Solving topological quantum matter on a quantum computer

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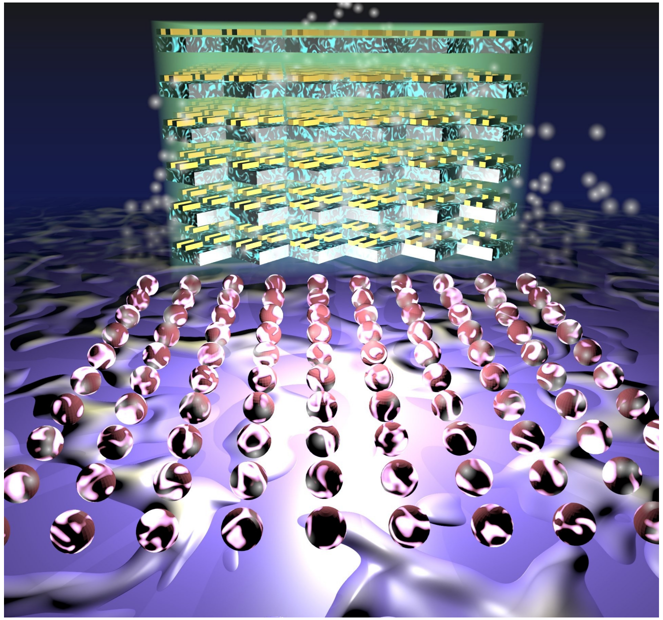
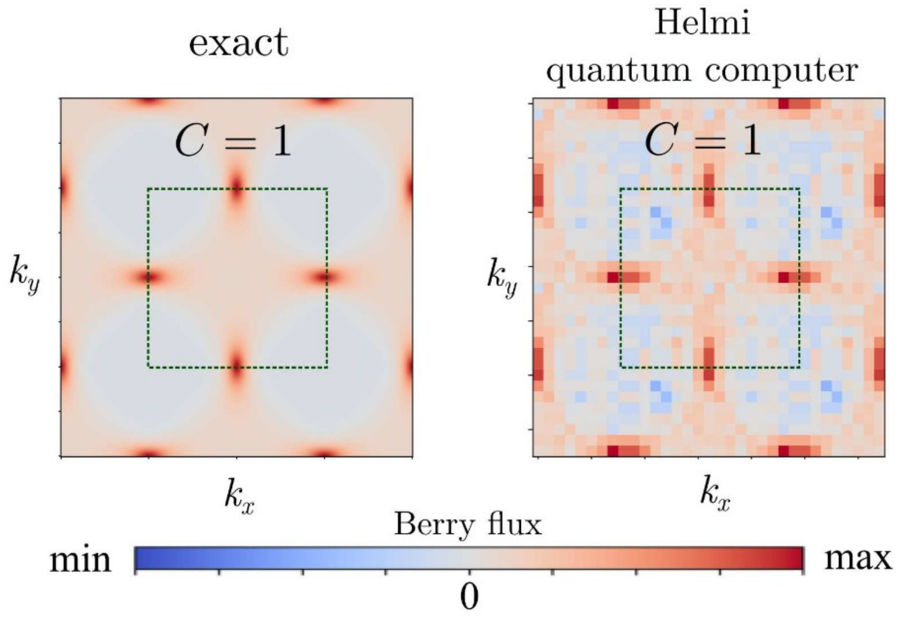


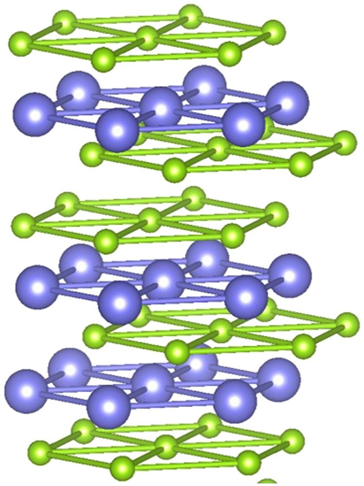


Phys. Rev. Research 6, 043288 (2024)

New Directions in Quantum and Quantum Reservoir Computing, Quantum Devices and Related Technologies
August 21st 2025, Aalto University, Finland

Emergence in quantum materials

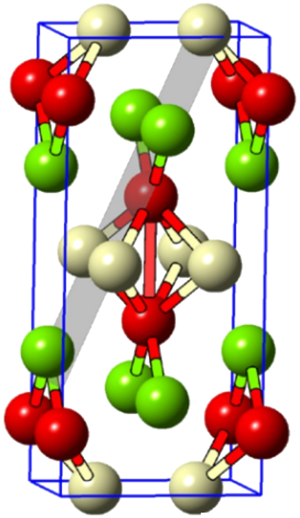
Topological materials



Bi_2Se_3

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

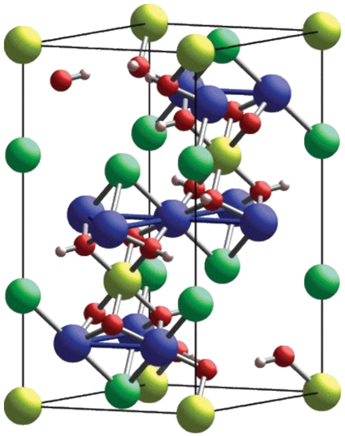
Unconventional superconductors



UTe_2

Nature 579, 523–527 (2020)

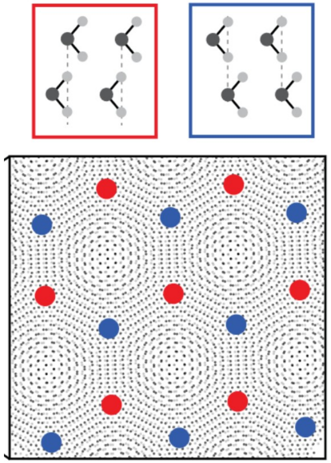
Quantum spin liquids



$ZnCu_3(OH)_6Cl_2$

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

Fractional topological matter



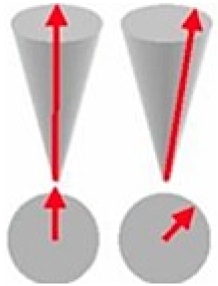
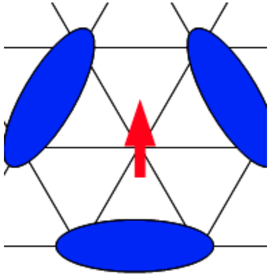
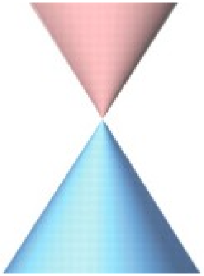
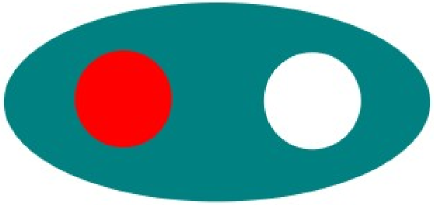
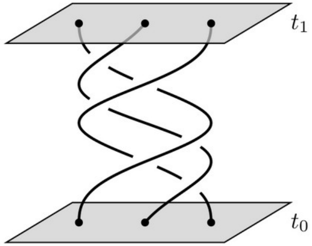
Twisted $MoTe_2$

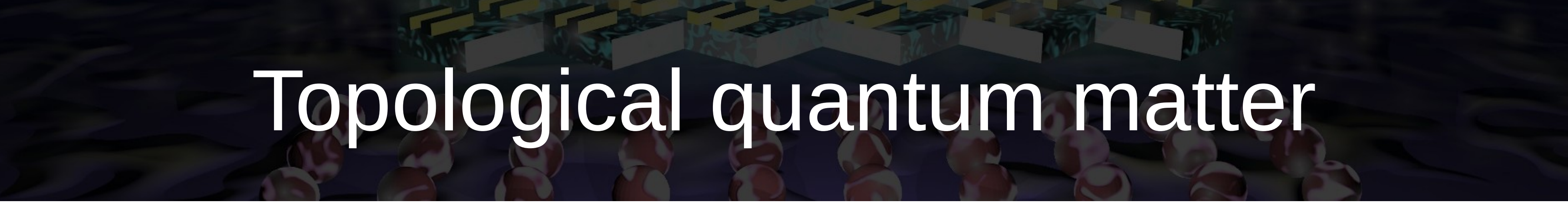
Nature 622, 63–68 (2023)

Quantum excitations in quantum materials

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

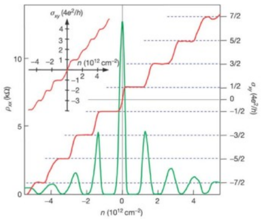
But in quantum materials, we can have emergent collective new excitations

Magnons	Spinons	Dirac fermions	Majorana fermions	Anyons
				
No charge Spin = 1	No charge Spin = ½	No mass Spin = ½ Charge = 1	No charge No spin Own antiparticle	No spin Charge=1/3 Not a boson Not a fermion



Topological quantum matter

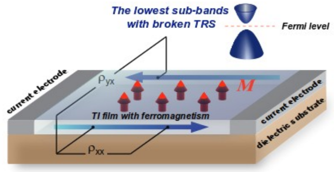
Quantum Hall effect



graphene

Nature 438, 197-200 (2005)

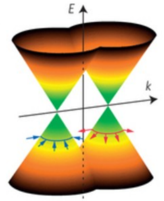
Quantum Anomalous Hall effect



Cr-doped $(Bi,Sb)_2Te_3$

Science 340.6129 (2013): 167-170

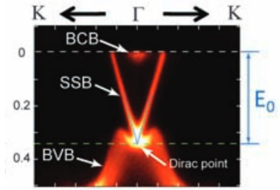
Weyl semimetal



TaAs

Nature Physics 11, 724–727 (2015)

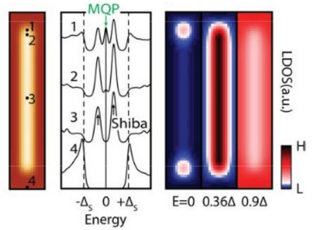
Quantum Spin Hall effect



Bi_2Se_3

Science 325.5937 (2009): 178-181

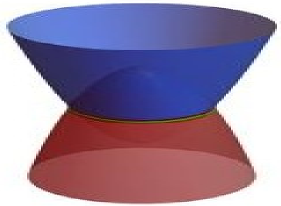
Topological superconductor



Fe@Pb

Science 346.6209 (2014): 602-607

Nodal line semimetals



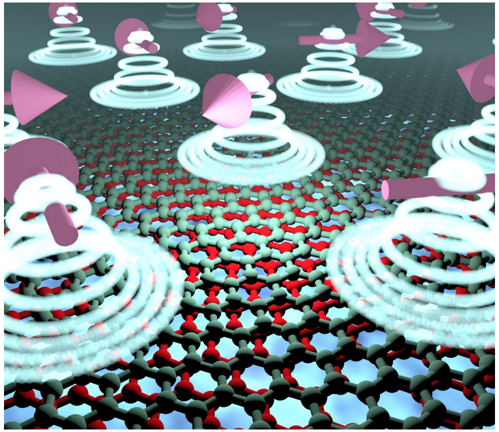
Mg_3Bi_2

Advanced Science 6.4 (2019): 1800897

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

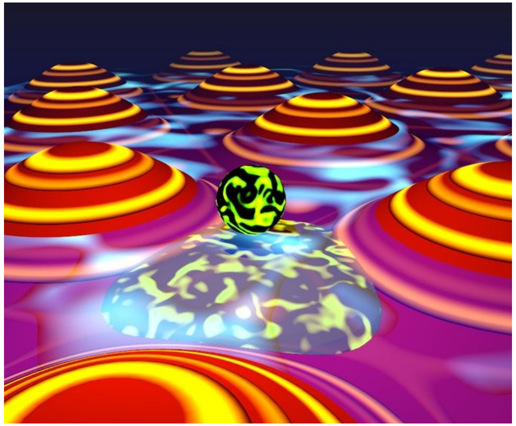
Many-body topological quantum matter

Quantum spin liquids



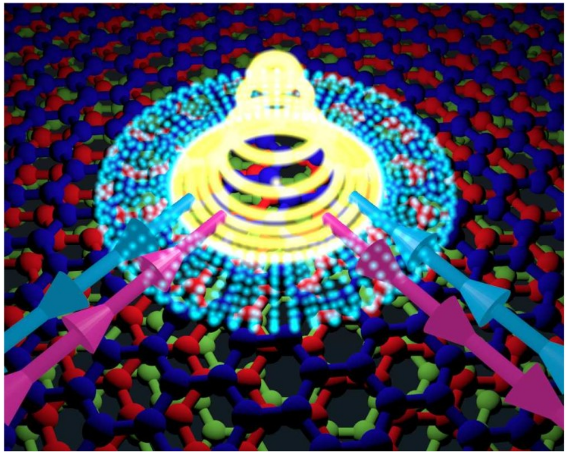
Reports on Progress in Physics 80.1 (2016): 016502.

Fractional Chern insulators



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

Parafermions

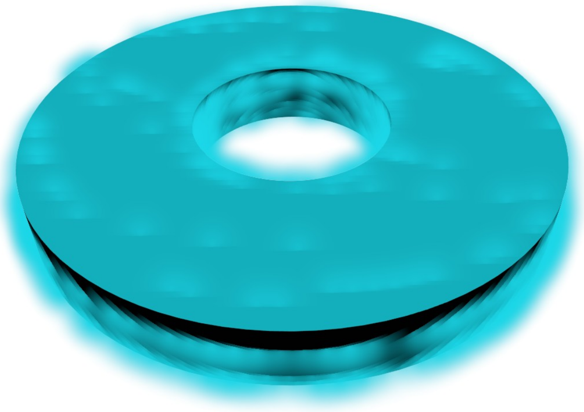


Annual Review of Condensed Matter Physics 7, 119-139 (2016)

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

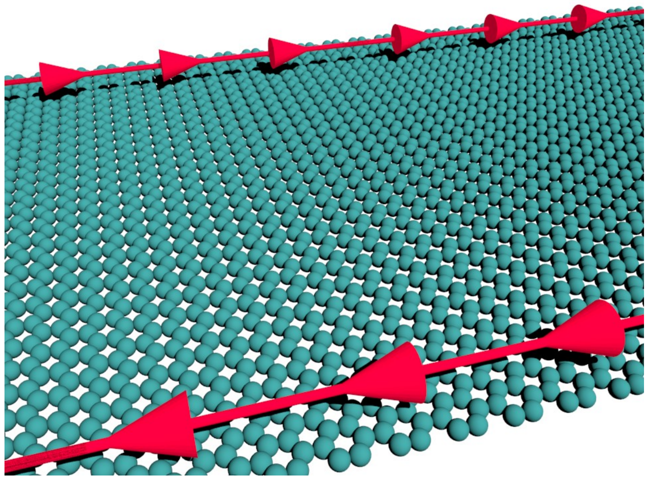
Macroscopic topological effects

Superconductivity



$$\Phi = \frac{h}{2e}$$ **<u>Quantization</u>** of flux

Chern topological insulators



$$\sigma_{xy} = \nu \frac{e^2}{h}$$ **<u>Quantization</u>** 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

