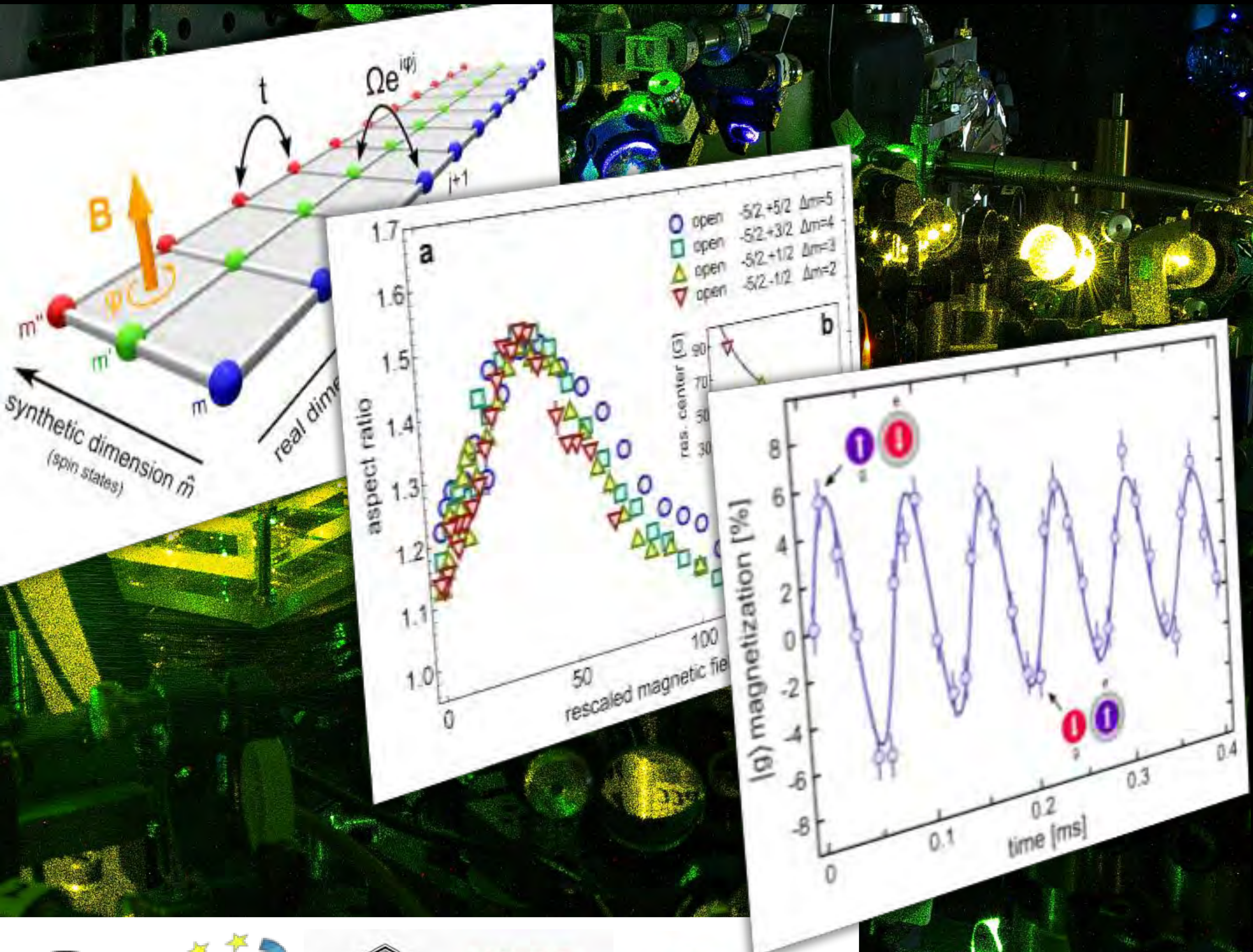
Novel quantum simulation with ultracold two-electron fermions



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June 6th 2016

European Laboratory for Non-Linear Spectroscopy

INO-CNR
Istituto Nazionale di Ottica

INRiM
Istituto Nazionale di Ricerca Metrologica

Outline

Introduction

Observation of interorbital spin-exchange

Tuning interactions via an Orbital resonance

Chiral edge states in synthetic dimensions

Outlook and summary

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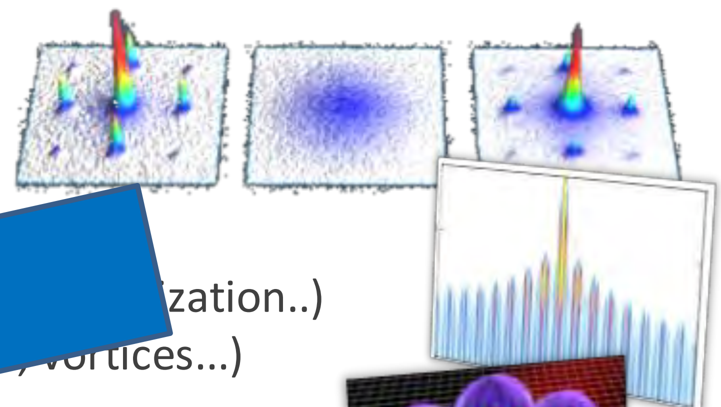
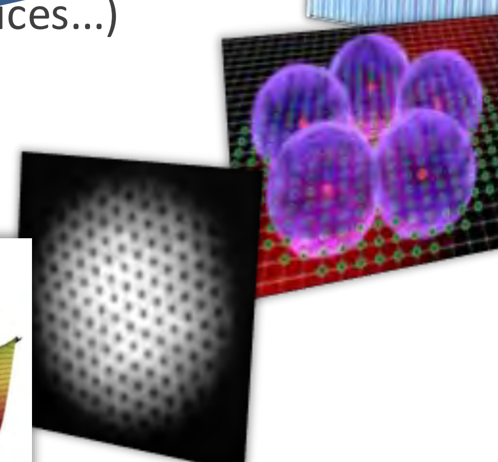
Ultracold Atoms – a powerful tool

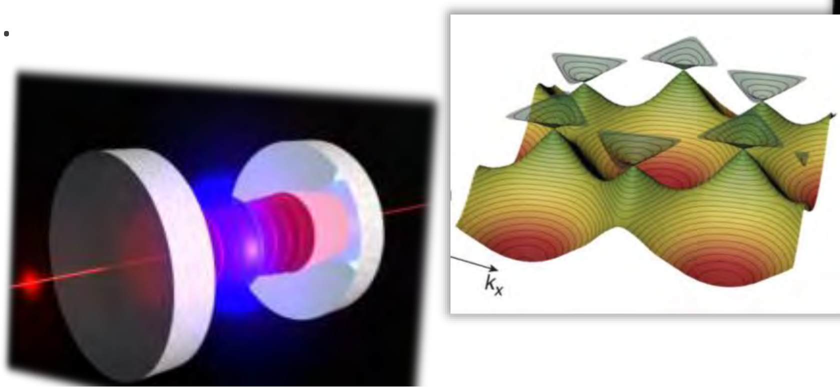
Ultracold Atoms represent an ideal testbench for many fundamental physical models with **unprecendent control at the quantum level**



- Superfluidity, BEC/BCS crossover
- Lattice Phase transiti… …ization..)
- Low dimen… …vortices…)
- Rydberg ato…
- Cavity QED
- Slow light
-………

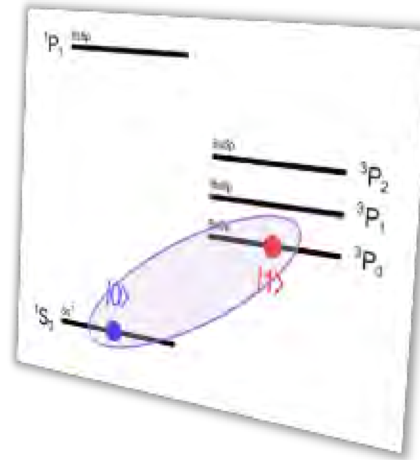
Mainly ALKALIS!





Alkaline-earth-like atoms

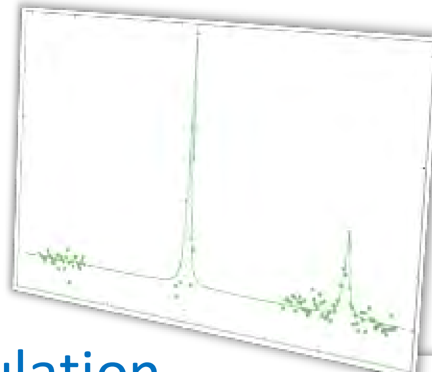
Unique properties deliver new opportunities in several fields:



➡ Quantum Information

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

➡ Precision Physics

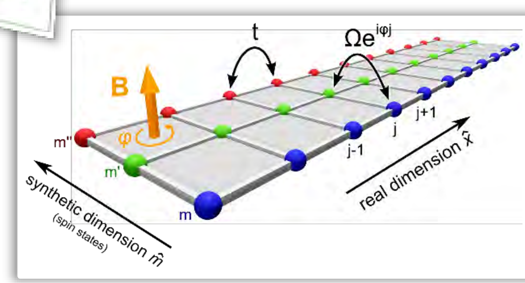


N. Hinkley et al., Science (2013)
B. J. Bloom et al., Nature (2014)
I. Ushijima et al., Nature Phot. (2015)

➡ «NEW» Quantum Simulation

- Topological models exploiting artifically induced gauge fields

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



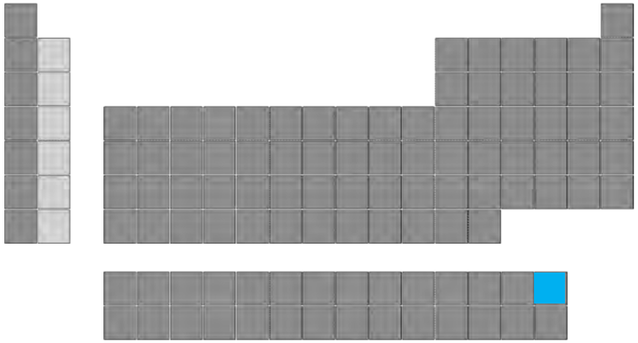
- «Extended» theories (e.g multi-spin Luttinger liquid)

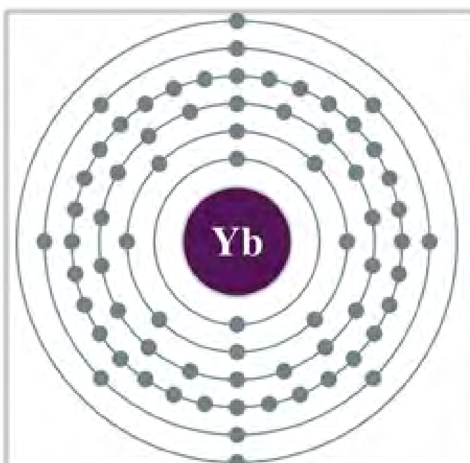
G. Pagano et al. Nature Phys. **10**, 198–201 (2014)

- Exploit an «extra» degree of freedom: ORBITALS

Kondo physics, orbital magnetism, tunability of interactions

Ytterbium



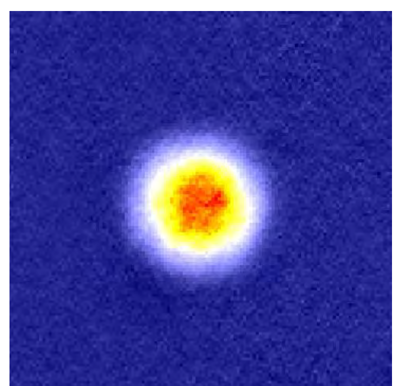


http://periodictable.com

Seven stable natural 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

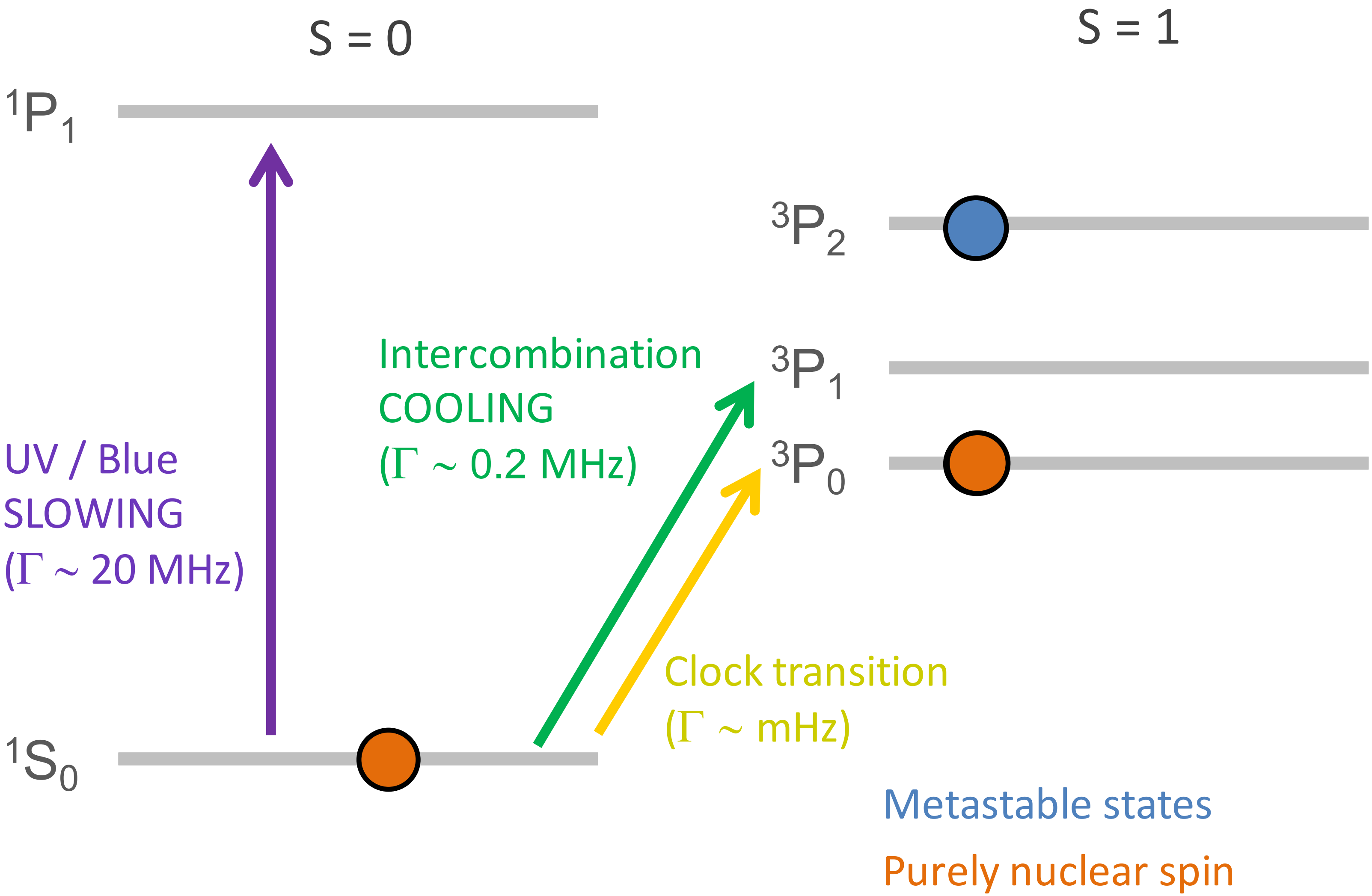
^{173}Yb Fermi gas



$T \sim 0.1\ T_F = 10$ nK
$N = 10^4$ atoms/spin

Yb (alkaline-earth-like) structure

Electronic configuration [...]2s → Singlet/Triplet states



SU(N) symmetry of interactions

Fermionic isotopes of Yb in the ground state $^1S_0$:

Purely nuclear spin (J=0)

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

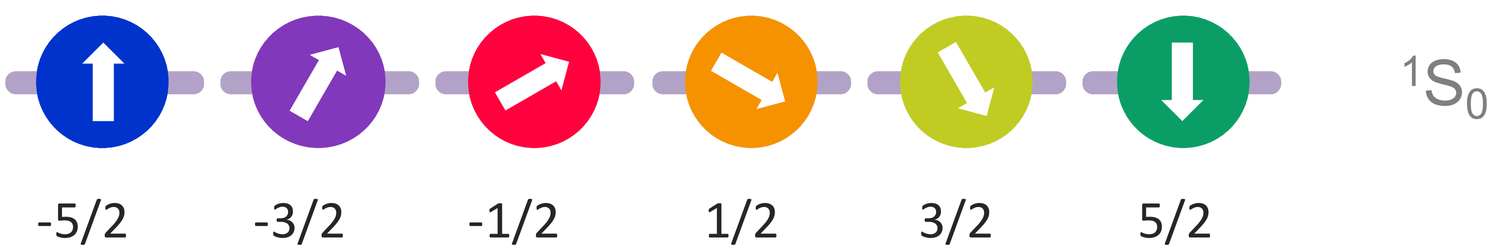
SU(N) symmetry

↓

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

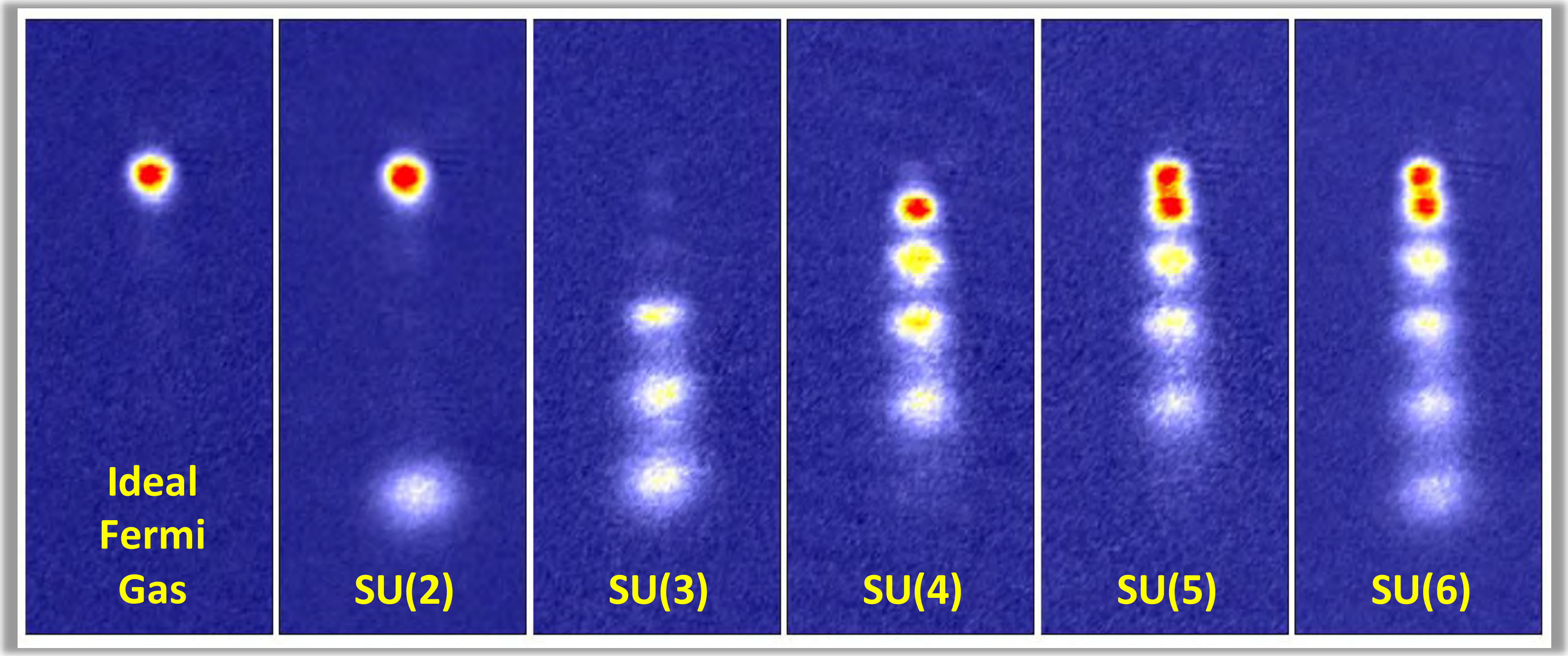
$a = +200\,a_0$ (^{173}Yb)

