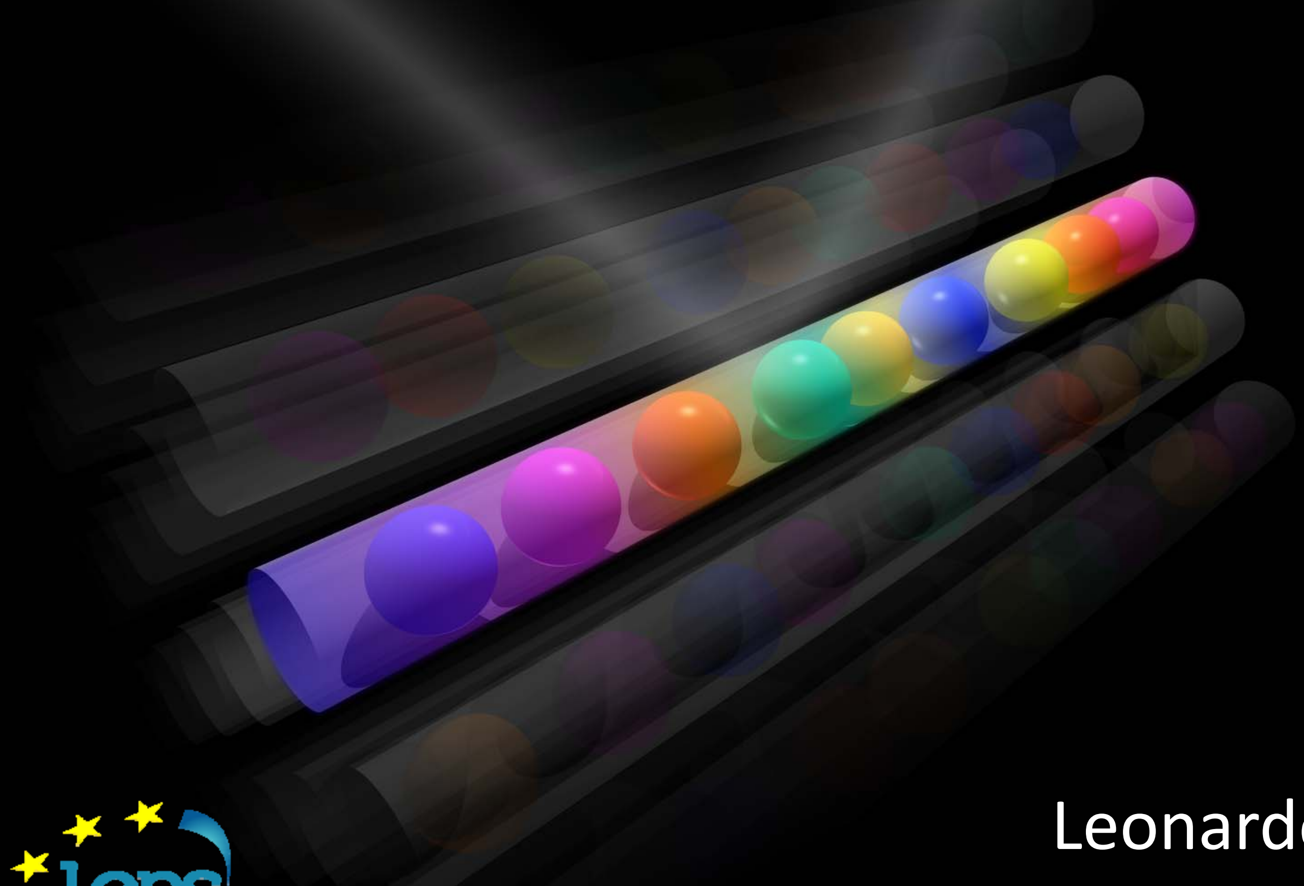
Quantum simulation with SU(N) fermions: orbital magnetism and synthetic dimensions

Frontiers in Quantum Simulation with Cold Atoms, Seattle, April 1st 2015



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University of Florence

Introduction

Multicolored SU(N) liquids of fermions

Two-orbital magnetism

Synthetic dimensions

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Multicolored SU(N) liquids of fermions

Two-orbital magnetism

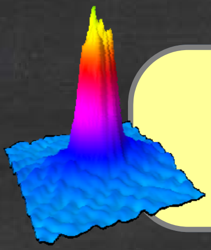
Synthetic dimensions

Two-electron atoms

A valuable atomic platform for quantum science and technology

Precision spectroscopy

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



Quantum gases

Y. Takasu et al., PRL (2003)
T. Fukuhara et al., PRL (2007)
S. Kraft et al., PRL (2009)
S. Stellmer et al., PRL (2009)
Y. N. Martinez et al., PRL (2009)

Ultracold two-electron atoms
(Yb, Sr, Ca)

New quantum simulation

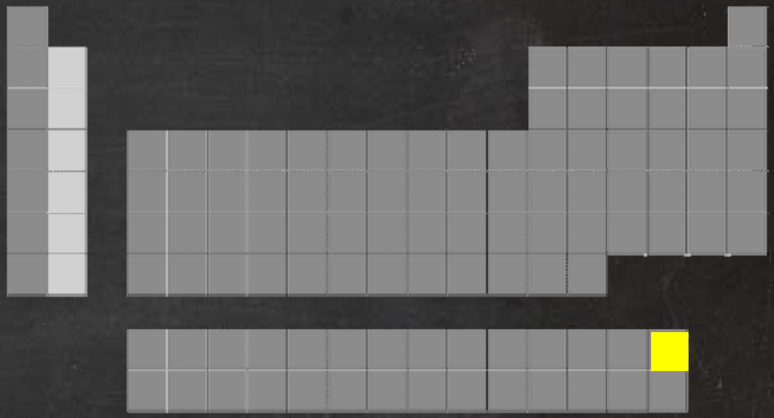
M. Cazalilla et al., NJP (2009)
A. Gorshkov et al., Nat. Phys. (2010)
D. Banerjee et al., PRL (2013)

Quantum information

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

Ytterbium

Ytterbium



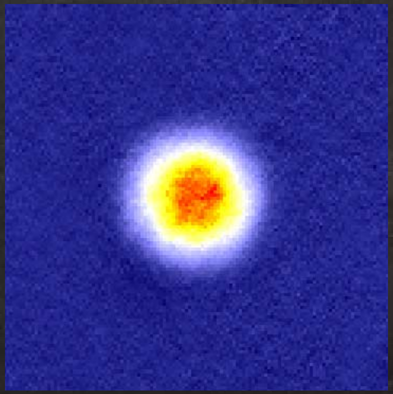
Electronic configuration [...]$6s^2$

Alkaline-earth-like structure

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

^{173}Yb Fermi gas



$T \sim 0.1\, T_F = 10$ nK

$N = 10^4$ atoms/spin

Nuclear spin

Purely nuclear spin I=5/2

No dipole-dipole interactions ⟶ 2-body contact interactions

$$V(\mathbf{r}) \simeq g\,\delta(\mathbf{r})$$

Same interaction between different spins ⟶ SU(6) symmetry

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

$a = +200\,a_0$

Long-lived electronic states

Metastable electronic state (~10 s lifetime)

Ultranarrow clock transition (doubly forbidden, ~10 s linewidth)

New possibilities for quantum simulation

Two internal degrees of freedom with long coherence times:

Nuclear spin / SU(N)

Electronic orbital

Introduction

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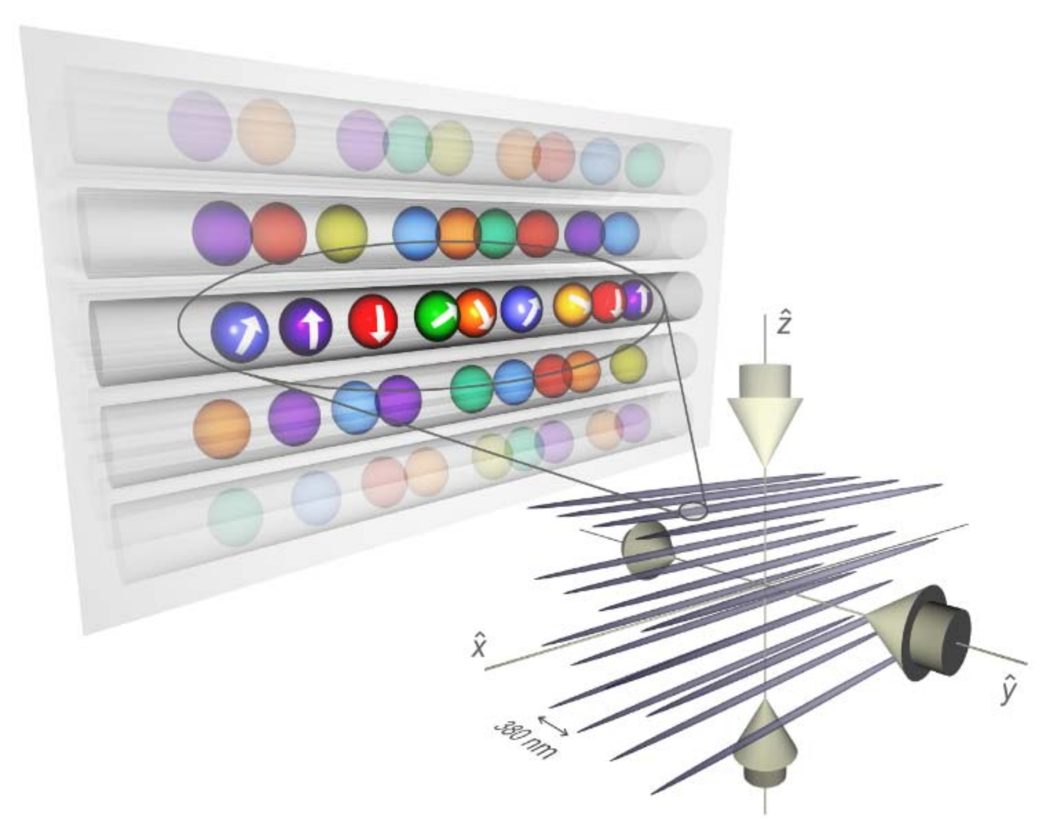
Synthetic dimensions

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

Strongly-interacting SU(N) fermions



Independent 1D quantum wires of strongly repulsive fermions

2D optical lattice

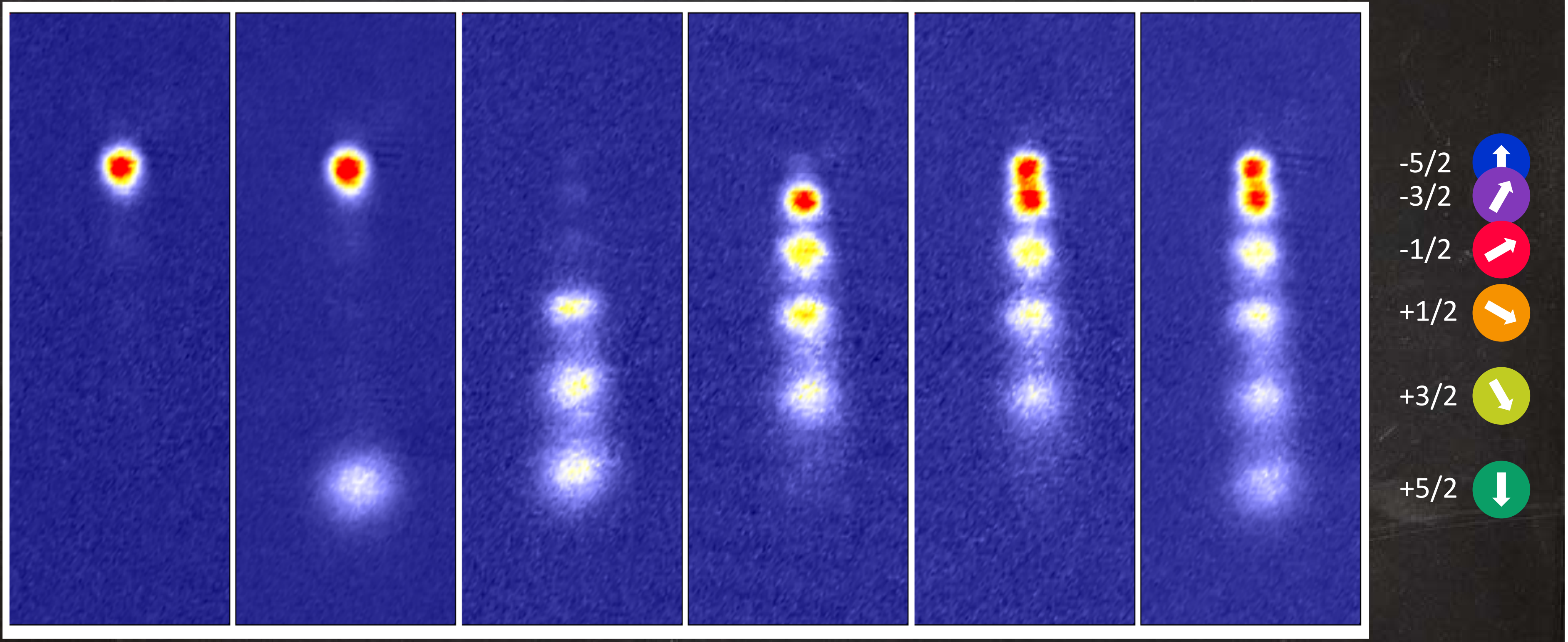
- approx. 100 fermionic wires
- lattice depth 40 E_{rec} (no tunnelling)
- 3D scattering length $a = +200\ a_0$

How does the physics of strongly interacting fermions change as a function of N?