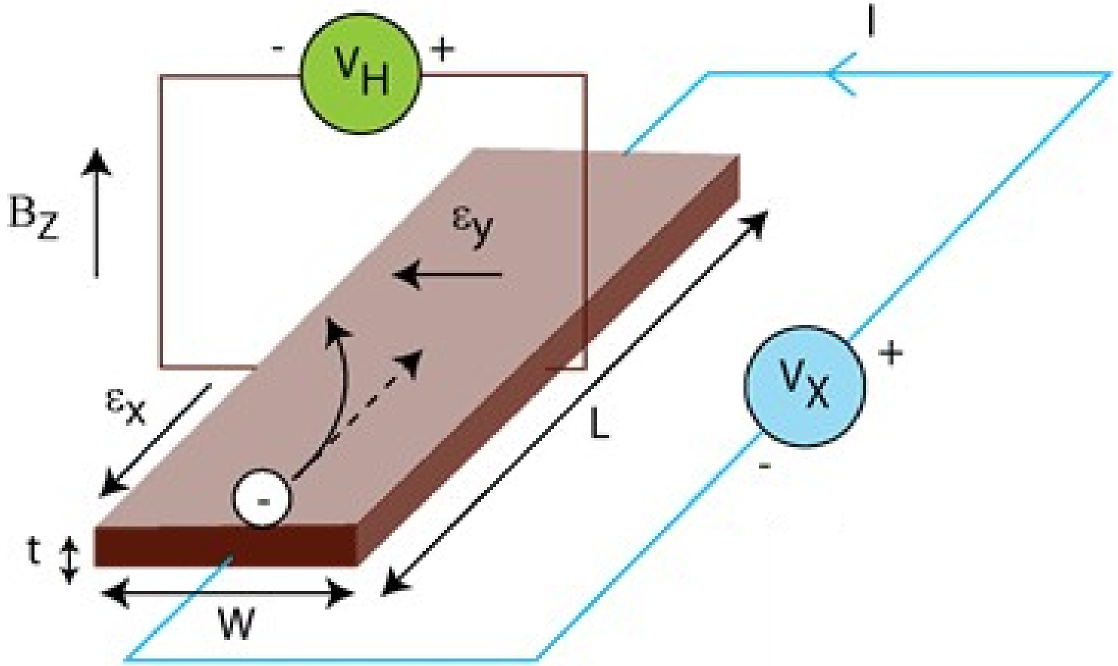
Exact classical methods (tiny systems)

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

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

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

← Chern number

The transverse conductivity is a topological invariant

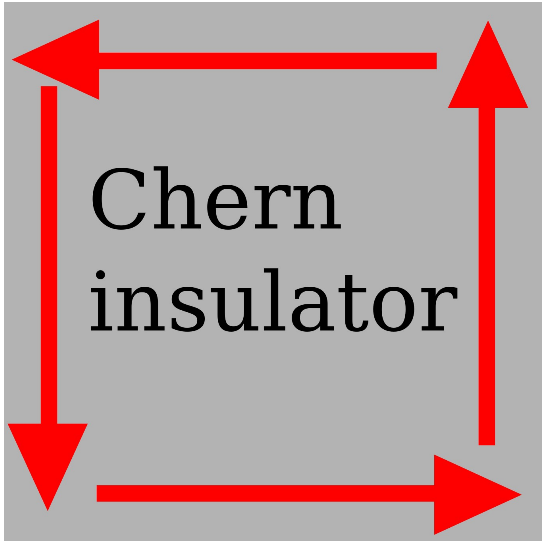
This means, it must take integer values regardless of defects in an insulator

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

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



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

This is a simple example of a topological state of matter

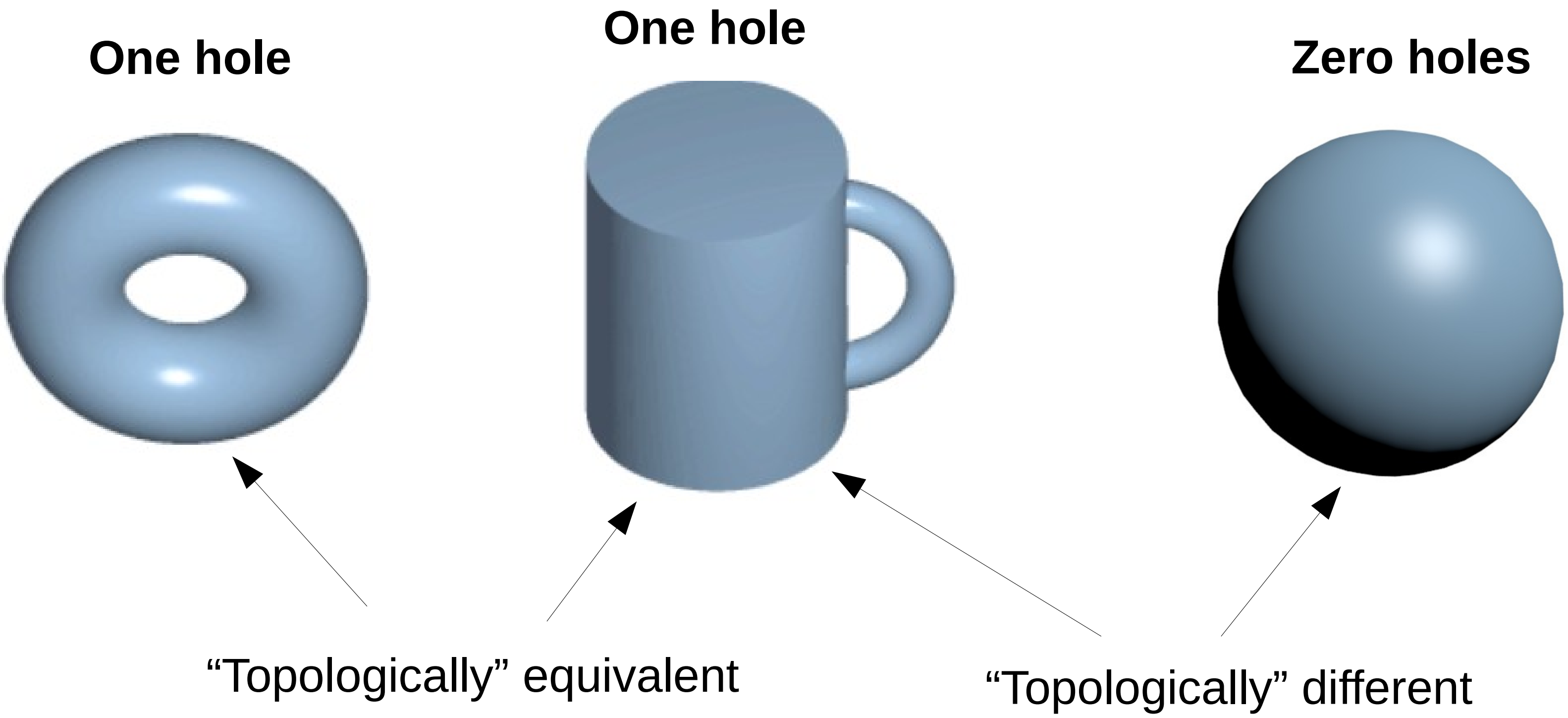
The idea of topological invariants

Holes in a 3d surface

Knots in curves

Topology classifies object that cannot smoothly deformed into one another

Topology and holes



Topological invariant in a Hamiltonian

We can classify Hamiltonians according to topological invariants

Hamiltonian

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

→

Wavefunction

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

↓

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

Metric
(Berry curvature)

←

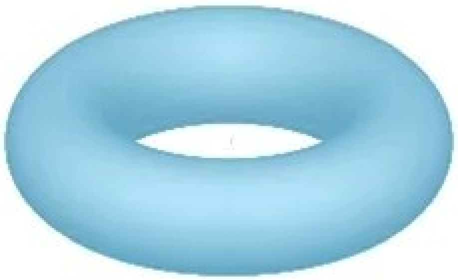
$$C = \int_{BZ} \Omega d^2\mathbf{k}$$

Topological invariant
(Chern number)

