Dresden University of Technology

DRESDEN concept

Emergent phenomena in quantum materials

Lukas Janssen

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Quantum SAX-QT

ct.qmat Complexity and Topology in Quantum Matter

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How to realize coherent quantum waves?

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Outline

(1) Introduction: Emergence

(2) Quantum materials

(3) Emergent phenomena for Quantum Saxony

(4) Summary

Outline

(1) Introduction: Emergence

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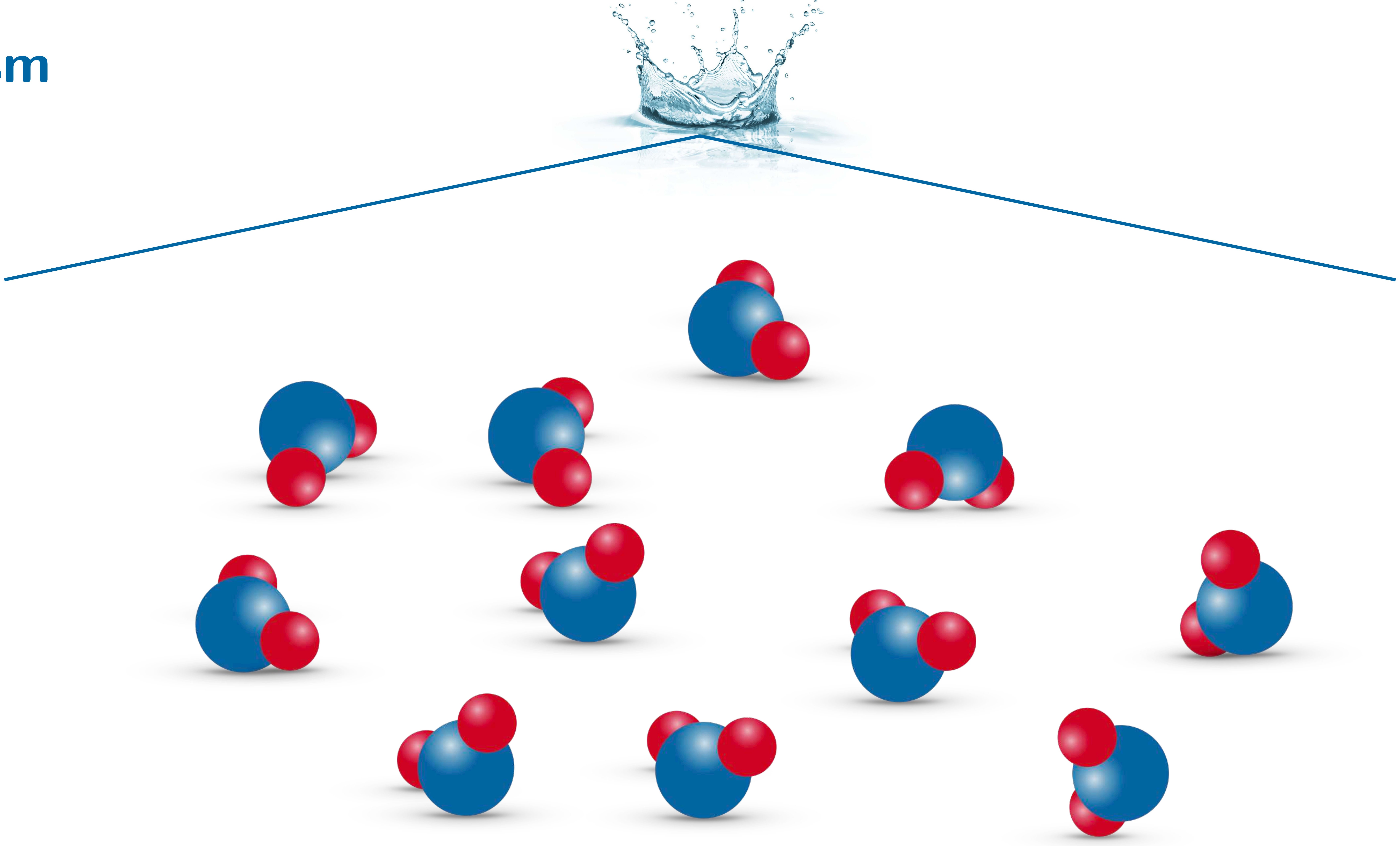
Reductionism

pinimg.com

Matter

Reductionism

Matter



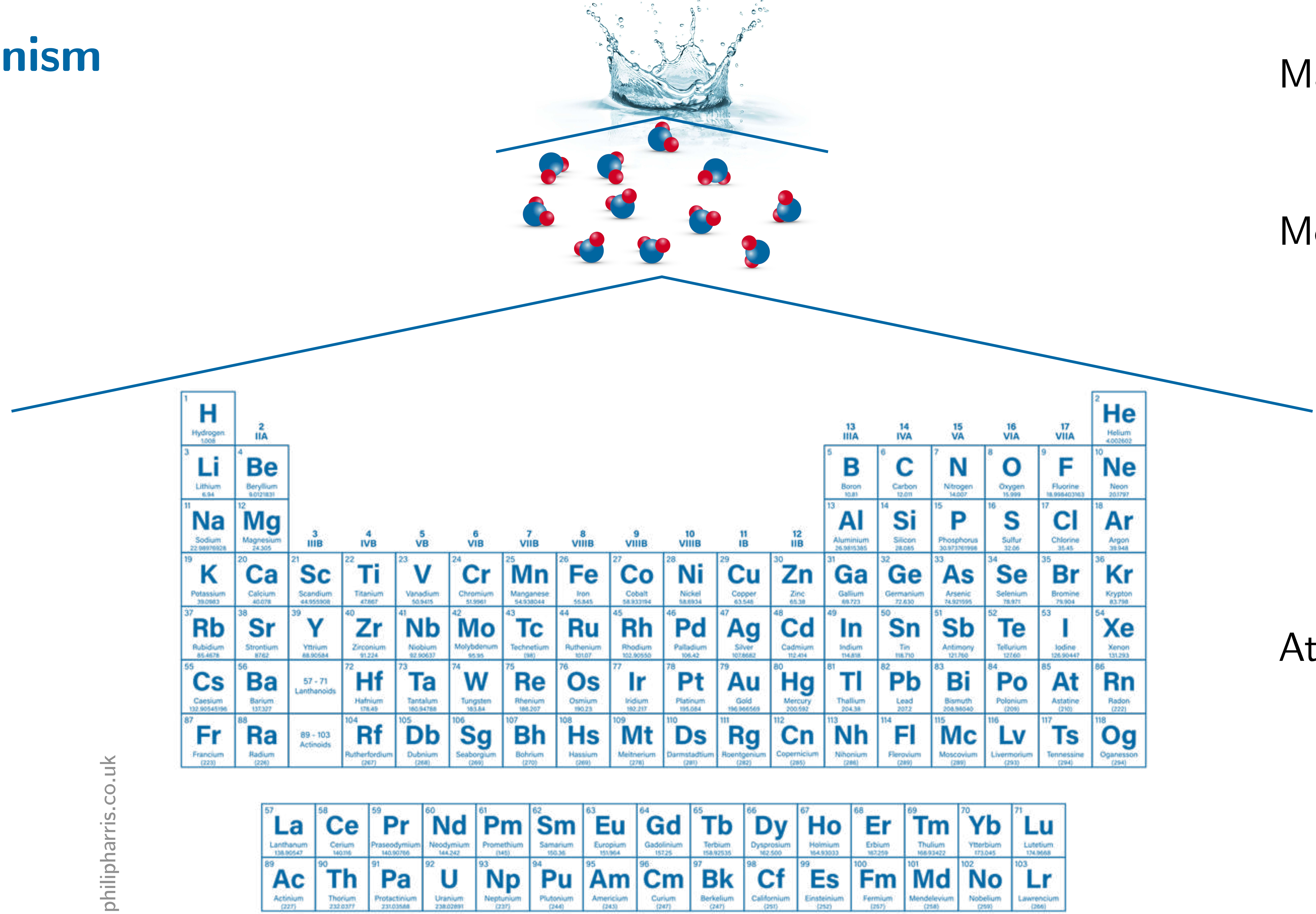
Molecules

Reductionism

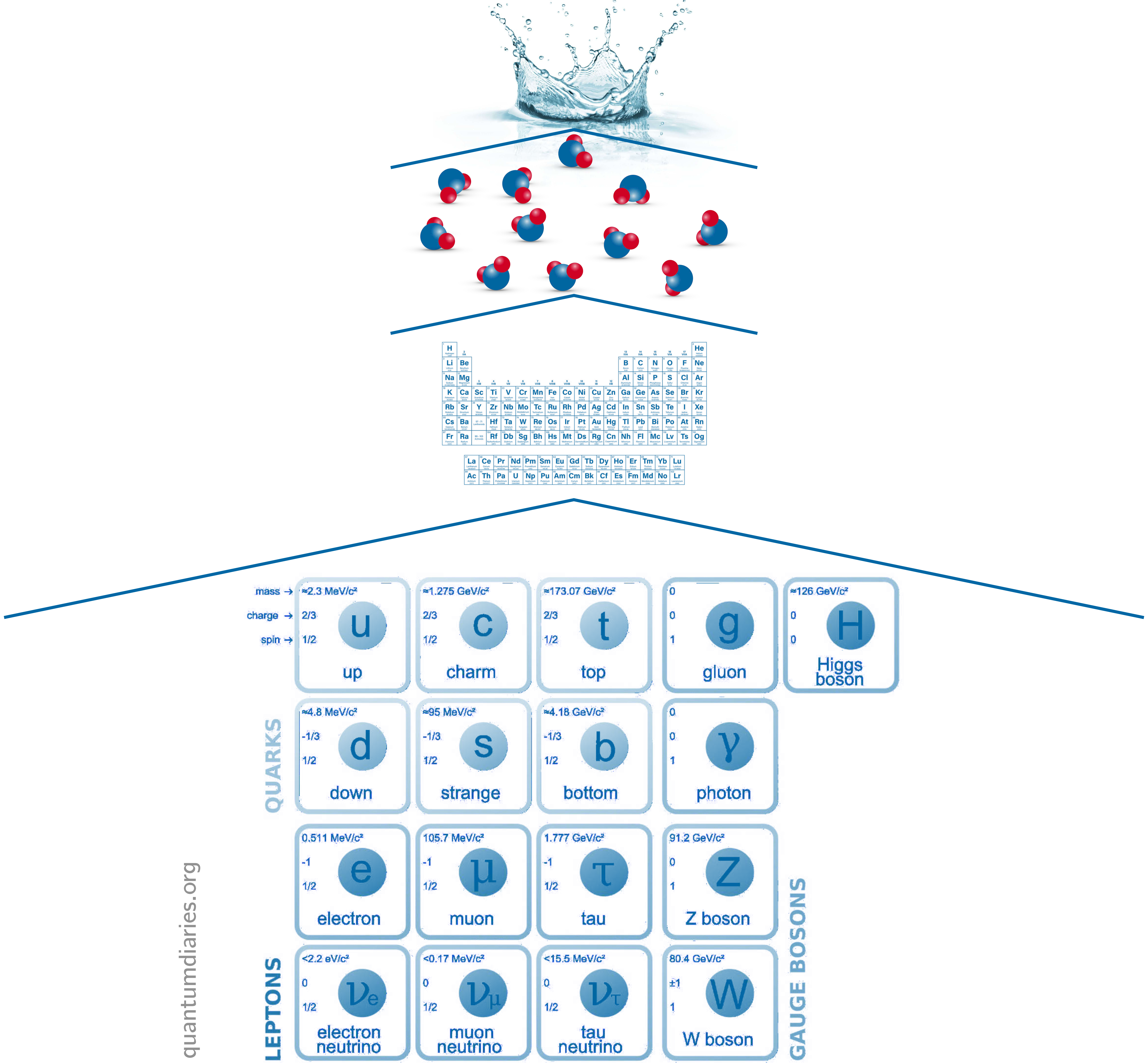
Matter

Molecules

Atoms



Reductionism



Matter

Molecules

Atoms

Elementary particles


FIELDS ARRANGED BY PURITY
MORE PURE
. . .
SOCIOLOGY IS JUST APPLIED PSYCHOLOGY
PSYCHOLOGY IS JUST APPLIED BIOLOGY
BIOLOGY IS JUST APPLIED CHEMISTRY
WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.
OH, HEY, I DIDN'T SEE YOU GUYS ALL THE WAY OVER THERE.
SOCIOLOGISTS
PSYCHOLOGISTS
BIOLOGISTS
CHEMISTS
PHYSICISTS
MATHEMATICIANS
imgur.com

Complexity

Emergence

The whole is greater than the sum of its parts!

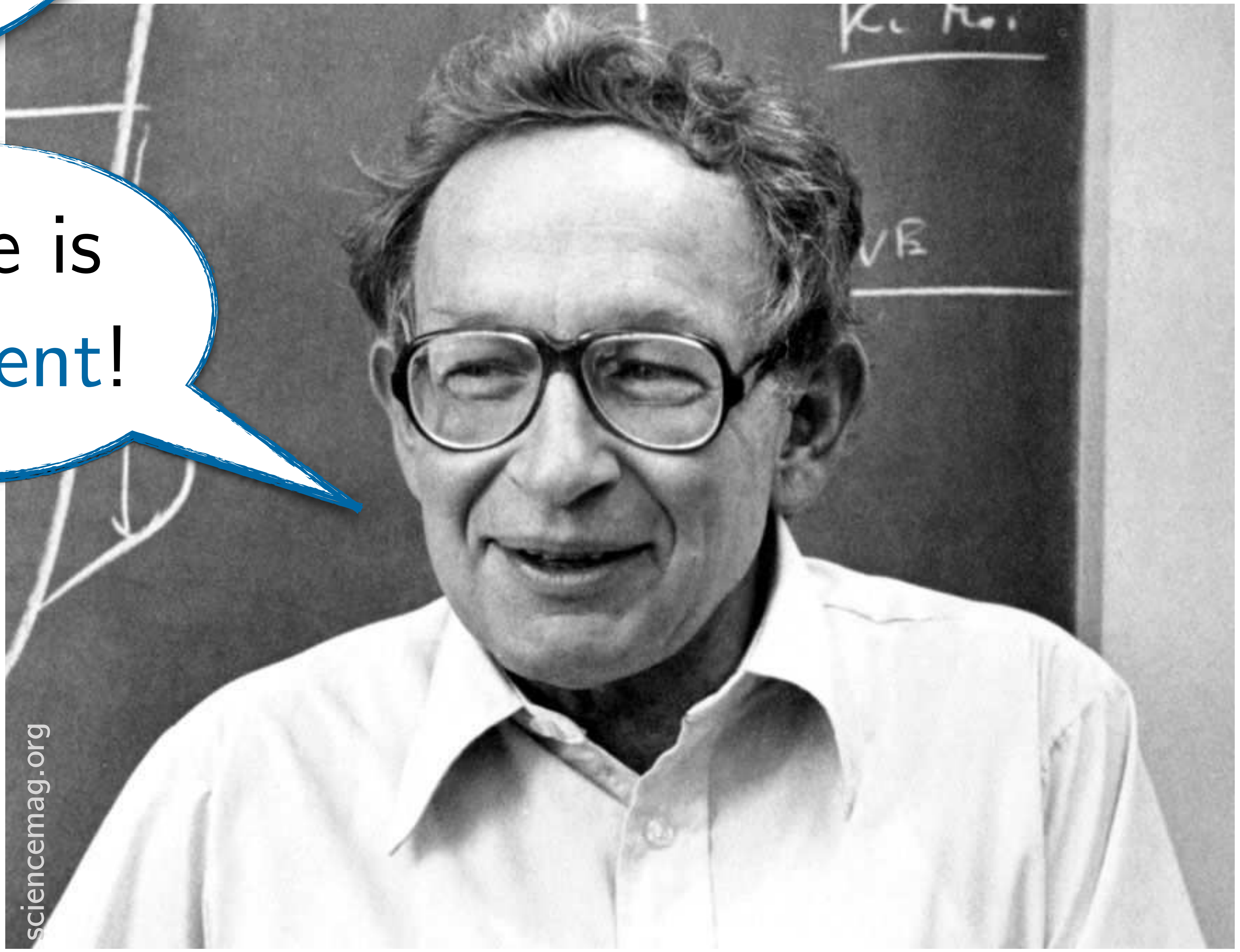
Aristotle, 385-322 BC

Emergence

The whole is greater than the sum of its parts!

More is different!

Aristotle, 385-322 BC



Anderson, 1923-2020 AD

[Anderson, Science '72]

Living bridges

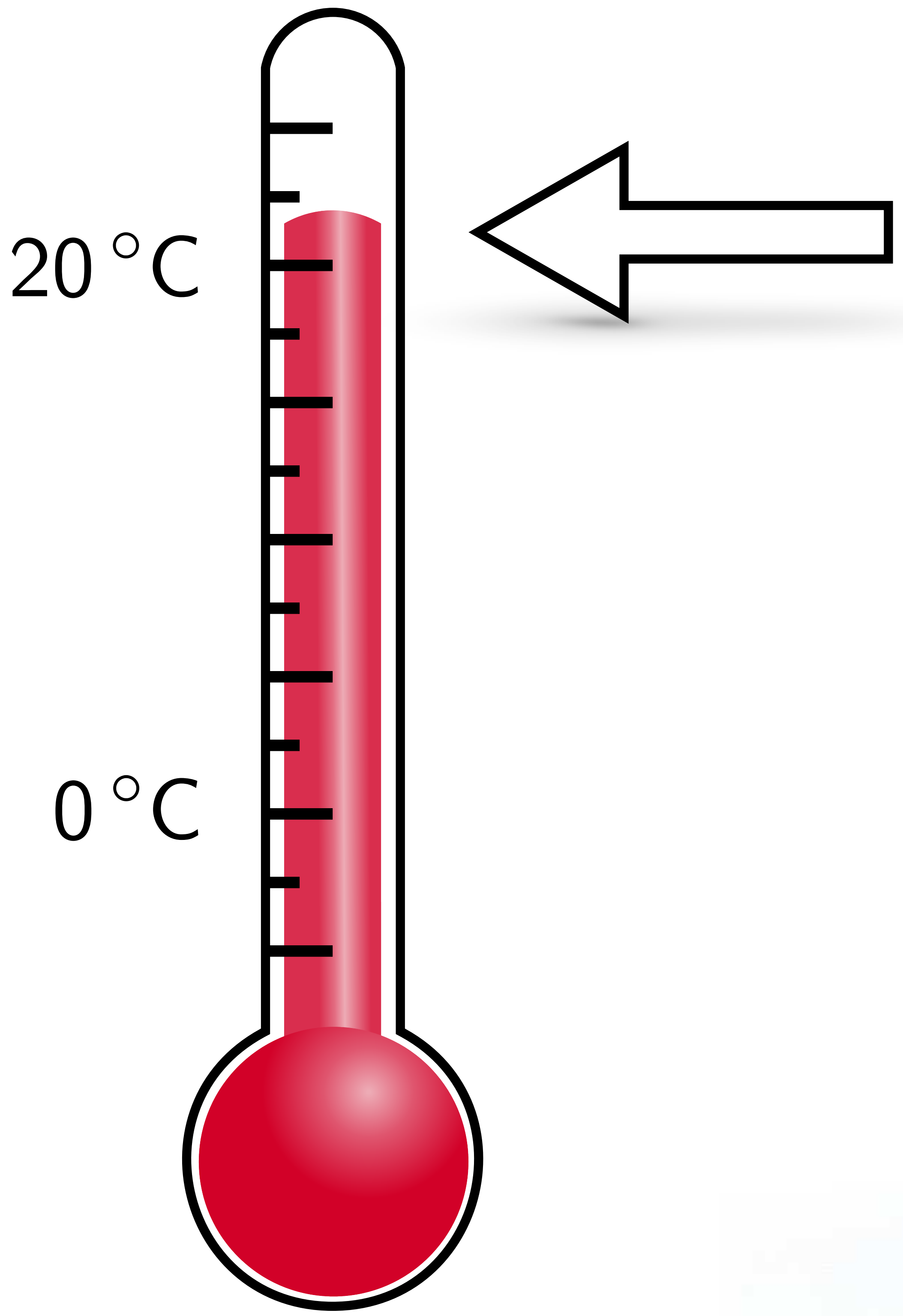
[Reid *et al.*, PNAS '15]

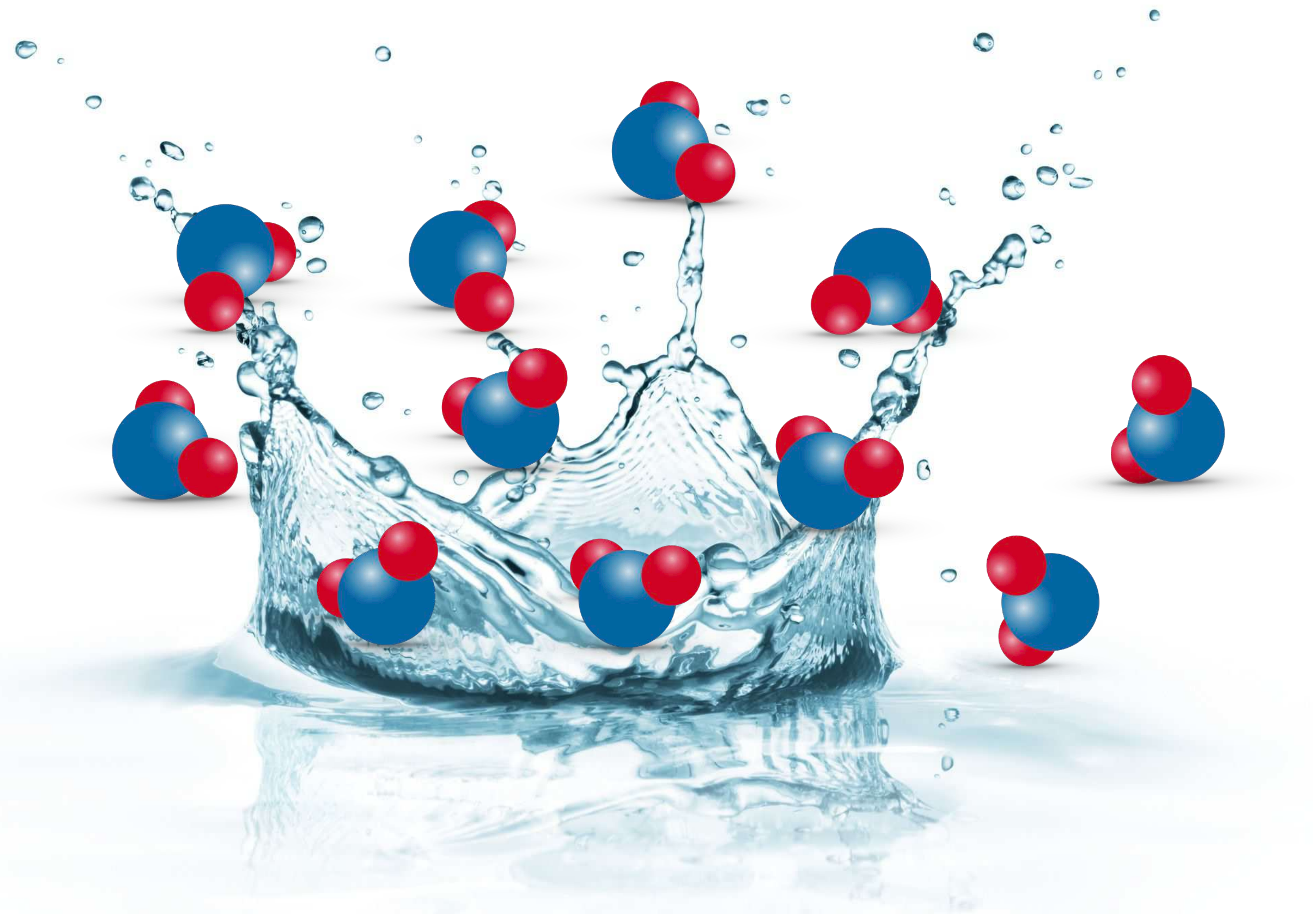
Living bridges

quantamagazine.org

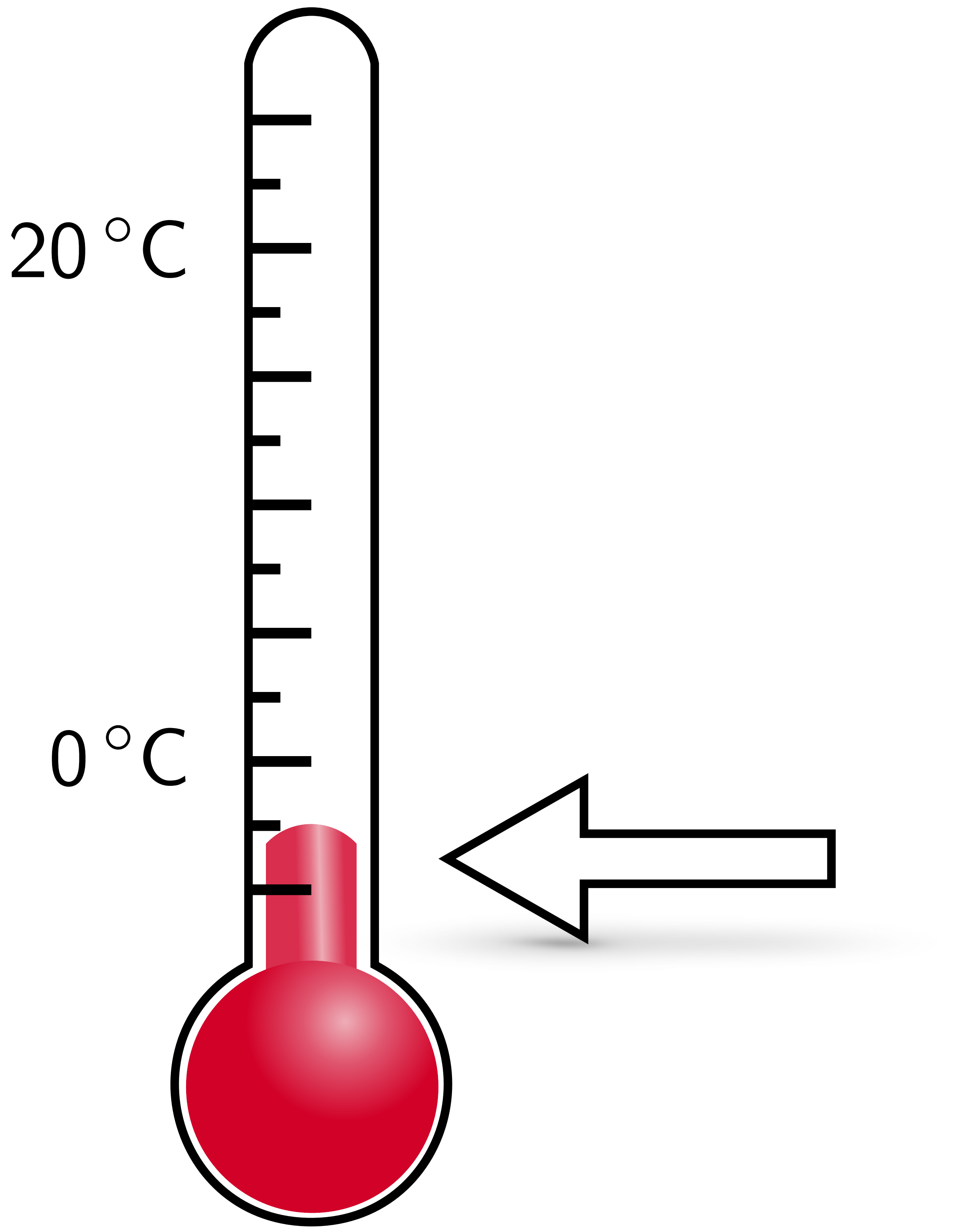
[Reid *et al.*, PNAS '15]

