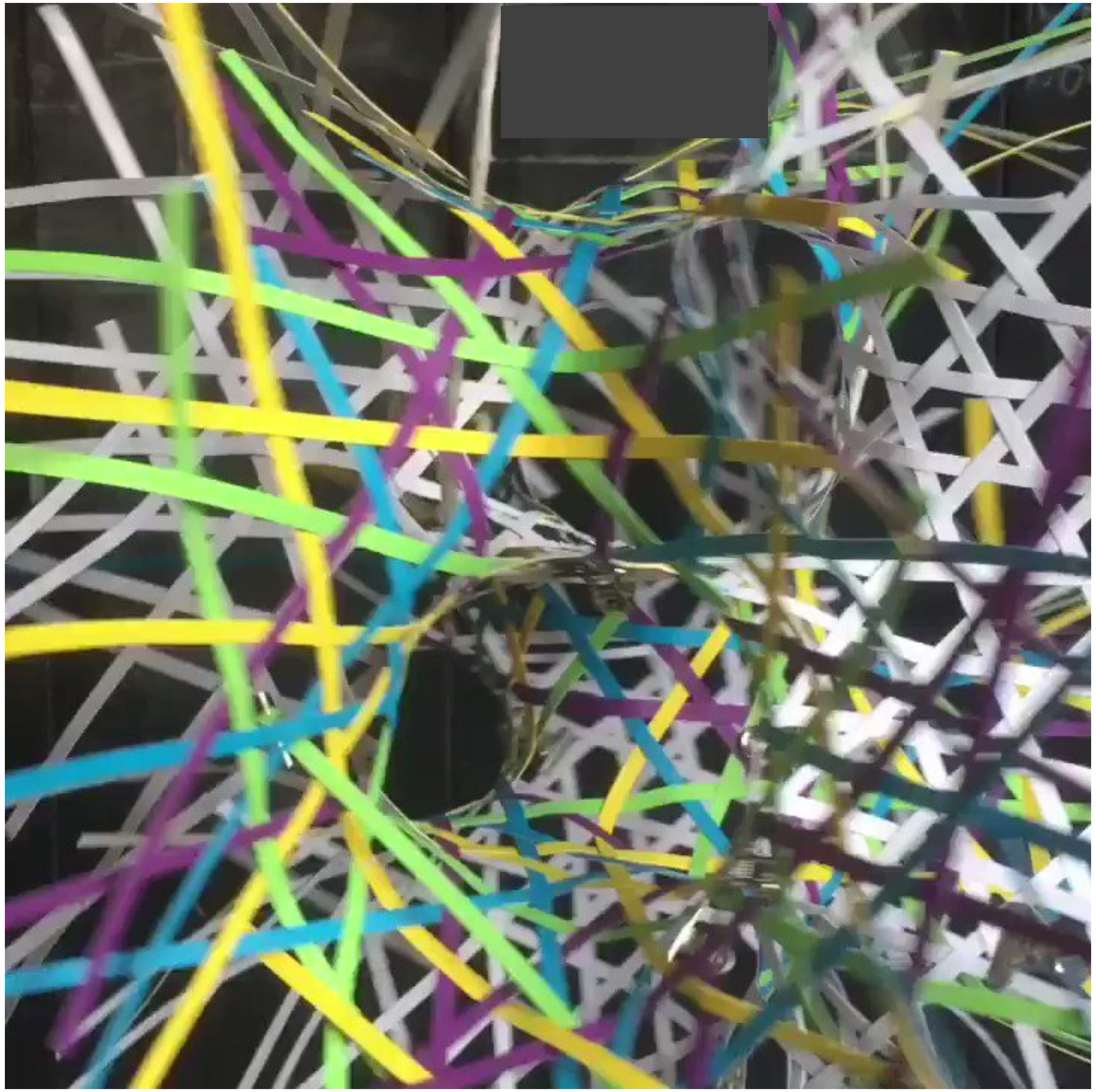


Image: Alison Martin

All but frustrating: When quantum materials meet topology

Roser Valentí
Institute of Theoretical Physics
University of Frankfurt
Germany

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

KITP

KITP, Chalk Talk
Tuesday, Sept. 17th 2019

- **Topology**
- **Quantum Physics**
- **Topology meets Quantum Materials**

Topology

Greek: τόπος „place“   λόγος „study“

Studies the **properties** of a geometric object that are **preserved** under **continuous deformations** (stretching, twisting,crumpling)

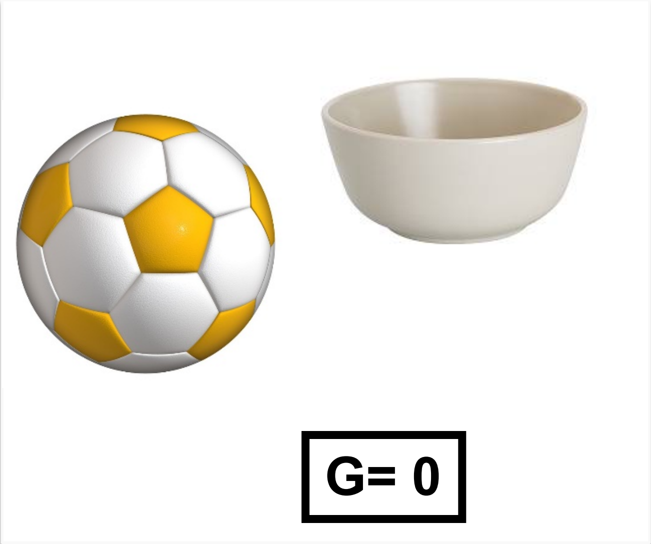


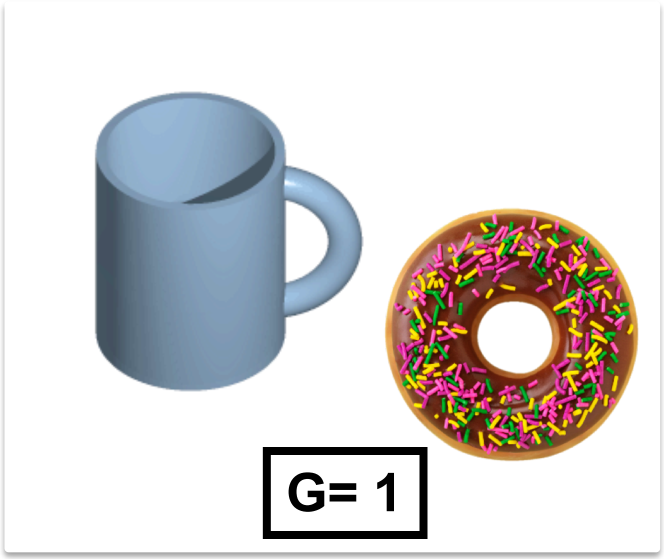




Topology

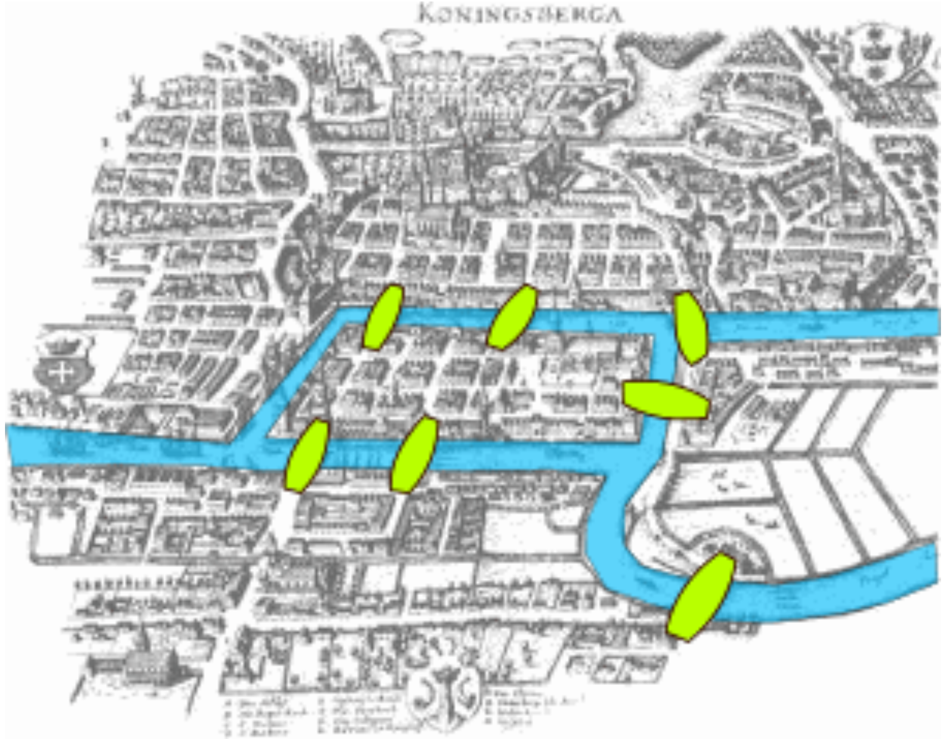
GENUS = number of holes ---- **Global** property

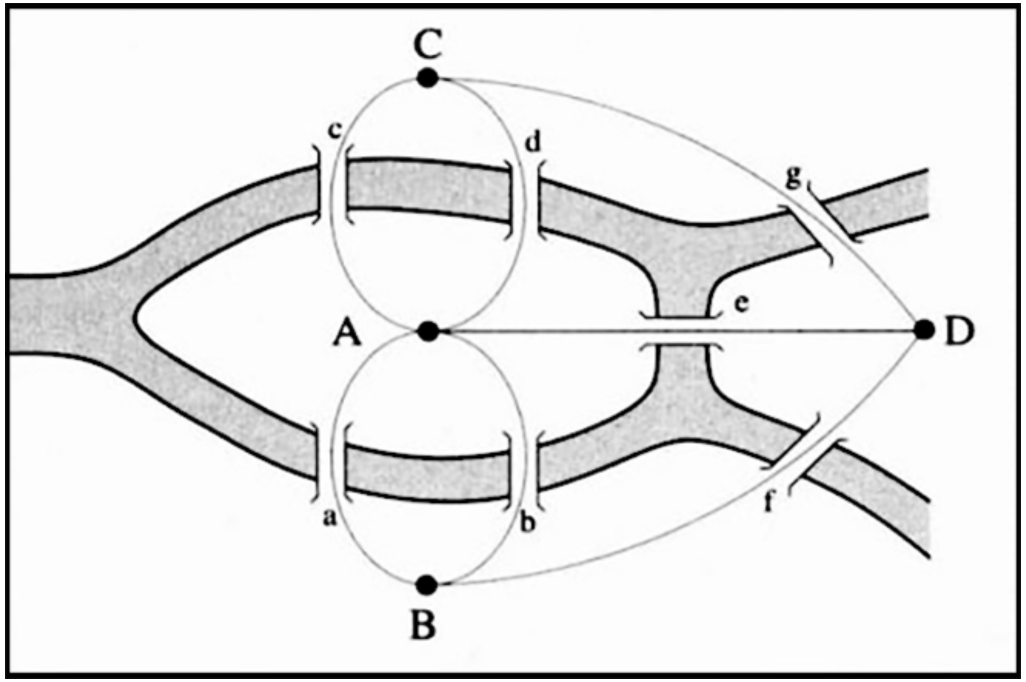




Studies the **properties** of a geometric object that are **preserved** under **continuous deformations** (stretching, twisting,crumpling)

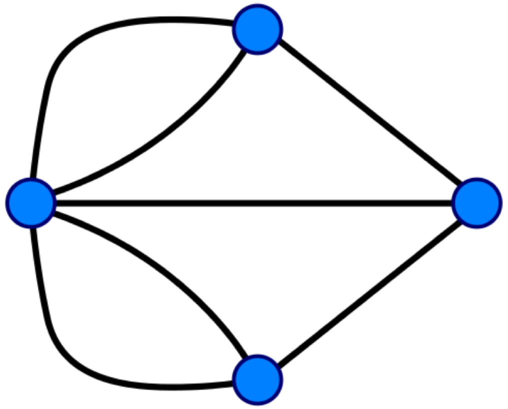
Origins





1736: Leonhard Euler (**seven bridges of Königsberg**)

Is it possible to devise a walk through the city that would cross each of those bridges only once?



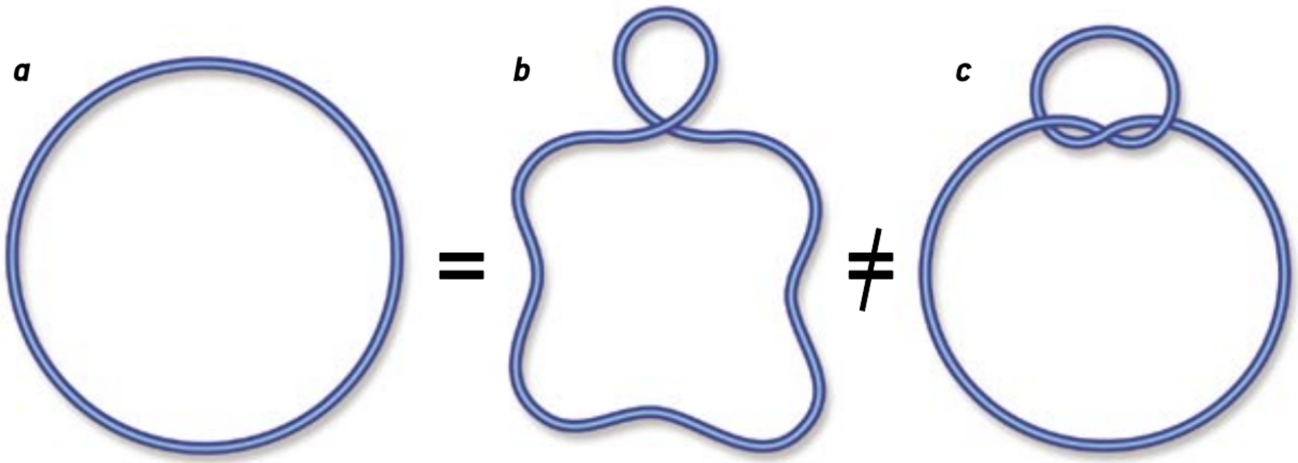
(graph theory)