Nuclear spin manipulation

Optical pumping + spin-selective detection (optical Stern-Gerlach)

SU(N) symmetry → no spin-changing collisions



1 spin

2 spins SU(2)

3 spins SU(3)

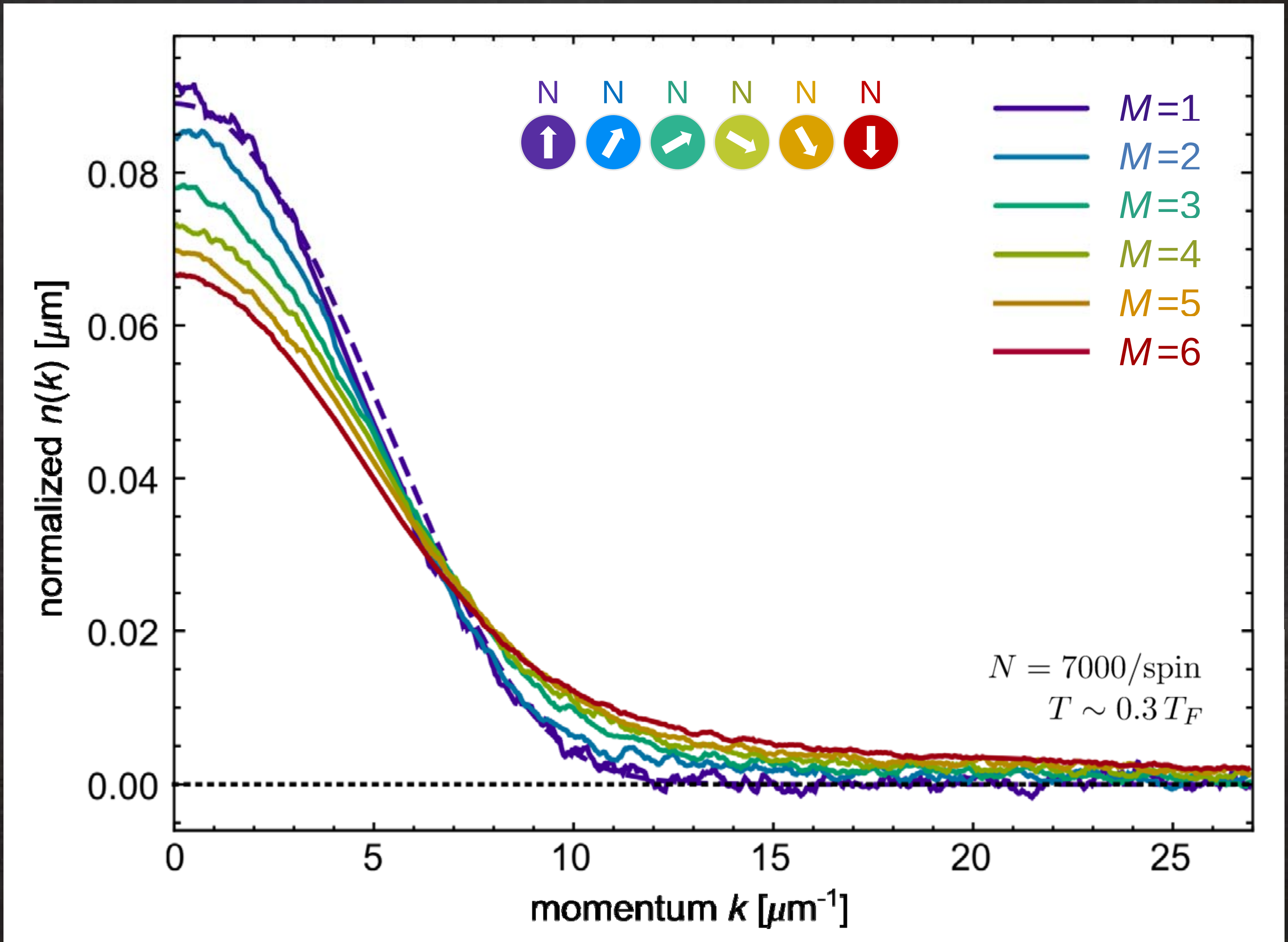
4 spins SU(4)

5 spins SU(5)

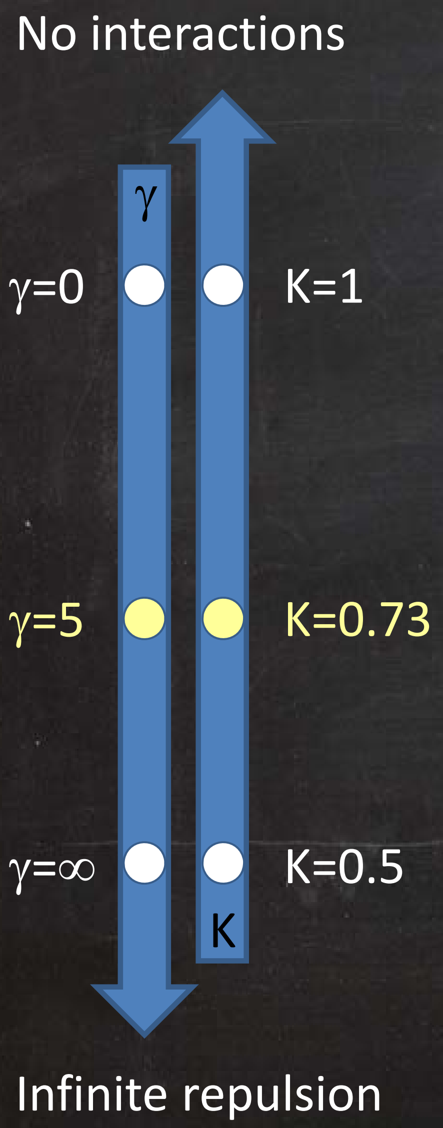
6 spins SU(6)

Momentum distribution

Momentum distribution measured after time-of-flight expansion:



Correlations in 1D spinful fermions



No interactions

γ

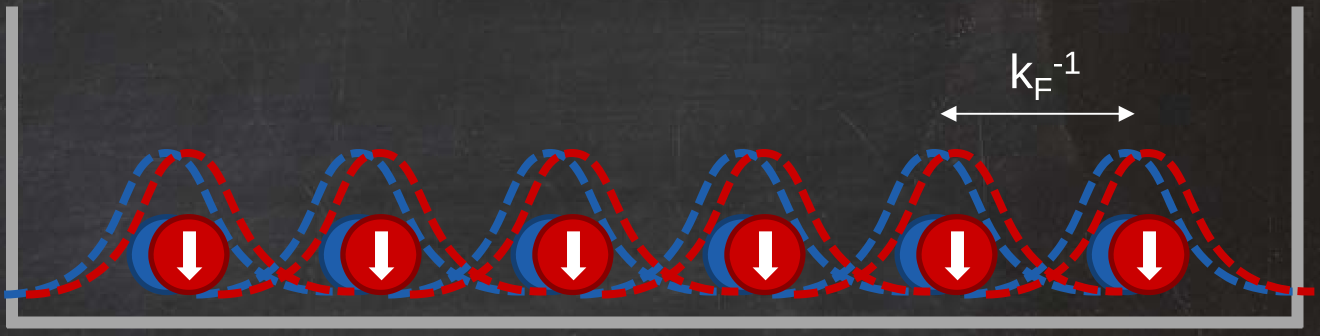
$\gamma=0$ K=1

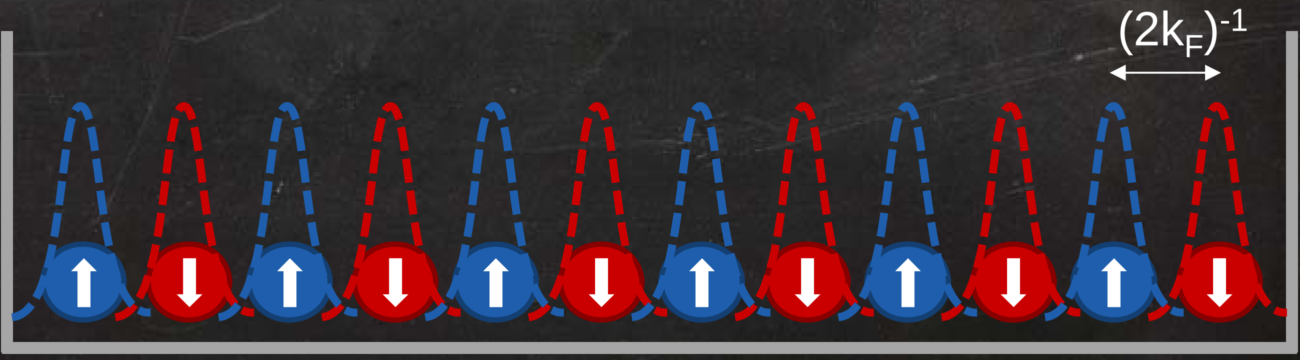
$\gamma=5$ K=0.73 ← **Our experiment – strongly correlated regime**

$\gamma=\infty$ K=0.5

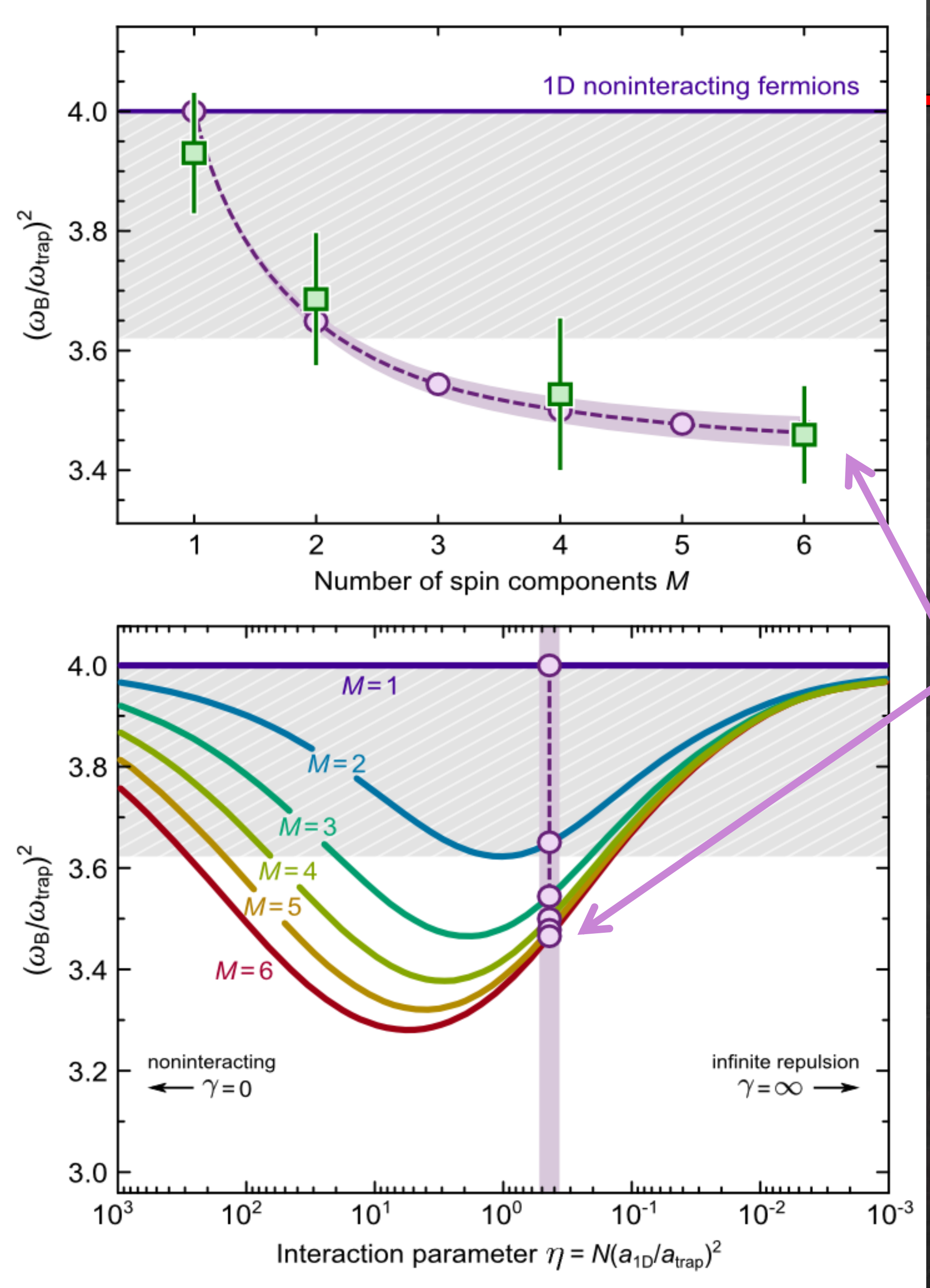
K

Infinite repulsion





Collective dynamics



Redshift of the breathing frequency caused by strong 1D interactions

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

«bosonization» of large-spin fermions

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

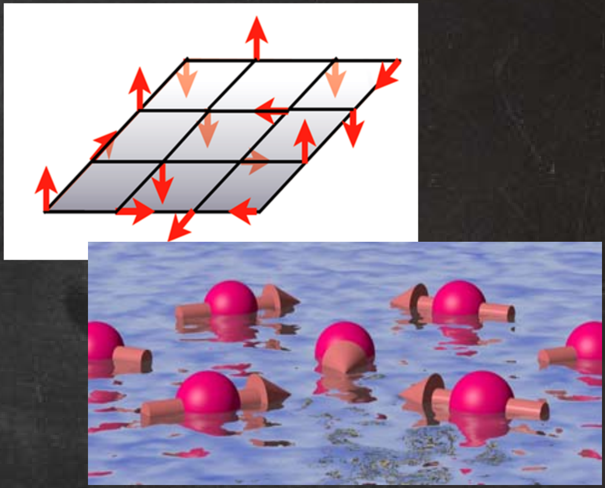
A very general result first demonstrated in

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

Outlook: SU(N) physics

A new experimental atomic system, with tunable interaction symmetry

SU(N) Fermi-Hubbard

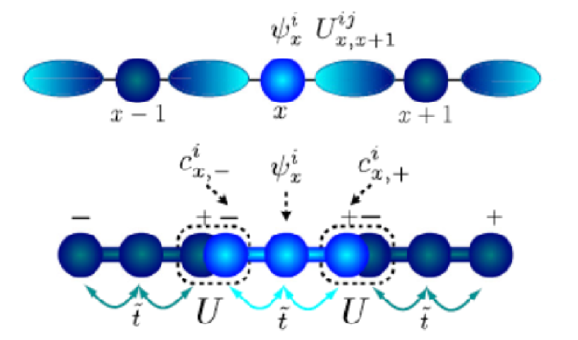


SU(N) magnetism, chiral spin liquids, …

M. Hermele et al., PRL **103**, 135301 (2009)
A. V. Gorshkov et al., Nature Phys. **6**, 289 (2010)
G. Szirmai et al., PRA **84**, 011611 (2011)
P. Sinkovicz et al., PRA **88**, 043619 (2013)

Poster: Conjun Wu

Quantum simulation of gauge theories



U(N), SU(N), CP(N) models

D. Banerjee et al., PRL **100**, 125303 (2013)

Posters: Debasish Banerjee, Marcello Dalmonte

Introduction

Multicolored SU(N) liquids of fermions

Two-orbital magnetism

Synthetic dimensions

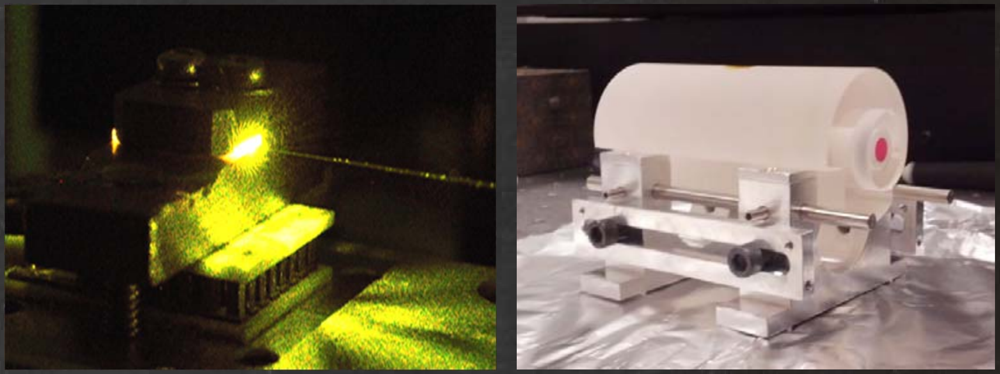
G. Cappellini et al., PRL **113**, 120402 (2014)

