU(3) fermions in an optical lattice

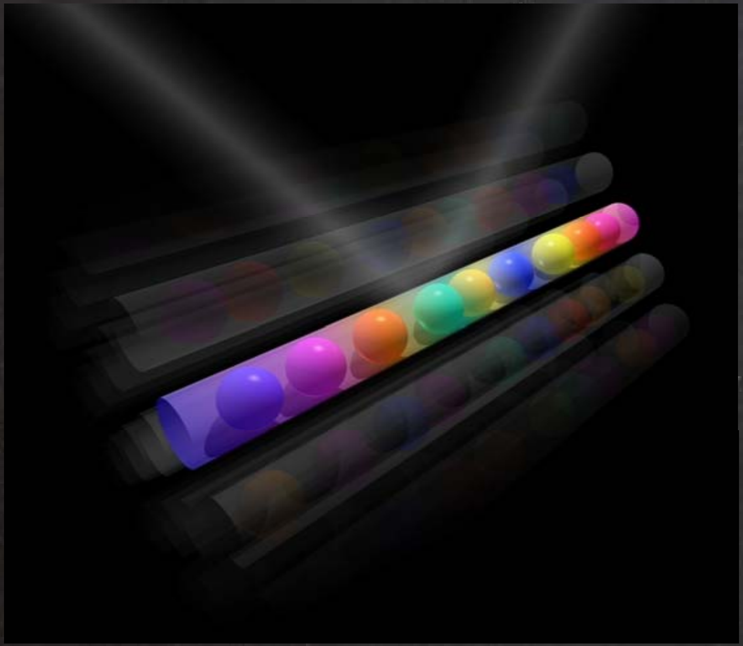
Color Superfluidity and "Baryon" Formation in Ultracold Fermions
A. Rapp et al., PRL **98**, 160405 (2007)
A. Rapp et al., PRA **85**, 043612 (2012)



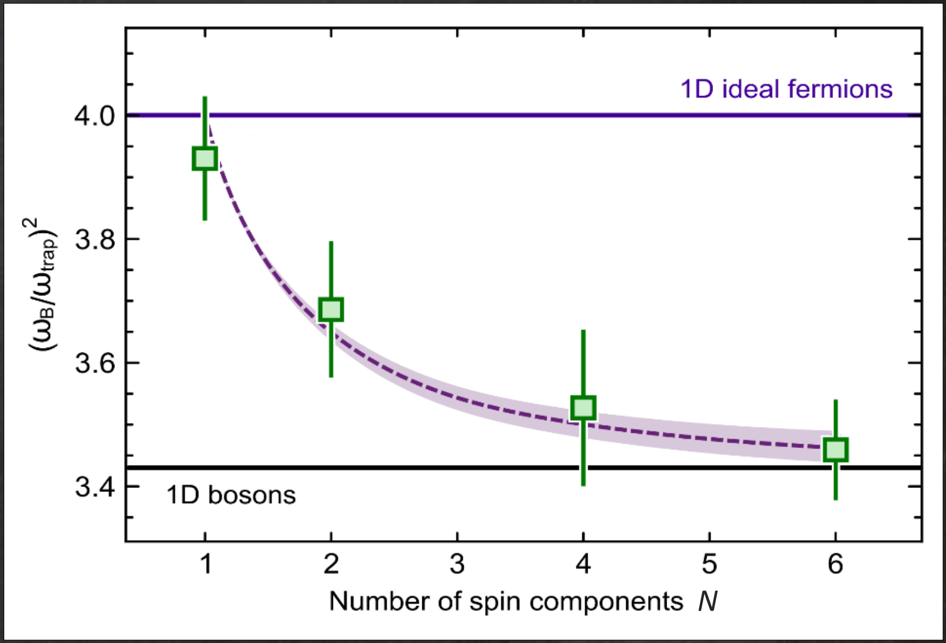
G. Pagano et al., Nature Phys. ***10***, *198 (2014)*

