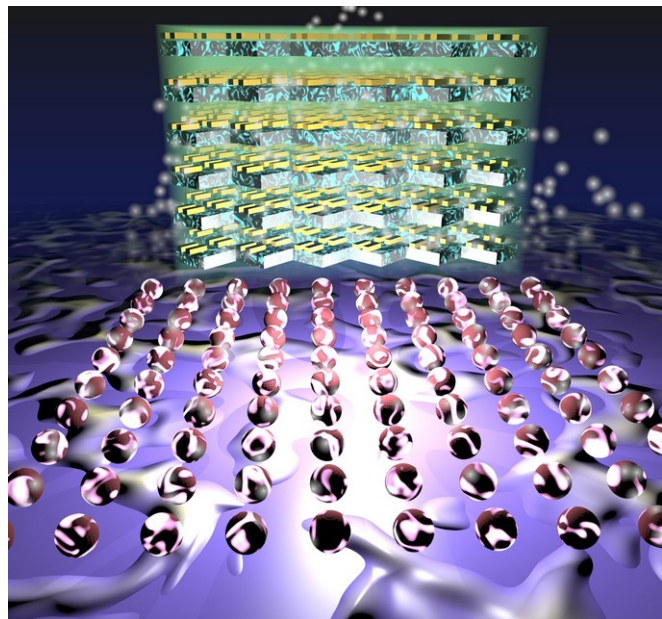


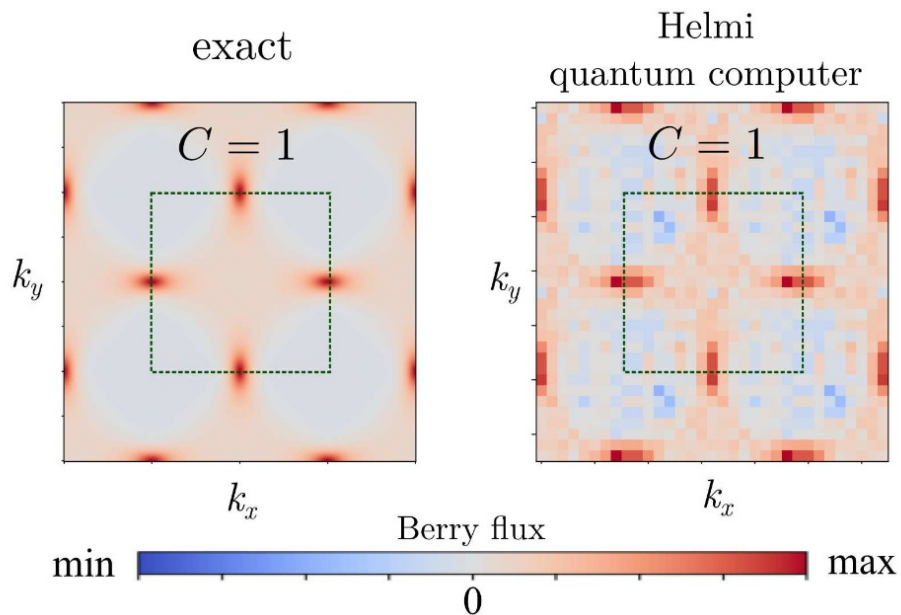
Solving topological quantum matter on a quantum computer

Jose Lado

Department of Applied Physics, Aalto University, Finland



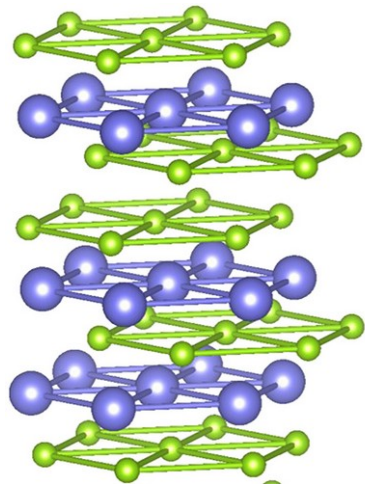
Phys. Rev. Research 6, 043288 (2024)



HIIT Foundations Friday, April 25th 2025

Emergence in quantum materials

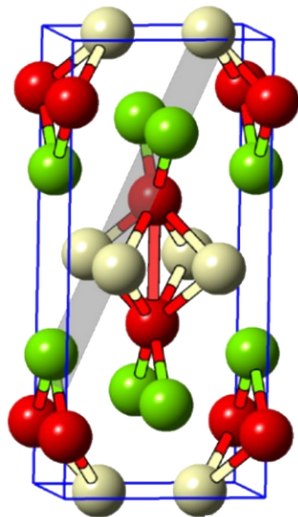
Topological materials



Bi_2Se_3

Science, 325(5937),
178-181 (2009)

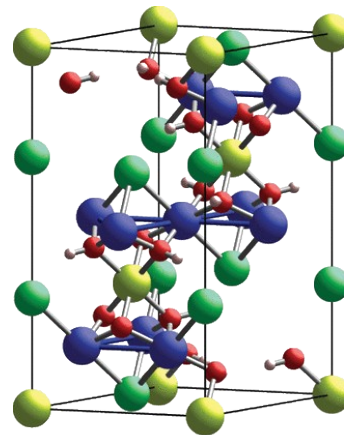
Unconventional superconductors



UTe_2

Nature 579,
523–527 (2020)

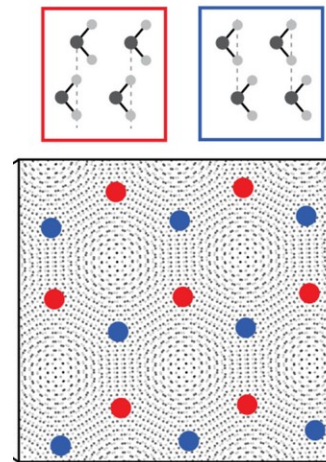
Quantum spin liquids



$\text{ZnCu}_3(\text{OH})_6\text{Cl}_2$

Science 350(6261),
655-658 (2015)

Fractional topological matter



Twisted MoTe_2

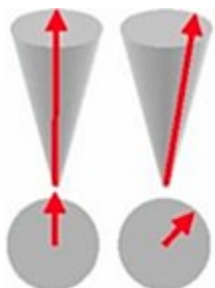
Nature 622, 63–68 (2023)

Quantum excitations in quantum materials

Quantum materials made of electrons (spin = $1/2$, charge = 1), protons, neutrons and photons

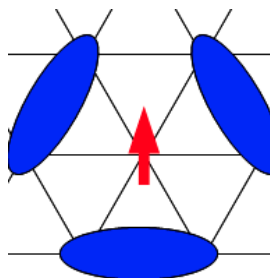
But in quantum materials, we can have emergent collective new excitations

Magnons



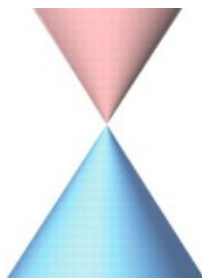
No charge
Spin = 1

Spinons



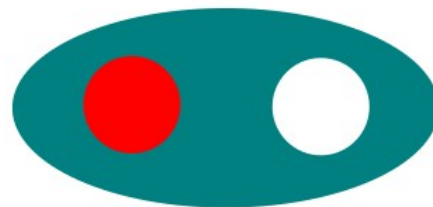
No charge
Spin = $1/2$

Dirac fermions



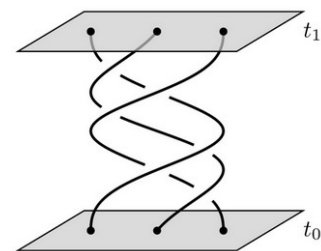
No mass
Spin = $1/2$
Charge = 1

Majorana fermions



No charge
No spin
Own antiparticle

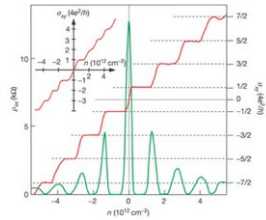
Anyons



No spin
Charge = $1/3$
Not a boson
Not a fermion

Topological quantum matter

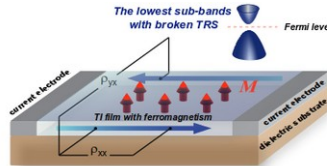
Quantum Hall effect



graphene

Nature 438, 197-200 (2005)

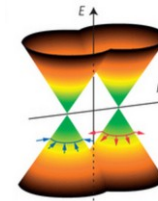
Quantum Anomalous Hall effect



Cr-doped
(Bi,Sb)₂Te₃

Science 340.6129 (2013): 167-170

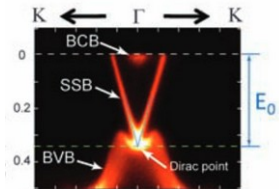
Weyl semimetal



TaAs

Nature Physics 11, 724–727 (2015)

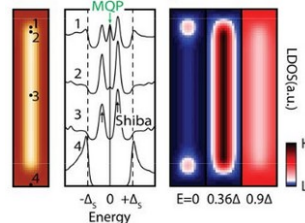
Quantum Spin Hall effect



Bi₂Se₃

Science 325.5937 (2009): 178-181

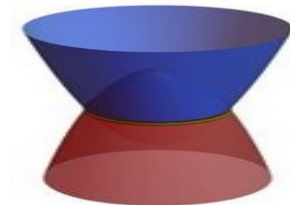
Topological superconductor



Fe@Pb

Science 346.6209 (2014): 602-607

Nodal line semimetals



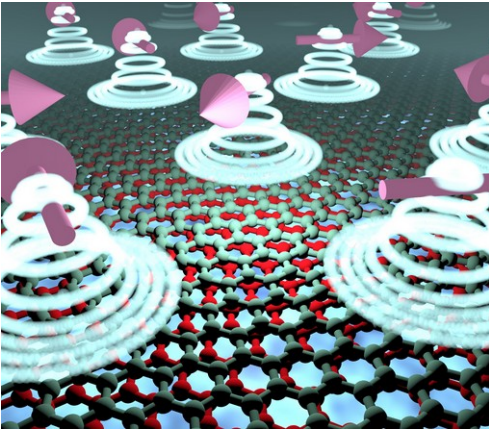
Mg₃Bi₂

Advanced Science 6.4 (2019): 1800897

All these states are described by effective isolated single-particle physics

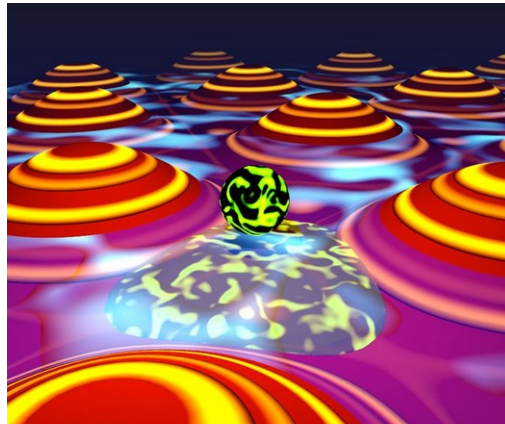
Many-body topological quantum matter

Quantum spin liquids



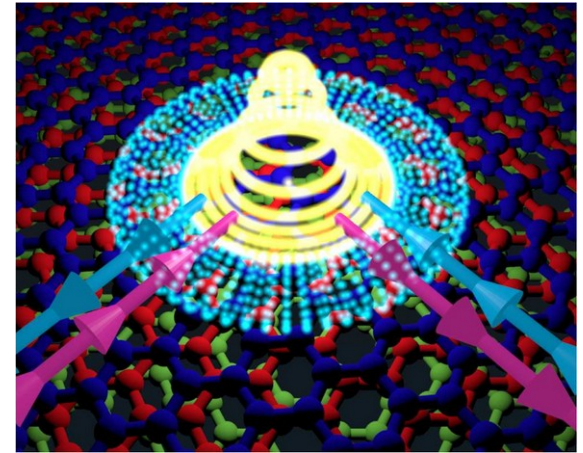
Reports on Progress in Physics 80.1 (2016): 016502.

Fractional Chern insulators



Rev. Mod. Phys. 71, S298 (1999)

Parafermions

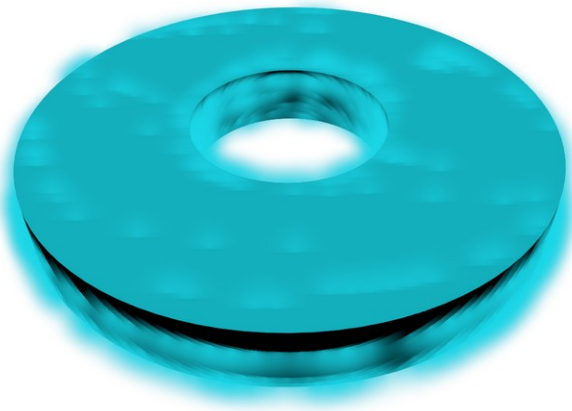


Annual Review of Condensed Matter Physics 7, 119-139 (2016)

***Topological many-body quantum matter is an open challenge
where quantum algorithms will potentially enable solving open challenges***

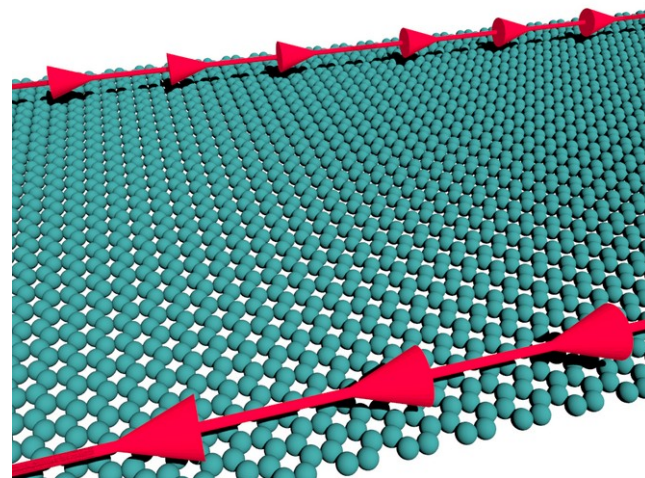
Macroscopic topological effects

Superconductivity



$$\Phi = \frac{h}{2e} \quad \text{Quantization of flux}$$

Chern topological insulators



$$\sigma_{xy} = \nu \frac{e^2}{h} \quad \text{Quantization of conductance}$$

Macroscopic (topological) quantum phenomena determine fundamental physical constants with the highest precision

The computational challenge in topological matter

Single particle topological matter

$$H = \sum c_i^\dagger c_j$$

N sites/atoms/orbitals

N computational resources

How can it be solved

Exact classical methods

Many-body topological matter

$$H = \sum c_i^\dagger c_j + V_{ijkl} c_i^\dagger c_j c_k^\dagger c_l$$

N sites/atoms/orbitals

2^N computational resources

How can it be solved

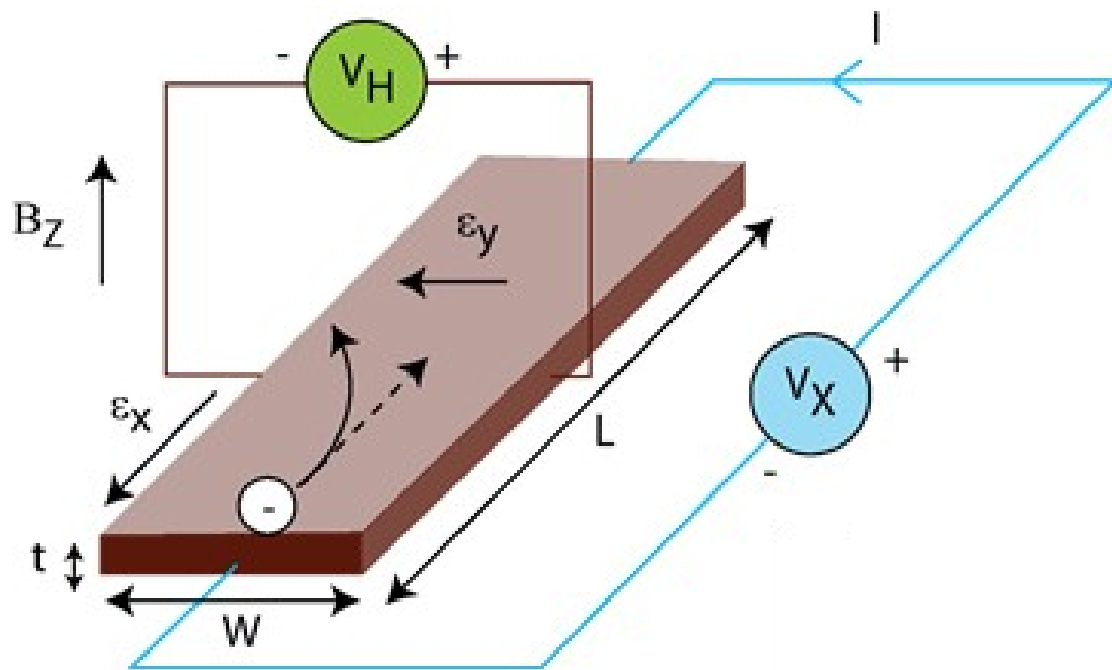
Exact classical methods (tiny systems)

Tensor network classical methods

Quantum computers (?)