- No **spin-changing collisions:**



Spin Detection

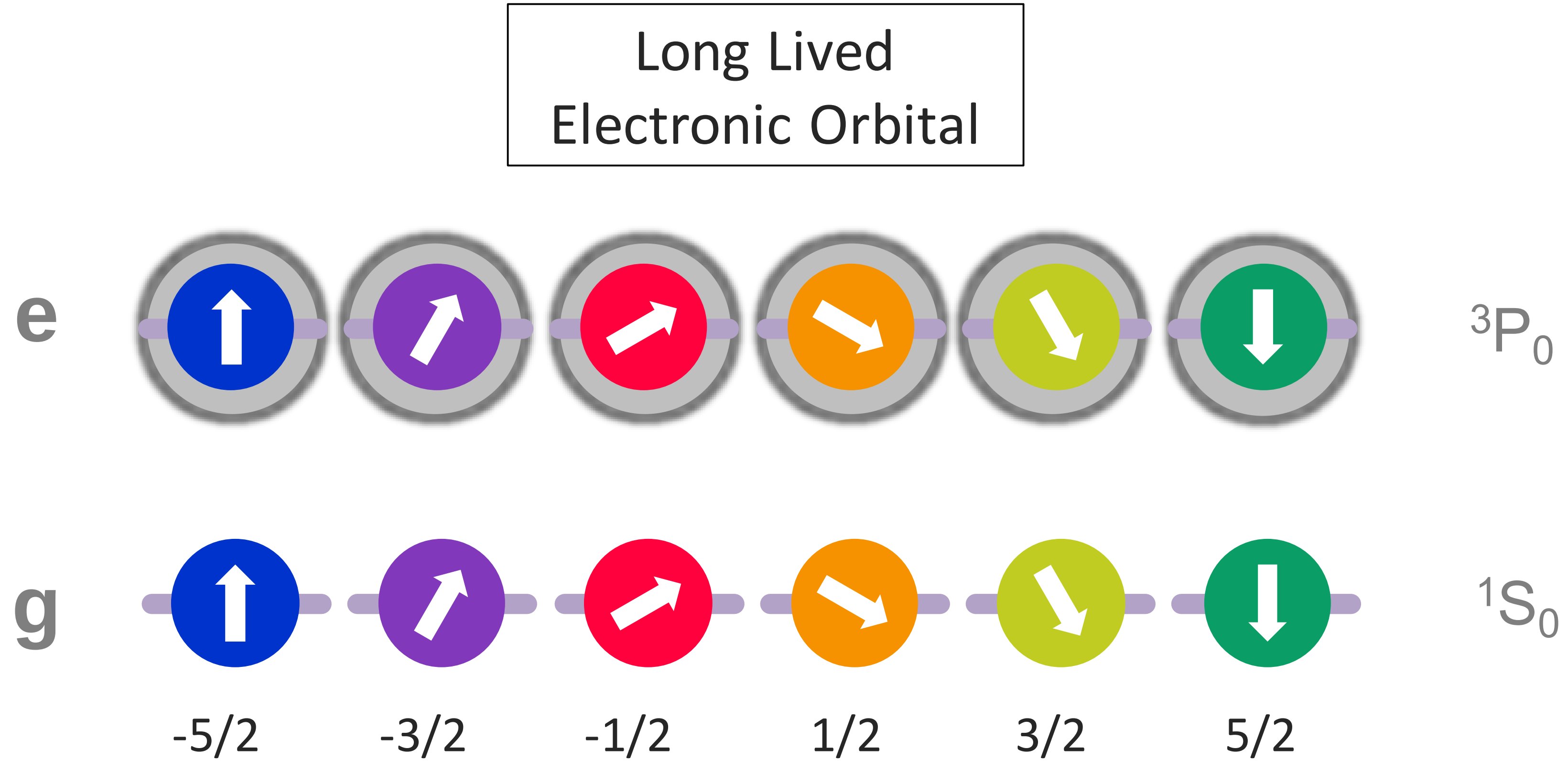
^{173}Yb Fermi gases in an arbitrary number of equally-populated components:



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

Long-lived electronic state

All isotopes of Yb: Metastable state $^3\mathbf{P}_0$ (~ 10 s lifetime for 173)



Note: SU(N) symmetry also holds for $^3\mathbf{P}_0$ (J=0)!!

New possibilities for Quantum Simulation

Two internal degrees of freedom with long life-(coherence-)times

Nuclear spin / SU(N)

Electronic orbital

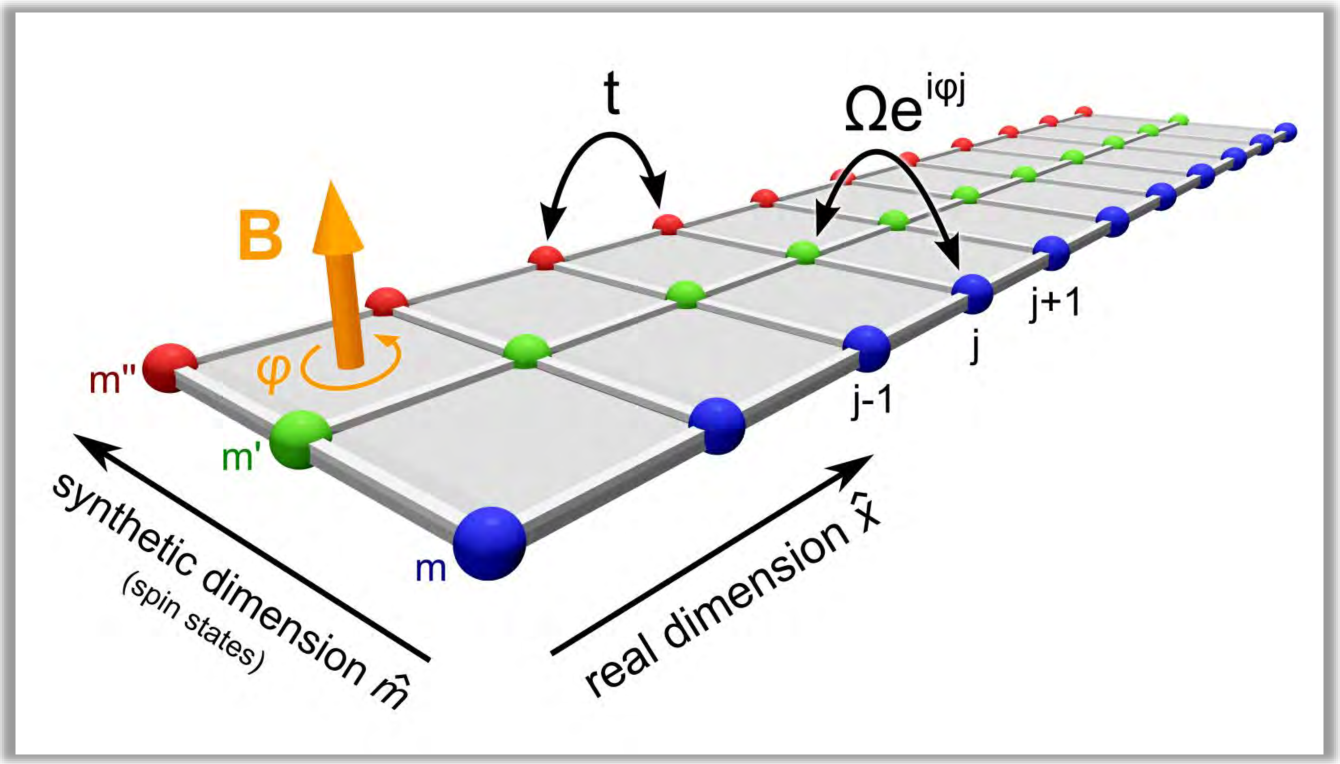
New possibilities for Quantum Simulation

Two internal degrees of freedom with long life-(coherence-)times

Nuclear spin / SU(N)

Electronic orbital

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

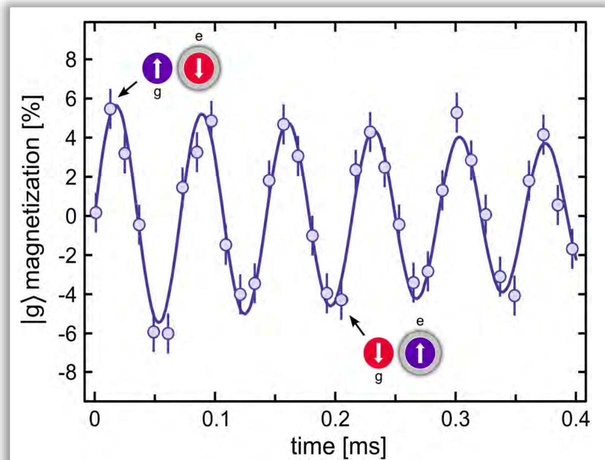


New possibilities for Quantum Simulation

Two internal degrees of freedom with long life-(coherence-)times

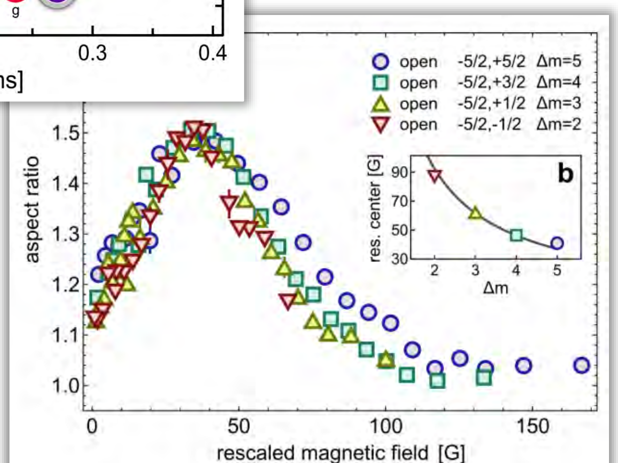
Nuclear spin / SU(N)

Electronic orbital



Coherent inter-orbital dynamics

G. Cappellini et al.
PRL **113**, 120402 (2014)



Orbital Feshbach Resonance

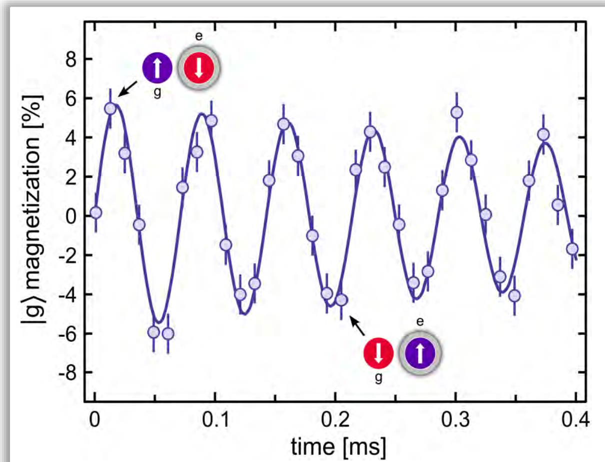
G. Pagano et al.
PRL **115**, 265301 (2015)

New possibilities for Quantum Simulation

Two internal degrees of freedom with long life-(coherence-)times

Nuclear spin / SU(N)

Electronic orbital



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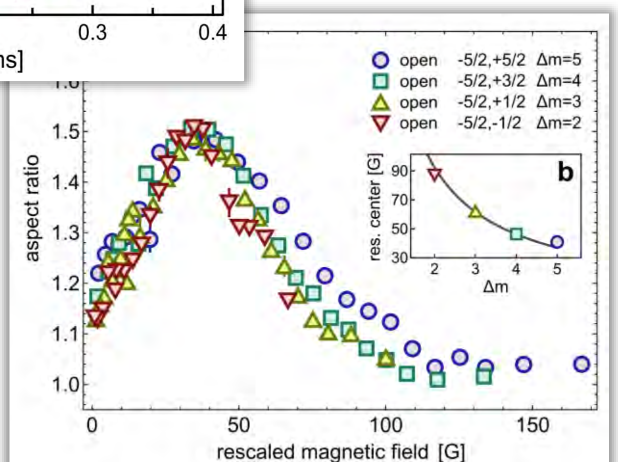
PRL **113**, 120402 (2014)



Orbital Feshbach Resonance

G. Pagano et al.
PRL **115**, 265301 (2015)

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G. Cappellini et al., PRL 113, 120402 (2014) Physics

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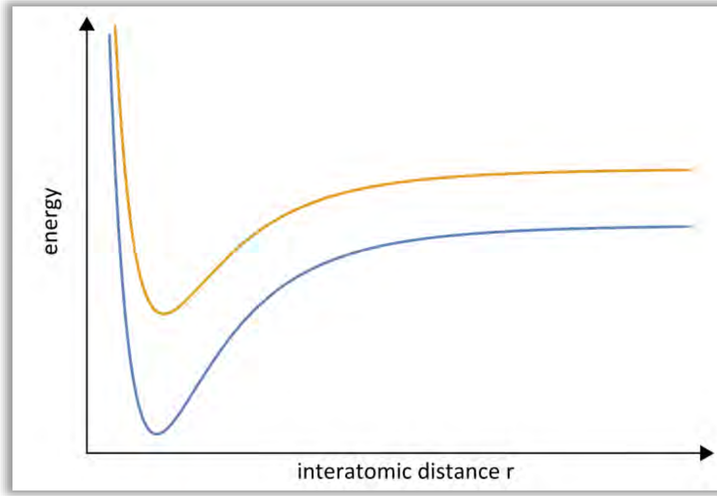
Spin-exchange interaction

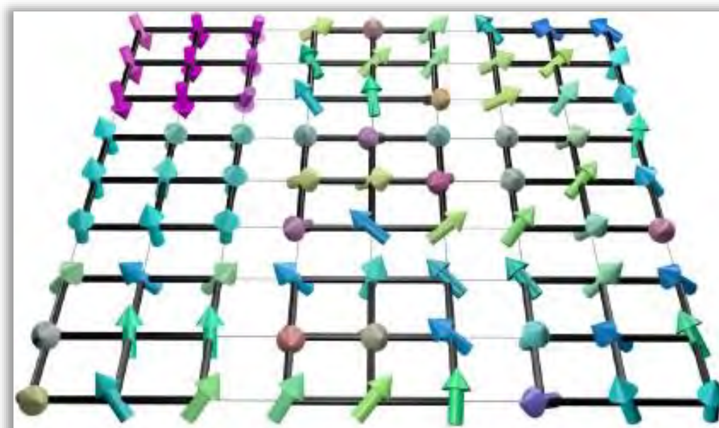
Exchange interaction originates from the exchange symmetry of the wavefunction:

$$\psi(1,2) = -\psi(2,1)$$

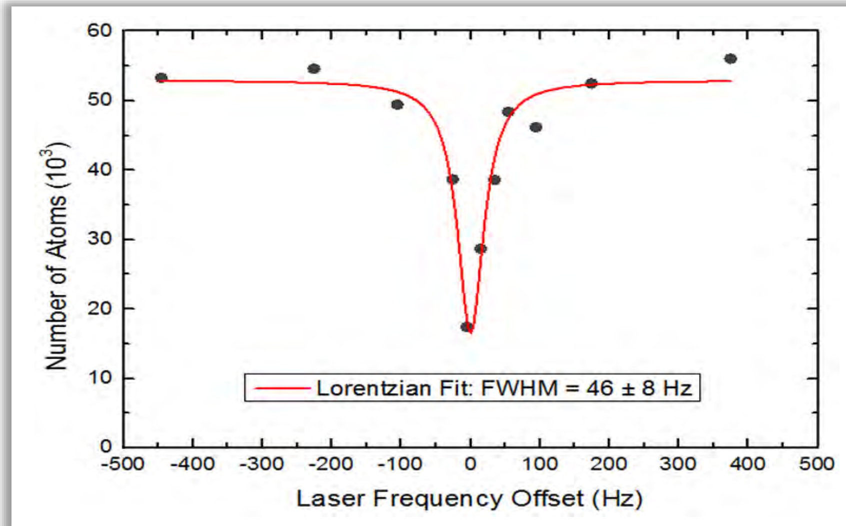
Molecular potentials

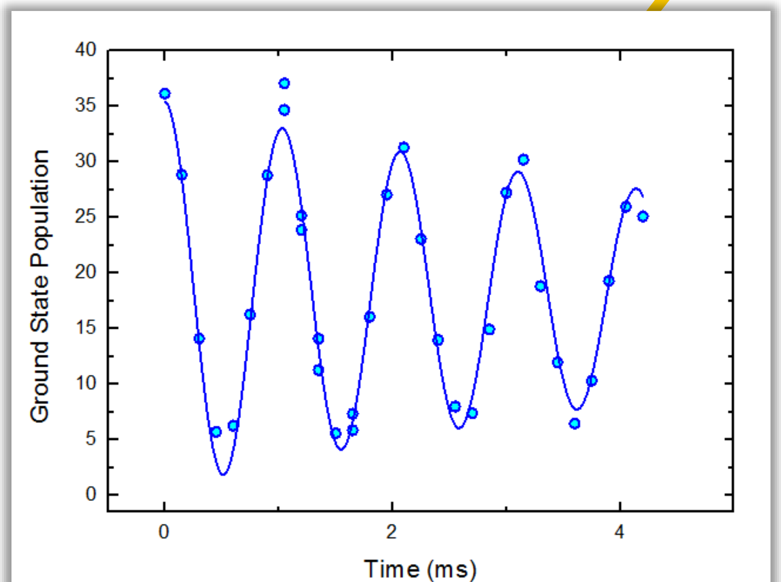


Magnetism



Orbital manipulation





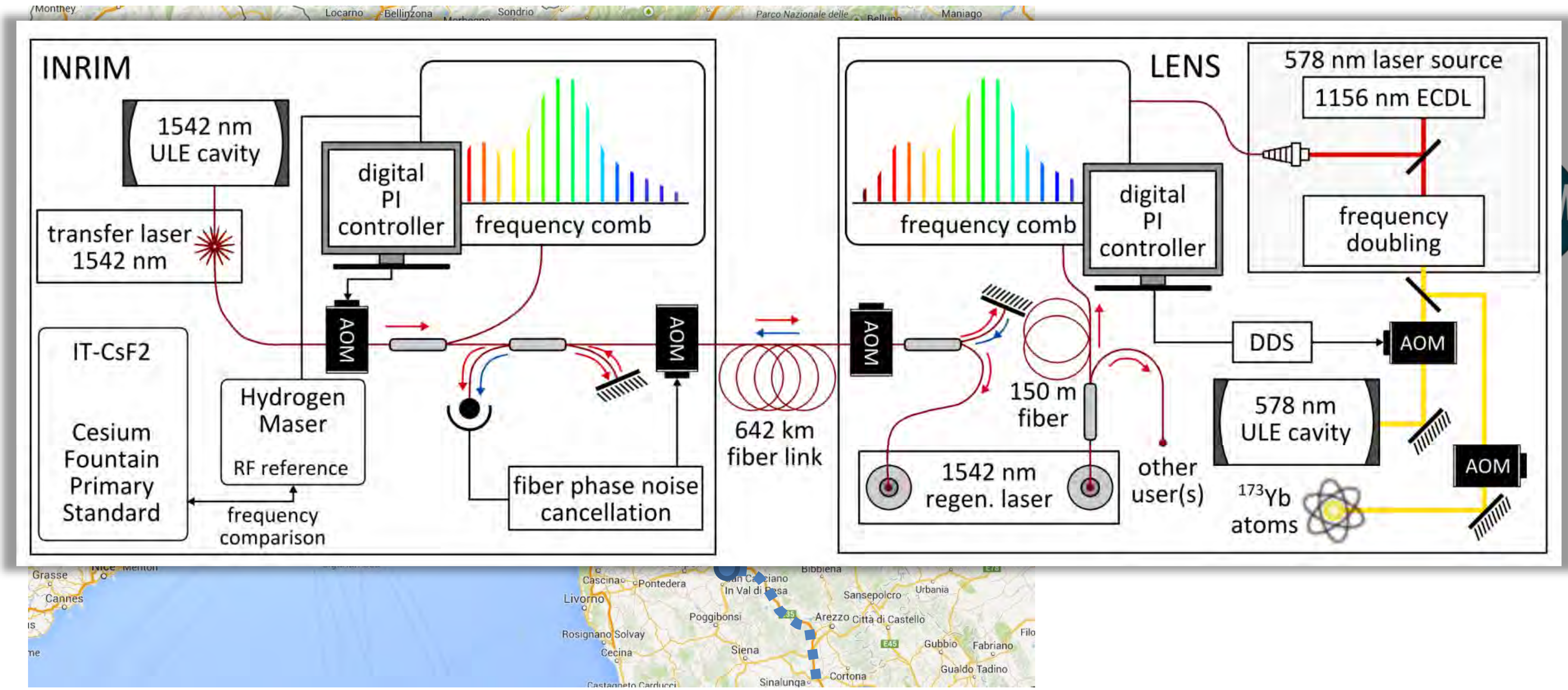
Optical Clock Technology for orbital manipulation