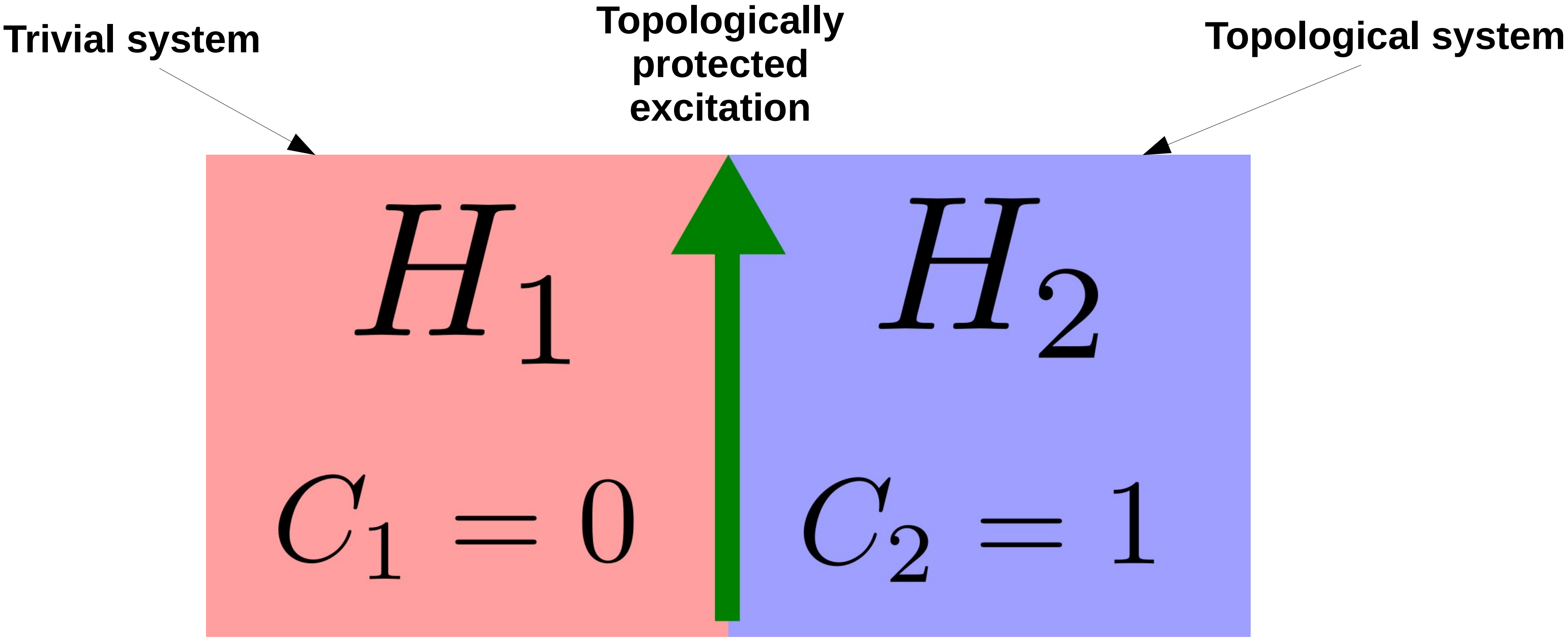
The role of a topological invariant

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

$$C = 1 \qquad\qquad C = 2$$

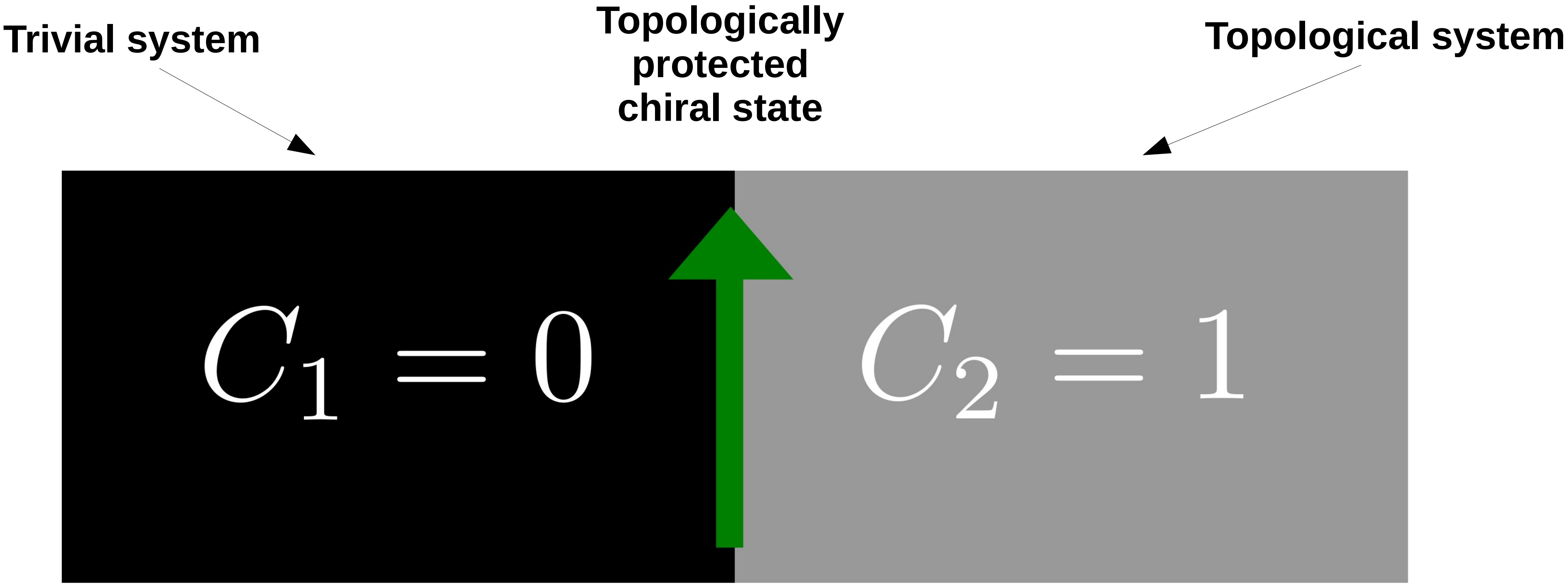


The consequence of different topological invariants



Topological excitations appear between topologically different systems

The edge states of a Chern insulator



<u>The edge states of the quantum Hall effect are topological excitations</u>

The edge states of a Chern insulator

No backscattering channel

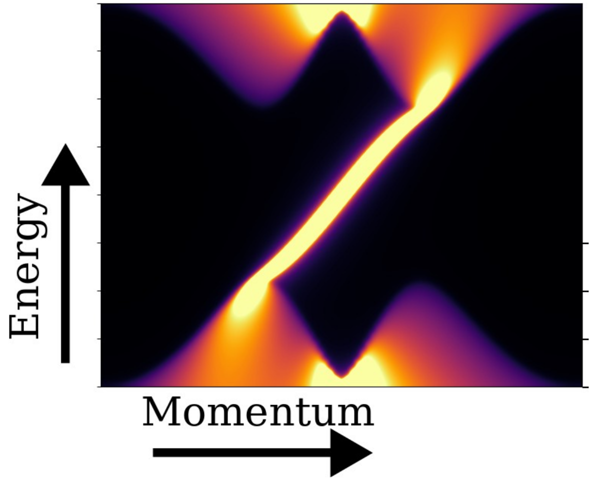
Perfect conductance

Topological protection

The edge states of the quantum Hall effect are topologically protected

Three important topological materials

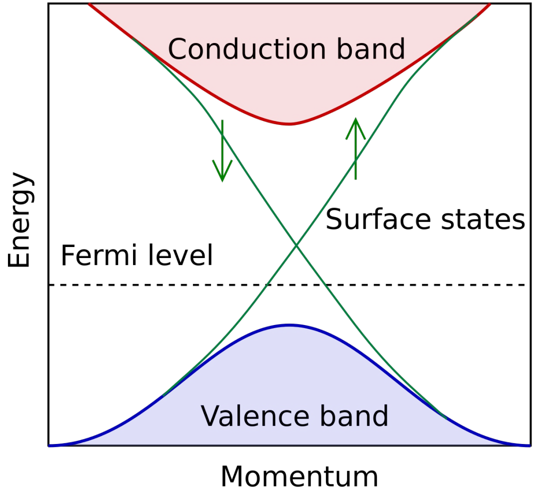
Chern insulators



Chiral states

Electronics

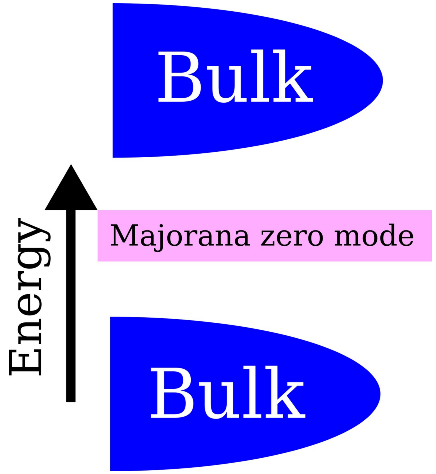
Quantum spin Hall insulators



Helical states

Spintronics

Topological superconductors

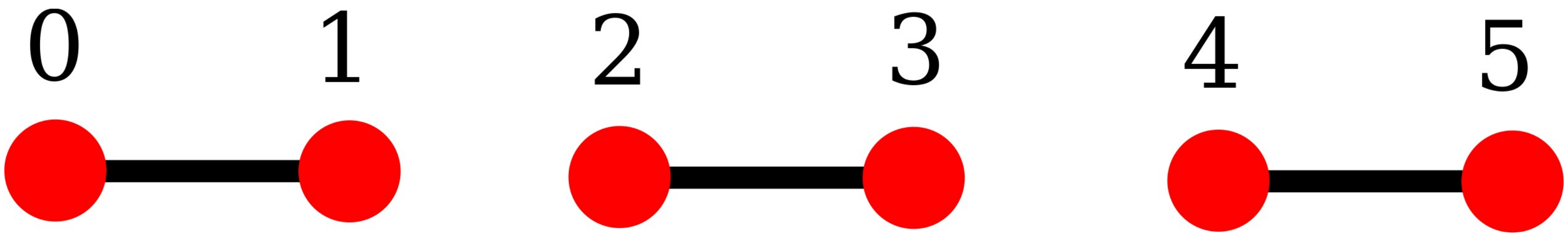


Majorana excitations

Topological quantum computing

A minimal model for a topological insulator: the SSH model

The SSH model



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

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

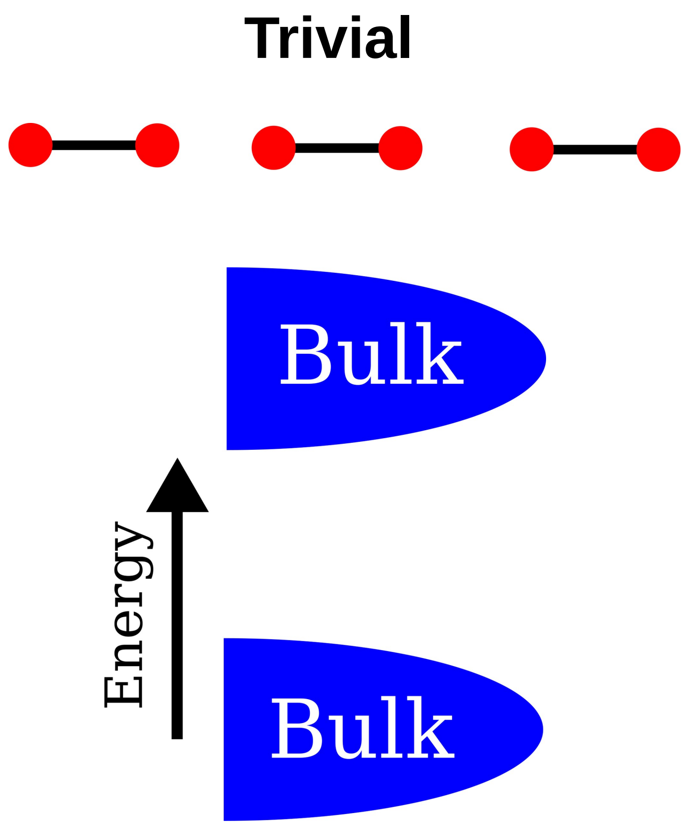
Let us consider a finite dimerized chain

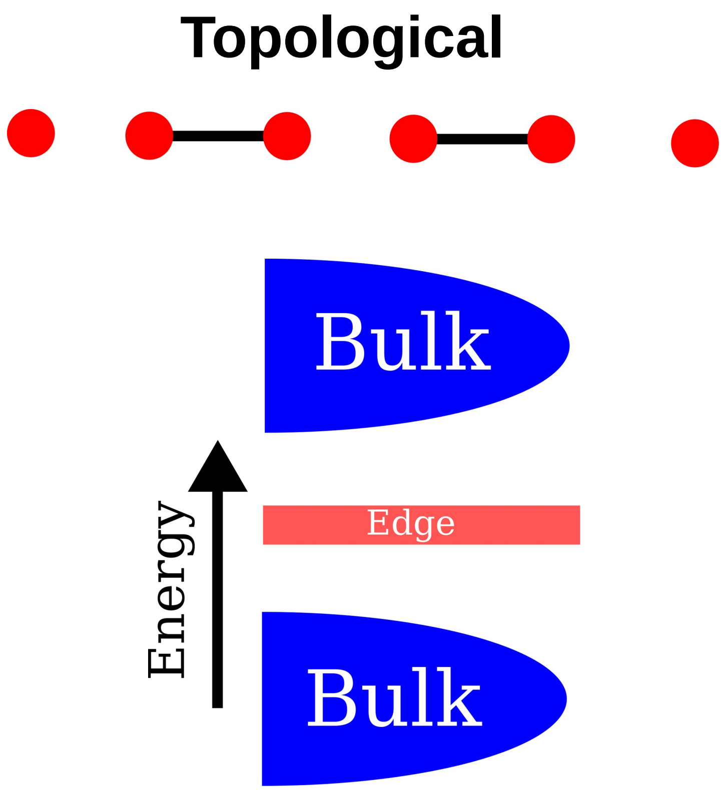
The two phases of the dimerized model

“Trivial” phase (gaped everywhere)

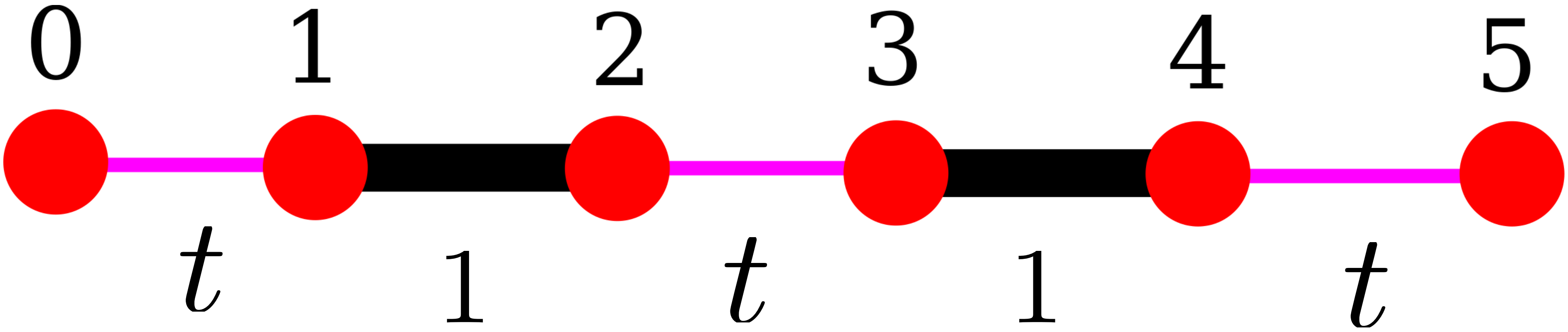
“Topological” phase (gapless zero modes)

The two phases of the dimerized model





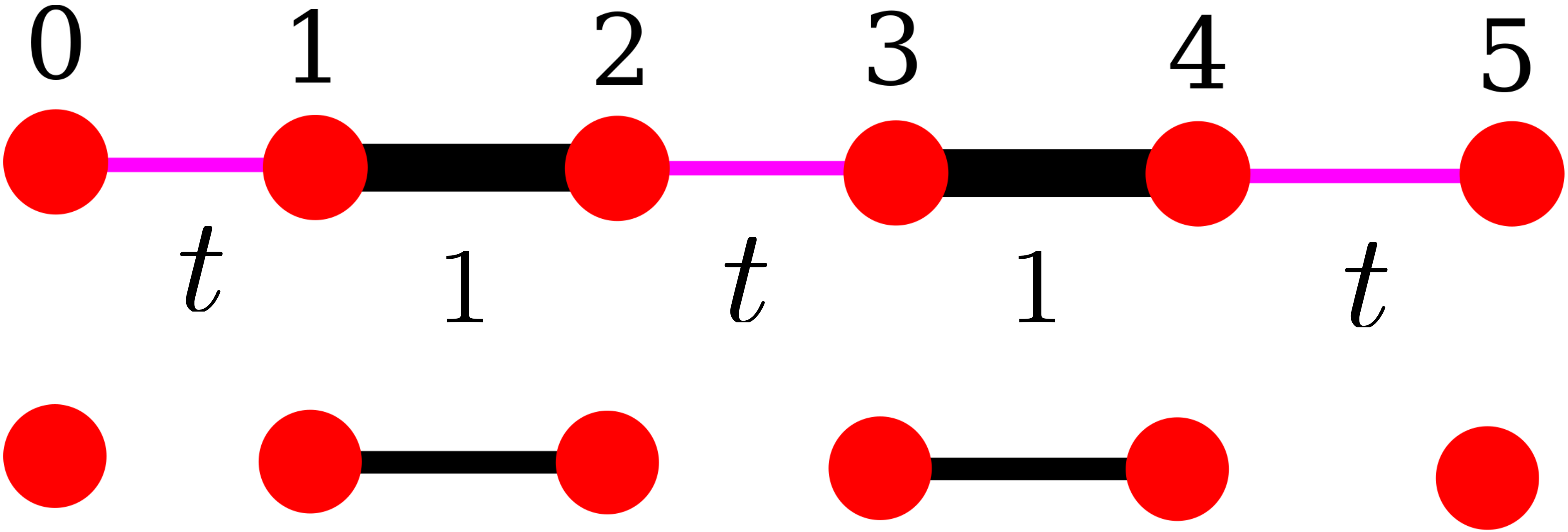
Coupling the dimers



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

Does this Hamiltonian have a surface zero mode?

Coupling the dimers

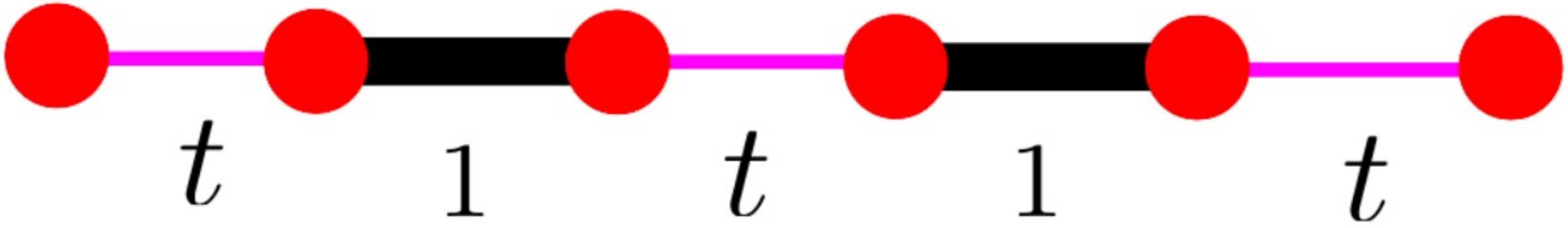


For t<1, both Hamiltonians are topologically equivalent

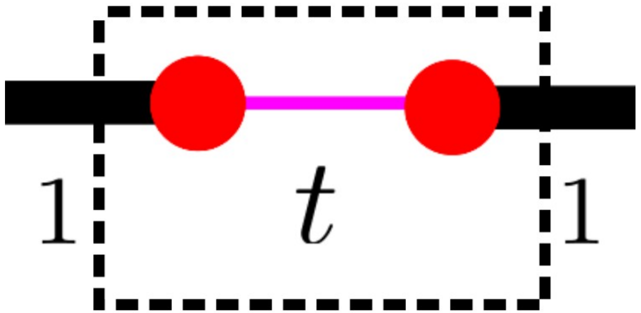
They can be deformed into one another without closing the bulk gap

