SYNTHETIC GAUGE FIELDS FOR ULTRACOLD ATOMS IN SYNTHETIC DIMENSIONS

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Outlook

Synthetic gauge fields

Synthetic dimensions

Synthetic gauge fields for neutral atoms

Theory: Jaksch&Zoller, NJP 2003
Osterloh et al., PRL 2005
Gerbier&Dalibard, NJP 2010
Bermudez et al., PRL 2010 (TRI Top. Ins.)
...
...
...

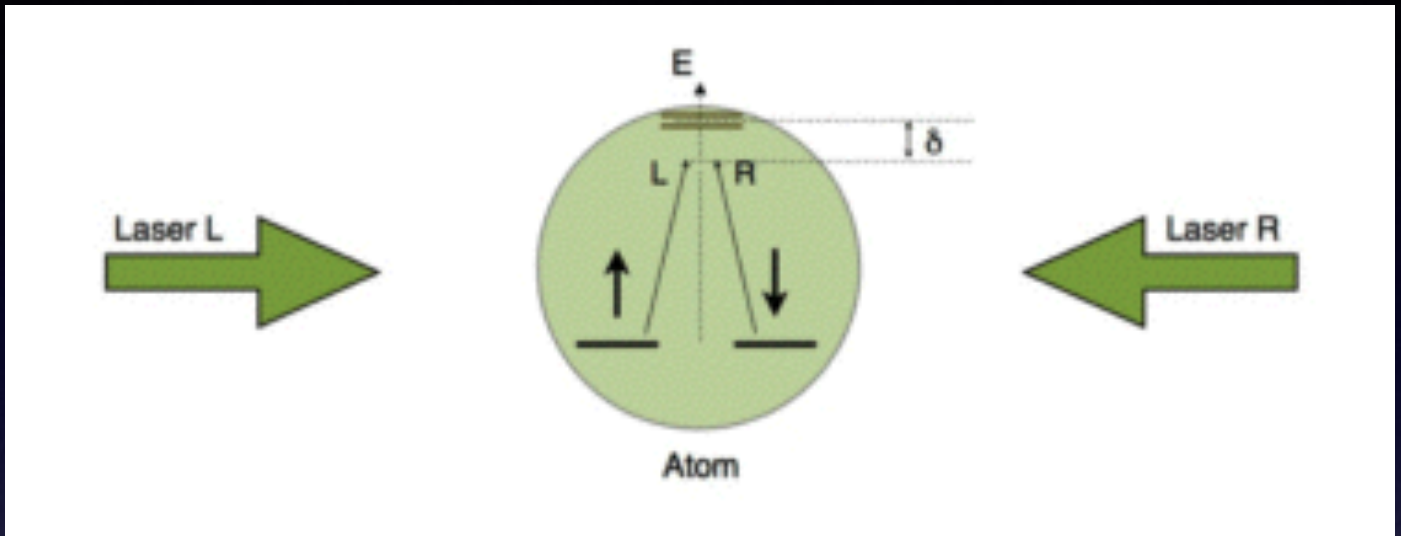
- adiabatic Raman passage
- adiabatic control of superpositions of degenerate dark states
- spatially varying Raman coupling
- Raman-induced transitions to auxiliary states in optical lattices

REVIEWS:

Artificial gauge potentials for neutral atoms
J. Dalibard, F. Gerbier, G. Juzeliunas, and P. Öhberg, RMP 2011

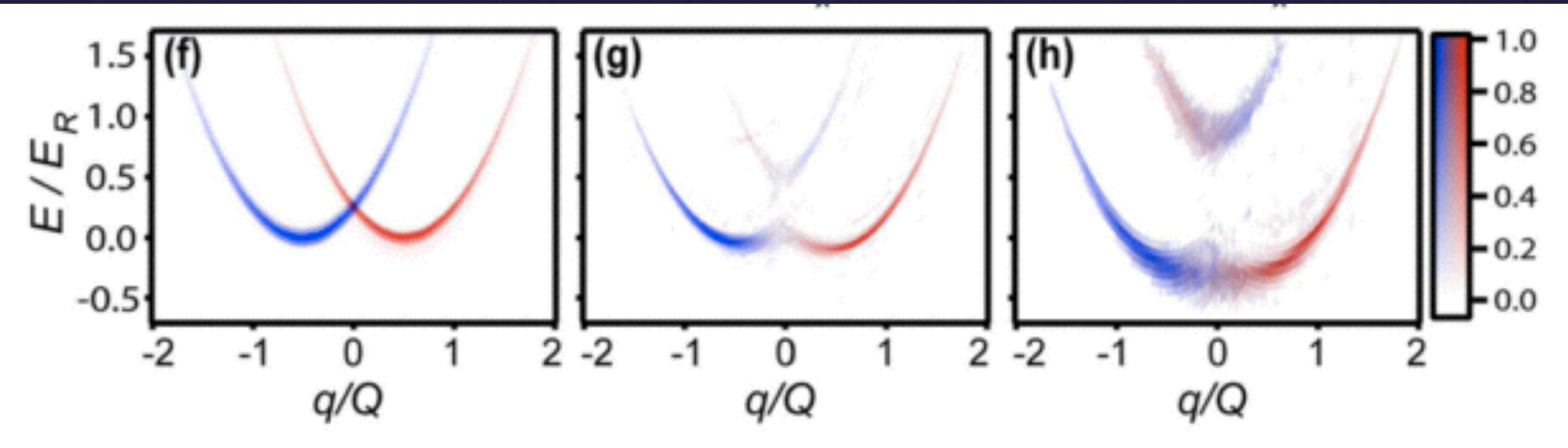
Light-induced gauge fields for ultracold atoms
N. Goldman, G. Juzeliunas, P. Öhberg, and I. Spielman, arXiv:1308.6553

Synthetic gauge fields for neutral atoms



$|\uparrow, q=k_x-Q/2\rangle$

$|\downarrow, q=k_x+Q/2\rangle$



spin-orbit gap

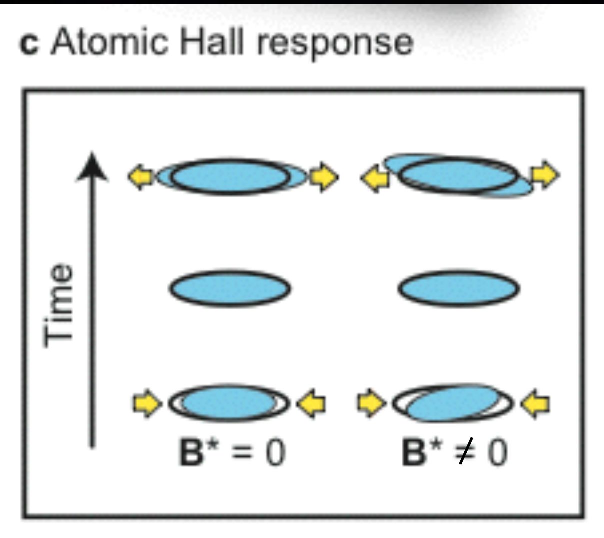
increasing intensity of Raman lasers

spin flip ↔ momentum kick, i.e., spin-orbit coupling

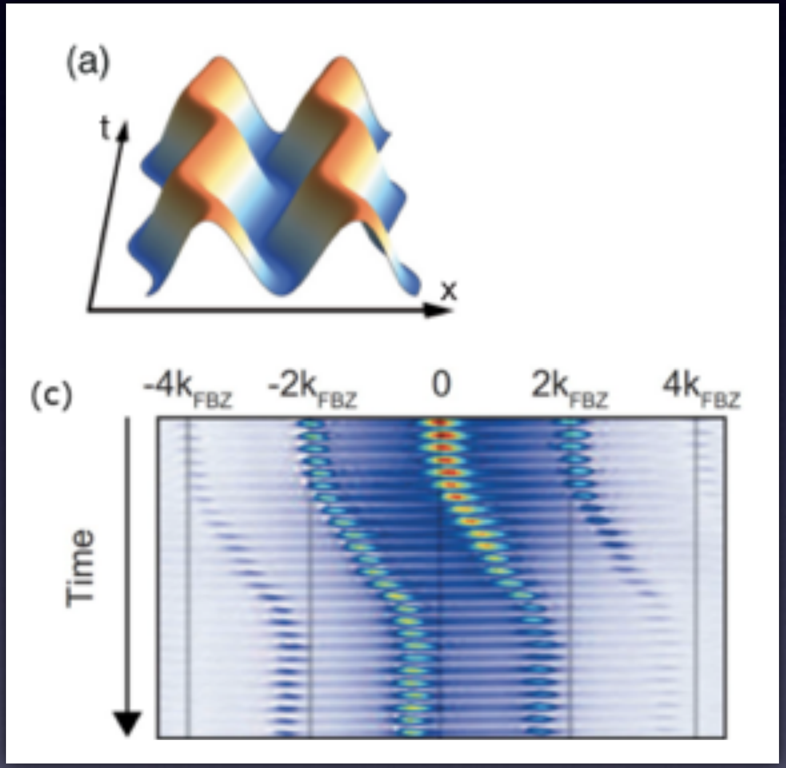
P. Wang et al., PRL 2012 (Shanxi U.)
L.W. Cheuk et al., PRL 2012 (MIT)

a field moving fast..

NIST: *Synthetic magnetic fields for ultracold neutral atoms*, Nature (2009)
A synthetic electric force acting on neutral atoms, Nature Phys. (2011)
Spin-orbit-coupled Bose-Einstein condensates, Nature (2011)
Observation of a superfluid Hall effect, PNAS (2012)
Peierls Substitution in an Engineered Lattice Potential, PRL (2012)

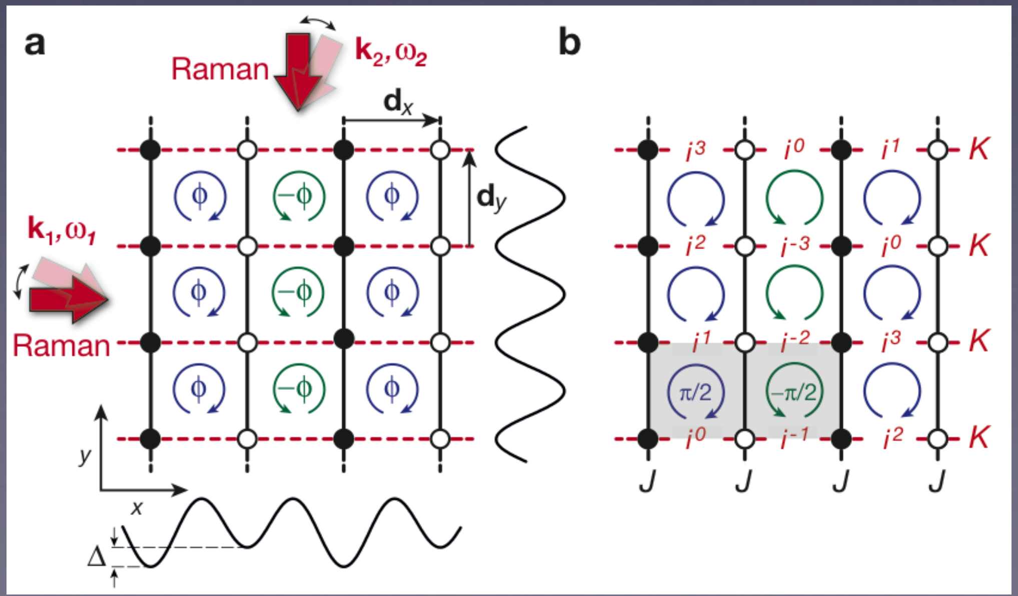


ICFO & Hamburg & Dresden:
Tunable Gauge Potential for Neutral Spinless Particles in Driven Optical Lattices, PRL (2012)
(method independent of the internal structure of the atoms!!)



