SYNTHETIC GAUGE FIELDS FOR ULTRACOLD ATOMS IN SYNTHETIC DIMENSIONS

Pietro Massignan

Quantum Optics Theory
ICFO - Institute of Photonic Sciences
Barcelona

ICFO Institut de Ciències Fotòniques

QUAGATUA
(M. LEWENSTEIN)

Phase transitions

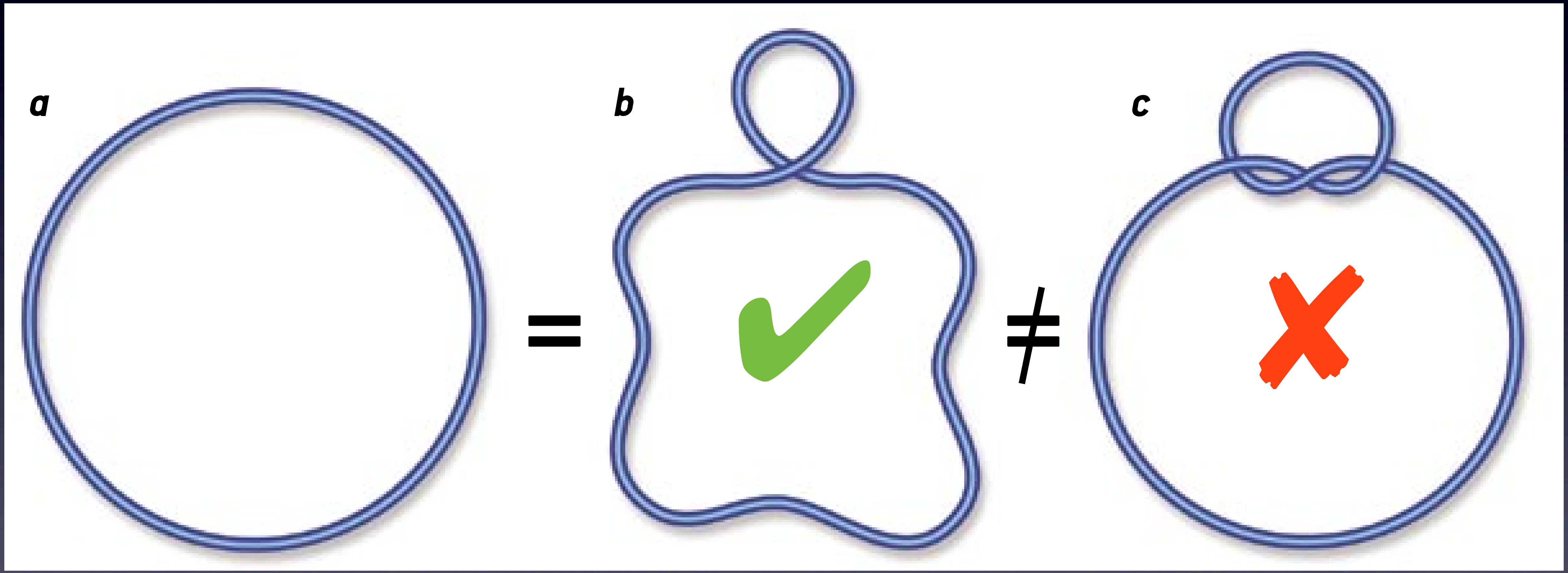
- Landau: most phases of matter may be classified by the symmetries they break
  - translational (solids)
  - rotational (magnets)
  - gauge (superfluids)
- BUT: some materials possess distinguishable phases without breaking symmetries
  (QH and QSH effect)

Topological phase transitions!

Topological properties

✔: stretching, bending

✘: cutting, joining



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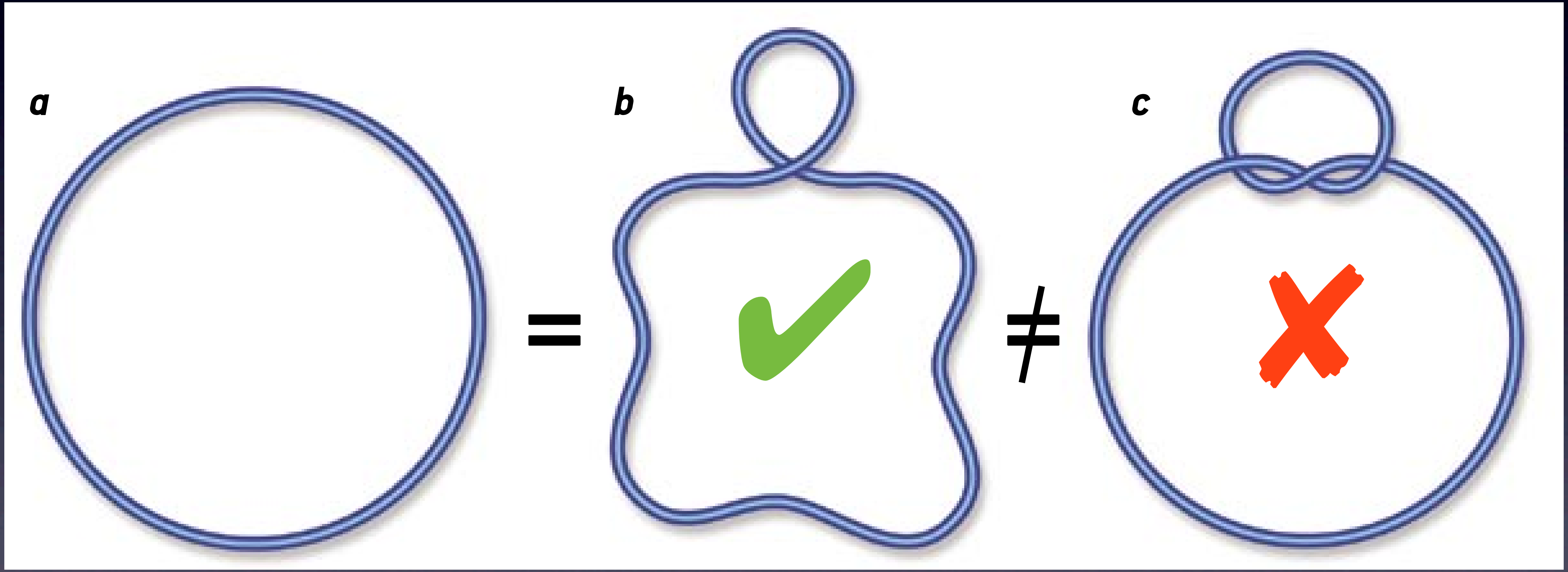


Concern the whole system (non-local)

