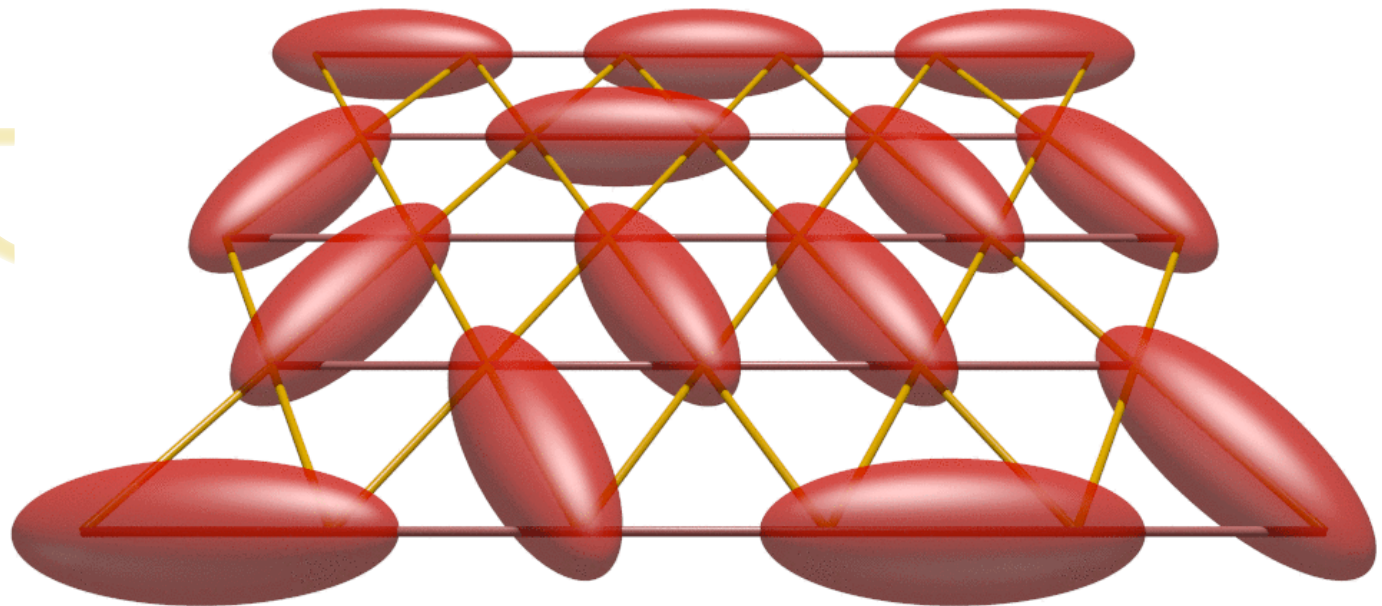


Strange Stuff: A Second Quantum Revolution



BANTAM BOOKS

The Dancing Wu Li Masters

An Overview of the New Physics

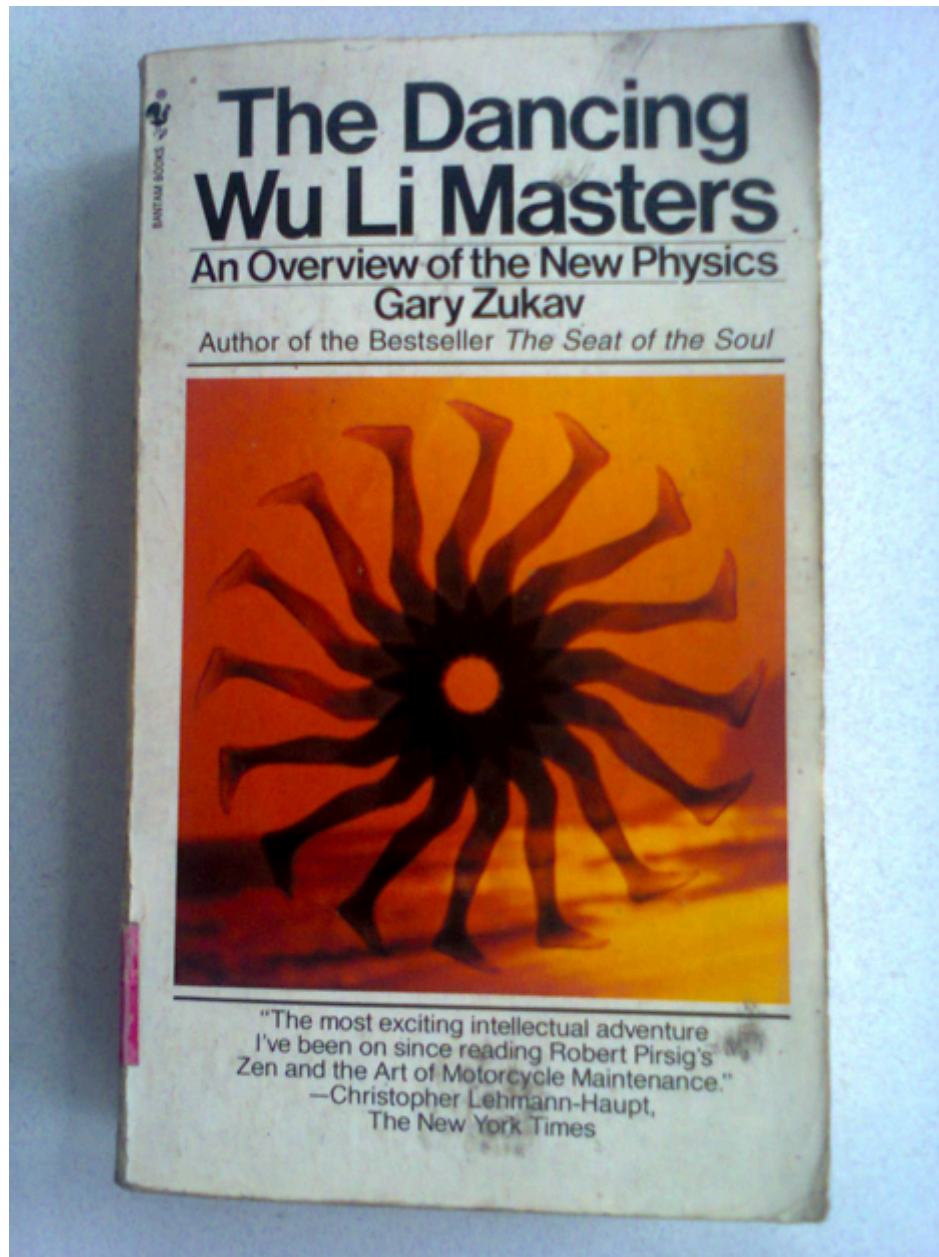
Gary Zukav

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."

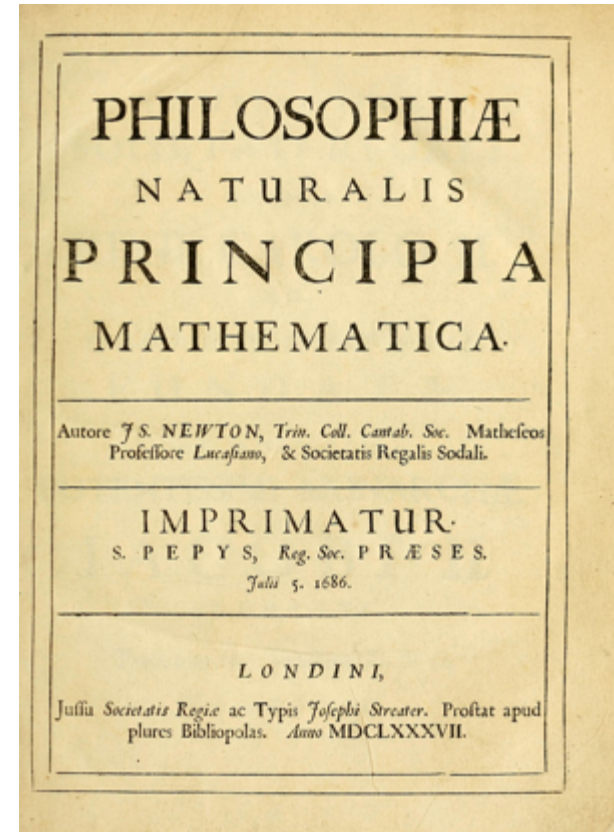
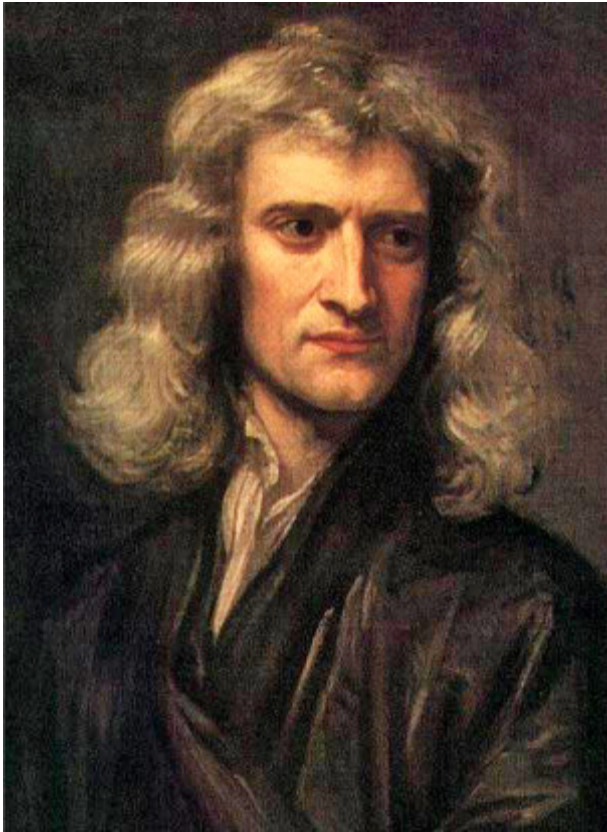
—Christopher Lehmann-Haupt,
The New York Times



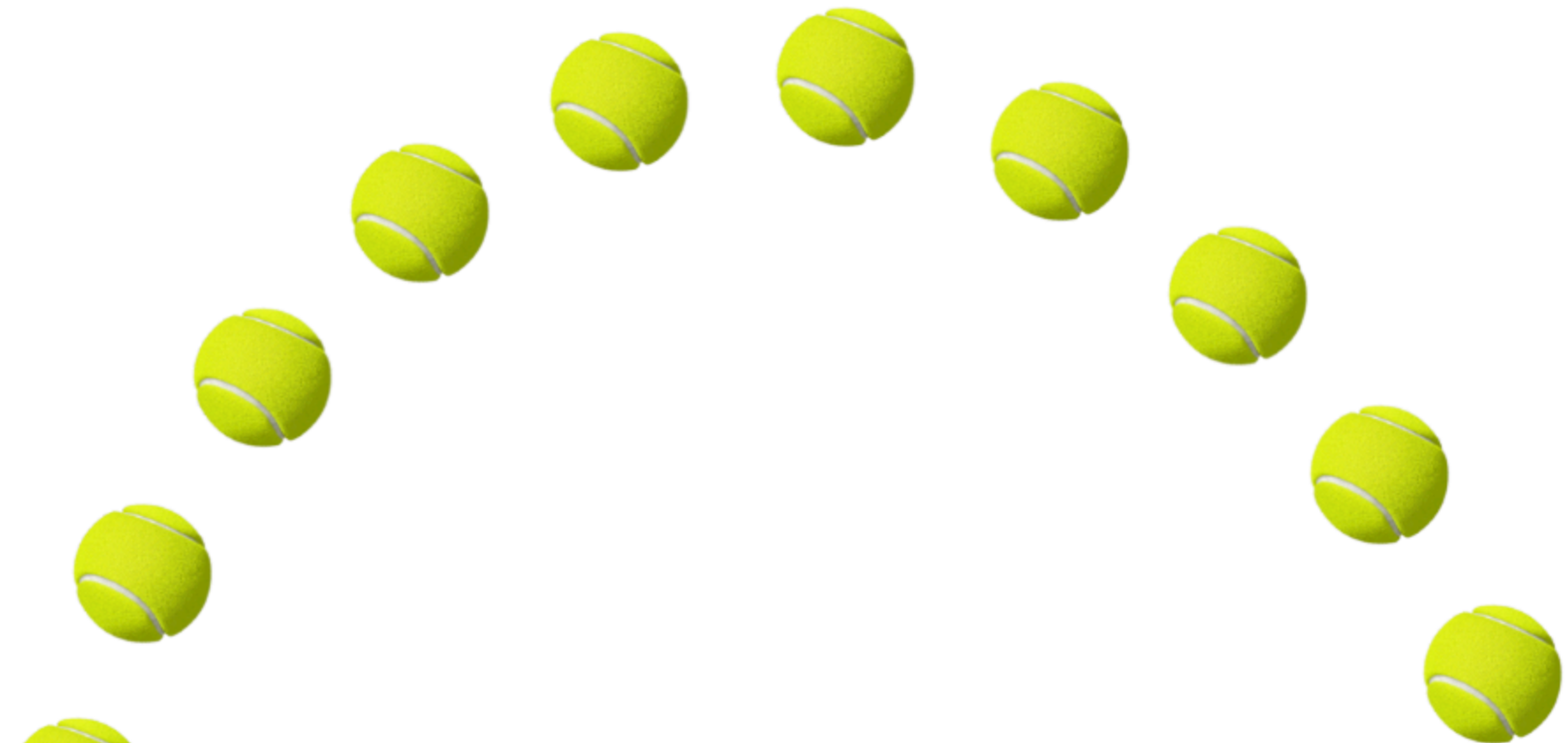
This talk:

quantum physics
(without the eastern
philosophy)

a recent revolution in
bringing quantum
weirdness into the
macro-world



$$F = ma$$



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

2/4

2 1/2

Homework Set 1a

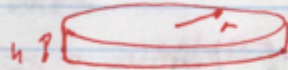
#1) 1-58



4.8m

poor sketches

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



$$918 \text{ kg/m}^3 = \frac{9 \times 10^{-2} \text{ kg}}{V}$$

$$918 \text{ kg/m}^3 \cdot V = 9 \times 10^{-2} \text{ kg}$$

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

$$9.80 \times 10^{-10} \text{ m}^3 \cdot \left(\frac{1 \times 10^6 \text{ cm}^3}{1 \text{ m}^3} \right) = 9.8 \times 10^{-4} \text{ cm}^3$$

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

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

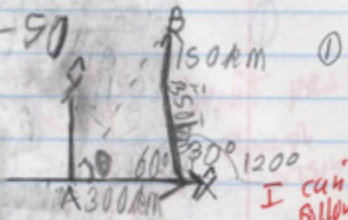
$$r = .018 \text{ cm}$$

$$d = 2r$$

$$d = 2(.018 \text{ cm})$$

$$d = .036 \text{ cm}$$

#2) 3-50



$$R_x = 300 \text{ km} \uparrow - (150 \text{ km} \sin 30^\circ)$$

$$R_x = 225 \text{ km} \uparrow$$

$$R_y = (150 \text{ km} \cos 30^\circ) \uparrow + 150 \text{ km} \uparrow$$

$$R_y = 280 \text{ km} \uparrow$$

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

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

$$\theta = 51^\circ \text{ north of east}$$

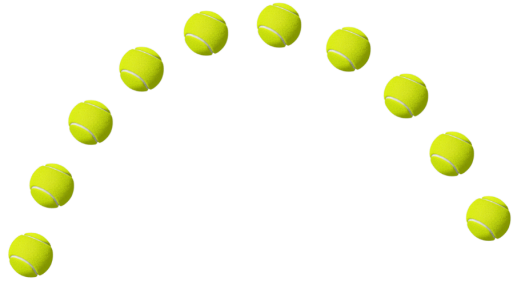
$$R = \sqrt{R_x^2 + R_y^2}$$

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

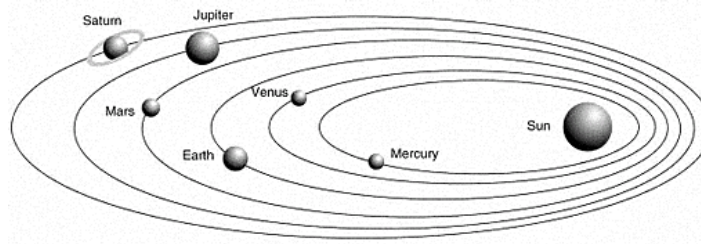
$$R = 359 \text{ km}$$

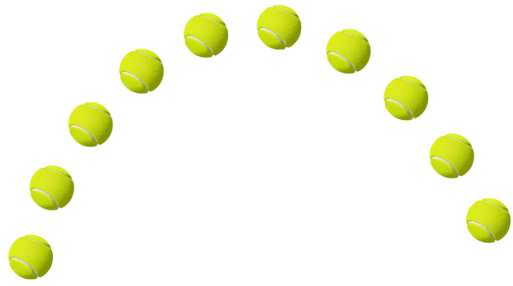
0.6

see soln.