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

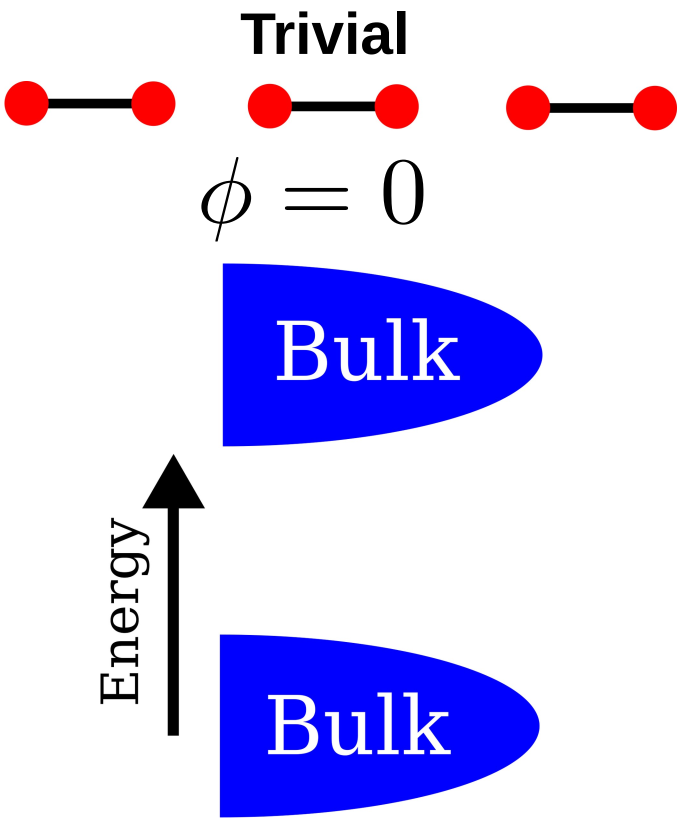
$$\phi = \int_{BZ} A dk$$

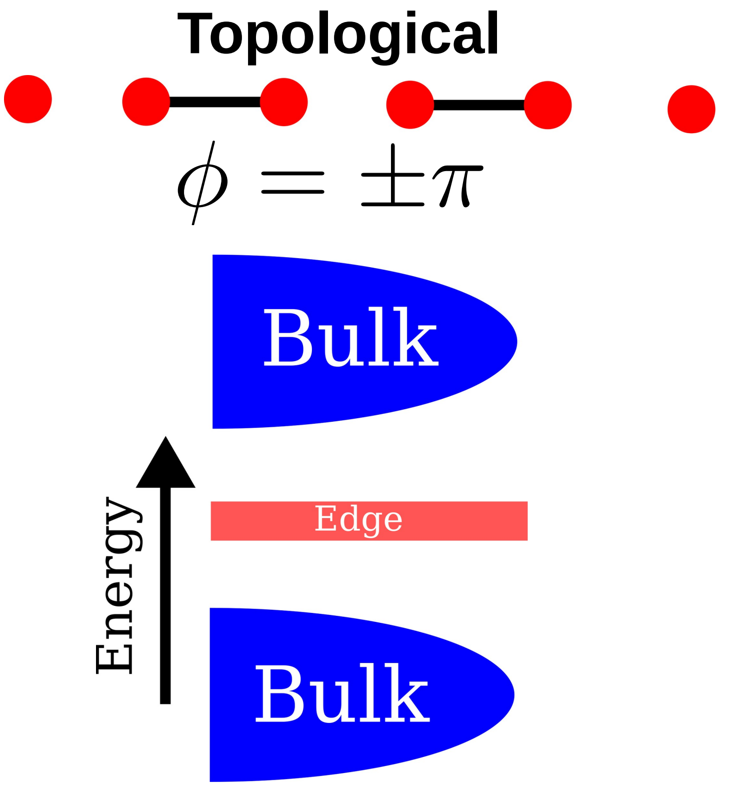
$$A = i\langle \Psi(k) | \partial_k | \Psi(k) \rangle$$

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

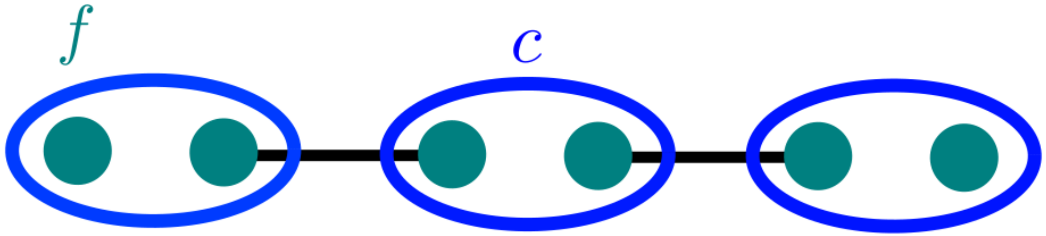
Topological superconductor

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

Conventional fermion

Majorana operator

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

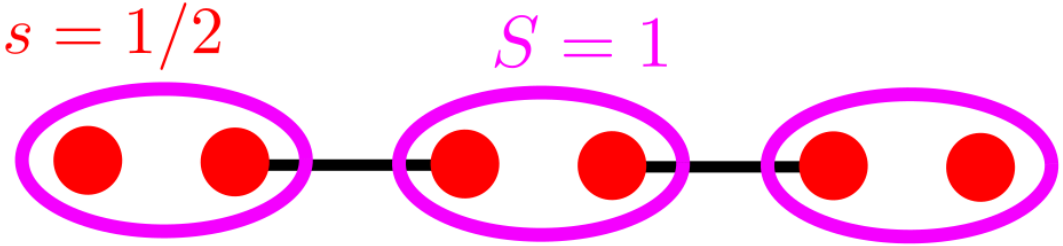


Topological quantum magnets

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

$$S \sim s_1 \otimes s_2$$

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



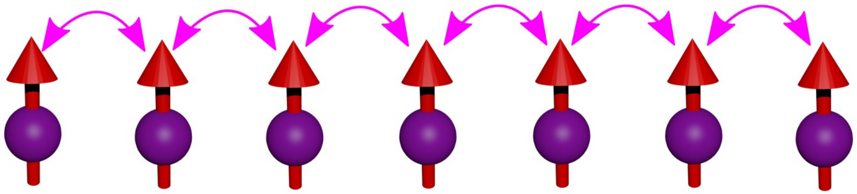
The computational challenge of quantum many-body systems

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

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

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

The quantum many-body problem

Let us take a simple many-body problem

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

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

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

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

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

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

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

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

We need to determine in total 2^L coefficients

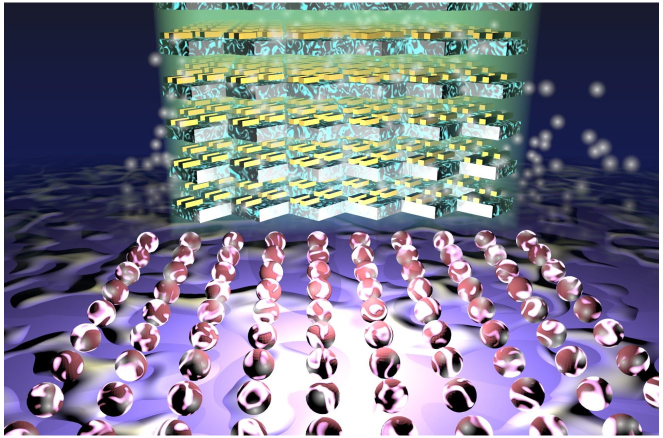
Is there an efficient way of storing so many coefficients?

The fundamental idea of tensor-networks

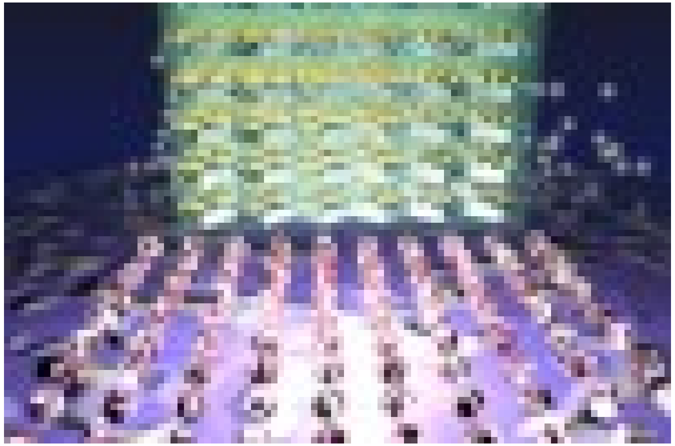
A many-body wavefunction a is a very high dimensional object

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

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

Let us imagine to propose a parametrization in this form

$$c_{s_1,s_2,\ldots.,s_L} = M_1^{s_1} M_2^{s_2} \ldots . M_L^{s_3}$$

dimension 2^L

dimension $\sim Lm^2$

(m dimension of the matrix)

State compression with tensor-networks

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

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

Matrix product state

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

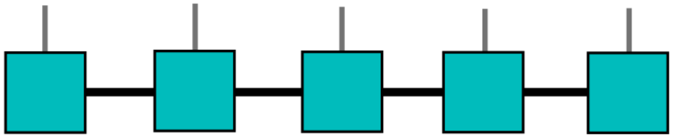
Annals of Physics 326, 96 (2011)

Exponentially large algebra with tensor networks

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

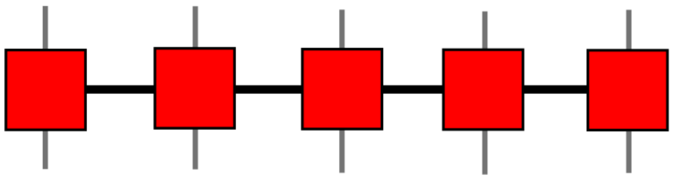
vector

$|\Psi\rangle \equiv$

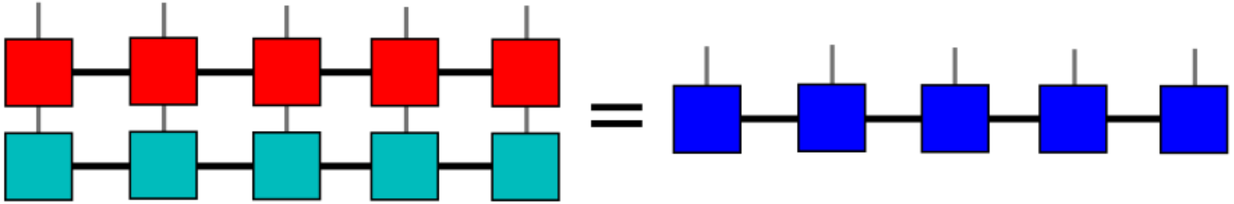


matrix

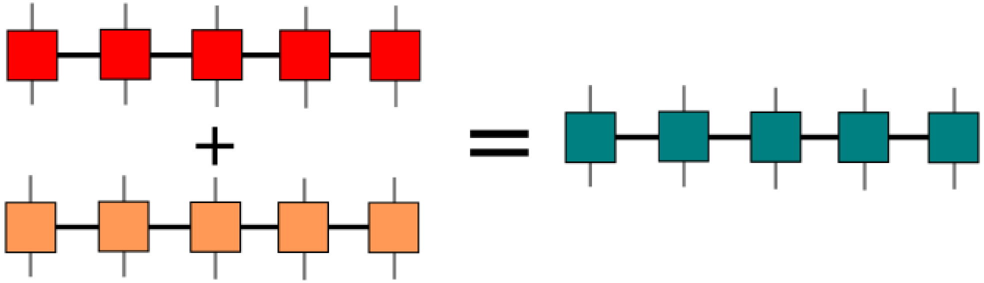
$\hat{A} \equiv$



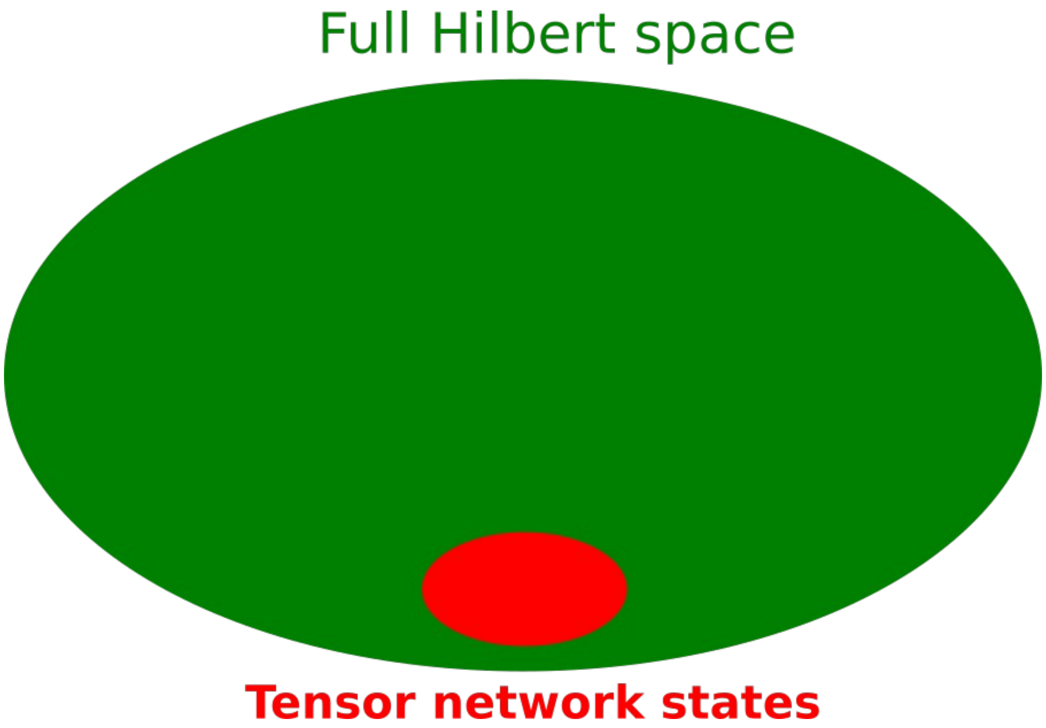
$|\Psi_2\rangle = \hat{A}|\Psi_1\rangle \equiv$



$\hat{A}_3 = \hat{A}_1 + \hat{A}_2 \equiv$



MPS as a parametrization of area law states



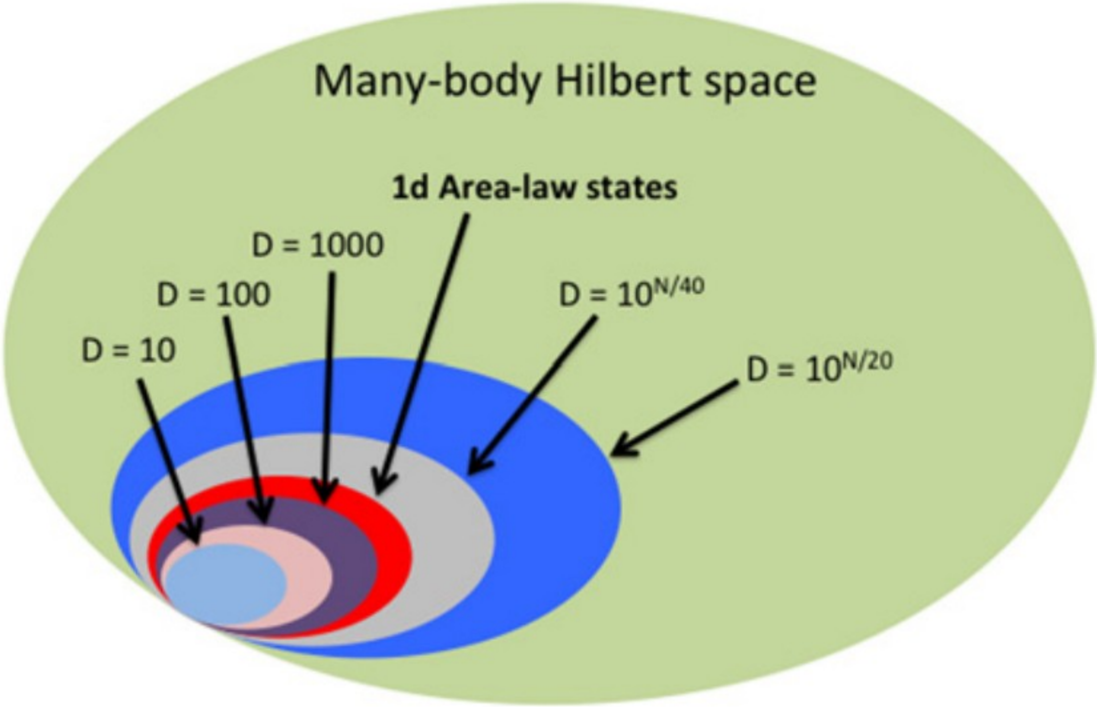
$$c_{s_1,s_2,....,s_L} = M_1^{s_1} M_2^{s_2} .... M_L^{s_3}$$