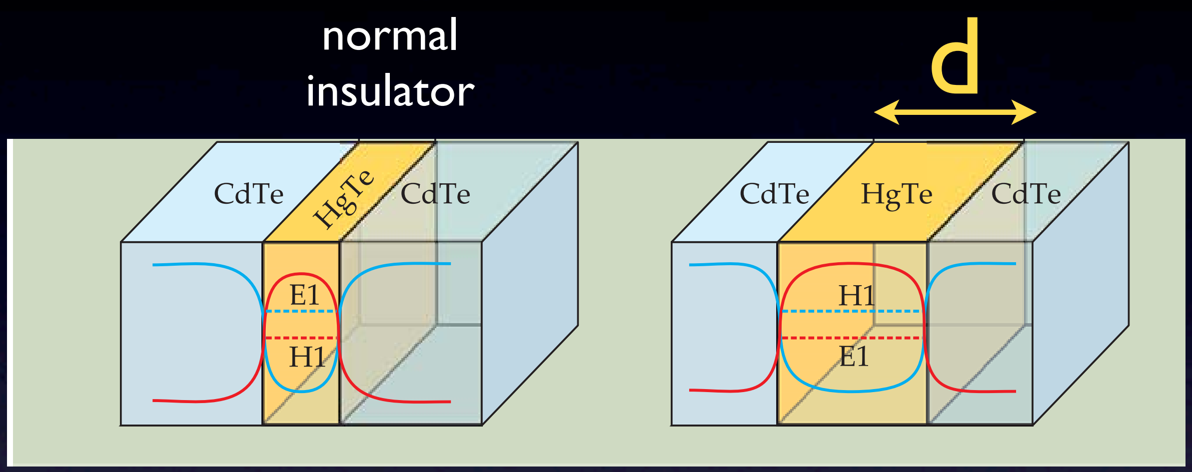
Characterized by integer numbers

Robust

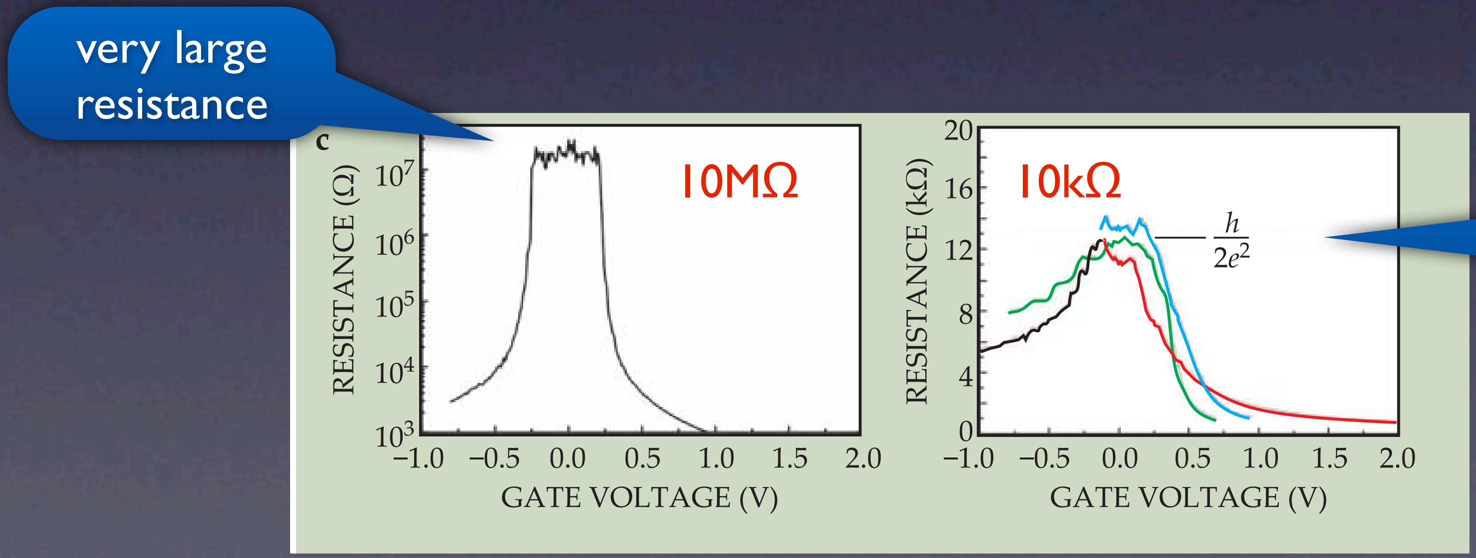
A topological insulator

Hg-Te quantum well

Hg: Mercury
Te: Telluride



Phase transition at $d=d_{crit}$:
normal-to-topological insulator



independent of d, when $d>d_{crit}$

2 quanta of conductance

Qi & Zhang, Physics Today 2010

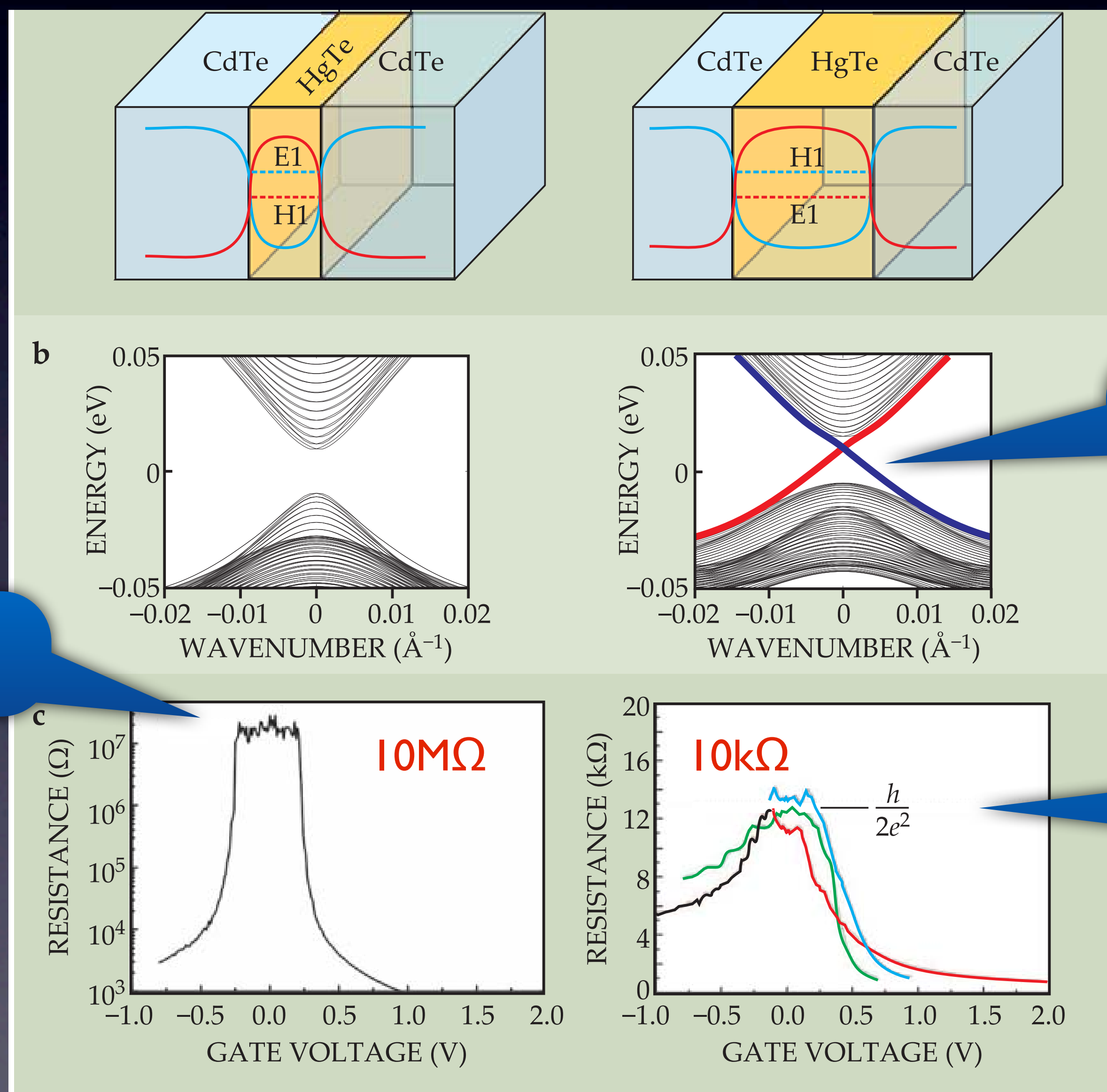
A topological insulator

Hg-Te quantum well

Hg: Mercury
Te: Telluride

normal
insulator

d



$d>d_{crit}$: topological insulator

edge states

Hg-Te has strong
spin-orbit coupling

very large
resistance

2 quanta of conductance
(independent of d, when $d>d_{crit}$)

Qi & Zhang, Physics Today 2010

interesting..., but where?

- exotic condensed matter systems

  (quantum wells, bismuth antimony alloys, Bi_2Se_3 crystals, ...)

- ν=5/2 FQH state (Pfaffian)

- ultracold atoms?