Introduction to topology in quantum materials

The Hall effect



$$J_x = \sigma_{xy} V_y$$

Hall conductivity

Measure the current perpendicular to a voltage

The Hall conductivity

The Hall conductivity is obtained as $\sigma_{xy} = \sum_{\alpha \in occ} \int \Omega_{\alpha} d^2 \mathbf{k}$

Berry curvature

$$\Omega_{\alpha} = \partial_{k_x} A_y^{\alpha} - \partial_{k_y} A_x^{\alpha}$$

Berry connection

$$A_{\mu}^{\alpha} = i \langle \partial_{k_{\mu}} \Psi_{\alpha} | \Psi_{\alpha} \rangle$$

$$\sigma_{xy} = \sum_{\alpha \in occ} \int \Omega_{\alpha} d^2 \mathbf{k} = \sum_{\alpha} C_{\alpha} = C \longleftarrow \text{Chern number}$$

The transverse conductivity is a topological invariant

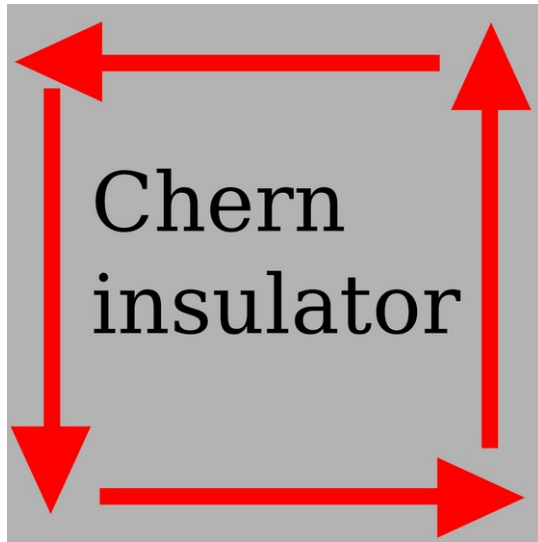
This means, it must take integer values regardless of defects in an insulator

Hall conductivity in an insulator

$$\sigma_{xy} = \sum_{\alpha \in occ} \int \Omega_{\alpha} d^2 \mathbf{k} = \sum_{\alpha} C_{\alpha} = C$$

The Chern number is quantized

$$C_{\alpha} = \int \Omega_{\alpha}(\mathbf{k}) d^2 \mathbf{k} = 0, \pm 1, \pm 2, \dots$$



*An insulator can have a finite
(and quantized) Hall conductivity*

**This is a simple example of
a topological state of matter**

The idea of topological invariants

Holes in a 3d surface



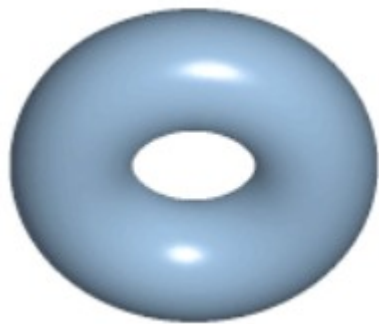
Knots in curves



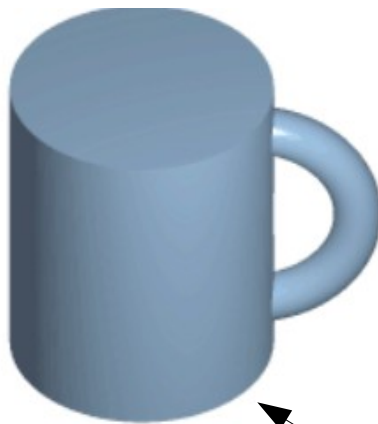
Topology classifies object that cannot smoothly deformed into one another

Topology and holes

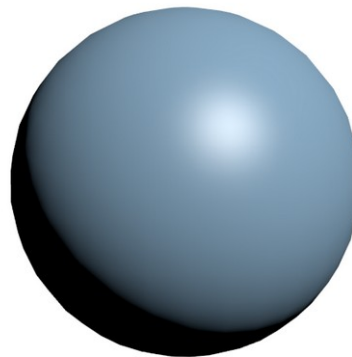
One hole



One hole



Zero holes



“Topologically” equivalent

“Topologically” different

Topological invariant in a Hamiltonian

We can classify Hamiltonians according to topological invariants

Hamiltonian

$$H(\mathbf{k})$$

Wavefunction

$$|\Psi(\mathbf{k})\rangle$$

$$C = \int_{BZ} \Omega d^2\mathbf{k}$$

Topological invariant
(Chern number)

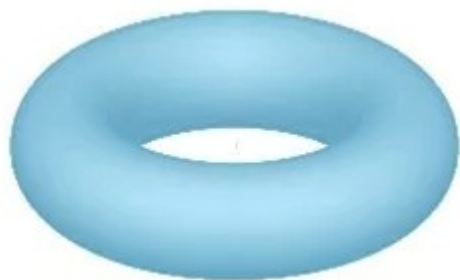
$$\Omega = \nabla \times \mathbf{A}|_z$$

Metric
(Berry curvature)

The role of a topological invariant

**Hamiltonians with different topological invariants
can not be deformed one to another**

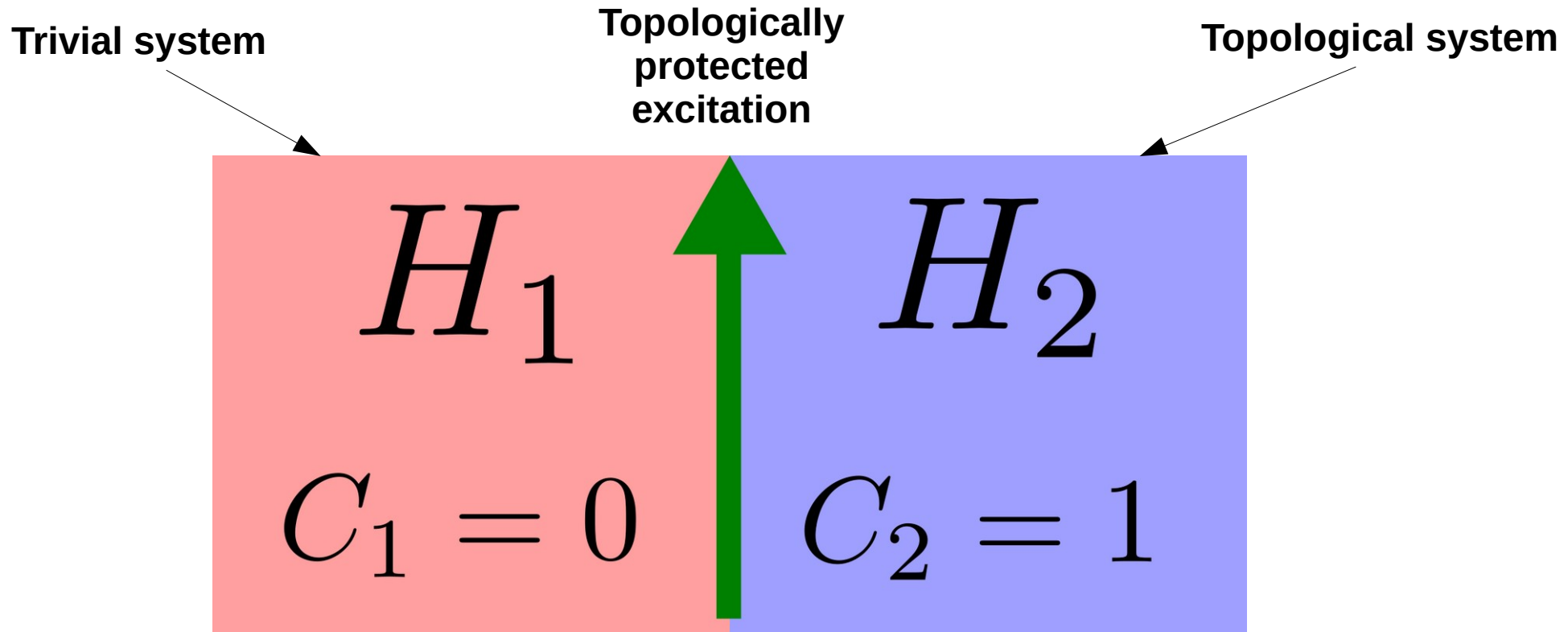
$$C = 1$$



$$C = 2$$



The consequence of different topological invariants



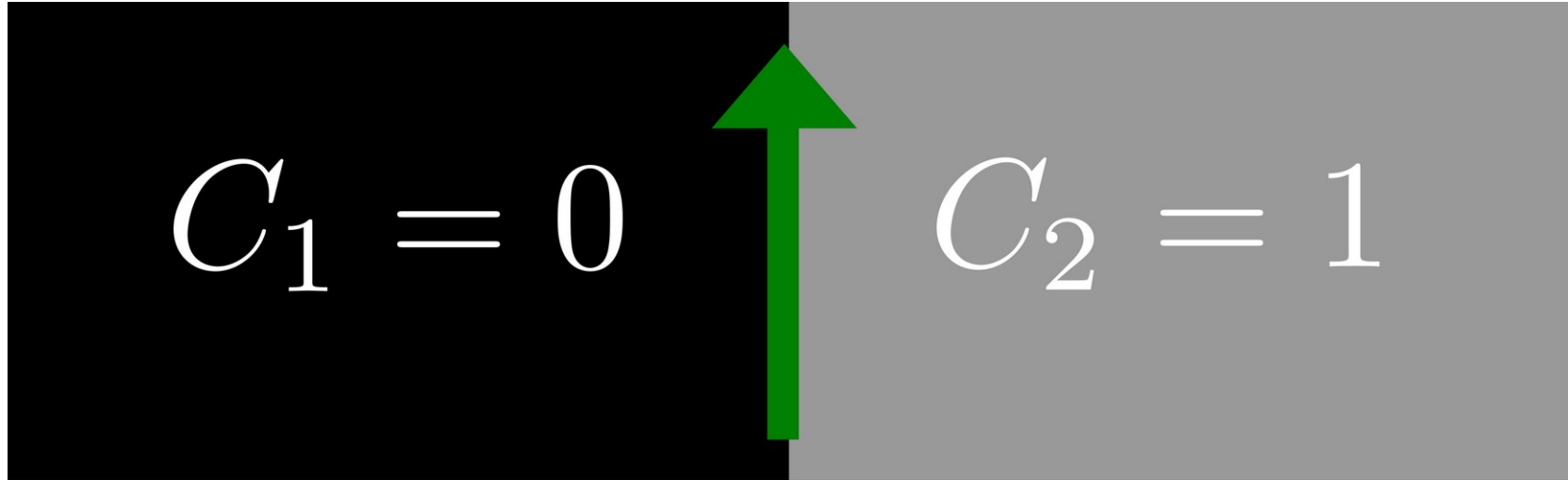
Topological excitations appear between topologically different systems