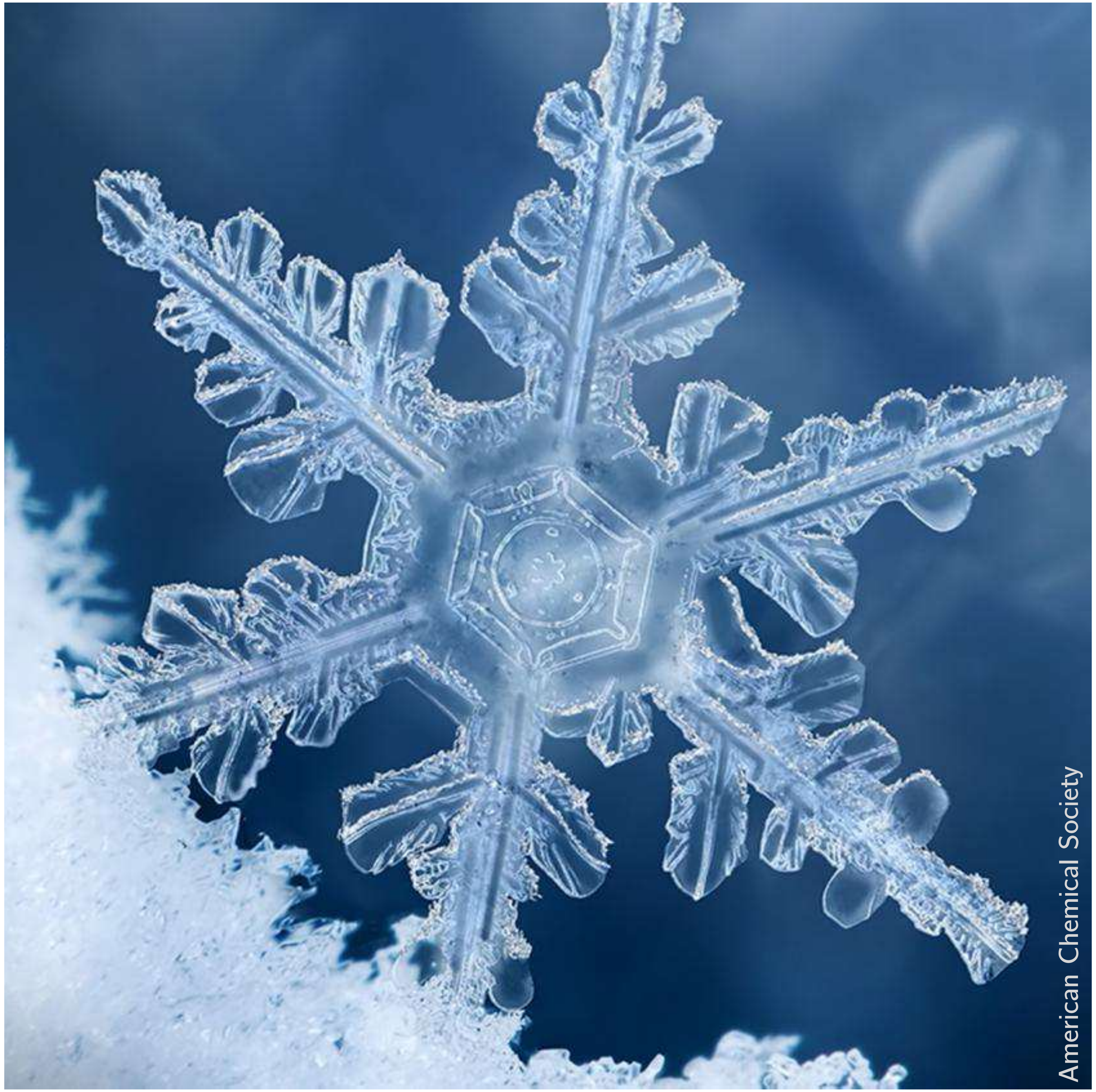
Snowflakes



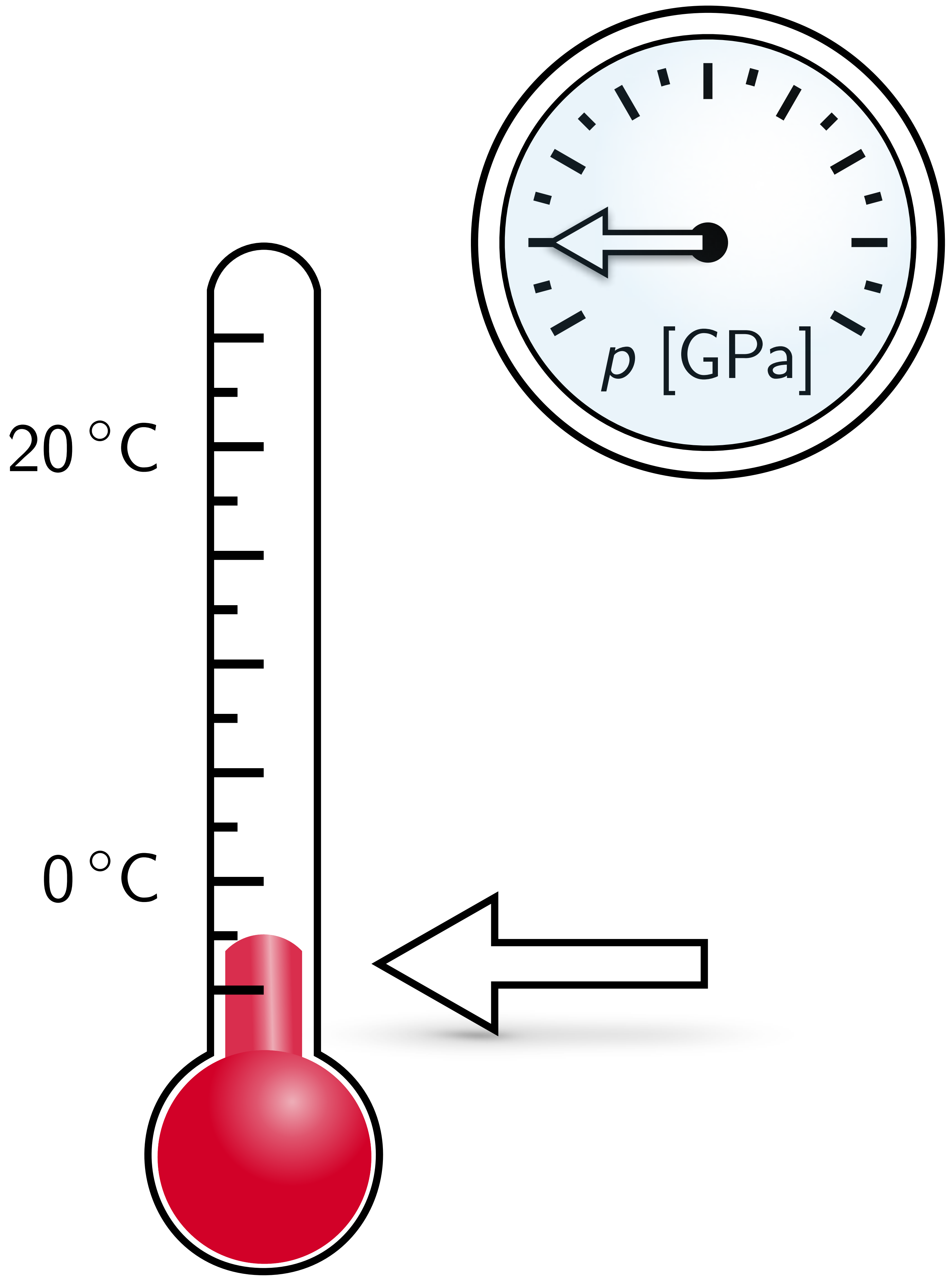


Snowflakes

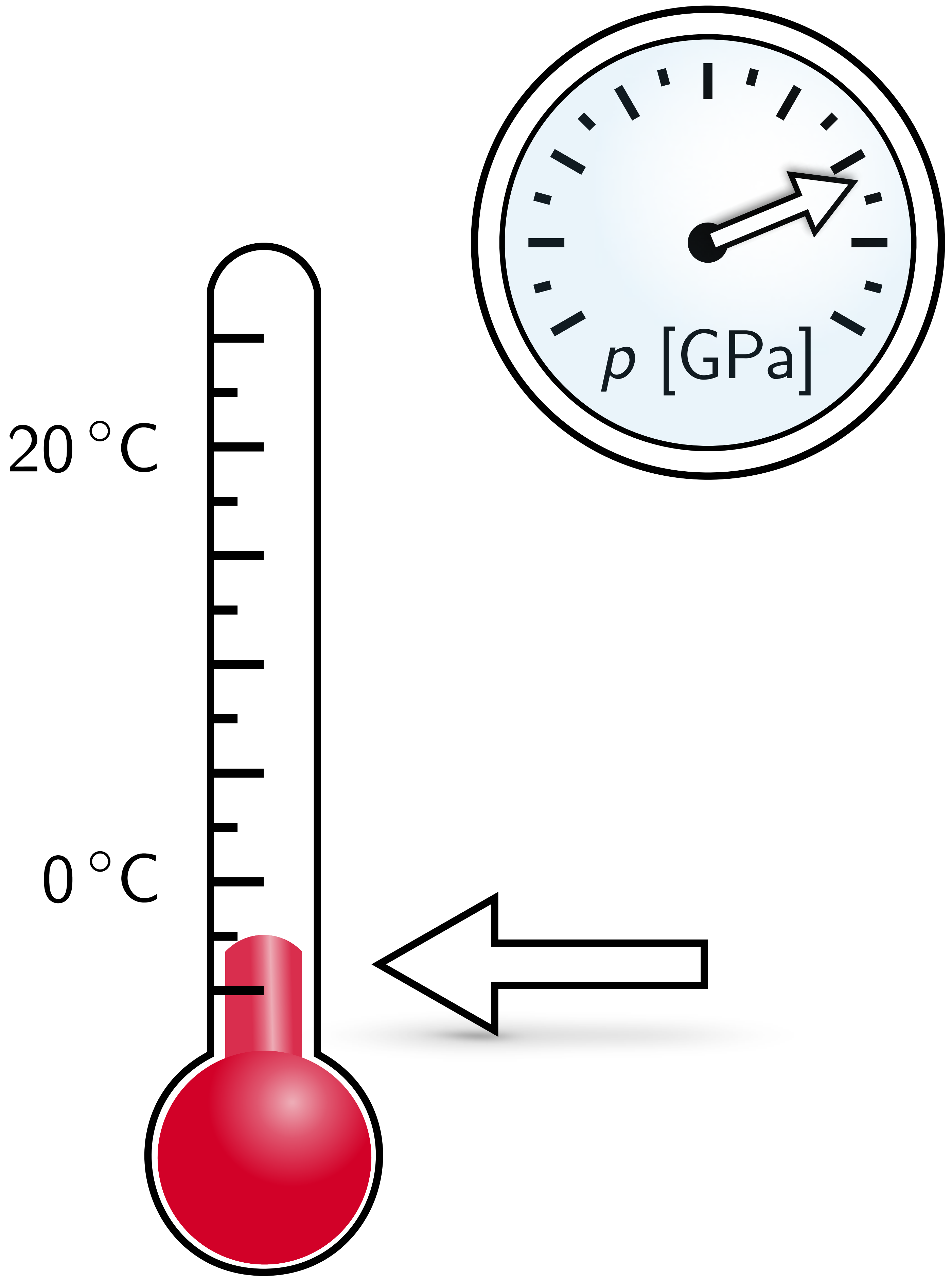


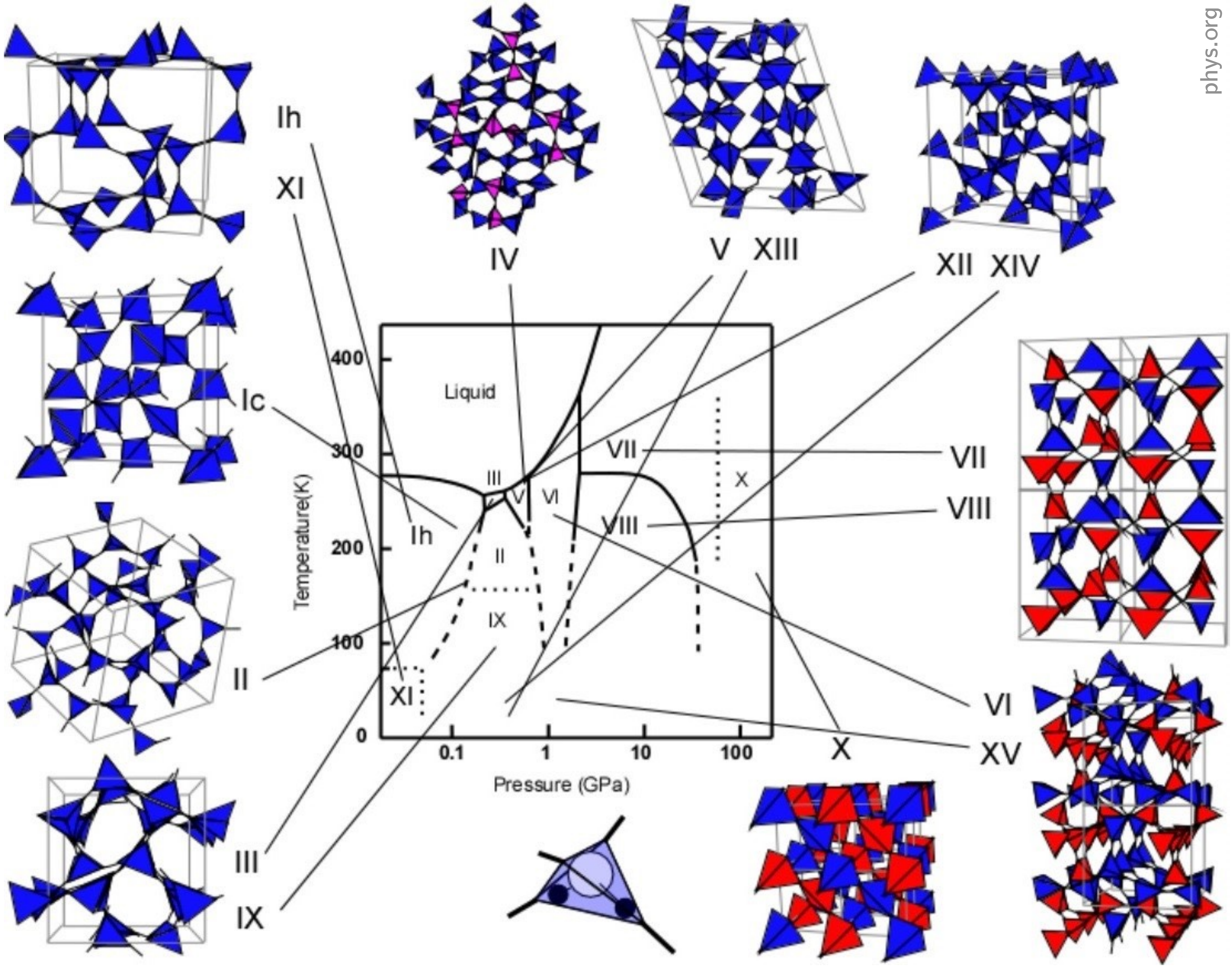


Phases of ice



Phases of ice

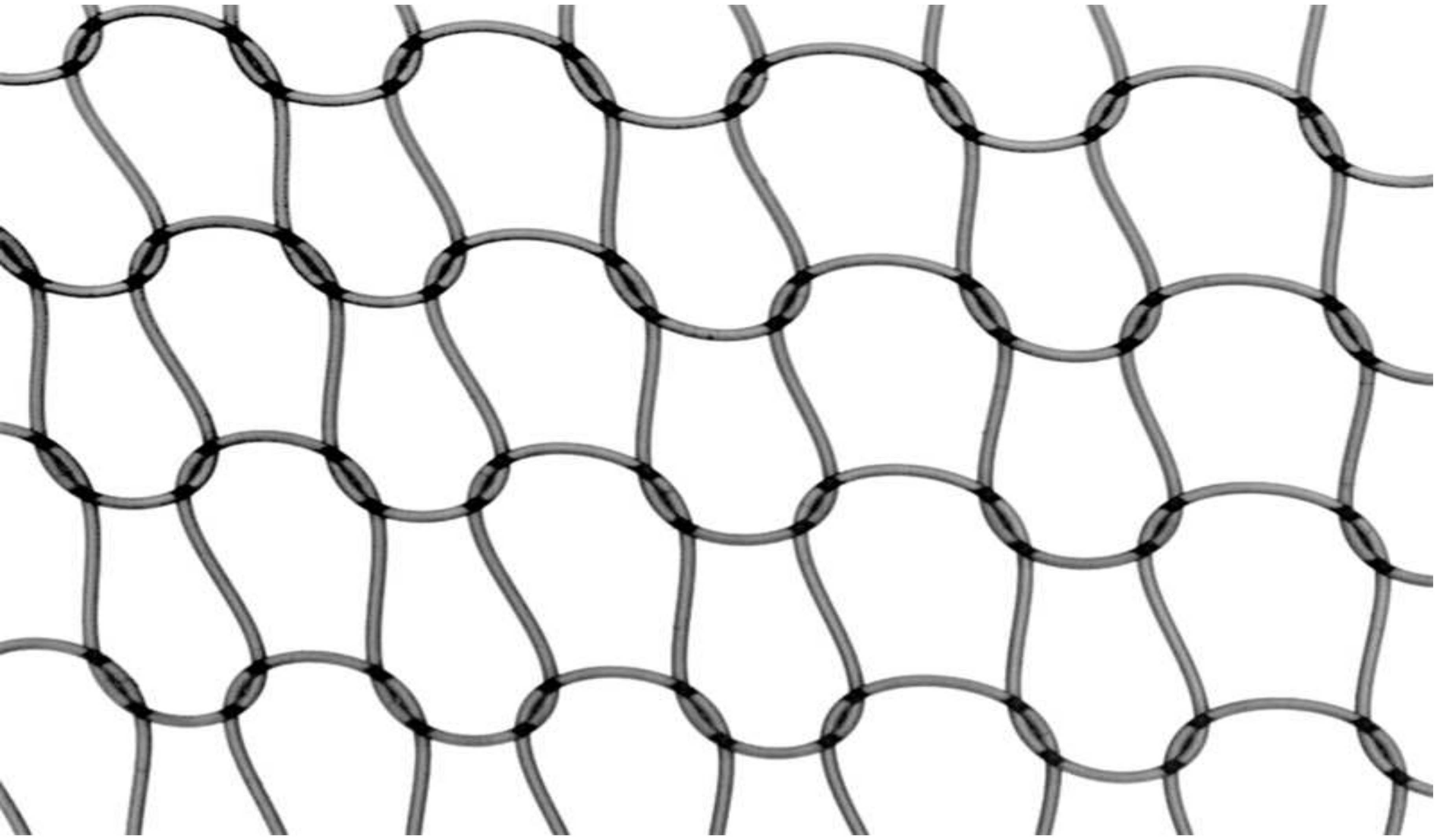




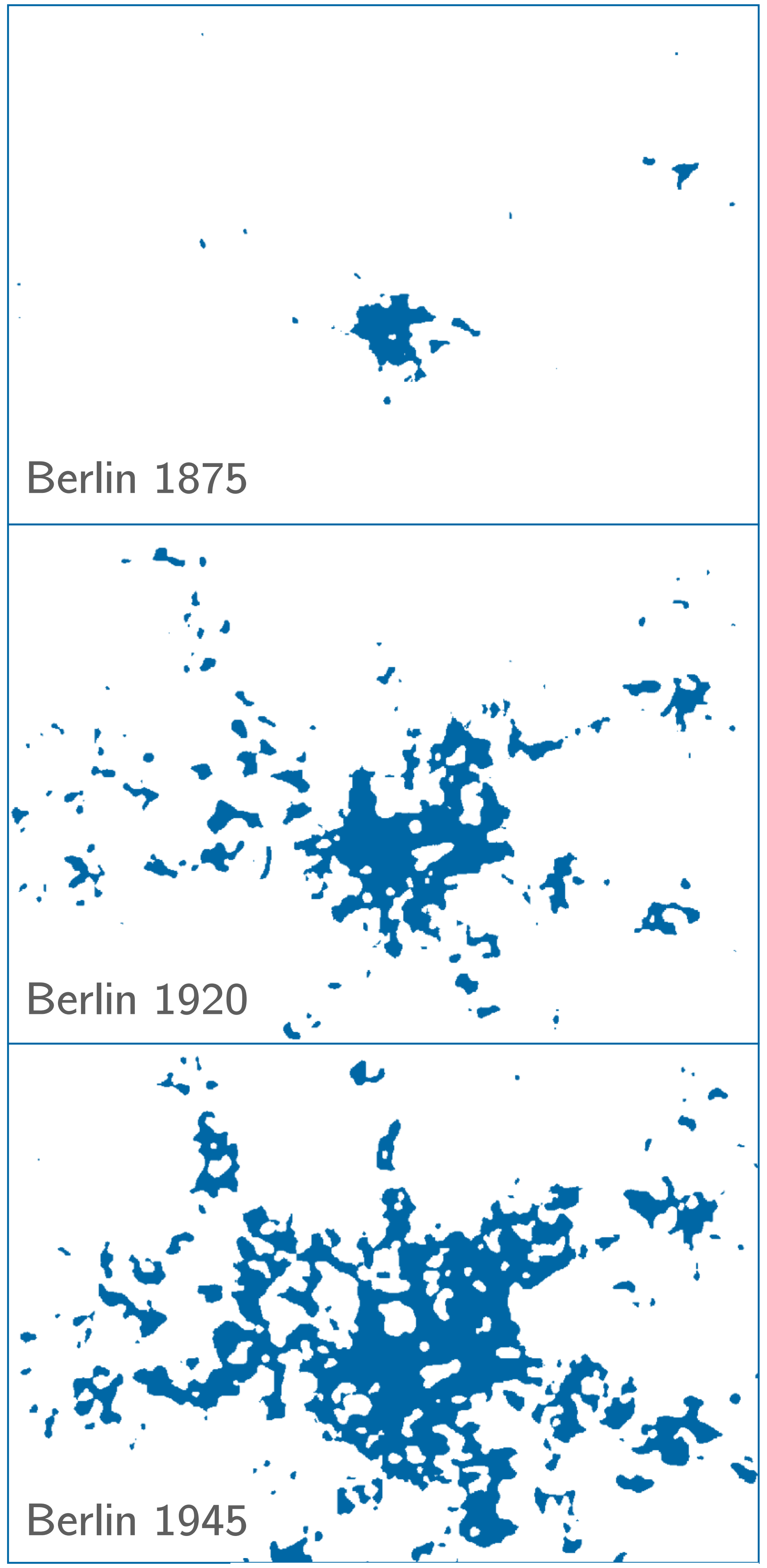
[Del Rosso *et al.*, Nat. Mat. '20]

Emergent phenomena

[Portugal *et al.*, Nature '14]



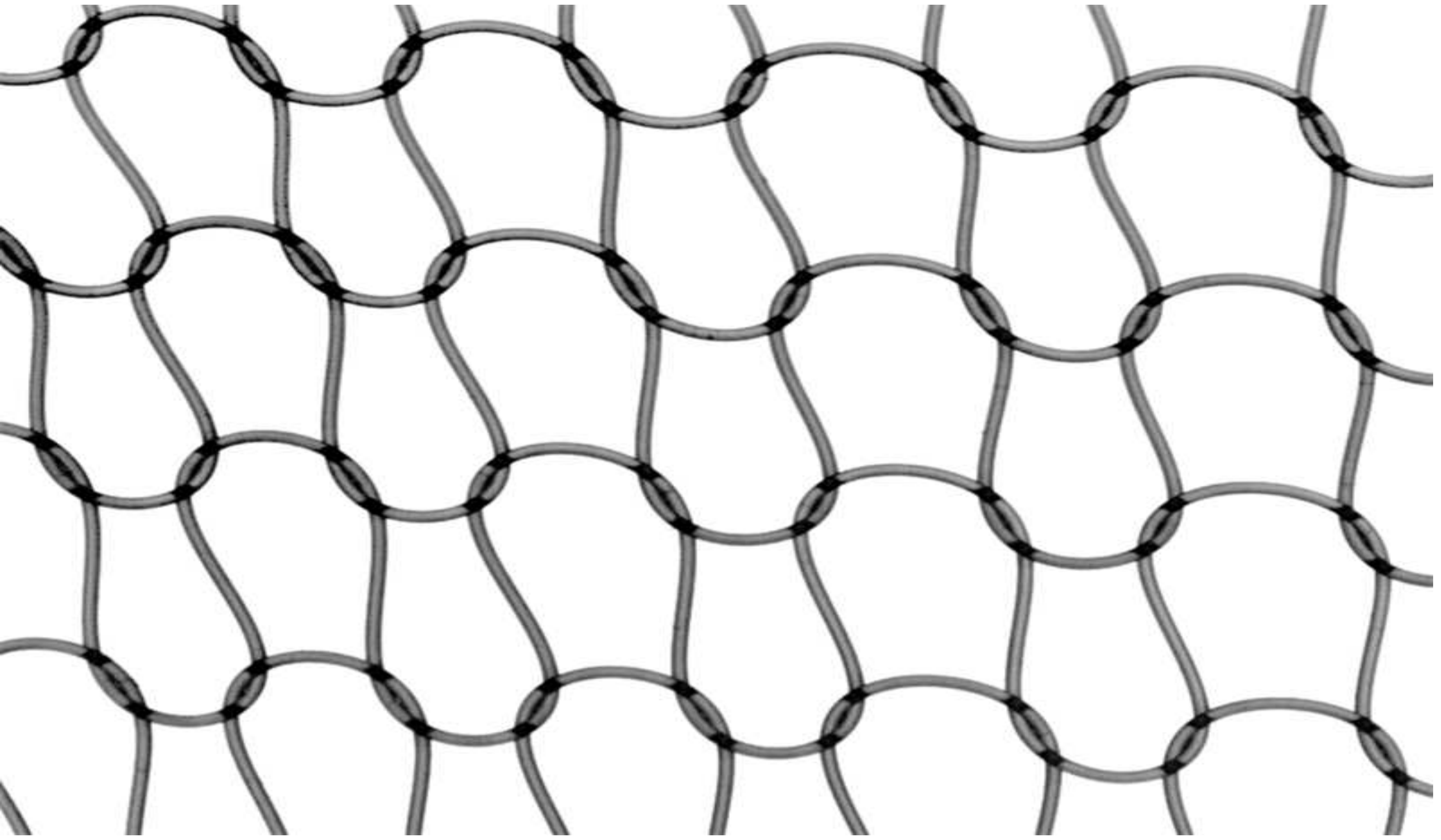
[Poincloux *et al.*, PRX '18]



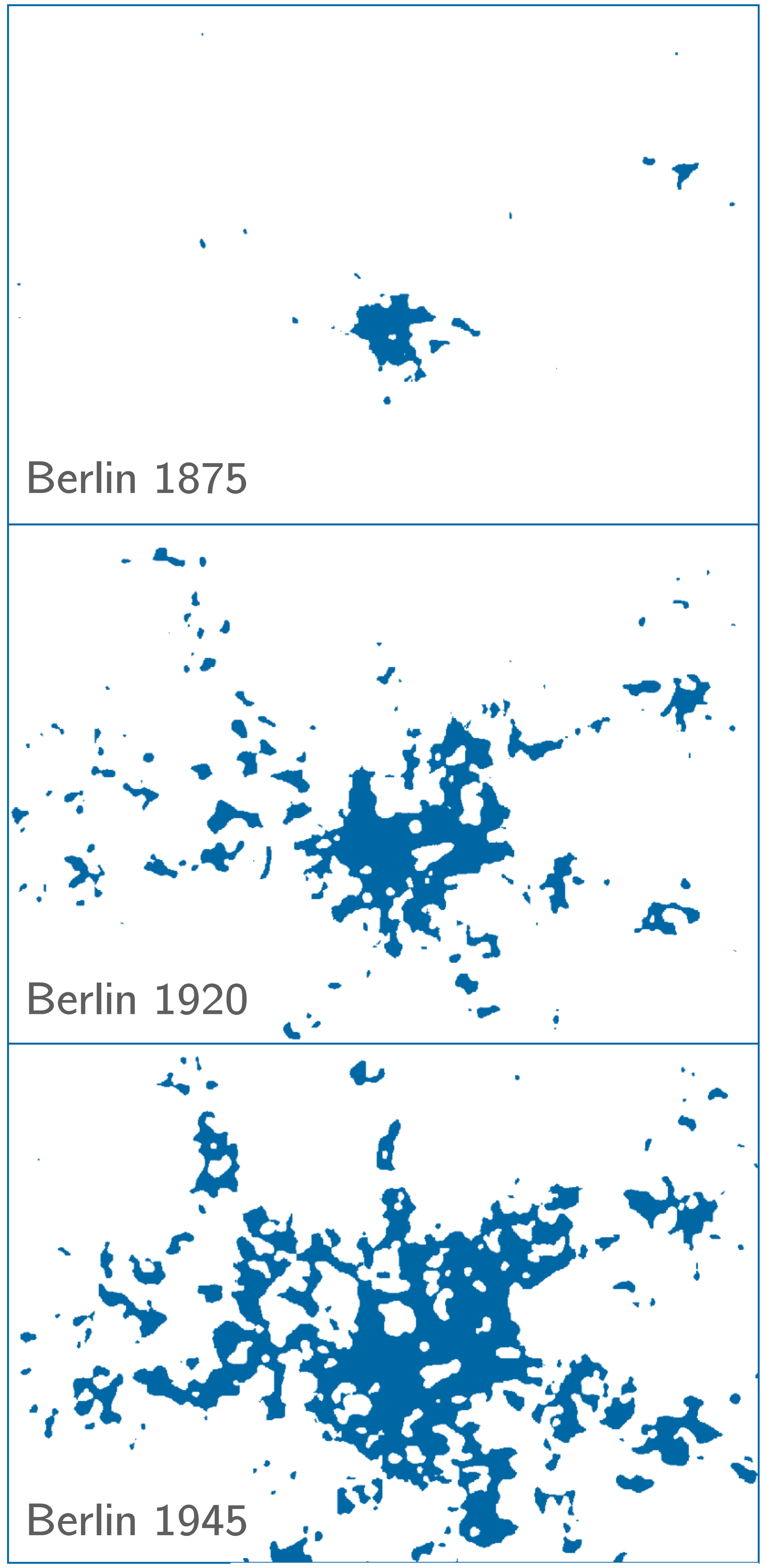
[Makse *et al.*, Nature '95]

Emergent phenomena

[Portugal *et al.*, Nature '14]



[Poincloux *et al.*, PRX '18]



[Makse *et al.*, Nature '95]

Many constituents
with simple rules

⇓

Complex structures
with new properties

Outline

(1) Introduction: Emergence

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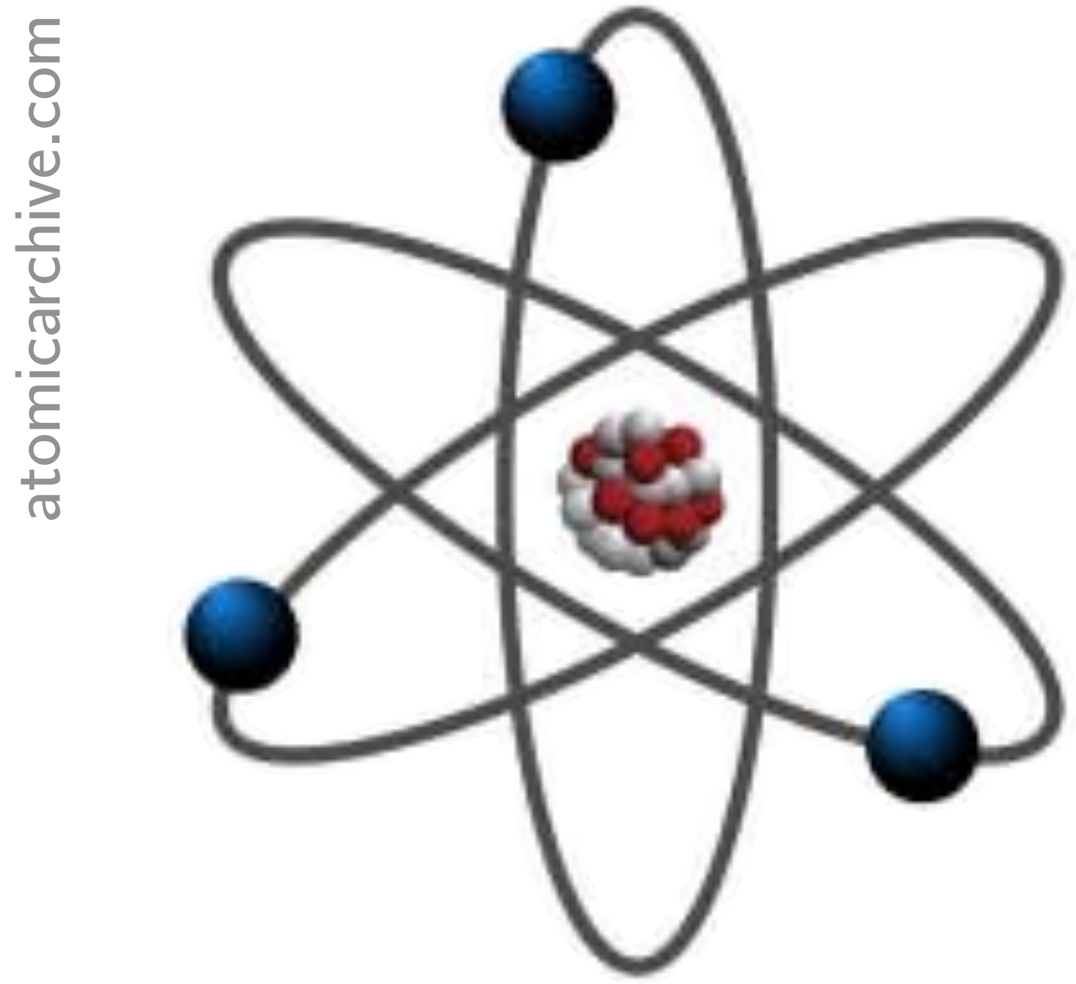
(3) Emergent phenomena for Quantum Saxony

(4) Summary

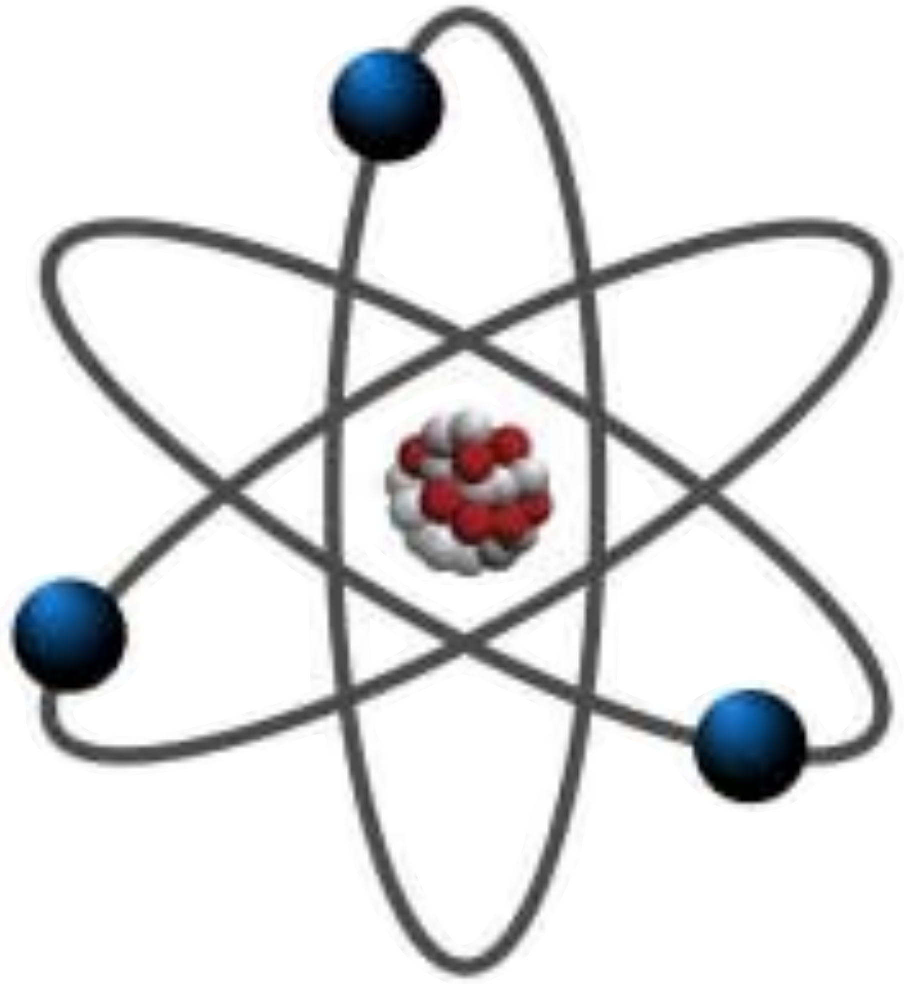
Quantum physics: From microscopics ...



Atom

Quantum physics: From microscopics ...

atomicarchive.com



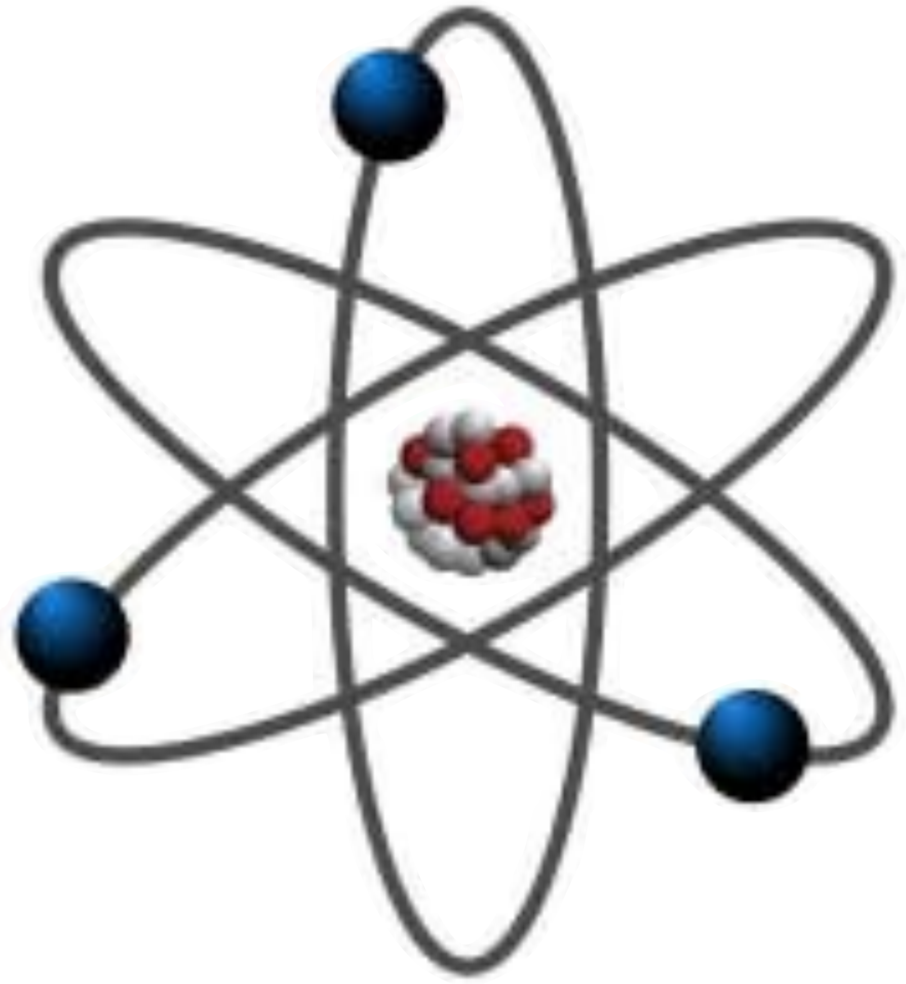
Atom

Schrödinger equation:

$$\mathrm{i}\hbar\frac{\mathrm{d}}{\mathrm{d}t}|\psi\rangle = \hat{H}|\psi\rangle$$

Quantum physics: From microscopics ...

atomicarchive.com

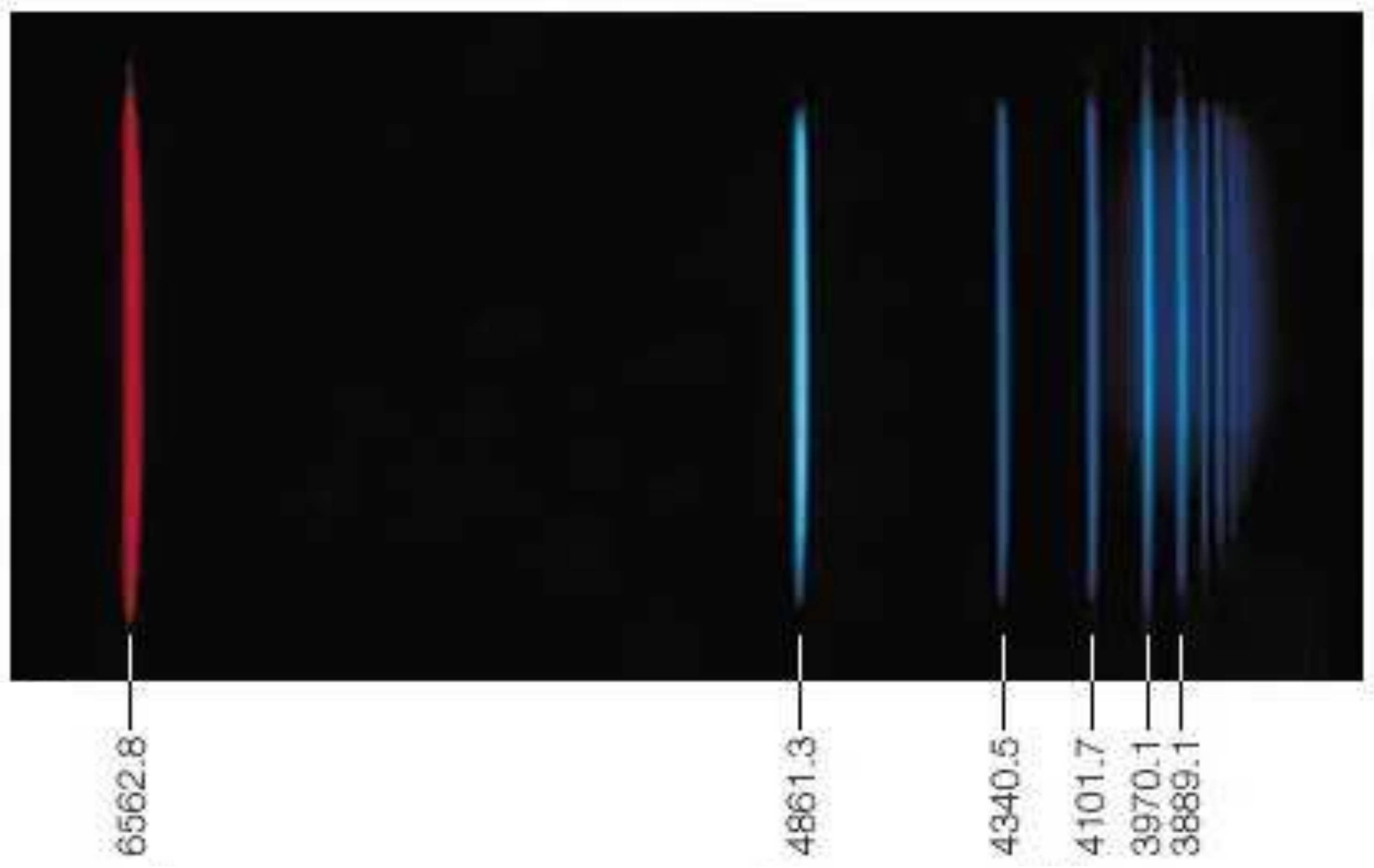


Atom

Schrödinger equation:

$$i\hbar \frac{\mathrm{d}}{\mathrm{d}t}|\psi\rangle = \hat{H}|\psi\rangle$$

Emission spectra:

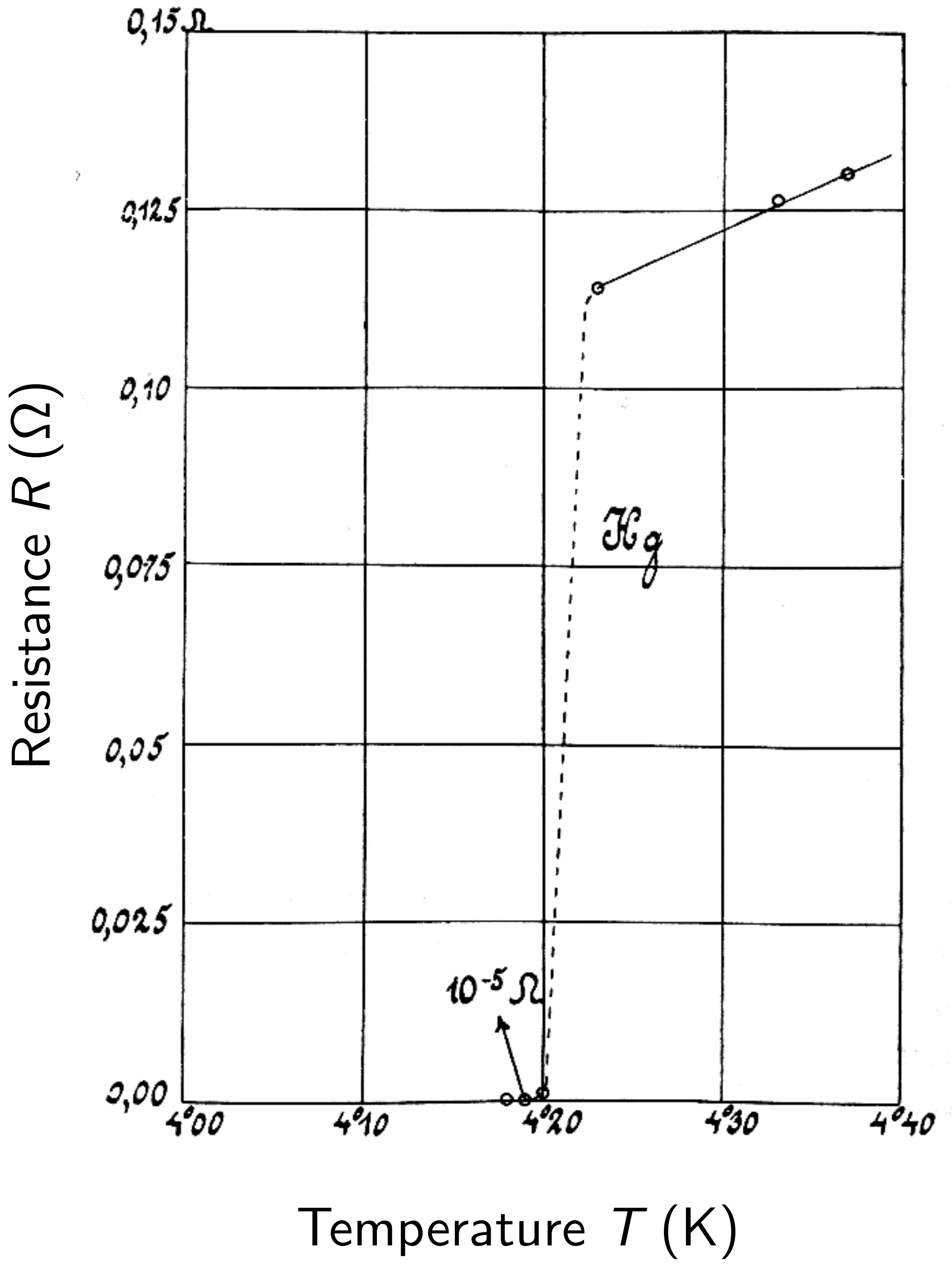


britannica.com

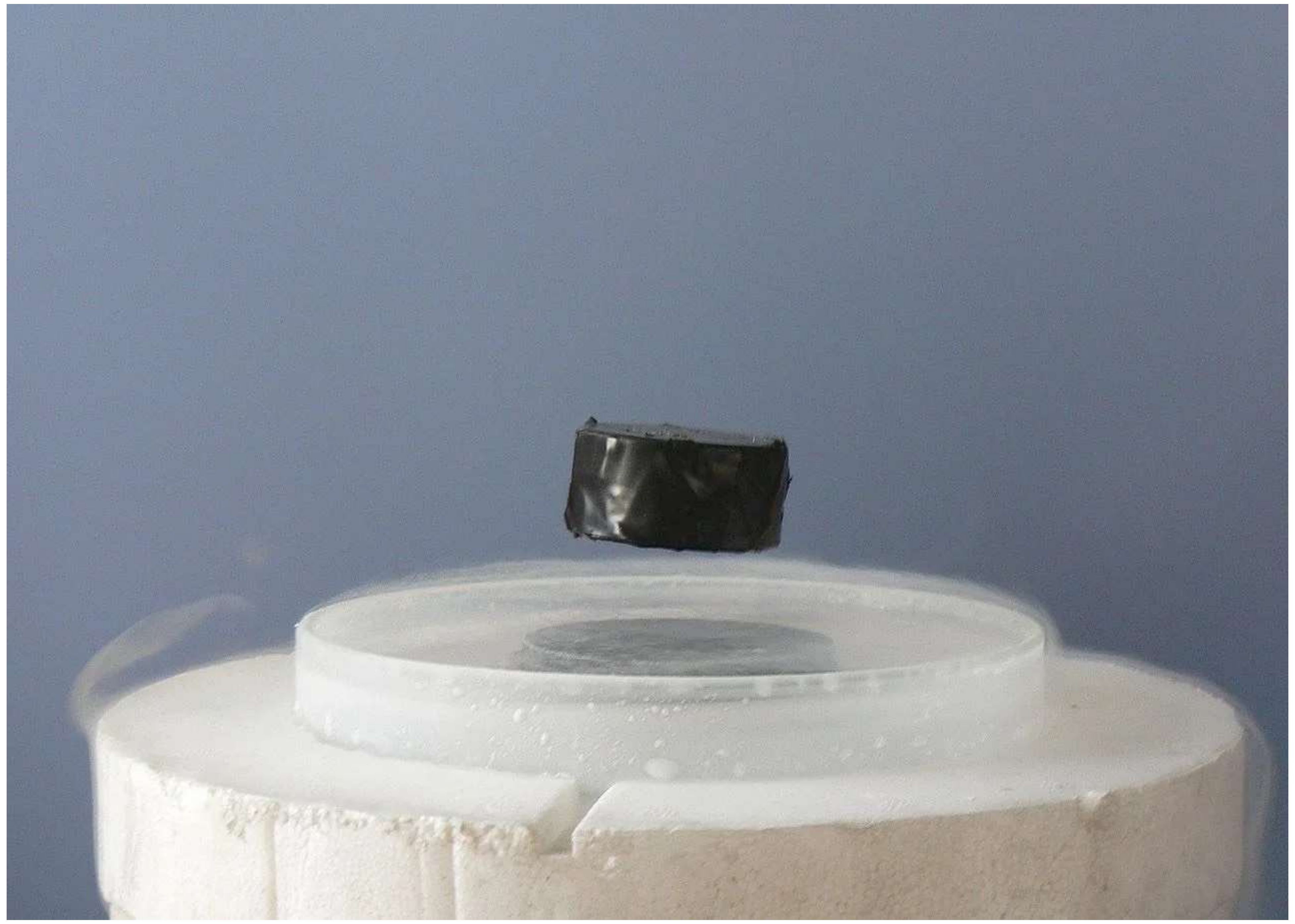
Wavelength λ (nm)

... to macroscopics ...

Example: Superconductivity



Perfect conductor



Perfect diamagnet

[H. Kamerlingh Onnes, KNAW Proc. 1911]

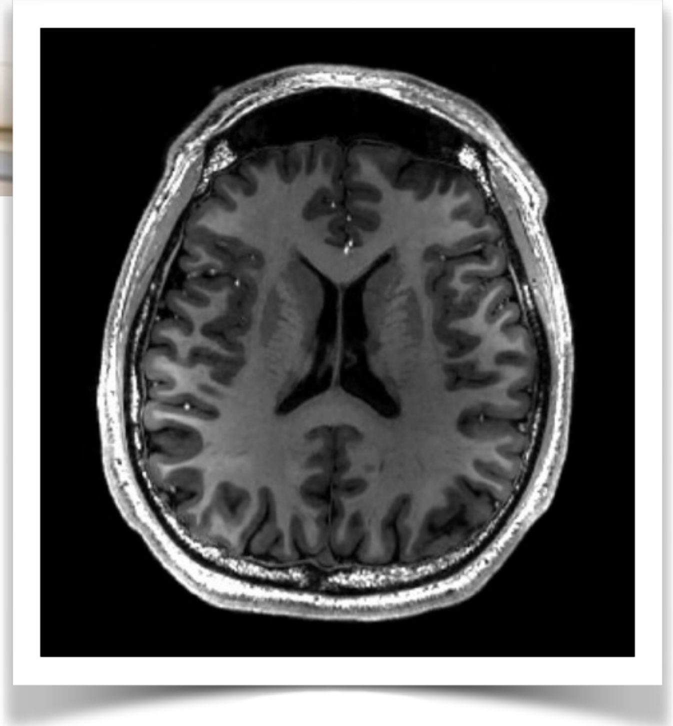
[Meissner & Ochsenfeld, Sci. Nat. 1933]

… to applications

Magnetic resonance imaging

onestophospital.co.uk

wikimedia.org



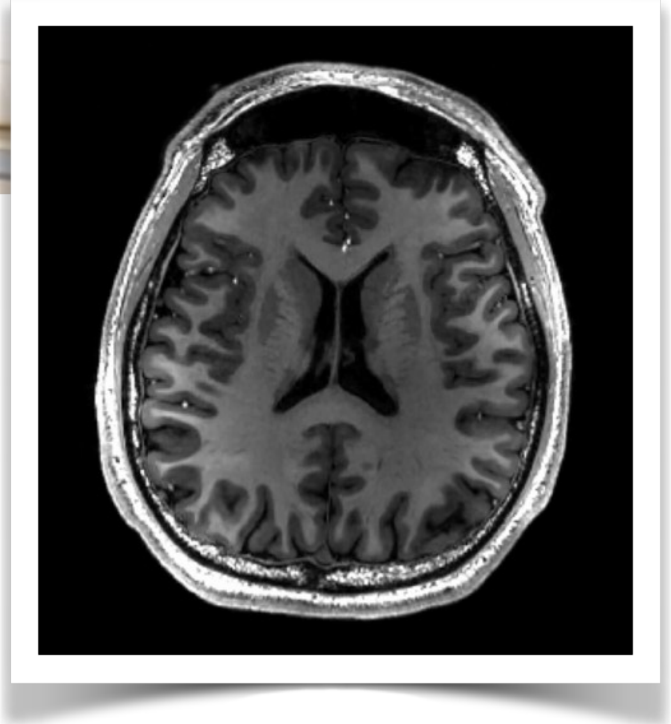
Human brain

… to applications

Magnetic resonance imaging

onestophospital.co.uk

wikimedia.org



Human brain

Superconducting power grid

nexans.com

Chicago's resilient electric grid

… to applications

Magnetic resonance imaging

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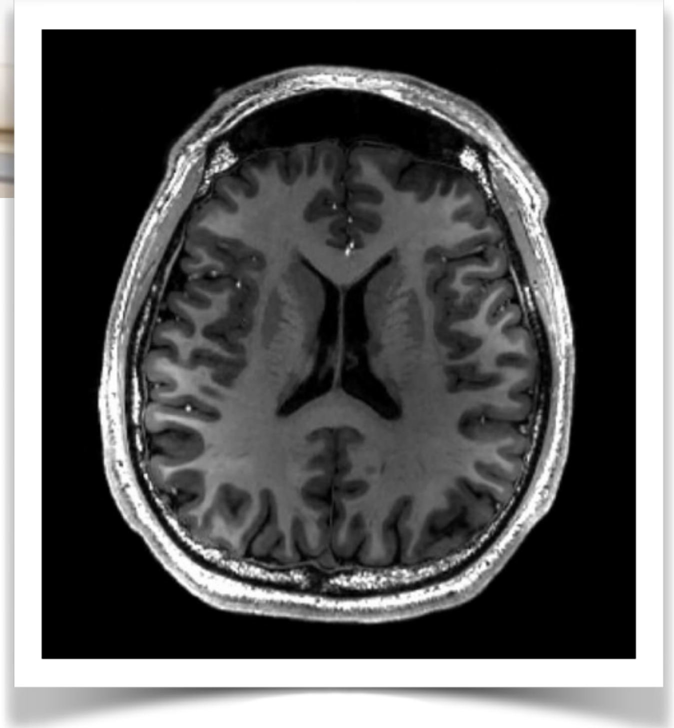
wikimedia.org



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Chicago's resilient electric grid

Superconducting maglev train

IFW Dresden

IFW's superconducting train

… to applications

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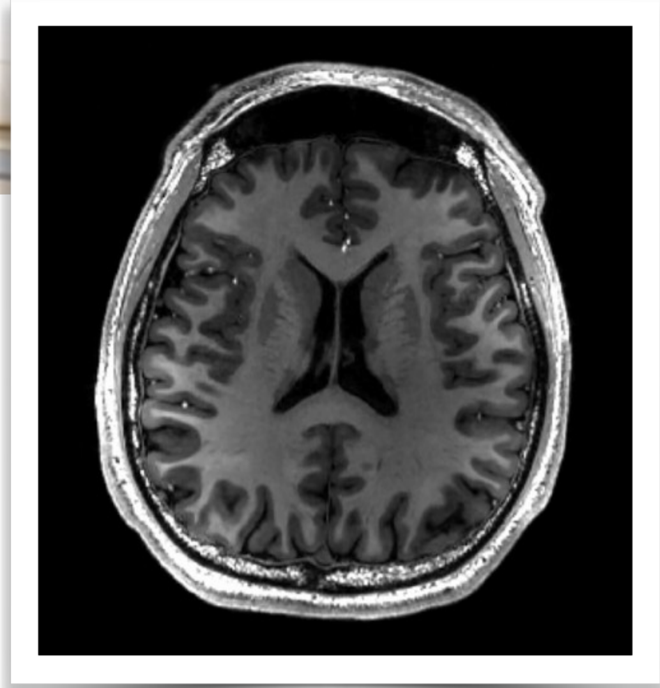


Human brain

Superconducting power grid

nexans.com

Chicago's resilient electric grid

Superconducting maglev train

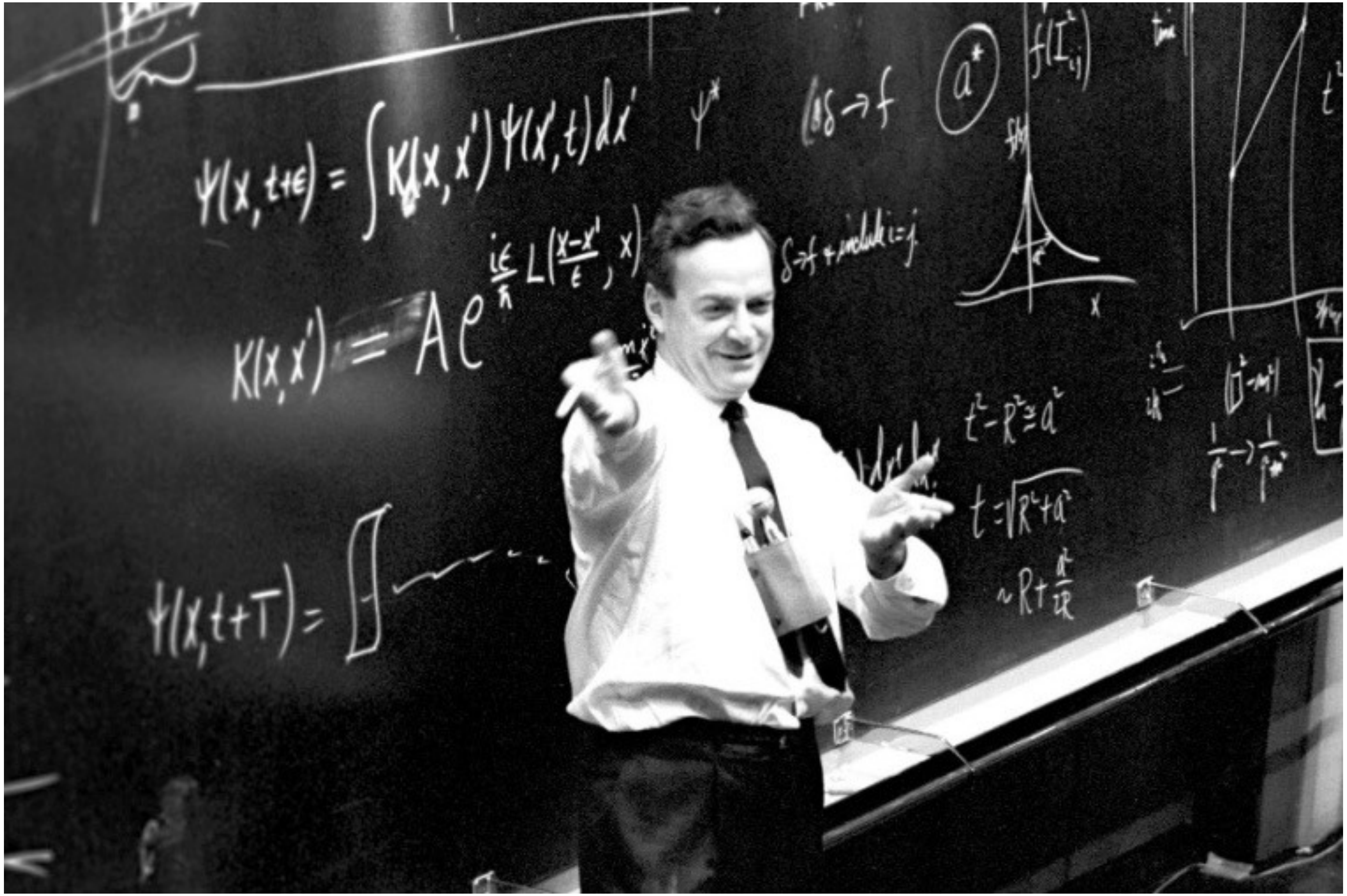
spiegel.de

Japan's SCMaglev

IFW Dresden

IFW's superconducting train

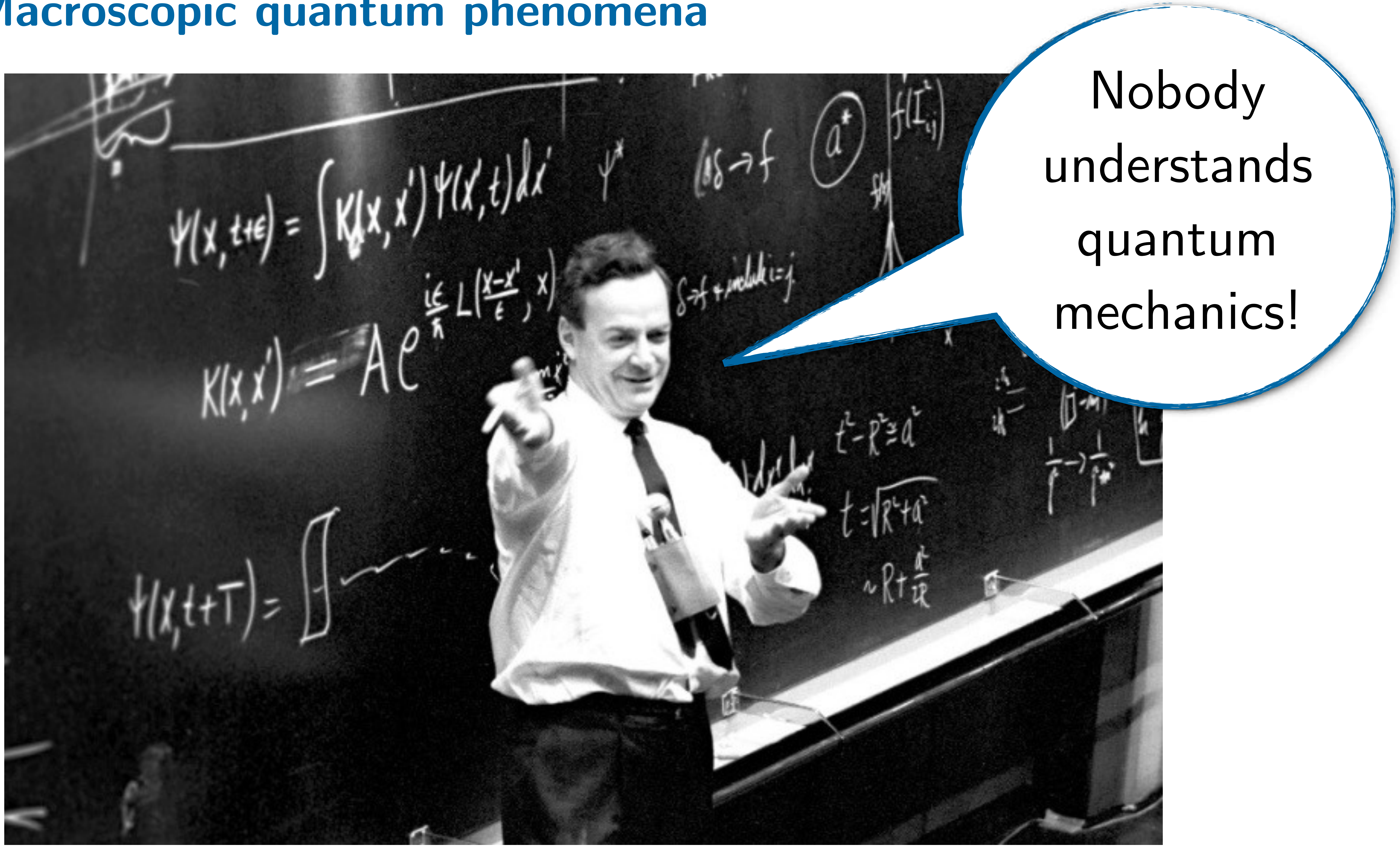
Macroscopic quantum phenomena



Richard Feynman

Macroscopic quantum phenomena

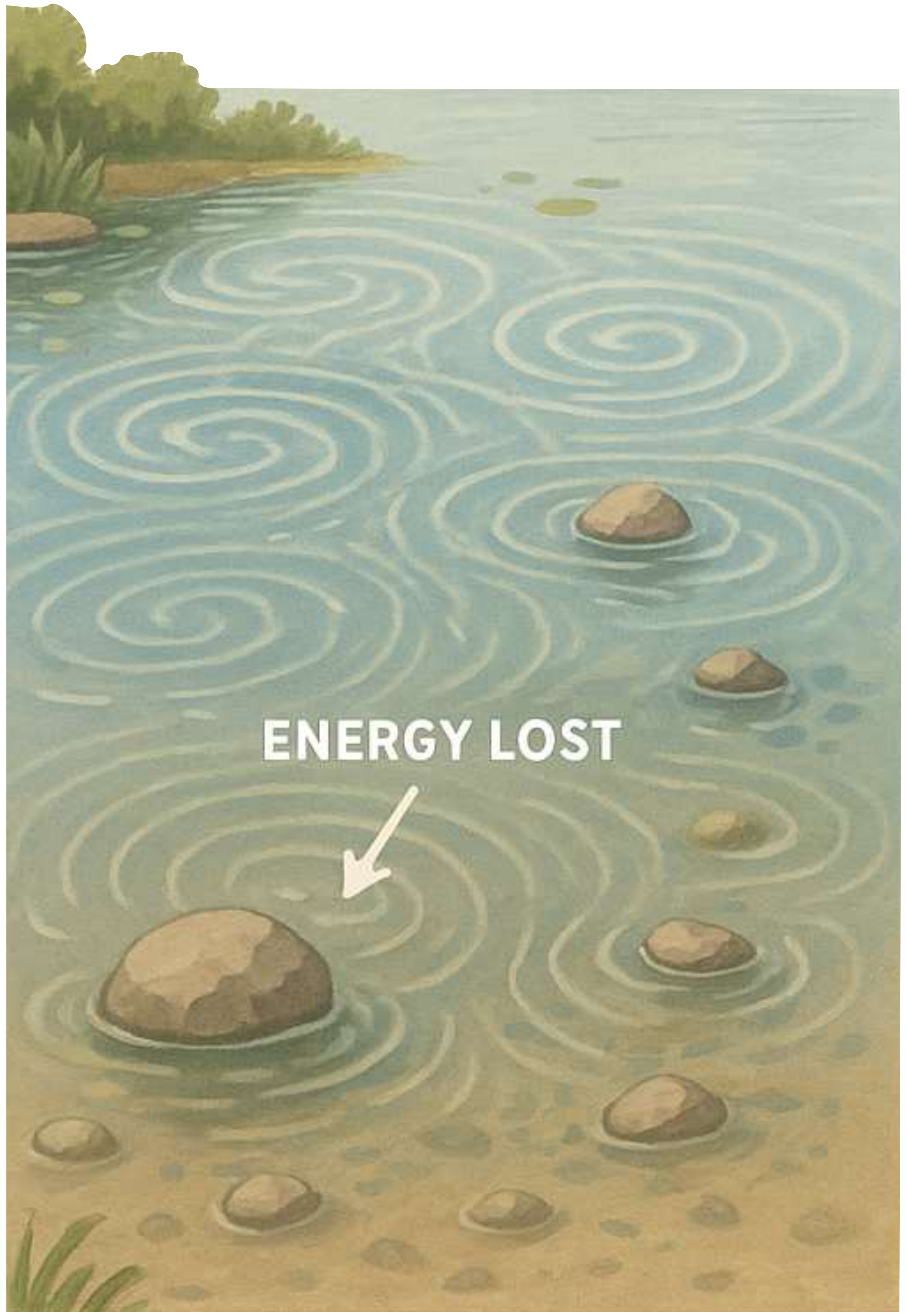
pro-physik.de



Richard Feynman

Macroscopic quantum phenomena

Normal metal



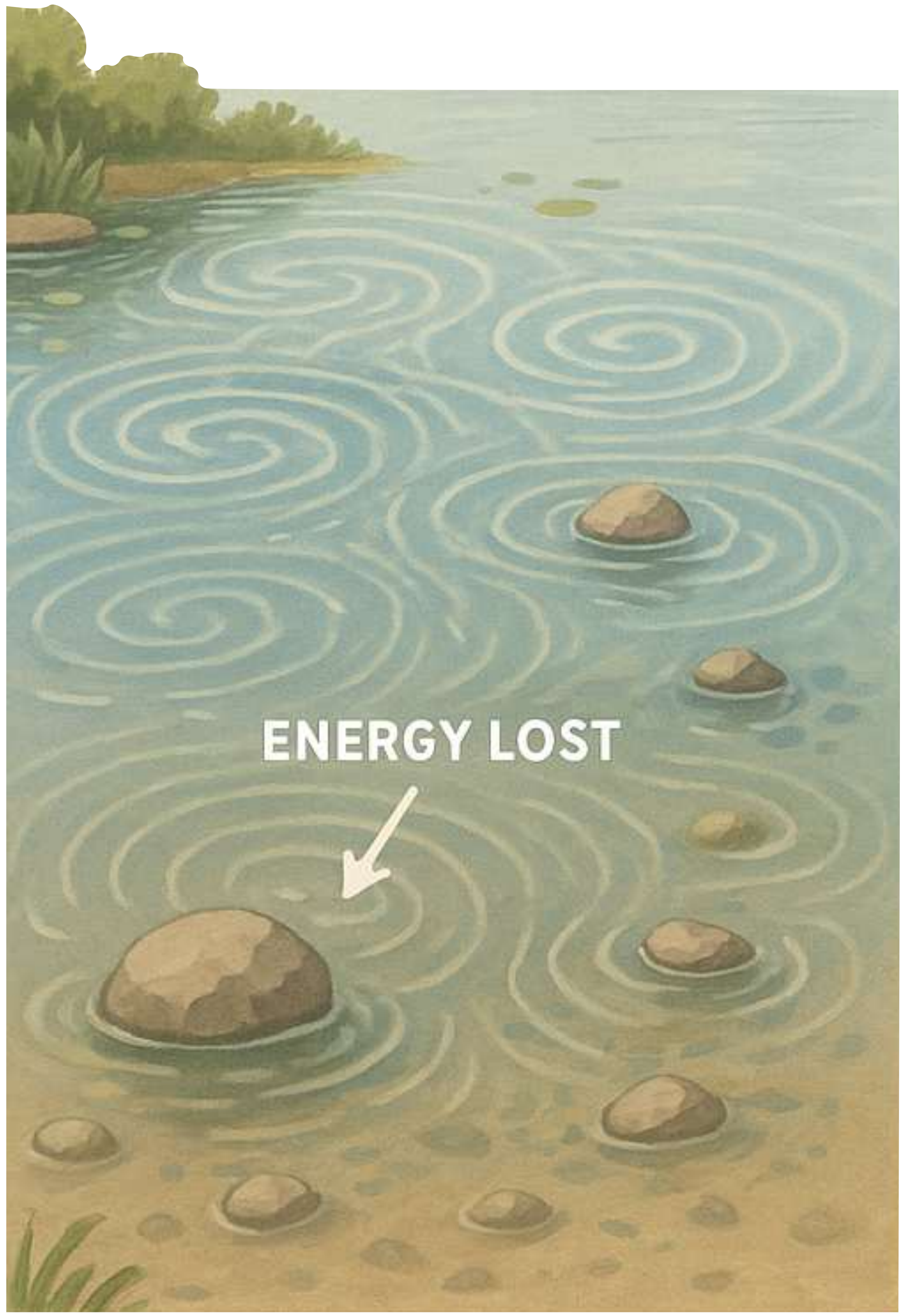
AI generated

Normal electrons

Macroscopic quantum phenomena

Normal metal

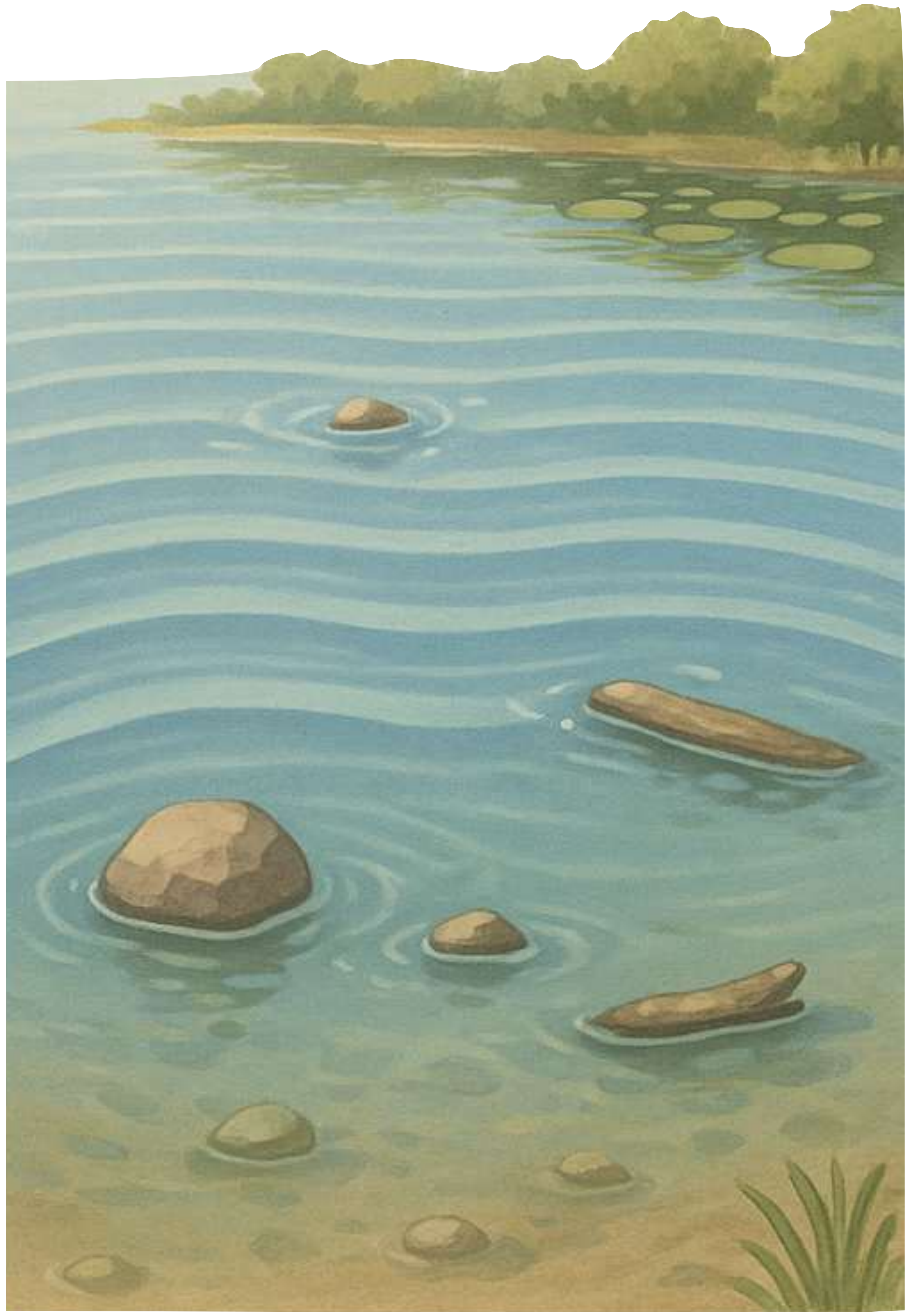
AI generated



Normal electrons

Superconductor

AI generated



Cooper pairs

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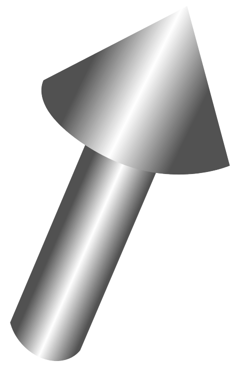
Qubits