Outlook of the talk

Synthetic gauge fields

↑↓ 2D s-wave fermionic SF
with $n_\uparrow \neq n_\downarrow$
and spin-orbit coupling

Synthetic dimensions

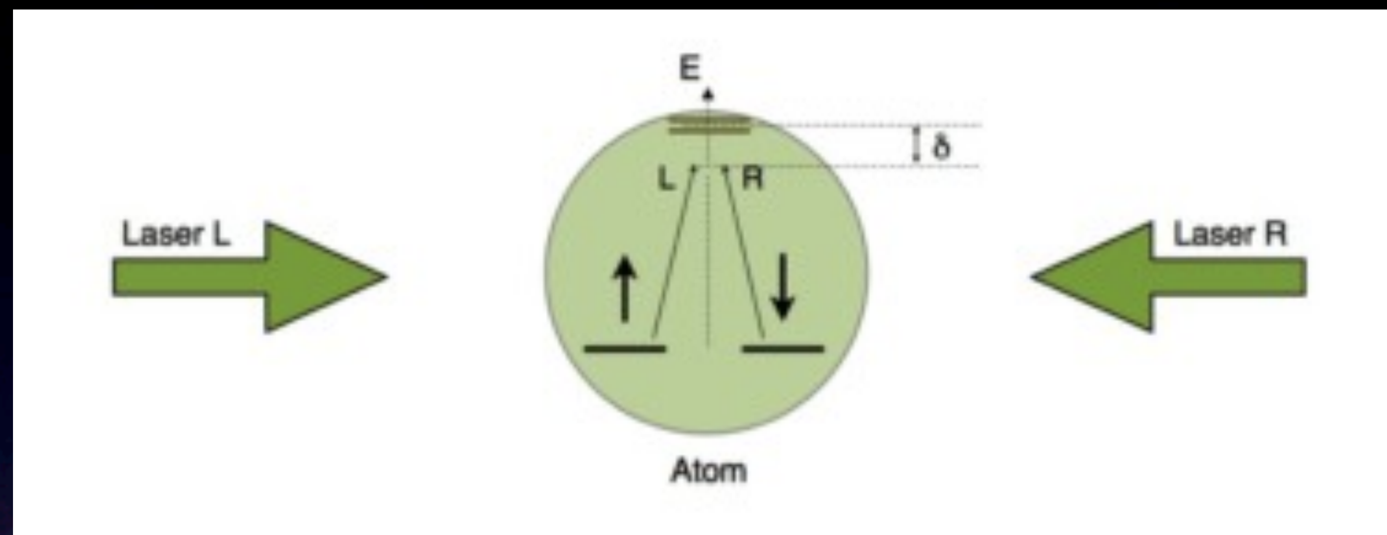
Synthetic gauge fields for neutral atoms

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

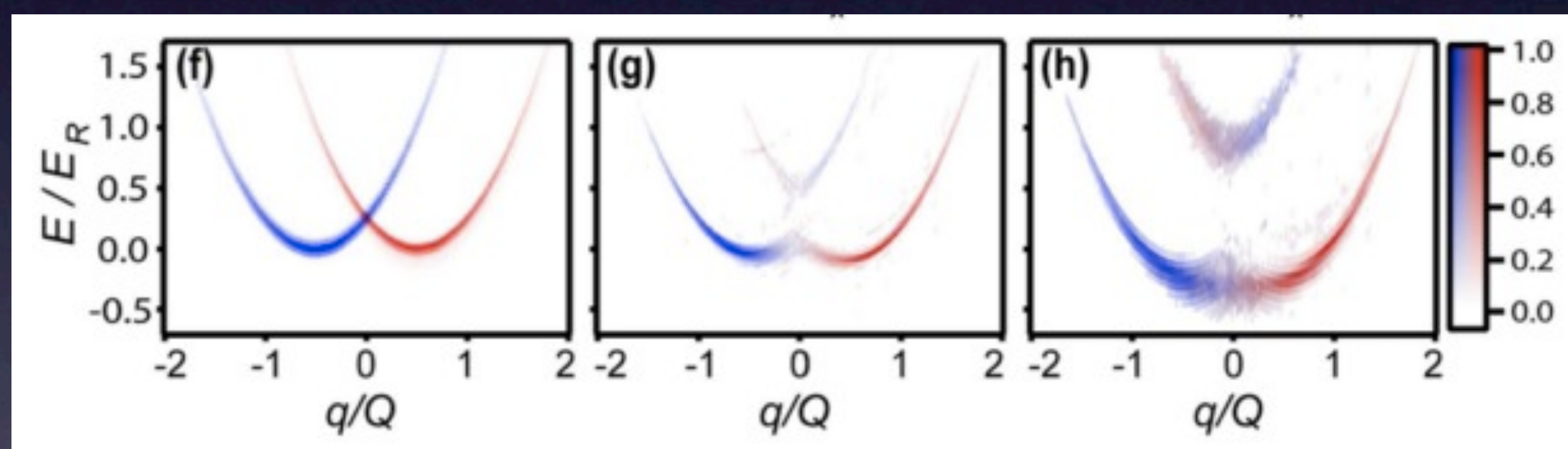
REVIEW: *Artificial gauge potentials for neutral atoms*
J. Dalibard, F. Gerbier, G. Juzeliūnas, and P. Öhberg, RMP 2011

Synthetic gauge fields for neutral atoms



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

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



spin-orbit gap

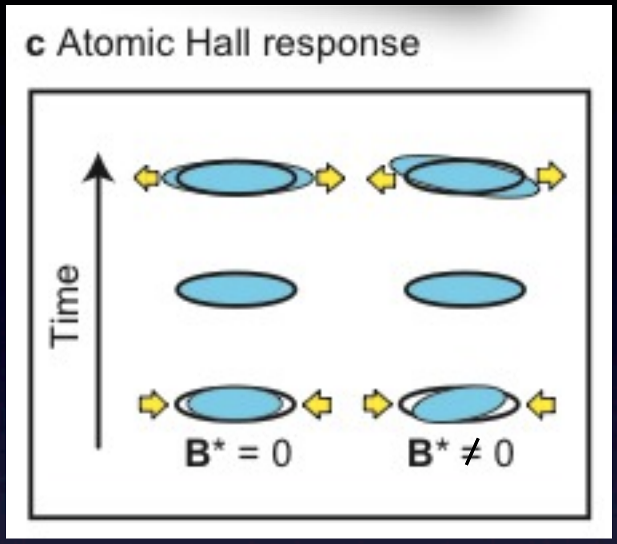
increasing intensity of Raman lasers →

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..

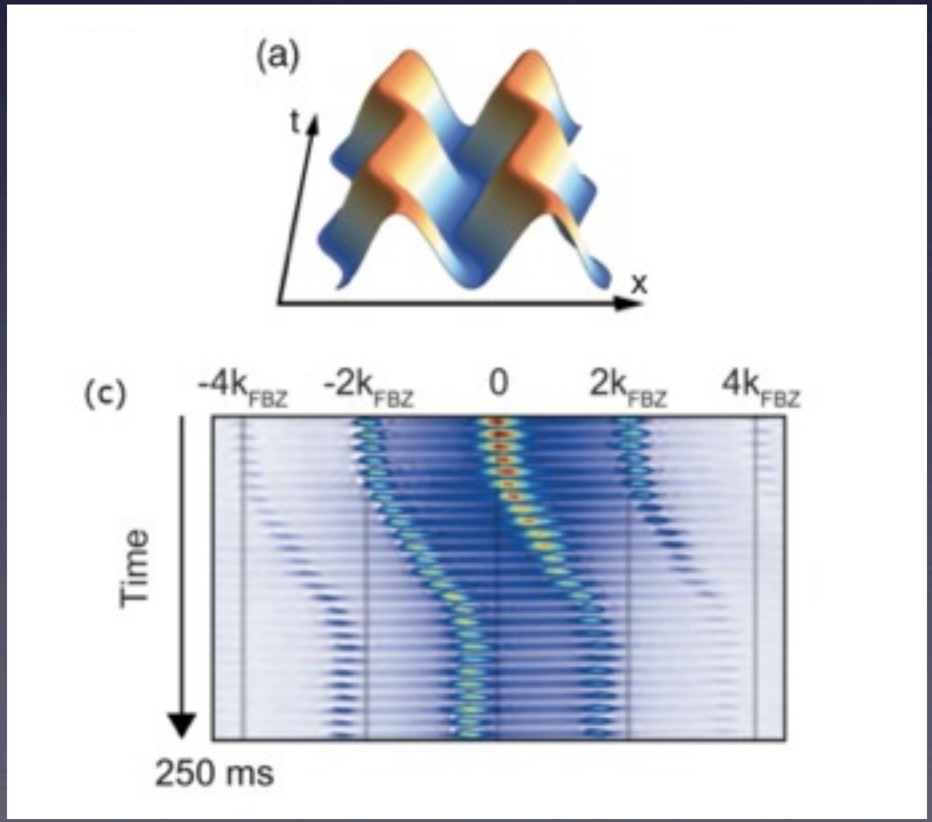
NIST: *Synthetic magnetic fields for ultracold neutral atoms*, Nature (2009)
A synthetic electric force acting on neutral atoms, Nature Phys. (2011)
Spin-orbit-coupled Bose-Einstein condensates, Nature (2011)
Observation of a superfluid Hall effect, PNAS (2012)
Peierls Substitution in an Engineered Lattice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