Multi-orbital physics

Optical clock transition

Optical clock technology:

Collaboration with
Yb clock team @ INRIM (Turin)



e

$^3P_0$

5/2 3/2 1/2 -1/2 -3/2 -5/2

578nm clock transition (~10 mHz linewidth)

g

$^1S_0$

5/2 3/2 1/2 -1/2 -3/2 -5/2

Optical clock transition

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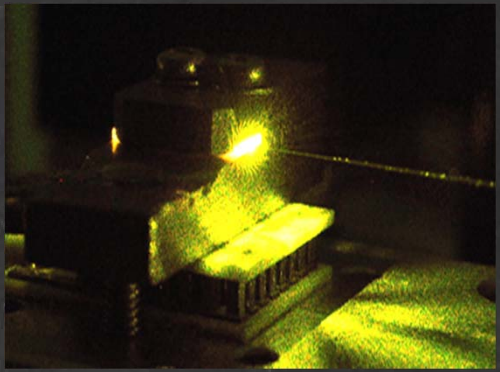
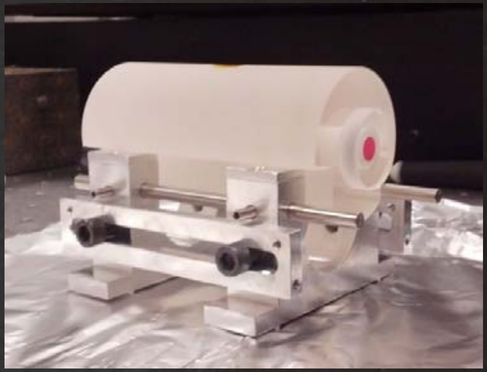
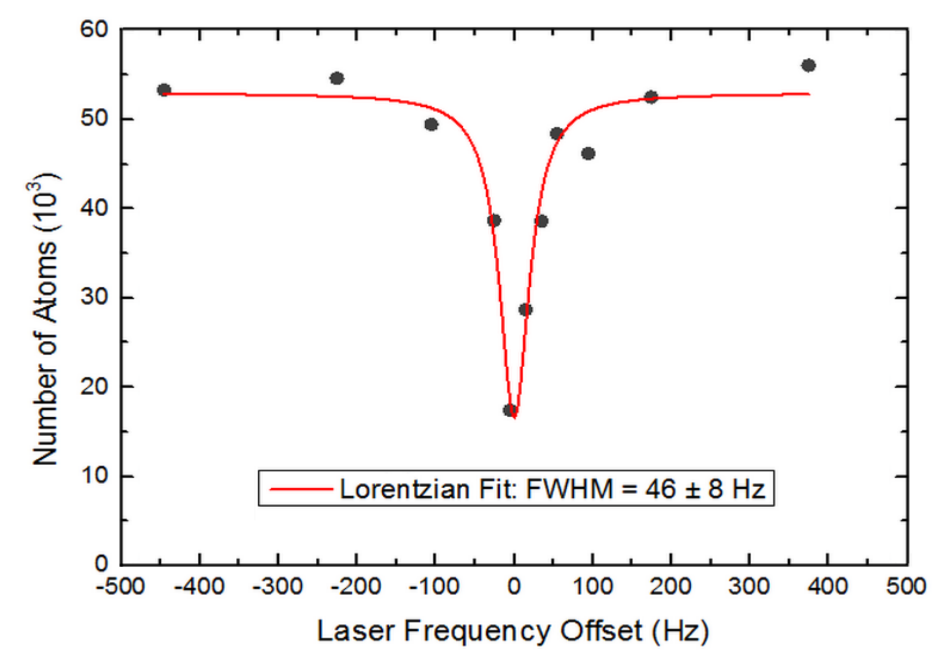
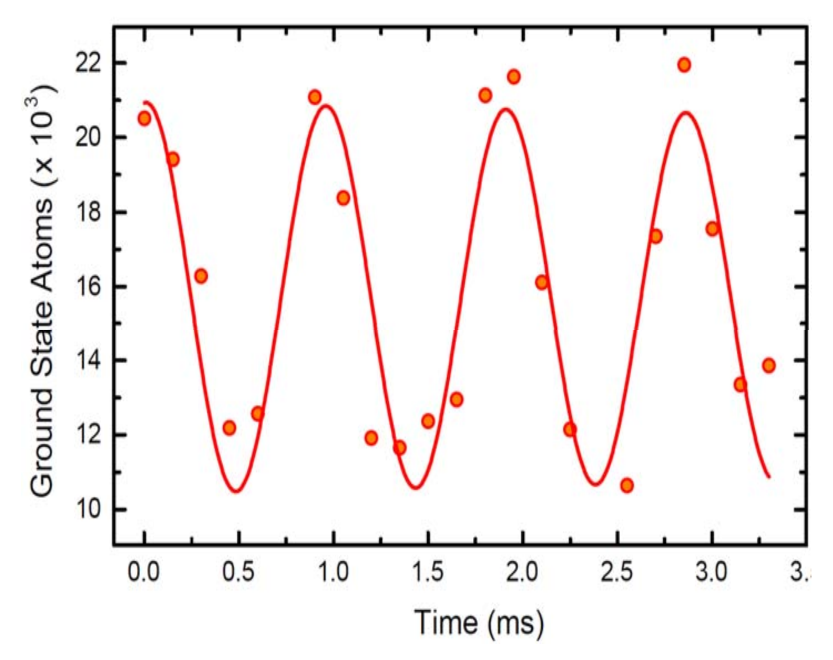




Clock transition (759nm "magic" lattice):

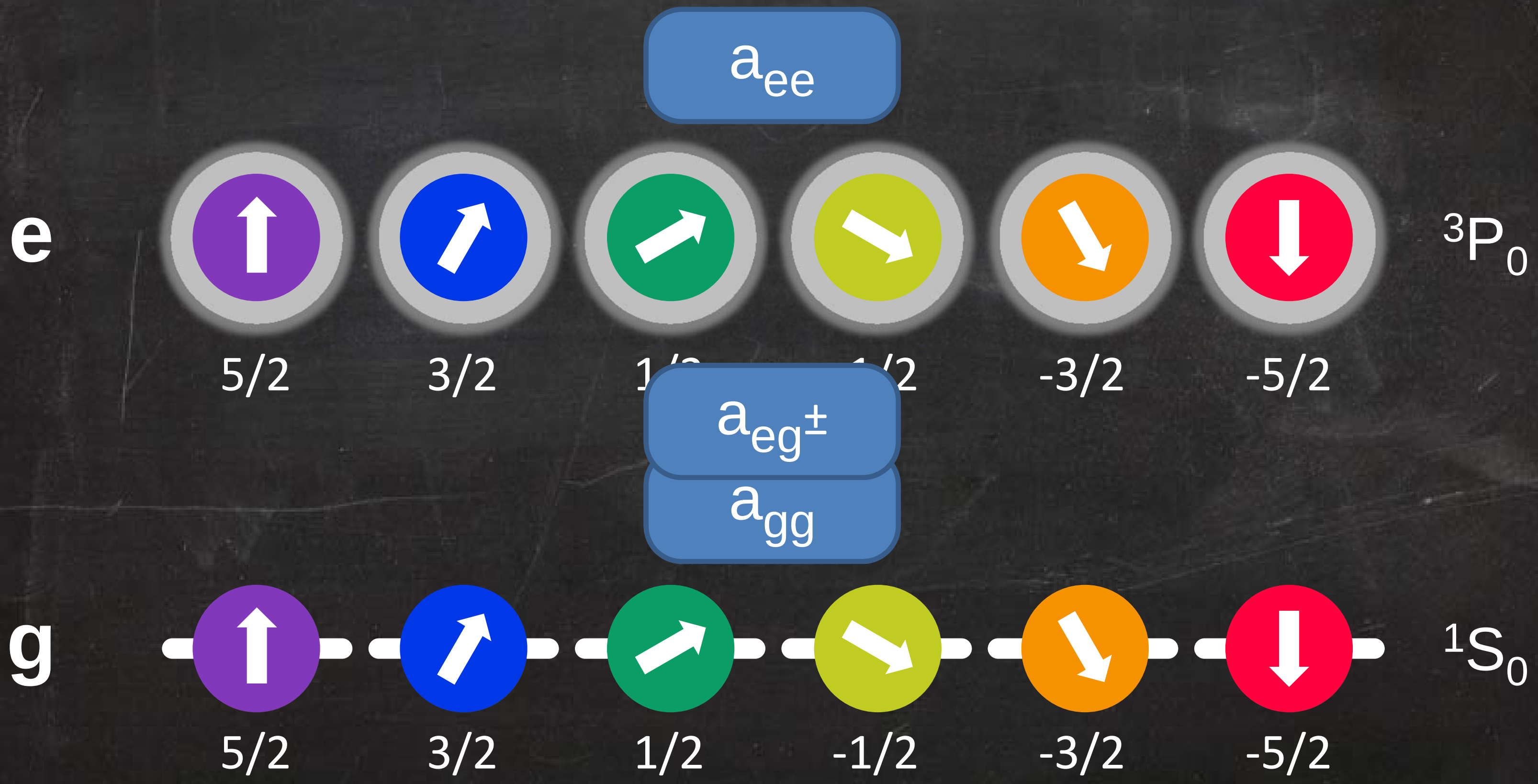


Rabi oscillations:



Multi-orbital physics

The interaction strength depends on the electronic state:



g-e spin-exchange interaction

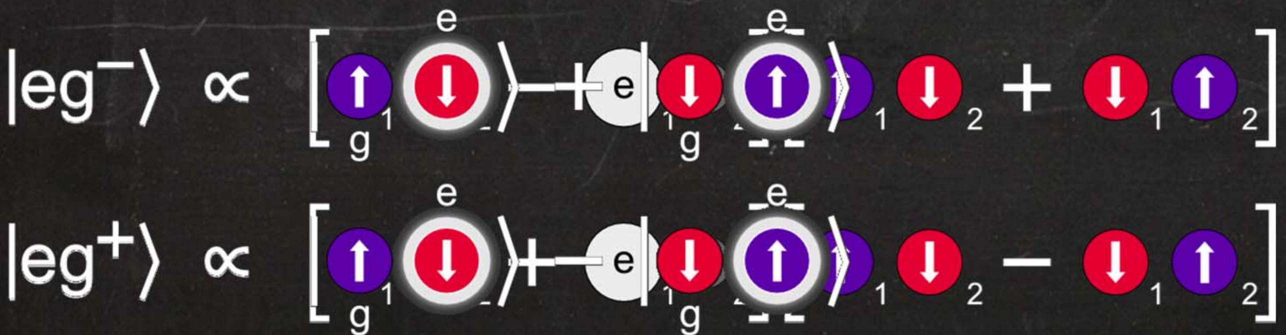
Two fermions (g+e) in a trap

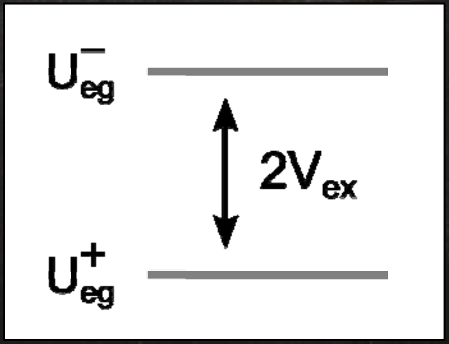
A. V. Gorshkov et al., Nature Phys. **6**, 289 (2010)

A local spin-exchange interaction between different "orbitals" arises:

Antisymmetrization of the two-particle states:

Different scattering lengths for the two states:

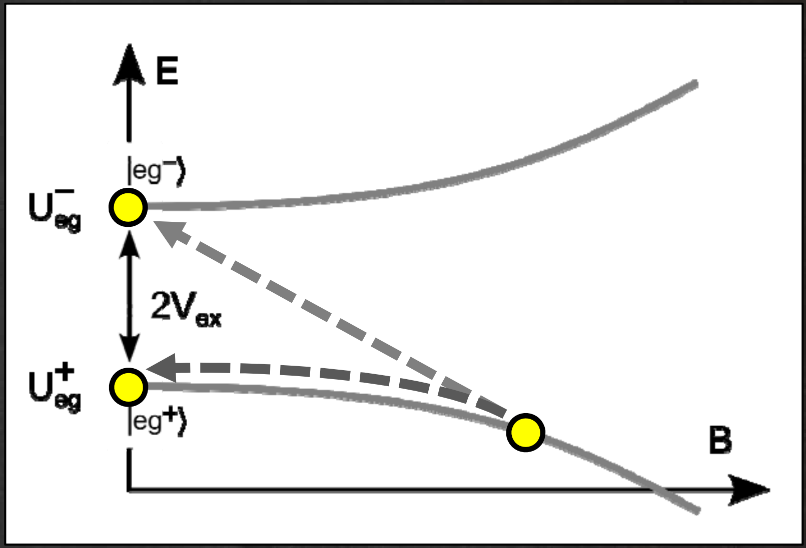




g-e spin-exchange oscillations

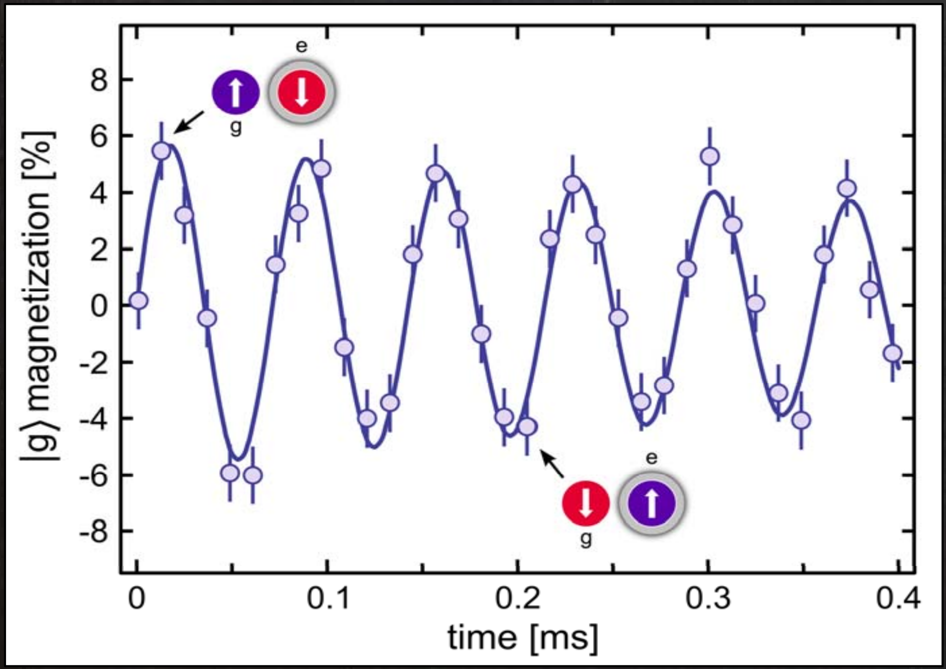
A magnetic field B induces a mixing between the two channels:

$$|\psi\rangle = \alpha|eg^{+}\rangle + \beta|eg^{-}\rangle$$



B field quench + free evolution

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



Ground-state magnetization:

