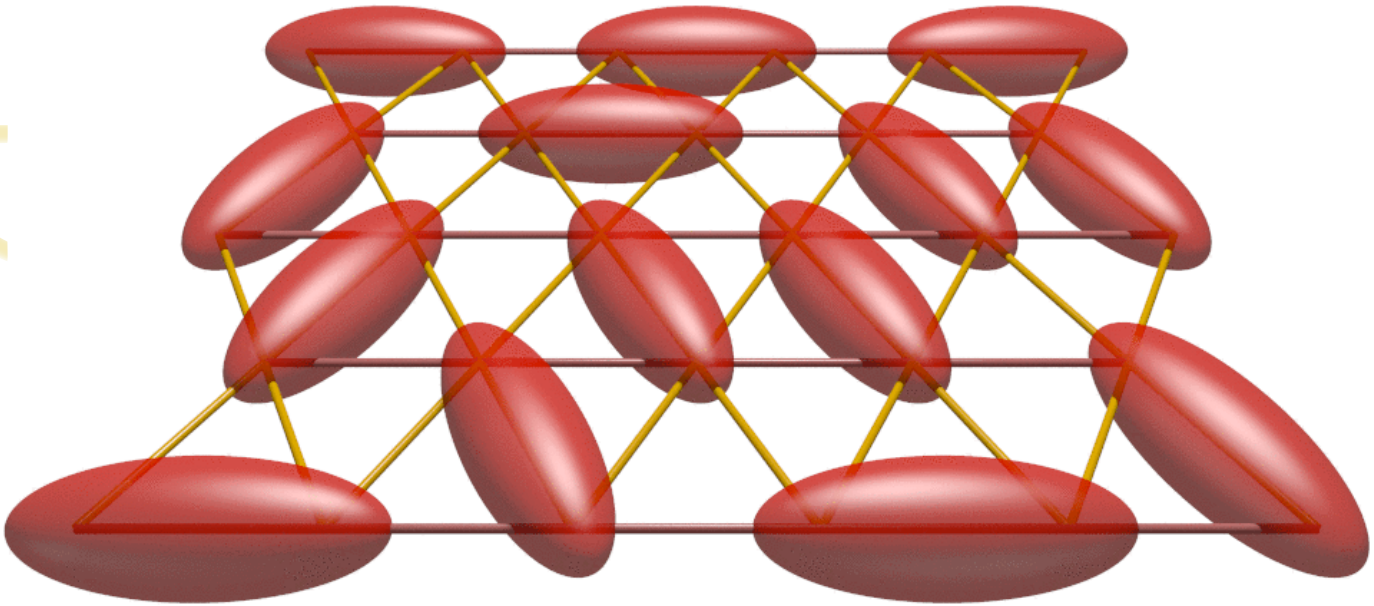
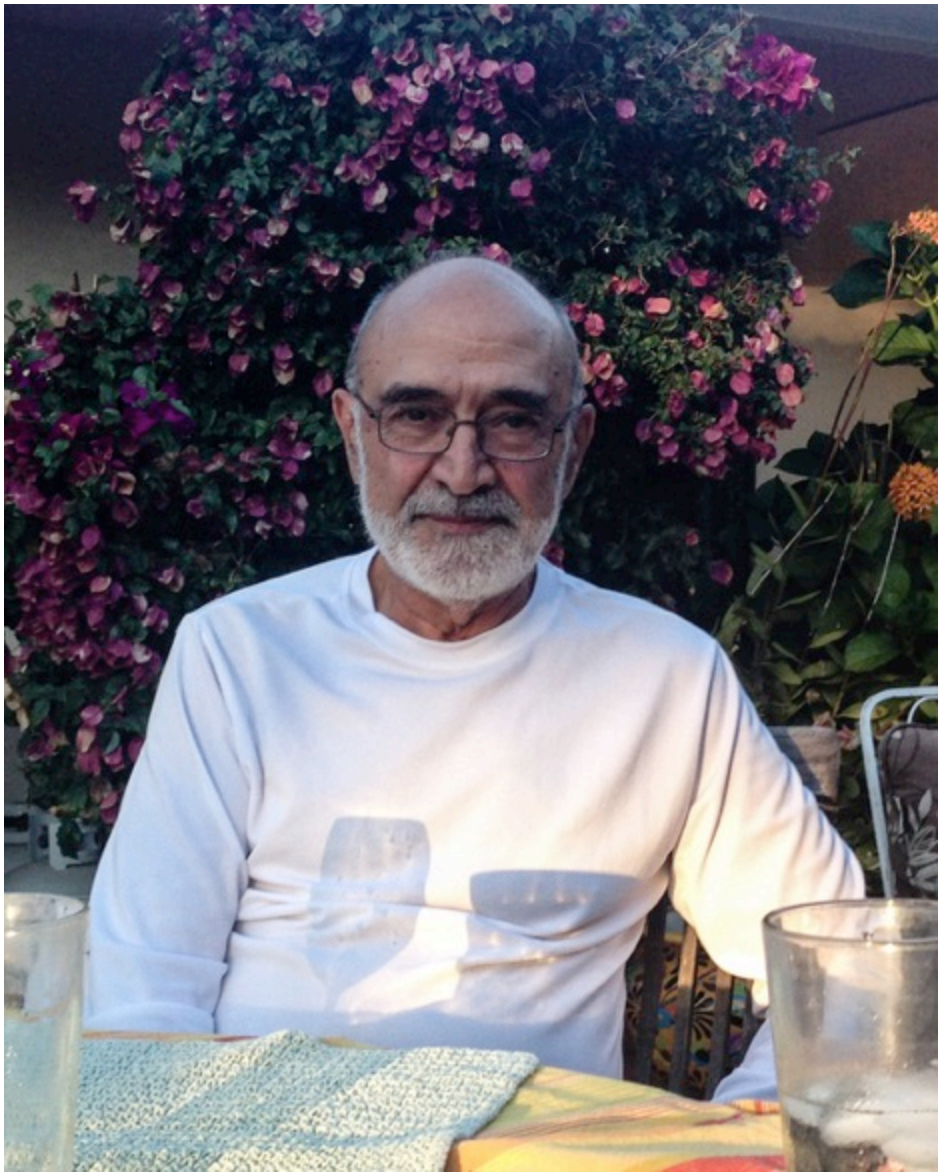
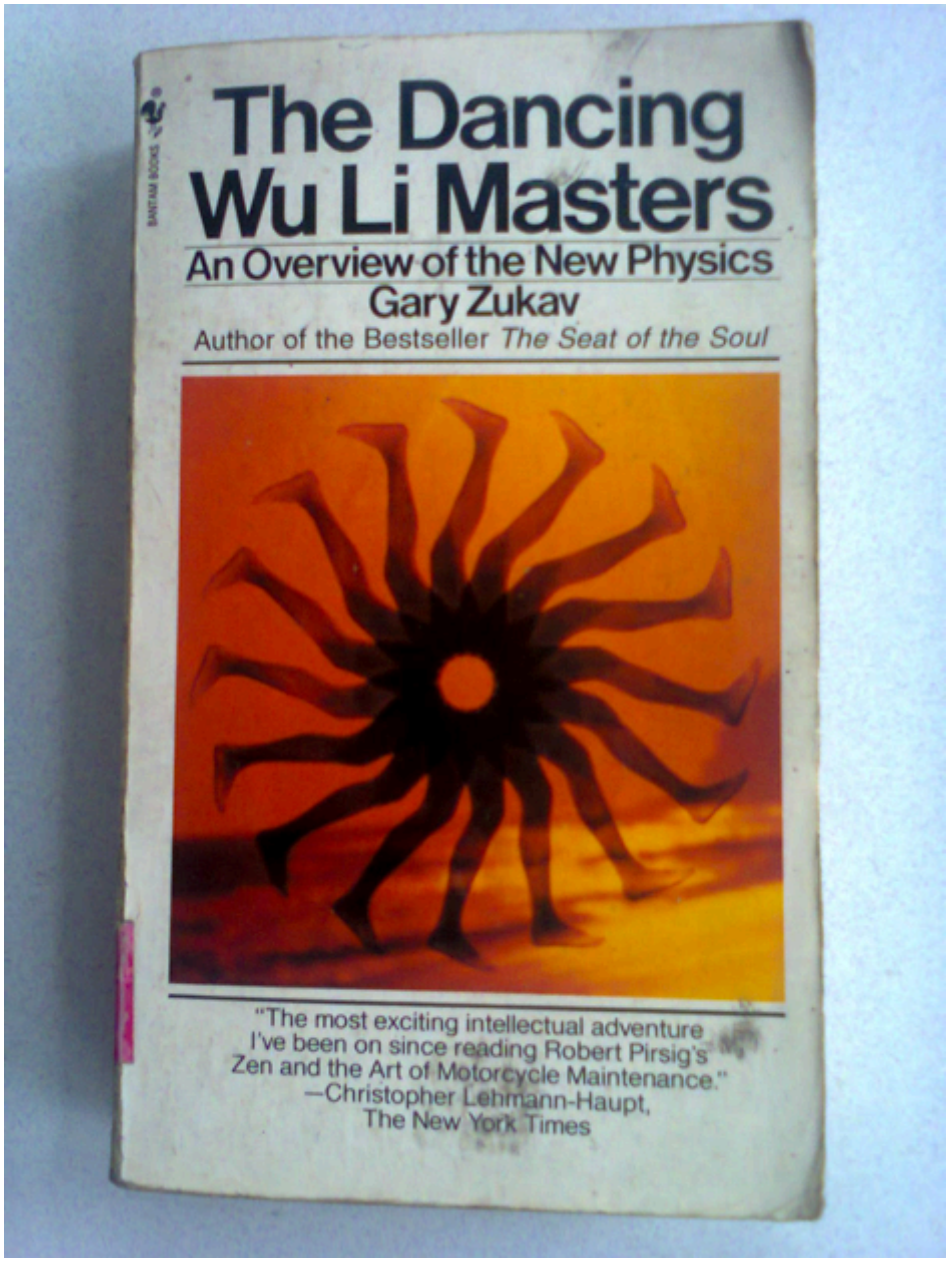
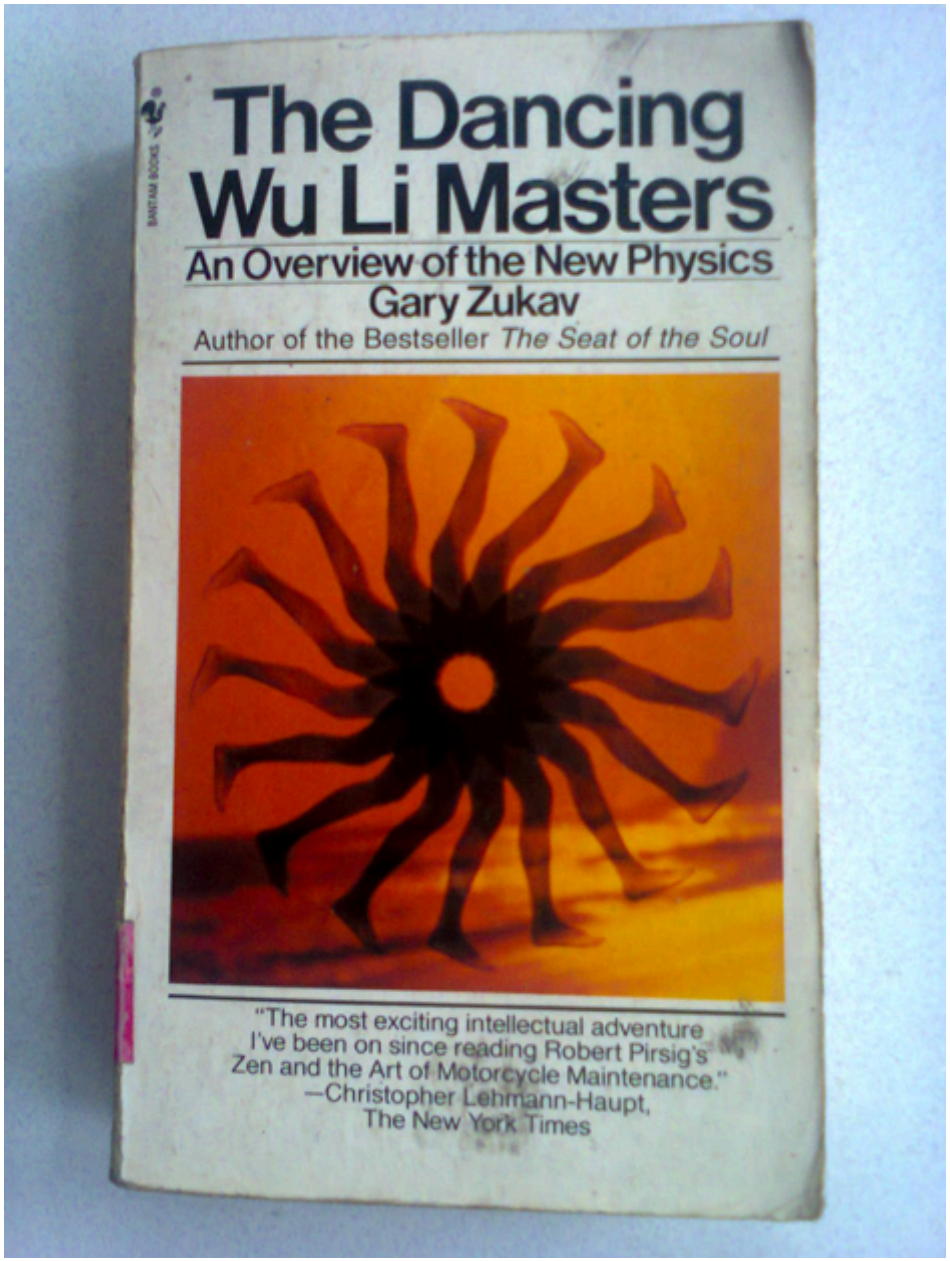
Strange Stuff: A Second Quantum Revolution





In loving memory

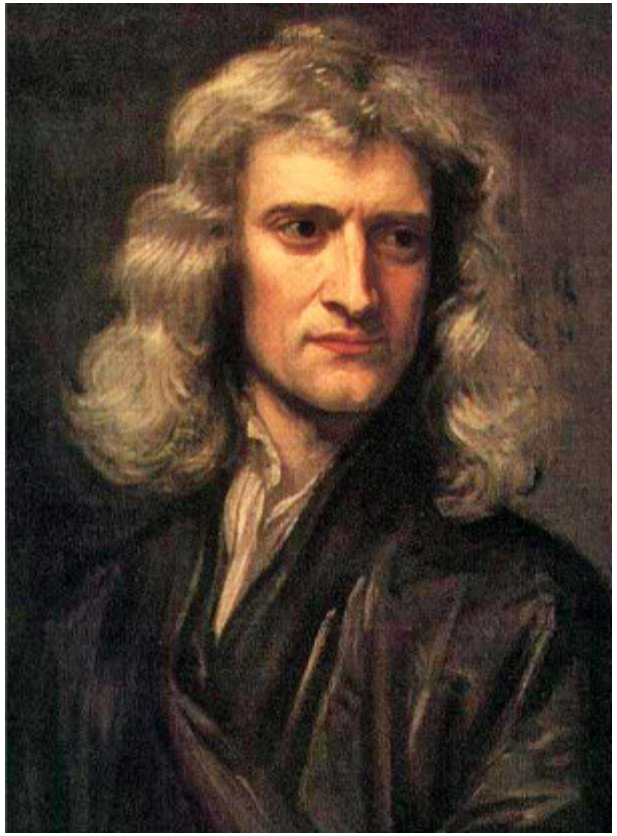

BANTAM BOOKS
The Dancing Wu Li Masters
An Overview of the New Physics
Gary Zukav
Author of the Bestseller The Seat of the Soul
"The most exciting intellectual adventure I've been on since reading Robert Pirsig's Zen and the Art of Motorcycle Maintenance."
—Christopher Lehmann-Haupt, The New York Times

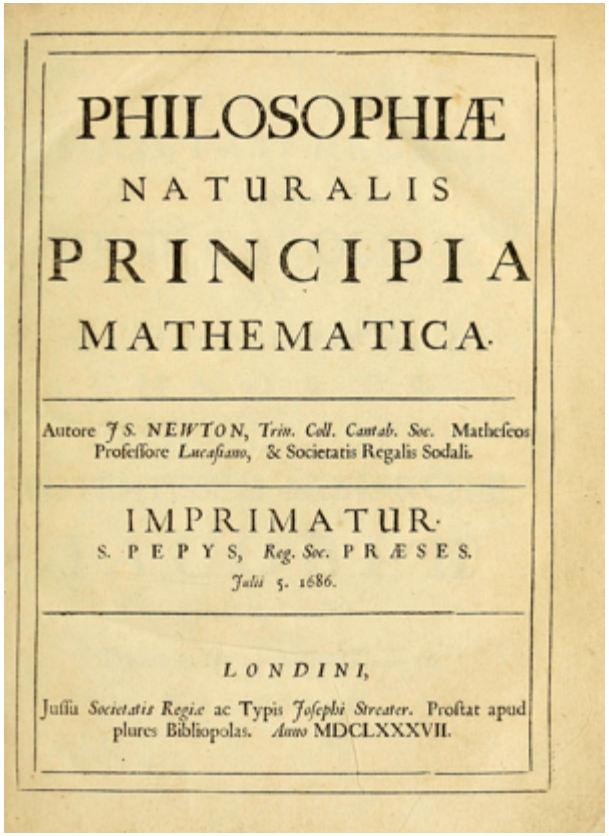


This talk:

quantum physics (without the eastern philosophy)

recent revolution in bringing quantum weirdness into the macro-world





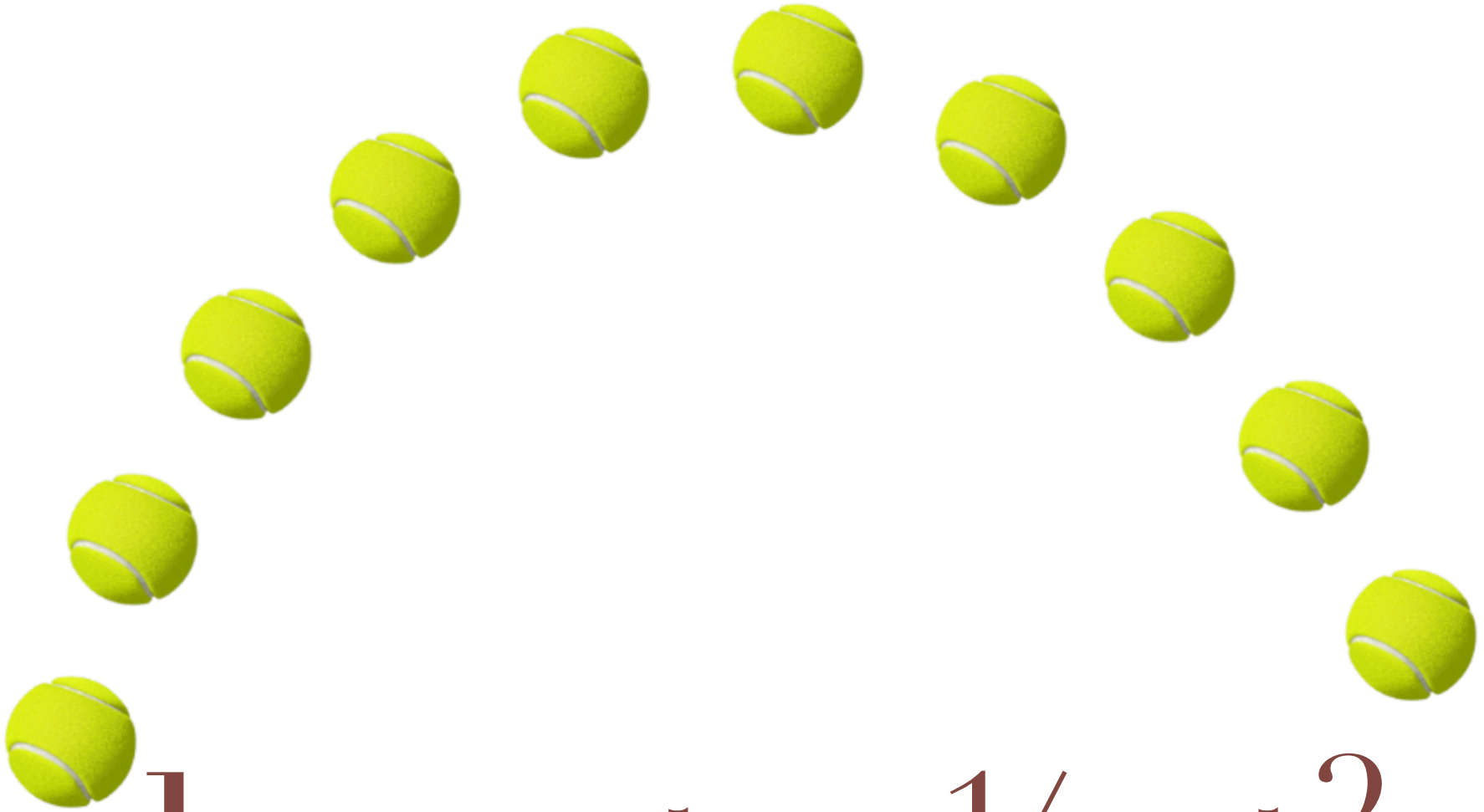
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

$$F = ma$$



$$h = vt - \tfrac{1}{2}gt^2$$

2/4

21/2

Homework Set 1a

#1) 1-58

(4.8m)

poor sketch

$P = \frac{m}{V}$

$918\ kg/m^3 = \frac{1 \times 10^{-7}\ kg}{V}$

$918\ kg/m^3\ V = 9 \times 10^{-7}\ kg$

$V = 9.80 \times 10^{-10}\ m^3$

$9.80 \times 10^{-10} m^3 \left(\frac{1 \times 10^6\ cm^3}{1\ m^3}\right)$

$9.8 \times 10^{-4}\ cm^3$

$V_{droplet\ of\ oil} = A_{circle}$

$9.8 \times 10^{-4}\ cm^3 = \pi r^2$

$r = .018\ cm$

$d = 2r$

$d = 2(.018\ cm)$

$d = .036\ cm$

#2) 3-50

I can't follow.

① $R_x = 300\ kN \rightarrow - (150\ kN \sin 30°) \leftarrow$

$R_x = 225\ kN \rightarrow$

$R_y = 150\ kN \cos 30° \uparrow + 150\ kN \uparrow$

$R_y = 280\ kN \uparrow$

-.6

$\tan\theta = \frac{R_y}{R_x}$

see soln.

