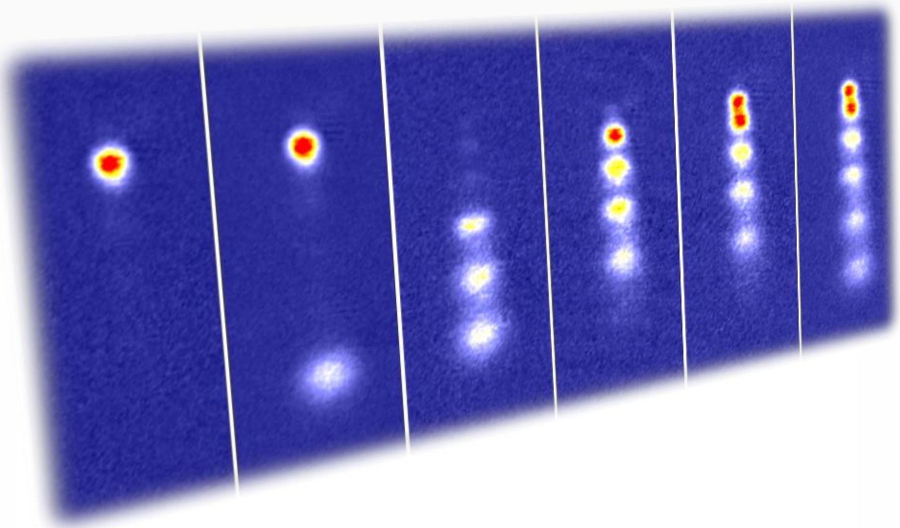
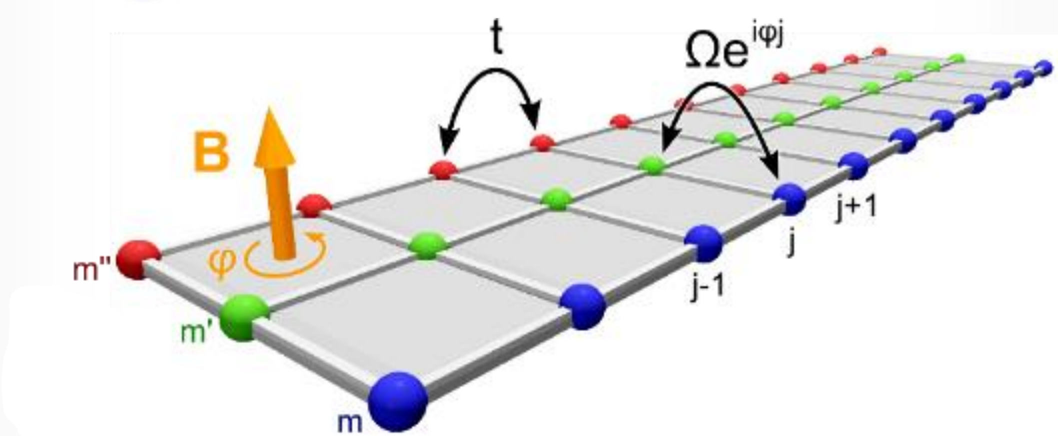
www.ino.it

INO-CNR
Istituto Nazionale di Ottica





Quantum Simulation of Solid-State Systems with Ultracold Atoms

Jacopo Catani

National Institute of Optics (INO-CNR)
Sesto Fiorentino (Florence)

LENS – University of Florence

PhD in Quantum technologies

Napoli 08/02/2019

ERC FISh QUANTERA PRIN MIUR

INO-CNR Istituto Nazionale di Ottica

Quantum Simulators: pillar of QT

Lens European Laboratory for Non-Linear Spectroscopy

UNIVERSAL

Feynman's approach

~~'Employing a **Universal Quantum Computer**~~
allows to simulate **any** Quantum System'

Quantum Simulators: pillar of QT

"AD HOC"

~~Feyn~~NormalMan's approach

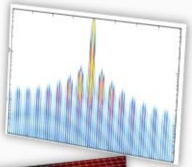
Retrieve properties of a «tricky» Quantum System by implementing a physically equivalent one

➡ **«Engineer» effective Hamiltonians**

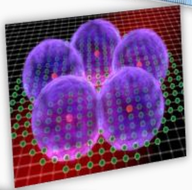
Ultracold Atoms – a powerful tool

Ultracold Atoms platform

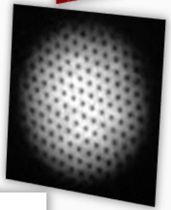
unprecedented **control** and **versatility** in **«Hamiltonian's design»**

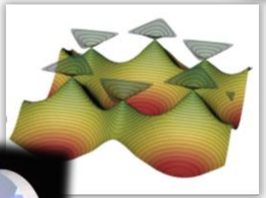


Quantum Simulation with UCA – last decade

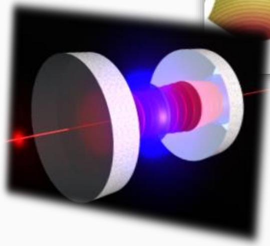


- Superfluidity, BEC/BCS crossover
- Lattice Phase transitions (Mott, Anderson Localization..)
- Low dimensional physics (Tonks gas, BKT, vortices...)
- Synthetic FIELDS -> Hall-like systems



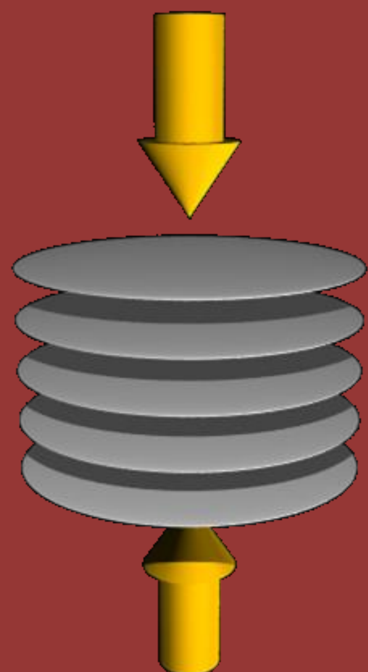


«Solid-state-like» systems



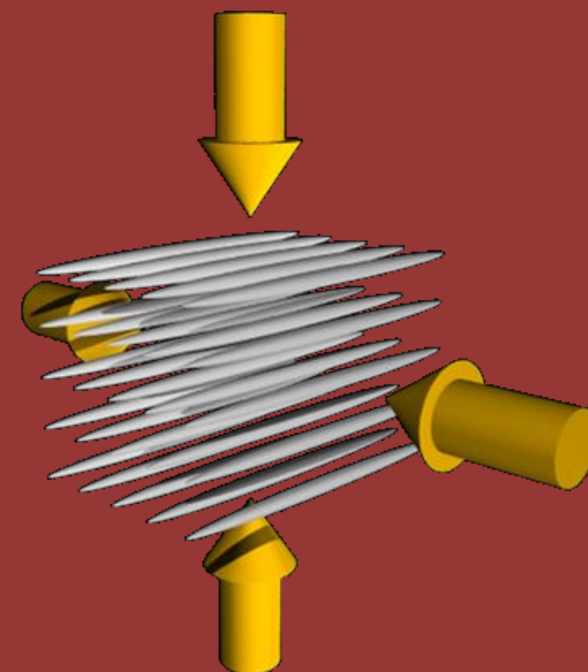
Quantum Manipulation through Light

Ultracold gases offer a unique platform in association to **OPTICAL LATTICES**



2D systems

BKT,
quantum Hall systems,
graphene, …



1D systems

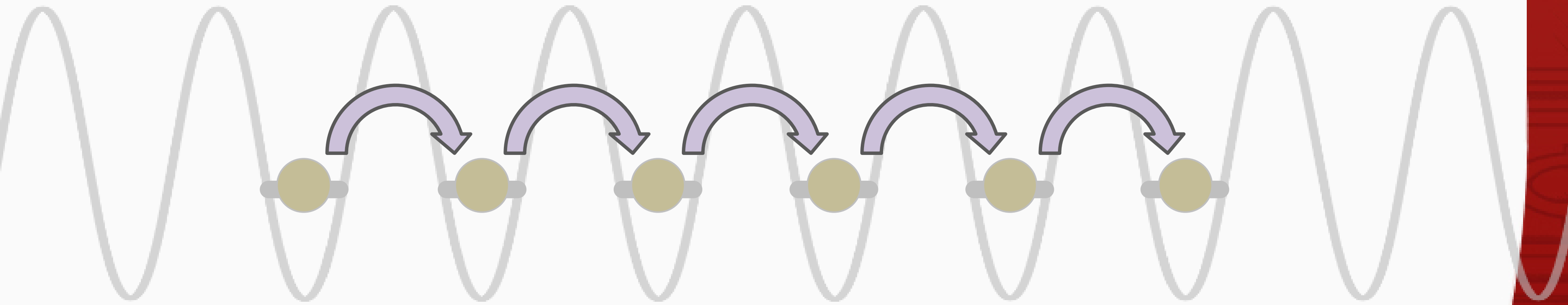
carbon nanotubes,
nanowires, …

Optical manipulation / lattices

Adjusting the light intensity allows for tuning of the tunneling

$$H = -t \sum_{\langle i,j \rangle,\sigma} \left(\hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + \mathrm{h.c.} \right) + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow} + \sum_{i} \varepsilon_i \hat{n}_i$$

Fermi-Hubbard (spin ½)



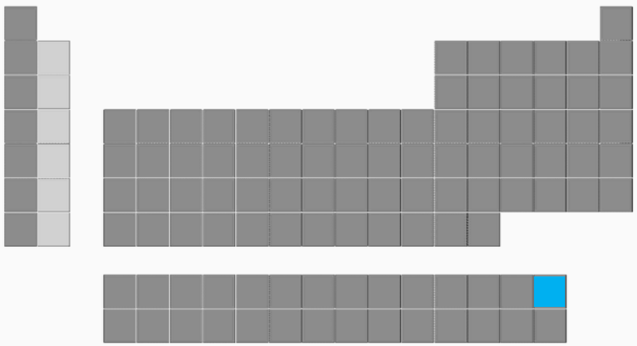
«Real» spatial lattice
Spacing as tight as $\lambda/2$
Depth U up to 100ths of recoils

INO-CNR
Istituto Nazionale di Ottica

Lens European Laboratory for Non-Linear Spectroscopy

Quantum gases of Ytterbium

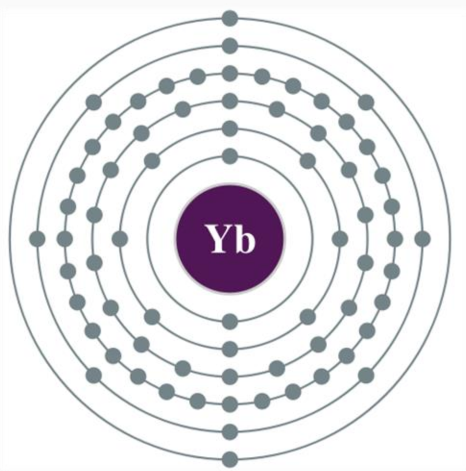
The large Ytterbium family...