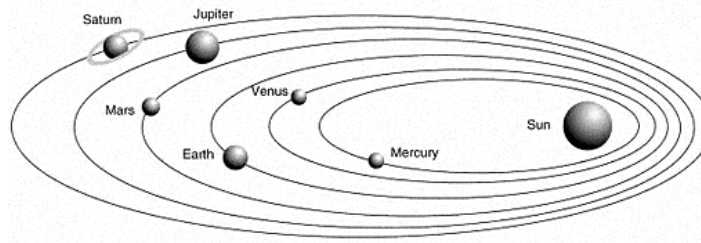


$$F = m a$$





~~$E = mc^2$~~





Planck



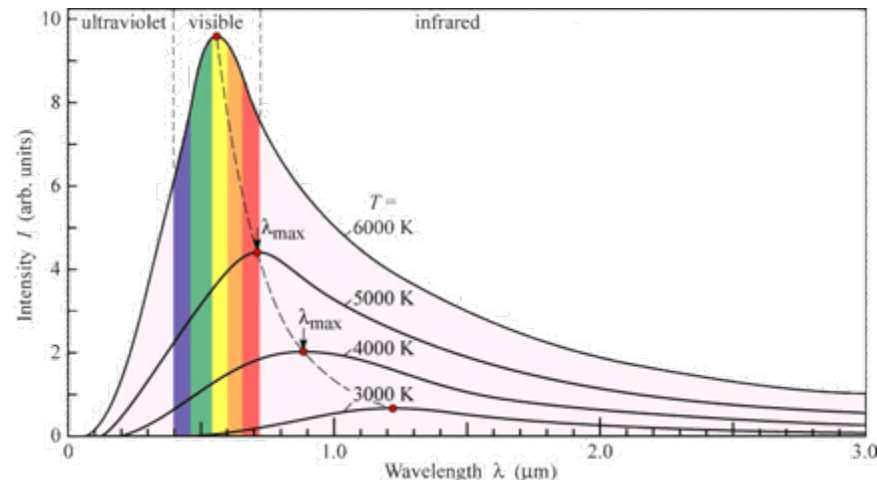
Bohr

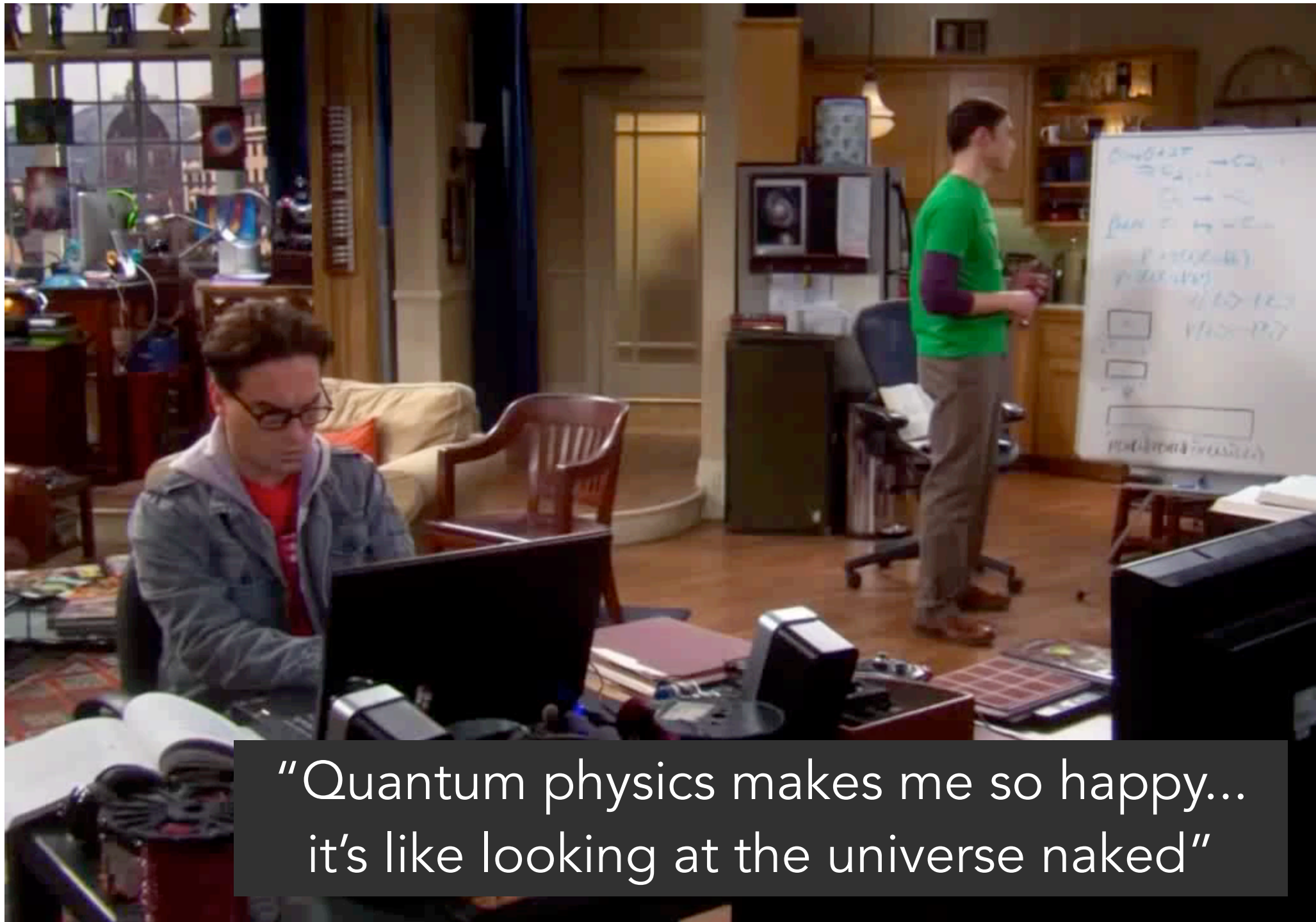


Schrödinger



Heisenberg





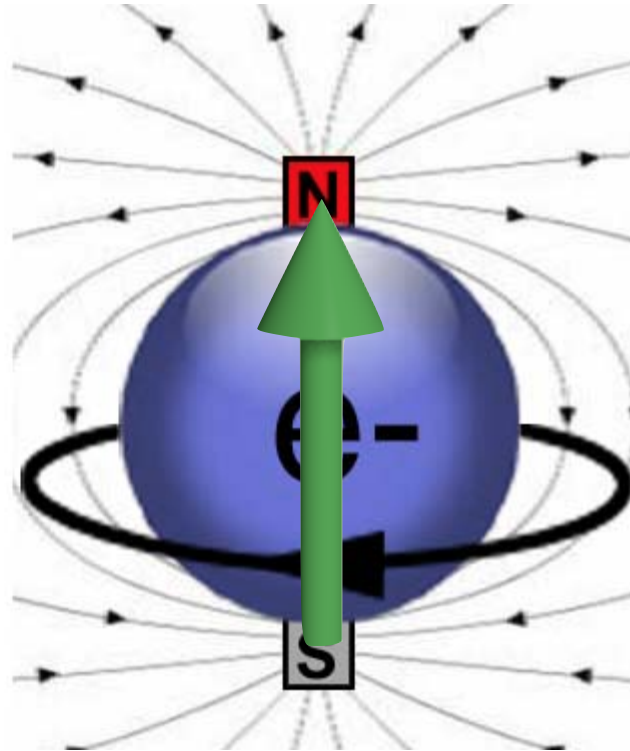
“Quantum physics makes me so happy...
it's like looking at the universe naked”