connectivity

Knots

1771: Alexandre-Theophile Vandermonde

XIX century: Listing, Gauss, Tait



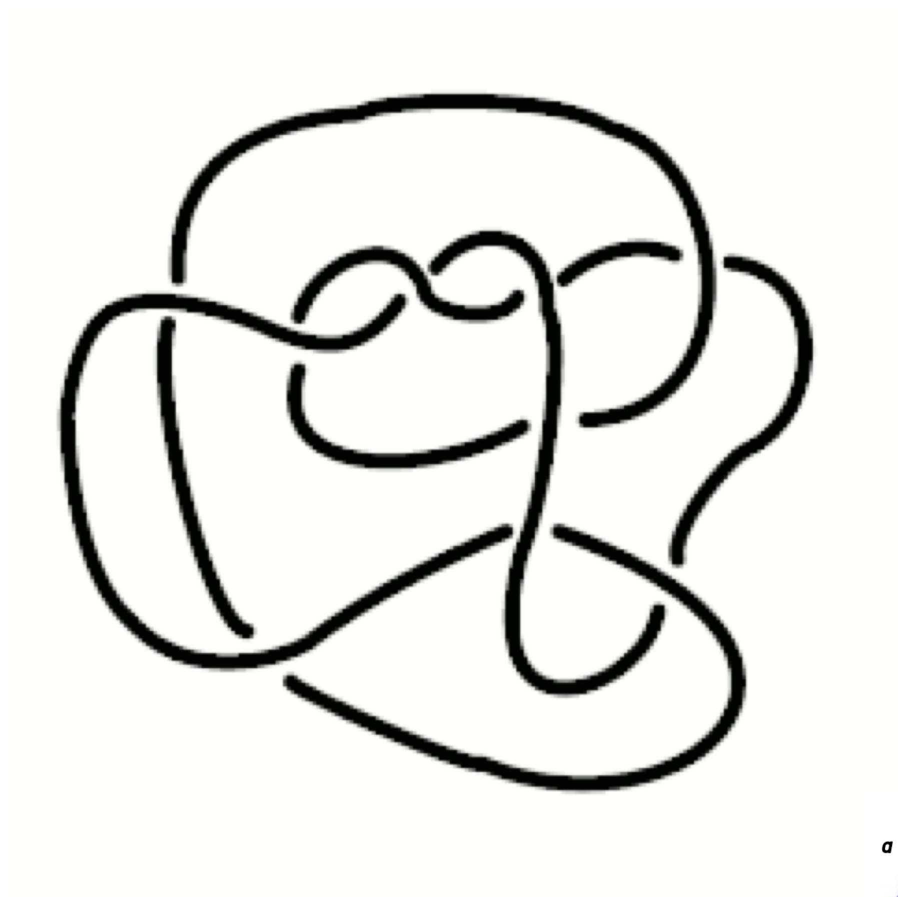
Celtic knot

Book of Kells
(Irland) ~ 800 AD

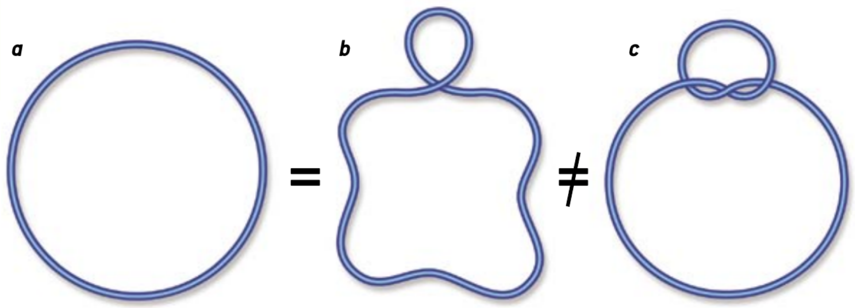
(knot theory)

Two knots are equivalent if one can be transformed into the other via deformations in 3 dimensions

Knots



https://en.wikipedia.org/wiki/Knot_theory

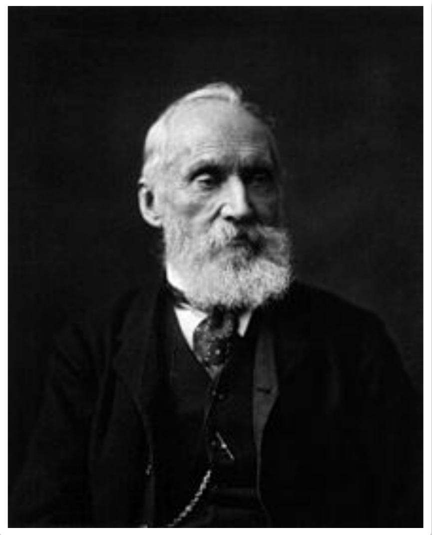


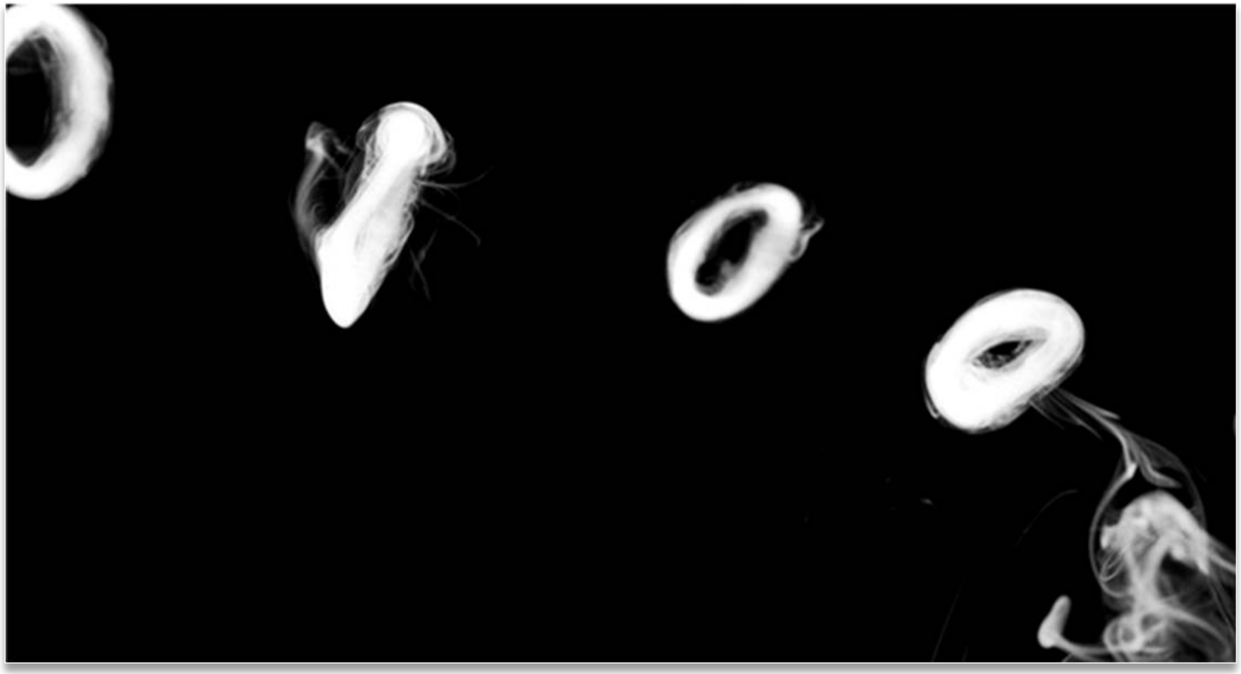
(knot theory)

First encounters: topology and physics

XIX century:
Peter Guthrie Tait

William Thomson
(Lord Kelvin)





stability of smoke rings?

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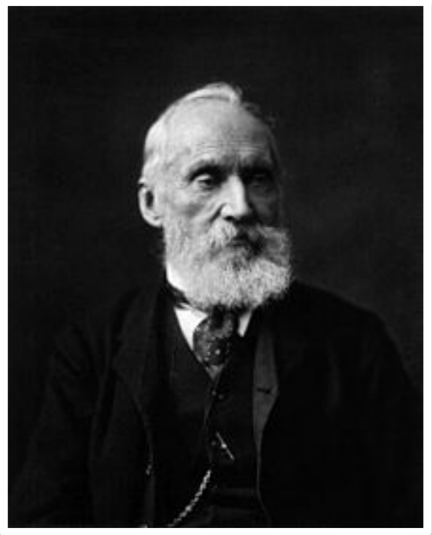
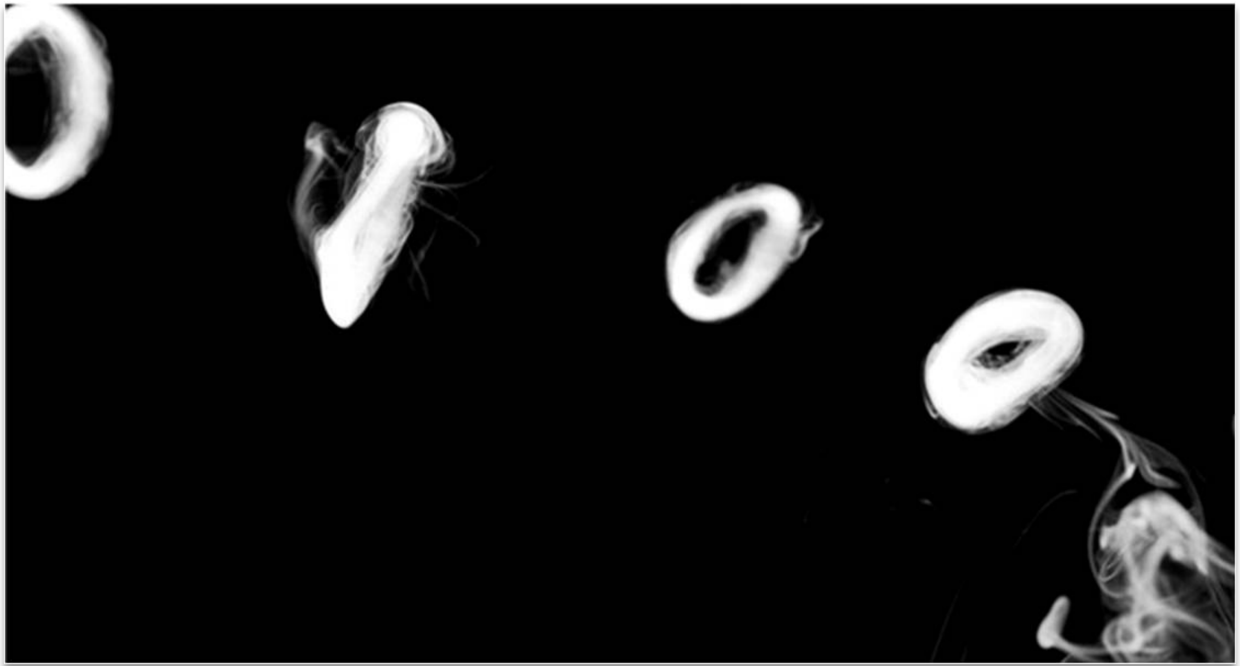




stability of smoke rings?

Thomson: Perhaps ***atoms*** are actually knots of swirling vortices in ***aether***?