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

$$c_{s_1,s_2,....,s_L} = M_1^{s_1} M_2^{s_2} ....M_L^{s_3}$$

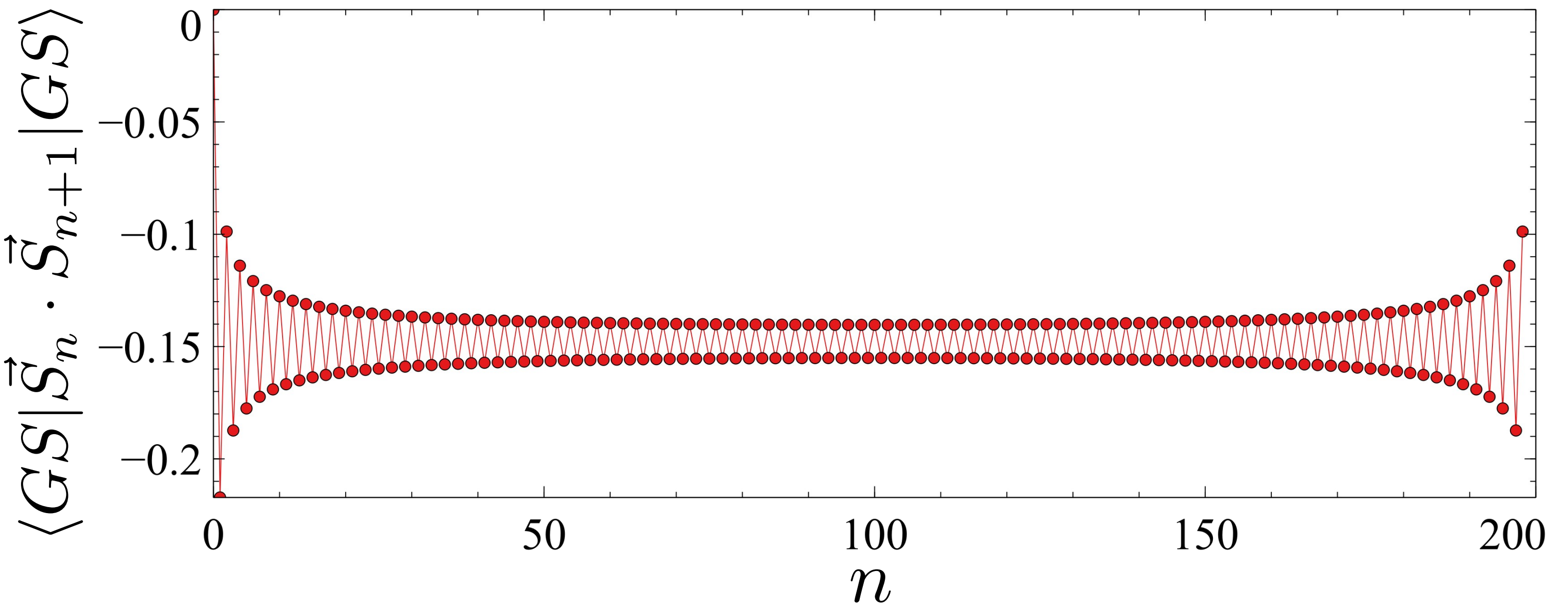
This ansatz can be generalized for time-evolution, excited states, or typical thermal states

The Heisenberg model with tensor-networks

Non-uniform Heisenberg model

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

$$J(n) = J_0 + \delta \cos \Omega n$$

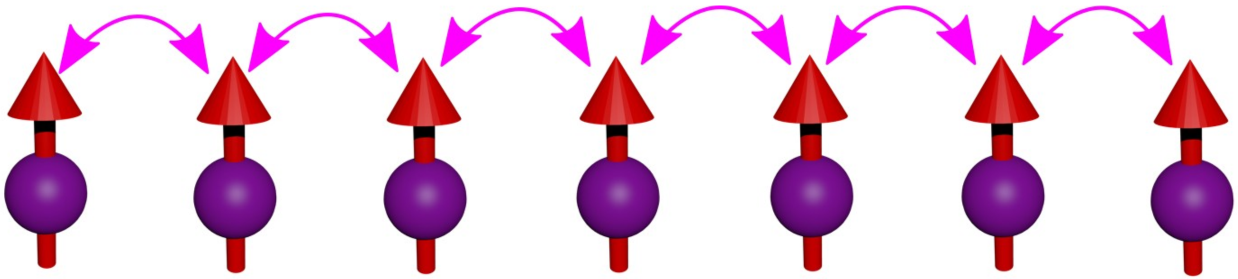


Tensor networks allow solving a 200 many-body spin model in a few seconds in a laptop

Many-body dynamical correlators

One dimensional Heisenberg Hamiltonian

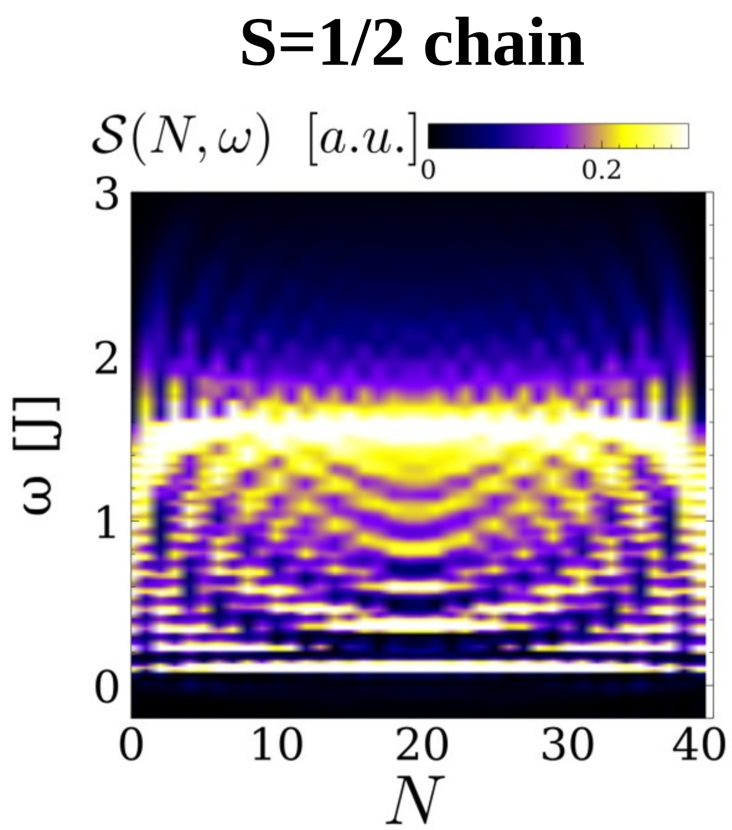
$$\mathcal{H} = \sum_{\langle ij \rangle} J \vec{S}_i \cdot \vec{S}_j$$