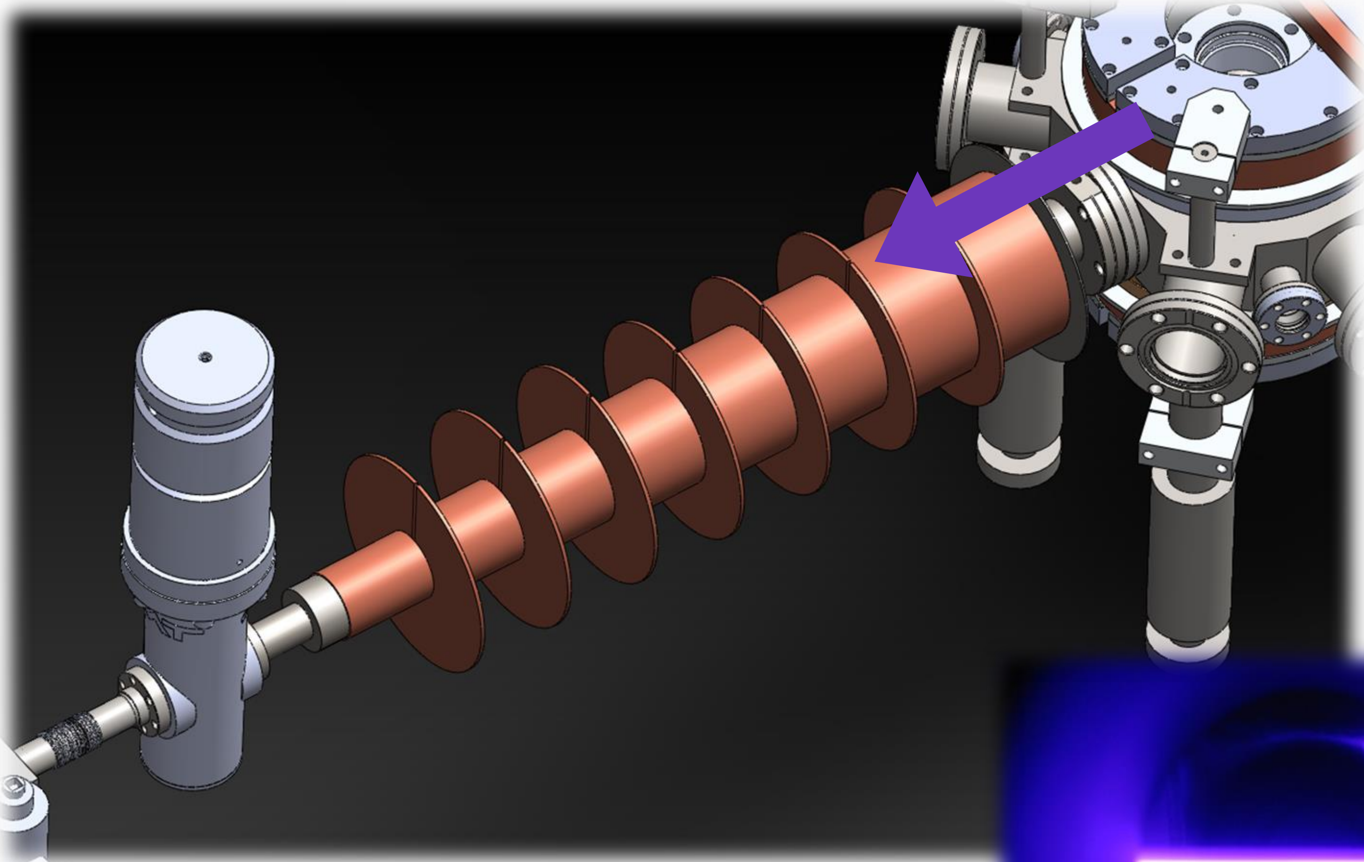
Natural Ytterbium comes in **seven** stable isotopes:

^{168}Yb	0.13%	I=0	boson
^{170}Yb	3.04%	I=0	boson
^{171}Yb	14.28%	I=1/2	fermion
^{172}Yb	21.83%	I=0	boson
^{173}Yb	16.13%	I=5/2	fermion
^{174}Yb	31.83%	I=0	boson
^{176}Yb	12.76%	I=0	boson

http://periodictable.com

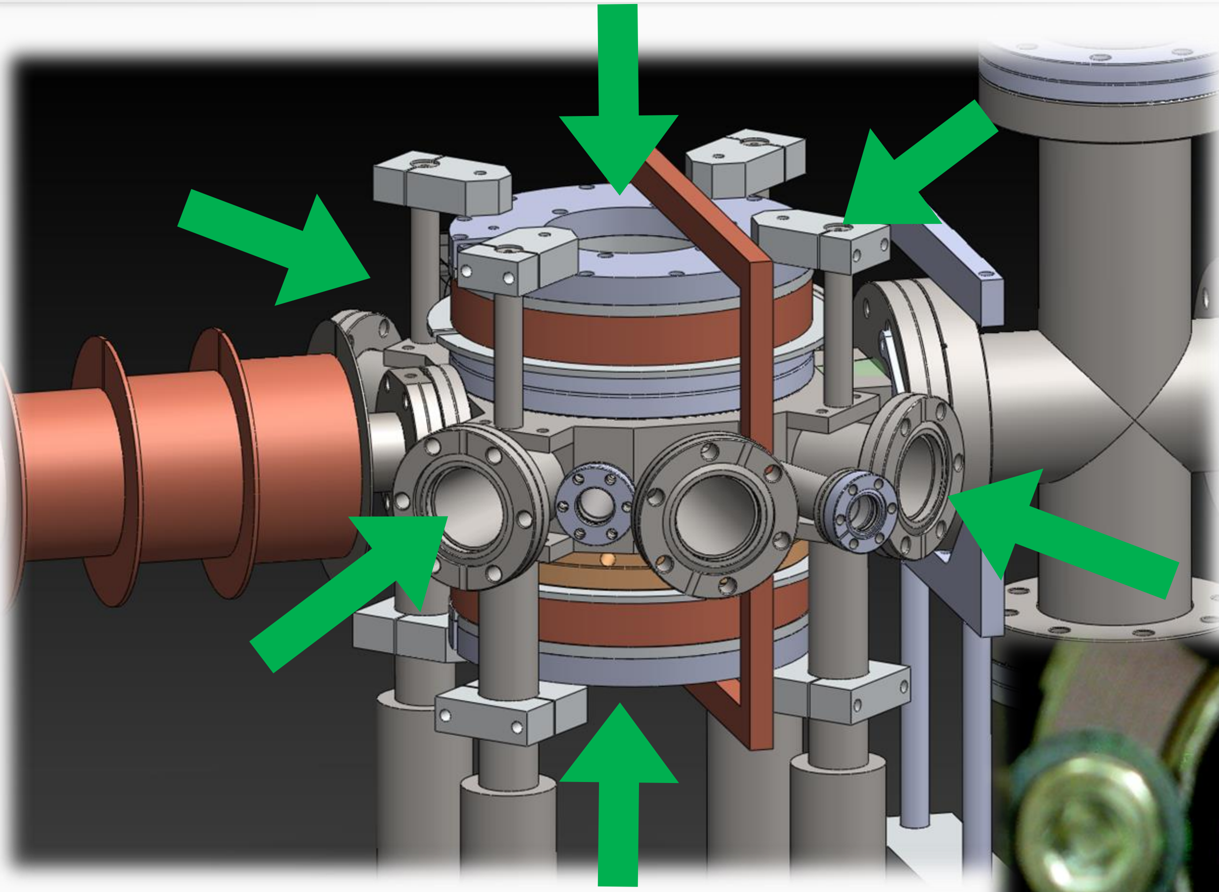


Atomic beam slowing



- Zeeman slower
  Strong $^1S_0 \rightarrow {}^1P_1$ transition (399 nm),
  800 MHz detuned
- Final atom velocity: ≈ 20 m/s

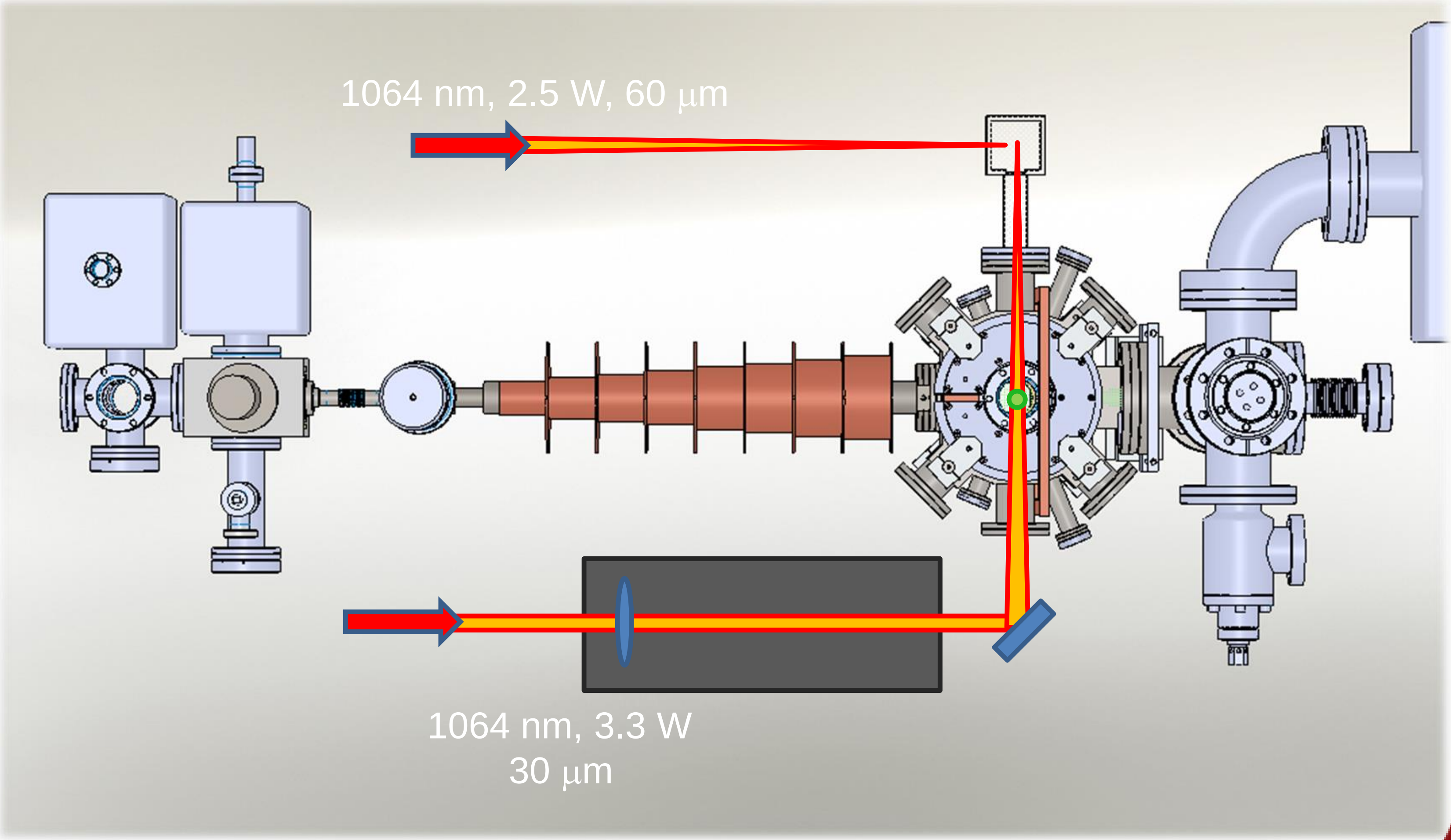
Laser cooling of Ytterbium



MAGNETO
OPTICAL
TRAP
(MOT)