Ψ

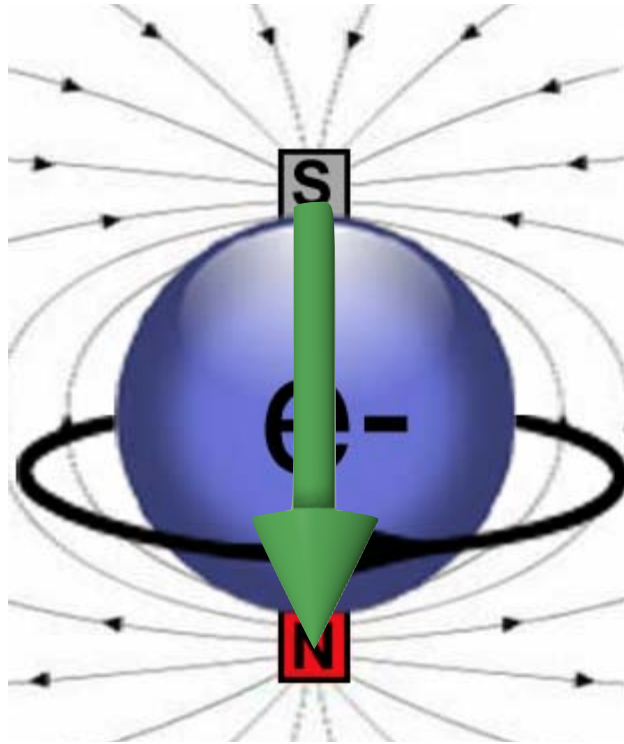
Superposition

Entanglement

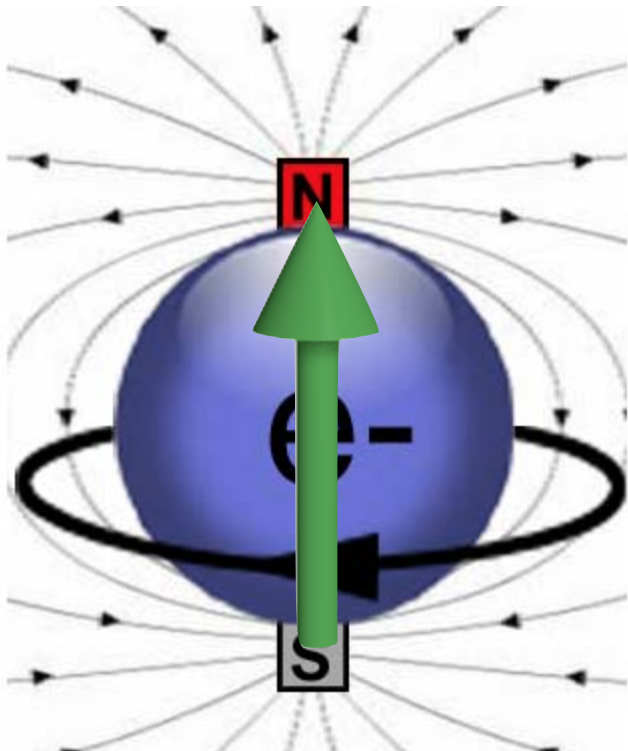
Quantum Superposition



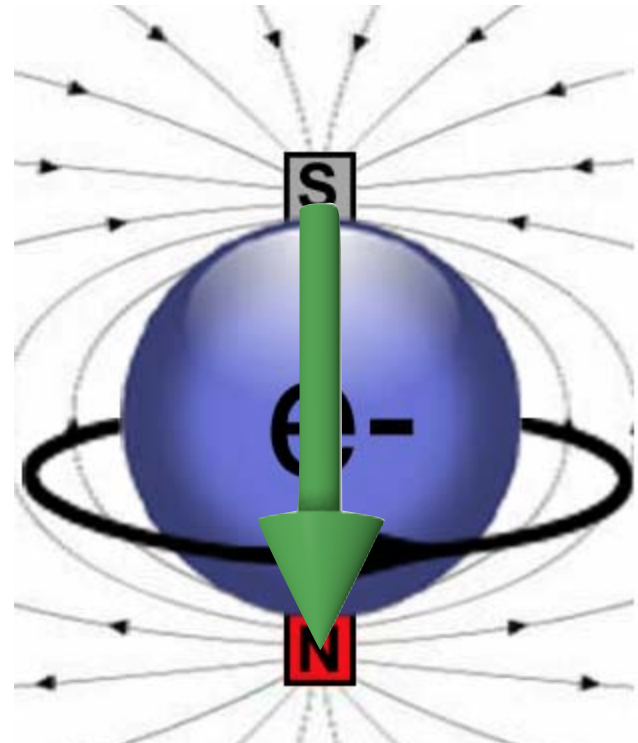
Up



Down

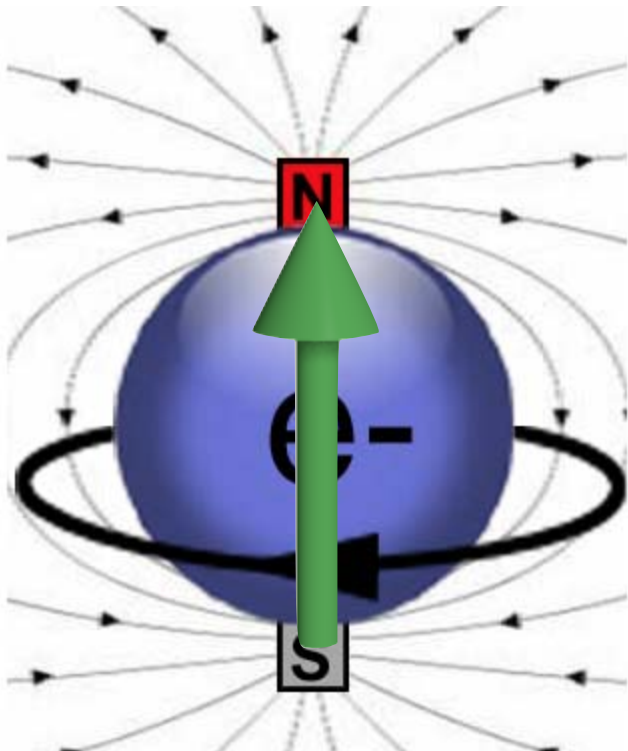


+

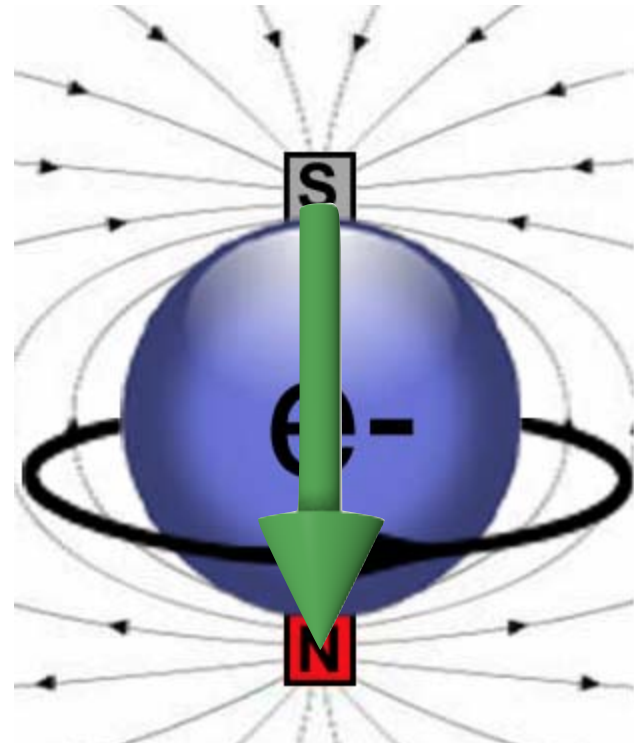


Both

“quantum superposition”



+



Both

Superposition

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

"state"

"wavefunction"

Superposition

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

“Amplitudes”

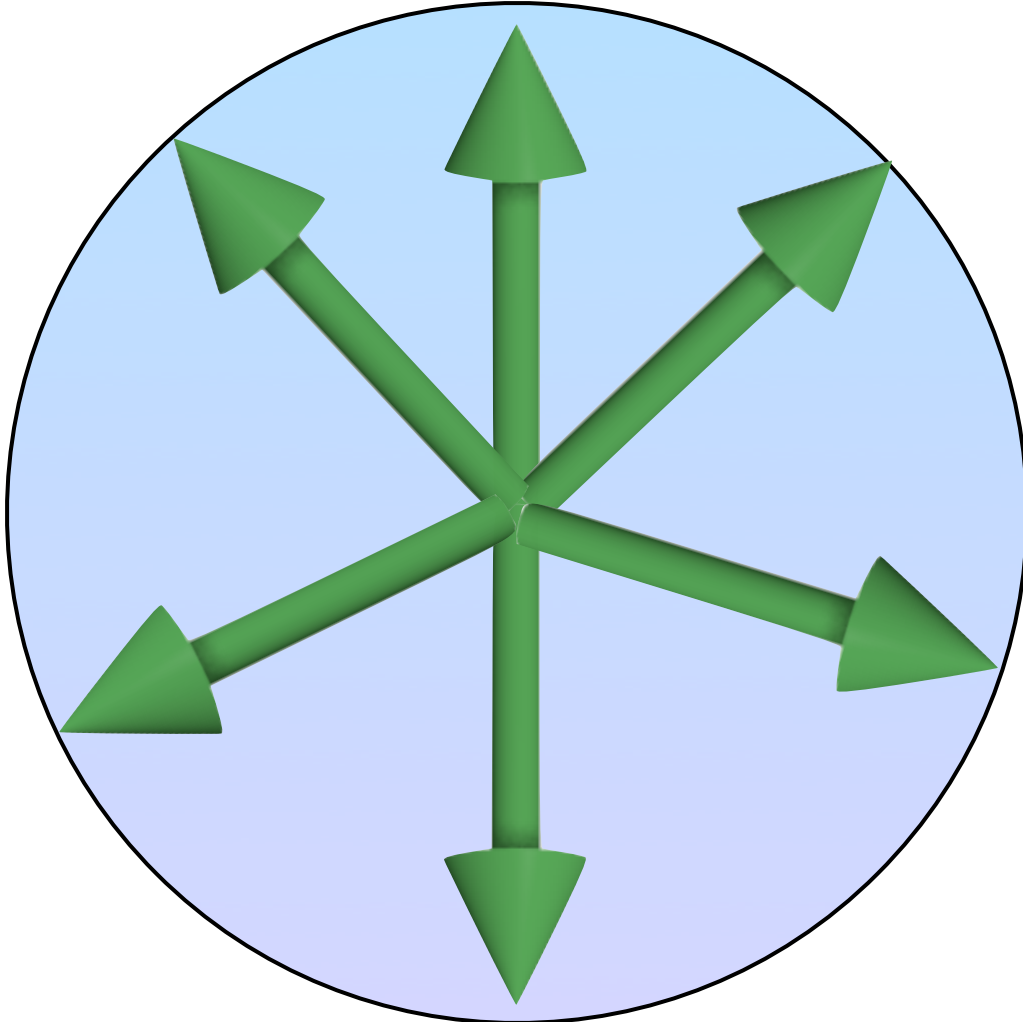
Superposition

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

“Amplitudes”

This is *information*. Reality = information?

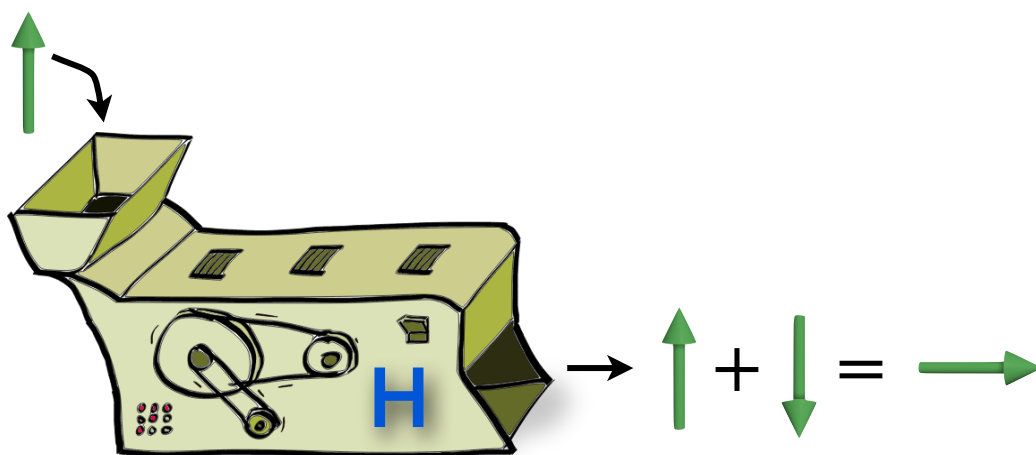
"1"



"0"

"qubit"

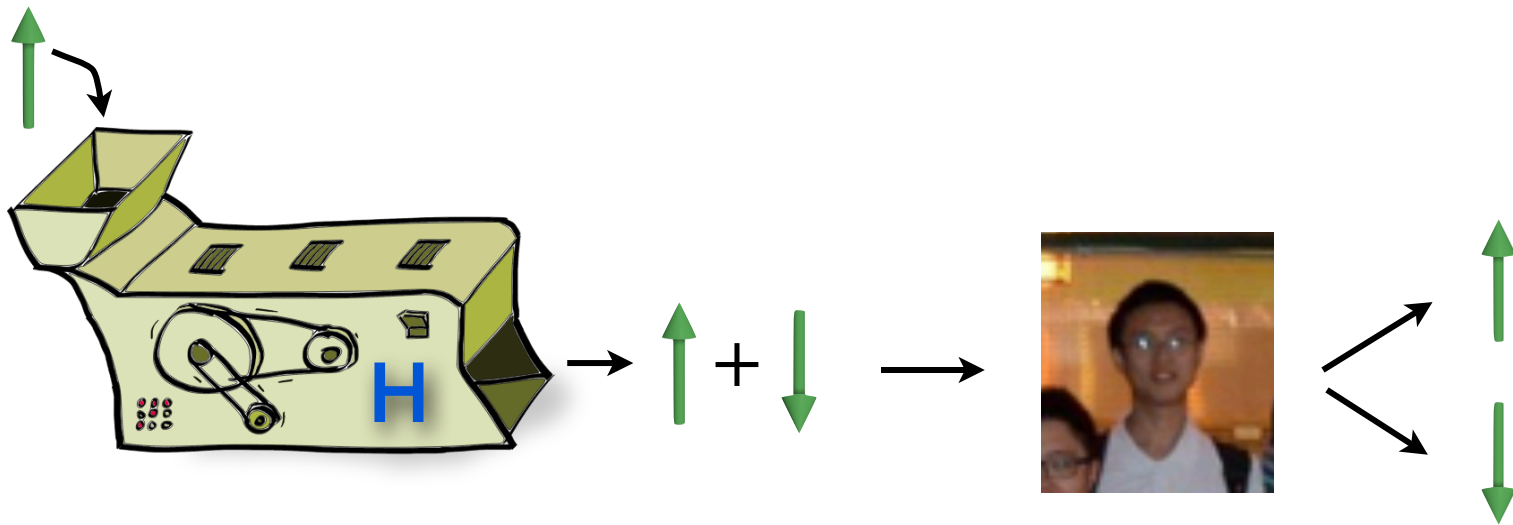
Superposition Machine



"Hadamard Gate"

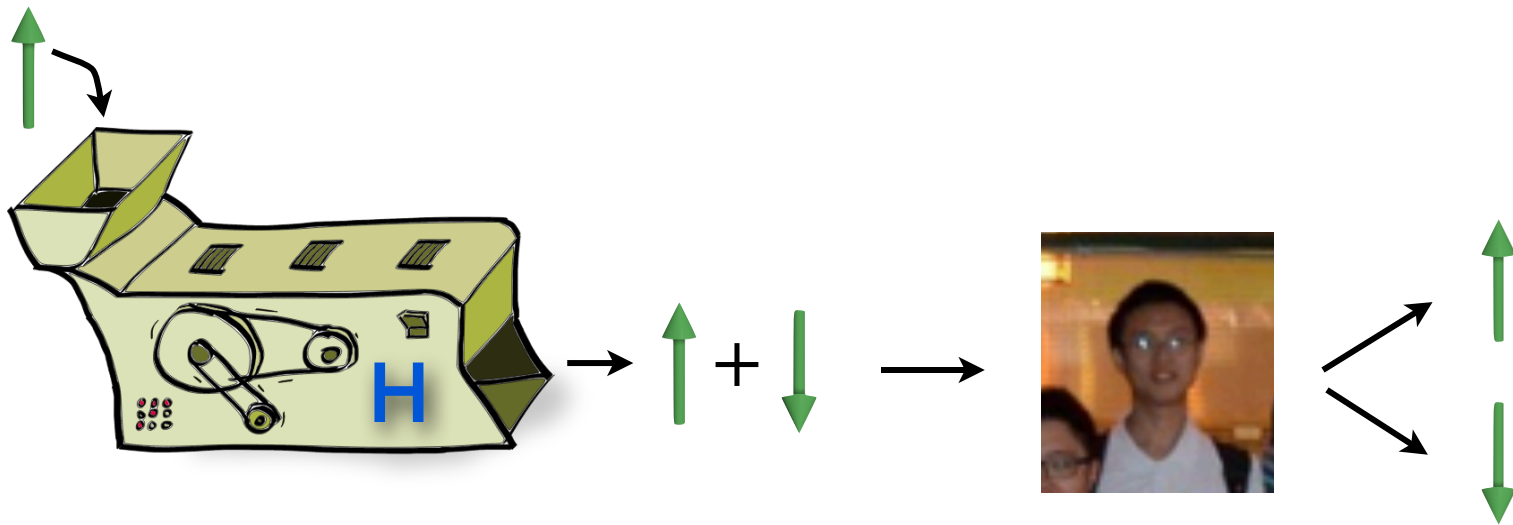
"Pi/2 pulse"

Superposition Machine



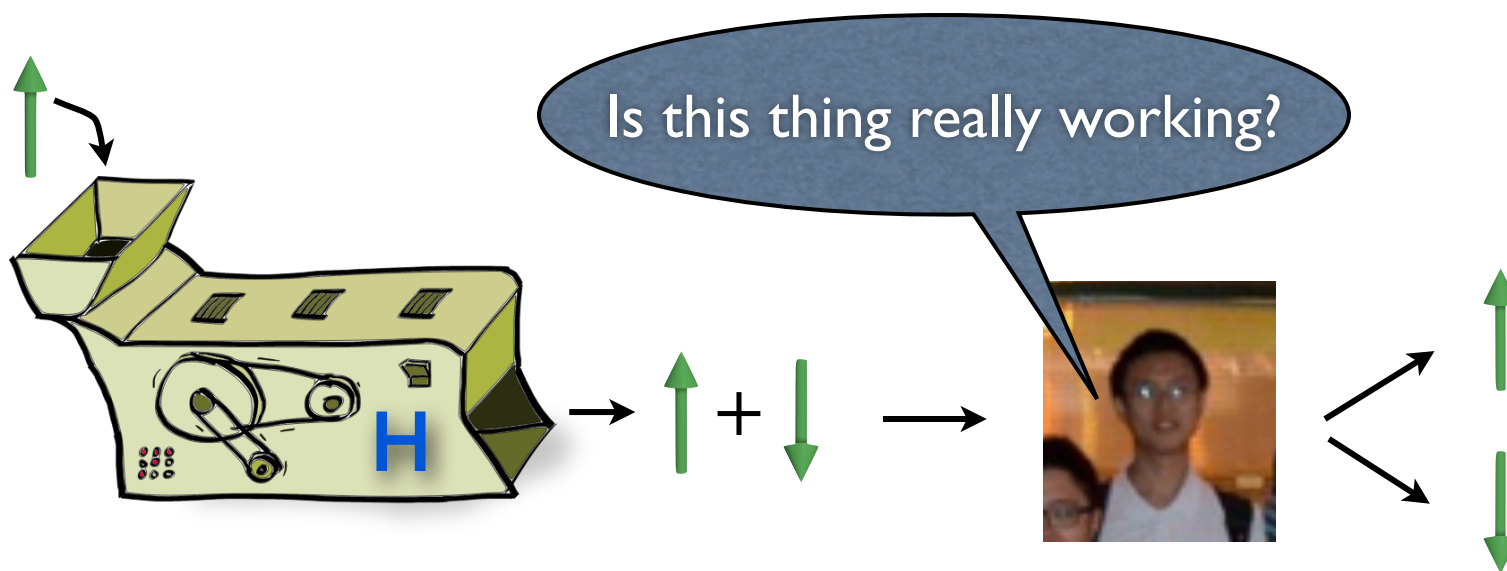
Observe up or down randomly,
with equal probability