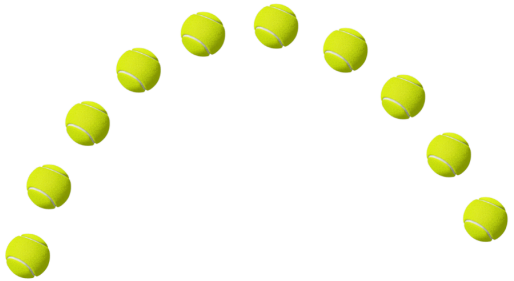
$\tan^{-1}\left(\frac{280\ kN \uparrow}{225\ kN \rightarrow}\right) = \theta$

$\theta = 51°$ north of east

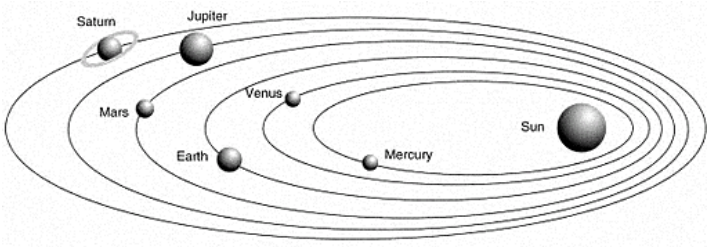
② $R = \sqrt{R_x^2 + R_y^2}$

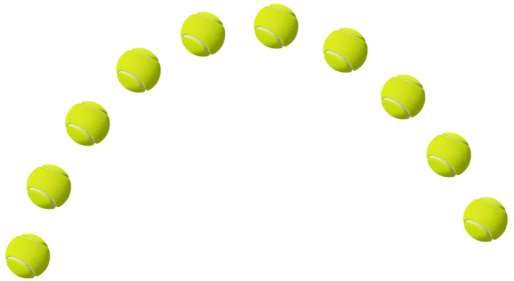
$R = \sqrt{(225\ kN)^2 + (280\ kN)^2}$

$R = 359\ kN$

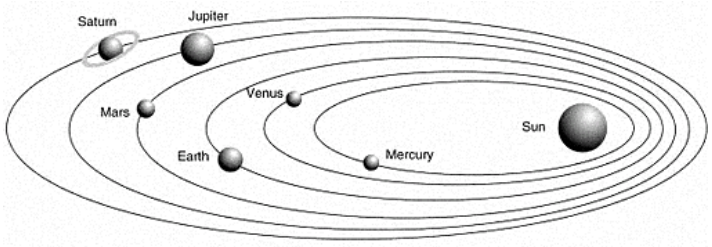


F = m a





$$F = m\,a$$

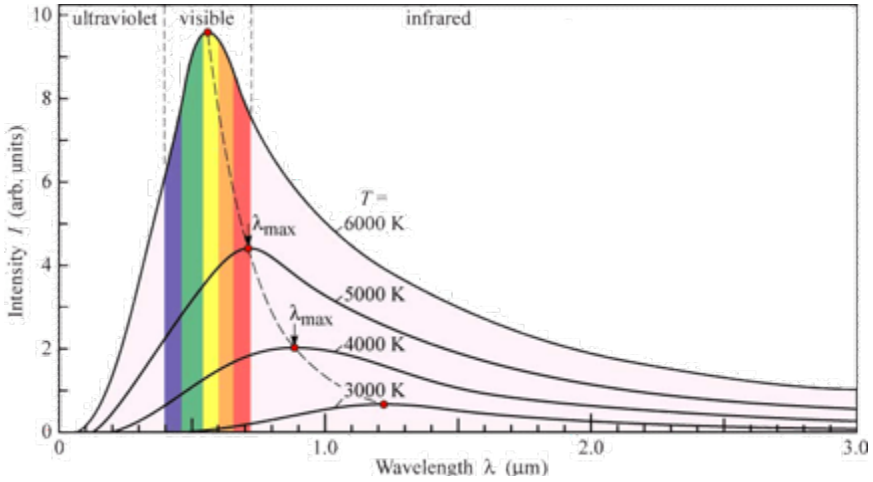


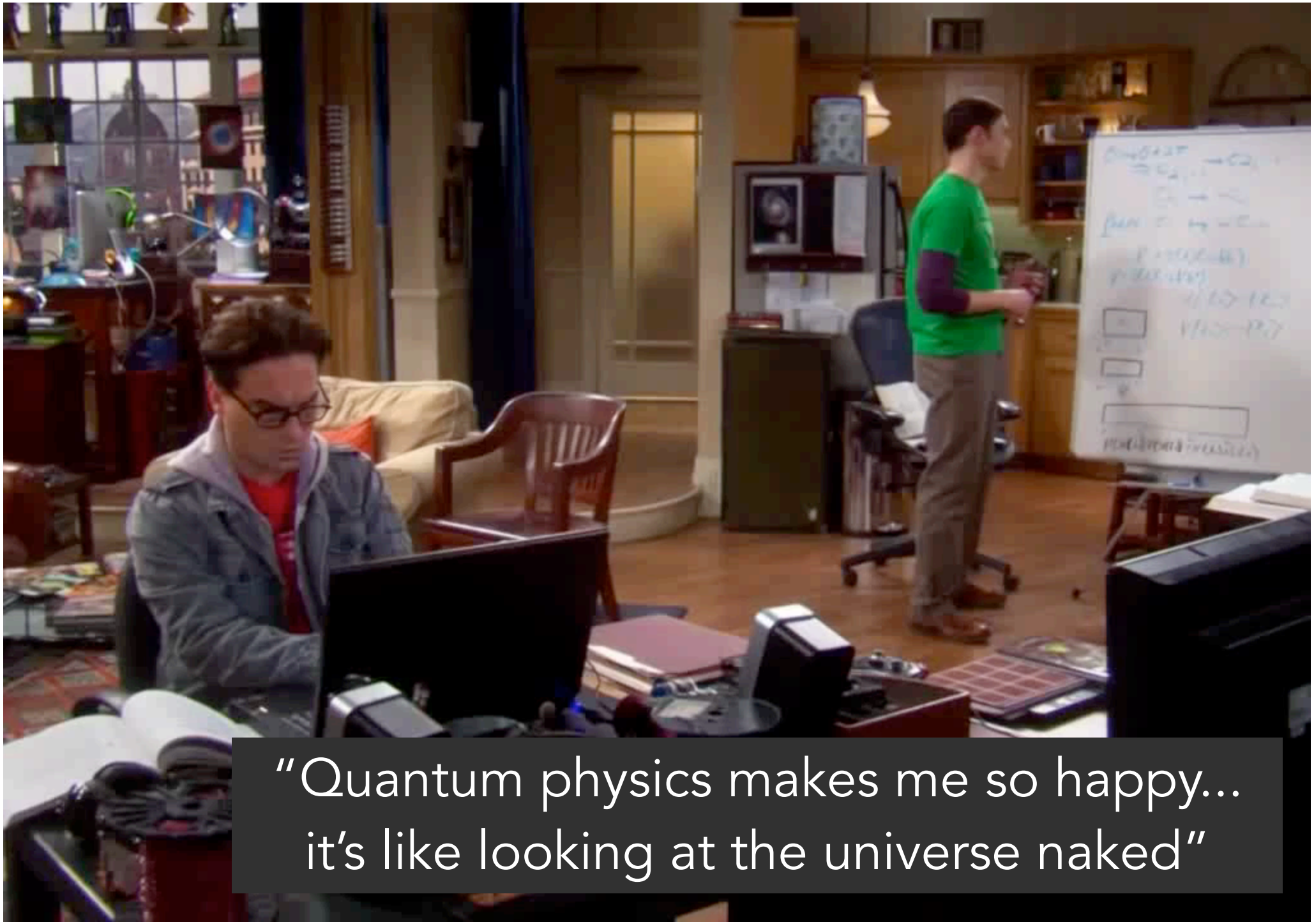
Planck

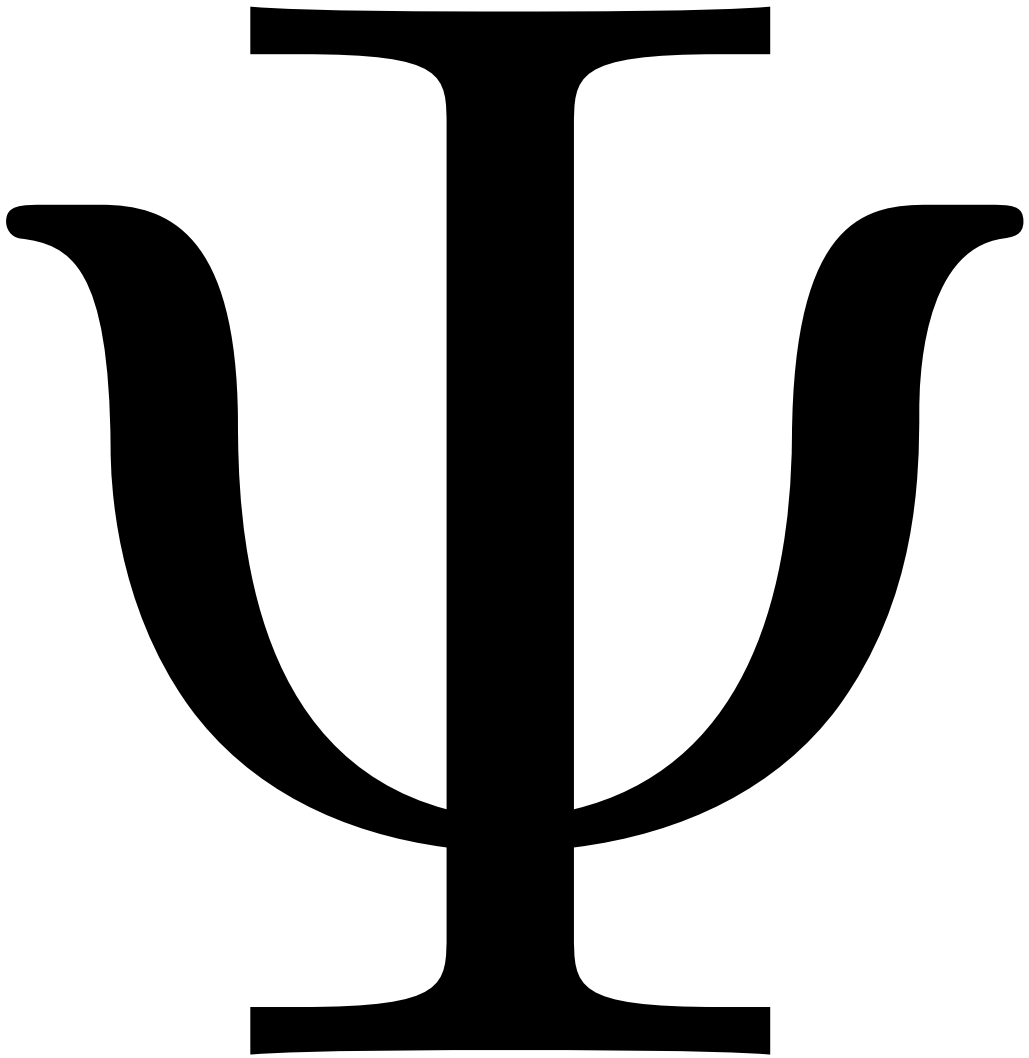
Bohr

Schrödinger

Heisenberg



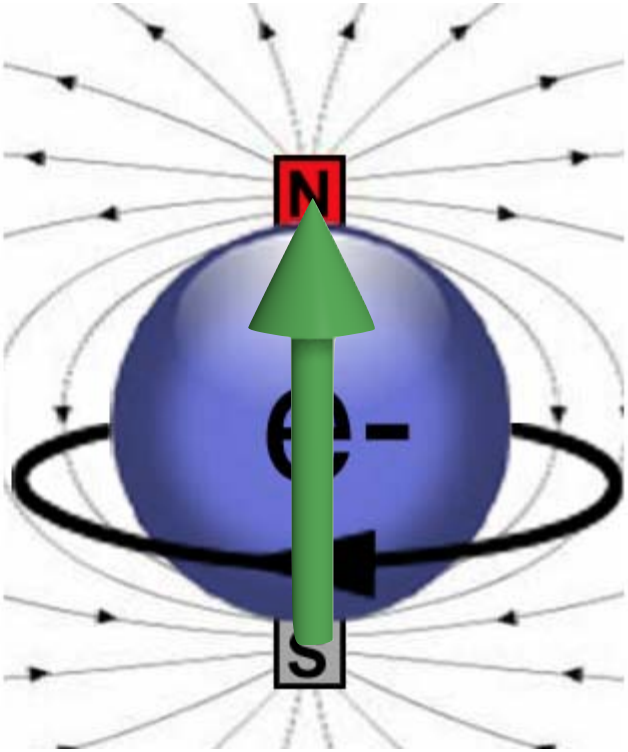

“Quantum physics makes me so happy...
it’s like looking at the universe naked”



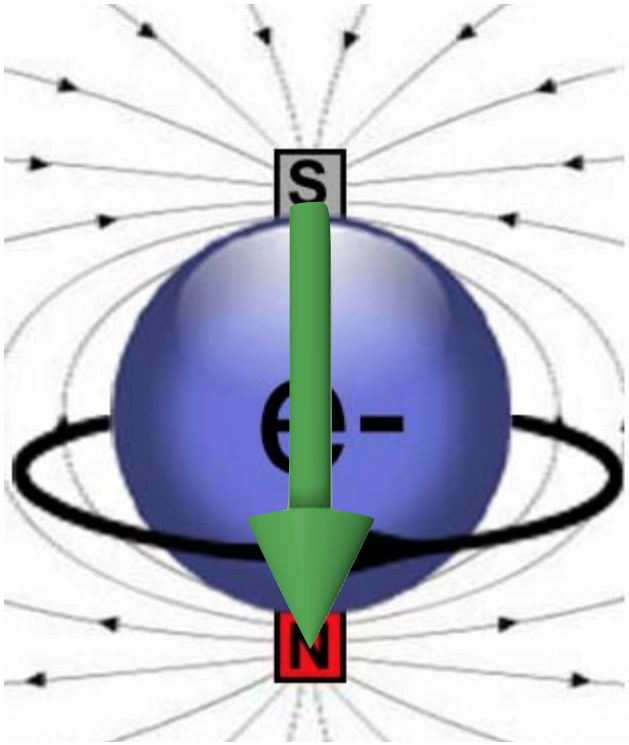
Superposition

Entanglement

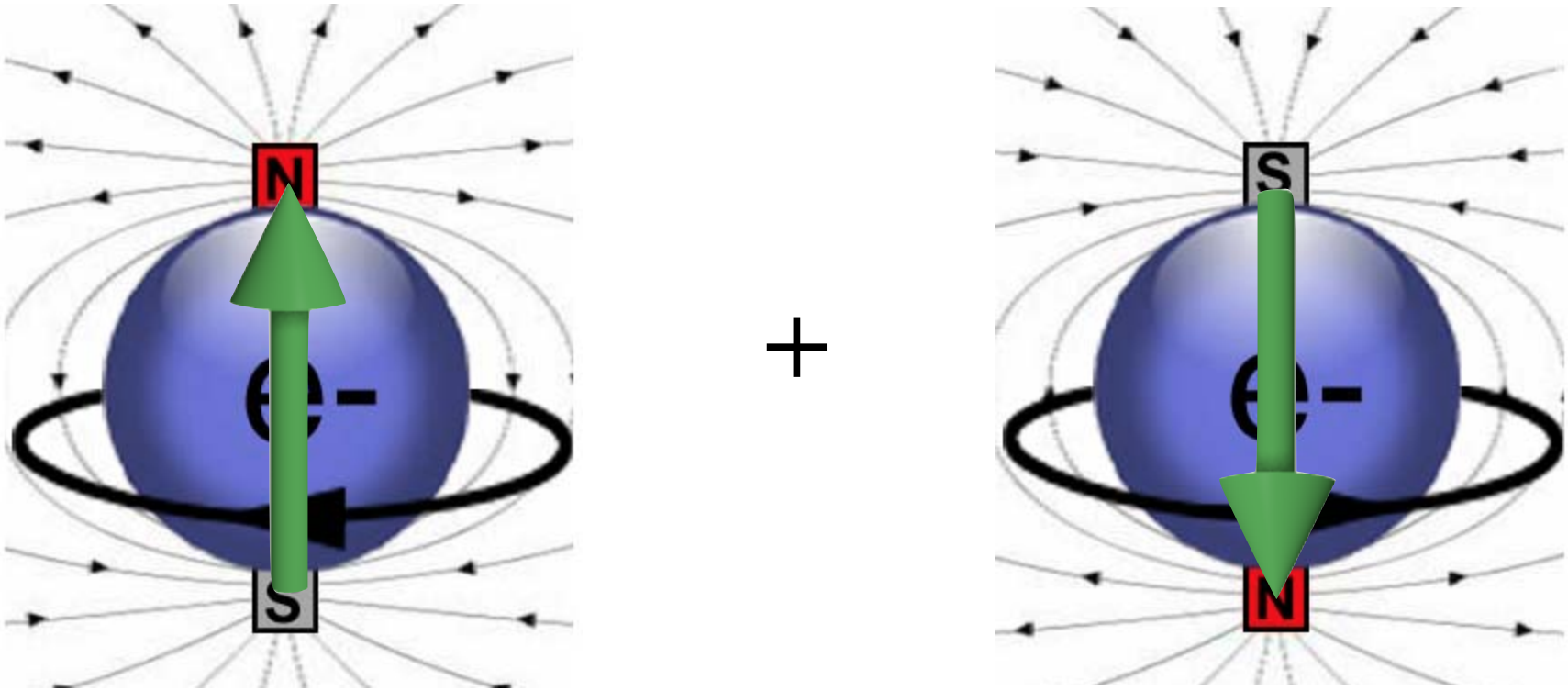
Quantum Superposition



Up

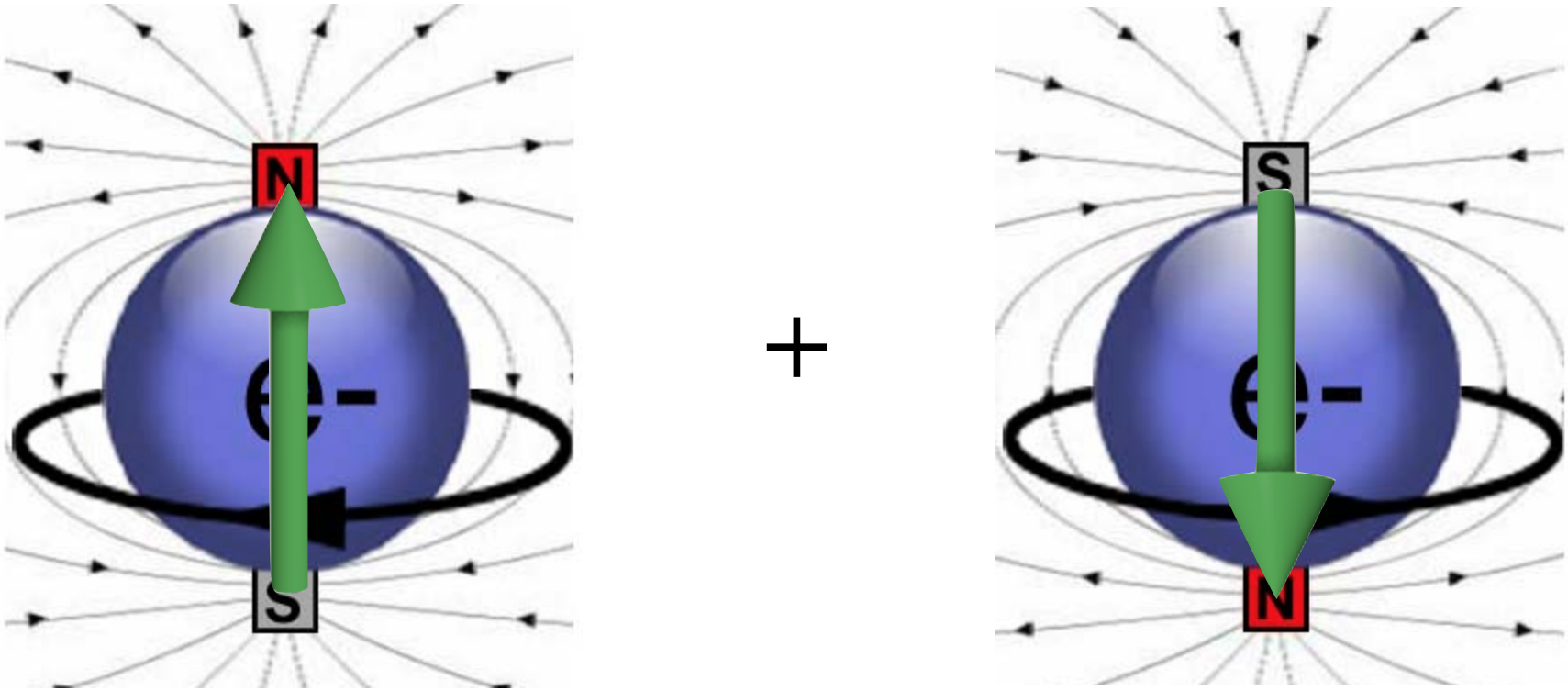


Down



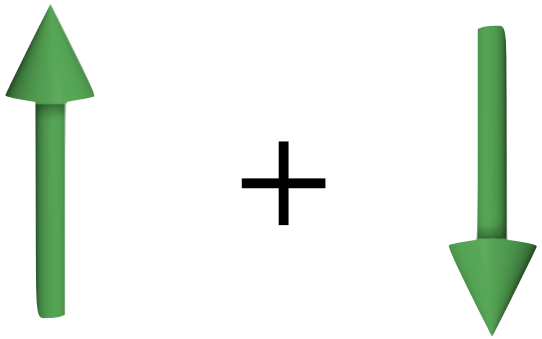
Both

"quantum superposition"



Both

Superposition

Ψ =  +

"state"

"wavefunction"

Superposition

$$\Psi = \#\uparrow + \#\downarrow$$

"Amplitudes"

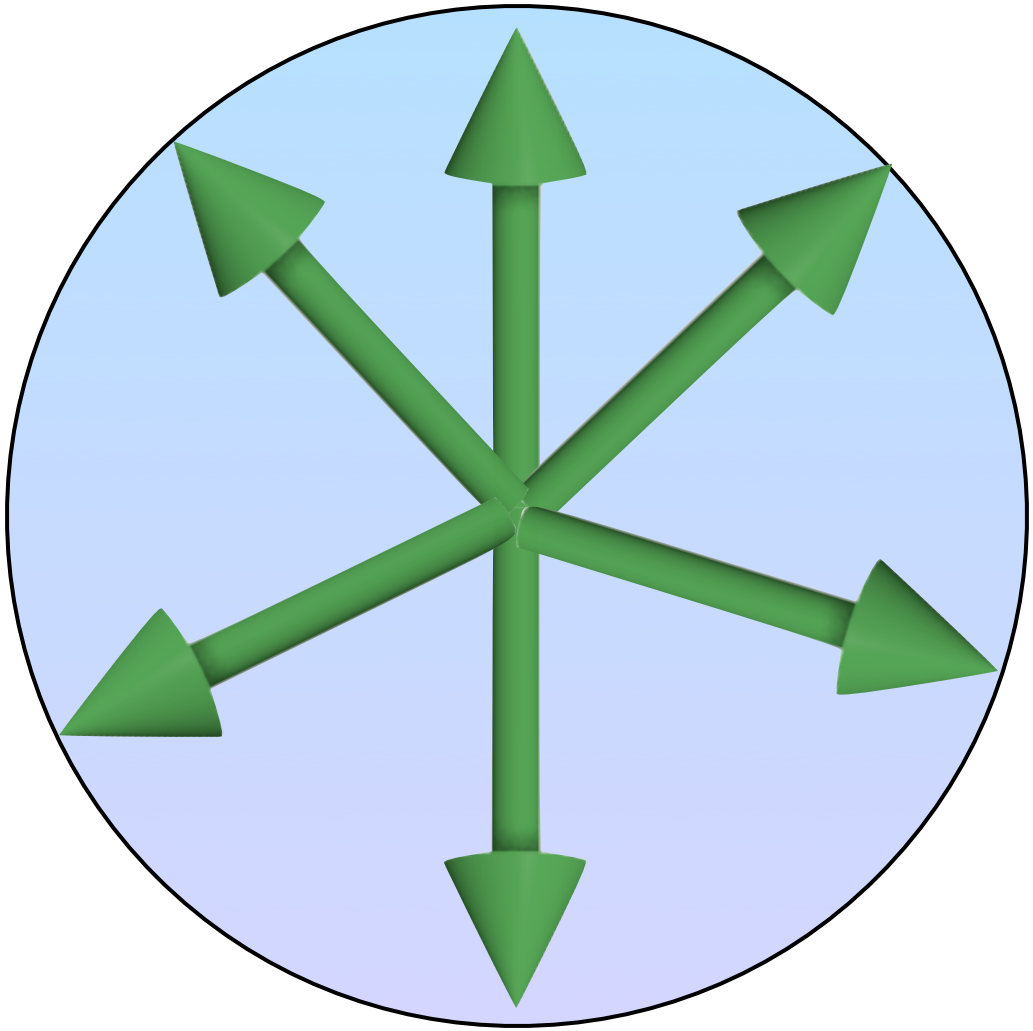
Superposition

$$\Psi = \#\uparrow + \#\downarrow$$

"Amplitudes"

This is *information*. Reality = information?