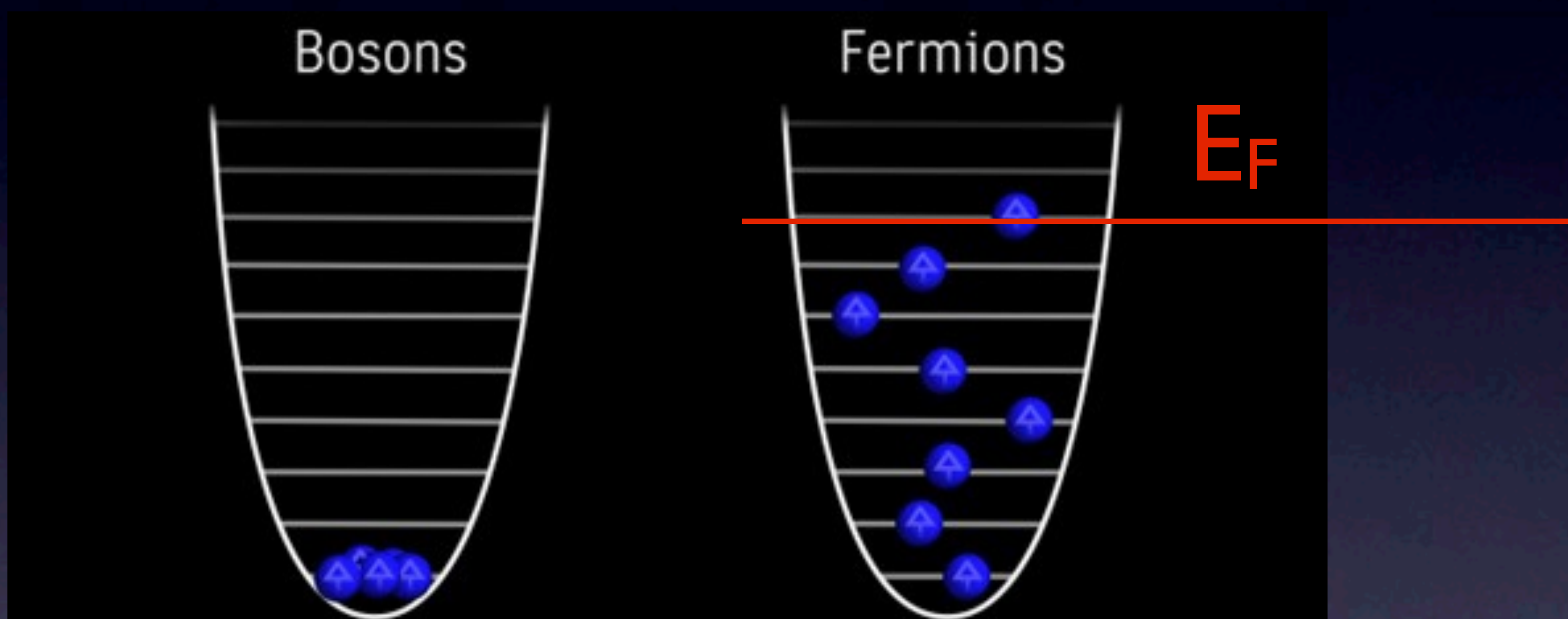
… … … …



↑-↓ fermionic SF with $n_\uparrow \neq n_\downarrow$ and spin-orbit coupling

Fermions vs. Bosons

Bosons condense in the lowest available energy state.



On the contrary, fermions have to due to obey the Pauli principle.

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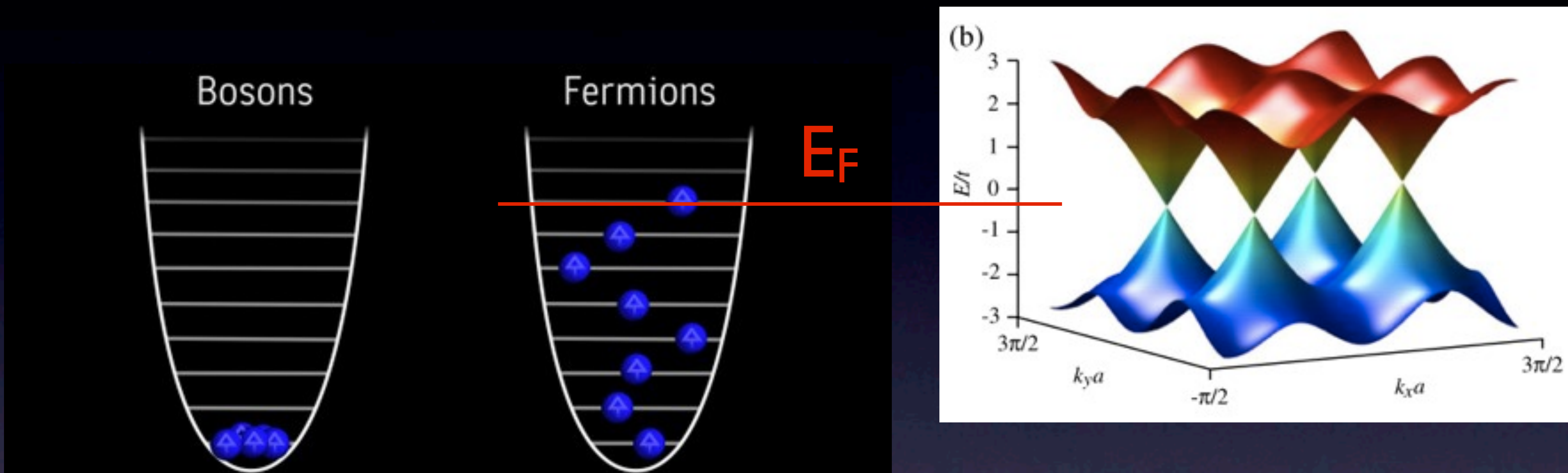

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By changing the number of particles, we are able to investigate the interesting excitations: the system becomes sensitive to the topological properties of the band structure.

↑↓ fermions in synthetic gauge fields

$$\mathbf{c}_{\mathrm{i}}^{\dagger} = (c_{\mathrm{i}\uparrow}^{\dagger}, c_{\mathrm{i}\downarrow}^{\dagger})$$

complex hoppings = Peierl's phases

$$\mathcal{H}_0 = -\mathrm{t}\sum_{\mathrm{i}}\left[\mathbf{c}_{\mathrm{i}+\hat{x}}^{\dagger}e^{i\sigma_y\alpha}\mathbf{c}_{\mathrm{i}} + \mathbf{c}_{\mathrm{i}+\hat{y}}^{\dagger}e^{i\sigma_x\beta}\mathbf{c}_{\mathrm{i}} + \mathrm{h.c.}\right]$$