Munich: *Experimental realization of strong staggered magnetic fields in an optical lattice*, PRL (2011)

… … … …



Synthetic dimensions

Q. Sim. & Extra Dimensions

Quantum simulation with ultracold atoms:

- Hubbard model (SF-MI transition, ...)
- synthetic gauge fields (relativistic dispersions, ...)
- strongly-correlated states (QH, spin liquids, ...)

Extra (=non-spatial) dimensions:

- attempts to unify gravitation with electro-weak forces (Kaluza-Klein, Yang-Mills, ...)
- thermal QFT: compactification of euclidean time leads to Matsubara frequencies

(extra-dim is usually discrete and compact)

quantum simulation ***of*** *an extra dimension?*

The main idea

- use a system with D spatial dimensions
- encode the (D+1)$^{\text{th}}$ dimension in a different degree of freedom (e.g., the spin)

$$\tilde{\mathbf{r}} = (\mathbf{r}, \sigma)$$

$$H = -\sum_{\mathrm{d}=1}^{D+1} \sum_{\tilde{\mathbf{r}}} J_{\mathrm{d}} \hat{a}^{\dagger}_{\tilde{\mathbf{r}}+\mathbf{u}_{\mathrm{d}}} \hat{a}_{\tilde{\mathbf{r}}} + \mathrm{h.c.}$$

$$= -\sum_{\sigma=1}^{N} \left[\sum_{d=1}^{D} \sum_{\mathbf{r}} J_{d} \hat{a}^{(\sigma)\dagger}_{\mathbf{r}+\mathbf{u}_{d}} \hat{a}^{(\sigma)}_{\mathbf{r}} + \underline{J_{\sigma} \hat{a}^{(\sigma+1)\dagger}_{\mathbf{r}} \hat{a}^{(\sigma)}_{\mathbf{r}}} \right] + \mathrm{h.c.}$$

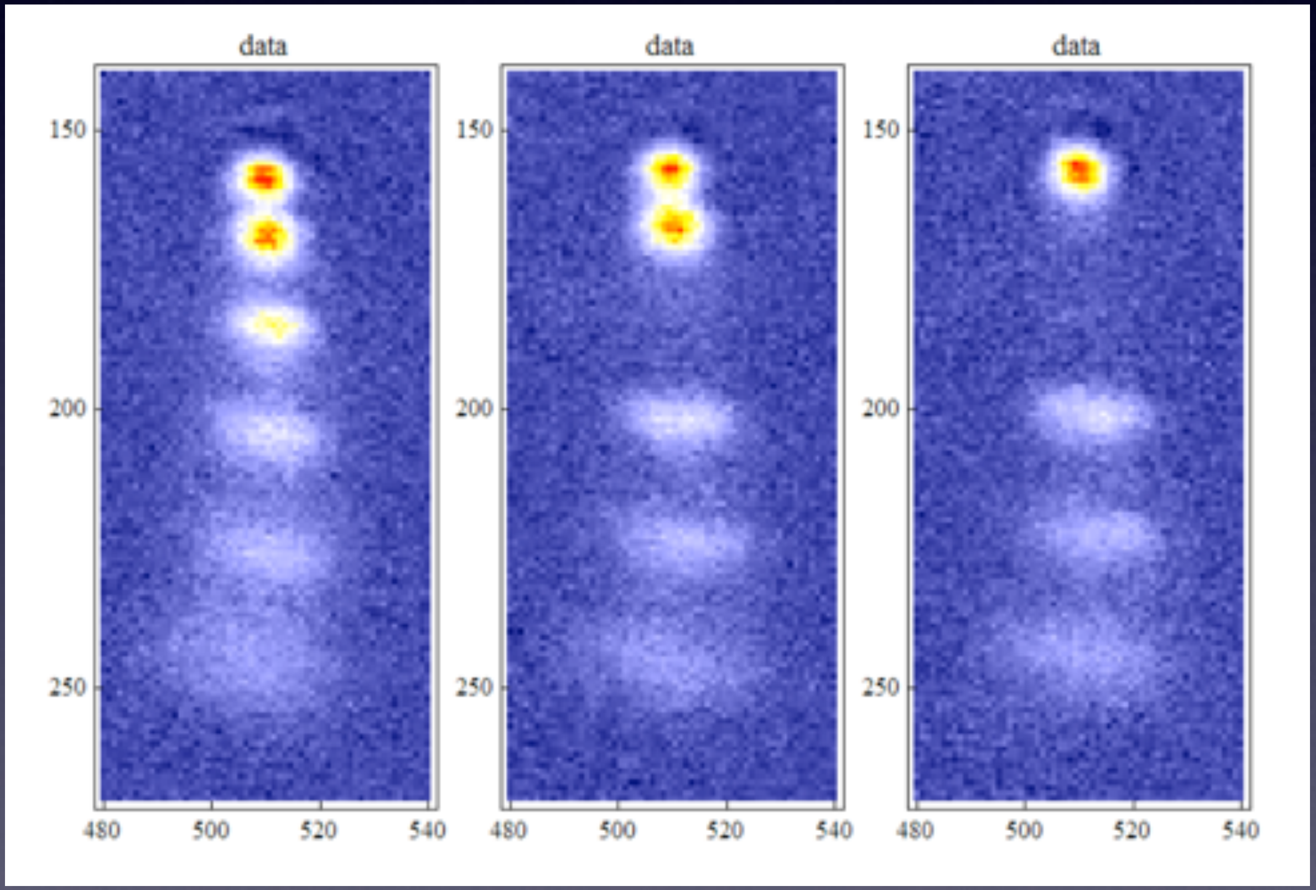
only nearest-neighbor "spin-tunneling"

O. Boada, A. Celi, J.I. Latorre, and M. Lewenstein, PRL 2012

Large N systems

species	N
Li	2,3,...
87	3
173	6
40	10
87	10
161-163	22
165	128

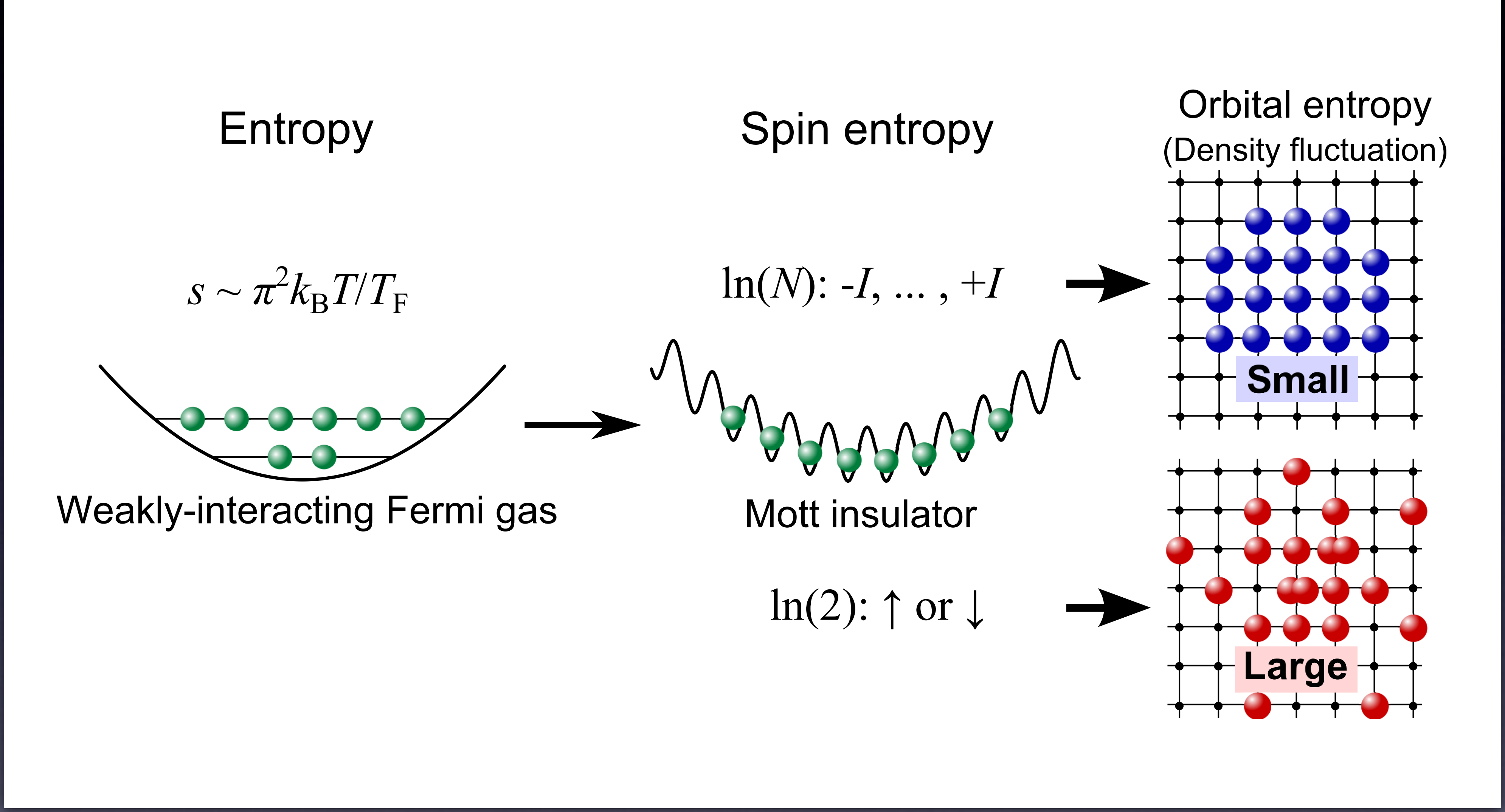
^{173}Yb at LENS:



†M. Saffman and K. Mølmer, PRA 2008

interactions in earth-alkali atoms are SU(N) invariant!