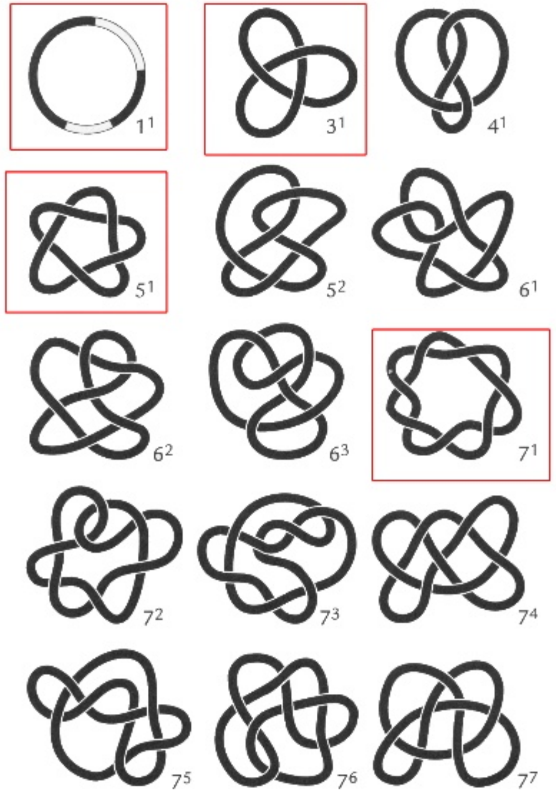
First encounters: topology and physics

1867: William Thomson

atoms = knotted vortices in aether

inspired **Tait** to **classify knots**

Carbon Oxygen Hydrogen



First encounters: topology and physics

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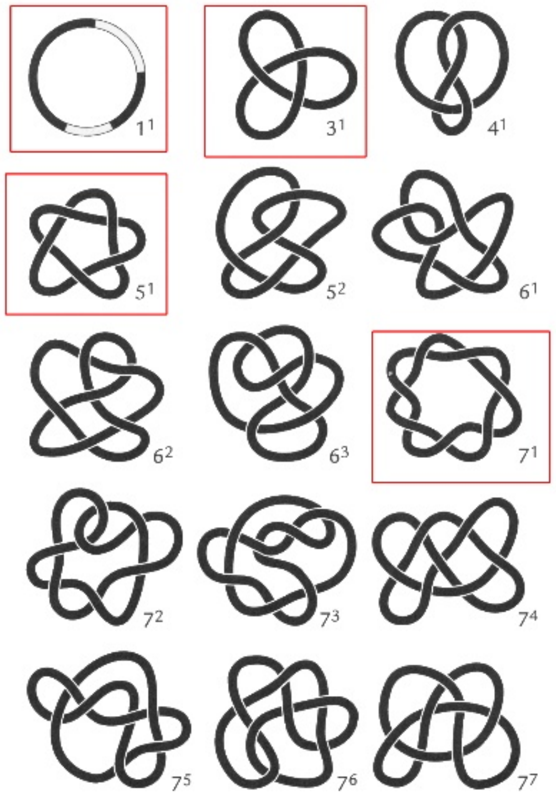
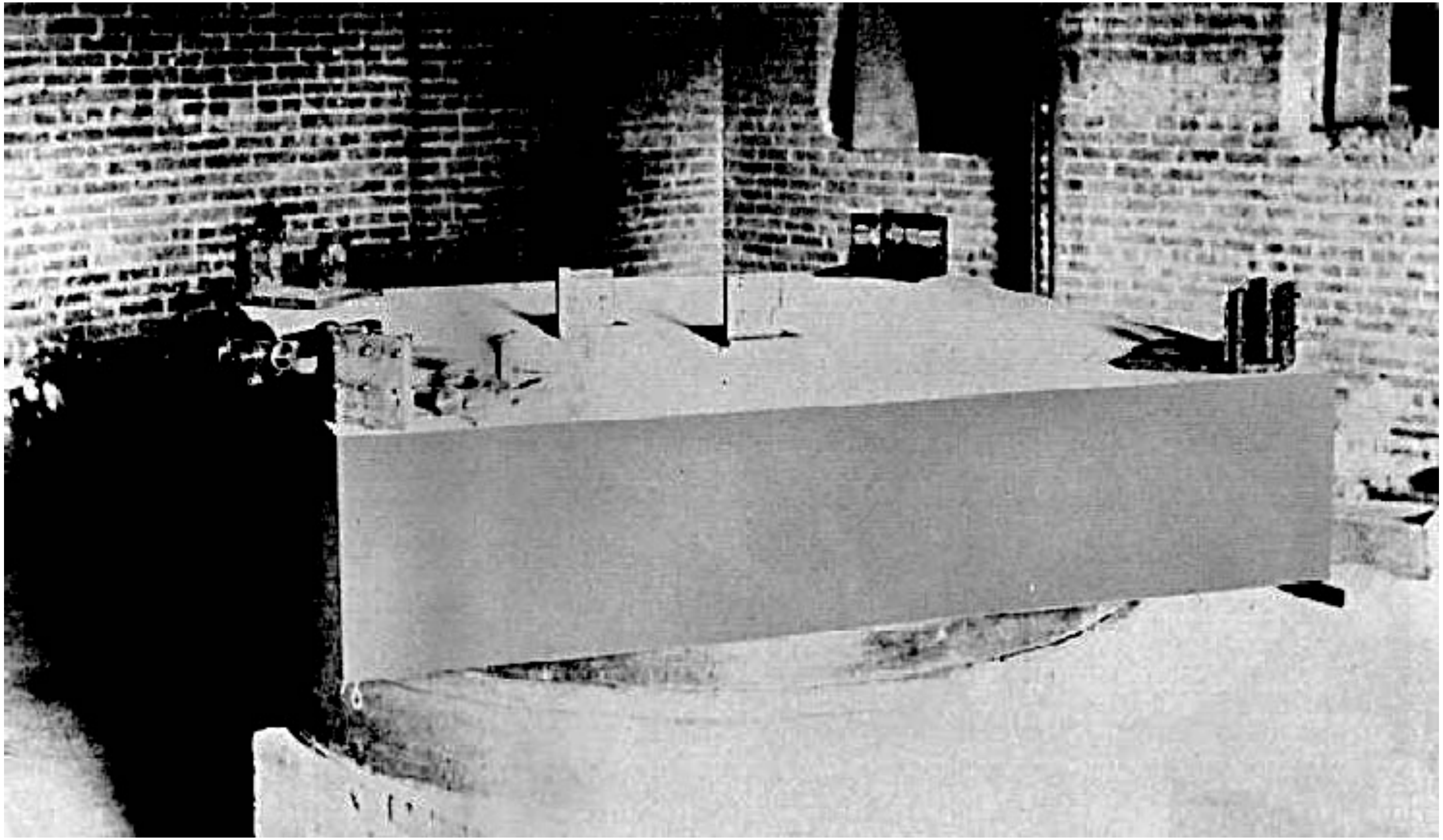


1887 Michelson-Morley experiment → inexistence of aether !!

Michelson-Morley experiment



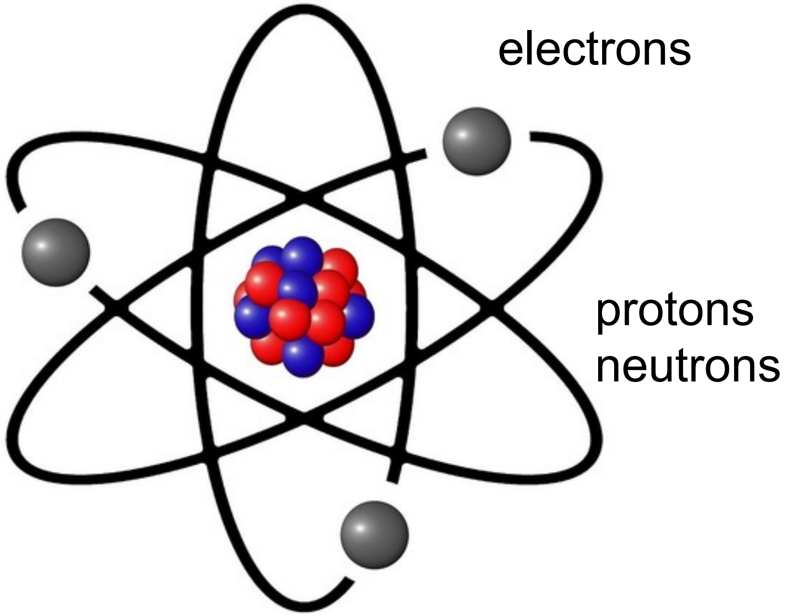
Cleveland, Ohio

1887 Michelson-Morley experiment → inexistence of aether !!

XXth century: Birth of quantum physics

Microscopic world (10^{-8} cm)

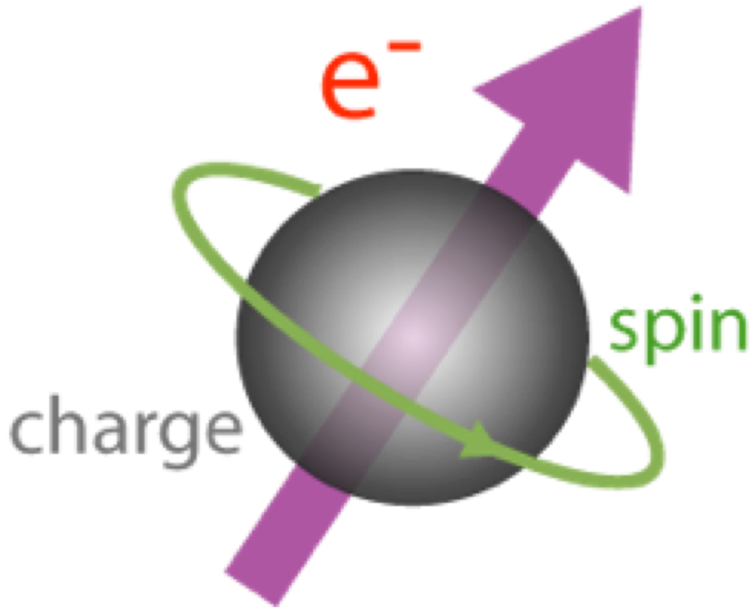
Bohr atom



Nils Bohr
(1885-1962)
Nobel Prize 1922

XXth century: Birth of quantum physics

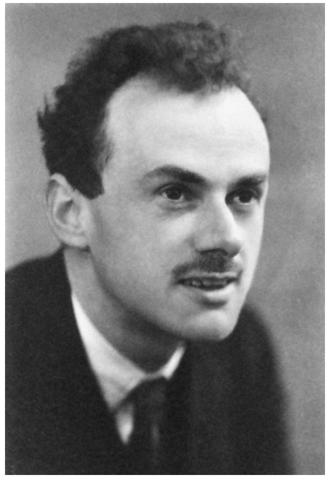
Microscopic world (10^{-8} cm)



spin=1/2

Enrico Fermi

(1901-1954) Nobel Prize 1938



Paul Dirac

(1902-1984) Nobel Prize 1933

XXth century: Birth of quantum physics

Microscopic world (10^{-8} cm)

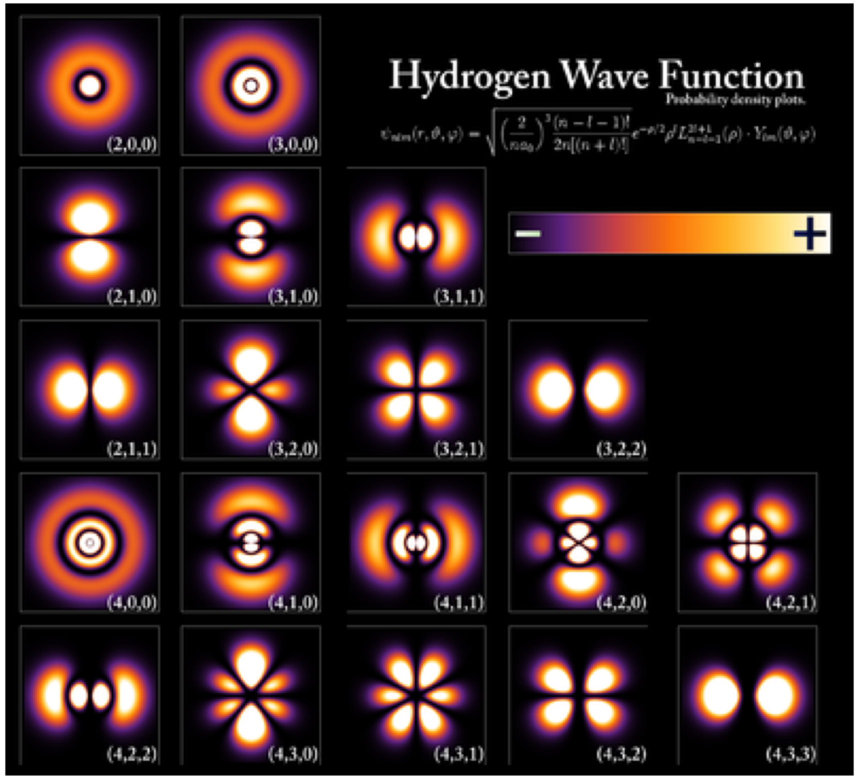
Electron wavefunction

$$\Psi(\mathbf{r}, t)$$

Schrödinger equation:

$$i\hbar \frac{\partial}{\partial t}\Psi(\mathbf{r}, t) = H\Psi(\mathbf{r}, t)$$

$$\left| \Psi(\mathbf{r}, t) \right|^2$$



Werner Heisenberg

(1901-1976) Nobel Prize 1932

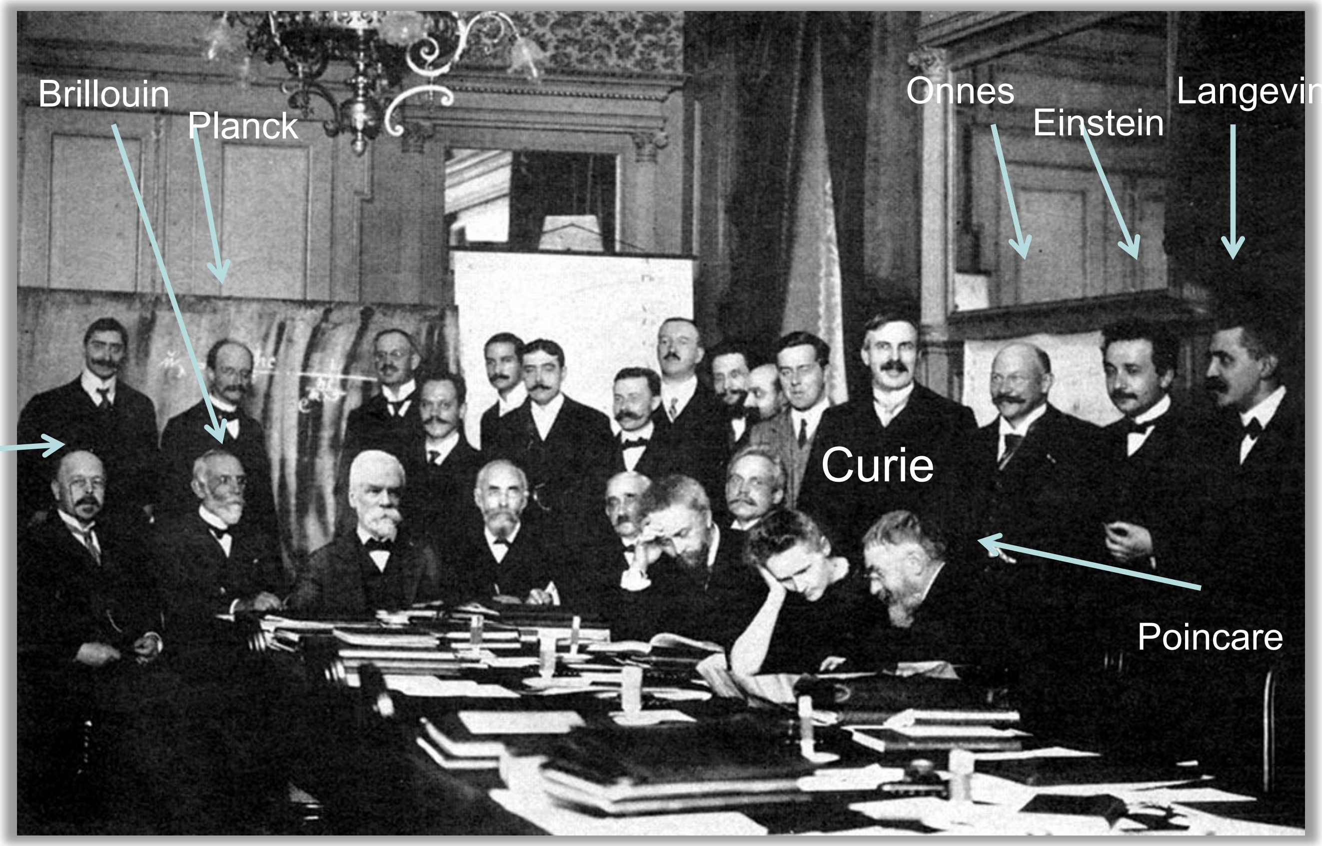
Erwin Schrödinger

(1887-1961) Nobel Prize 1933

XXth century: Birth of quantum physics

„Radiation and quanta“

Nernst

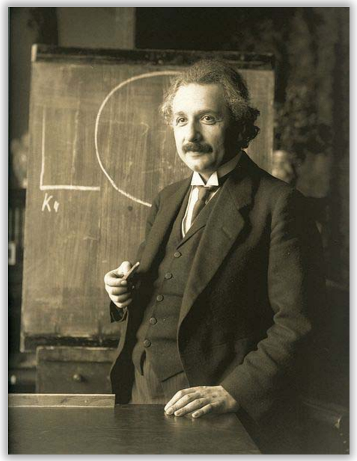


1911: 1st Solvay Conference
(Brussels)

