

# Quantum Simulations with Two-Electron Atoms

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LENS – University of Florence

Enrico Fermi Summer School

Varenna – 23-24 July 2016

## Introduction

## Two-Electron Atoms

## 1D Luttinger Liquids with Tunable Spin

## Synthetic Hall Systems with $2e^-$ Atoms

## Edge States in Synthetic Hall systems

# Ultracold Atoms – a powerful tool

Ultracold Atoms:



unprecedented control and flexibility over «Hamiltonian's design»

## Quantum Simulation – last decade

- Superfluidity, BEC/BCS crossover
- Lattice Phase transitions (Mott, Anderson Localization..)
- Low dimensional physics (Tonks gas, BKT, vortices...)
- Many more coming up...(synthesizing fields, dimensions...)

# Ultracool results (1D)

## 1D bosons

Tonks and super-Tonks gas

T. Kinoshita et al., Science 2004  
B. Paredes et al., Nature 2004  
E. Haller et al., Science 2009

2- and 3-body correlations

B. Laburthe Tolra et al., PRL 2004  
T. Kinoshita et al., PRL 2005  
V. Guarnera et al., PRA 2012

Mott and pinning transition

T. Stoferle et al., PRL 2004  
E. Haller et al., Nature 2010

integrability and non-equilibrium

T. Kinoshita et al., Nature 2006  
M. Cheneau et al., Nature 2012

quasiBEC and phase fluctuations

J. Estève et al., PRL 2006  
S. Hofferberth et al., Nature 2007

transport of impurities

S. Palzer et al., PRL 2009  
J. Catani et al., PRA 2012  
T. Fukuhara et al., Nat. Phys. 2013

## 1D fermions

formation of molecules

H. Moritz et al., PRL 2005

unbalanced superfluidity

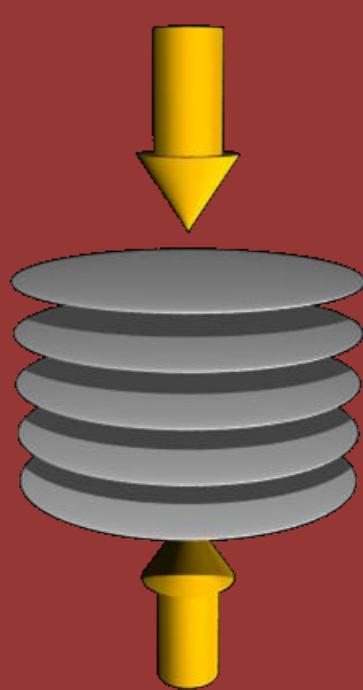
Y. Liao et al., Nature 2010

few-fermions physics

G. Zurn et al., PRL 2012

# Manipulation through Light

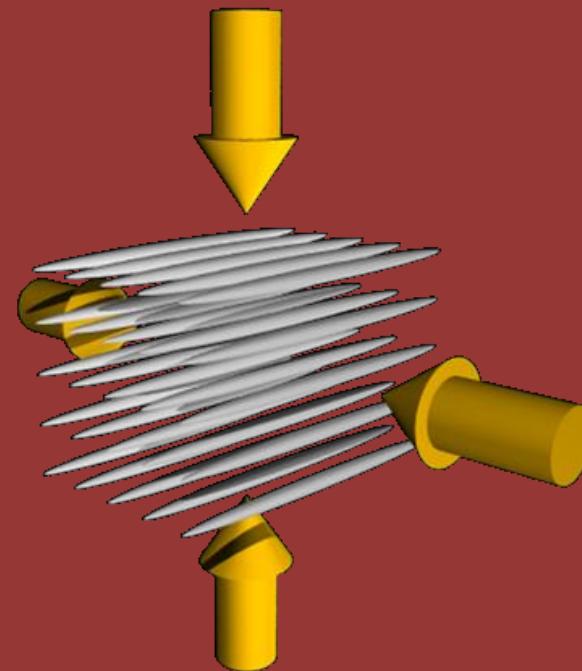
Ultracold gases offer a unique platform in association to **OPTICAL LATTICES**



2D systems

BKT,  
quantum Hall systems,  
graphene, ...

optical  
lattice



1D systems

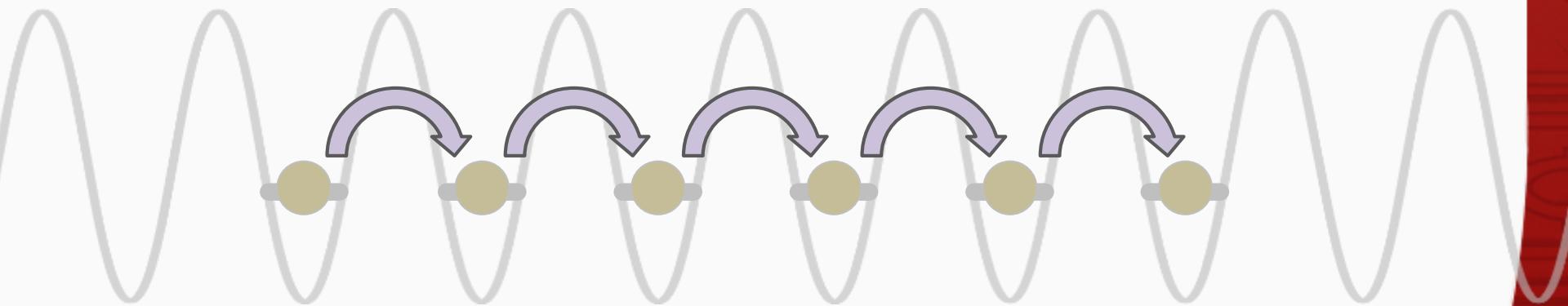
carbon nanotubes,  
nanowires, ...

# Optical manipulation / lattices

Adjusting the light intensity allows for tuning of the tunneling

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

Fermi-Hubbard (spin  $\frac{1}{2}$ )



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



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...mostly alkalis...

*Two-electron atoms*

Unique properties deliver **extended possibilities** w/respect to alkalis

## «NEW» Quantum Simulation

1- Engineer long standing **Topological Models** (Hall, Haldane, Harper, Hofstadter,.)  
with **improved control**

**Afternoon lecture**

2- Provide novel testbenches for «more-than-real» theoretical models

**This lecture**

- M. Cazalilla et al., NJP (2009)
- A. Gorshkov et al., Nat. Phys. (2010)
- D. Banerjee et al., PRL (2013)
- N. Goldman et al., Rep. Prog. Phys. 77,  
126401 (2014)

*Two-electron atoms*

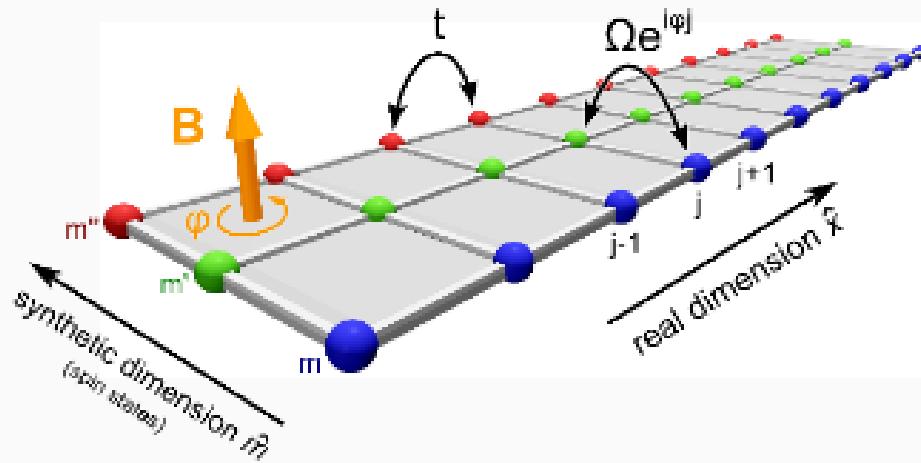
Unique properties deliver **extended possibilities** w/ respect to alkalis

## «NEW» Quantum Simulation



### 1 - «SYNTHETIC DIMENSIONS»: EDGE STATES in ATOMIC HALL RIBBONS

M. Mancini et al., Science 349, 6255 (2015)



# Alkaline-earth-like atoms

*Two-electron atoms*

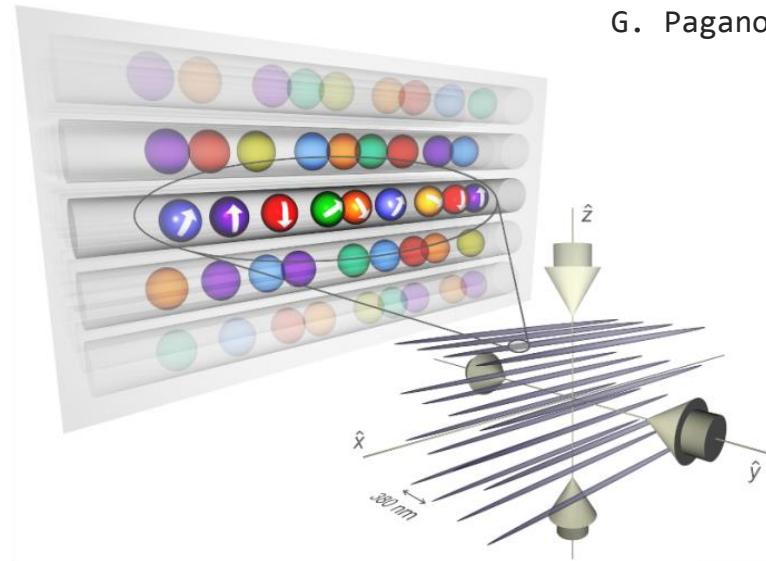
Unique properties deliver **extended possibilities** w/respect to alkalis

## «NEW» Quantum Simulation



### 2 - «SPIN TUNING KNOB»: 1D LIQUID of FERMIONS BEYOND SPIN 1/2

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



# Alkaline-earth-like atoms

*...also for*

Quantum Information

A. J. Daley, Quantum Inf. Proc.  
B. (2011)

«Precision» physics

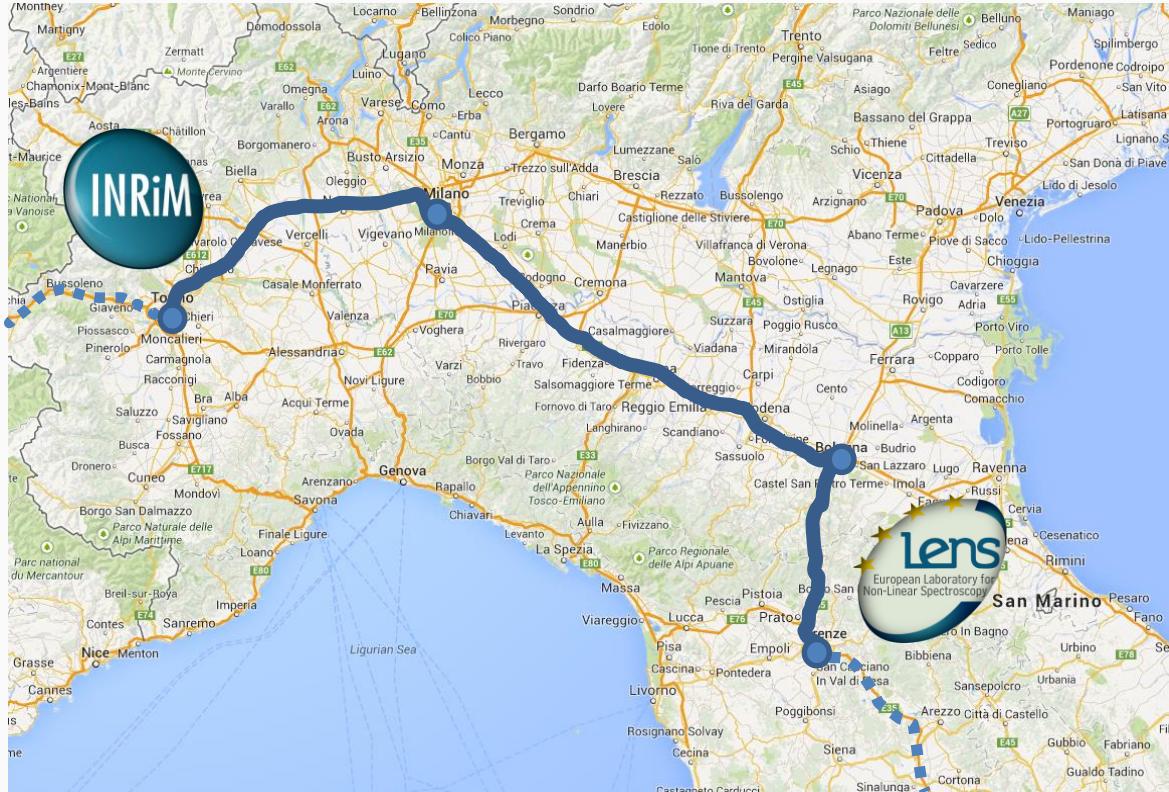
N. Hinkley et al., Science (2013)  
B. J. Bloom et al., Nature (2014)  
I. Ushijima et al., Nature Phot. (2015)



# Fiber-link for precision physics

650km-long dedicated optical frequency link:

C. Clivati et al., OPEX (2015)



Collaboration with  
Metrological  
Institute



dissemination of  
absolute time reference  
**BEYOND GPS LIMIT**

Absolute frequency of  $^{173}\text{Yb}$  clock transition

$$f = 518\ 294\ 576\ 845\ 268\ (10)\ \text{Hz}$$

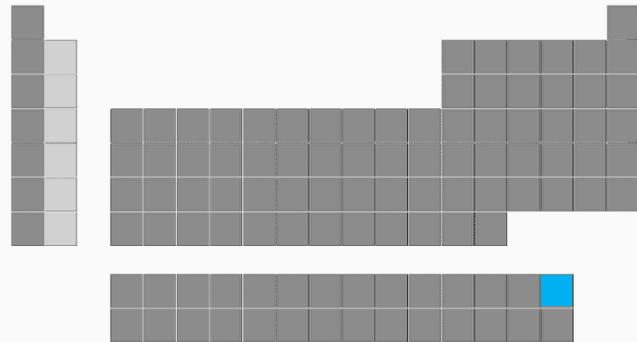


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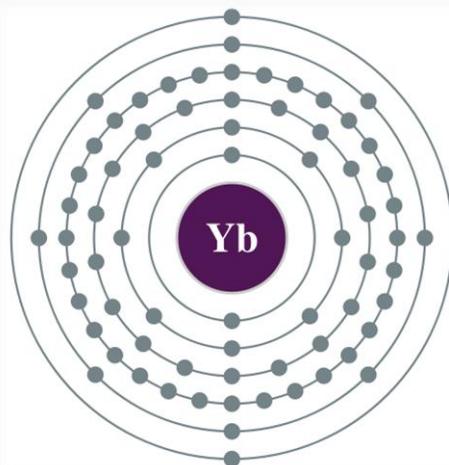


# Ytterbium

# The large Ytterbium family...



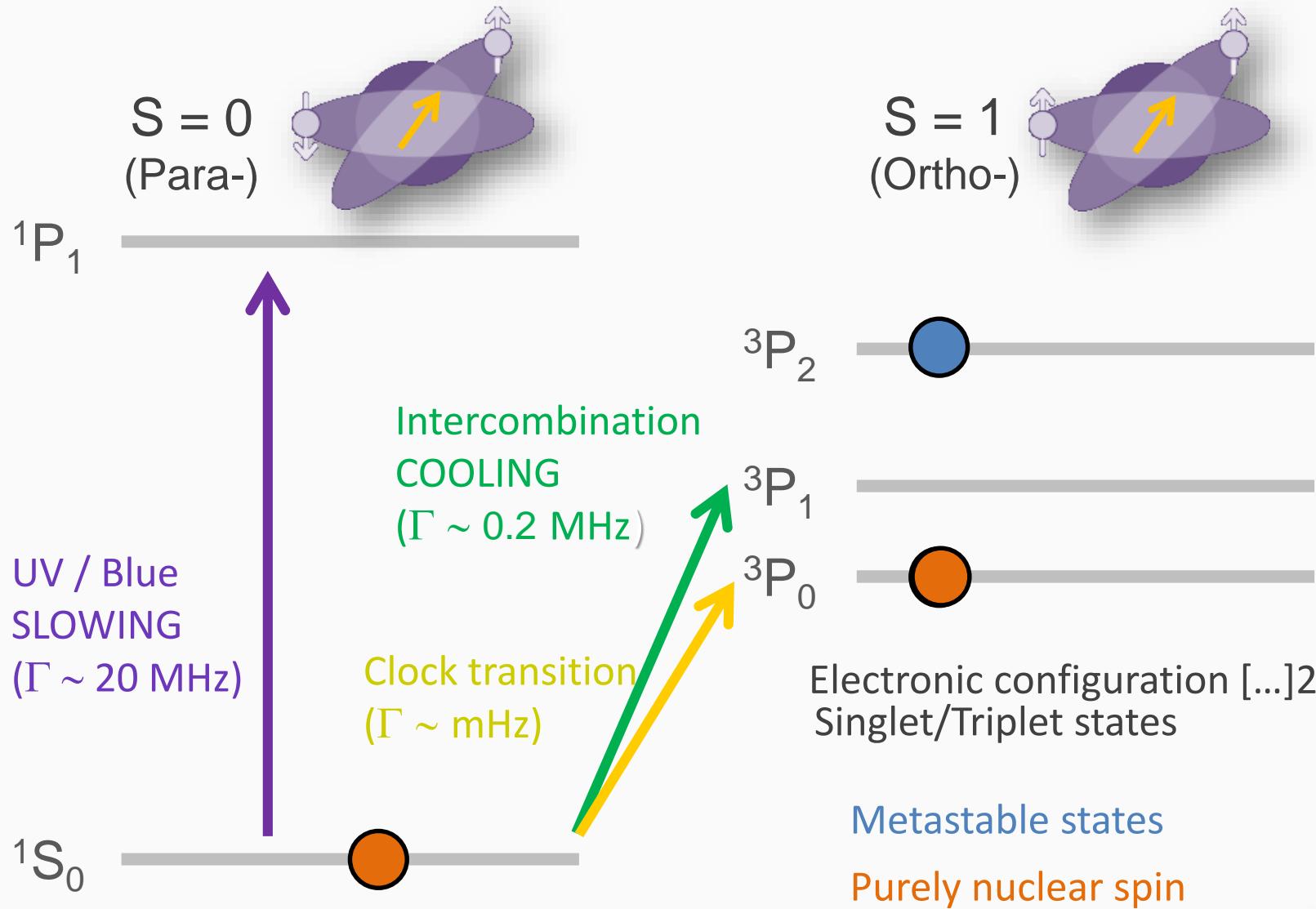
<http://periodictable.com>



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

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

# Yb (alkaline-earth-like) structure



# Main properties

## Fermionic isotopes of Yb: Purely nuclear spin gs MANIFOLD

M. Cazalilla and A. M. Rey,  
Rep. Prog. Phys. **77**, 124401 (2014).



- Interaction strengths between different nuclear spin states are **the same**

SU(2l+1) symmetry

- No spin-changing collisions: any mixture is **stable** against spin relaxation



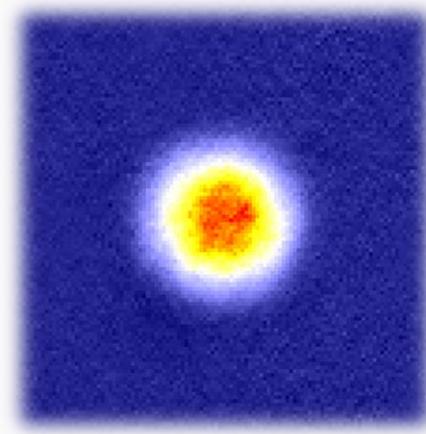
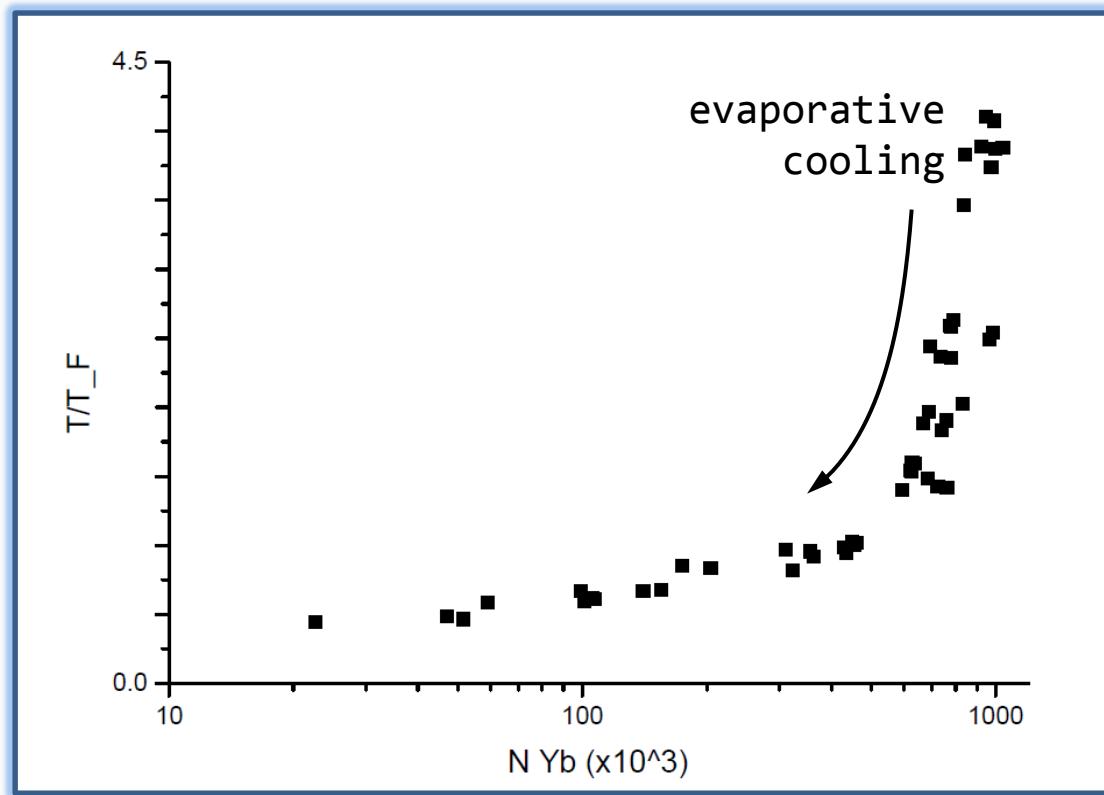
# Quantum degeneracy - Fermions

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

(6 components)

Nuclear spin  $I=5/2$

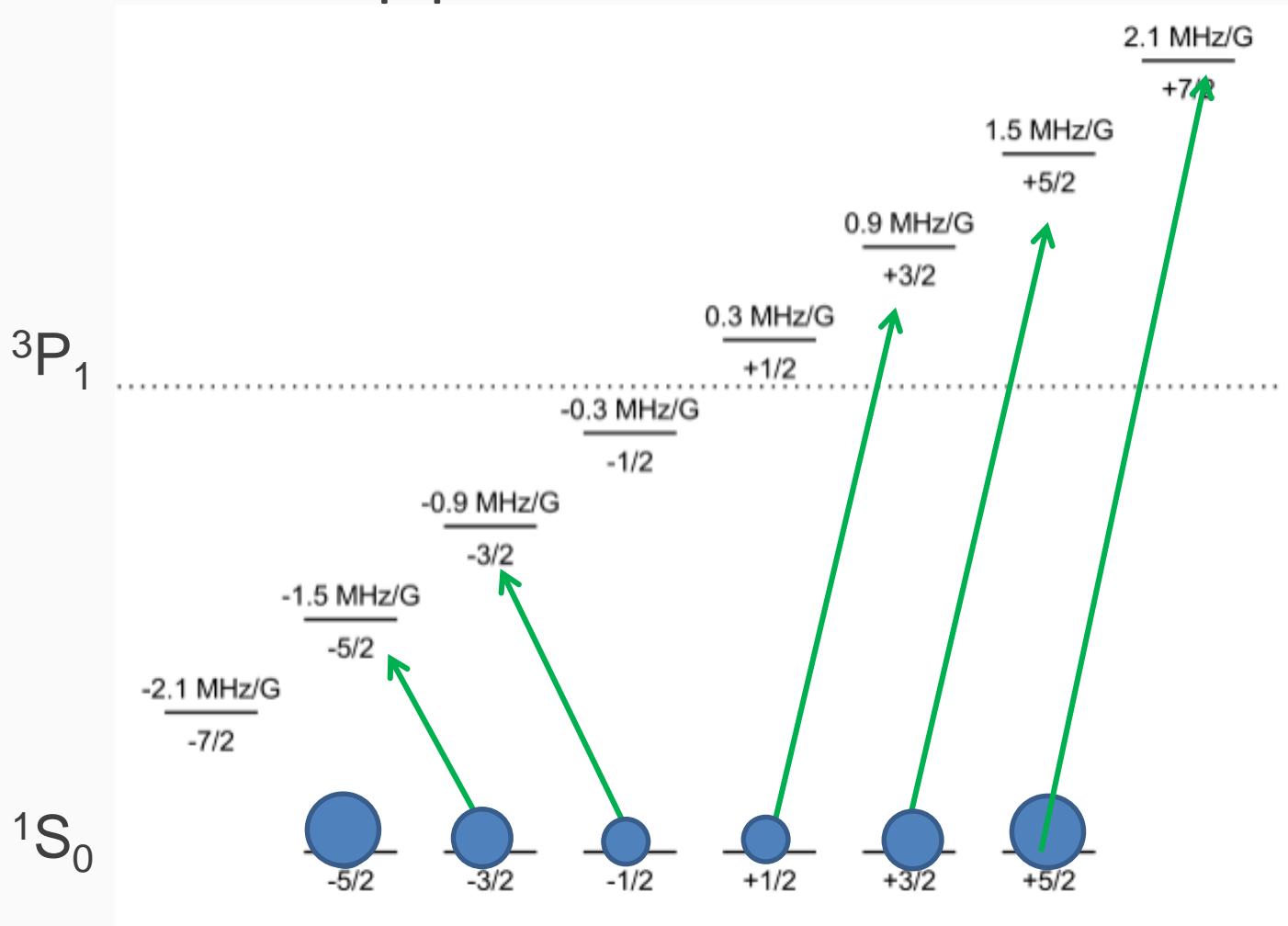
-5/2 ————— +5/2



$^{173}\text{Yb}$  Fermi gas  
 $T/T_F < 0.1$  (20 nK!)  
 $N = 1 \times 10^4$  atoms/spin