1D SU(N) fermions

1D multicomponent SU(N) fermions



Frequency of the 1D breathing mode:



For $N \to \infty$ the breathing frequency approaches that of spinless bosons

«bosonization» of large-spin fermions

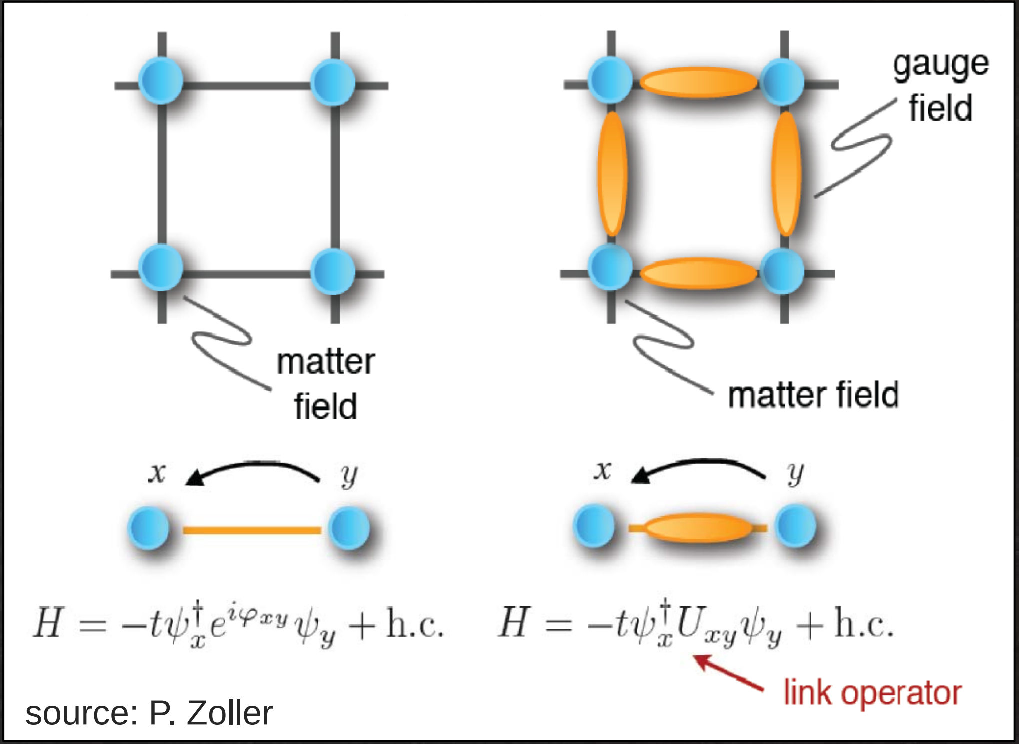
C. N. Yang & Y. Yi-Zhuang, CPL **28**, 020503 (2011)

Quantum simulation of gauge theories

Quantum simulation of fermionic matter coupled to gauge fields

Recent proposals for the implementation of lattice gauge fields and gauge theories in Yb atoms with laser-assisted tunnelling in structured optical lattices

