SYNTHETIC GAUGE FIELDS FOR ULTRACOLD ATOMS IN SYNTHETIC DIMENSIONS

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Outlook

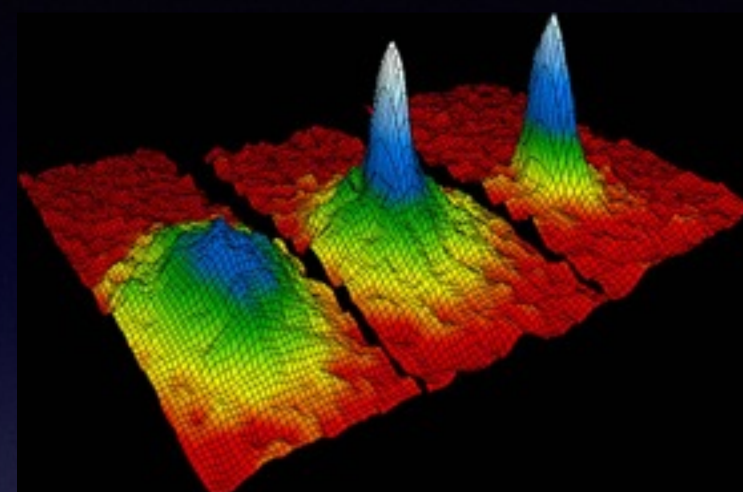
Ultracold quantum gases

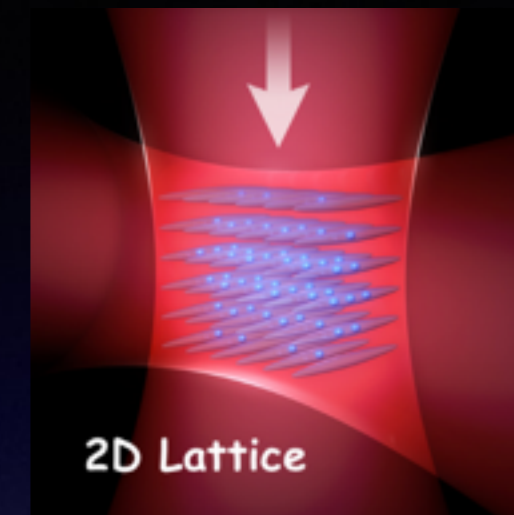
Synthetic gauge fields

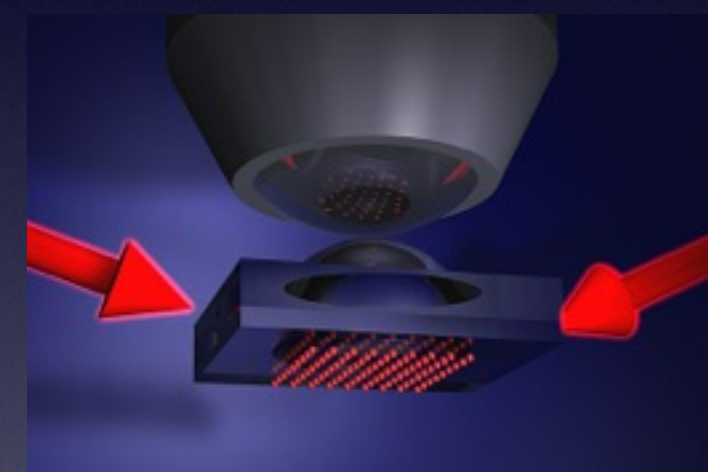
Synthetic dimensions

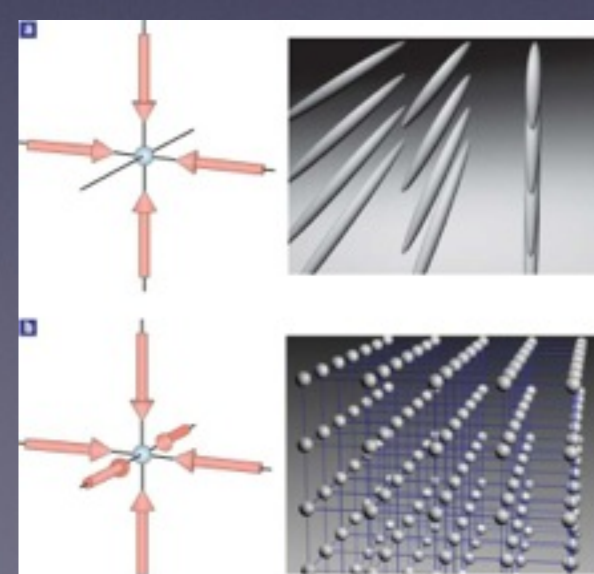
Ultracold quantum gases

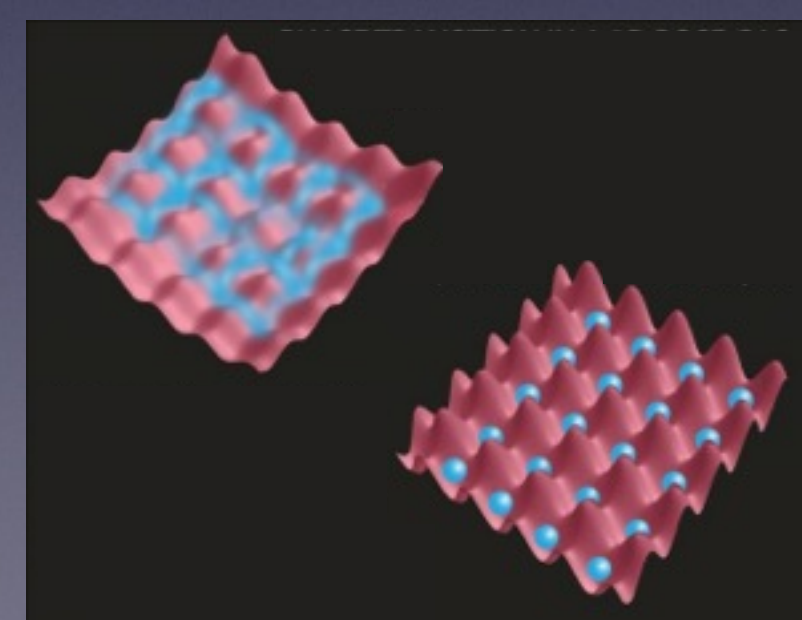
- neutral atoms (~alkali)
- bosons/fermions
- very dilute gas (d~µm)
- ultracold ($T<T_c$~100nK)
- slow (E~kHz)
- isolated
- clean (but dopable)
- negligible spin-orbit coupling (but..)
- tuneable:
  - ⋆ chemical potential
  - ⋆ interactions
  - ⋆ geometries





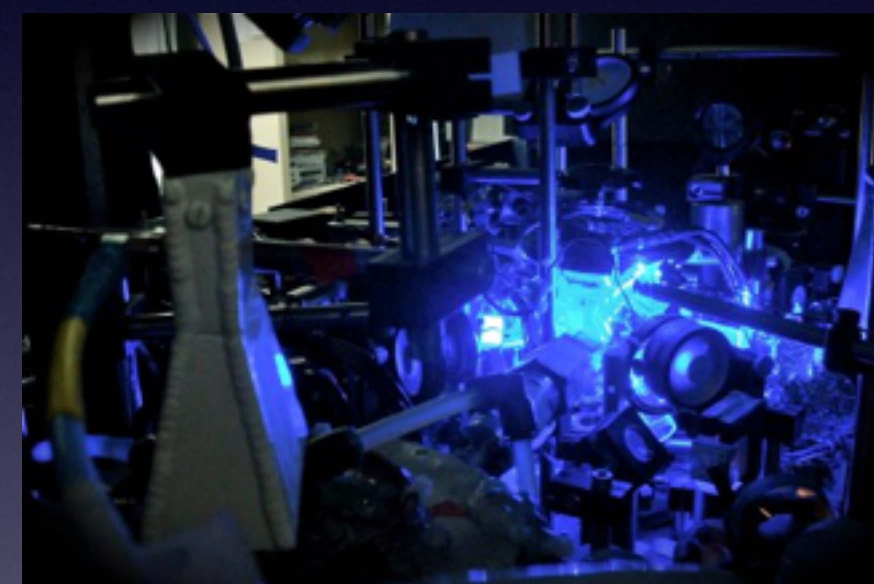






Ideal quantum playground

$$i\hbar\partial_t|\psi\rangle = (H_0 + H_{\text{int}} + H_{\text{so}} + \ldots)|\psi\rangle$$