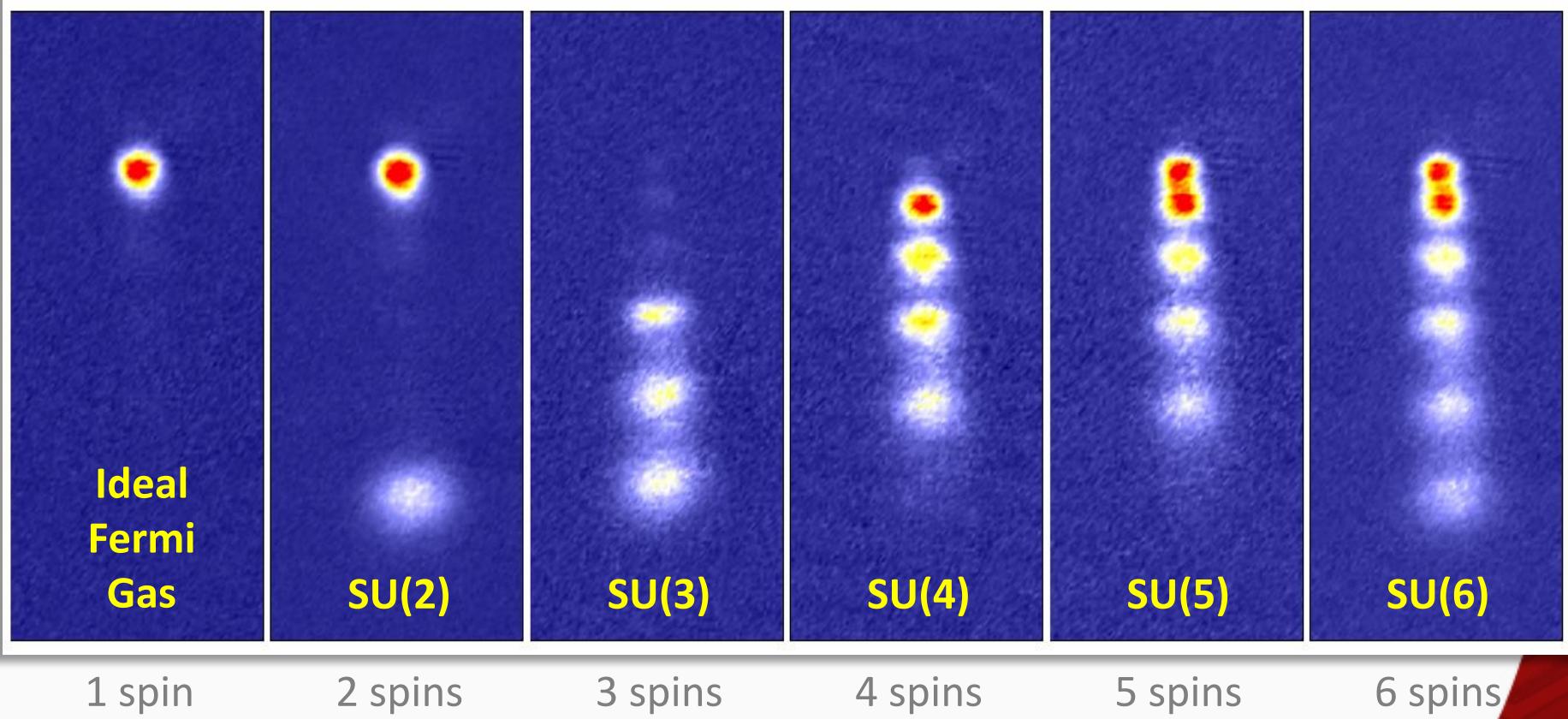
# Spin Manipulation

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



# Spin Manipulation

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



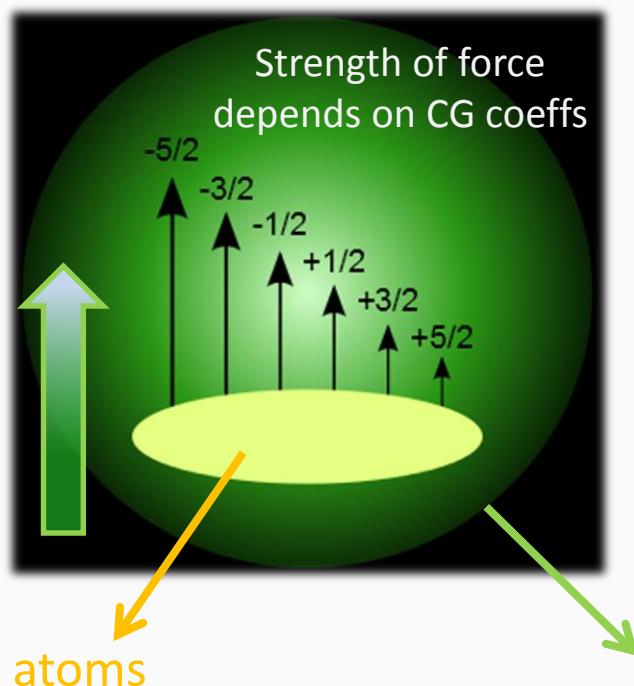
# Spin detection

## Optical Stern-Gerlach detection

(spin separation through an intensity gradient)

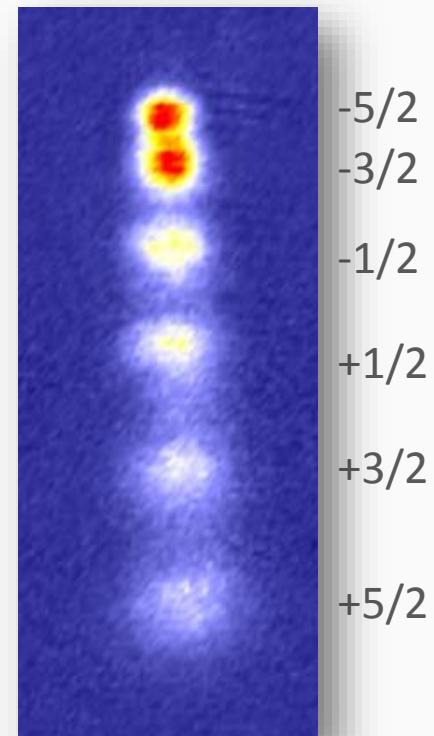
T. Sleator et al., Phys. Rev. Lett. 68, 1996–1999 (1992)

State-dependent optical dipole force during TOF  
based on quasi-resonant AC-Stark shift



optical Stern-Gerlach beam  
556 nm,  $\sigma^-$ ,  $3000\Gamma$  detuning,  $B=3$  Gauss

All spin components  
resolved





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# Low-D interacting Fermi Gases

## Interacting Fermi gases

2D, 3D

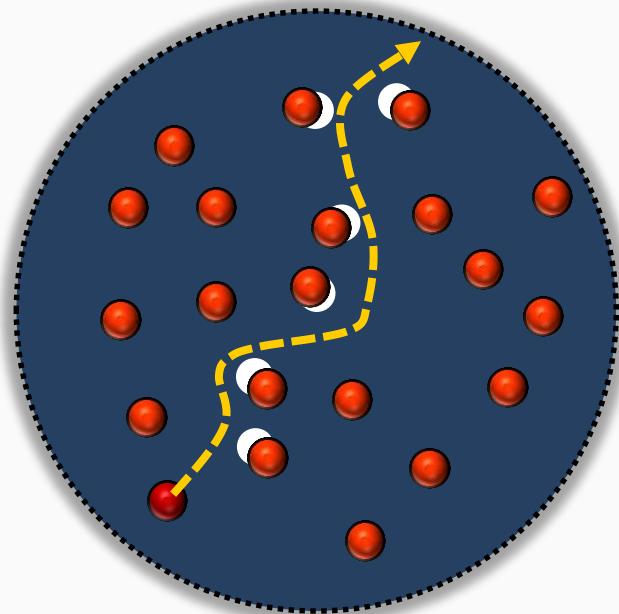
Fermi Liquid

1D

Fermi non-liquid

- Similarities to ideal gas
- Landau Quasiparticle** approach
- Many body properties are caught

- Reduced dim. **boosts interactions**
- Landau's approach fails due to the **collective** character of excitations at low  $q$





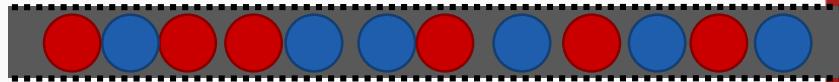
# 1D interacting fermions - Models



# Low-energy physics → Tomonaga - Luttinger model (1950) (1963)

Solution : Lieb, Mattis (1965)

$$H \sim \frac{u}{2} \int dx \left[ K \Pi^2 + \frac{1}{K} (\partial_x \phi)^2 \right]$$



**K = 1** non interacting

## **K = 0.5** infinite repulsion



**ALL low- $q$  excitations are collective (bosonic)**  
**(linear phonon-like dispersion)**

**Differential sound propagation**  
**(Spin-charge separation)**



# 1D interacting fermions - Models

Spin-1/2 fermions



VOLUME 19, NUMBER 23

PHYSICAL REVIEW LETTERS

4 DECEMBER 1967

## SOME EXACT RESULTS FOR THE MANY-BODY PROBLEM IN ONE DIMENSION WITH REPULSIVE DELTA-FUNCTION INTERACTION\*

C. N. Yang

Institute for Theoretical Physics, State University of New York, Stony Brook, New York

(Received 2 November 1967)

The repulsive  $\delta$  interaction problem in one dimension for  $N$  particles is reduced, through the use of Bethe's hypothesis, to an eigenvalue problem of matrices of the same sizes as the irreducible representations  $R$  of the permutation group  $S_N$ . For some  $R$ 's this eigenvalue problem itself is solved by a second use of Bethe's hypothesis, in a generalized form. In particular, the ground-state problem of spin- $\frac{1}{2}$  fermions is reduced to a generalized Fredholm equation.

See also M. Gaudin, Phys. Lett. A 24, 55 (1967)

Yang-Gaudin, 1967

Fermions with higher spin symmetry



VOLUME 20, NUMBER 3

PHYSICAL REVIEW LETTERS

15 JANUARY 1968

## FURTHER RESULTS FOR THE MANY-BODY PROBLEM IN ONE DIMENSION

Bill Sutherland

Institute for Theoretical Physics, State University of New York, Stony Brook, New York

(Received 8 December 1967)

The problem of  $N$  particles interacting in one dimension by a repulsive delta-function potential is solved, when the wave function  $\psi$  transforms like any irreducible representation  $R_\psi$  of  $S_N$  for which the Young tableau consists of a finite number of either rows or columns.

Sutherland, 1968

Not «naturally»  
available!

# Two-electron atoms...

...can go supernatural !



**(LARGE) SPIN TUNABILITY !**

Strongly-interacting  $M$ -component (large-spin) fermions



How does the physics change as a function of  $M$ ?



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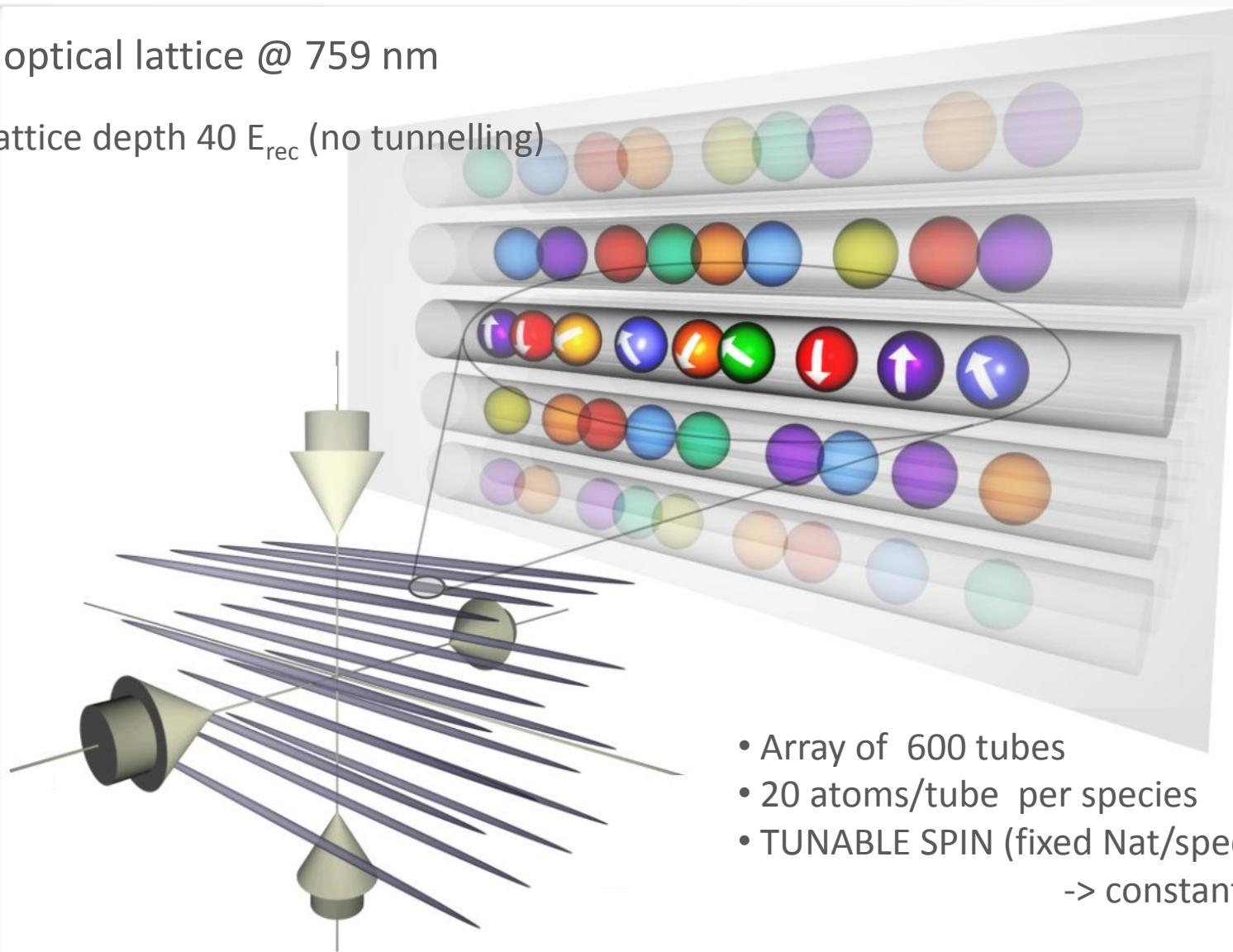


# Creating Spinful Interacting 1D Fermi Gases

# Creating 1D Liquids of Fermions

2D optical lattice @ 759 nm

- Lattice depth  $40 E_{\text{rec}}$  (no tunnelling)



- Array of 600 tubes
- 20 atoms/tube per species
- TUNABLE SPIN (fixed Nat/specie  
-> constant  $k_F$ )

# Ground state properties

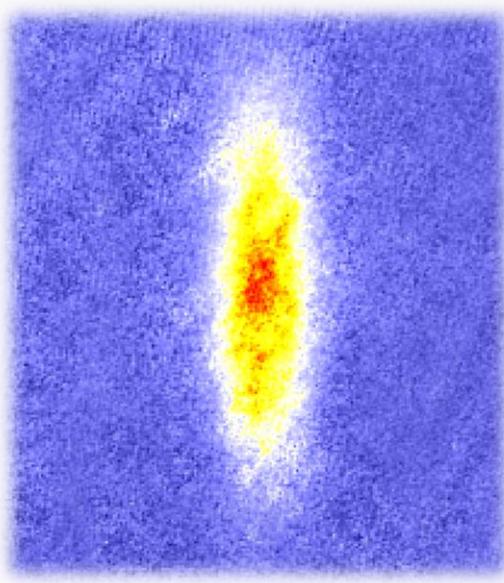
# Ground state properties – $n(k)$

Probing the effect of strong interactions – momentum distribution

1d Fermi systems

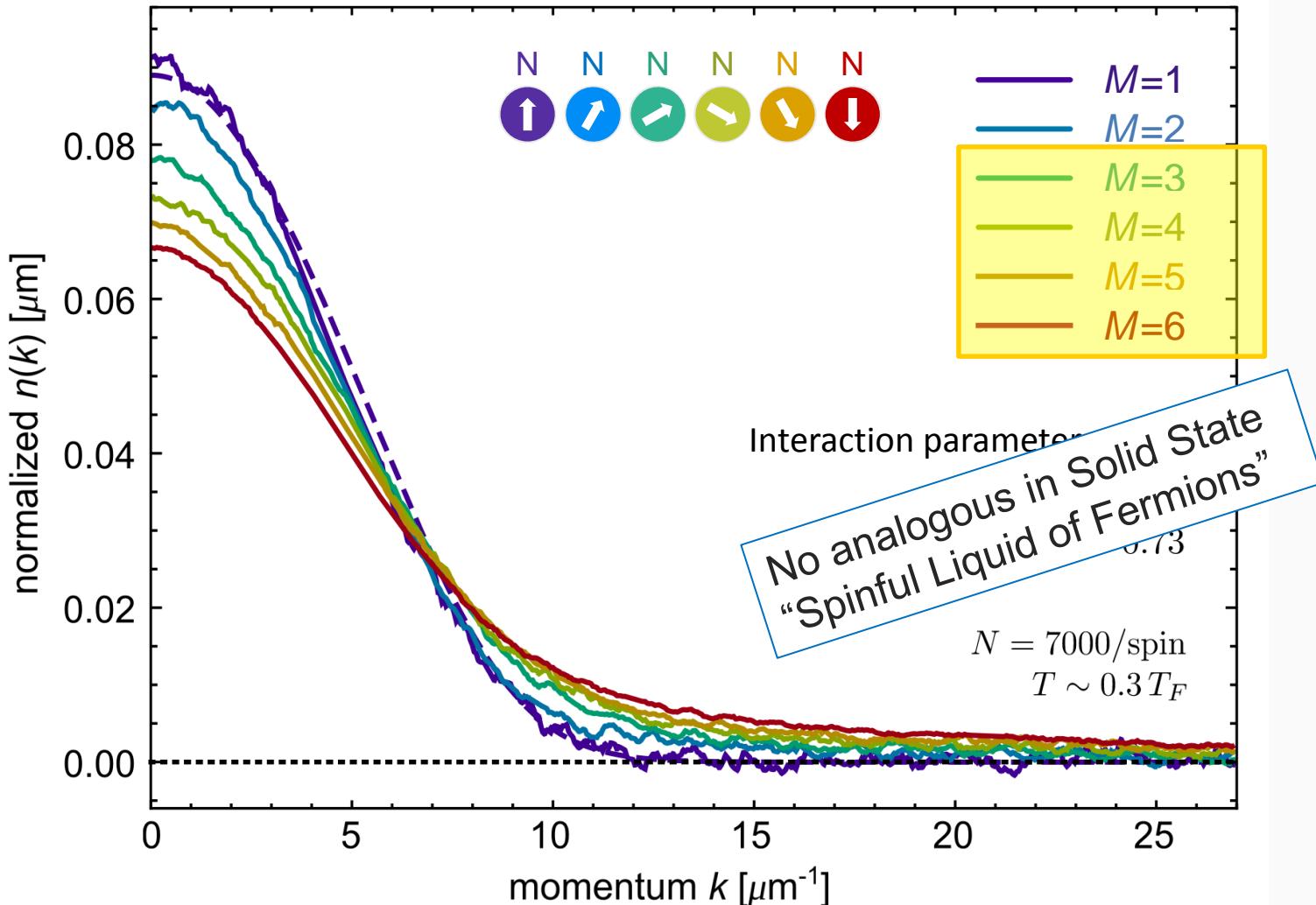


TOF expansion



# Ground state properties – $n(k)$

Probing the effect of strong interactions – momentum distribution

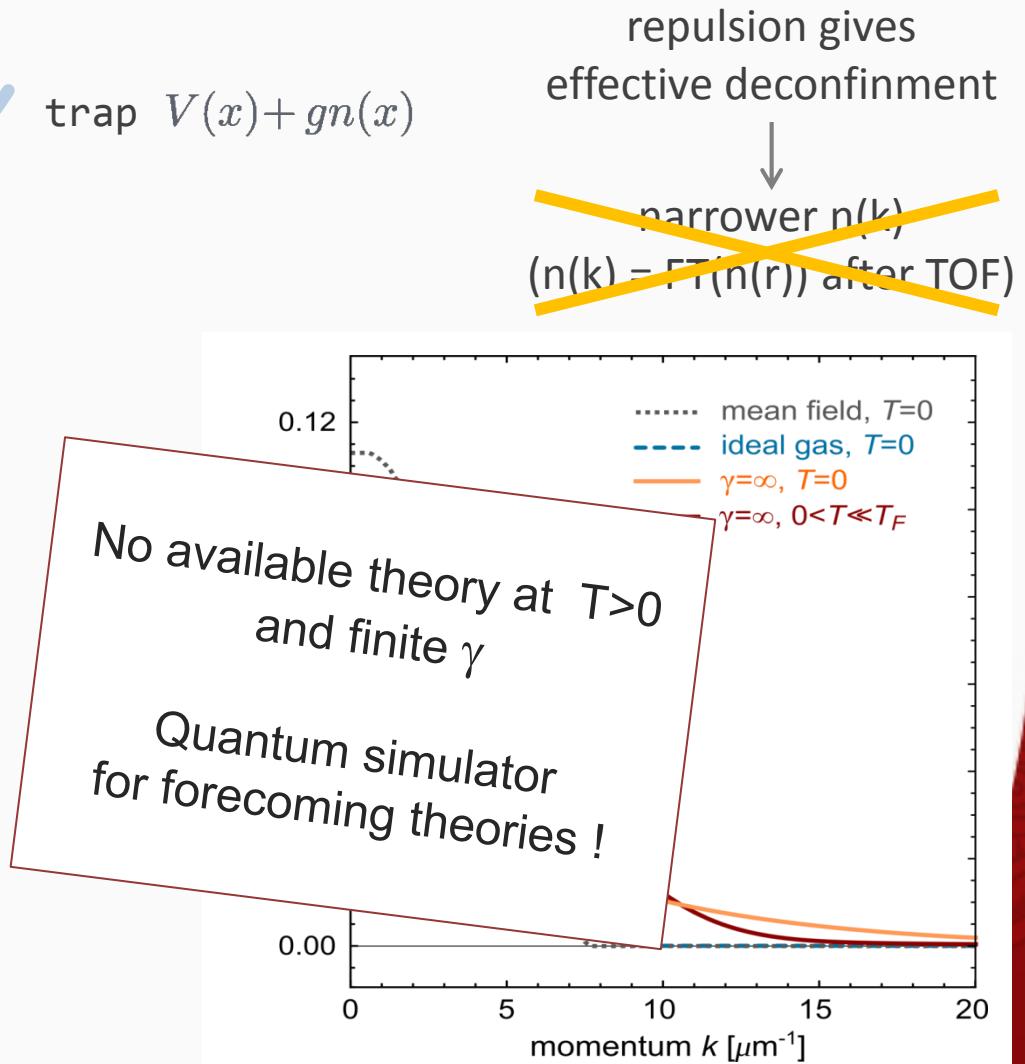


# Ground state properties – $n(k)$

Broadening not explained by a mean-field treatment of interactions



Broadening of  $n(k)$  is evidence of **strong correlations** in the 1D many-body system



Ogata & Shiba, PRB **41**, 2326 (1990)

Cheianov et al., PRA **71**, 033610 (2005)