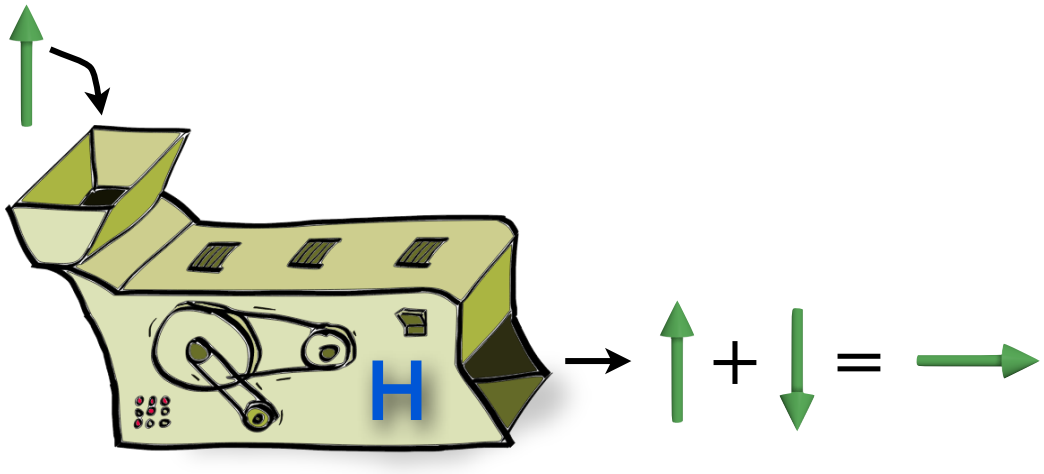
"1"



"0"

"qubit"

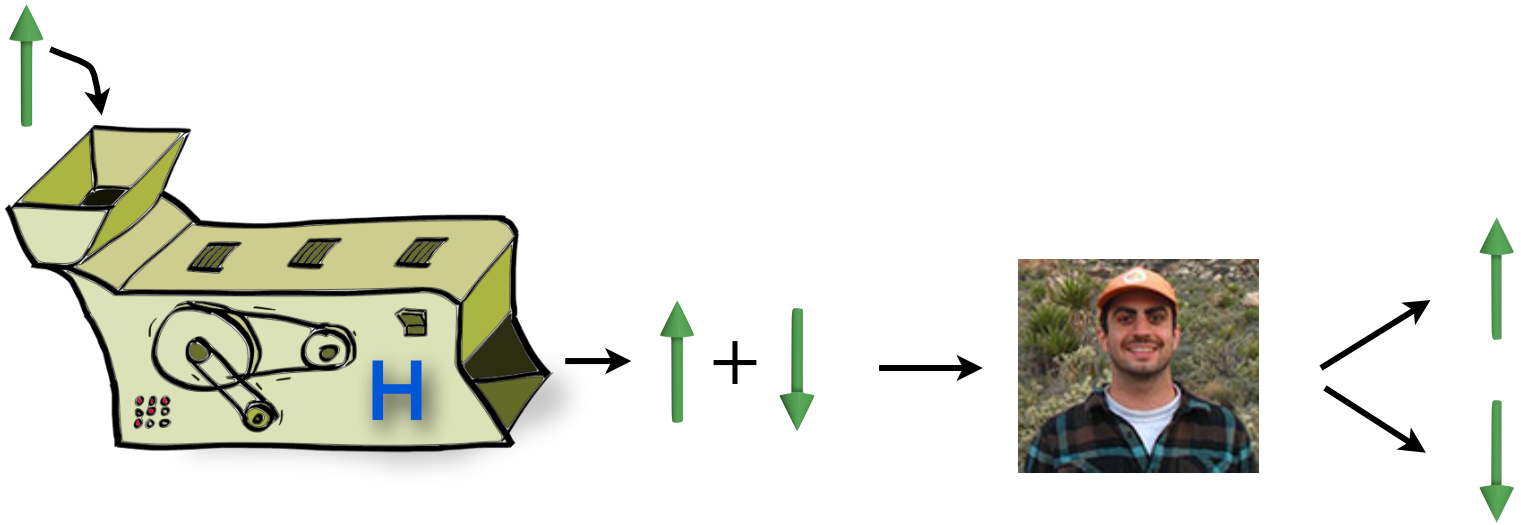
Superposition Machine



"Hadamard Gate"

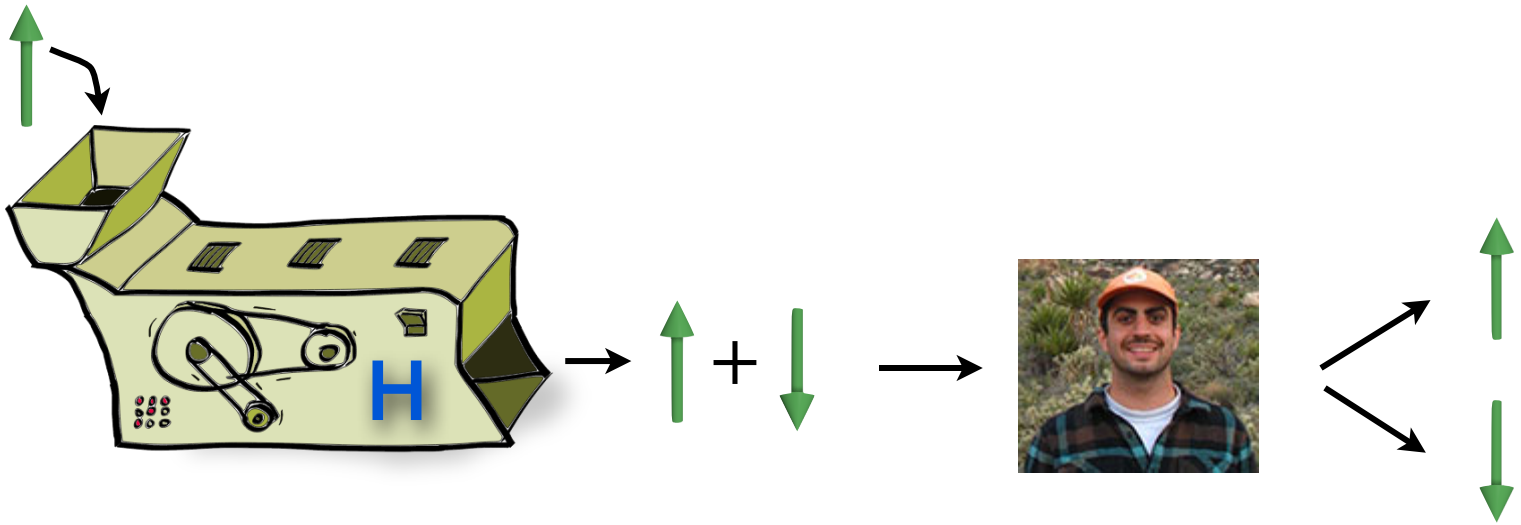
"Pi/2 pulse"

Superposition Machine



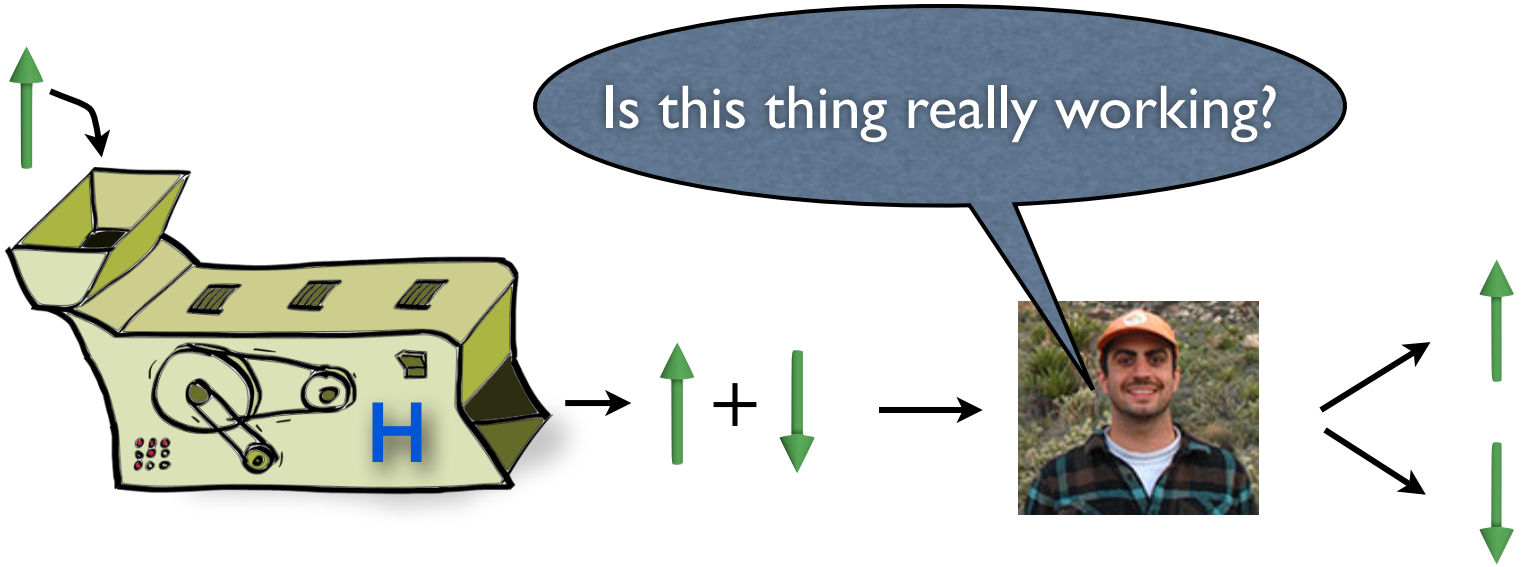
Observe up or down randomly,
with equal probability

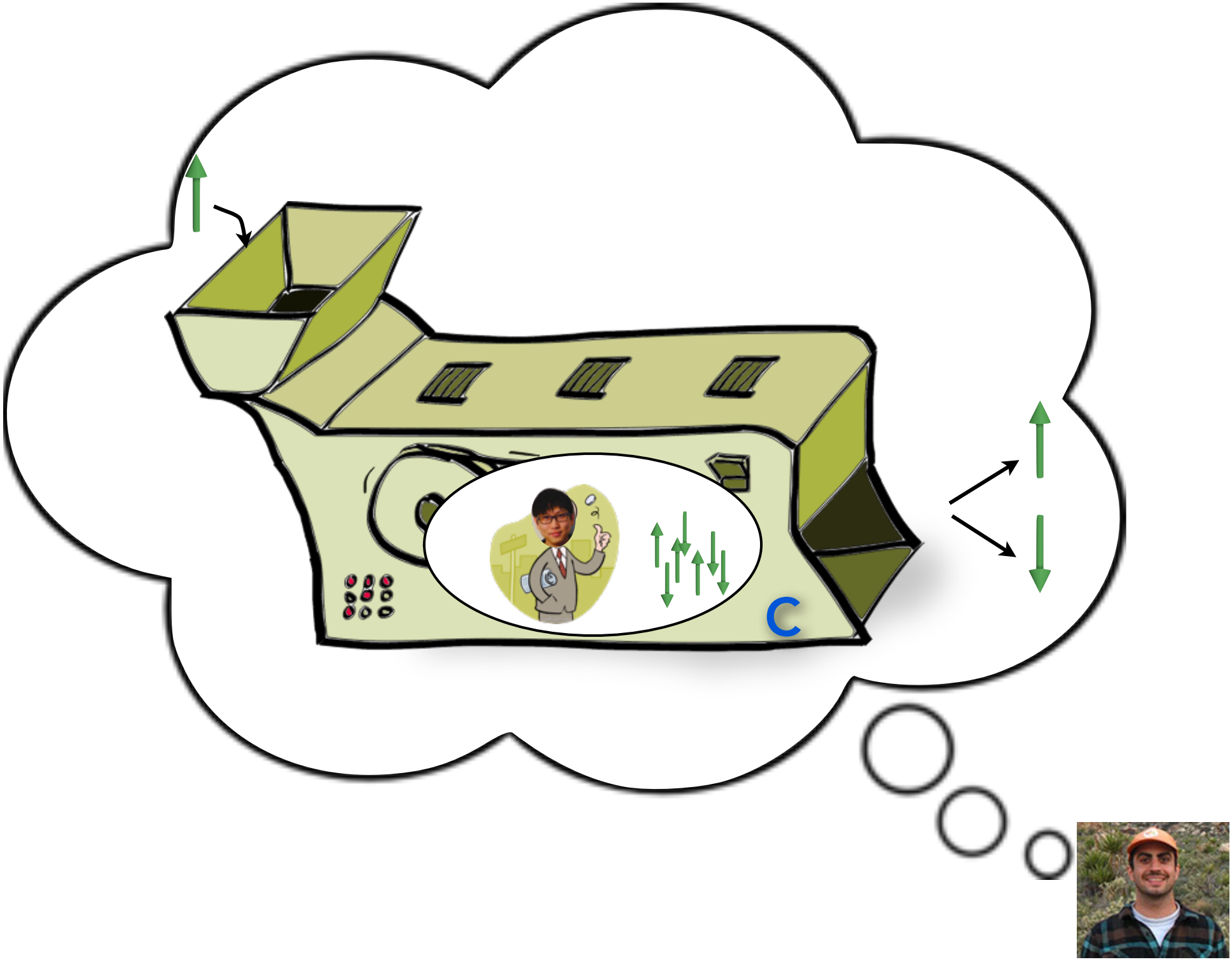
Superposition Machine



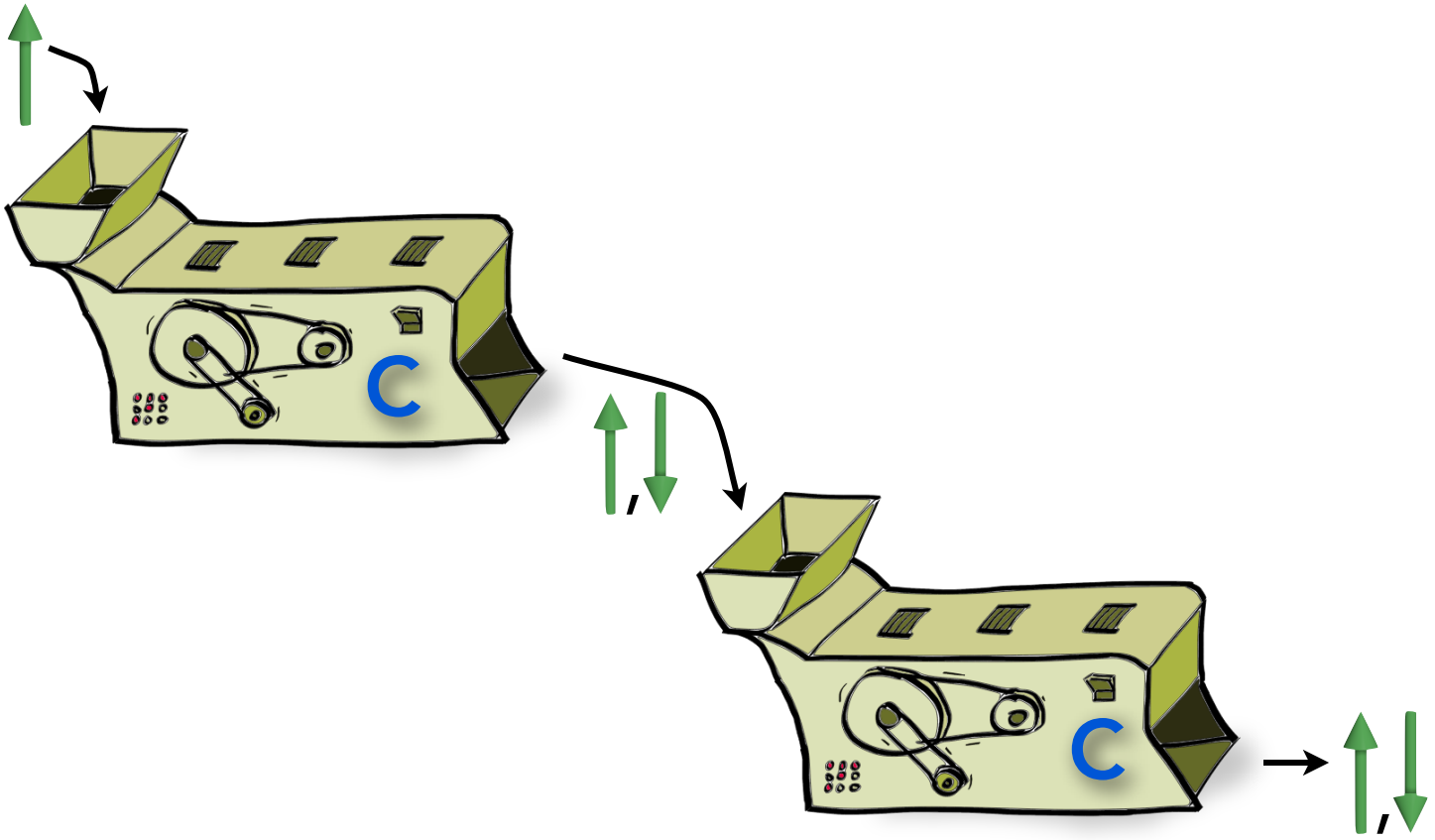
Measurement induced “collapse”
of the wavefunction