SU(6) Mott insulator

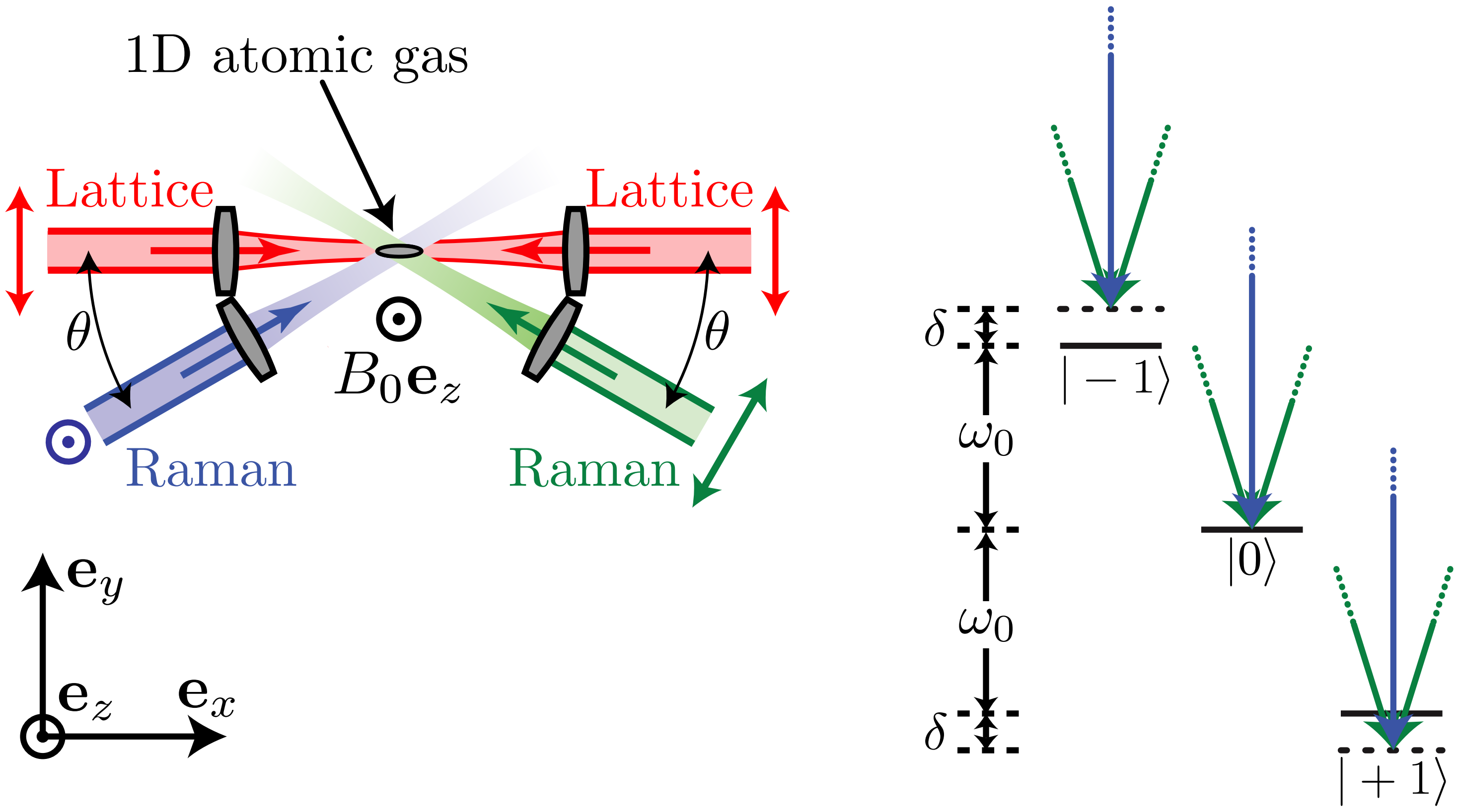


S. Taie, R. Yamazaki, S. Sugawa, and Y. Takahashi, Nature Phys. 2012

Novel cooling mechanisms?

Implementation

Proposal:
- F=1 ^{87}Rb atoms in a 1D optical lattice (deep, but not in the Mott regime)
- two linearly polarized λ_R Raman beams, providing recoil $k_R = 2\pi\cos\theta/\lambda_R$
- uniform magnetic field in the orthogonal direction



Effective magnetic field: $\mathbf{\Omega}_T = \delta\mathbf{e}_z + \Omega_R\left[\cos\left(2k_Rx\right)\mathbf{e}_x - \sin\left(2k_Rx\right)\mathbf{e}_y\right]$

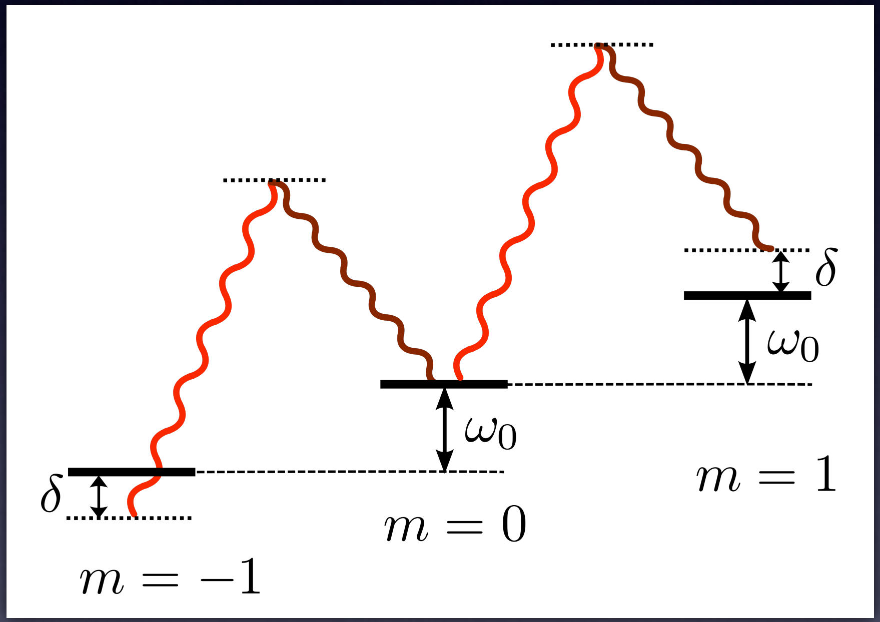
Atom-light coupling: $H_{\rm al} = \mathbf{\Omega}_T\cdot\mathbf{F} = \delta F_z + (F_+e^{ik_Rx} + F_-e^{-ik_Rx})\Omega_R/2$

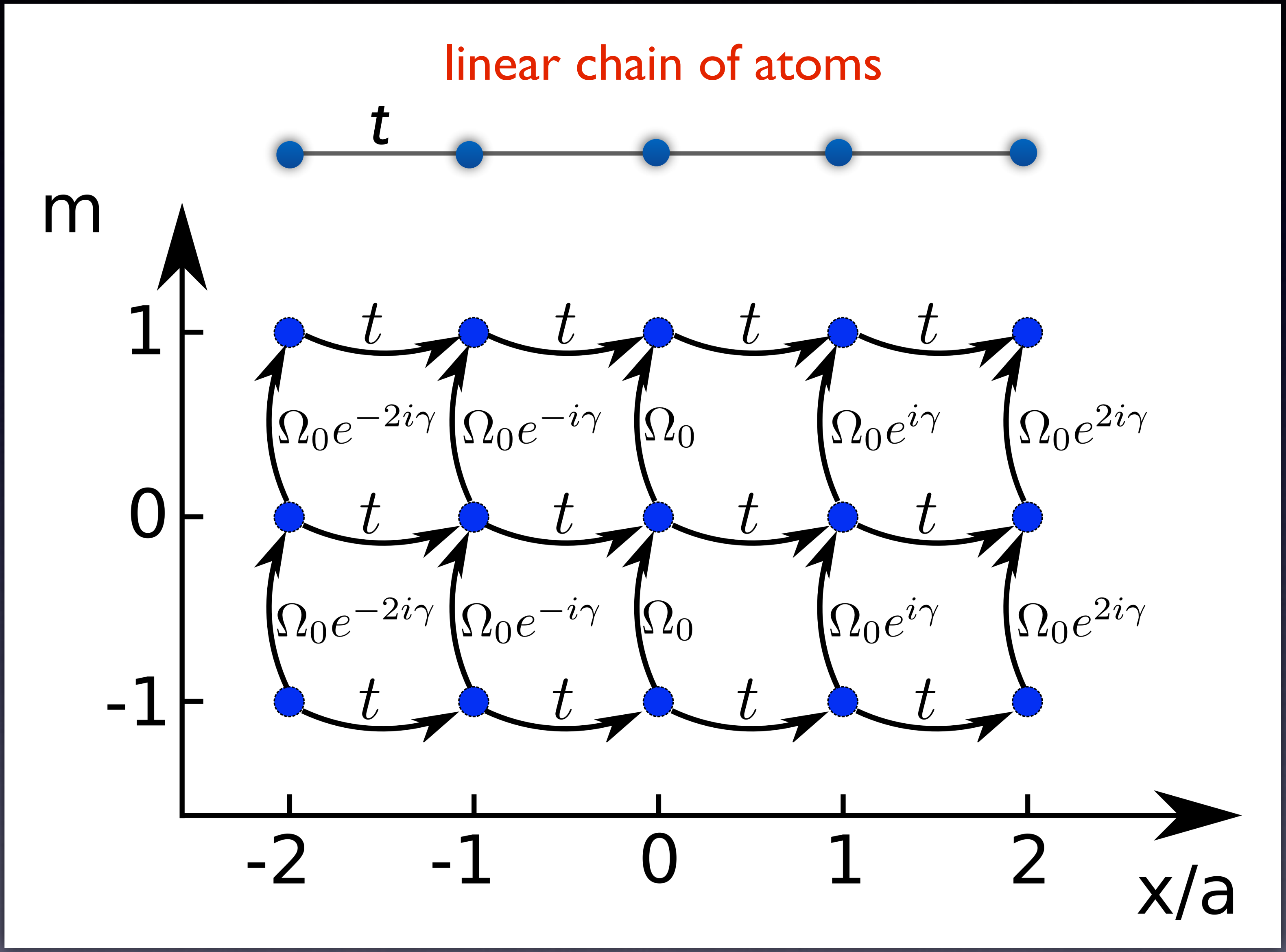
Raising (or *spin-hopping*) operator: $F_+\left|m\right\rangle = g_{F,m}\left|m+1\right\rangle$