The edge states of a Chern insulator

Trivial system

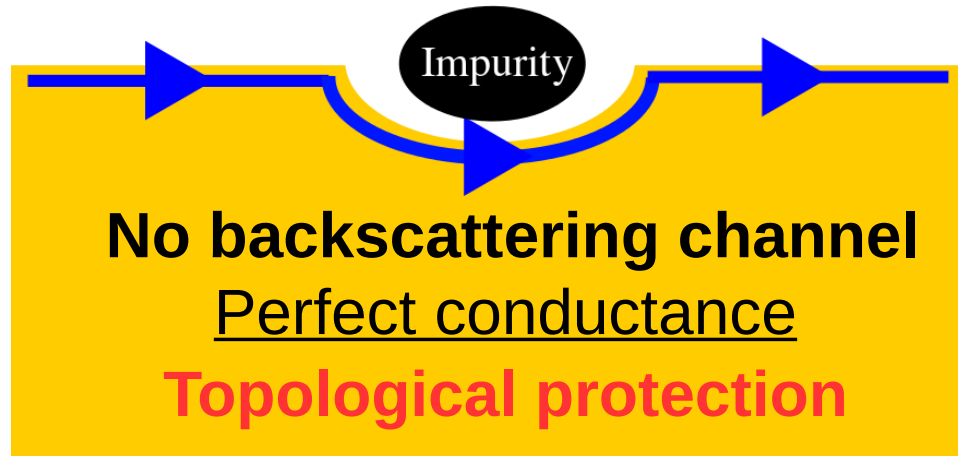
Topologically
protected
chiral state

Topological system



The edge states of the quantum Hall effect are topological excitations

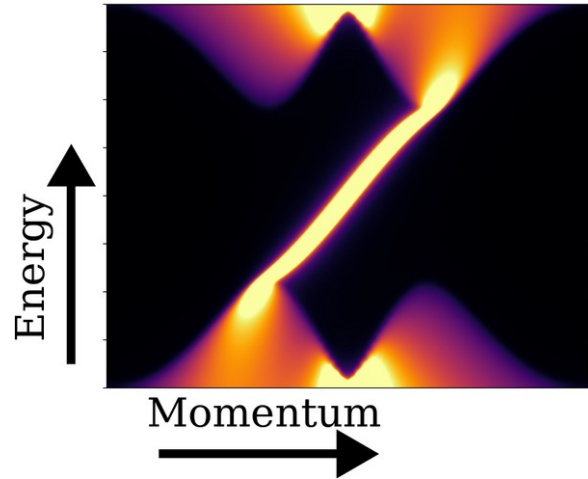
The edge states of a Chern insulator



The edge states of the quantum Hall effect are topologically protected

Three important topological materials

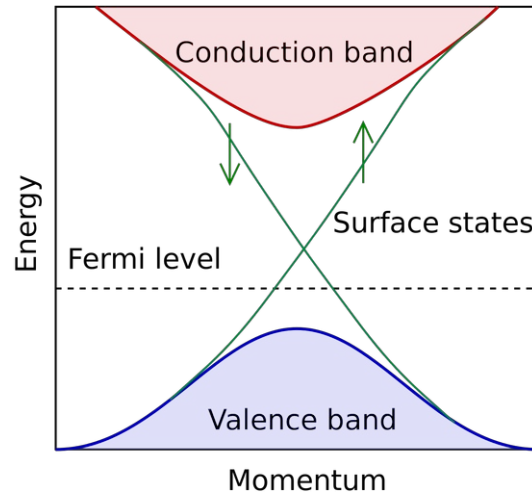
Chern insulators



Chiral states

Electronics

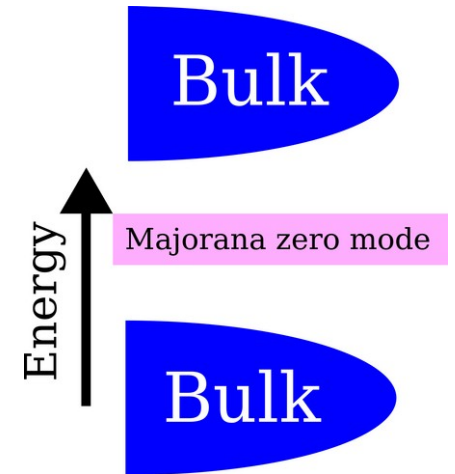
Quantum spin Hall insulators



Helical states

Spintronics

Topological superconductors

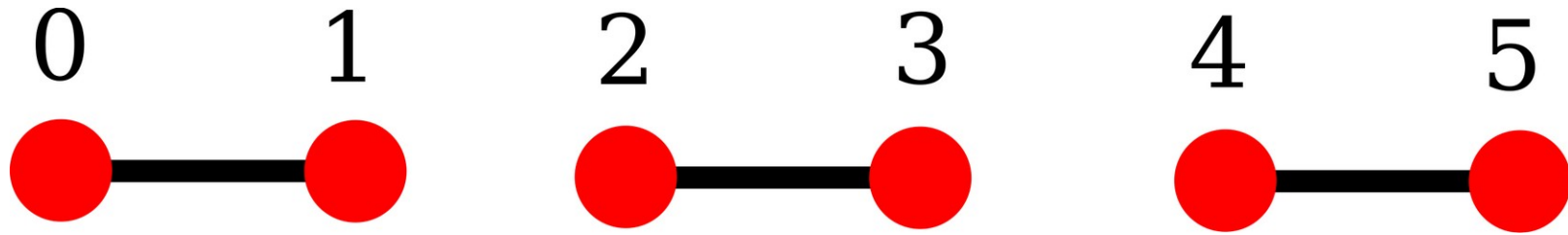


Majorana excitations

*Topological quantum
computing*

A minimal model for a topological insulator: the SSH model

The SSH model



$$H = \sum_{n=0}^4 [1 + (-1)^n] / 2 c_n^\dagger c_{n+1} + h.c.$$

$$H = c_0^\dagger c_1 + c_2^\dagger c_3 + c_4^\dagger c_5 + h.c.$$

Let us consider a finite dimerized chain

The two phases of the dimerized model

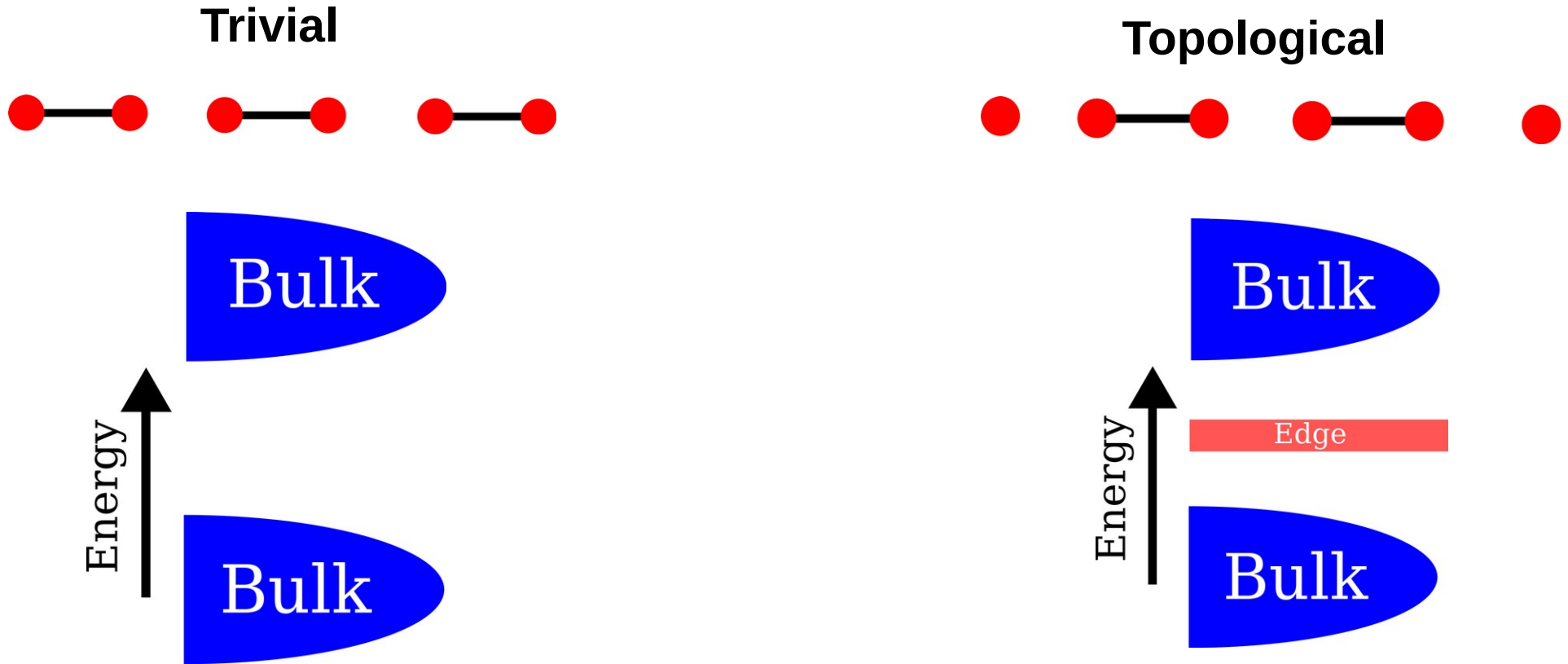
“Trivial” phase (gaped everywhere)



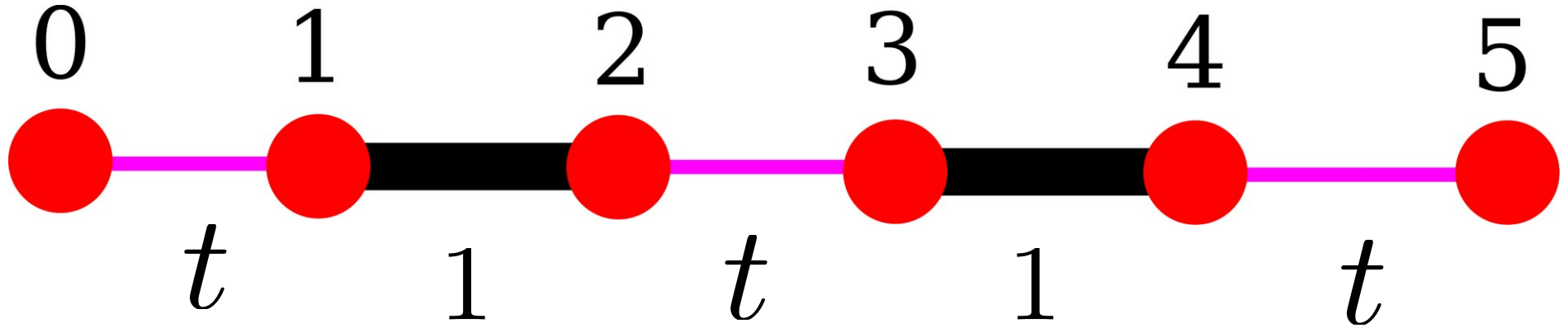
“Topological” phase (gapless zero modes)



The two phases of the dimerized model



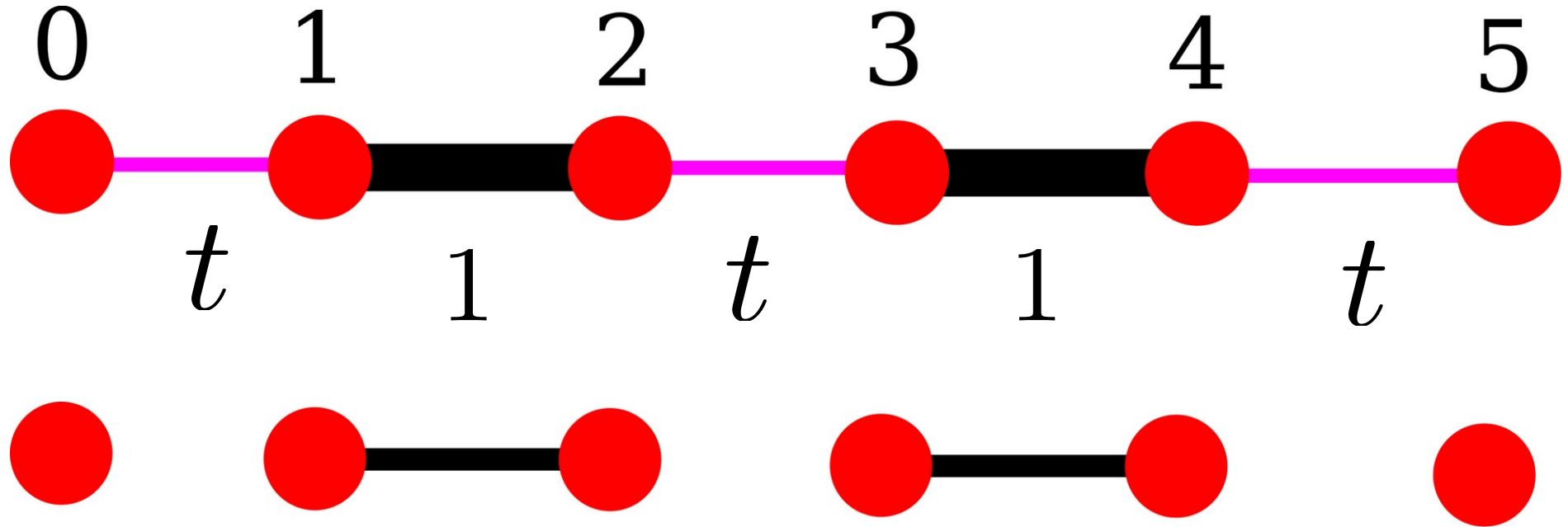
Coupling the dimers



$$H = tc_0^\dagger c_1 + c_1^\dagger c_2 + tc_2^\dagger c_3 + c_3^\dagger c_4 + h.c.$$

Does this Hamiltonian have a surface zero mode?

Coupling the dimers

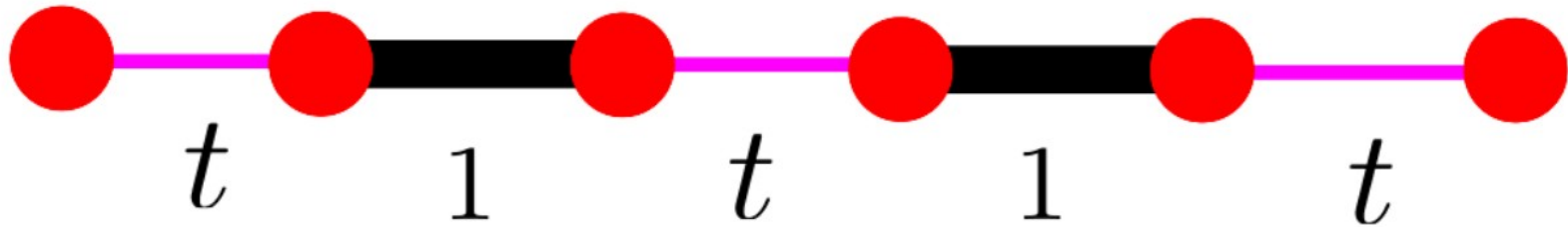


For $t < 1$, both Hamiltonians are topologically equivalent

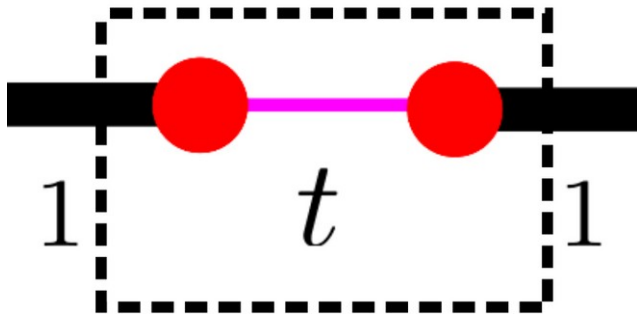
They can be deformed into one another without closing the bulk gap

The bulk Hamiltonian in the dimerized model

For a finite system of this form



The unit cell is



The Hamiltonian is

$$H = \begin{pmatrix} 0 & t + e^{ik} \\ t + e^{-ik} & 0 \end{pmatrix}$$

The bulk invariant in the dimerized model

Hamiltonian

$$H = \begin{pmatrix} 0 & t + e^{ik} \\ t + e^{-ik} & 0 \end{pmatrix}$$

Zak phase

$$\phi = \int_{BZ} A dk$$
$$A = i \langle \Psi(k) | \partial_k | \Psi(k) \rangle$$

Two different possible values for the Zak phase

$$\phi = 0$$

$$t > 1$$

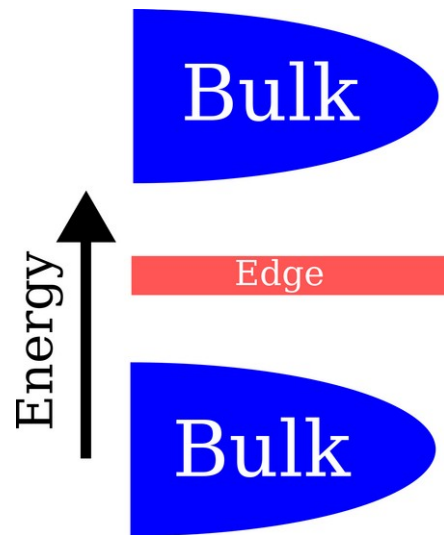
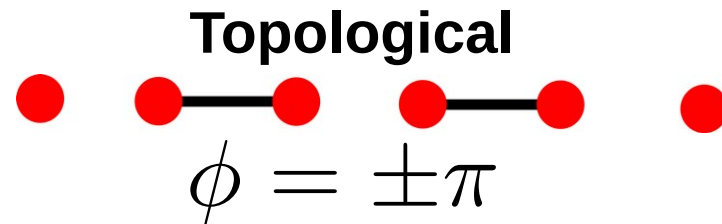
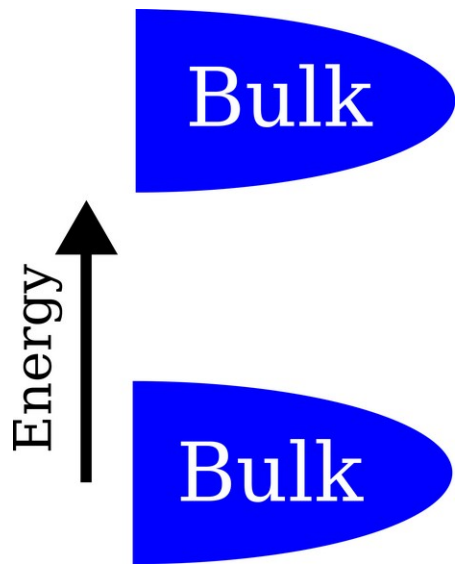
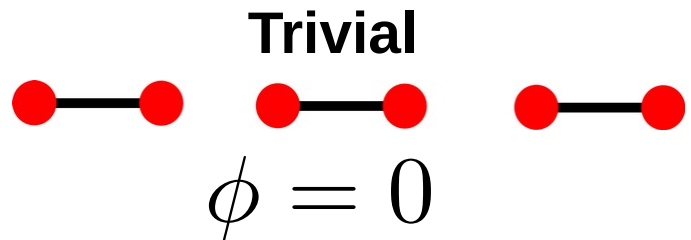
Trivial insulator

$$\phi = \pm\pi$$

$$t < 1$$

Topological insulator

The bulk-boundary correspondence in the dimerized model



Physical relevance of dimerized models

Some topological orders are equivalent to dimerized models upon a mathematical transformation