Superposition Machine

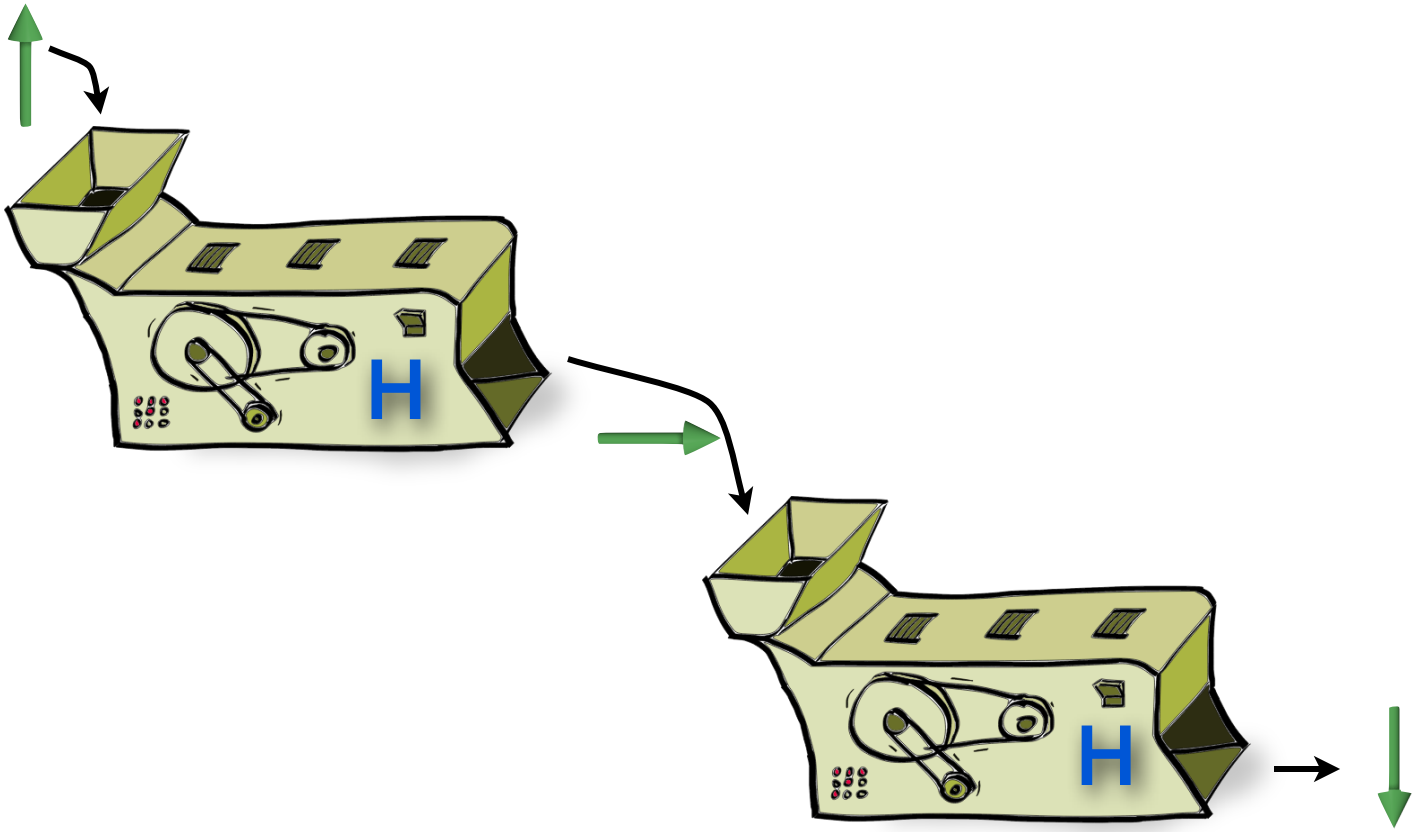



C

Classical Fraud



Quantum



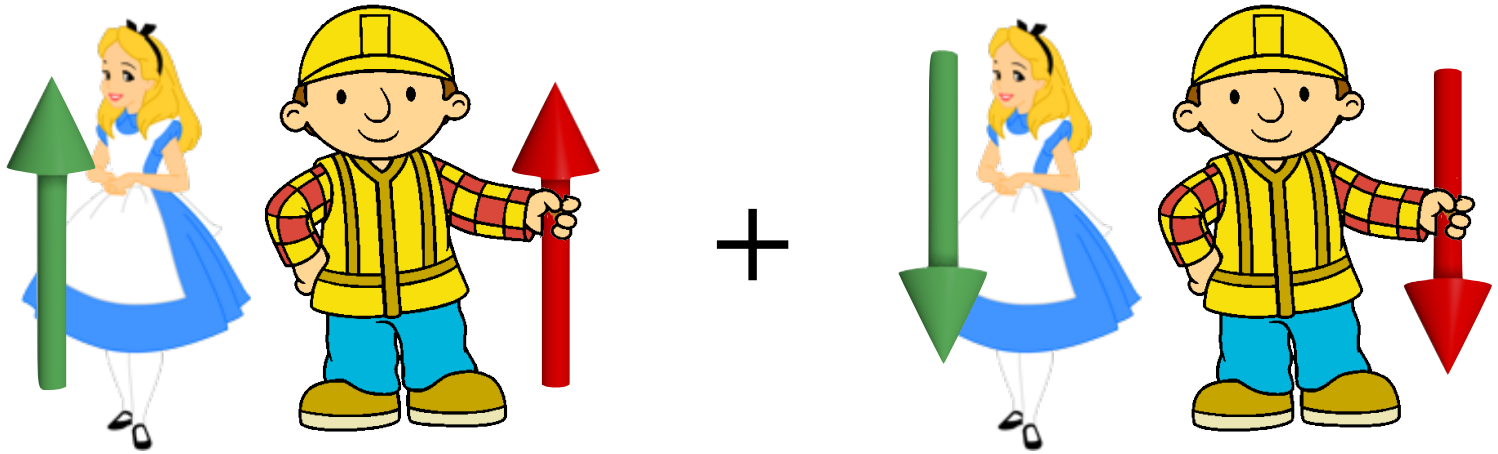
down **every** time

Quantum Entanglement

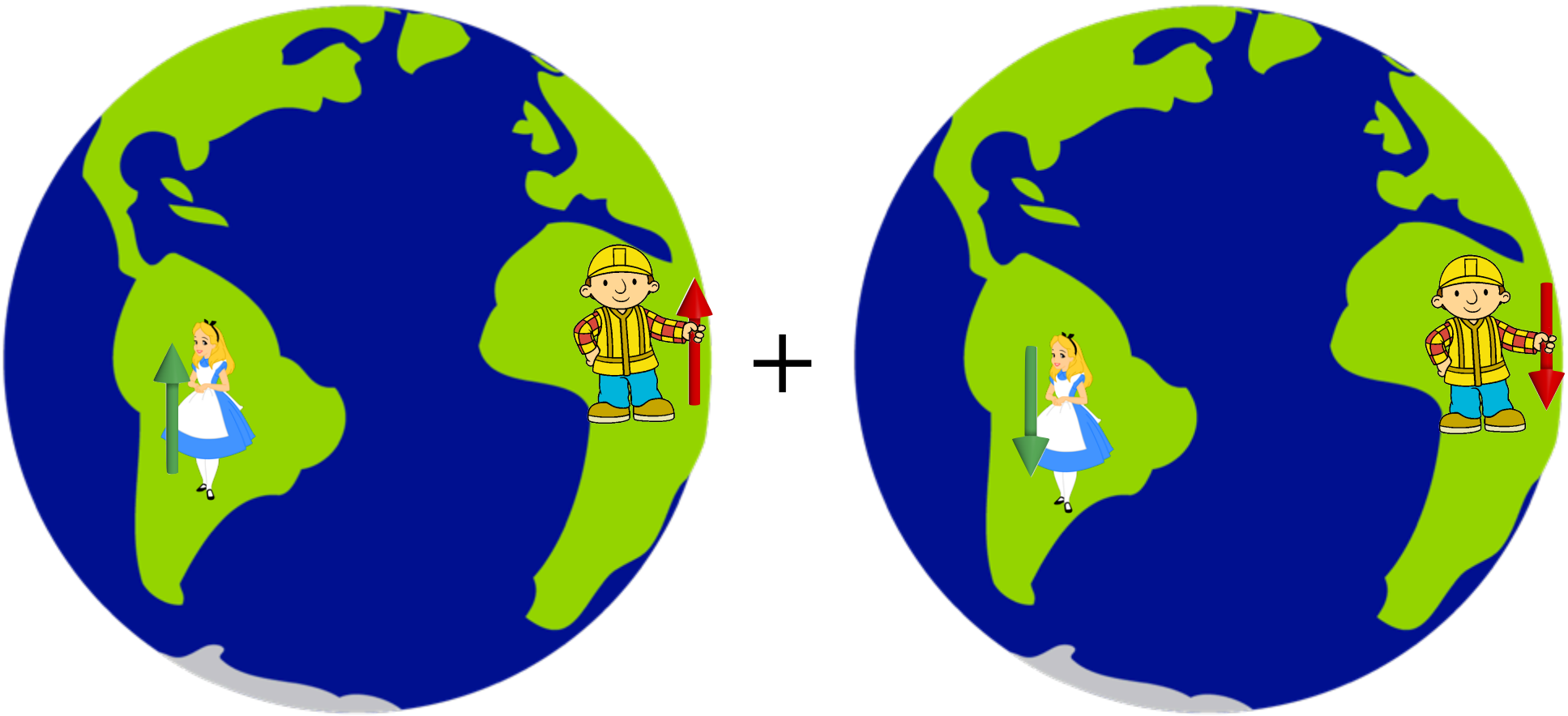
Entanglement

Entanglement

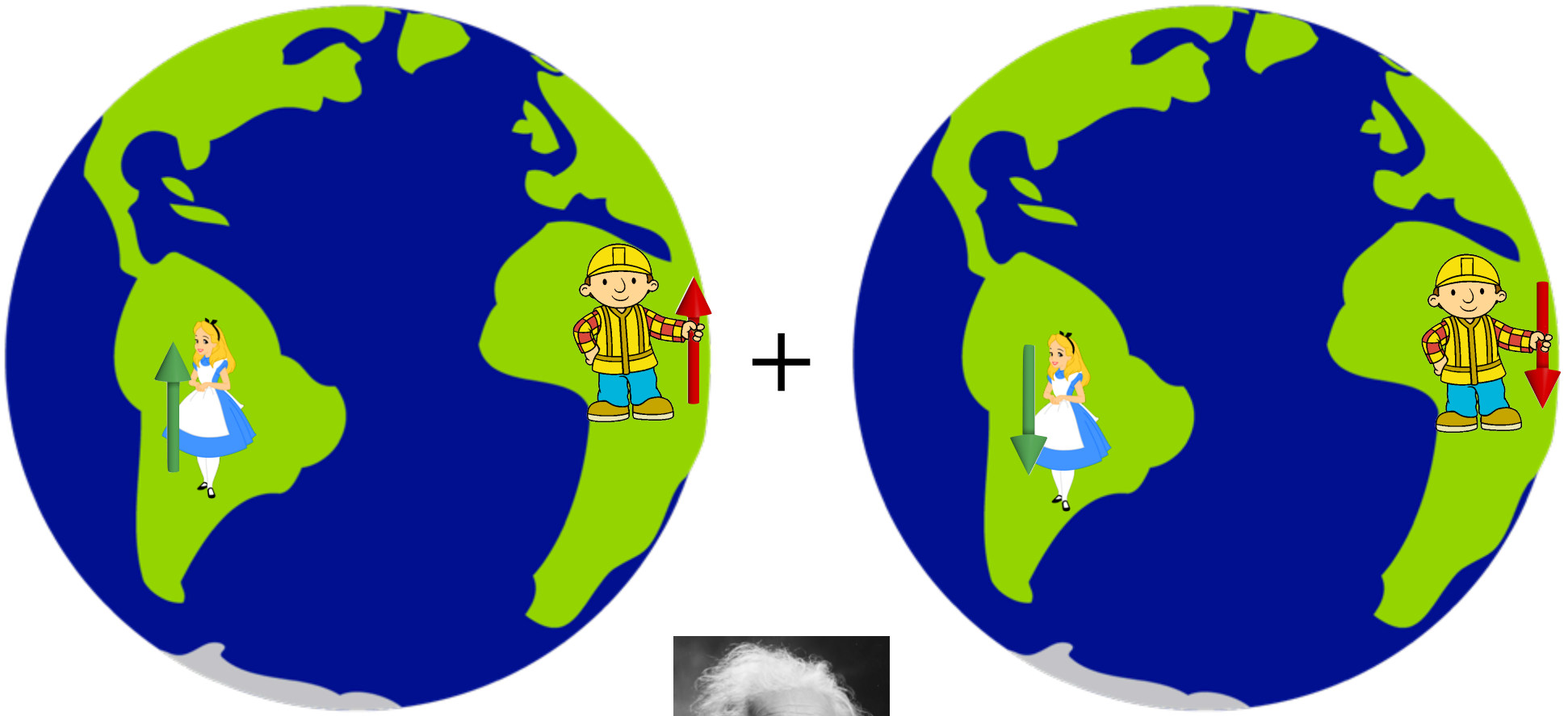
Entanglement

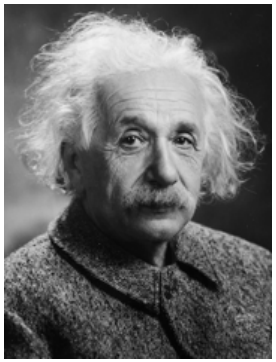


Entanglement

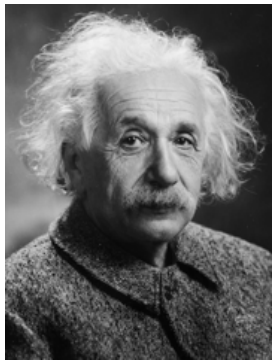


Einstein-Podolsky-Rosen Pair



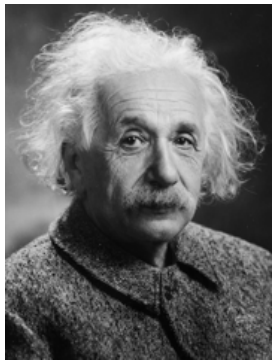


Einstein-Podolsky-Rosen Pair

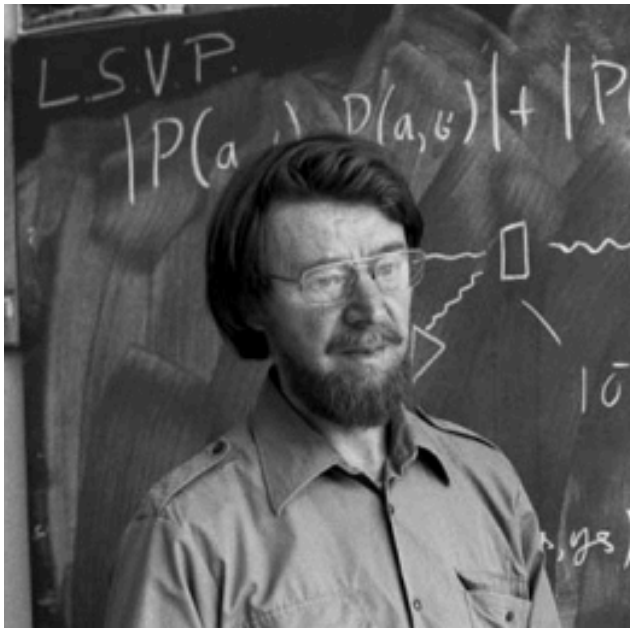


“quantum non-locality”

Einstein-Podolsky-Rosen Pair

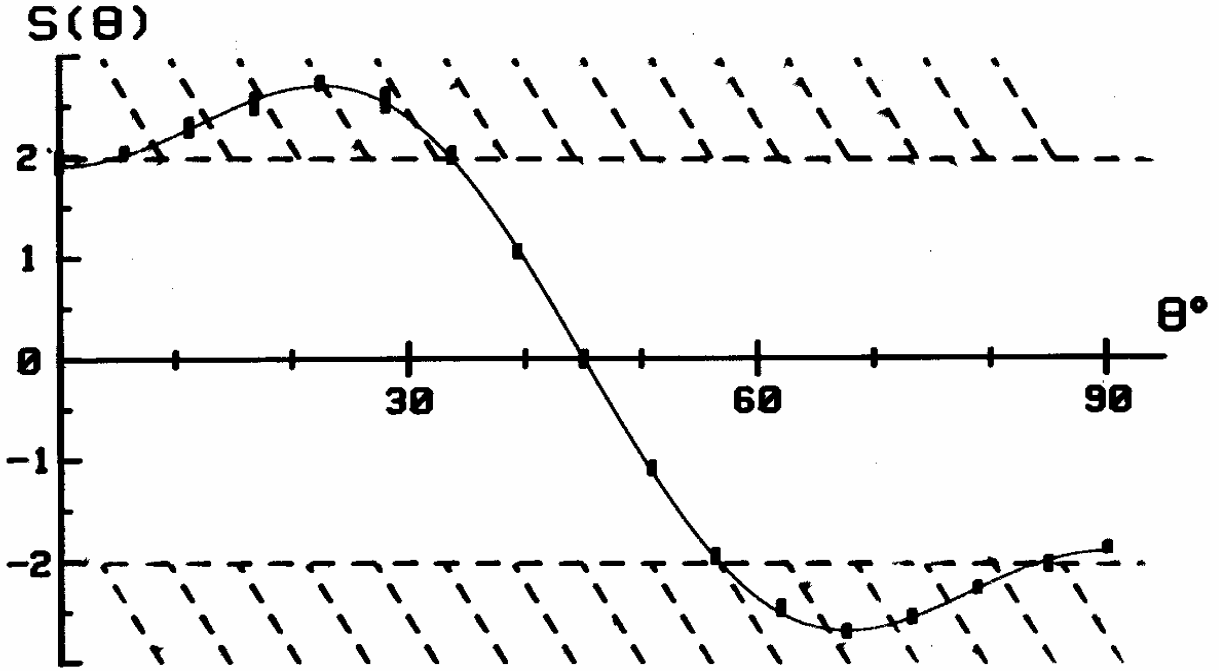


“quantum non-locality”



John Bell

Alain Aspect



no local realism

MagiQ

id Quantique

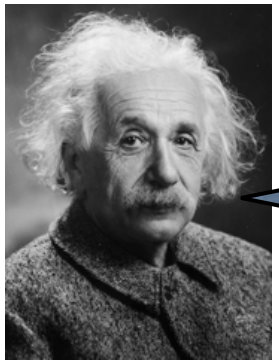
A Quantum Leap for Cryptography

labs Quintessence

SEQURENET

A Quantum Key to Network Security

Einstein-Podolsky-Rosen Pair



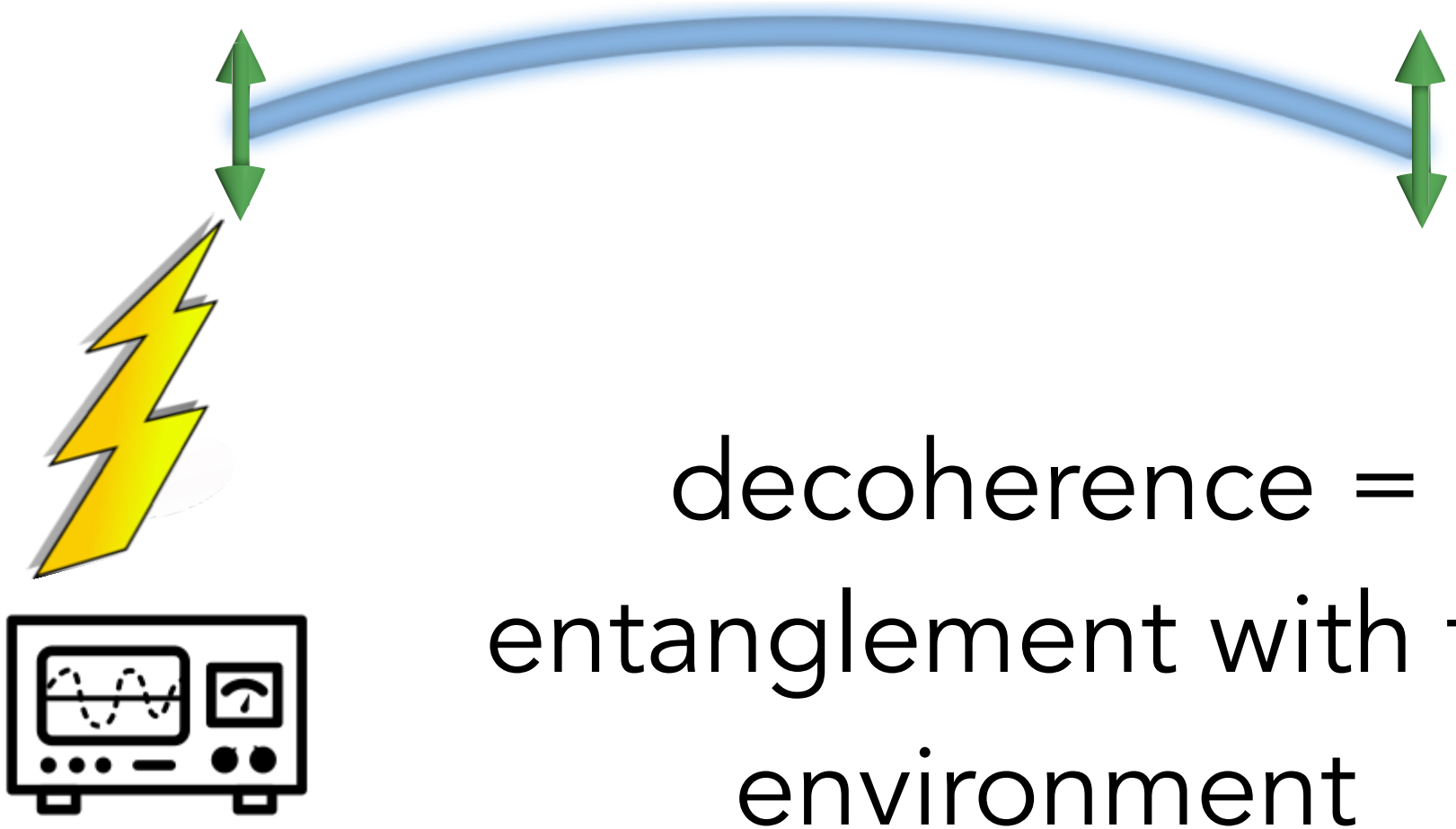
spukhafte Fernwirkung!

Collapse or decoherence

Collapse or decoherence

Collapse or decoherence

Collapse or decoherence



decoherence =
entanglement with the
environment

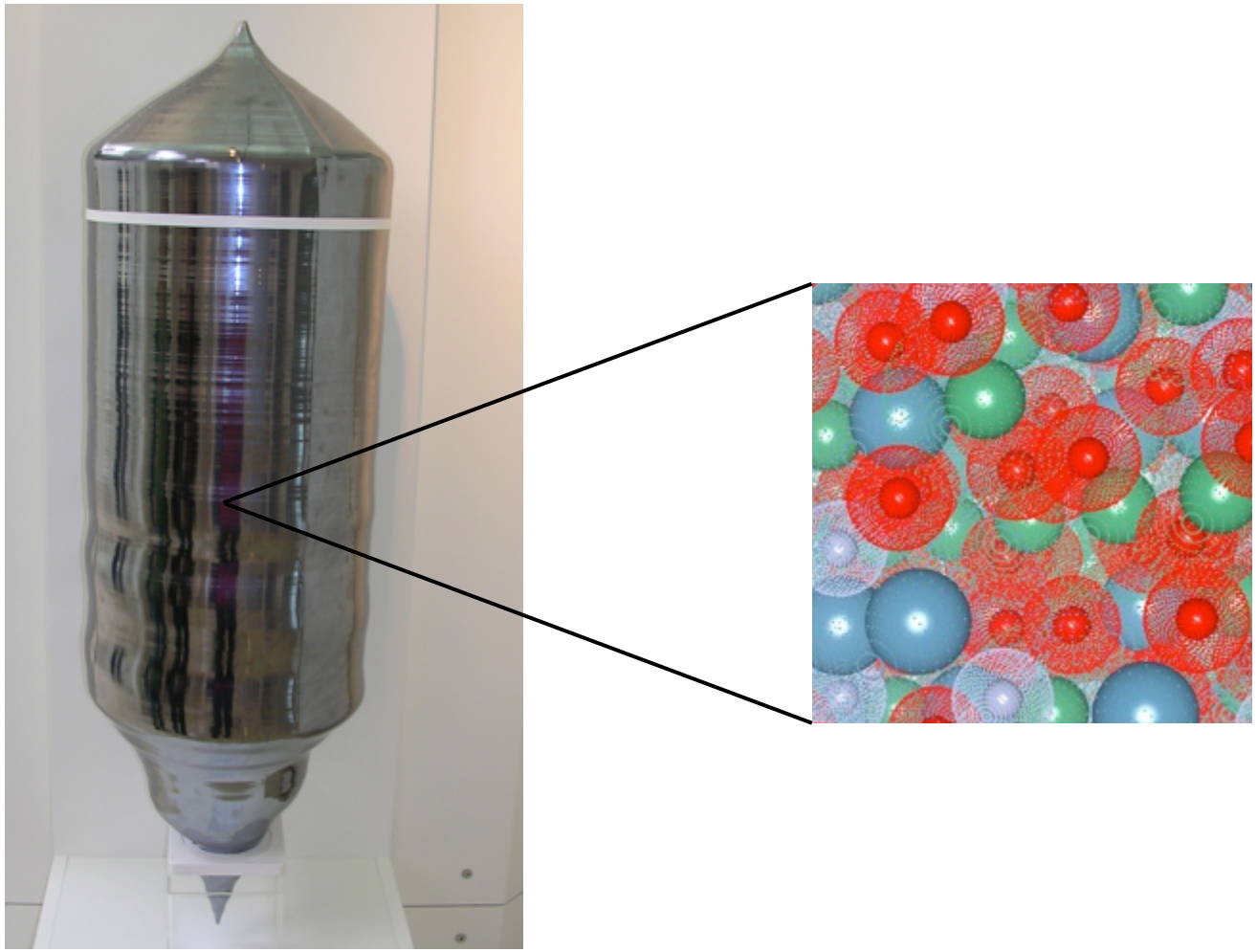
Collapse or decoherence

decoherence =
entanglement with the
environment

uncontrolled entanglement

controlled entanglement

Dense matter



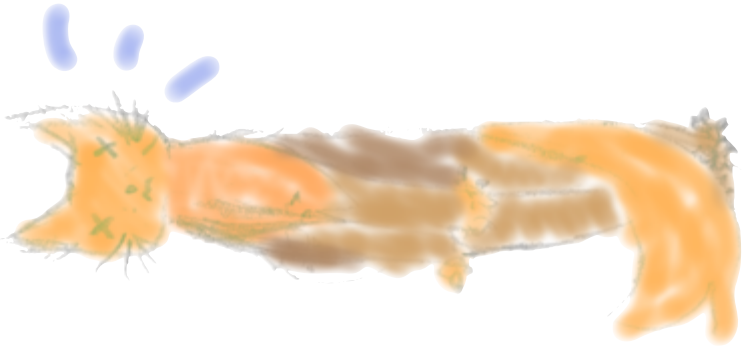
# of electrons in 1 cm cube of Si:

1,000,000,000,000,000,000,000,000

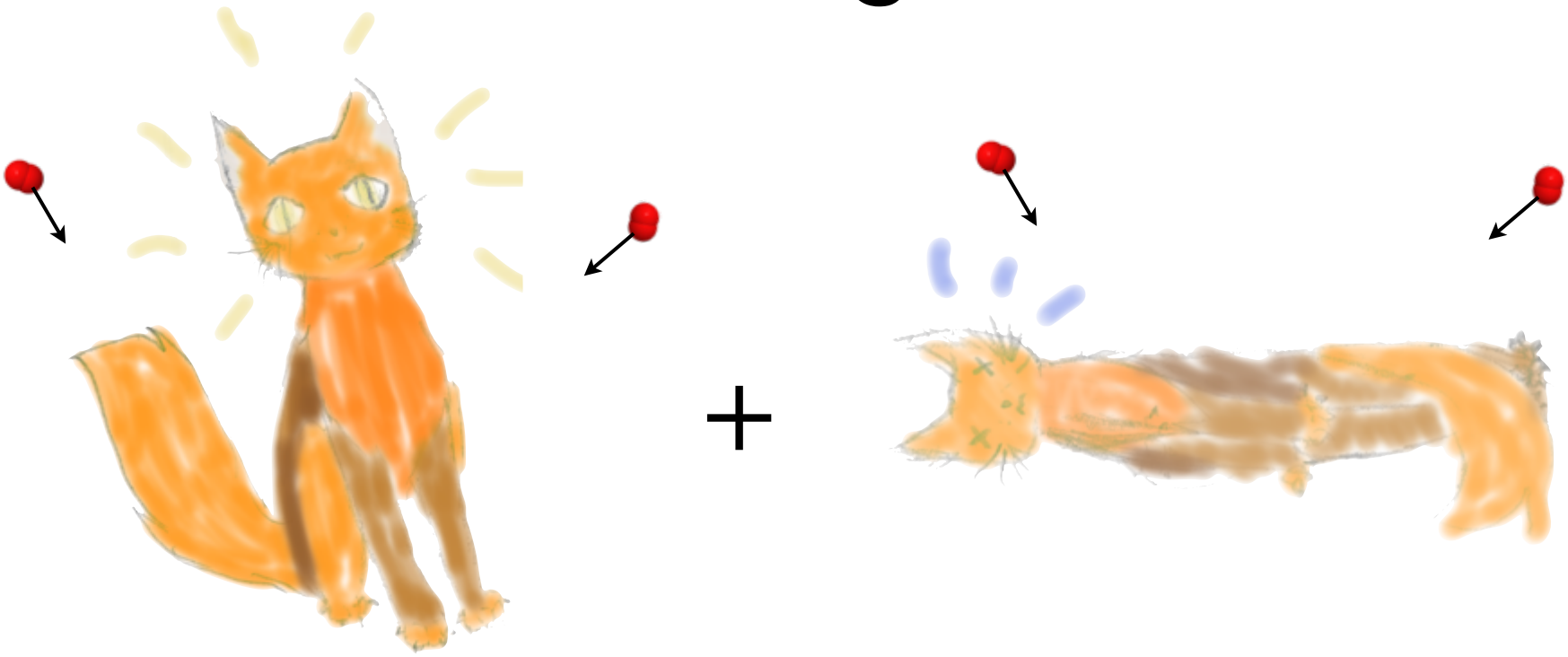
≈ # of stars in the *universe*

Schrödinger's Cat

+

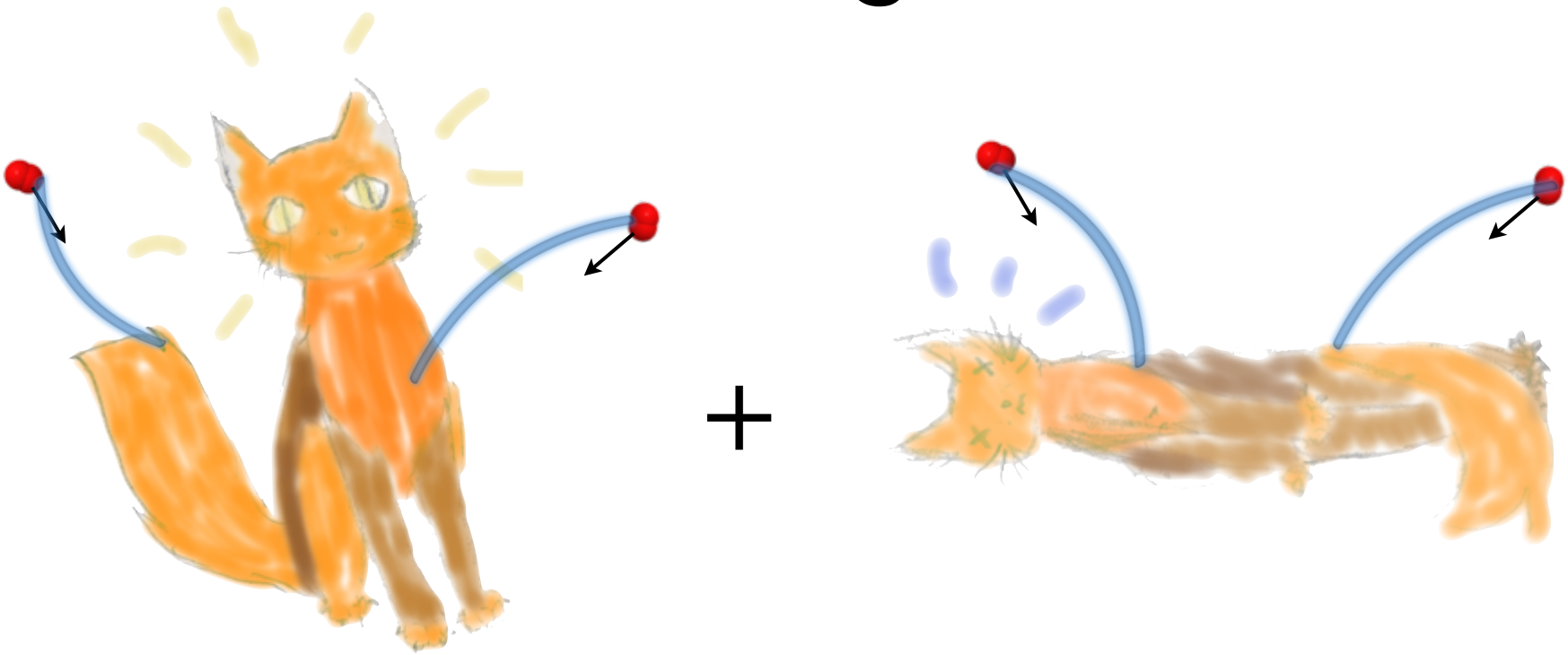


Schrödinger's Cat



measurement of any hair of the cat will collapse the superposition

Schrödinger's Cat

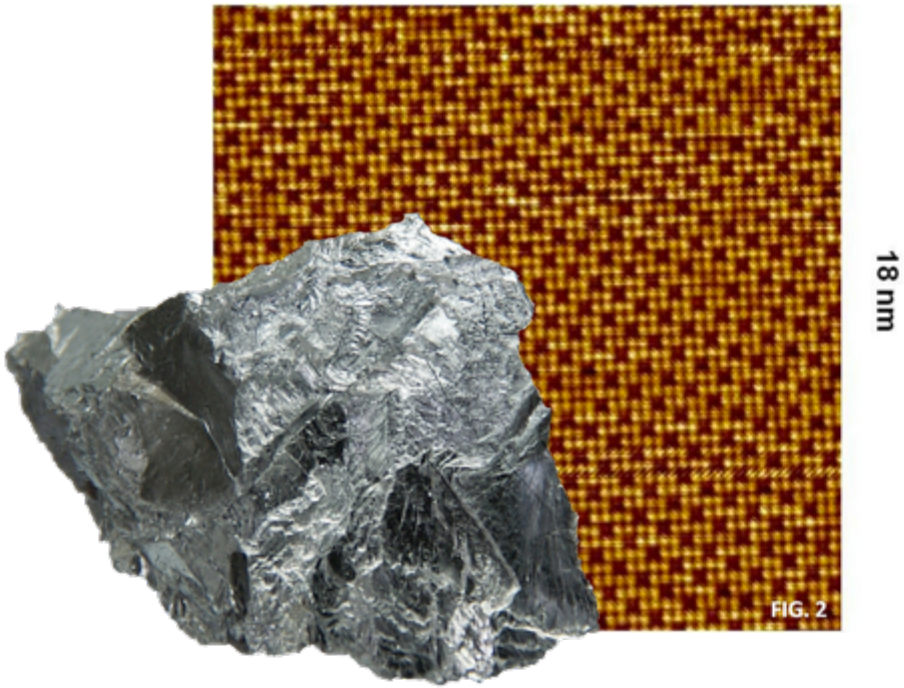


UNSTABLE to decoherence - uncontrolled entanglement with the environment

Billion dollar question: how much entanglement can be *stably* created?