External non-Abelian gauge fields yield a fictitious spin-orbit coupling

Add attractive interactions

↓

BCS superfluid

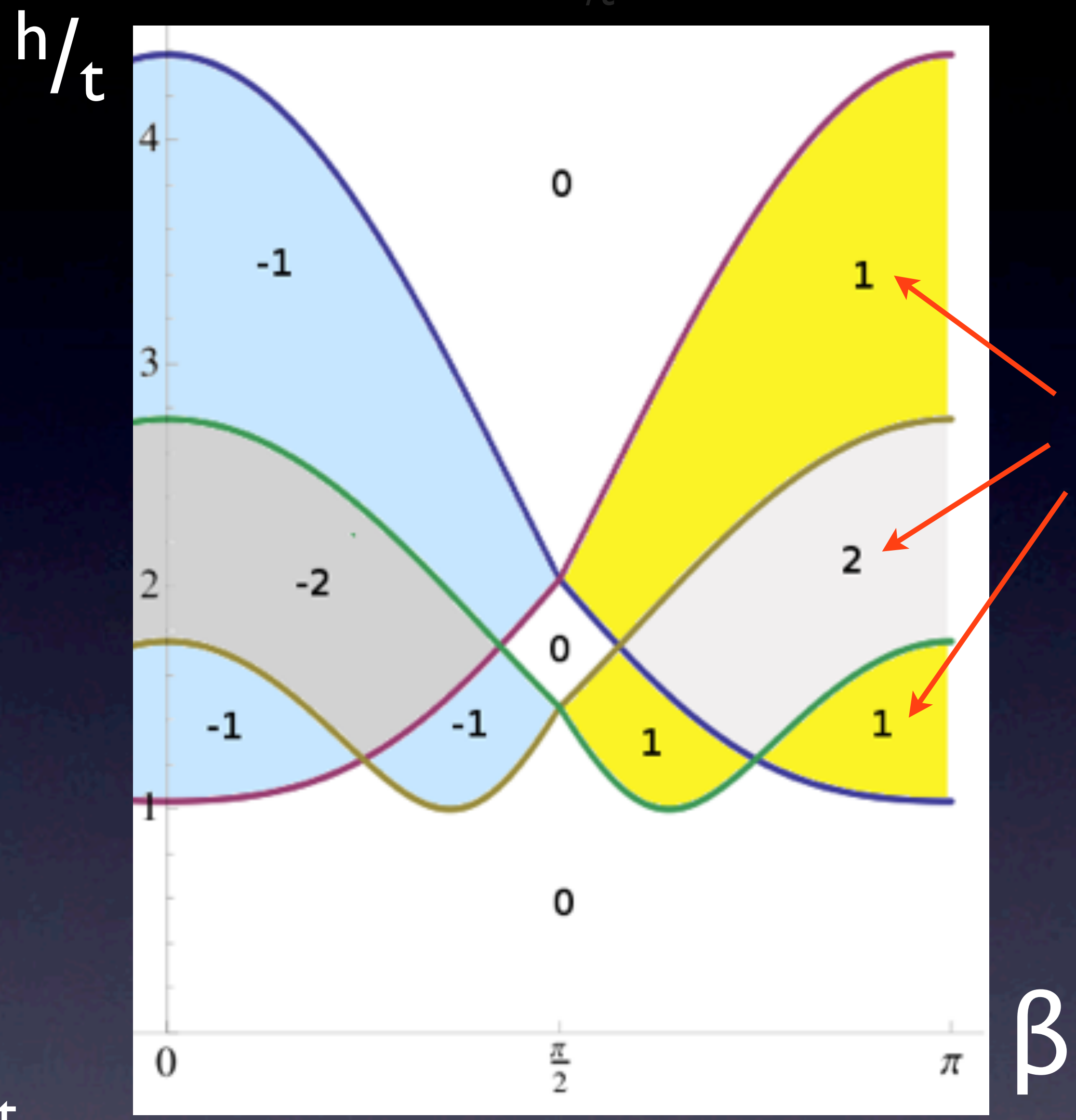
↓

Sato, Takahashi & Fujimoto, PRL 2009
Sau Jay, Lutchyn, Tewari and Das Sarma, PRL 2010

strong imbalance ⇒ topological states

Time-reversal and spin-rotation invariances are destroyed by the Zeeman and SO terms
as a consequence our BCS Hamiltonian belongs to the most general symmetry class "D"
(Altland&Zirnbauer, PRB 1997)
its topological phases are indexed in terms of an integer number

Topological phases



$h=\mu_\uparrow-\mu_\downarrow$

Chern numbers

easy to calculate!
(see J. Bellissard, condmat/9504030)

Gap closing at $(\mathbf{k}_0, \tilde{h})$:

$$\mathcal{H}_{\rm eff}(\mathbf{k},h) = E(\mathbf{k},h) + \vec{\sigma}\cdot\vec{f}(\mathbf{k},h)$$
$$\Delta\mathrm{CN}(\tilde{h}) = \mathrm{sign}\{\det[J_{\vec{f}}(\mathbf{k}_0,\tilde{h})]\}.$$

$\Delta=t$
$\alpha=\pi/4$
$\mu=-0.5t[|\cos(\alpha)|+|\cos(\beta)|]$

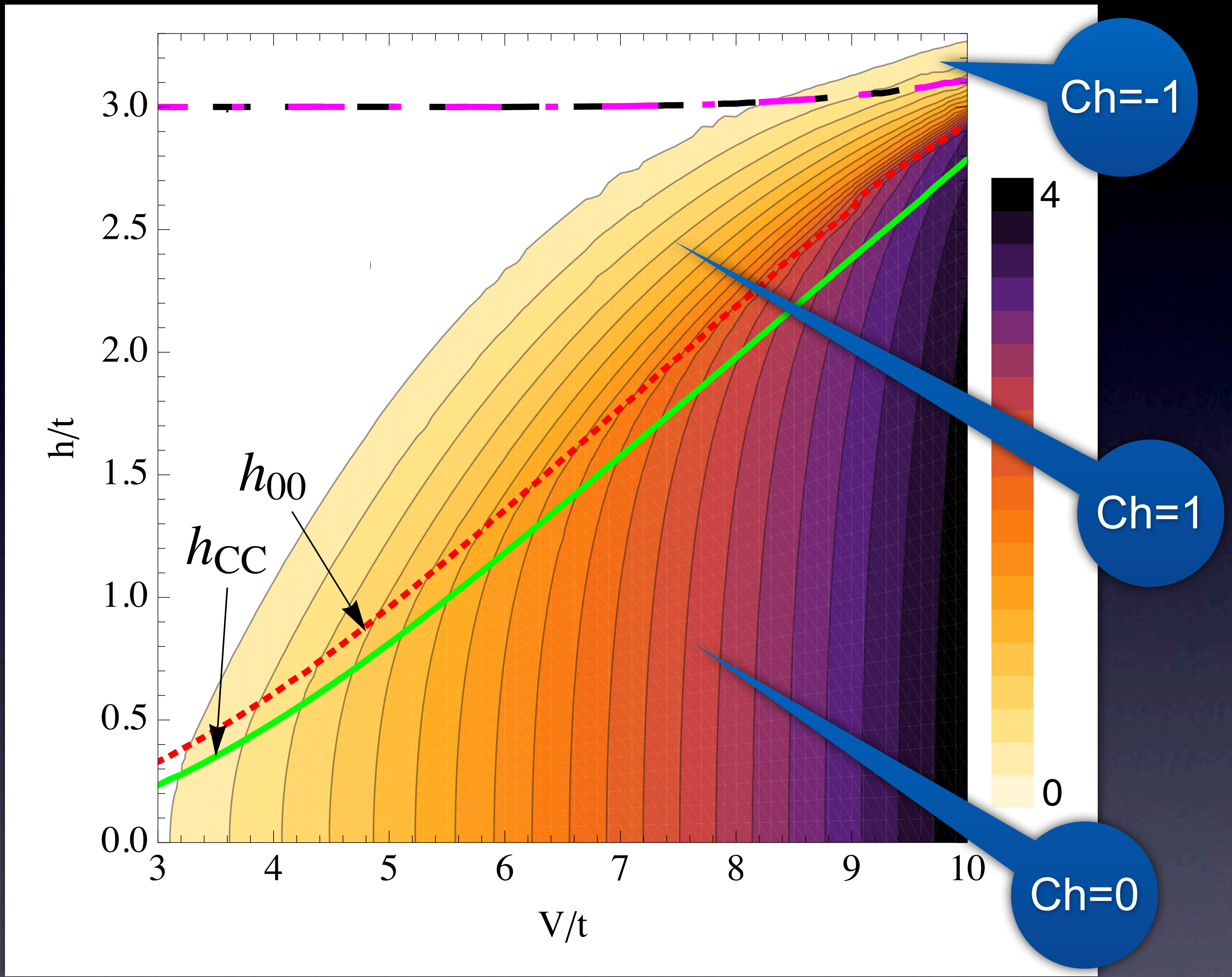
A. Kubasiak, P.M. & M. Lewenstein, EPL 2010