$g_{F,m} = \sqrt{F\left(F+1\right) - m\left(m+1\right)}$

Implementation

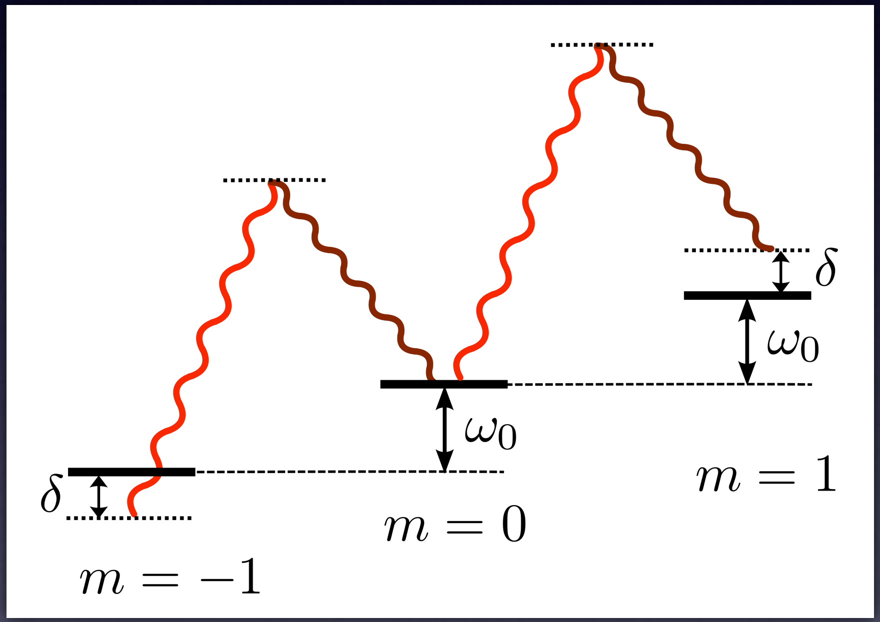
laser-assisted position-dependent spin-tunneling

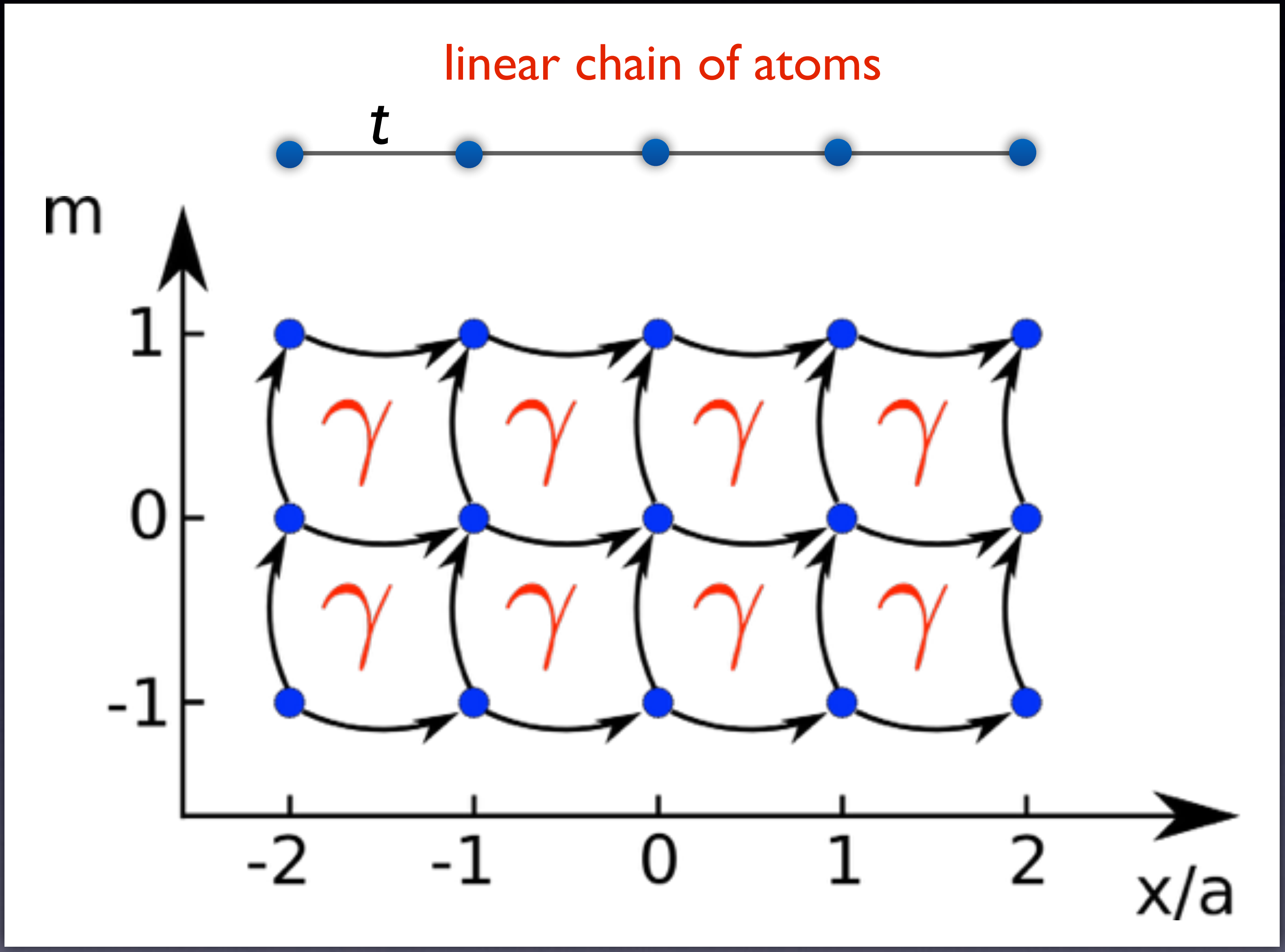




Implementation

laser-assisted
position-dependent
spin-tunneling

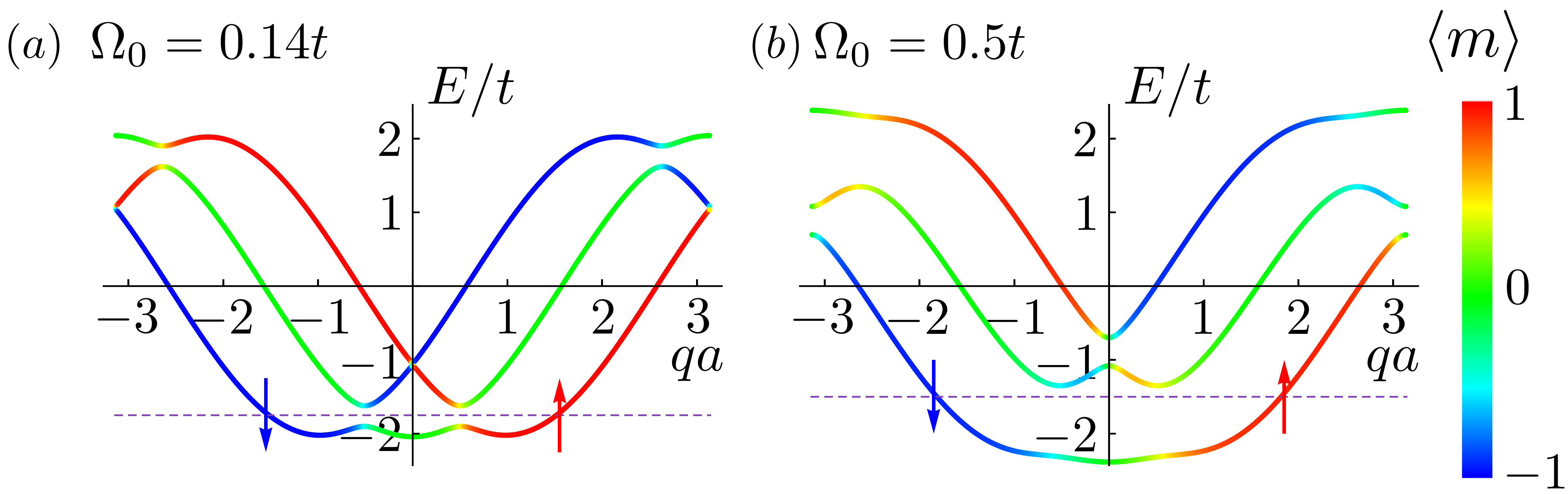




yields strong and non-staggered magnetic fluxes
and "∞-ranged interactions"

A. Celi, PM, J. Ruseckas, N. Goldman, I. Spielman, G. Juzeliunas, and M. Lewenstein, arXiv:1307.8349

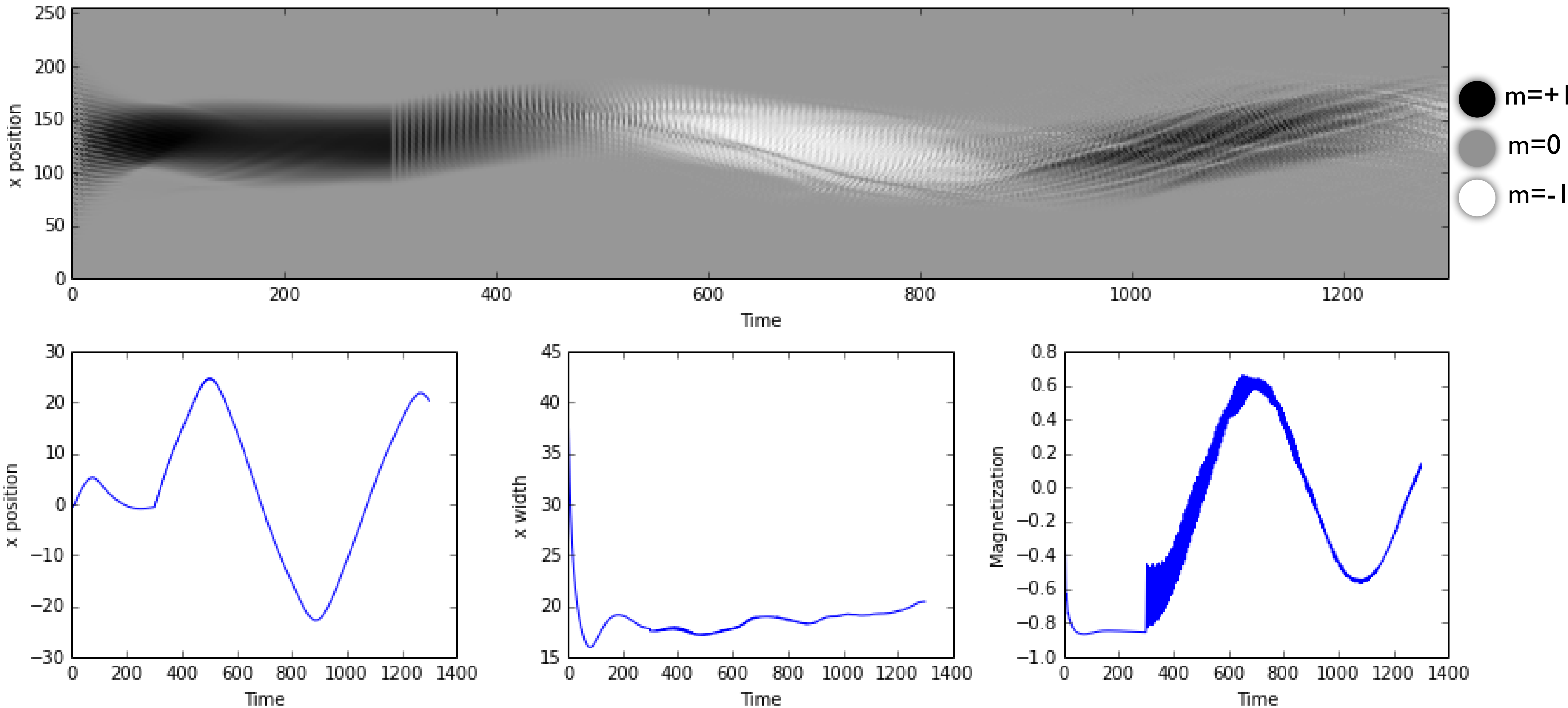
Spectrum



States inside the Raman-gap have $|\langle m \rangle| \approx F$,
i.e., are **chiral edge states on the synthetic lattice**