G. Cappellini, et al.,
Rev. Sci. Instrum. **86**, 073111 (2015)

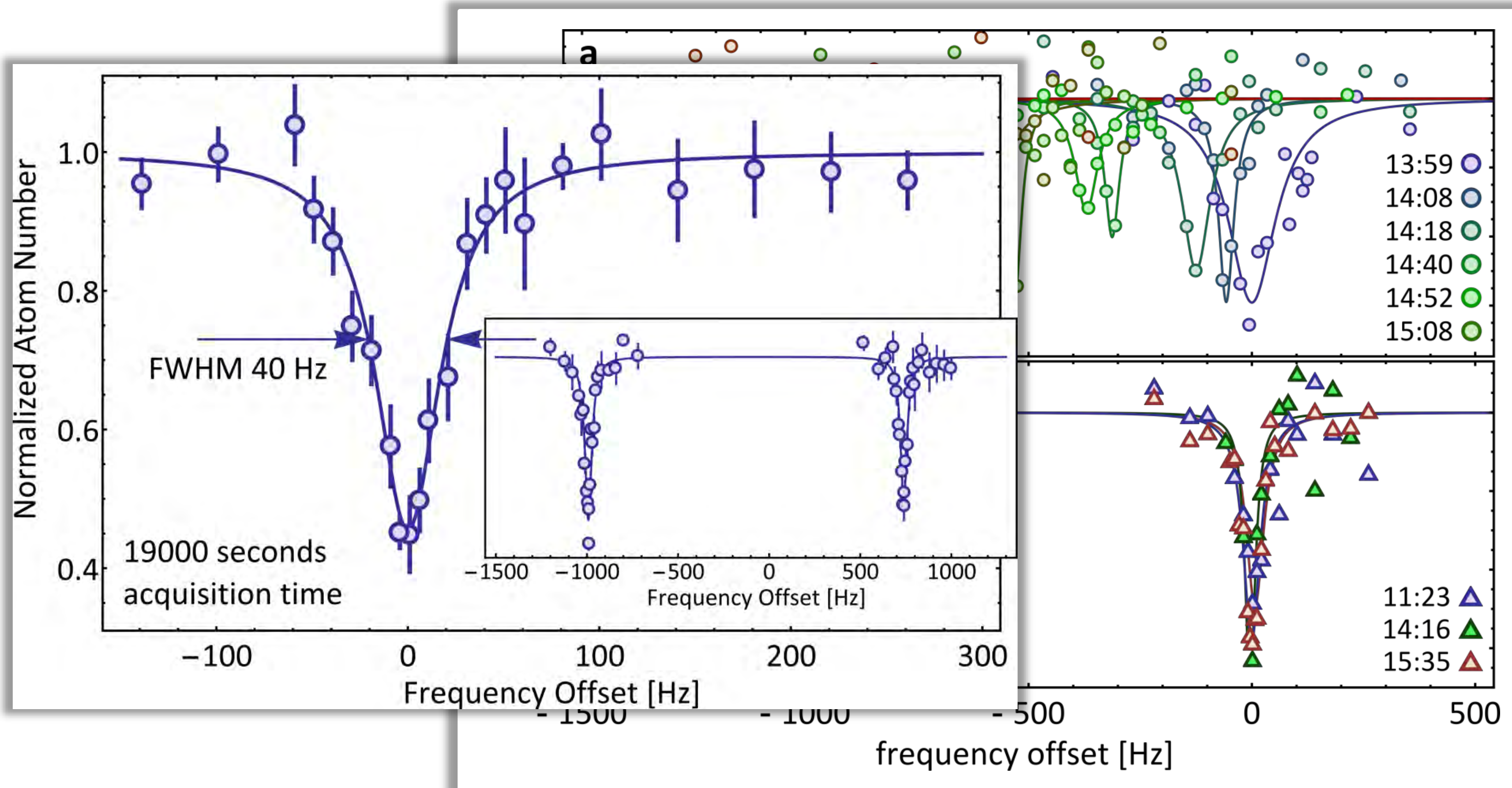
Clock technology 2.0

650km-long optical frequency link:

D. Calonico et al., Appl. Phys. B **117**, 979 (2014*)*



Beyond GPS long-term stability



Absolute frequency of ^{173}Yb clock transition

f = 518 294 576 845 268 (10) Hz

(10^{-14} in 10^4 seconds)

→ Dissemination of absolute time reference **BEYOND GPS LIMIT**

C. Clivati et al., Opt. Express **24**, 11865 (2016)

Interorbital Spin-Exchange

Two fermions (g+e) in a trap

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

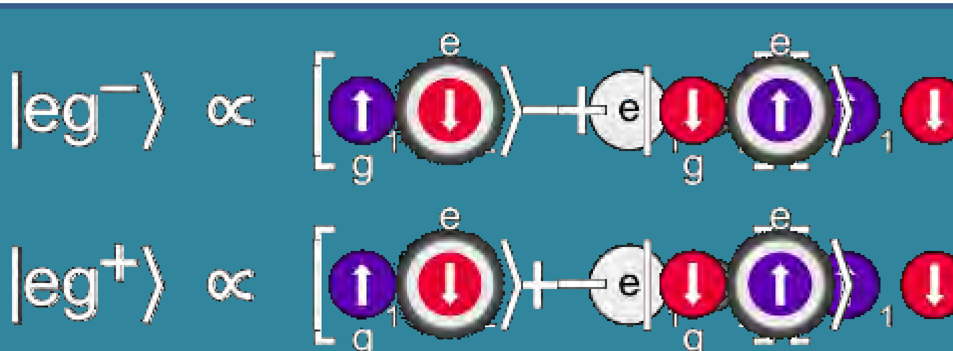
V_{ex} can drive dynamics in the system!

How to induce and detect such dynamics?

Antisymmetrization of the two-particle state:

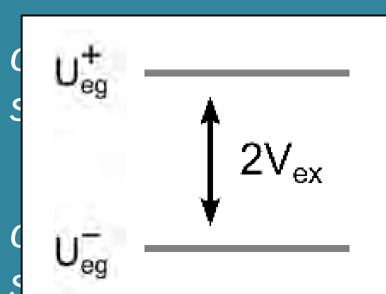
Different scattering lengths for the two eigenstates:

EXCHANGE INTERACTION



$a_{eg}^{+} = 3300\ a_0$

$a_{eg}^{-} = 220\ a_0$



Interorbital Spin-Exchange

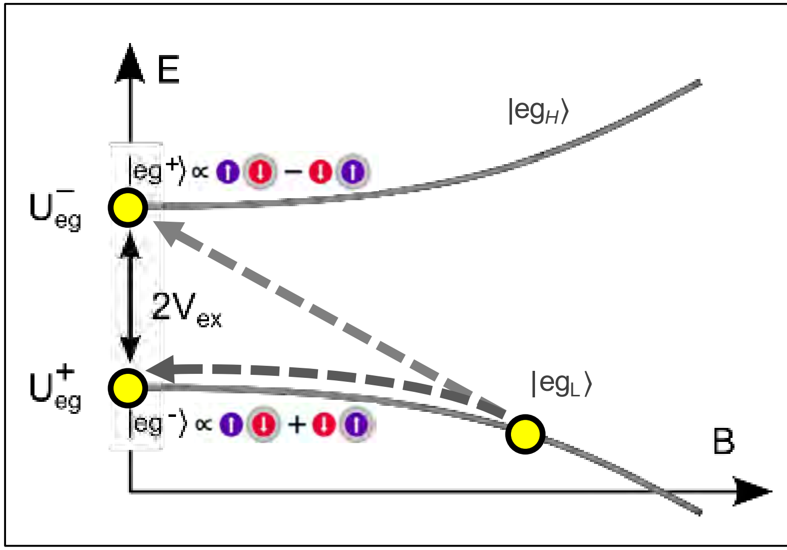
G. Cappellini et al., PRL **113**, 120402 (2014)

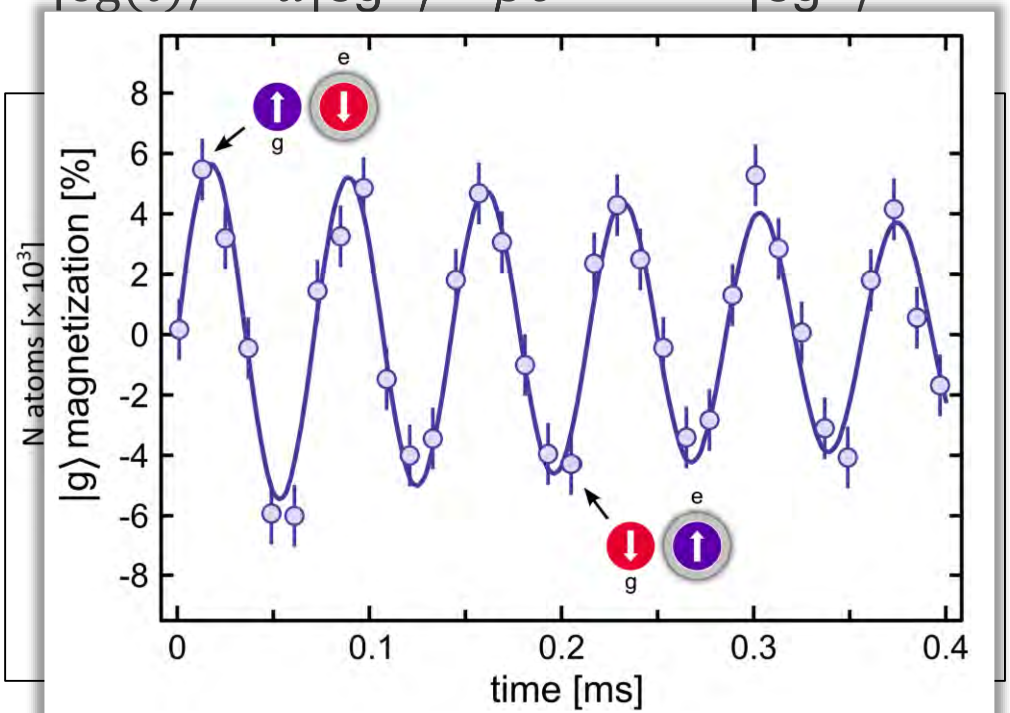
Let's add a magnetic field B:
Mixing between the two channels

$$|eg_L\rangle = \alpha|eg^+\rangle + \beta|eg^-\rangle$$ $\alpha^2=\beta^2= 1/2$ @ large **B**

PREPARATION
π-pulse +B field quench + free evolution

$$|eg(t)\rangle = \alpha|eg^+\rangle + \beta e^{-i2V_{ex}t/\hbar}|eg^-\rangle$$





Ground-state magnetization:

$$|\langle g\uparrow|eg(t)\rangle|^2 = \frac{1}{2} + \alpha\beta\cos\left(\frac{2V_{ex}}{\hbar}t\right)$$

Spectrum of the 578nm clock transition
in a 3D optical lattice

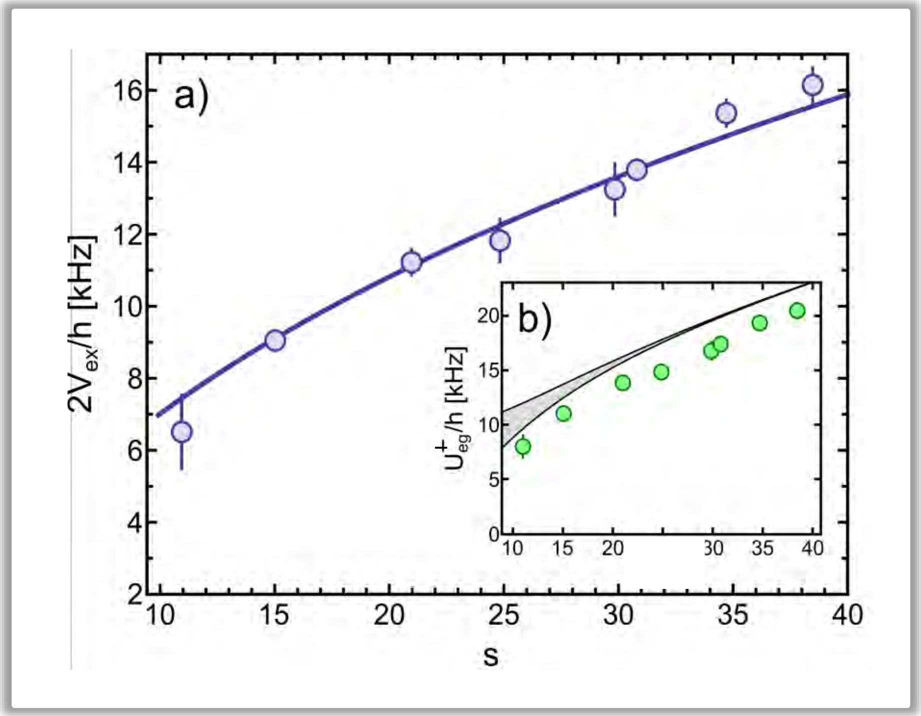
Direct observation of long-lived interorbital spin-exchange oscillations

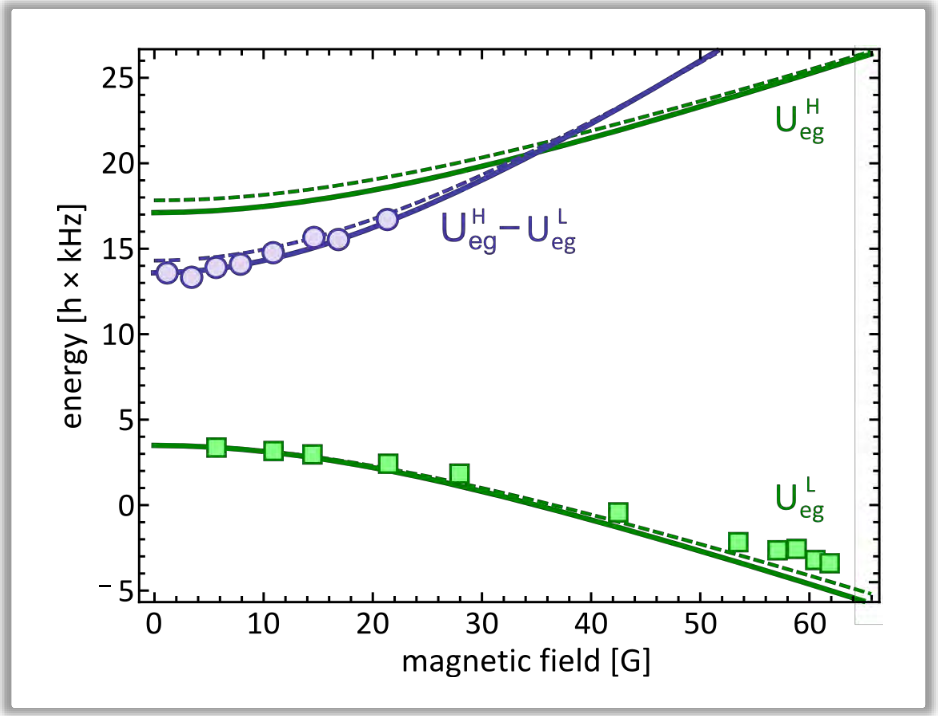
See also
F. Scazza et al., Nat. Phys. **10**, 779 (2014)

Interorbital Spin-Exchange

*G. Cappellini et al., PRL **113**, 120402 (2014)*

Very large spin-exchange energy!!! $V_{ex} >> k_B T$ (<h x 1 kHz)





Strong repulsion in the $|eg^+\rangle$ state, close to the lattice band separation

Beyond standard Hubbard treatment of interactions ("fermionization" of spatial wavefunction)

T. Busch et al., Found. Phys. 28, 549 (1998)

$a_{eg}^- = 220\ a_0$

$a_{eg}^+ = 3300\ a_0$

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G. Pagano et al., PRL 115, 265301 (2015) Physics

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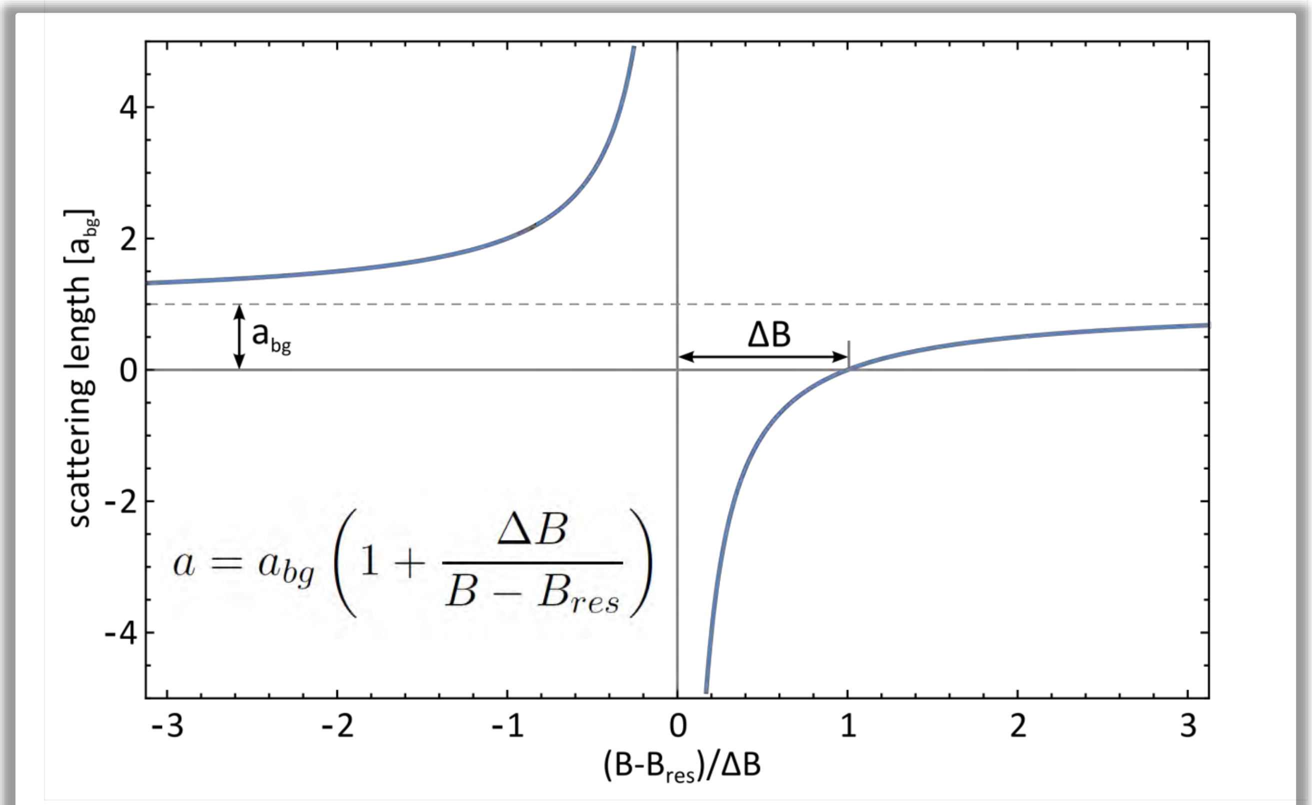
Tunability of interactions: Feshbach resonances