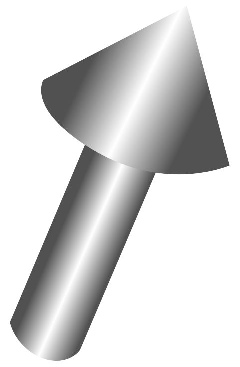
Spin 1/2:



$$|\psi\rangle = \quad |\uparrow\rangle$$

Qubits

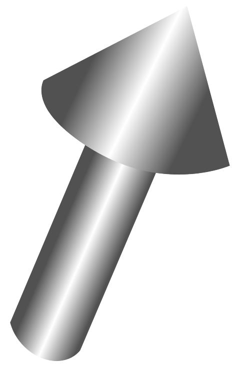
Spin 1/2:



$$|\psi\rangle = \qquad\qquad |\downarrow\rangle$$

Qubits

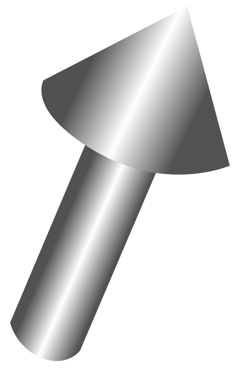
Spin 1/2:



$$|\psi\rangle = \alpha\,|\uparrow\rangle \; + \; \beta\,|\downarrow\rangle$$

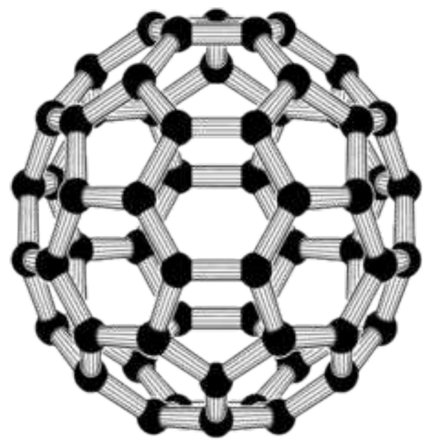
Qubits

Spin 1/2:



$$|\psi\rangle = \alpha\,|\uparrow\rangle \; + \; \beta\,|\downarrow\rangle$$

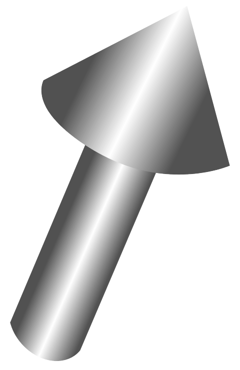
Spin-split quantum dot:



$$|\psi\rangle = \alpha\,|0\rangle \; + \; \beta\,|1\rangle$$

Qubits

Spin 1/2:



$$|\psi\rangle = \alpha\,|\uparrow\rangle \; + \; \beta\,|\downarrow\rangle$$
$$\widehat{=}\,\alpha\begin{pmatrix}1\\0\end{pmatrix}+\beta\begin{pmatrix}0\\1\end{pmatrix}$$

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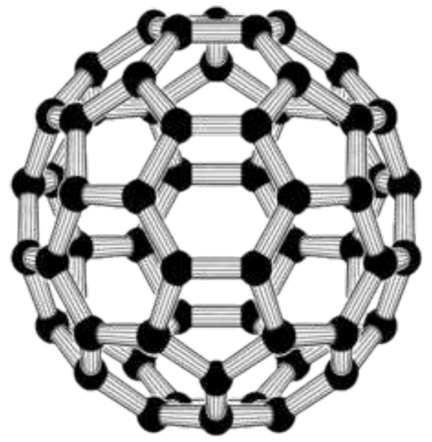

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Qubits

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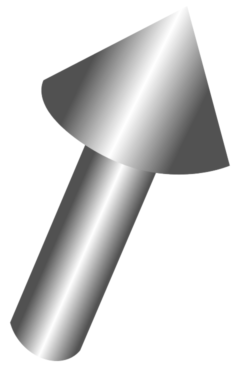

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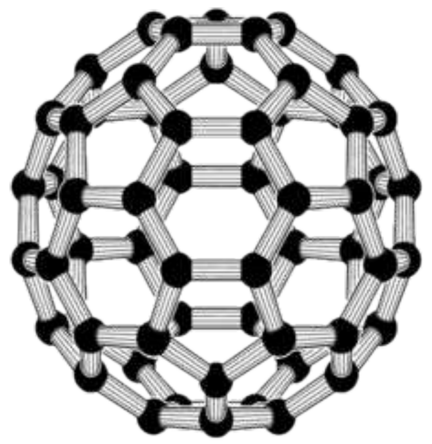
Complex numbers

Spin-split quantum dot:



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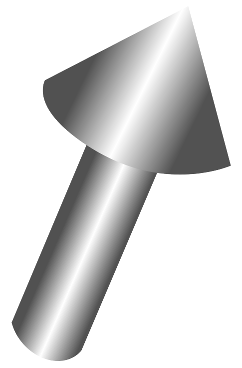

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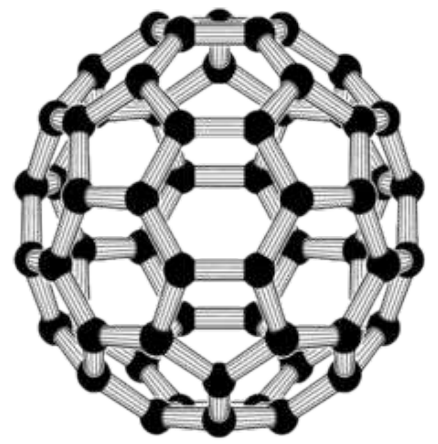

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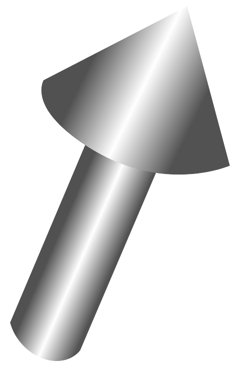
Complex numbers

Density matrix:

$$\rho = |\psi\rangle\langle\psi| \mathrel{\widehat{=}} \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$$

Qubits

Spin 1/2:



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Complex numbers

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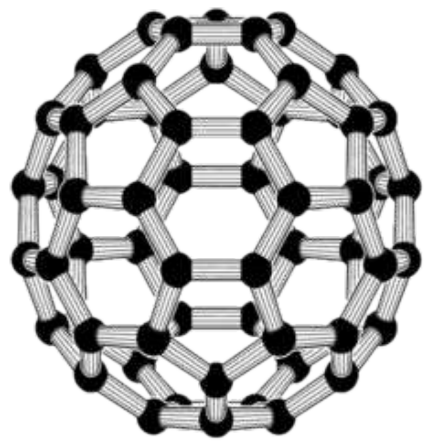

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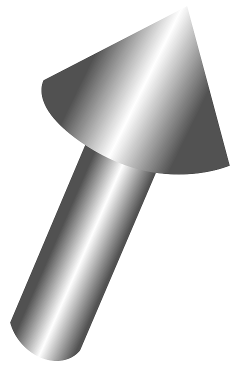
“Coherences”

Qubits

Spin 1/2:



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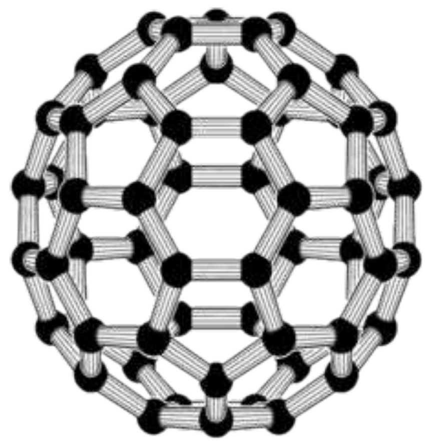
Complex numbers

Spin-split quantum dot:



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Complex numbers

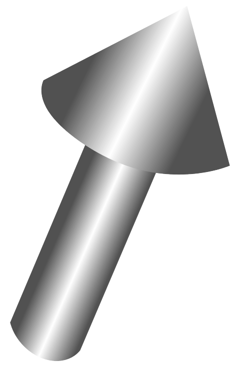
Density matrix: $$\rho = |\psi\rangle\langle\psi| \mathrel{\widehat{=}} \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$$

"Coherences"

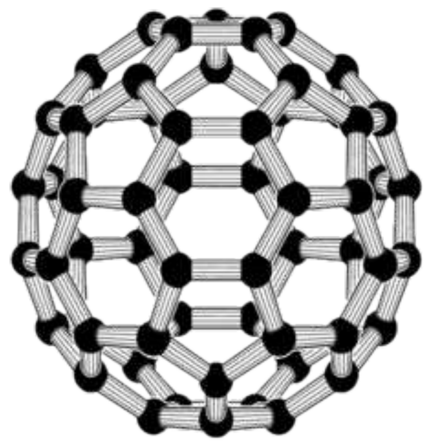
Decoherence: $$\rho \to \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

Qubits

Spin 1/2:



Spin-split quantum dot:



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Complex numbers

$$|\psi\rangle = \alpha\,|0\rangle \;+\; \beta\,|1\rangle$$
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Complex numbers

Density matrix:

$$\rho = |\psi\rangle\langle\psi| \;\widehat{=}\; \begin{pmatrix}|\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2\end{pmatrix}$$

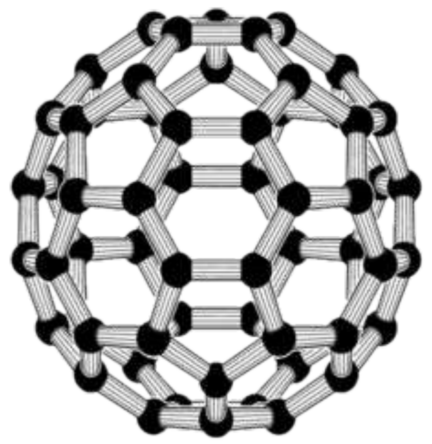
"Coherences"

Decoherence:

$$\rho \rightarrow \begin{pmatrix}|\alpha|^2 & 0 \\ 0 & |\beta|^2\end{pmatrix}$$

Classical bit

Qubits

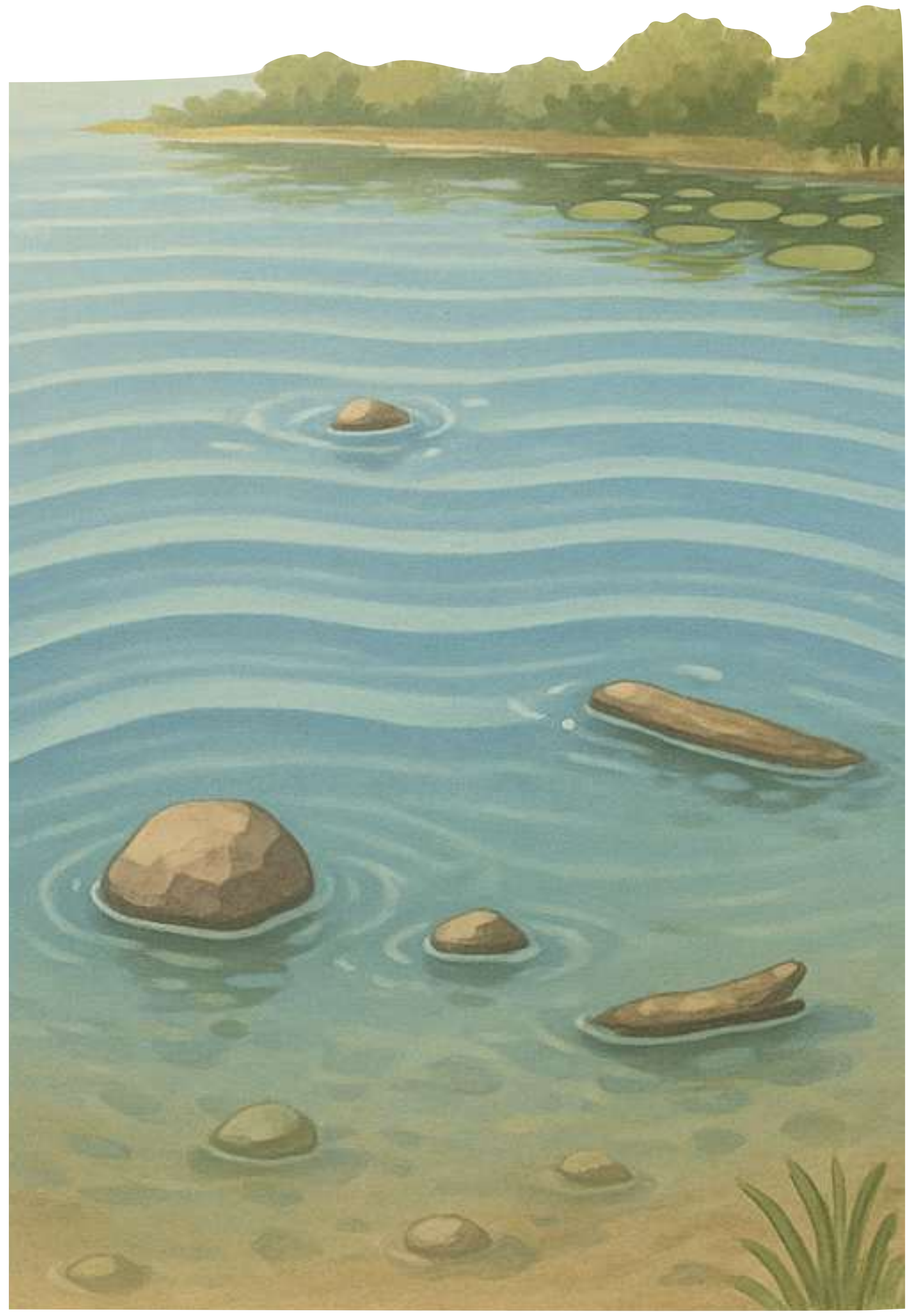


Spin 1/2: ... quantum dot:

$$|\psi\rangle = \alpha\,|\uparrow\rangle \; + \; \beta\,|\downarrow\rangle \qquad \ldots\; \alpha\,|0\rangle \; + \; \beta\,|1\rangle$$

$$\widehat{=}\, \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} \ldots \qquad \ldots \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Density matrix:

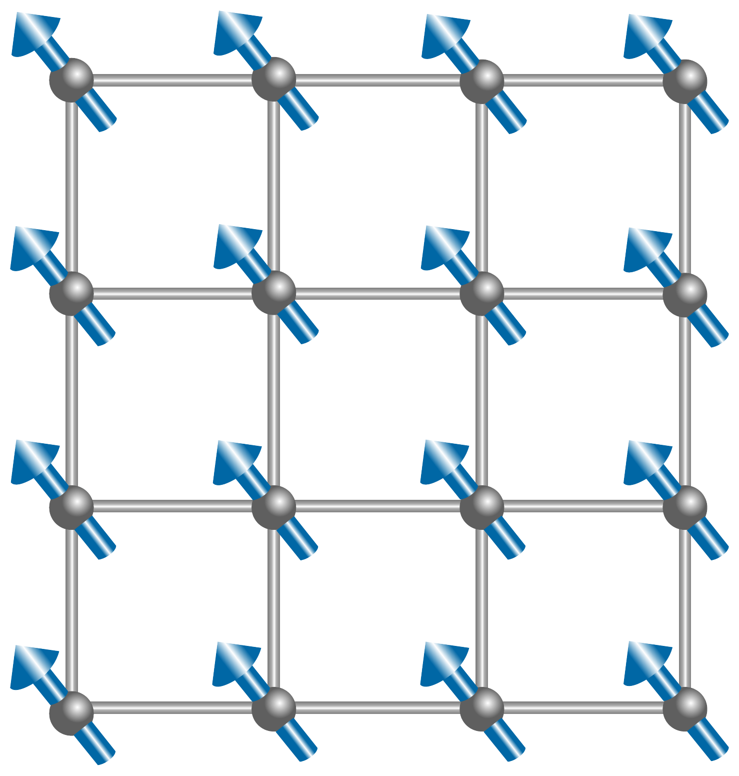


Coherent quantum wave?

Decoherence: $\rho \rightarrow \begin{pmatrix} \ldots & \ldots \\ 0 & |\beta|^2 \end{pmatrix}$ Classical bit

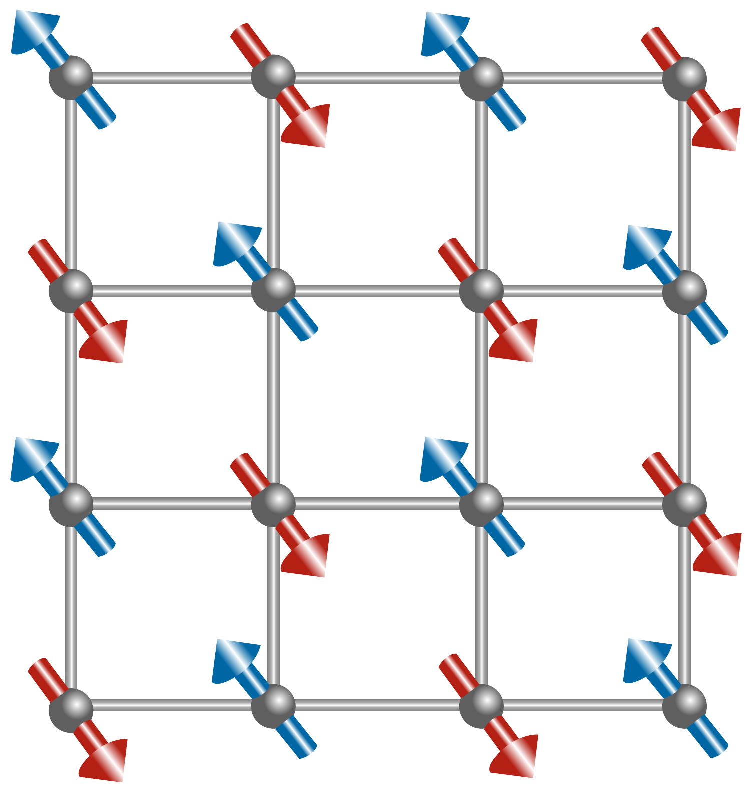
Possible states of matter?

Symmetry classification:



Ferromagnet

Spin: $\quad SU(2) \to U(1)$



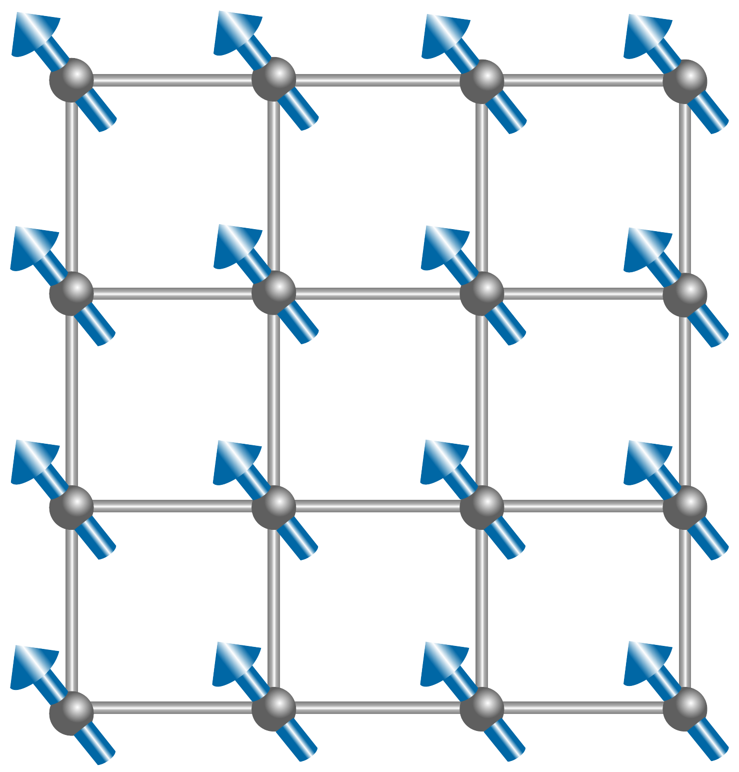
Antiferromagnet

Spin: $\quad SU(2) \to U(1)$

Lattice: $\quad T_a \to T_{2a}$

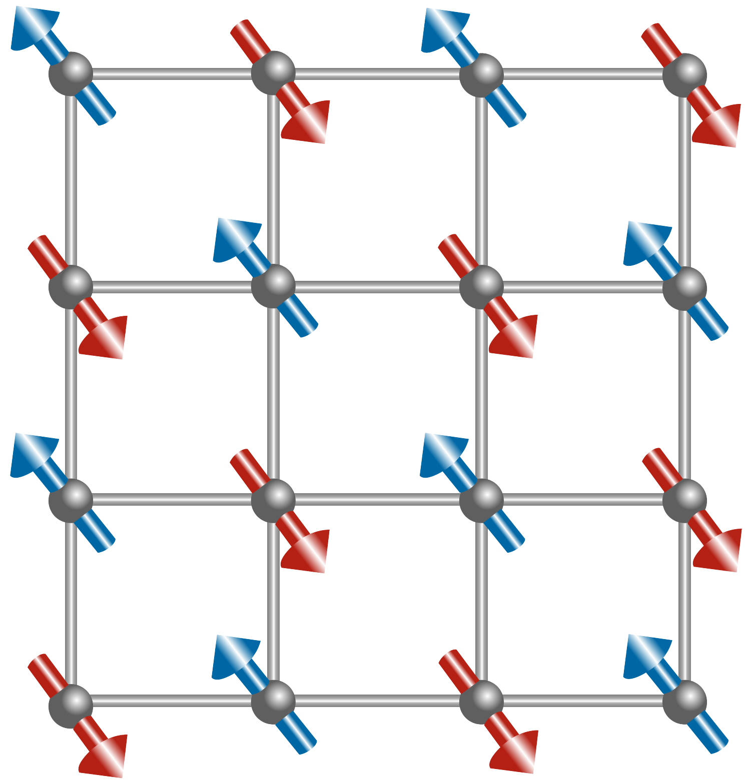
Possible states of matter?

Symmetry classification:



Spin: $\quad SU(2) \to U(1)$

Ferromagnet

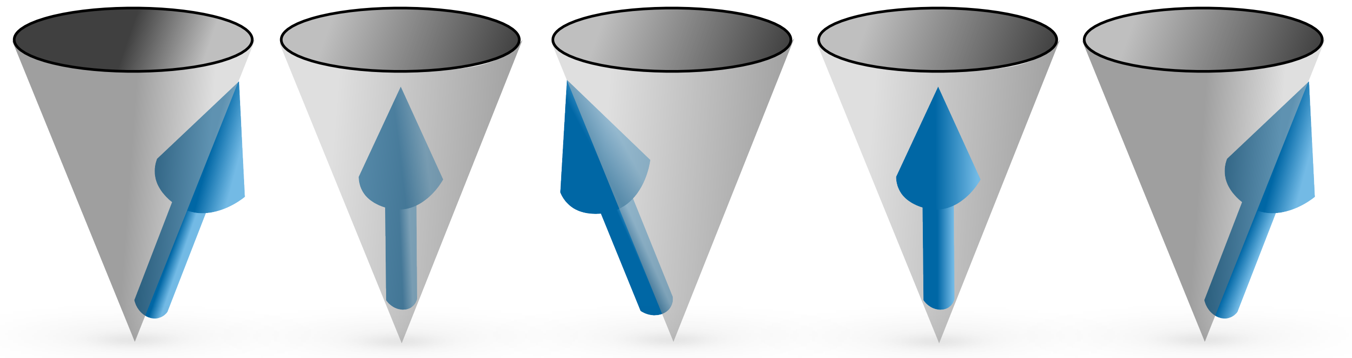


Spin: $\quad SU(2) \to U(1)$

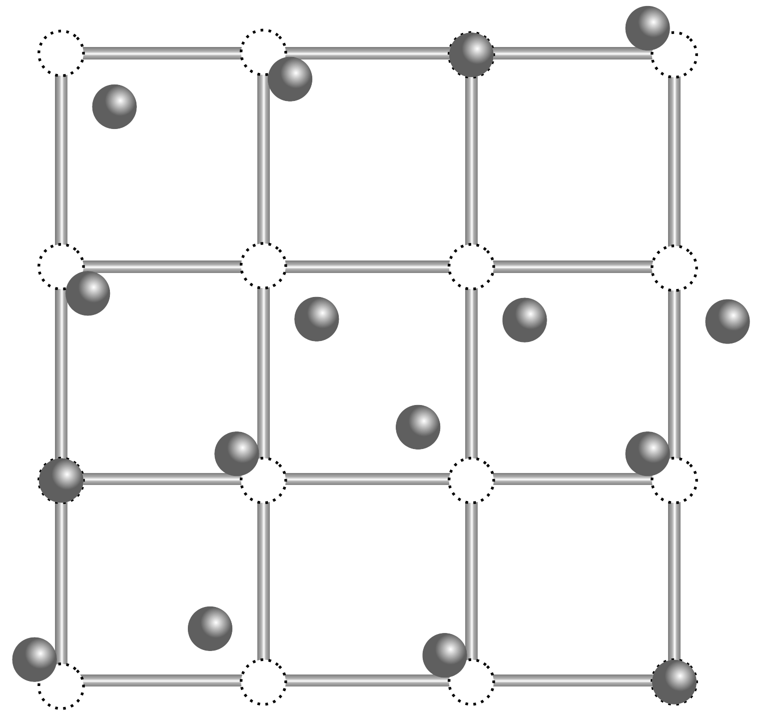
Lattice: $\quad T_a \to T_{2a}$

Antiferromagnet

Effective excitations: Quasiparticles



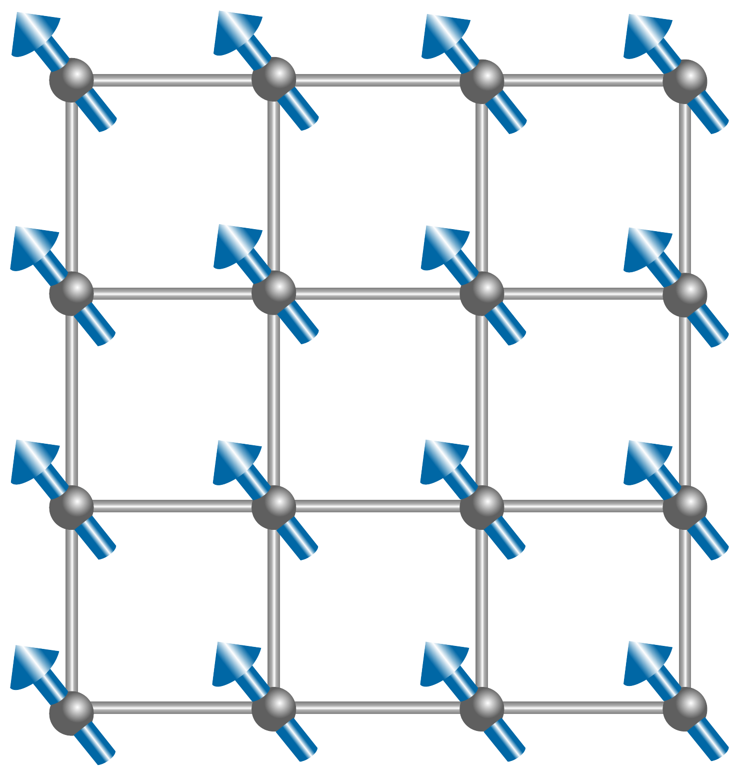
Spin: Magnons



Lattice: Phonons

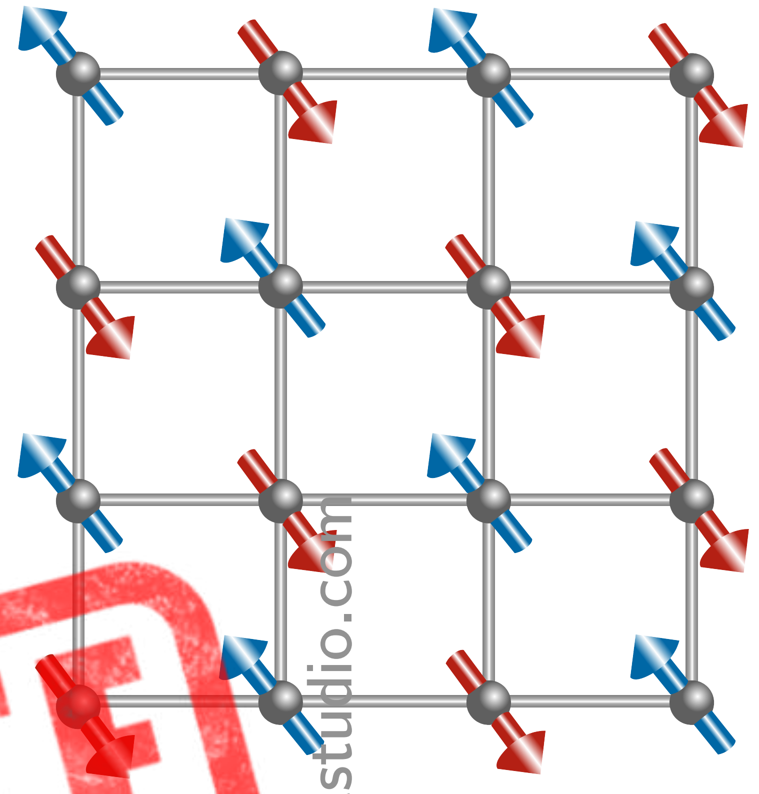
Possible states of matter?

Symmetry classification:



Ferromagnet

Spin: $SU(2) \to U(1)$

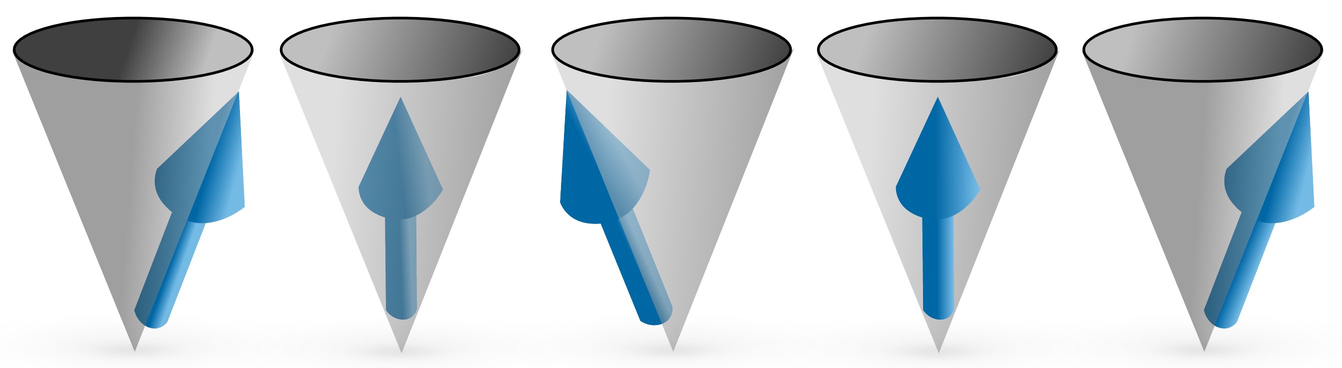


Antiferromagnet

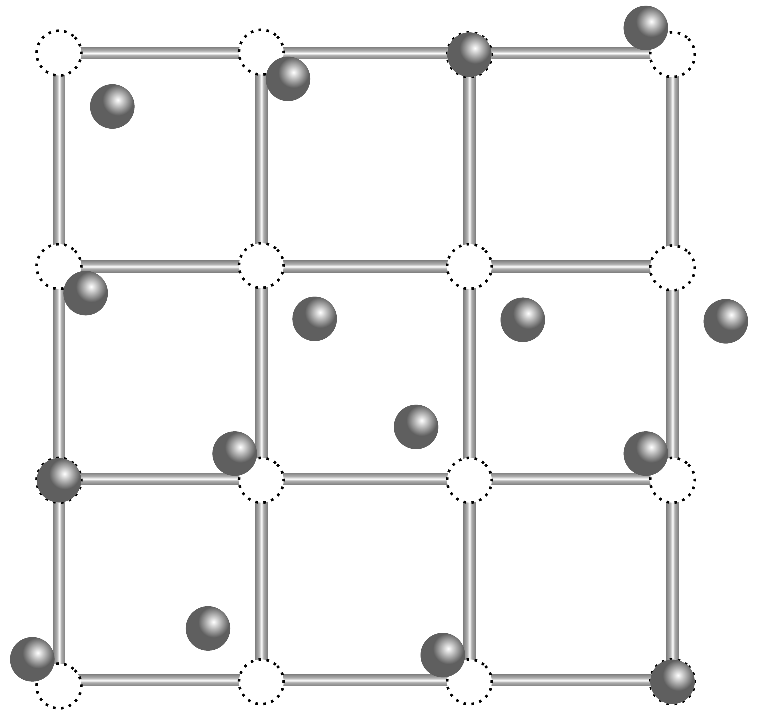
Spin: $SU(2) \to U(1)$

Lattice: $T_a \to T_{2a}$

Effective excitations: Quasiparticles



Spin: Magnons



Lattice: Phonons

Ingredient #1: Topology

Topological insulator:

metallic

insulating

[Kane, Mele, PRL ’05]
[König *et al.*, Science ’07]

Ingredient #1: Topology

Topological insulator:

Band inversion:

$(n+1)\,s$ $\Rightarrow$ $(n+1)\,s_{1/2}$

small $\vec{L}\cdot\vec{\sigma}$

$n\,p_{3/2}$

$n\,p$ $\quad$ $n\,p_{1/2}$

[Kane, Mele, PRL '05]
[König *et al.*, Science '07]

Ingredient #1: Topology

Topological insulator:

Band inversion:

$(n+1)\,s$

$n\,p$

$\Rightarrow$ small $\vec{L}\cdot\vec{\sigma}$

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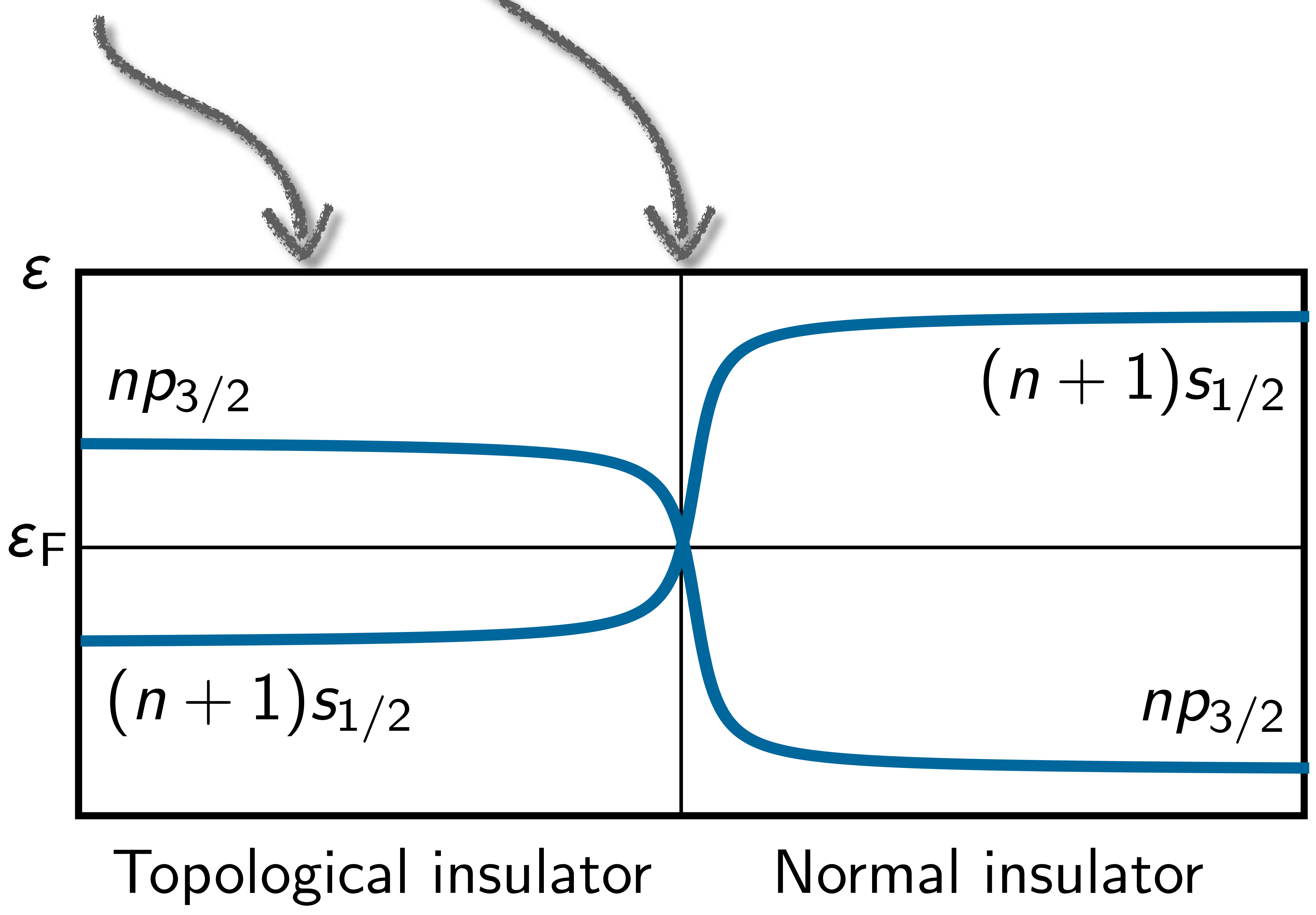