Spin imbalance vs. pair breaking

without SO coupling:
analytic CC limit
($h_{CC} = \Delta_0/\sqrt{2}$)

with SO coupling:
self-consistent calculation of Δ
from the BCS gap equation

$\alpha=\beta=\pi/4$ $\mu=-3t$



A. Kubasiak, PM & M. Lewenstein, EPL 2010

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)

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

The main idea

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

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

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

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

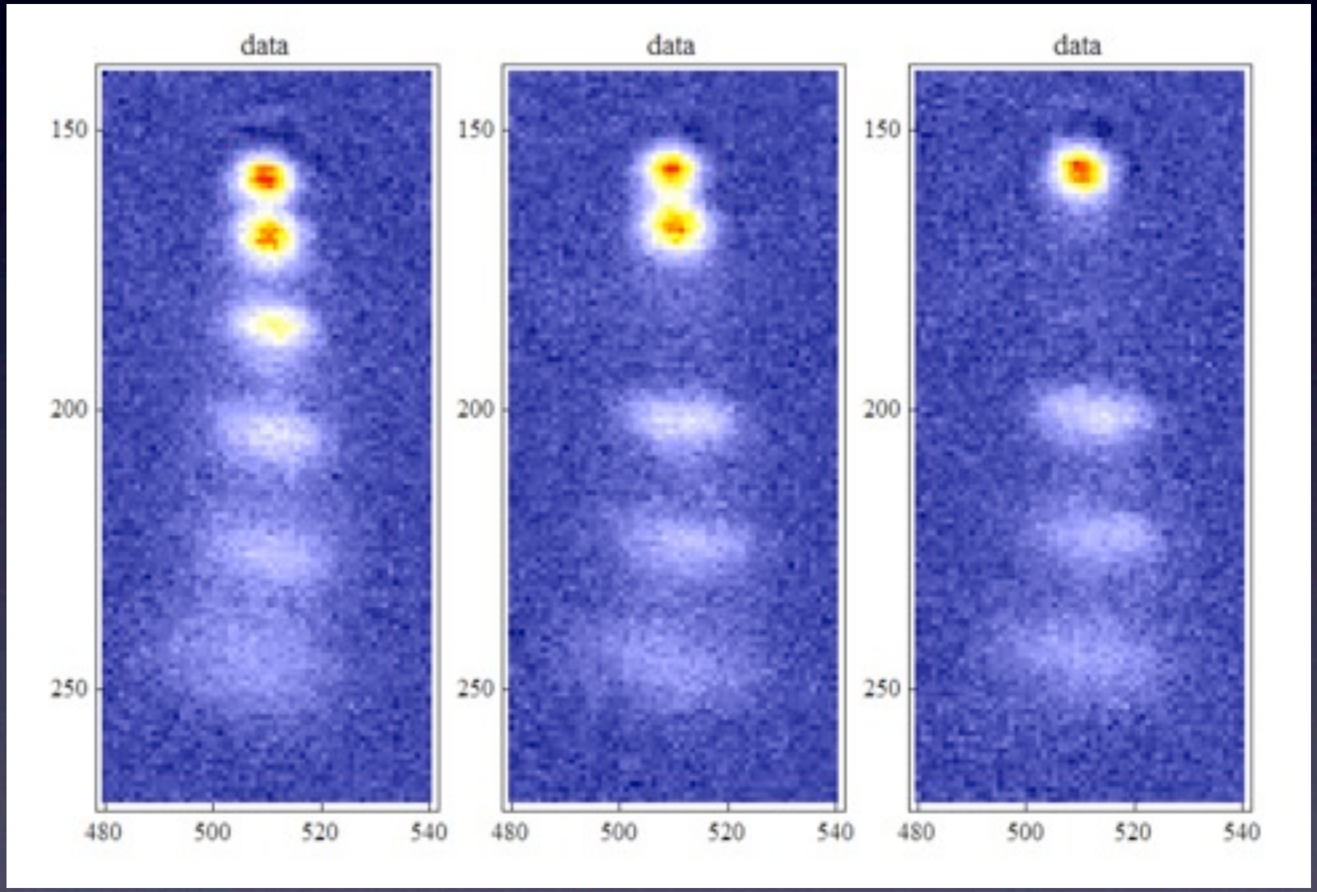
important: allow only nearest-neighbor "spin-tunneling"

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

Large N systems

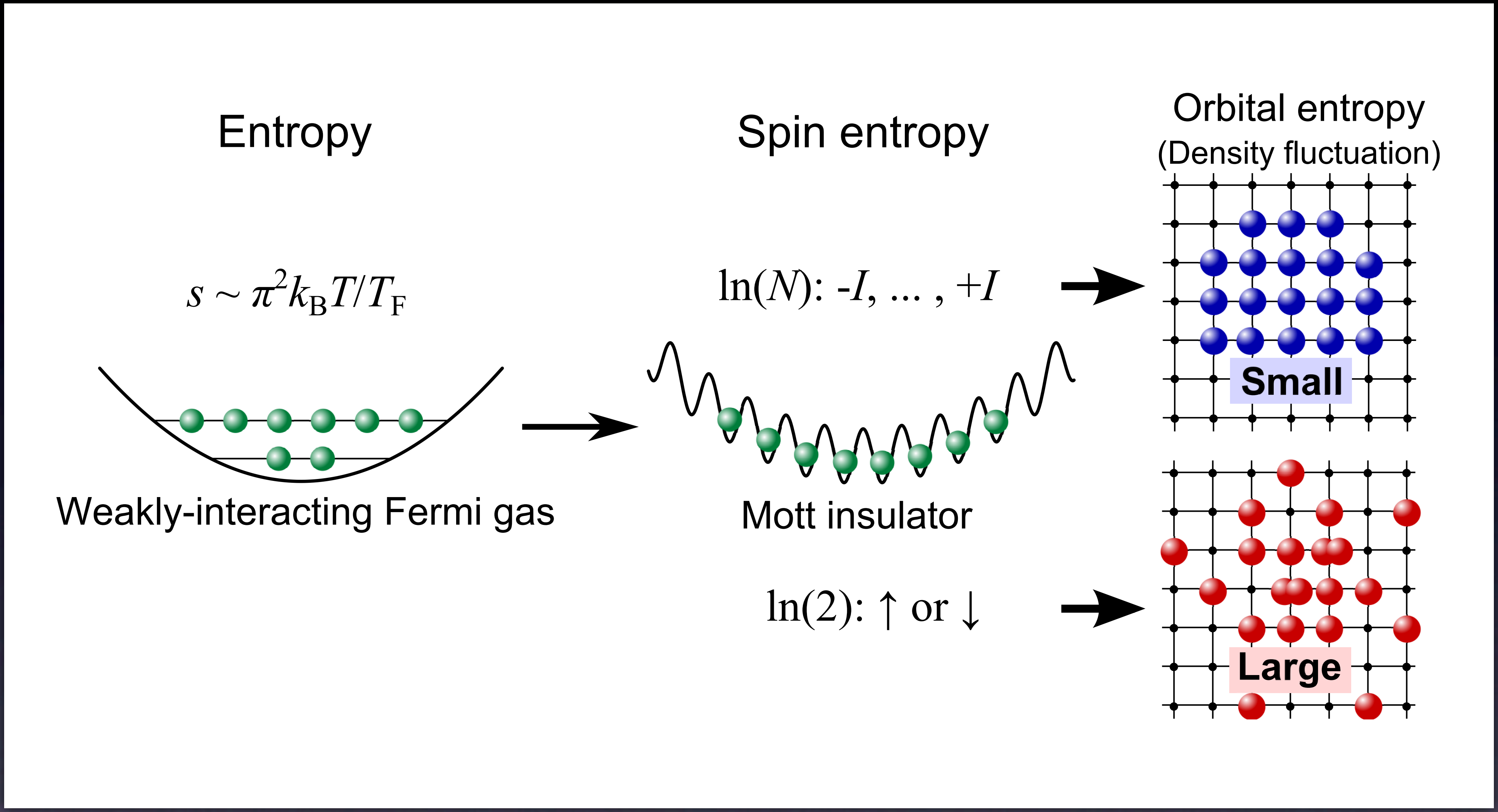
species	N
Li	2,3,...
^{87}Rb	3
^{173}Yb	6
^{40}K	2,...,10
^{87}Sr	10
^{165}Ho	120