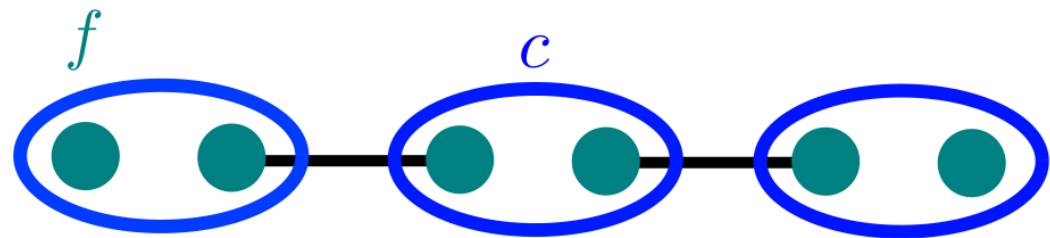
Topological superconductor

$$H = \sum_n c_n^\dagger c_{n+1} + c_n c_{n+1} + h.c.$$

Conventional
fermion

Majorana
operator

$$c_n = \gamma_{2n-1} + i\gamma_{2n}$$

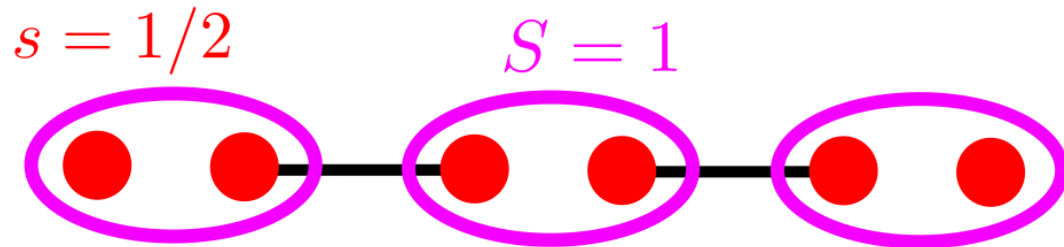


Topological quantum magnets

$$H = \sum_n \vec{S}_n \cdot \vec{S}_{n+1}$$

$$S \sim s_1 \otimes s_2$$

$$(S=1) \quad s_{1,2} = 1/2$$



The computational challenge of
quantum many-body systems

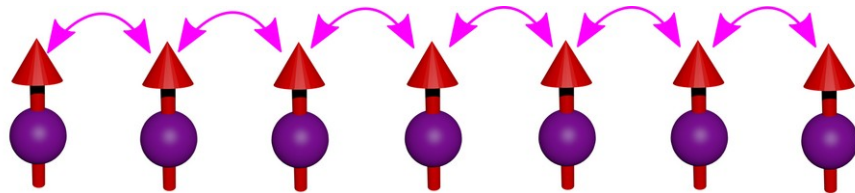
The problem of dimensionality

In a many-body problem, the size of our vectors grows as

$$2^L$$

where L is the number of sites

$$\mathcal{H} = \sum_{\langle ij \rangle} J \vec{S}_i \cdot \vec{S}_j$$



For a single-particle tight binding problem, we can reach up to 10^8 sites in a laptop

For a many-problem, we cannot even store states for systems bigger than $L = 30$ sites

$$2^{30} \sim 10^9$$

The quantum many-body problem

Let us take a simple many-body problem

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

And let us imagine that we have L different sites on our system and $S=1/2$

For example, for $L=2$ sites the elements of the basis are

$$|\uparrow\uparrow\rangle \quad |\uparrow\downarrow\rangle \quad |\downarrow\uparrow\rangle \quad |\downarrow\downarrow\rangle$$

For $L=3$ sites the elements of the basis are

$$\begin{array}{cccc} |\uparrow\uparrow\uparrow\rangle & |\uparrow\uparrow\downarrow\rangle & |\uparrow\downarrow\uparrow\rangle & |\uparrow\downarrow\downarrow\rangle \\ |\downarrow\uparrow\uparrow\rangle & |\downarrow\uparrow\downarrow\rangle & |\downarrow\downarrow\uparrow\rangle & |\downarrow\downarrow\downarrow\rangle \end{array}$$

The quantum many-body problem

Let us take a simple many-body problem

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

And let us imagine that we have L different sites on our system and $S=1/2$

For $L=4$ sites, the elements of the basis are

$ \uparrow\uparrow\uparrow\uparrow\rangle$	$ \uparrow\uparrow\uparrow\downarrow\rangle$	$ \uparrow\uparrow\downarrow\uparrow\rangle$	$ \uparrow\uparrow\downarrow\downarrow\rangle$
$ \uparrow\downarrow\uparrow\uparrow\rangle$	$ \uparrow\downarrow\uparrow\downarrow\rangle$	$ \uparrow\downarrow\downarrow\uparrow\rangle$	$ \uparrow\downarrow\downarrow\downarrow\rangle$
$ \downarrow\uparrow\uparrow\uparrow\rangle$	$ \downarrow\uparrow\uparrow\downarrow\rangle$	$ \downarrow\uparrow\downarrow\uparrow\rangle$	$ \downarrow\uparrow\downarrow\downarrow\rangle$
$ \downarrow\downarrow\uparrow\uparrow\rangle$	$ \downarrow\downarrow\uparrow\downarrow\rangle$	$ \downarrow\downarrow\downarrow\uparrow\rangle$	$ \downarrow\downarrow\downarrow\downarrow\rangle$

The quantum many-body problem

Let us take a simple many-body problem

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

A typical wavefunction is written as

$$|\Psi\rangle = \sum c_{s_1, s_2, \dots, s_L} |s_1, s_2, \dots, s_L\rangle$$

We need to determine in total 2^L coefficients

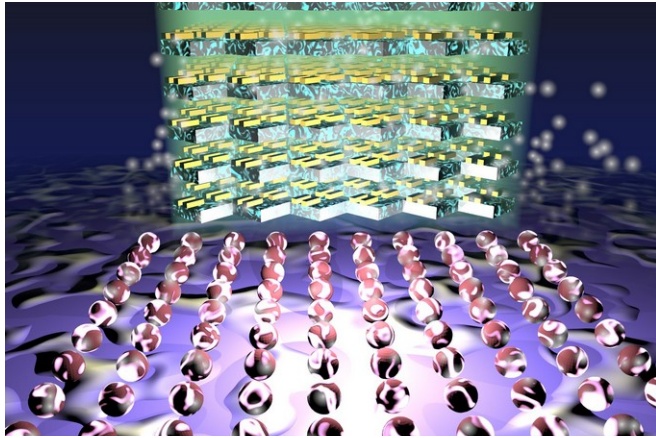
Is there an efficient way of storing so many coefficients?

The fundamental idea of tensor-networks

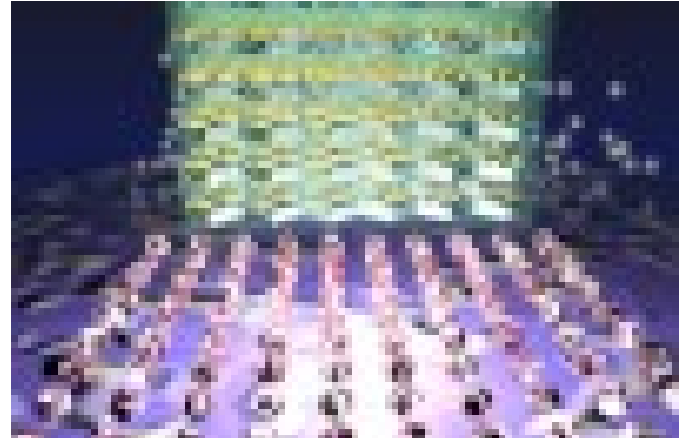
A many-body wavefunction is a very high dimensional object

$$|\Psi\rangle = \sum c_{s_1, s_2, \dots, s_L} |s_1, s_2, \dots, s_L\rangle$$

Tensor-networks allow “compressing” all that information in a very efficient way



“True wavefunction”



“Tensor-network wavefunction”

The matrix-product state ansatz

For this wavefunction $|\Psi\rangle = \sum c_{s_1, s_2, \dots, s_L} |s_1, s_2, \dots, s_L\rangle$

Let us imagine to propose a parametrization in this form

$$c_{s_1, s_2, \dots, s_L} = M_1^{s_1} M_2^{s_2} \dots M_L^{s_L}$$

dimension 2^L dimension $\sim Lm^2$

(m dimension of the matrix)

State compression with tensor-networks

Given a many-body wavefunction, we can parametrize the components as

$$|\Psi\rangle = \sum_{\{s\}} \text{Tr} \left[M_1^{(s_1)} M_2^{(s_2)} \dots M_N^{(s_N)} \right] |s_1 s_2 \dots s_N\rangle$$



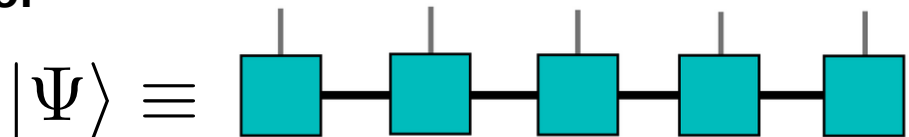
Matrix product state

The previous representation allows drastically reducing the memory required to store a state

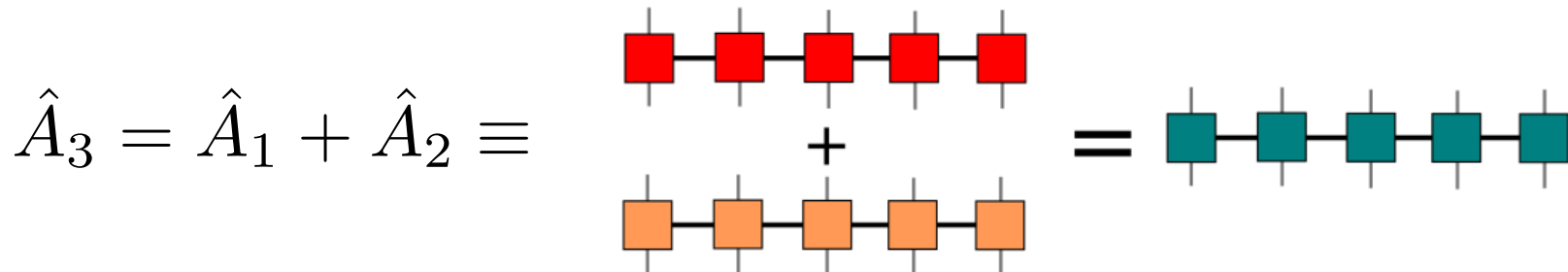
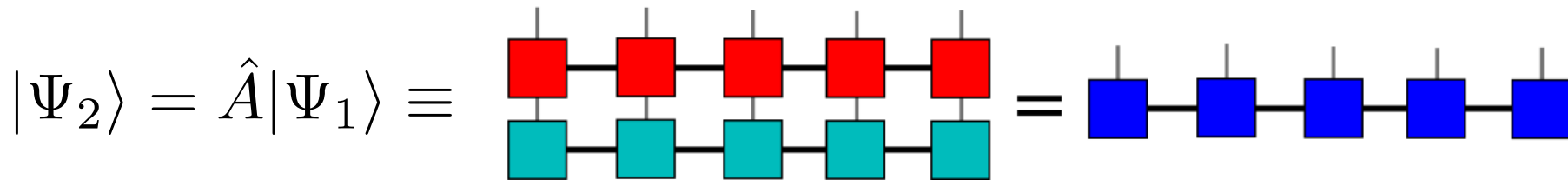
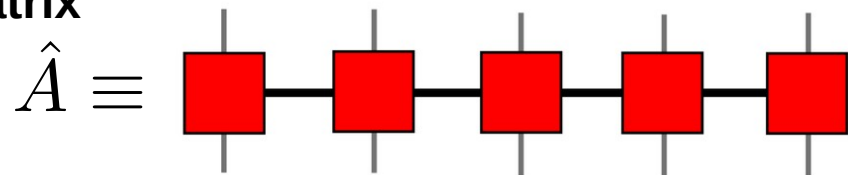
Exponentially large algebra with tensor networks

Tensor network allow to (approximately) operate in exponentially large vector spaces

vector

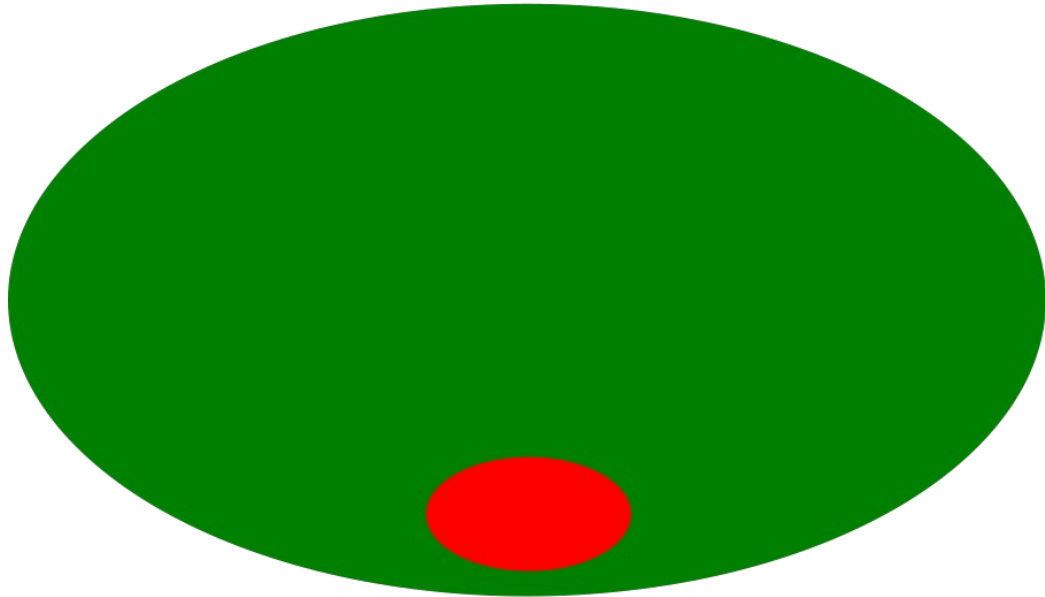


matrix



MPS as a parametrization of area law states

Full Hilbert space



Tensor network states

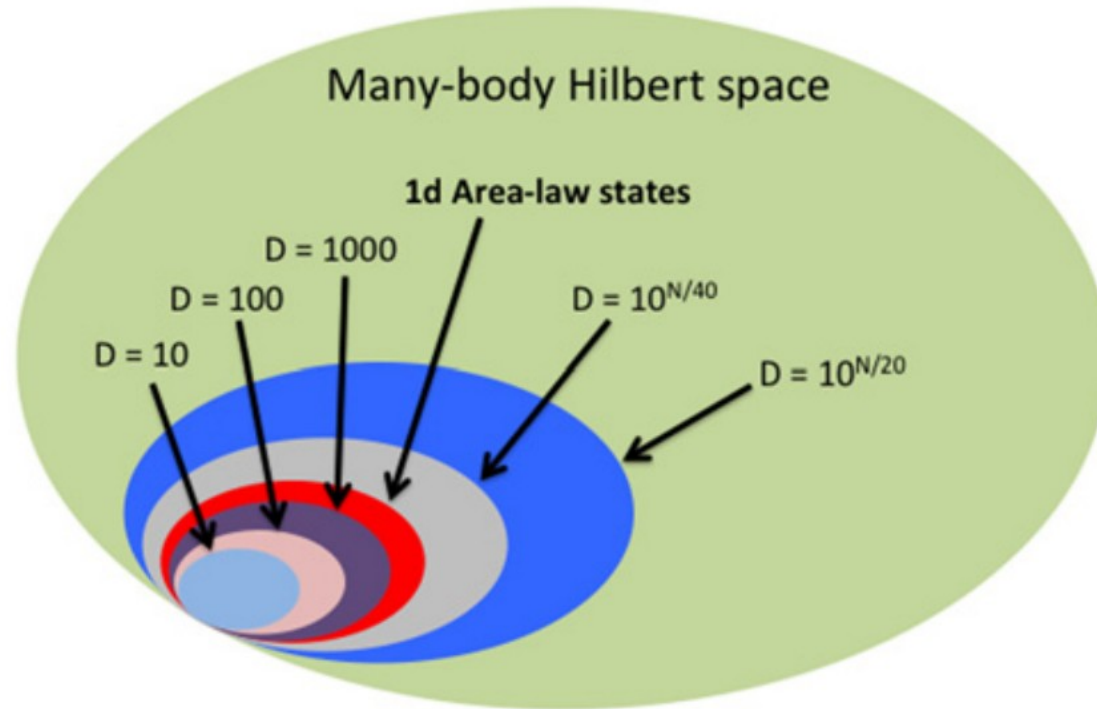
$$c_{s_1, s_2, \dots, s_L} = M_1^{s_1} M_2^{s_2} \dots M_L^{s_L}$$