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

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

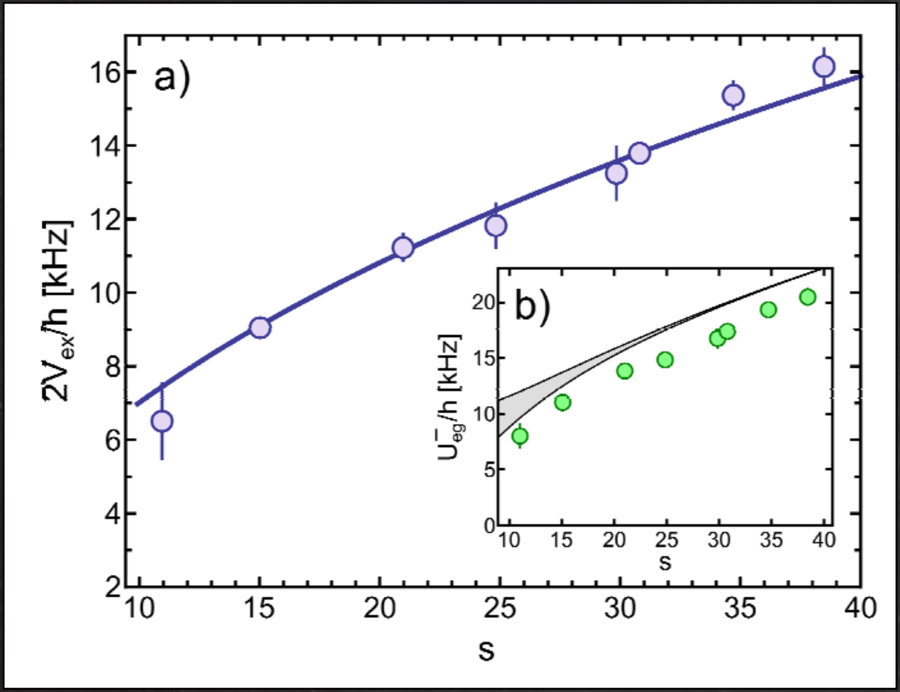
direct observation of long-lived interorbital spin-exchange oscillations

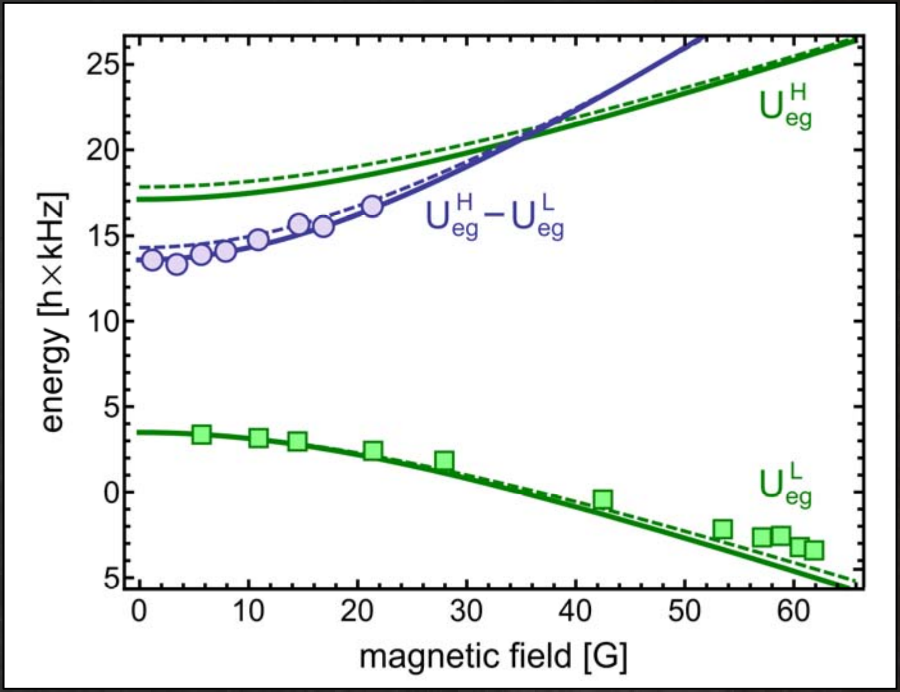
G. Cappellini et al., PRL **113**, 120402 (2014)

g-e spin-exchange interaction

Very large spin-exchange energy!!!

$V_{ex} >> k_B T$





Strong repulsion in the antisymmetric 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)

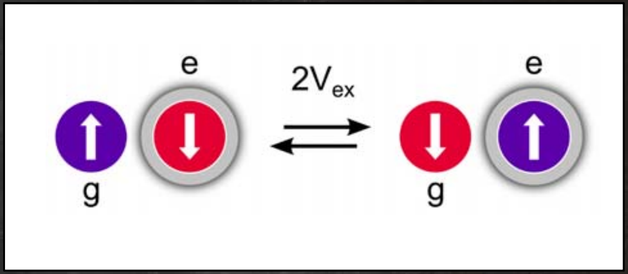
$a_{eg}^{+} = 220\ a_0$

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

Outlook: two-orbital physics

Nuclear spin + electronic orbital: two stable internal degrees of freedom

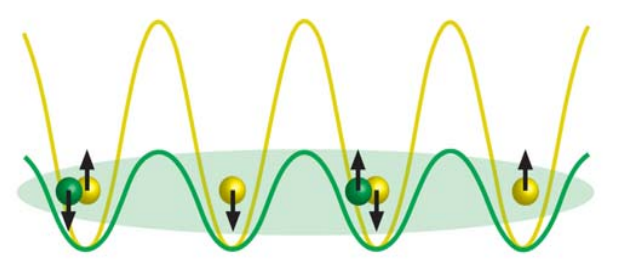
Quantum information processing



Coherent control of nuclear and electronic state

Two entangled internal degrees of freedom

Quantum simulation of two-orbital physics



Strong spin-orbital interaction

SU(N) orbital magnetism, Kondo lattice model

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

Talk: Ana Maria Rey

Ultranarrow transitions: new manipulation/detection

Many-body physics with metrological control

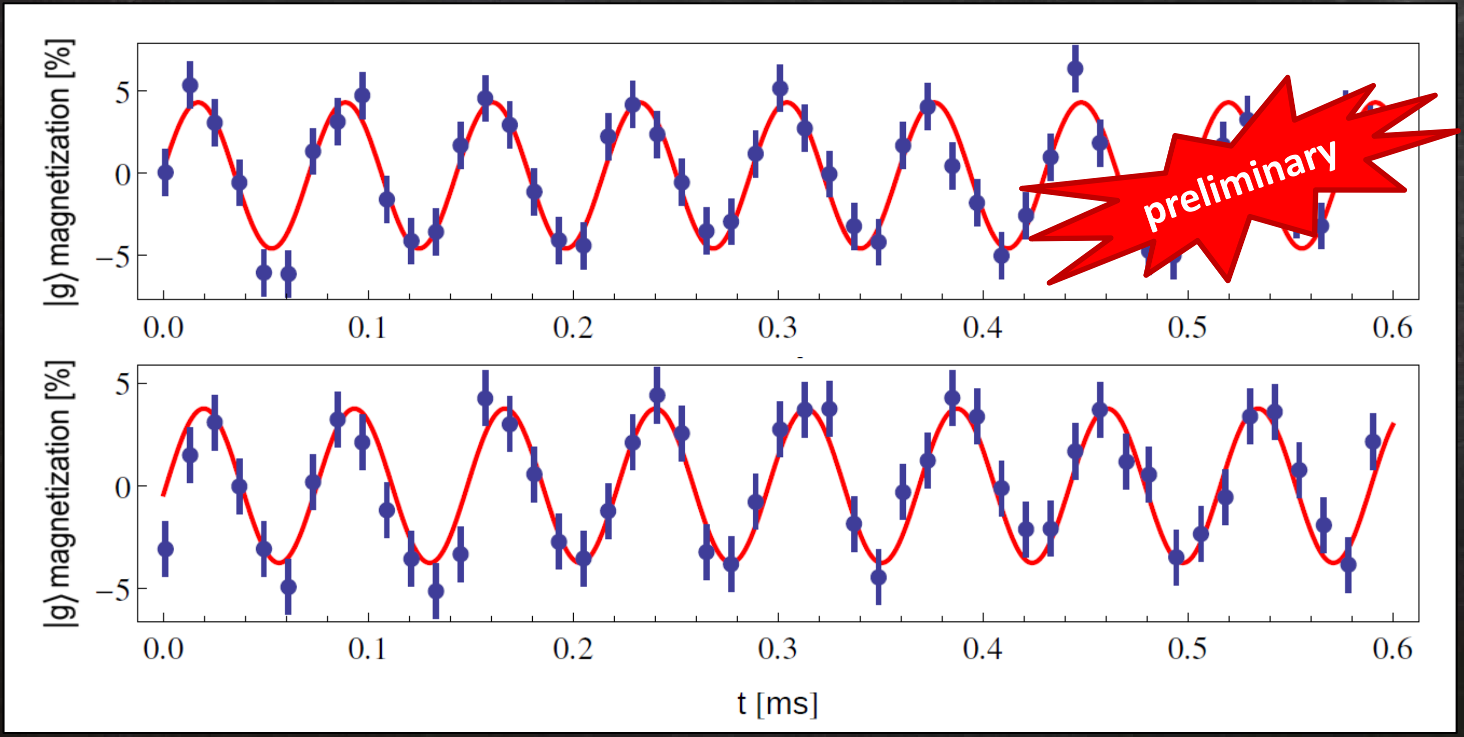
SU(N) symmetry in g-e interaction

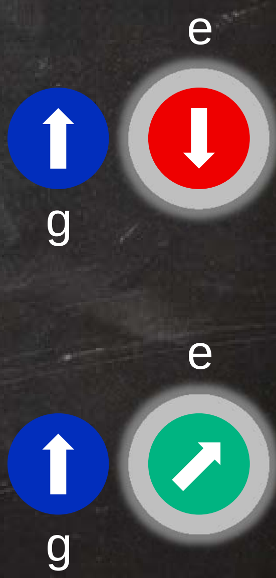
SU(N)-symmetric interactions in two-electron atoms

see related work:

X. Zhang et al., Science **345**, 1467 (2014)	**Sr**
F. Scazza et al., Nat. Phys. **10**, 779 (2014)	**Yb**

Measurement of spin-exchange frequency is a very accurate probe of SU(N) symmetry





Introduction

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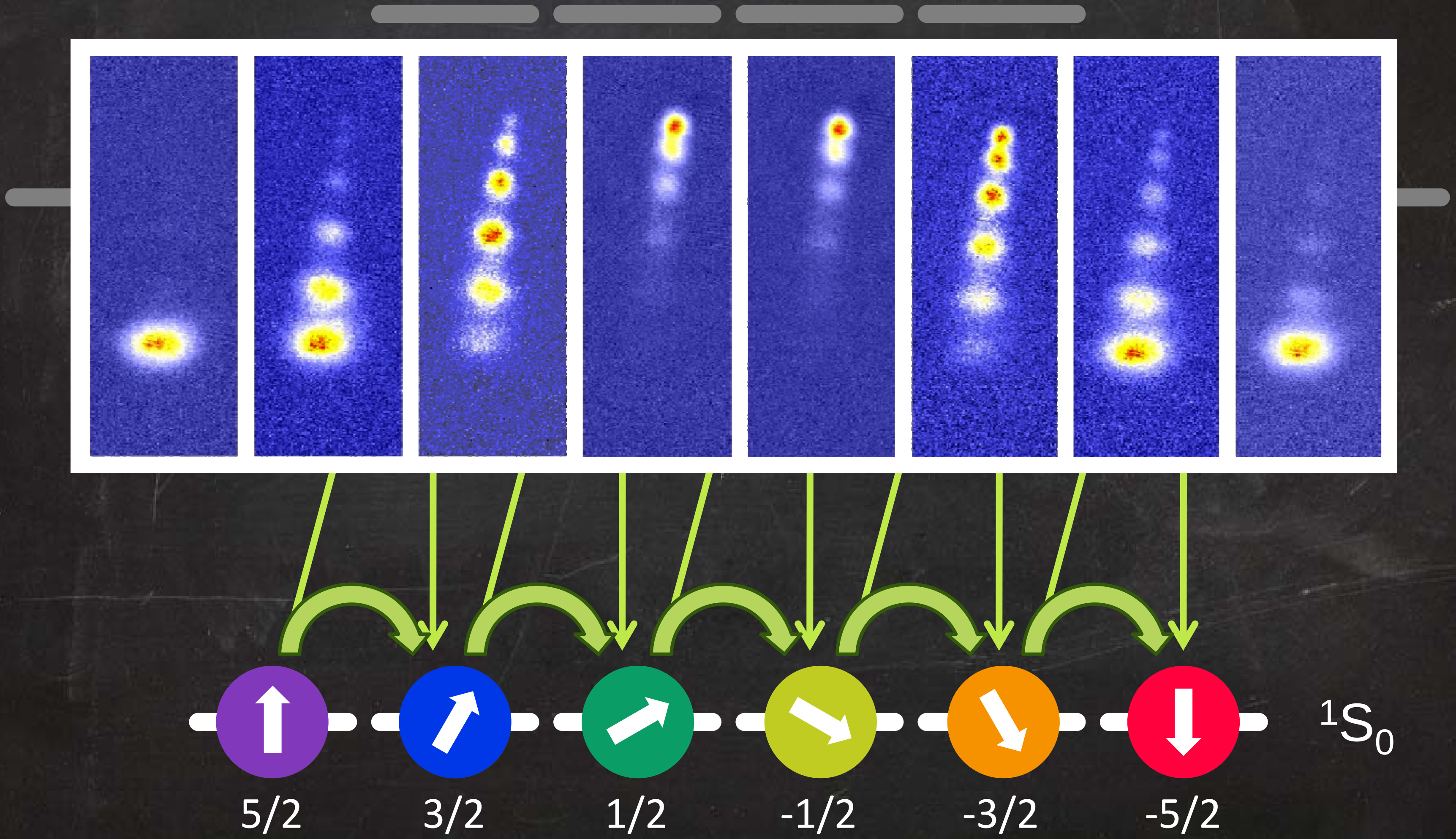
Synthetic dimensions