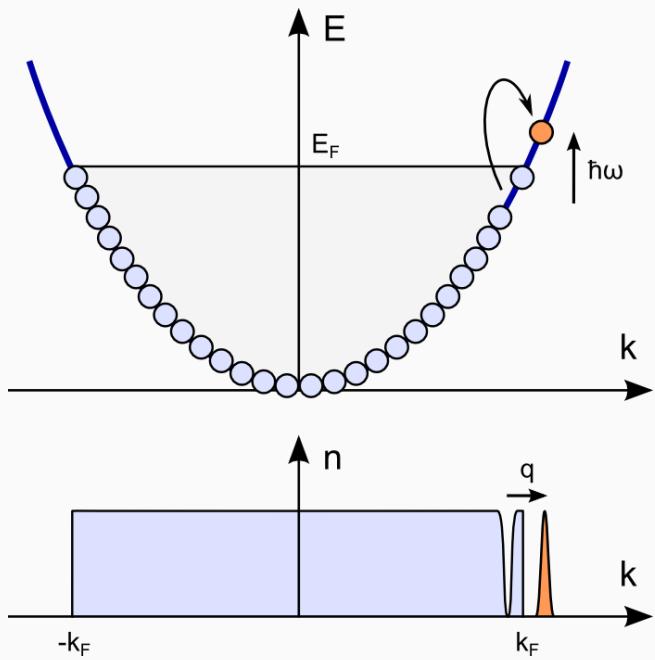
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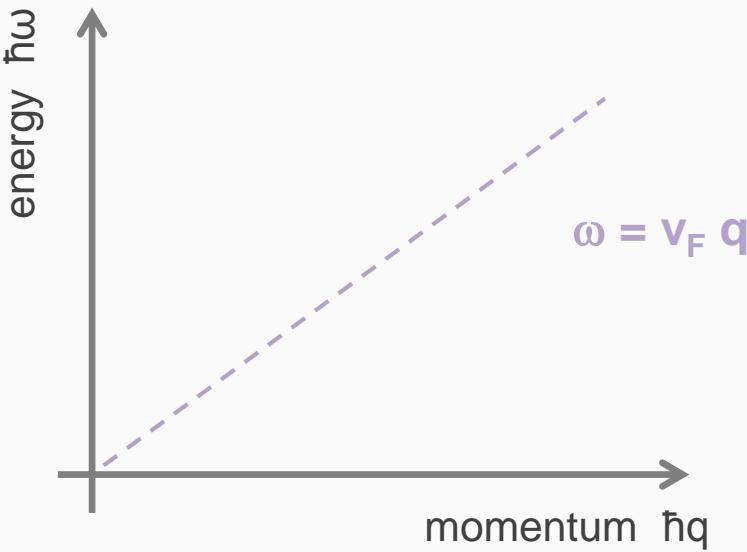
# Excitations in a Spinful Luttinger Liquid

# Excitations (1D Ideal Gas)

1 component: ideal 1D Fermi gas  
particle-hole excitations

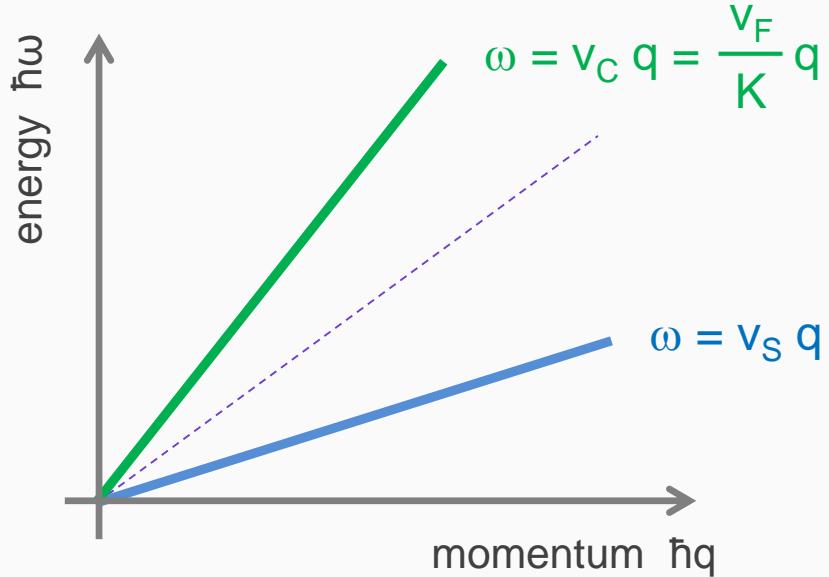
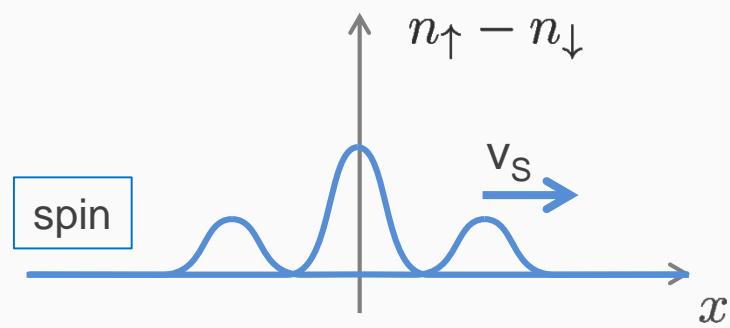
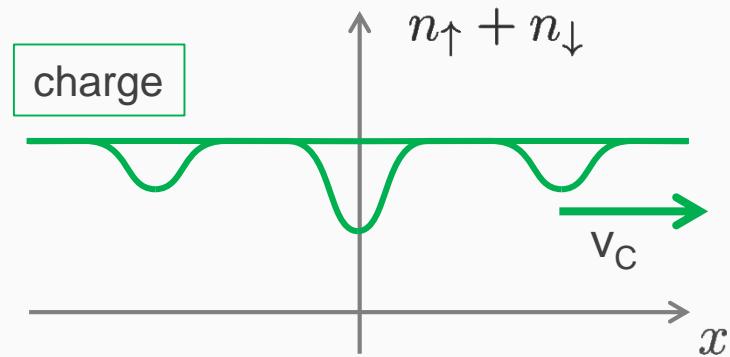


$$\hbar\omega = E_{part.} - E_{hole} = \frac{\hbar^2}{2m} [(k + q)^2 - k^2] \simeq \frac{\hbar k_F}{m} \hbar q$$



# Excitations (1D Liquid – Luttinger)

2-component: **1D Luttinger liquid**  
**collective** (bosonic) excitations

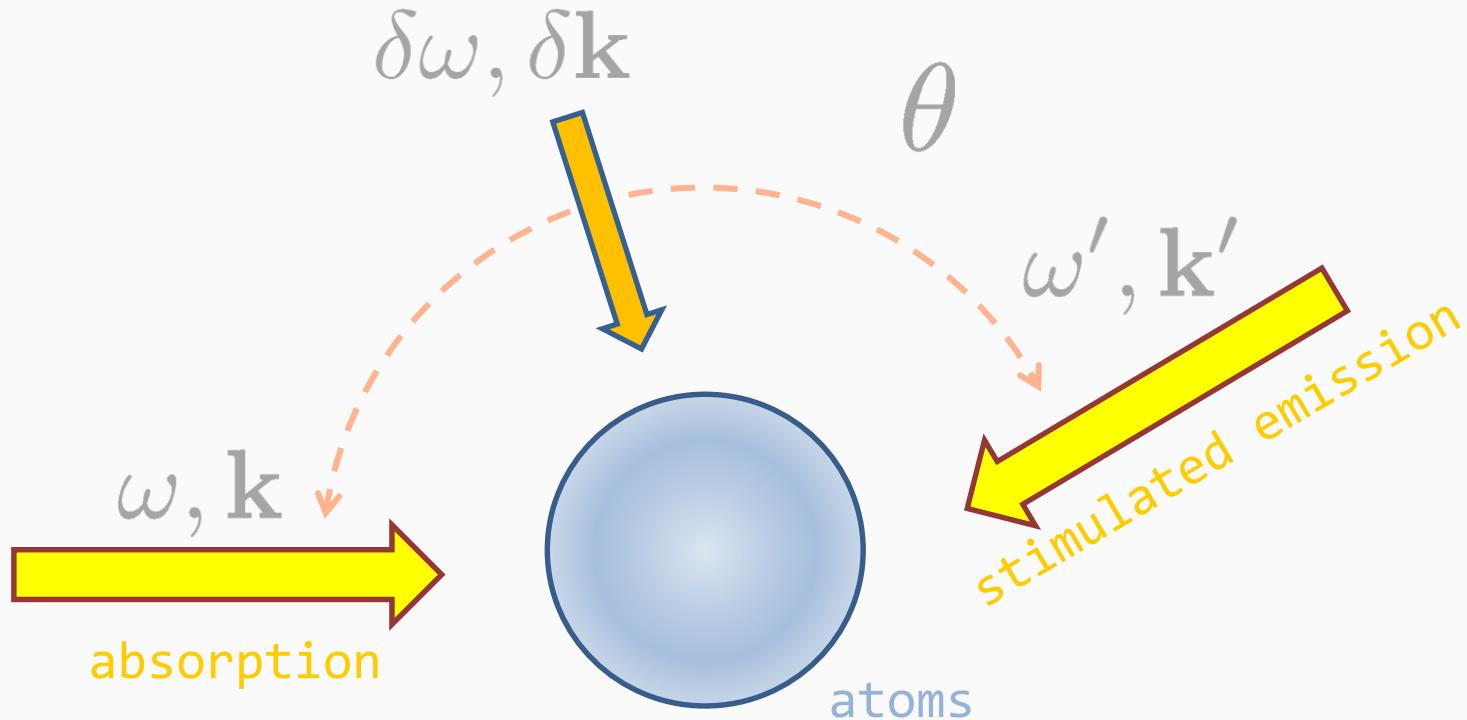


- A. Recati et al., PRL **90**, 020401 (2003)  
 C. Kollath et al., PRL **95**, 176401 (2005)  
 M. Polini & G. Vignale, PRL **98**, 266403 (2007)

spin-charge separation

# Probing the energy spectrum

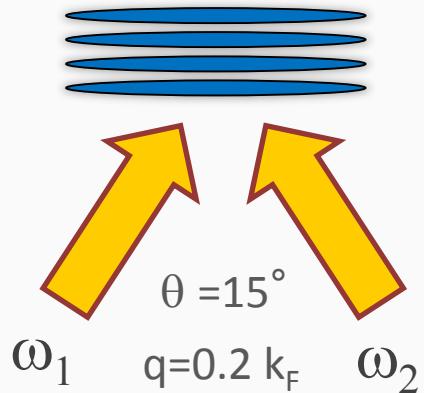
Inelastic scattering of light : **BRAGG SCATTERING**



Stimulated two-photon (Raman) transition  
Selection of energy and momentum

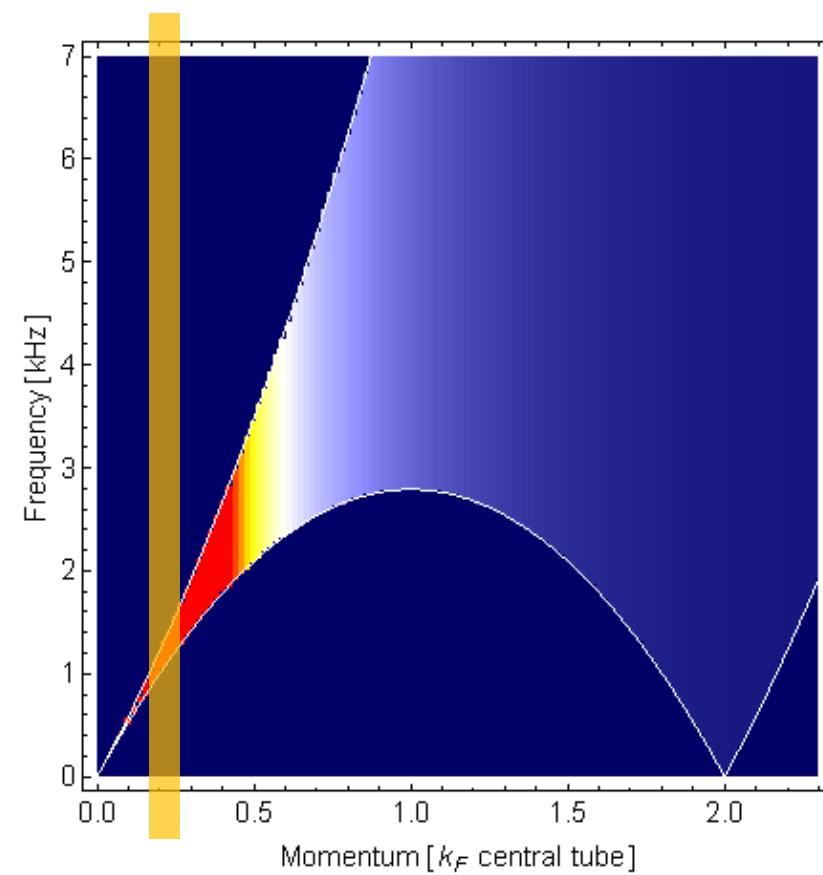
$$\begin{aligned}\delta\omega &= \omega - \omega' \\ \delta k &\simeq 2k \sin(\theta/2)\end{aligned}$$

# Probing the energy spectrum



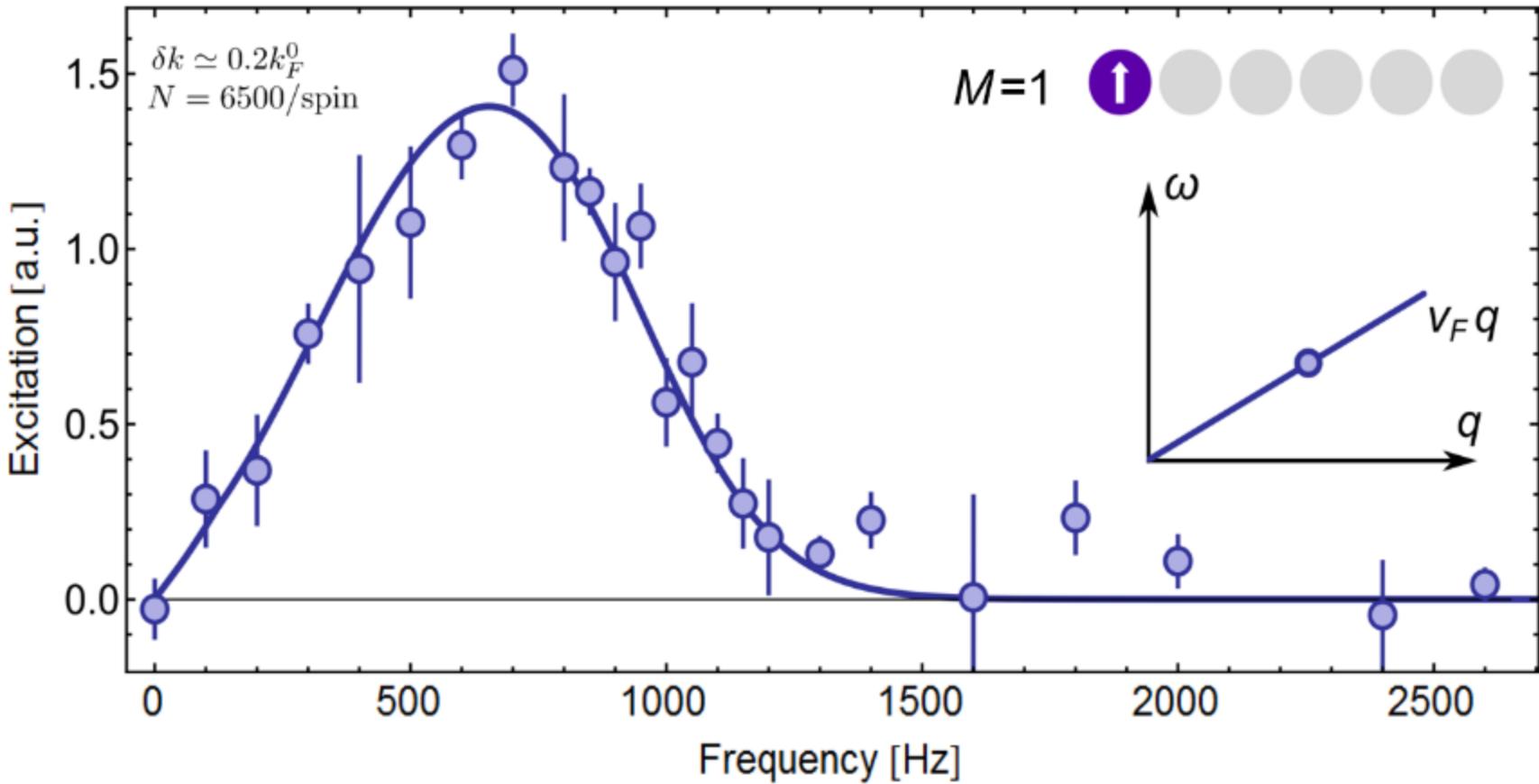
$$E = \hbar (\omega_1 - \omega_2)$$

Low-Energy (small  $q$ ) excitations: LUTTINGER spectrum



# Probing the energy spectrum

30 ms excitation, observing the cloud's size in TOF

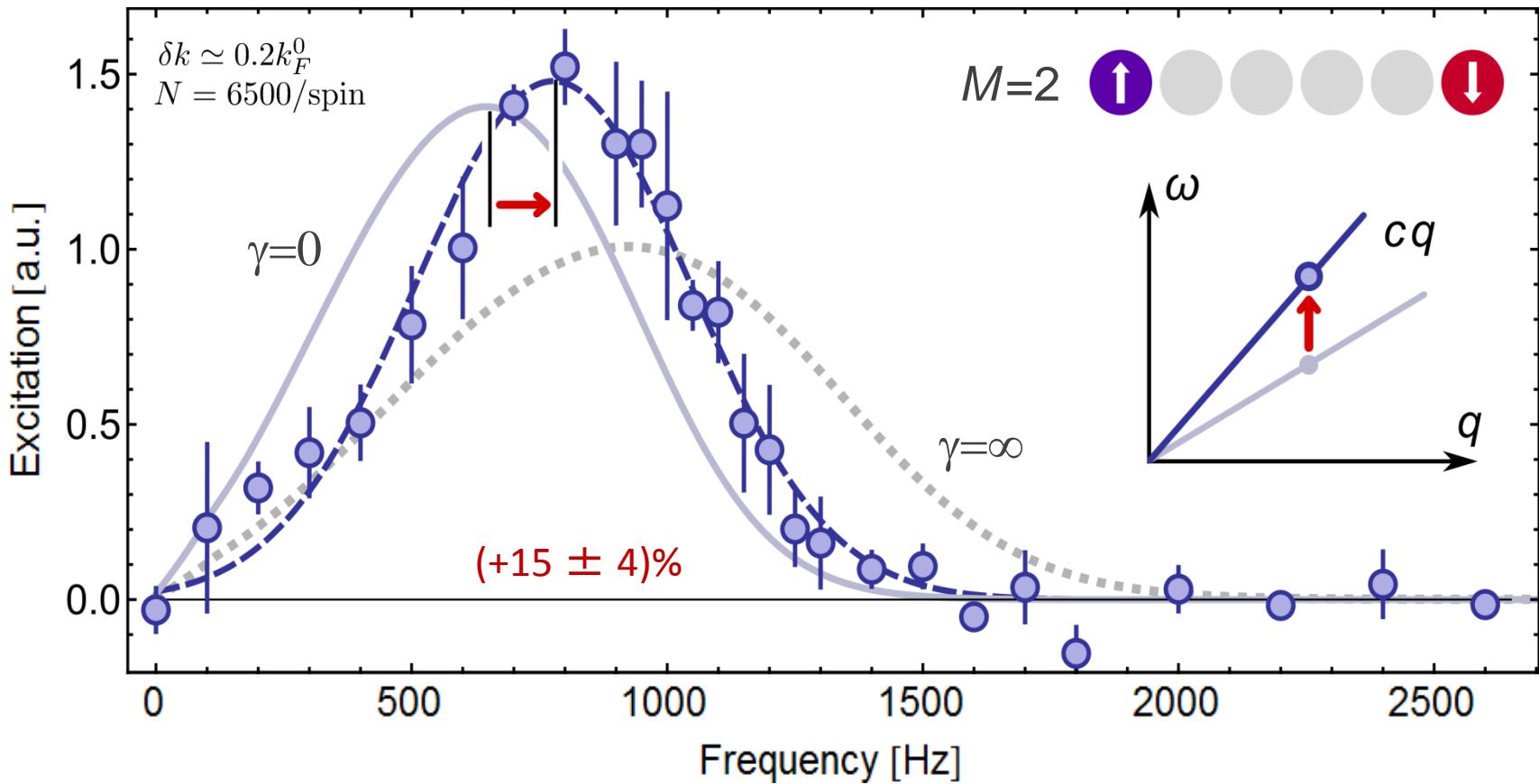


# Probing the energy spectrum

30 ms excitation, observing the cloud's size in TOF

Shift in the excitation peak frequency

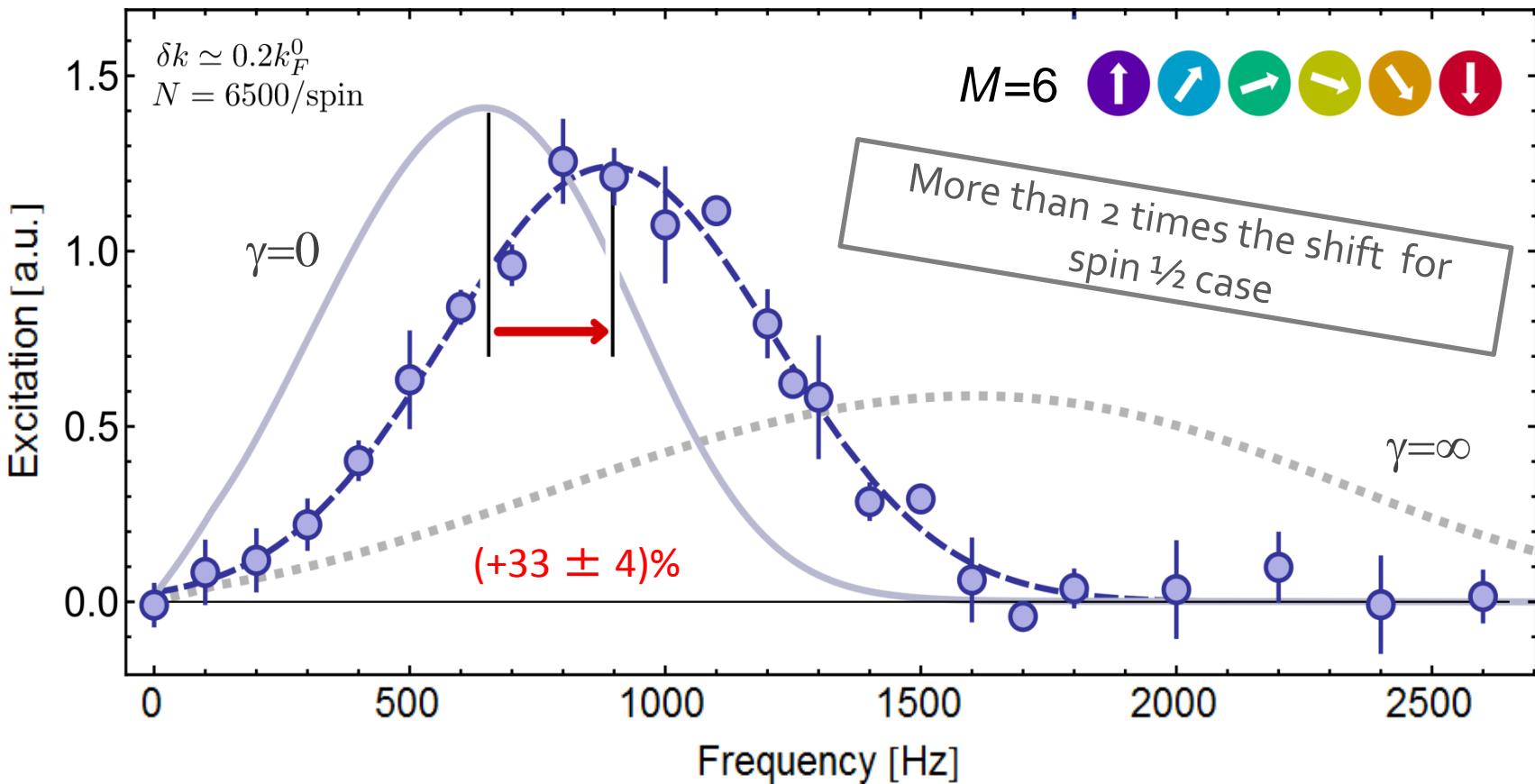
(+10 ± 2)% expected by Bethe ansatz solution