^{173}Yb at LENS:



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

SU(6) Mott insulator

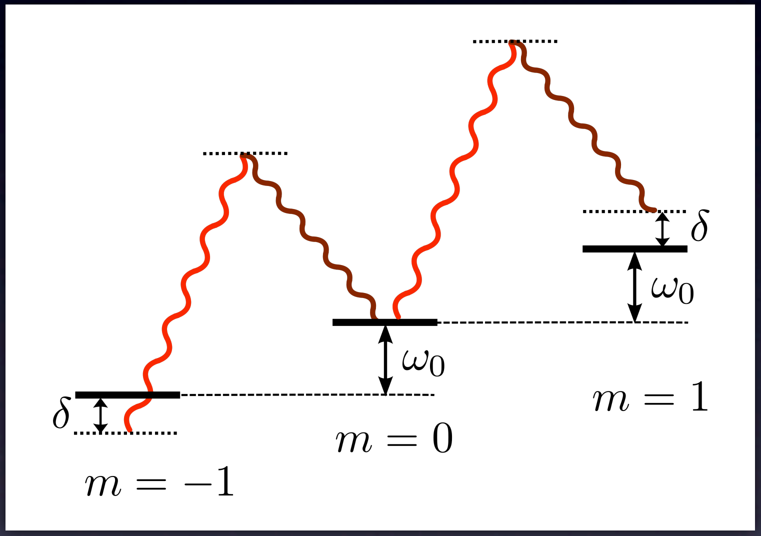


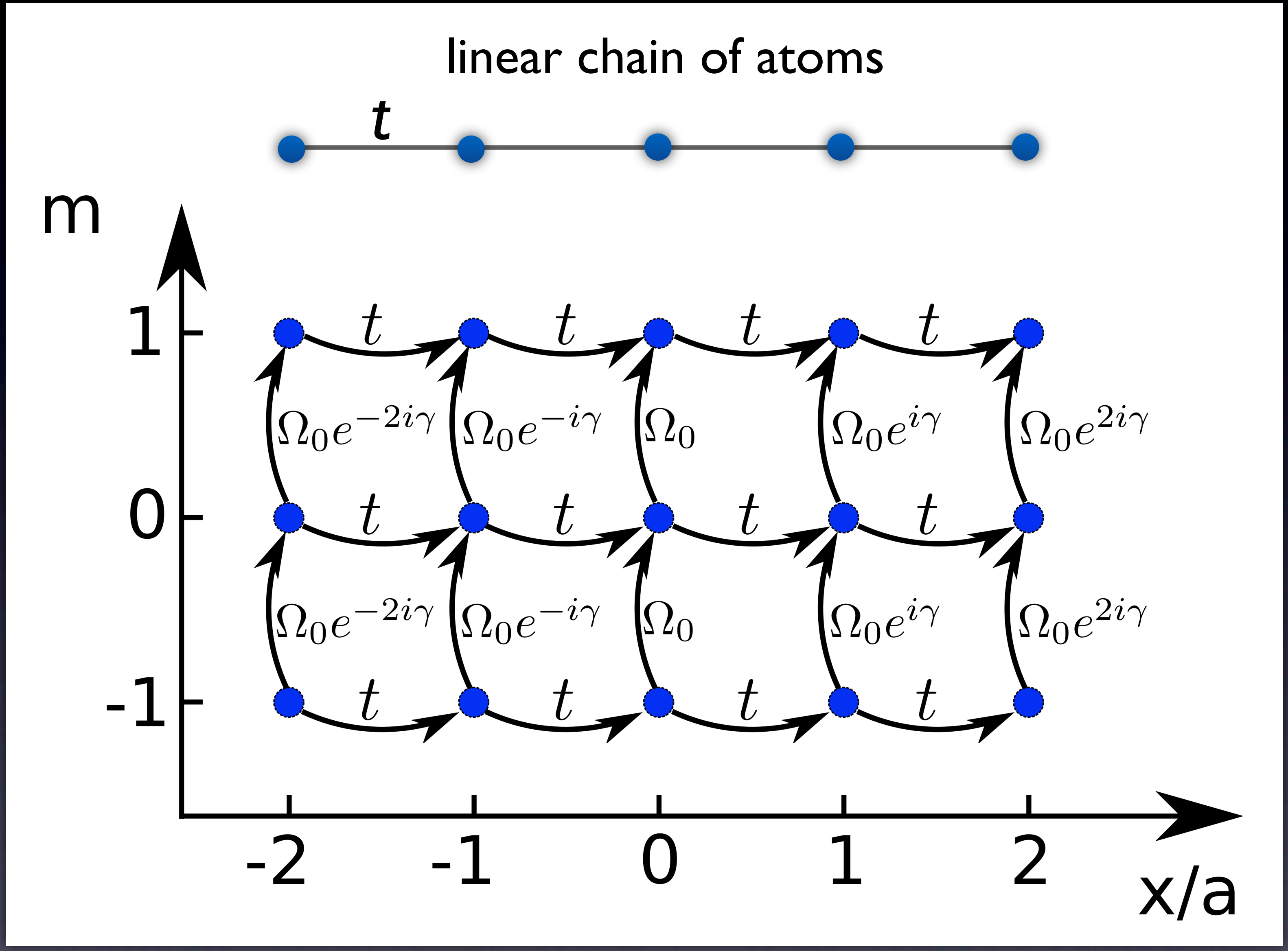
S. Taie, R. Yamazaki, S. Sugawa, and Y. Takahashi, Nature Phys. 2012

Novel cooling mechanisms?

Implementation

laser-assisted spin-tunneling

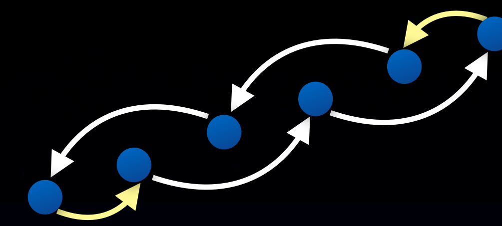




yields strong and non-staggered magnetic fluxes and long-ranged interactions

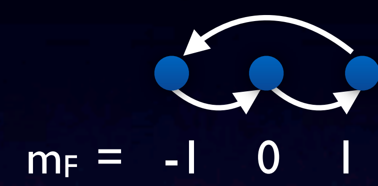
PM, A. Celi, I. Spielman, G. Juzeliunas, and M. Lewenstein, in preparation

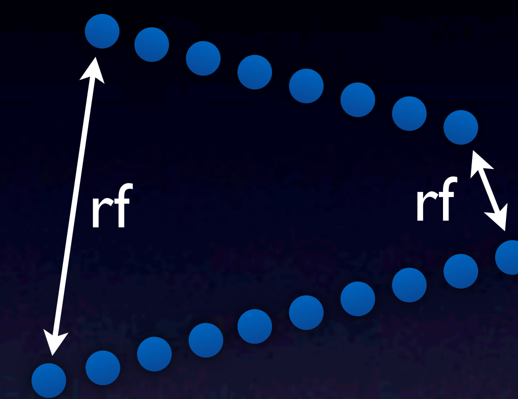
Interesting topologies

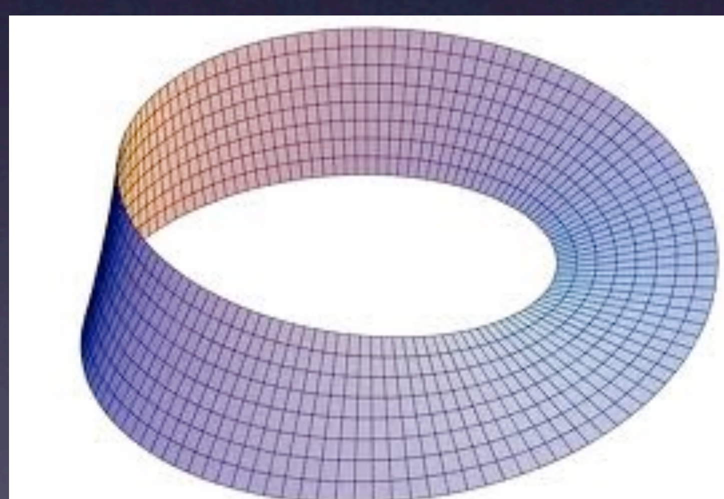


possible boundary conditions along the spin direction:

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





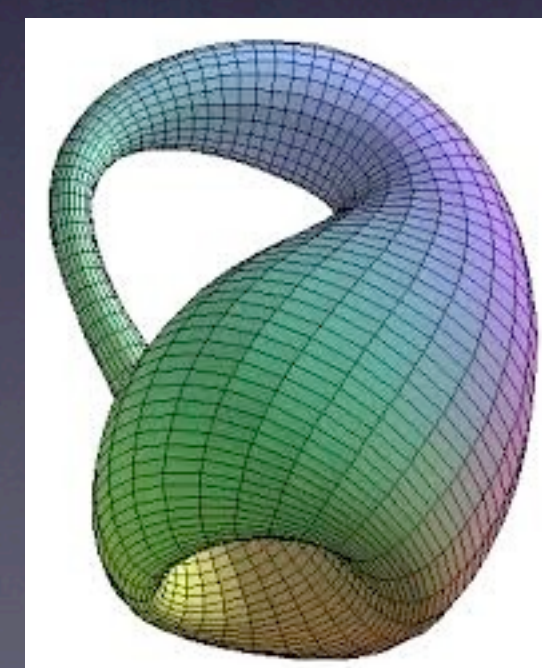


Möbius strip

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

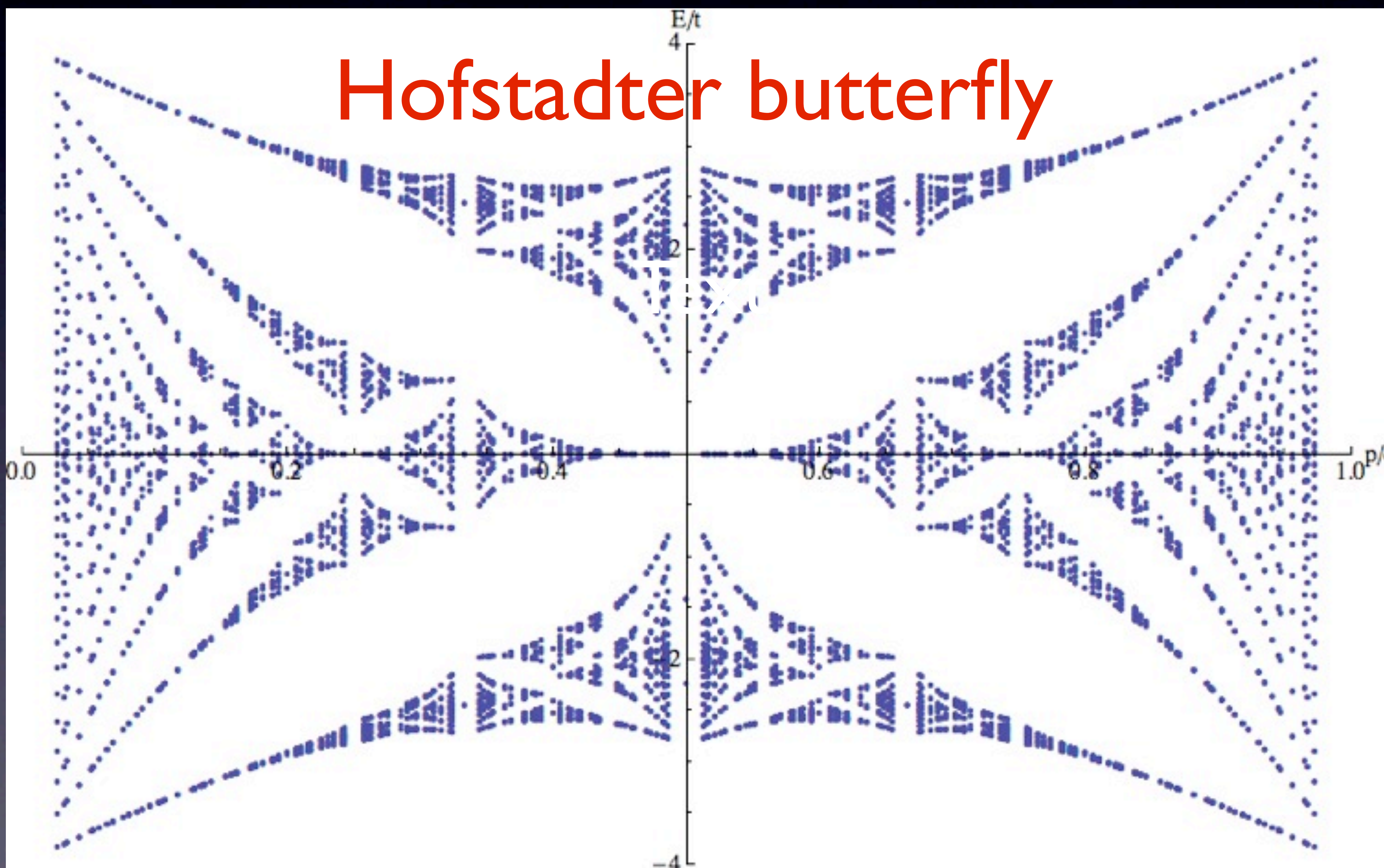
Klein bottle

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



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

$$\Phi = 2\pi(p/q)$$

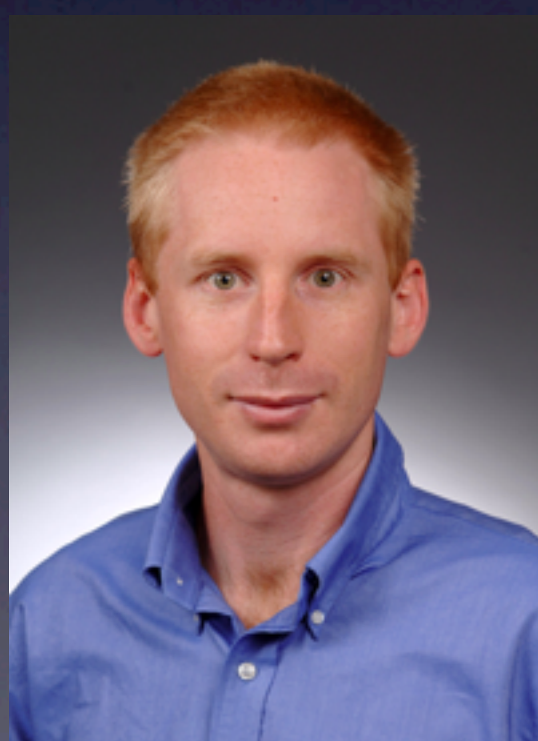


in collaboration with


Maciej Lewenstein


Alessio Celi


Gediminas Juzeliunas


Ian Spielman


Anna Kubasiak


Anna Sanpera

Conclusions

- Gauge fields yield *non-trivial topological phases*
- Superfluidity in ↑↓ fermions is stabilized by a non-Abelian gauge field
- Using an internal d.o.f. as an extra-dimension:

★ quantum simulation of high-energy theories, and D>3 systems (e.g., crit. exp. of ph. trans.)

★ novel cooling schemes possible?

PM, A. Sanpera & M. Lewenstein, PRA(R) 2010
A. Kubasiak, PM & M. Lewenstein, EPL 2010
O. Boada, A. Celi, J.I. Latorre, and M. Lewenstein, PRL 2012
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