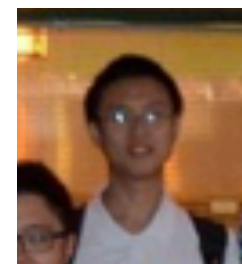
Superposition Machine



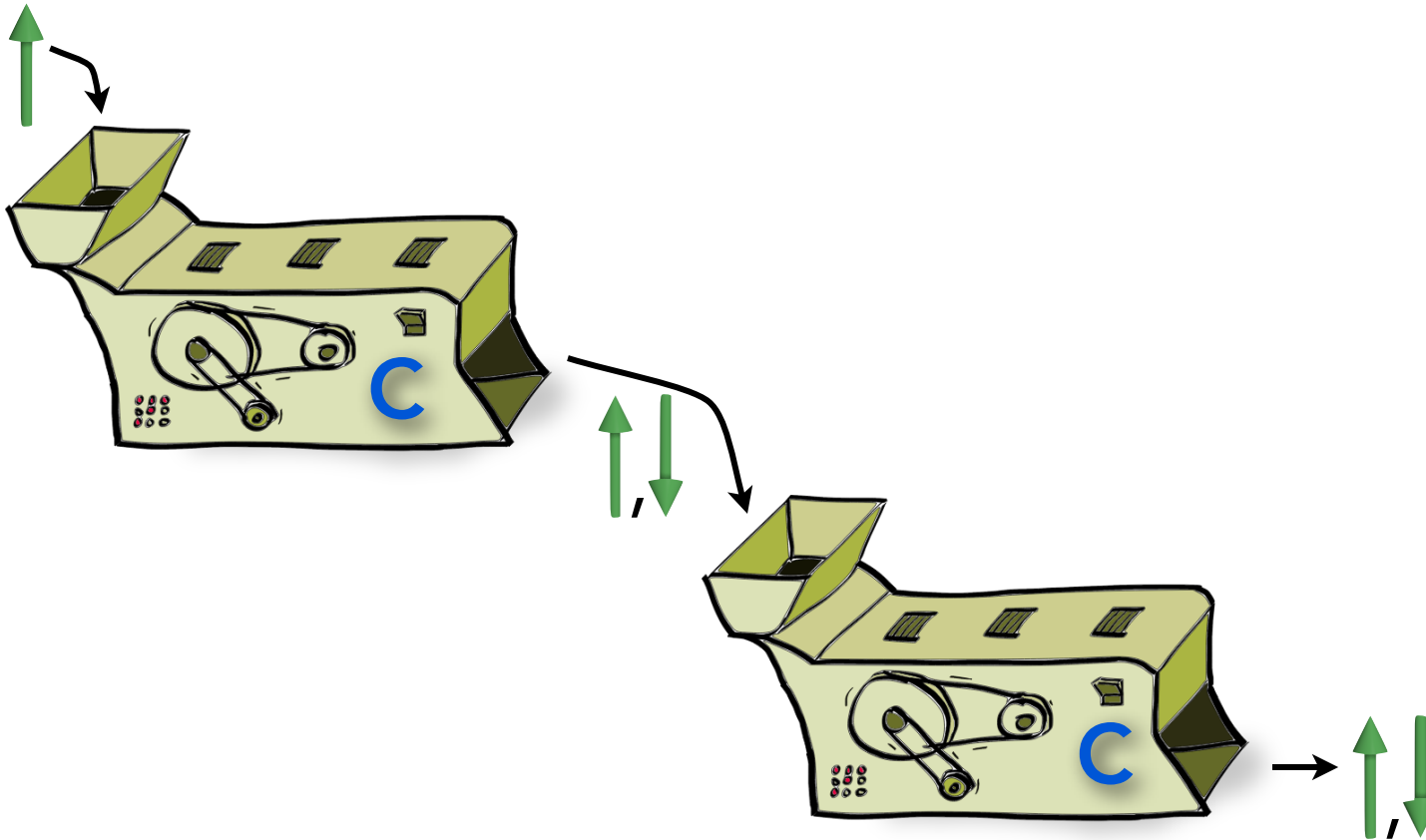
Measurement induced "collapse"
of the wavefunction