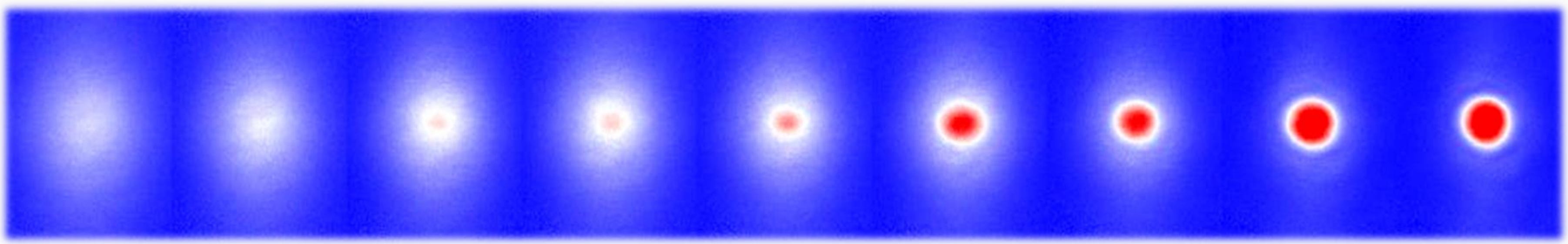
- Temperature: ≈ 30 μK
- Number of atoms ≈ 10^9

Optical transport of atomic sample



Quantum degeneracy - Bosons

Time-of-flight images: momentum distribution



T ≈ 400 nK

Thermal

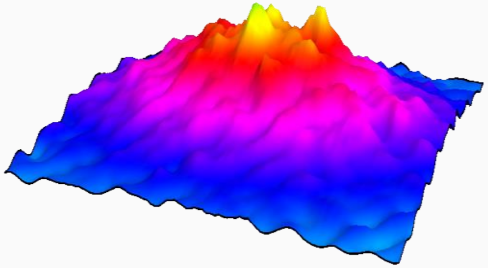
N_{tot} ≈ 1 million

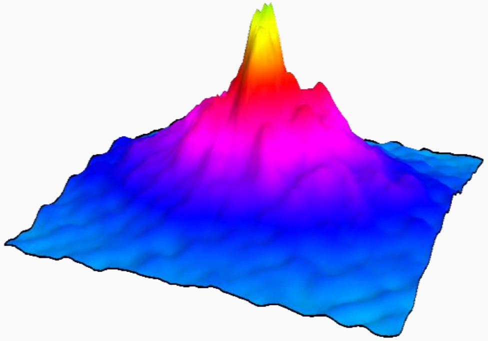
T ≈ 70 nK

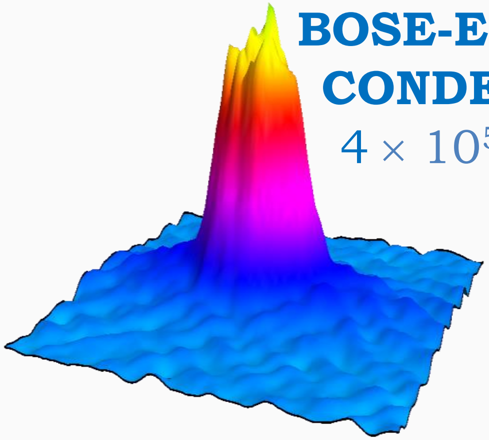
Pure

BOSE-EINSTEIN CONDENSATE

4×10^5 atoms







INO-CNR Istituto Nazionale di Ottica

Quantum degeneracy - Fermions

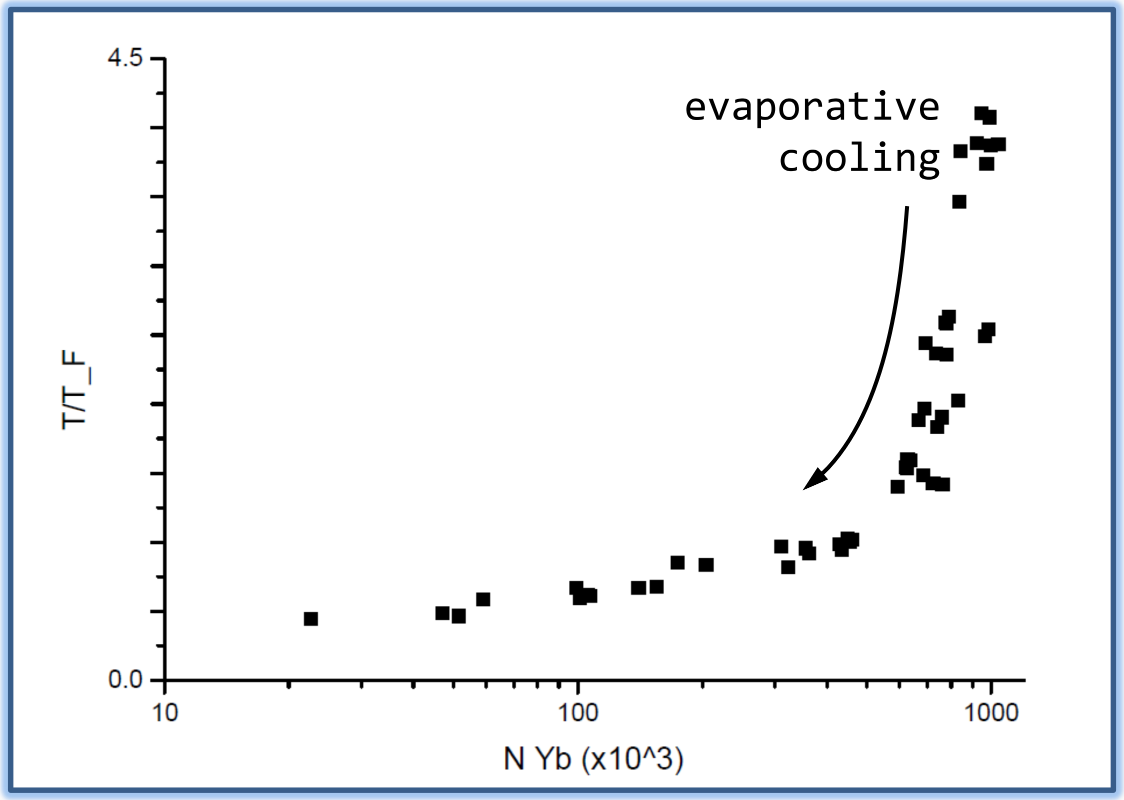
Lens European Laboratory for Non-Linear Spectroscopy

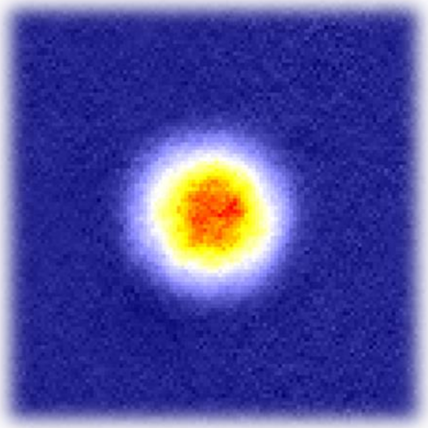
^{173}Yb: evaporative cooling of a **spin mixture**

(6 components)

Nuclear spin I=5/2

-5/2 +5/2





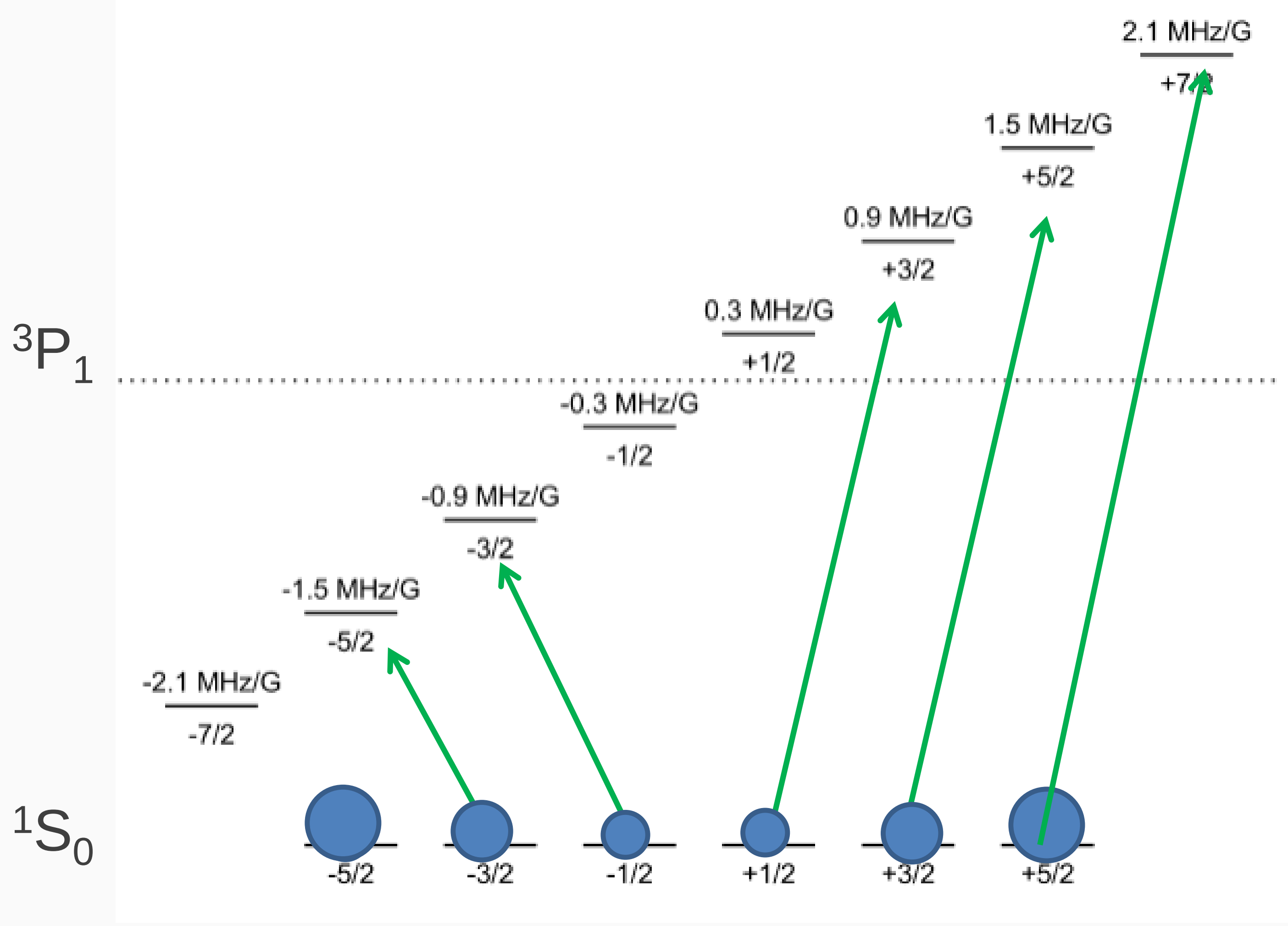
^{173}Yb Fermi gas

$T/T_F < 0.1$ (20 nK!)