# Probing the energy spectrum

30 ms excitation, observing the cloud's size in TOF

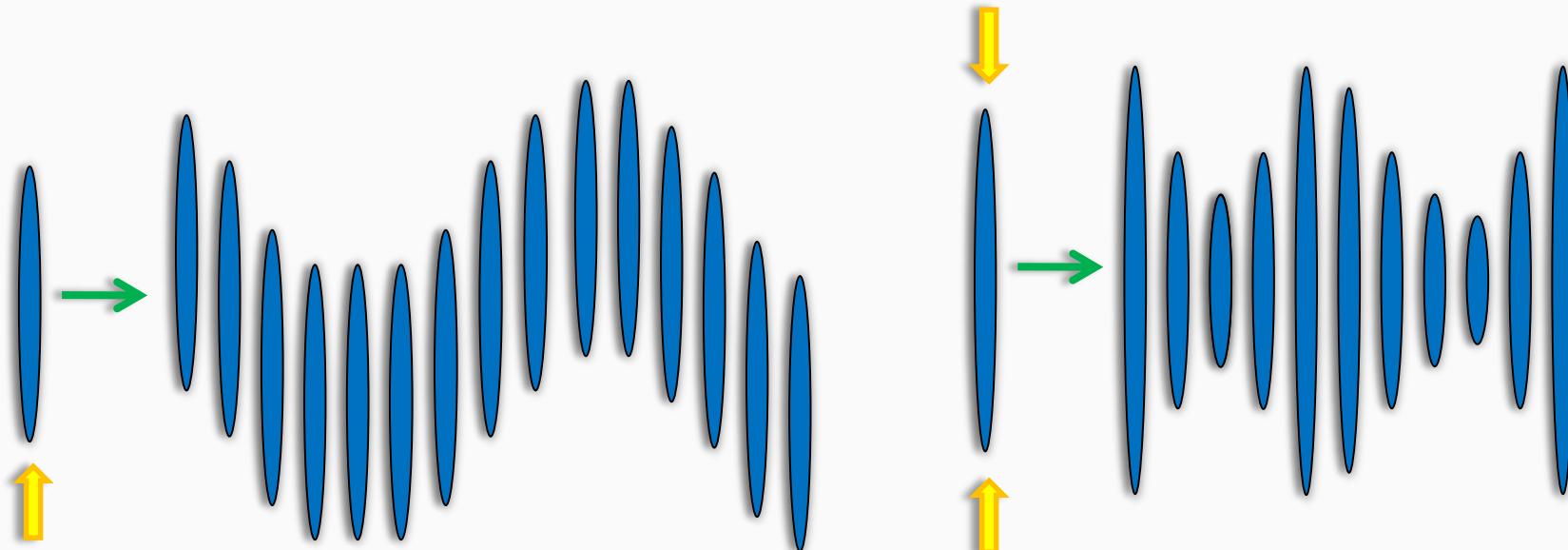
Larger shift for increased number of spin components



# Collective excitations & dynamics

Excitation of low-q “shape” modes

**OUR EXP:** collective **breathing mode** VS **dipole mode**  
Small change in the combined trap **shape** (ODT+lattice)

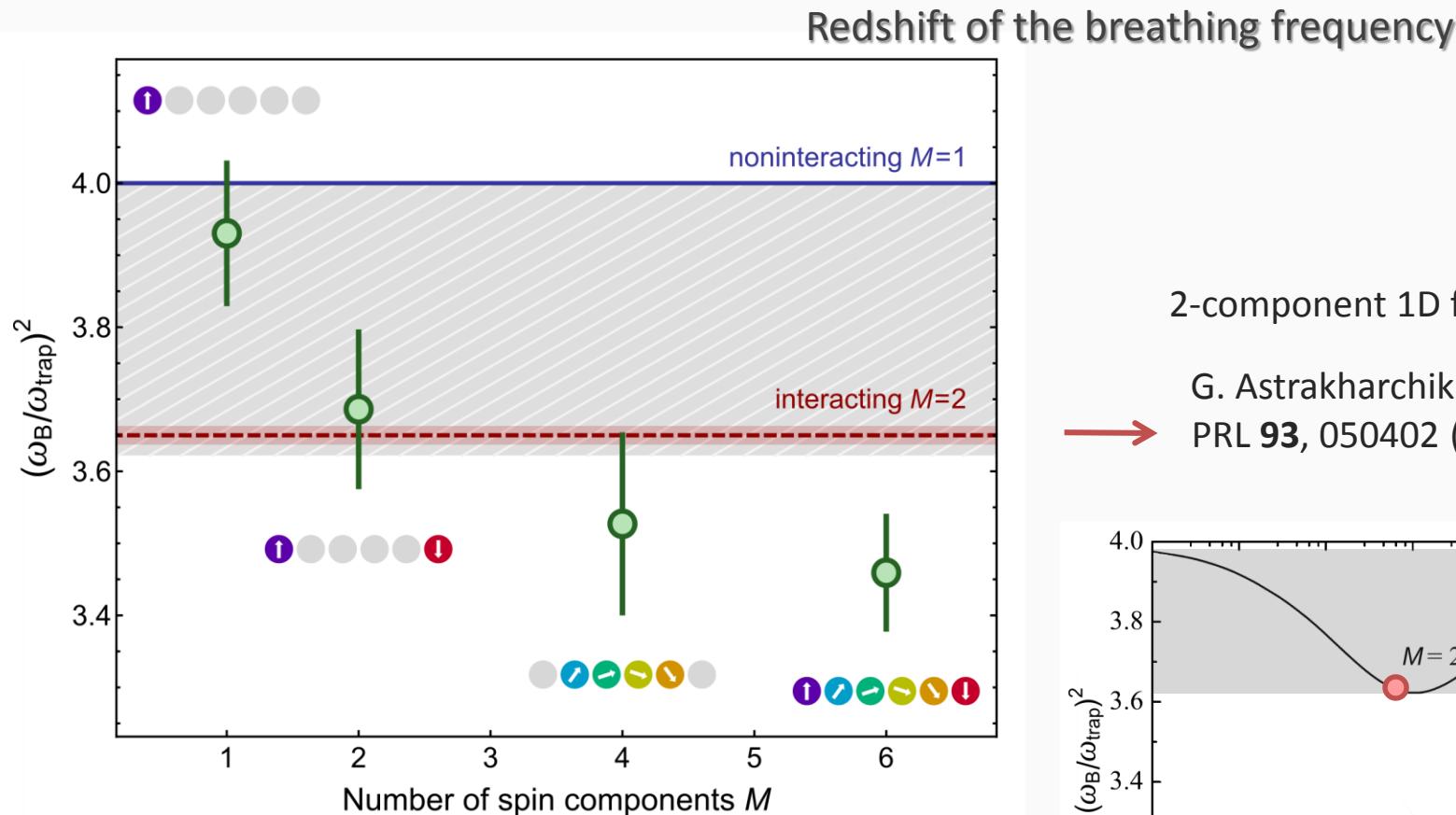


$\omega_{\text{ideal}} = \omega_{\text{trap}}$   
Independent on  $K$

$\omega_{\text{ideal}} = 2 \omega_{\text{trap}}$   
Should depend on  $K$

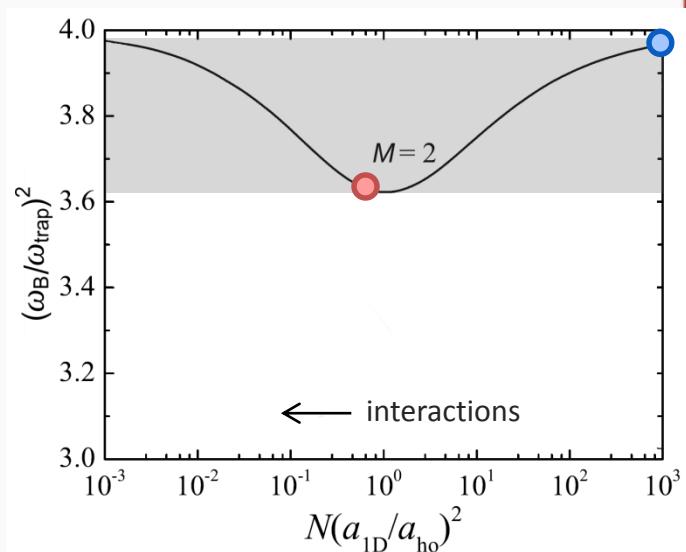
# Collective excitations & dynamics

Frequency of the breathing mode:



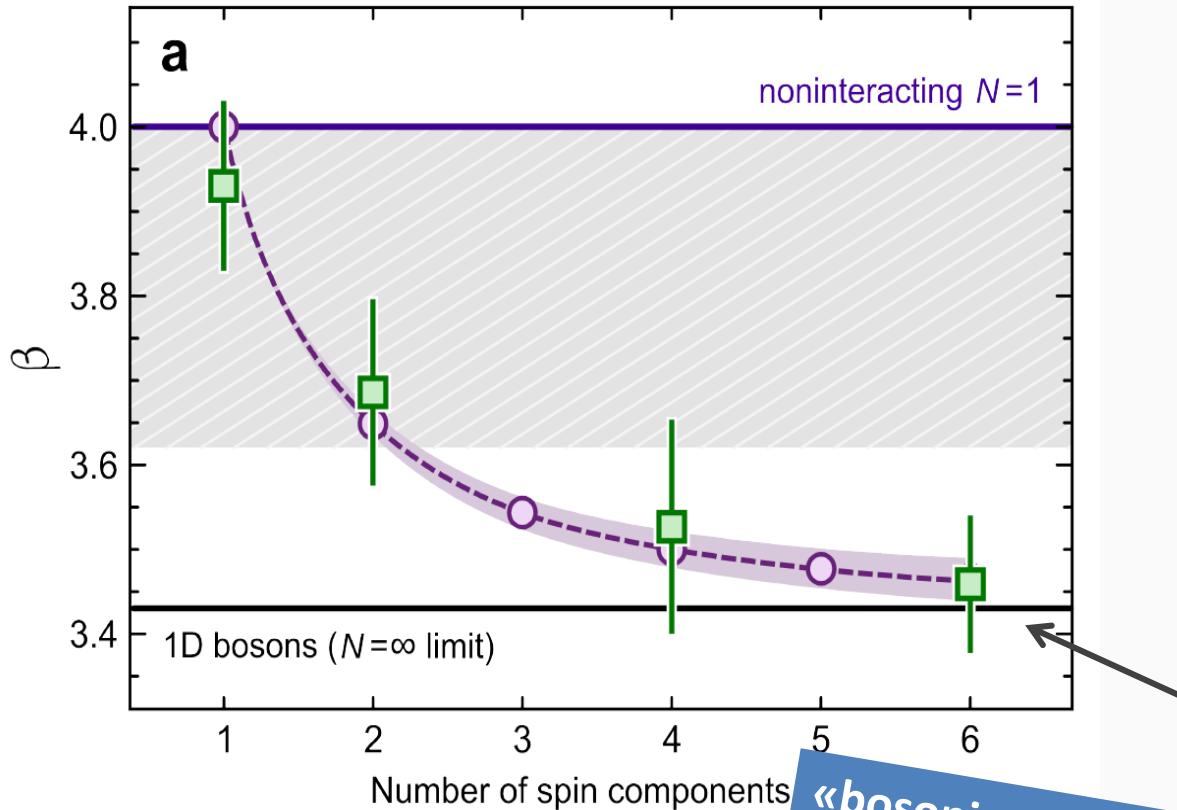
2-component 1D fermions

G. Astrakharchik et al.,  
PRL 93, 050402 (2004)



# Multi-component model

More insight:



Compare our data with results  
of a Bethe-Ansatz-based,  
hydrodynamic  
**multi-component model**

H. Hu and X.-J. Liu  
Swinburne (AUS)

Close to predictions for  
**SPINLESS BOSONS**

«**bosonization**» of large-spin fermions

# Bosonization of Large-Spin 1D Fermions

A very general result first demonstrated in 2011 by C. N. Yang

CHIN. PHYS. LETT. Vol. 28, No. 2 (2011) 020503

## One-Dimensional $w$ -Component Fermions and Bosons with Repulsive Delta Function Interaction \*

C. N. YANG(杨振宁)<sup>1,2\*\*</sup>, YOU Yi-Zhuang(尤亦庄)<sup>1</sup>

<sup>1</sup>Institute for Advanced Study, Tsinghua University, Beijing 100084

<sup>2</sup>Institute of Theoretical Physics, Chinese University of Hong Kong, Hong Kong

The ground state energy for such a system was studied in the 1960s, first in 1963 by Lieb and Liniger<sup>[1]</sup> for spinless Bosons, then in 1967 by Yang<sup>[2]</sup> for spin 1/2 Fermions, finally in 1968 by Sutherland<sup>[3]</sup> for 3 component Fermions. This last result is readily generalizable to any value of  $w$  = number of components. In the present paper we complete this series of studies by solving the problem for  $w$  component Bosons via a detour through  $\infty$  component Fermions.



*Theorem 2.*

$$Y_{F\infty}(Z) = Y_{B1}(Z).$$

For  $M \rightarrow \infty$  a 1D fermionic liquid exhibit properties of a **bosonic spinless liquid**:

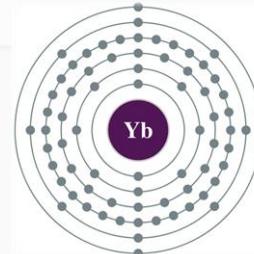
- The **ground-state energy** per particle  $E(\gamma)$
- The **local pair-correlation function**  $g^{(2)}_{\sigma,\sigma'}(0)$

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

X.-W. Guan et al., PRA **85**, 033633 (2012)

# Today's summary

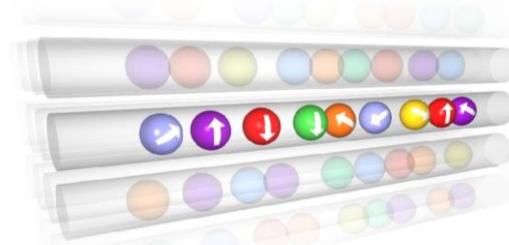
## Properties of Two-electron Atoms for Qu-Sim



## Strongly interacting 1D fermions beyond Spin $\frac{1}{2}$

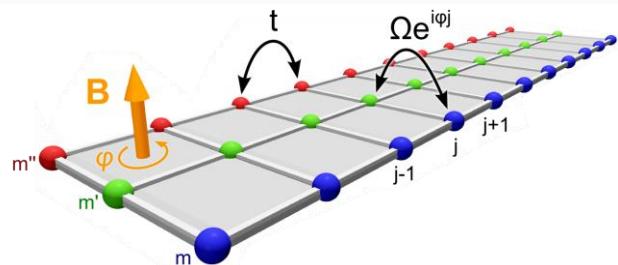
- 1D interacting fermions: Models
- Non-trivial Ground State properties for Large Spin
- Excitation spectrum / collective modes for Large Spin

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



## An Atomic Hall system with «artificial» dimensions

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



# Outline - 2

## Introduction

## Two-Electron Atoms

## 1D Luttinger Liquids with Tunable Spin

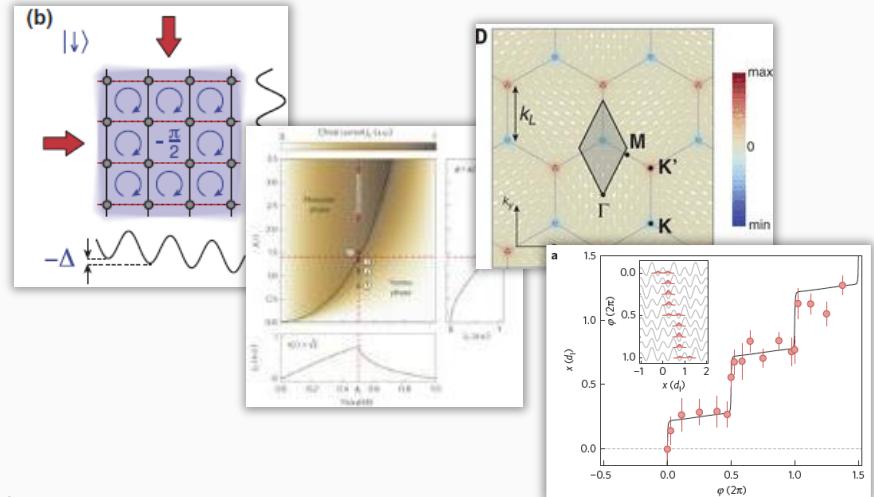
## Hall-like systems with $2e^-$ Atoms

## Edge States in Synthetic Hall systems

# Topological States in atomic systems

**BULK TOPOLOGICAL MATTER:** tackled by recent experimental results

- Aidelsburger et al., PRL **111**, 185301 (2013)
- H. Miyake, et al. PRL. **111**, 185302 (2013).
- M. Atala et al., Nature Phys. **10**, 588 (2014).
- L. Duca et al., Science **347**, 288 (2015)
- Aidelsburger et al., Nature Phys. **11**, 162 (2015)
- M. Lohse at al. Nature Phys. (2015)
- S. Nakajima et al., Nat. Phys. AOP (2016)

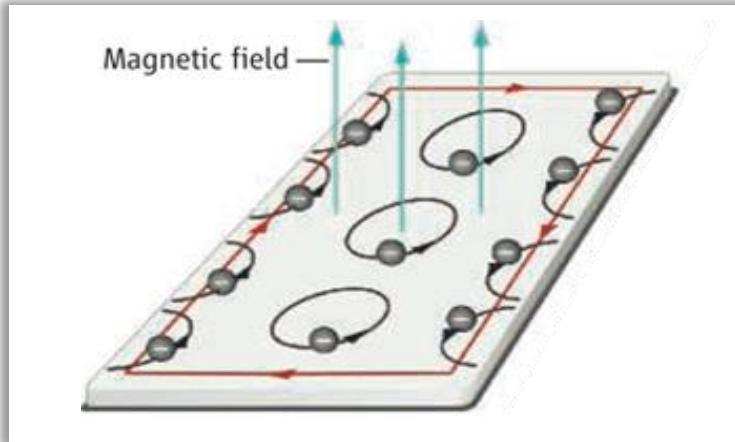


**EDGE STATES:** hallmark of topological systems  
(e.g. Quantum Hall)  
**lack of experimental observation with fermions**

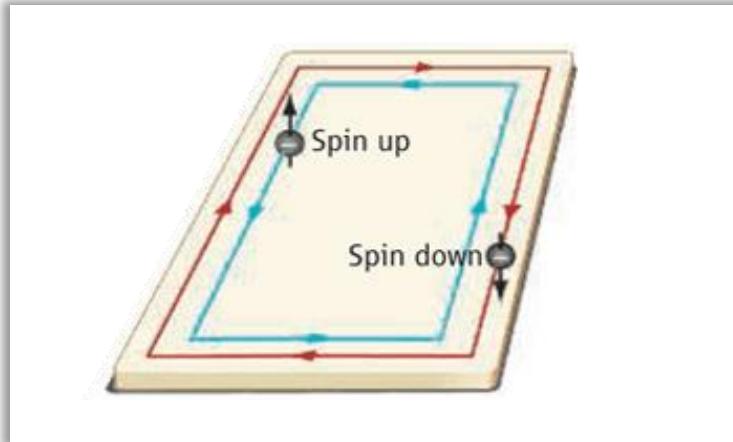
- Proposal for atoms
- A. Celi et al., PRL **112**, 043001 (2014)

# Edge States

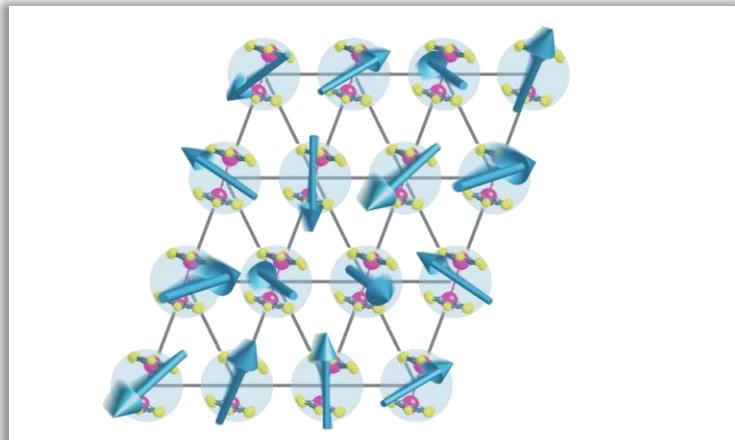
## Quantum Hall effect



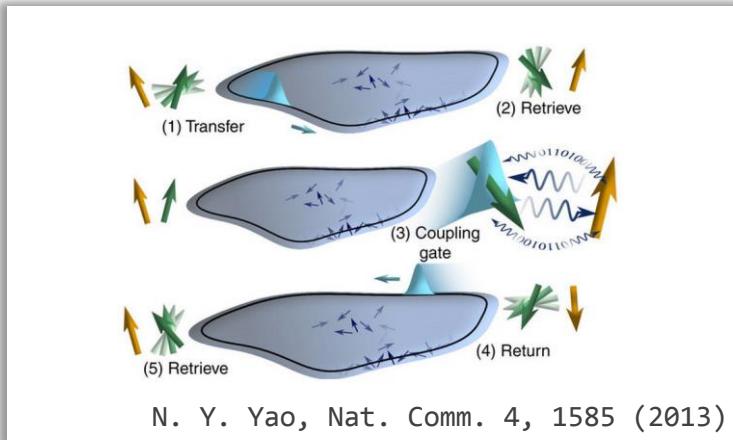
## Topological insulators



## Chiral spin liquids



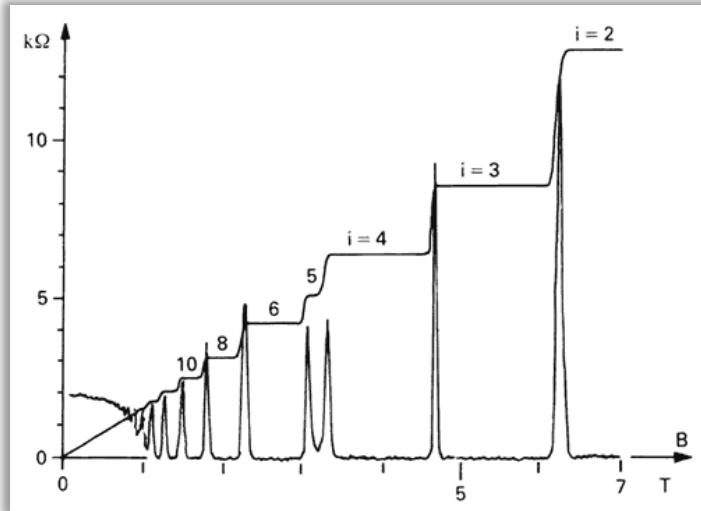
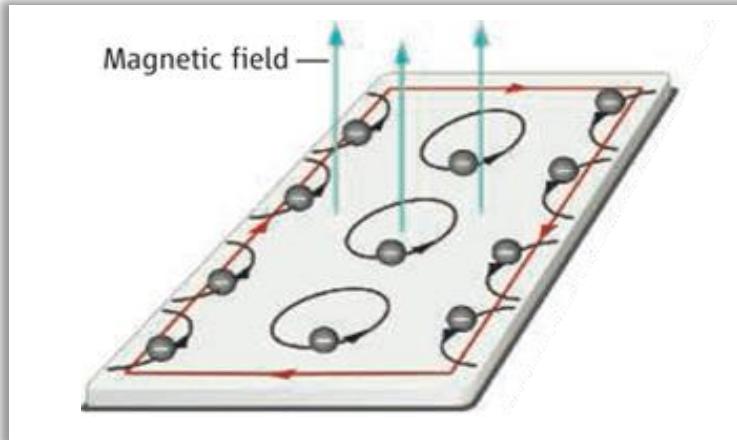
## Quantum technology



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

# QHE in a nutshell

## Quantum Hall effect



## 2D Charged Particles ( $e^-$ ) in $\mathbf{B}$ field

- Quantized Cyclotron Orbits  
Insulating **Bulk States**
- Skipping Orbit at boundaries  
Superconducting **Edge States**



- Quantized plateaux in transv. conductance for critical values of  $\mathbf{B}$

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

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

...a small detail

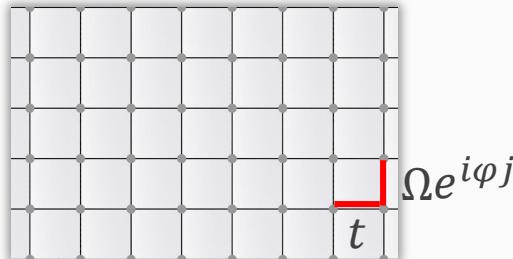
...atoms are neutral

# Harper-Hofstadter model

**charged particle** in a 2d lattice + magnetic field

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

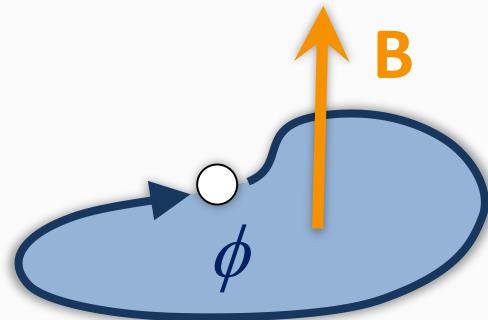
$$H = -t \sum_{j,m} (c_{j,m}^\dagger c_{j+1,m} + h.c.) - \Omega \sum_{j,m} (e^{i\varphi_j} c_{j,m}^\dagger c_{j,m+1} + h.c.)$$



Can be imprinted by laser beams!

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

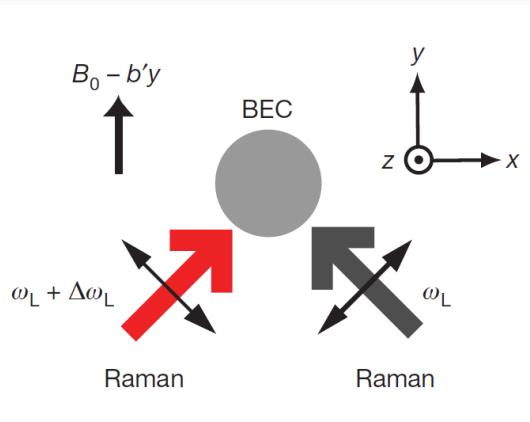
Aharonov-Bohm geometric phase  
Embeds **B** field and charge



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

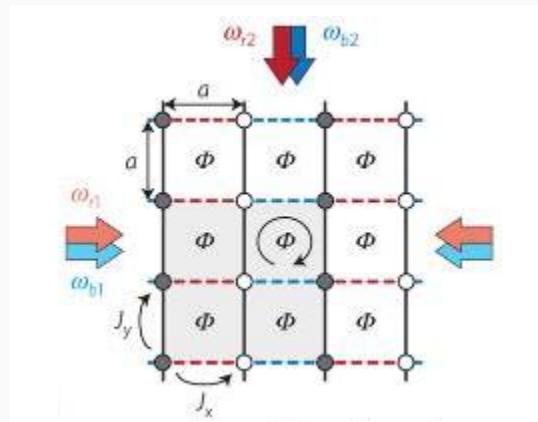
# Artificial Gauge Potentials

Raman transitions



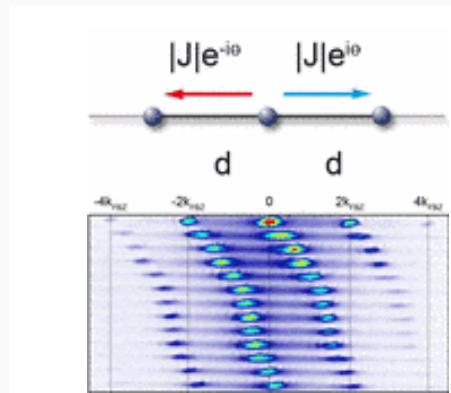
NIST, LENS...