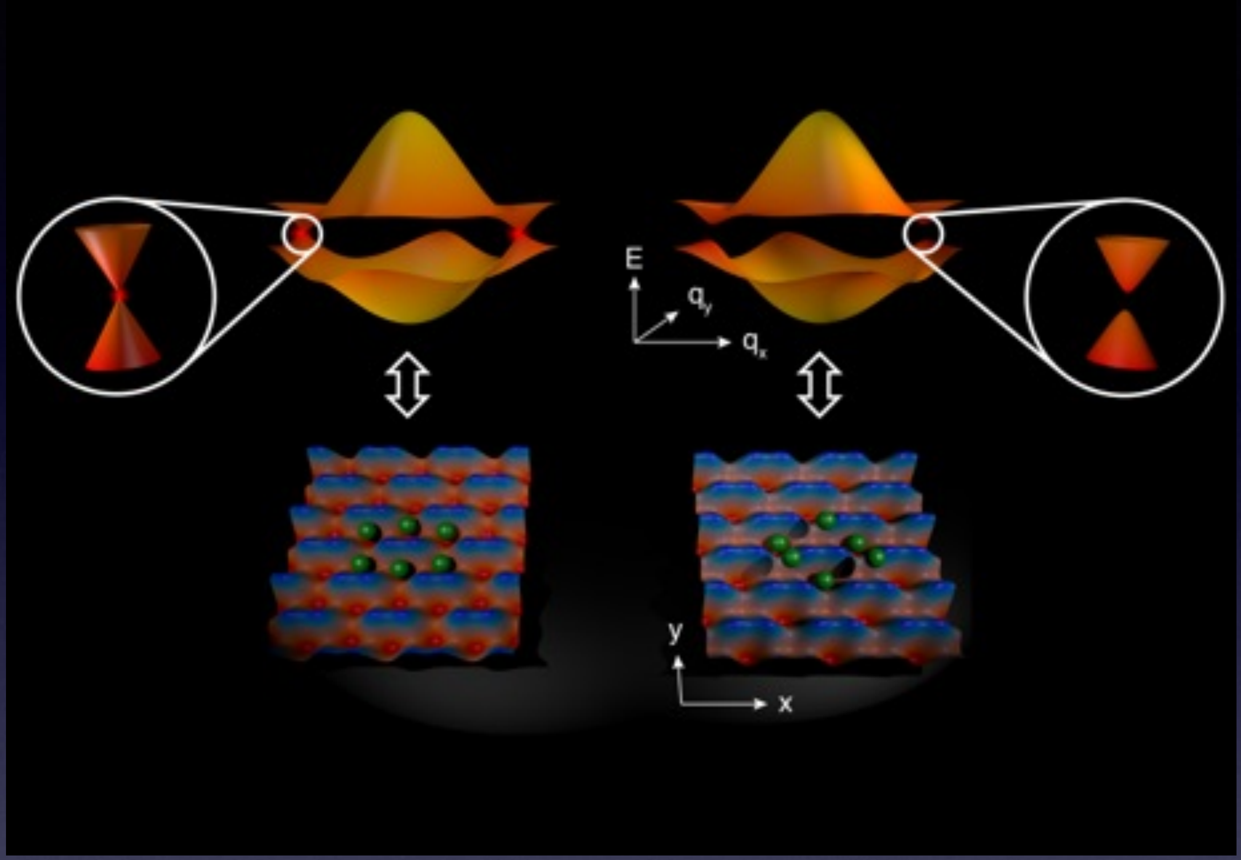
Topological states predicted in:

- fermionic p-wave superfluids*
- 1D atomic chains in a superfluid bath
- fermionic s-wave superfluids in non-Abelian gauge fields**
- …

My contributions in these directions:
* PM, Sanpera, and Lewenstein, PRA (2010)
** Kubasiak, PM, and Lewenstein, EPL (2010)

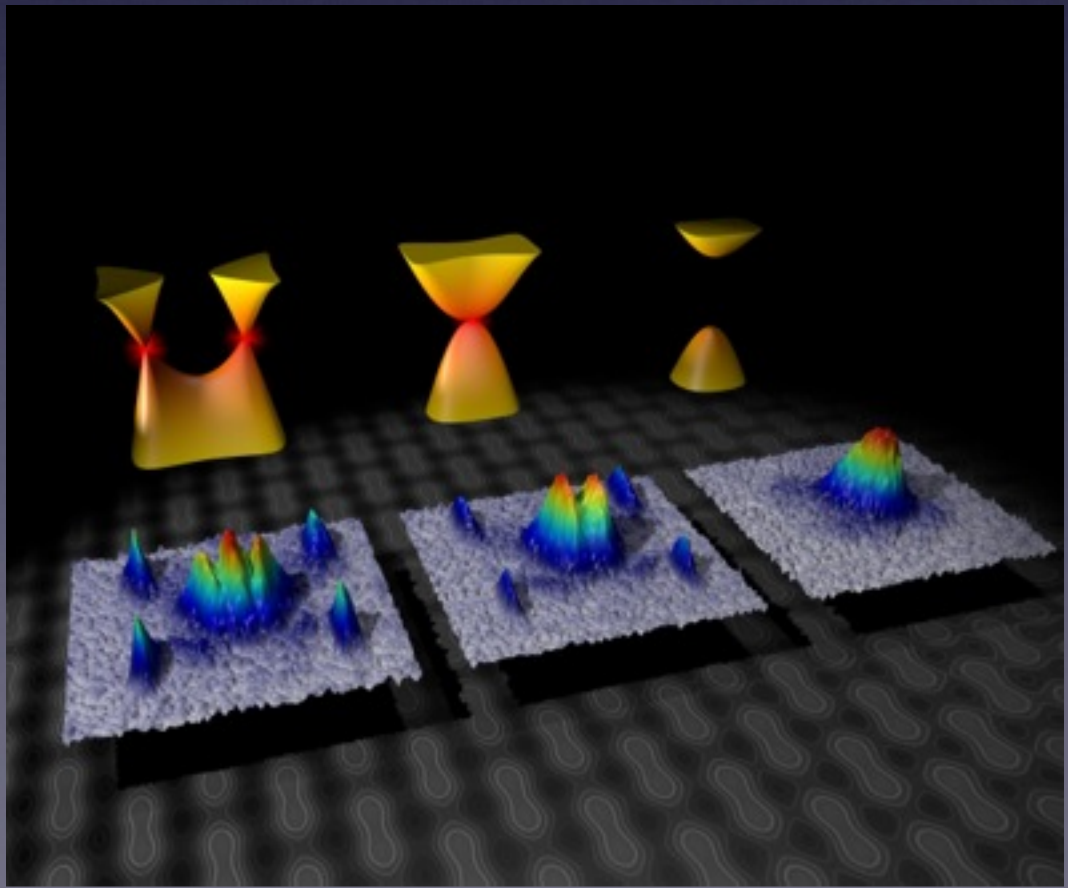
Tuning the honeycomb

(a graphene emulator with variable lattice geometry)



- break A/B sublattice inversion symmetry makes Dirac fermions massive
- deform the lattice to displace, merge and annihilate pairs of Dirac cones

ETH group: Tarruell et al., Nature (2012)



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Gauge fields in QM

Free space (minimal coupling): $\frac{p^2}{2m} \longrightarrow \frac{(\mathbf{p} - e\mathbf{A})^2}{2m}$

$\phi_{n,m} = \frac{e}{\hbar} \int_{\mathbf{r}_{n,m}}^{\mathbf{r}_{n+1,m}} \mathbf{A} \cdot \mathrm{d}\mathbf{s}$

Lattice (Peierls' subst.): $-t \sum_{\langle n,m \rangle} a^\dagger_{n+1,m} a_{n,m} \longrightarrow -t \sum_{\langle n,m \rangle} \mathrm{e}^{i\phi_{n,m}} a^\dagger_{n+1,m} a_{n,m}$

Problem: atoms are charge-neutral
Solution: engineer synthetic ones?