$N = 1\times10^4$ atoms/spin

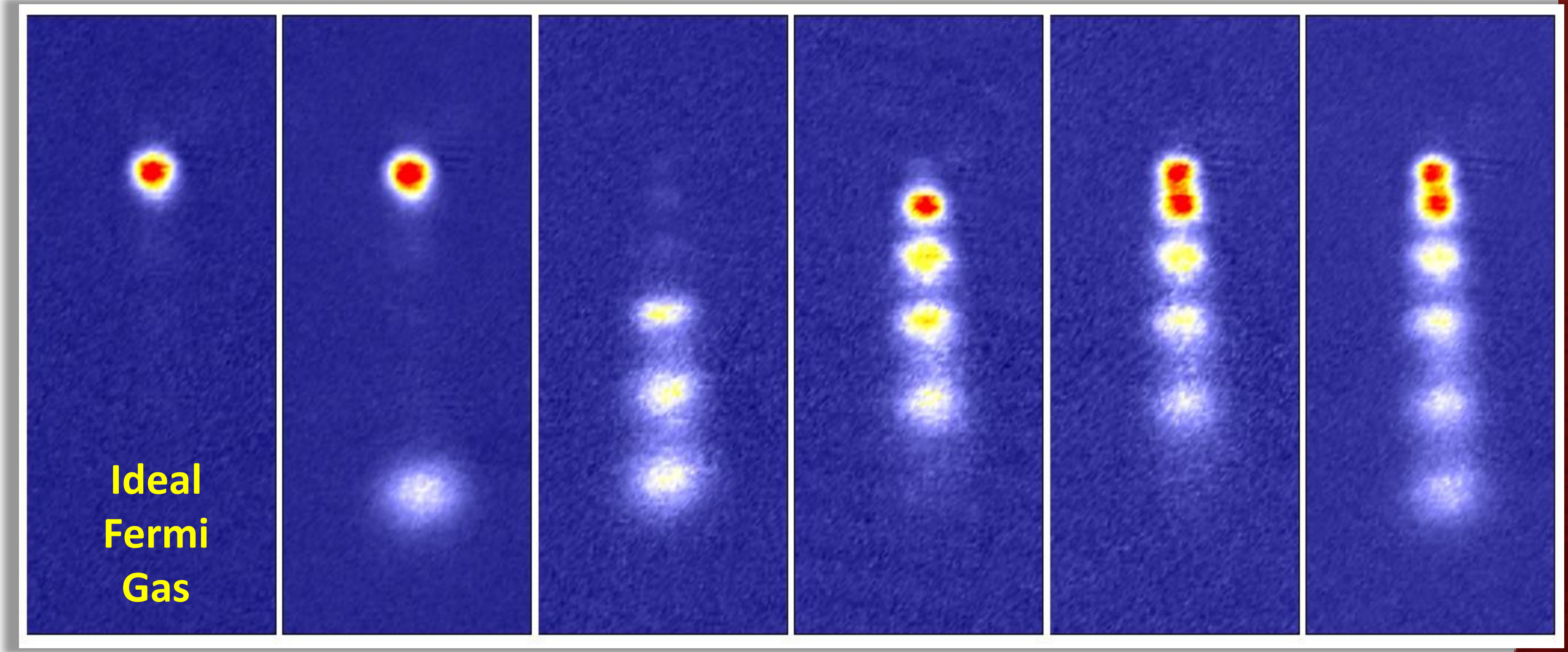
Spin Manipulation

Optical pumping through sequence of resonant light pulses and B field
control of the population in each Zeeman sublevel



Spinful Quantum Gases

^{173}Yb Fermi gases in an arbitrary number of equally-populated components:



1 spin | 2 spins | 3 spins | 4 spins | 5 spins | 6 spins

INO-CNR
Istituto Nazionale di Ottica

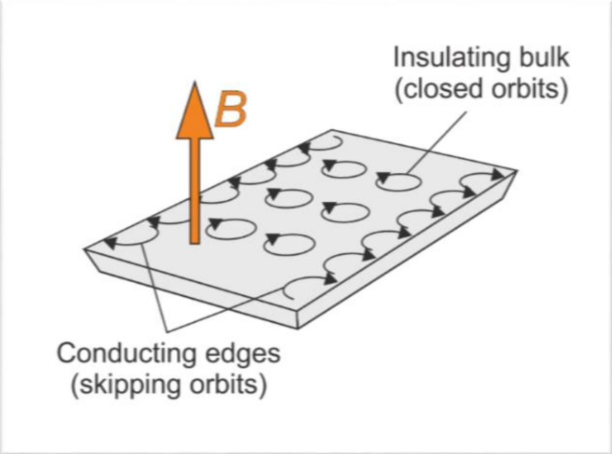
Lens
European Laboratory for Non-Linear Spectroscopy

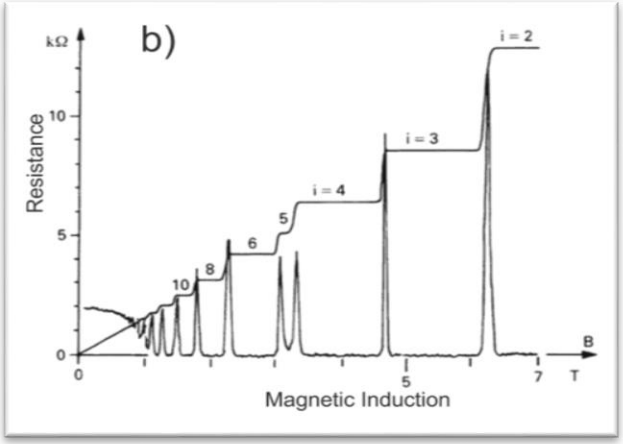
Engineering Hall Systems with Atoms

Quantum Hall Effect in a Nutshell

Quantum Hall effect

(th. Ando, Matsumoto,Uemura 1975, Laughlin 1981)
(exp: Von Klitzing 1990)





Charged 2D Particles (e^-) in strong **B** field

- Quantized Cyclotron Orbits (Landau levels)
  Insulating **Bulk** States
- Skipping Orbits at boundaries
  Superconducting **Edge** States

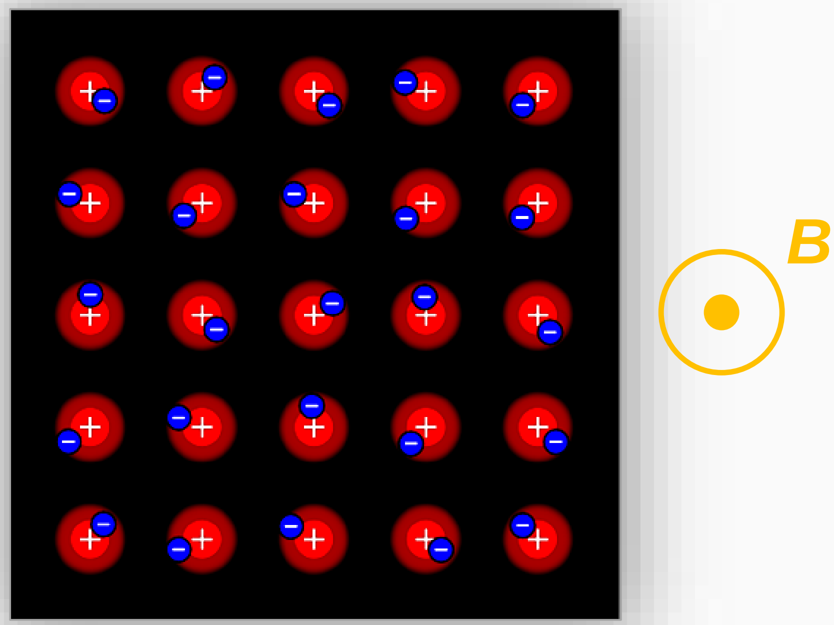
- Quantized plateaux in transv. conductance for critical values of **B**

$$\sigma = \nu \frac{e^2}{h}$$

$$B = \frac{n_0 h}{e\nu}$$

Simulating crystals under *B* fields with atoms

Underlying lattice structure: exploit advantages in manipulation of atomic systems



…electrons are **CHARGED PARTICLES**, whilst ATOMS are **NEUTRAL**…

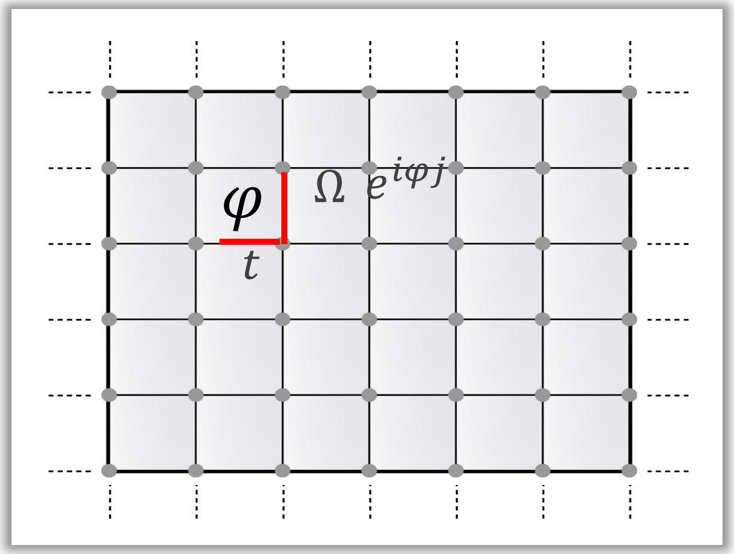
…what's the trick…?

Harper – Hofstadter Hamiltonian

charged particle in a 2d lattice + magnetic field

Harper, Proc. Phys. Soc. A **68**, 874 (1955)

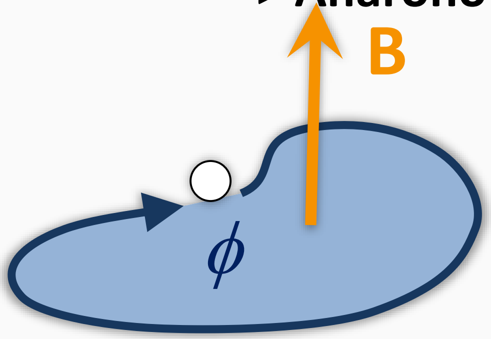
$$H = -t\sum_{j,m}\left(c^{\dagger}_{j,m}c_{j+1,m} + h.c.\right) - \Omega\sum_{j,m}\left(e^{i\varphi j}c^{\dagger}_{j,m}c_{j,m+1} + h.c.\right)$$



Geometric (Peierls) phase

Embeds **B field** and **charge**

-> Aharonov-Bohm!