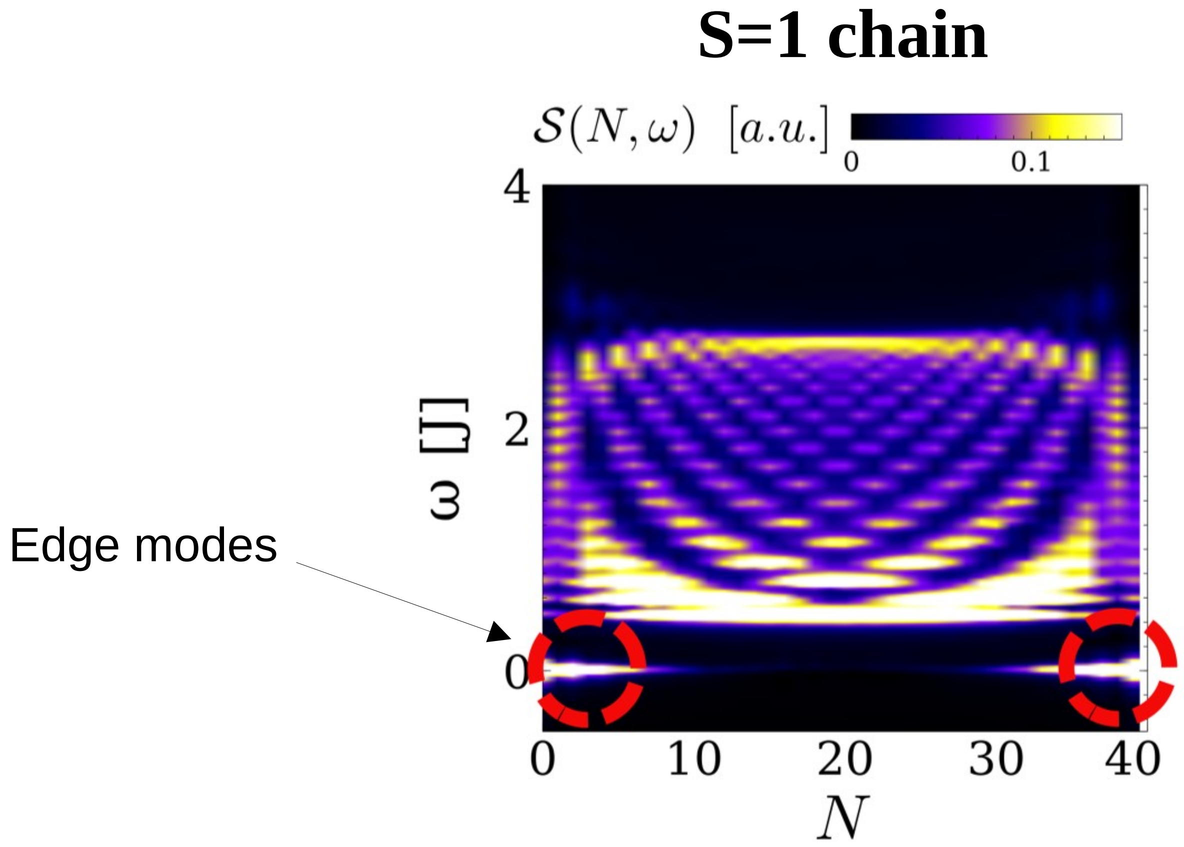


Tensor networks allow computing dynamical correlators

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

Dynamical structure factor of a Heisenberg model





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

dmrgpy

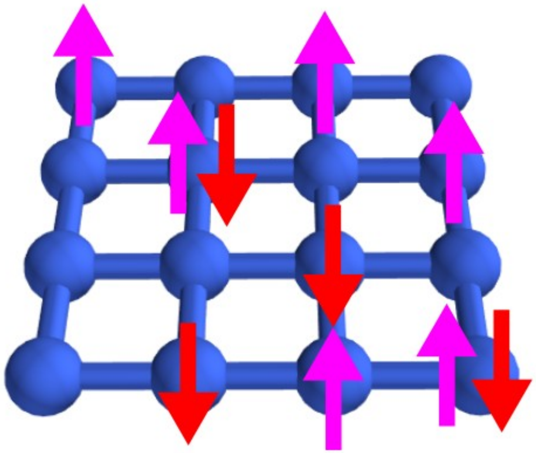
```
from dmrgpy import spinchain
spins = ["S=1" for i in range(40)] # S=1 chain
sc = spinchain.Spin_Chain(spins) # create spin chain object
h = 0 # initialize Hamiltonian
for i in range(len(spins)-1):
  h = h + sc.Sx[i]*sc.Sx[i+1]
  h = h + sc.Sy[i]*sc.Sy[i+1]
  h = h + sc.Sz[i]*sc.Sz[i+1]
sc.set_hamiltonian(h)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

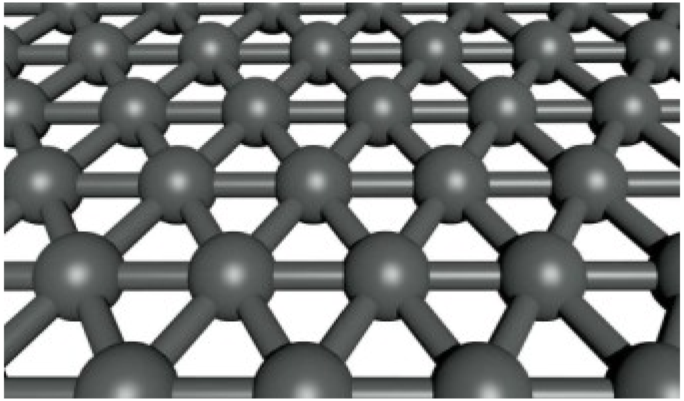
Solving the 2D Hubbard model at finite doping



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

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

Solving the 2D Heisenberg model in frustrated lattices

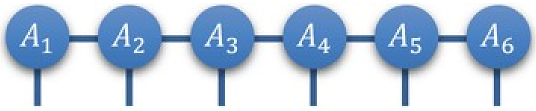


$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

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

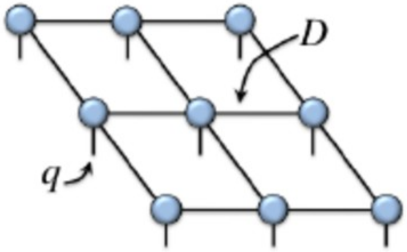
Many-body state compression

Matrix-product states



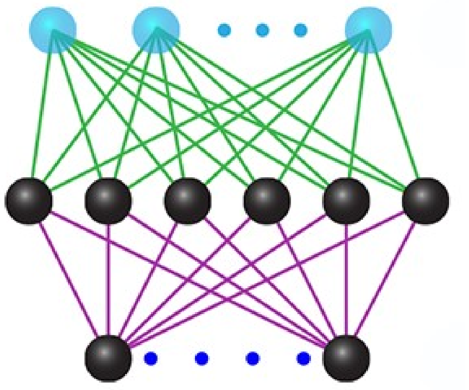
Phys. Rev. Lett. 69, 2863 (1992)

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 $\langle A\rangle = \langle\Psi(t)|A|\Psi(t)\rangle$

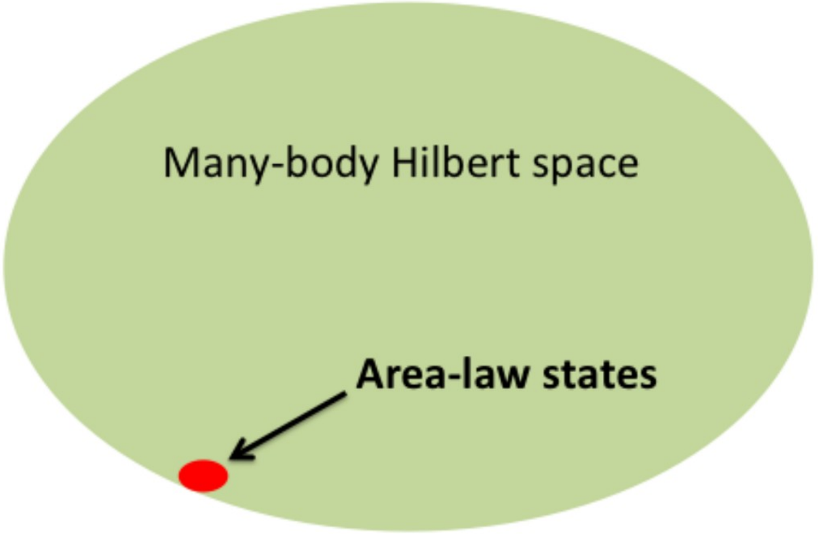
Quantum computers enabling simulating dynamics that may require exponentially large resources

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



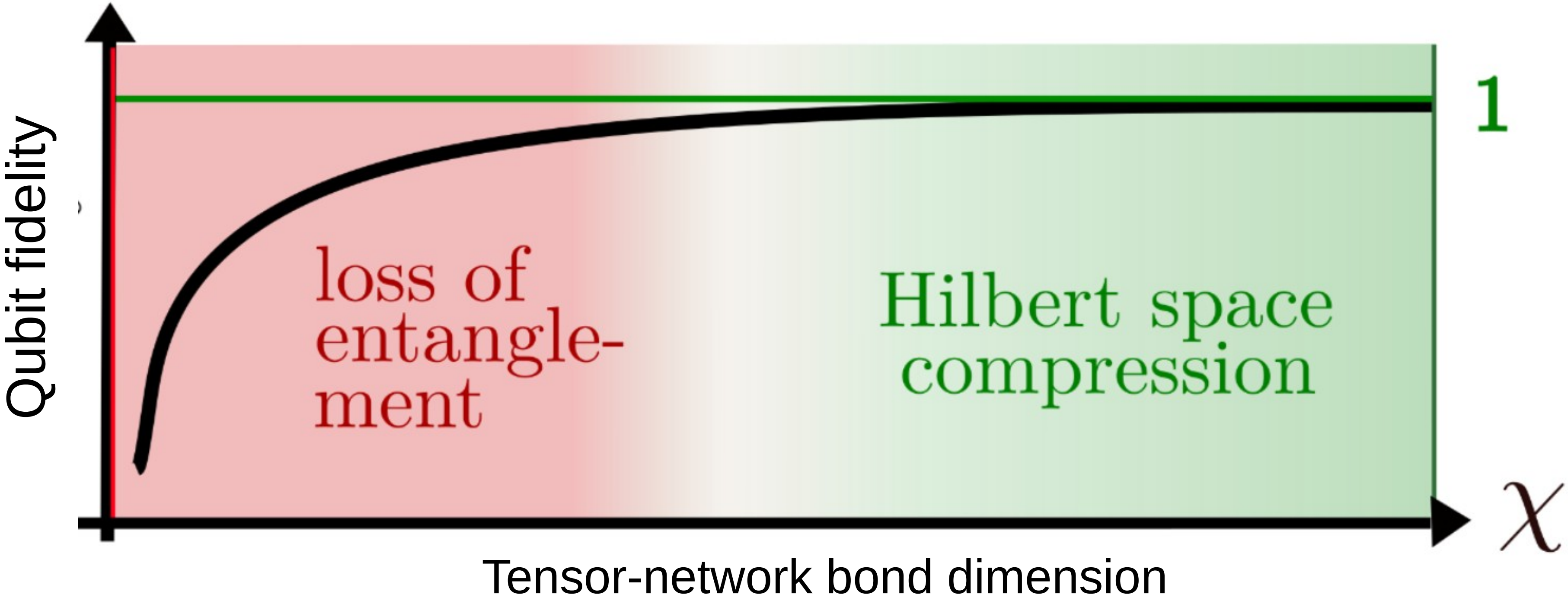
Both constrains put bounds to the entanglement of accessible states

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?



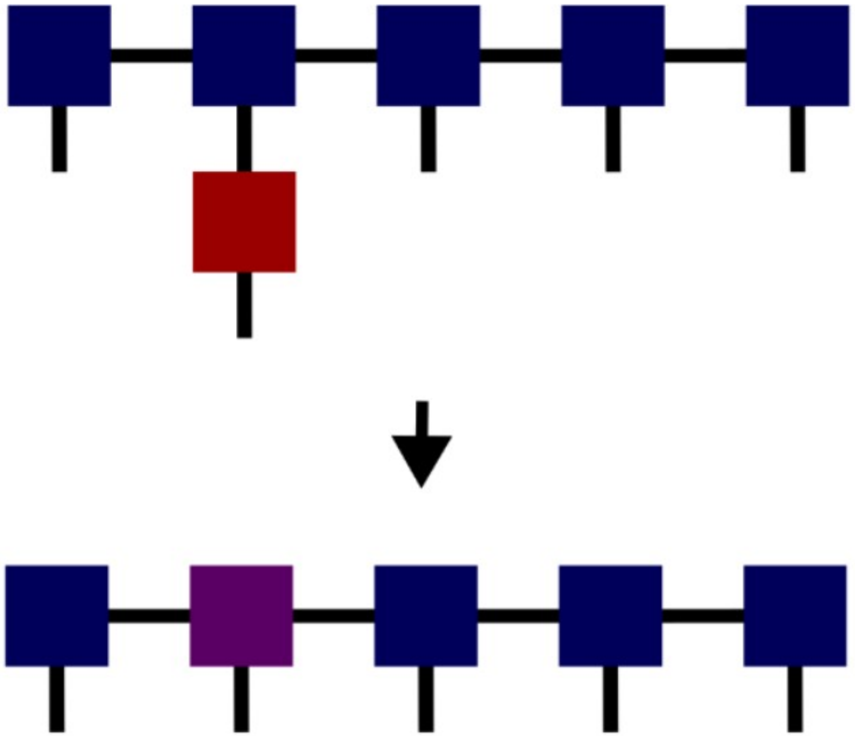
The finite tensor-network bond dimension can be understood as a finite qubit fidelity

Applying a single qubit gate to a tensor network

Original MPS

Single qubit gate

Transform MPS



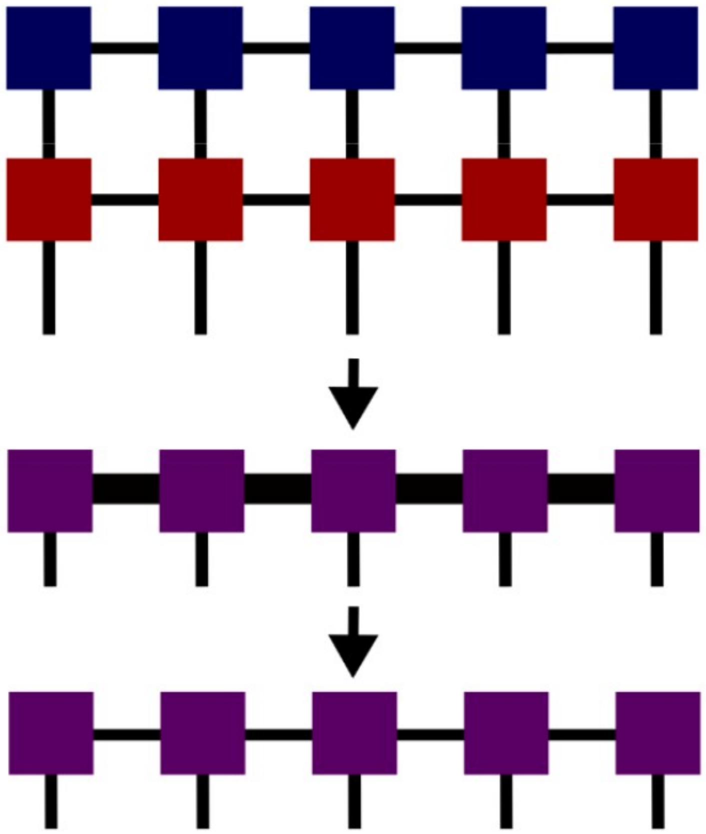
Applying a multi-qubit gate to a tensor network

Original MPS

Multi-qubit gate

Higher dimension updated MPS

Compressed updated MPS

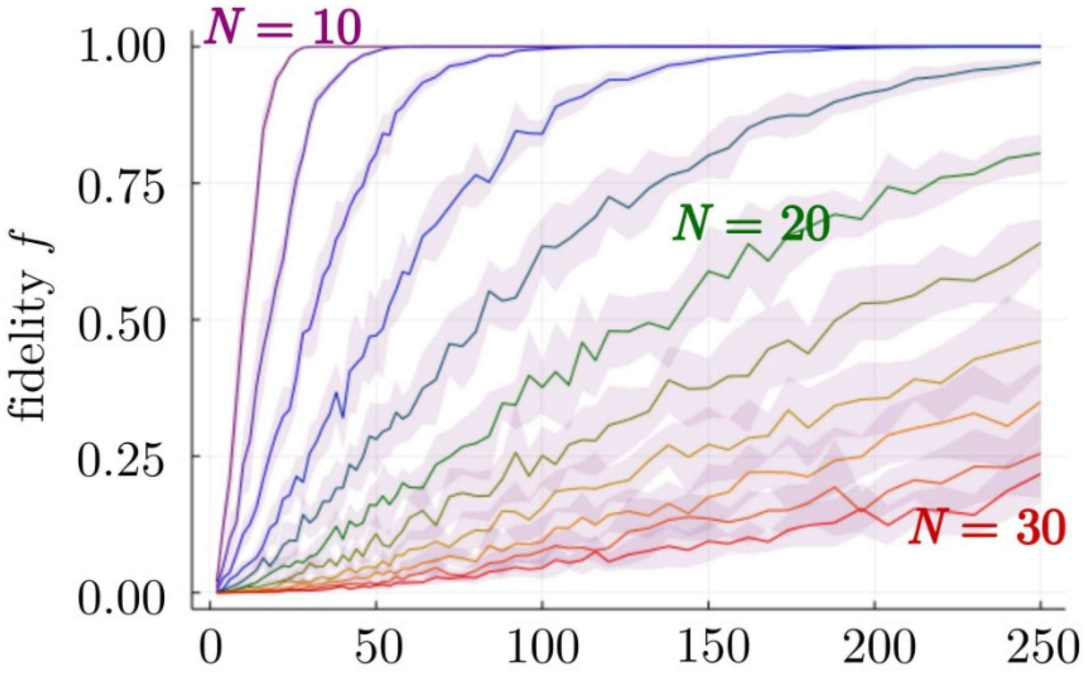


Three quantum algorithms with tensor-network quantum circuits

- ***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

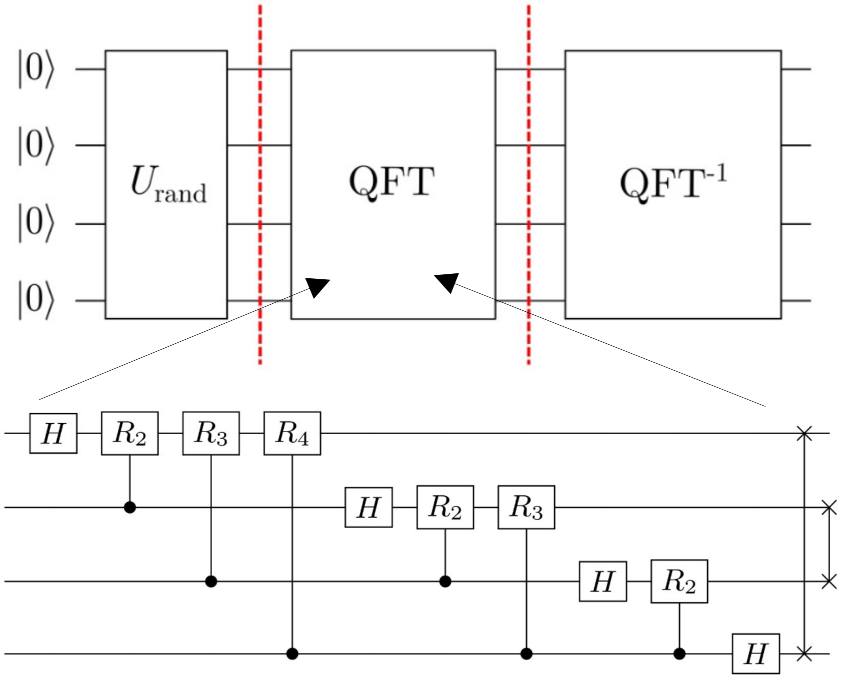