MPS have an entanglement entropy
bounded by the bond dimension

$$S \sim \log(m)$$

A controlled way of parametrizing the Hilbert space

Sketch of the space parametrized with bond dimension D



The matrix-product state ansatz

- This ansatz enforces a maximum amount of entanglement entropy in the state $S \sim \log m$
- One-dimensional problems have ground states that can be captured with this ansatz

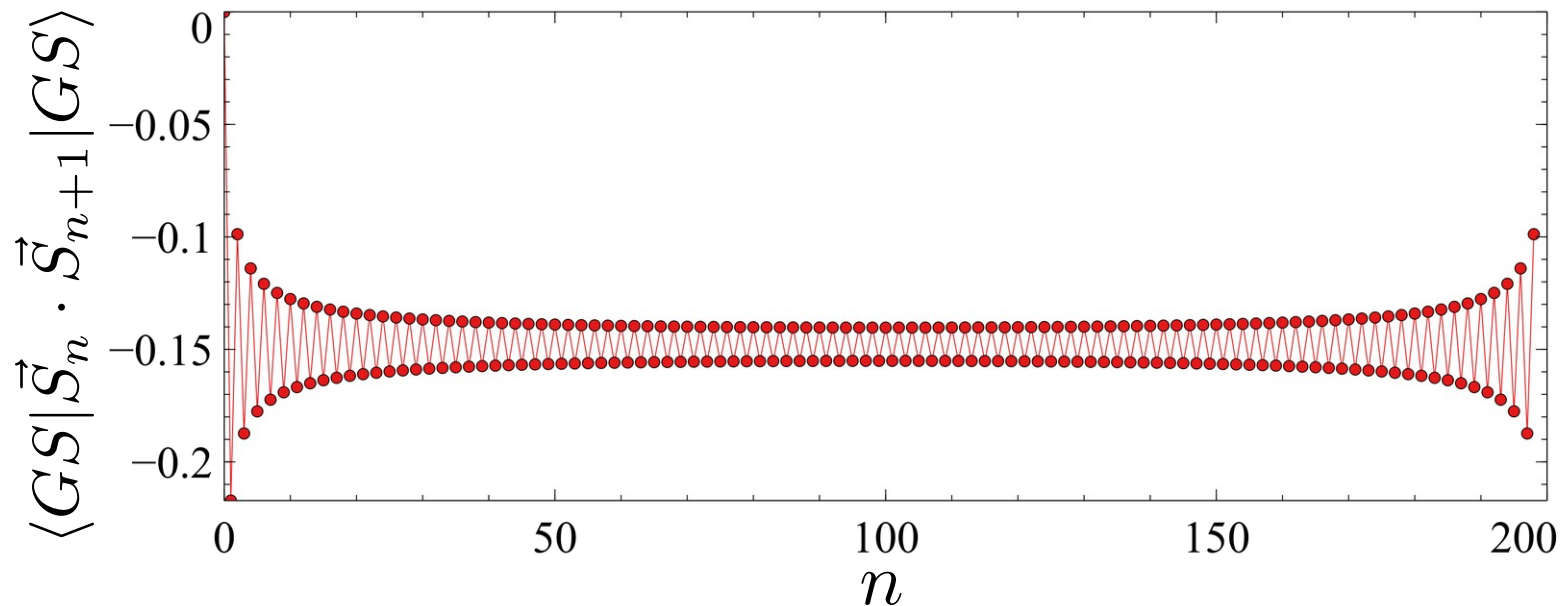
$$c_{s_1, s_2, \dots, s_L} = M_1^{s_1} M_2^{s_2} \dots M_L^{s_L}$$

This ansatz can be generalized for time-evolution, excited states, or typical thermal states

The Heisenberg model with tensor-networks

Non-uniform Heisenberg model

$$\mathcal{H} = \sum_n J(n) \vec{S}_n \cdot \vec{S}_{n+1}$$
$$J(n) = J_0 + \delta \cos \Omega n$$

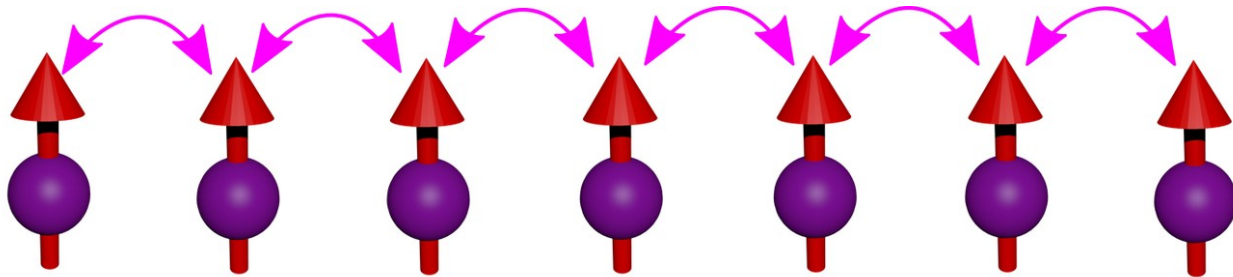


Tensor networks allow solving a 200 many-body spin model in a few seconds in a laptop

Many-body dynamical correlators

One dimensional Heisenberg Hamiltonian

$$\mathcal{H} = \sum_{\langle ij \rangle} J \vec{S}_i \cdot \vec{S}_j$$

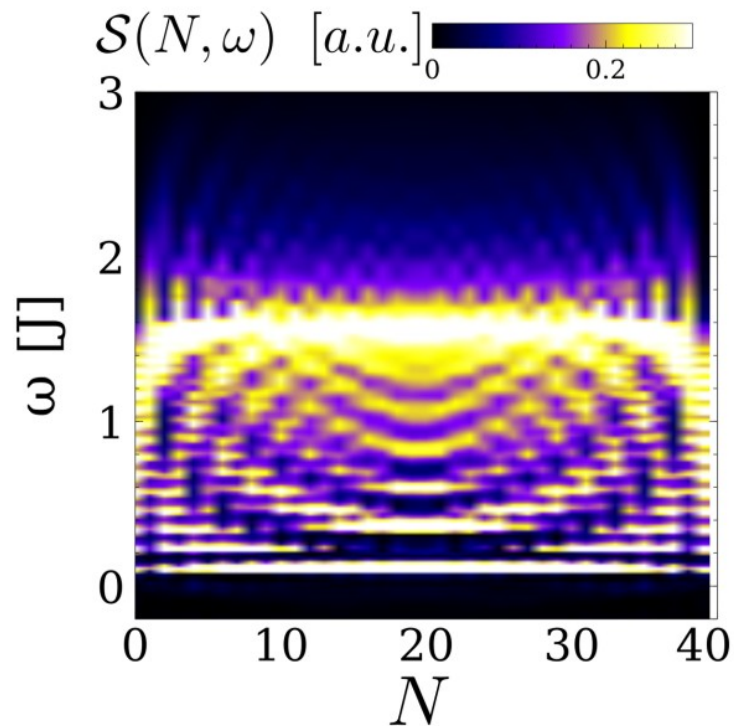


Tensor networks allow computing dynamical correlators

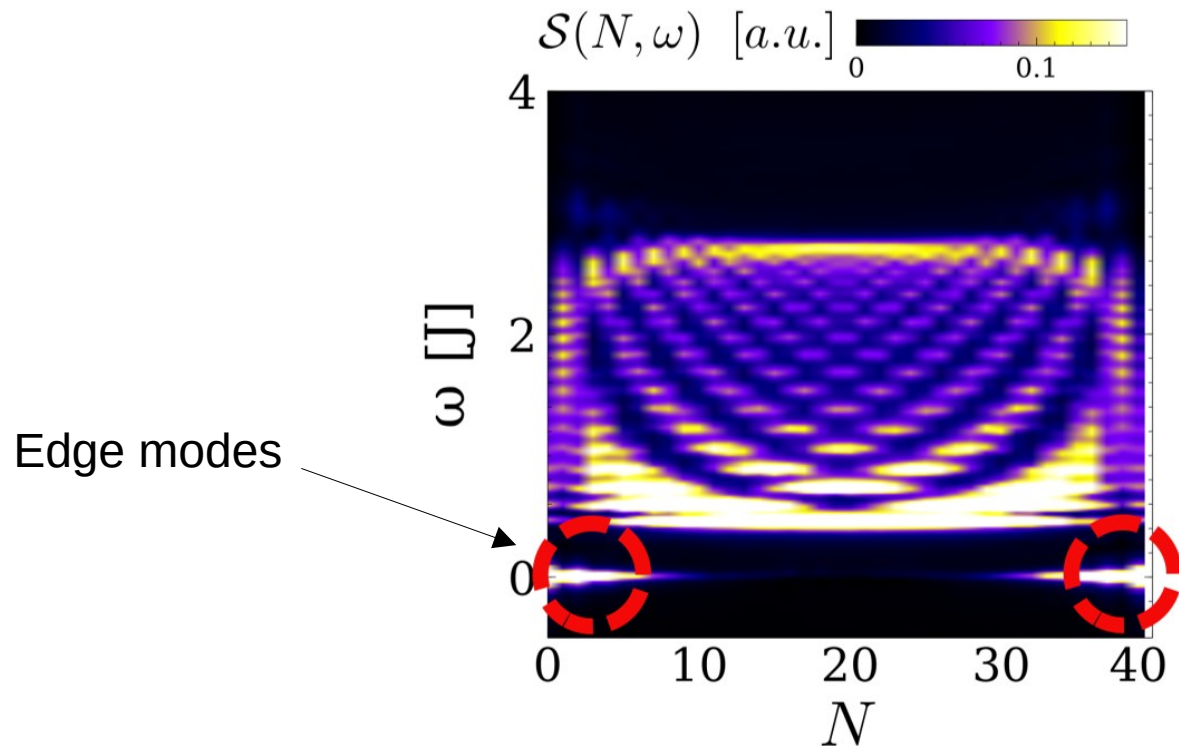
$$\mathcal{S}(N, \omega) = \langle GS | S_N^z \delta(\omega - \mathcal{H} + E_0) S_N^z | GS \rangle$$

Dynamical structure factor of a Heisenberg model

S=1/2 chain



S=1 chain



Open-source software for tensor-network many-body algorithms

dmrgpy

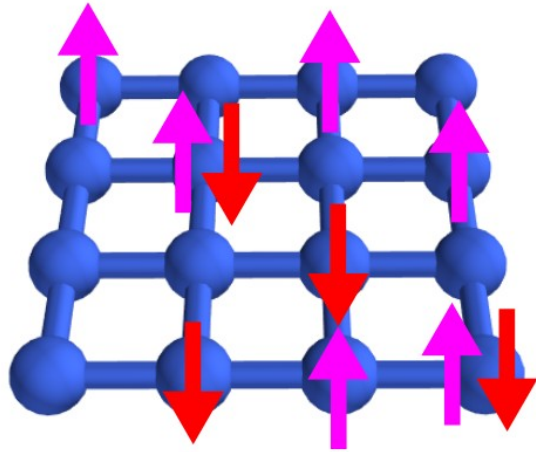
```
from dmrgpy import spinchain
spins = ["S=1" for i in range(40)] # S=1 chain
sc = spinchain.Spin_Chain(spins) # create spin chain object
h = 0 # initialize Hamiltonian
for i in range(len(spins)-1):
    h = h + sc.Sx[i]*sc.Sx[i+1]
    h = h + sc.Sy[i]*sc.Sy[i+1]
    h = h + sc.Sz[i]*sc.Sz[i+1]
sc.set_hamiltonian(h)
sc.get_dynamical_correlator(name=(sc.Sz[0], sc.Sz[0]))
```

Generic Python library for tensor-network kernel polynomial algorithms for spins, fermions, parafermions, with static and dynamical solvers

<https://github.com/joselado/dmrgpy>

Some paradigmatic problems solved with matrix product states

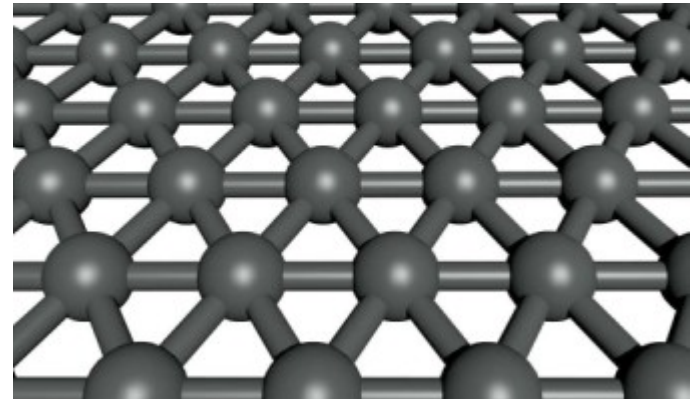
Solving the 2D Hubbard model at finite doping



$$H = \sum_{ij,s} t_{ij} c_{is}^\dagger c_{js} + \sum_i U c_{i\uparrow}^\dagger c_{i\uparrow} c_{i\downarrow}^\dagger c_{i\downarrow}$$

Science, 365(6460), 1424-1428 (2019)

Solving the 2D Heisenberg model in frustrated lattices

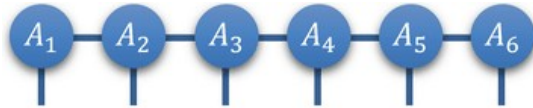


$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

Phys. Rev. Lett. 123, 207203 (2019)

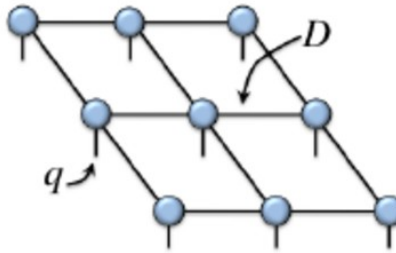
Many-body state compression

Matrix-product states



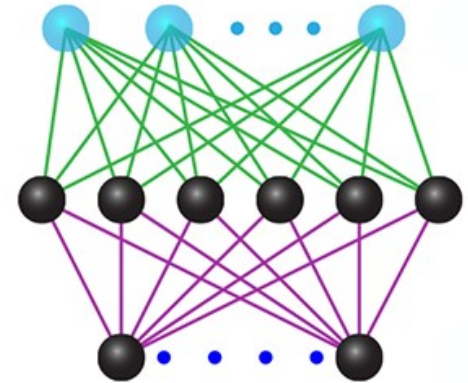
Phys. Rev. Lett. 69, 2863 (1992)

Projected entangled pair-states



Annals of Physics 326, 96 (2011)

Neural-network quantum states



Science 355.6325 (2017): 602-606.