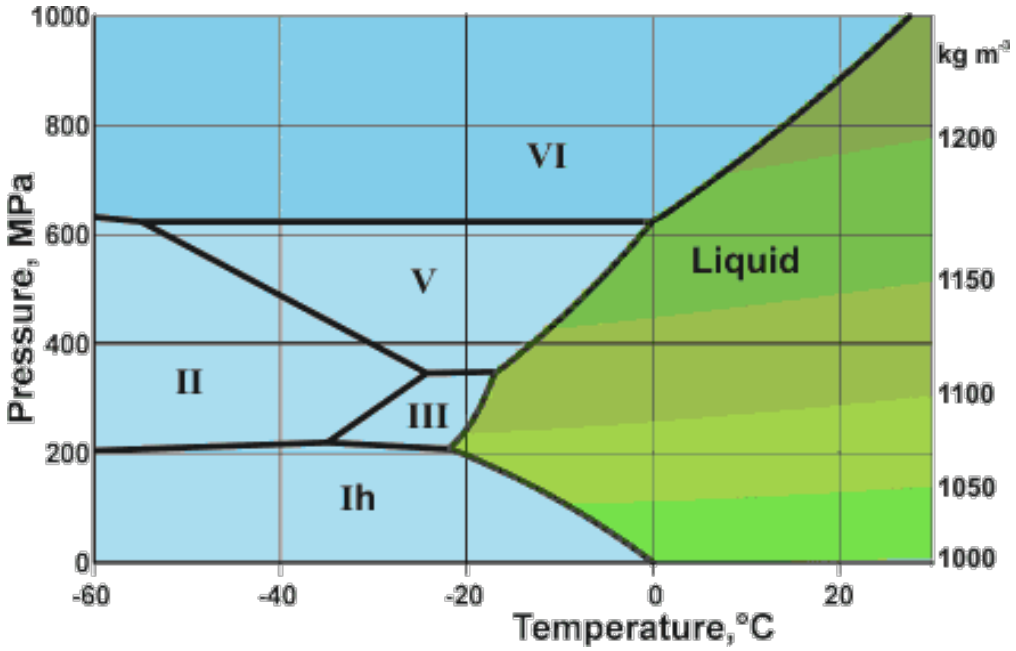
Can we get non-local
entanglement from local forces?

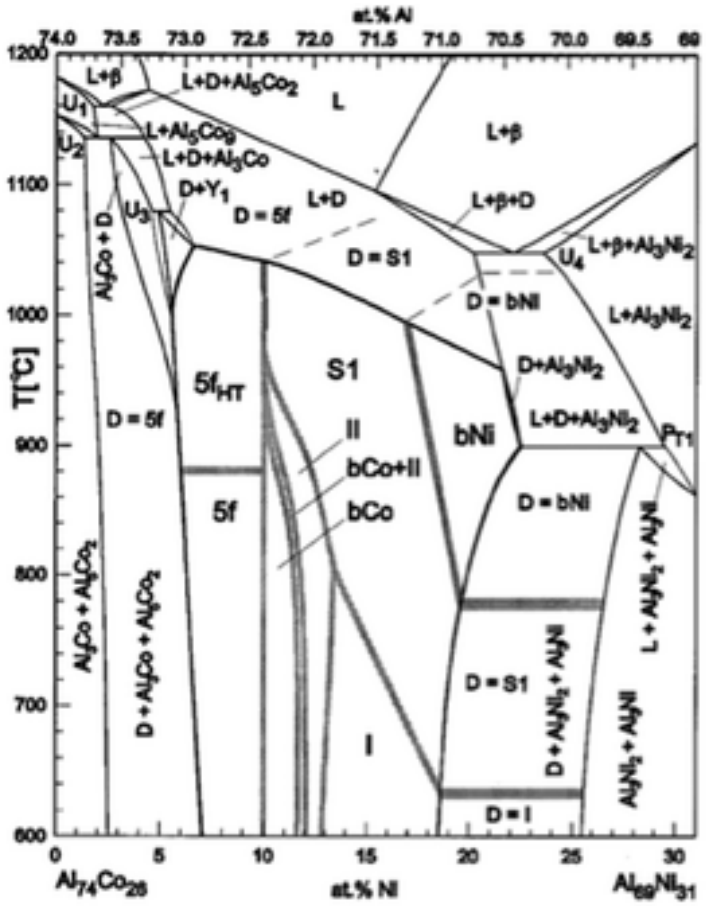
Emergence



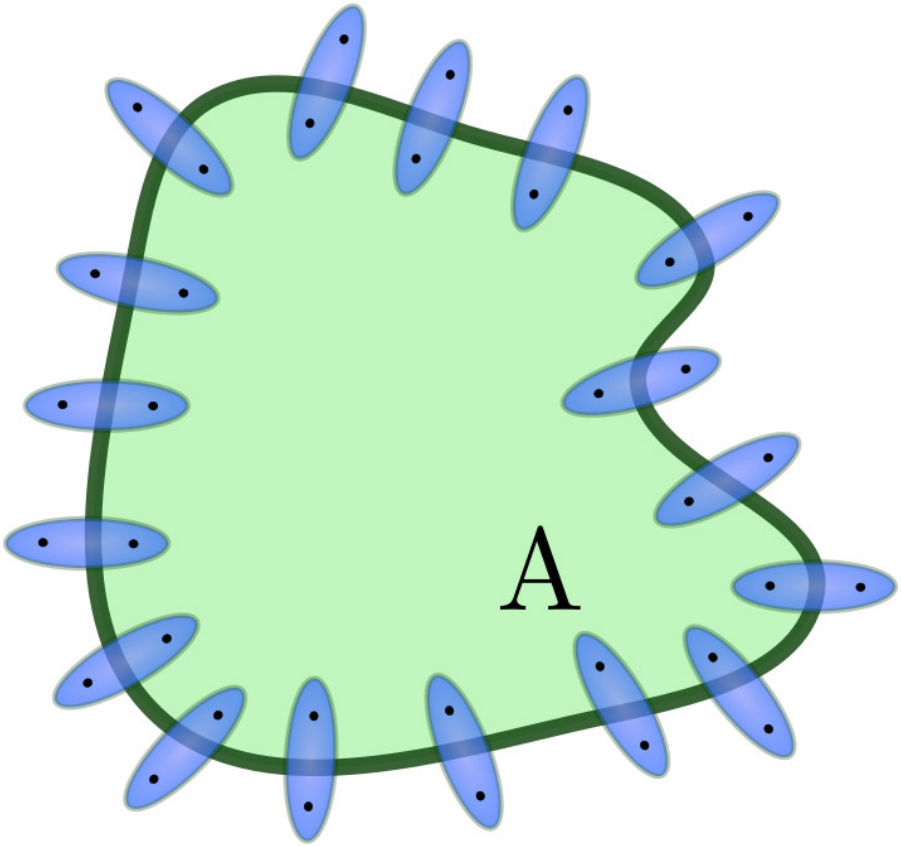
Emergence

Many *phases of matter*





"Area law"



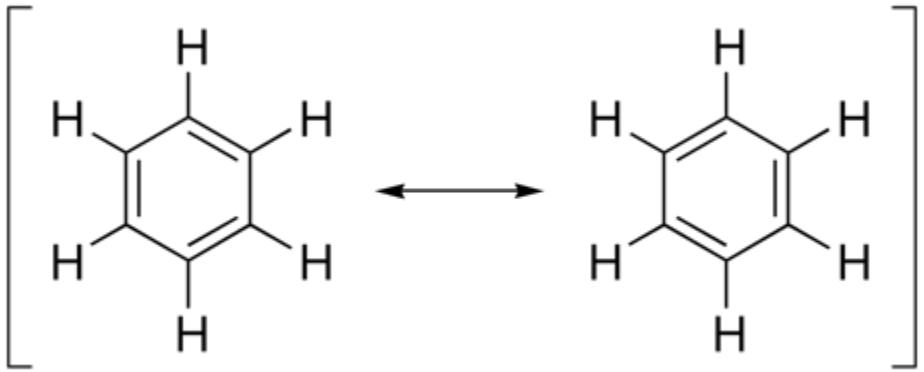
"Short range entanglement"

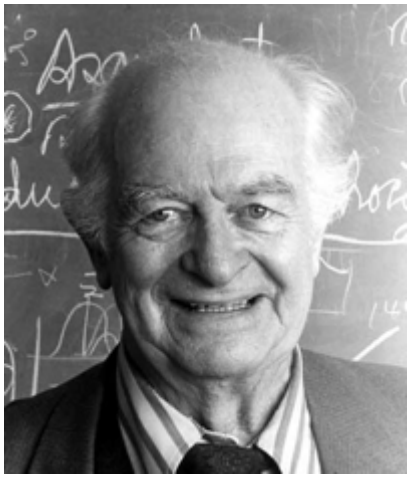
Strange Stuff

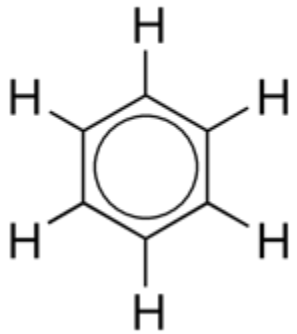
"Resonating valence bonds"

benzene

C_6H_6







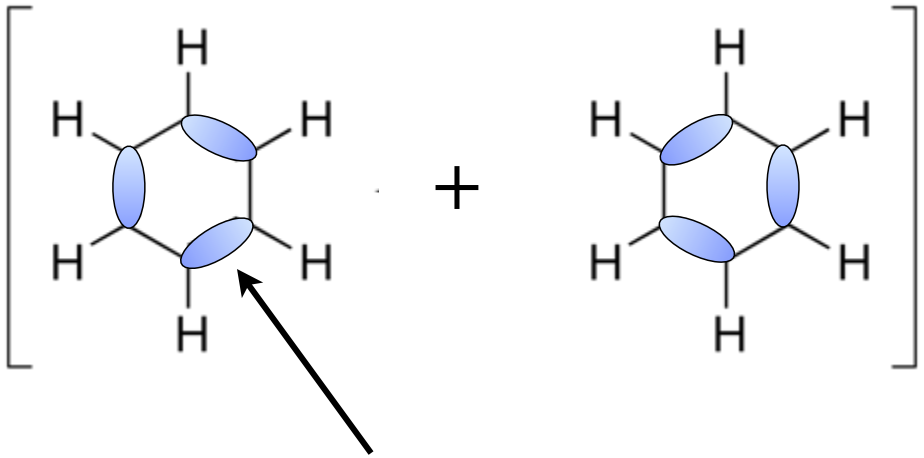
Linus Pauling ~ 1930

Strange Stuff

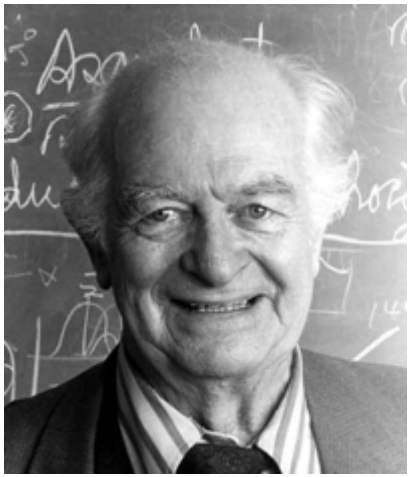
"Resonating valence bonds"

benzene

C_6H_6



chemical bond = EPR pair!



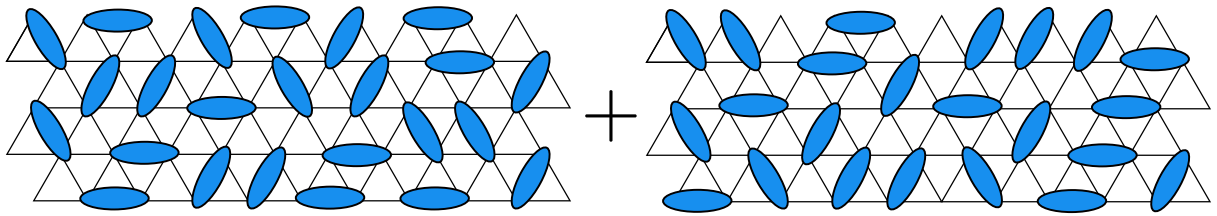
Linus Pauling ~ 1930

Strange Stuff

Phil Anderson, 1973

a “quantum liquid” of spins

Ψ =

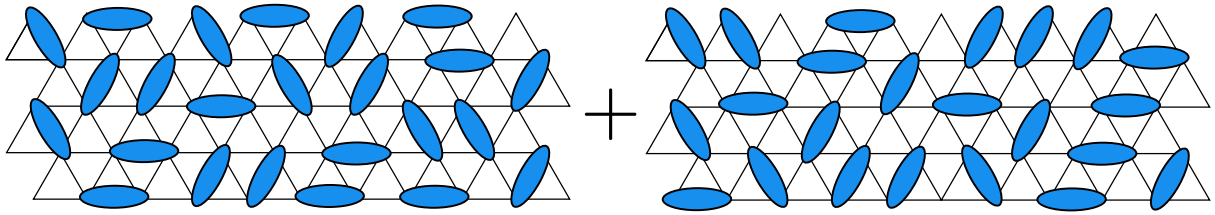


+…

Resonating **V**alence **B**ond state

Quantum spin liquid

Ψ =



+...

For ~500 spins, there are more amplitudes than there are atoms in the visible universe!

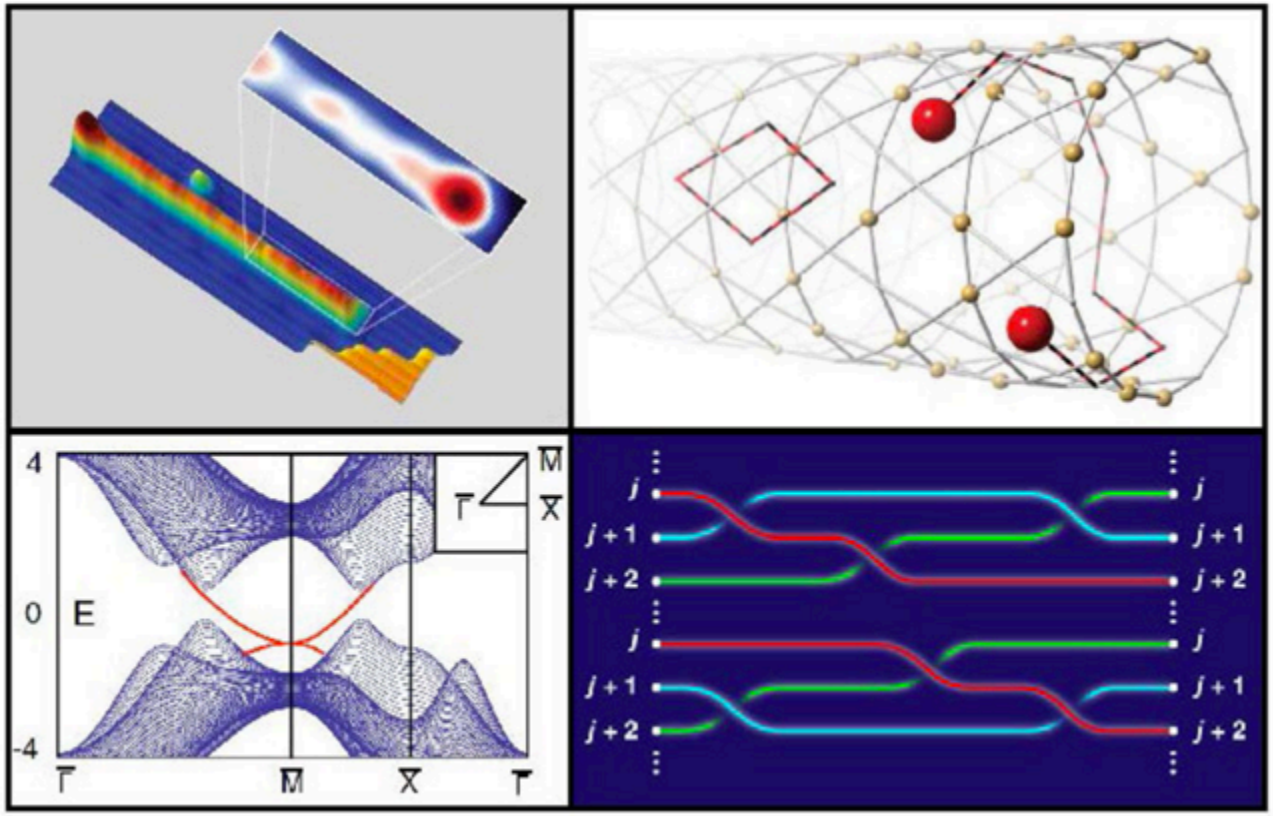
Is it robust?

Boulder School 2016: Topological Phases of Quantum Matter

July 11-August 5, 2016

Scientific Coordinators

Jason F. Alicea (Caltech)
Joseph Checkelsky (MIT)
Victor Gurarie (Boulder)
Michael Hermele (Boulder)
Director: Leo Radzihovsky (Boulder)