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

Can be *imprinted* by **laser beams!**

ARTIFICIAL GAUGE FIELDS

D. Jaksch and P. Zoller, NJP **5**, 56 (2003)

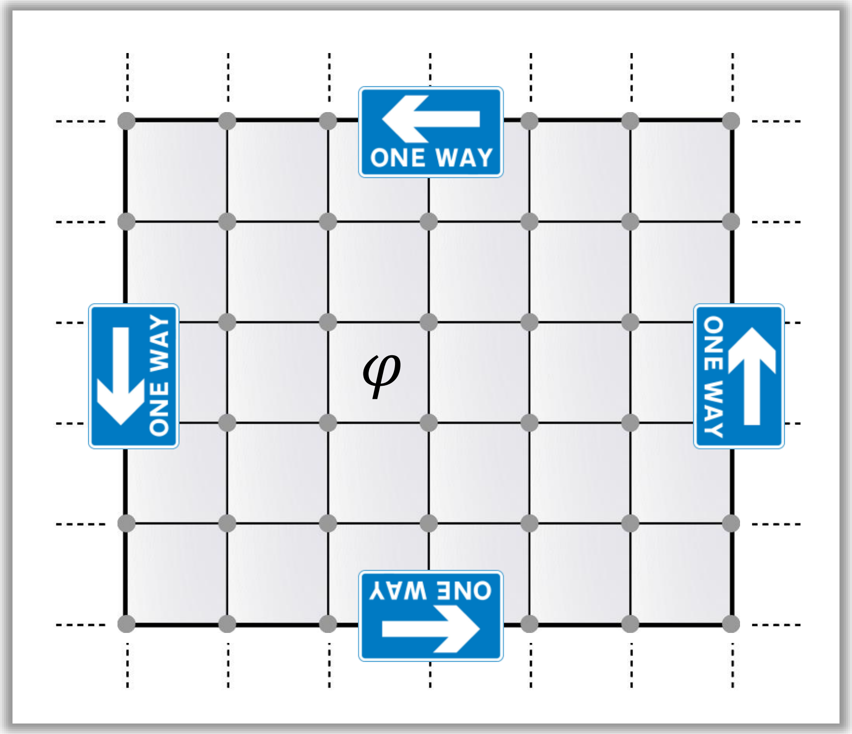
Harper-Hofstadter model features

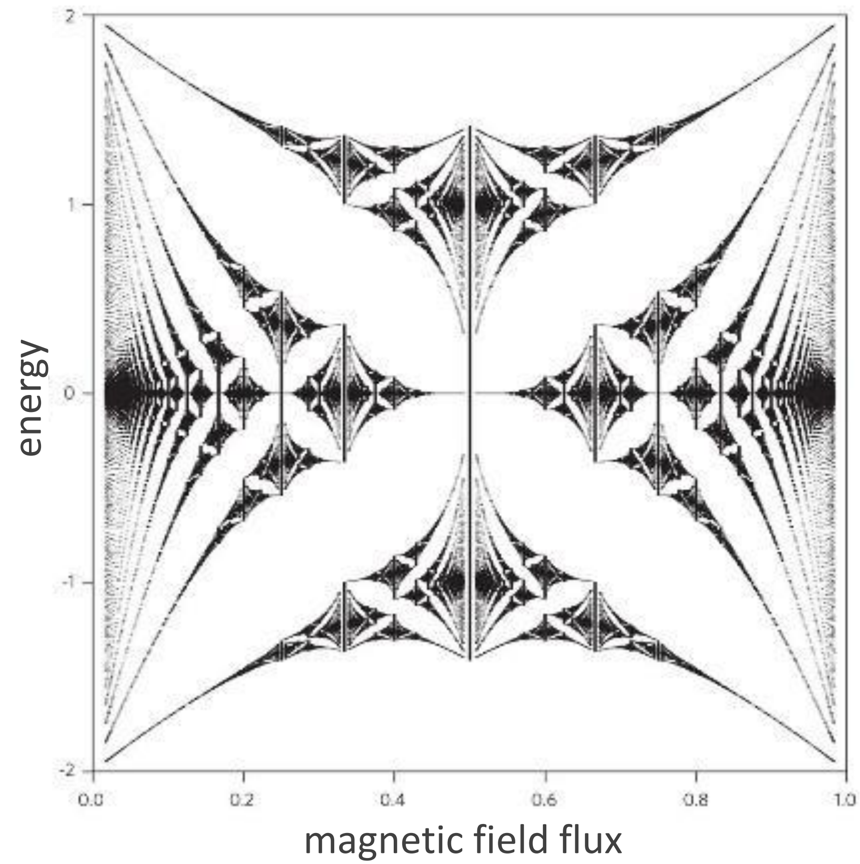
Features of the model

Hofstadter, PRB **14**, 2239 (1976)
Promptly left Physics for Cognitive Science

chiral edge currents

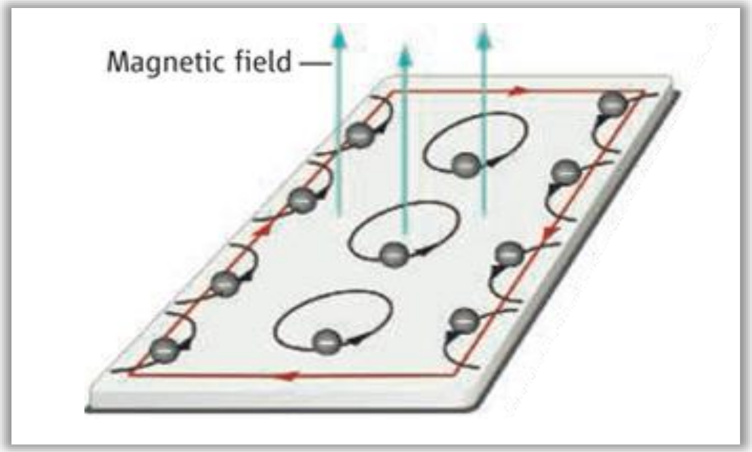
Hofstadter «Butterfly» spectrum



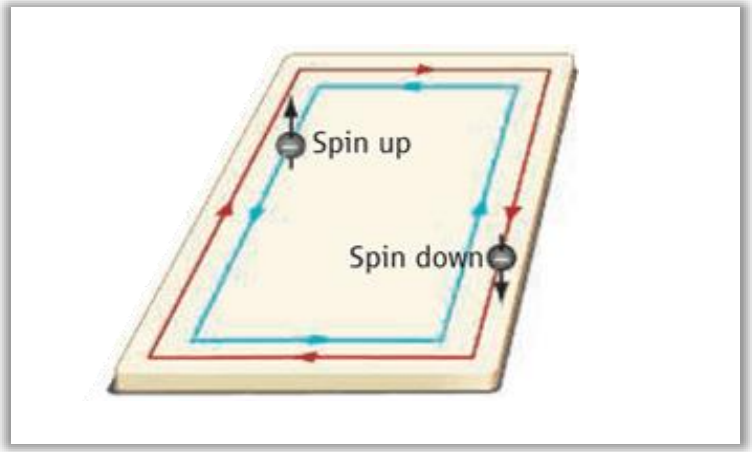


Edge States

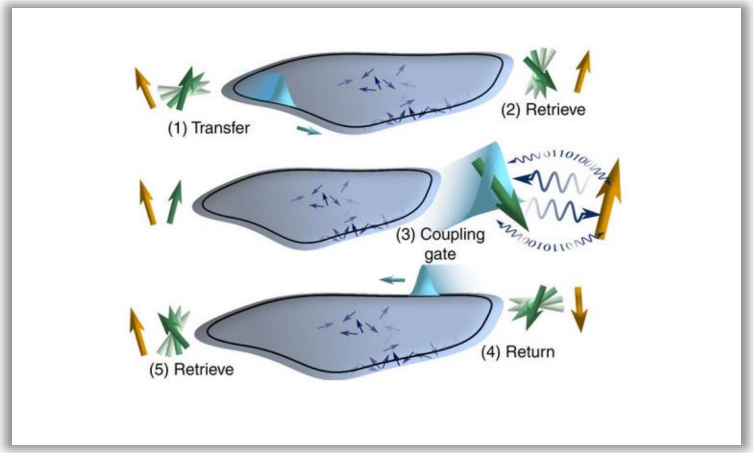
Quantum Hall effect