Other compressed many-body states could be potentially used for noisy quantum circuit simulation

Plan for today

- Emulating quantum circuits with tensor-networks

Phys. Rev. Research 6, 033325 (2024)

- Computing topological invariants in a superconducting quantum computer

Phys. Rev. Research 6, 043288 (2024)

Marcel Niedermeier



Marc Nairn



Christian Flindt



Tensor-networks for noisy quantum circuits

What is a quantum computer

Time evolution of quantum systems are described by $-i\frac{\partial}{\partial t}|\Psi\rangle = H(t)|\Psi\rangle$

Whose solution is $|\Psi(t)\rangle = e^{i\int_{t=0}^t H(t')dt'}|\Psi(t=0)\rangle$

A quantum computer is a controllable quantum system where

$|\Psi(t=0)\rangle$ and $H(t)$ can be controlled

The results of the computation consist on observables $\langle A \rangle = \langle \Psi(t) | A | \Psi(t) \rangle$

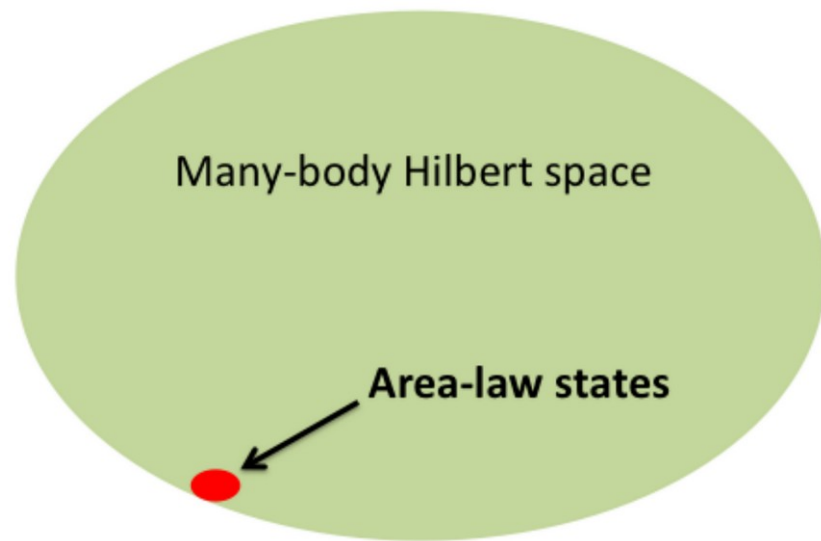
Quantum computers enabling simulating dynamics that may require exponentially large resources

*A method to simulate large quantum many-body dynamics (tensor networks)
also allows to simulate large quantum computers*

How much entanglement do we need

Qubit fidelity limits which states we can create in a quantum circuit

Tensor-network bond dimension limits which states we parametrize

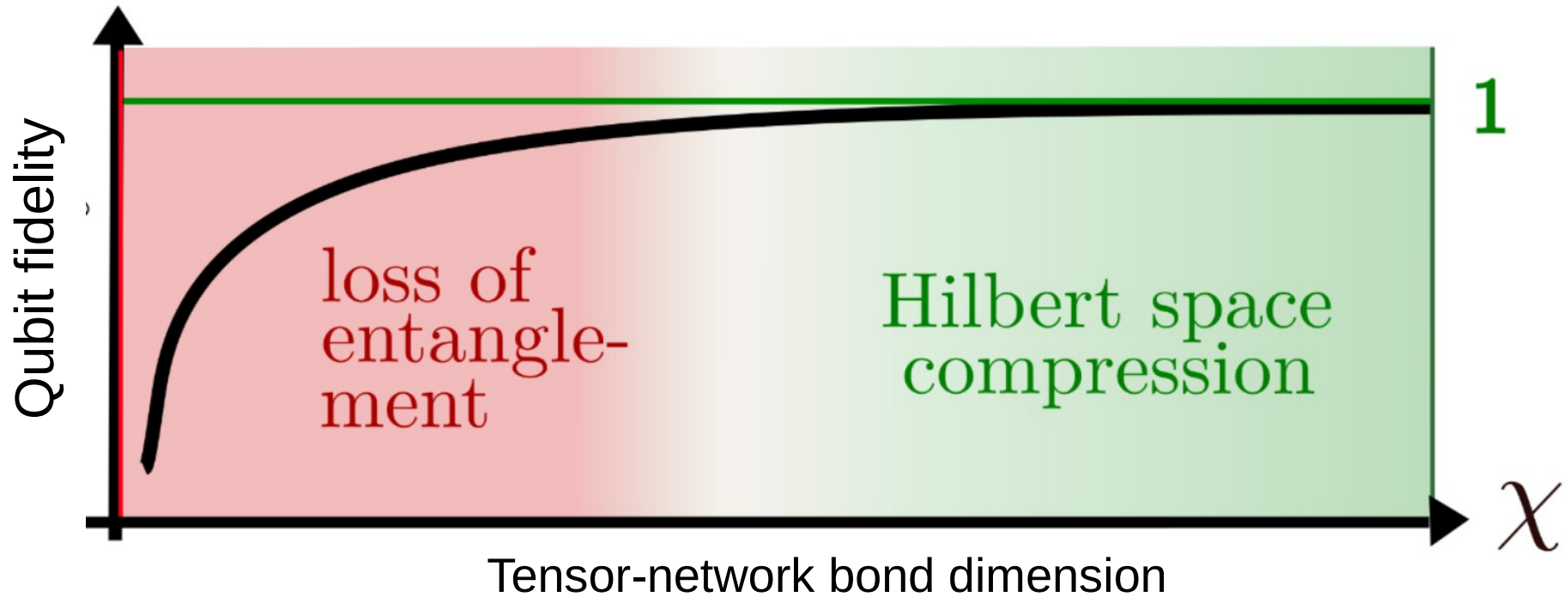


Both constraints put bounds to the entanglement of accessible states

Phys. Rev. X 10, 041038 (2020)

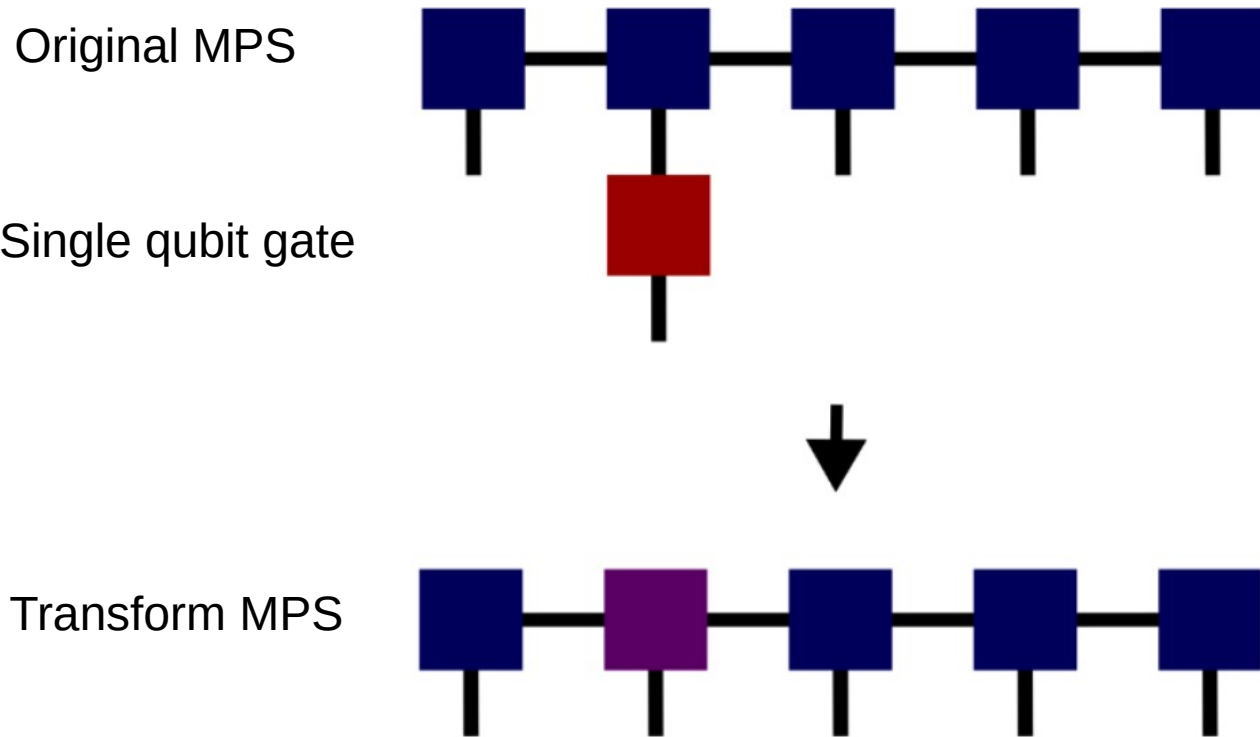
Do we need the whole Hilbert space to successfully run a quantum algorithm?
Could we get meaningful results even if we can only access part of the Hilbert space?

What is the relation between a noisy qubit and a tensor network?



The finite tensor-network bond dimension can be understood as a finite qubit fidelity

Applying a single qubit gate to a tensor network



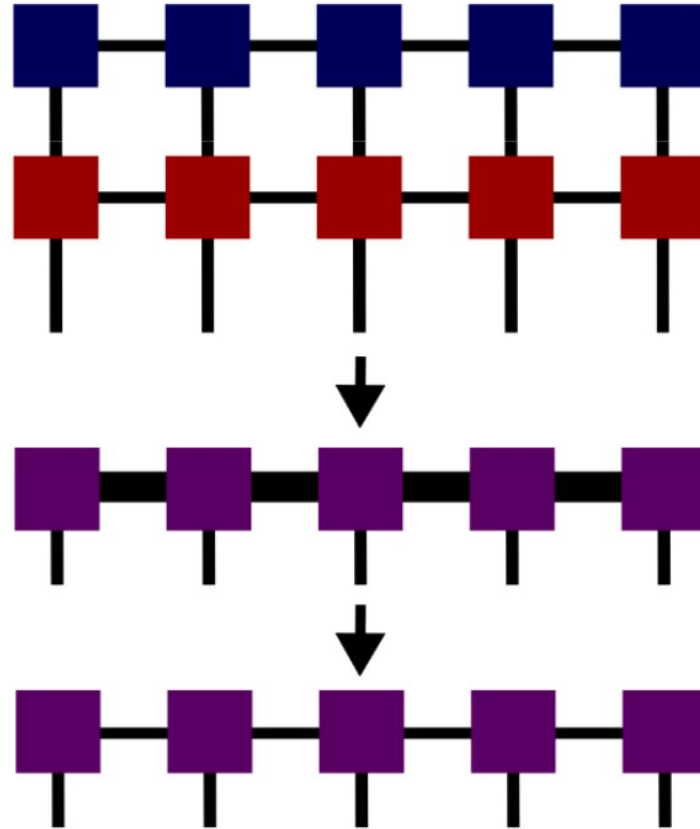
Applying a multi-qubit gate to a tensor network

Original MPS

Multi-qubit gate

Higher dimension updated MPS

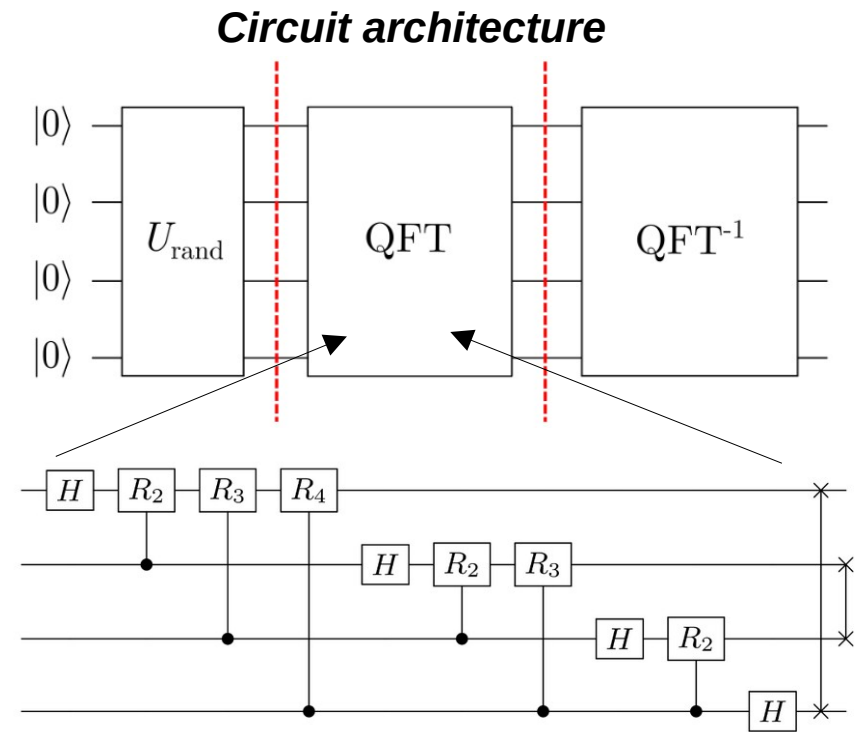
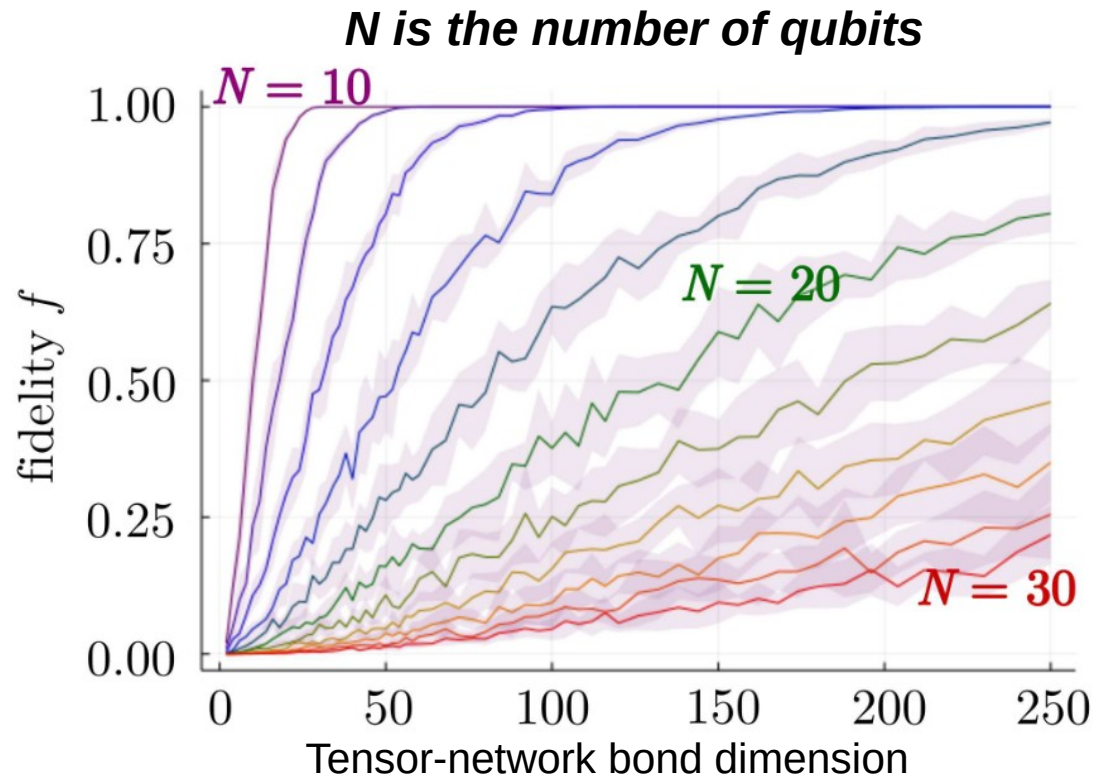
Compressed updated MPS



Three quantum algorithms with tensor-network quantum circuits

- ***Quantum Fourier transform:*** quantum analogue of the discrete Fourier transform
- ***Grover's algorithm:*** find elements in a database
- ***Quantum counting algorithm:*** counting the number of solutions for a given search problem

The quantum Fourier transform

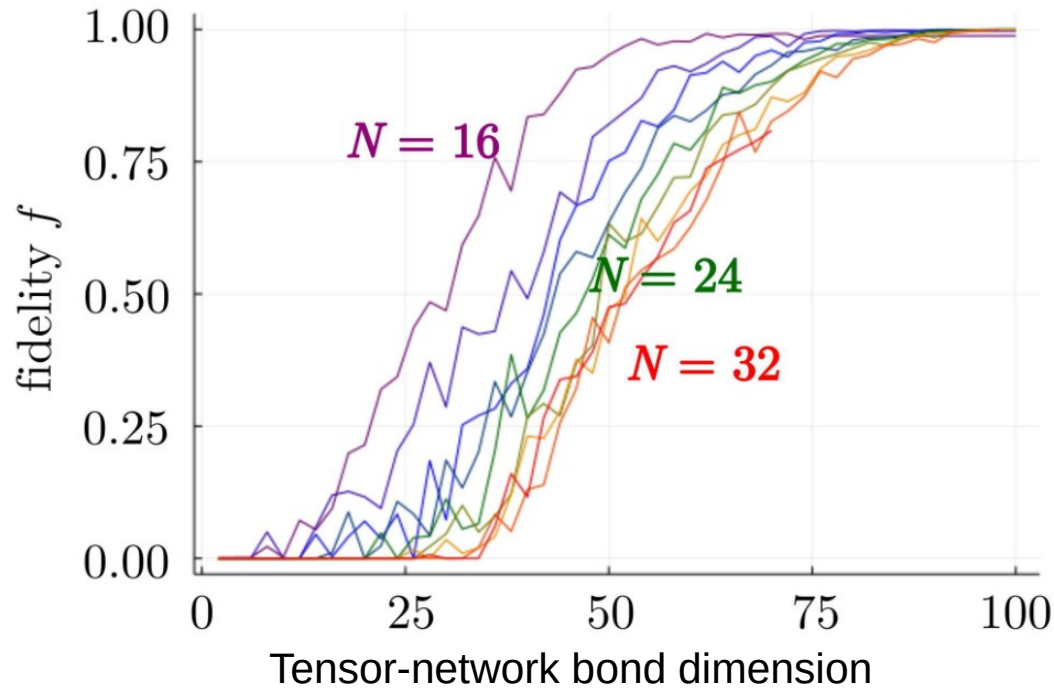


QFT Fidelity

$$f = |\langle \Psi'_0 | \Psi_0 \rangle|^2 \quad |\Psi'_0\rangle = \text{QFT}^{-1} \text{QFT} |\Psi_0\rangle$$