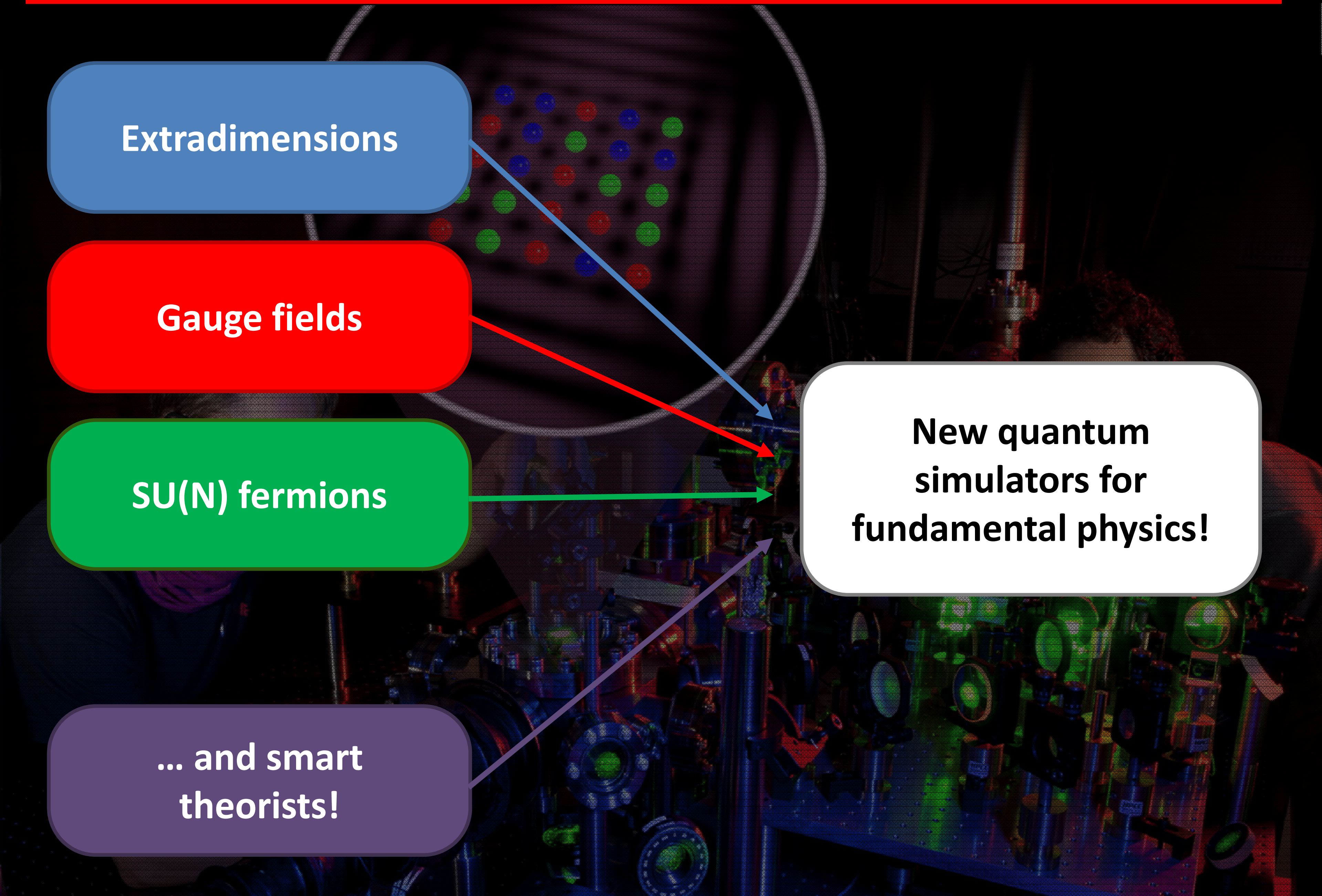
- Abelian and non-abelian gauge fields for ultracold atoms
- Dynamical gauge fields (simple instances of lattice gauge theories)



Theory collaboration:
M. Dalmonte & P. Zoller (Innsbruck)
U. J. Wiese (Bern)

Atomic Quantum Simulation of U(N) and SU(N) Non-Abelian Lattice Gauge Theories
D. Banerjee et al., PRL **110**, 125303 (2013)

Outlook



Extradimensions

Gauge fields

SU(N) fermions

… and smart theorists!

New quantum simulators for fundamental physics!

Credits

Marco Mancini

Giacomo Cappellini

Lorenzo Livi

Guido Pagano

Jacopo Catani

Carlo Sias

Massimo Inguscio

Leonardo Fallani

Discussions and collaborations: M. Dalmonte, P. Zoller (Innsbruck)
R. Fazio (Pisa) M. Lewenstein (Barcelona)
S. Montangero, T. Calarco (Ulm) and many others…