A Feshbach resonance occurs when $E_c \sim \Delta\mu B$

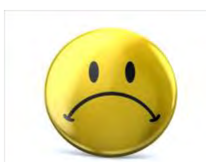
In G.S. alkali atoms, hyperfine interaction couples OC and CC

↓

Magnetic Feshbach Resonance

PROBLEM…

In G.S. Alkaline-Earth-Like atoms the Hyperfine interaction is absent!
No «magnetic» Feshbach coupling



Tunability of interorbital interactions

PRL **115,** 135301 (2015) PHYSICAL REVIEW LETTERS week ending 25 SEPTEMBER 2015

Orbital Feshbach Resonance in Alkali-Earth Atoms

Ren Zhang,[1] Yanting Cheng,[1] Hui Zhai,[1,*] and Peng Zhang[2,3,†]
[1]*Institute for Advanced Study, Tsinghua University, Beijing 100084, China*
[2]*Department of Physics, Renmin University of China, Beijing 100872, China*
[3]*Beijing Key Laboratory of Opto-electronic Functional Materials & Micro-nano Devices, Renmin Univeristy of China, Beijing 100872, China*
(Received 24 April 2015; revised manuscript received 28 July 2015; published 21 September 2015)

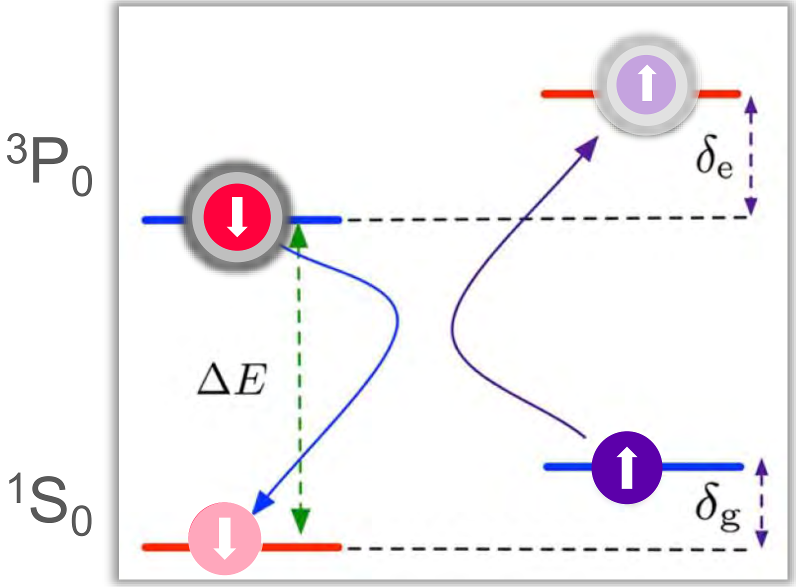
Selected for a Viewpoint in *Physics*
PRL **115,** 265301 (2015) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2015

Strongly Interacting Gas of Two-Electron Fermions at an Orbital Feshbach Resonance

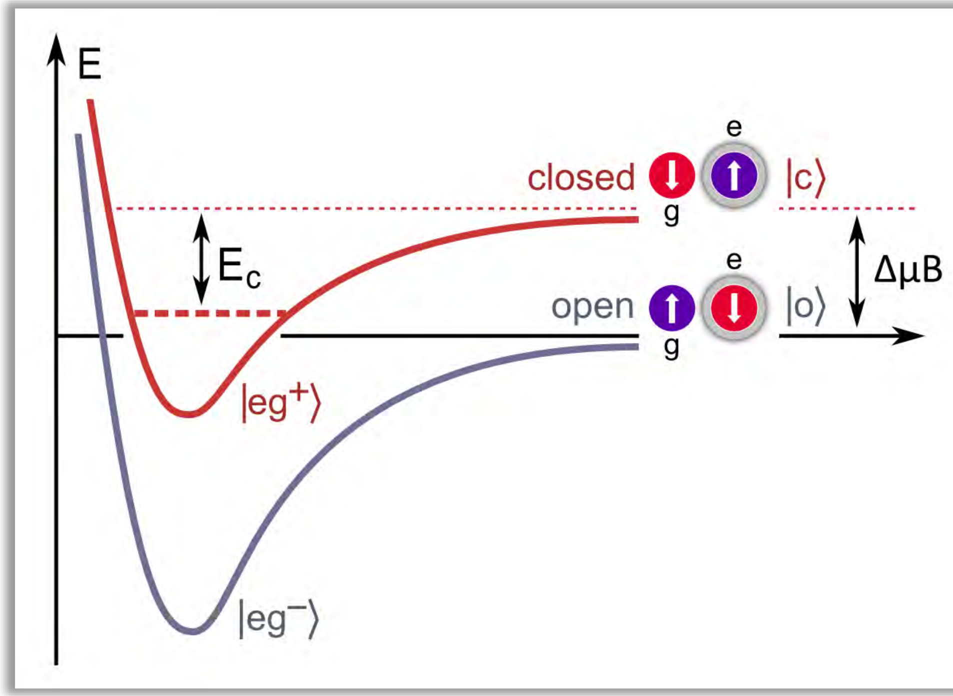
G. Pagano,[1] M. Mancini,[1] G. Cappellini,[2] L. Livi,[2] C. Sias,[3,2] J. Catani,[4,2,5] M. Inguscio,[3,1,2] and L. Fallani[1,2,5]
[1]*Department of Physics and Astronomy, University of Florence, I-50019 Sesto Fiorentino, Italy*
[2]*LENS European Laboratory for Nonlinear Spectroscopy, I-50019 Sesto Fiorentino, Italy*
[3]*INRIM Istituto Nazionale di Ricerca Metrologica, I-10135 Torino, Italy*
[4]*INO-CNR Istituto Nazionale di Ottica del CNR, Sezione di Sesto Fiorentino, I-50019 Sesto Fiorentino, Italy*
[5]*INFN Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, I-50019 Sesto Fiorentino, Italy*
(Received 14 September 2015; published 21 December 2015)

Related work by M. Höfer et al., Phys. Rev. Lett. (same issue)

Orbital Resonance Mechanism



Adapted from R. Zhang et al., PRL 2015



Scattering potential (in the OC and CC basis)

$$\hat{V} = \hat{V}_d(|o\rangle\langle o| + |c\rangle\langle c|) + \hat{V}_{ex}(|c\rangle\langle o| + |o\rangle\langle c|)$$

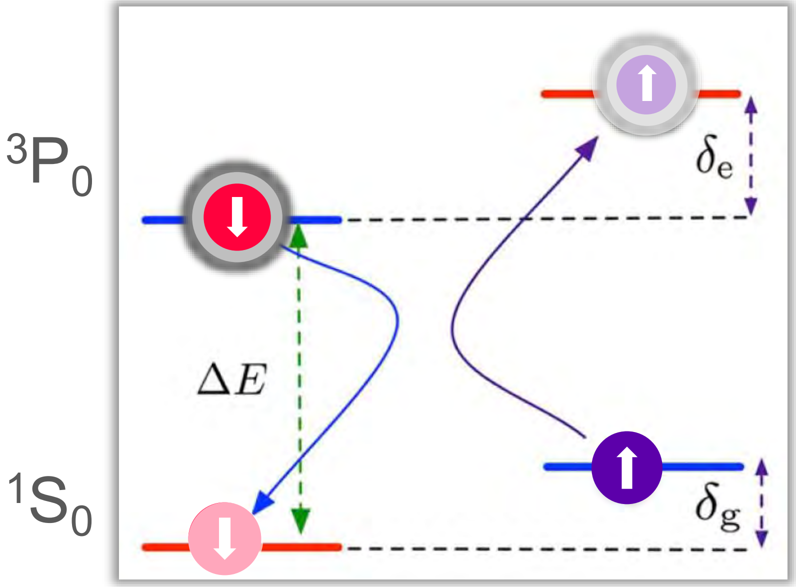
$$a_d = \frac{a_{eg}^+ + a_{eg}^-}{2} \qquad a_{ex} = \frac{a_{eg}^+ - a_{eg}^-}{2}$$

$a_{eg}^- = 220\ a_0$

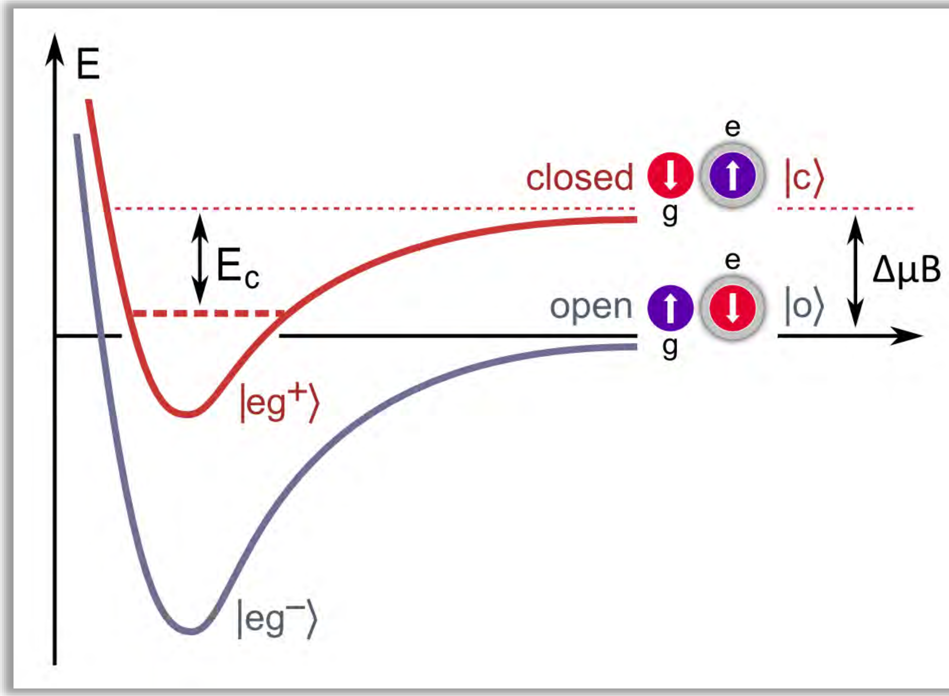
$a_{eg}^+ = 3300\ a_0$

1) Strong scattering unbalance implies **strong coupling between OC and CC**

Orbital Resonance Mechanism



Adapted from R. Zhang et al., PRL 2015



$$|E_c| = \hbar^2/ma_d^2$$

$$\Delta\mu = \delta_e - \delta_g = \delta g \mu_N \Delta m$$

→ Resonance for $B \sim \frac{E_c}{\Delta\mu}$

$\delta g\mu_N$ = 113 Hz/Gauss …BUT… $a_d > 10^3\, a_0$

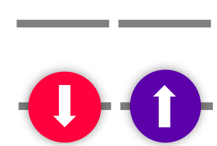
2) Large background CC scattering length lowers resonant B field around a few tens of Gauss

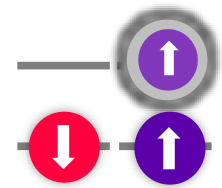
Not true for other alkali-earth(-like) atoms e.g. Sr (which has a deep bound state)

Strongly interacting orbital gas

60 kats @ 0.15 T_F

$\omega = 2\pi(13, 138, 188)$ Hz

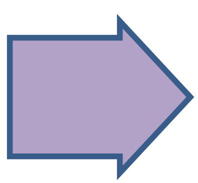


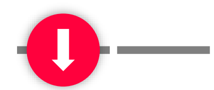


1D Lattice
(Lamb-Dicke)

578nm, 400 μs
High B
Recover 3D

TOF expansion
@ finite B (first 5 ms)





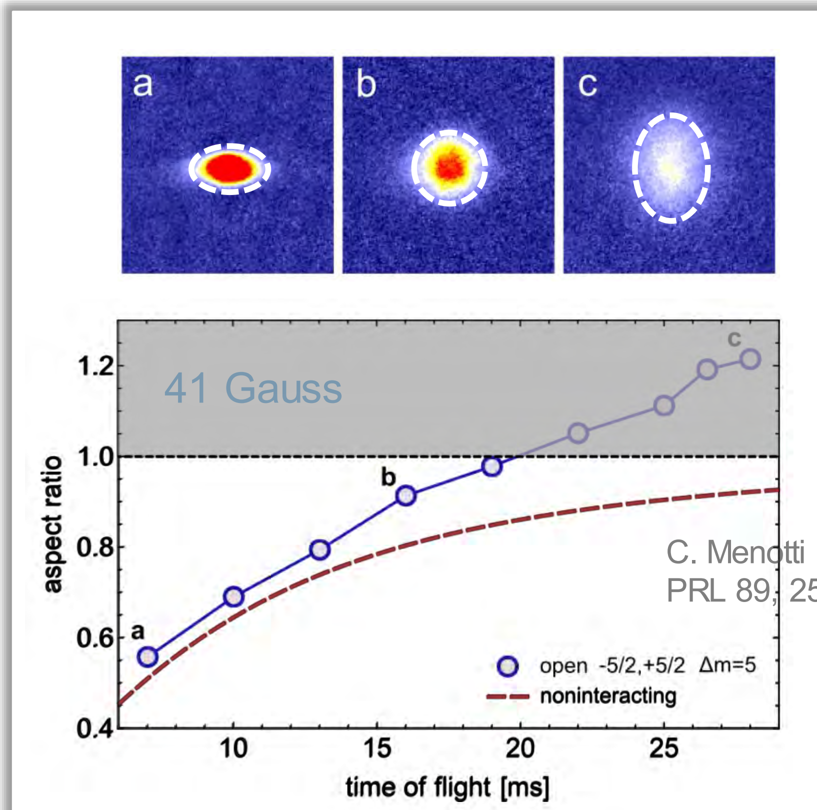
Aspect Ratio of the orbital gas

G. Pagano et al., PRL ***115****, 265301 (2015)*

Aspect Ratio (AR) Rx/Ry gives information on interaction energy through release energy (TOF)

K. M. O'Hara et al., Science **298**, 2179 (2002).

NONINTERACTING: Rx/Ry → 1



C. Menotti et al.
PRL 89, 250402 (2002)

INVERSION OF ASPECT RATIO

STRONGLY INTERACTING FERMI GAS IN THE **HYDRODINAMIC REGIME**

Observation of OrbFR

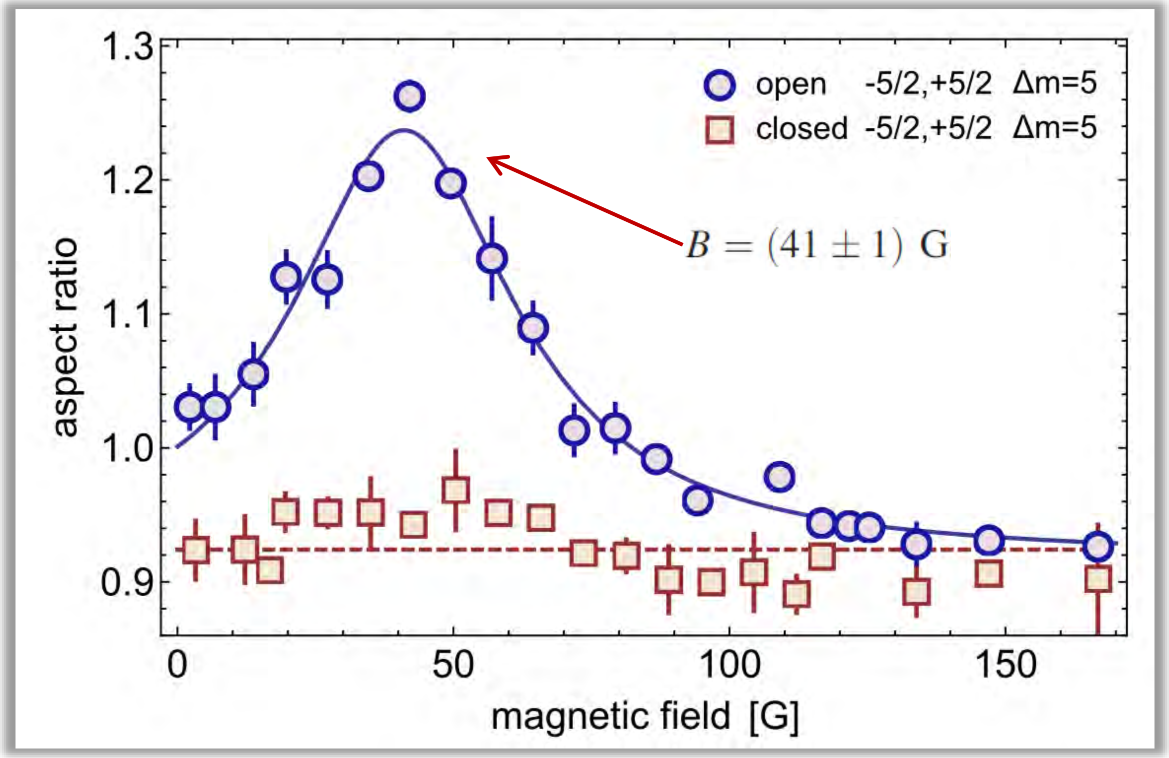
*G. Pagano et al., PRL **115**, 265301 (2015)*

AR anisotropy is used to characterize the scattering strength as a function of **B**

C. A. Regal and D. S. Jin, PRL **90**, 230404 (2003)

AR anisotropy resonance in open channel

No resonance observed in closed channel



Scaling law of resonance centers

*G. Pagano et al., PRL **115**, 265301 (2015)*

Yb features SU(N)-symmetric interactions in the $^1S_0$ and $^3P_0$ manifolds

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

E_c **does not depend on *Δm***

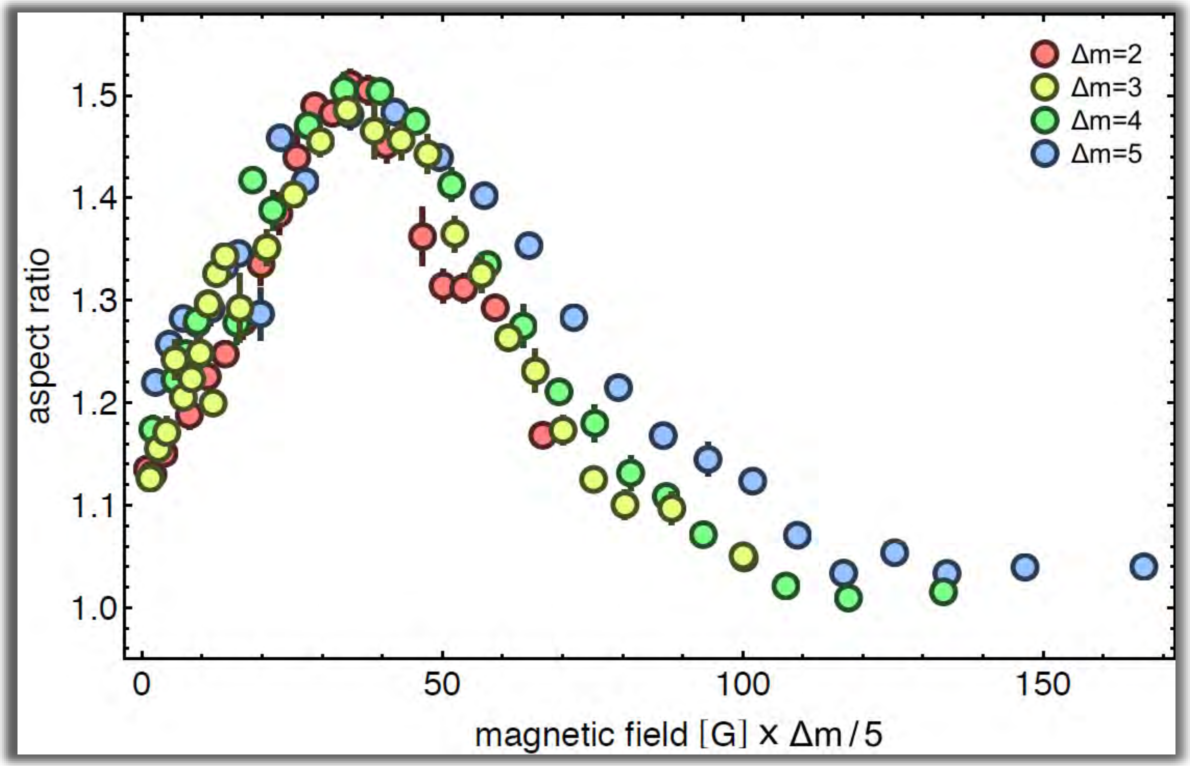
$$|E_c| = \hbar^2 / m a_d^2$$

But Δμ does

$$\Delta\mu B = \delta g \mu_N \Delta m B$$

Resonance for $B \sim \frac{E_c}{\Delta\mu}$

B_0 **should scale as 1 / *Δm***



COLLAPSE OF DATASETS ONTO A UNIVERSAL CURVE!