Topology

Kitaev

Wen

Topology

Thouless

Kane

Kitaev

Wen

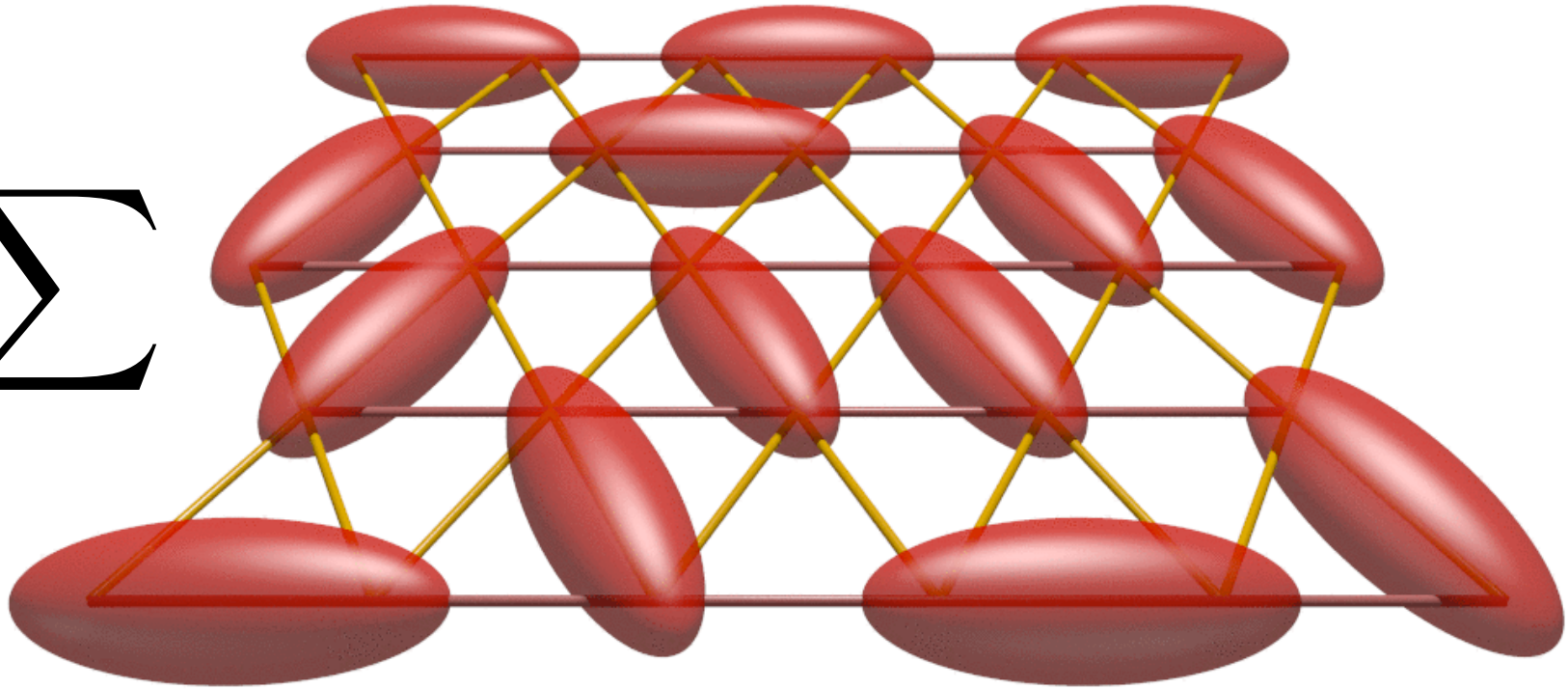
Topology

Thouless

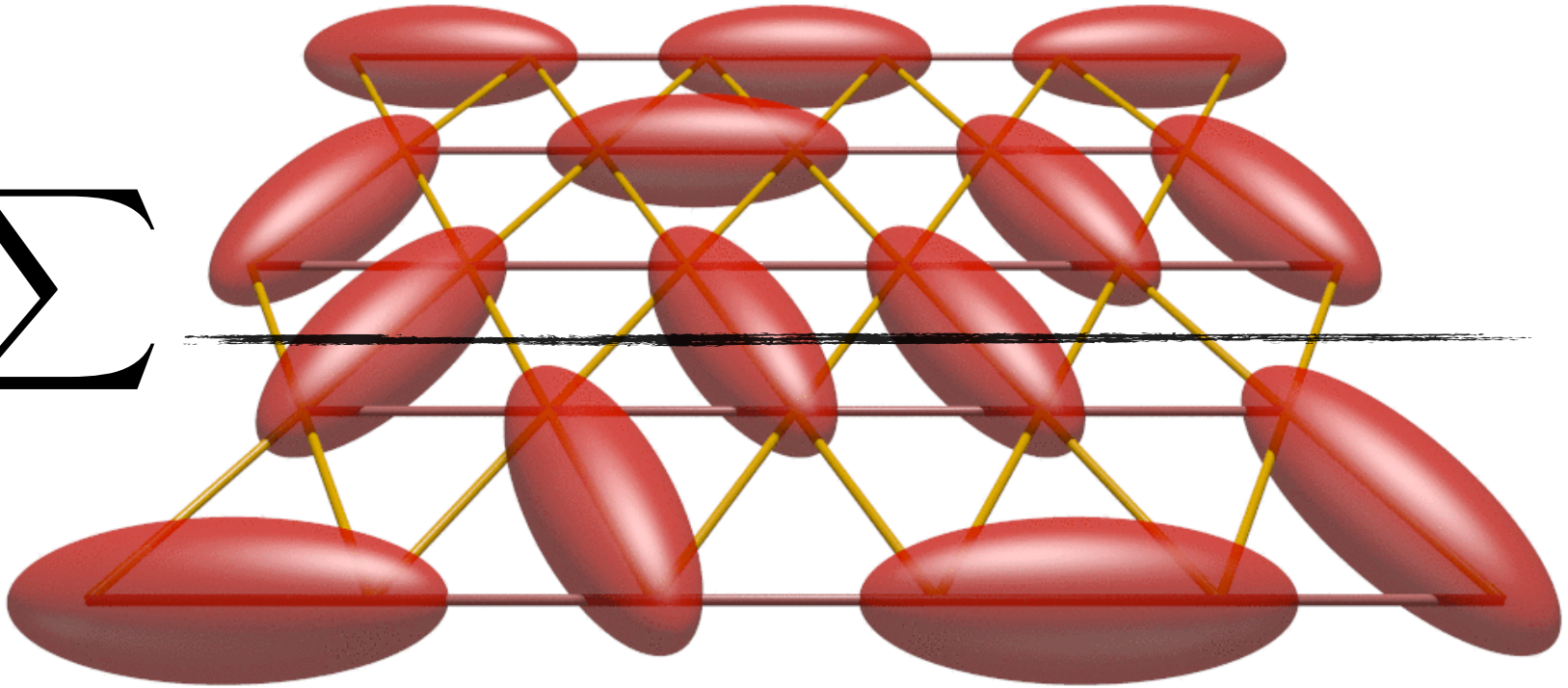
Kane

"Topological invariant" = *genus*: the number of holes

$$\Psi = \sum$$

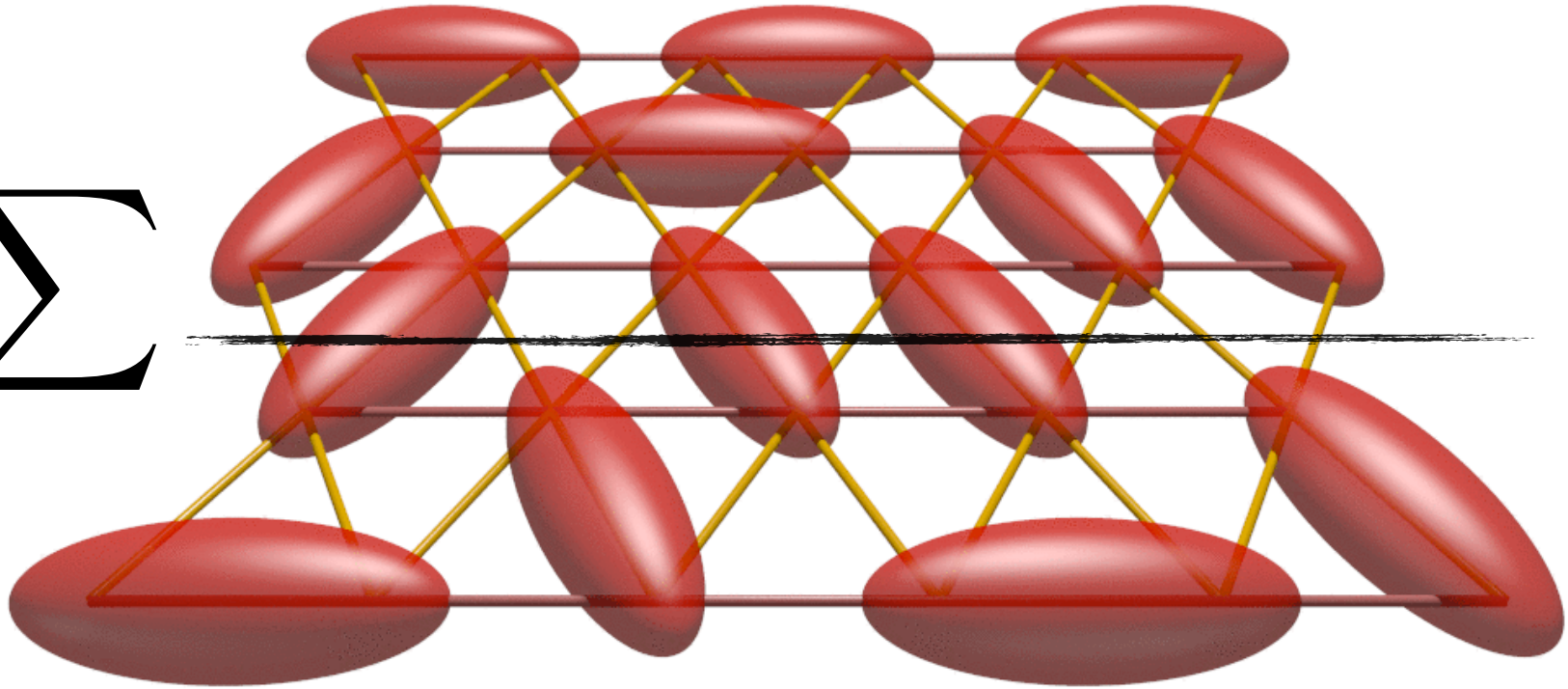


$$\Psi = \sum$$



Odd/even-ness of valence bonds crossing the line is a topological invariant

$$\Psi = \sum$$

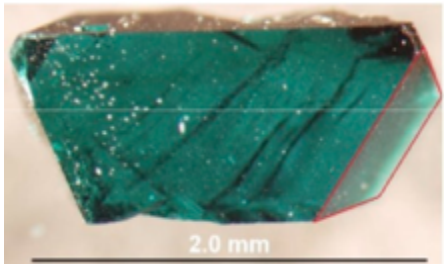


Quantum information is stored in such topological invariants and is distributed globally

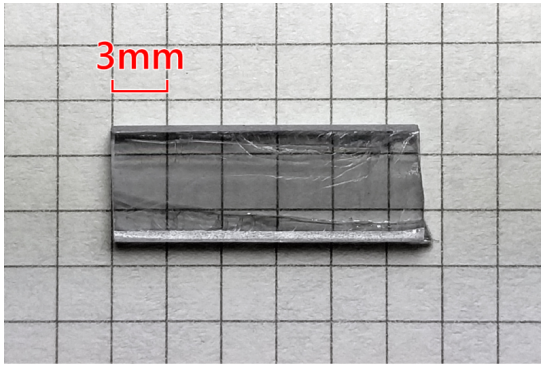
Topological Protection

In theory: thousands of different topological "phases of matter"

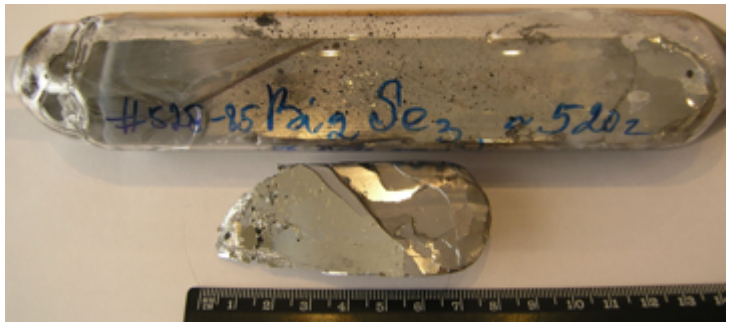
Strange stuff



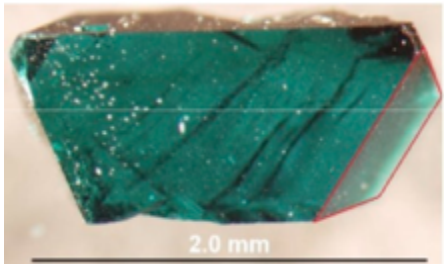
herbertsmithite, a natural mineral discovered in Chile



$YbMgGaO_4$, synthesized last year



Bi_2Se_3, a semiconductor used as a thermoelectric



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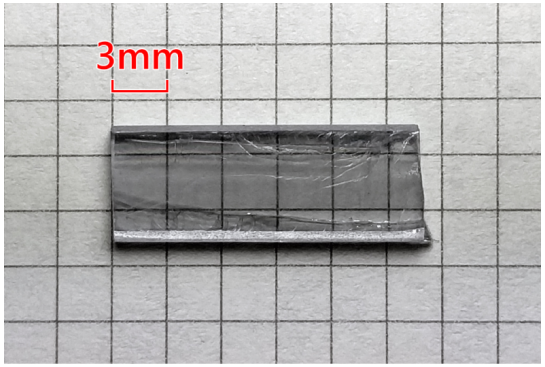
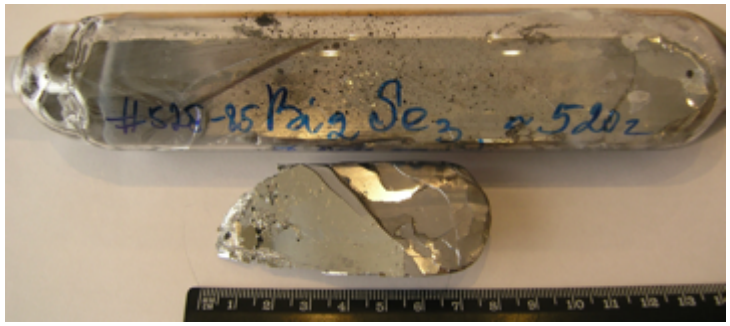


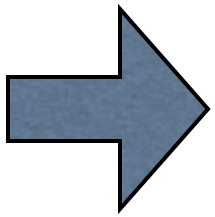
$YbMgGaO_4$, synthesized last year

Quantum-ness is not obvious!!



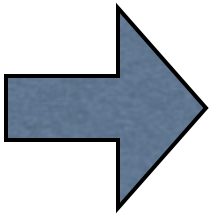
Bi_2Se_3, a semiconductor used as a thermoelectric

Strange stuff



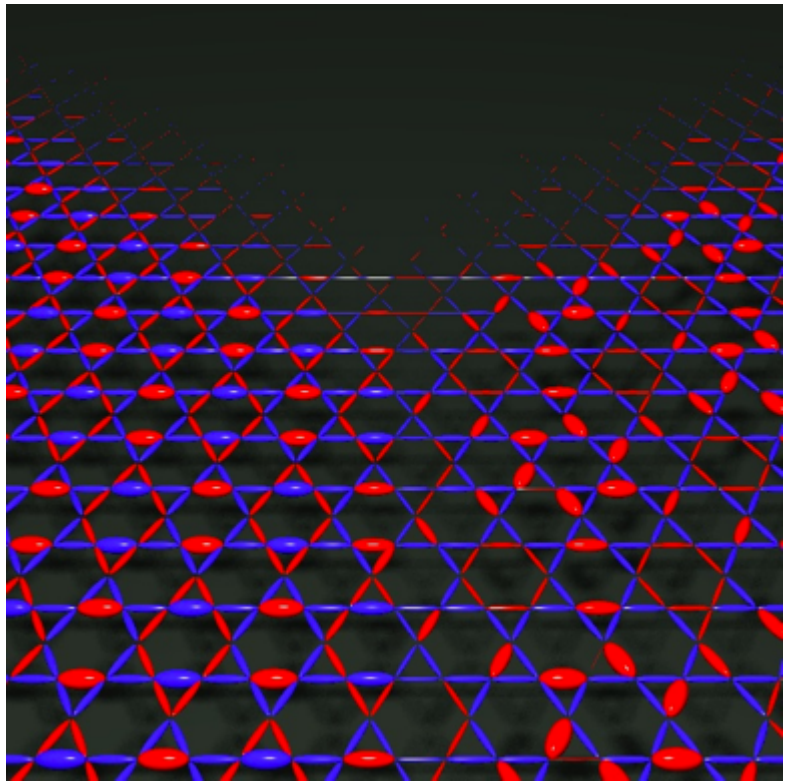
Peculiar particles

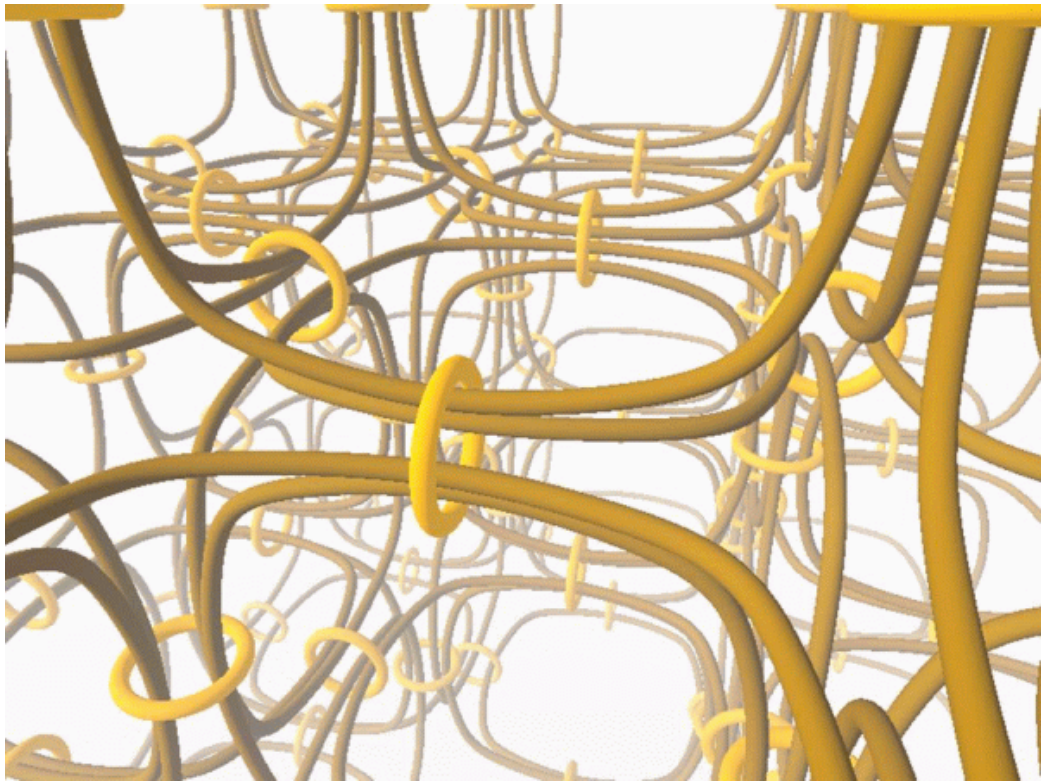
Strange stuff



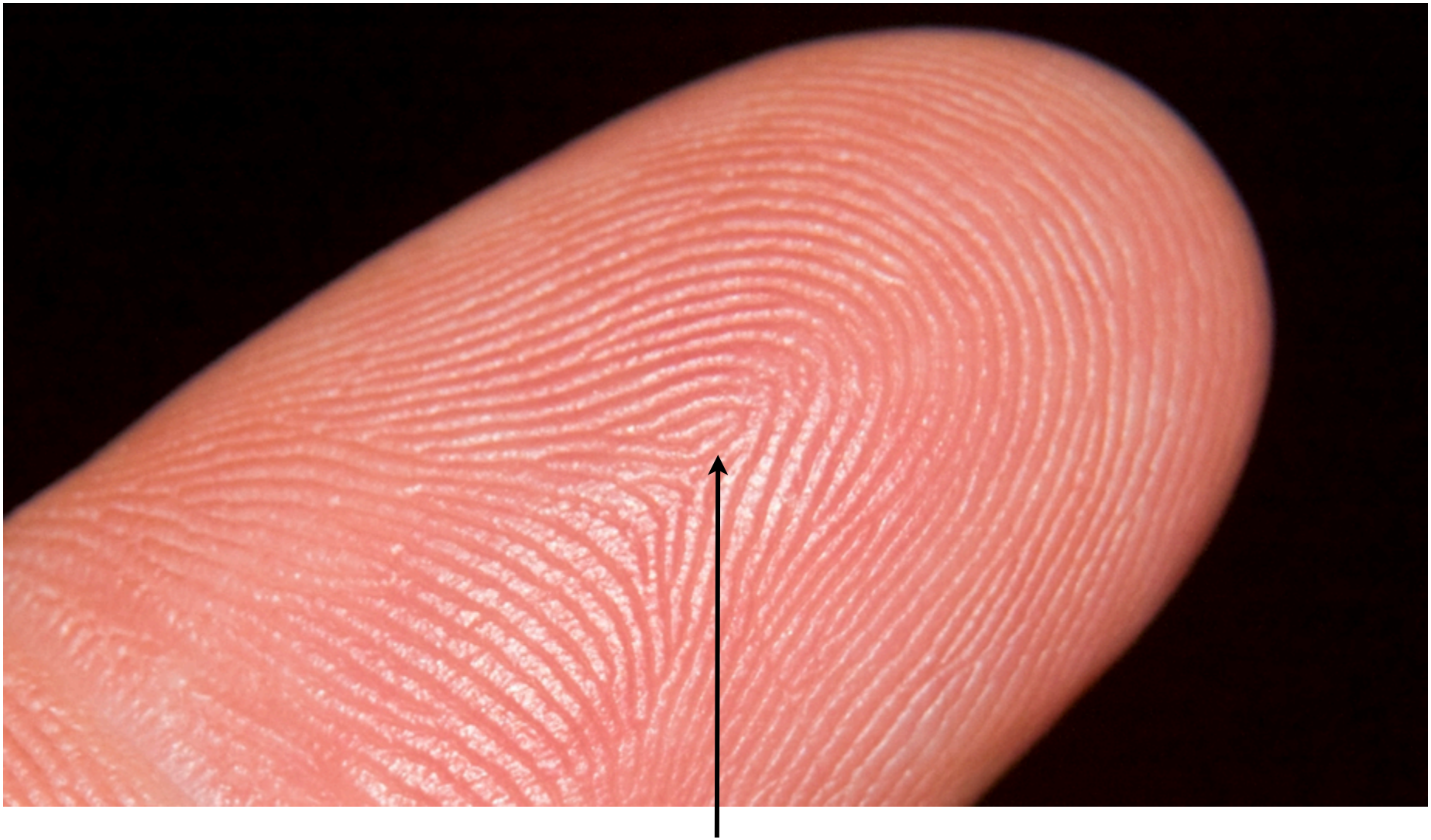
Peculiar particles

"quasi-particles"



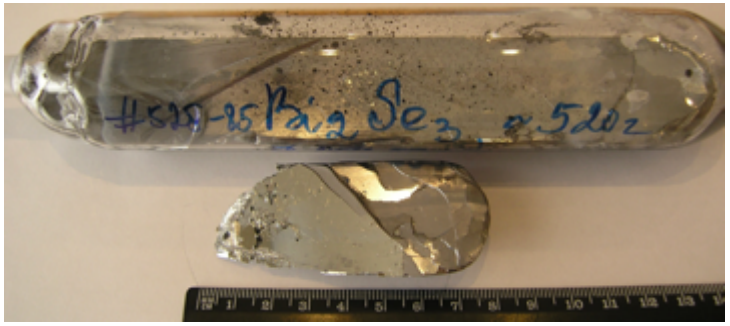


A quantum texture



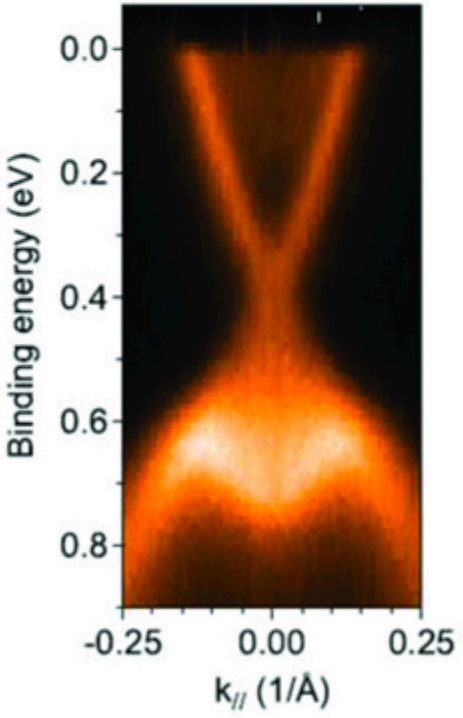
a topological defect

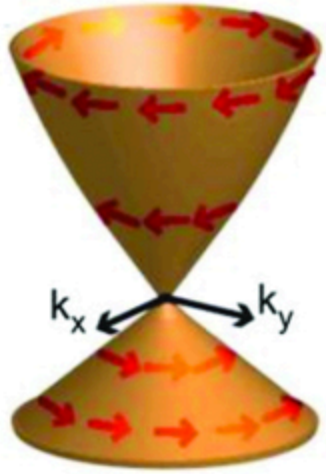
Topological Insulator



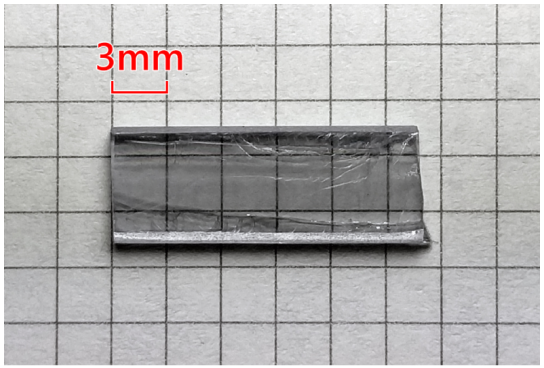
Massless Dirac fermion

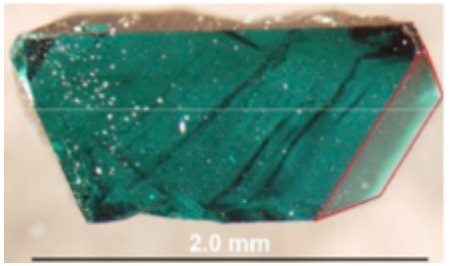
"artificial neutrino"

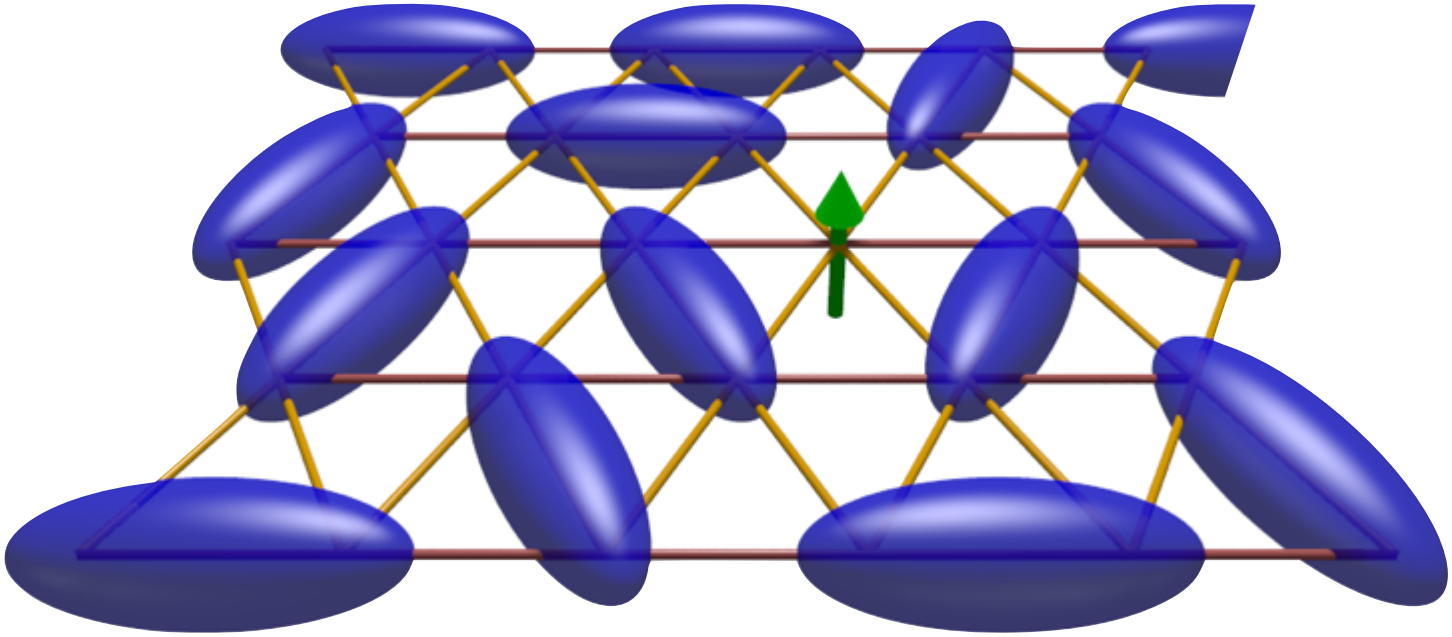




Spin Liquid

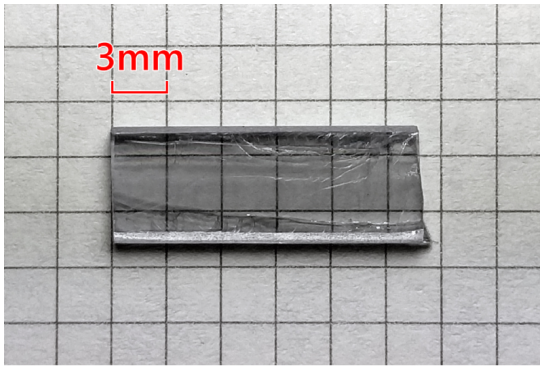


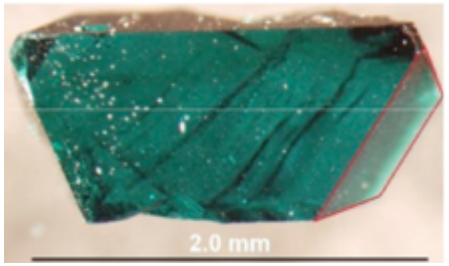


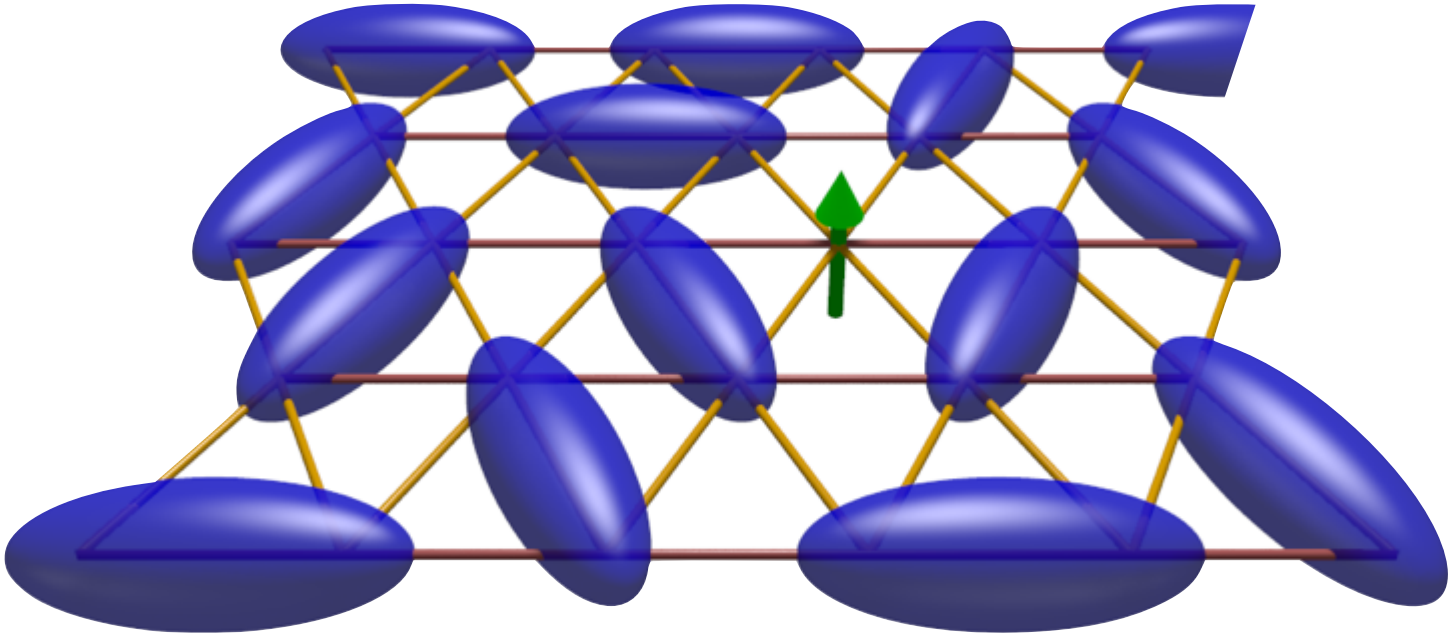


"spinon"