collaboration with M. Rider, P. Zoller, M. Dalmonte

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

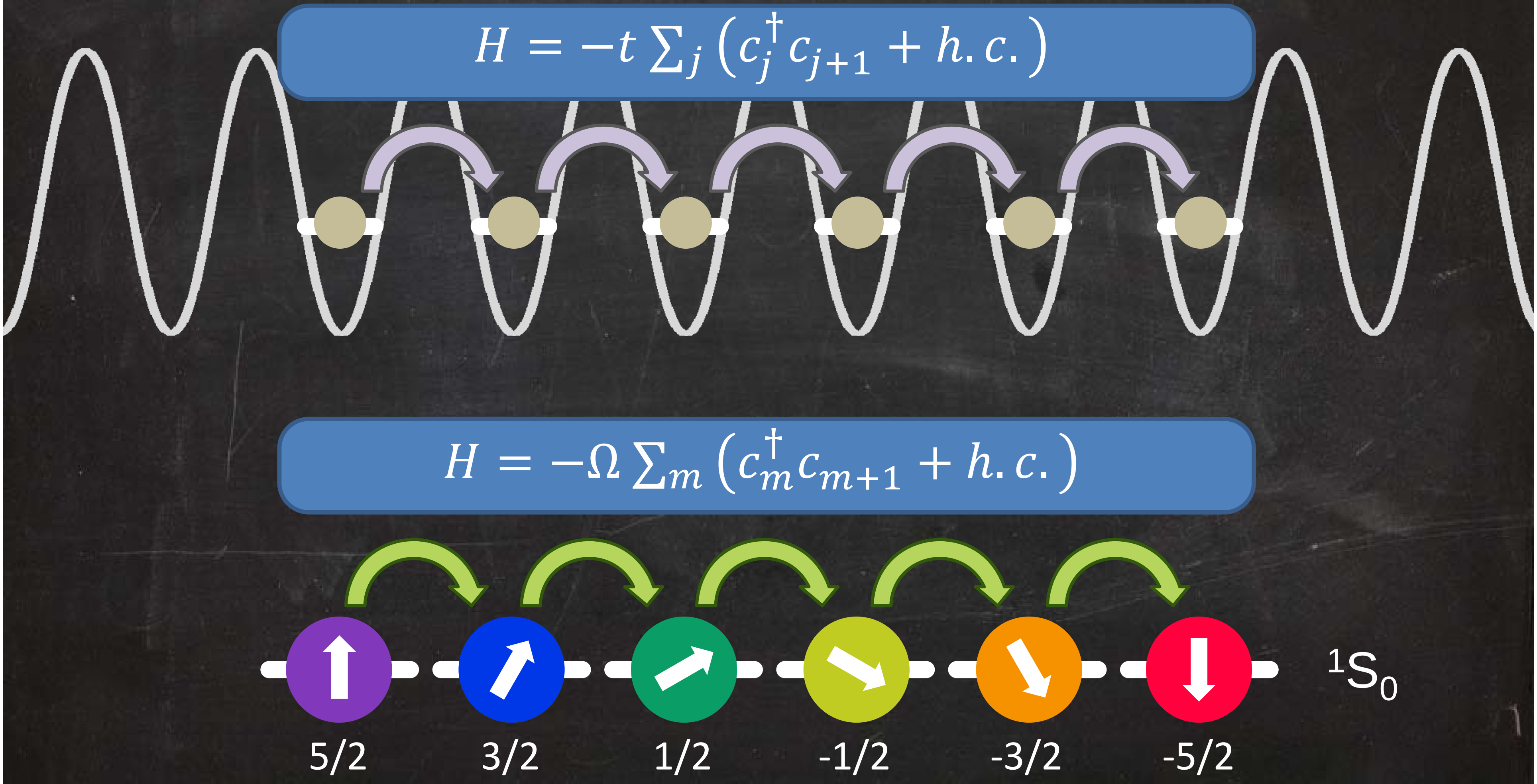
Coherent coupling of nuclear spin

Raman transitions coupling coherently different nuclear spin states:



Coherent coupling of nuclear spin

Analogous to coherent tunnelling coupling in an optical lattice:



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

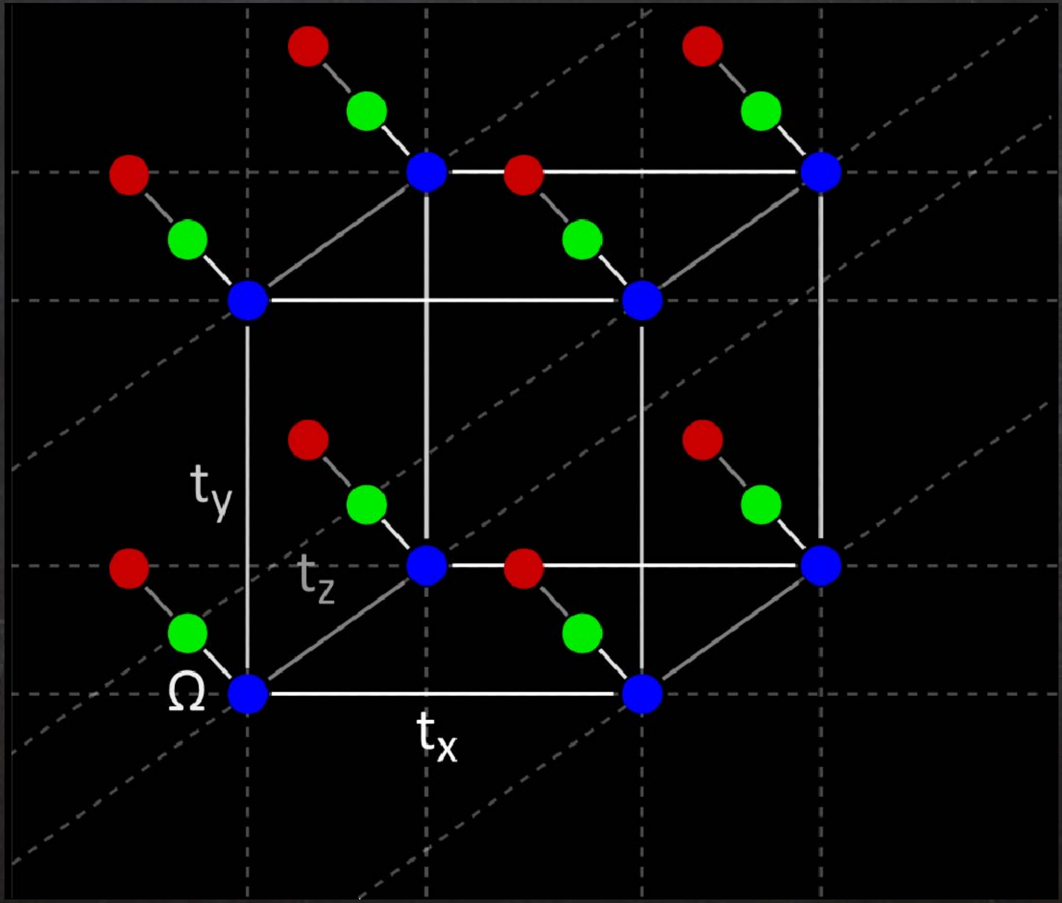
$$H = -\Omega \sum_m \left(c_m^\dagger c_{m+1} + h.c. \right)$$

Simulating an "extra dimension"

Raman transitions coupling coherently different nuclear spin states:

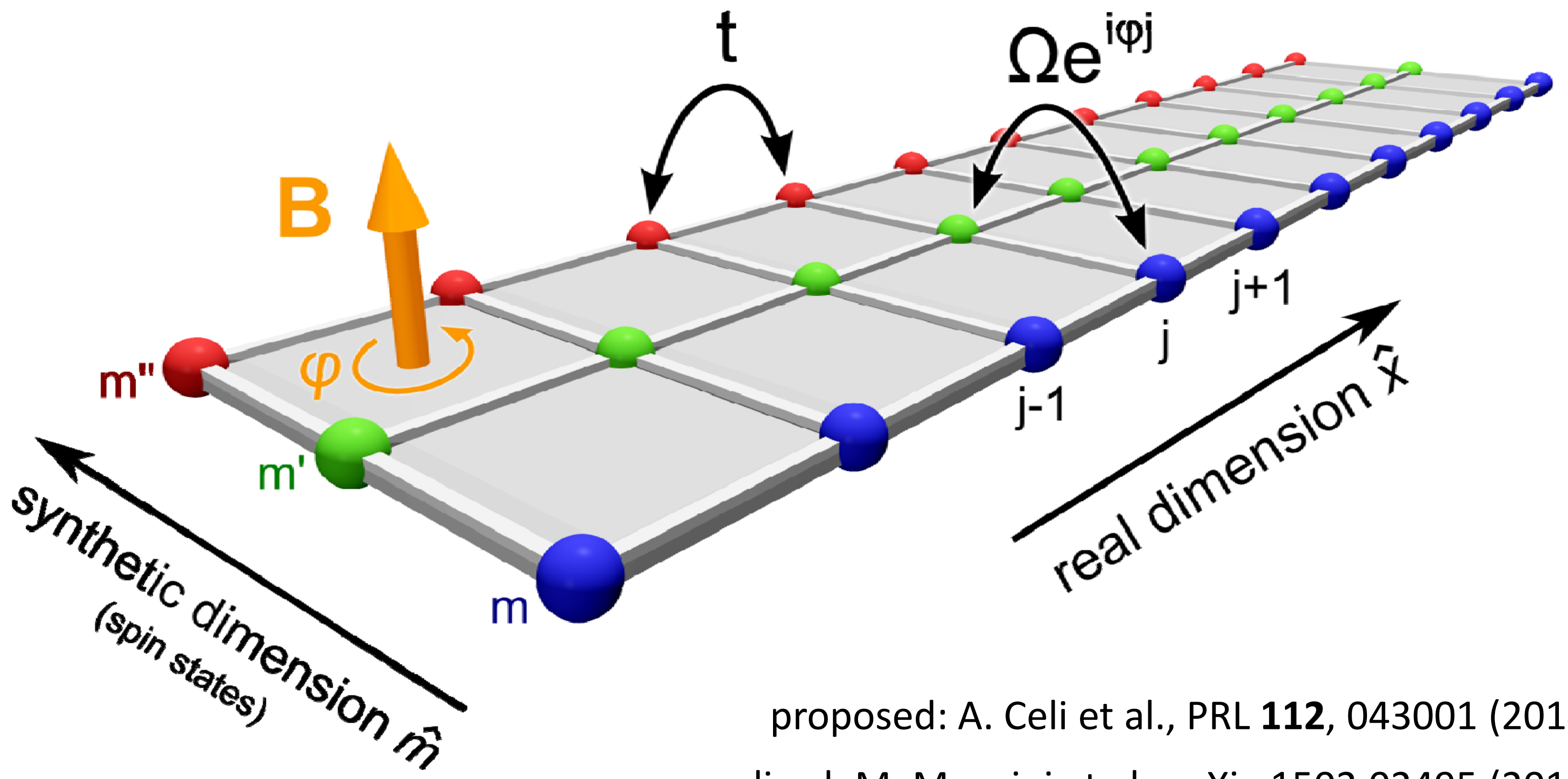
Realization of a synthetic lattice dimension

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



An atomic Hall ribbon

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



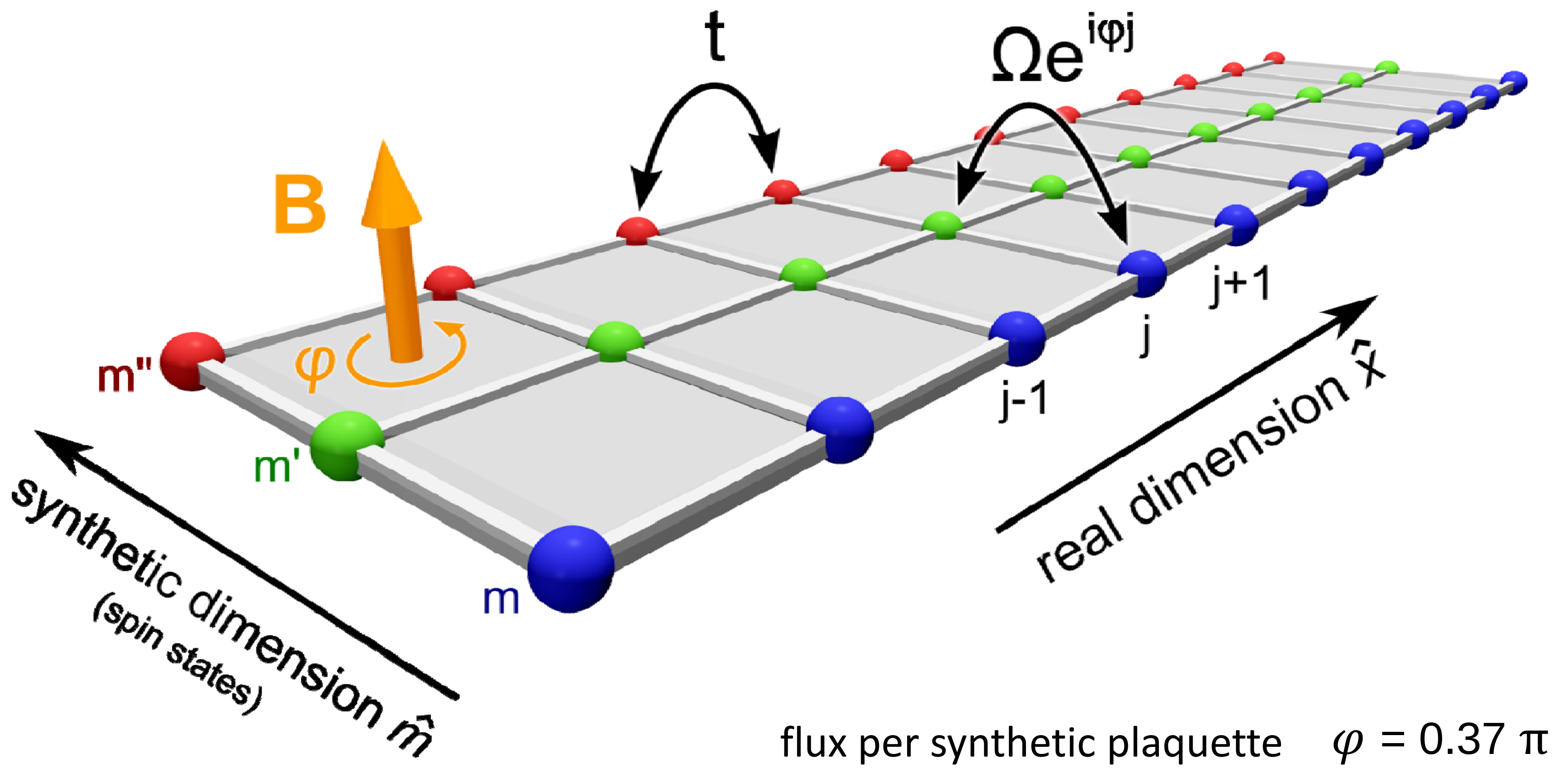
proposed: A. Celi et al., PRL **112**, 043001 (2014)