Laser-assisted tunnelling



MPQ, MIT

Lattice shaking



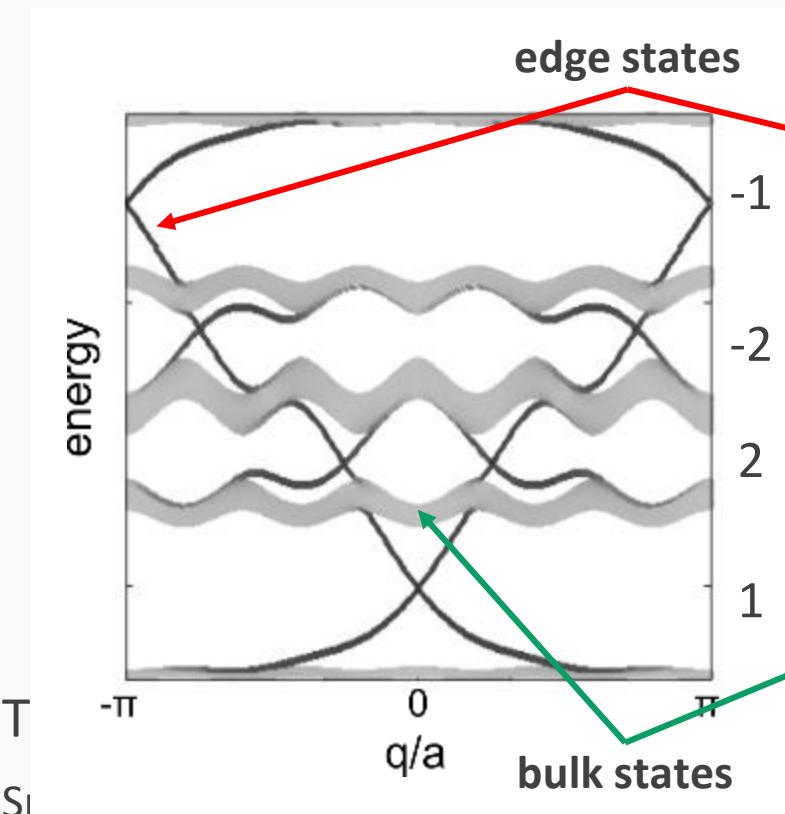
Hamburg, ETH, MPQ, ...

# Harper-Hofstadter model

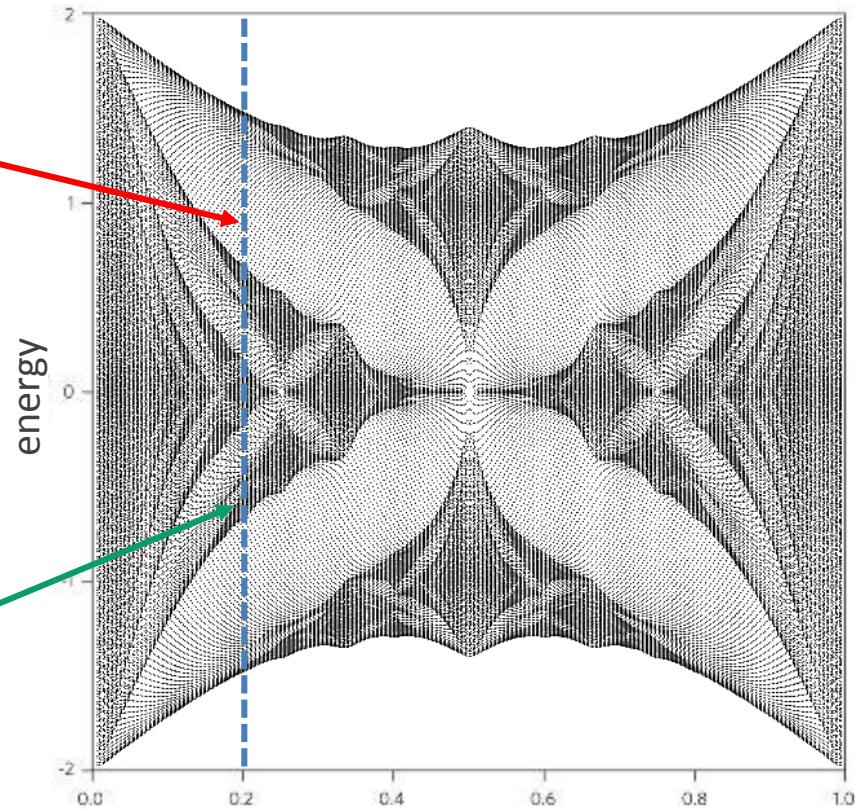
charged particle in a 2d lattice + magnetic field

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

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

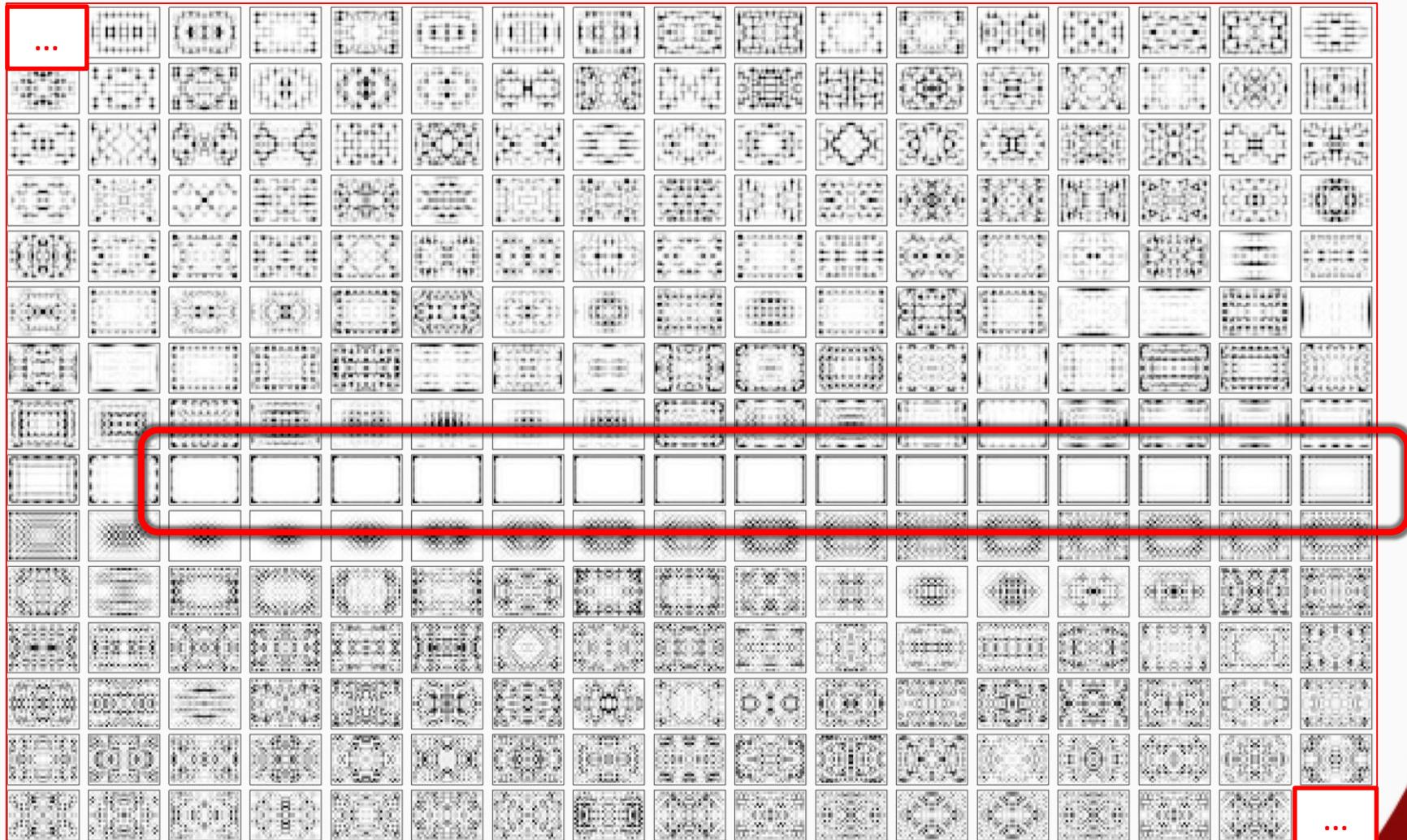


in a 2d lattice + magnetic field (bulk states)  
**Bulk-edge correspondance:**  
# edge states = Chern #



# Bulk vs Edge states

Eigenstates of the Harper-Hofstadter model in a finite-sized system (30x20 lattice)

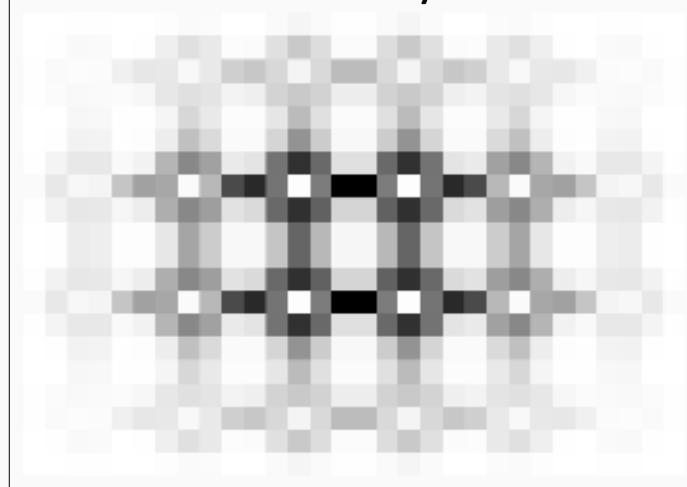


# Bulk vs Edge States

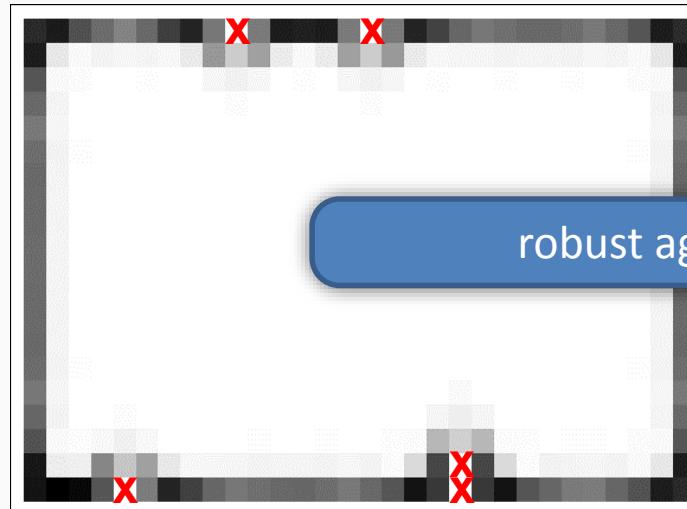
Bulk – Edge differences

Bulk state:

density:

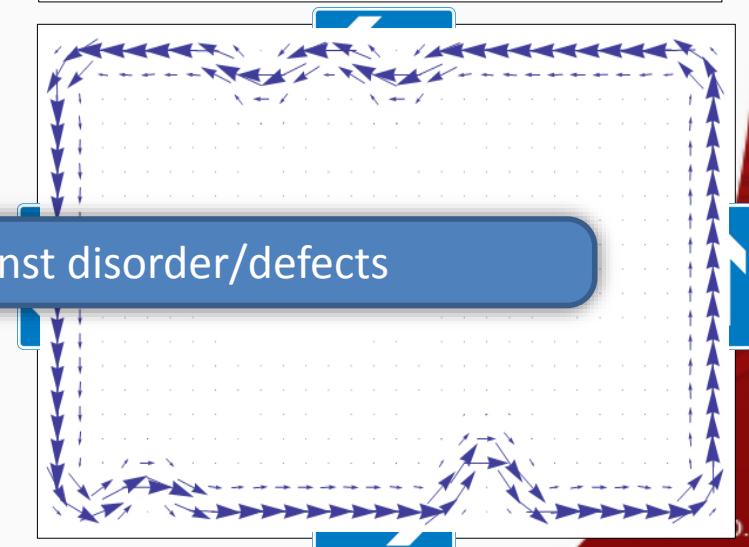
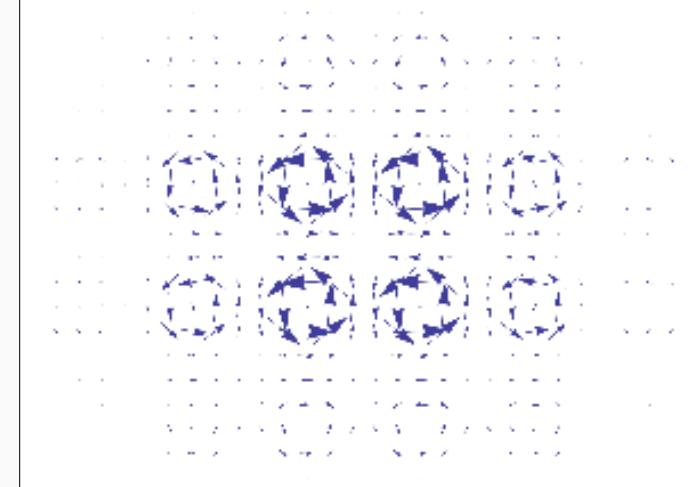


Edge state:



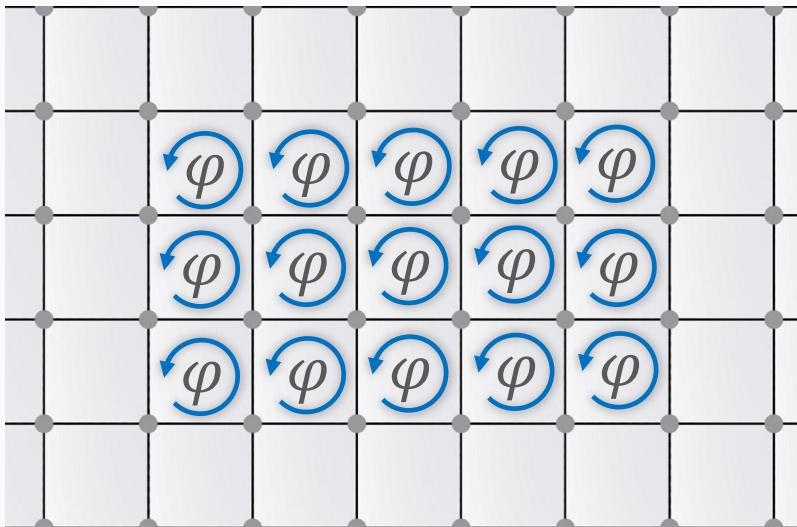
robust against disorder/defects

current:



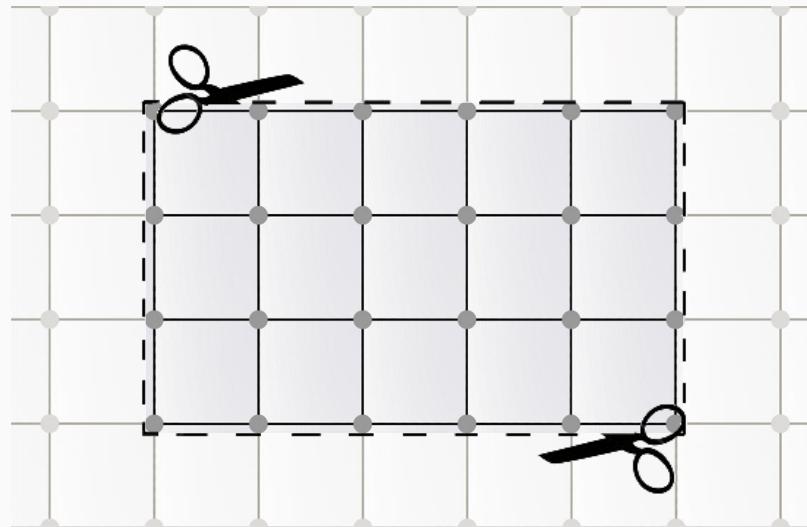
# Recipe for edge states

Topological matter



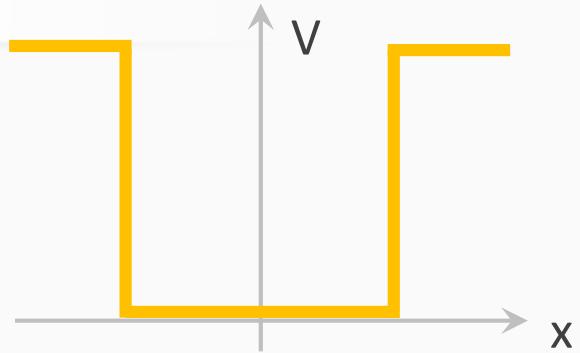
Imprint the phase through  
atom-light interaction in optical lattices

A system with sharp edges

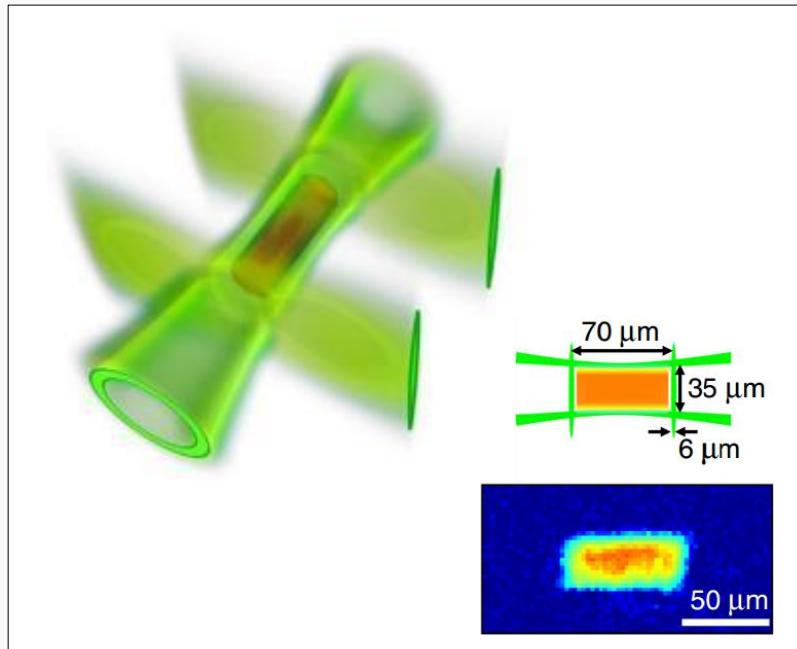


A new idea for ultracold atoms:  
***add a sharp, synthetic dimension!***

# Other recipes

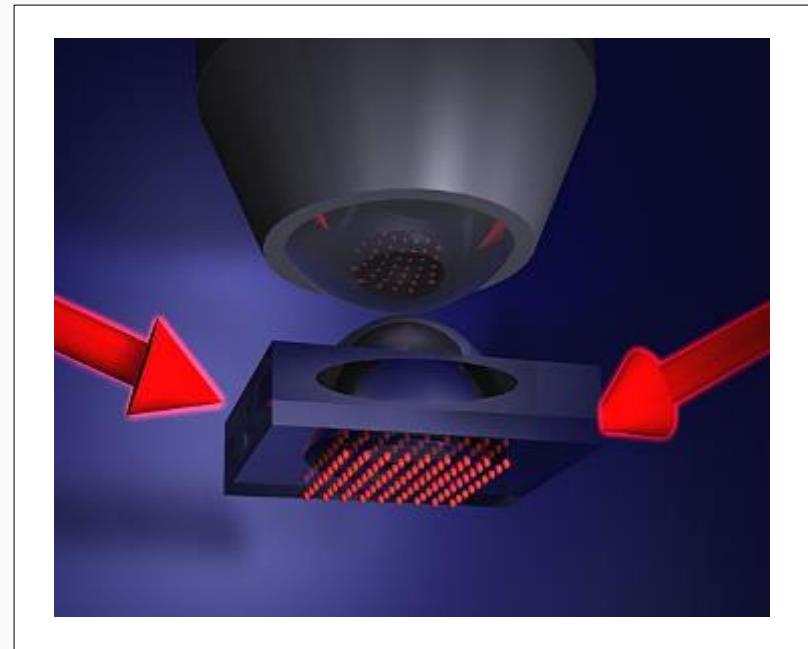


Box potentials



Cambridge, ENS, MIT, ...

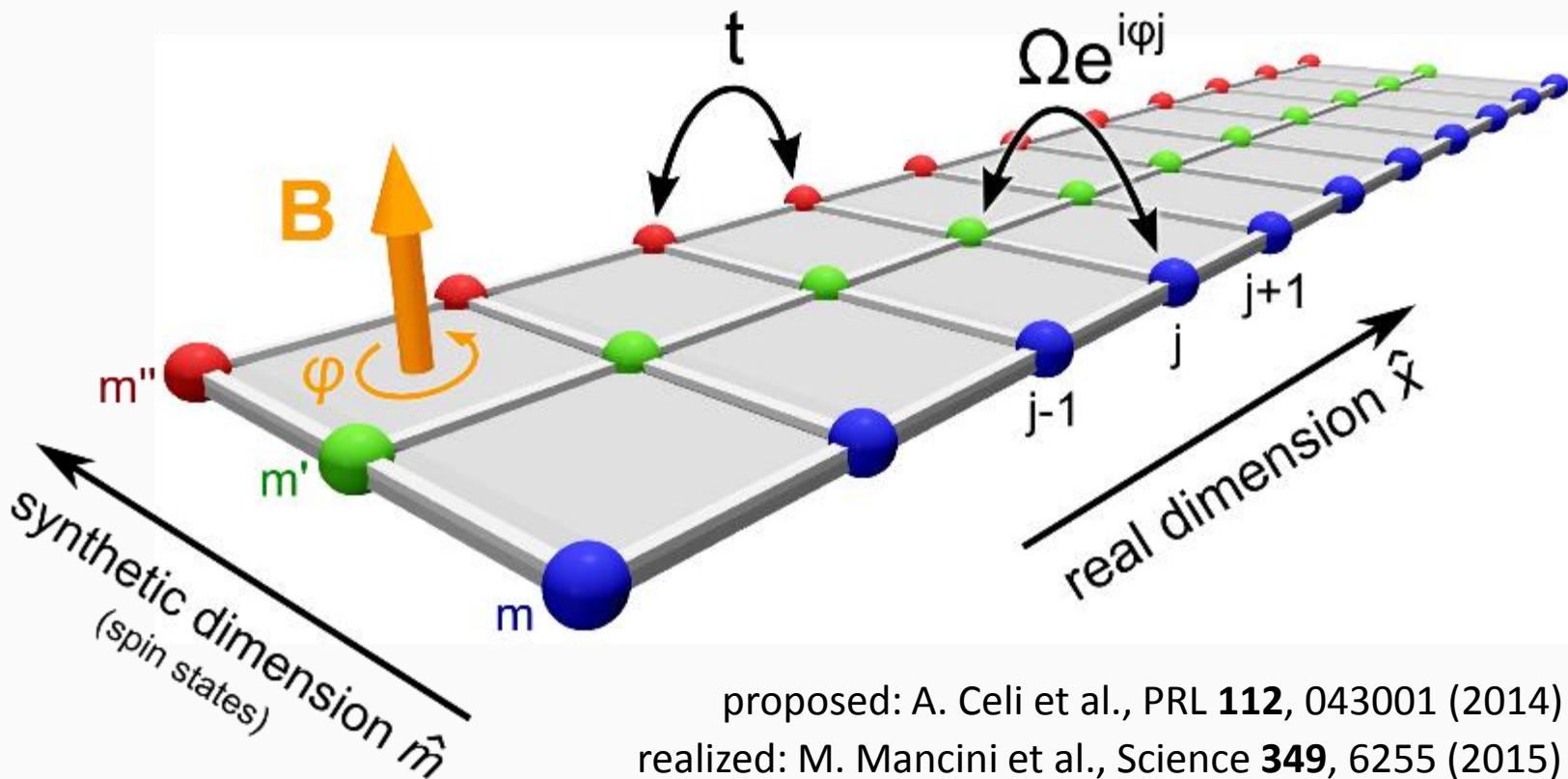
Single-site imaging&control



Harvard, MPQ, ...