Superposition Machine

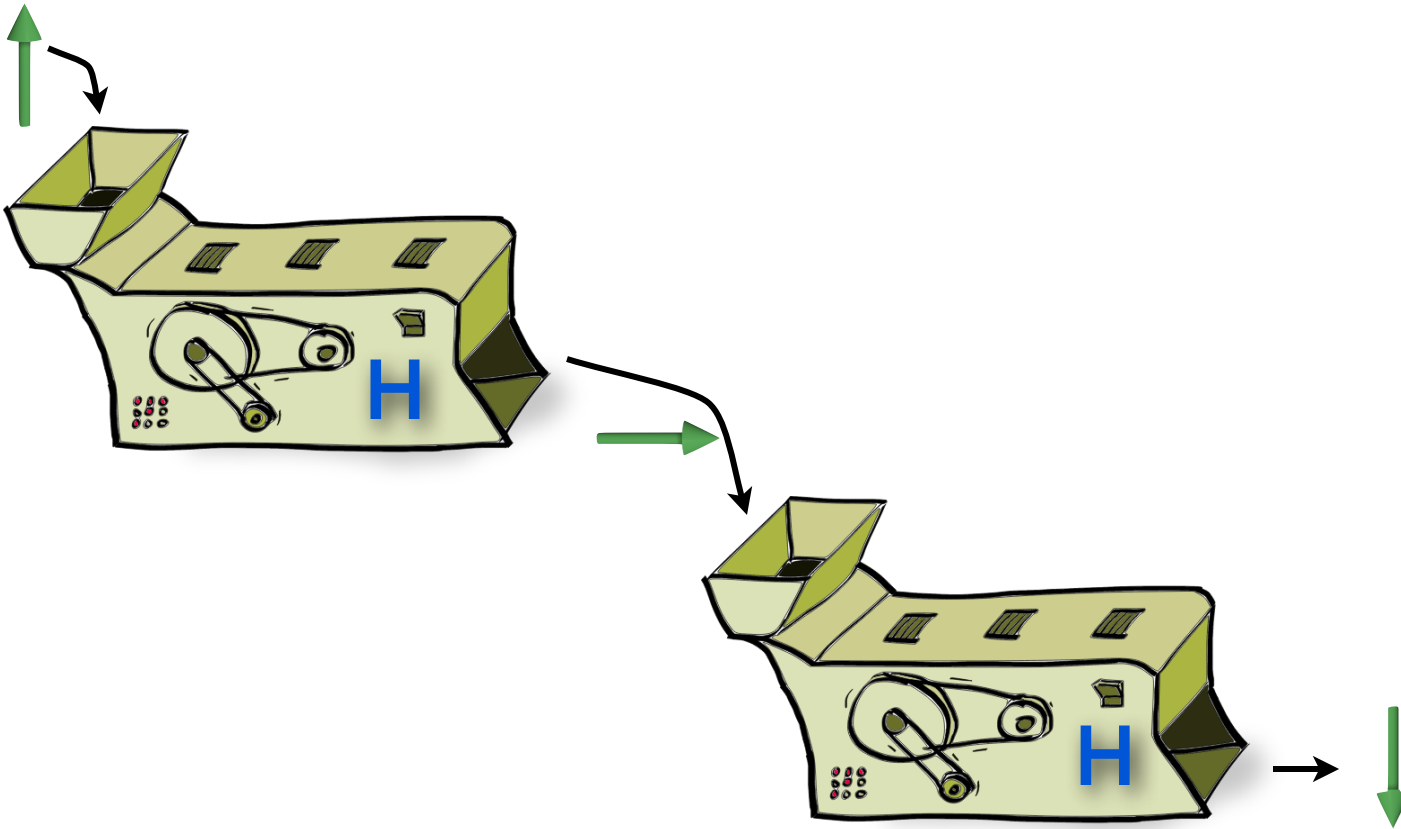




Classical Fraud



Quantum



down **every** time

Quantum Entanglement

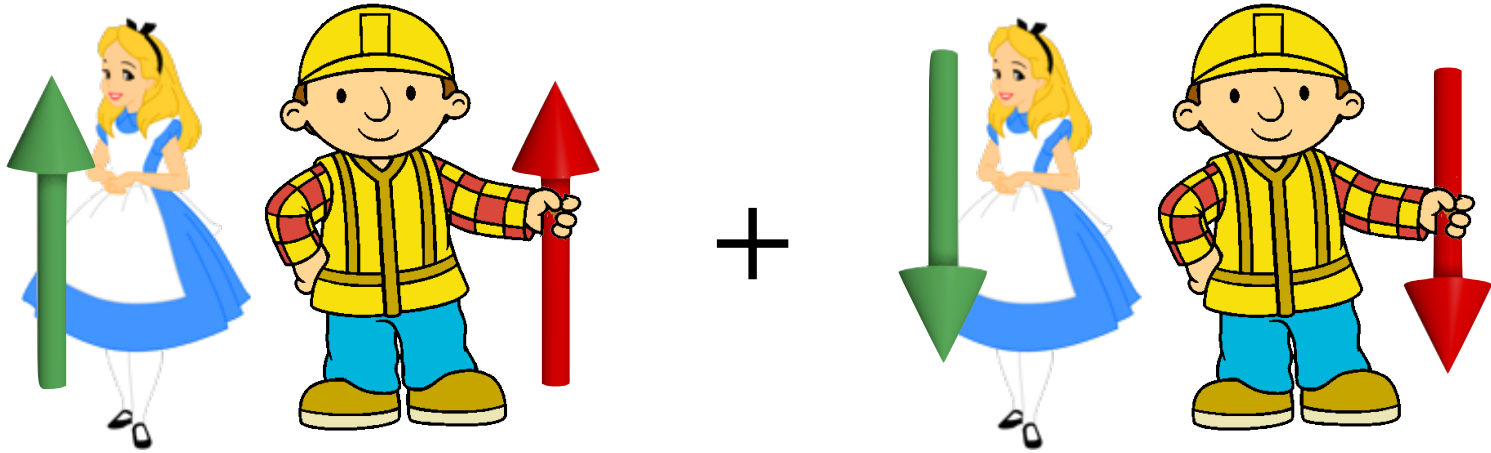
Entanglement



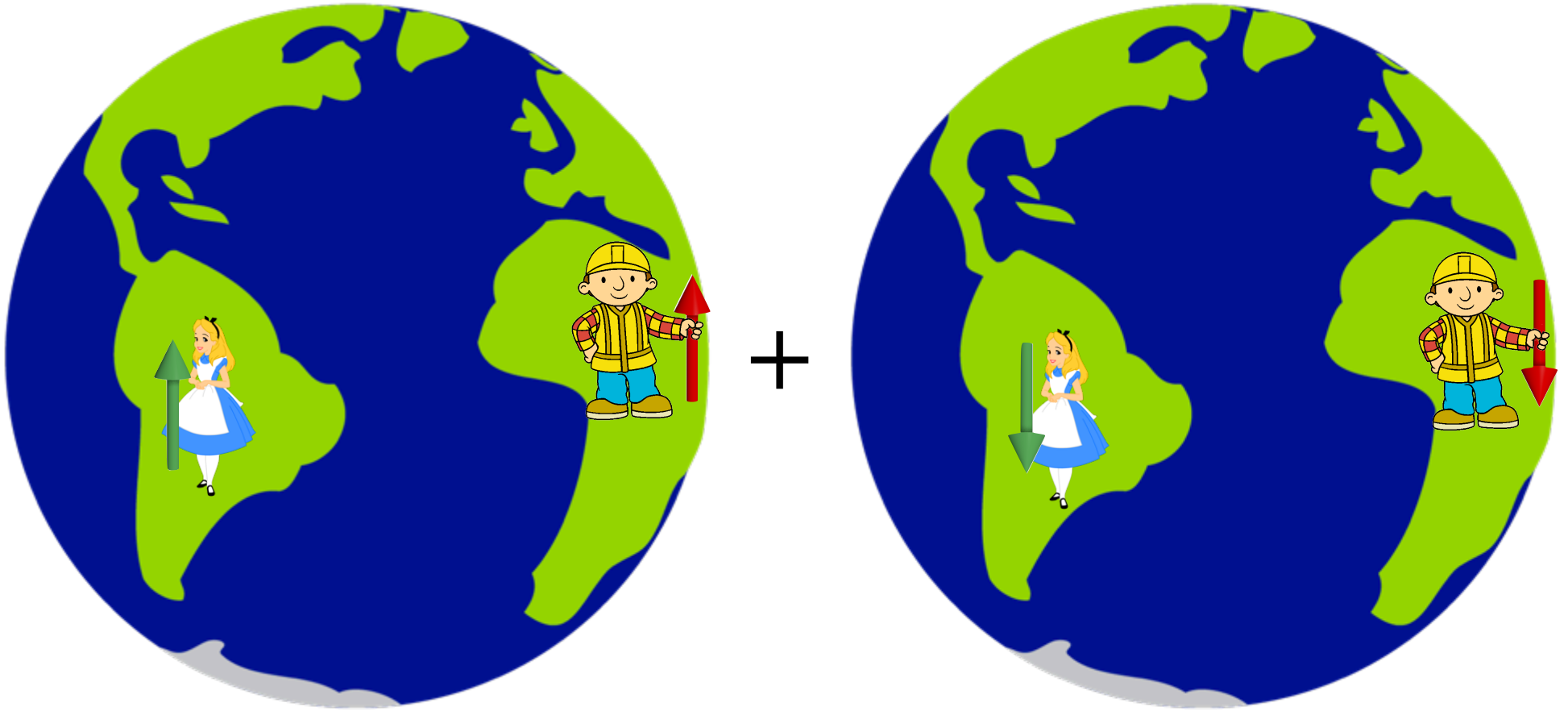
Entanglement



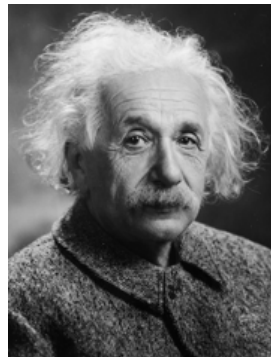
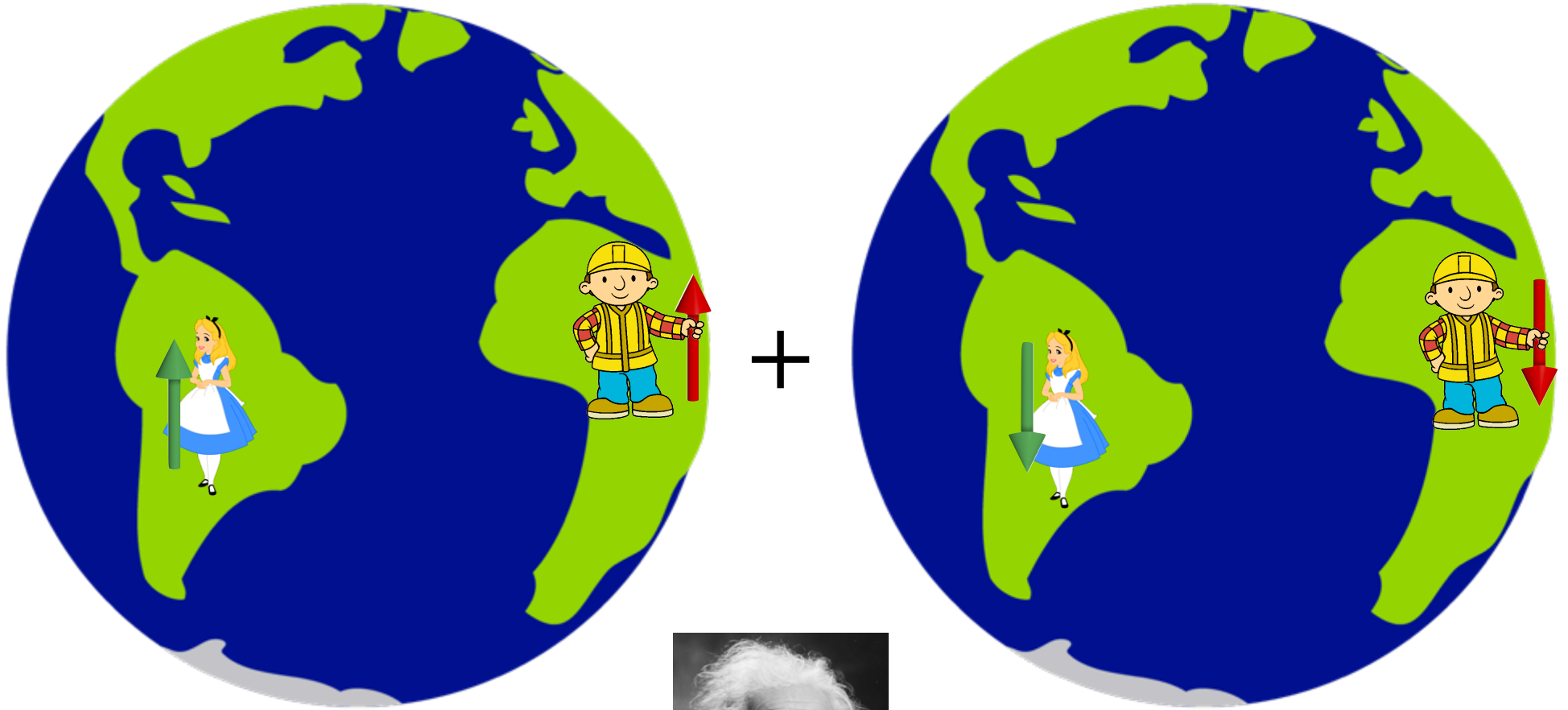
Entanglement



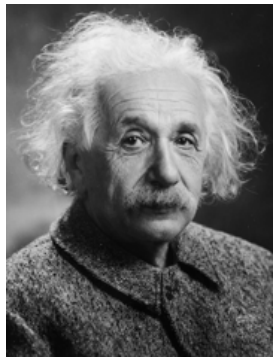
Entanglement



Einstein-Podolsky-Rosen Pair

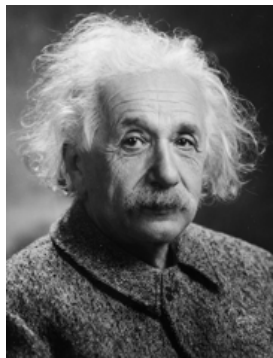


Einstein-Podolsky-Rosen Pair

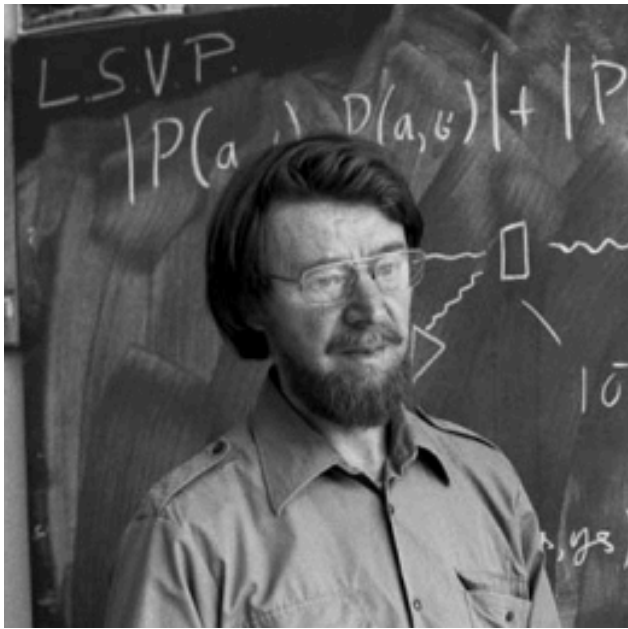


"quantum non-locality"

Einstein-Podolsky-Rosen Pair



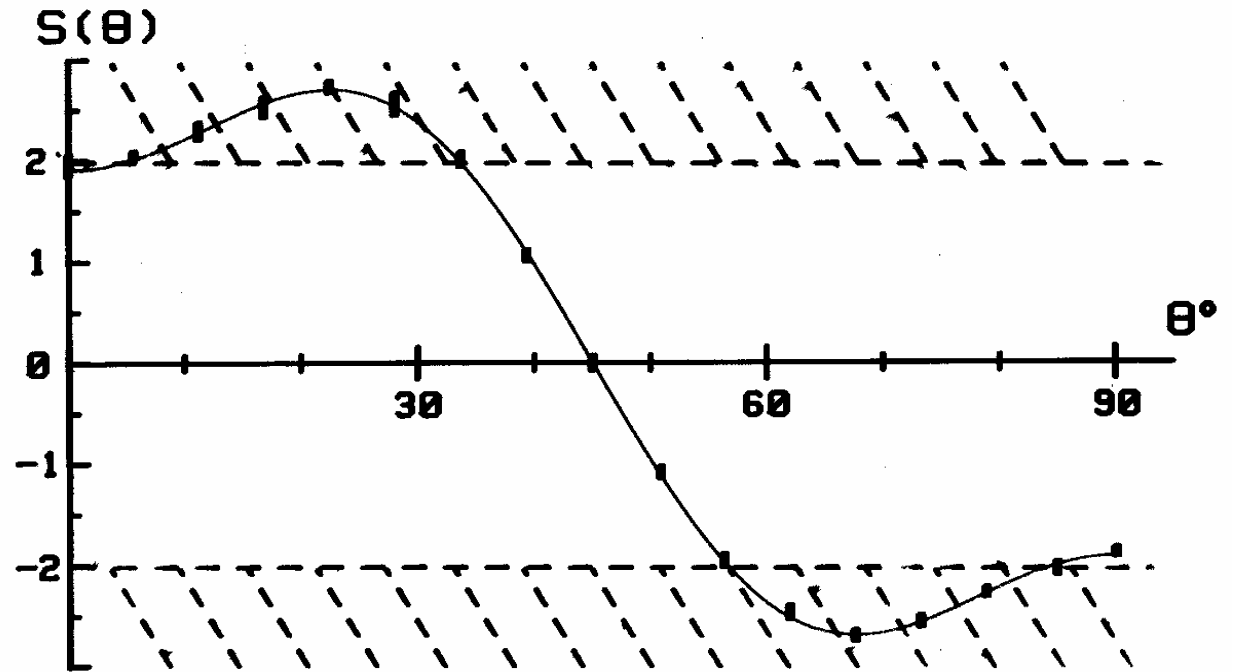
"quantum non-locality"



John Bell



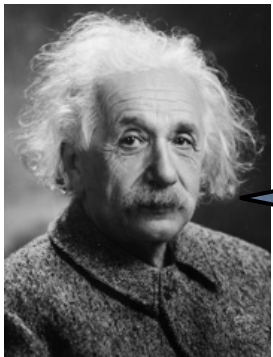
Alain Aspect



no local realism



Einstein-Podolsky-Rosen Pair



spukhafte Fernwirkung!

Collapse or decoherence



Collapse or decoherence



Collapse or decoherence



metior ergo sum?



Collapse or decoherence



decoherence =
entanglement with the
environment

Collapse or decoherence



decoherence =
entanglement with the
environment



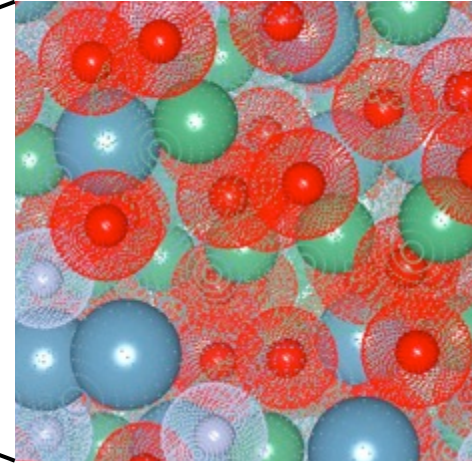
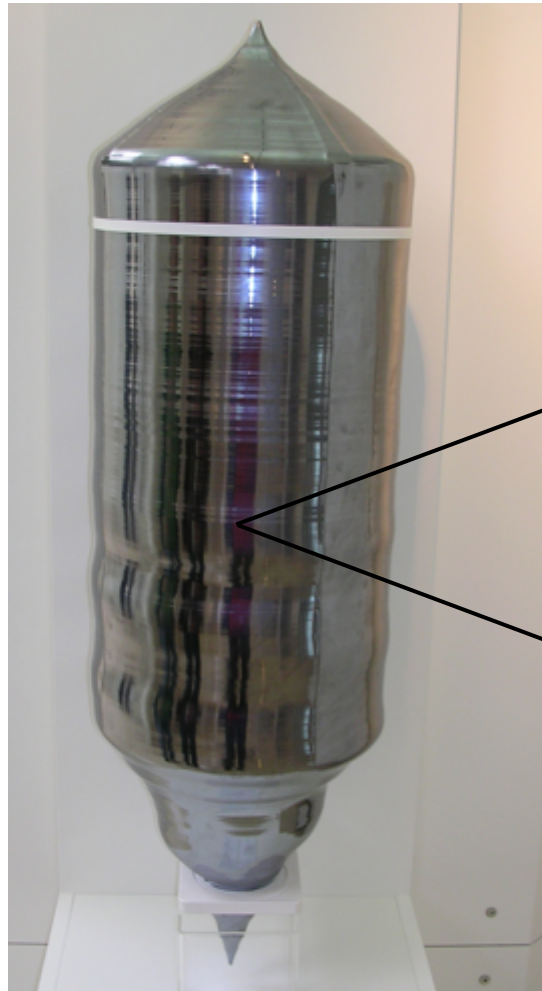
uncontrolled entanglement



controlled entanglement



Dense
matter



of electrons in 1 cm cube of Si:

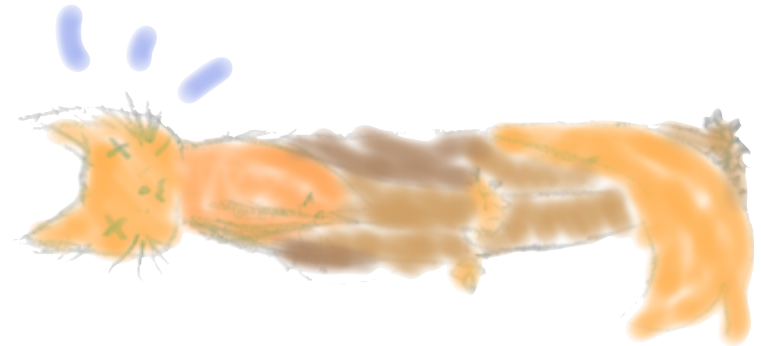
1,000,000,000,000,000,000,000,000

\approx # of stars in the *universe*

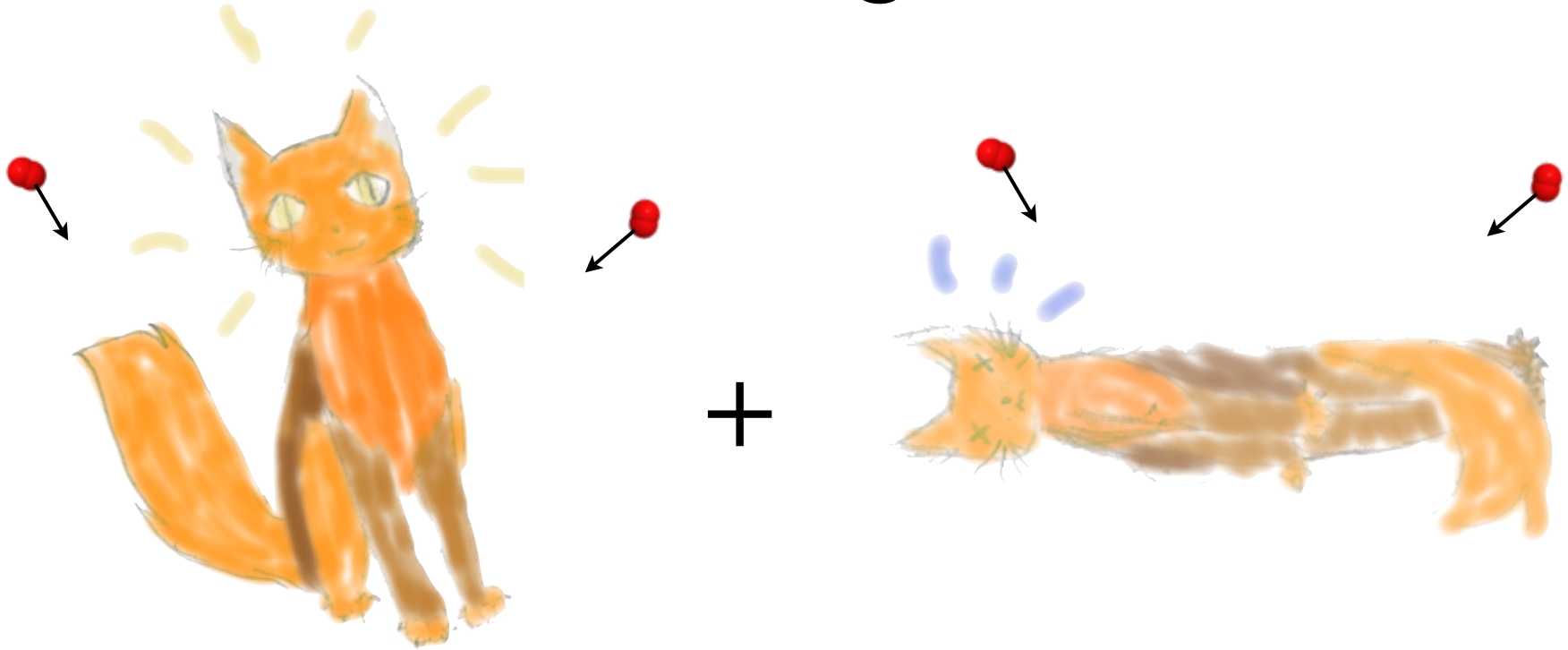
Schrödinger's Cat



+

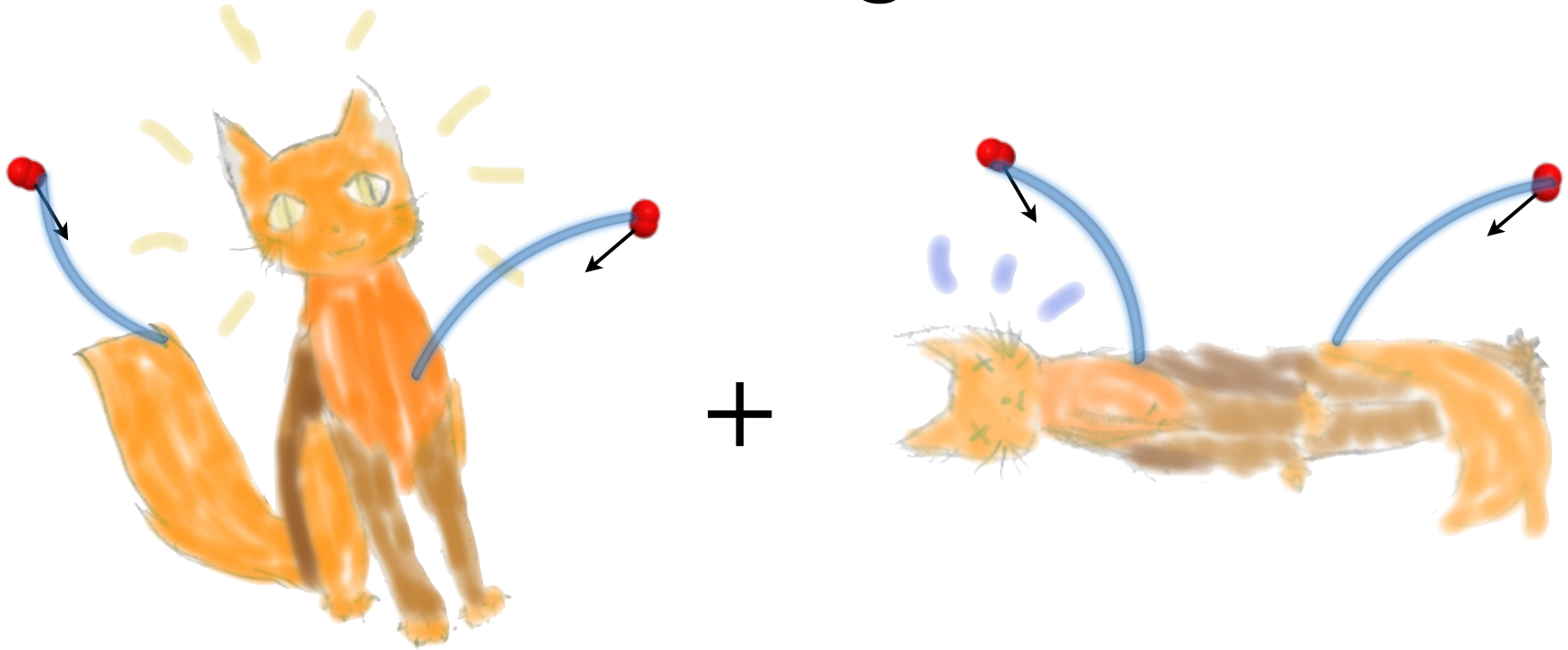


Schrödinger's Cat



measurement of any hair of the cat will collapse
the superposition

Schrödinger's Cat

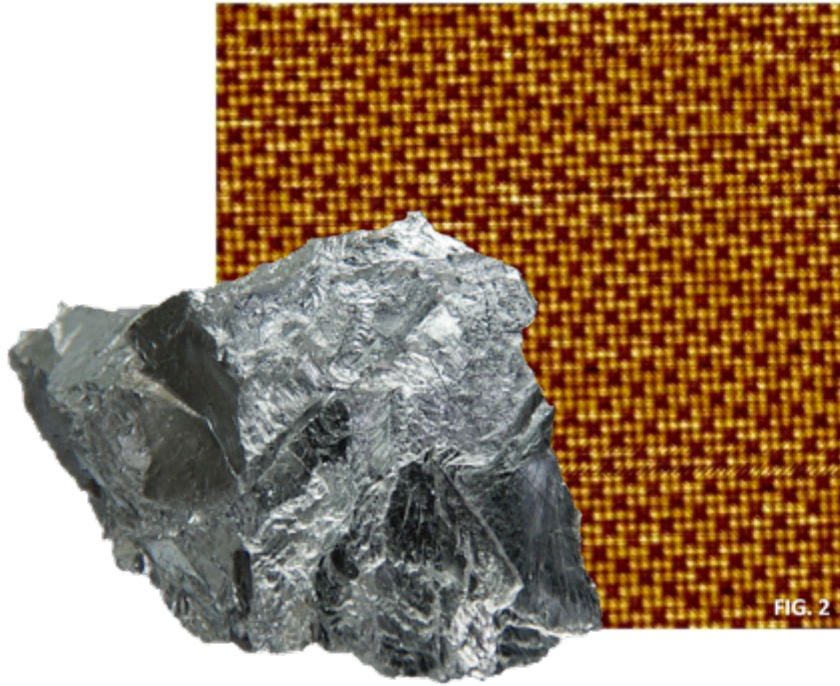


UNSTABLE to decoherence - uncontrolled entanglement with the environment

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

Can we get non-local entanglement from local forces?

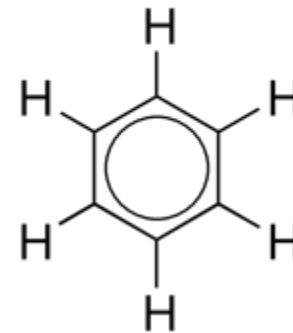
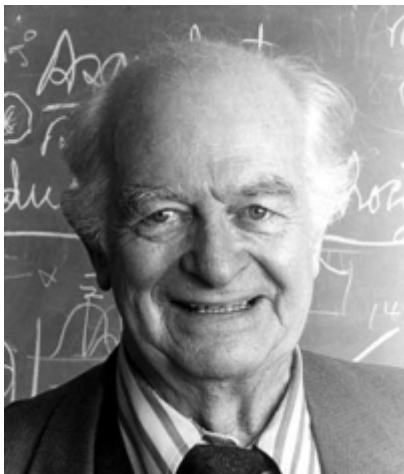
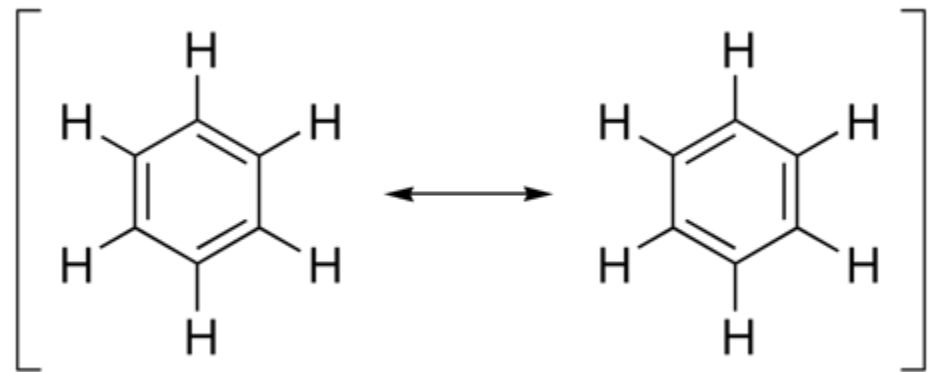
Emergence



Strange Stuff

“Resonating valence bonds”

benzene
 C_6H_6

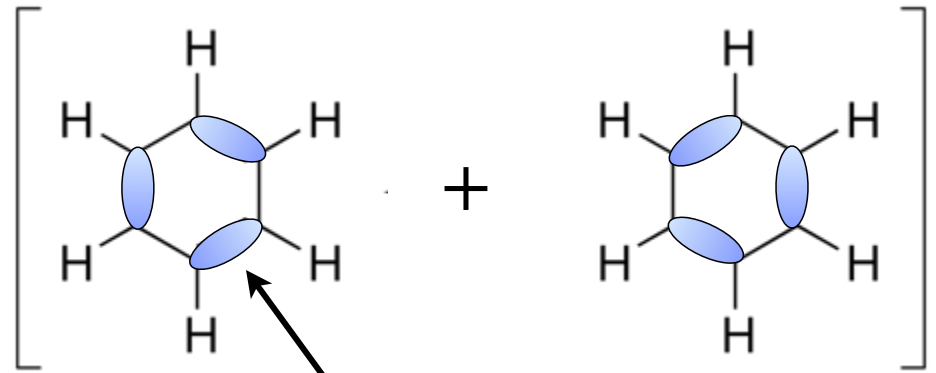


Linus Pauling ~ 1930

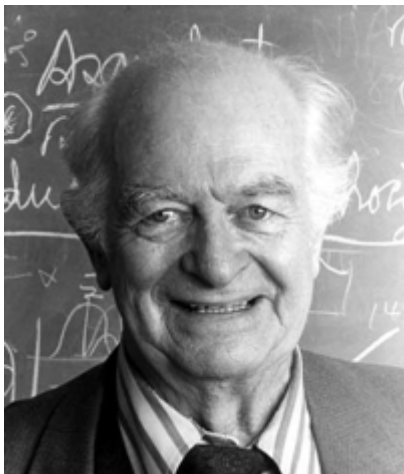
Strange Stuff

“Resonating valence bonds”

benzene
 C_6H_6



chemical bond = EPR pair!



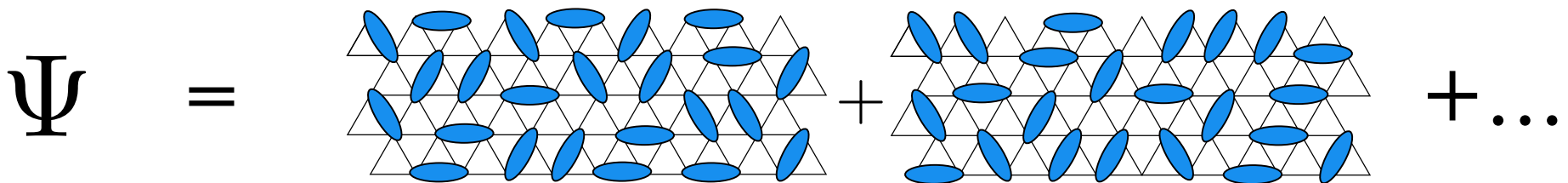
Linus Pauling ~ 1930

Strange Stuff



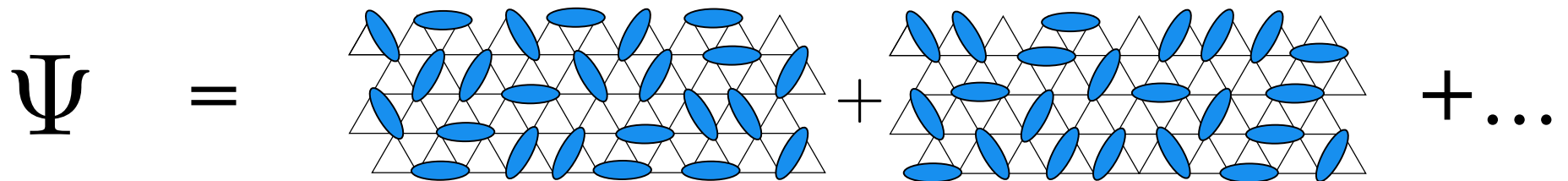
Phil Anderson, 1973

a "quantum liquid" of spins



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

Quantum spin liquid



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





Is it robust?