[Kane, Mele, PRL '05]
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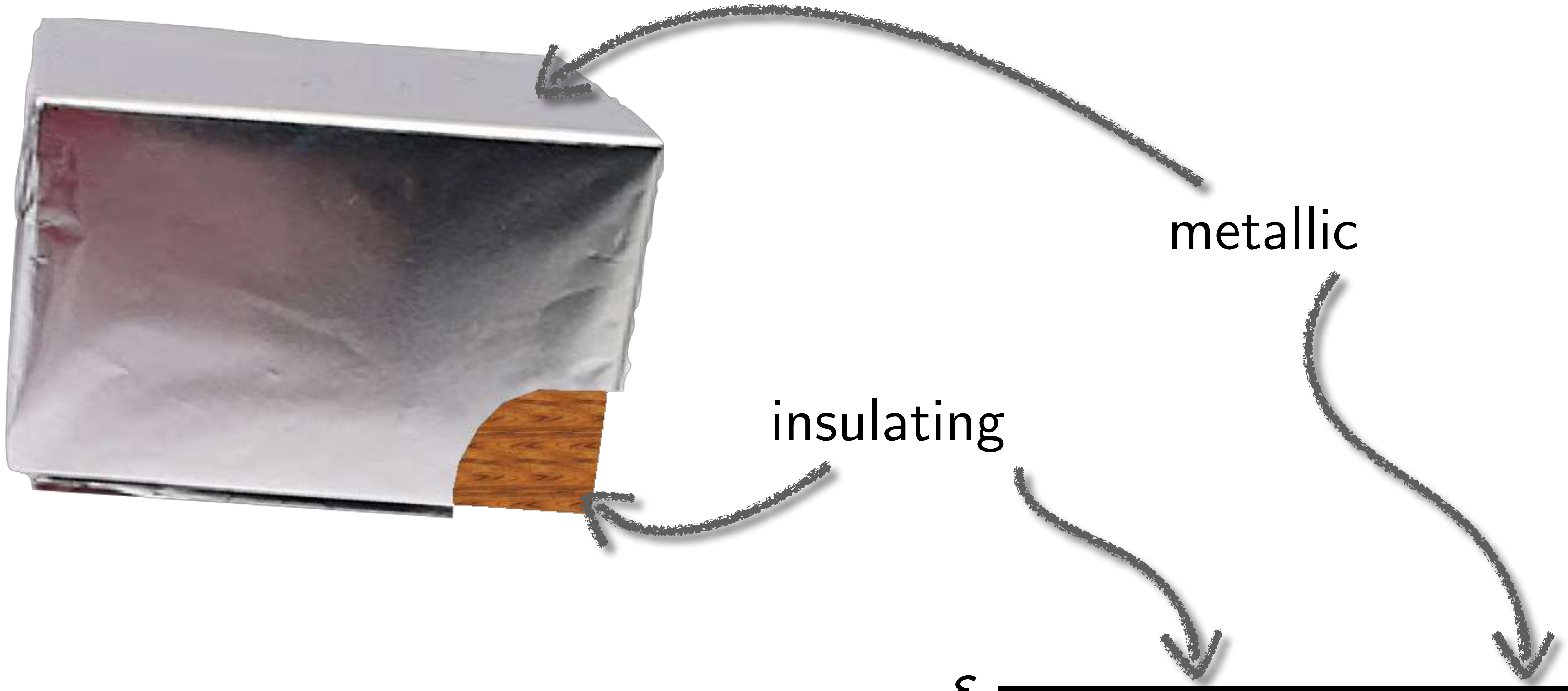
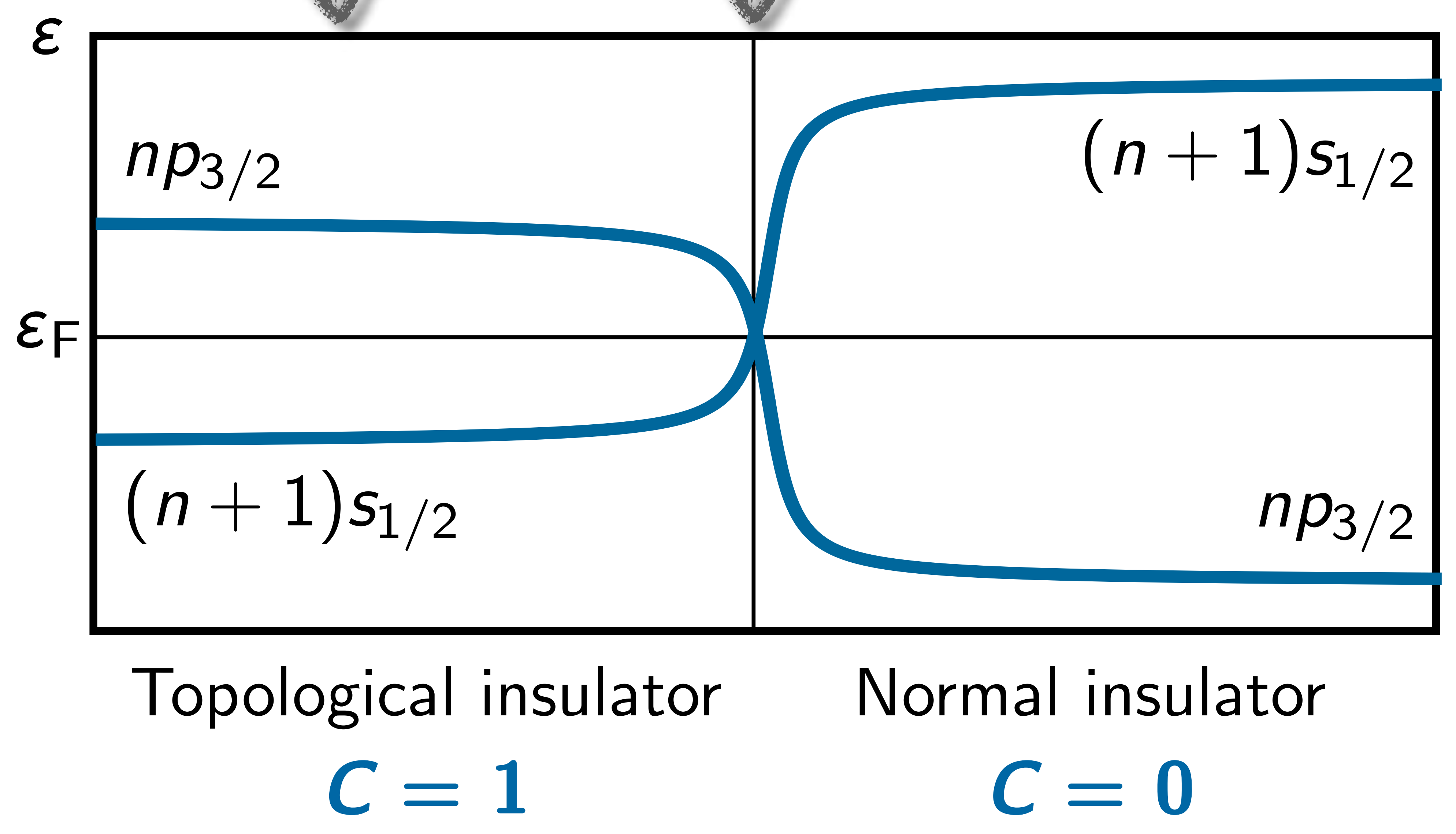
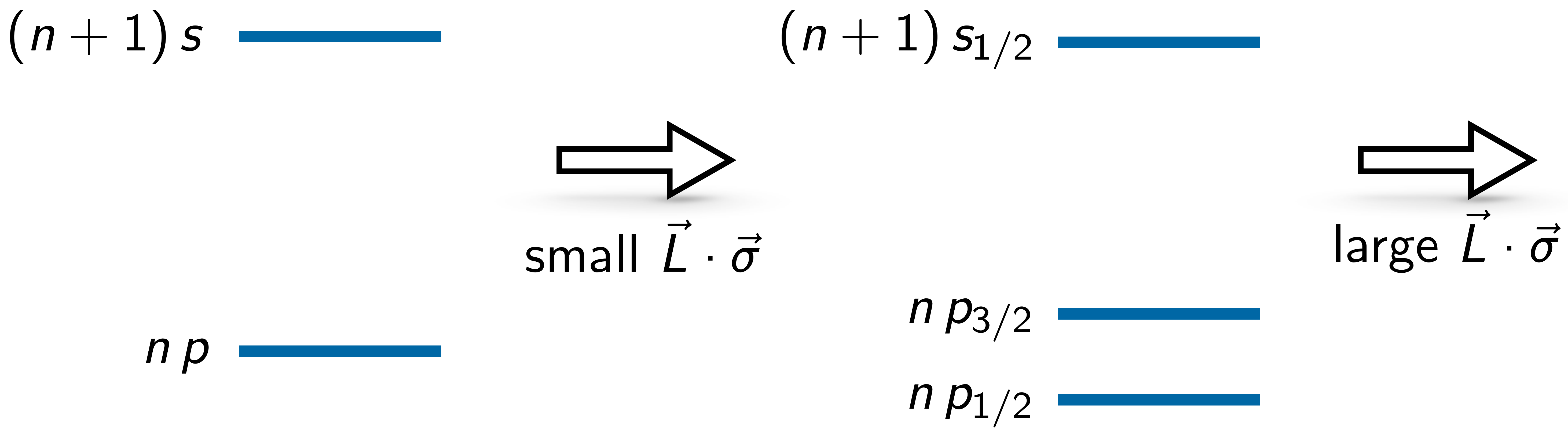
Ingredient #1: Topology

Topological insulator:





Band inversion:



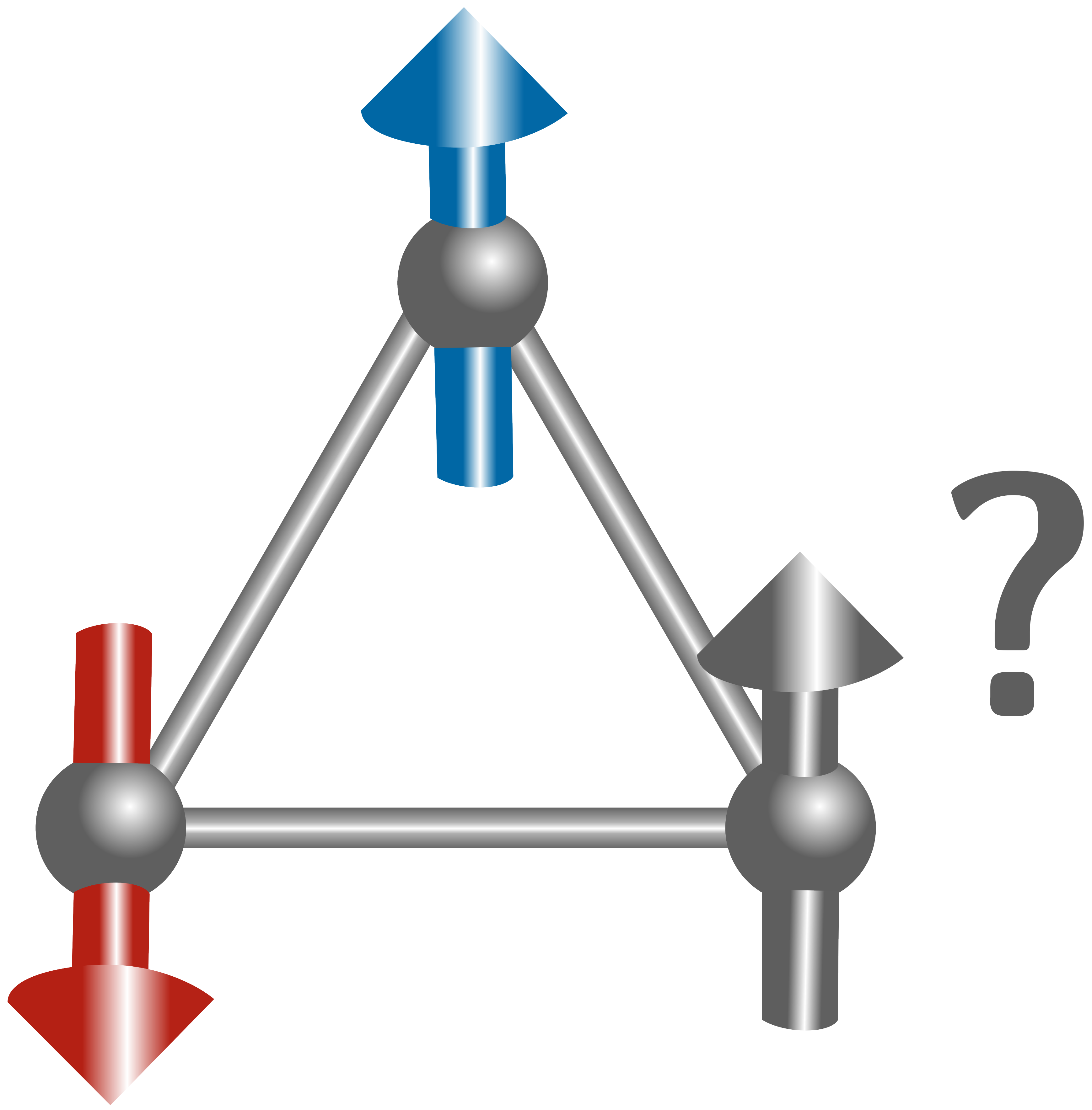
[Kane, Mele, PRL '05]

[König *et al.*, Science '07]

Ingredient #2: Frustration

Antiferromagnetic interaction:

$$\mathcal{H}_{ij} = J S_i^z S_j^z \qquad\qquad J > 0$$



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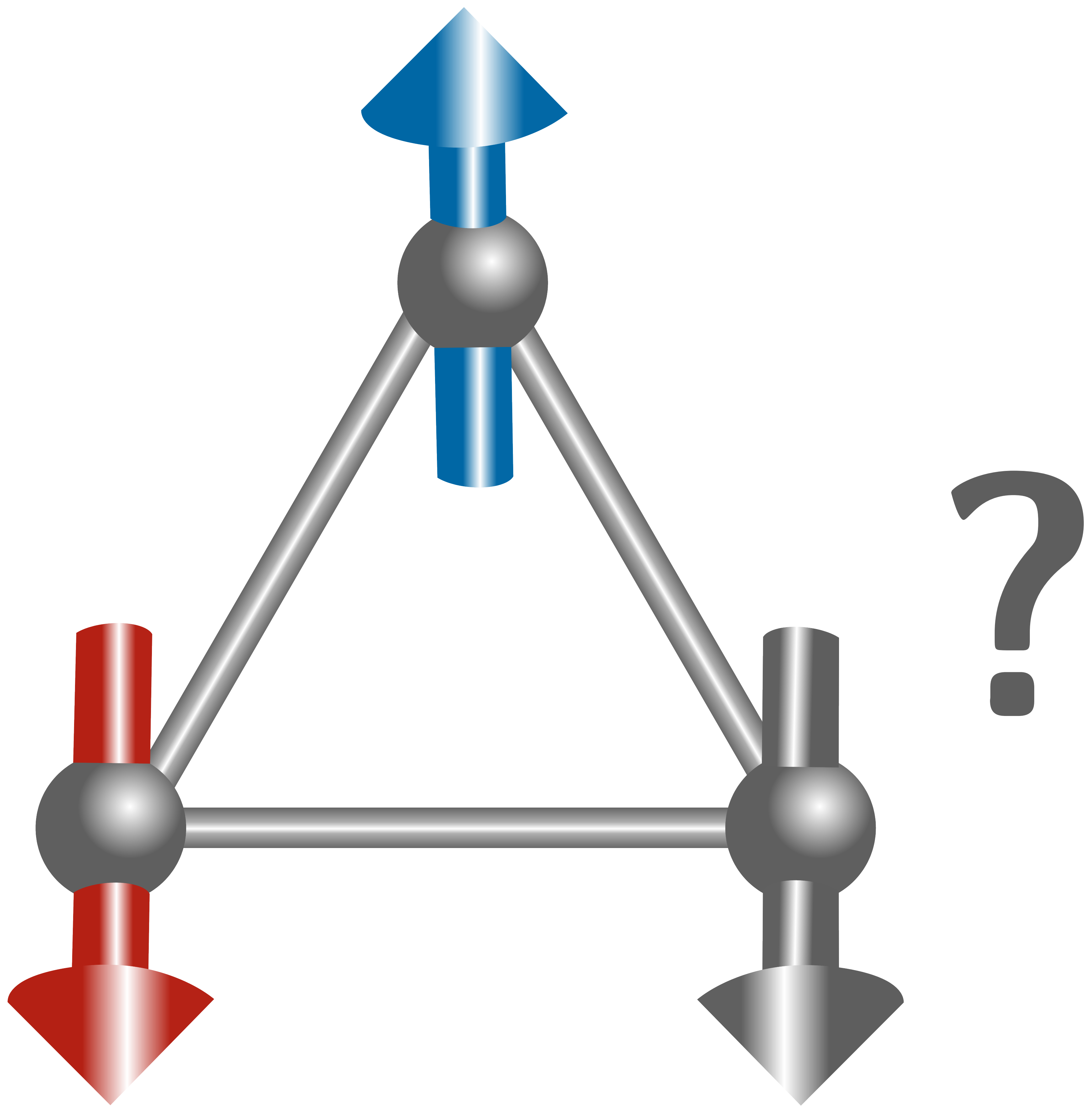

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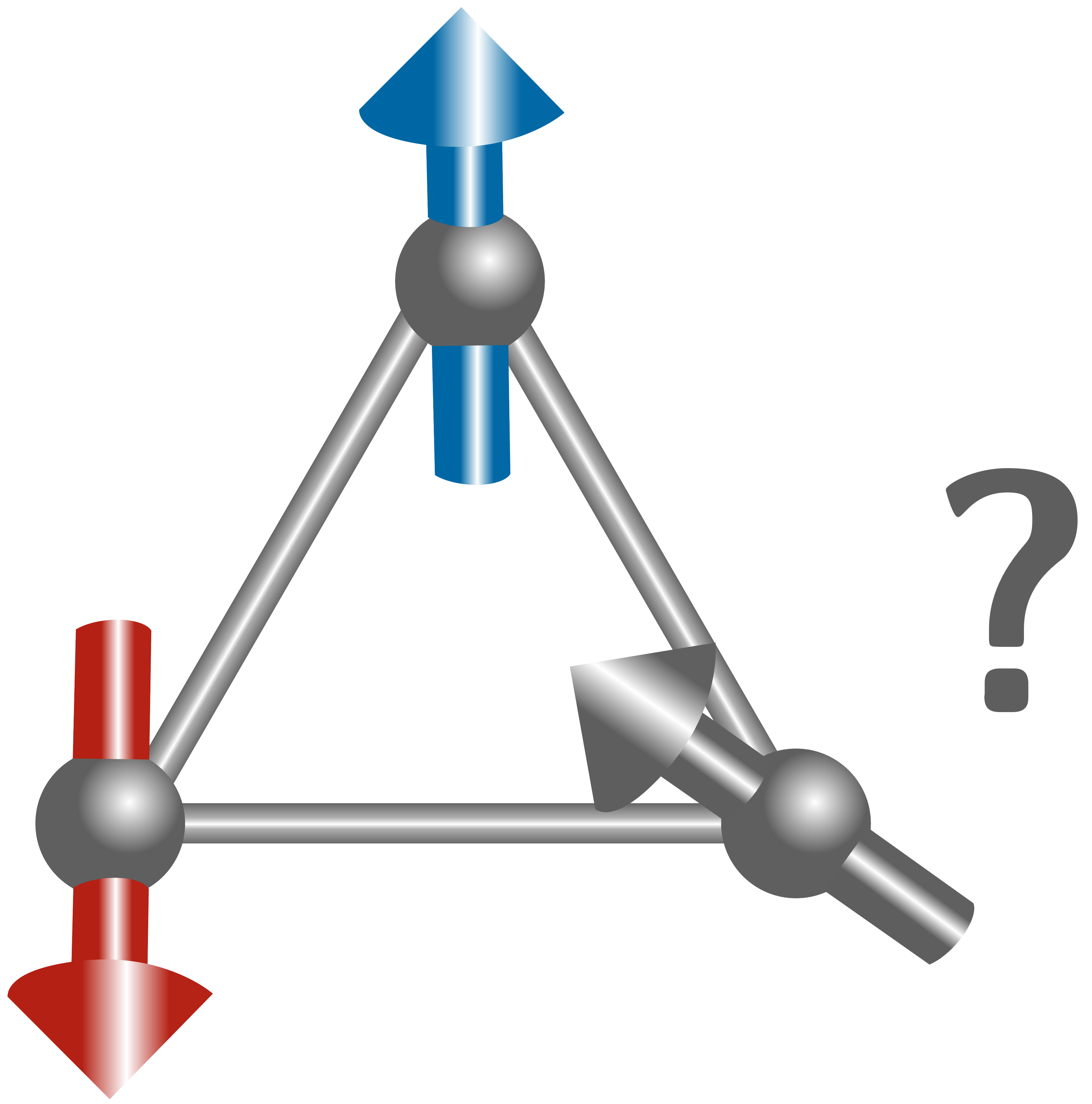


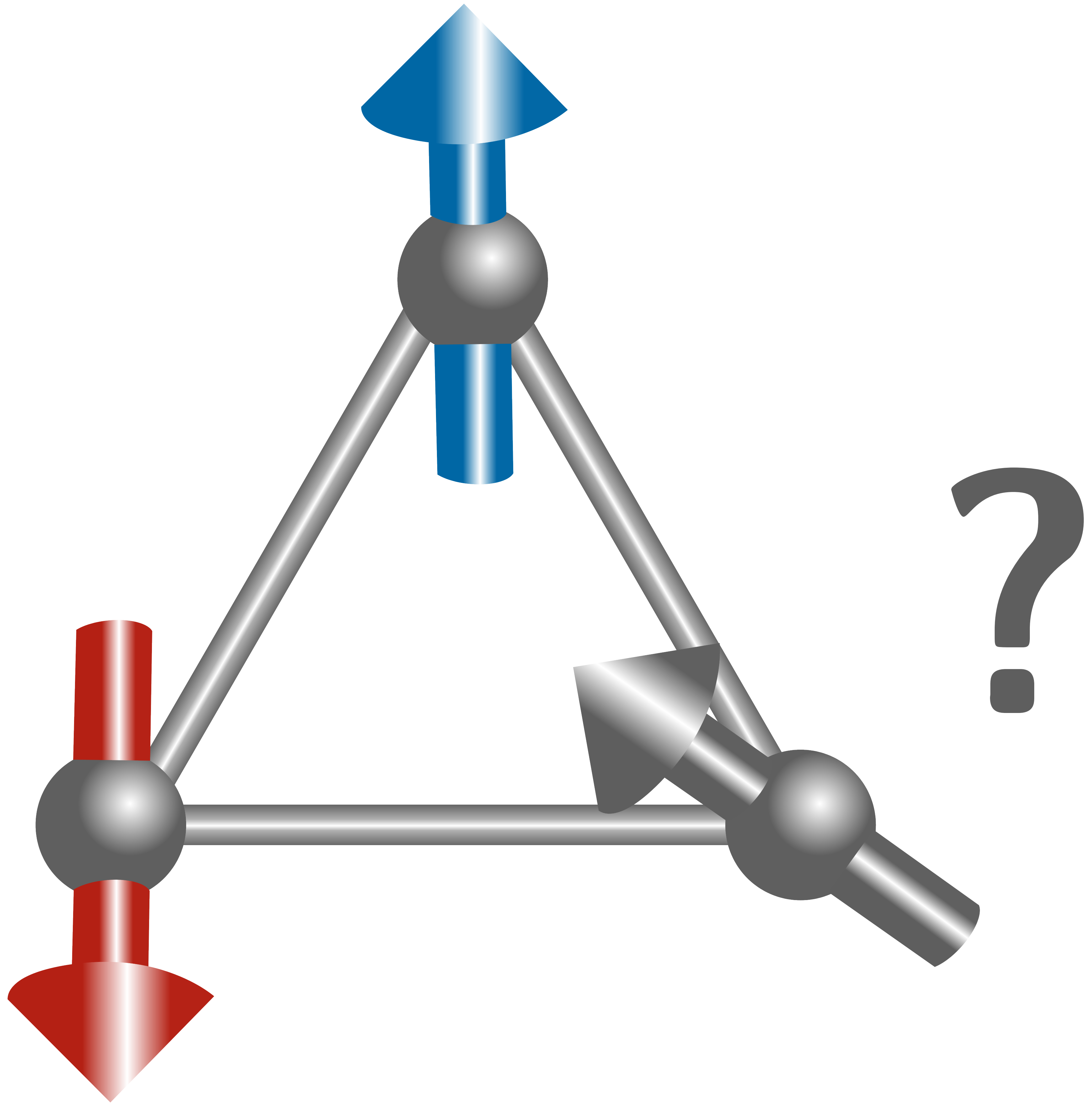
Ingredient #2: Frustration

Antiferromagnetic interaction:

$$\mathcal{H}_{ij} = J S_i^z S_j^z \qquad\qquad J > 0$$

Frustration:

Incompatible interactions



Ingredient #2: Frustration

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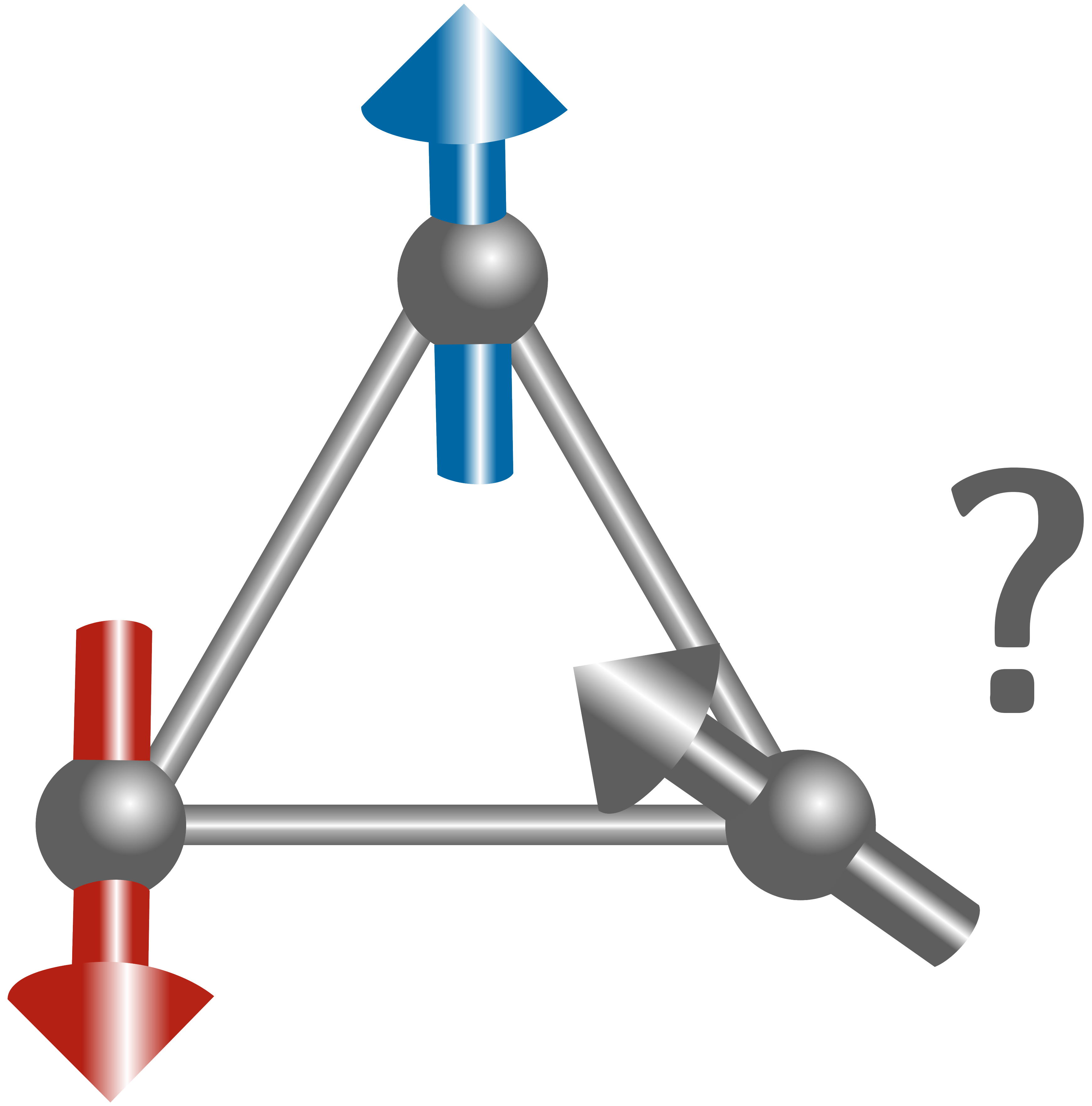


Frustration:

Incompatible interactions

New states of matter
with exotic excitations

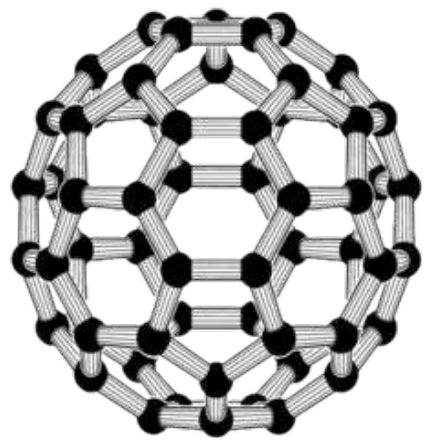
Majorana fermions

Conventional fermions:

$$f$$

$$f^\dagger$$

Majorana fermions

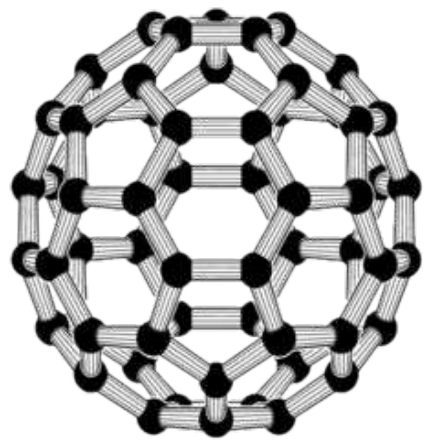


Conventional fermions:

$$f \qquad\qquad \text{with} \qquad f|1\rangle = |0\rangle \qquad f|0\rangle = 0$$

$$f^{\dagger} \qquad\qquad\qquad\qquad f^{\dagger}|1\rangle = 0 \qquad f^{\dagger}|0\rangle = |1\rangle$$

Majorana fermions



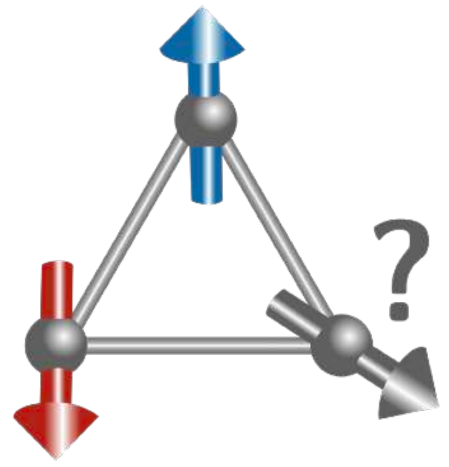
Conventional fermions:

$$\begin{matrix} f \\ f^\dagger \end{matrix} \qquad \text{with} \qquad \begin{matrix} f|1\rangle = |0\rangle & f|0\rangle = 0 \\ f^\dagger|1\rangle = 0 & f^\dagger|0\rangle = |1\rangle \end{matrix}$$

Particle number:

$$n = f^\dagger f \qquad = \begin{cases} 1 \\ 0 \end{cases}$$

Majorana fermions



$$f = \tfrac{1}{2}(c_1 + \mathrm{i}c_2) \qquad\qquad f|1\rangle = |0\rangle \qquad f|0\rangle = 0$$

with

$$f^\dagger = \tfrac{1}{2}(c_1 - \mathrm{i}c_2) \qquad\qquad f^\dagger|1\rangle = 0 \qquad f^\dagger|0\rangle = |1\rangle$$

Particle number:

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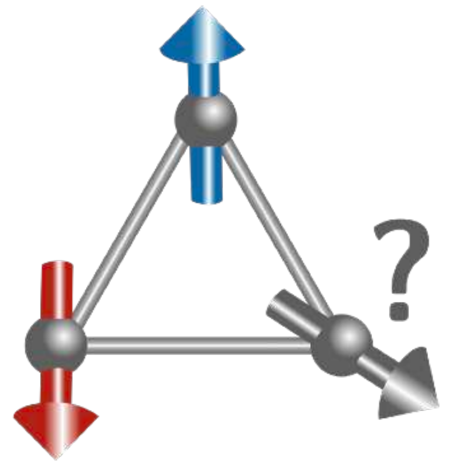
Majorana fermions



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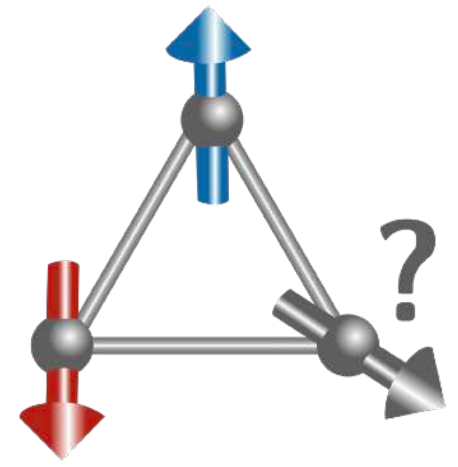
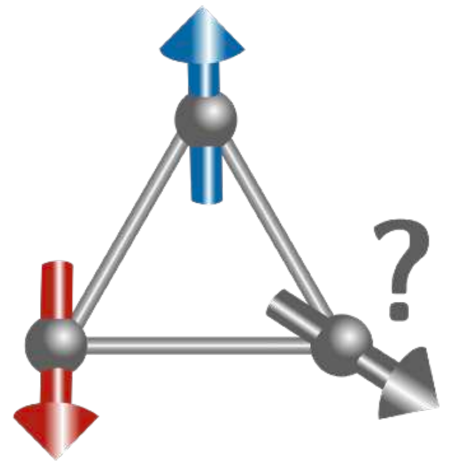


$$\begin{aligned} f &= \tfrac{1}{2}(c_1 + \mathrm{i}c_2) \\ f^\dagger &= \tfrac{1}{2}(c_1 - \mathrm{i}c_2) \end{aligned} \qquad \text{with} \qquad \begin{aligned} f|1\rangle &= |0\rangle \qquad & f|0\rangle &= 0 \\ f^\dagger|1\rangle &= 0 \qquad & f^\dagger|0\rangle &= |1\rangle \end{aligned}$$