# Atomic Hall Ribbon

Investigating edge states in a **hybrid lattice** (combined **real + synthetic D**)



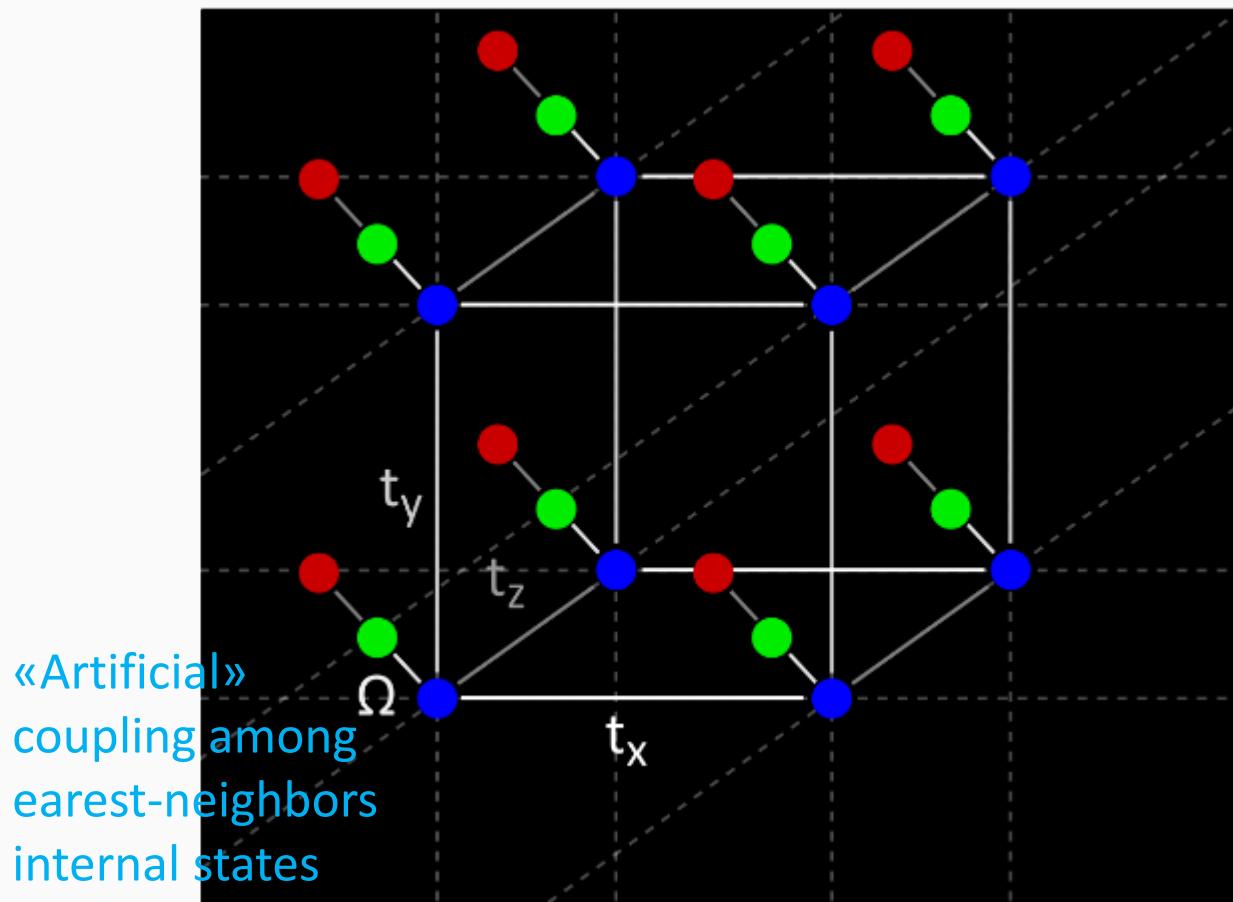
proposed: A. Celi et al., PRL **112**, 043001 (2014)  
 realized: M. Mancini et al., Science **349**, 6255 (2015)

See also related work B. K. Stuhl et al., Science **349**, 6255 (2015)

# Quantum simulation of an extra dimension

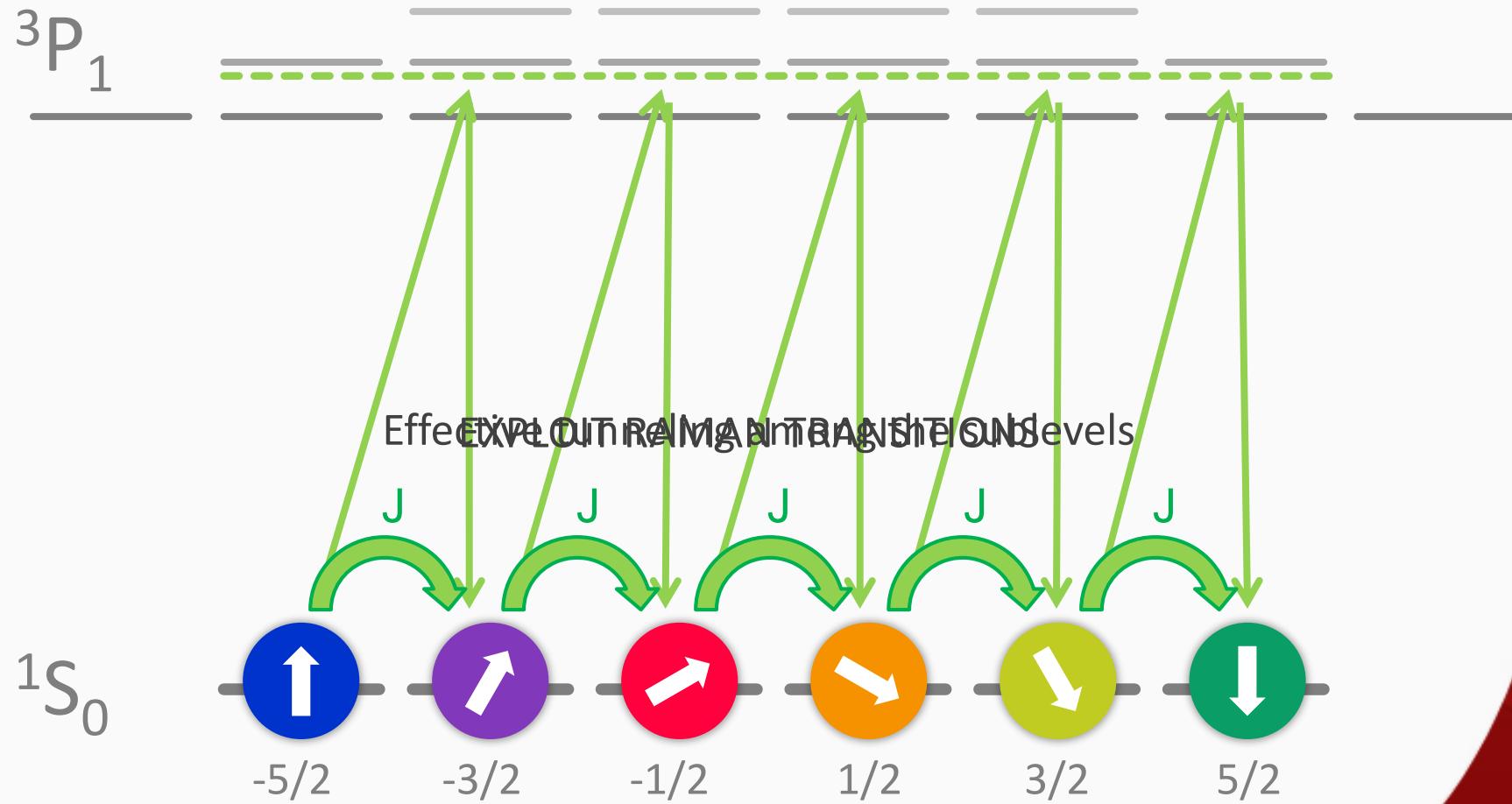
Use internal DOF in order to «simulate»  
EXTRA DIMENSIONAL lattice sites

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



# Coherent coupling in g-s manifold

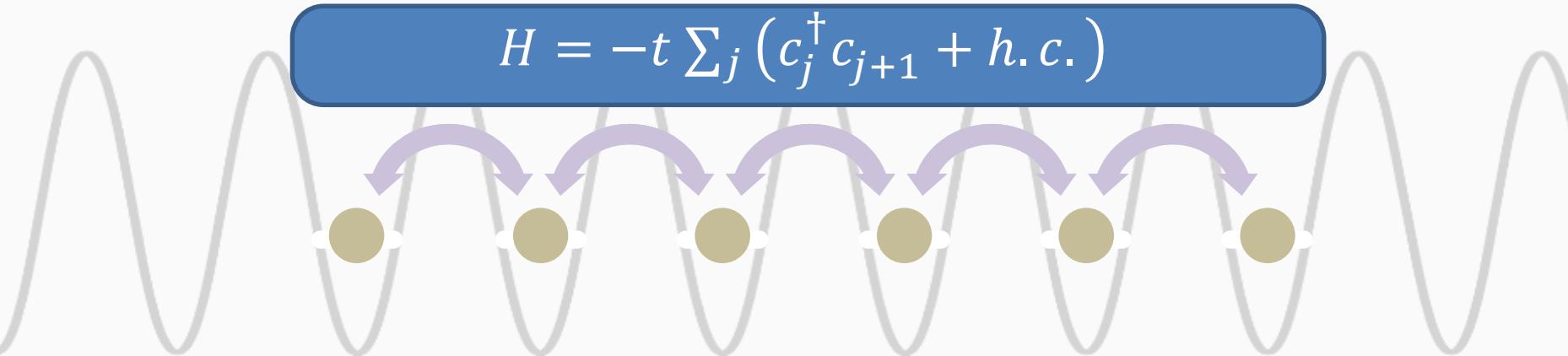
Coherent coupling between different internal states



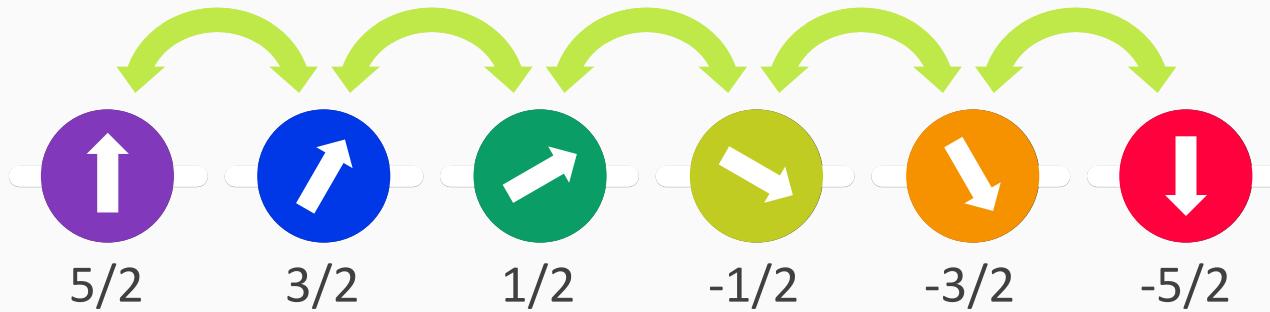
# Coherent coupling in g-s manifold

Analogous to coherent tunnelling coupling in an optical lattice:

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

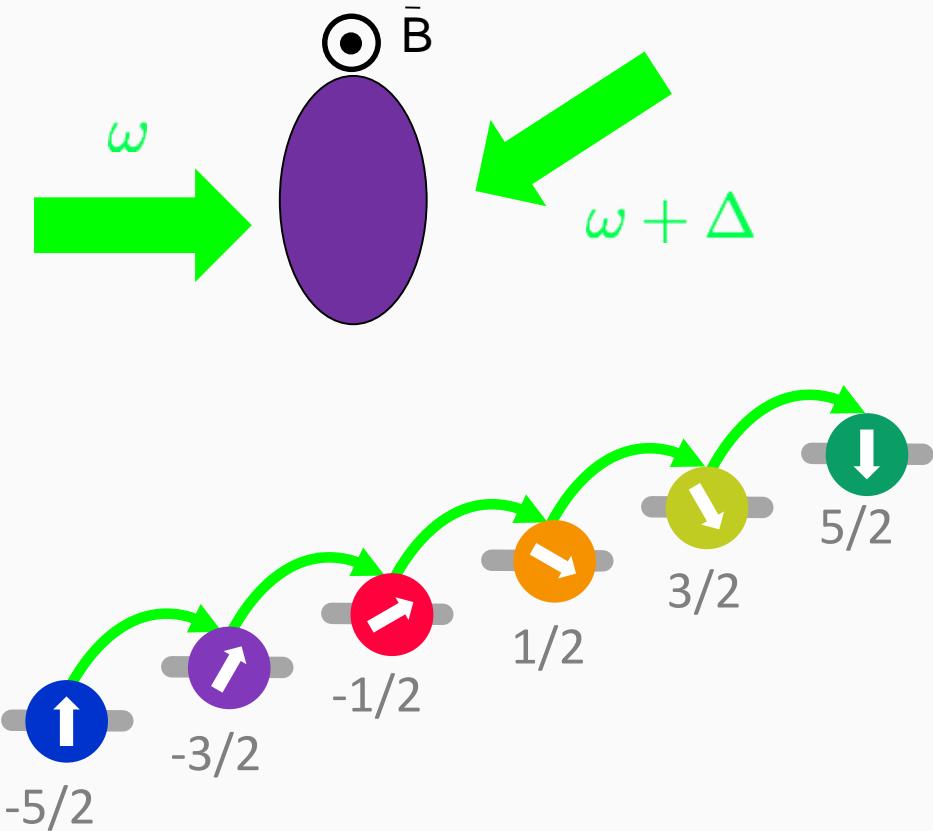
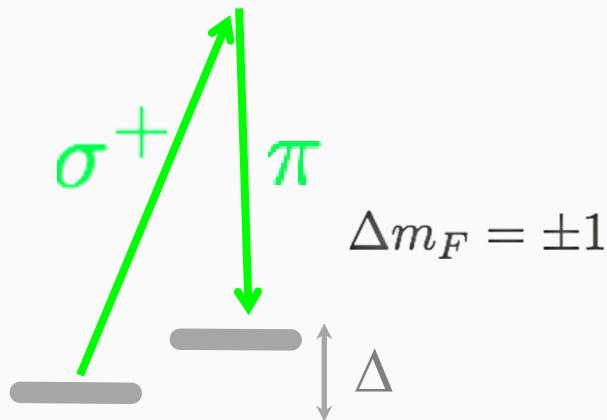


$$H = -\Omega \sum_m (c_m^\dagger c_{m+1} + h.c.)$$



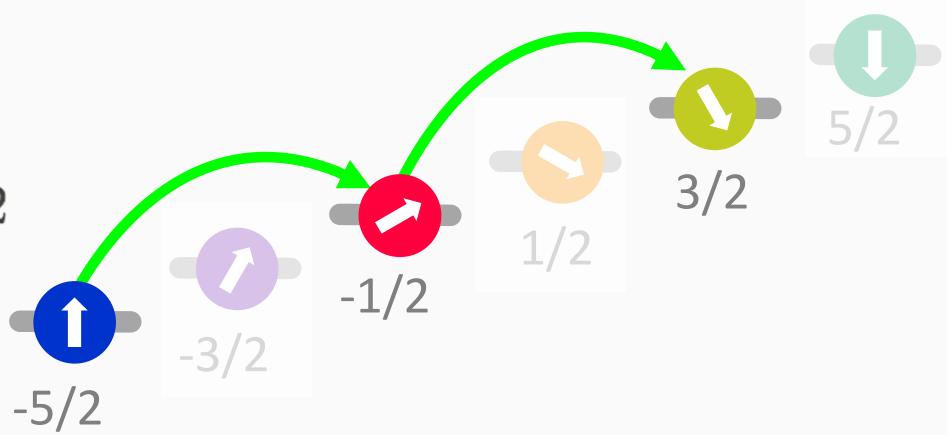
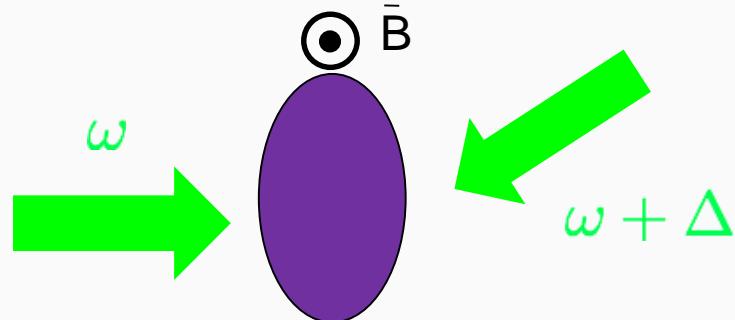
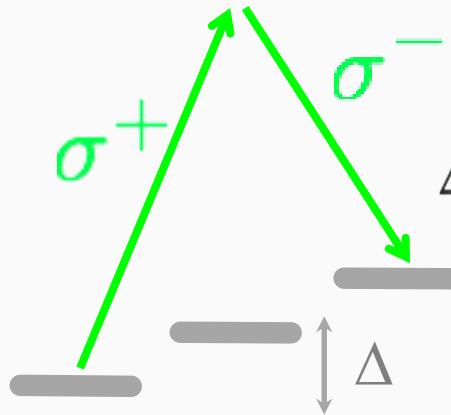
# Raman couplings

Raman beams  
configuration



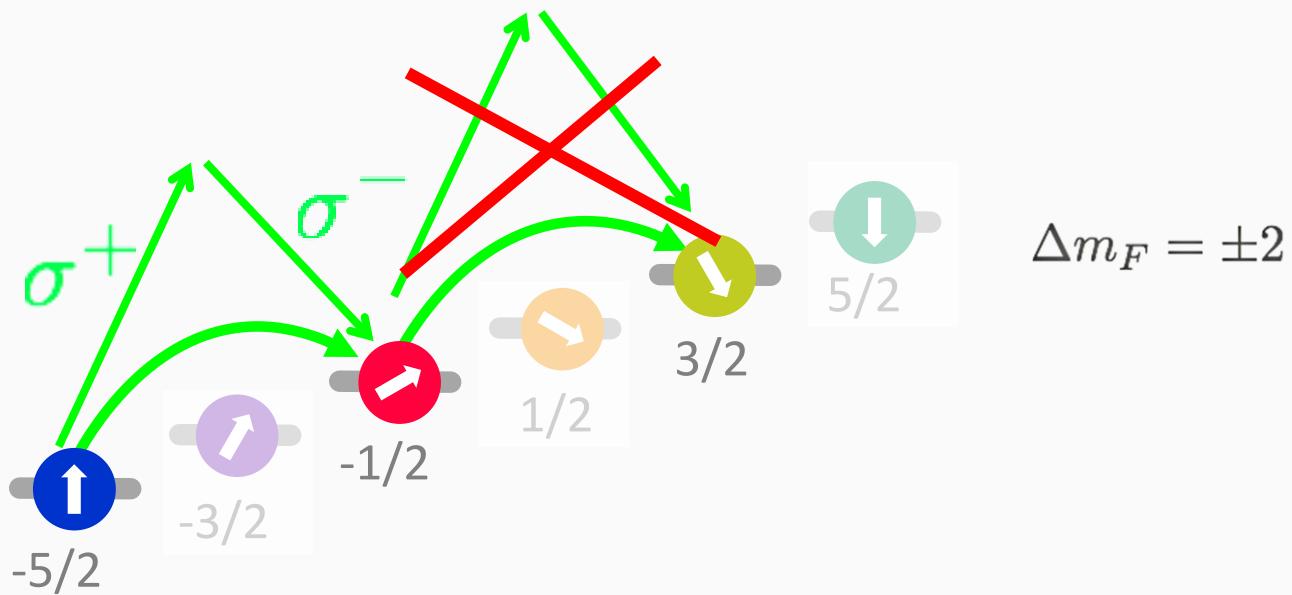
# Raman couplings

Raman beams  
configuration



# Population oscillations, skipping 3 states

- State dependent Clebsch-Gordan coefficients: different couplings
- State/polarization dependent light shifts: different resonance values



# Hybrid dimensions

## Feature #1

Complex laser-assisted tunneling →  
Raman coupling of internal states

$$E_1 = E_0 e^{i\mathbf{k} \cdot \mathbf{r}}$$

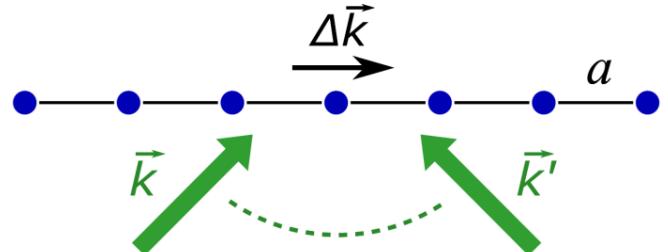
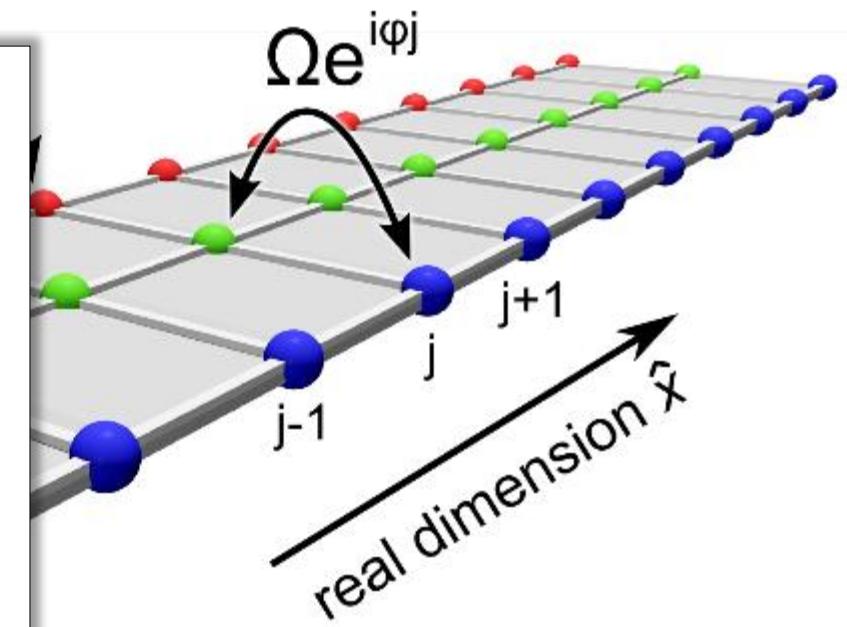
$$E_2 = E_0 e^{i\mathbf{k}' \cdot \mathbf{r}}$$

two-photon Rabi frequency:

$$\Omega(\mathbf{r}) = \frac{\Omega_2^*(\mathbf{r})\Omega_1(\mathbf{r})}{2\Delta}$$

$$= |\Omega| e^{i(\mathbf{k}-\mathbf{k}') \cdot \mathbf{r}} = |\Omega| e^{i\Delta\mathbf{k} \cdot \mathbf{a} \cdot j}$$

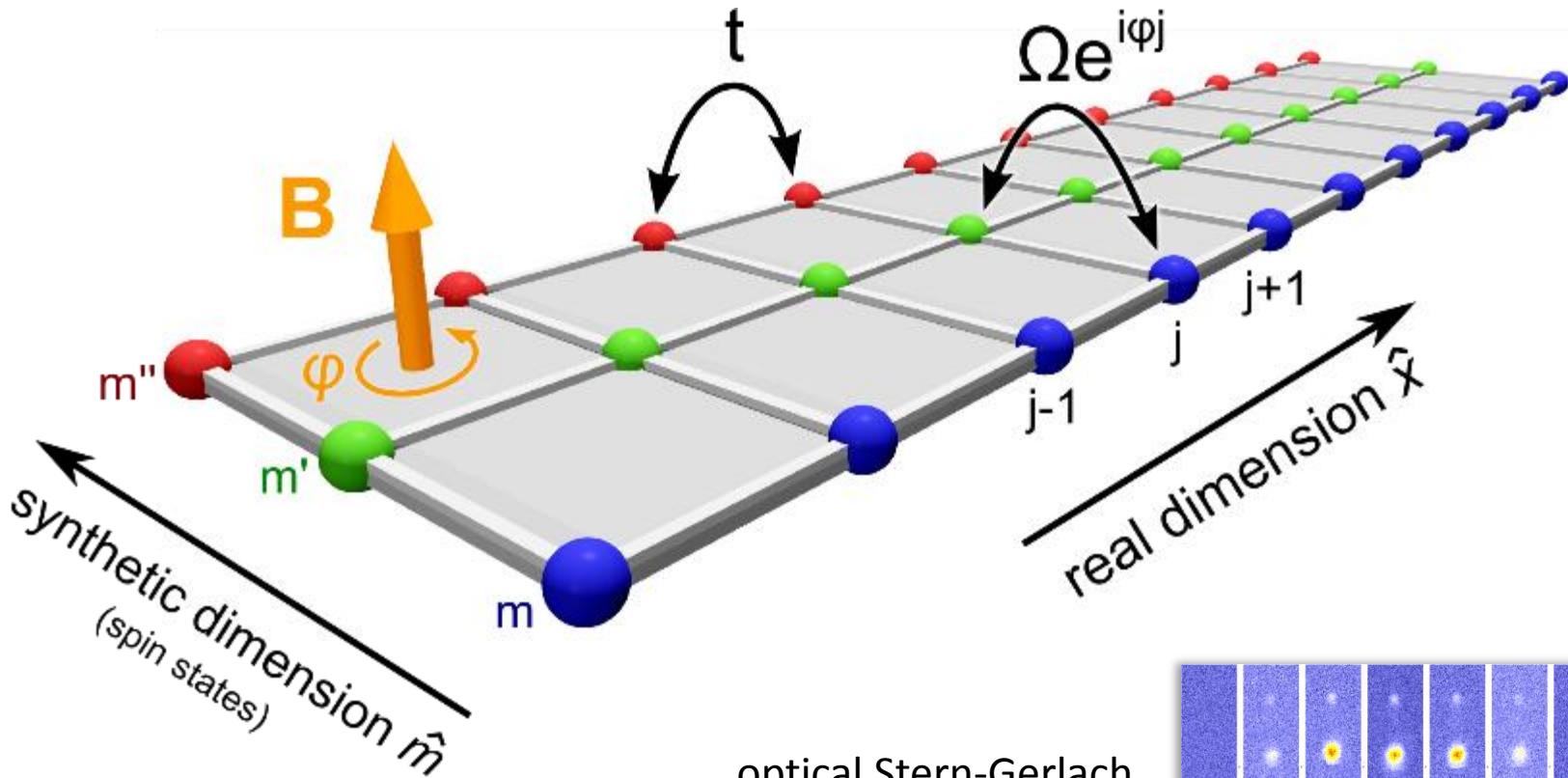
$$\Omega_j = |\Omega| e^{i\varphi_j} \quad \varphi = \Delta k \cdot a = 0.37 \pi$$