Topological insulators



ROBUSTNESS > Quantum technology

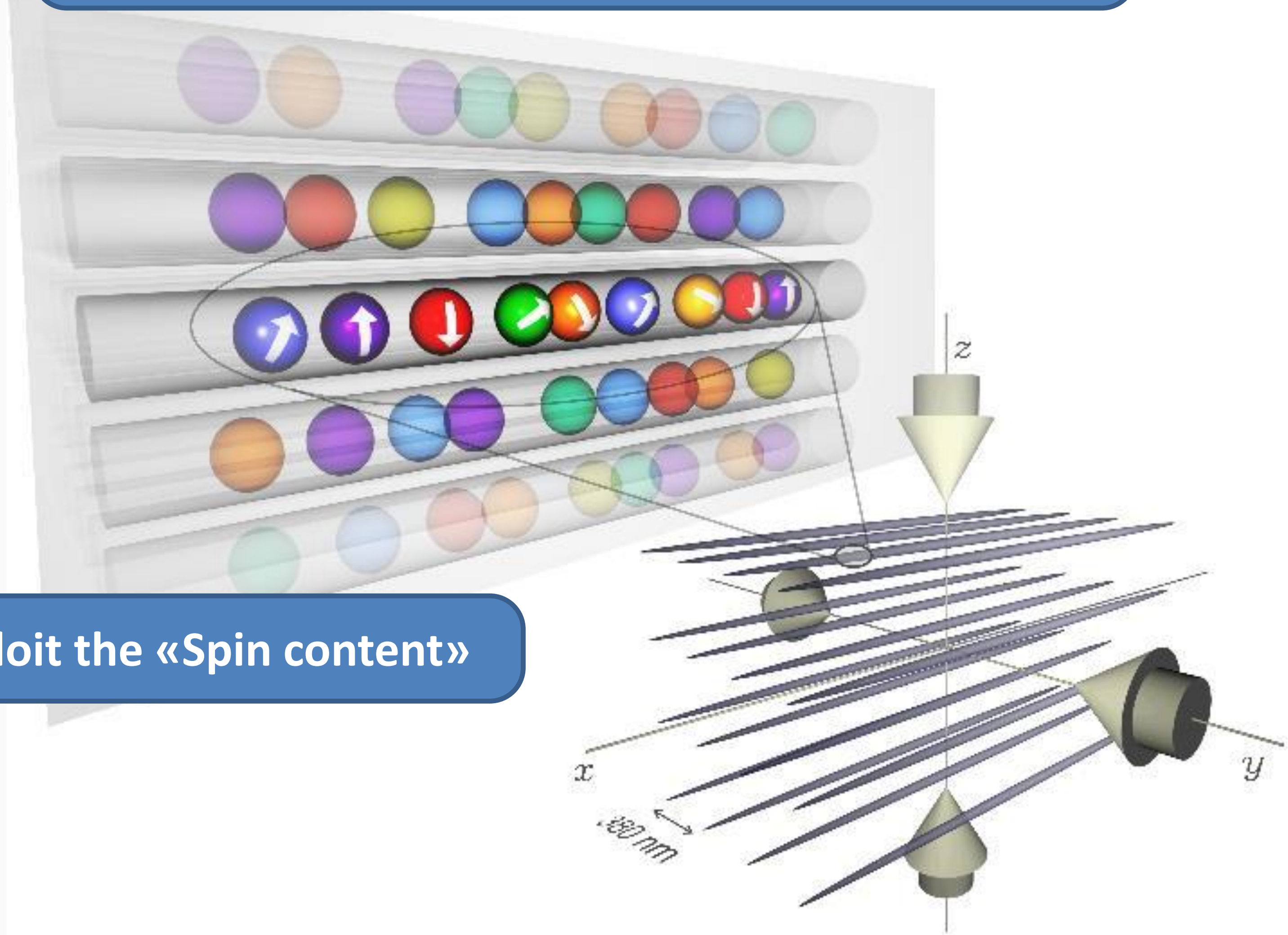


N. Y. Yao, Nat. Comm. 4, 1585 (2013)

…preparation of Atomic Hall ribbons..

Implementing Hall Ribbons with Atoms

1 . 1D Atomic «Wires» using a 2D optical lattice

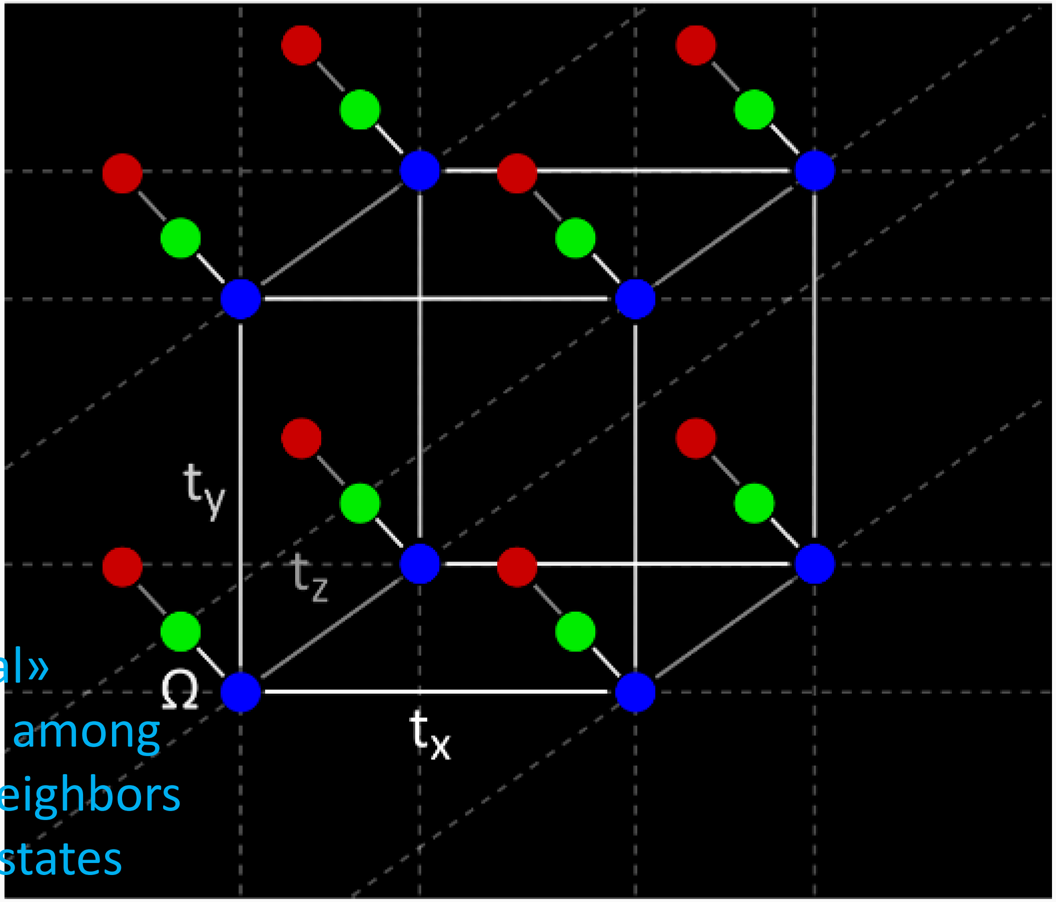


2 .Exploit the «Spin content»

A “synthetic” extra-dimension

Use internal DOF in order to «simulate»
EXTRA DIMENSIONAL lattice sites

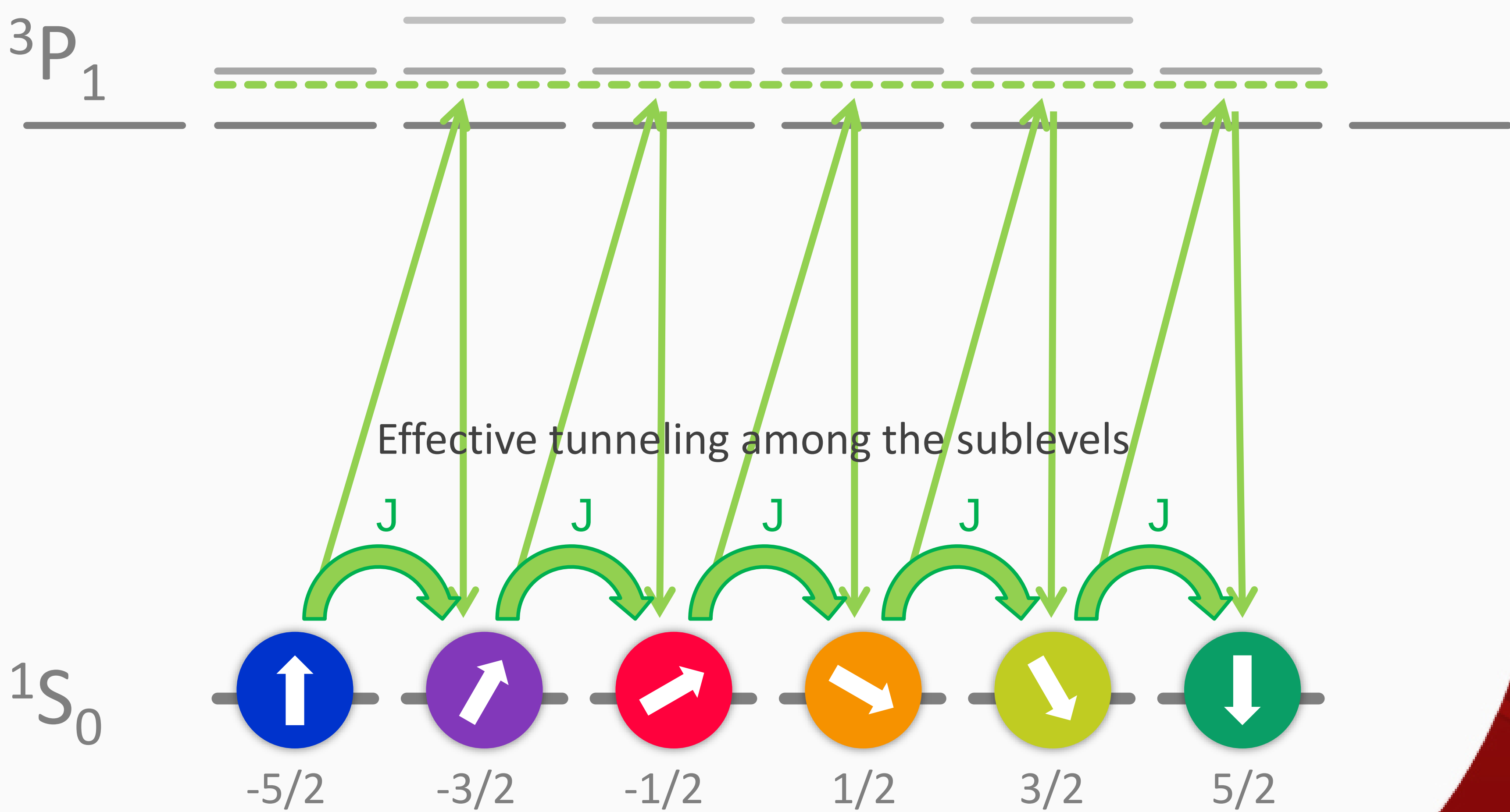
Boada et al., PRL 108, 133001 (2012)



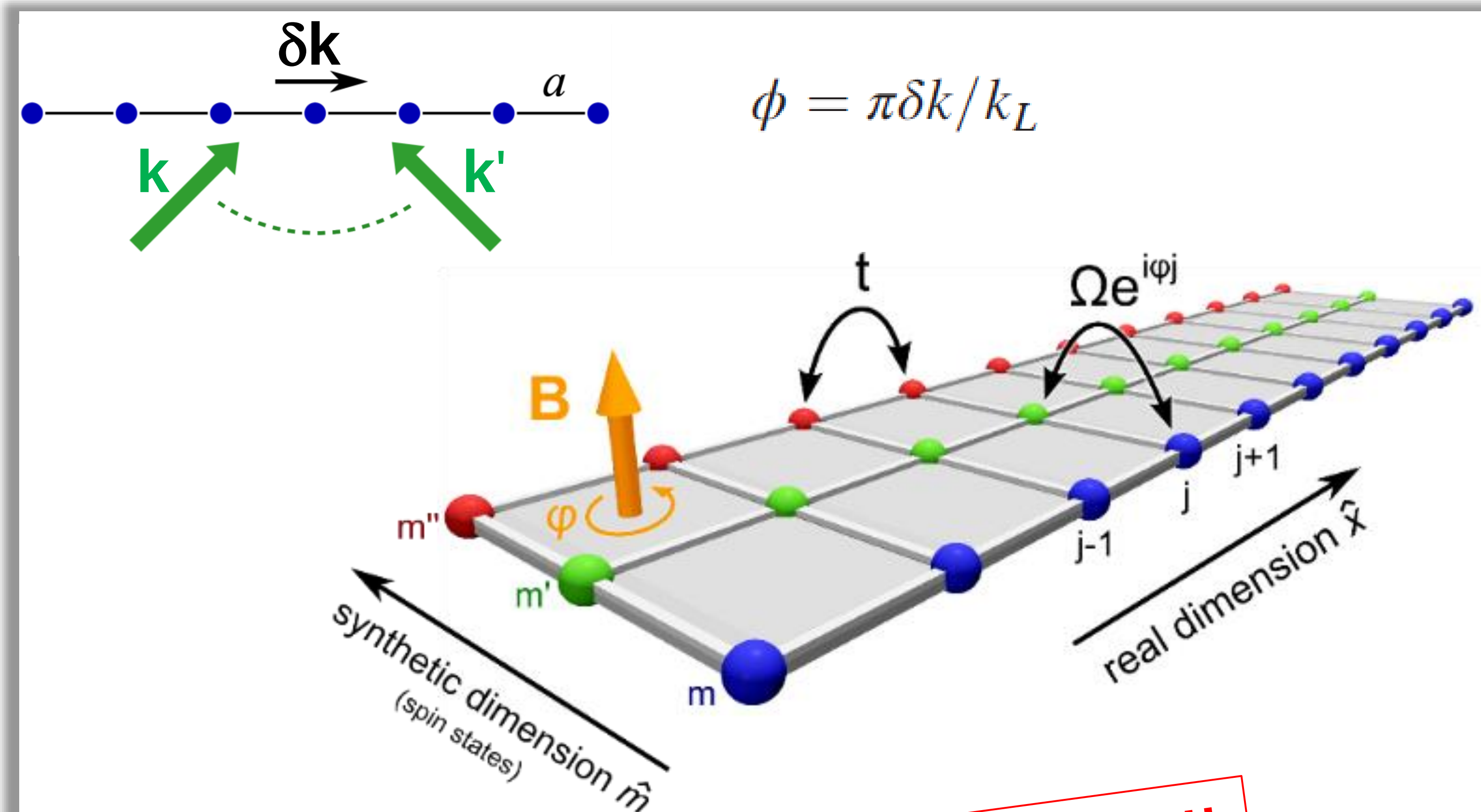
«Artificial»
coupling among
earest-neighbors
internal states