The quantum Fourier transform

***N* is the number of qubits**



Tensor-network bond dimension

Circuit architecture



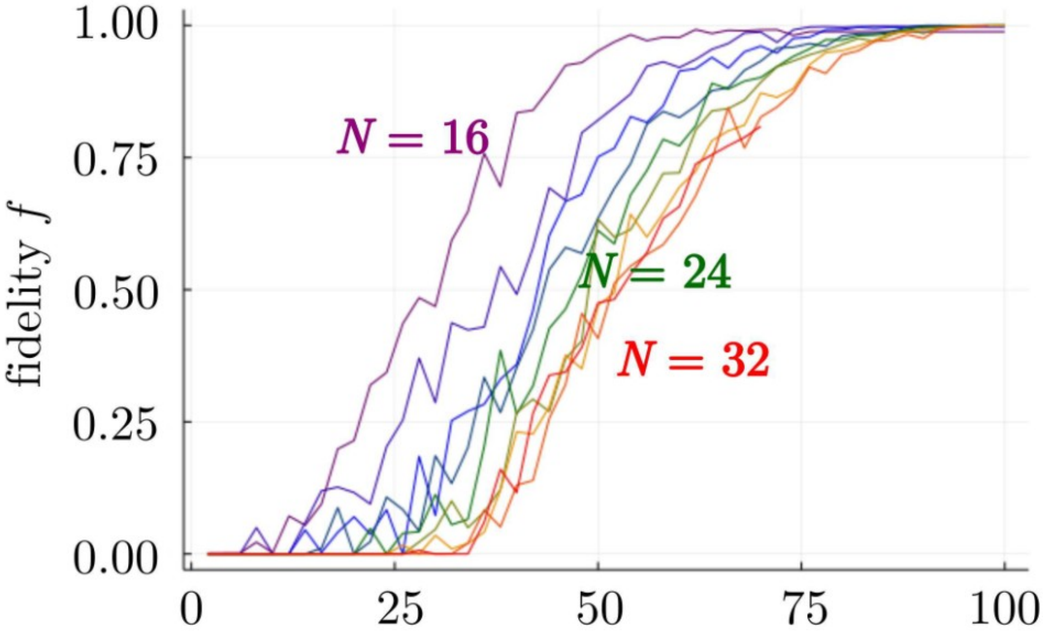
QFT Fidelity

$$f = |\langle \Psi_0' | \Psi_0 \rangle|^2 \quad |\Psi_0'\rangle = \mathrm{QFT}^{-1}\mathrm{QFT}\,|\Psi_0\rangle$$

Phys. Rev. Research 6, 033325 (2024)

Grover’s search algorithm

N is the number of qubits



Tensor-network bond dimension

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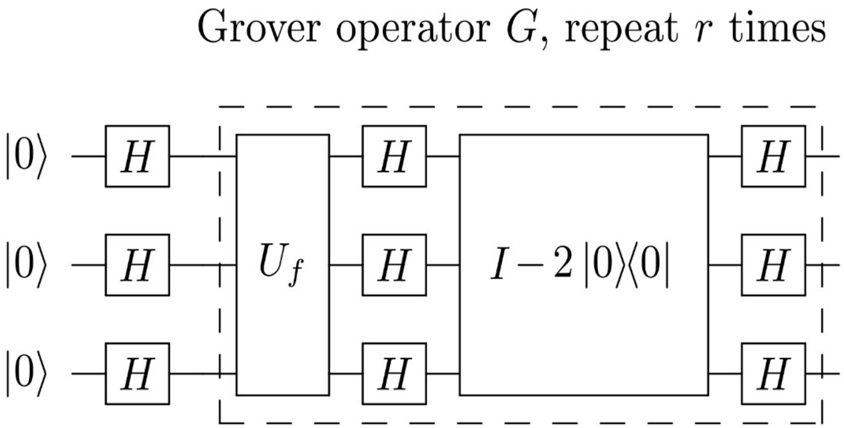
Circuit architecture



Grover fidelity (m marked elements)

$$f_r = \frac{1}{m}\sum_{i}^{m} \left| \langle \omega_i | \Psi_r \rangle \right|^2$$

Quantum counting algorithm

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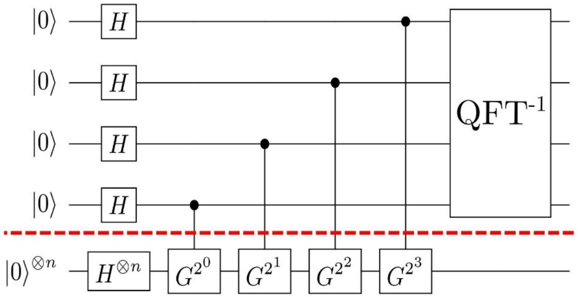
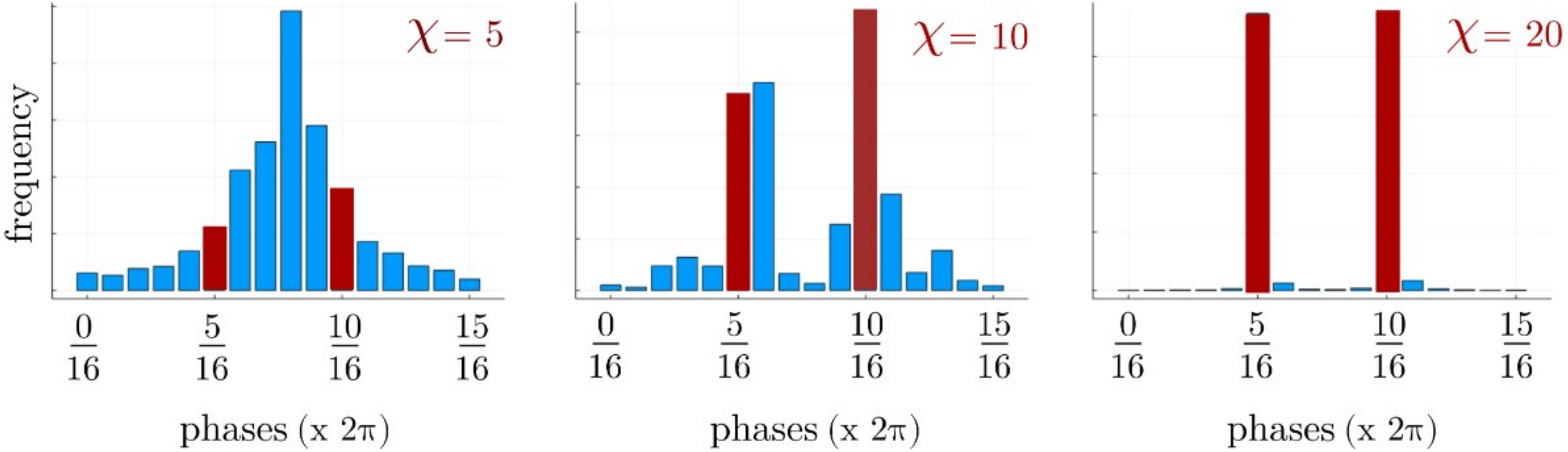
Circuit architecture



Phases of marked elements (correct in red)

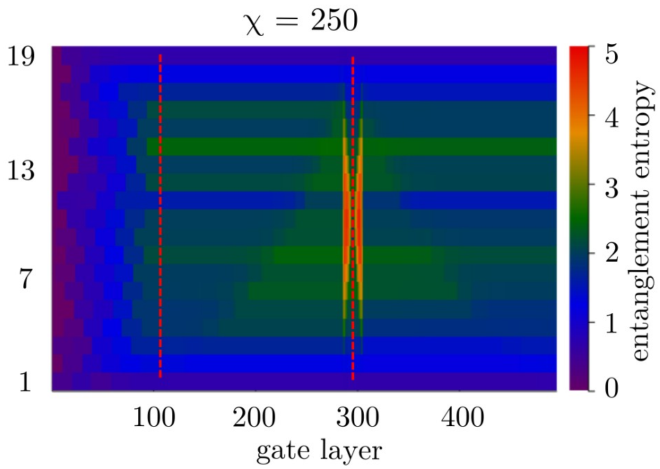
low-quality circuit



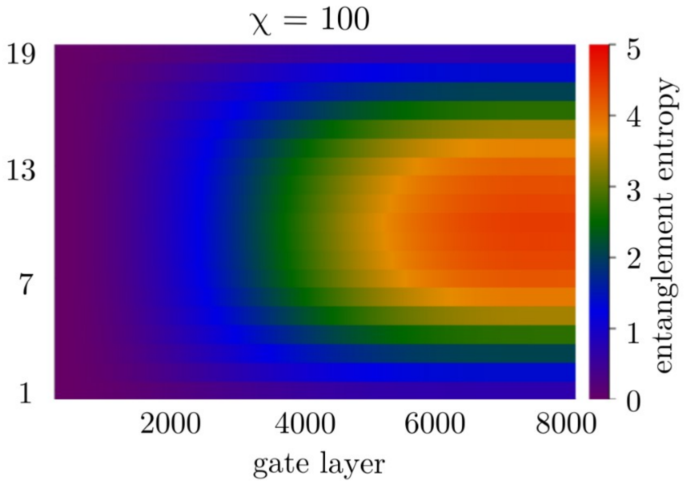
high-quality circuit

Entanglement propagation in the quantum-circuit

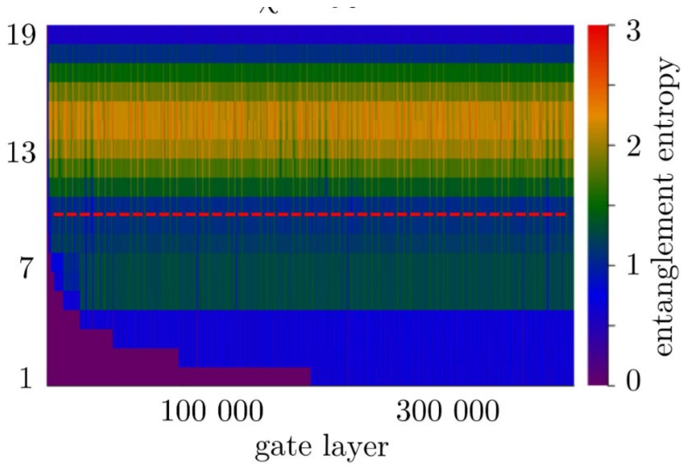
Quantum Fourier transform



Grover’s algorithm



Quantum counting algorithm



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

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Quantum circuits for topological quantum materials

Topological invariant in a Hamiltonian

We can classify Hamiltonians according to topological invariants

Hamiltonian

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

→

Wavefunction

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

↓

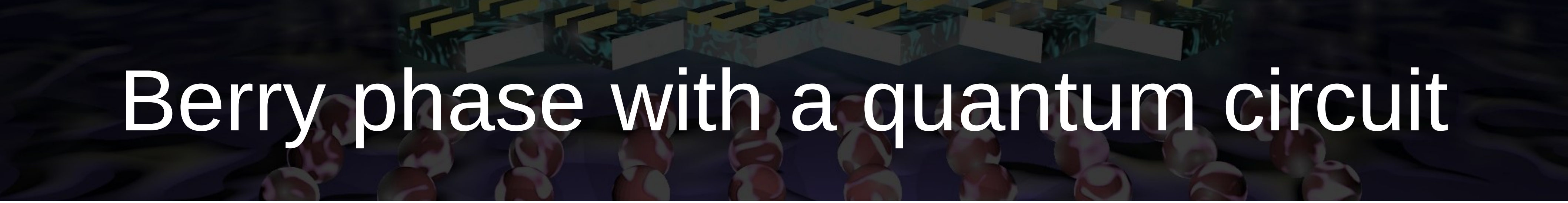
$$\Omega = \nabla \times \mathbf{A}\big|_z$$

Metric
(Berry curvature)

←

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

Topological invariant
(Chern number)



Berry phase with a quantum circuit

Take the eigenstates of the Hamiltonian

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

Evolve them in reciprocal space

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

Geometric phase

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

Dynamical phase

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

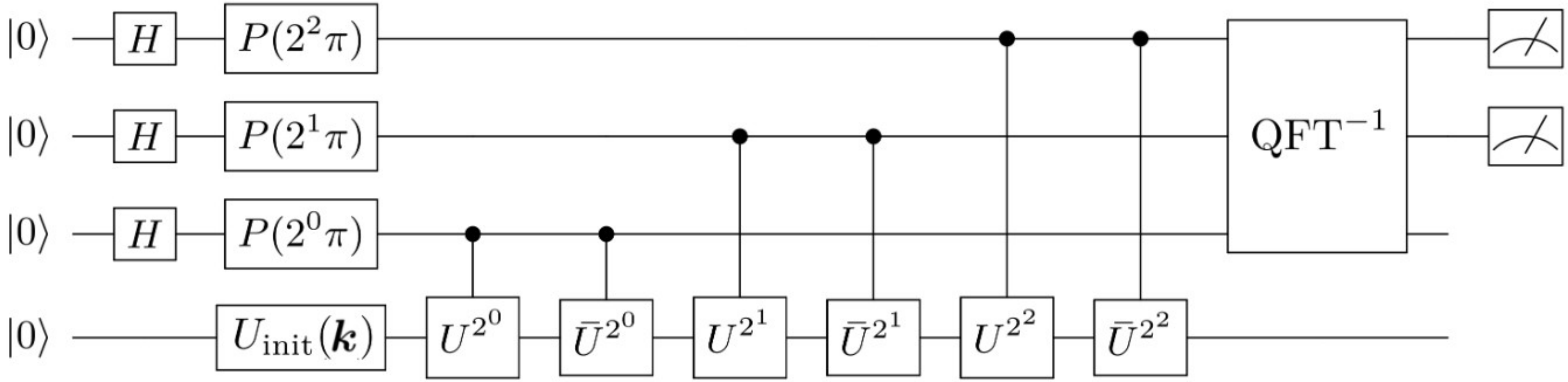
We want to cancel out the dynamical phase, so we can evolve first forward and then backwards in time