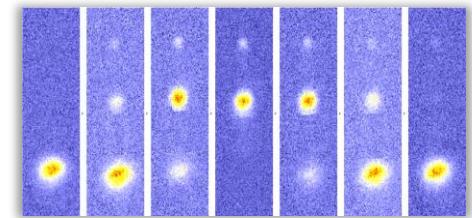
# Hybrid dimensions

Feature #2

Sharp and addressable edges  
Single-site imaging along synthetic dimension



optical Stern-Gerlach  
Spin-selective imaging





INO-CNR  
ISTITUTO  
NAZIONALE DI  
OTTICA



# Observing Chiral Edge Currents

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

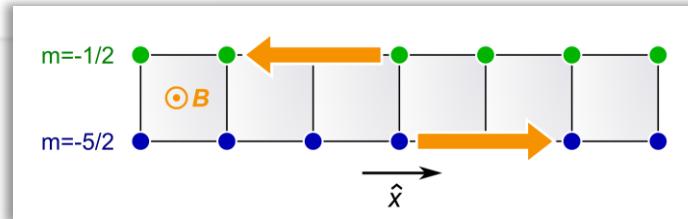
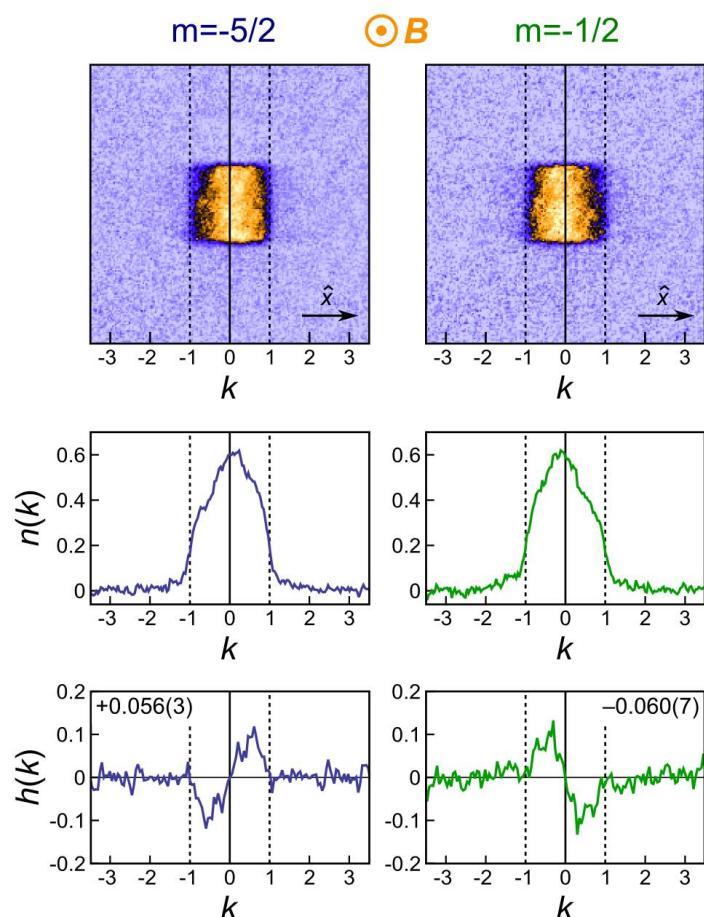


# 2-Leg Ladders

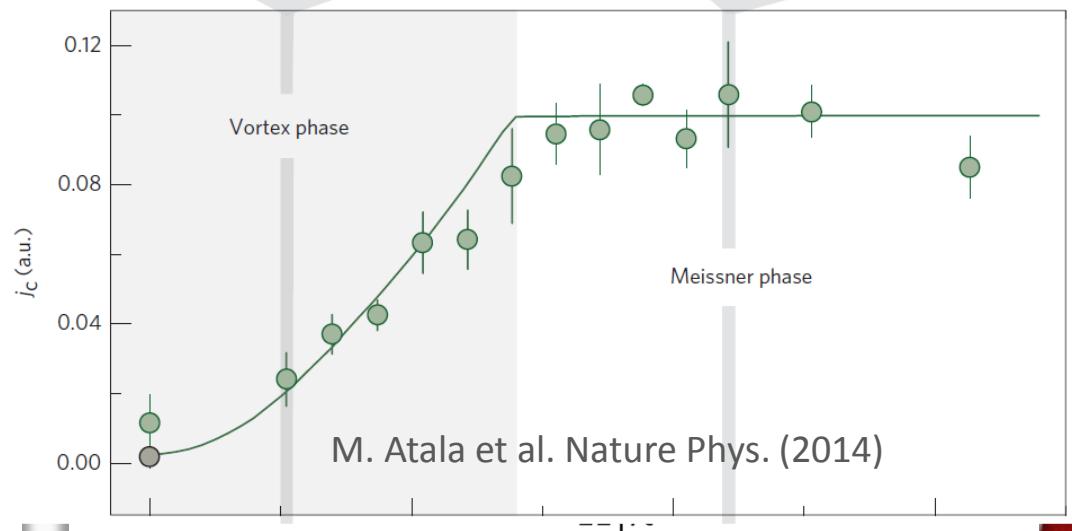
Adiabatic loading of a 2-leg ladder (*no bulk/edge*)

Lattice filling:  $\sim 0.75$  atoms / real site

Lattice momentum distribution:



Chiral phase transition



$h(k) = n(k) - n(-k)$   
Flat if no currents are flowing

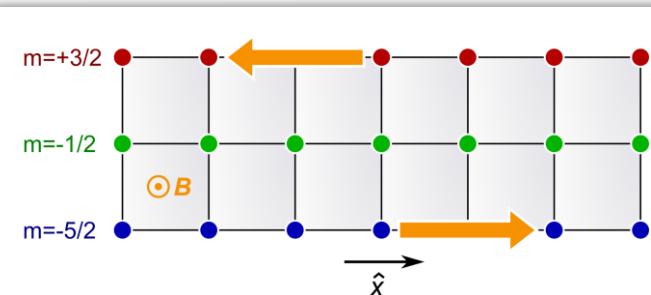
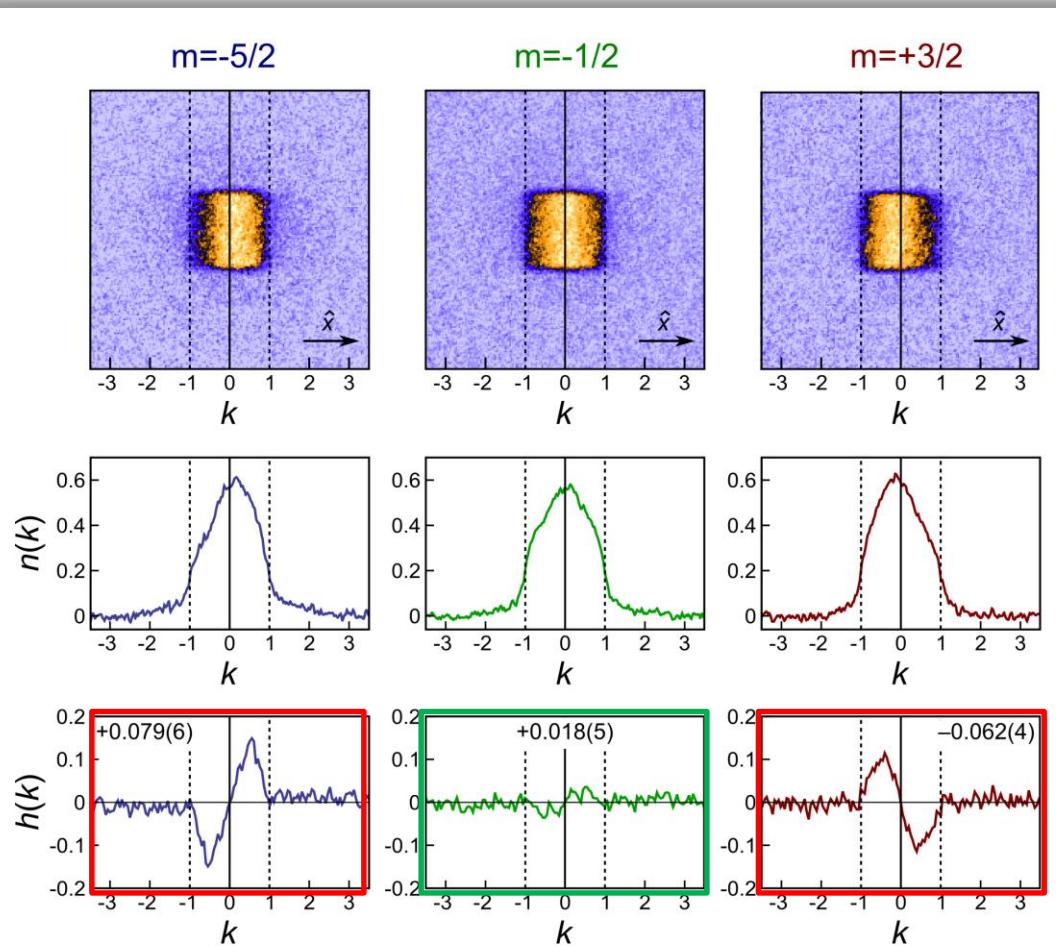
theory by M. Rider, P. Zoller, M. Dalmonte



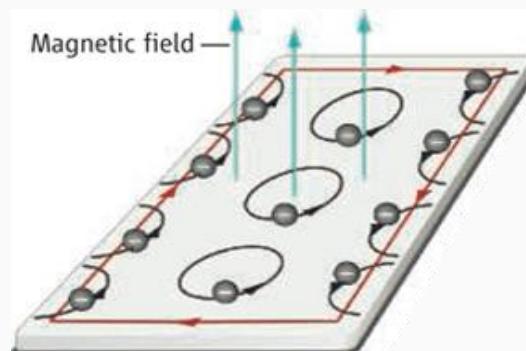
# 3-Leg Ladders

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

Lattice momentum distribution:

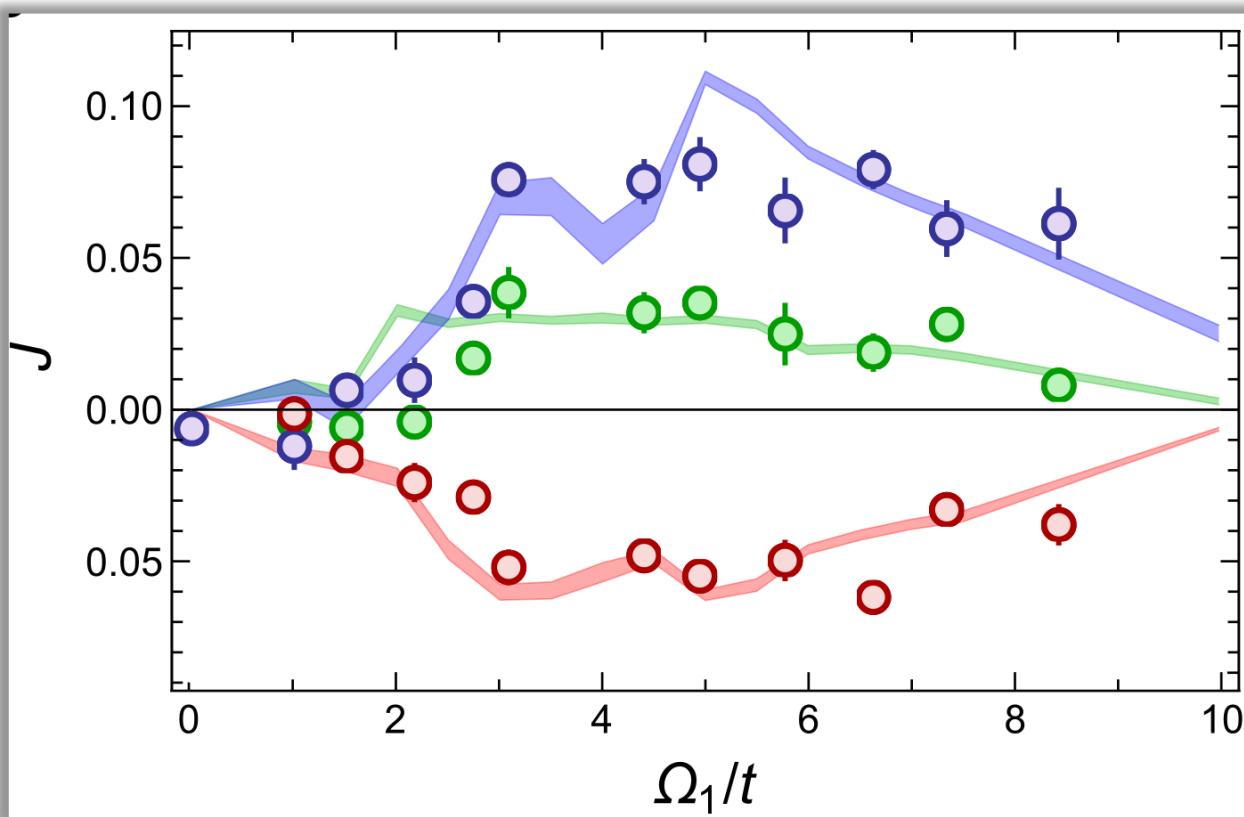
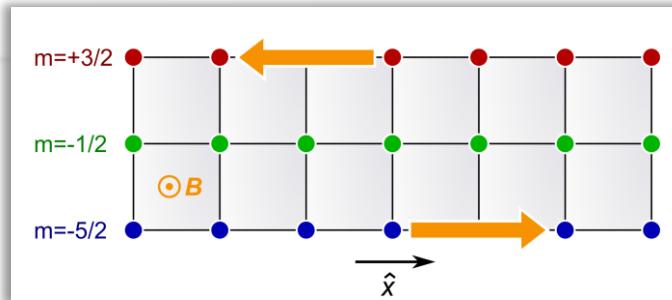


Conducting edges  
no bulk current



# 3-Leg Ladders

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

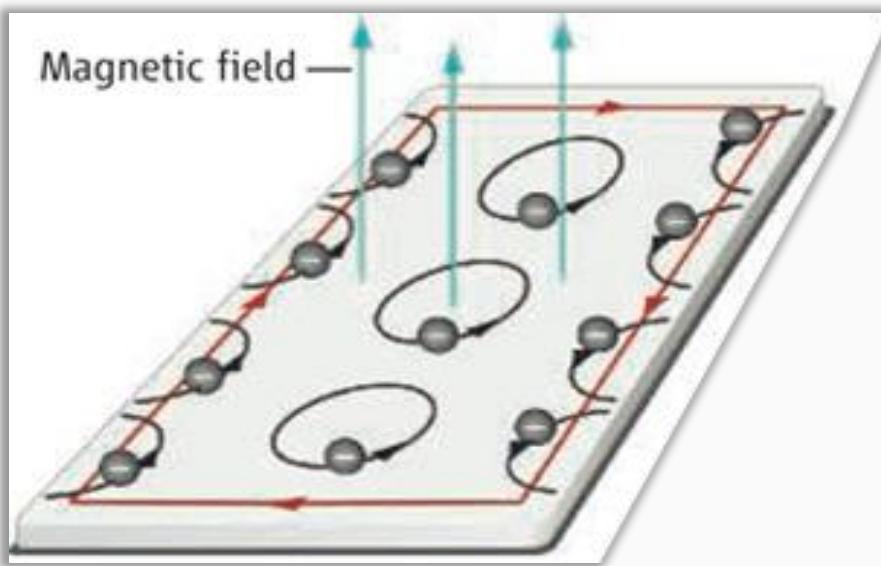


$$\Omega_2 \simeq 1.41\Omega_1$$

# Carriers dynamics

**Bulk states** are performing **localized circular orbits**

**Edge states** are bouncing off the surface: **skipping orbits**



# Carriers dynamics

Evolution of a gaussian wavepacket prepared on the edge:

30x20 lattice



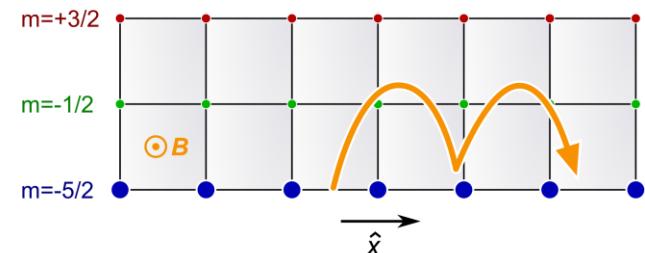
Edge-truncated chiral cyclotron dynamics  
"Skipping" orbits



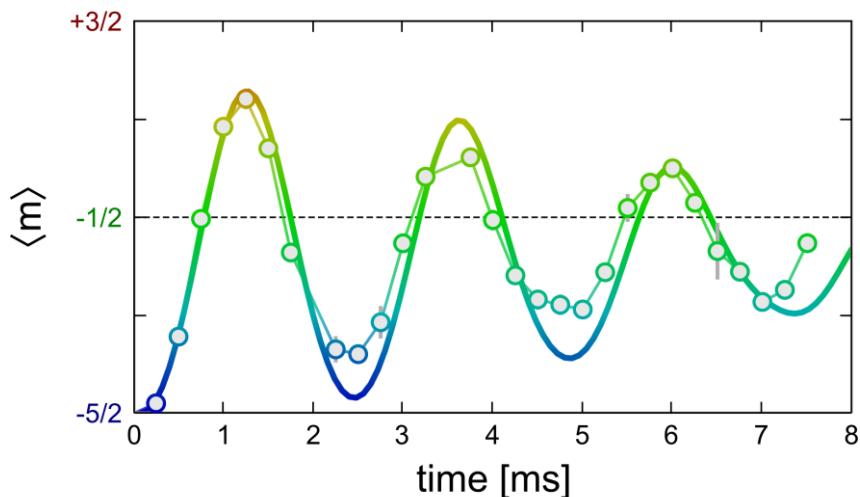
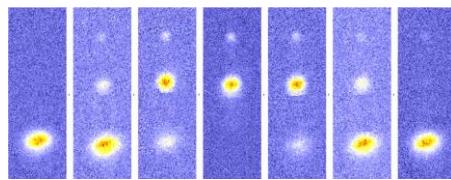
# Observation of skipping orbits

Initial state prepared on a **single edge**

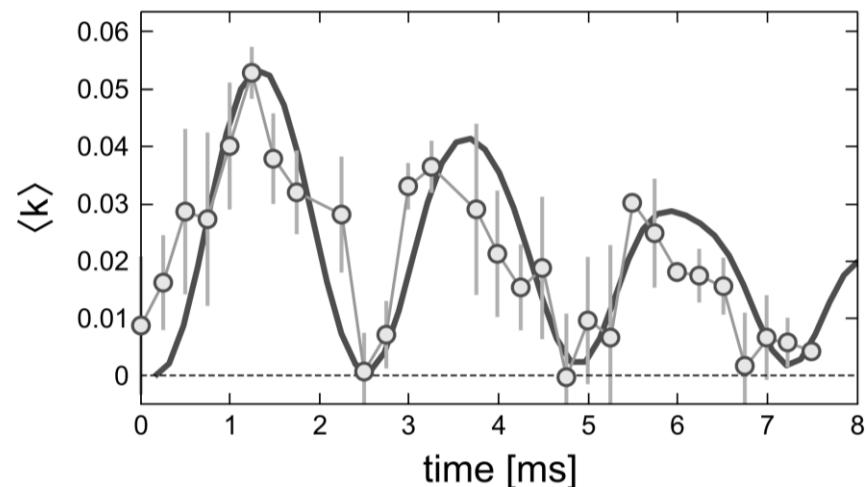
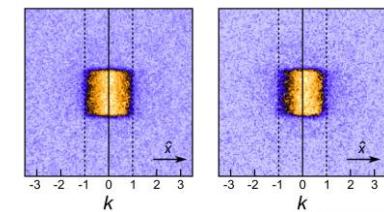
Observe dynamics after **sudden activation**  
of synthetic tunneling



Magnetization:

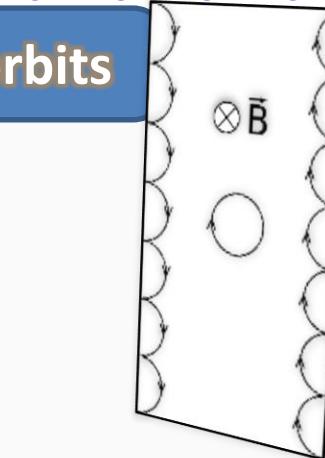
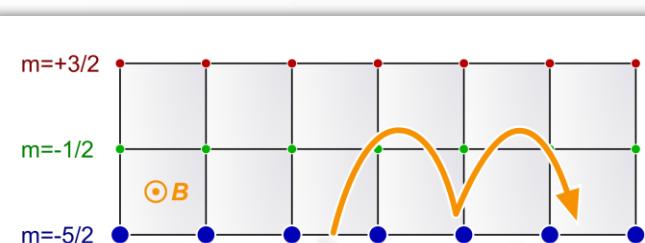
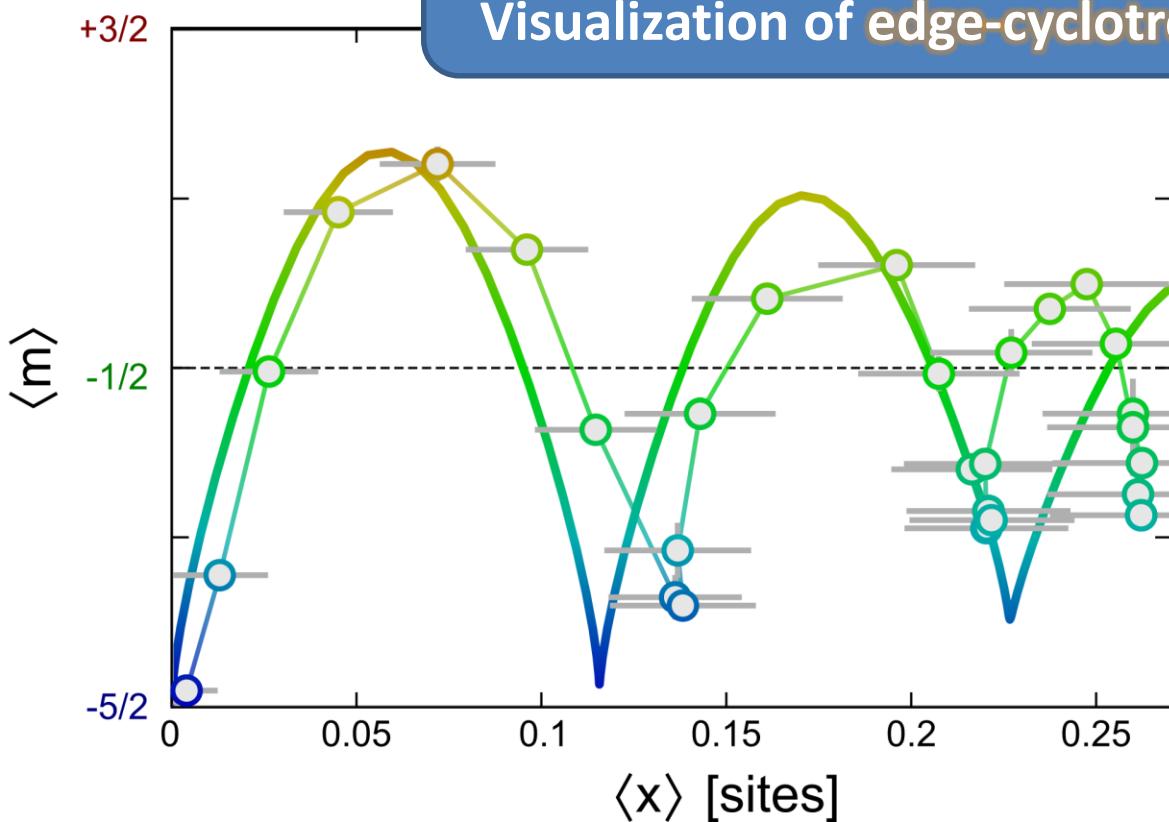


Momentum:



# Observation of skipping orbits

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



Quantum-Hall-like  
dynamics!