2016 Nobel prize for topology in
physics

Topology





Kitaev



Wen

Topology



Thouless



Kane





Kitaev



Wen

Topology



Thouless

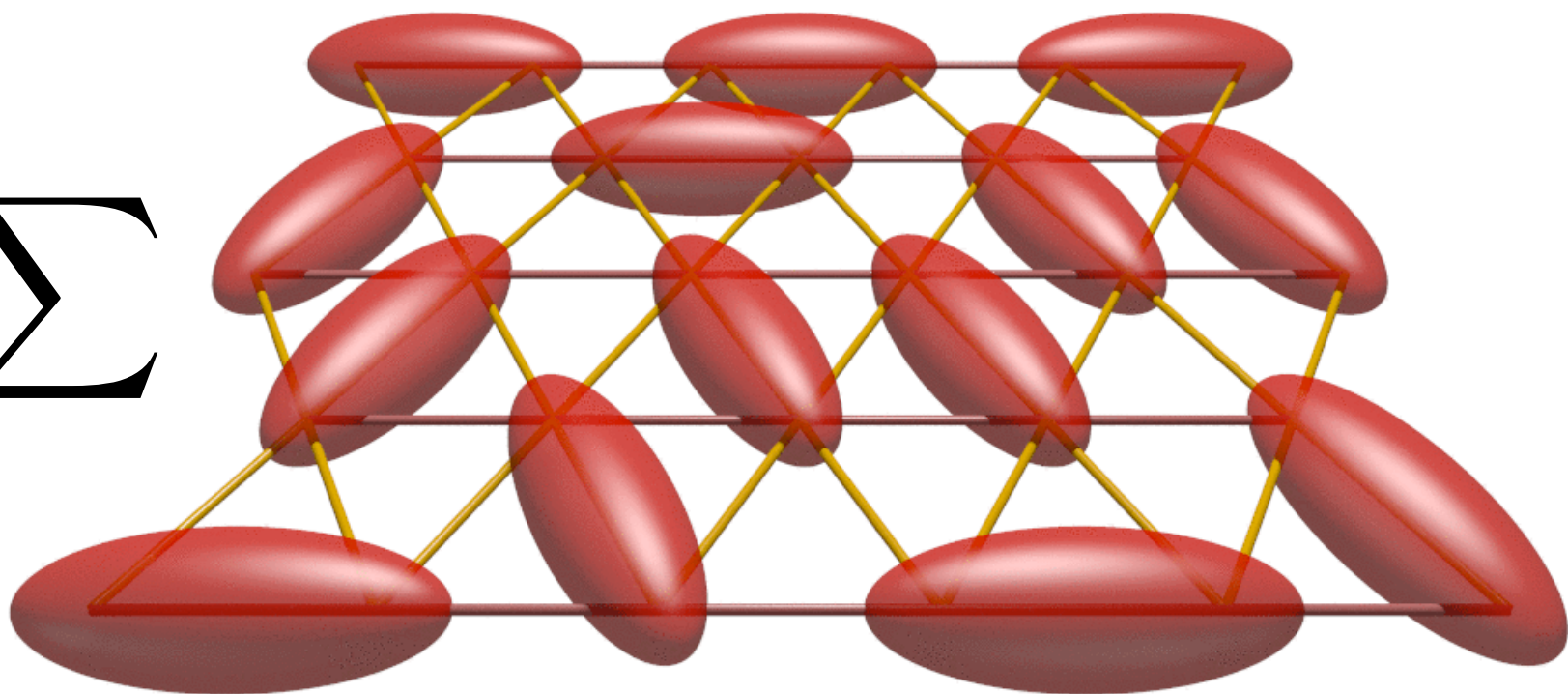


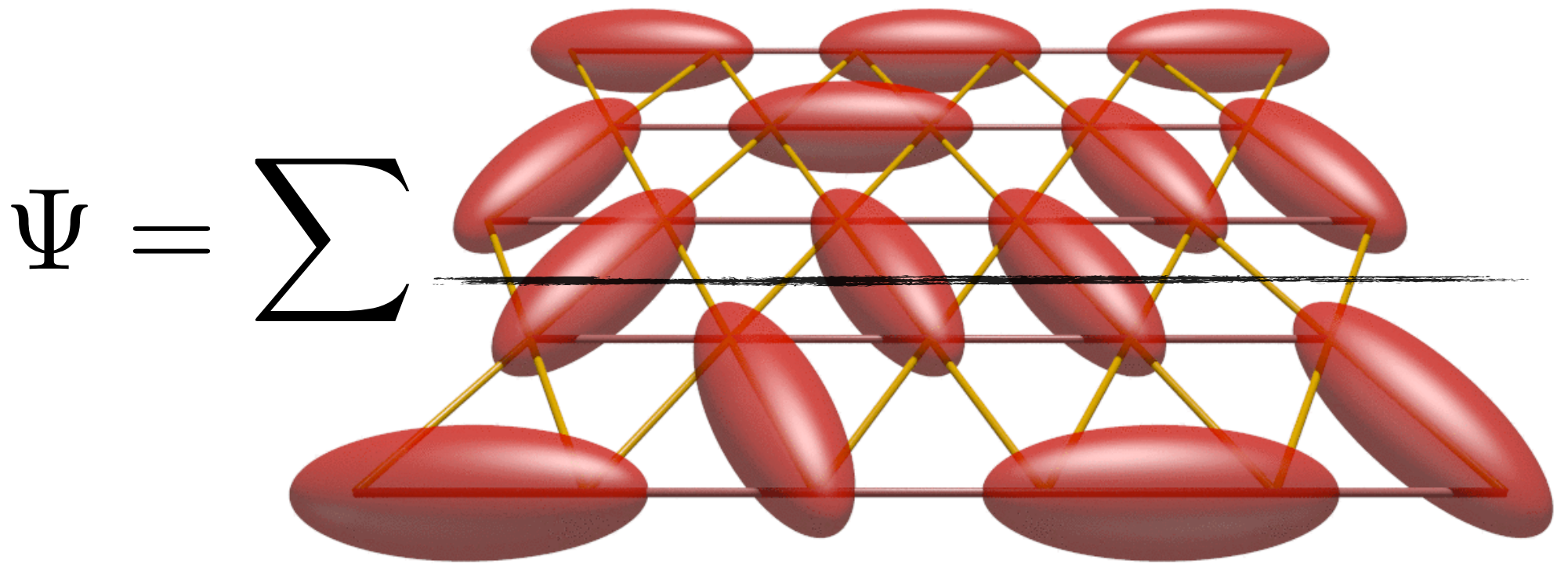
Kane



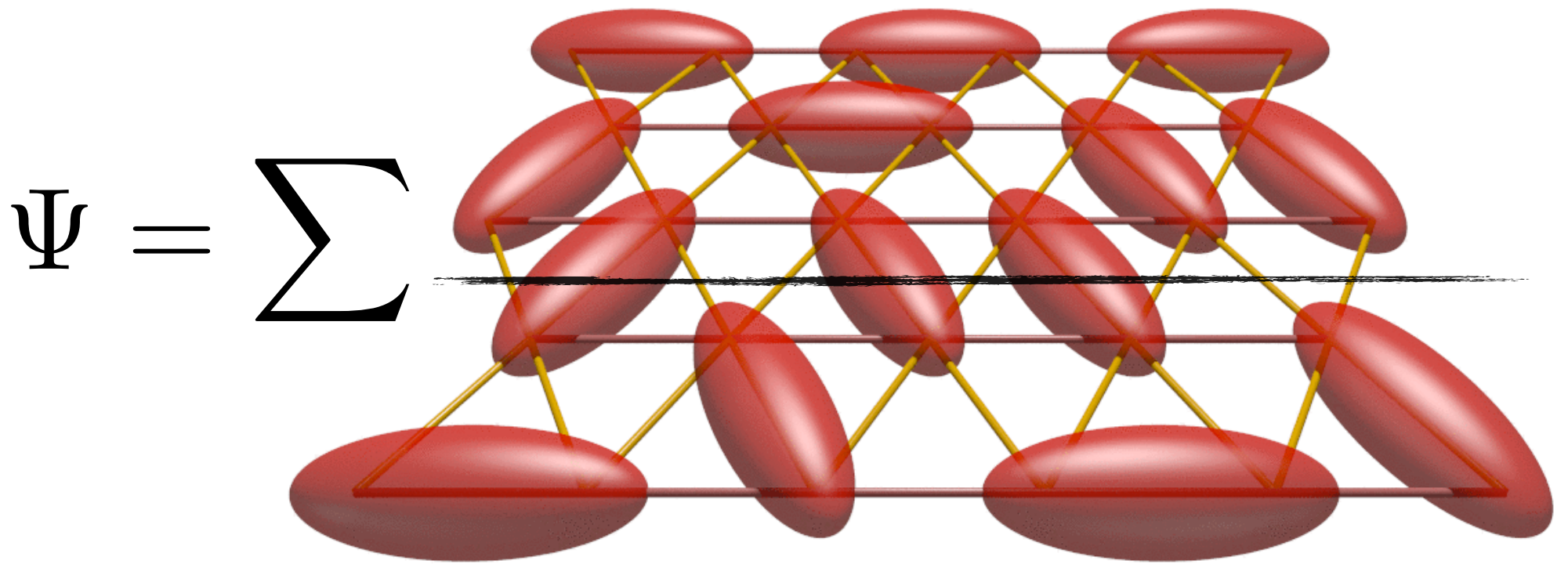
"Topological invariant" = *genus*: the number of holes

$$\Psi = \sum$$





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



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



no local errors allowed!



Topological Protection

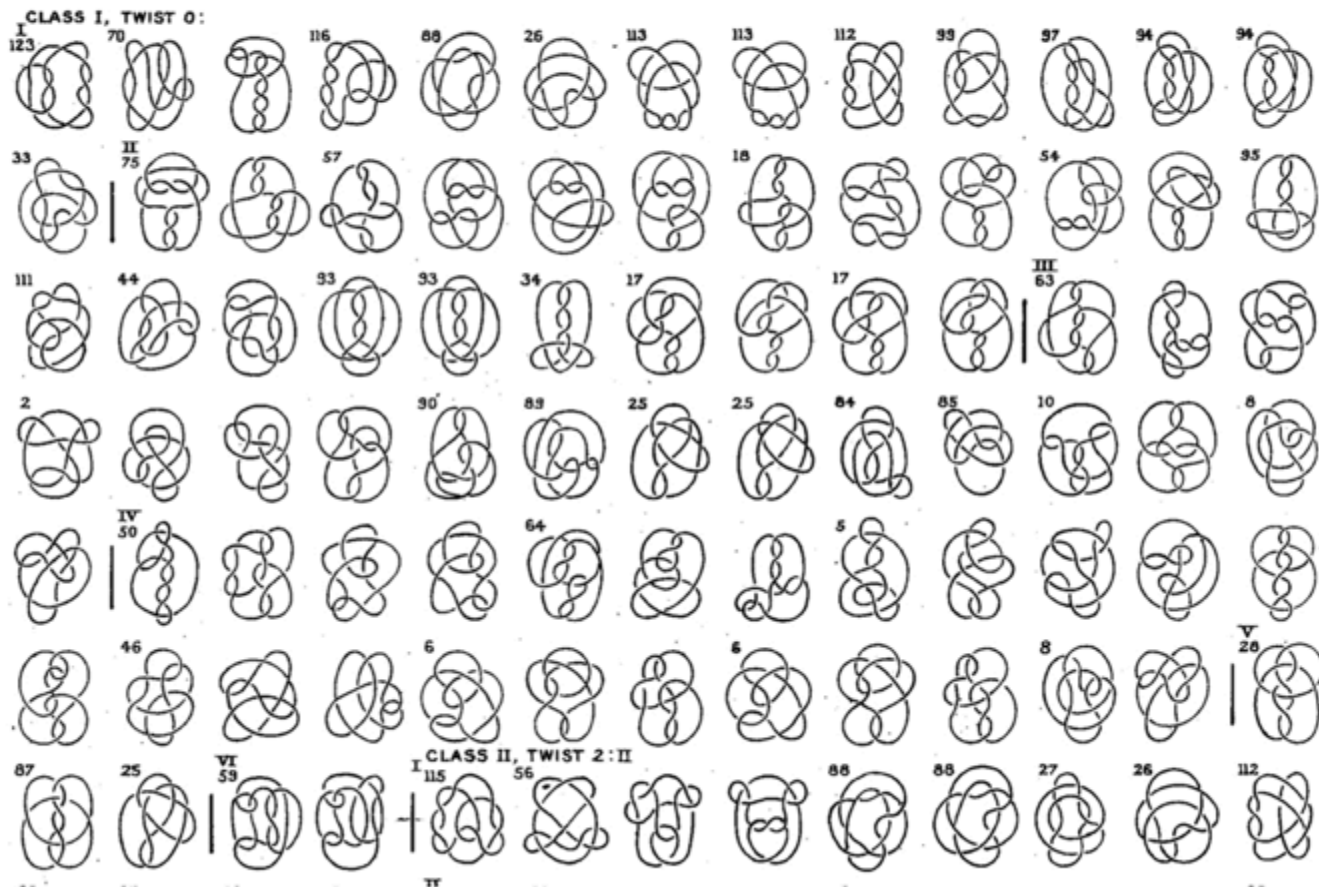
In theory: thousands of different topological
“phases of matter”

Trans. Roy. Soc. Edin.

Vol. XXXIX.

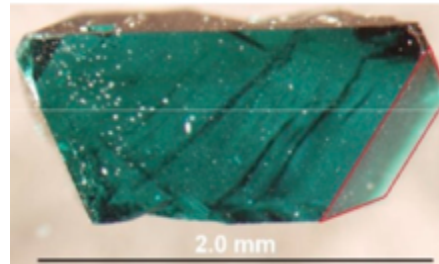
PROF. LITTLE: NON-ALTERNATE ± KNOTS.

PLATE I.

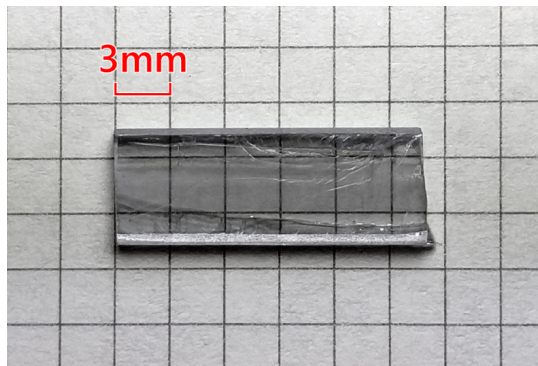


Strange stuff

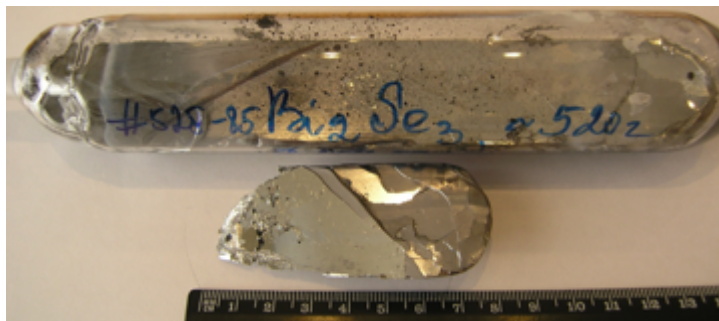




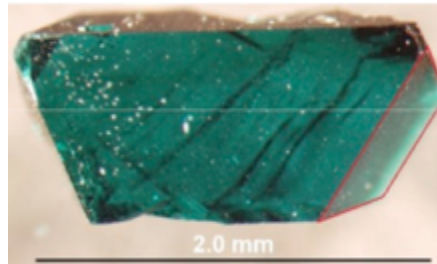
herbertsmithite, a natural mineral discovered in Chile



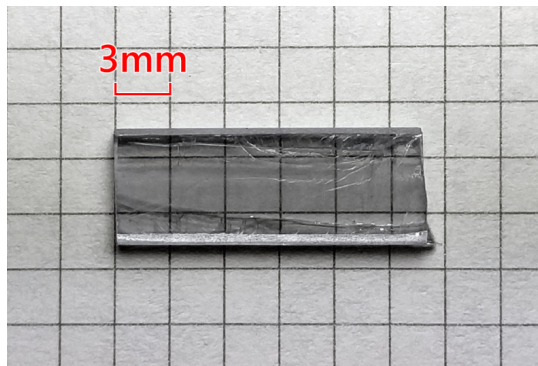
YbMgGaO_4 , synthesized 2015



Bi_2Se_3 , a semiconductor used as a thermoelectric



herbertsmithite, a natural mineral discovered in Chile



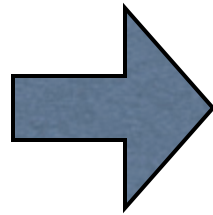
YbMgGaO_4 , synthesized 2015



Bi_2Se_3 , a semiconductor used as a thermoelectric

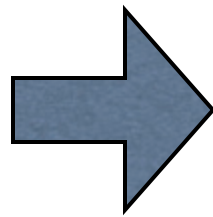
Quantum-ness is
not obvious!!