Spin Liquid

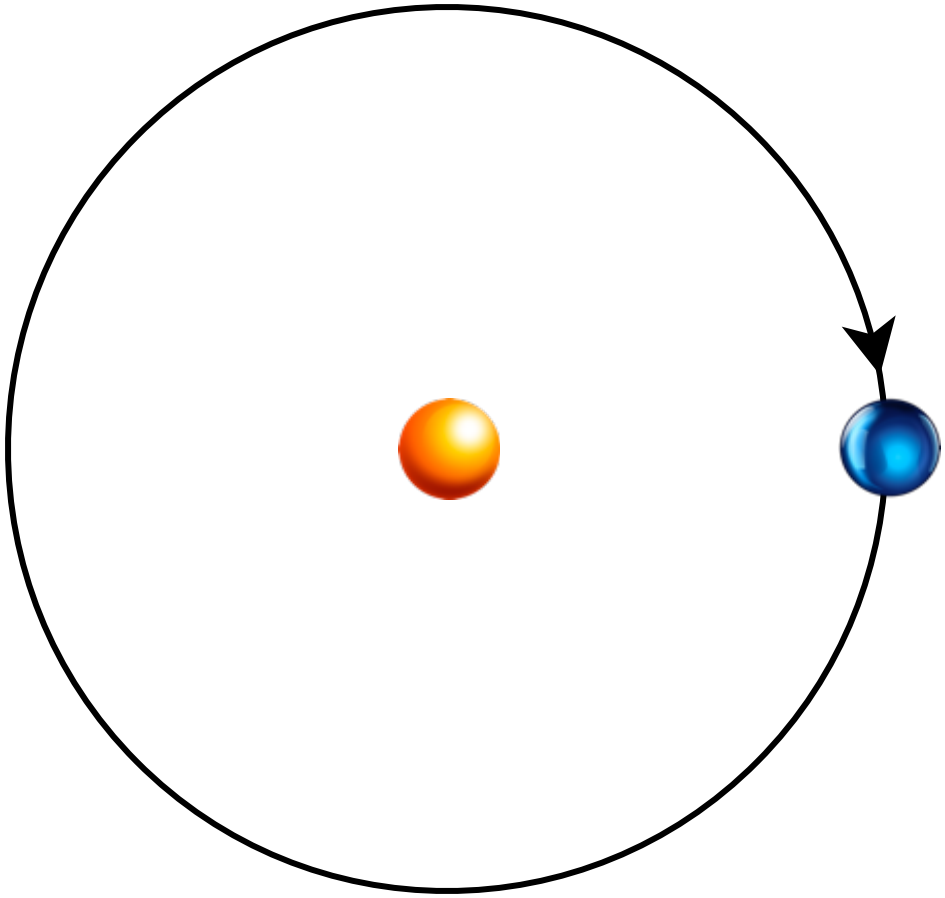




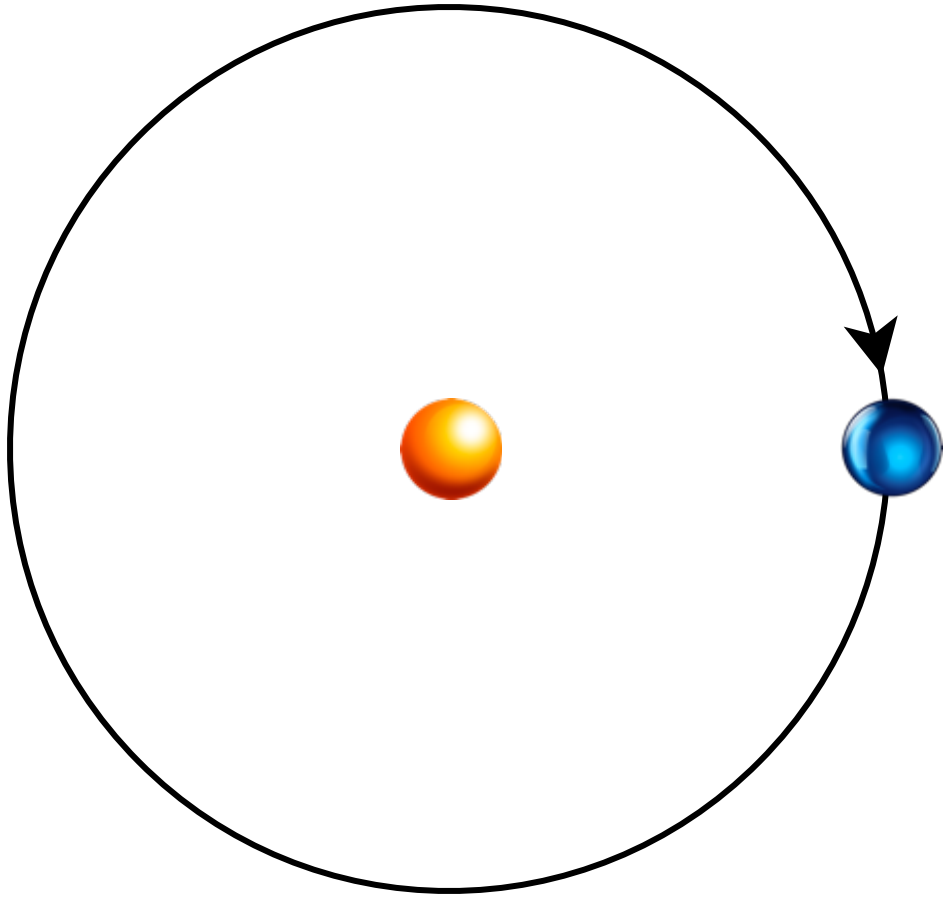


"spinon"

Anyons

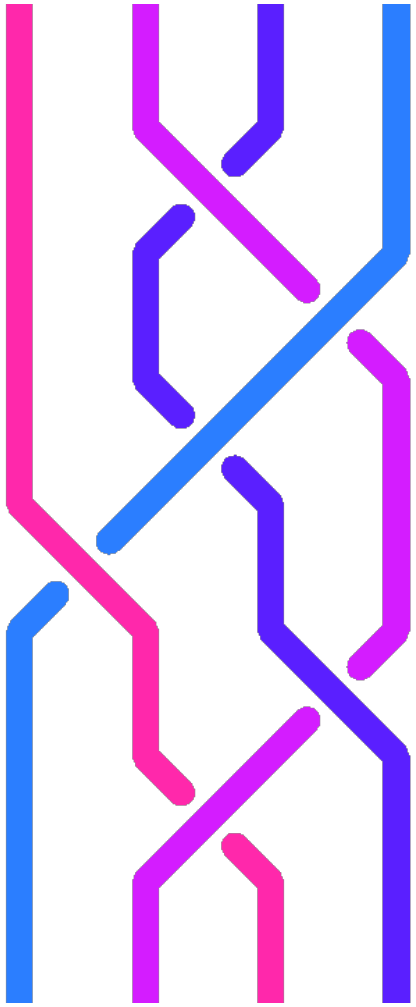


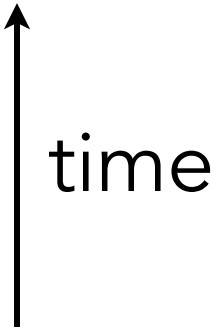
Anyons

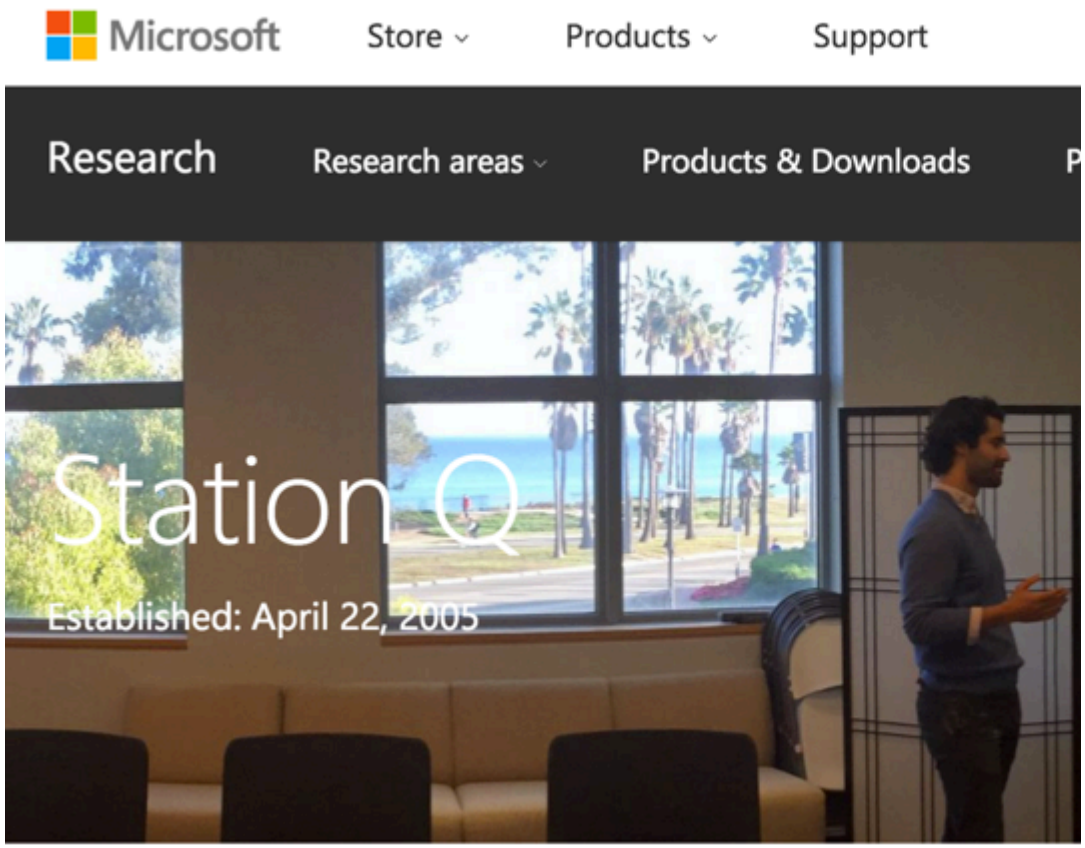


Amplitudes in entangled superposition are changed!

Anyons







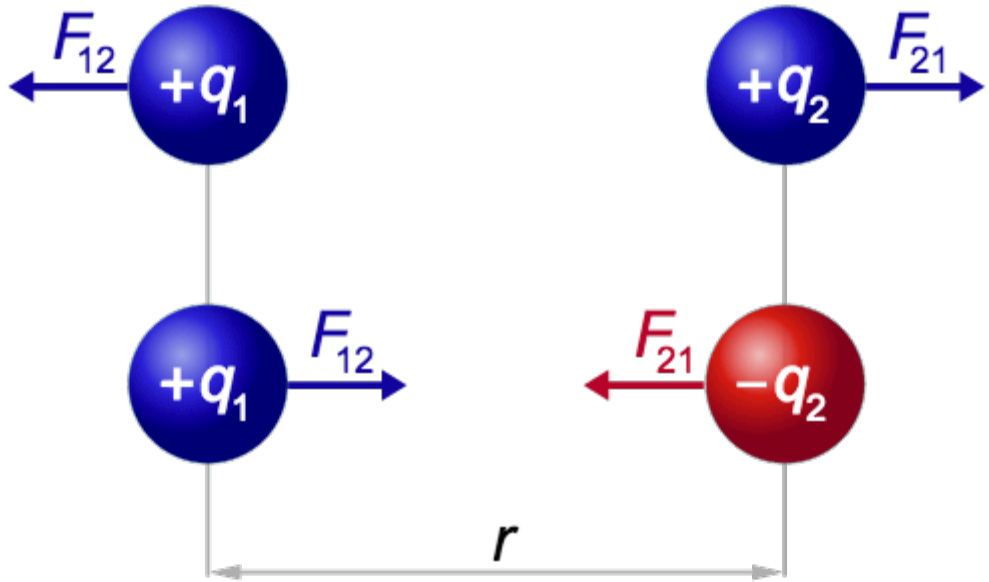
Future computers may be very strange indeed!

Fundamental applications?
Can elementary particles and forces of our world emerge from entanglement?

Coulomb, 1785

DES recherches qui précèdent, il réſultera :

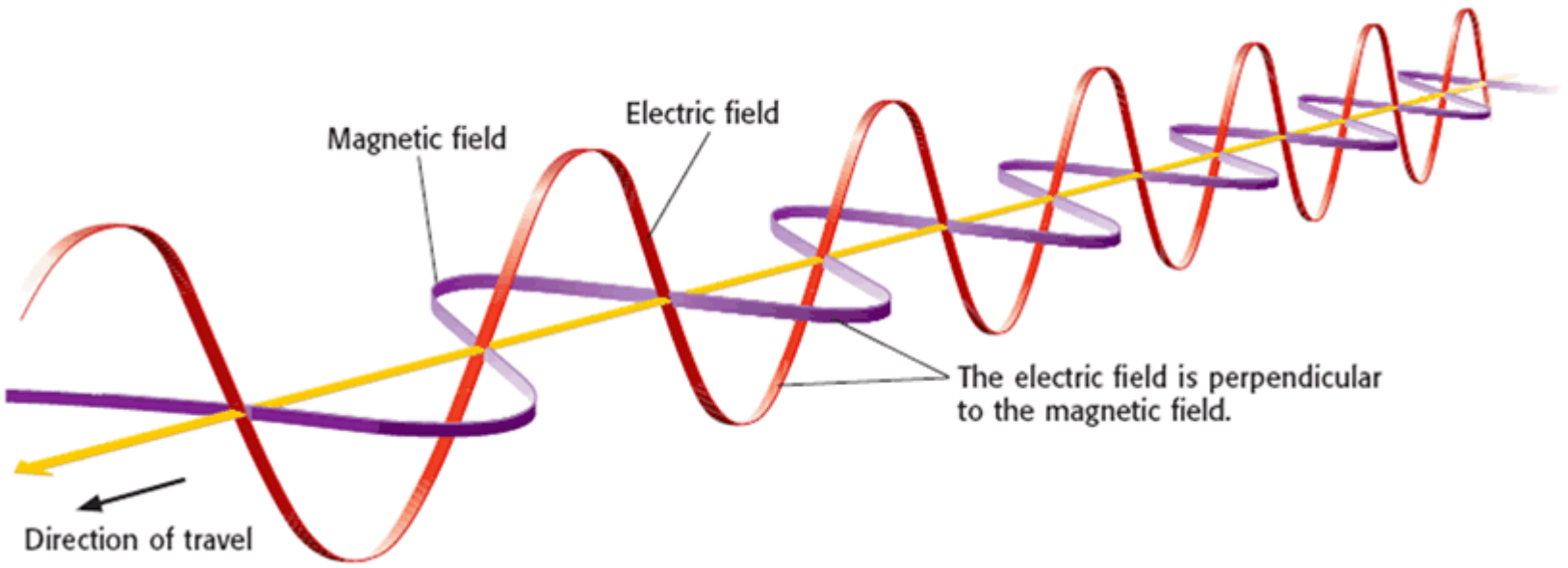
1.° Que l'action, ſoit répulſive, ſoit attractive de deux globes électriſés, & par conſéquent de deux molécules électriques, eſt en raiſon compoſée des denſités du fluide électrique des deux molécules électriſées, & inverſe du carré des diſtances.



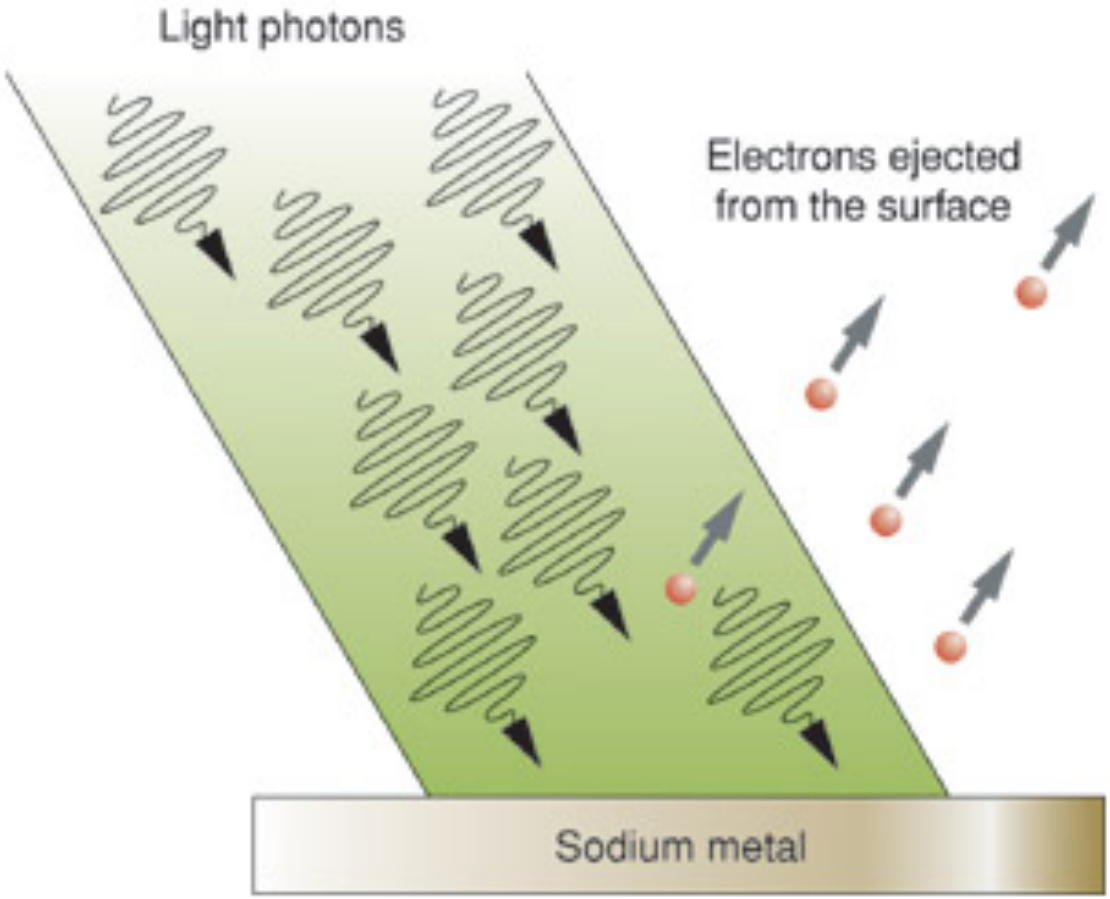
$$F_{12} = F_{21} = k \frac{q_1 q_2}{r^2}$$