(collab. with Rider Dalmonte,  
Zoller)

see related work at (NIST):  
B. K. Stuhl et al.,  
Science 349, 6255 (2015)



# Observation of skipping orbits

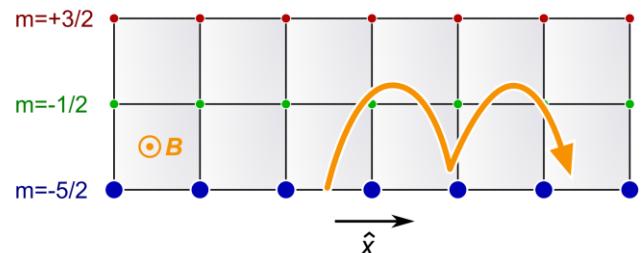
By knowing the (single-)band dispersion the **real space orbits**  $m(\langle x(t) \rangle)$  are reconstructed

$$\mathcal{E}(k) = 2t [1 - \cos(kd)]$$

$$v_k = \frac{1}{\hbar} \frac{\partial \mathcal{E}(k)}{\partial k} = \frac{2td}{\hbar} \sin(kd)$$

$$\langle v(\tau) \rangle = \frac{2td}{\hbar} \int n(k, \tau) \sin(kd) dk.$$

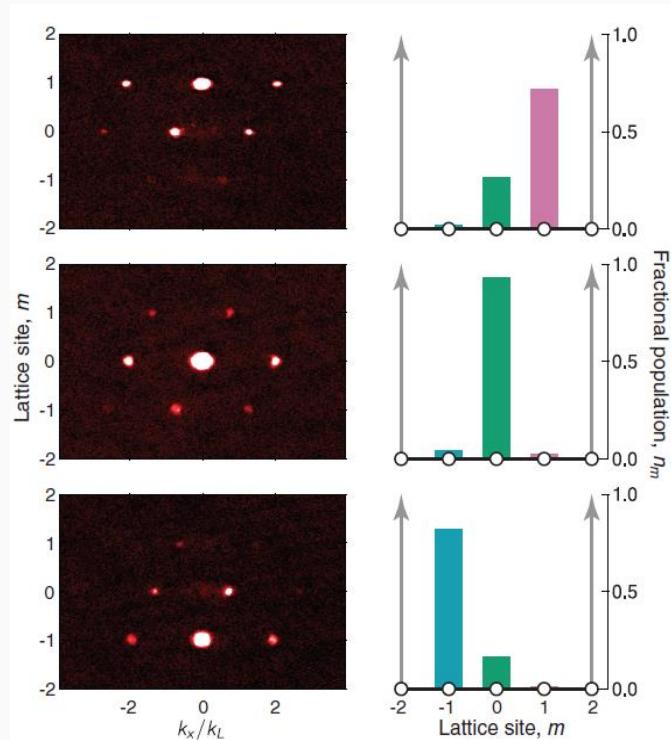
$$\langle x(\tau) \rangle = \int_0^\tau \langle v(\tau') \rangle d\tau'.$$



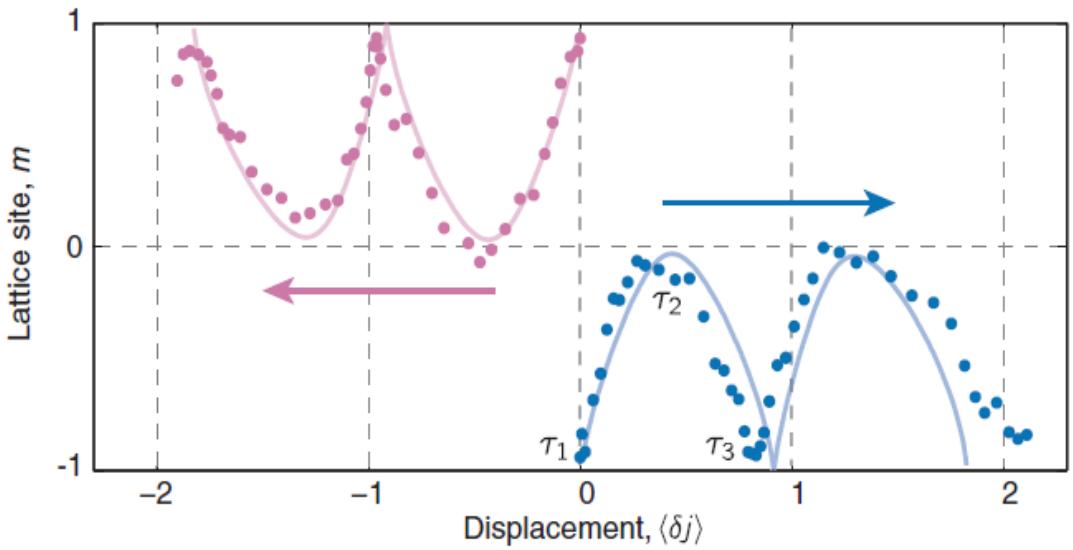
# Related work with bosons @ JQI

Engineering synthetic dimensions with 3-component  $^{87}\text{Rb}$  BEC:

Edge states:

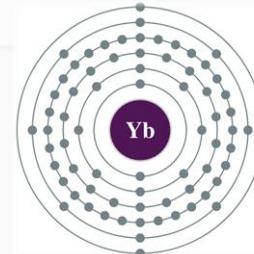


Skipping orbits:



# Summary

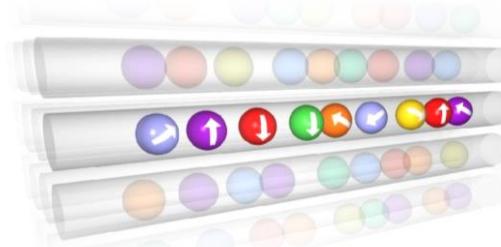
## Properties of Two-electron Atoms for Qu-Sim



## Strongly interacting 1D fermions beyond Spin $\frac{1}{2}$

- 1D interacting fermions: Models
- Non-trivial Ground State properties for Large Spin
- Excitation spectrum for Large Spin

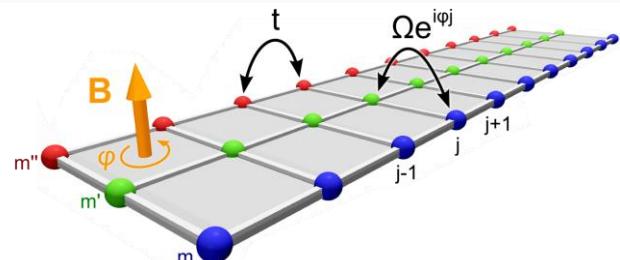
G. Pagano et al., *Nature Phys.* **10**, 198 (2014)



## An Atomic Hall system with «artificial» dimensions

- Chiral Edge States in 2 and 3 legs systems
- Visualization of Skipping Orbit

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



# Outlook

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## 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)

4D quantum Hall effect

H. Price et al., PRL **115**, 195303 (2015)

Transport in Hall Bars

### Interactions

Fractional charge pumping

T.-S. Zeng et al., PRL **115**, 095302 (2015)

New states, fractional helical liquids

S. Barbarino et al., Nat. Comm. **6**, 8134 (2015)  
J. C. Budich et al., PRB **92**, 245121 (2015)

### Engineering topology

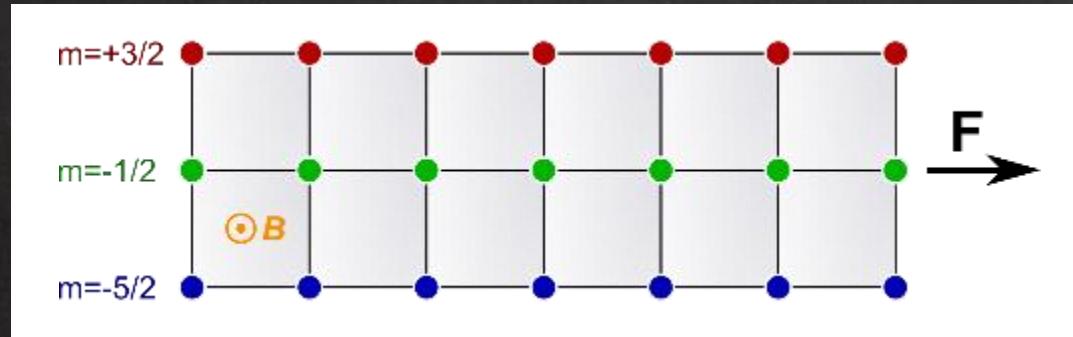
Open and periodic boundary conditions

Rings, cylinders, tori, Moebius strips...

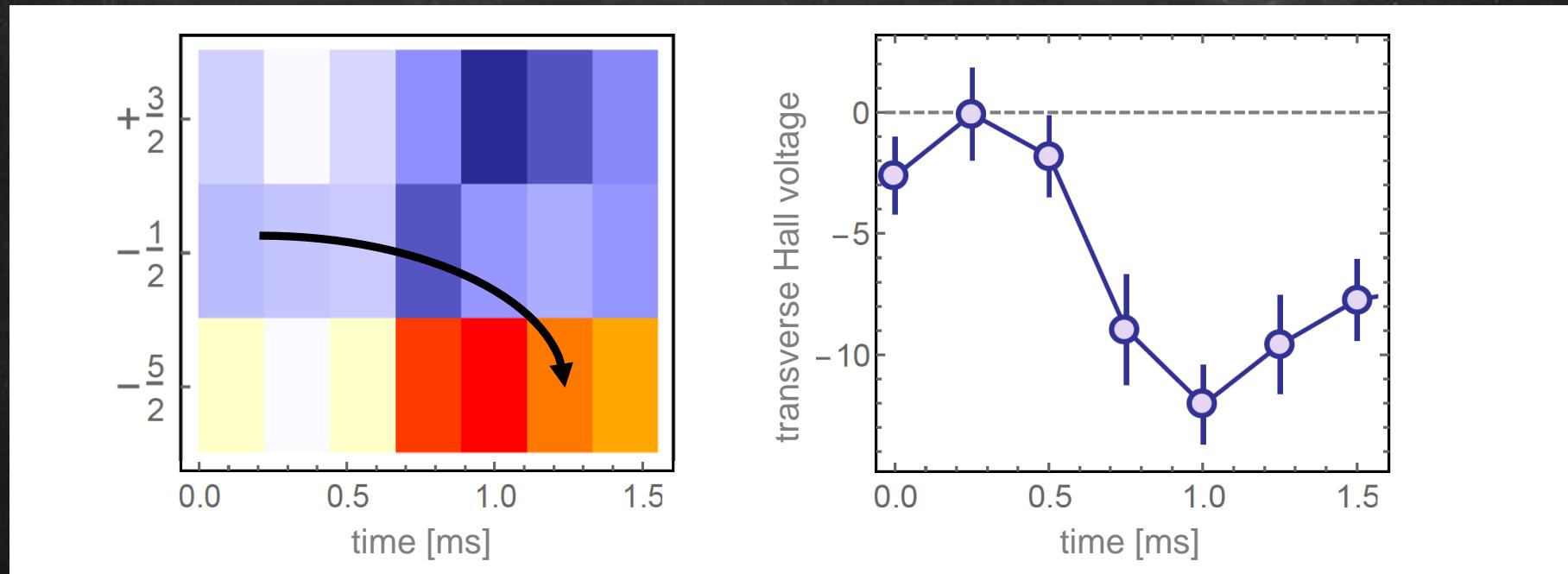
O. Boada et al., NJP **17**, 045007 (2015)

# Hall transport

Preliminary: «synthetic» transport induced by a force along the «real» direction



Hall drift in  
synthetic dimension



## Synthetic dimensions: a brand new concept for atomic physics experiments

### New manipulation/detection possibilities

Hall bar transport

Measurement of topological invariants

4D quantum Hall effect

L. Wang et al., PRL **110**, 166802 (2013)

H. Price et al., PRL **115**, 195303 (2015)

### Interactions

Fractional charge pumping

New states, fractional helical liquids

T.-S. Zeng et al., PRL **115**, 095302 (2015)

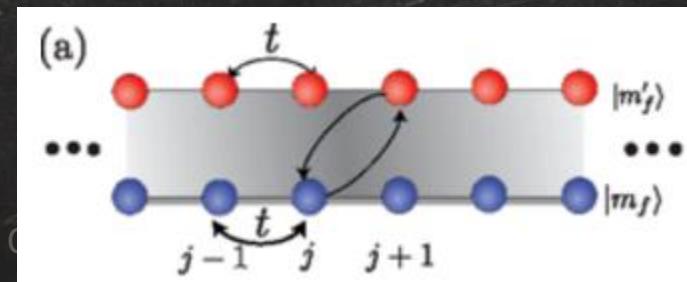
S. Barbarino et al., Nat. Comm. **6**, 8134 (2015)

J. C. Budich et al., PRB **92**, 245121 (2015)

### Engineering topology

Open and periodic boundary conditions

Rings, cylinders, tori, Moebius strips...



## Synthetic dimensions: a brand new concept for atomic physics experiments

### New manipulation/detection possibilities

Hall bar transport

Measurement of topological invariants

4D quantum Hall effect

L. Wang et al., PRL **110**, 166802 (2013)

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### Interactions

Fractional charge pumping

New states, fractional helical liquids

T.-S. Zeng et al., PRL **115**, 095302 (2015)

S. Barbarino et al., Nat. Comm. **6**, 8134 (2015)  
J. C. Budich et al., PRB **92**, 245121 (2015)

### Engineering topology

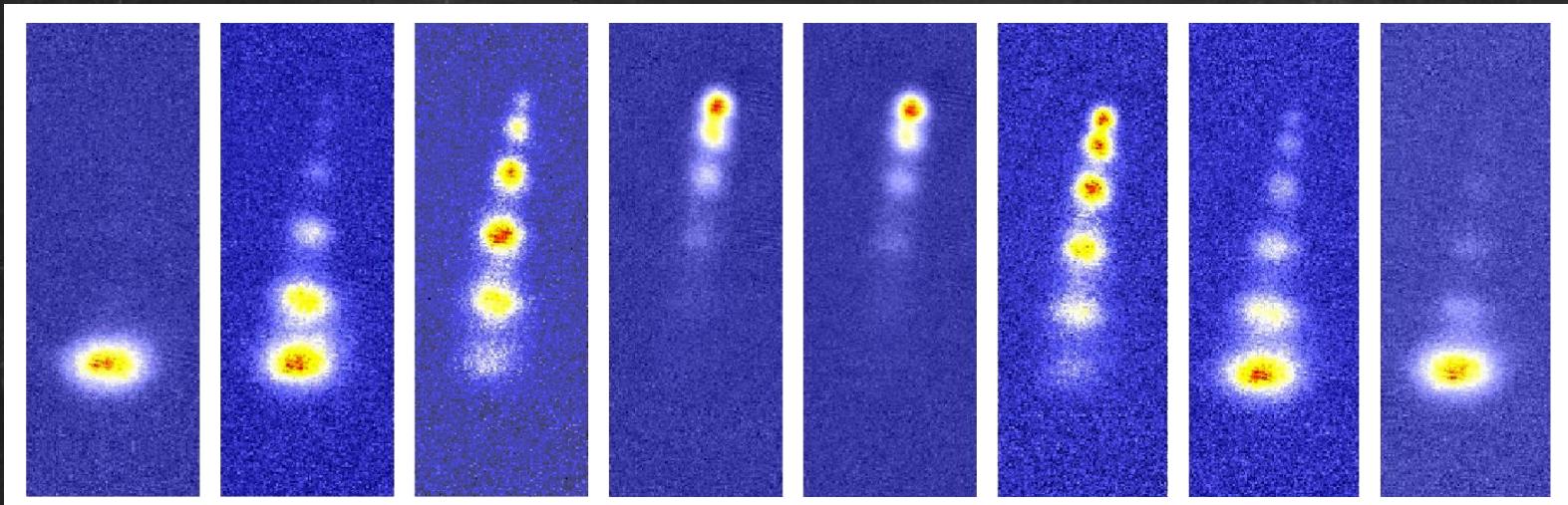
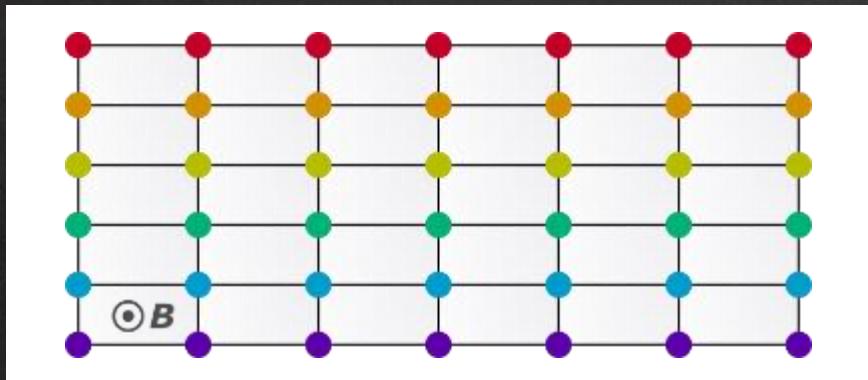
Increase synthetic size

Open and periodic boundary conditions: Rings, cylinders, tori, Moebius strips...

O. Boada et al., NJP **17**, 045007 (2015)

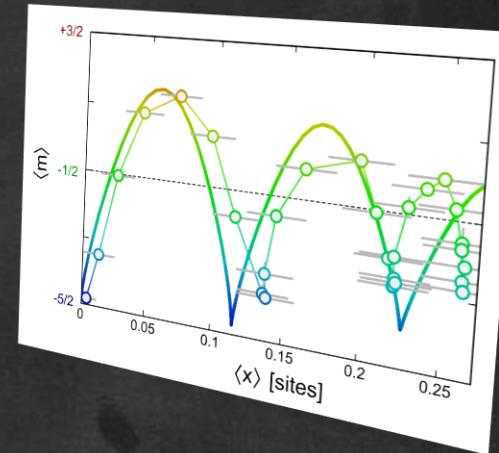
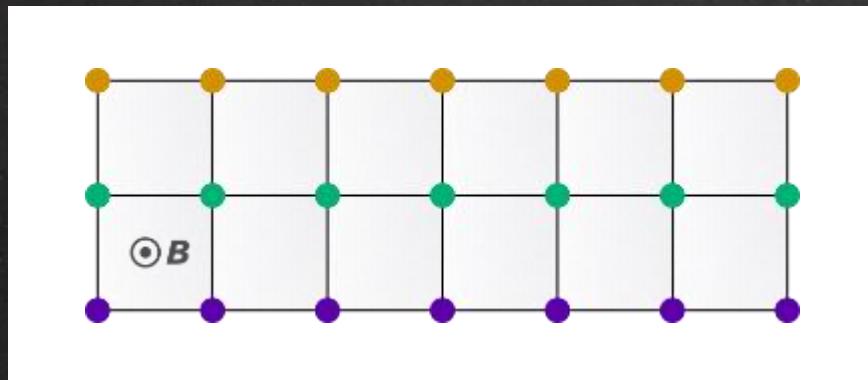
# Does (synthetic) size matter?

Extending the synthetic length:

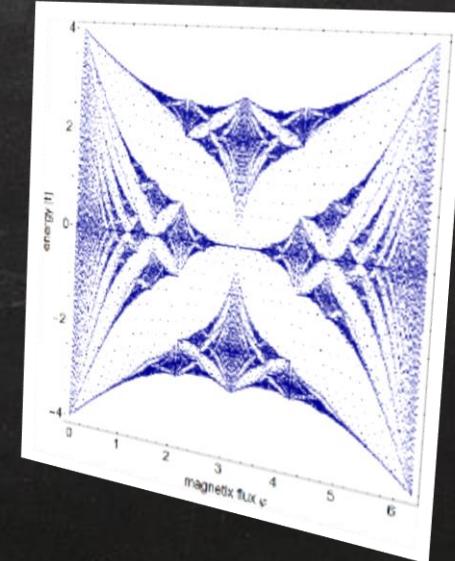
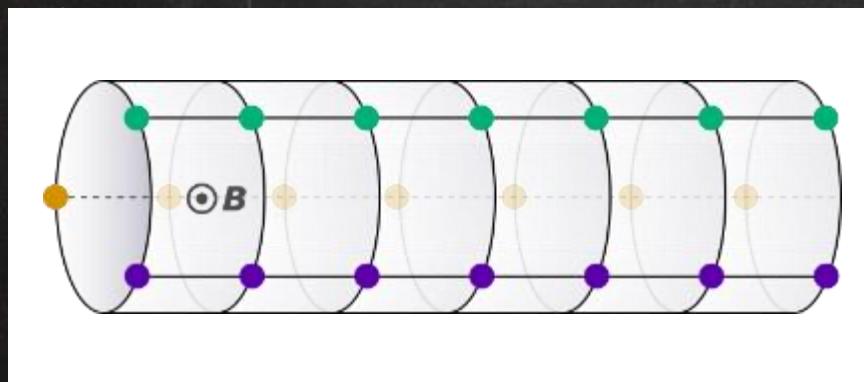


# Open or close the (synthetic) boundaries?

Open boundary condition along spin direction → **edge** physics



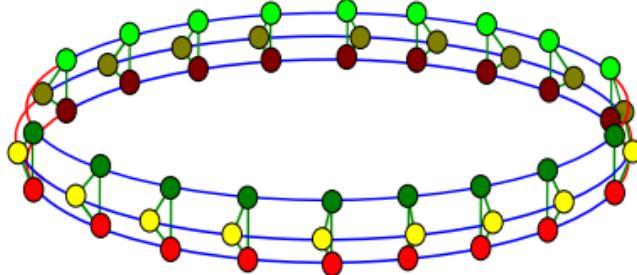
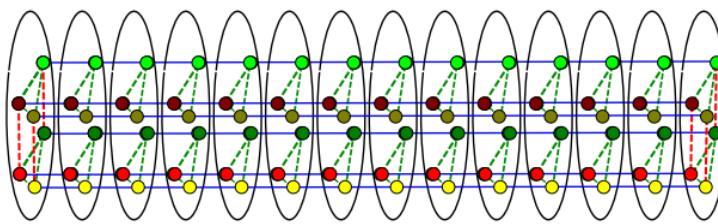
Closed boundary condition along spin direction → **bulk** physics



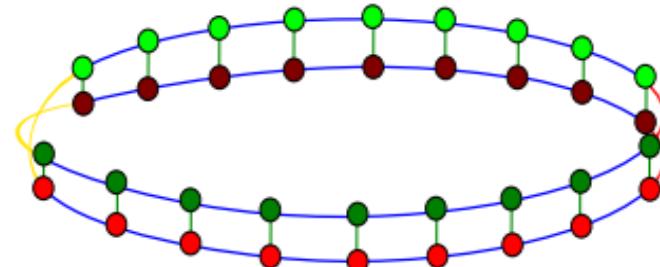
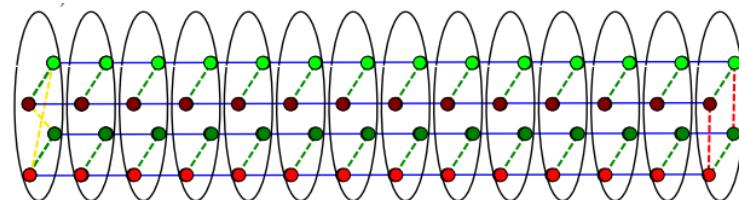
Synthesizing complex/nontrivial topologies:

O. Boada et al., NJP **17**, 045007 (2015)

Torus



Moebius strip



## Synthetic dimensions: a brand new concept for atomic physics experiments

### New manipulation/detection possibilities

Hall bar transport

Measurement of topological invariants

4D quantum Hall effect

L. Wang et al., PRL **110**, 166802 (2013)

H. Price et al., PRL **115**, 195303 (2015)

### Interactions + gauge fields

Fractional charge pumping

New states, fractional helical liquids

T.-S. Zeng et al., PRL **115**, 095302 (2015)

S. Barbarino et al., Nat. Comm. **6**, 8134 (2015)

J. C. Budich et al., PRB **92**, 245121 (2015)

### Engineering exotic topologies

Open and periodic boundary conditions

Rings, cylinders, tori, Moebius strips...

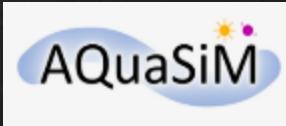
O. Boada et al., NJP **17**, 045007 (2015)

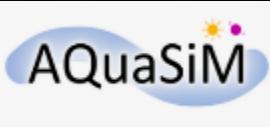
# Credits



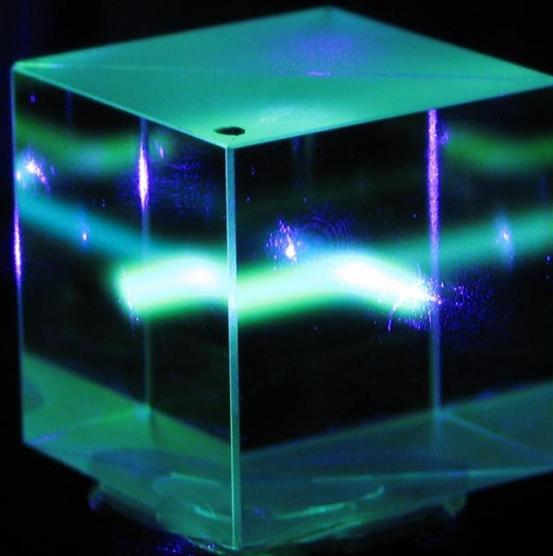
Exp. collaboration with INRIM (Torino):  
C. Clivati, M. Pizzocaro, D. Calonico, F. Levi

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PhD and PostDoc positions 😊



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