Lifetime of a strongly interacting orbital gas

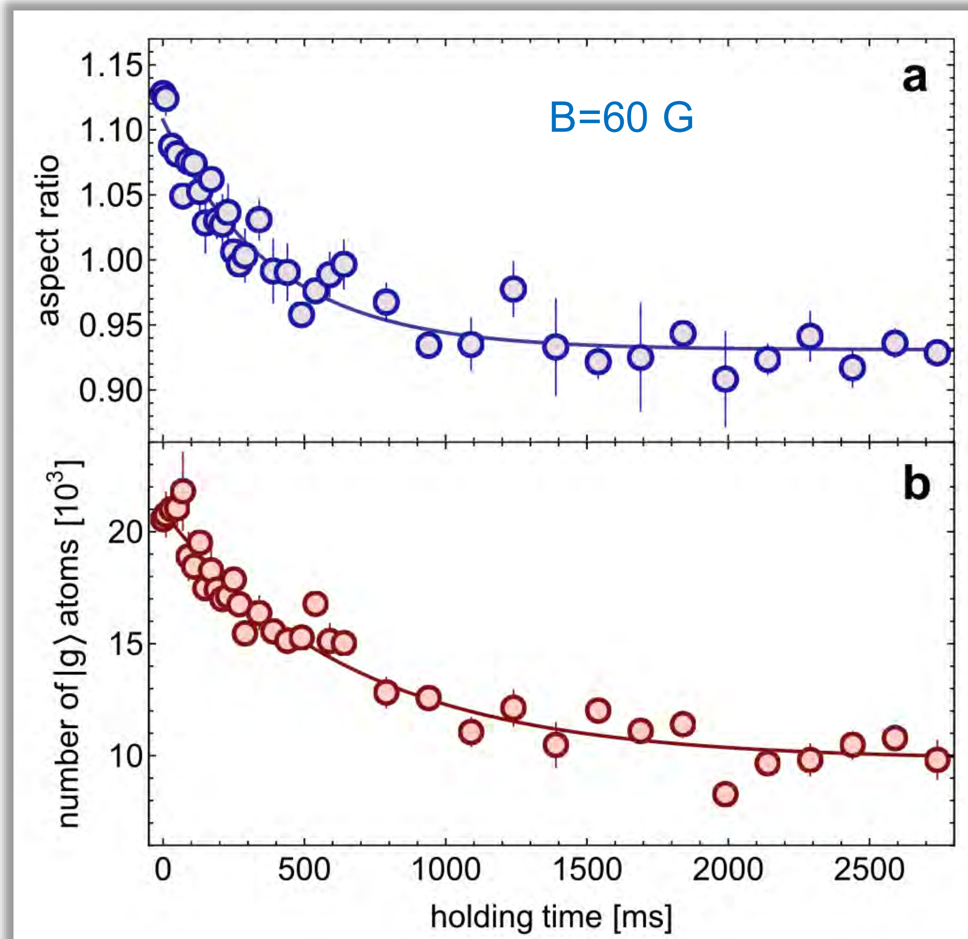
Rx/Ry and Atom Losses as a function of hold times

- Long lifetimes $\tau \simeq 380$ ms
- Single exponential decay

  Main contribution from inelastic e-g collisions

- No shape excitations
- No Spin exchange is observed

  (3D) $\Delta\mu B \gg V_{ex}$



G. Pagano et al., PRL **115**, 265301 (2015)

Lifetime of a strongly interacting orbital gas

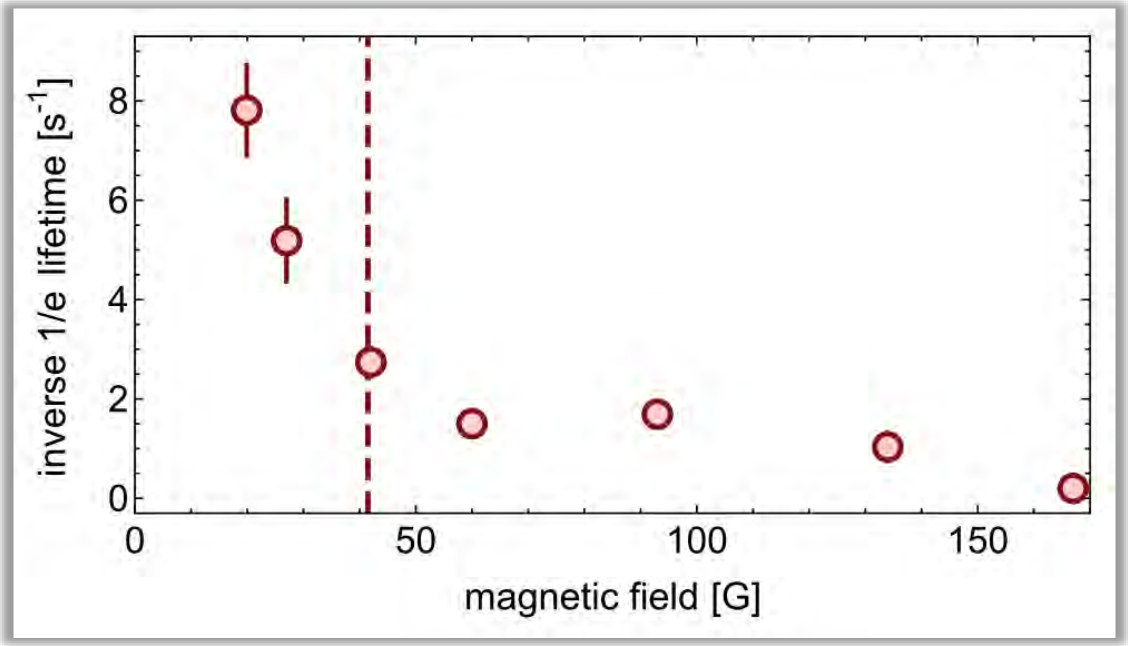
Atom number decay ACROSS THE RESONANCE

- Asymmetric behavior

  Stronger losses on BEC side
  (Multiple exp. decay)

- Long Lifetime

  >300 ms on resonance



Promising tool for Many-Body studies of Orbital interacting Gases

*G. Pagano et al., PRL **115**, 265301 (2015)*

Outline

Introduction

Observation of interorbital spin-exchange

Tuning interactions via an Orbital resonance

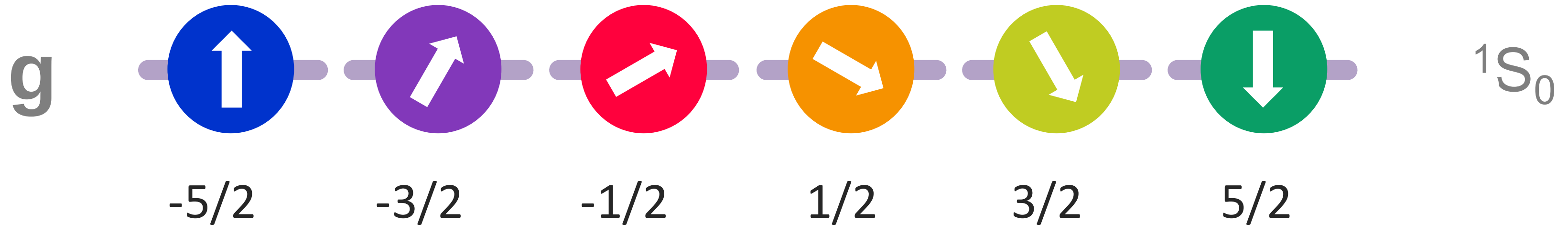
Chiral edge states in synthetic dimensions

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

Outlook and summary

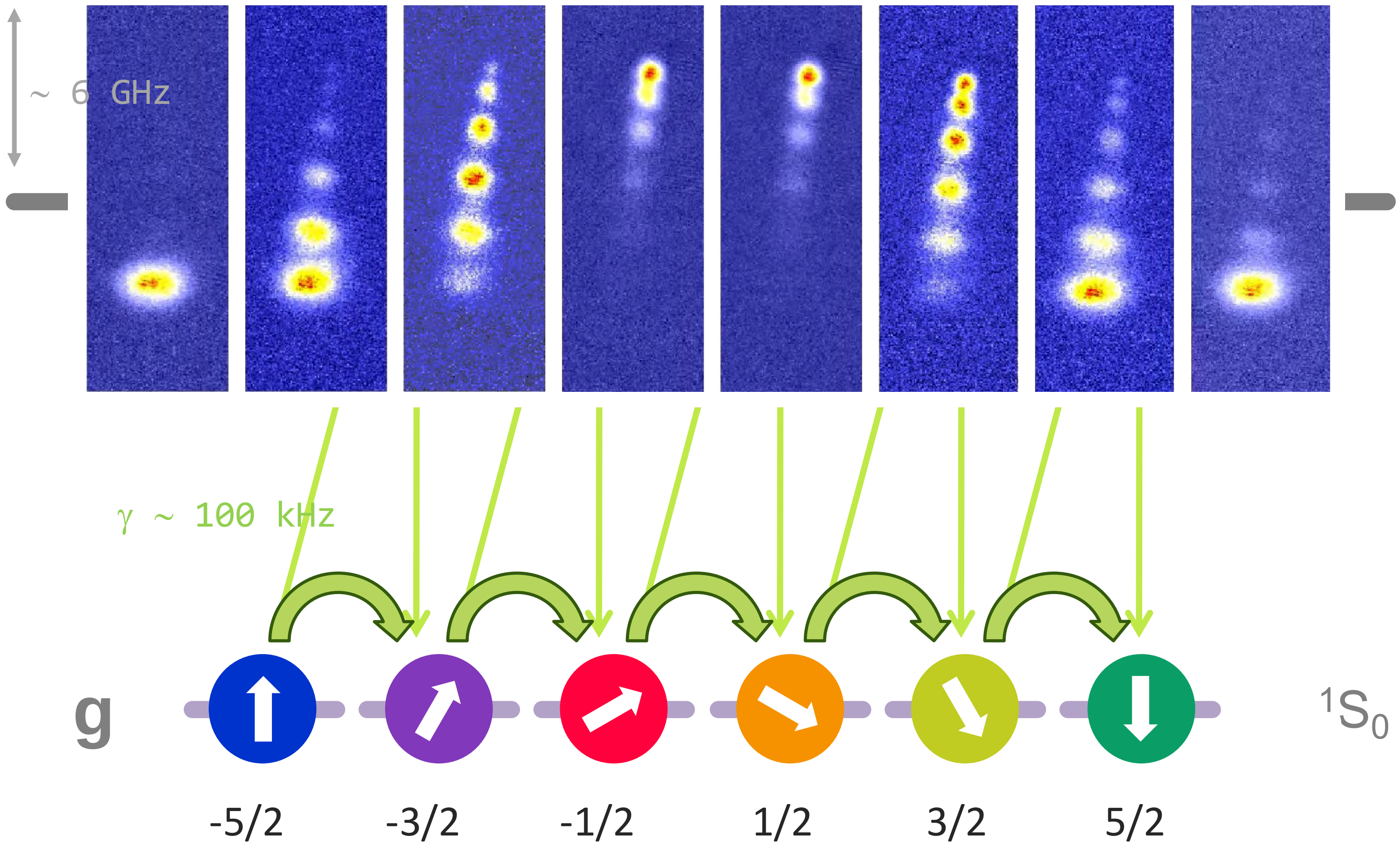
Simulating an “extra dimension”

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



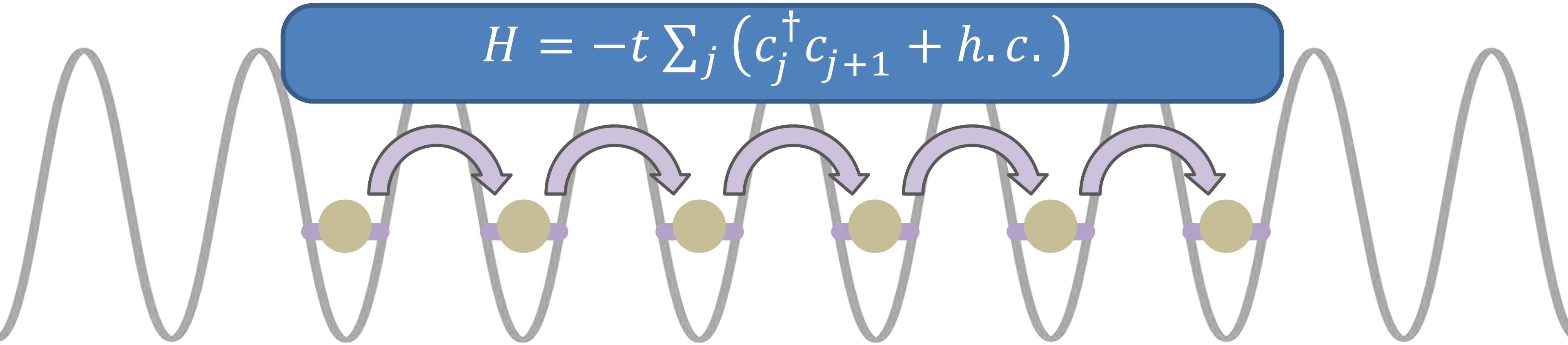
Simulating an “extra dimension”

Raman transitions coupling coherently different nuclear spin states:

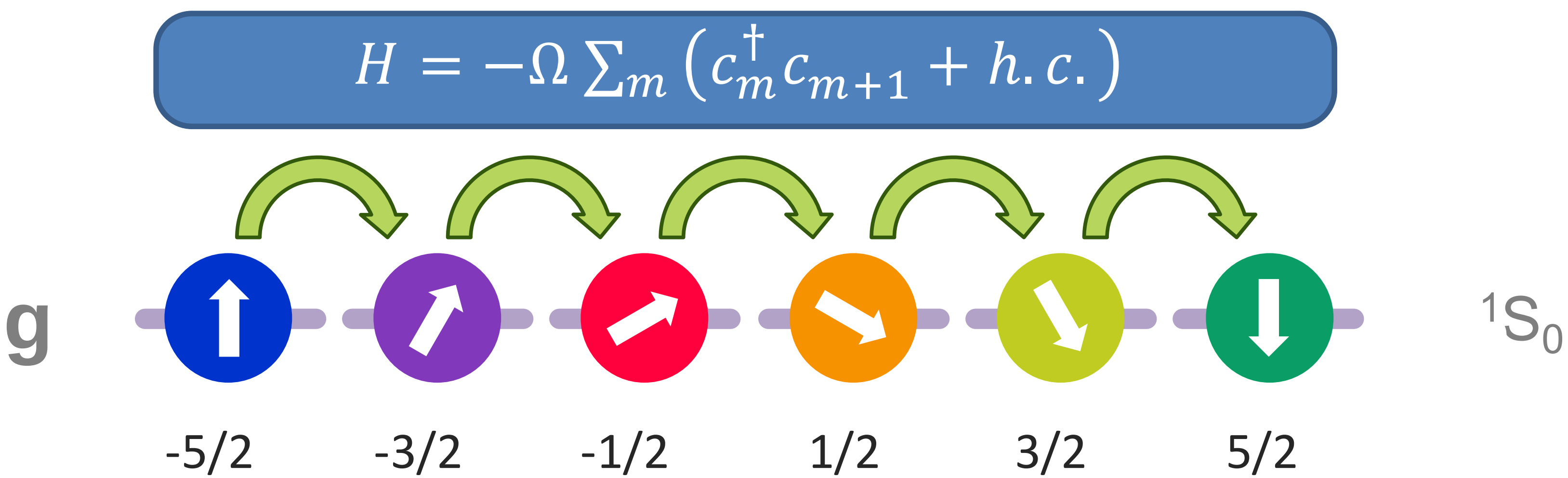


Simulating an "extra dimension"

Analogous to coherent tunnelling coupling in an optical lattice:



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

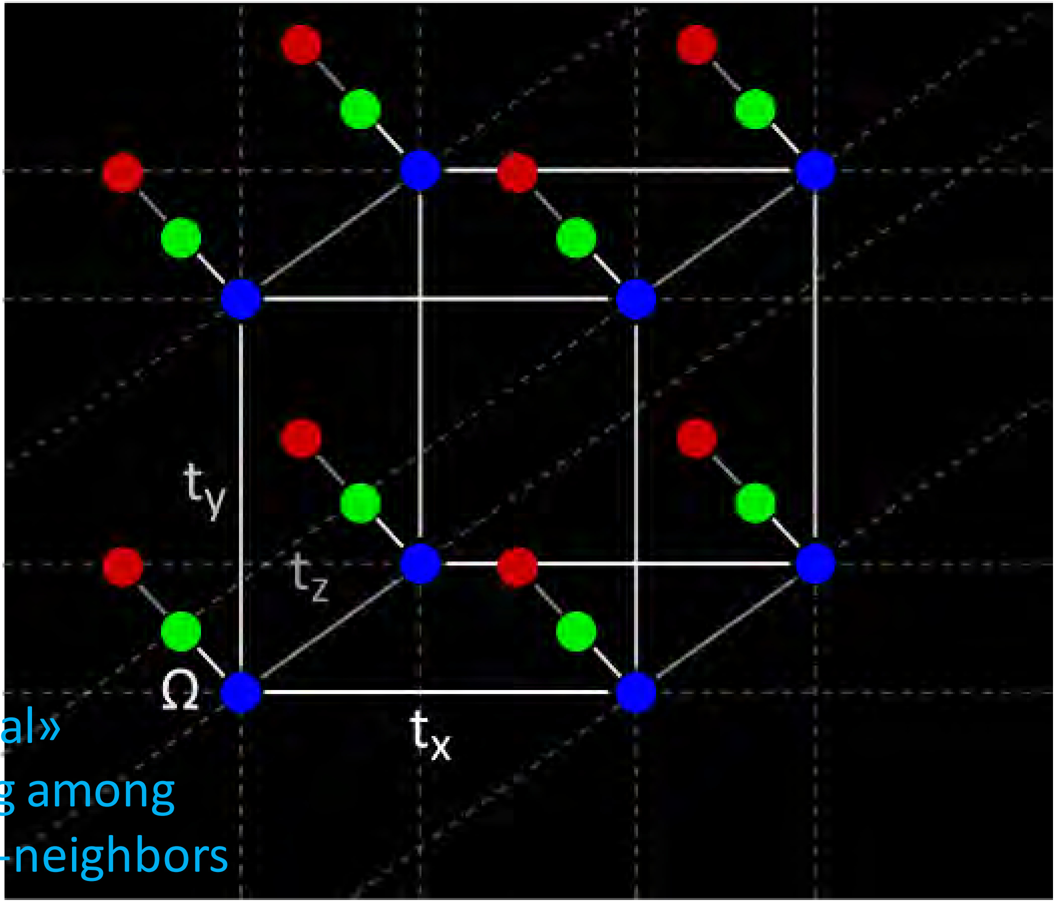


$$H = -\Omega \sum_m \left(c_m^\dagger c_{m+1} + h.c. \right)$$

Simulating an "extra dimension"