Proposals: Jaksch&Zoller, NJP 2003
Osterloh et al., PRL 2005
… (and hundreds of papers more) …

Methods:

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

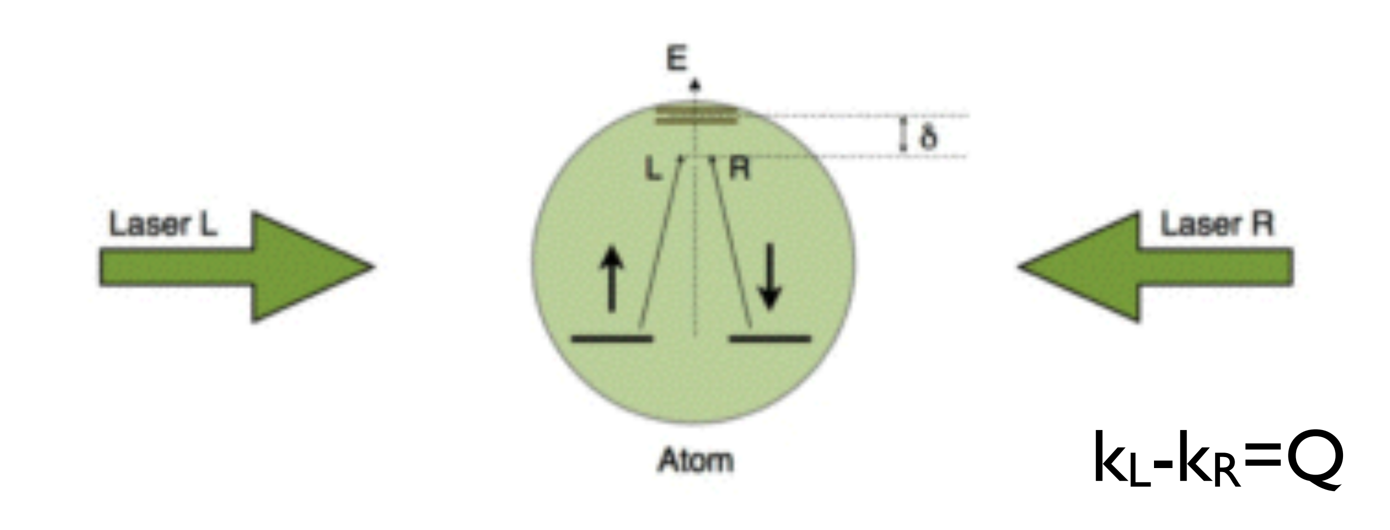
REVIEWS:

Artificial gauge potentials for neutral atoms
Dalibard, Gerbier, Juzeliunas, and Öhberg, RMP (2011)

Light-induced gauge fields for ultracold atoms
Goldman, Juzeliunas, Öhberg, and Spielman, arXiv (2014)
(Rep. Prog. Phys., in press)

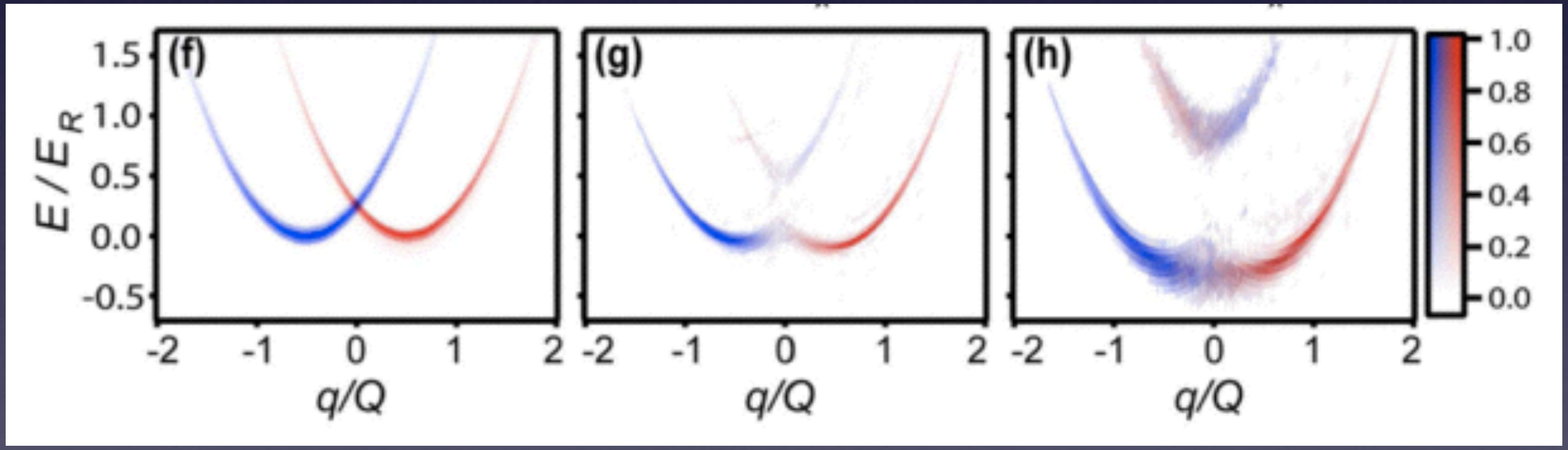
Spin-orbit coupling for neutral atoms

off-resonant
two-photon
Raman transitions



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

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



spin-orbit gap

increasing intensity of Raman lasers

spin flip ↔ momentum kick

Lin et al., Nature 2011 (JQI-NIST)
P.Wang et al., PRL 2012 (Shanxi U.)
L.W. Cheuk et al., PRL 2012 (MIT)

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Q. Sim. & Extra Dimensions

Quantum simulation with ultracold atoms:

- Hubbard model, MI/SF transition, …
- relativistic dispersions, sonic black holes, …
- strongly-correlated states (QH, spin liquids, …)

Extra dimensions (=non-spatial):

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

extra-dims are usually discrete and compact

quantum simulation <u>of</u> an extra dimension?

The simple idea

- use a system with D spatial dimensions
- encode the (D+1)th dimension in an internal degree of freedom (e.g., the spin)

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

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

$$= -\sum_{\sigma=1}^{N} \left[\sum_{d=1}^{D} \sum_{\mathbf{r}} \underbrace{J_d \hat{a}^{(\sigma)\dagger}_{\mathbf{r}+\mathbf{u}_d} \hat{a}^{(\sigma)}_{\mathbf{r}}}_{\text{usual hopping (conserves spin)}} + \underbrace{J_\sigma \hat{a}^{(\sigma+1)\dagger}_{\mathbf{r}} \hat{a}^{(\sigma)}_{\mathbf{r}}}_{\text{couple consecutive spin states ("spin hopping")}} \right] + \mathrm{h.c.}$$

usual hopping (conserves spin)