Letters Einstein → Max von Laue

BERLIN	OXFORD	PRINCETON
Datum: 16. VIII. 1926	Datum: 26. V. 1933	Datum: 23. III. 1934
Datum: 12. VII. 1927		Datum: 21. X. 1935 Elsa Einstein
Datum: 29. IX. 1928		Datum: 29. VII. 1936 Max von Laue
Datum: 3. X. 1928		Datum: 29. VIII. 1936
Datum: 21. I. 1929		
Datum: 30. I. 1929		

Universitätsarchiv
Goethe University Frankfurt



Albert Einstein
(1878-1955) Nobel Prize 1921

Max von Laue
(1879-1960) Nobel Prize 1914

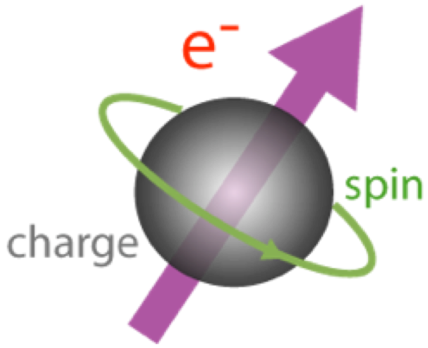
XXIst century

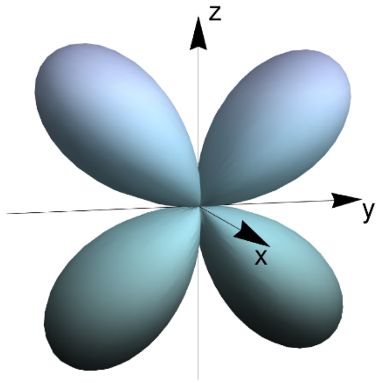
Quantum Materials

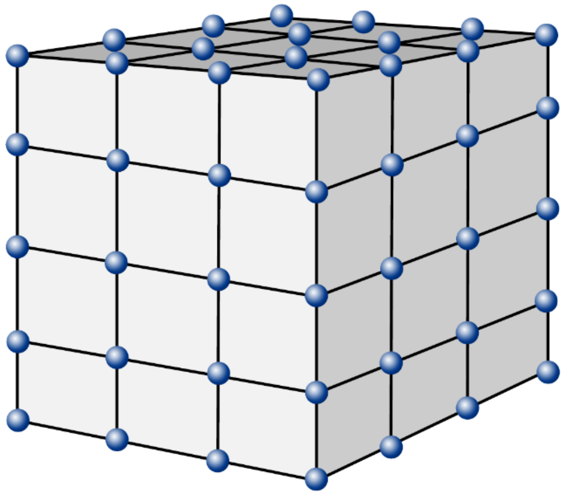
- Interacting many-body systems:

  10^{23} electrons within a cm^3

- Simultaneous action of several degrees of freedom:







⇒ ***Emergence of distinct phases of matter***

Emergence

Flock of birds

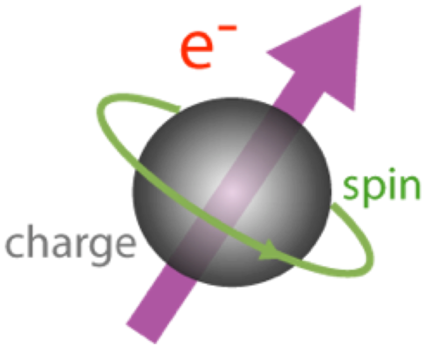
Behavior not foreseeable from the knowledge of the constituents alone

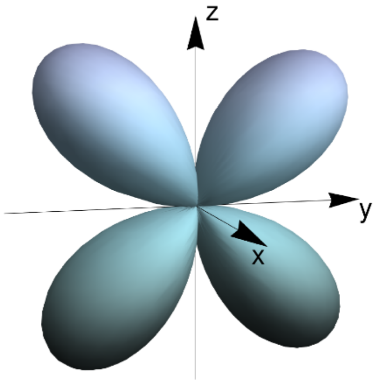
Quantum Materials

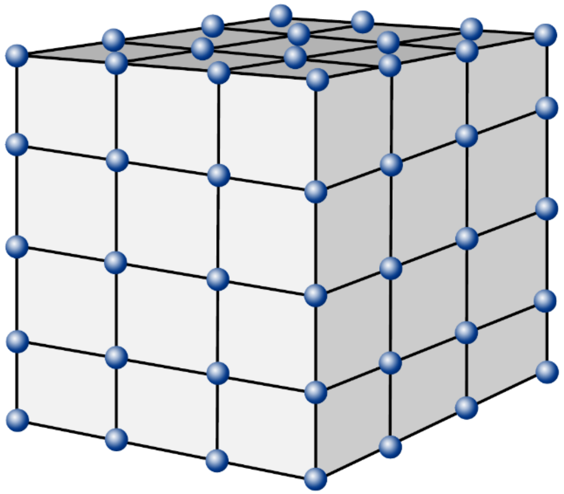
- Interacting many-body systems:

  10^{23} electrons within a cm^3

- Simultaneous action of several degrees of freedom:







⇒ ***Emergence of distinct phases of matter***

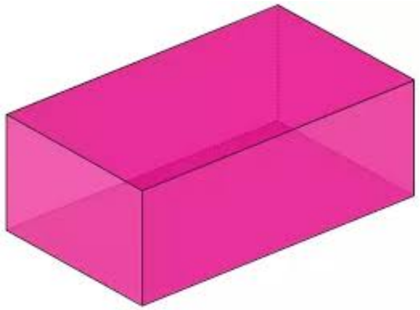
“Old way”

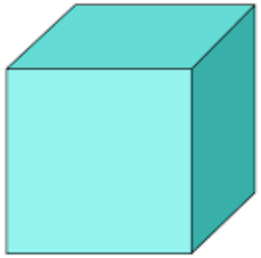
Quantum Materials

symmetry

invariance of an object under a transformation (rotation, translation,…)

useful to classify phases of matter through changes of symmetry (Landau)





Quantum Materials

“Old way”

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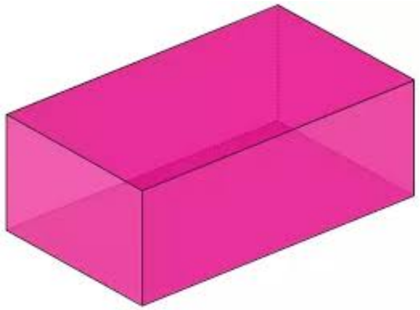
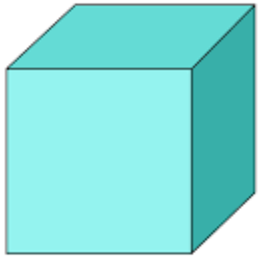


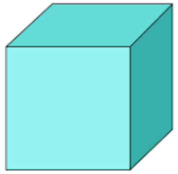


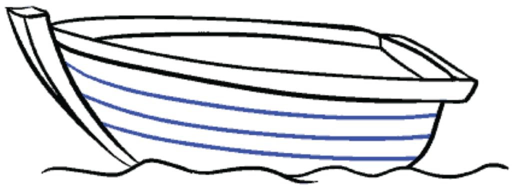
“New way”

topology

deals with properties that are preserved under continuous deformations

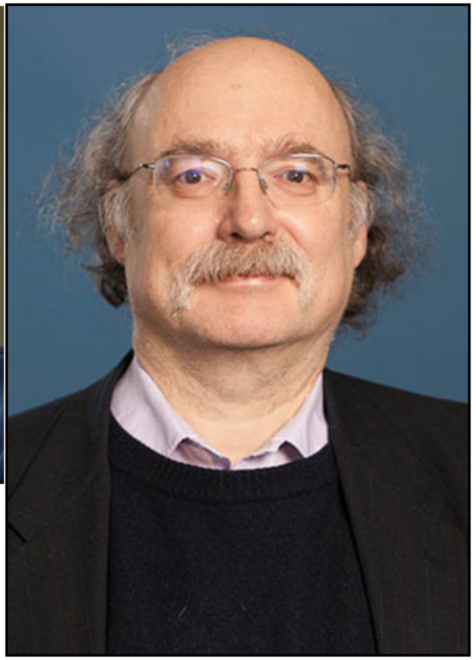
useful to classify topological phases of matter





pioneers in using the language of topology to describe quantum states

Physics Nobel Prize 2016



David Thouless
Washington University
Seattle USA

Michael Kosterlitz
Brown University
Providence USA

Duncan Haldane
Princeton University,
USA

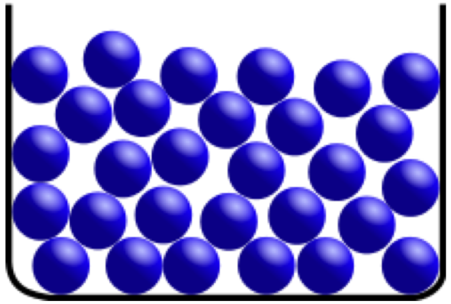
„for theoretical discoveries of topological phase transitions and topological phases of matter“

Phase transitions

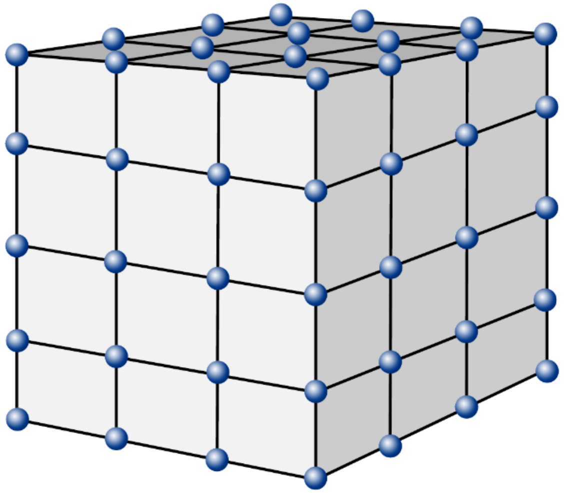
liquid

solid

lowering Temperature



translational symmetry



disordered atoms

ordered atoms

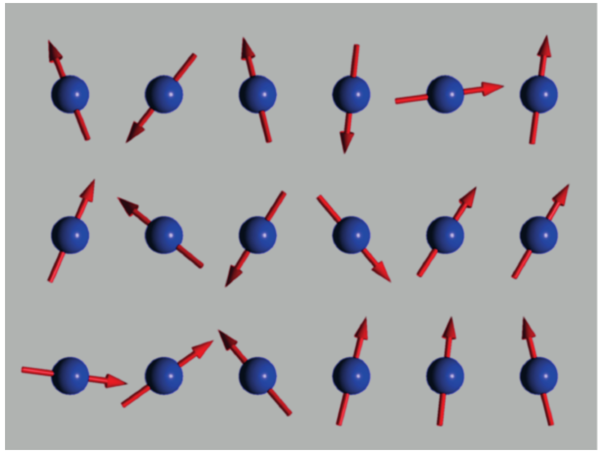
Phase transitions: paramagnet→ ferromagnet

(Landau theory of phase transitions 1937)

paramagnet

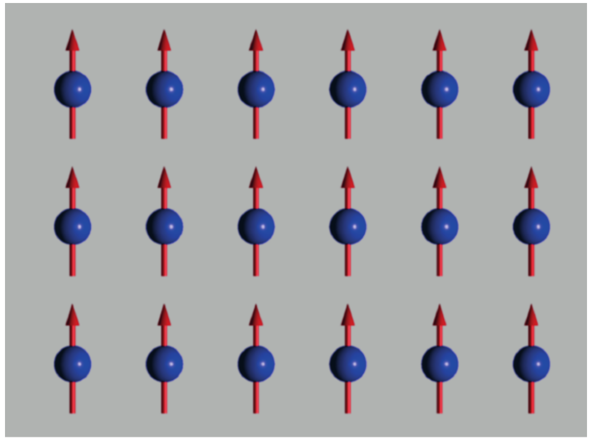
lowering Temperature

ferromagnet



disordered spins

Spin rotation symmetry



ordered spins

Order Parameter = magnetization

Phase Transitions

1966: N.D. Mermin, H. Wagner → in 2D a Heisenberg magnet cannot order

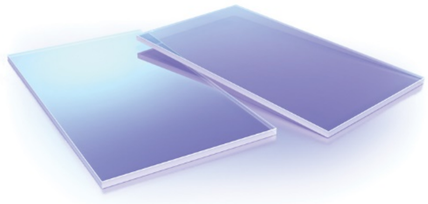
1967: P. Hohenberg → in 2D superconductivity and superfluidity shouldn‘t exist

Problem:

Numerical evidence of phase transitions in 2D

??