Edge state dynamics

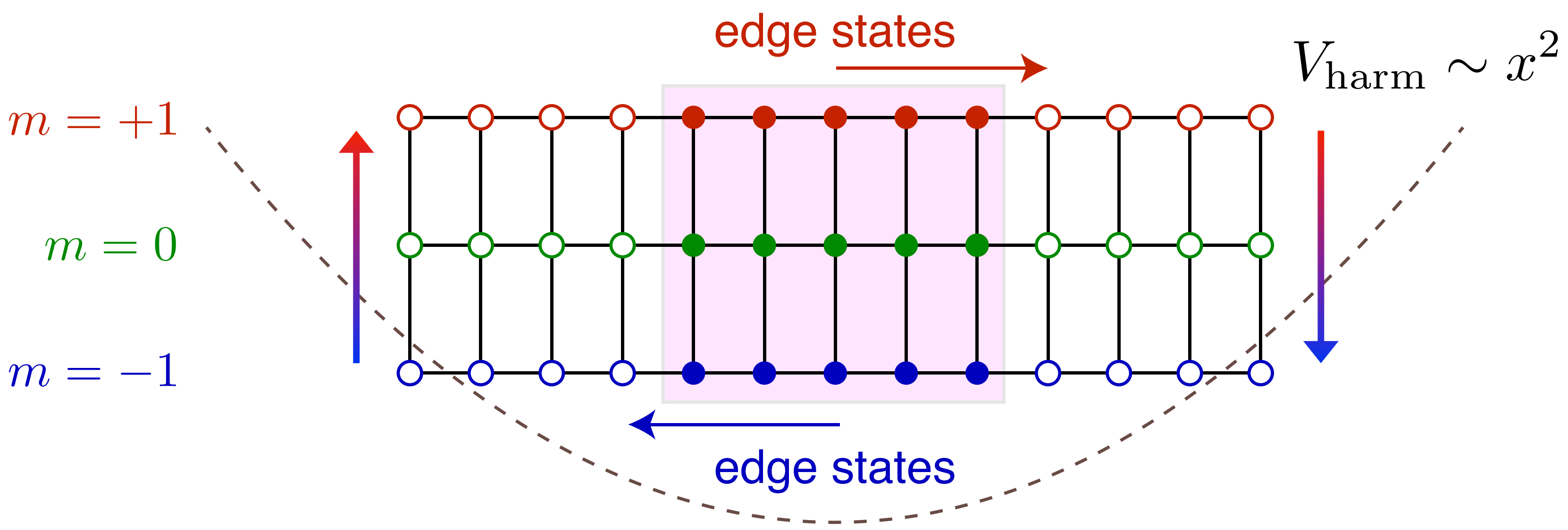
An F=1 ^{87}Rb gas in a harmonic trap
fot t<300, an energy detuning keeps the gas in m=+1
the detuning is set to zero for t>300, starting out of phase oscillations in x- and spin-directions



Edge state dynamics

An “F=1 Fermi gas” in a harmonic trap

for t<0, the gas is confined by hard walls in the shaded region



$\Omega_0 = 0.5t$

$\Phi = 1/2\pi$

$E_F = -1.4t$

Edge state dynamics

An "F=1 Fermi gas" in a harmonic trap

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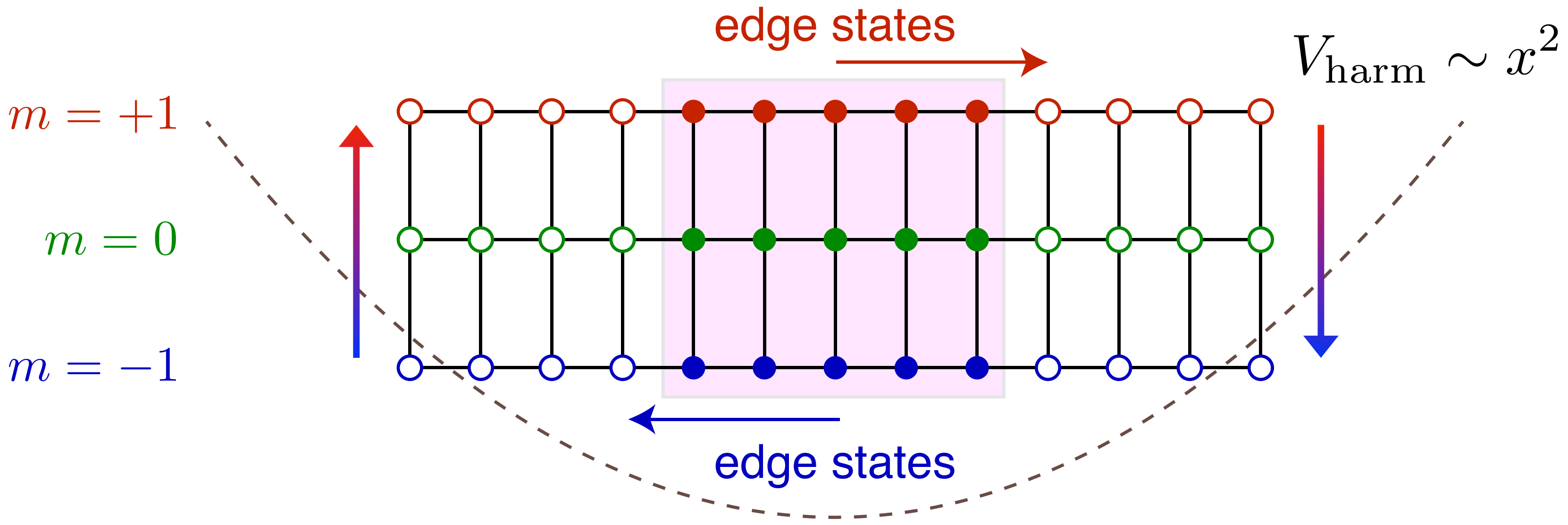
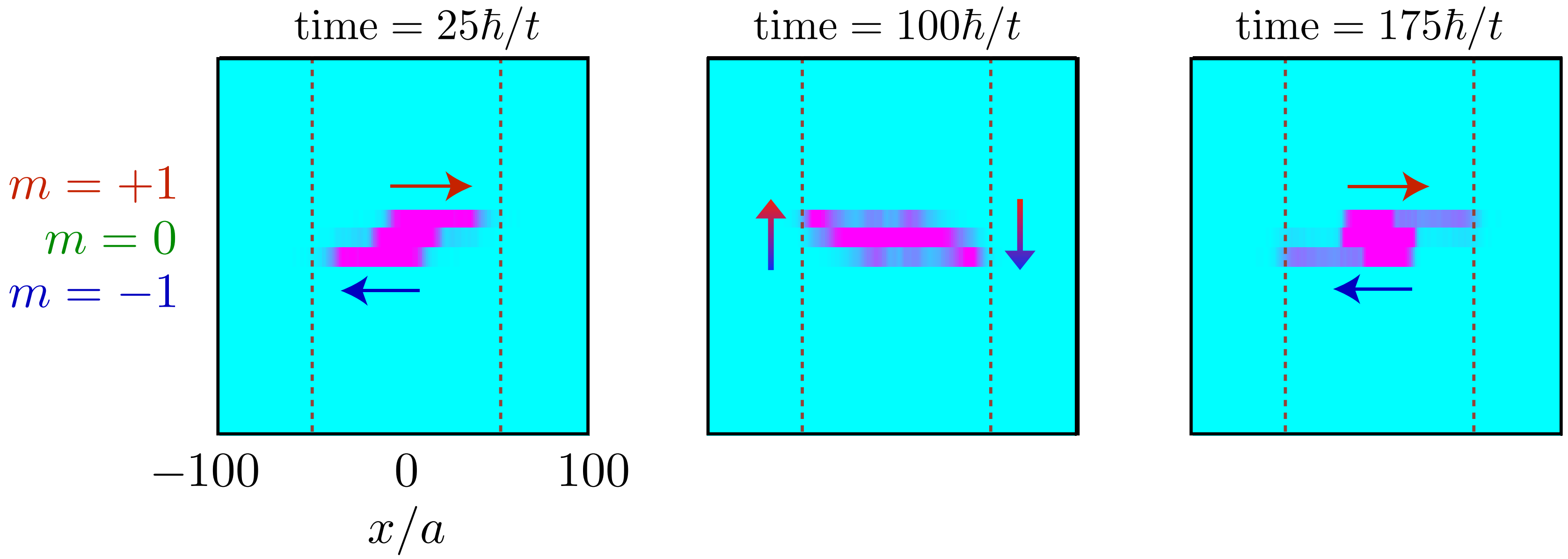