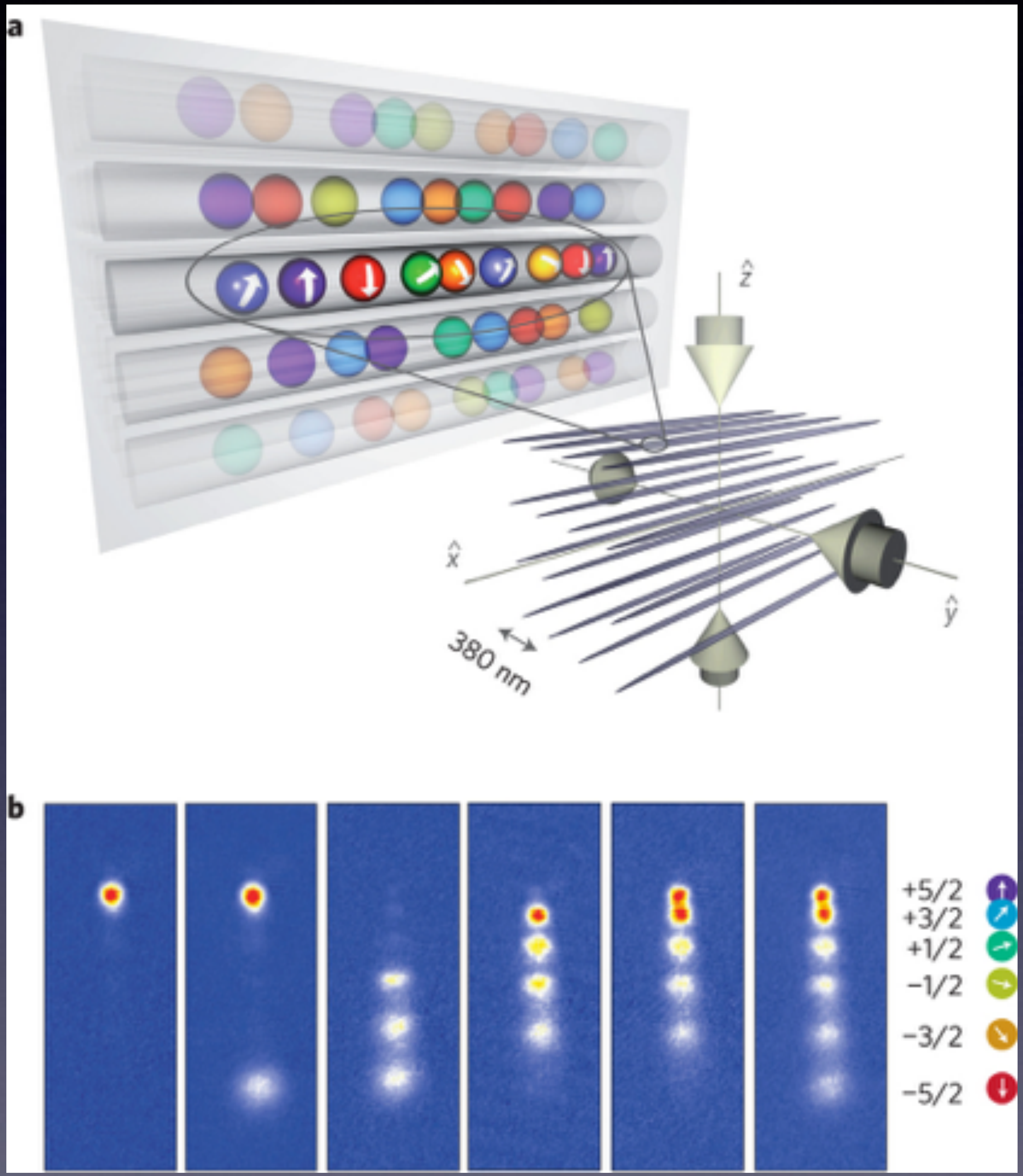
couple consecutive spin states (”spin hopping”)

Celi, PM, Ruseckas, Goldman, Spielman, Juzeliunas, and Lewenstein, PRL (2014)

Large N systems

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

^{173}Yb @ LENS:
Pagano et al.
Nat. Phys. (2014)

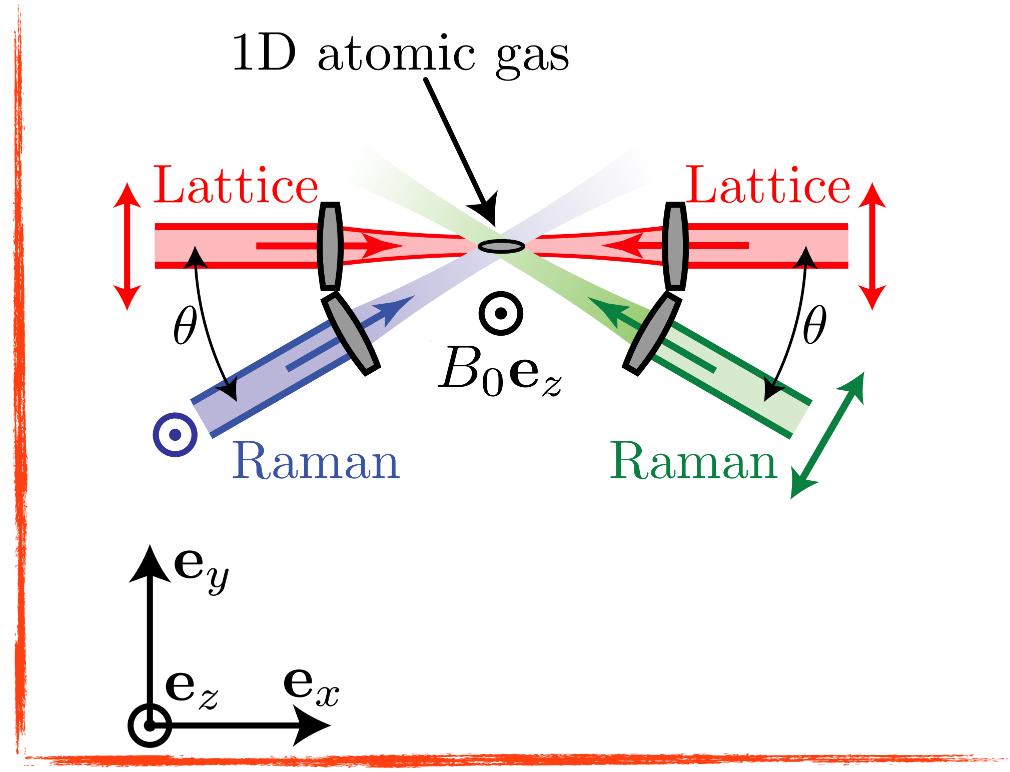


interactions in earth-alkali atoms are SU(N) invariant!

Simplest implementation

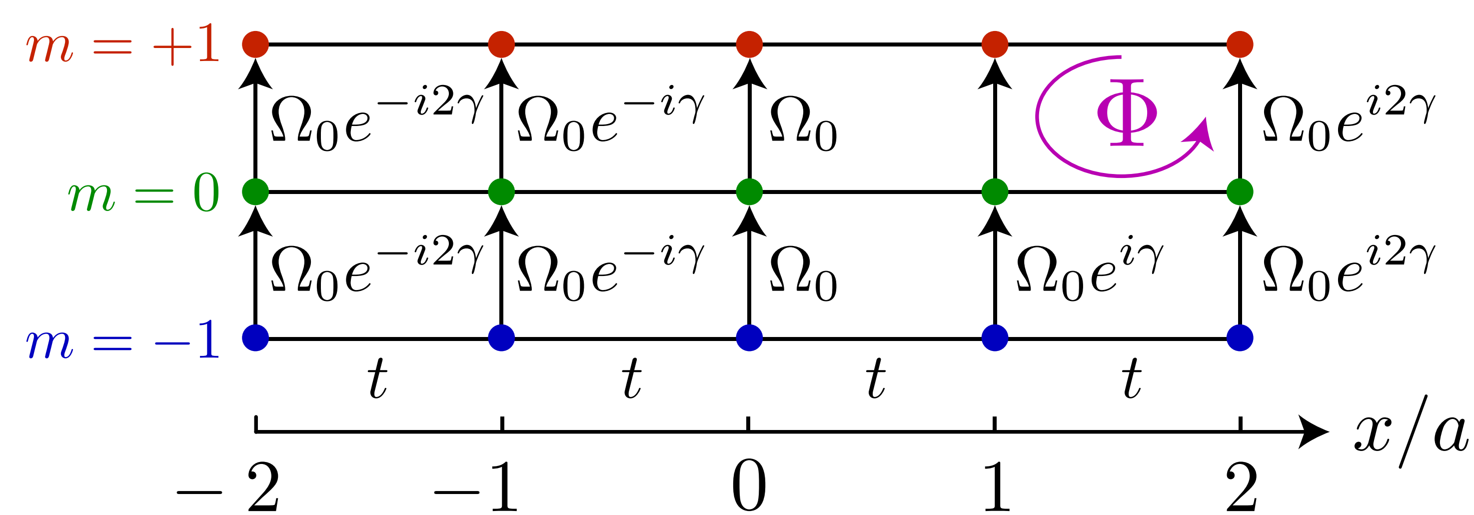
Requires:

- atoms with three addressable internal states in a 1D optical lattice (e.g., F=1 ^{87}Rb)
- two λ_R Raman beams, providing recoil $k_R = 2\pi \cos\theta/\lambda_R$
- uniform B-field in the z-direction