Stanley, Kapplan (1966), Wegner (1967), Berezinskii (1970)



hair swirl

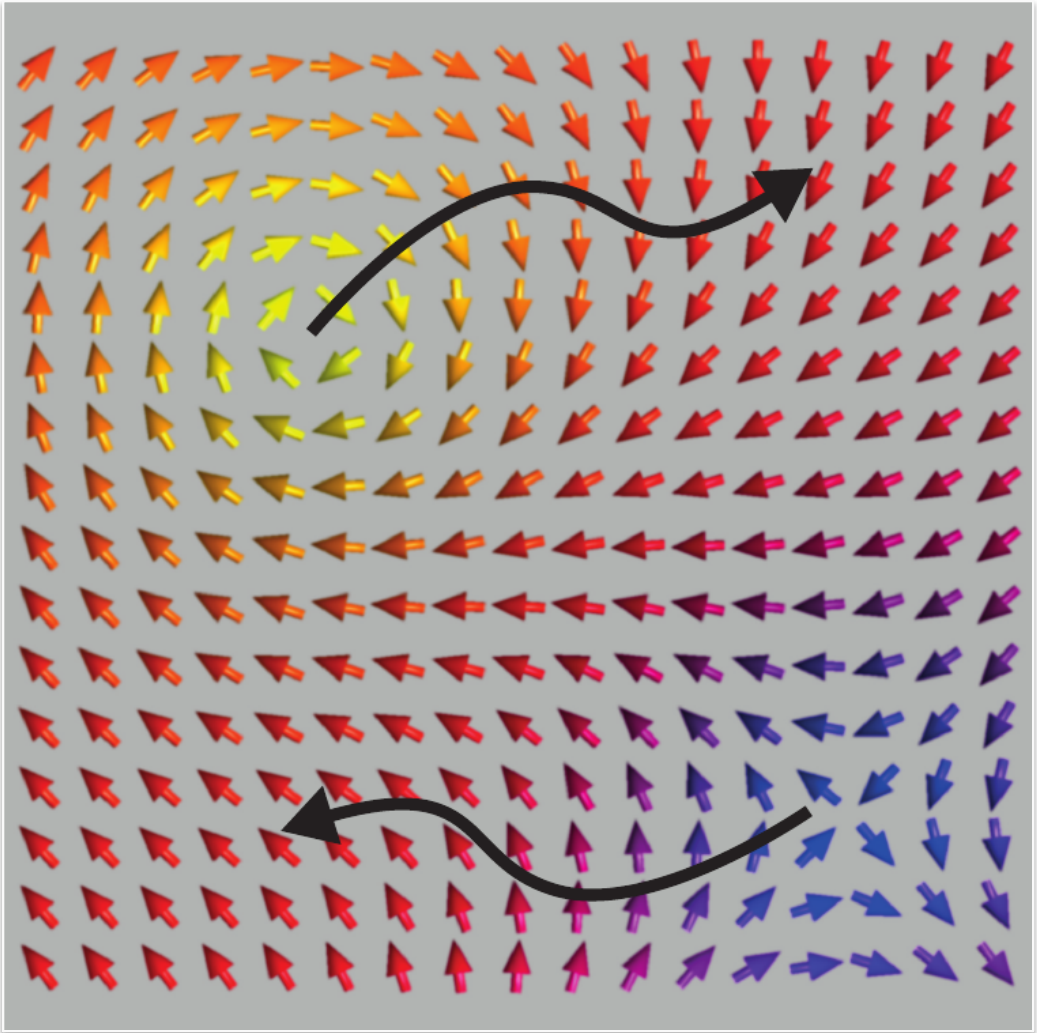
SYSTEM OF SPINS

Vortex-antivortex

Microscopic world (10^{-8} cm)

vortex:
G=1

winding 2π



antivortex:
G=-1

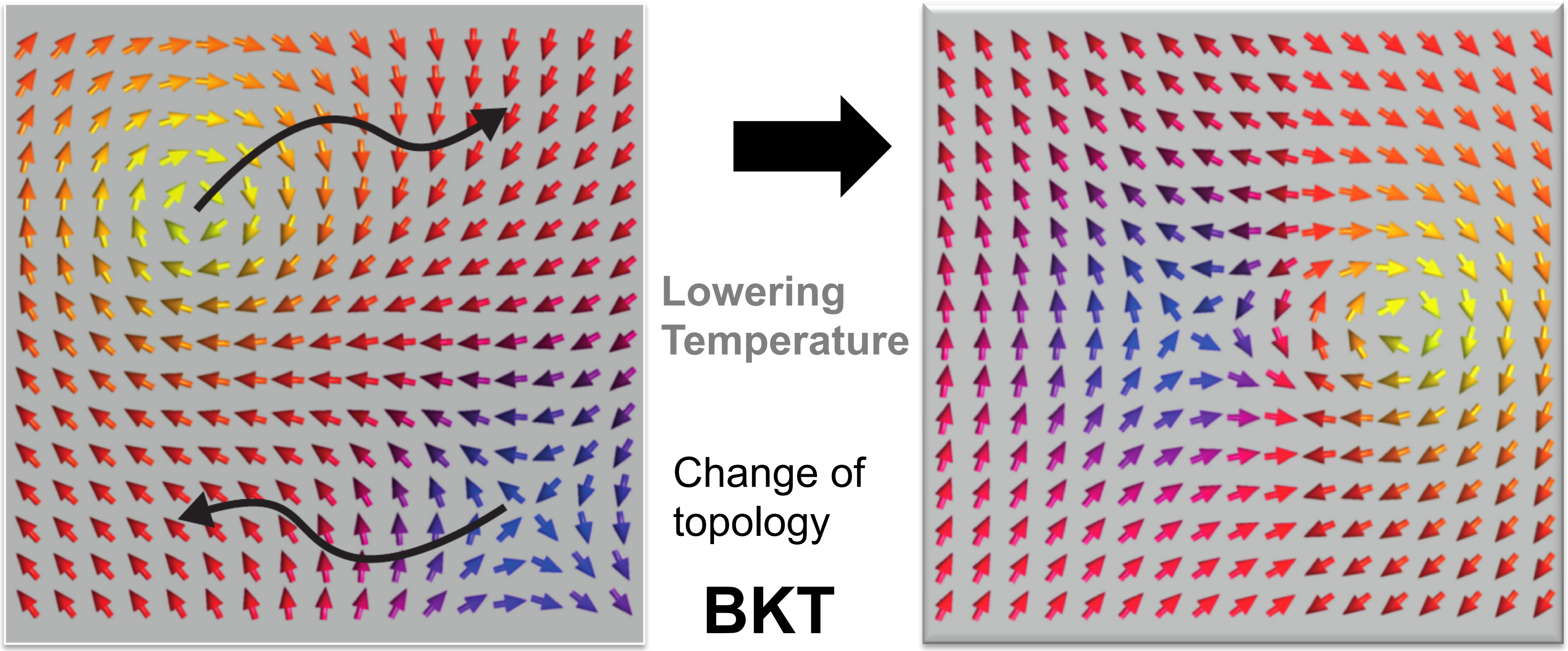
winding -2π

it is impossible to transform a **vortex** to an **antivortex** through a continuous transformation, but they can form pairs. **Pair G=0**

SYSTEM OF SPINS

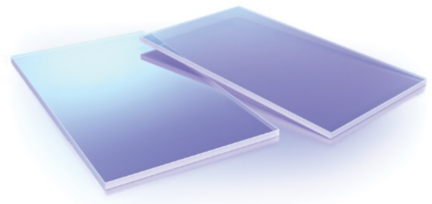
BKT phase transition

Kosterlitz and Thouless
J. Phys. C 5, L124 (1972); 6, 1181 (1973), **Berezinskii** (1972)



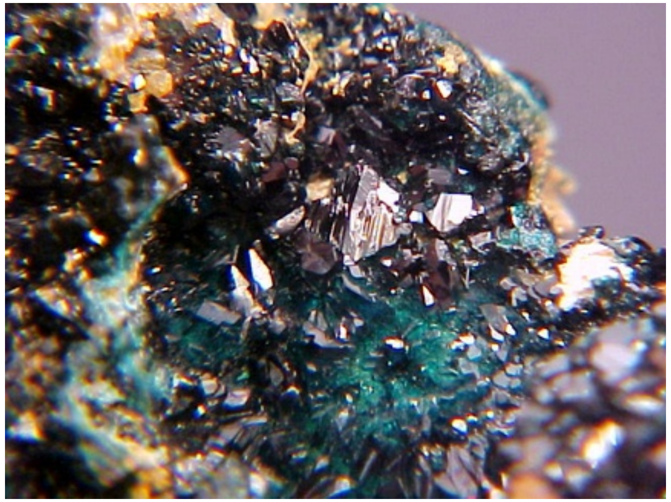
unpaired vortex – antivotex

paired vortex – antivotex



In 2D, **topological defects (vortex**) can undergo a phase transition without symmetry change → new topological state

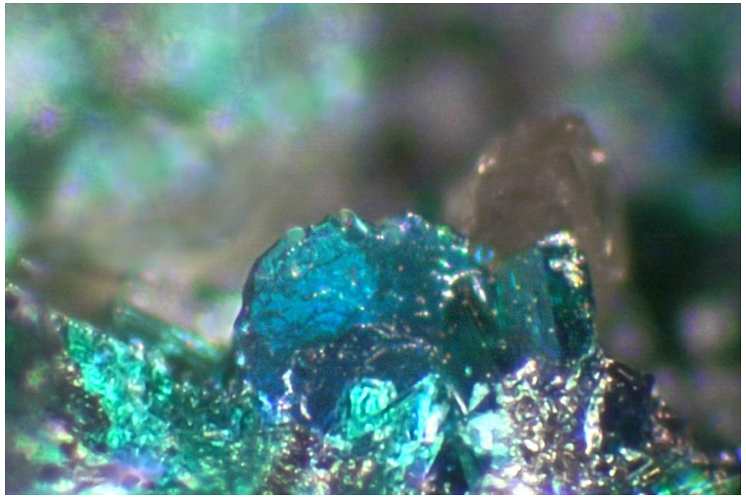
Quantum Materials



herbertsmithite

kapellasite

haydeeite



barlowite

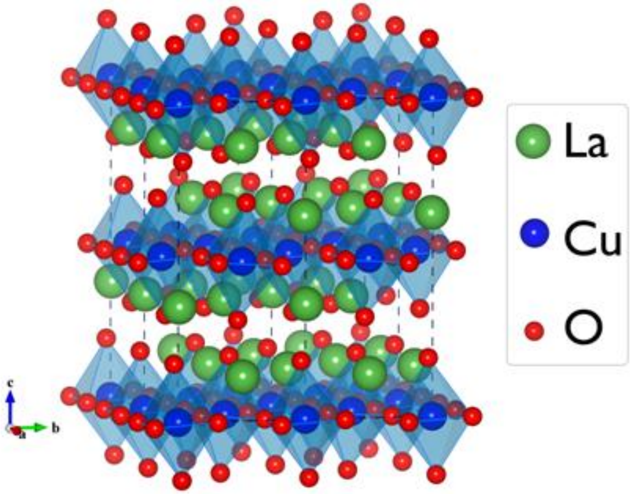
Topological phases in quantum materials

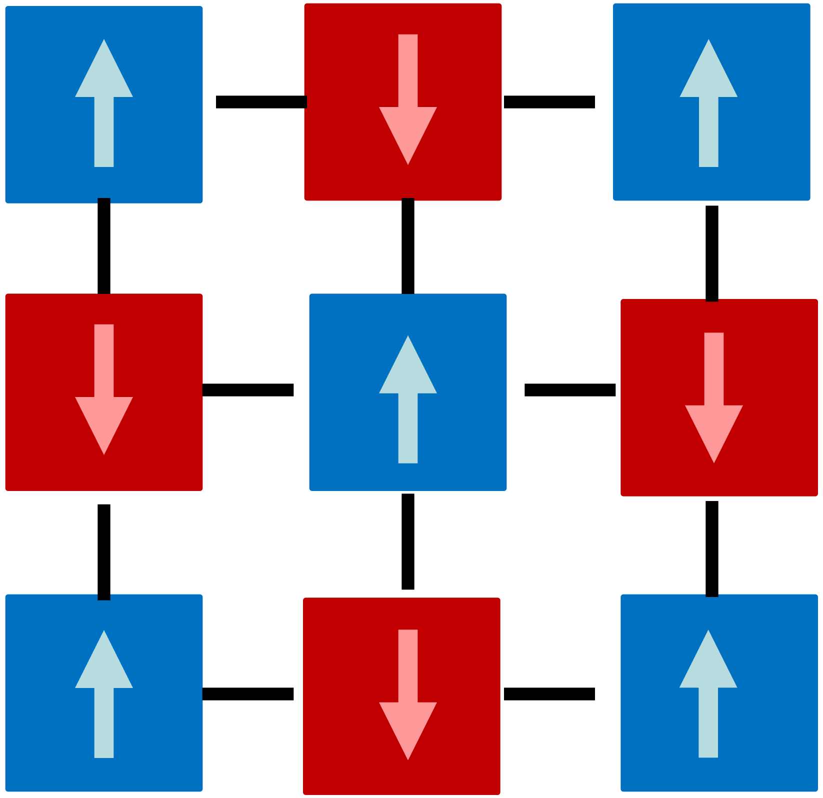
Spin liquids

Antiferromagnet

square lattice

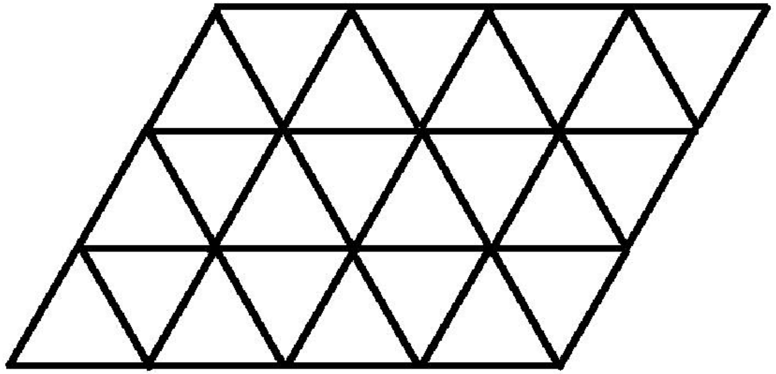
La_2CuO_4

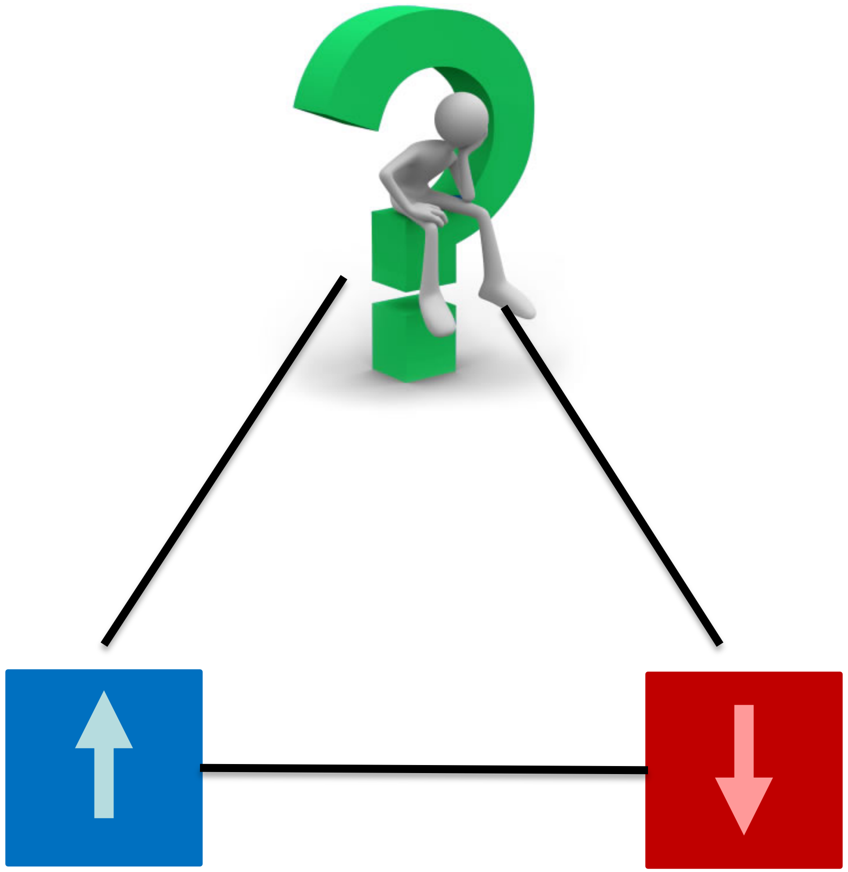




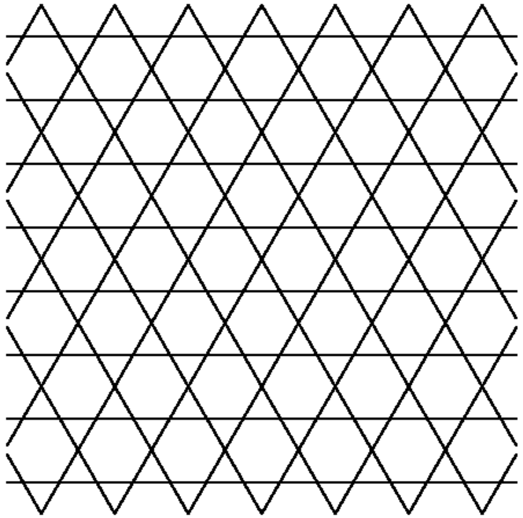
Geometric Frustration

triangular lattice





Kagome lattice



Spin liquid

P.W. Anderson
Mat.Res.Bull 8, 153 (1973)