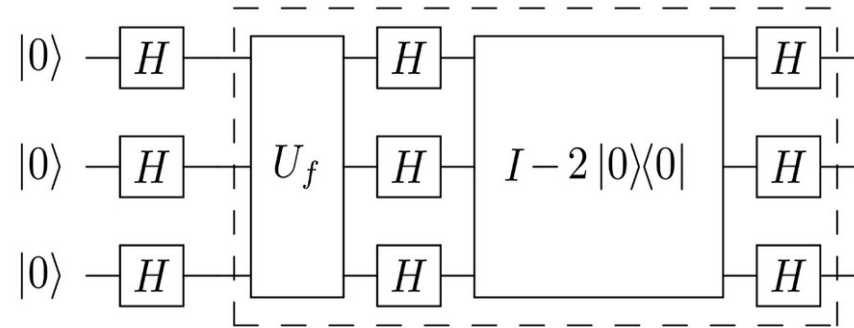
Grover's search algorithm

N is the number of qubits



Circuit architecture

Grover operator G , repeat r times



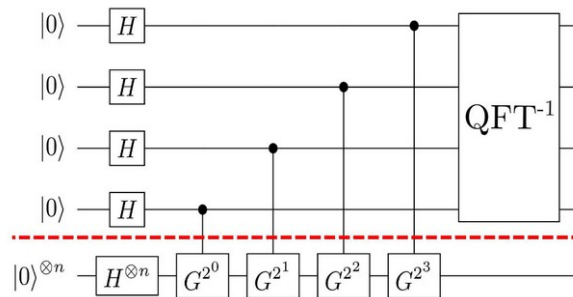
Grover fidelity (m marked elements)

$$f_r = \frac{1}{m} \sum_i^m |\langle \omega_i | \Psi_r \rangle|^2$$

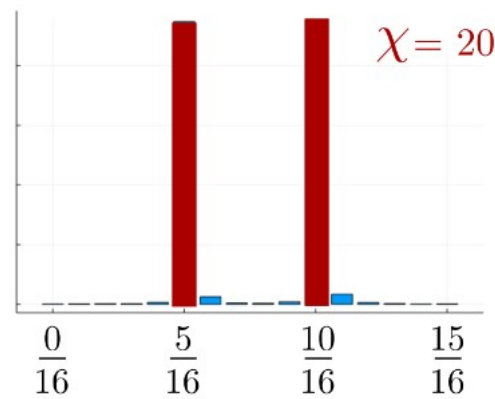
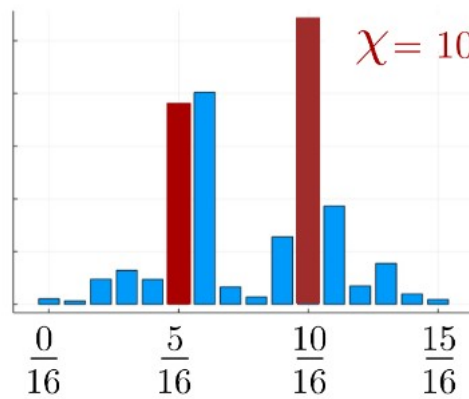
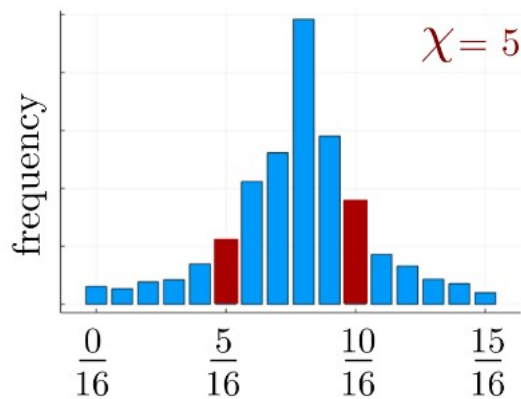
Quantum counting algorithm

Phys. Rev. Research 6, 033325 (2024)

Circuit architecture



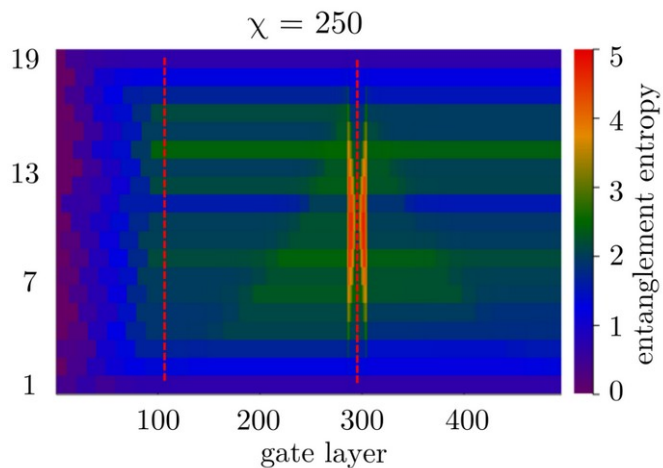
Phases of marked elements (correct in red)



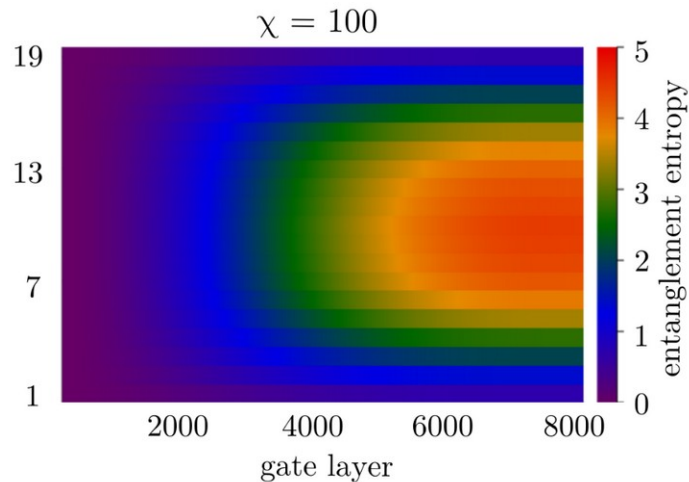
high-quality circuit

Entanglement propagation in the quantum-circuit

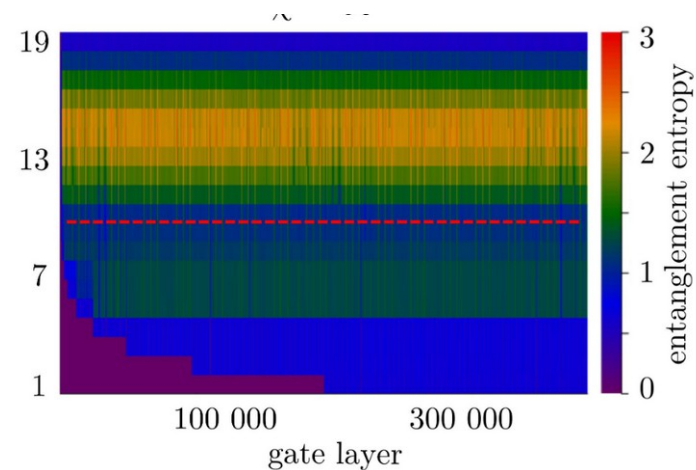
Quantum Fourier transform



Grover's algorithm



Quantum counting algorithm



Entanglement builds up in concrete locations and steps of the quantum circuit

Quantum circuits for topological quantum materials

Topological invariant in a Hamiltonian

We can classify Hamiltonians according to topological invariants

Hamiltonian

$$H(\mathbf{k})$$

Wavefunction

$$|\Psi(\mathbf{k})\rangle$$

$$C = \int_{BZ} \Omega d^2\mathbf{k}$$

Topological invariant
(Chern number)

$$\Omega = \nabla \times \mathbf{A}|_z$$

Metric
(Berry curvature)

Berry phase with a quantum circuit

Take the eigenstates of the Hamiltonian

$$H(\mathbf{k}) |n(\mathbf{k})\rangle = E_n(\mathbf{k}) |n(\mathbf{k})\rangle$$

Evolve them in reciprocal space

$$U(T, 0) |n(\mathbf{k})\rangle = e^{i(\Theta_B - \Theta_D)} |n(\mathbf{k})\rangle$$

Geometric phase

$$\Theta_B = i \int_0^T dt \langle n(\mathbf{k}(t)) | \partial_t | n(\mathbf{k}(t)) \rangle$$

Dynamical phase

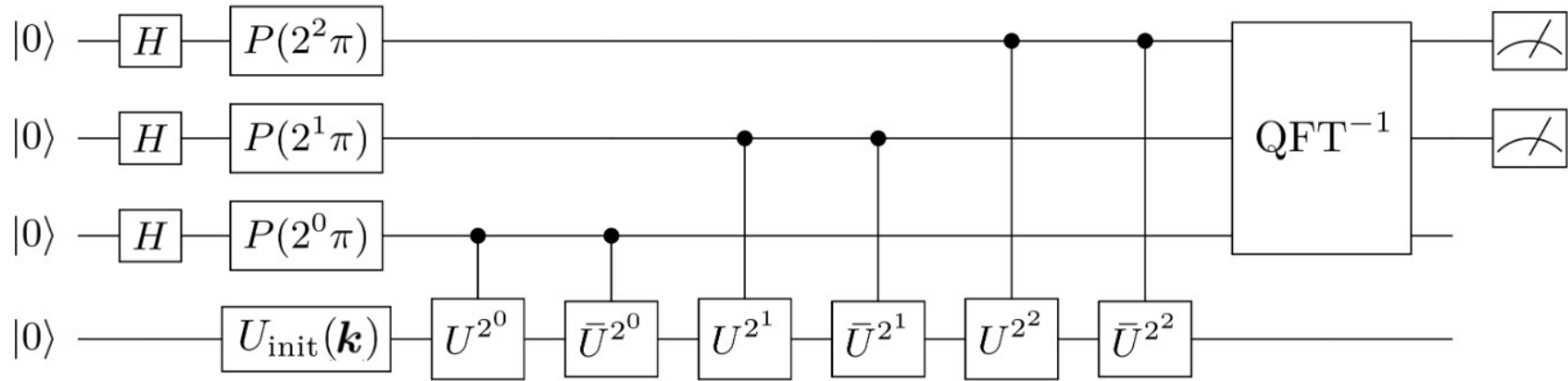
$$\Theta_D = \int_0^T dt E_n(\mathbf{k}(t))$$

We want to cancel out the dynamical phase, so we can evolve first forward and then backwards in time

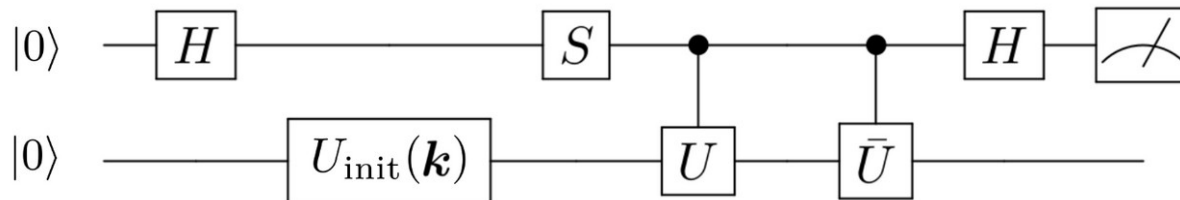
$$\bar{U}(T, 0) U(T, 0) |n(\mathbf{k})\rangle = e^{i2\Theta_B} |n(\mathbf{k})\rangle$$

Quantum circuits to compute topological invariants

Berry phase with quantum phase estimation (based on QFT)



Berry flux (based on Hadamard test)



Two ways of computing a Chern number

Method 1: Integrate the Berry Curvature

$$C = \frac{1}{2\pi} \int_{BZ} d^2\mathbf{k} \Omega(\mathbf{k})$$

Method 2: Pumping of the Wannier charge centers

$$X_W(k_y) = i \int_{-\pi}^{\pi} dk_x \langle n(\mathbf{k}) | \partial_{k_x} | n(\mathbf{k}) \rangle / 2\pi$$

(and count how many times they wind)

Five implementations of the topological invariant

- Helmi quantum computer
- Exact quantum circuit emulator
- Noisy quantum circuit emulator
- Tensor-network quantum circuit emulator
- Exact classical algorithm

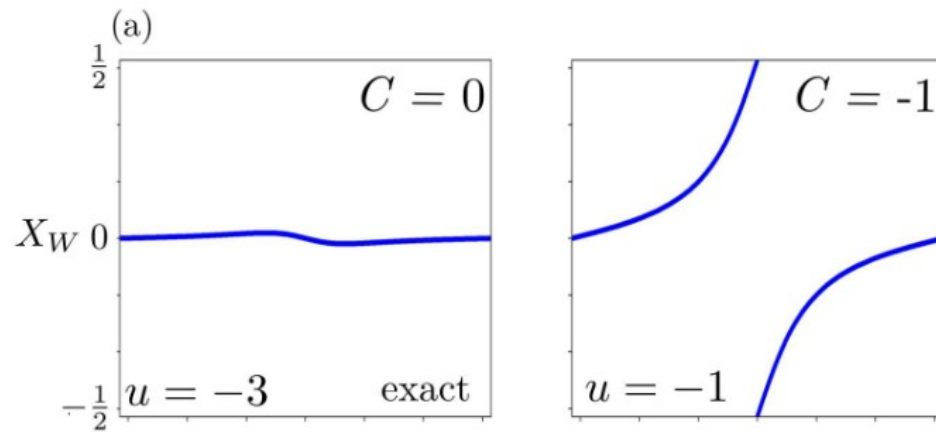
Helmi quantum computer



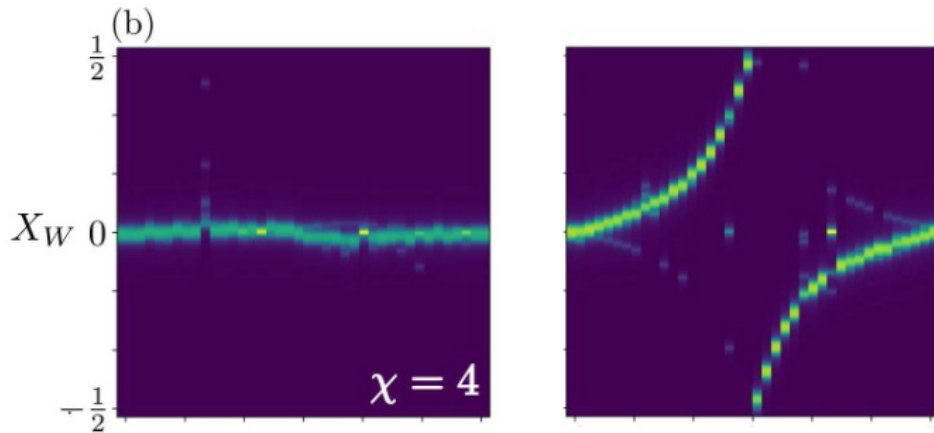
“Helmi, the first Finnish quantum computer, co-developed by VTT and IQM Quantum Computers, is operated by VTT in Espoo, Finland. Helmi is based on superconducting technology, and presently provides five qubits. Upgrades to 20, then 50 qubits is planned for the near future.”