Particle number:

$$n = f^\dagger f = \tfrac{1}{2}(1 + \mathrm{i}c_1 c_2) = \begin{cases} 1 & \text{if } \mathrm{i}c_1 c_2 = 1 \\ 0 & \text{if } \mathrm{i}c_1 c_2 = -1 \end{cases}$$

Majorana fermions



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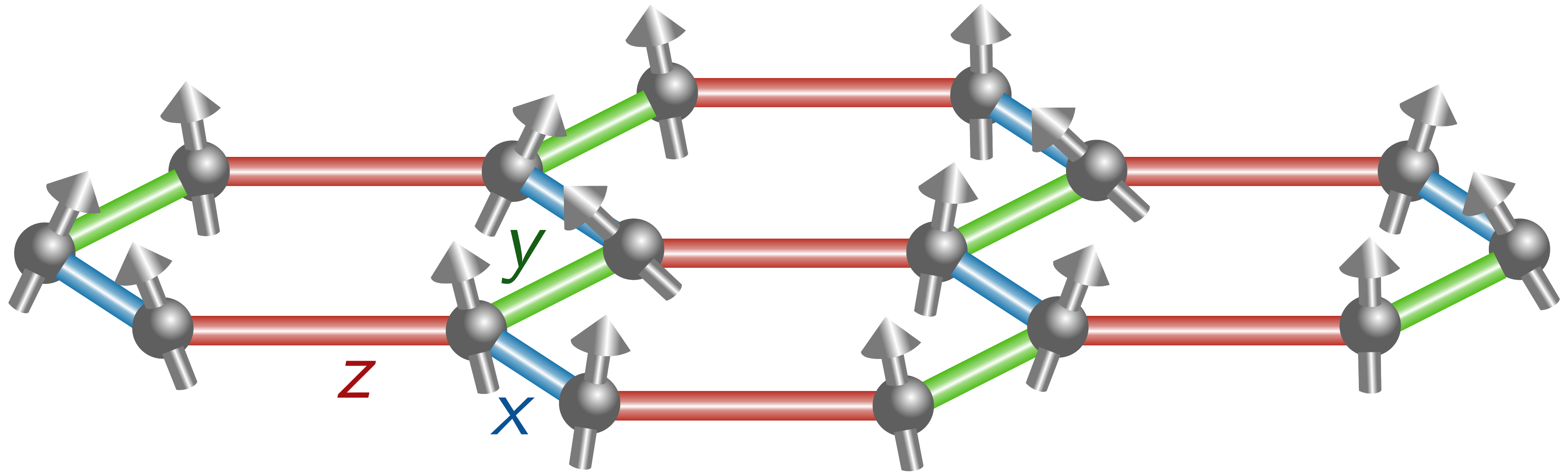
Potential delocalized information storage ✔

Kitaev quantum magnets

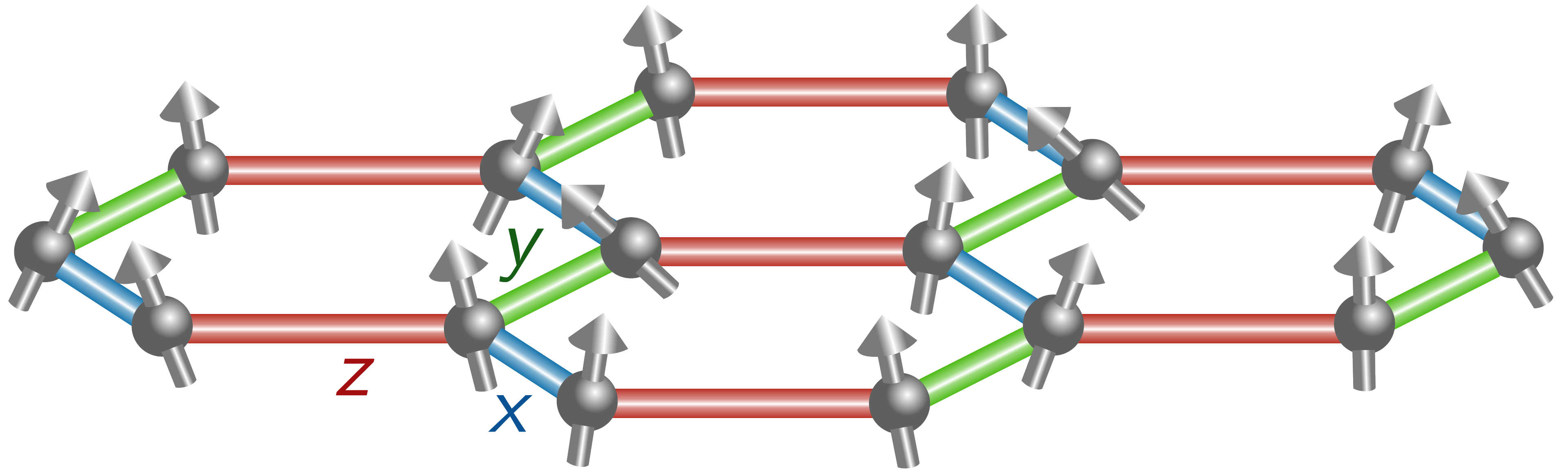


Hamiltonian:

$$\mathcal{H} = -K \left(\sum_{\langle ij \rangle_x} S_i^x S_j^x + \sum_{\langle ij \rangle_y} S_i^y S_j^y + \sum_{\langle ij \rangle_z} S_i^z S_j^z \right)$$

[Kitaev, Ann. Phys. '06]

Kitaev quantum magnets



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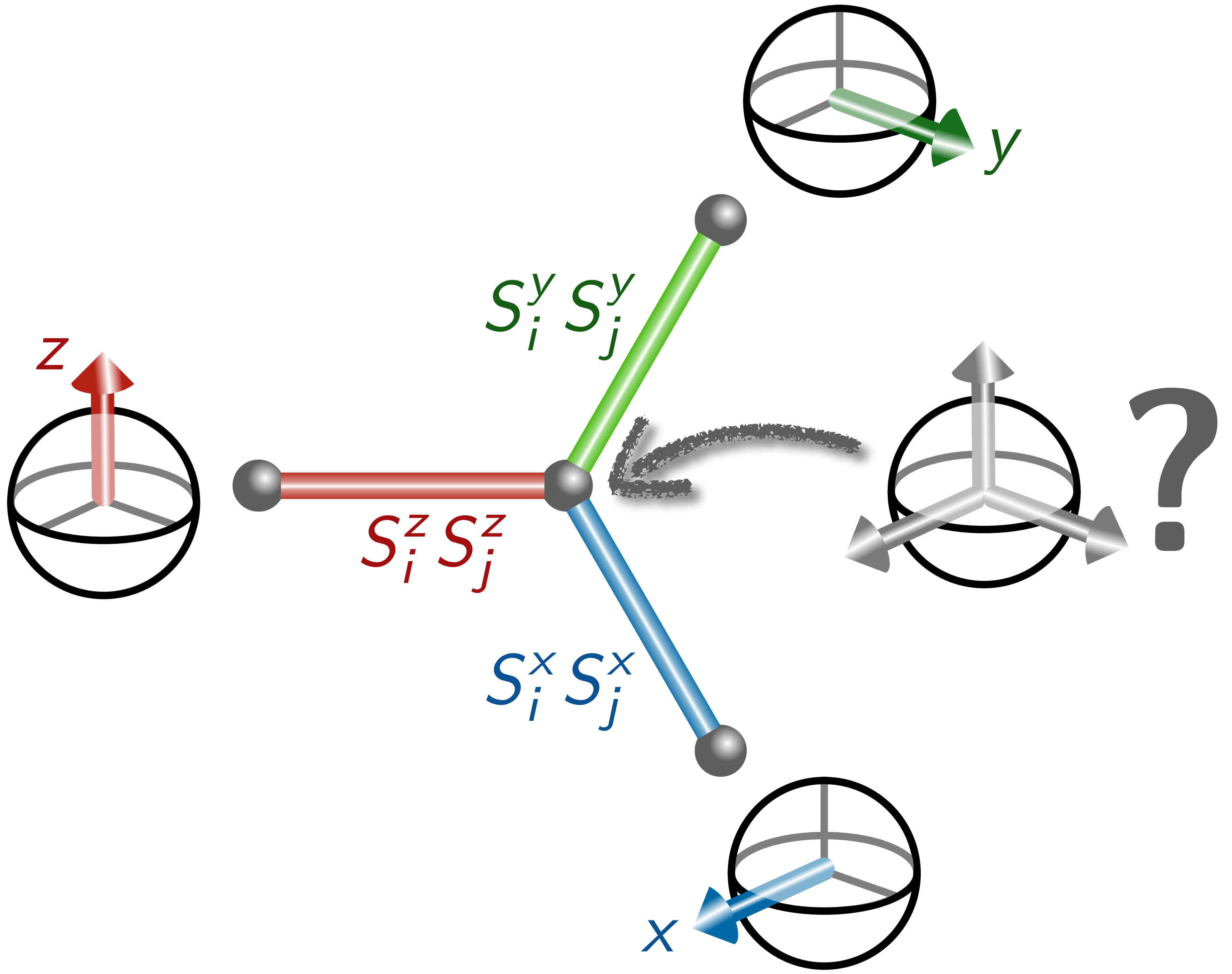
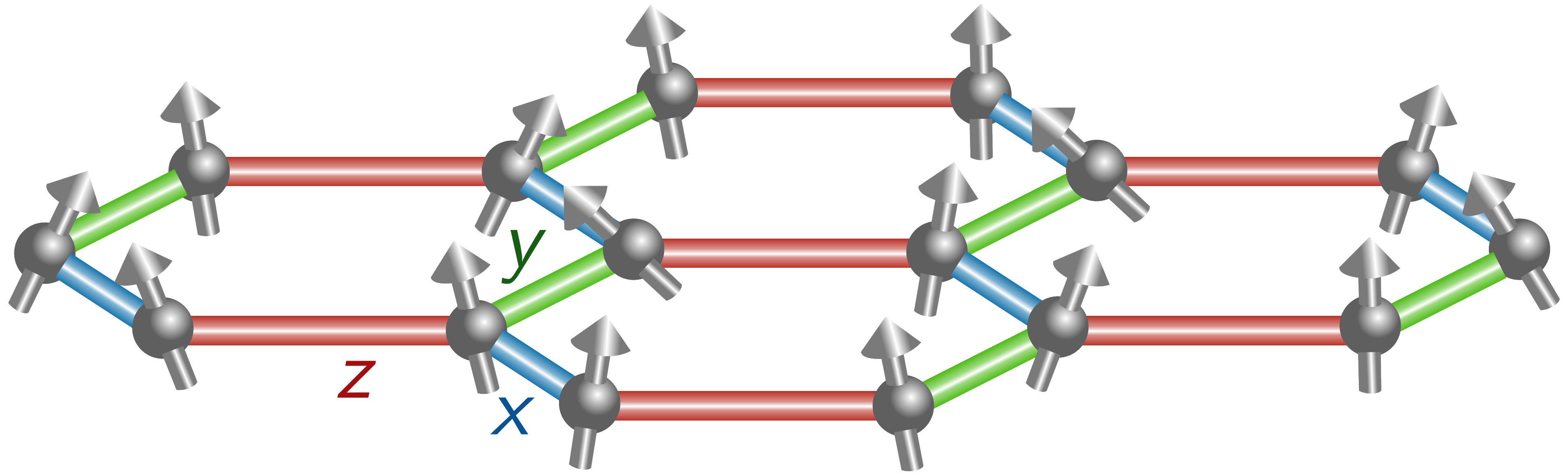
Frustration:



[Kitaev, Ann. Phys. ’06]

Kitaev quantum magnets



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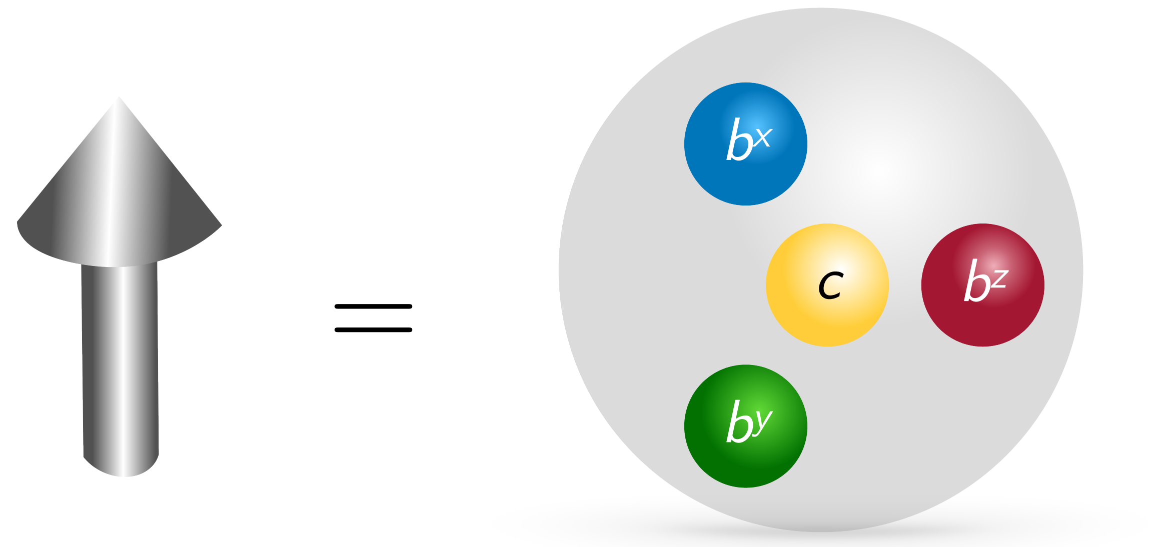
Majorana representation:

$$\begin{aligned} S_i^x &= \frac{i\hbar}{2} b_i^x c_i \\ S_i^y &= \frac{i\hbar}{2} b_i^y c_i \\ S_i^z &= \frac{i\hbar}{2} b_i^z c_i \end{aligned}$$

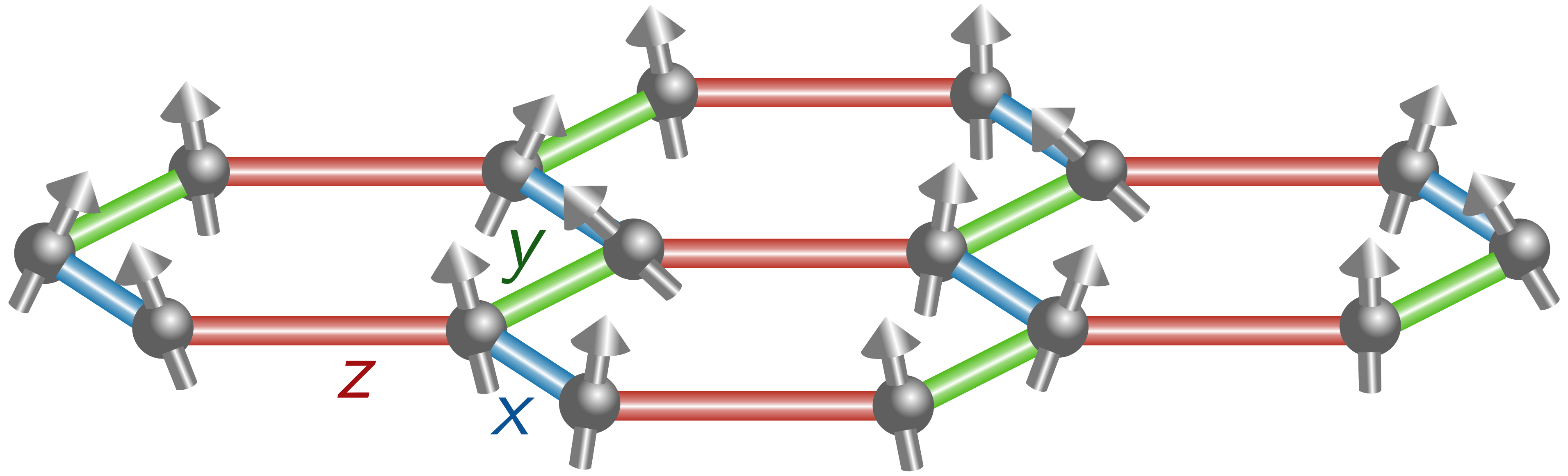


Spin

4 Majoranas
with gauge constraint

[Kitaev, Ann. Phys. '06]

Kitaev quantum magnets



Hamiltonian:

$$\mathcal{H} = -K\left(\sum_{\langle ij\rangle_x} S_i^x S_j^x + \sum_{\langle ij\rangle_y} S_i^y S_j^y + \sum_{\langle ij\rangle_z} S_i^z S_j^z\right) = -\frac{\mathrm{i}\hbar^2 K}{4}\sum_{\langle ij\rangle_\alpha}(\mathrm{i}b_i^\alpha b_j^\alpha)c_i c_j$$

Majorana representation:

$$S_i^x = \frac{\mathrm{i}\hbar}{2} b_i^x c_i$$
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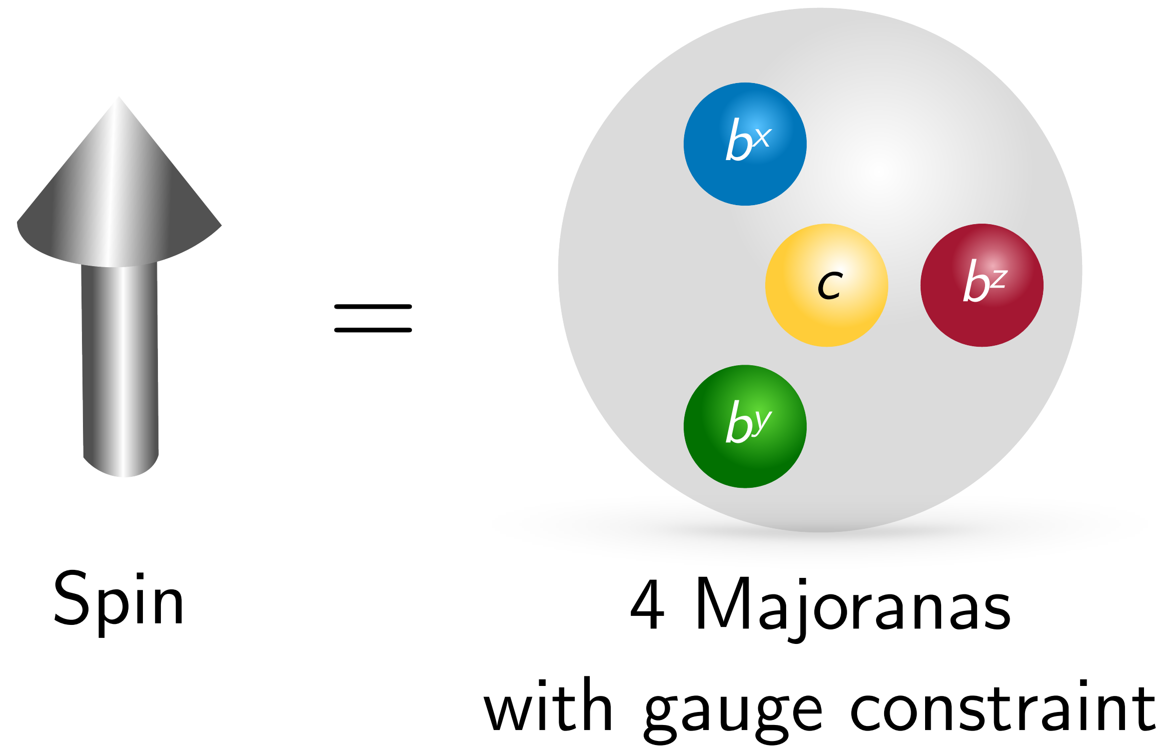
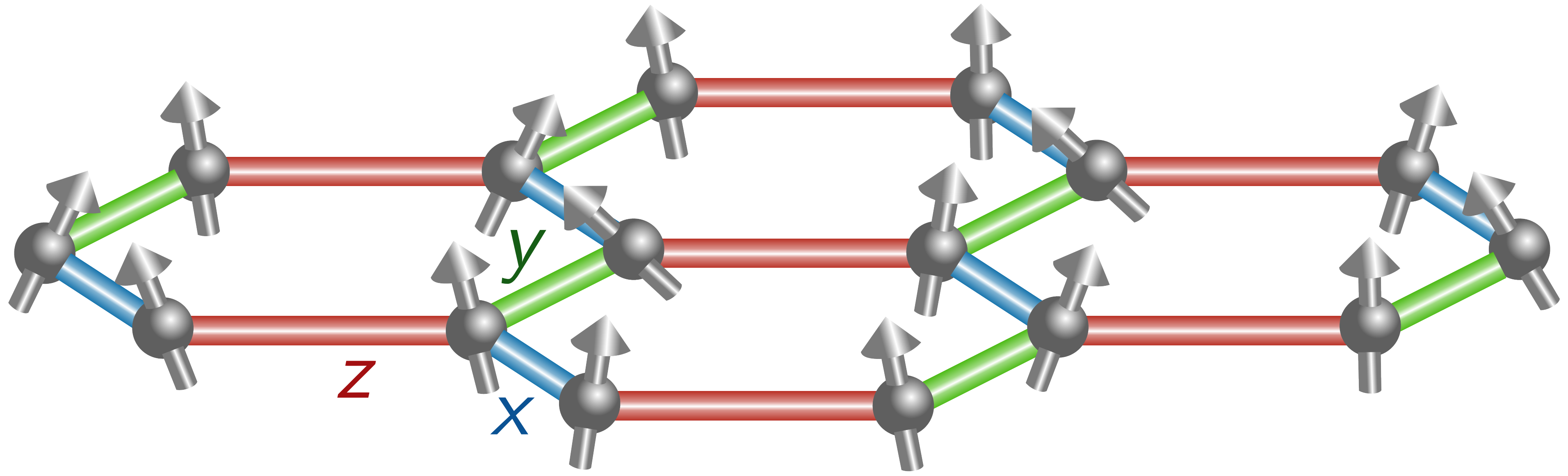


[Kitaev, Ann. Phys. '06]

Kitaev quantum magnets



Hamiltonian:

$$\mathcal{H} = -K \left(\sum_{\langle ij \rangle_x} S_i^x S_j^x + \sum_{\langle ij \rangle_y} S_i^y S_j^y + \sum_{\langle ij \rangle_z} S_i^z S_j^z \right) = -\frac{i\hbar^2 K}{4} \sum_{\langle ij \rangle_\alpha} \underbrace{(i b_i^\alpha b_j^\alpha)}_{\equiv \hat{u}_{ij} = \hat{u}_{ij}^\dagger} c_i c_j \qquad \text{with } \left[\hat{u}_{ij}, \tilde{\mathcal{H}}\right] = 0$$

Majorana representation:

$$S_i^x = \frac{i\hbar}{2} b_i^x c_i$$
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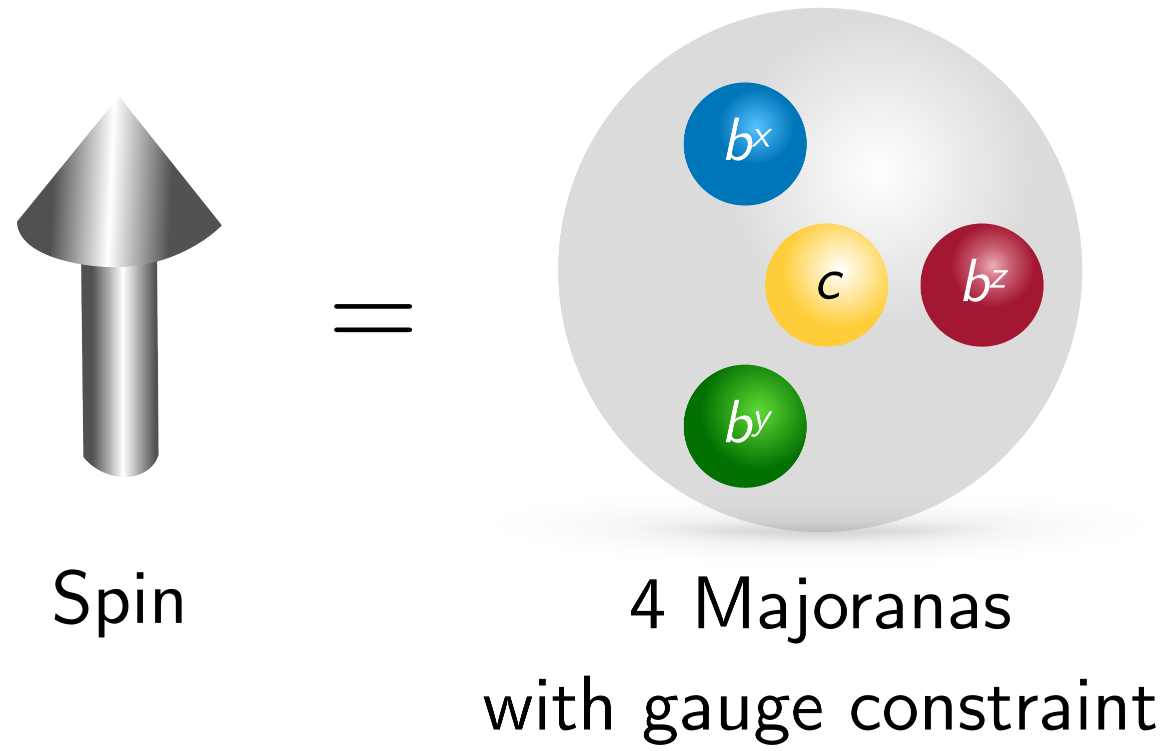
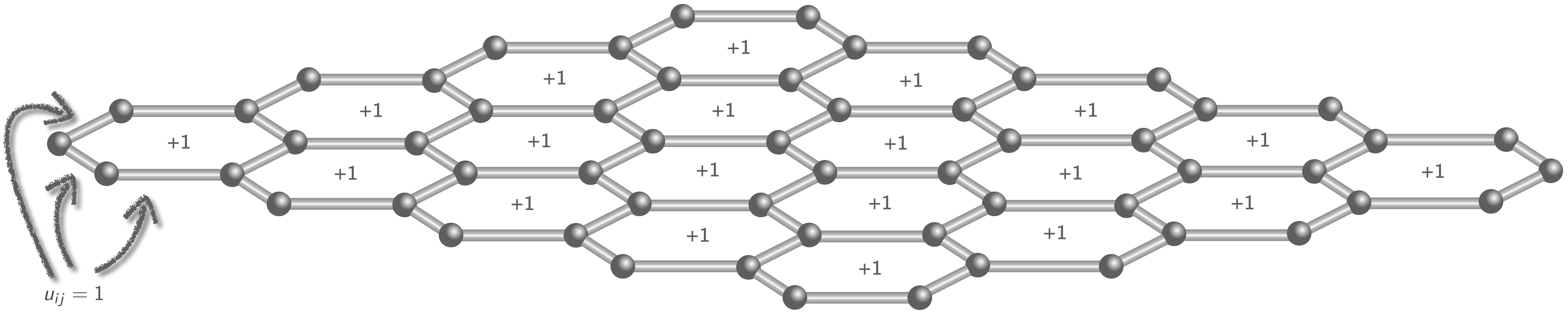
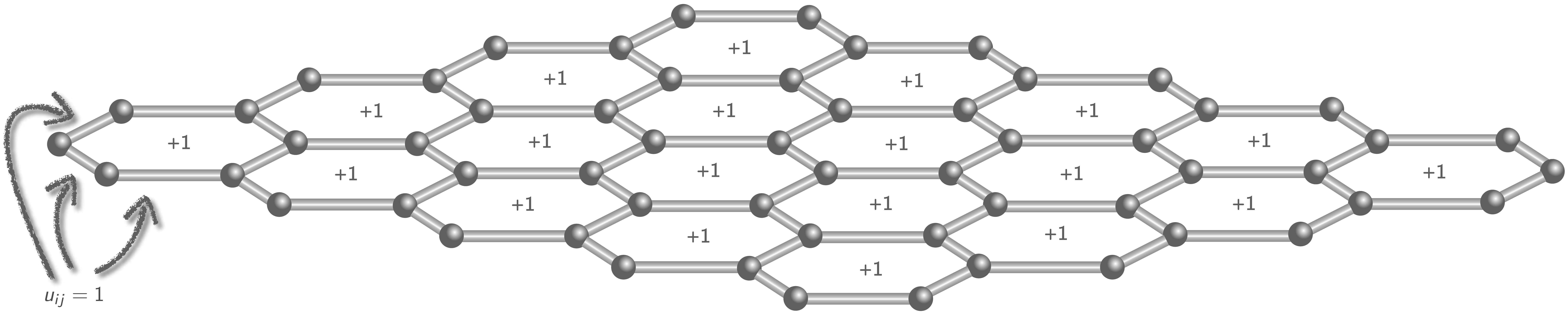


[Kitaev, Ann. Phys. '06]

Kitaev quantum spin liquid: Ground state



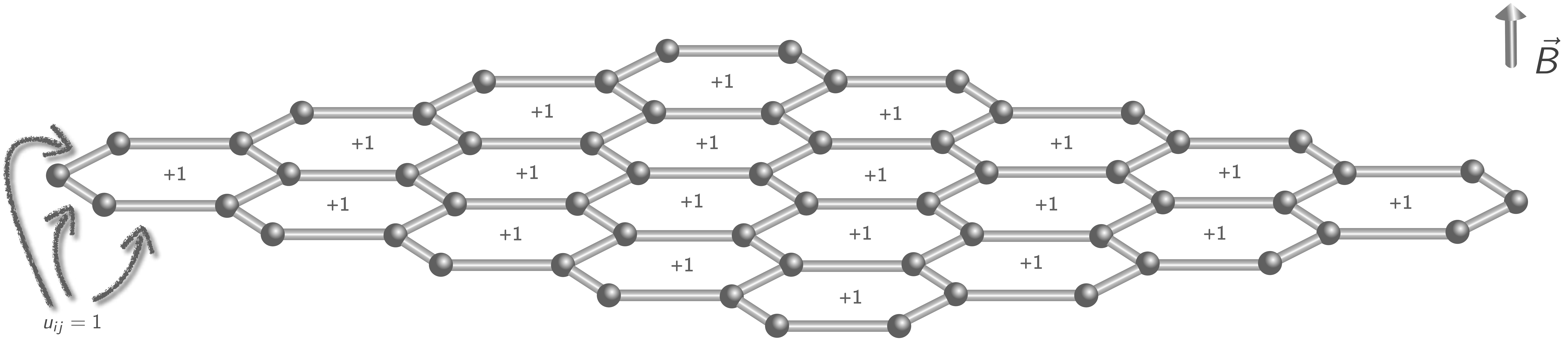
Kitaev quantum spin liquid: Ground state



Majorana spectrum:

$B = 0$

Kitaev quantum spin liquid: Ground state



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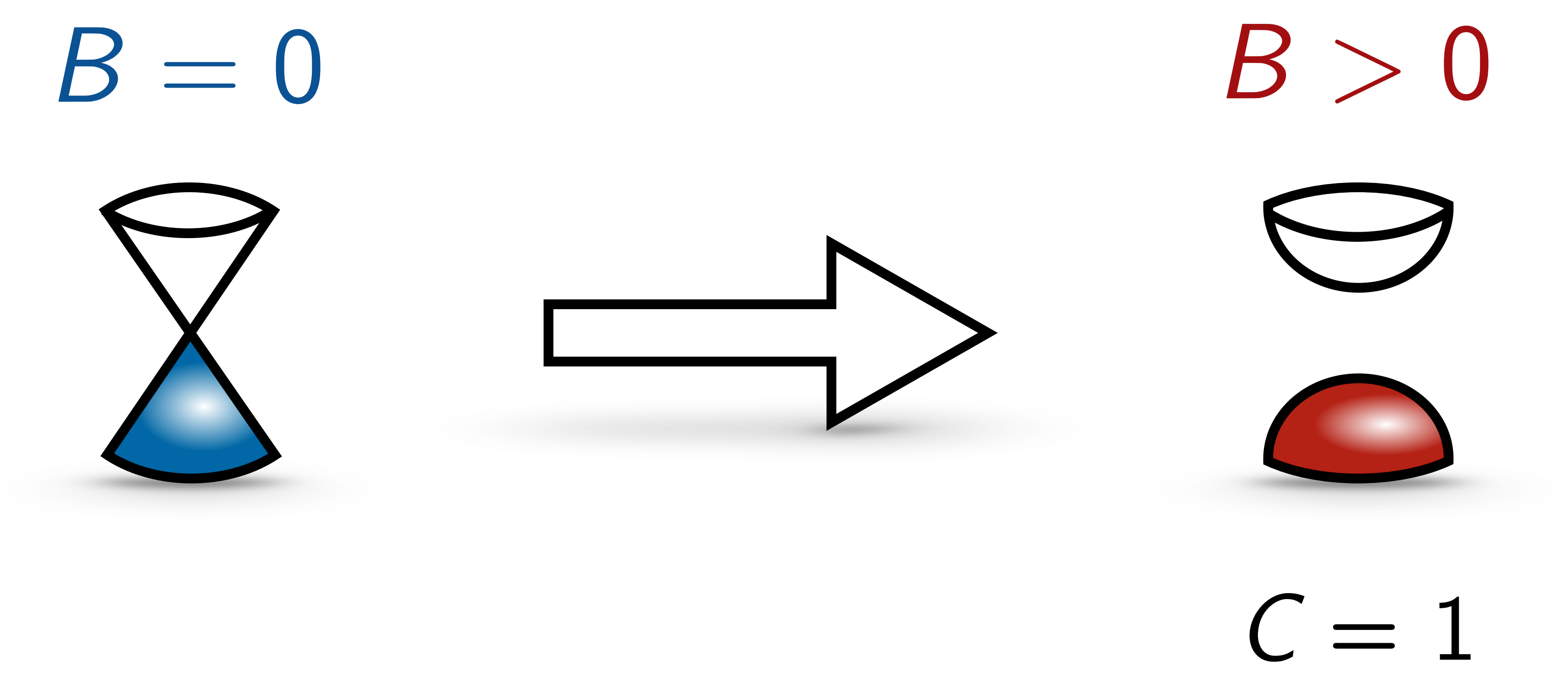
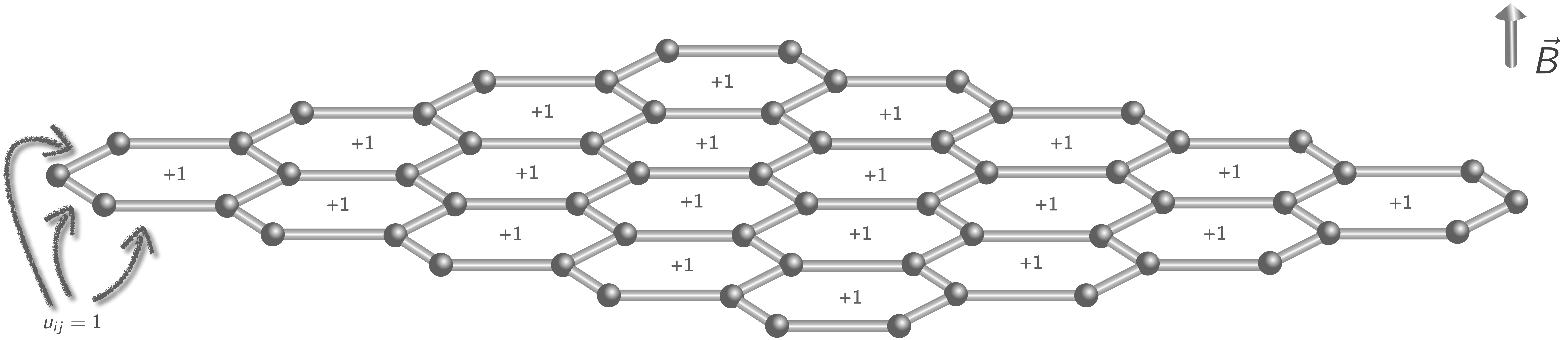
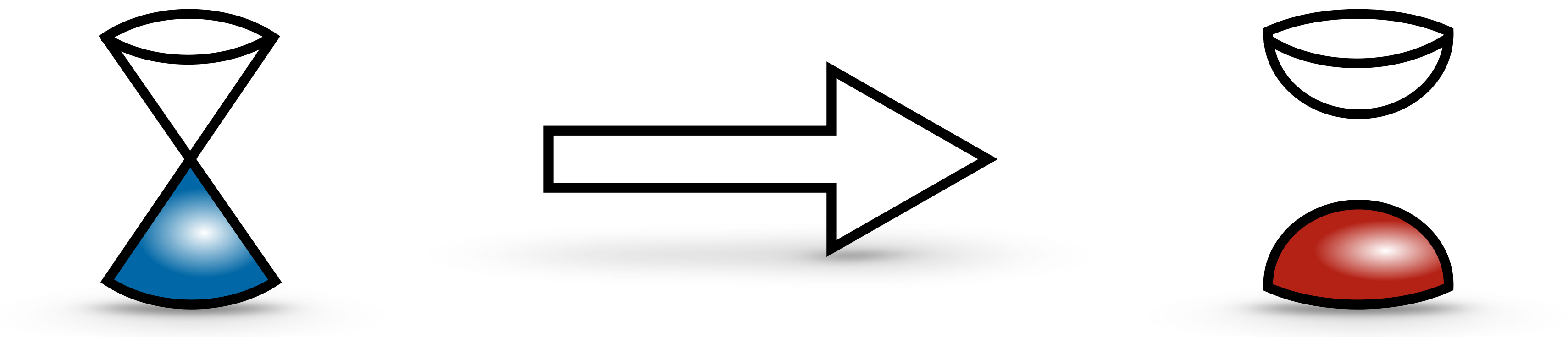