Nobel Prize 1977

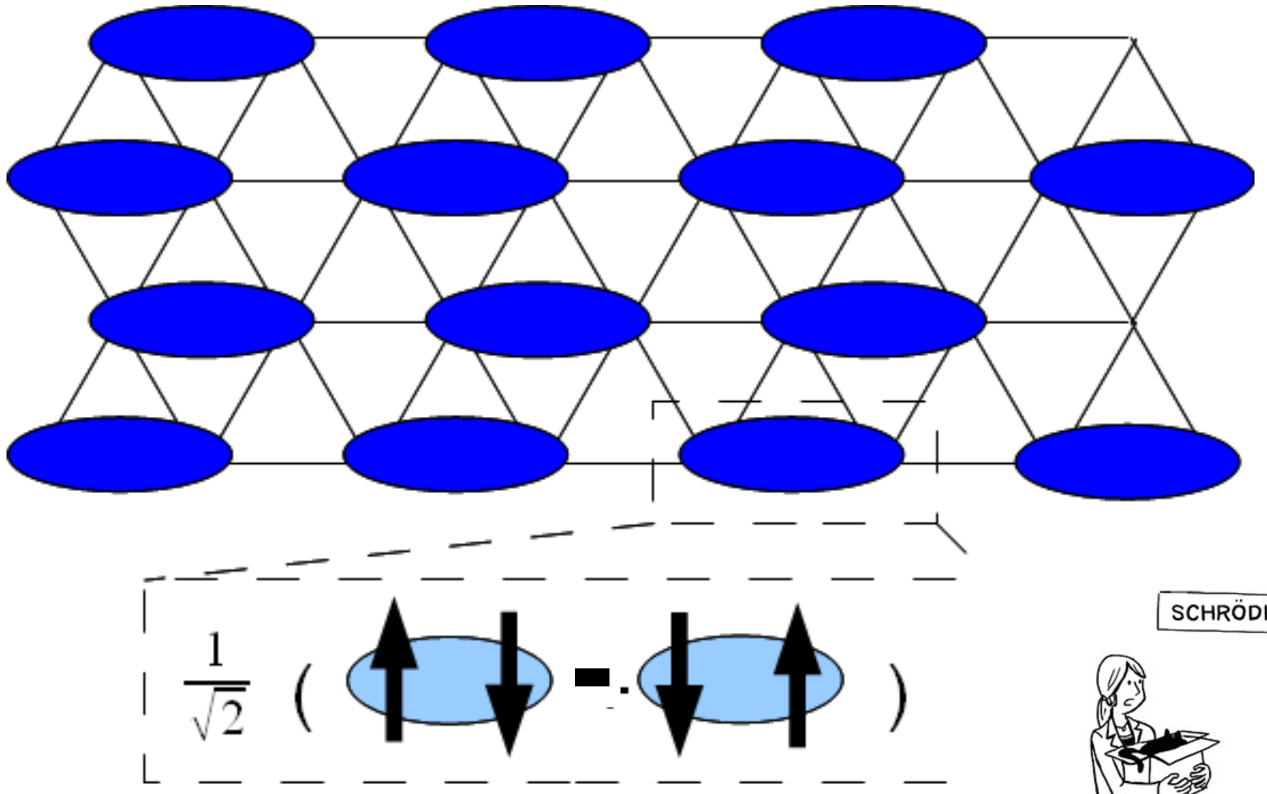
- Importance of **quantum effects** to induce new types of states (*Spin liquid, resonating valence bond state*, …)

T. Imai, Y. Lee Physics Today 69 (2016)

L. Balents, Nature 464, 199 (2010)

Spin liquid

triangular lattice

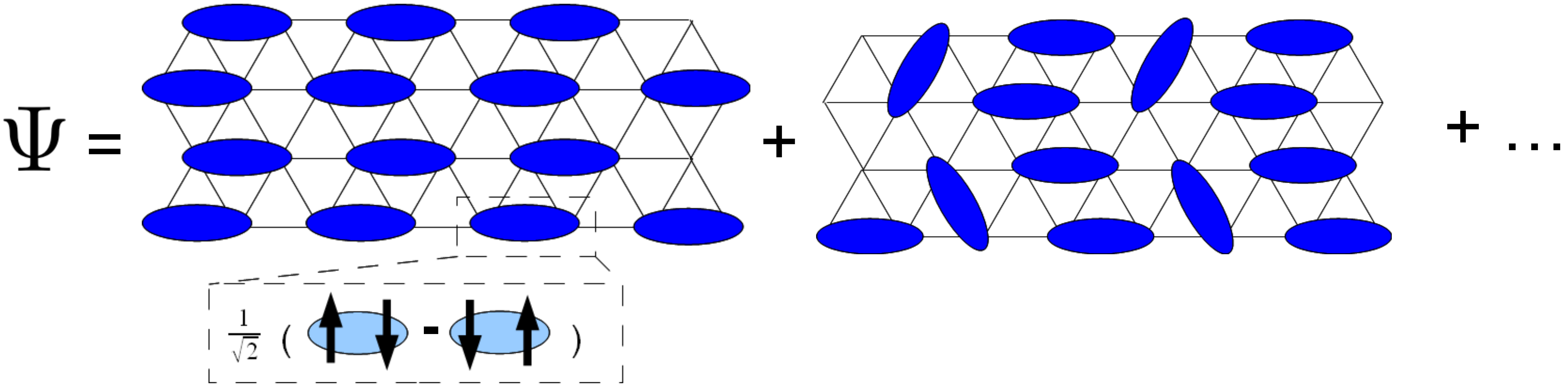


„valence bonds“

"I have good news and bad news"

Spin liquid

triangular lattice

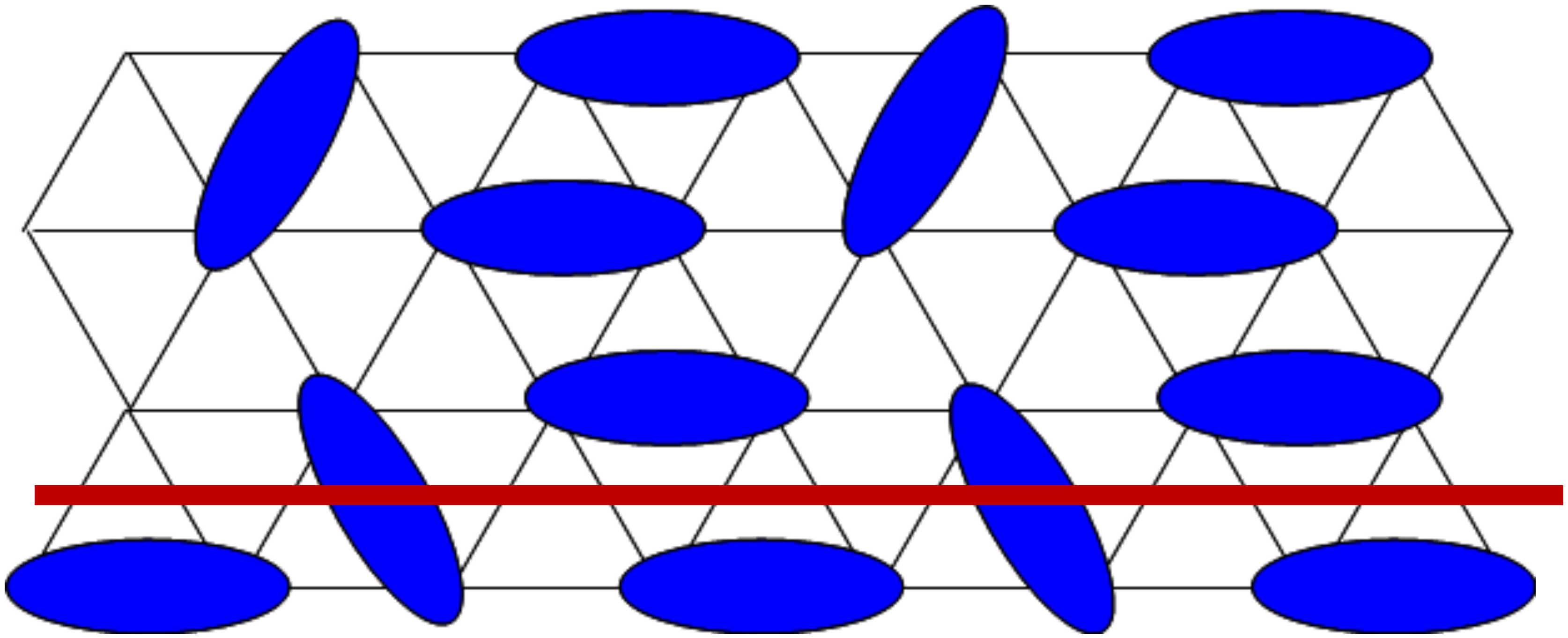


„resonating valence bonds“

„linear superposition of quantum states“

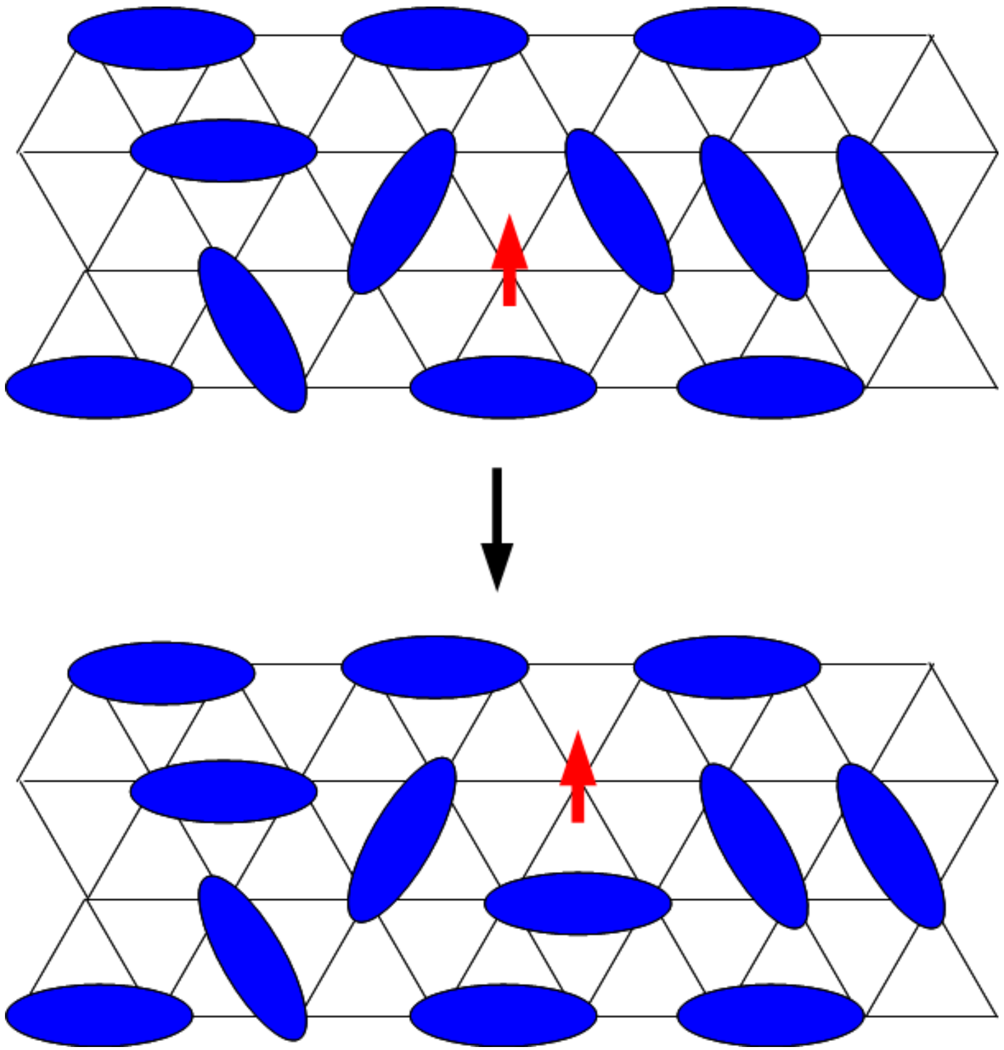
Spin liquid

Topological long range order



Topological invariant:
even or odd number of valence bonds crossing the red line

Emergence of exotic “quasi-particles”



spinon: particle with spin and no charge

Emergence of exotic “quasi-particles”