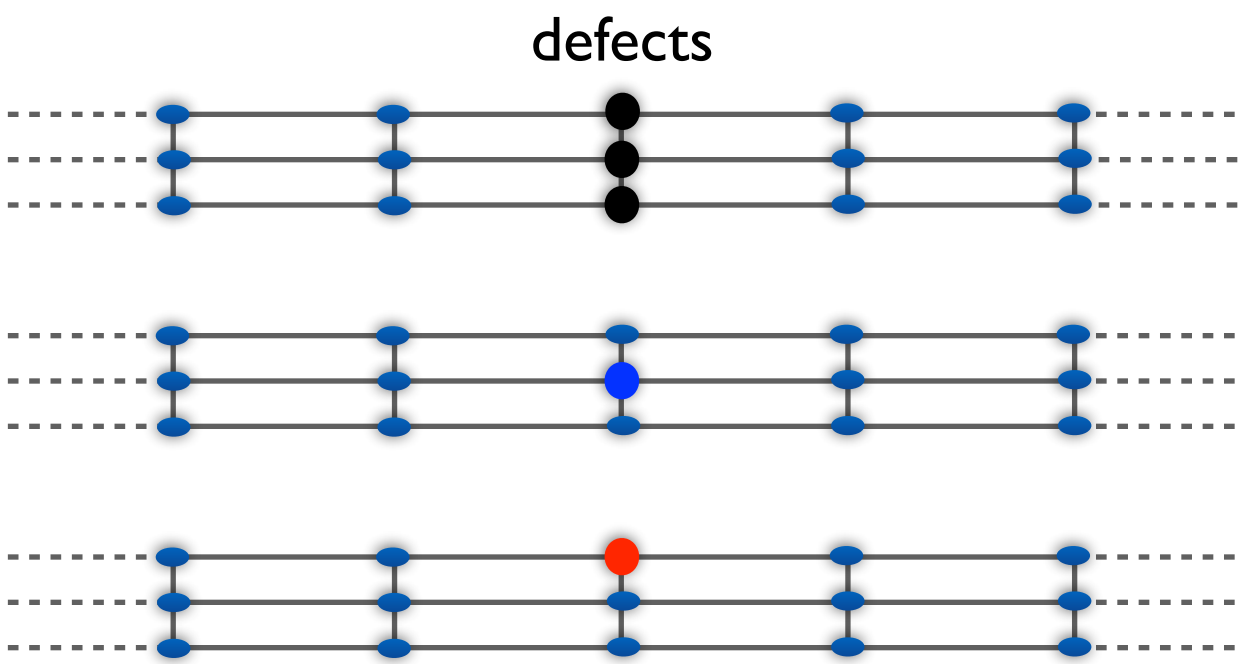


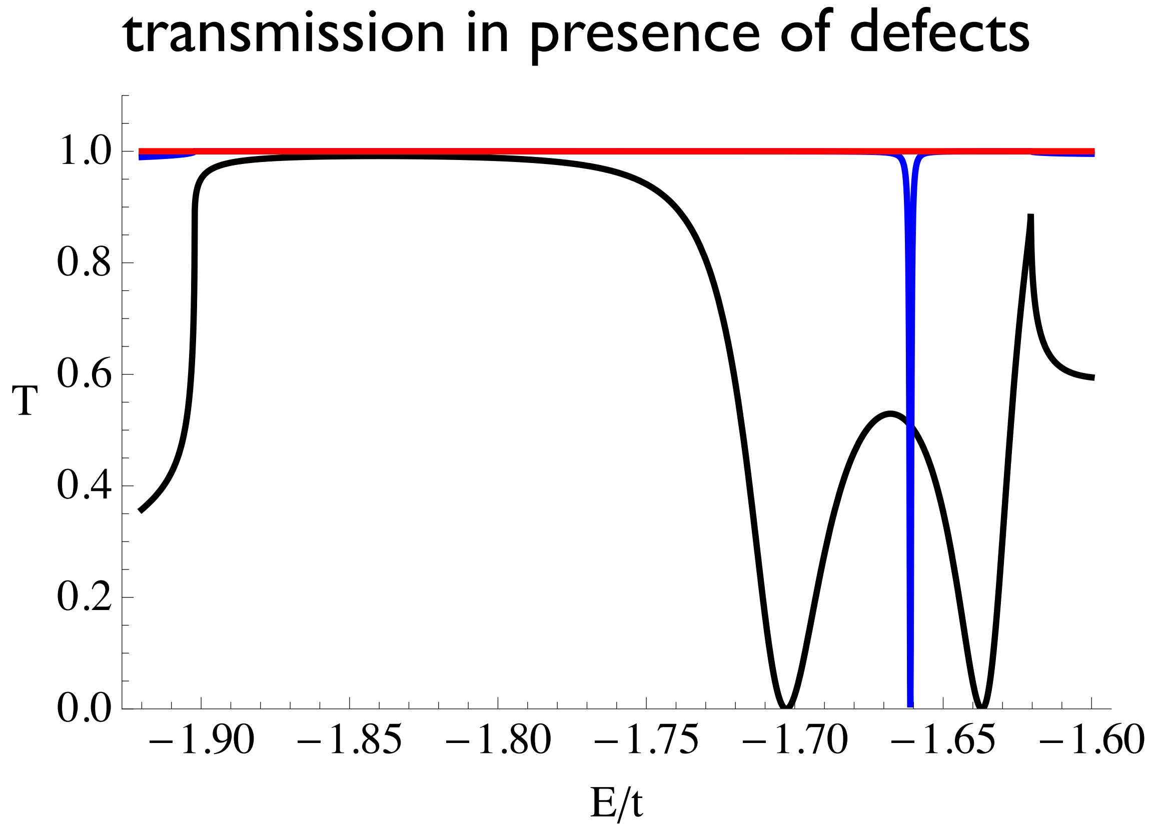
$\Omega_0 = 0.5t$

$\Phi = 1/2\pi$

$E_F = -1.4t$

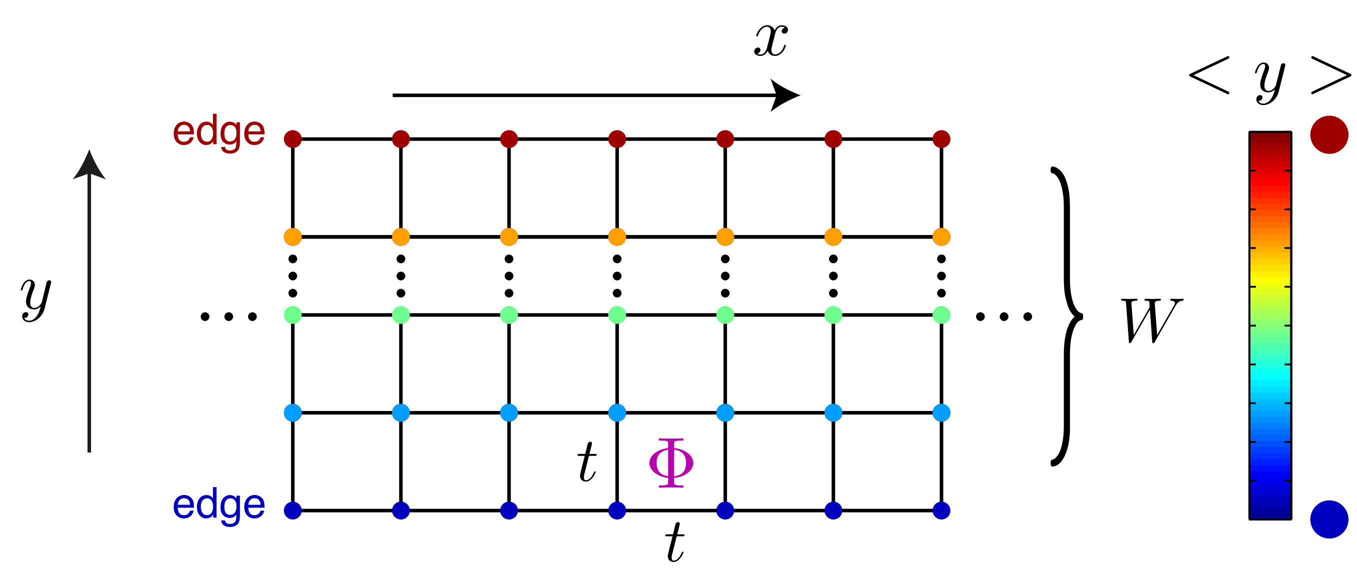
Transmission across defects

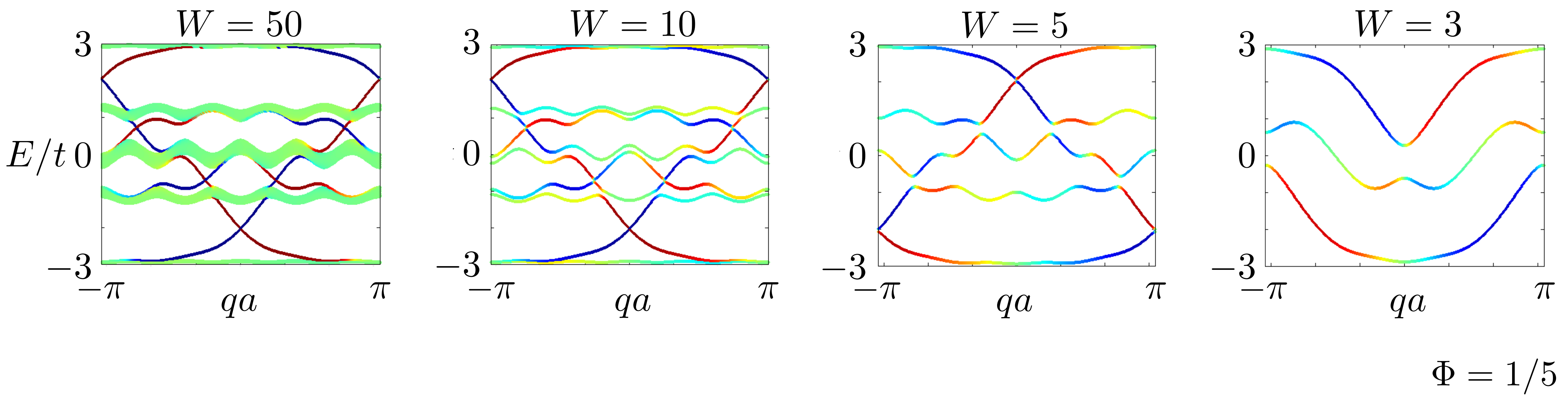




Hofstadter strip

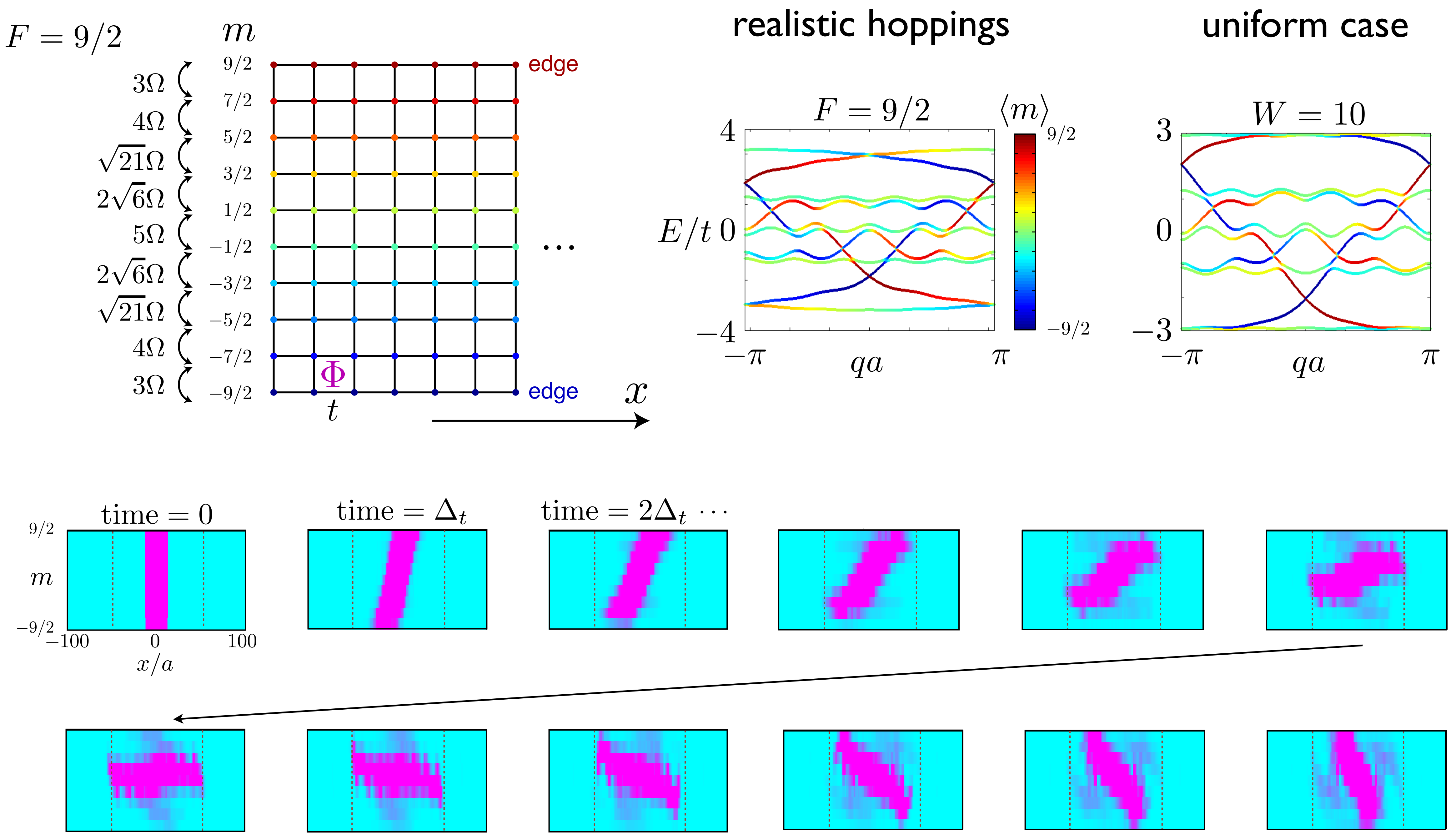
Regular 2D square N*W lattice, pierced by a uniform magnetic field:





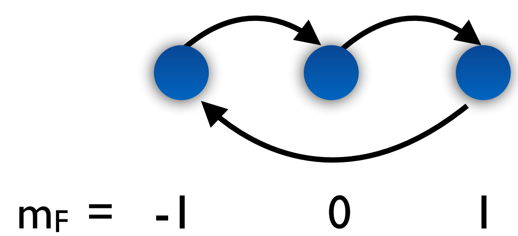
for a detailed discussion of the case W=2, see also: D. Hügel and B. Paredes, arXiv:1306.1190

Edge state dynamics for ^{40}K



From open to closed b.c.

+



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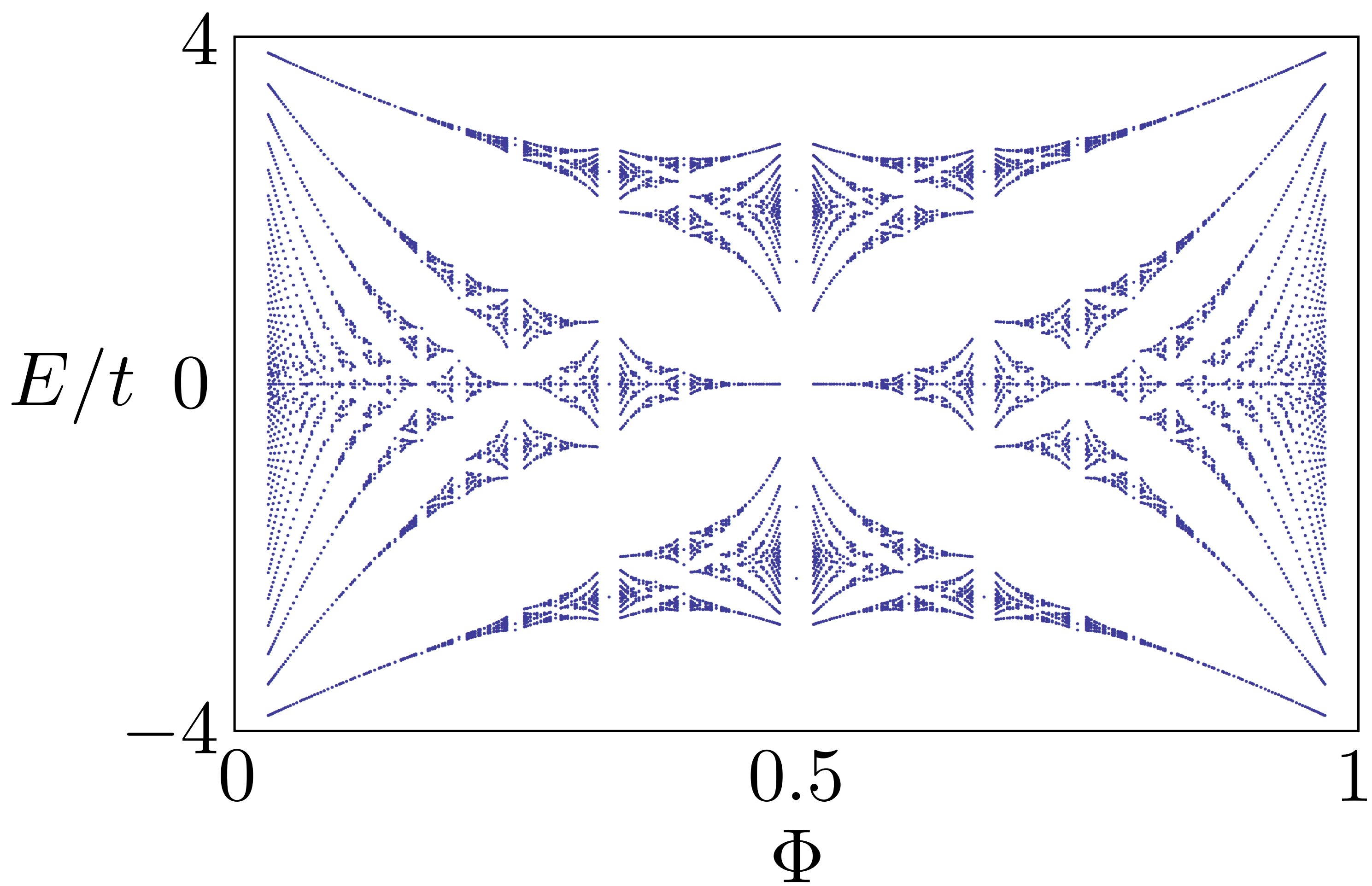
Energy spectrum of spin-1 atoms with closed b.c. and non-zero flux

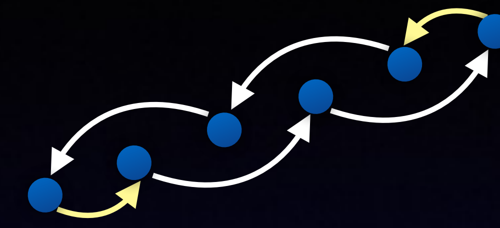
Periodic boundary conditions along $\mathbf{e}_m$ can be induced with an extra coupling $|m=1\rangle \leftrightarrow |m=-1\rangle$ accompanied by a momentum recoil k_R along $\mathbf{e}_x$.
The system becomes periodic IFF $\Phi=P/Q$ with P,Q co-prime integers.

# of loops needed for periodicity: l/W where $l=LCM(W,Q)$ [thus Q or $Q/3$ for W=3]

The spectrum has the fractal structure of a **Hofstadter butterfly**:

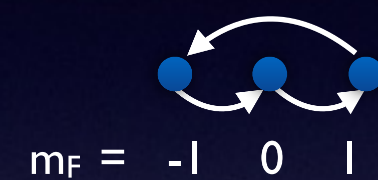


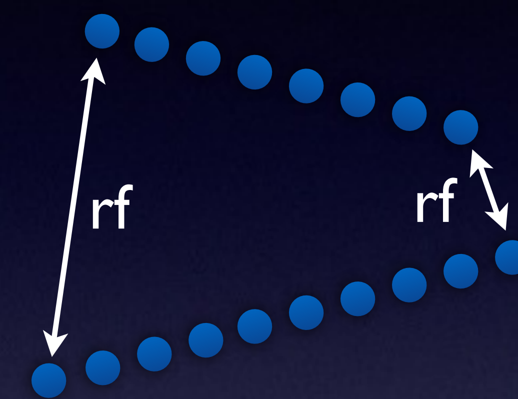
Interesting topologies

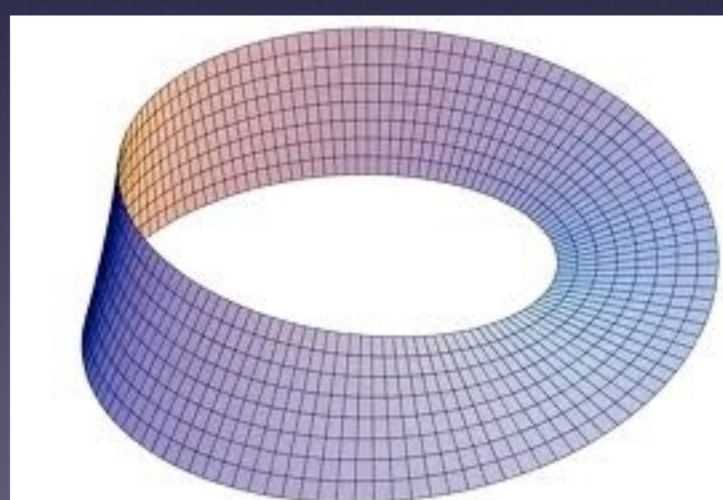


possible boundary conditions along the spin direction:

- open
- closed
- twisted (a closed loop encircles a phase)





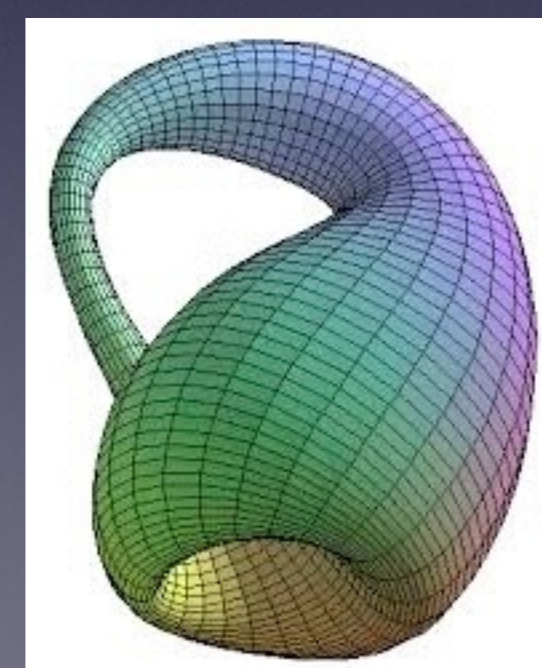


Möbius strip

linear chain in the spatial dir.,
π/2 twist in spin

Klein bottle

ring in the spatial dir.,
π/2 twist in spin



Interactions: SU(W)-invariant case

$$H_{\text{int}} = \frac{\mathcal{U}}{2} \sum_n \mathcal{N}_n(\mathcal{N}_n - 1) \quad \text{with} \quad \mathcal{N}_n \equiv \sum_m a^\dagger_{n,m} a_{n,m}$$

Interactions are local along $\mathbf{e}_m$, but infinite in range along $\mathbf{e}_m$!