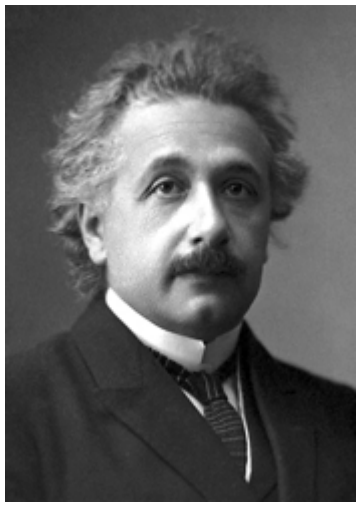
Electromagnetism

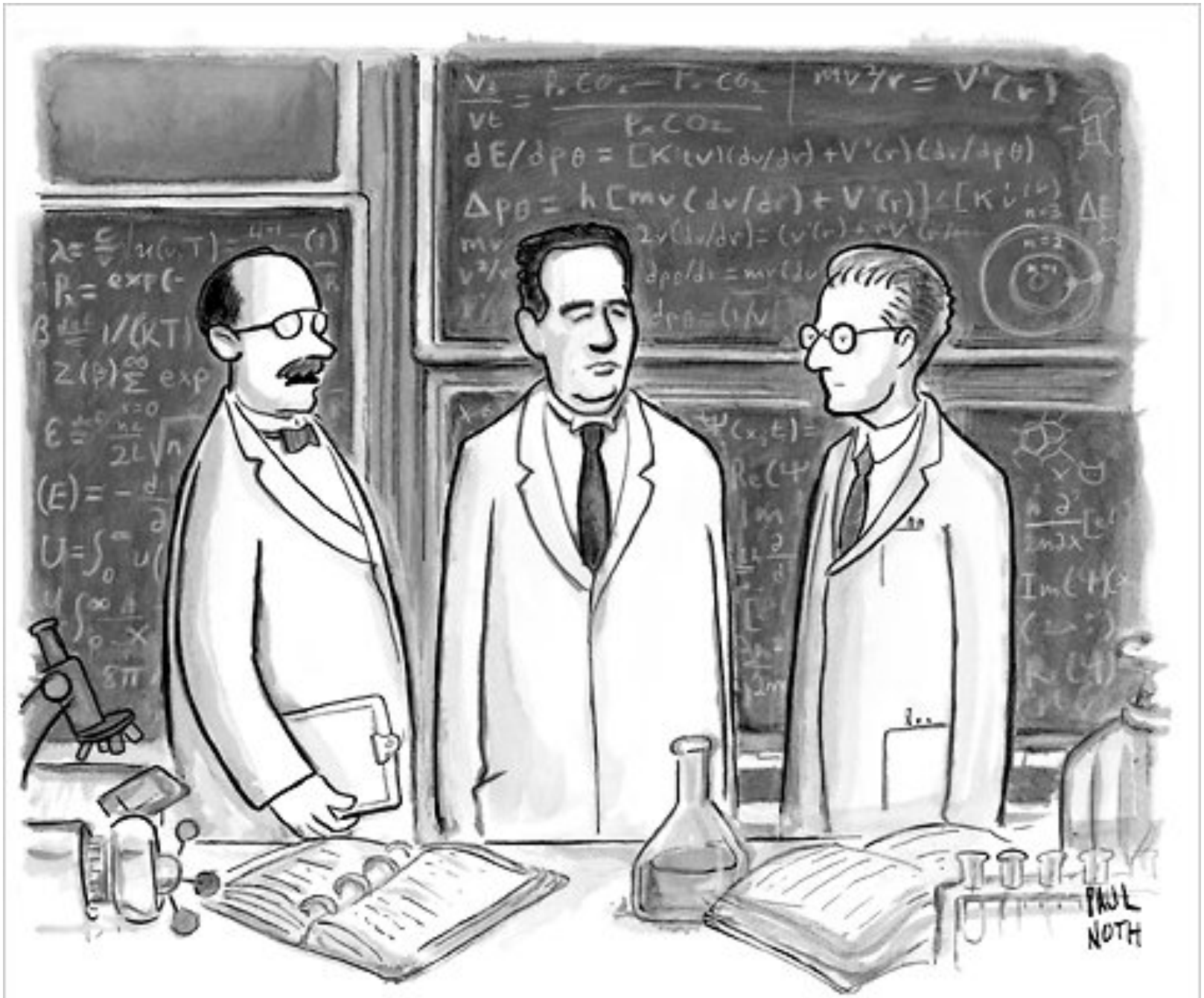
James Clerk Maxwell



Photoelectric effect

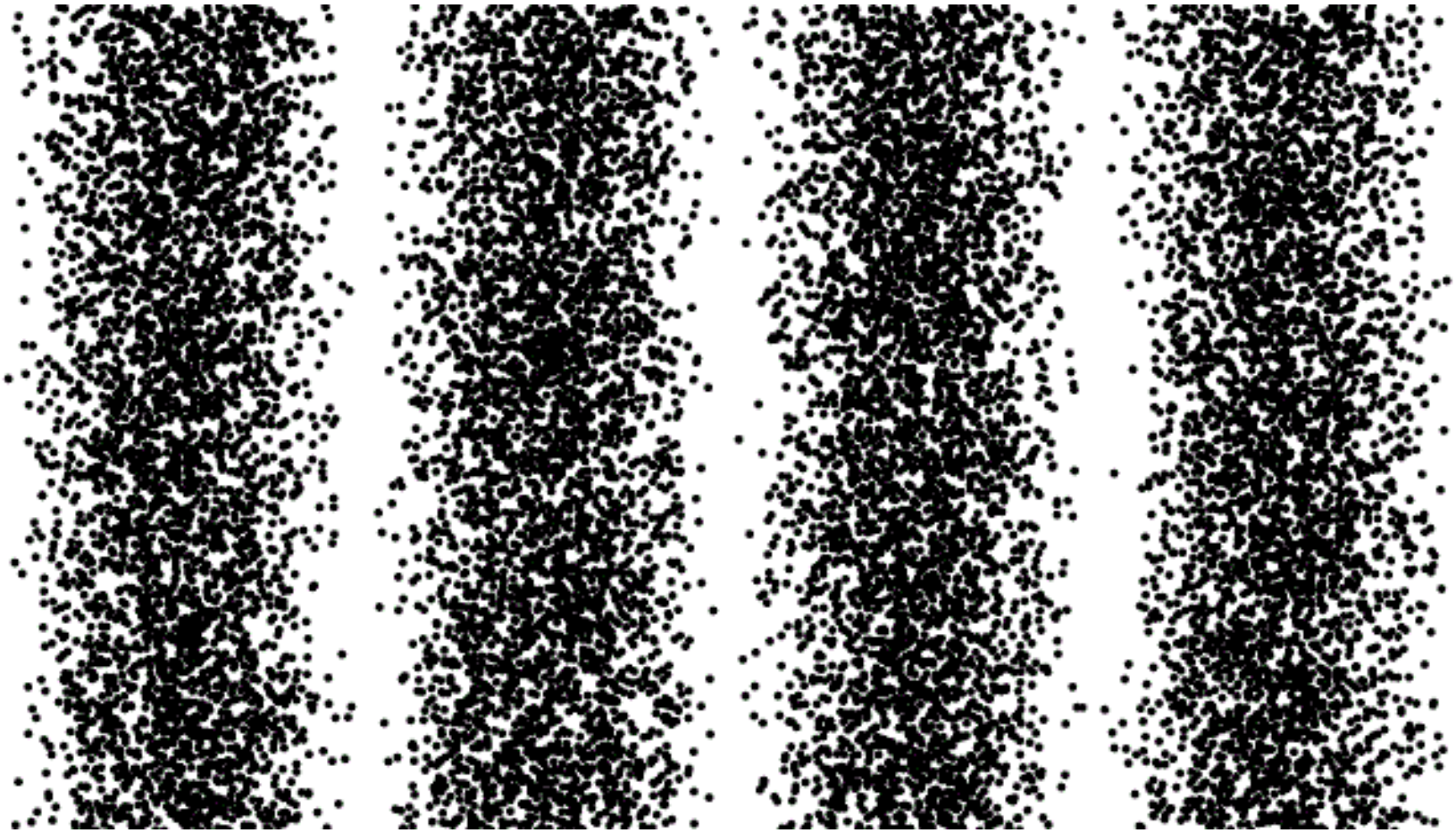






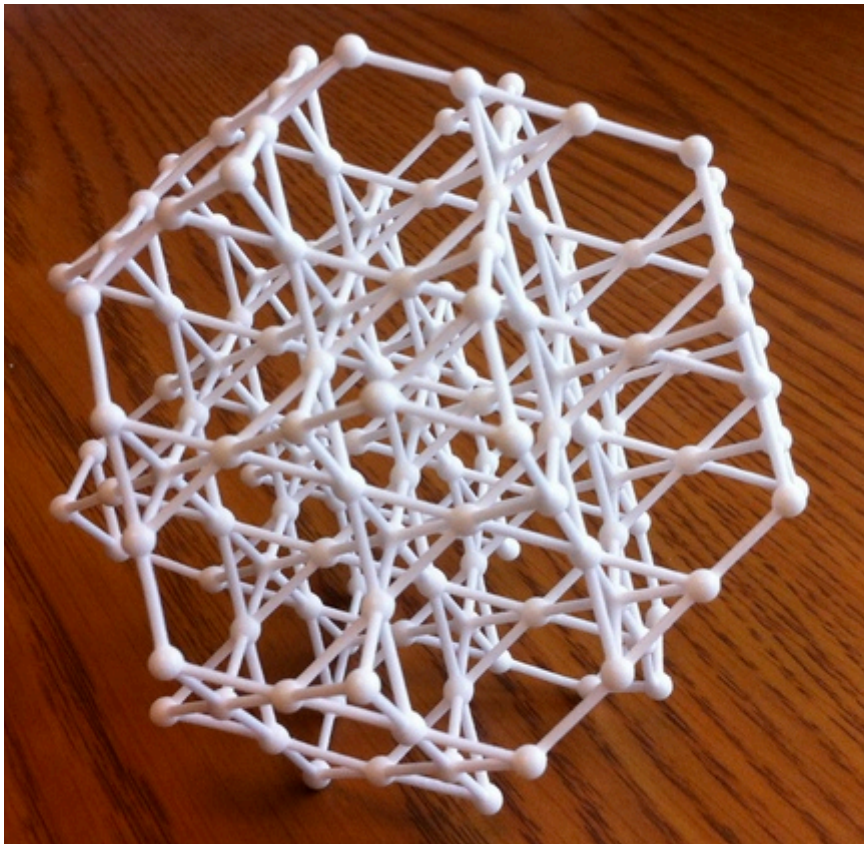
"We've agreed to count it as both a wave and a particle for tax purposes."

Particle-wave duality



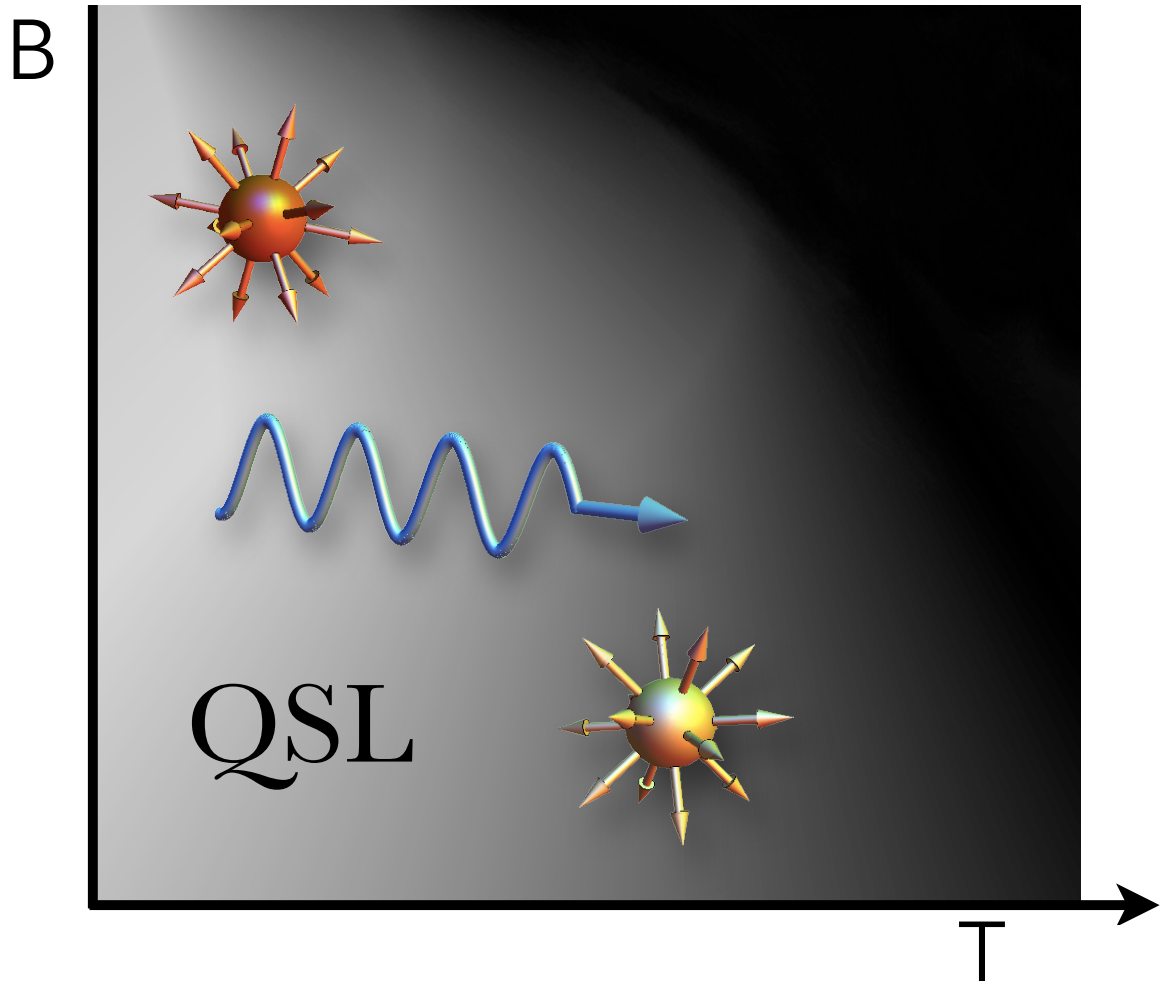
But where does
electromagnetism come from?

Mike Hermele



Lucile Savary

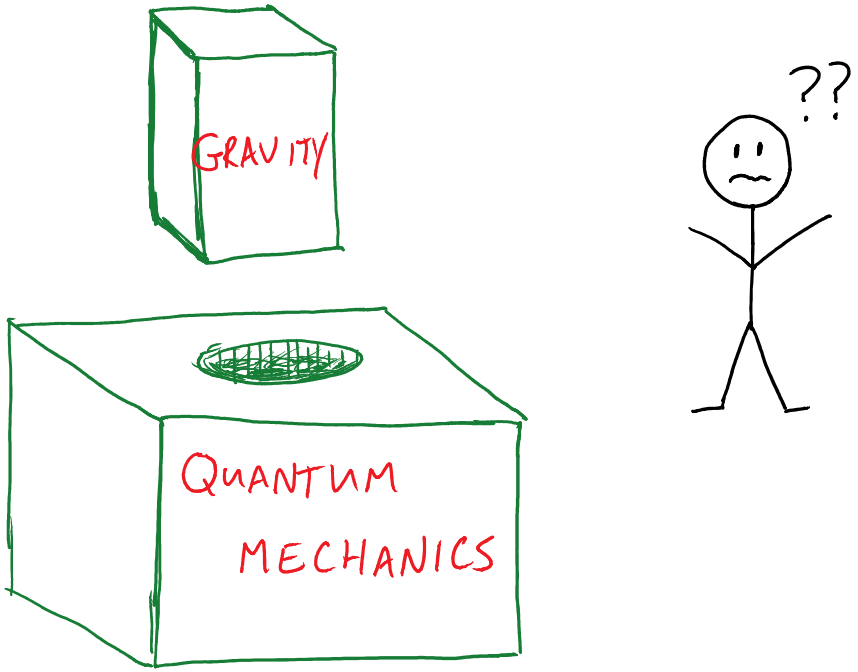
$Yb_2Ti_2O_7$



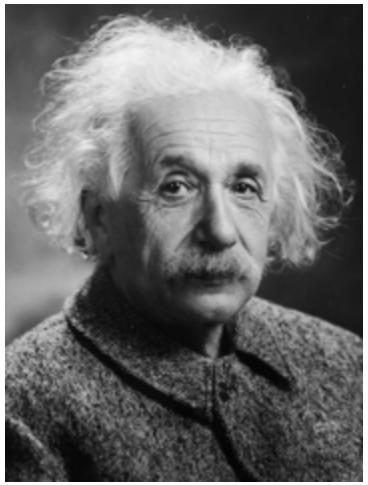
Gravity

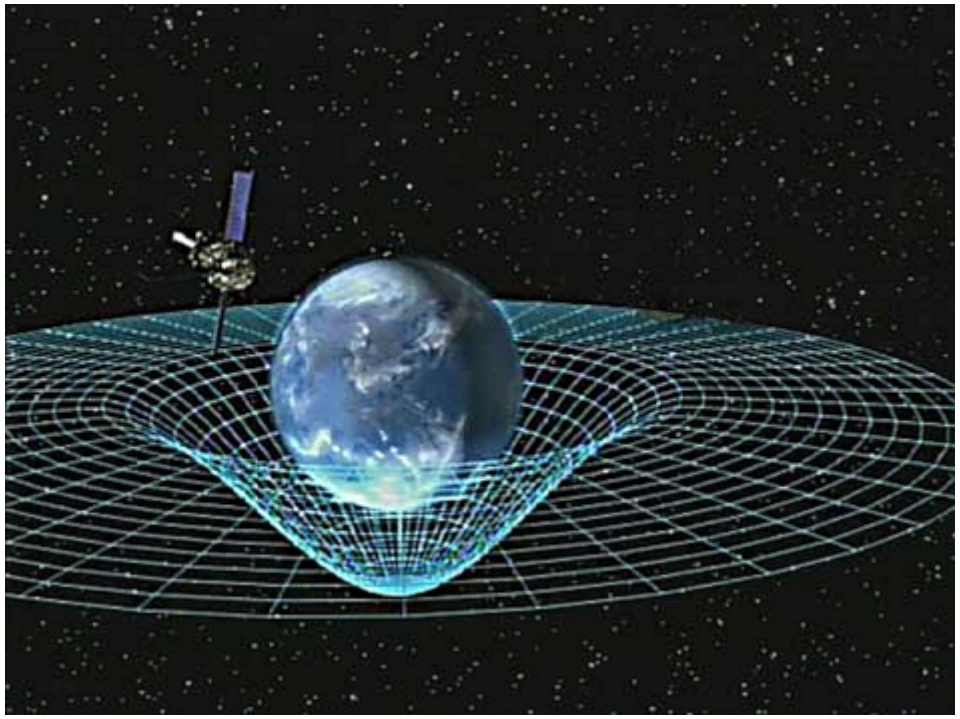
Mark Van Raamsdonk, UBC

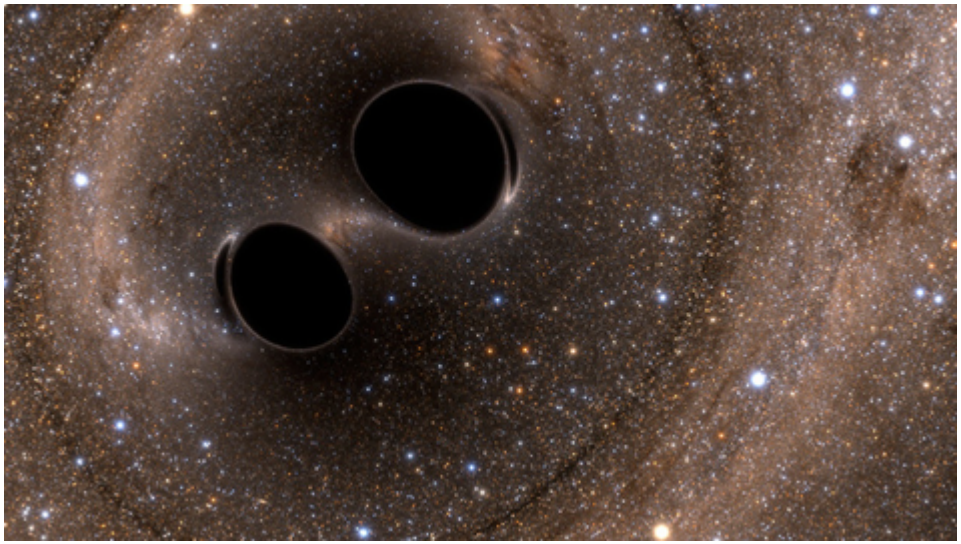
KITP, April 2015



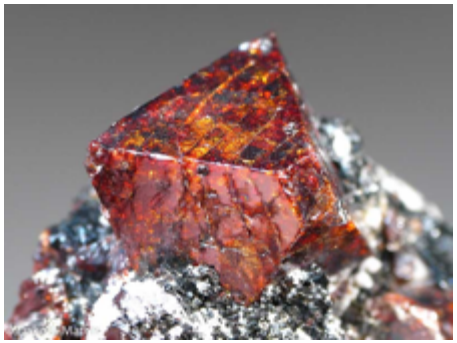
There is no theory of quantum gravity







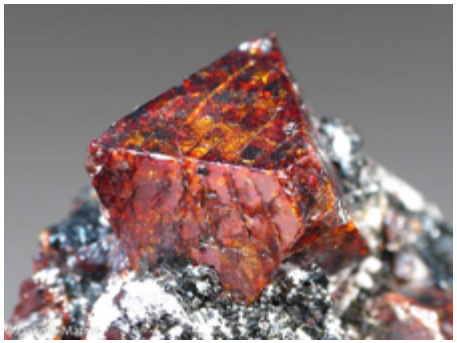
explaining gravity is explaining the emergence of space-time itself



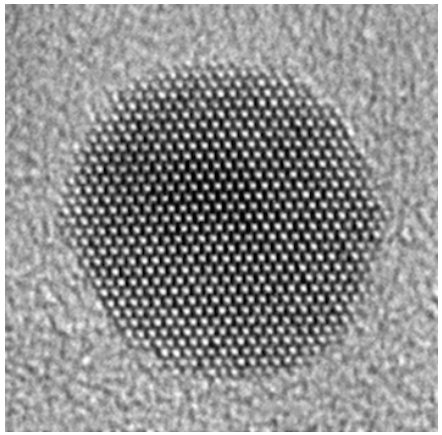
electromagnetism

???

gravity?

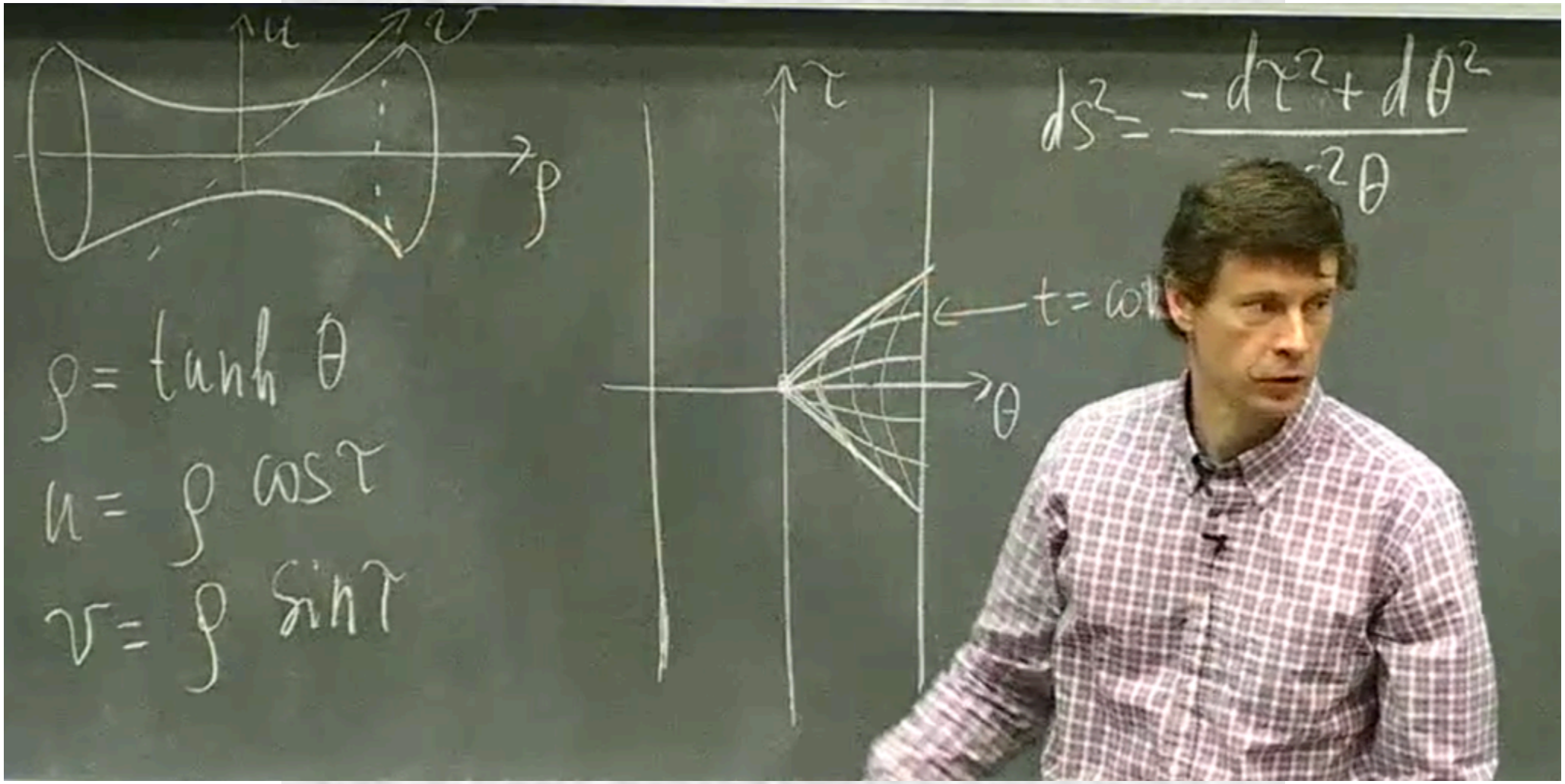


electromagnetism

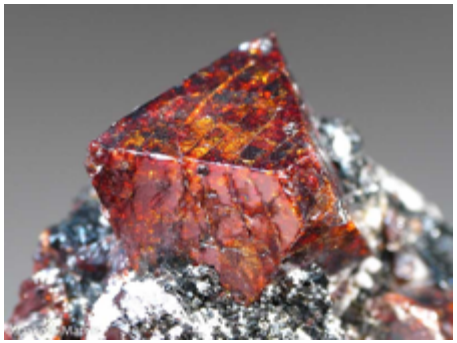


gravity?

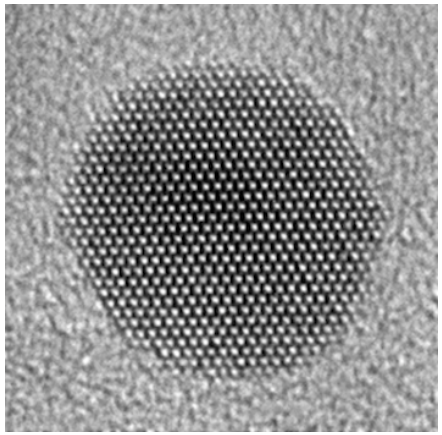
Sachdev-Ye-Kitaev Model



April 2015



electromagnetism



1+1-dimensional gravity in anti-de Sitter space

Everything we call real is made of things that cannot be regarded as real.

If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet.

Thank you