“Synthetic” lattice through Raman Trans.

3. Raman Coupling between Spins



Implementing Hall Ribbons with Atoms



«Hybri

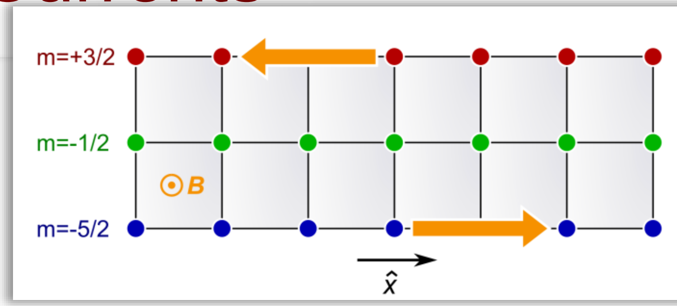
Synthetic Fields up to 10000 T !!

realized: M. Mancini et al., Science **349**, 6255 (2015)
proposed: A. Celi et al., PRL **112**, 043001 (2014)

Observation of Edge Currents

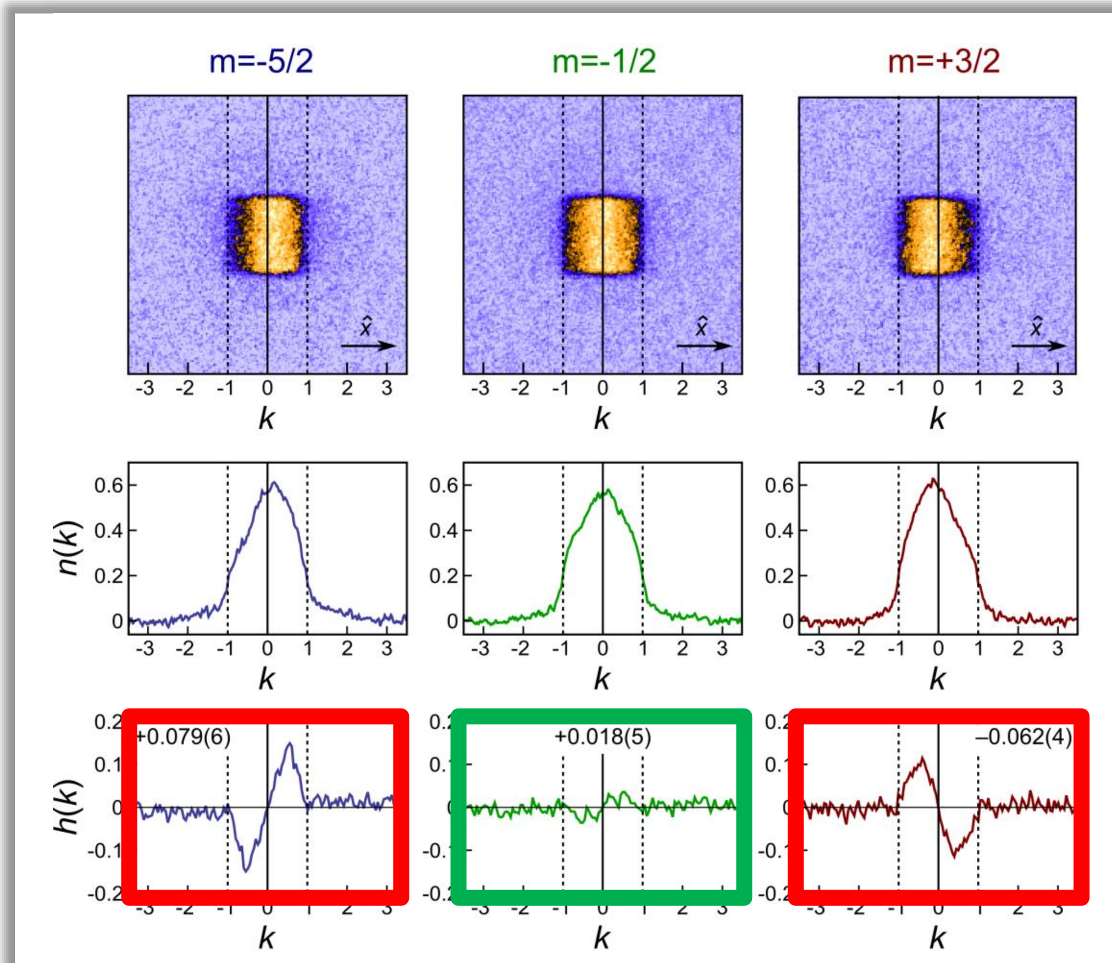
M. Mancini et al., Science ***349****, 1510 (2015)*

Observation of Edge Currents



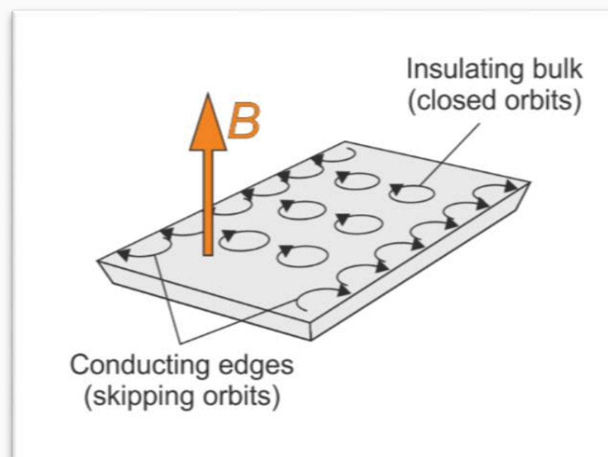
Adiabatic loading of a 3-leg ladder (***edges + bulk***)

Lattice momentum distribution:



Conducting edges

no bulk current

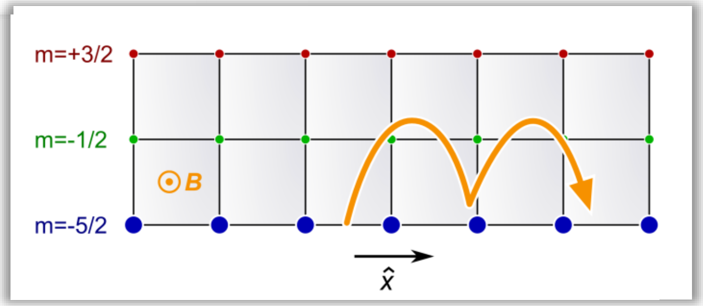


Observation of Skipping Orbits

M. Mancini et al., Science ***349****, 1510 (2015)*

INO-CNR
Istituto Nazionale di Ottica

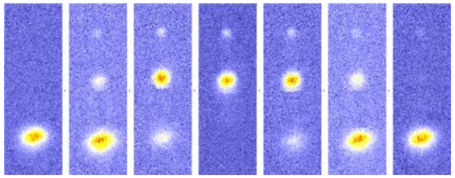
Observation of Skipping Orbits

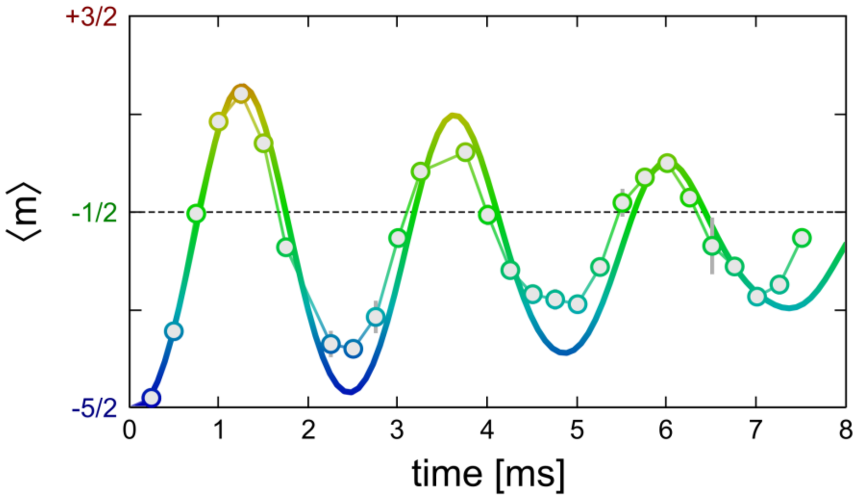


Initial state prepared on a **single edge**

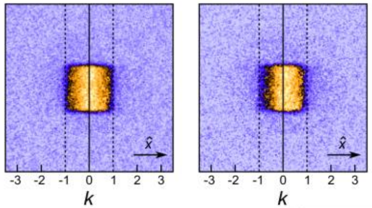
Observe dynamics after **sudden activation** of synthetic tunneling