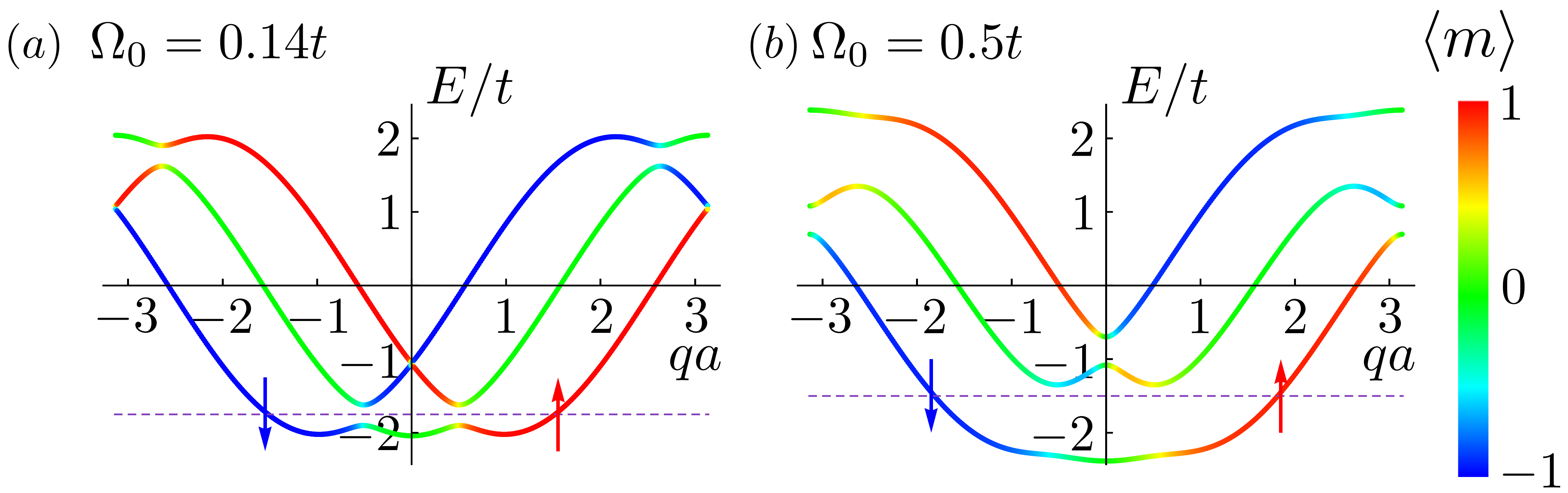
Yields:

- laser-assisted, position-dependent complex spin-tunnellings
- non-staggered magnetic flux Φ
  (and <u>large</u>, easily up to π-flux!)
- "∞-ranged" interactions



Celi, PM, Ruseckas, Goldman, Spielman, Juzeliunas, and Lewenstein, PRL (2014)

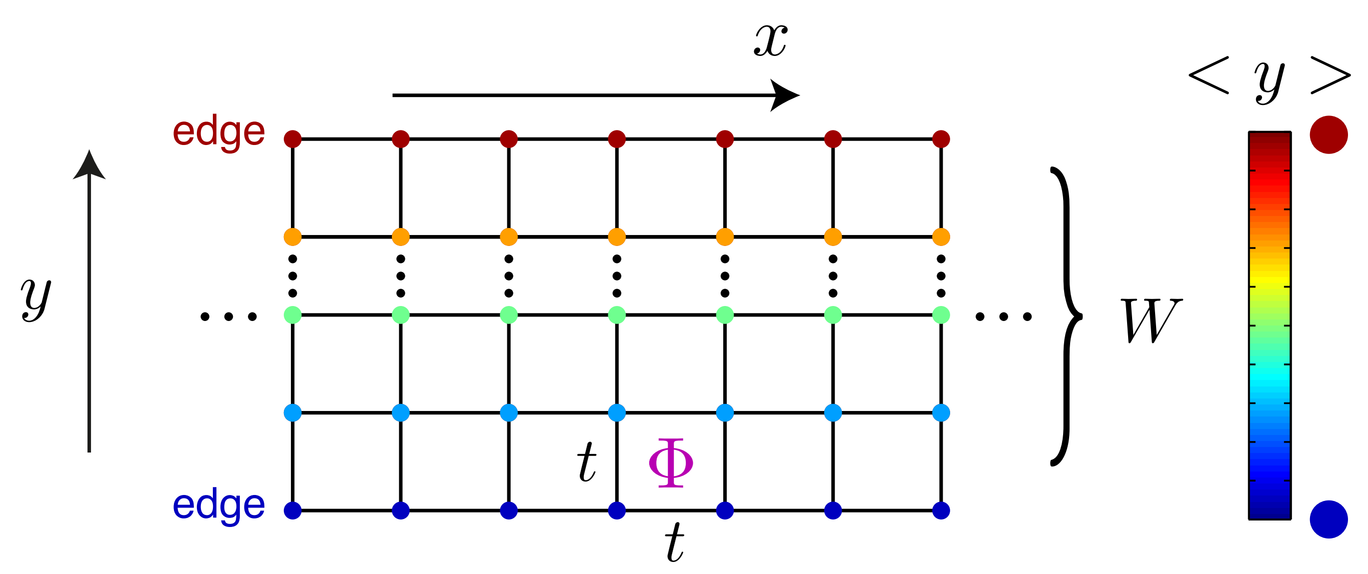
Spectrum with 3 internal states

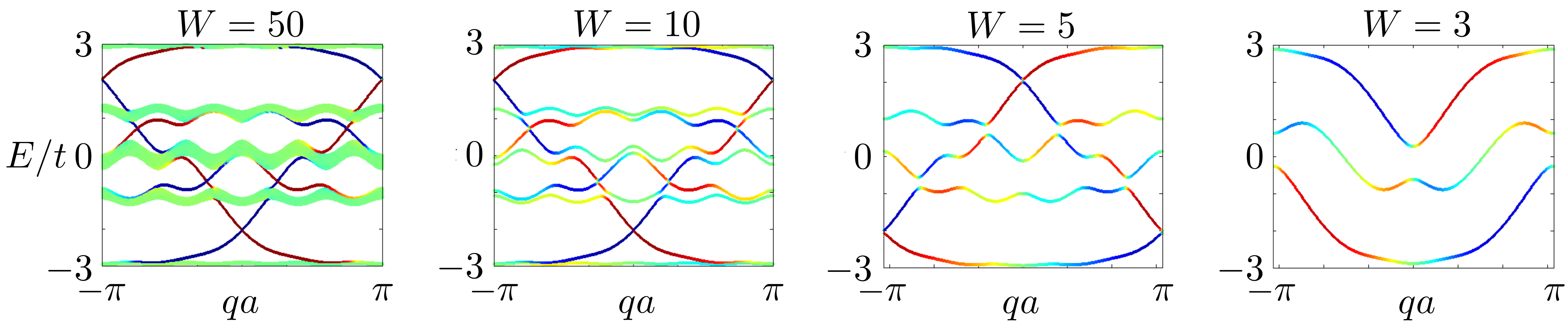


States inside the Raman-gap have $\langle m \rangle \approx \pm 1$
i.e., are **chiral edge states on the synthetic lattice**
(analogous to those found in QH systems)

Hofstadter strip

Our system continuously connects to the textbook problem of a regular 2D square lattice, pierced by a uniform magnetic field:



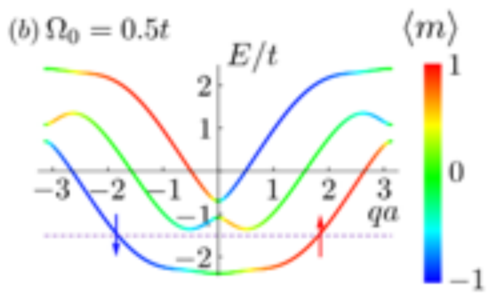


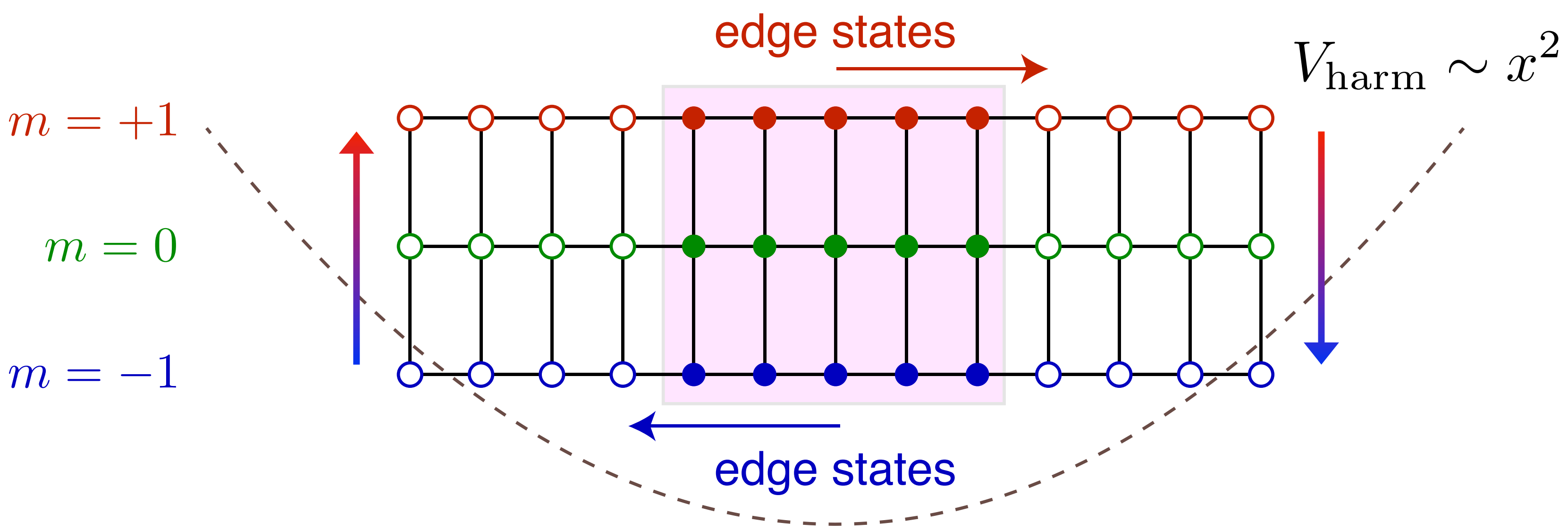
$\Phi = 1/5$

Edge state dynamics

A three-component Fermi gas ("F=1") in a harmonic trap

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





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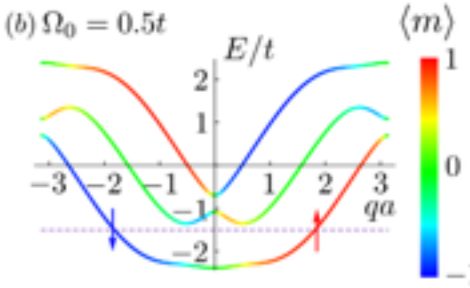

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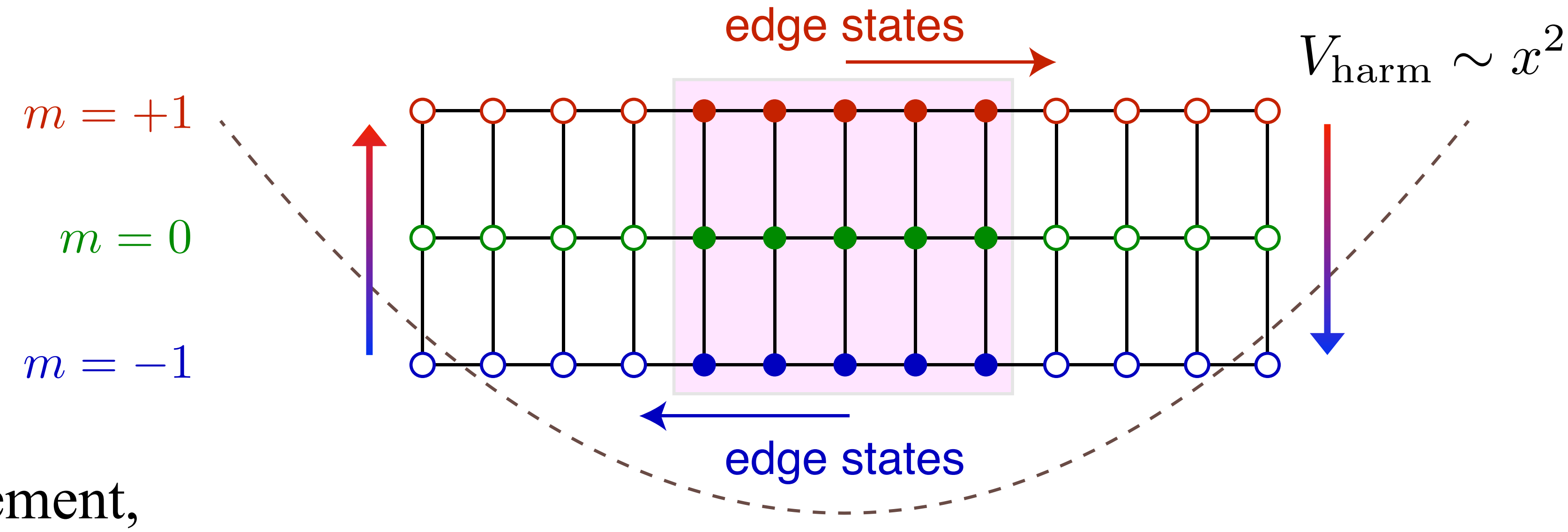
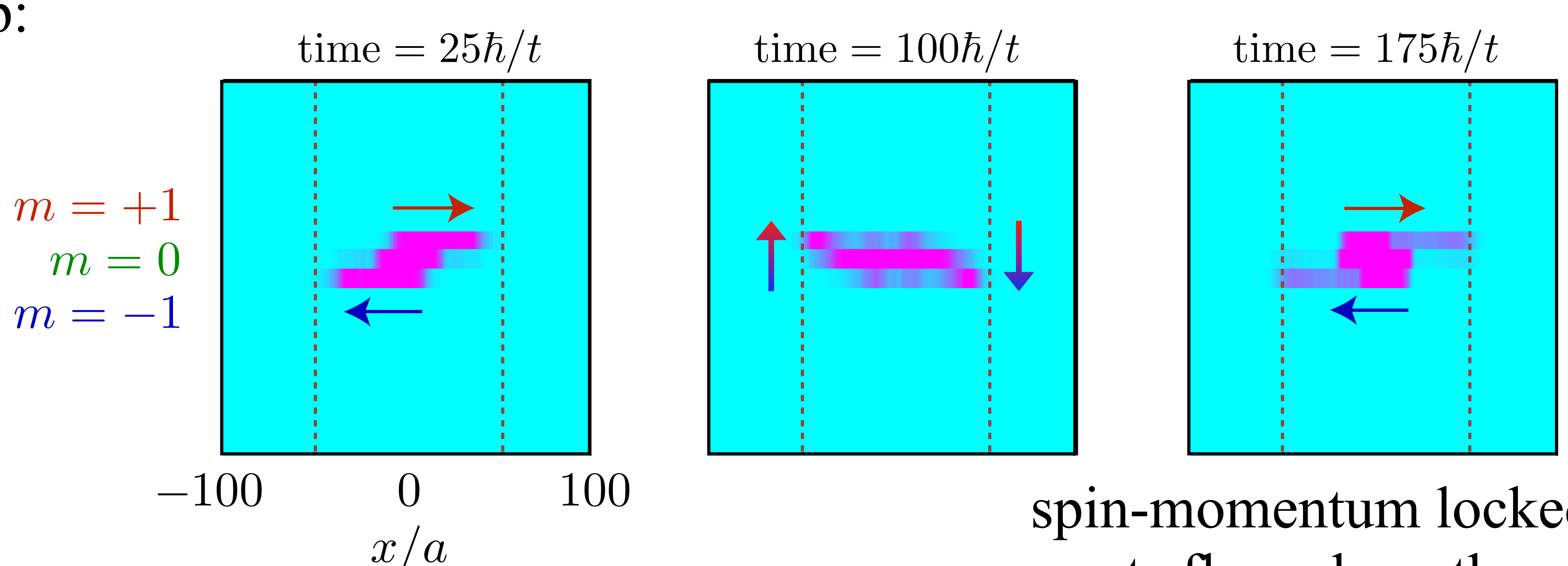


remove the “pink” confinement,
but leave the harmonic trap:



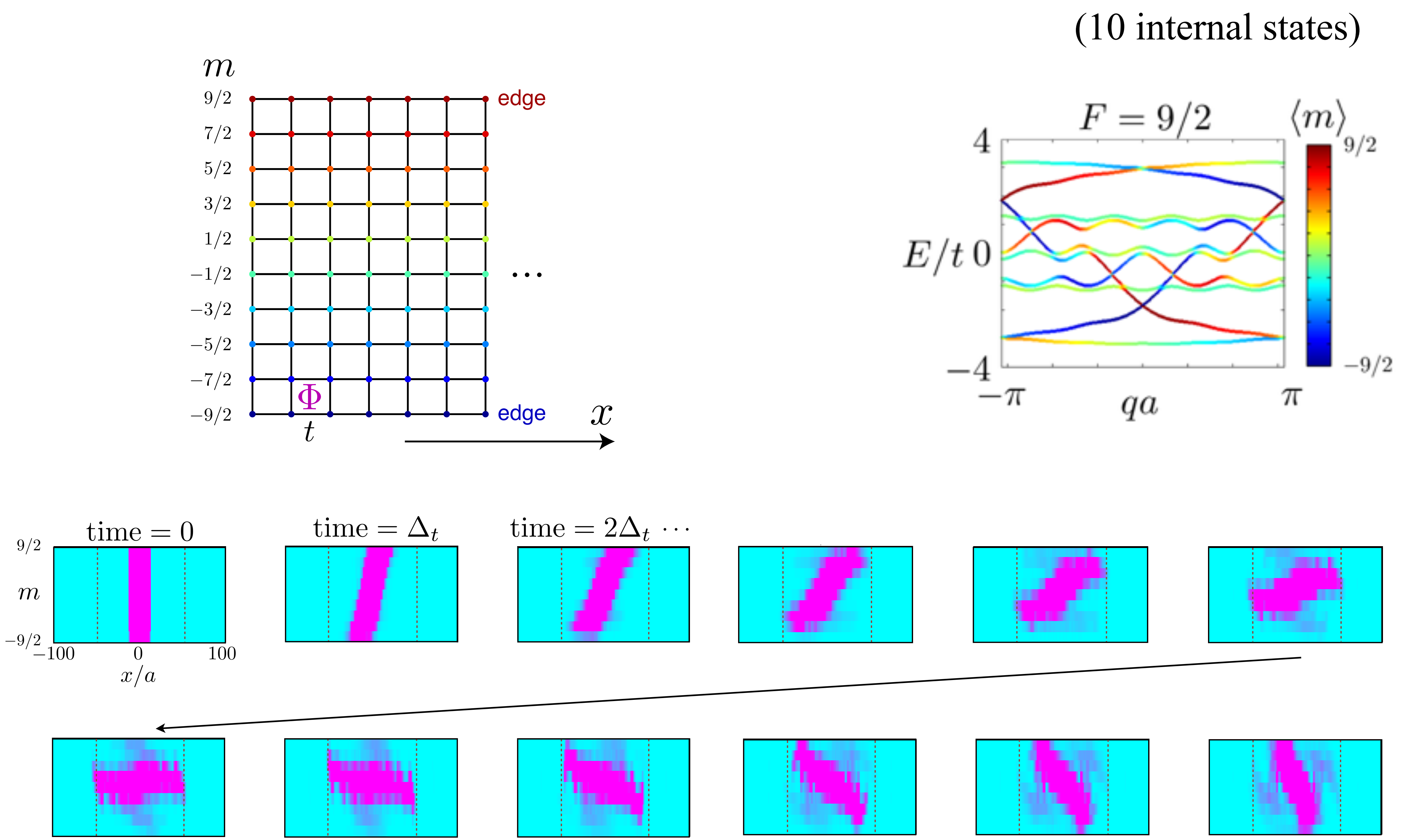
$\Omega_0 = 0.5t$

$\Phi = 1/2\pi$

$E_F = -1.4t$

spin-momentum locked
currents flow along the edge

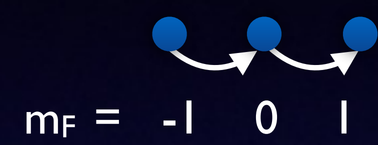
Edge state dynamics for ^{40}K

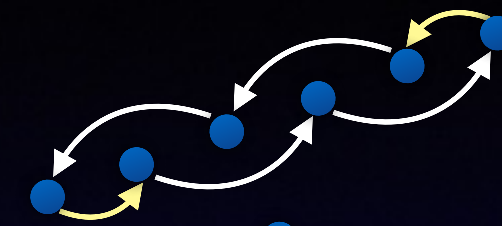


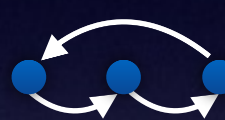
Interesting topologies

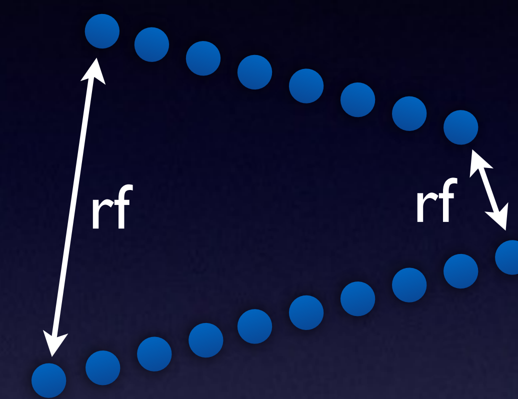
possible boundary conditions along the spin direction:

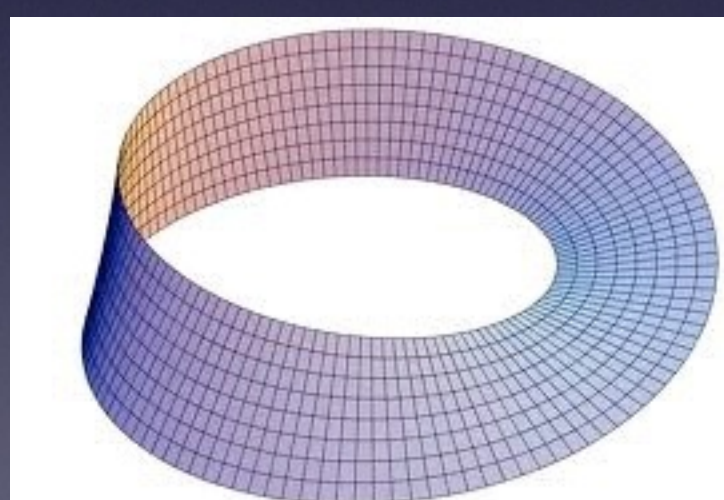
- open
- closed
- twisted









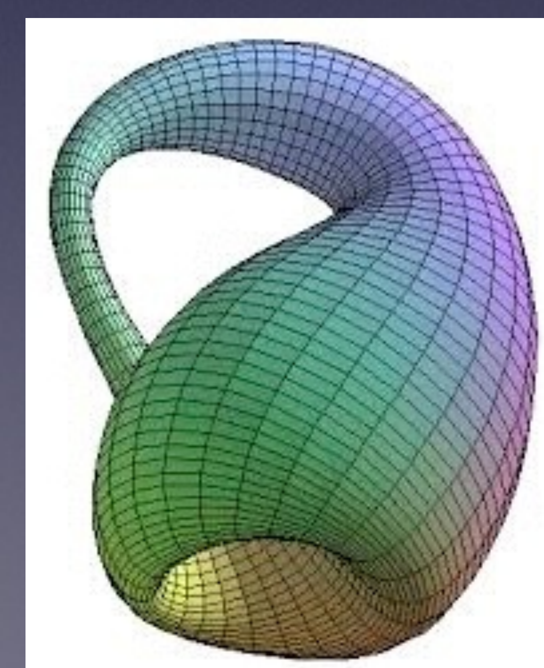


Möbius strip

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

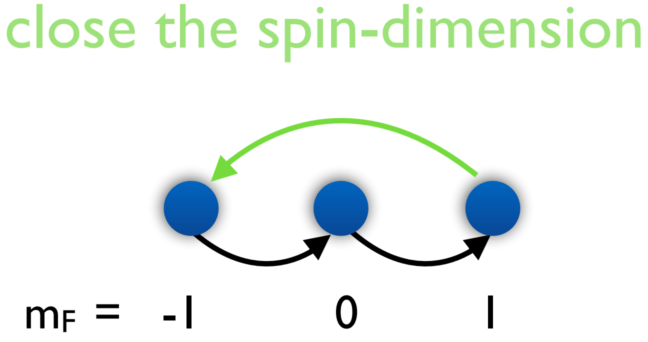
Klein bottle

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



From open to closed b.c.