Kitaev quantum spin liquid: Ground state



Majorana spectrum:

$B = 0$ $\quad$ $B > 0$

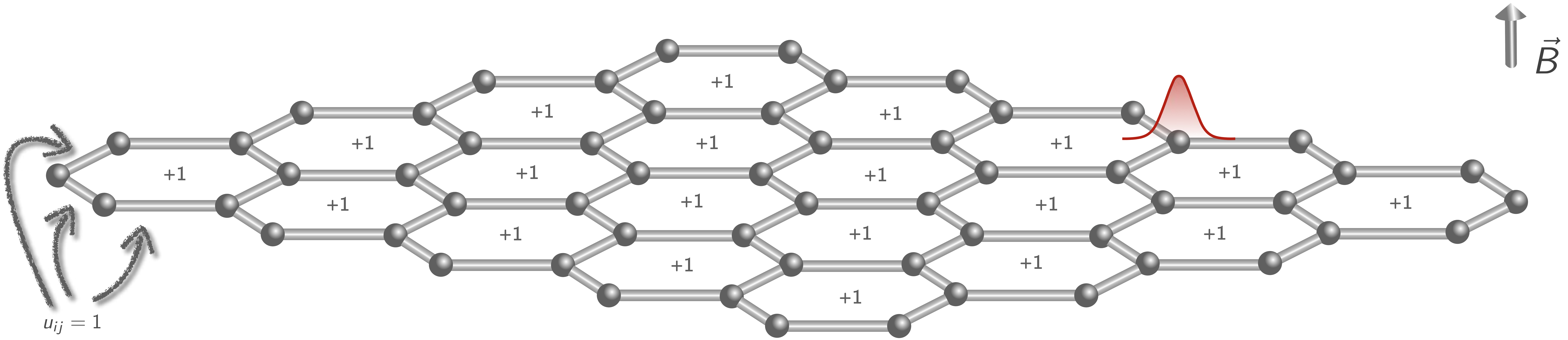


$C = 1$

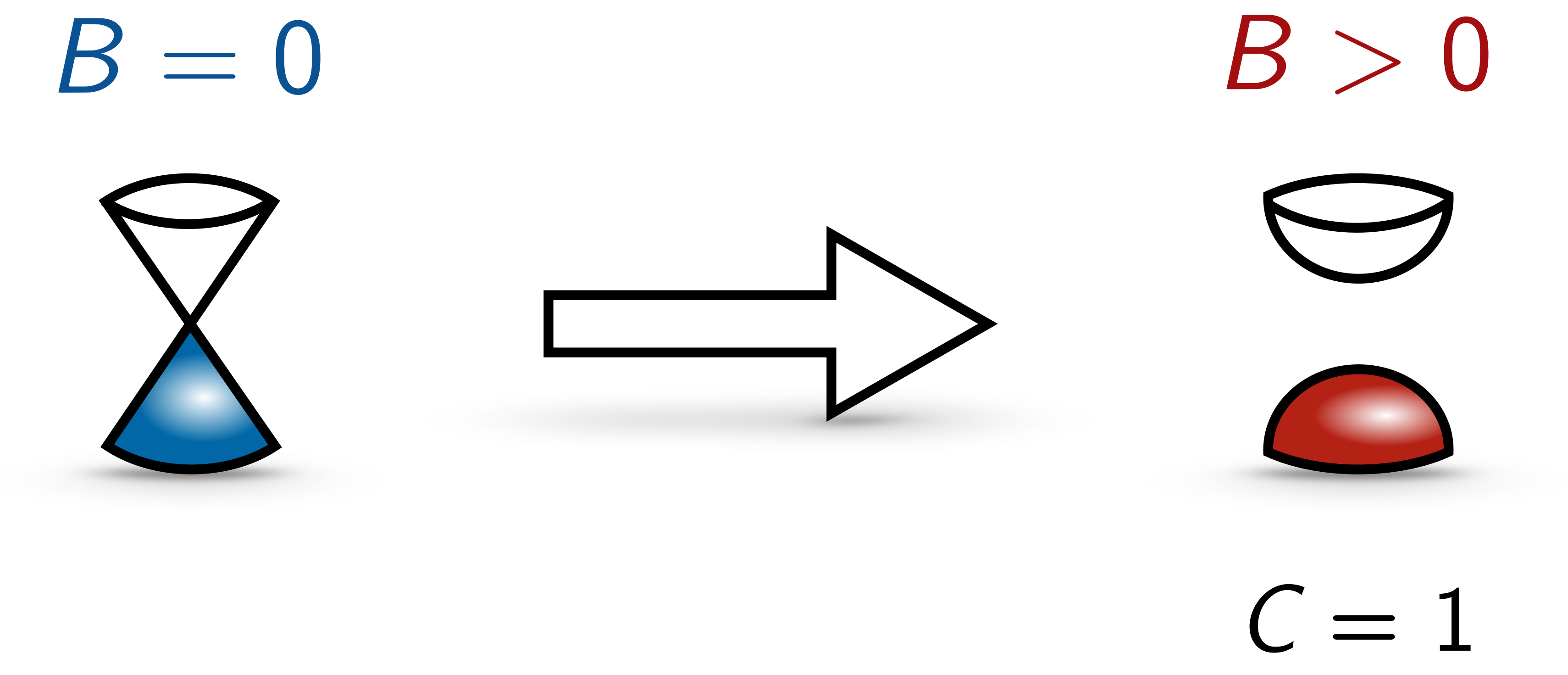
Fractionalized version of topological insulator

... half-quantized thermal Hall response

Kitaev quantum spin liquid: Excitations



Majorana spectrum:



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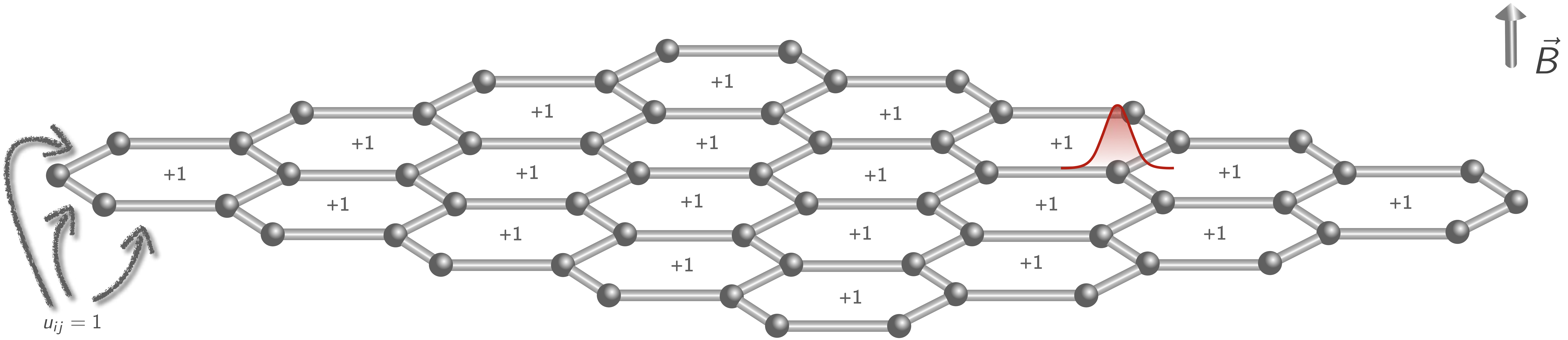
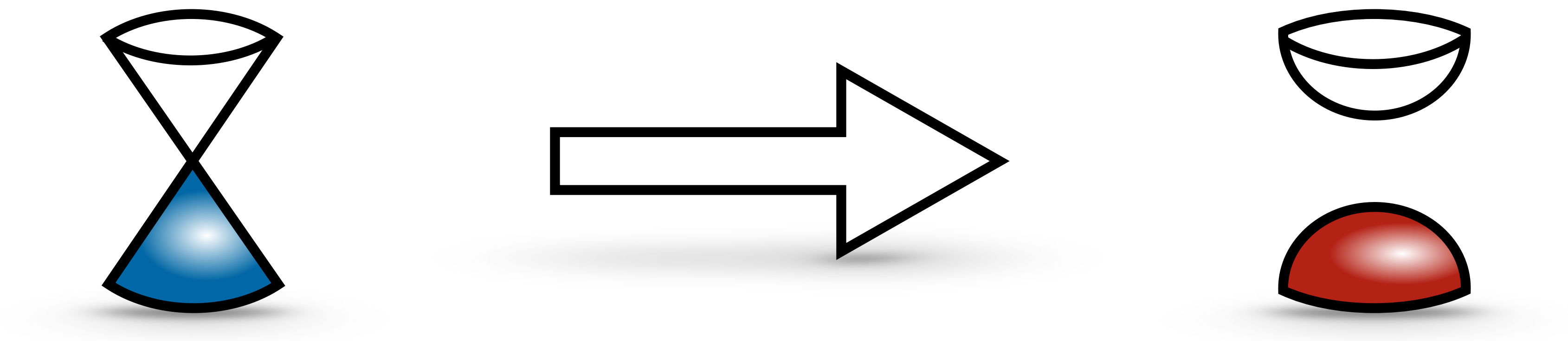
Kitaev quantum spin liquid: Excitations



Majorana spectrum:

$B = 0$ $B > 0$



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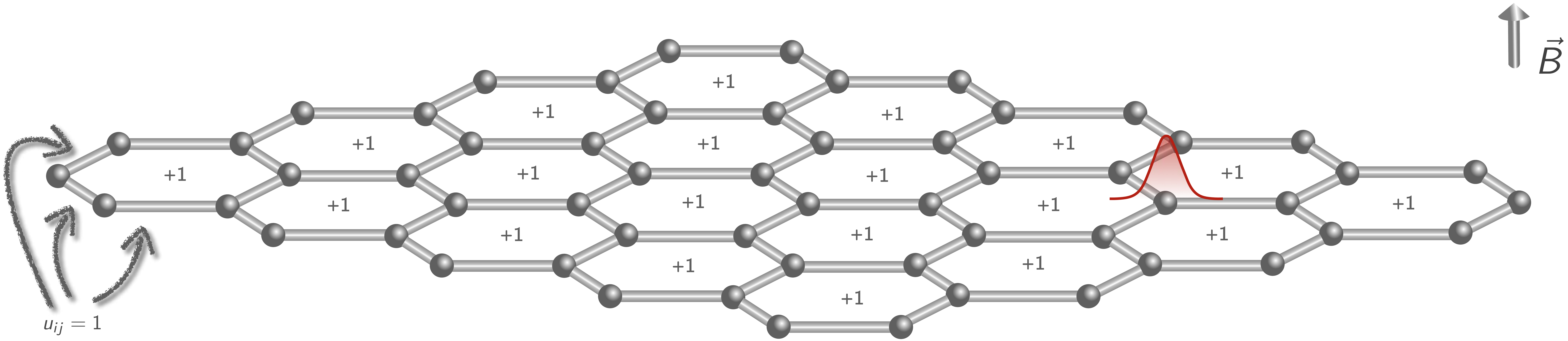
Kitaev quantum spin liquid: Excitations



Majorana spectrum:

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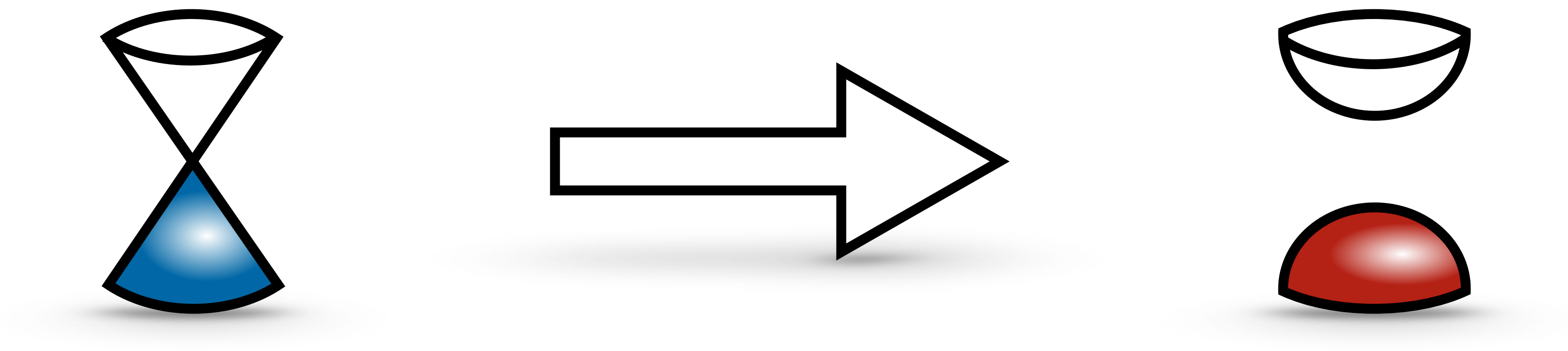

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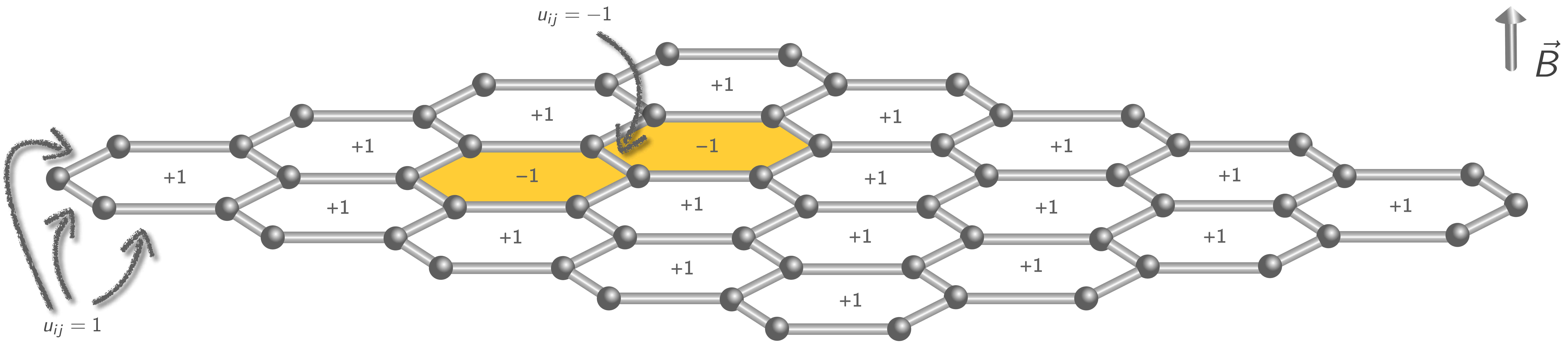
Kitaev quantum spin liquid: Excitations



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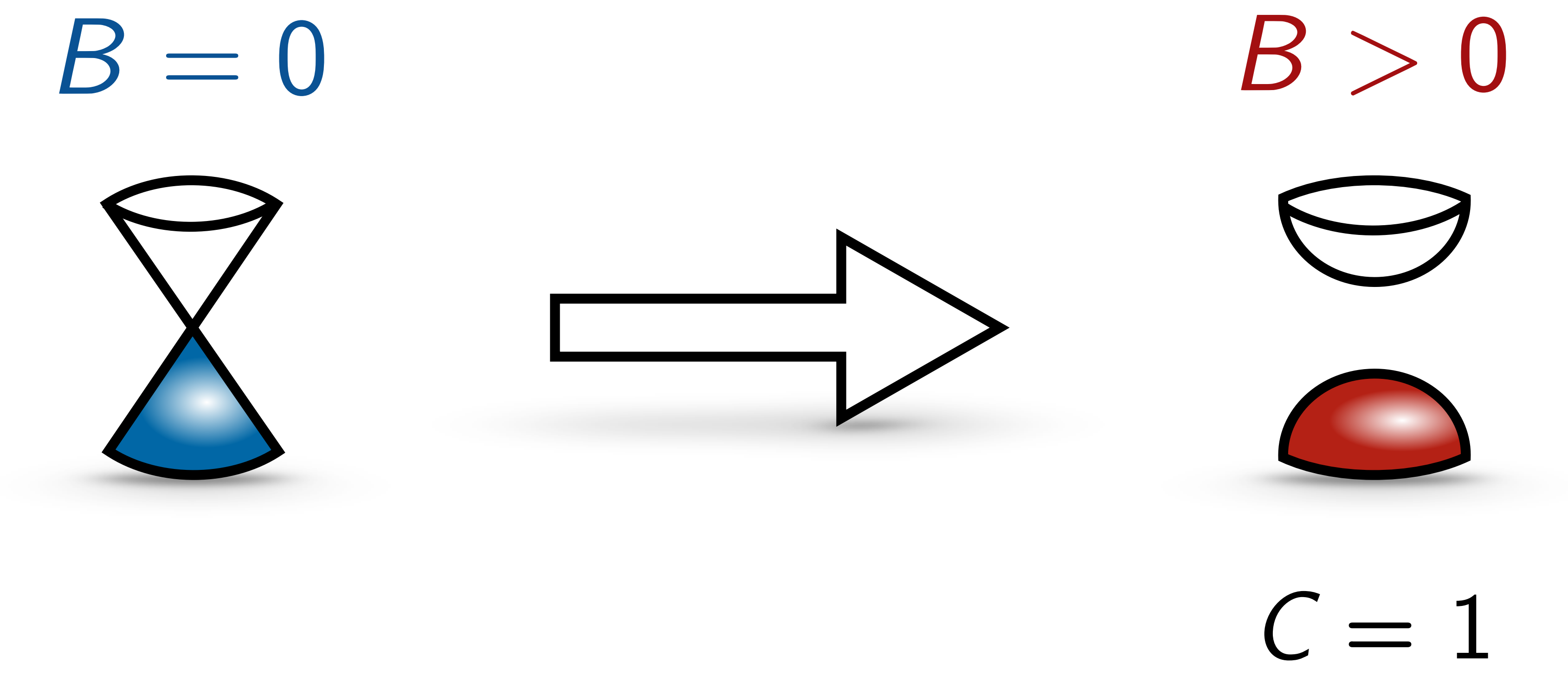

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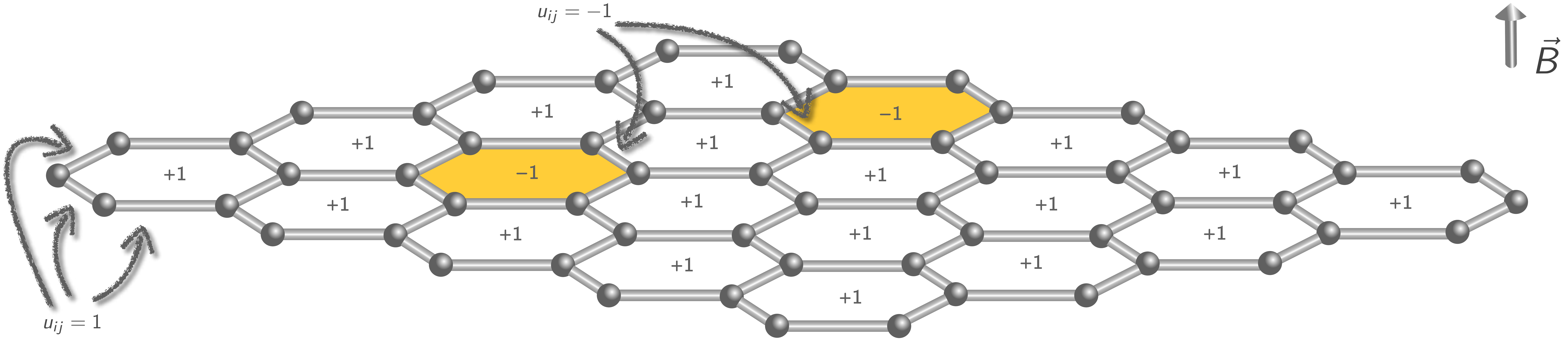
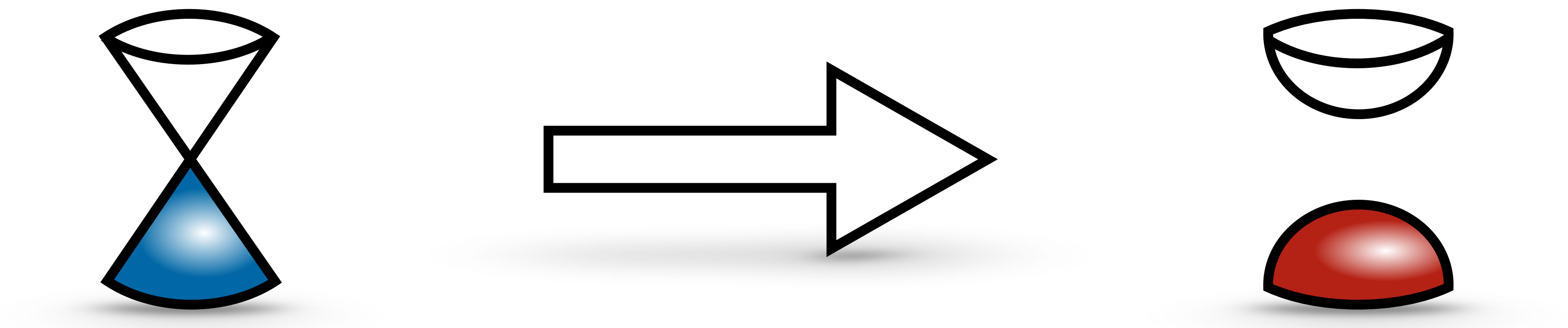
... half-quantized thermal Hall response

Kitaev quantum spin liquid: Excitations



Majorana spectrum:

$B = 0$ $B > 0$



$C = 1$

Fractionalized version of topological insulator

... half-quantized thermal Hall response

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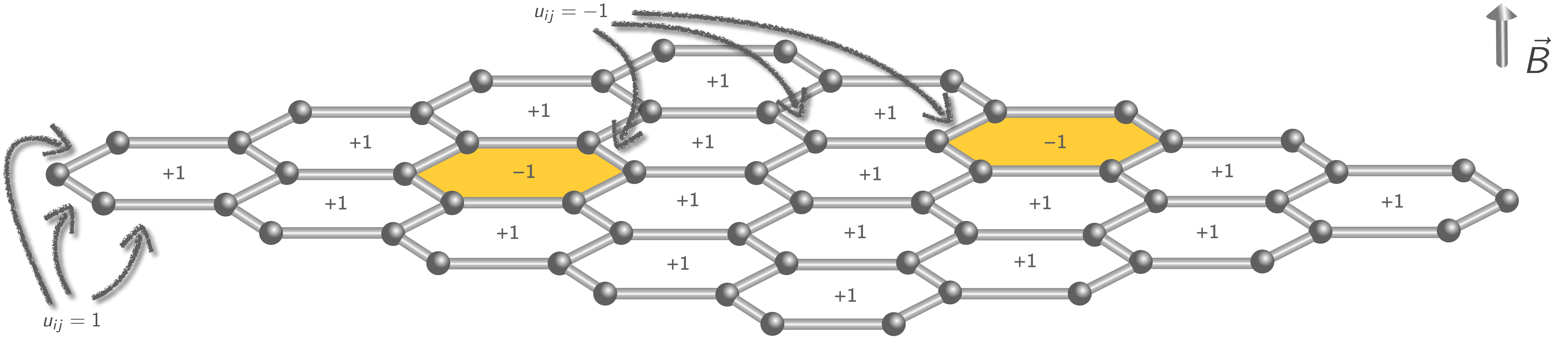

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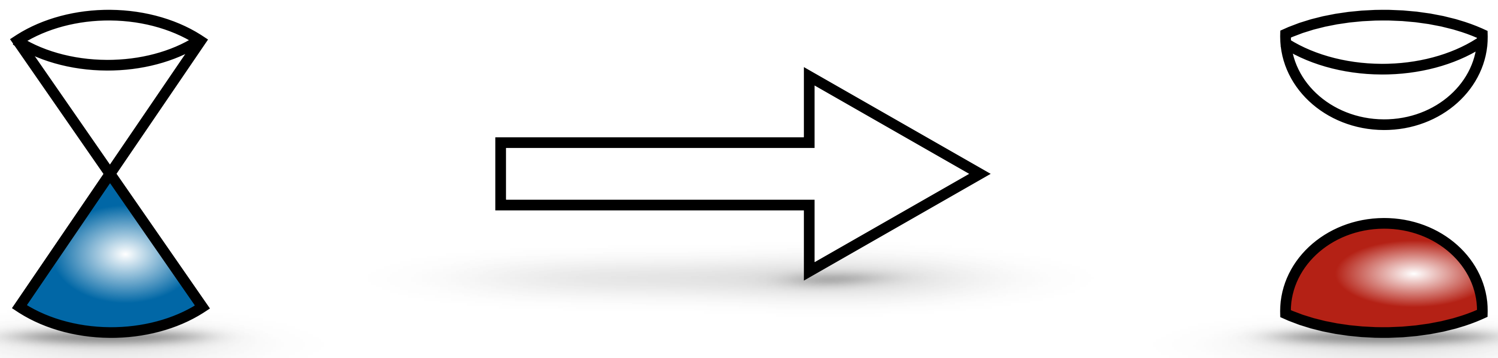

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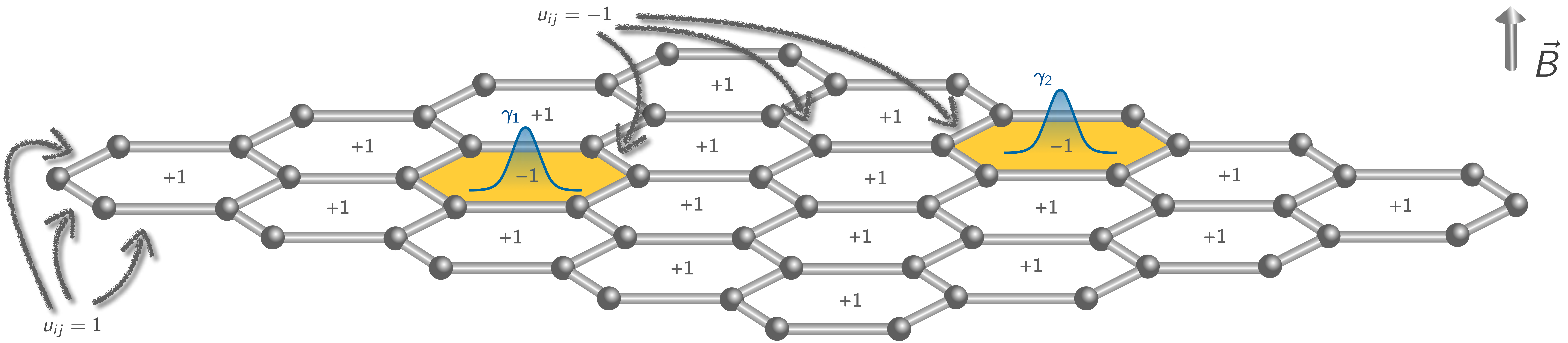

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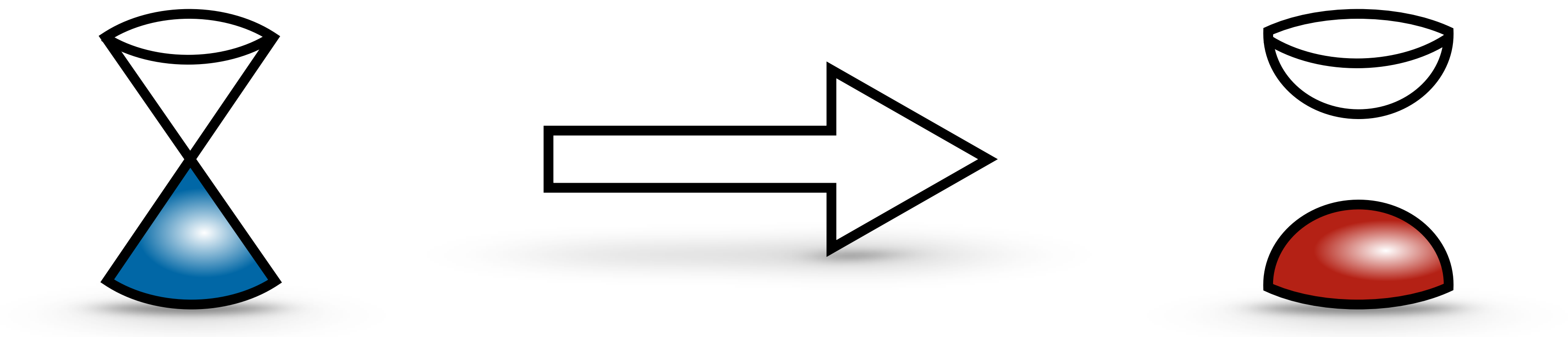

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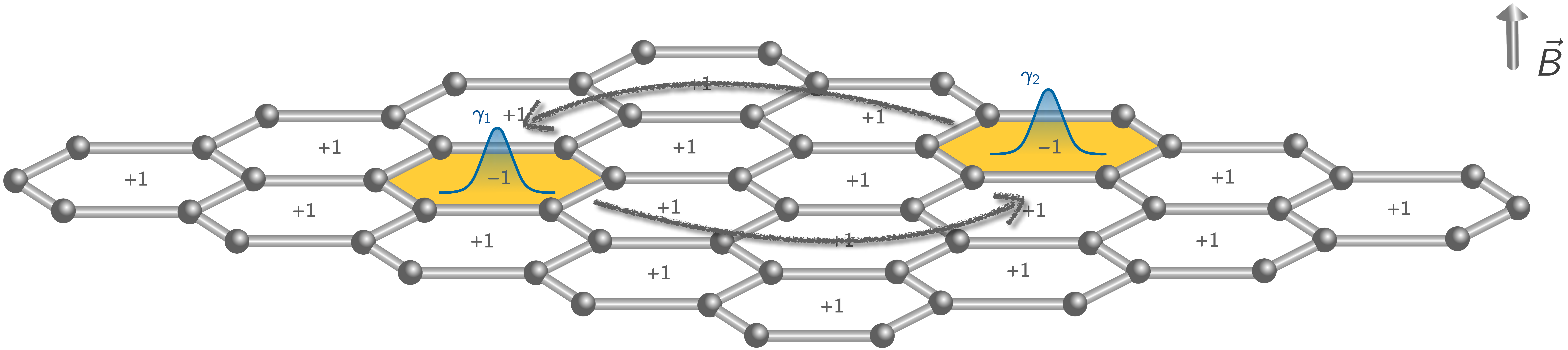

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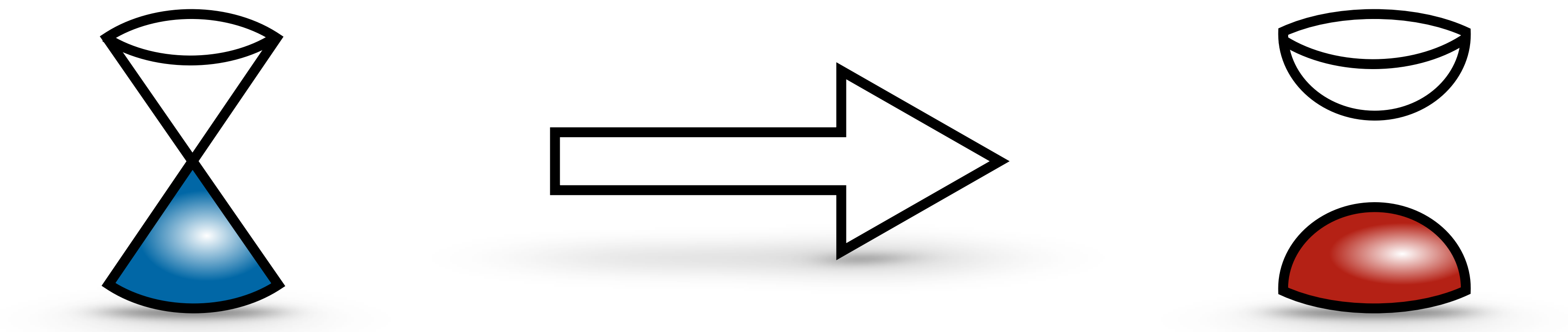

$C = 1$

Braiding:

$$\begin{pmatrix} \gamma_1 \\ \gamma_2 \end{pmatrix} \mapsto \pm \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \gamma_1 \\ \gamma_2 \end{pmatrix}$$