<https://fiqci.fi/>

Chern number from Wannier winding

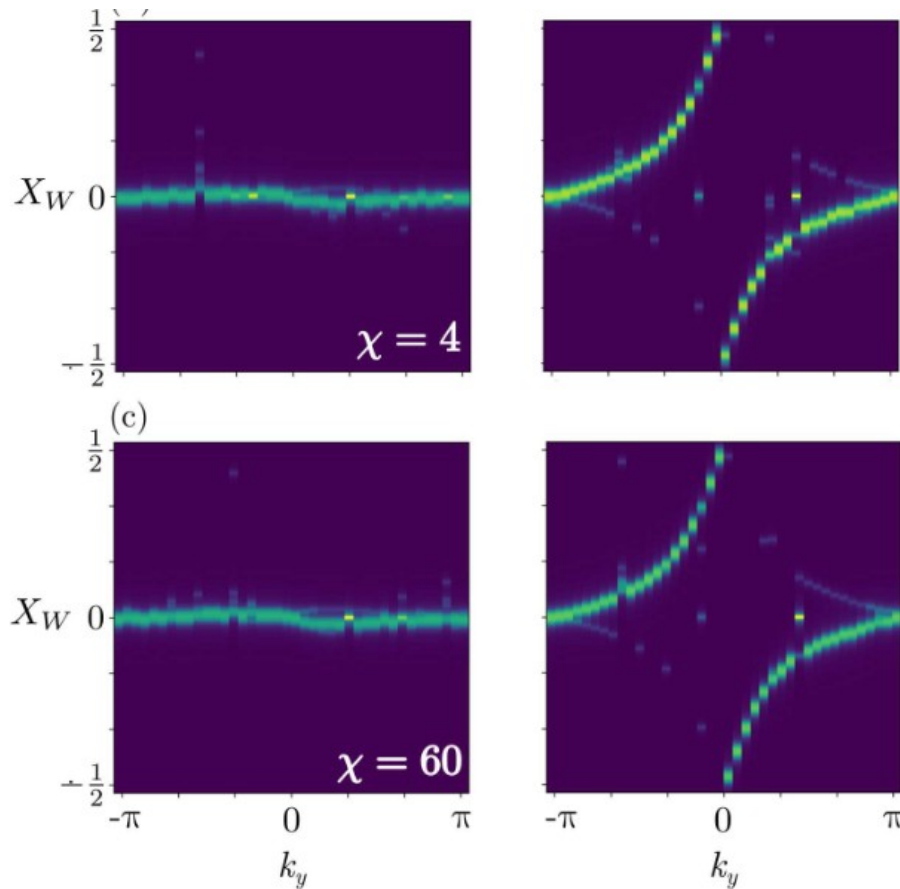


Exact classical simulation



Tensor network simulator

Chern number from Wannier winding



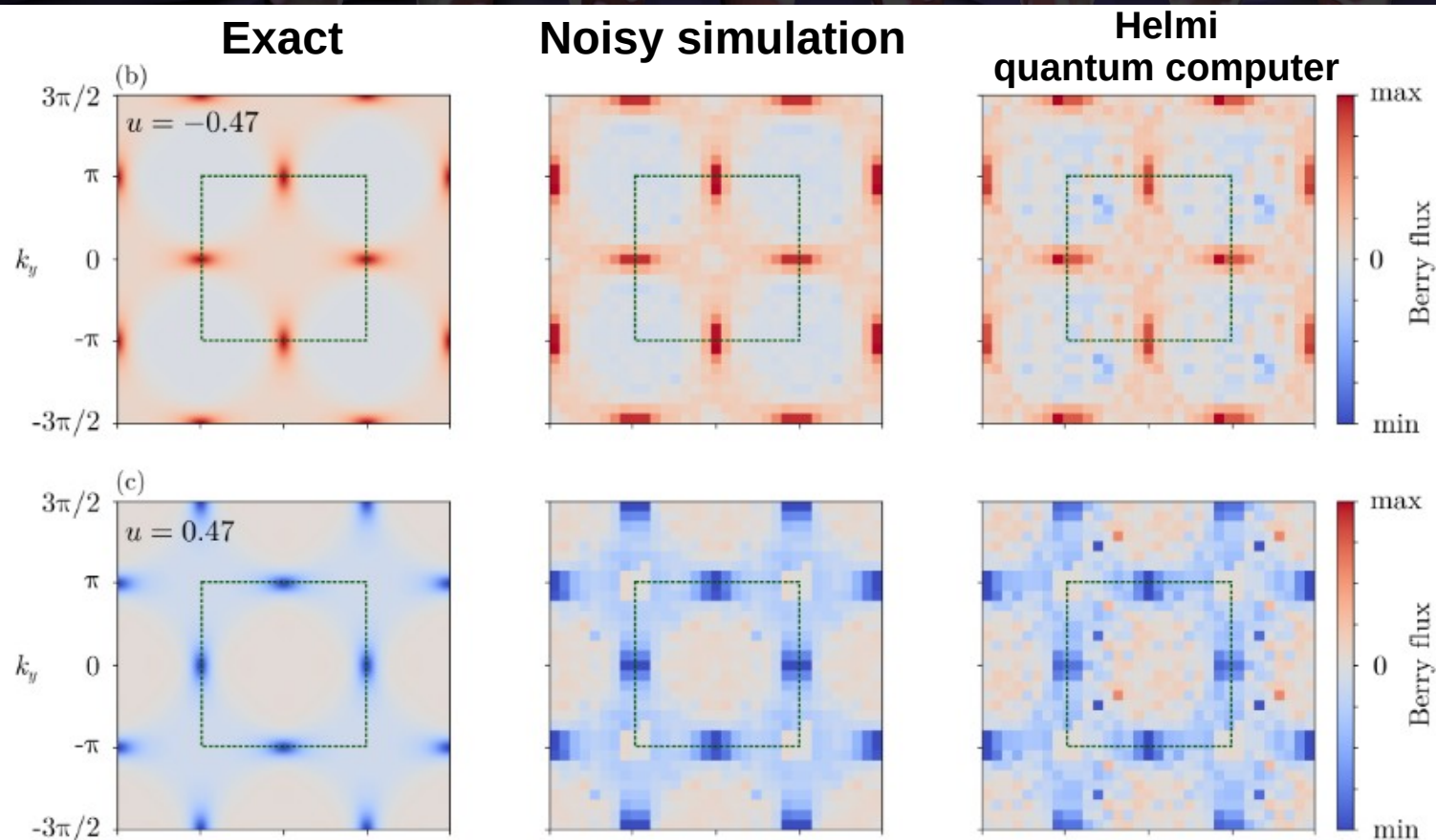
Low bond dimension

Tiny part of the Hilbert space

High bond dimension

Most of the Hilbert space

Chern number from Berry curvature integration

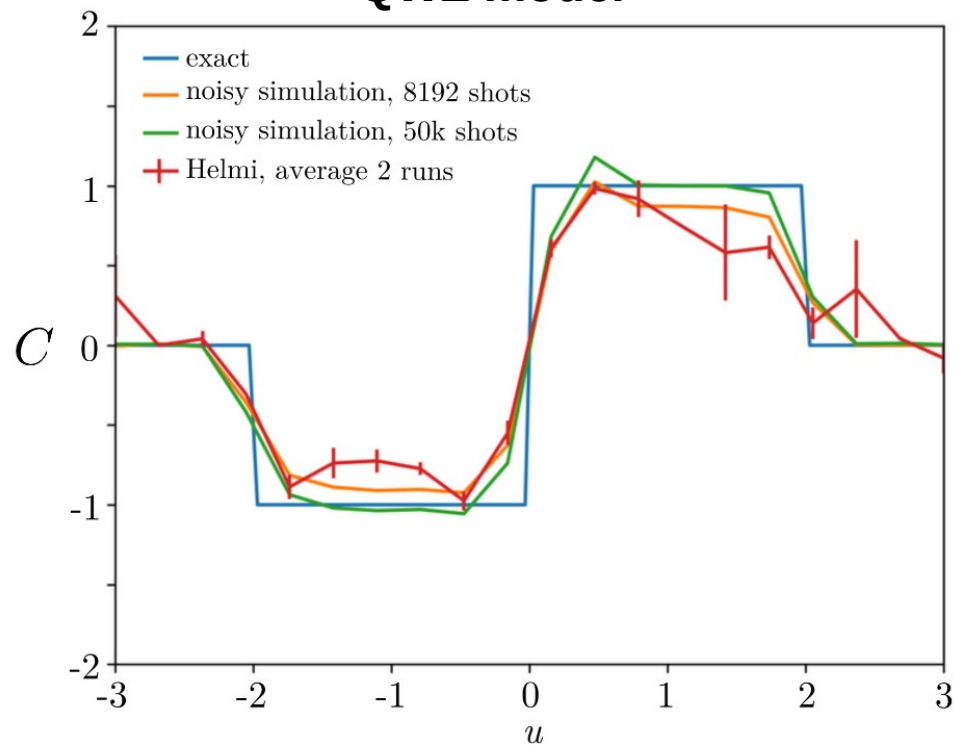


$$C = 1$$

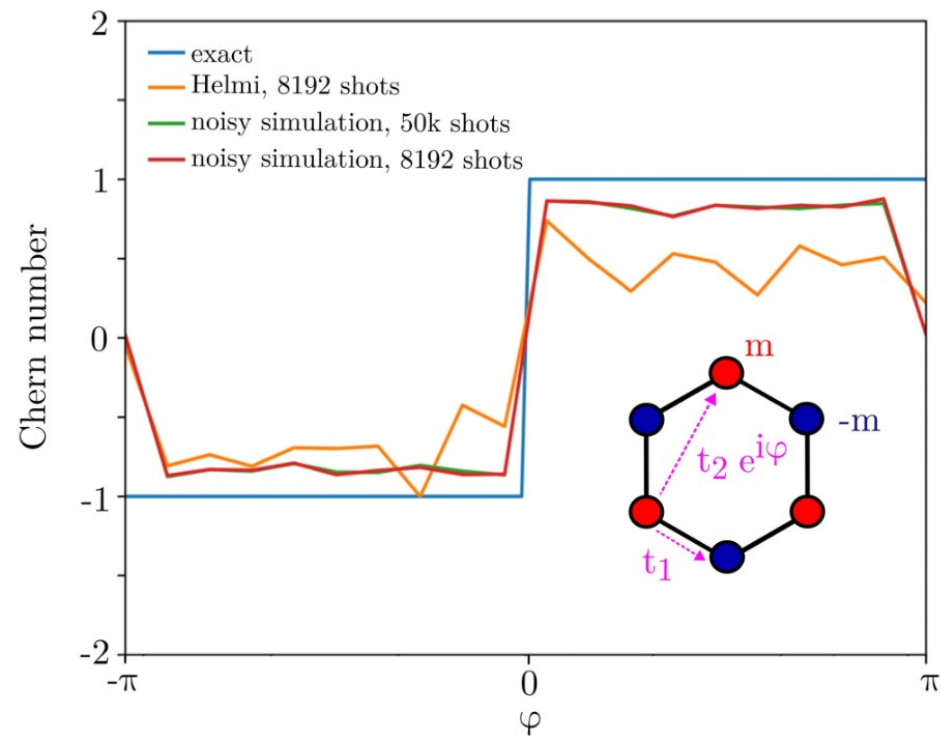
$$C = -1$$

Topological phase diagram

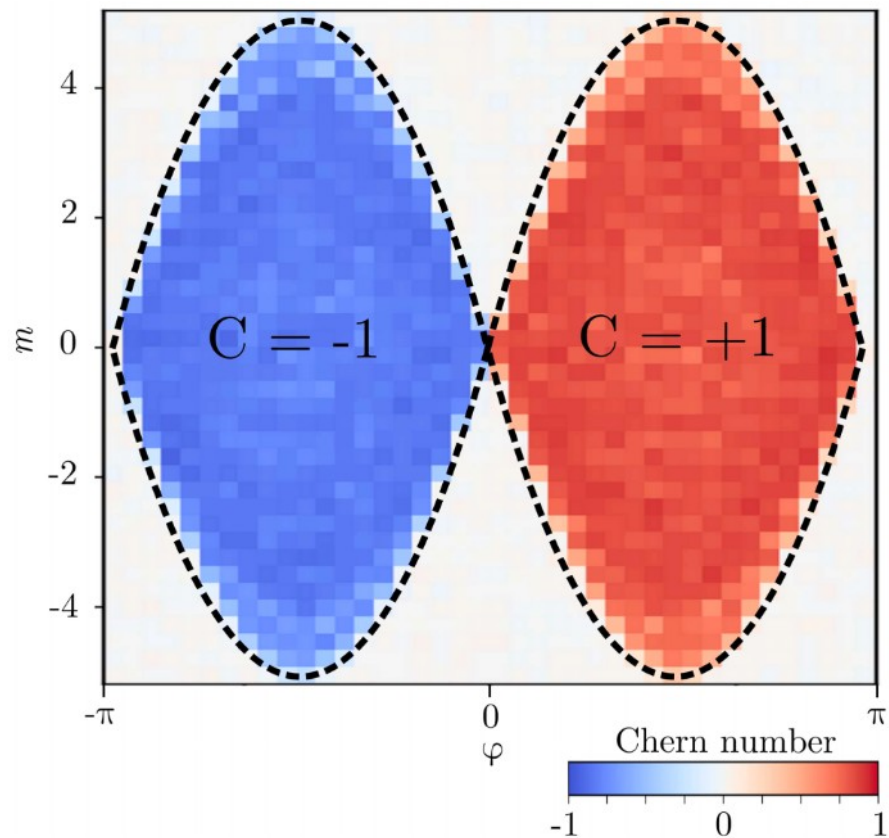
QWZ model



Haldane model



Topological phase diagram



Haldane model

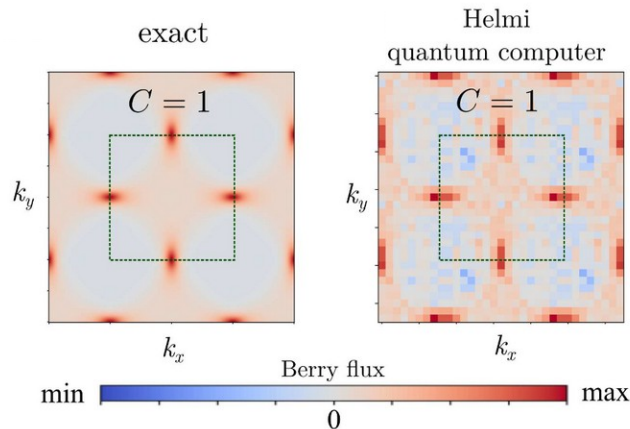
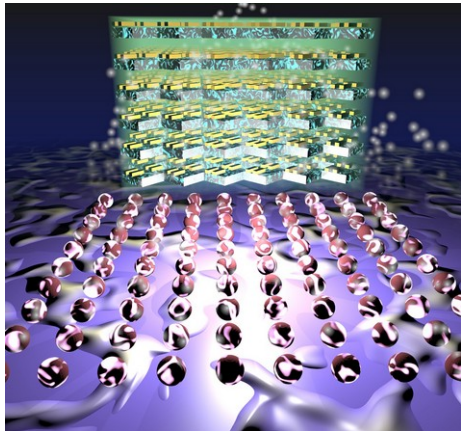
Noisy calculations provide qualitatively correct topological phase diagrams

Future steps in topology on quantum computers

- Next FiQCI quantum computers (20 and 50 qubits) would allow tackling many-body topological models
 - One dimensional topological spin liquids ($S=1$ Haldane)
 - Two dimensional topological spin liquids ($S=1/2$)

Take home

Currently available quantum computers allow computing topological invariants, and can be effectively benchmarked with tensor-networks



Funding from



Phys. Rev. Research 6, 033325 (2024)
Phys. Rev. Research 6, 043288 (2024)

Thank you