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

An atomic Hall ribbon

Feature #1

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

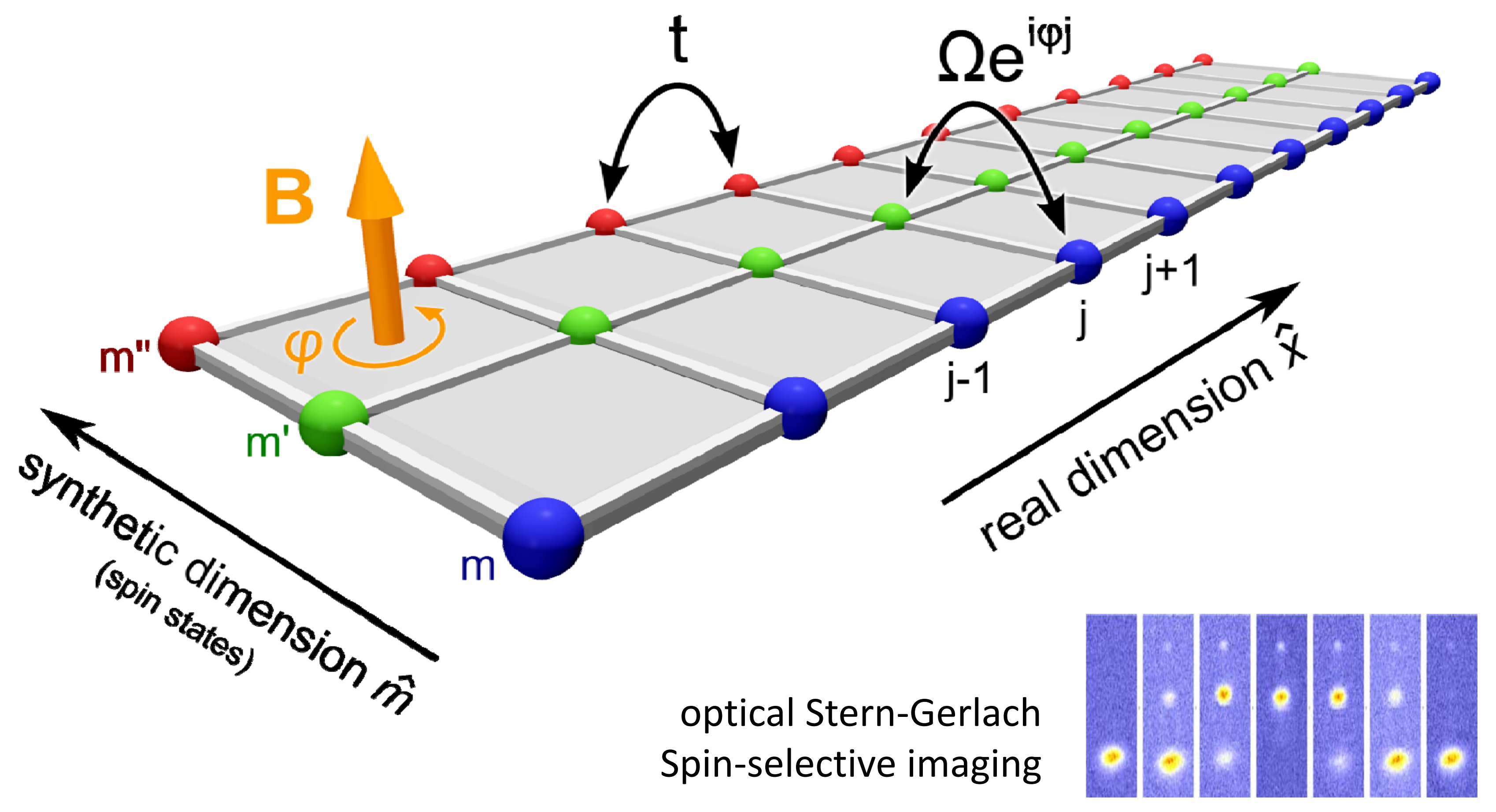


flux per synthetic plaquette $\varphi = 0.37\,\pi$
low filling: <1 atom per real-space site

An atomic Hall ribbon

Feature #2

Sharp and addressable edges
Single-site imaging along synthetic dimension

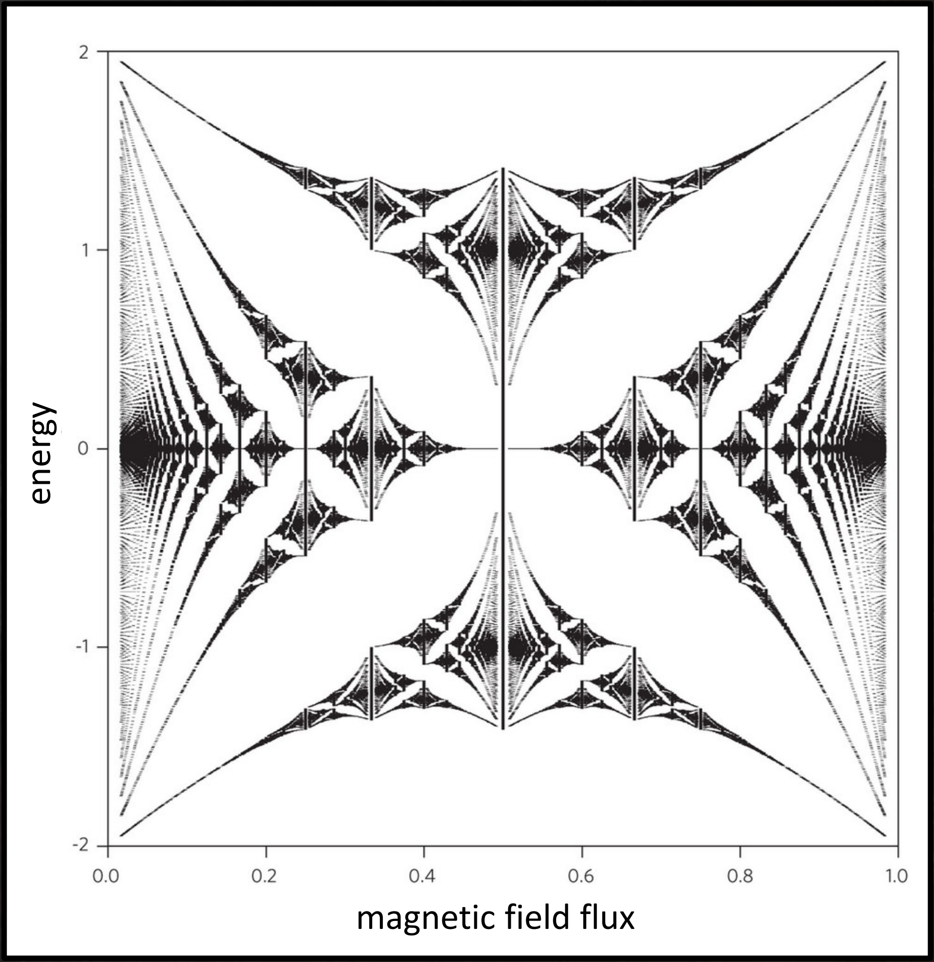


optical Stern-Gerlach
Spin-selective imaging

Harper-Hofstadter model

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

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

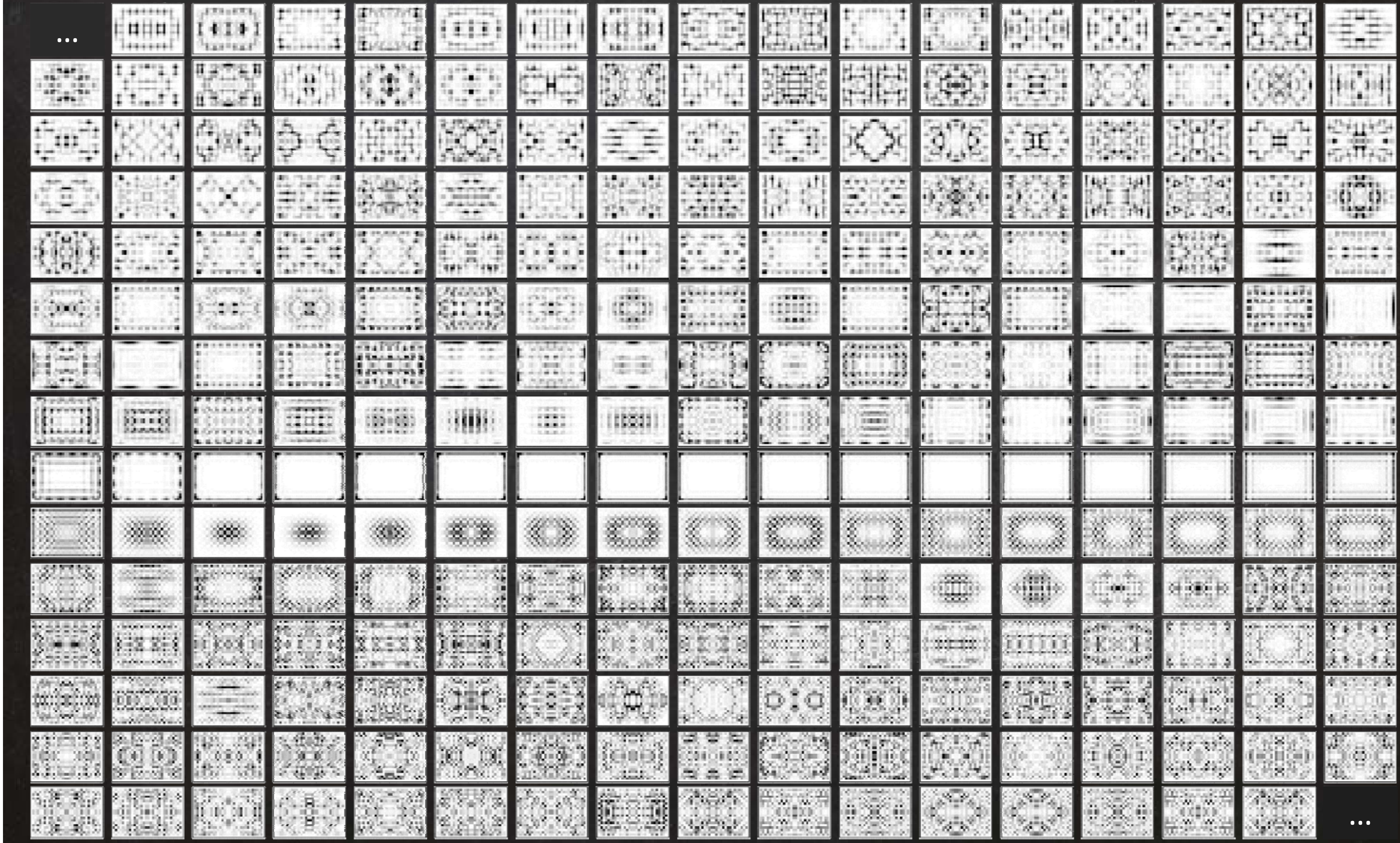


The Hofstadter butterfly

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

Bulk and edge states

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



Bulk and edge states

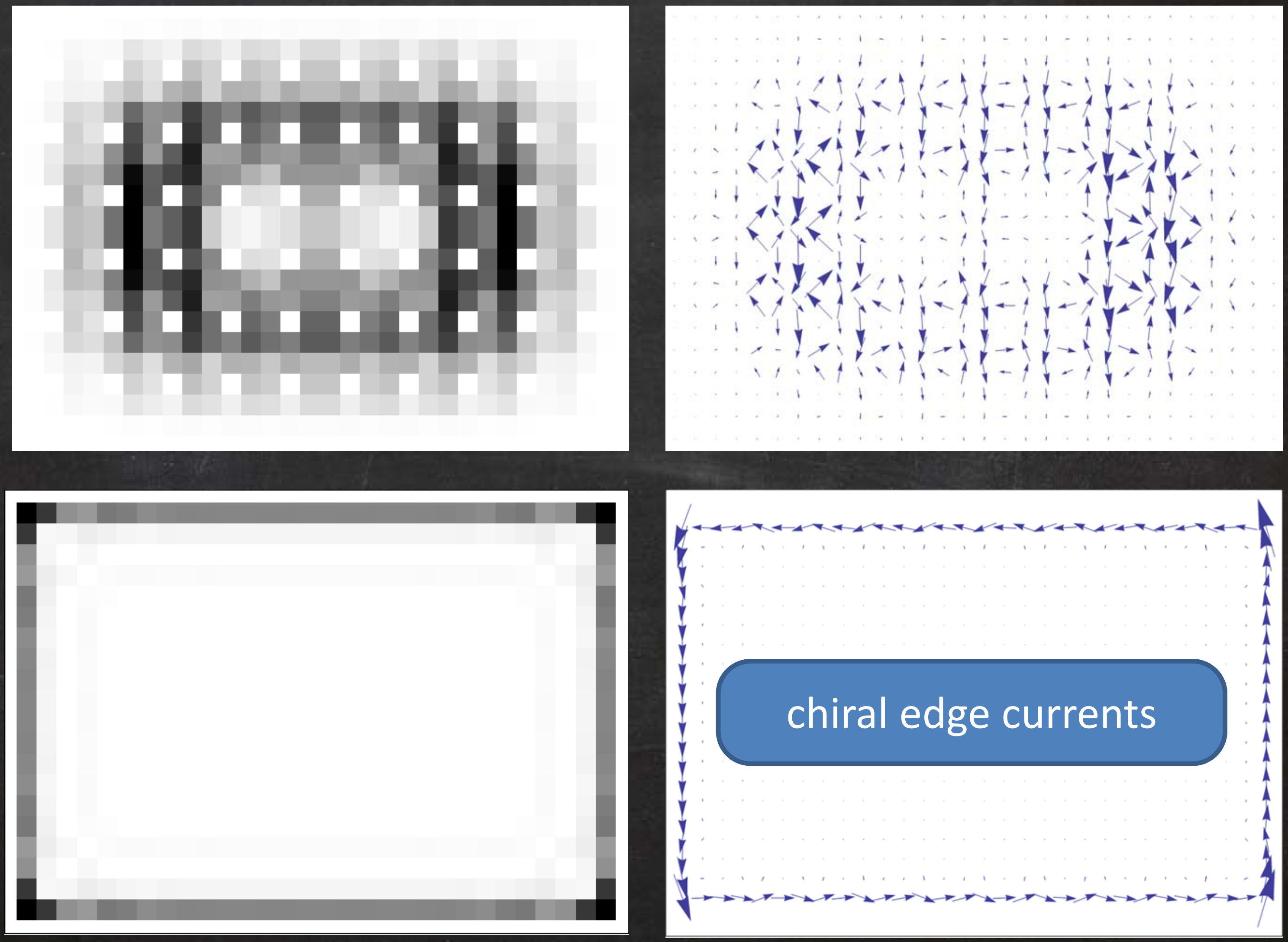
30x20 lattice

density:

current:

Bulk state:

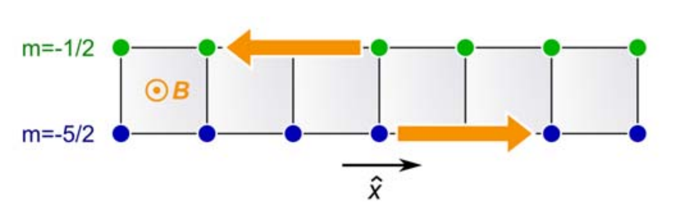
Edge state:



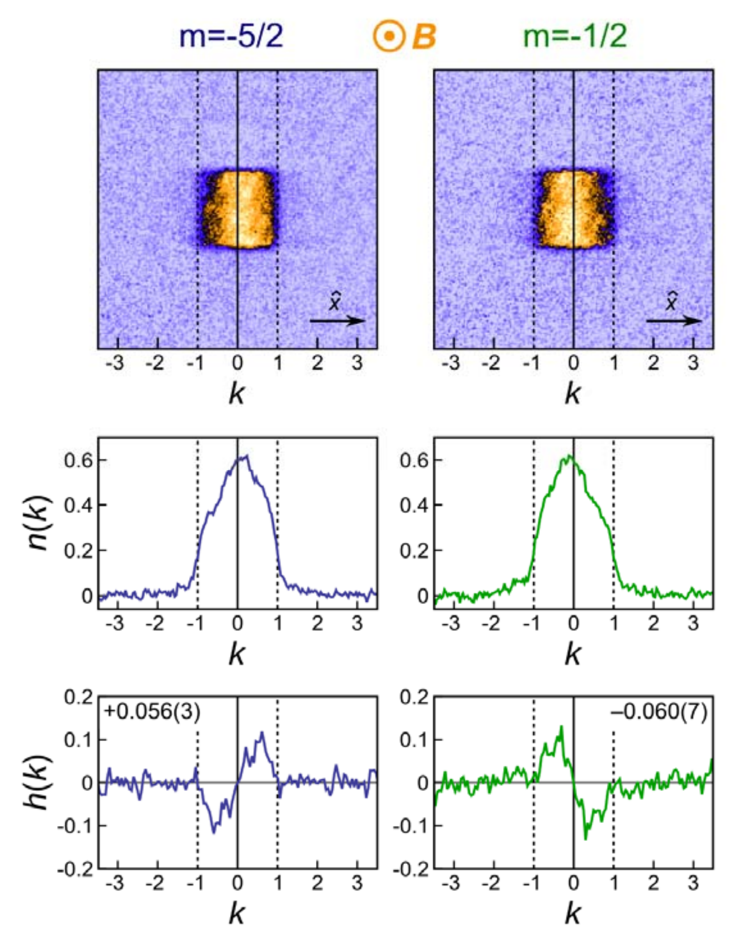
chiral edge currents

2-leg ladders

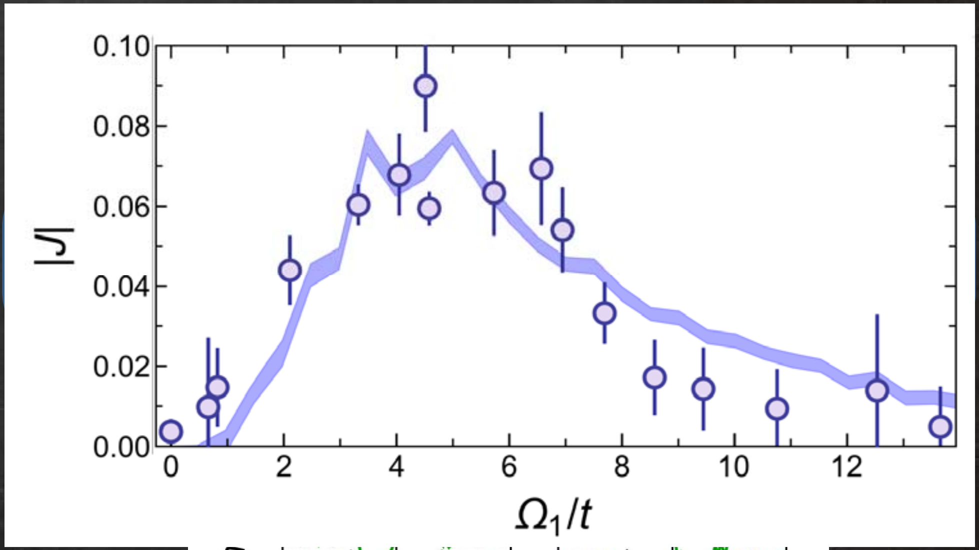
Adiabatic loading of a 2-leg ladder (edges only)



Lattice momentum distribution:



Chiral phase transition



(see also M. Atala et al., Nature Phys. 2012)

$$h(k) = n(k) - n(-k)$$

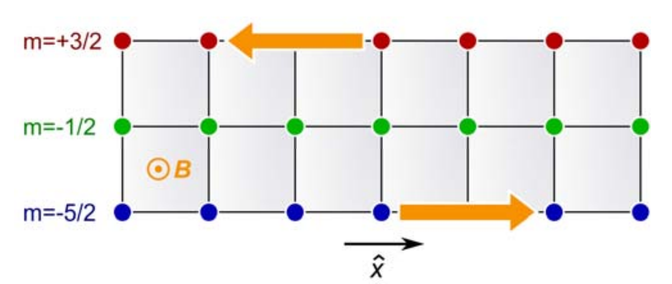
theory

$$J = \int_0^1 h(k)\,dk$$

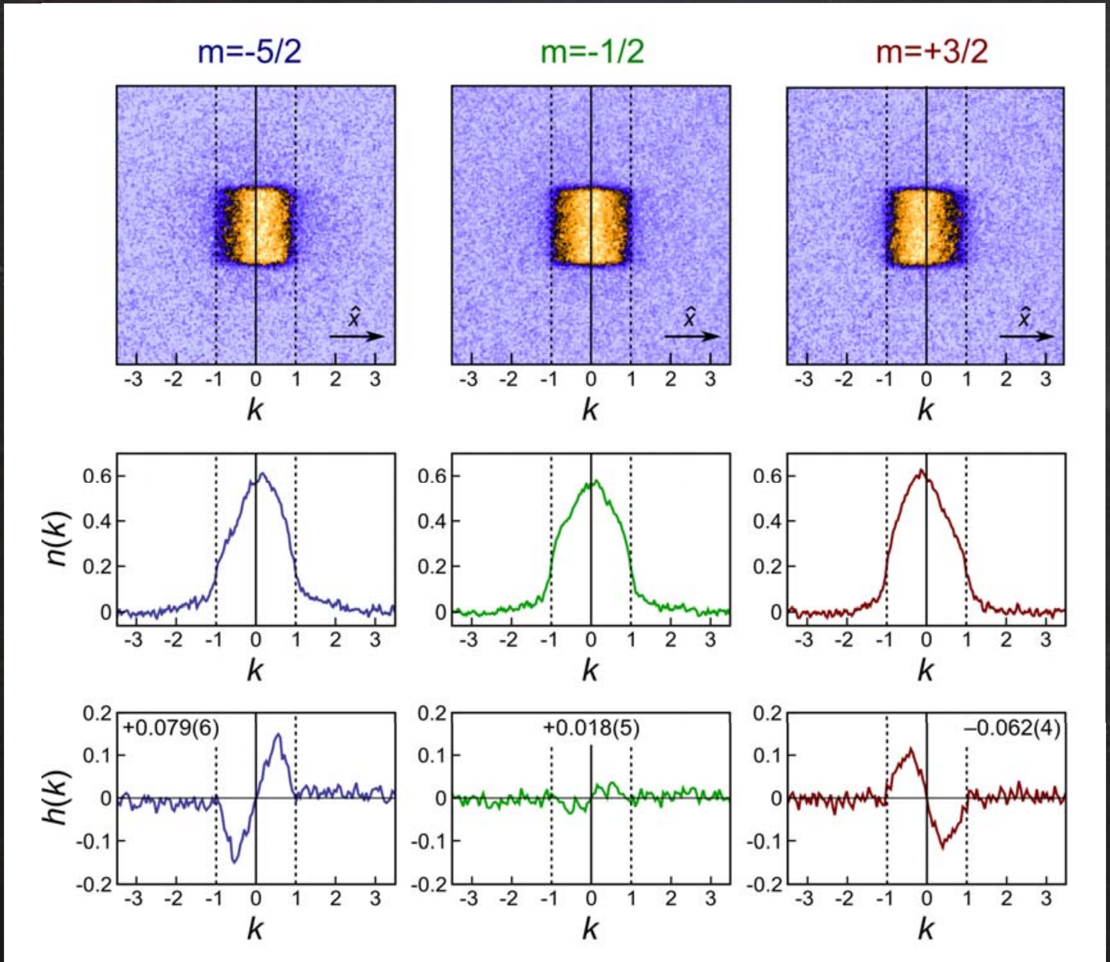
monte

3-leg ladders

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



Lattice momentum distribution:

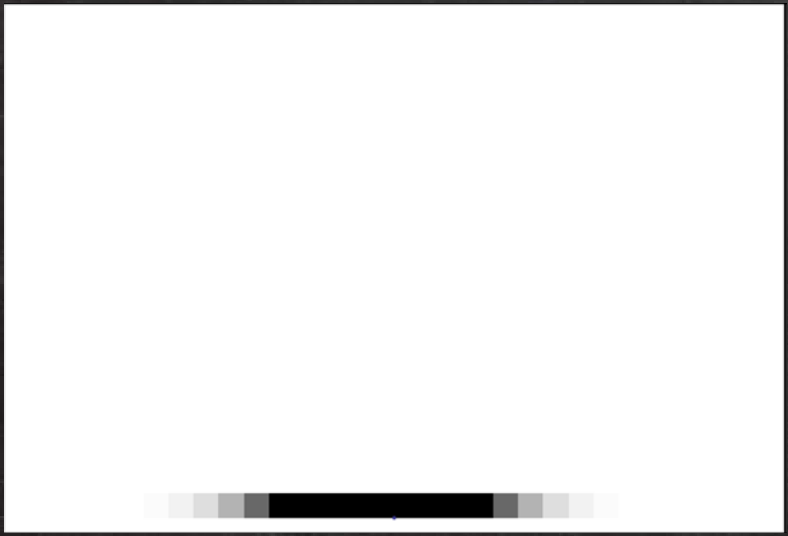


Conductive edges and no bulk current

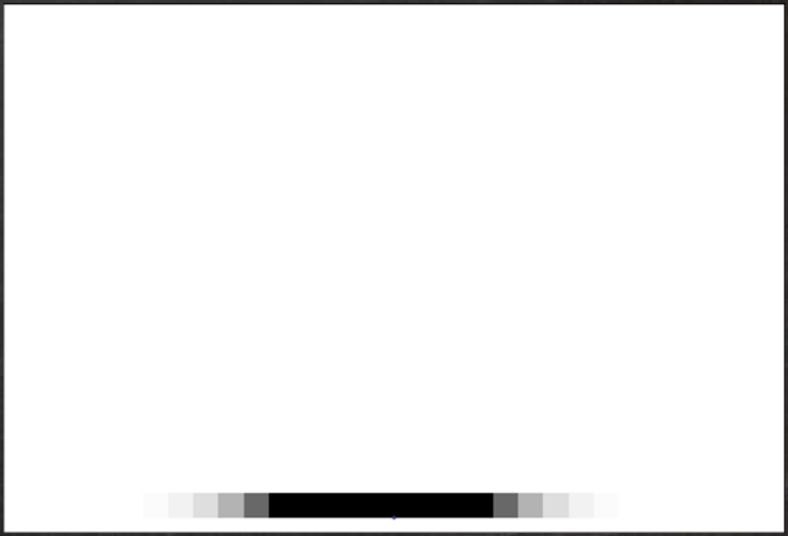
Edge-cyclotron orbits

Evolution of a wavepacket prepared on the edge:

φ = 0



φ > 0

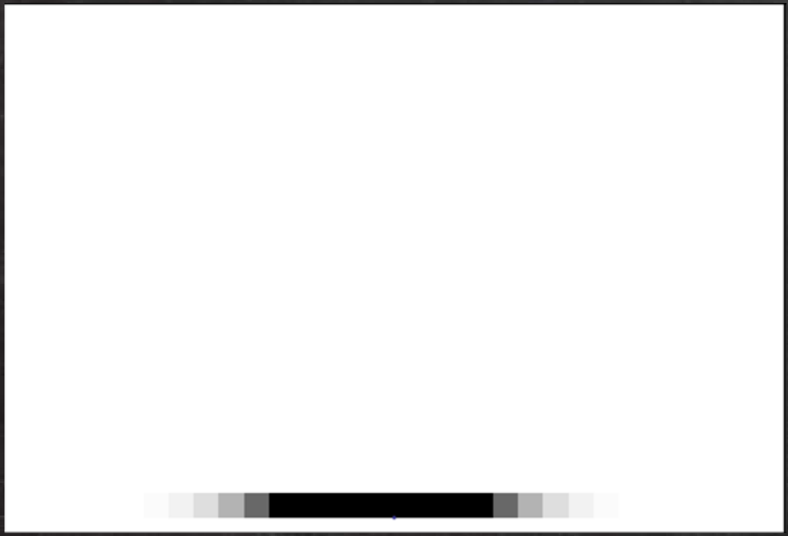


30x20 lattice

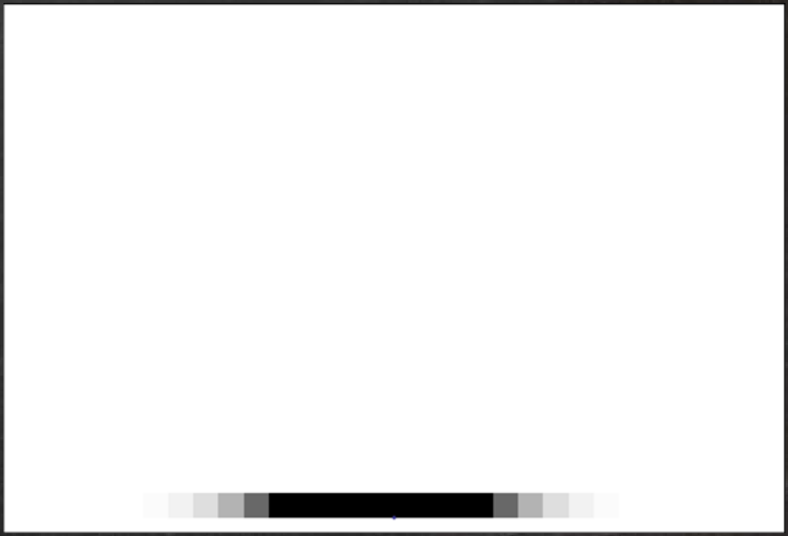
Edge-cyclotron orbits

Evolution of a wavepacket prepared on the edge:

φ = 0



φ > 0



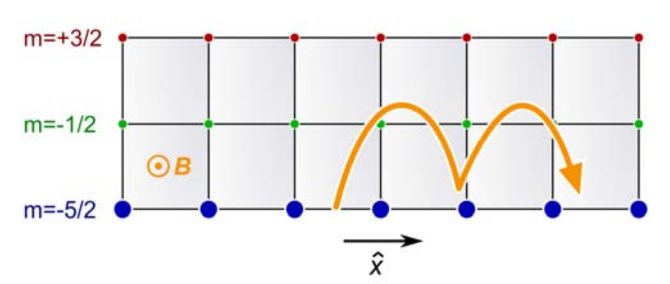
Chiral cyclotron dynamics
"Skipping" orbits