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

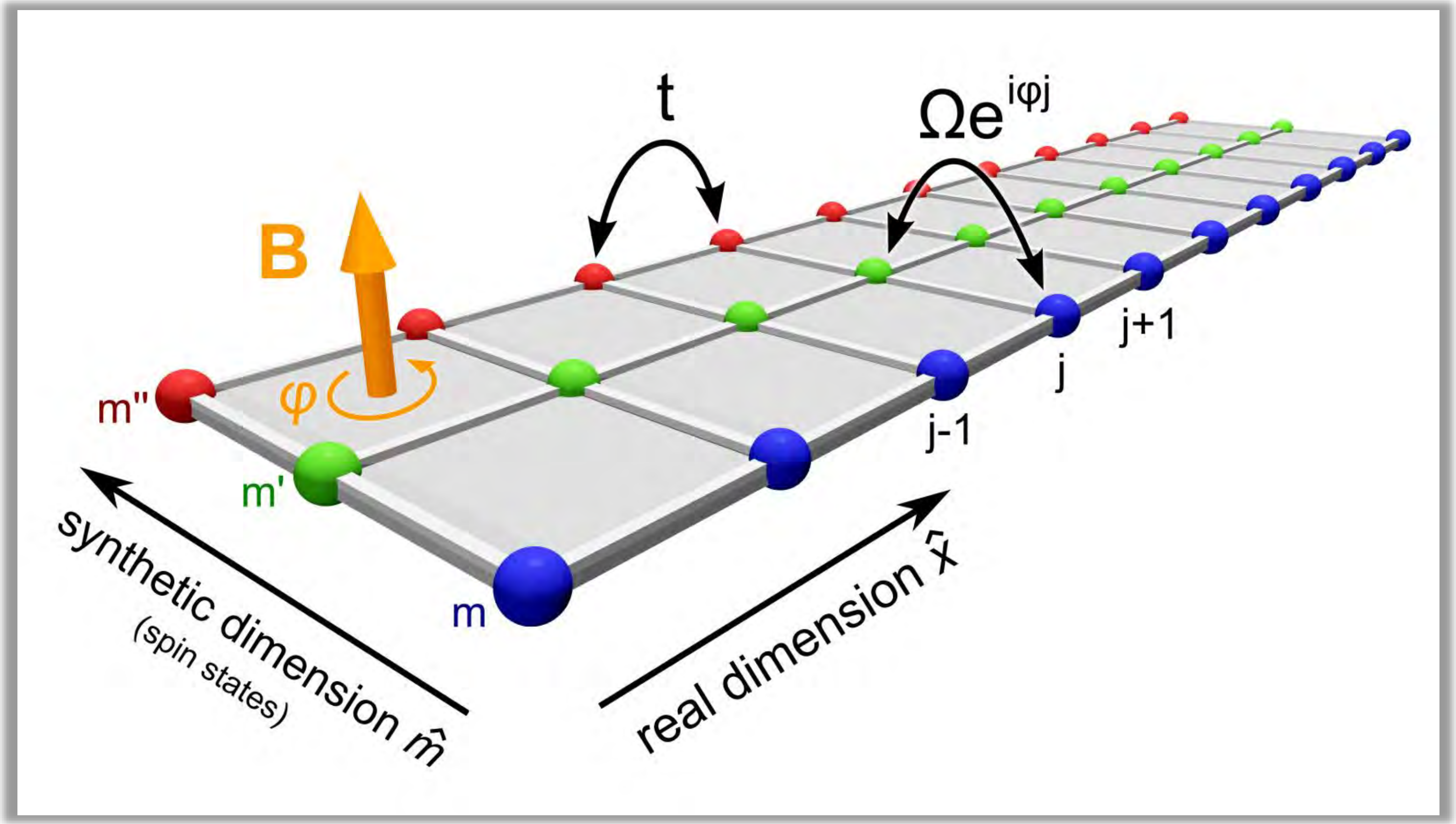
Boada et al., PRL 108, 133001 (2012)



«Artificial» coupling among nearest-neighbors internal states

An atomic Hall ribbon

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



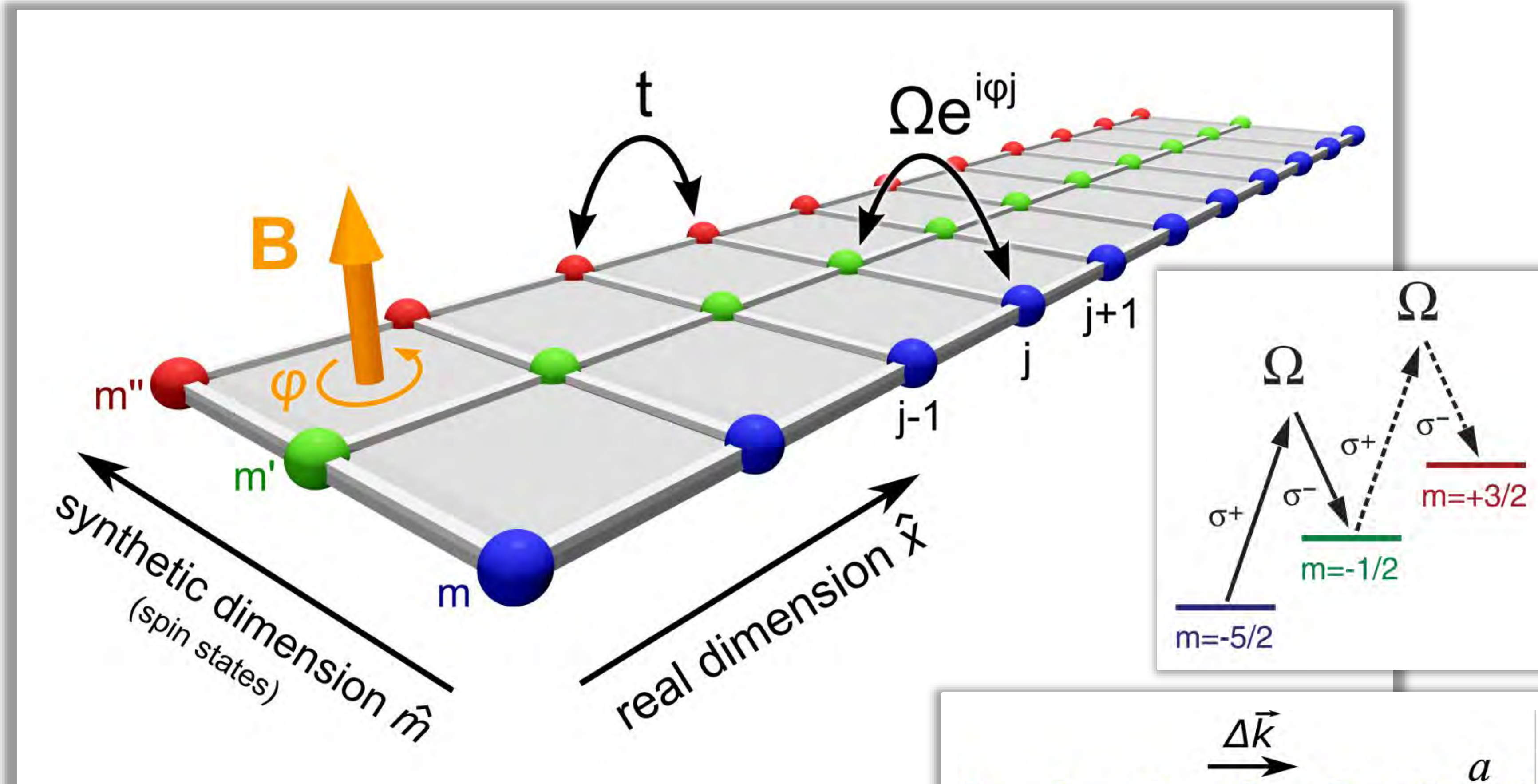
proposed: A. Celi et al., PRL **112**, 043001 (2014)

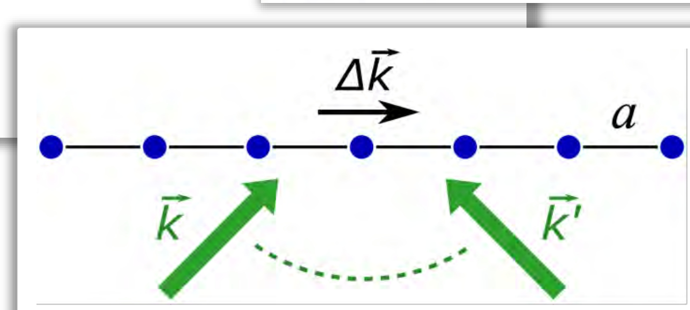
realized: M. Mancini et al., Science **349**, 1510 (2015)
B. K. Stuhl et al., Science **349**, 1514 (2015)

An atomic Hall ribbon

Feature #1

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





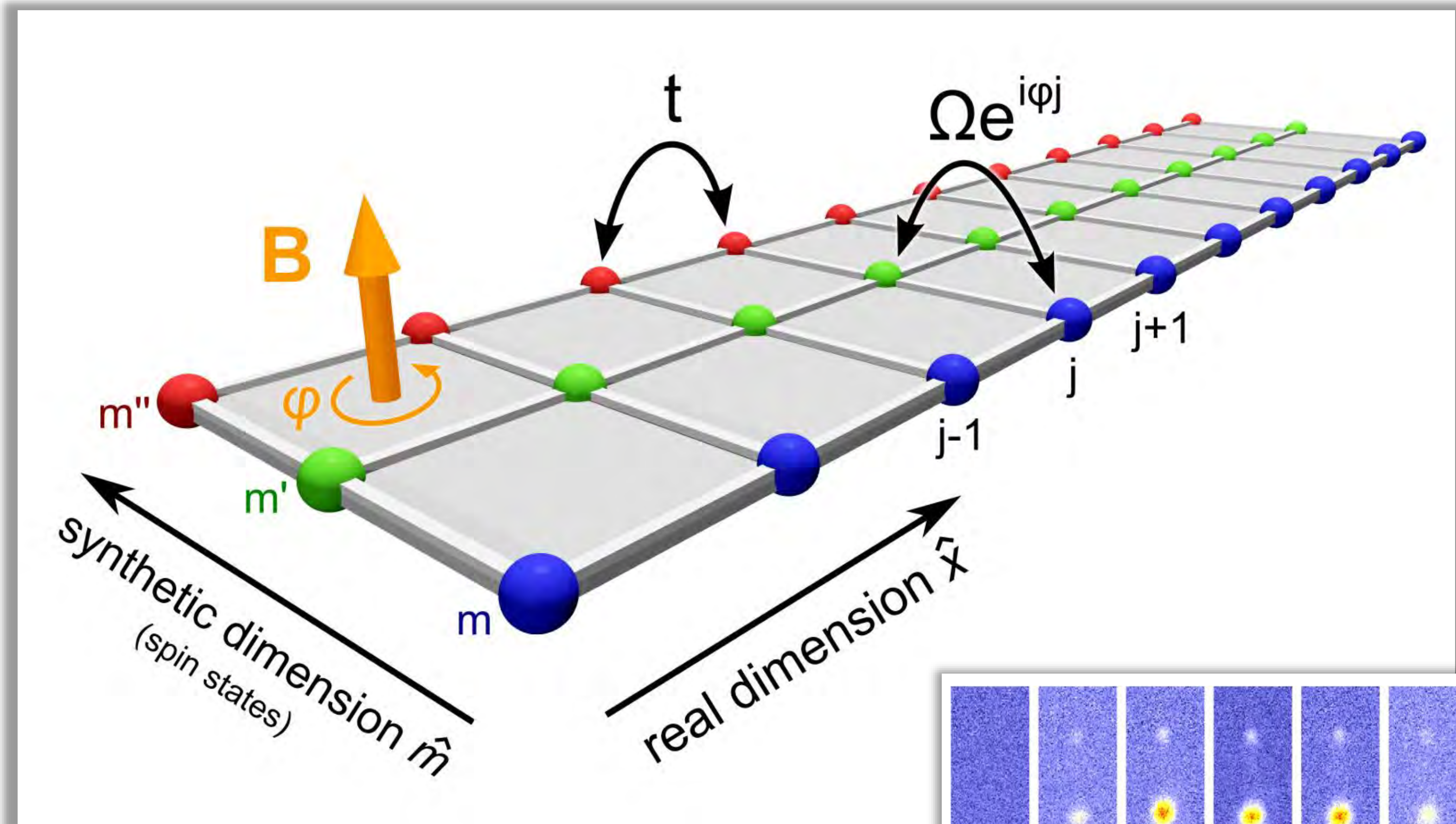
flux per synthetic plaquette $\varphi = \Delta k \cdot a = 0.37\,\pi$

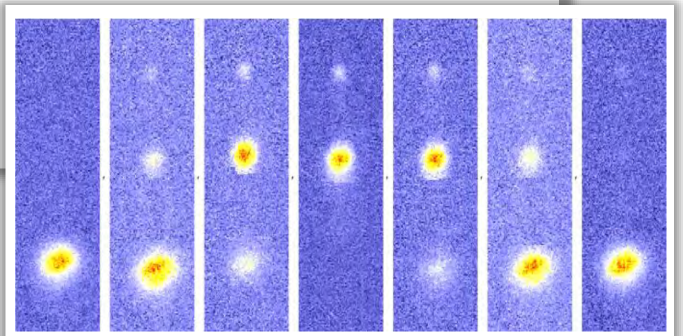
An atomic Hall ribbon

Feature #2

Sharp and addressable edges

Single-site imaging along synthetic dimension





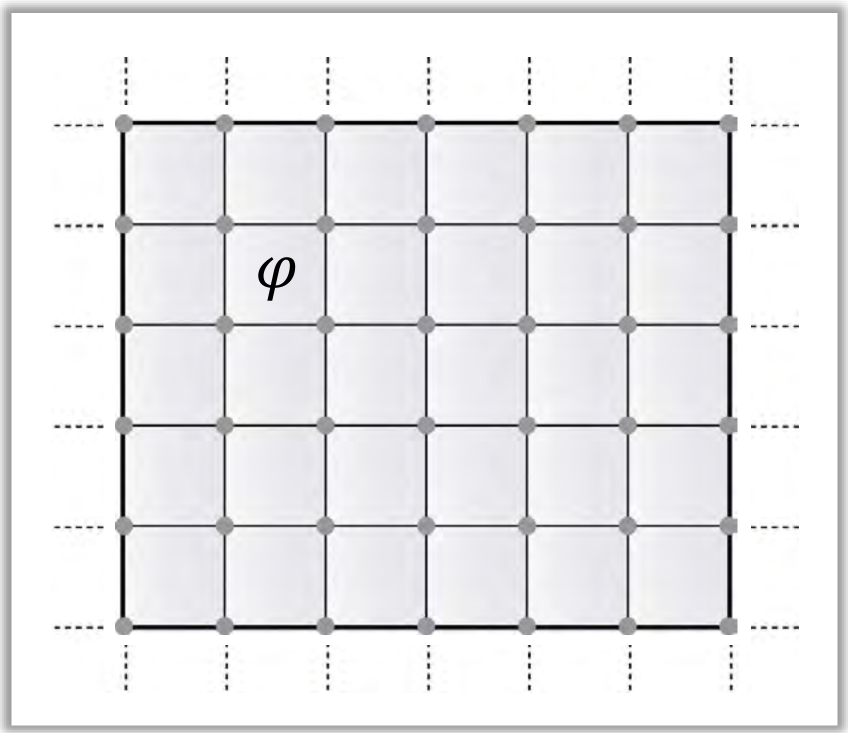
optical Stern-Gerlach
Spin-selective imaging

Bulk and edge states

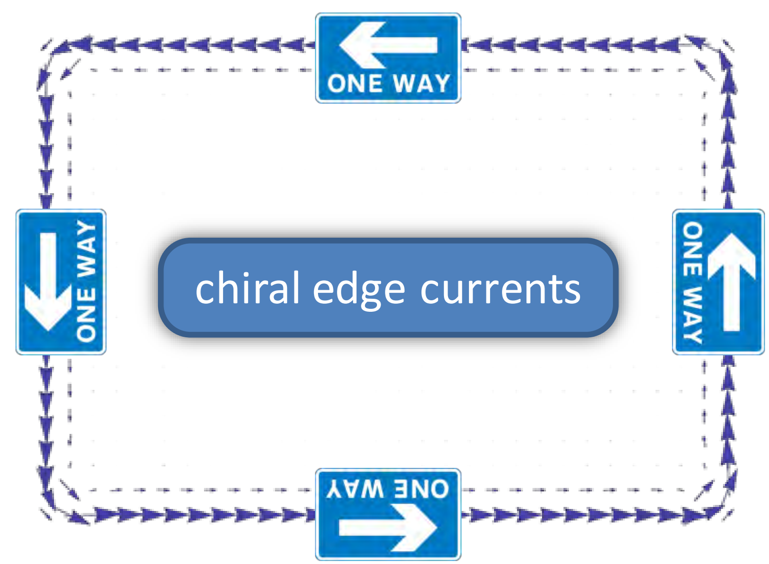
Harper-Hofstadter model: a charged particle in a square lattice + magnetic field