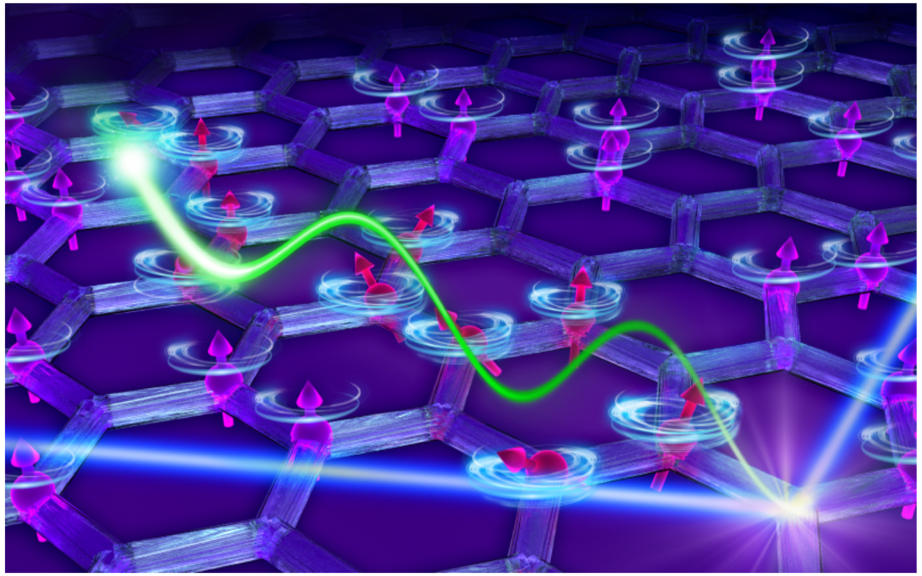
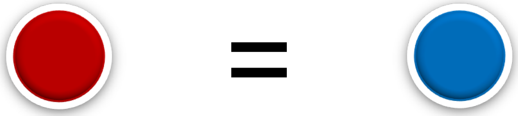


Image:ORNL/Jill Hemman

Majorana Fermions

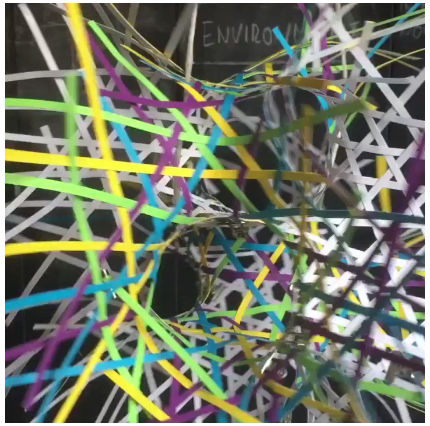
e- e+



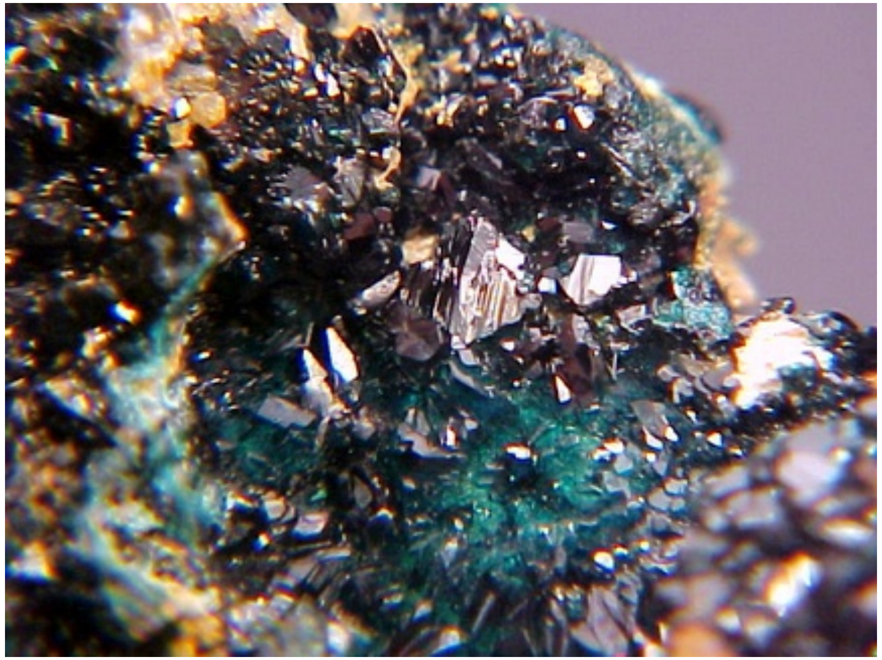
$$c_i^\dagger = c_i \quad , \quad c_i^2 = 1 \quad , \quad \{c_i, c_j\} = 0$$

Ettore Majorana

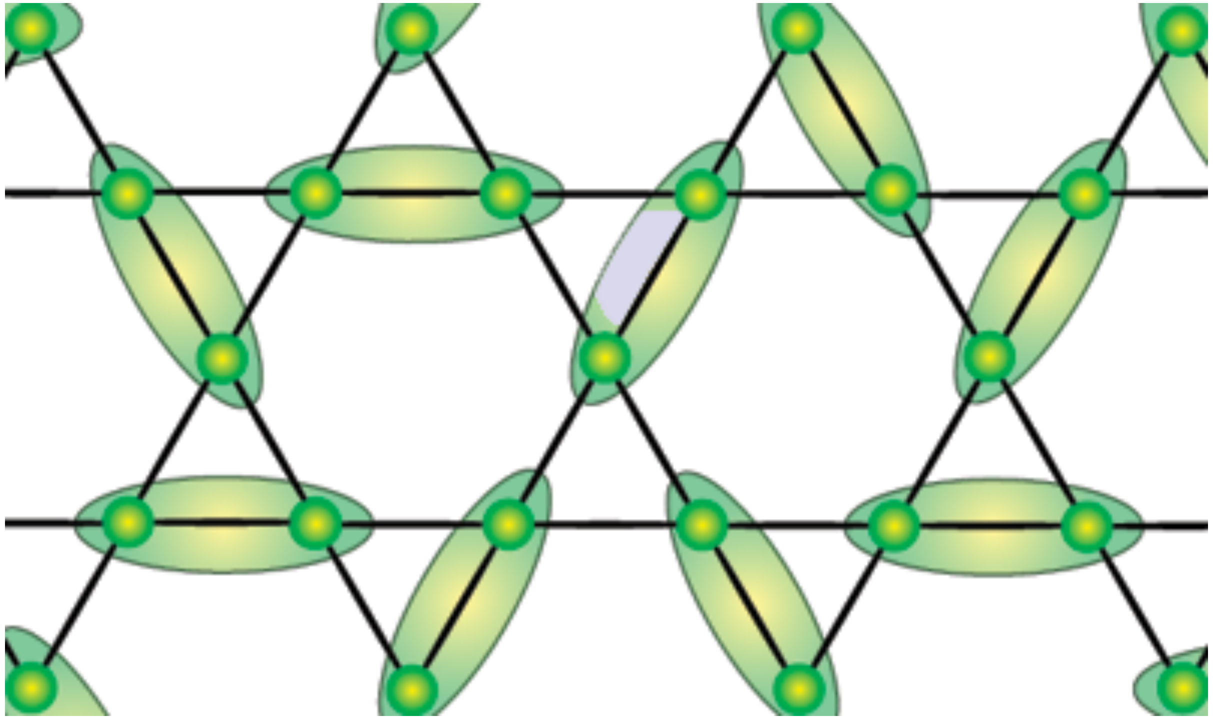
where to find these quantum states in nature?



Herbertsmithite $ZnCu_3(OH)_6Cl_2$



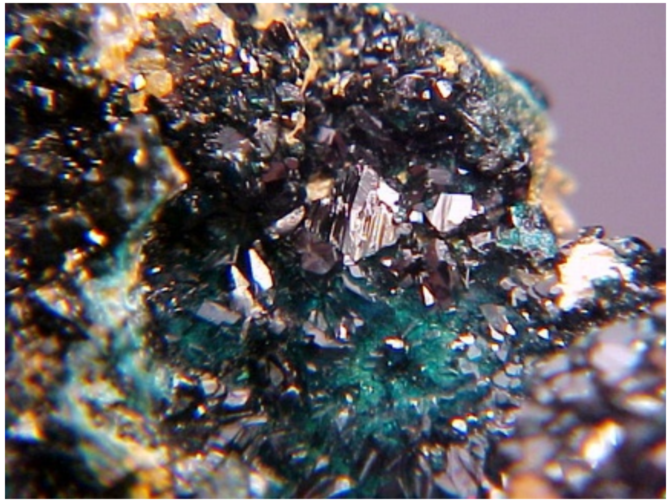
Kagome lattice



Picture: Lucile Clark

Spin liquid with spinon excitations

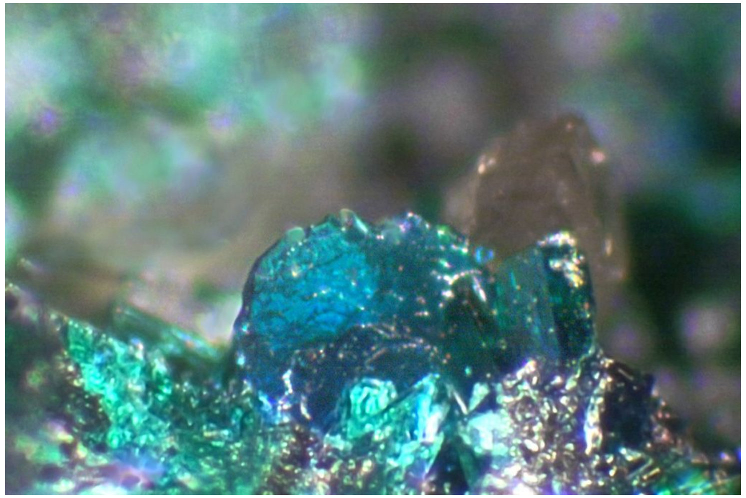
Quantum Materials



herbertsmithite

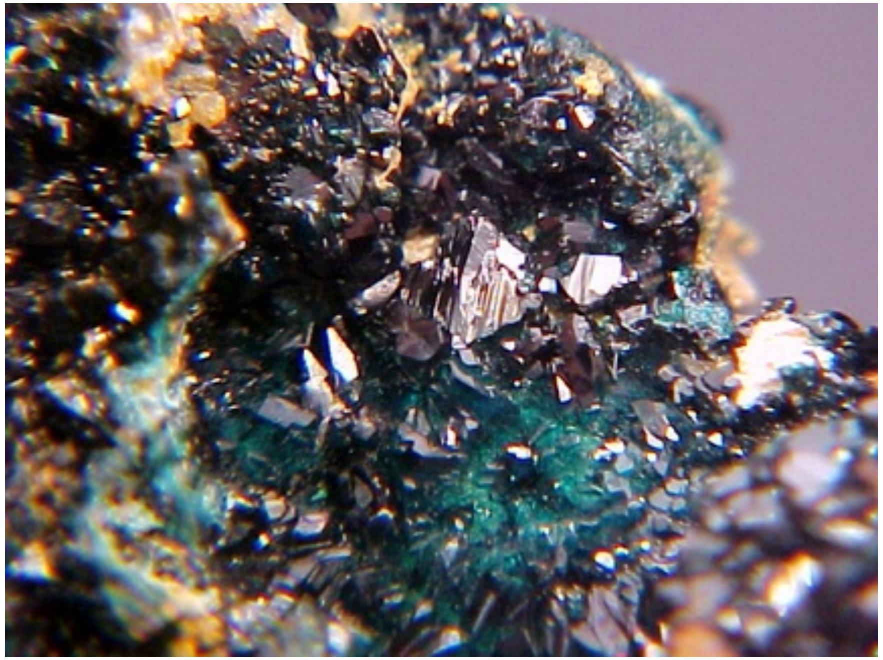
haydeeite

kapellasite



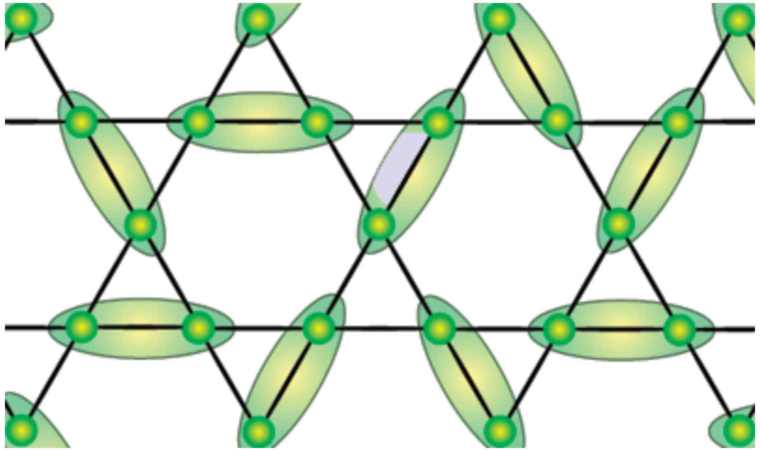
barlowite

Quantum Materials



challenge

?



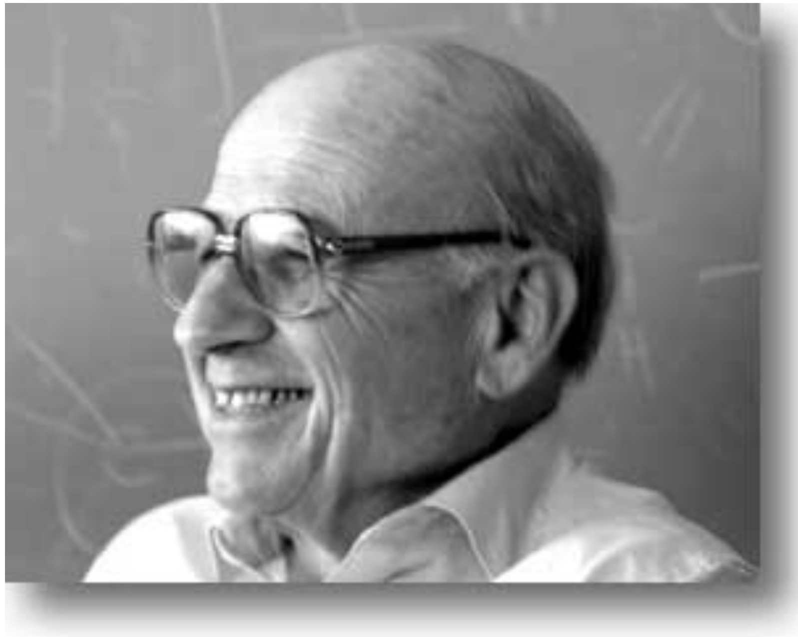
$$i\hbar \frac{\partial}{\partial t} \Psi(\mathbf{r}, t) = H \Psi(\mathbf{r}, t)$$

- 10^{23} coupled equations!!!