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

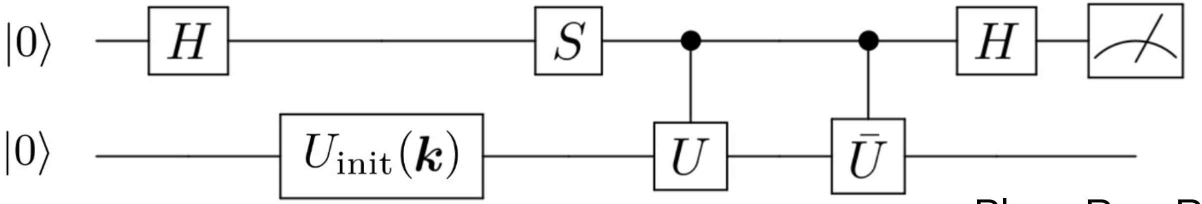
Phys. Rev. Research 6, 043288 (2024)

Quantum circuits to compute topological invariants

Berry phase with quantum phase estimation (based on QFT)



Berry flux (based on Hadamard test)



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Two ways of computing a Chern number

Method 1: Integrate the Berry Curvature

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

Method 2: Pumping of the Wannier charge centers

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

(and count how many times they wind)

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Five implementations of the topological invariant

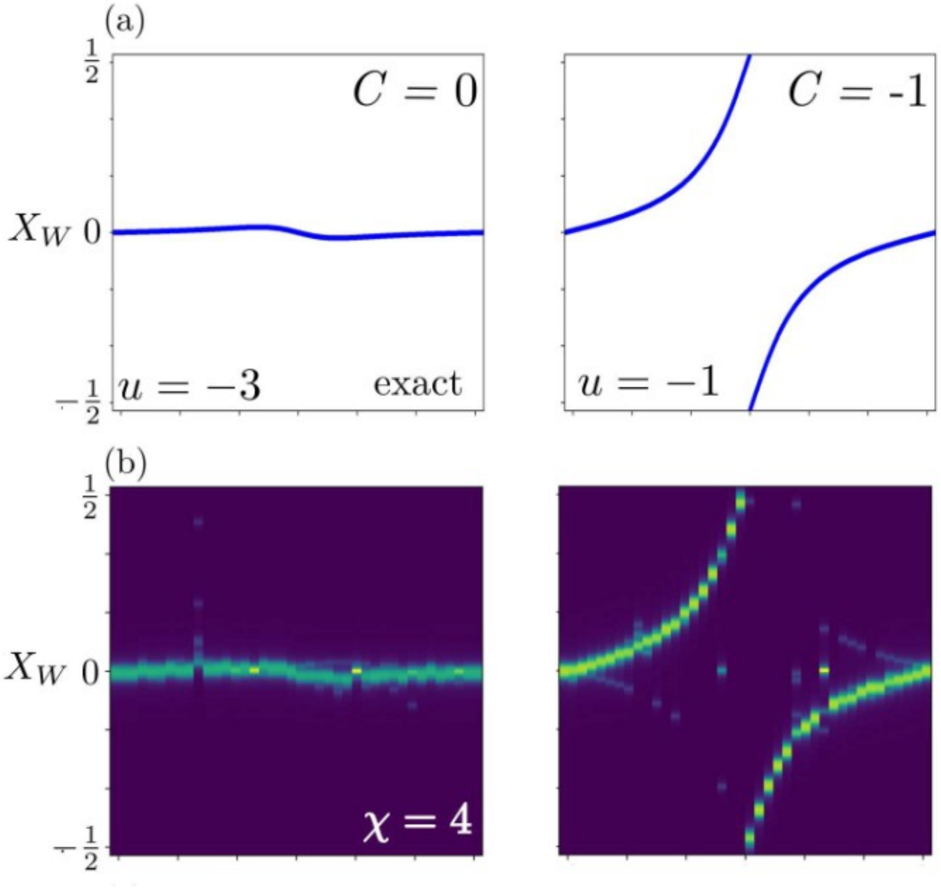
- Helmi quantum computer
- Exact quantum circuit emulator
- Noisy quantum circuit emulator
- Tensor-network quantum circuit emulator
- Exact classical algorithm

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 provides five qubits.

https://fiqci.fi/

Chern number from Wannier winding



Exact classical simulation

Tensor network simulator

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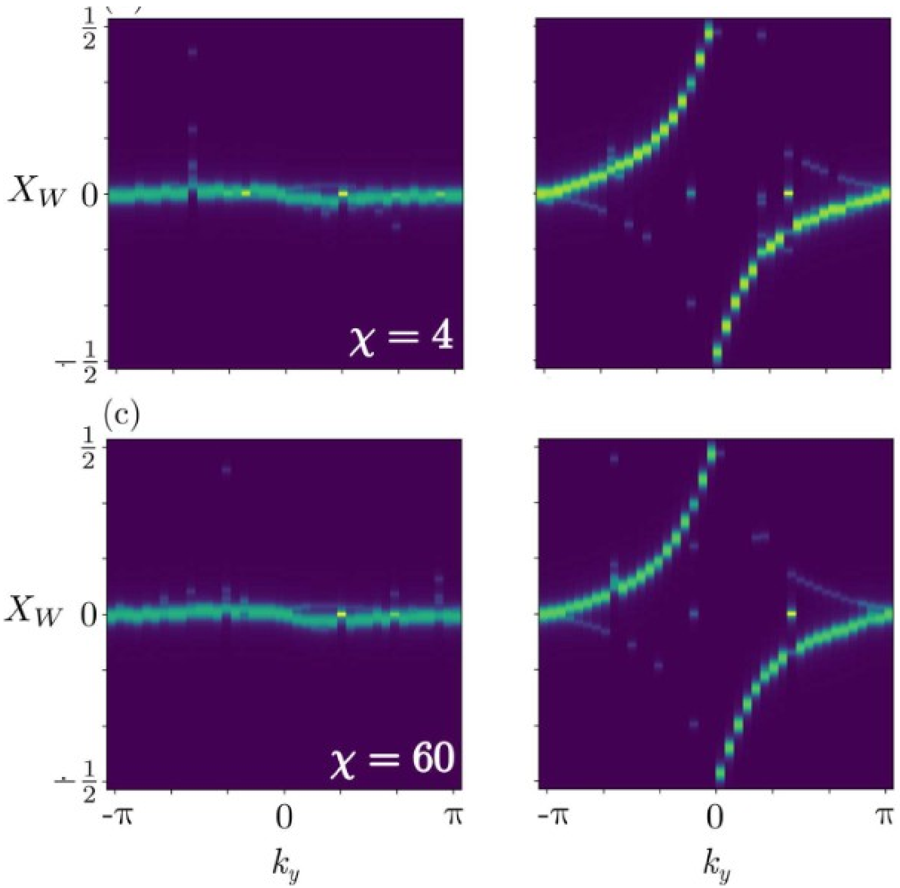
Chern number from Wannier winding



Low bond dimension

Tiny part of the Hilbert space

High bond dimension

Most of the Hilbert space

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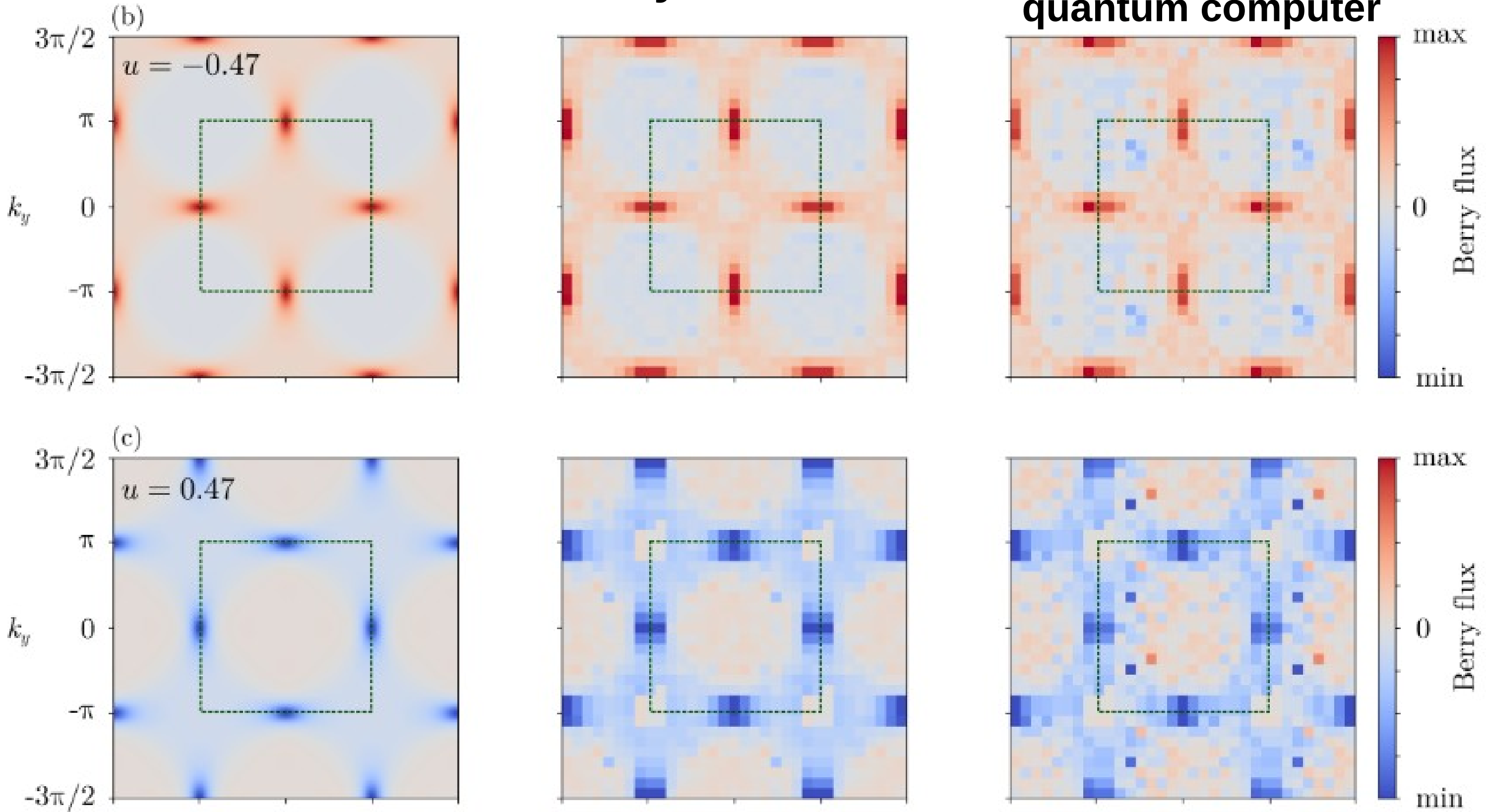
Chern number from Berry curvature integration

Exact **Noisy simulation** **Helmi quantum computer**



$$C = 1$$

$$C = -1$$

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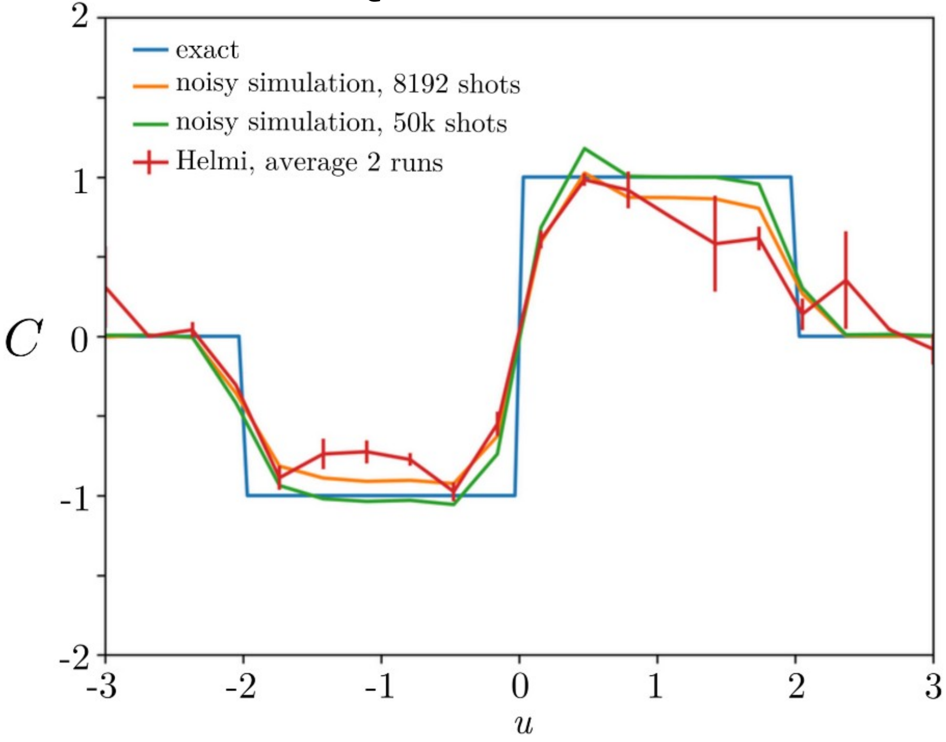
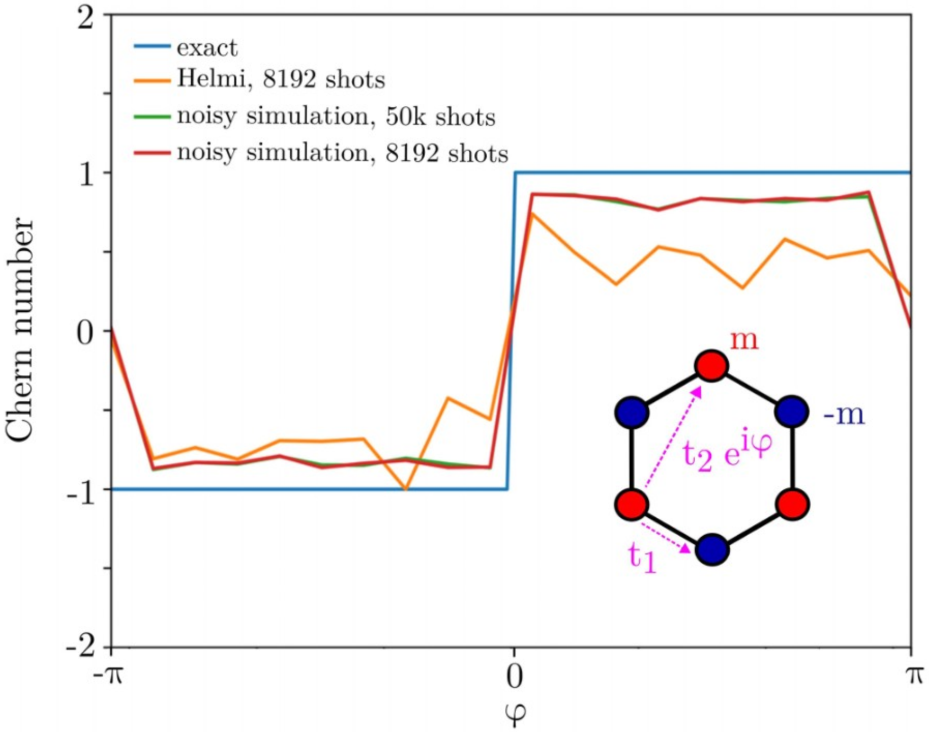
Topological phase diagram

QWZ model



Haldane model



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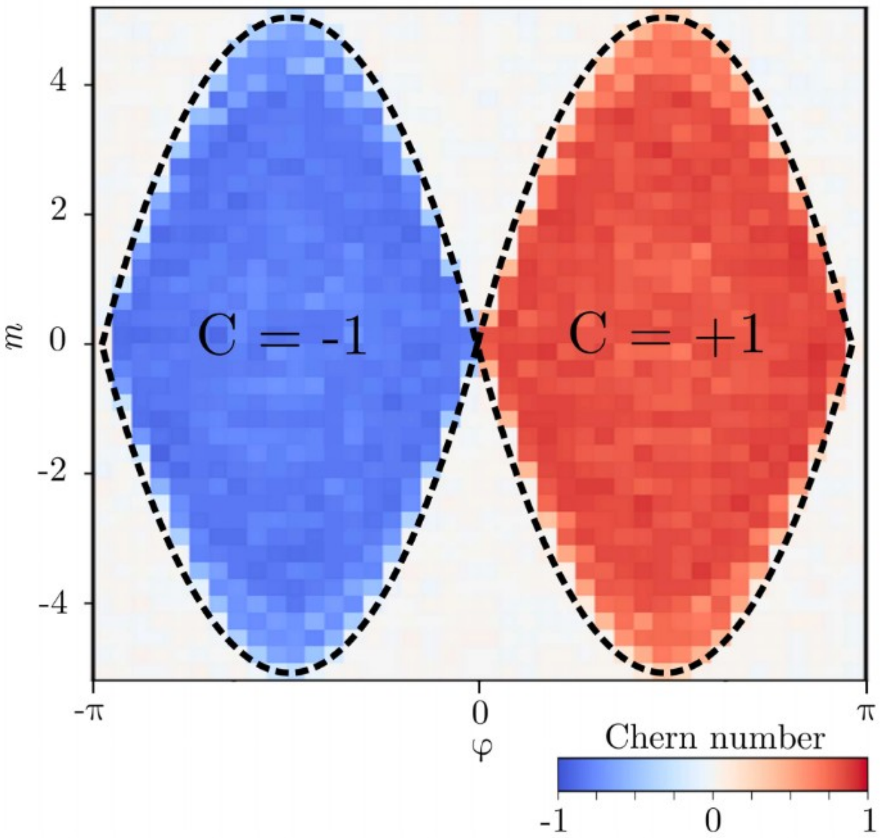
Topological phase diagram



Haldane model

Noisy calculations provide qualitatively correct topological phase diagrams

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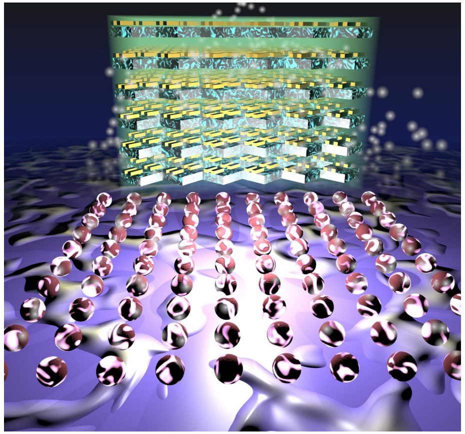
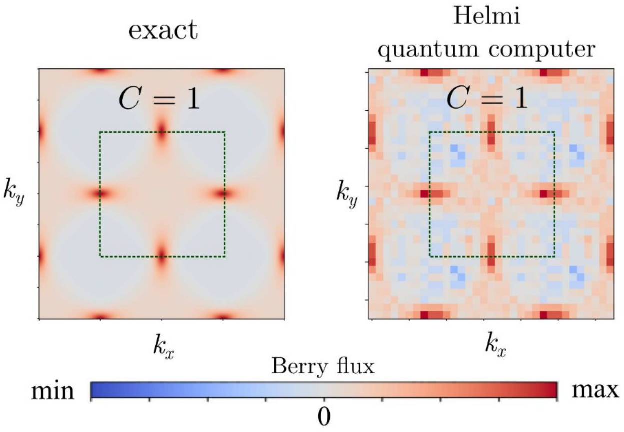
Take home

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





Funding from

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Finnish Quantum Flagship FQF

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