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

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



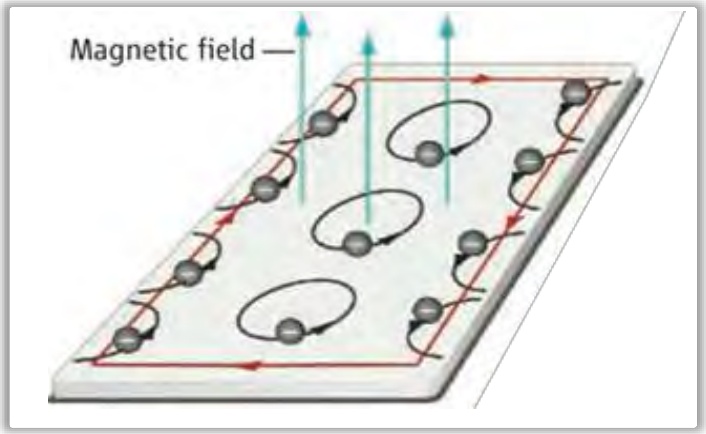
Edge states



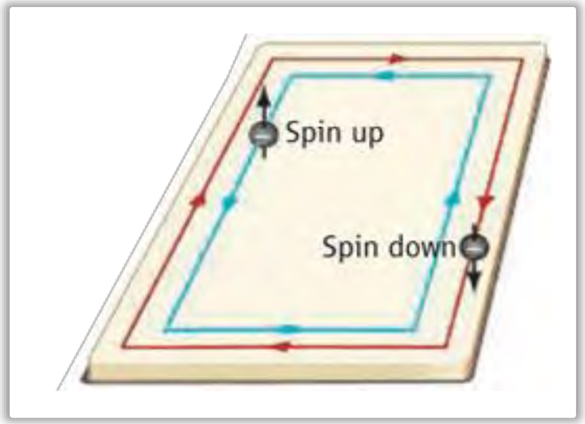
Edge states

Edge states are a hallmark of topological states of matter

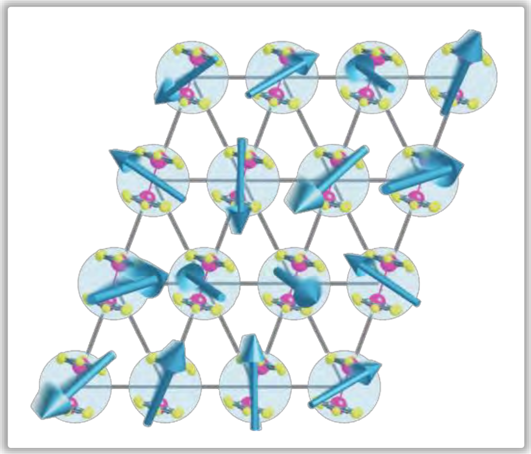
Quantum Hall effect



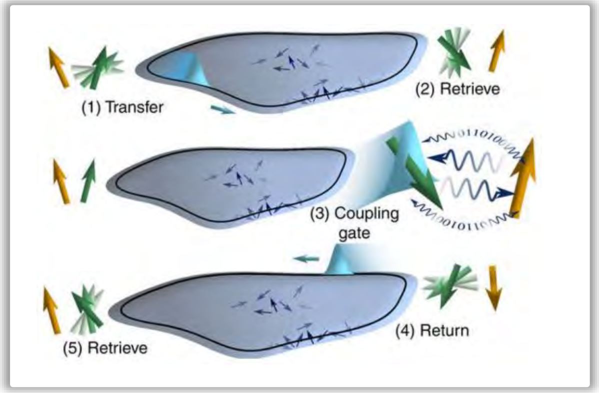
Topological insulators



Chiral spin liquids



Quantum technology

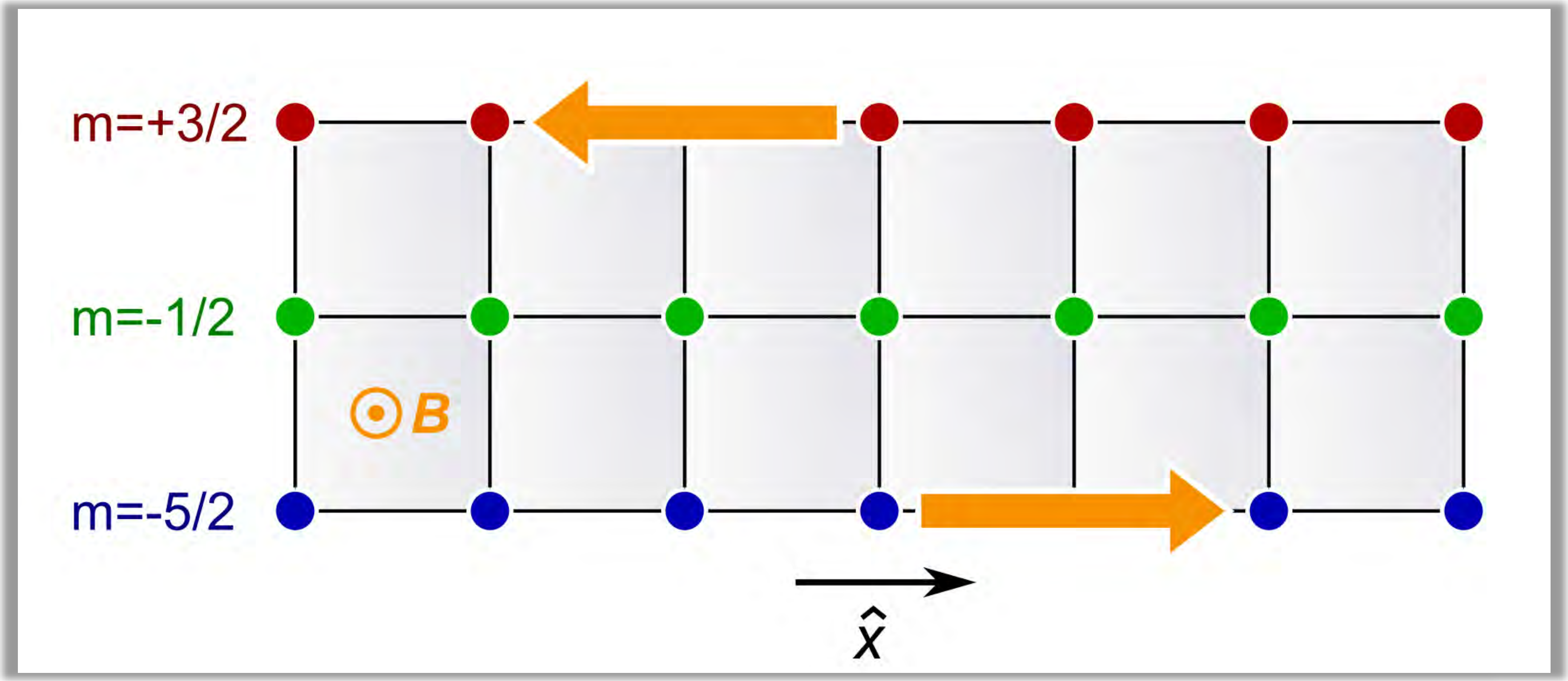


N. Y. Yao, Nat. Comm. 4, 1585 (2013)

3 - leg fermionic ladder

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

Adiabatic loading of a 3-leg ladder



Lattice filling: ~0.75 atoms / real site

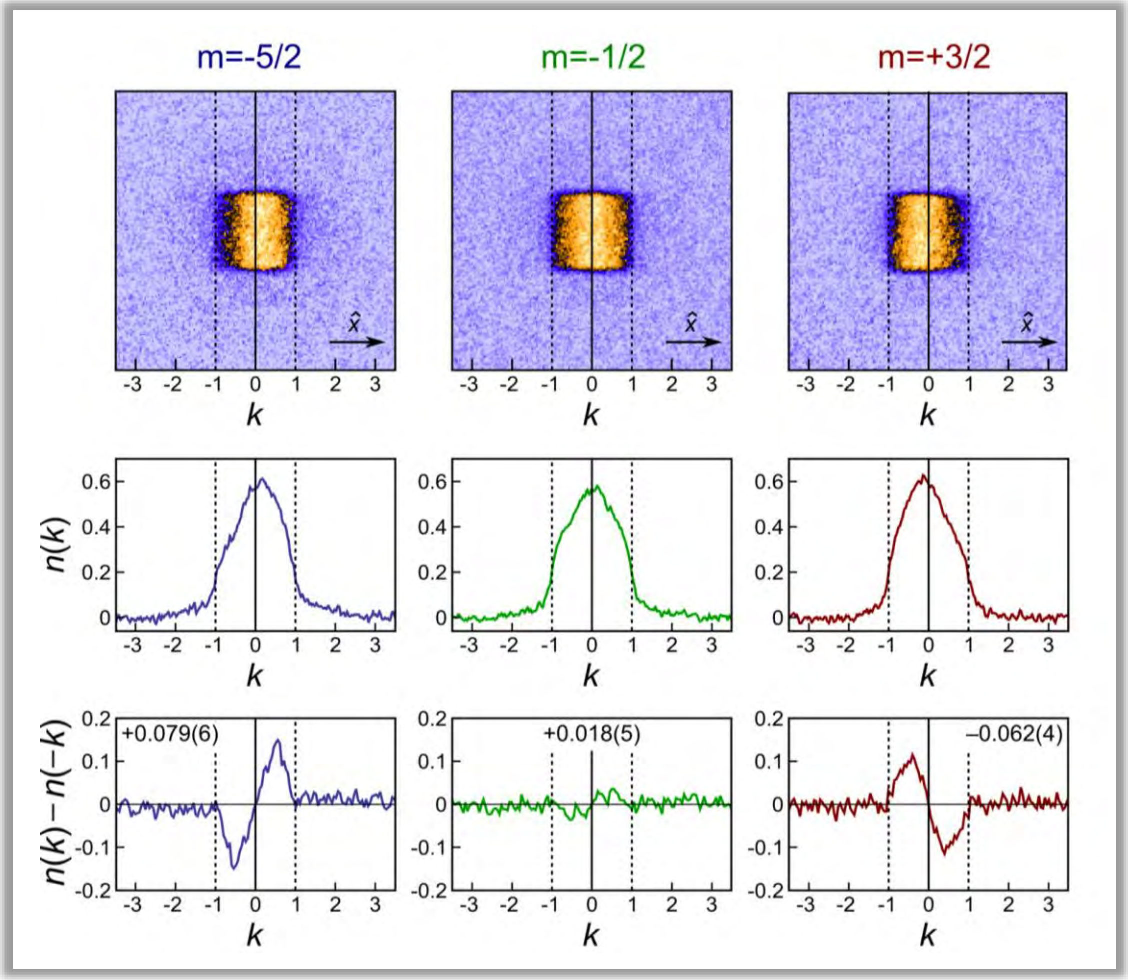
*M. Mancini et al., Science **349**, 1510 (2015)*

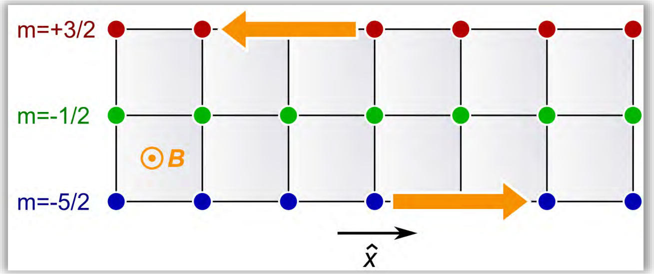
3 - leg fermionic ladder

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

Adiabatic loading of a 3-leg ladder

Lattice momentum distribution:



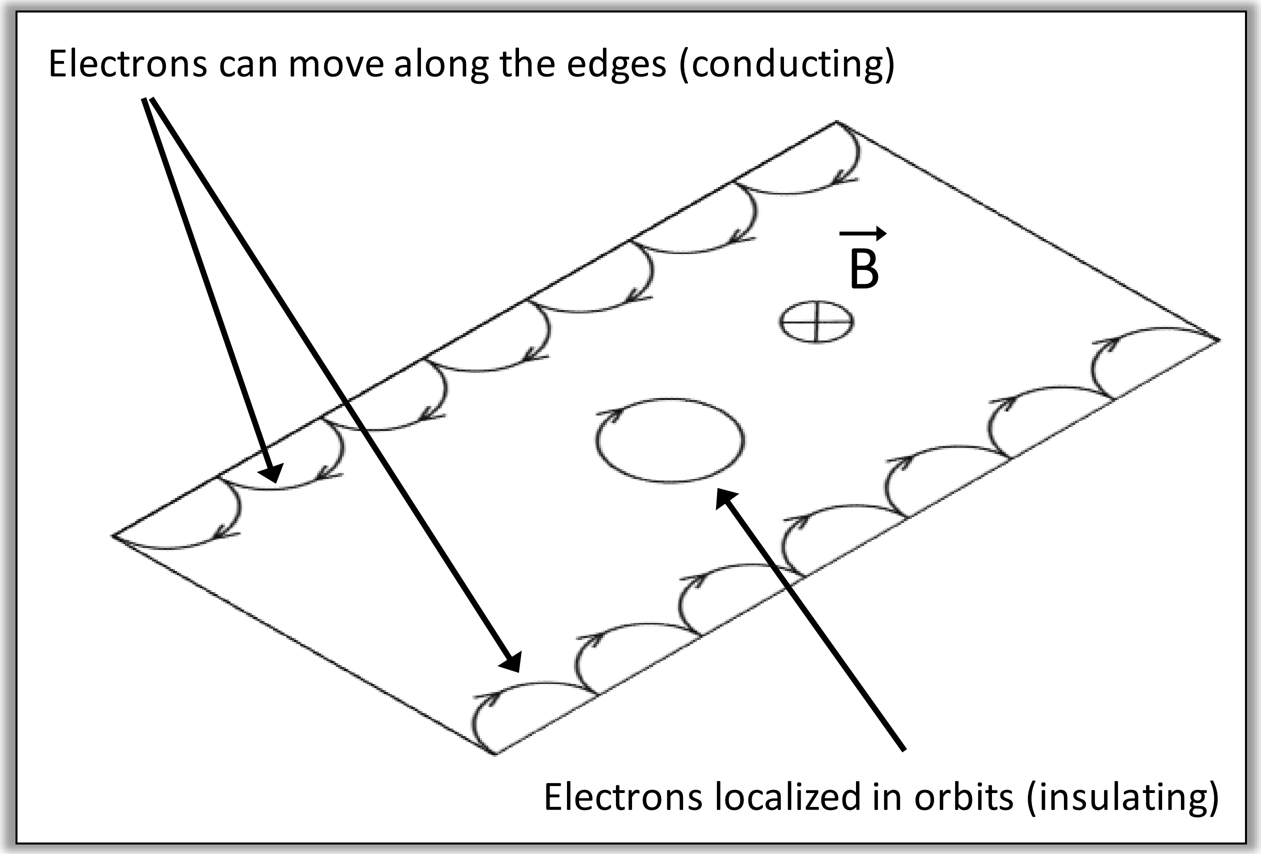


Observation of chiral edge currents and "insulating" bulk

Edge cyclotron orbits

Evolution of a wavepacket prepared on the edge:

30x20 lattice



Edge cyclotron orbits

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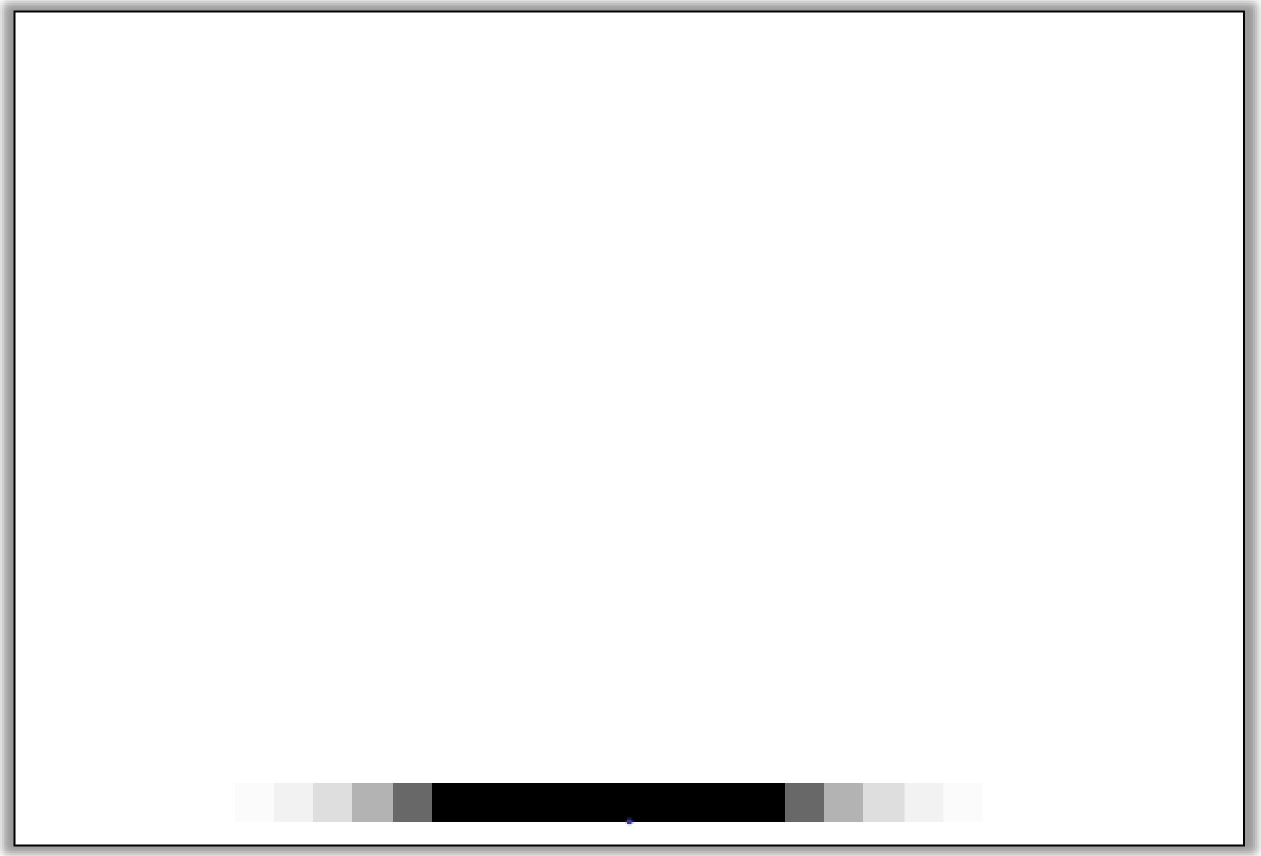


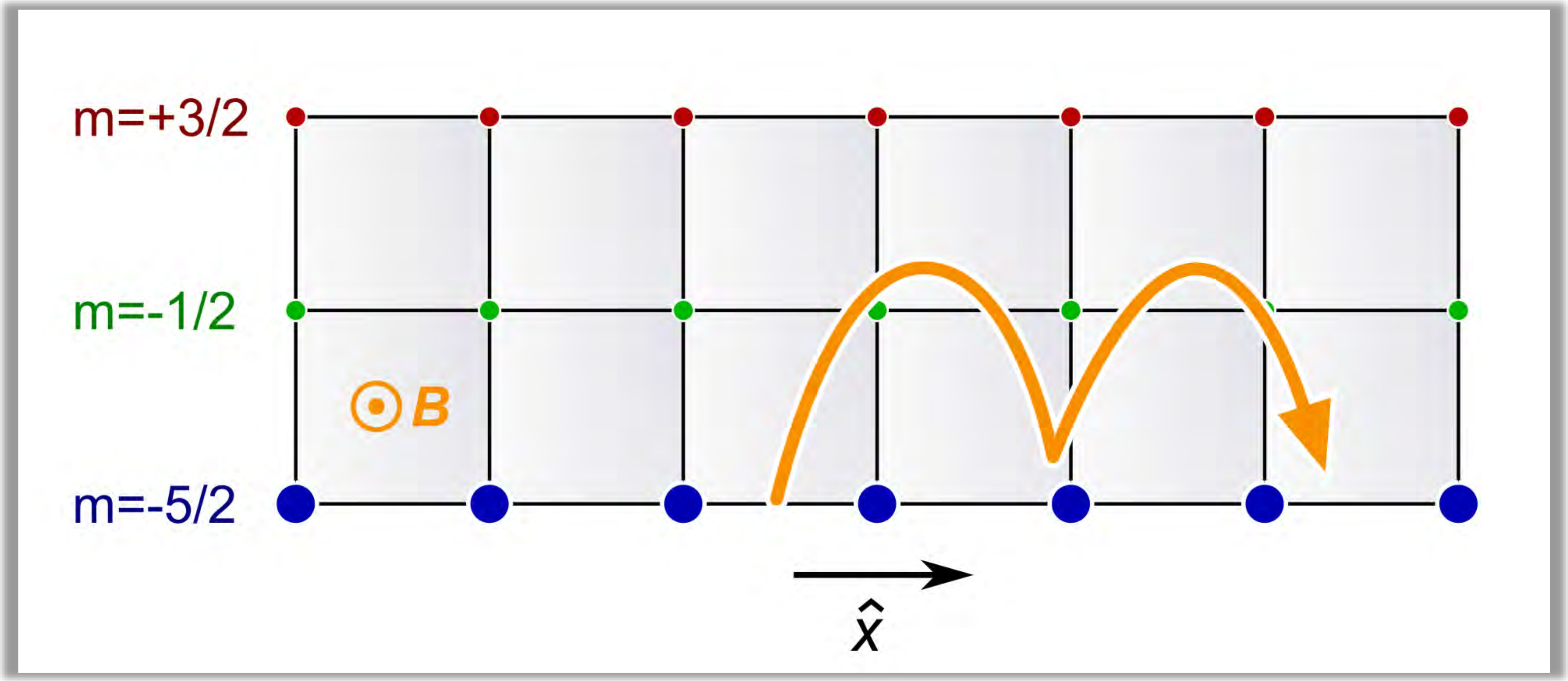
Edge-truncated chiral cyclotron dynamics
"Skipping" orbits