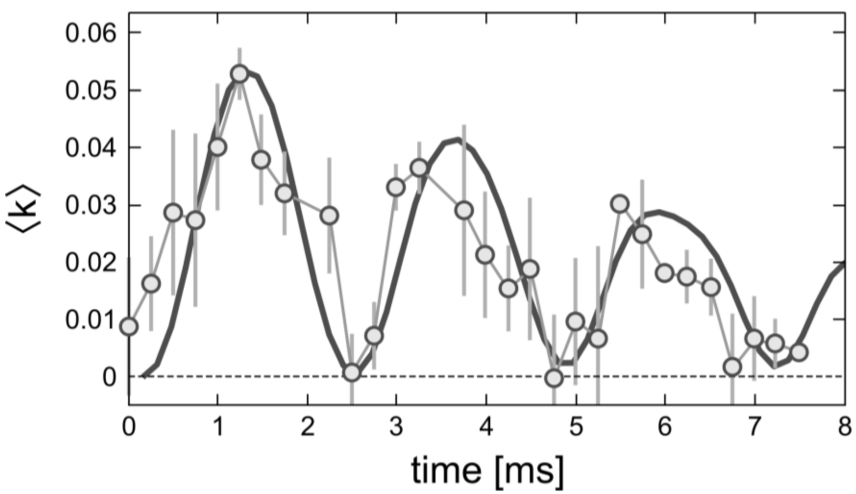
Magnetization:





Momentum:



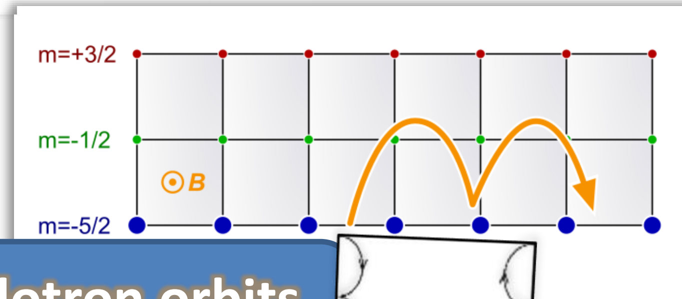


M. Mancini et al., Science ***349****, 1510 (2015)*

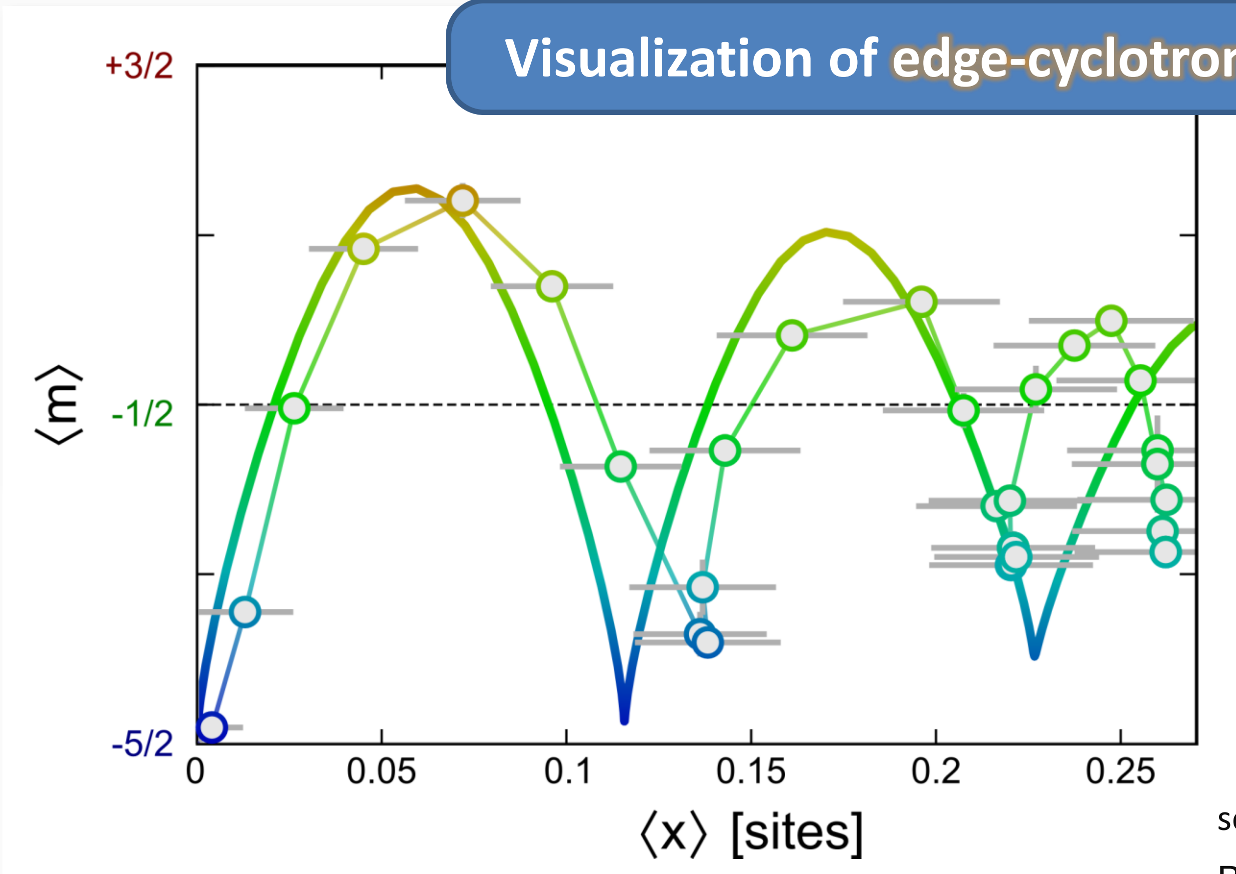
INO-CNR Istituto Nazionale di Ottica

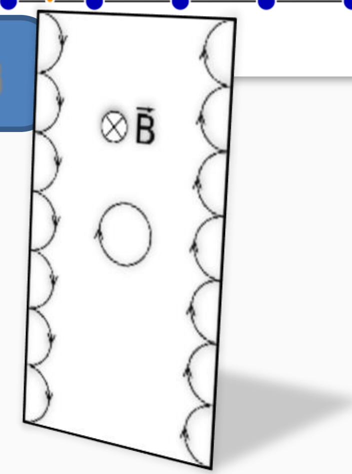
Observation of Skipping Orbits

By knowing the (single-)band dispersion the **real space orbits** $m(\langle x(t)\rangle)$ are reconstructed



Visualization of edge-cyclotron orbits





Quantum-Hall-like dynamics!

see related work at (NIST):

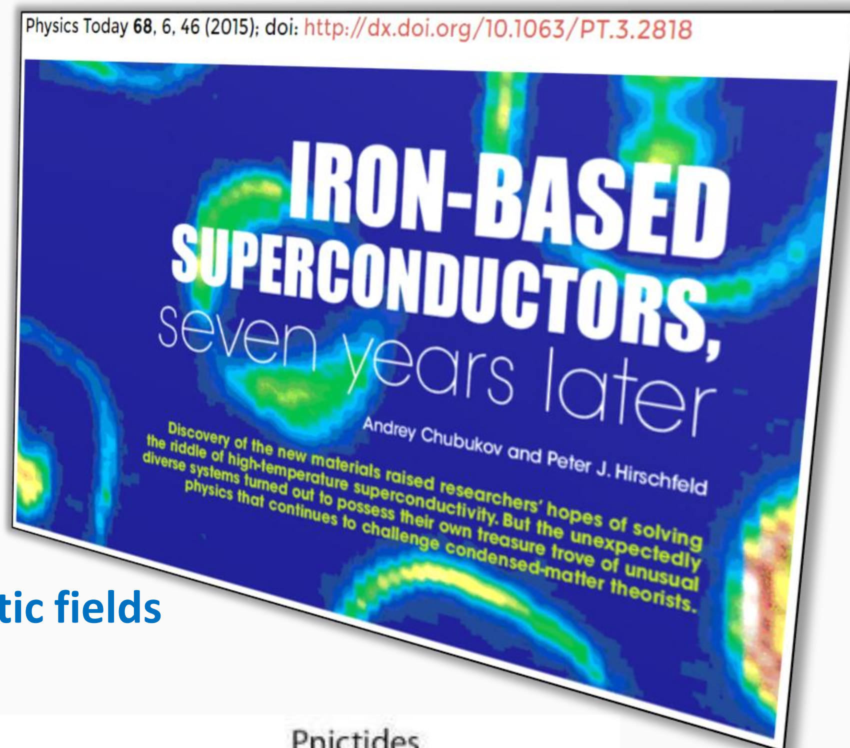
B. K. Stuhl et al.,
Science **349**, 6255 (2015)

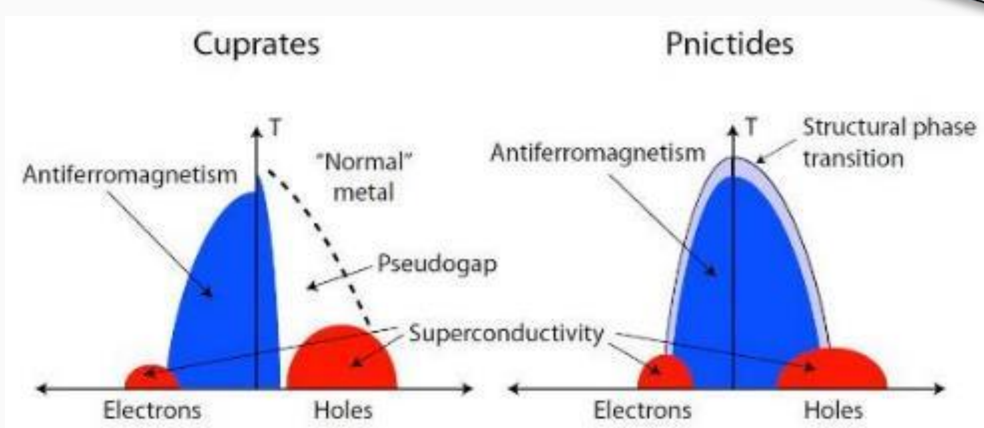
Perspectives (one out of many..)

Multi-orbital (iron-based)
High-Tc superconductors with **interactions**

↓

Simulation via
Multi-component (nuclear and/or orbital)
Atomic Mott-Insulators in **artificial magnetic fields**

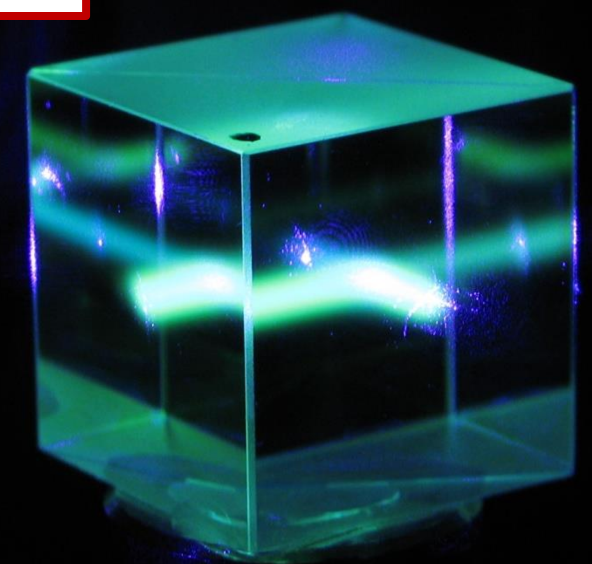




from http://research.physics.berkeley.edu/lanzara/research/pnictide.html

PostDoc positions ☺

Thanks for your Attention !



INO-CNR
Istituto Nazionale di Ottica