For SU(W)-invariant interactions, there exists a basis $\{c_{n,j}\}$ in which the Hamiltonian is diagonal in the spin direction. Denoting its eigenvalues by $\{\epsilon_{n,j}\}$ we can minimize the energy for fixed $\langle H_{\text{int}} \rangle$ by populating only the states with lowest ϵ_{n,j_n}, as this minimizes the kinetic term $\langle H \rangle$.

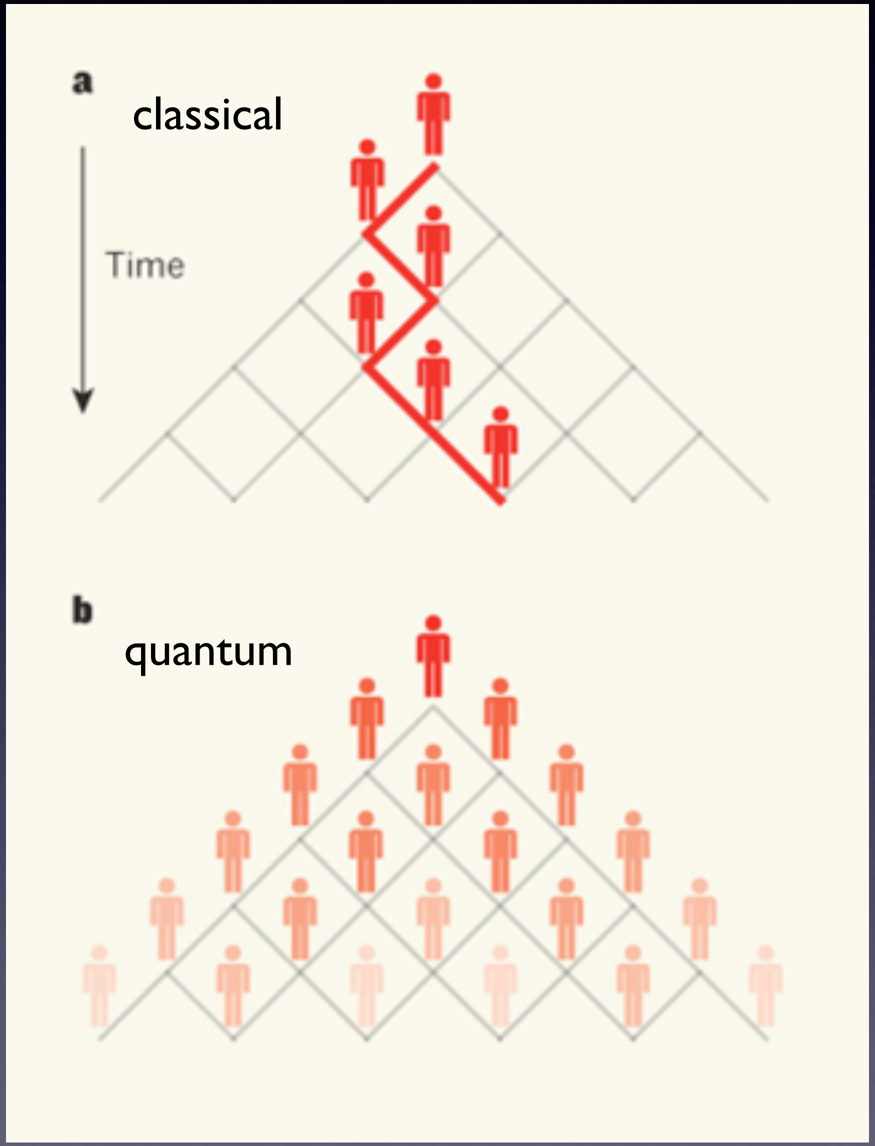
Ground state of the interacting system:

•if the local (spin) ground state is not degenerate, the global ground state can be mapped to the one of a 1D uniform Bose-Hubbard chain

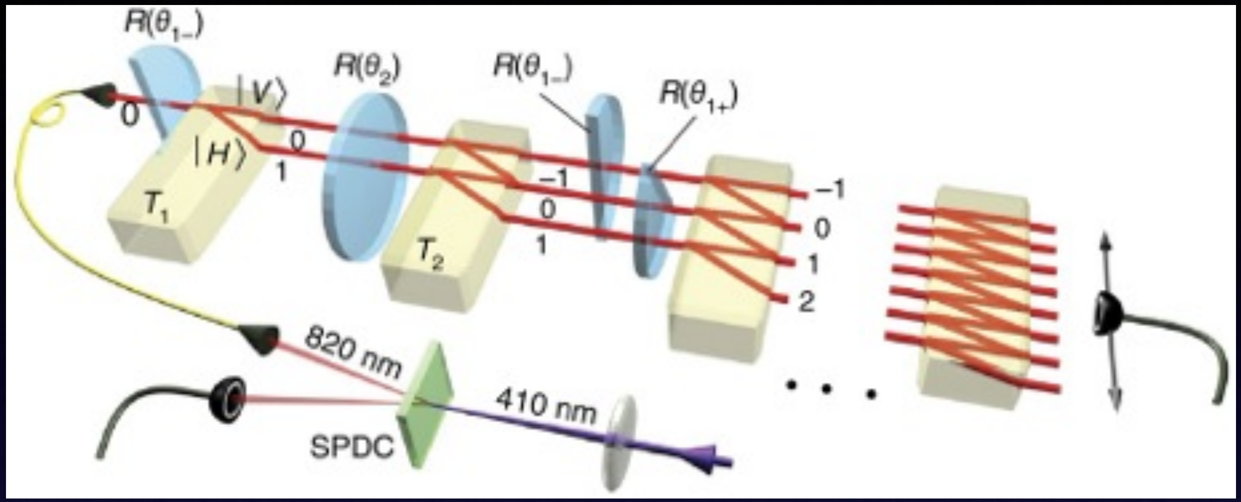
•if $\epsilon_{n,j}$ is minimal for two of the W values of j, the ground state of the 1D chain will possess a primitive cell containing Q consecutive lattice points

(degeneracy is possible only for closed spin-b.c. and rational Φ. For open b.c., the eigenvalues are independent of γ and of n, and never degenerate)

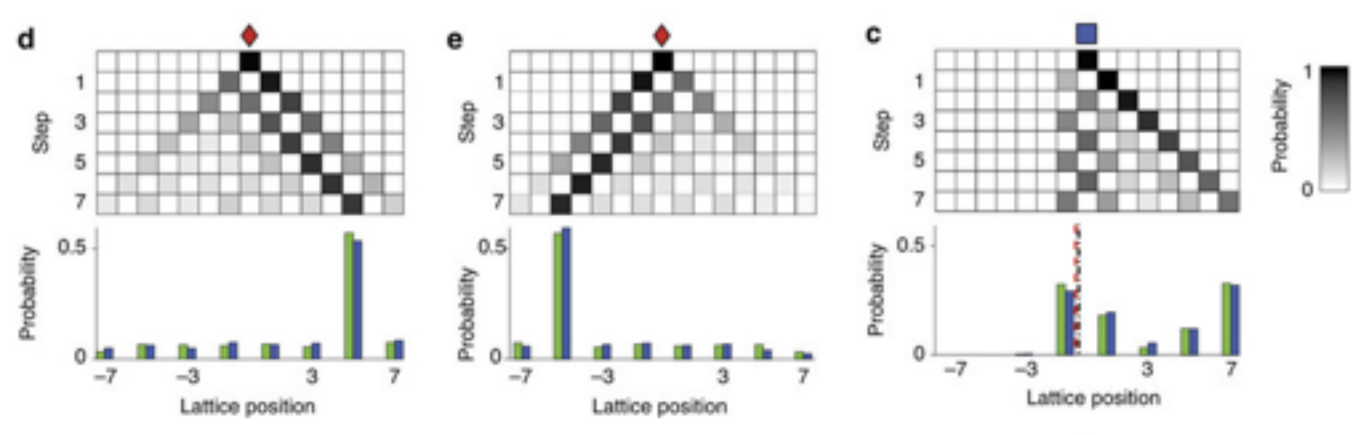
Quantum walks



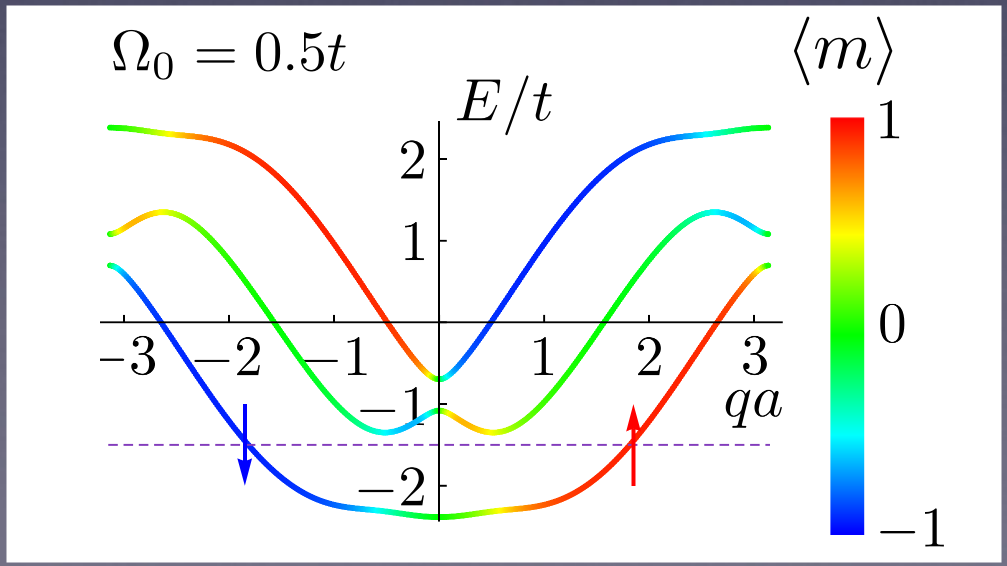
spin↑ move right,
spin↓ move left



Experimental realization in photonic systems
T. Kitagawa et al., Nat. Comm. **3**, 882 (2012)



use edge states
as q. walkers?



Conclusions

- Synthetic gauge fields yield *non-trivial hopping phases*
- Using an internal d.o.f. as an extra-dimension:
  - ★ uniform fluxes and robust edge states
  - ★ ∞-ranged interactions
  - ★ novel cooling schemes possible?
  - ★ quantum simulation of high-energy theories, and D>3 systems? (e.g., critical exponents of phase transitions)

Synthetic gauge fields in synthetic dimensions

A. Celi, P. Massignan, J. Ruseckas, I. Spielman, G. Juzeliunas, and M. Lewenstein, arXiv:1307.8349