Edge cyclotron orbits

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

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

Quenched dynamics after activation of synthetic tunneling



Edge cyclotron orbits

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

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

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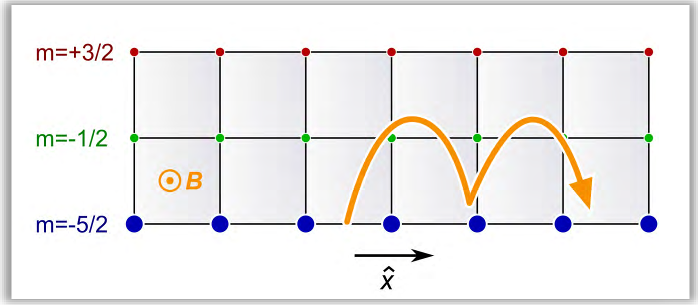
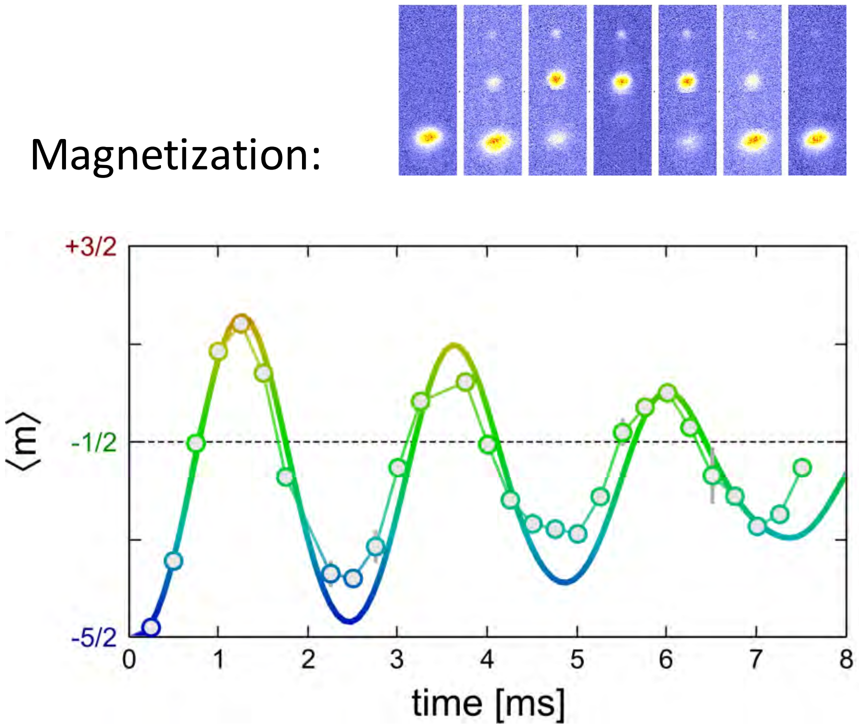
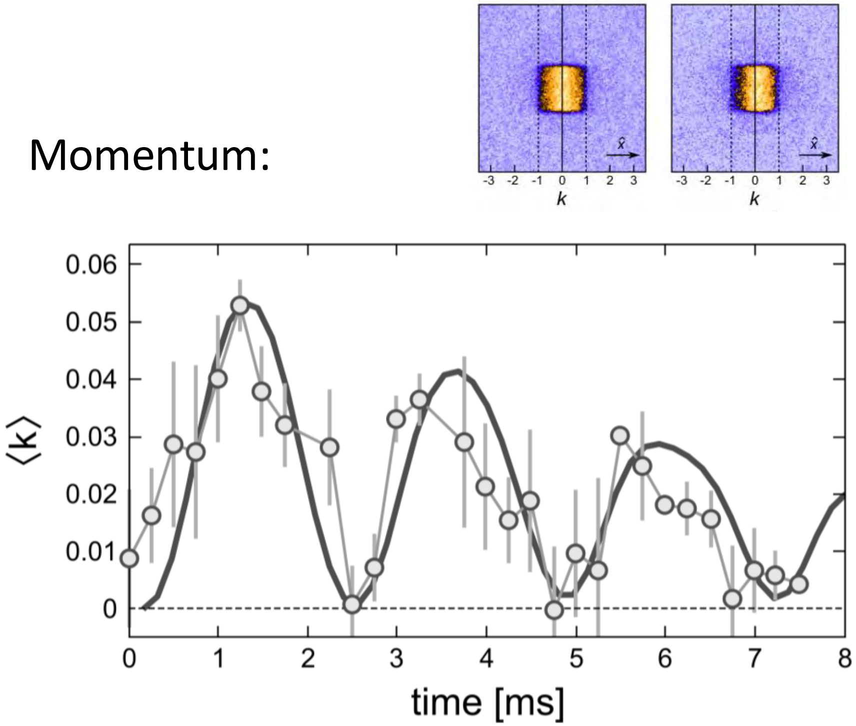


Magnetization:



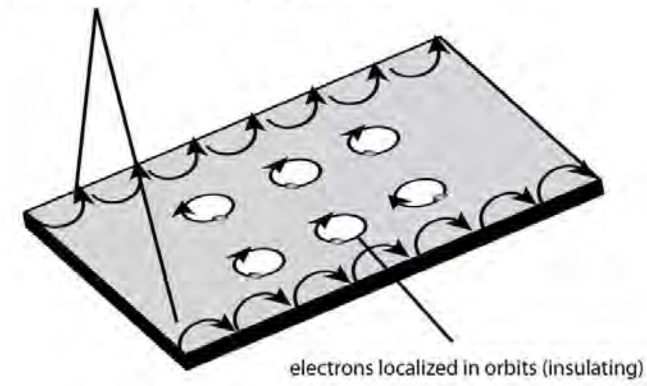
Momentum:



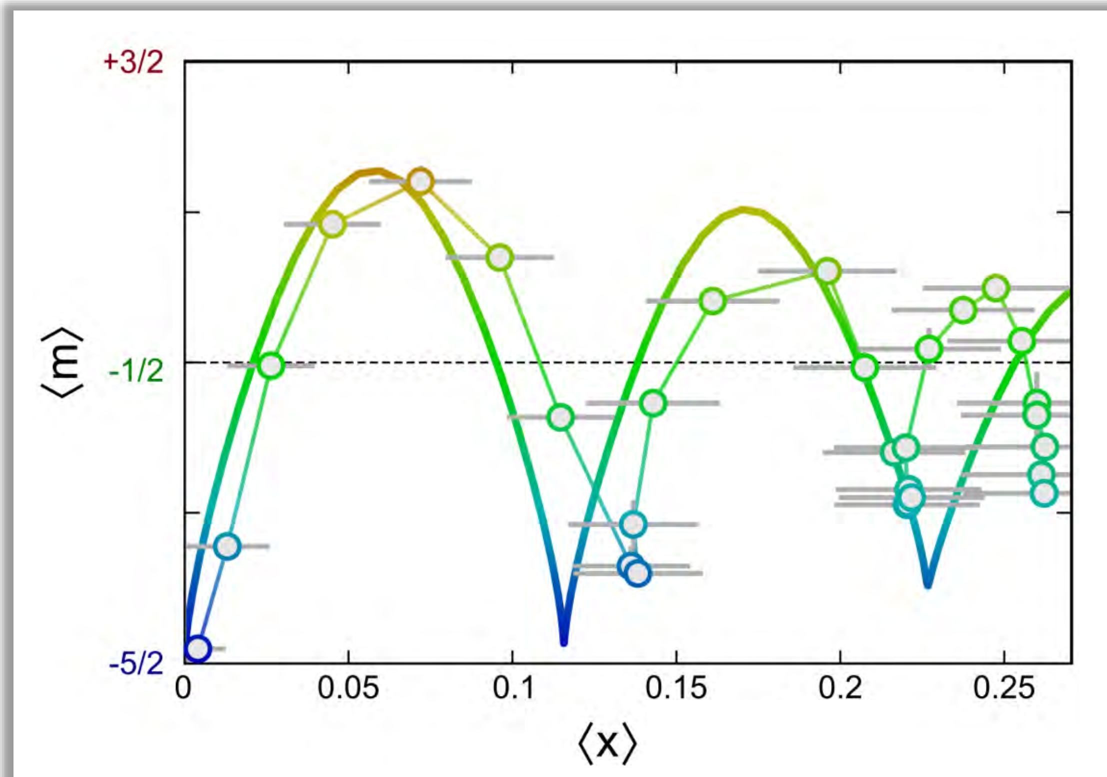
Edge cyclotron orbits

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

A hallmark of quantum Hall physics:



Visualization of edge-cyclotron orbits



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

Related work at JQI/NIST:
B. K. Stuhl et al., Science **349**, 1514 (2015)

Outline

Introduction

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Tuning interactions via an Orbital resonance

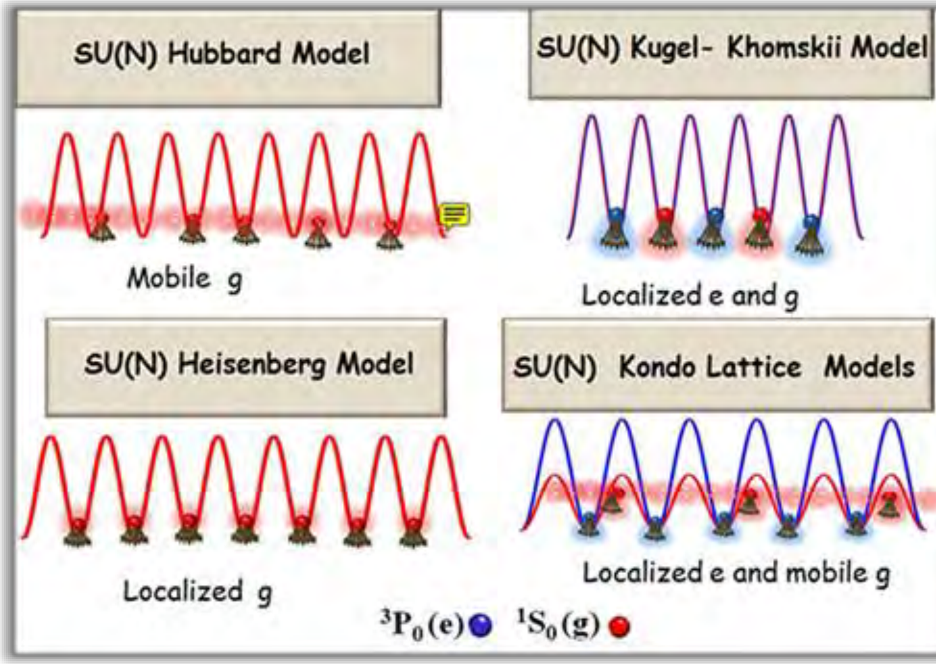
Chiral edge states in synthetic dimensions

Outlook and summary

Outlook

- SU(N) symmetry + orbital manipulation + lattices:

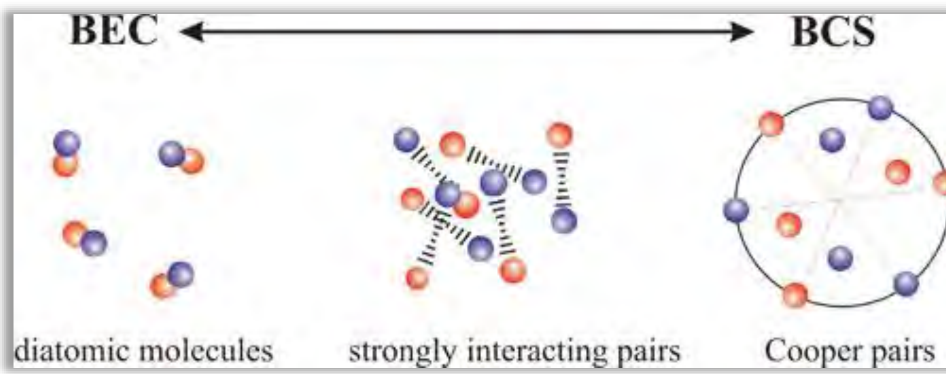
unique platform for exploring fundamental multi-band magnetic models



From A.M. Rey group

- Interorbital interaction tunability:

explore the BEC/BCS crossover in fermions with orbital degree of freedom



Outlook

Synthetic dimensions: a brand new concept for atomic physics experiments

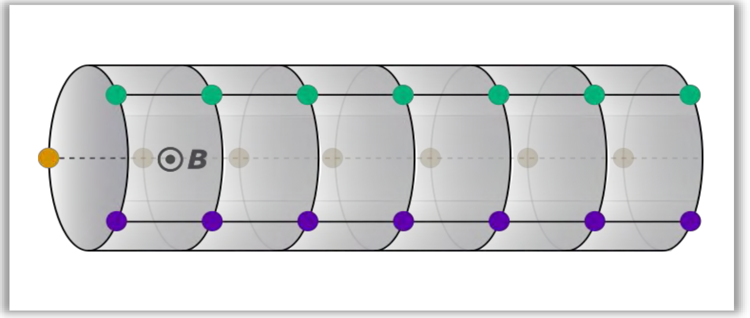
- Interactions + gauge fields

New states, fractional helical liquids

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

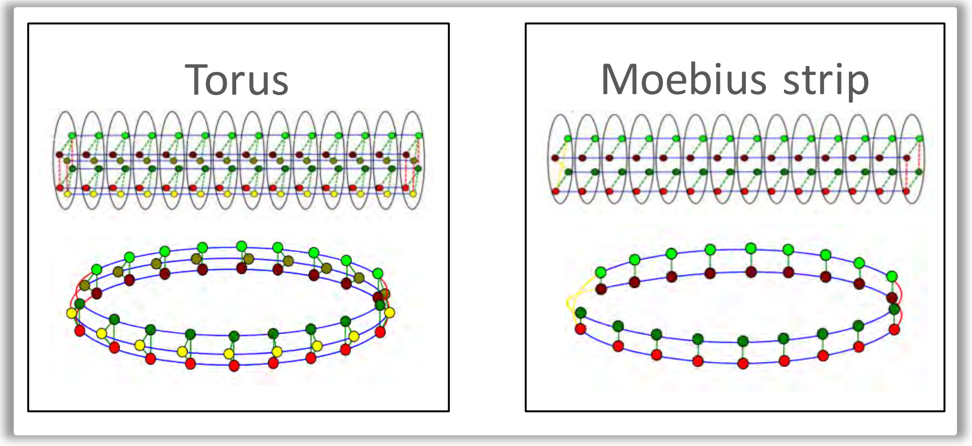
- Engineering topology

Open and periodic boundary conditions



Rings, cylinders, tori, Moebius strips…

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

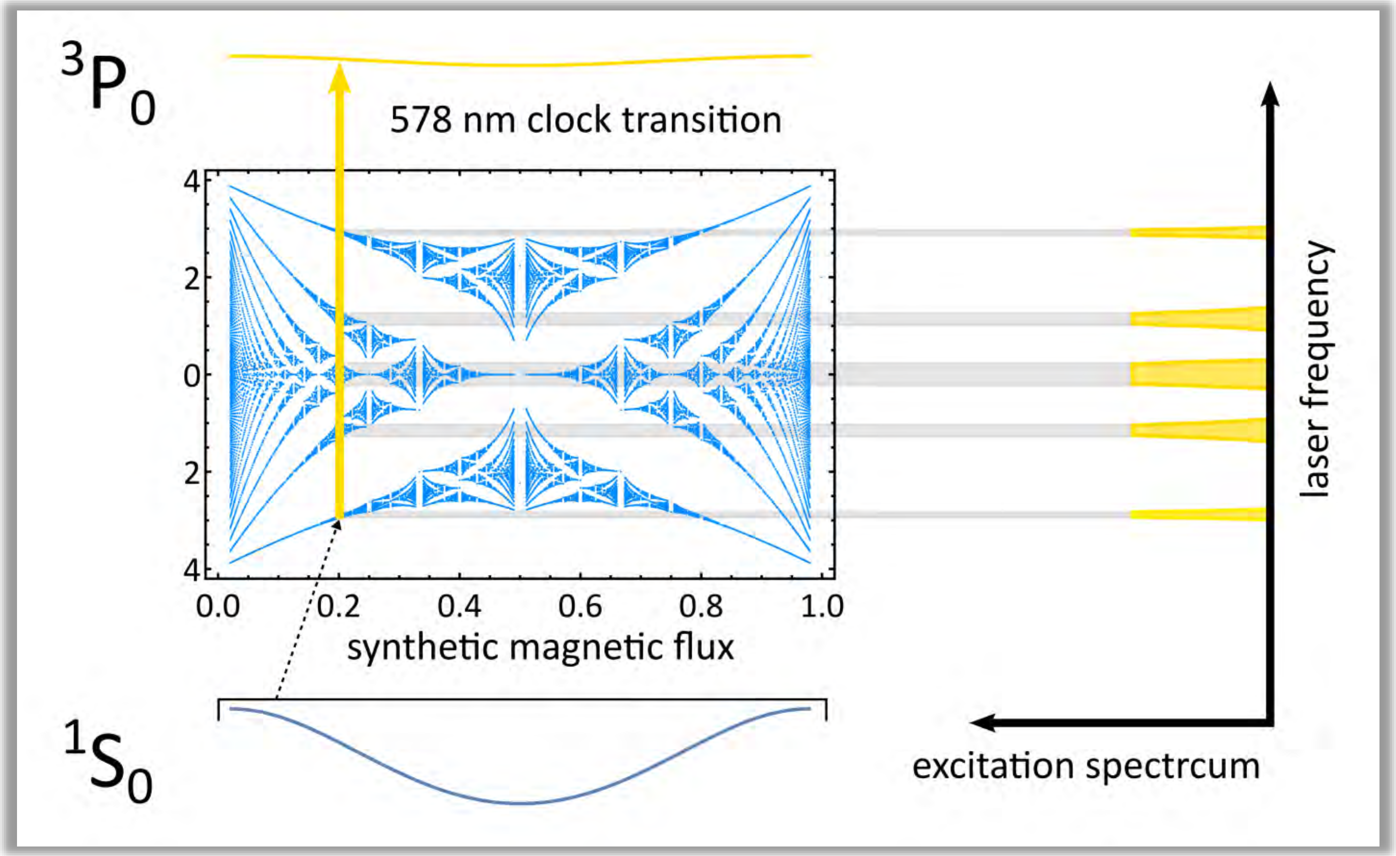


Outlook

- State-dependant lattices + clock laser + synthetic PBC

↓

Bulk physics: Hofstadter butterfly



Credits

Lorenzo Livi
G. C.
Jacopo Catani
Massimo Inguscio
Leonardo Fallani

Marco Mancini
Guido Pagano
Carlo Sias

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

Theory collaboration with Innsbruck:
M. Rider, M. Dalmonte, P. Zoller

Funding from ERC (CoG 2016), EU, MIUR, INFN

Summary

Coherent Interorbital Spin-Exchange Dynamics

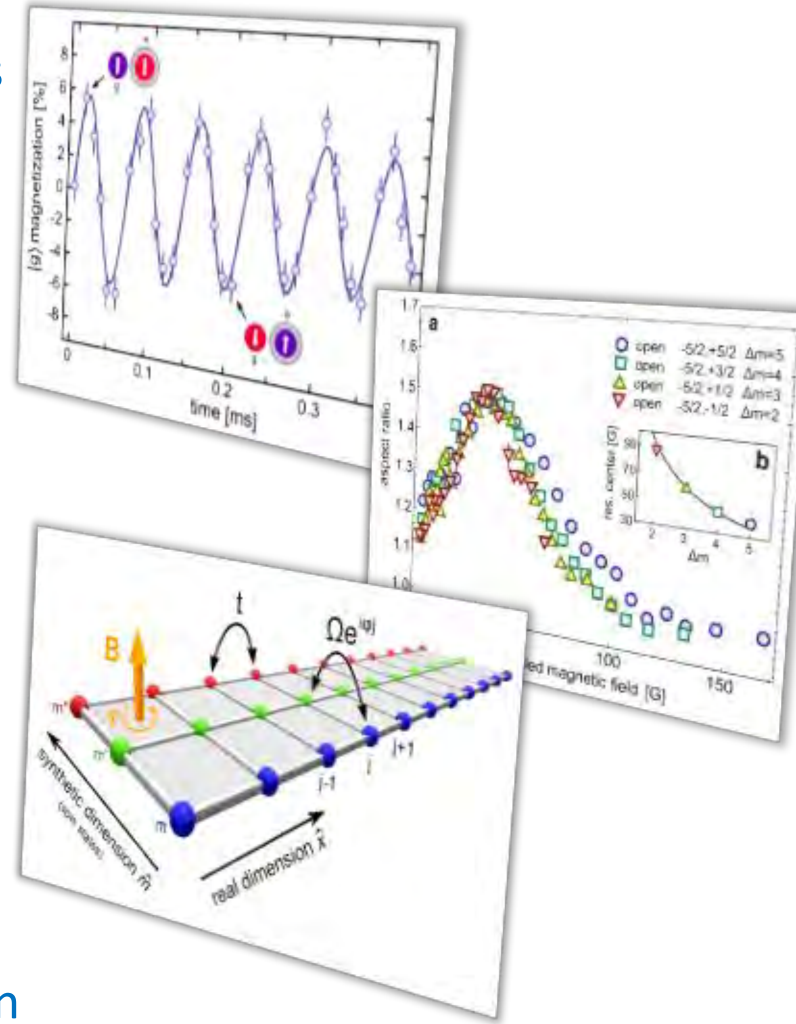
G. Cappellini et al., PRL **113**, 120402 (2014)

Orbital Feshbach Resonance

G. Pagano et al., PRL **115**, 265301 (2015)

Fermions in synthetic dimensions

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



Optical fiber absolute frequency dissemination

C. Clivati et al., Opt. Express **24**, 11865 (2016)

Strongly interacting 1D SU(N) fermions

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