+



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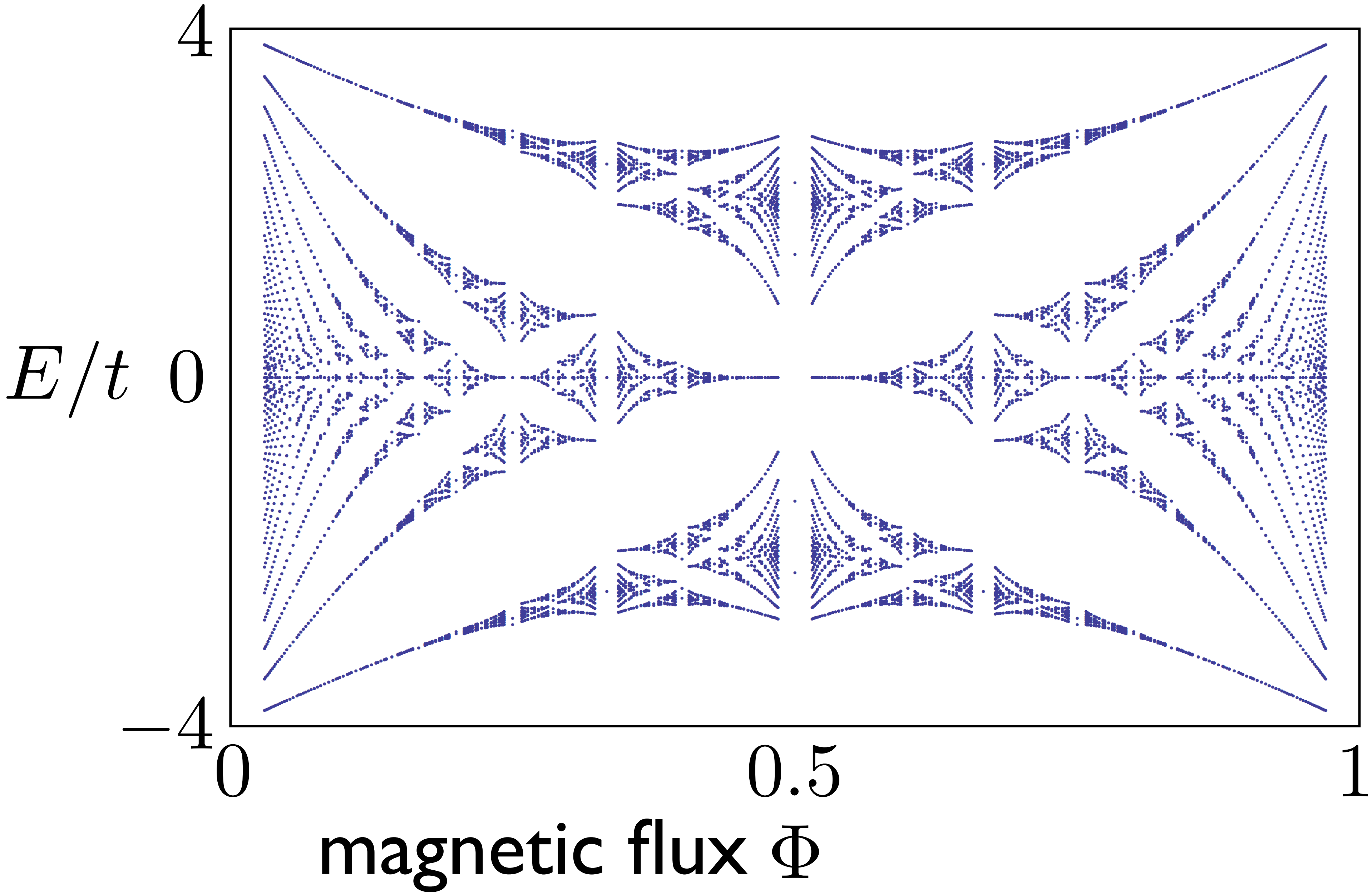
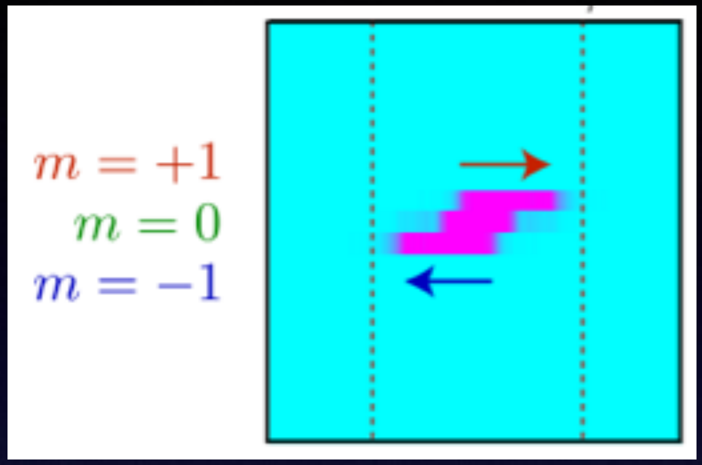
Spectrum of a 3-component gas with closed b.c.

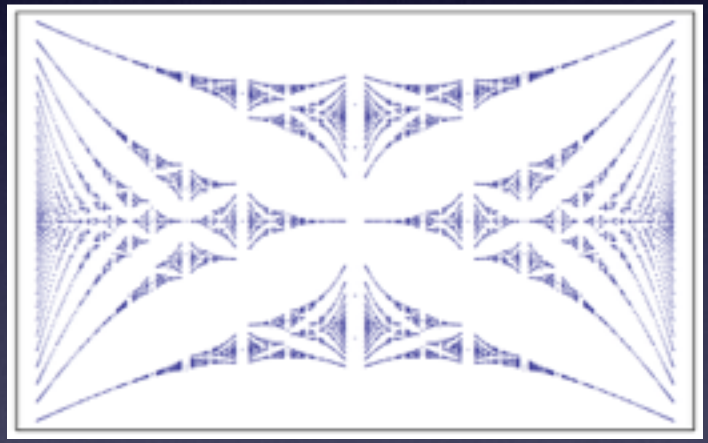
The spectrum has the fractal structure of a **Hofstadter butterfly**:

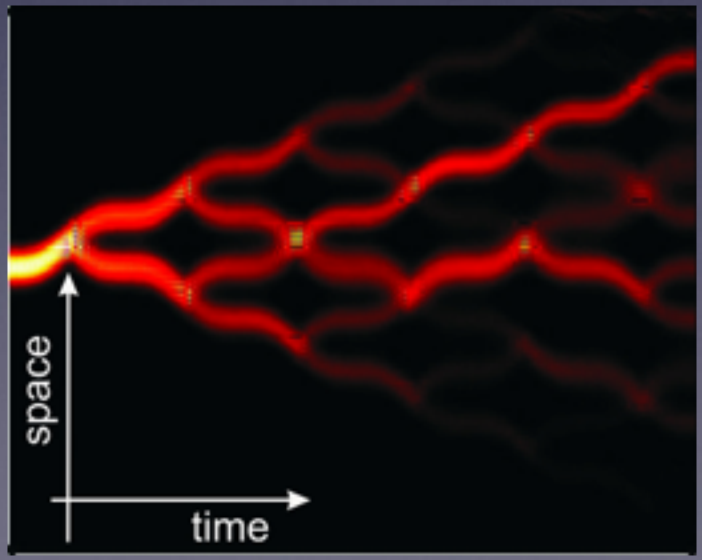


Outlook / Conclusions

- Q. gases: an ideal arena for topological properties
- Exploiting an internal d.o.f. as an extra-dimension:
  - ★ uniform and large fluxes
  - ★ direct imaging of edge states and their helicity
  - ★ Hofstadter fractal spectrum
- Role of interactions on edge state robustness
- Simulations of Quantum Random Walks
- Quantum simulation of high-energy theories, and 4D systems (e.g., critical exponents of phase transitions)







Celi, PM, Ruseckas, Spielman, Juzeliunas, and Lewenstein

Synthetic gauge fields in synthetic dimensions

Phys. Rev. Lett. **112**, 043001 (2014)