... non-Abelian anyons

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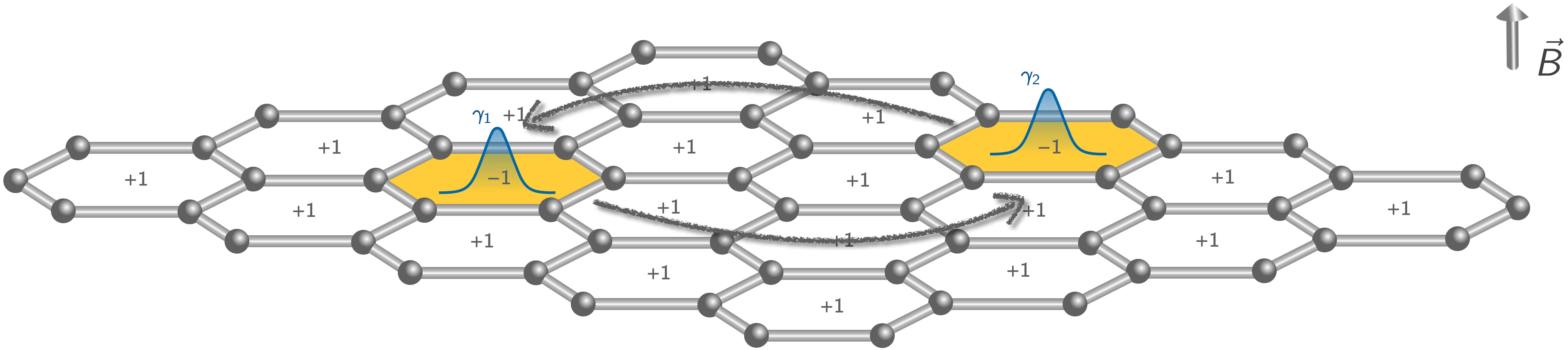

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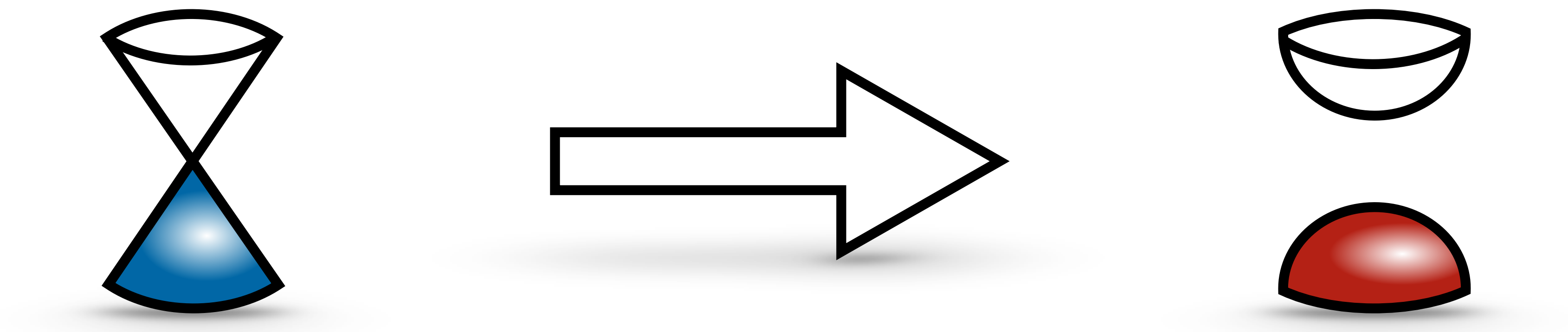

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... non-Abelian anyons

$\Rightarrow$ Fault-tolerant quantum computing

[Kitaev, Ann. Phys. '06]

Outline

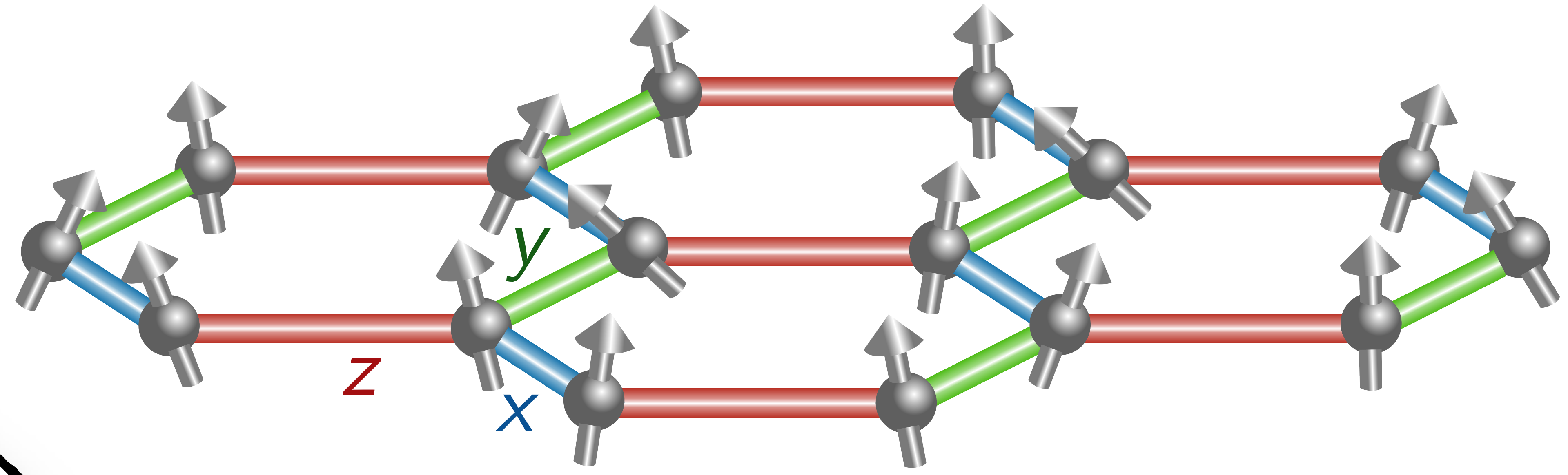
(1) Introduction: Emergence

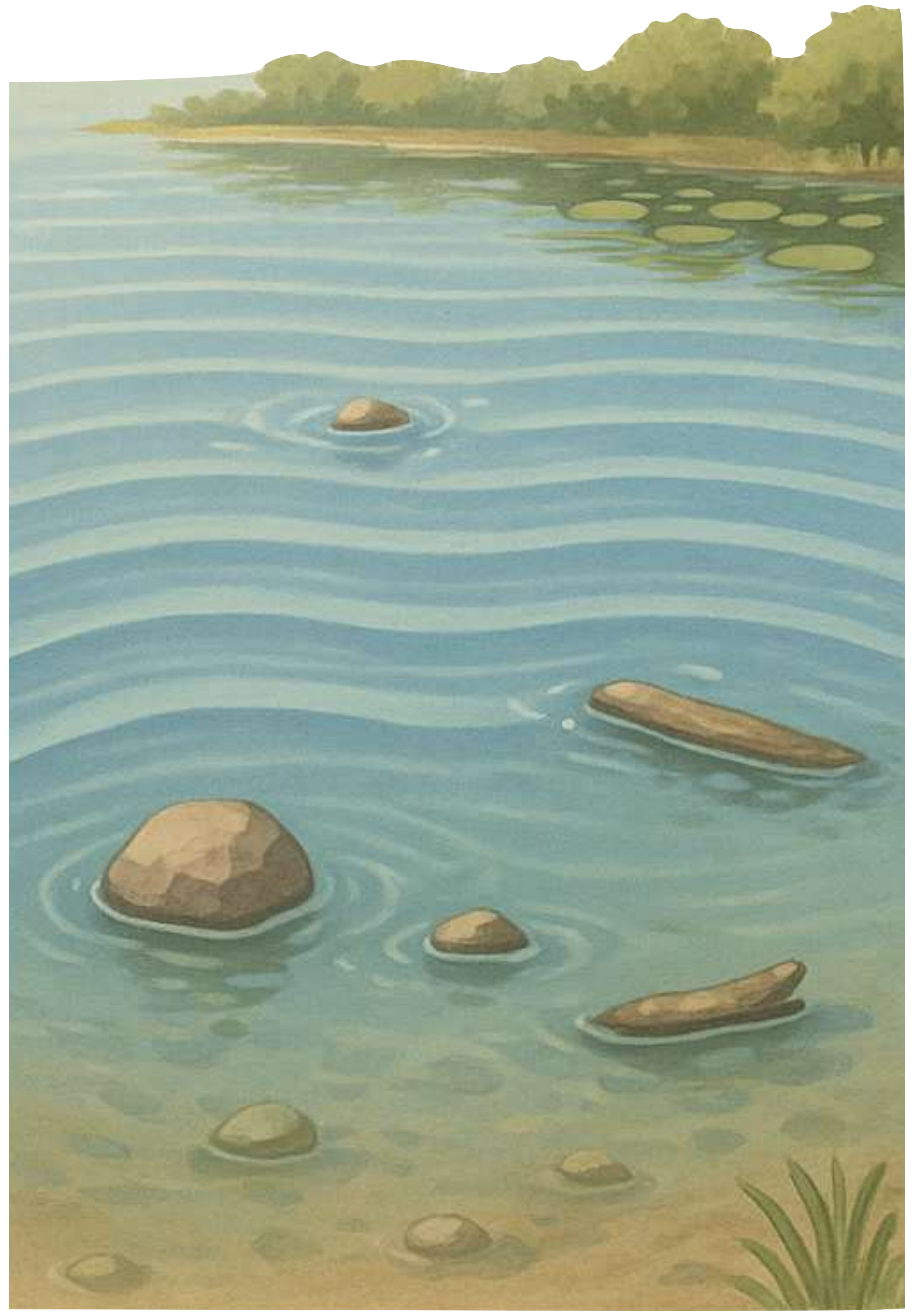
(2) Quantum materials

(3) Emergent phenomena for Quantum Saxony

(4) Summary

Emergent phenomena in quantum materials

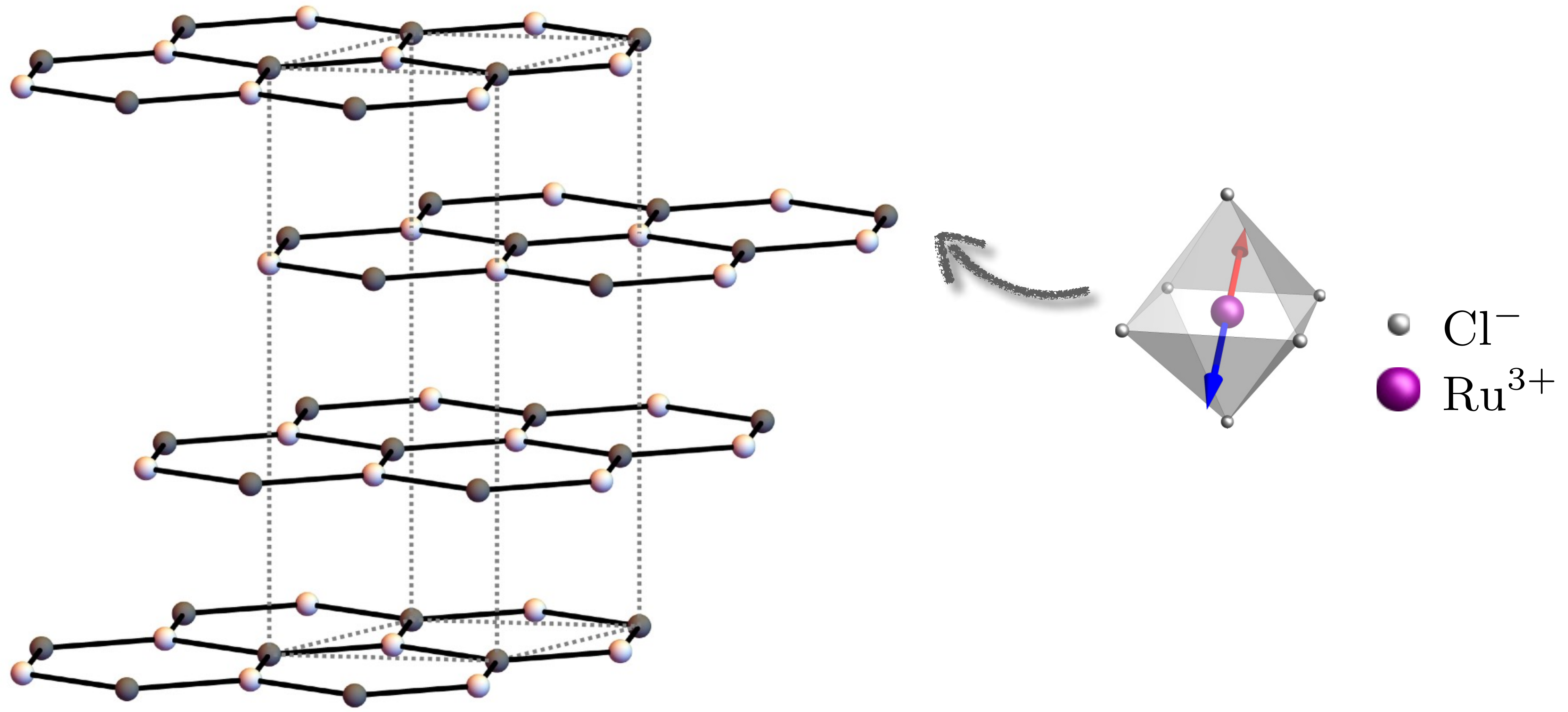


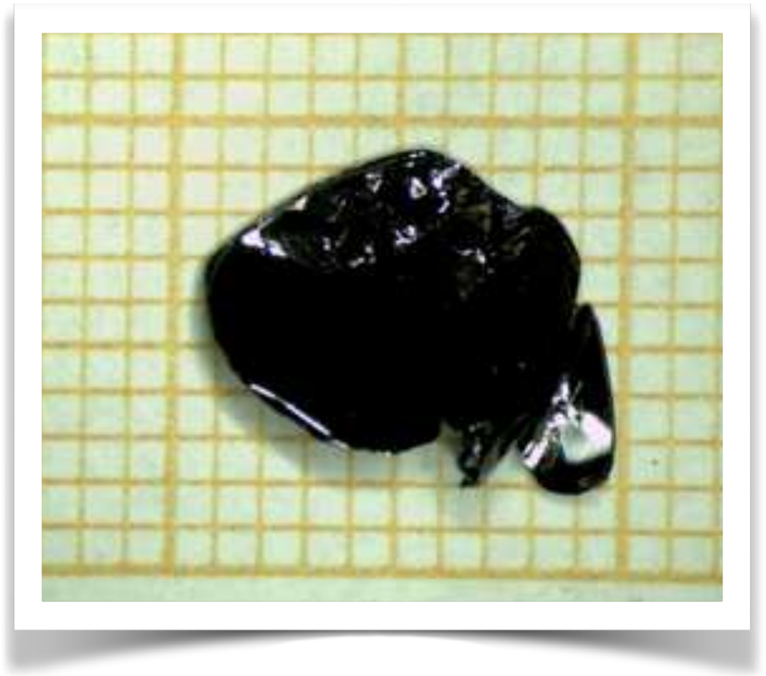


Coherent quantum wave

α-RuCl$_3$

Crystal structure:



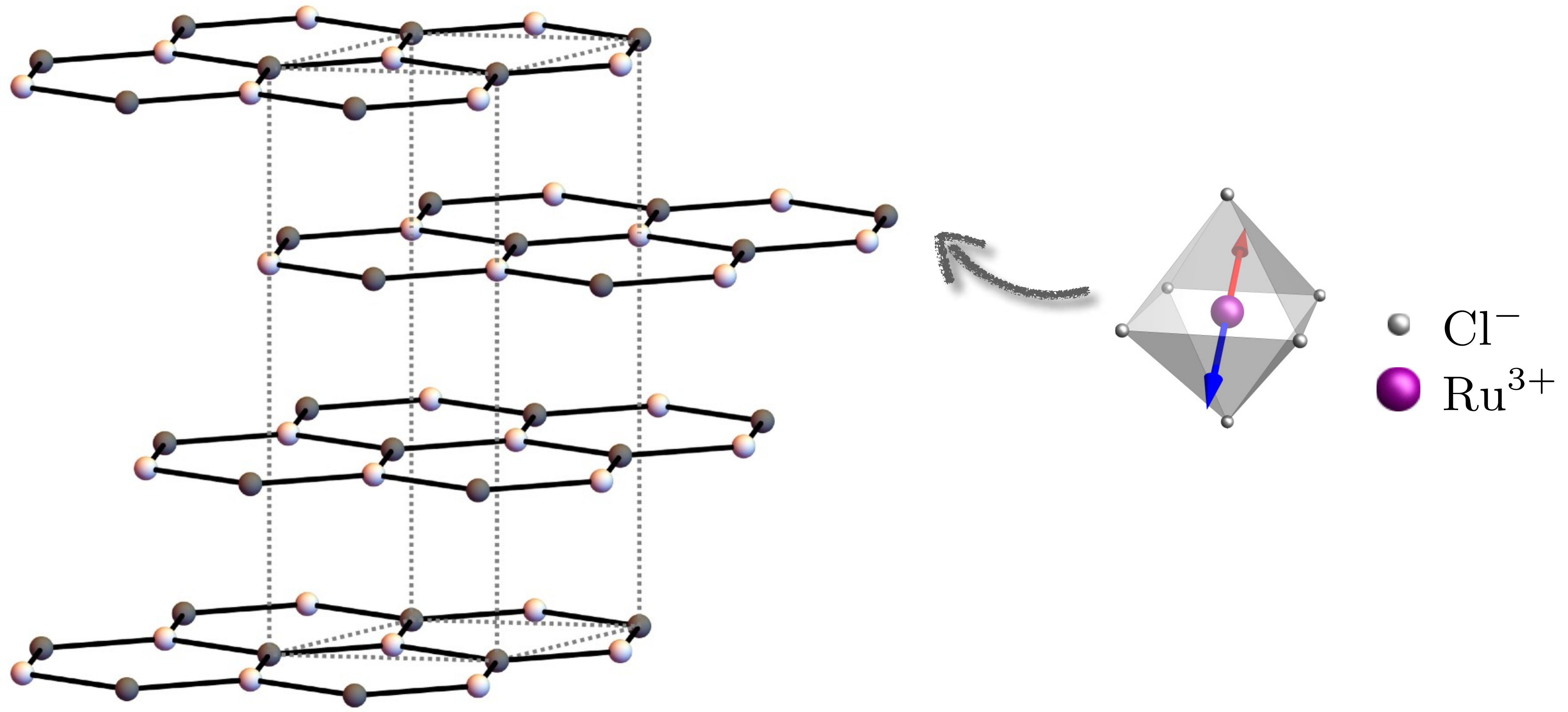


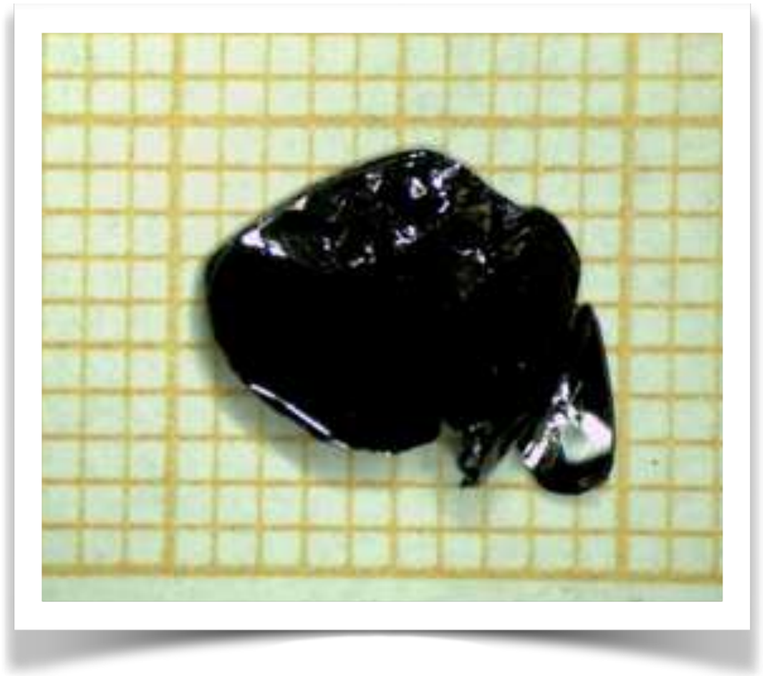
Credit: S. Wurmehl

[Balz *et al.*, PRB '21]

α-$RuCl_3$

Crystal structure:





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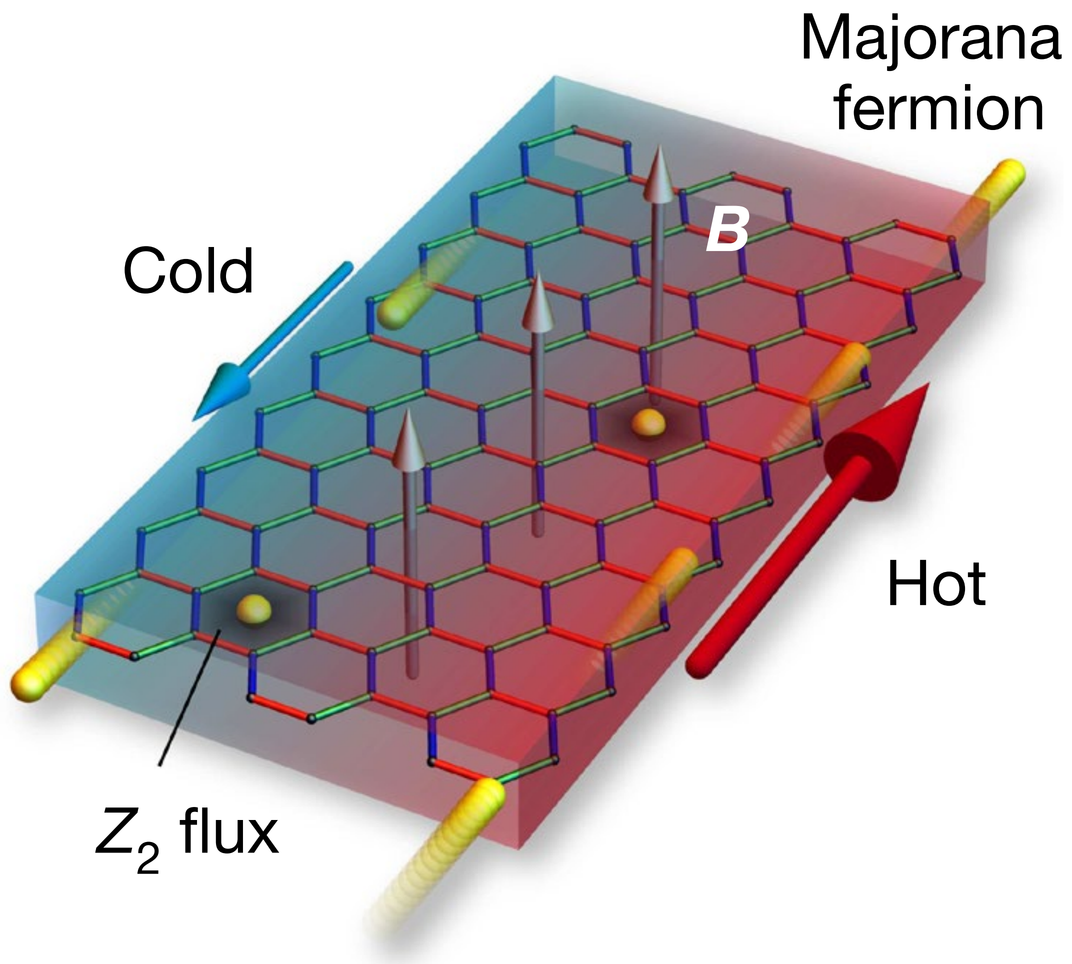
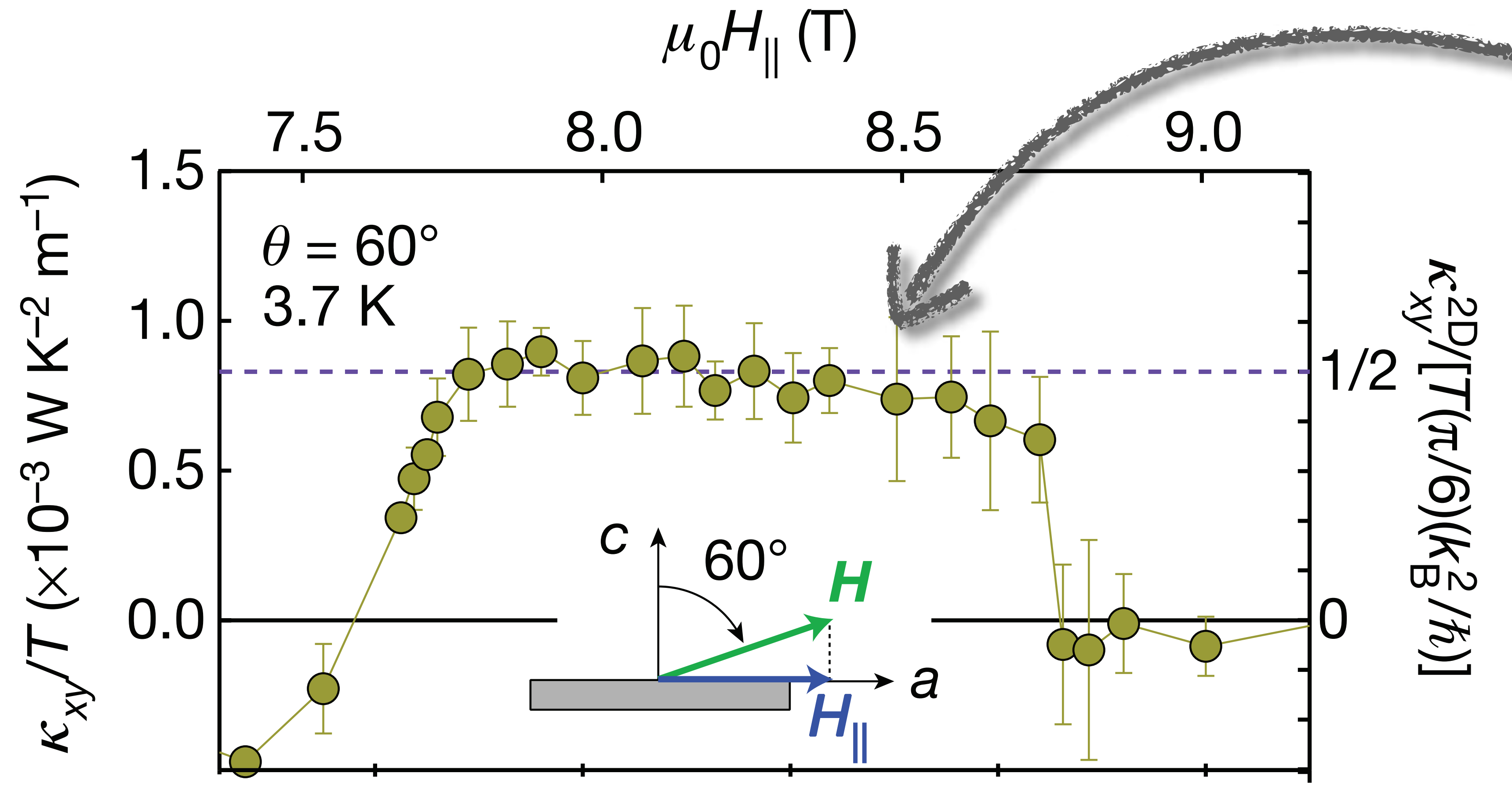
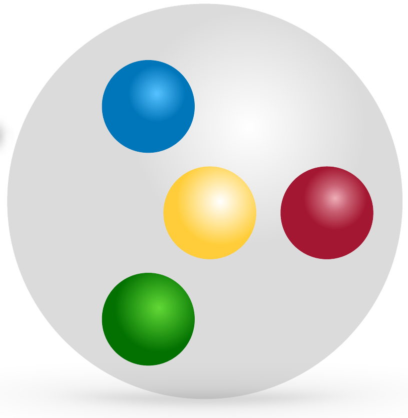
[Balz *et al.*, PRB ’21]

Half-integer quantum Hall effect:





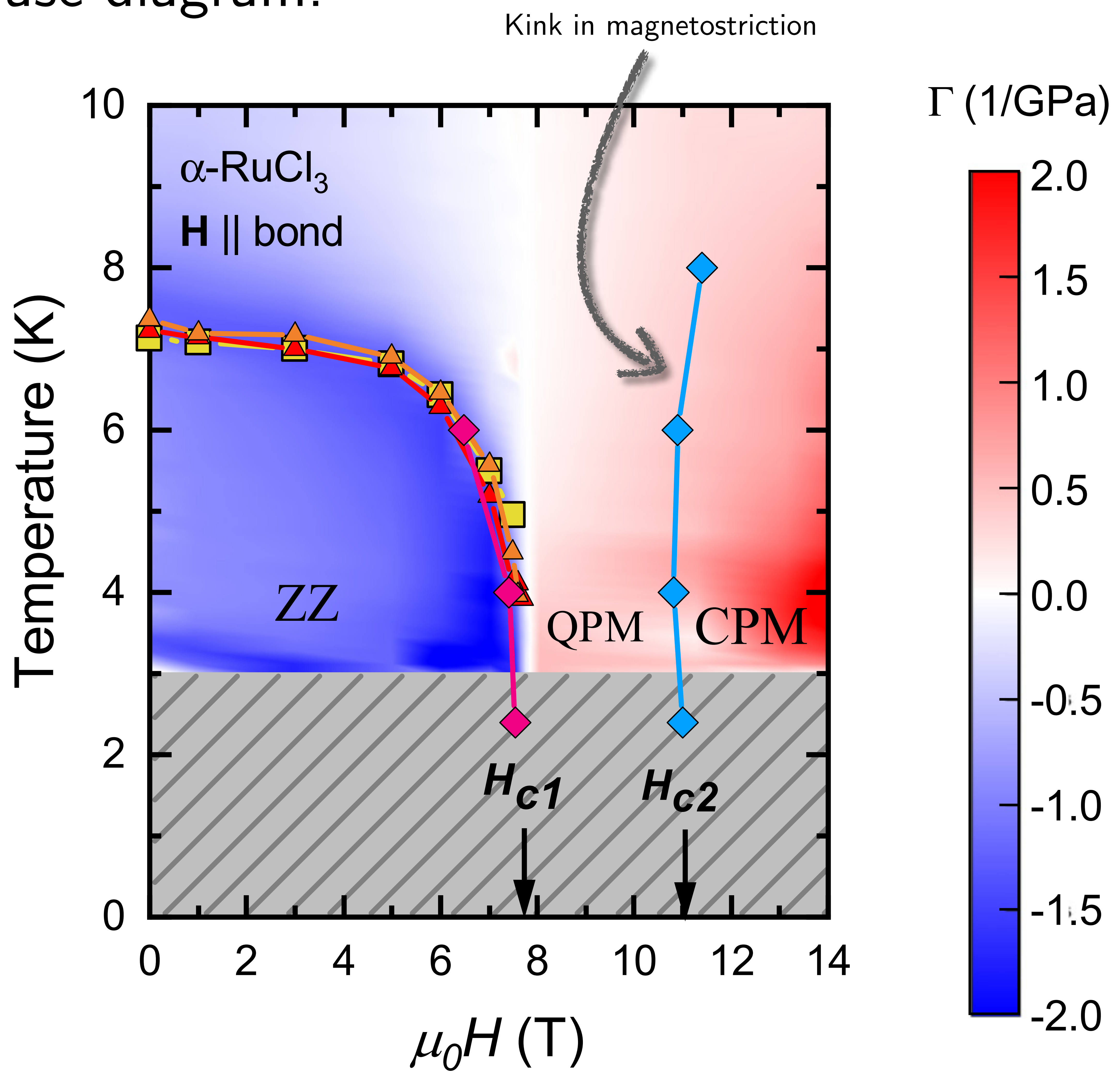


Majoranas?

[Kasahara *et al.*, Nature ’18]
[Yokoi *et al.*, Science ’21]

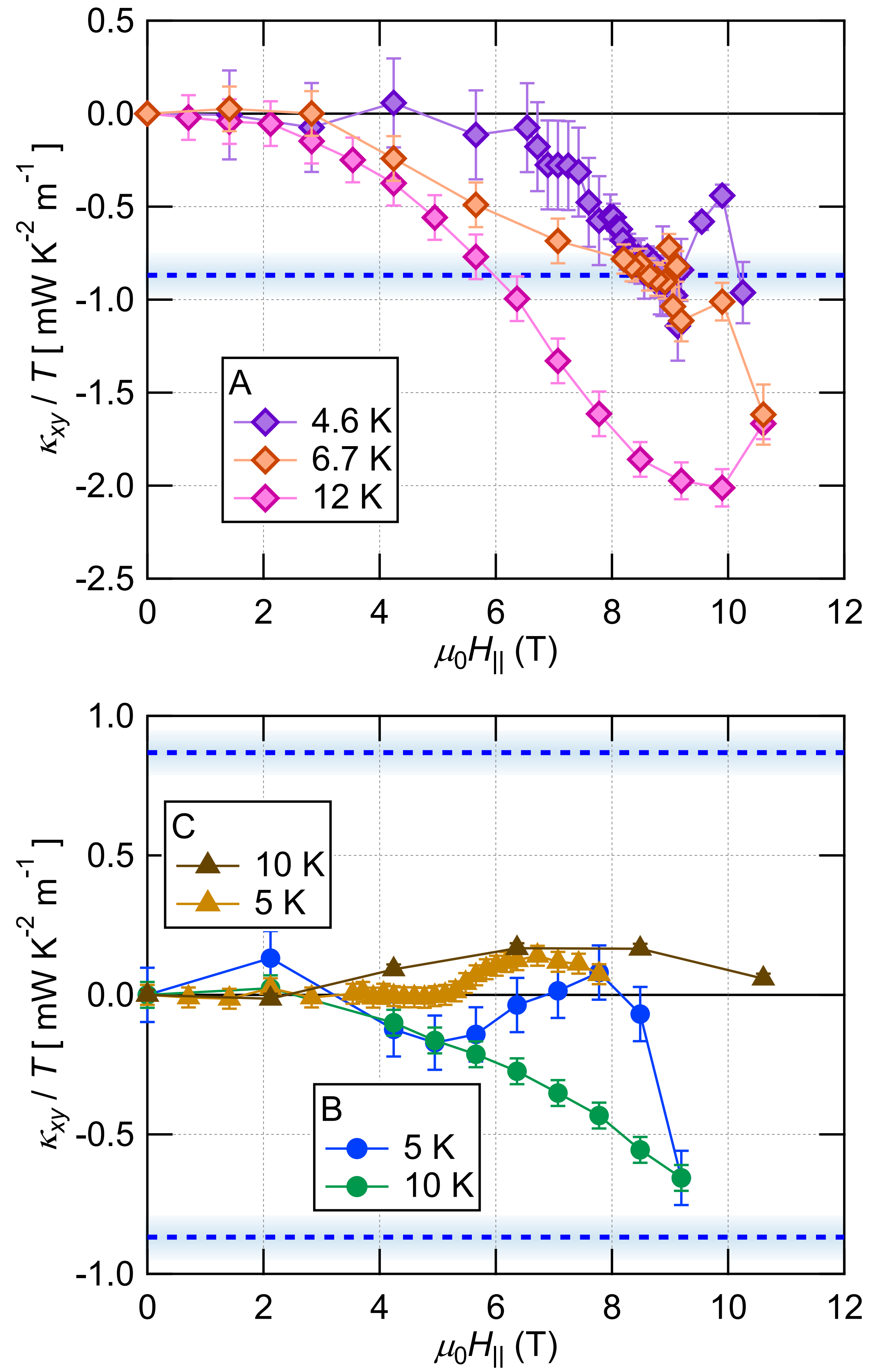
α-RuCl₃: Quantum phase diagram

Phase diagram:



[Gass *et al.*, PRB ’20]

Sample dependence:



[Yamashita *et al.*, PRB ’20]