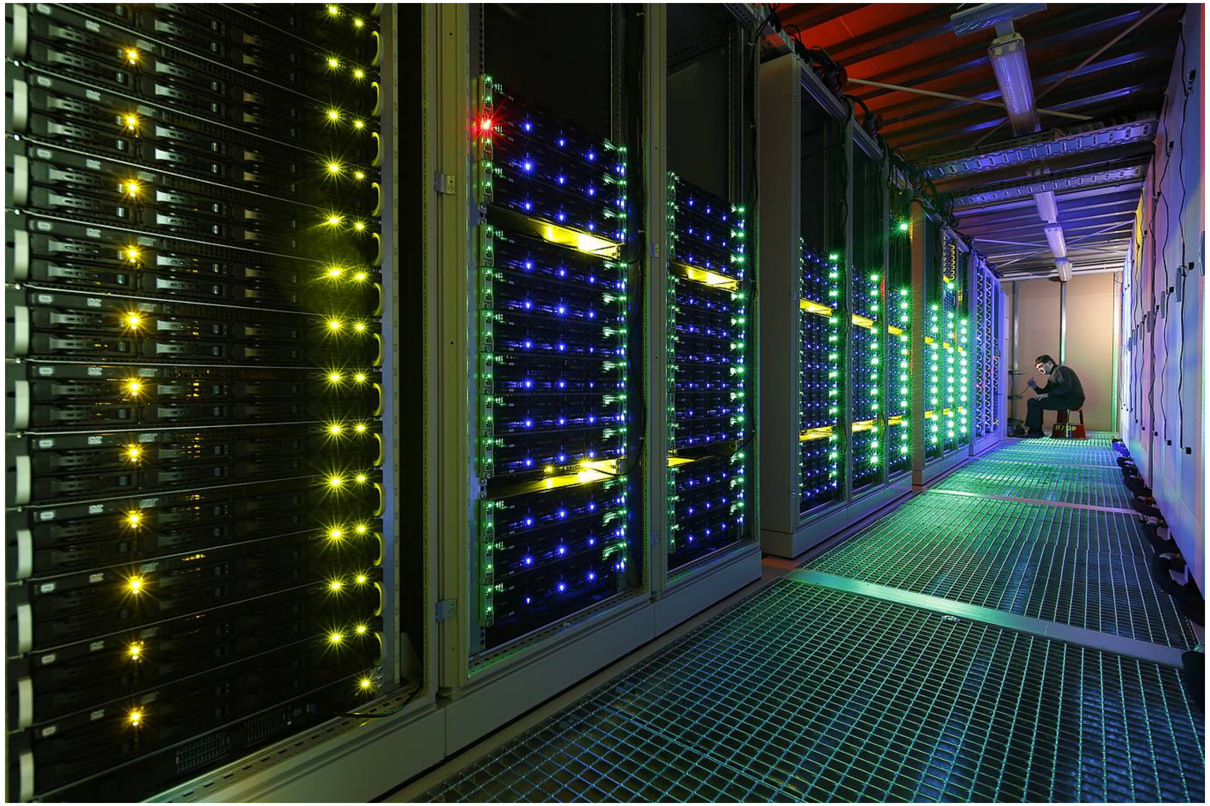
Density Functional Theory

Walter Kohn
(1923-2016)
Nobel Prize in 1998

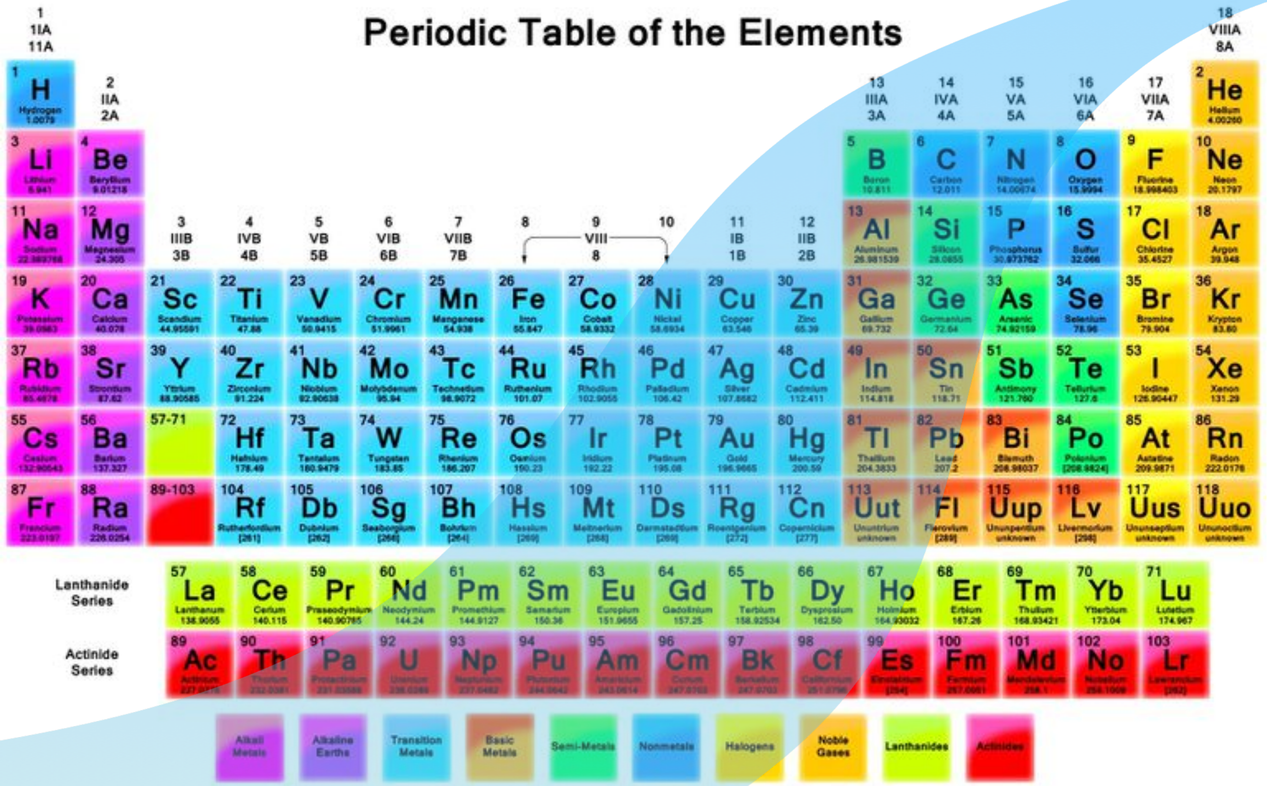
Founding Director of ITP (now KITP)



Solve numerically the Schrödinger equations for the constitutent interacting electrons



Computational simulations



Design new interacting materials with exotic properties

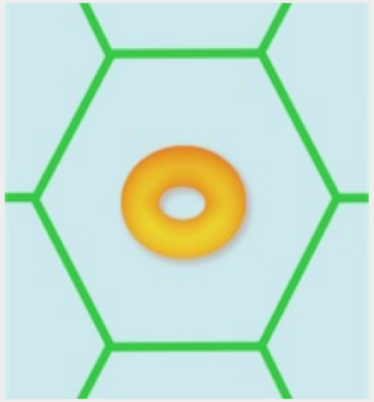
Topological Quantum Matter: Concepts and Realizations

Coordinators: Andriy Nevidomskyy, Nic Shannon, Ronny Thomale, and Roser Valenti

Scientific Advisors: Yukitoshi Motome, Natasha Perkins, Oleg Tchernyshyov

One of the recurring central themes in physics is the search for exotic phases of matter stemming from strong correlations between constituent particles. Among these, topological states have become a major research direction in the past decade, from quantum spin liquids, to topological insulators and superconductors, to examples in photonics and mechanical systems. Despite a plethora of promising visions towards application and implementation, a number of serious challenges remain. One of them is the lack of reliable models, with the exception of very few that lend themselves to an exact solution, to address the emergence and stability of topological phases in the presence of strong interactions. Another major challenge is the difficulty in elevating the description of topological phases from the zero-temperature ground state to finite temperatures, which is necessary to probe them experimentally, and ultimately render them accessible at technologically operable conditions.

To successfully address these problems, this program will bring together theorists, computational physicists, and a broad range of experimentalists. The goal is to stimulate the dialogue between practitioners of different approaches, to identify, as concretely as possible, the open problems in the field, and by bringing together experts from different communities, to help advance the research frontier.



DATES

Aug 26, 2019 - Nov 22, 2019

INFORMATION

Apply

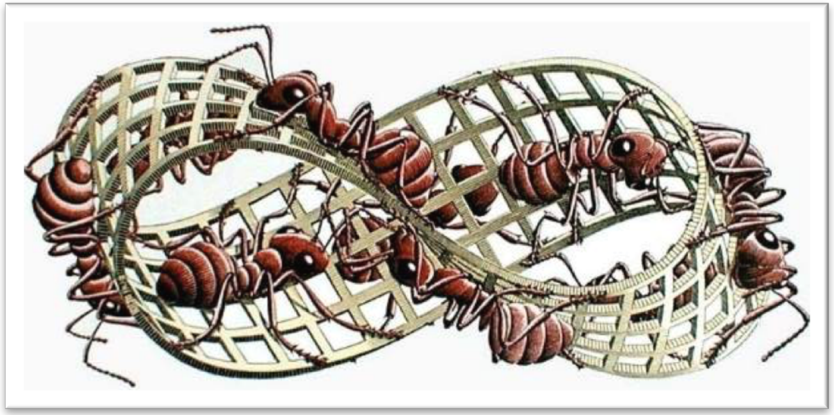
Application deadline has passed:

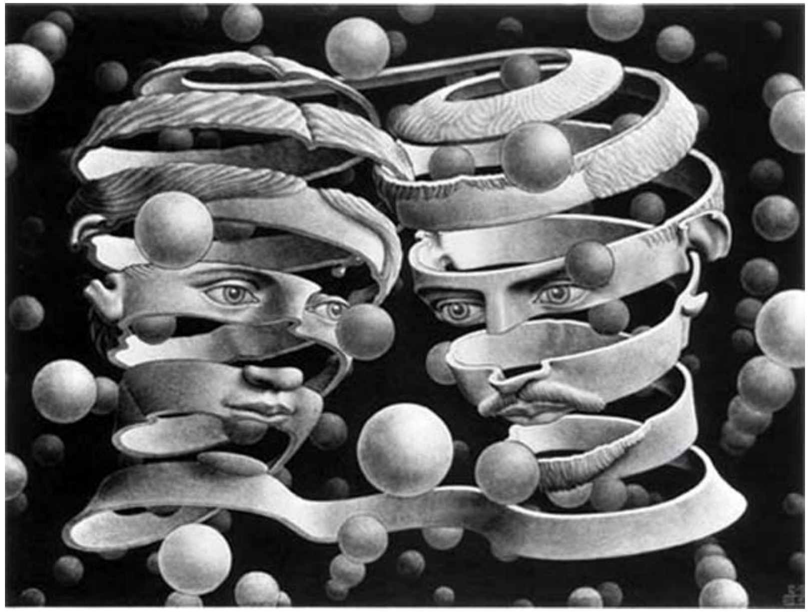
Sep 9, 2018

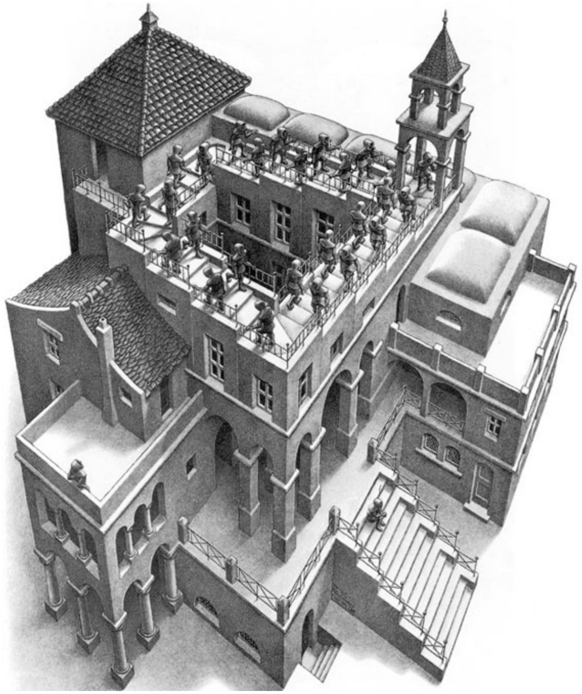
Primary deadline above date.

Rolling admissions after

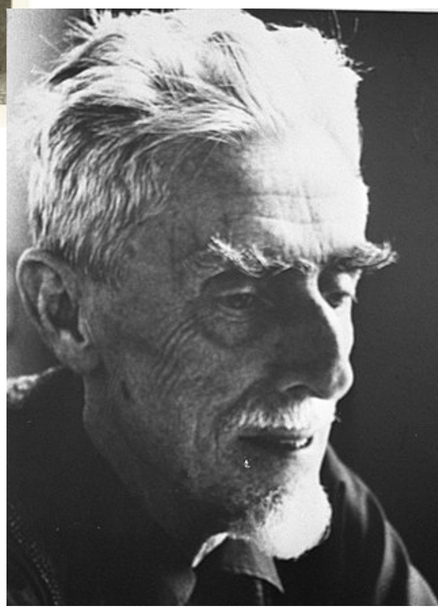
Topology, Physics and Art







Maurits Cornelius
Escher (1989-1872)



THANK YOU!

Emergence of exotic “quasi-particles”

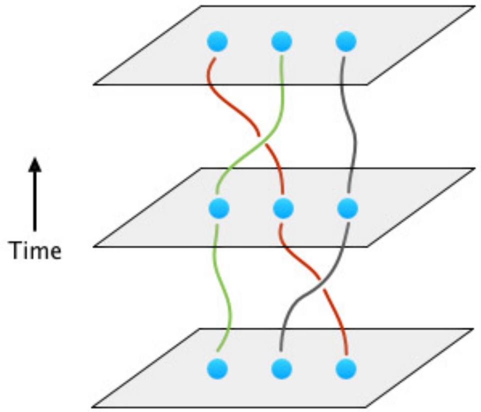
Anyons

(Alexei Kitaev)

Topological quantum computers

Braiding anyons

Qubit: 2 anyons



Operations protected by topology