30x20 lattice

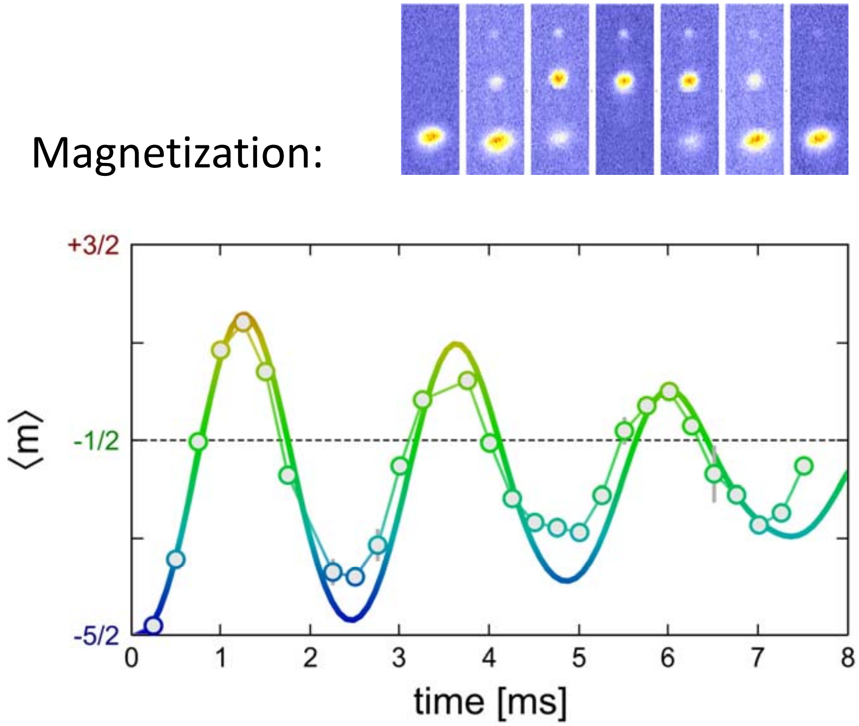
Edge-cyclotron orbits

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

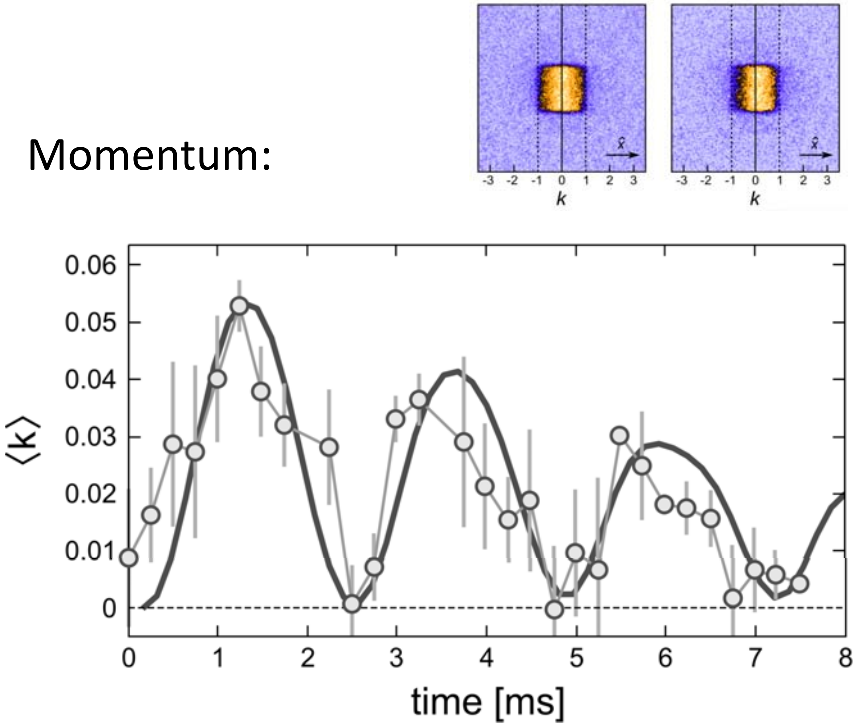
Quenched dynamics after activation of synthetic tunneling



Magnetization:



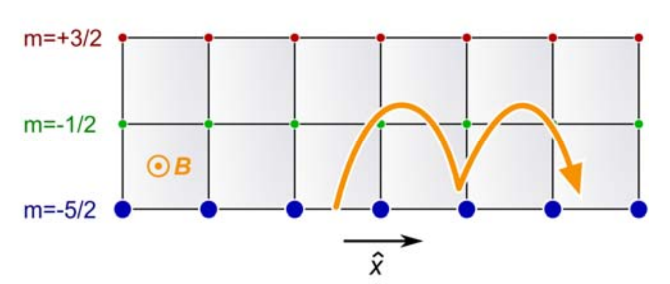
Momentum:

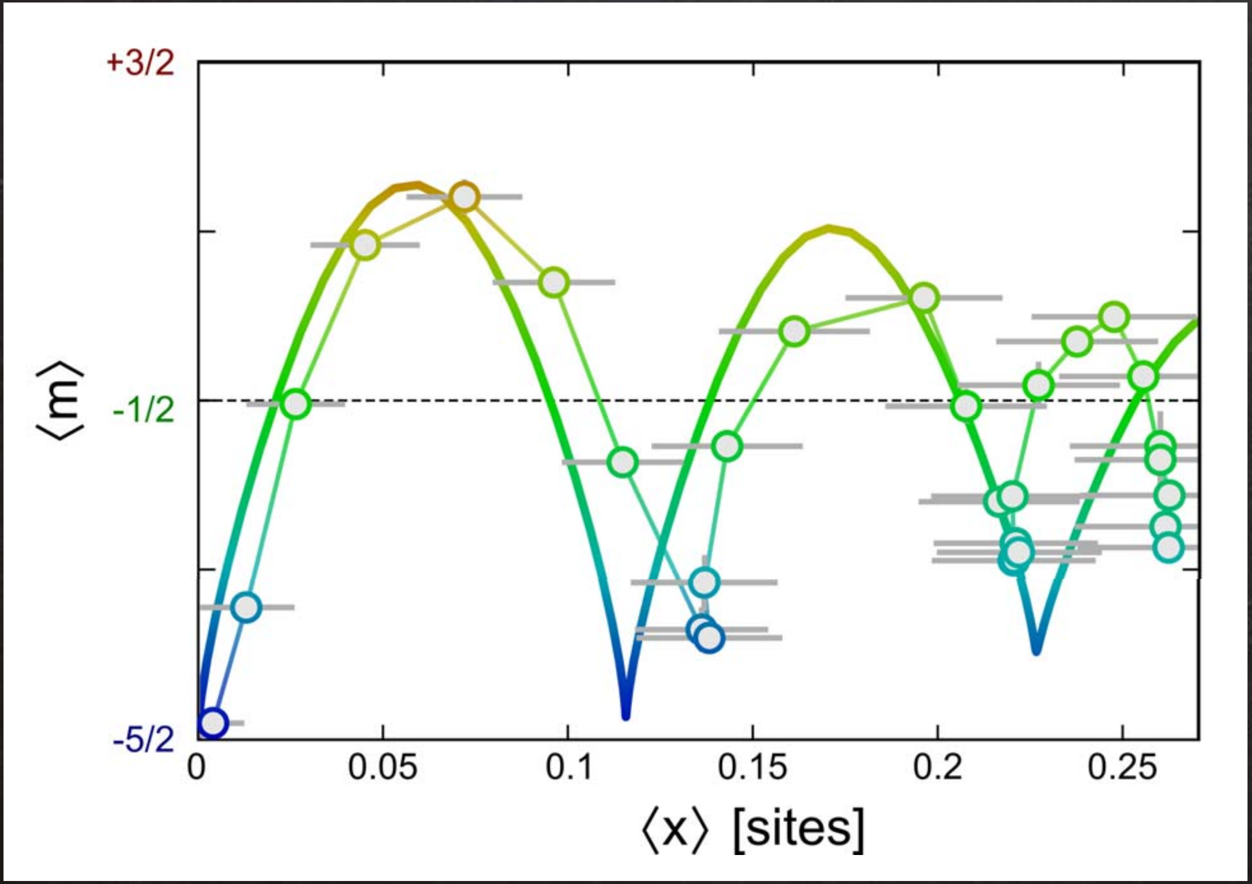


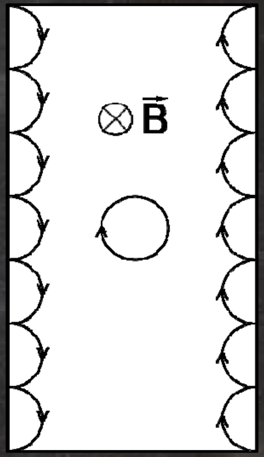
Edge-cyclotron orbits

Visualization of edge-cyclotron orbits

A hallmark of quantum Hall physics







see related work by Spielman's group (NIST):

B. K. Stuhl et al., arXiv:1502.02496 (2015)

Outlook: synthetic dimensions

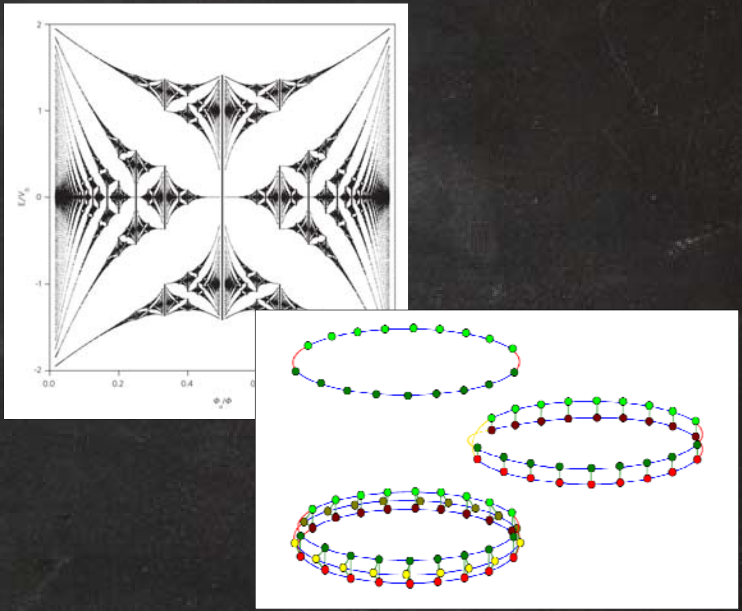
Synthetic dimensions: a brand new concept for atomic physics experiments

New manipulation/detection possibilities

Engineering topology

Periodic boundary conditions
Rings, cylinders, tori, Moebius strips…

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



Interactions + gauge fields

Fractional quantum Hall effect

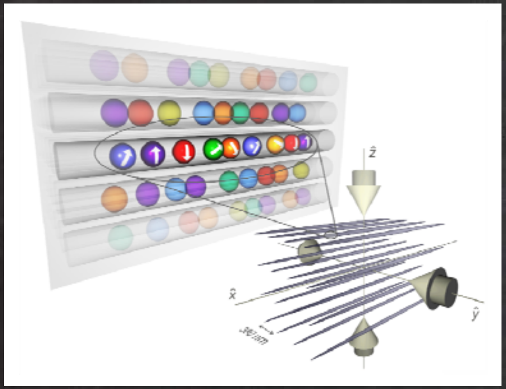
New interaction-induced quantum phases

Anisotropic interactions

Discussions with Innsbruck, Pisa, …

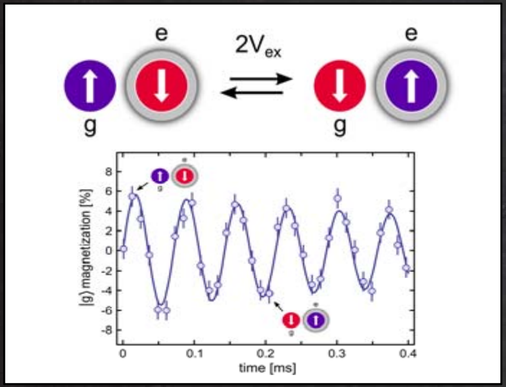
Talk: Hui Zhai, Poster: Leonardo Mazza

Summary



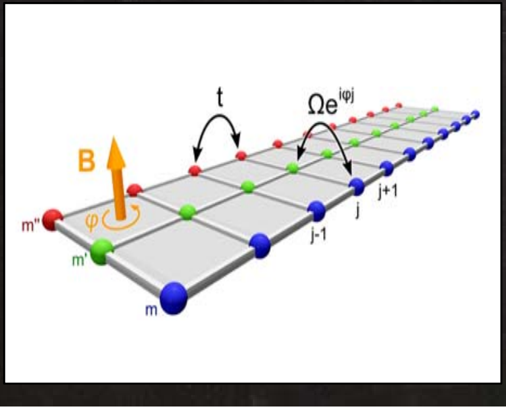
Multicomponent 1D liquids of fermions

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



Two-orbital magnetism

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



Edge states in synthetic dimensions

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

Credits

Marco
Mancini

Giacomo
Cappellini

Lorenzo
Livi

Guido
Pagano

Jacopo
Catani

Carlo
Sias

Massimo
Inguscio

Leonardo
Fallani

Funding from EU, ERC, MIUR

two-electron atoms (Yb)

superfluid fermions (Li)

quantum interferometry (K)

disorder (K)

lens

European Laboratory for Non-Linear Spectroscopy

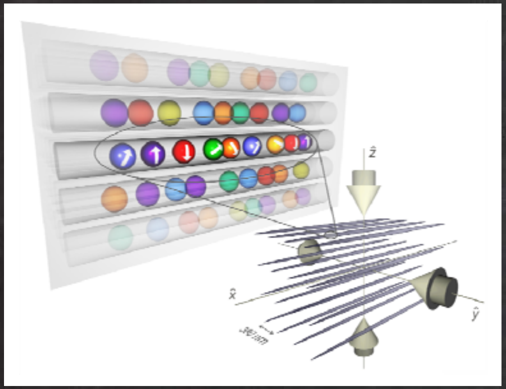
bose-bose mixtures (Rb/K)

atom chip (Rb)

fermi-fermi mixtures (Cr/Li)

trapped ion + atoms (Ba+/Li)

Thank you!



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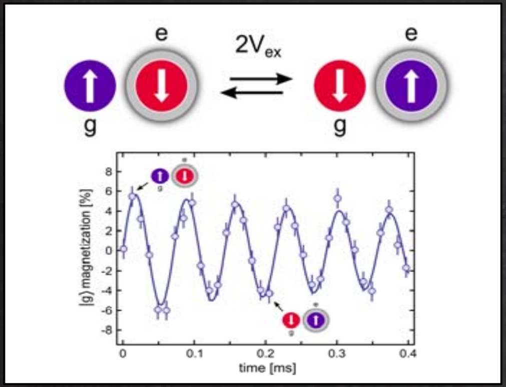
G. Pagano et al., Nature Phys. **10**, 198 (2014)



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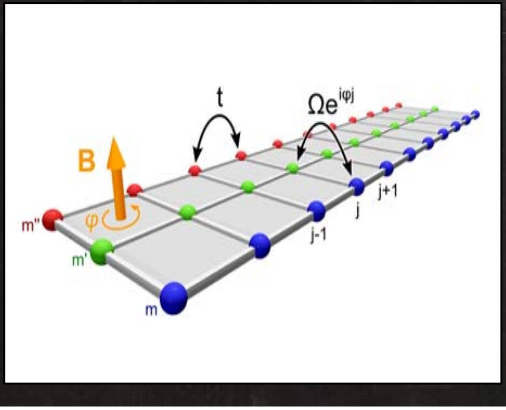

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