Strange
stuff



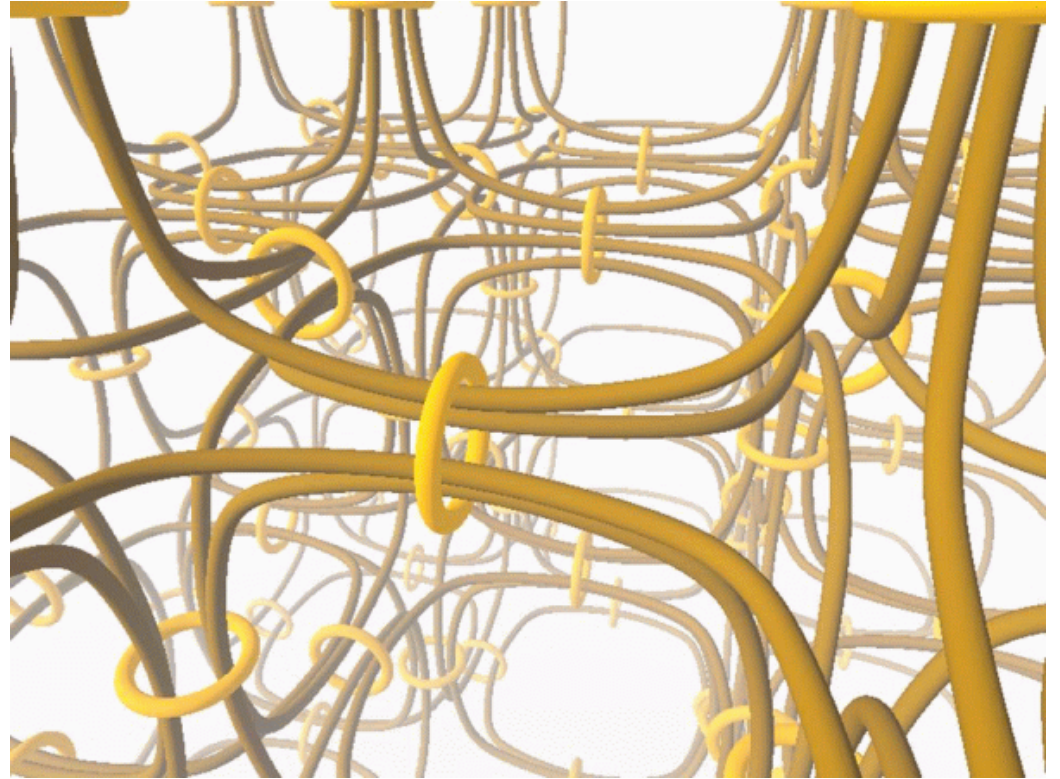
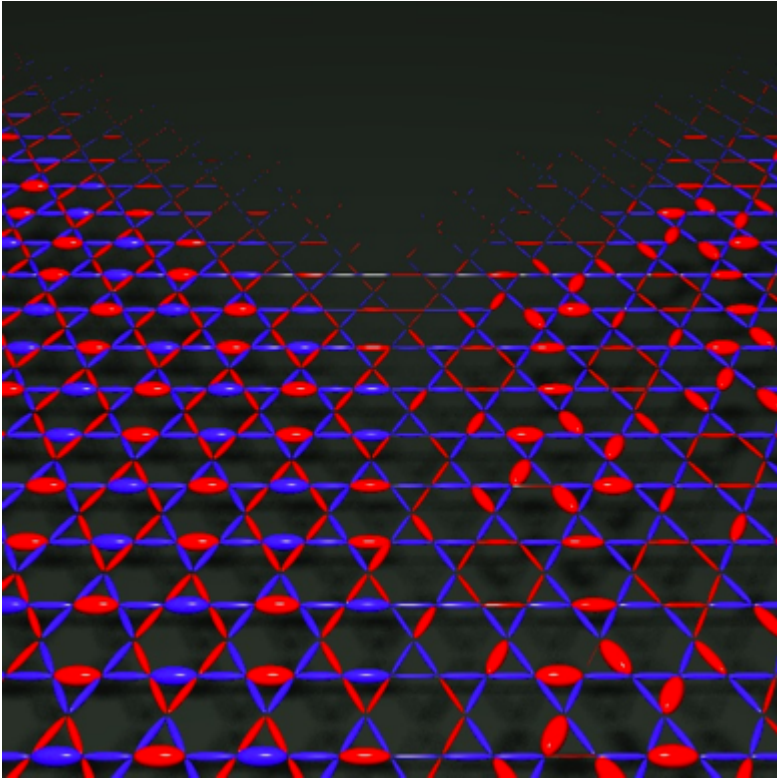
Peculiar
particles

Strange
stuff

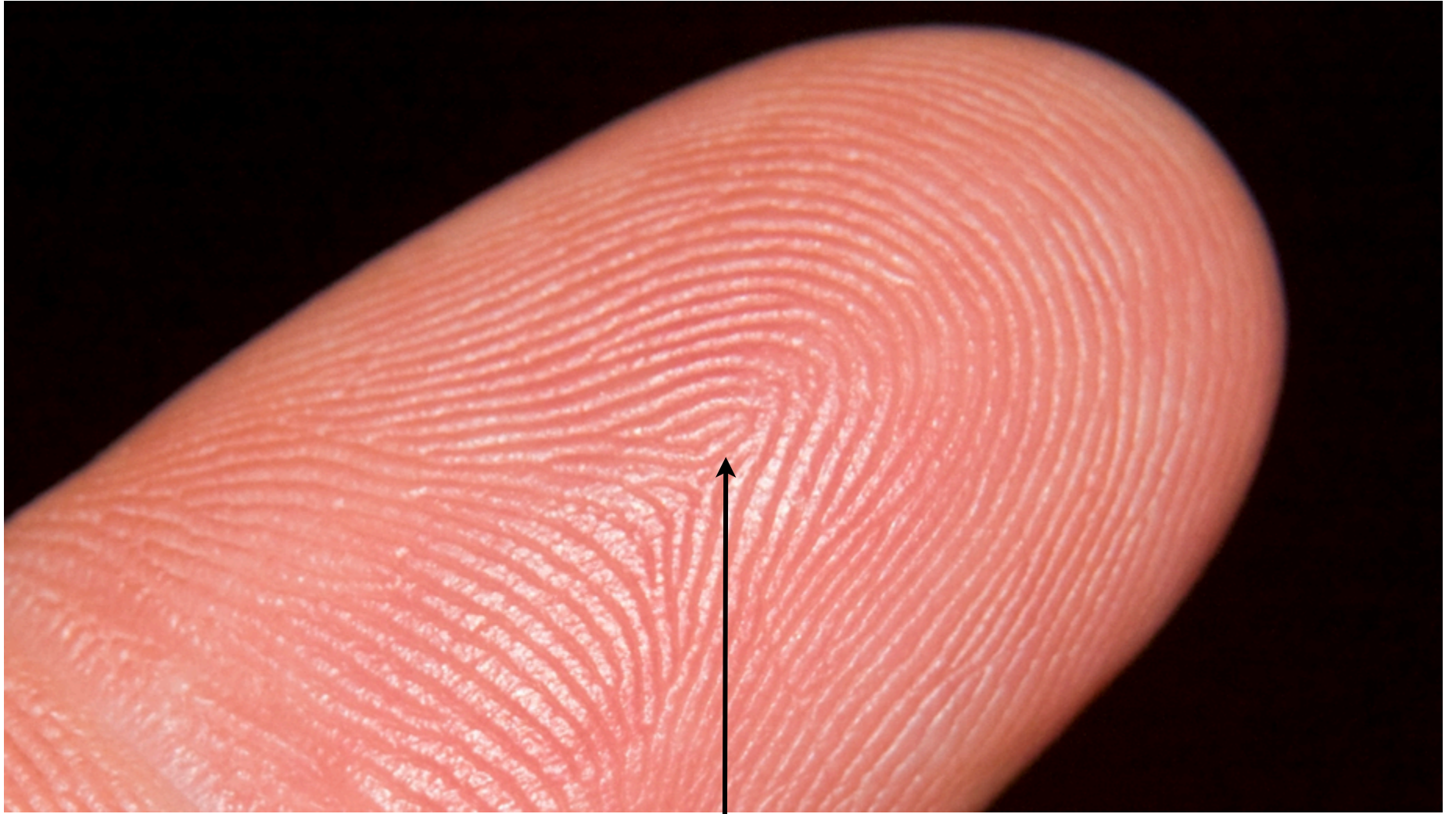


Peculiar
particles

“quasi-particles”

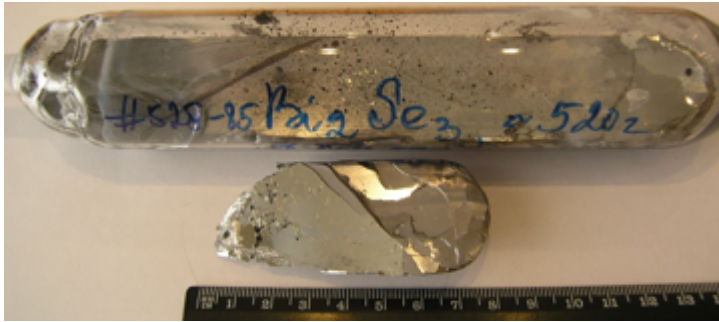


A quantum texture

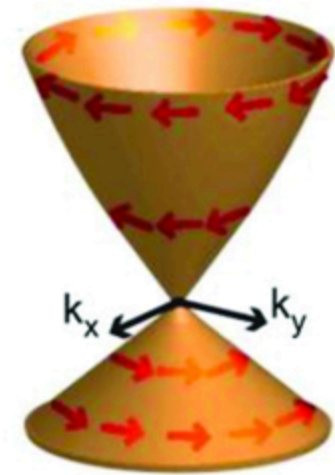
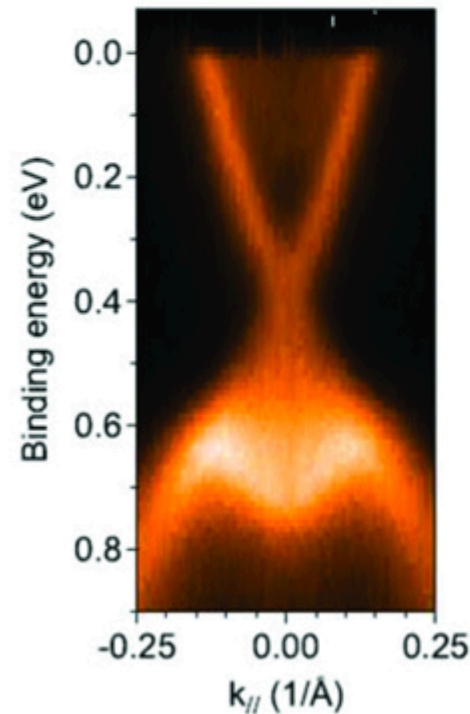


a topological defect

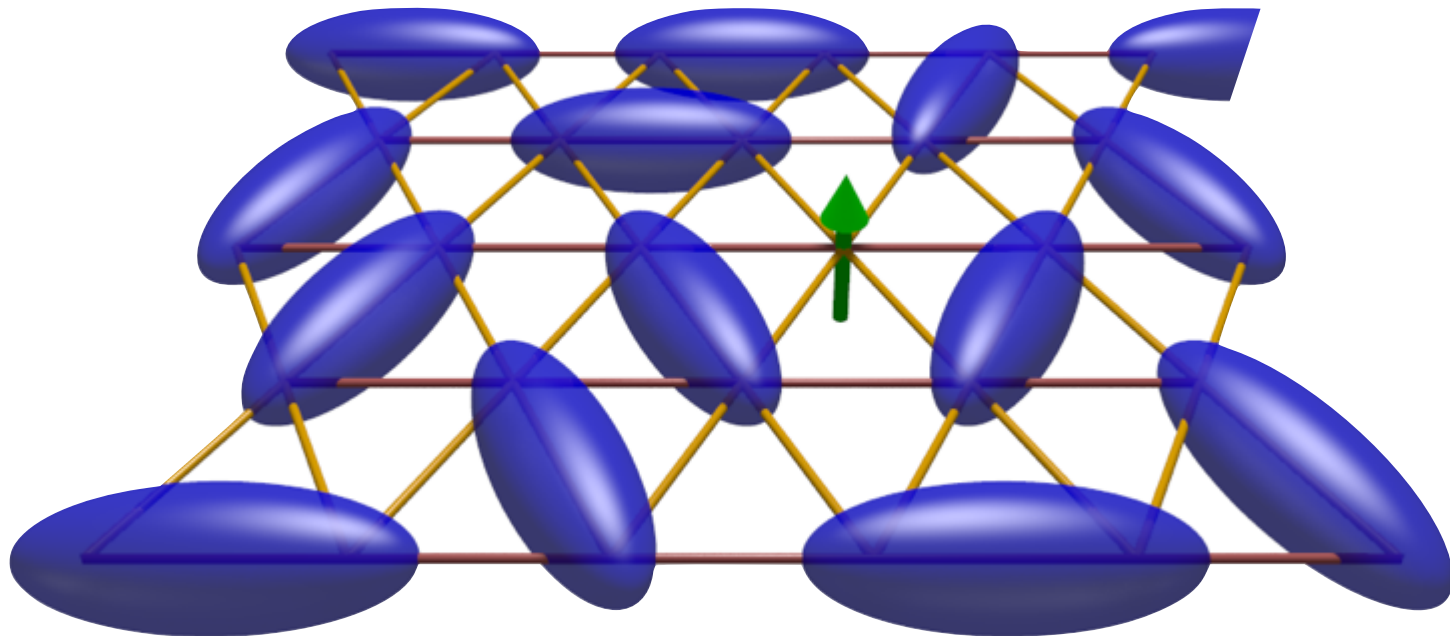
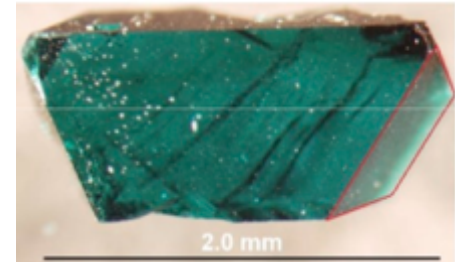
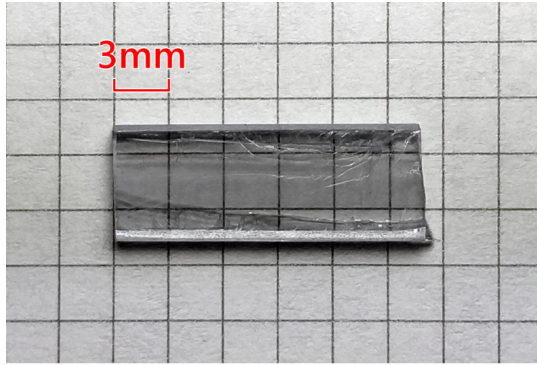
Topological Insulator



Massless Dirac fermion
"artificial neutrino"

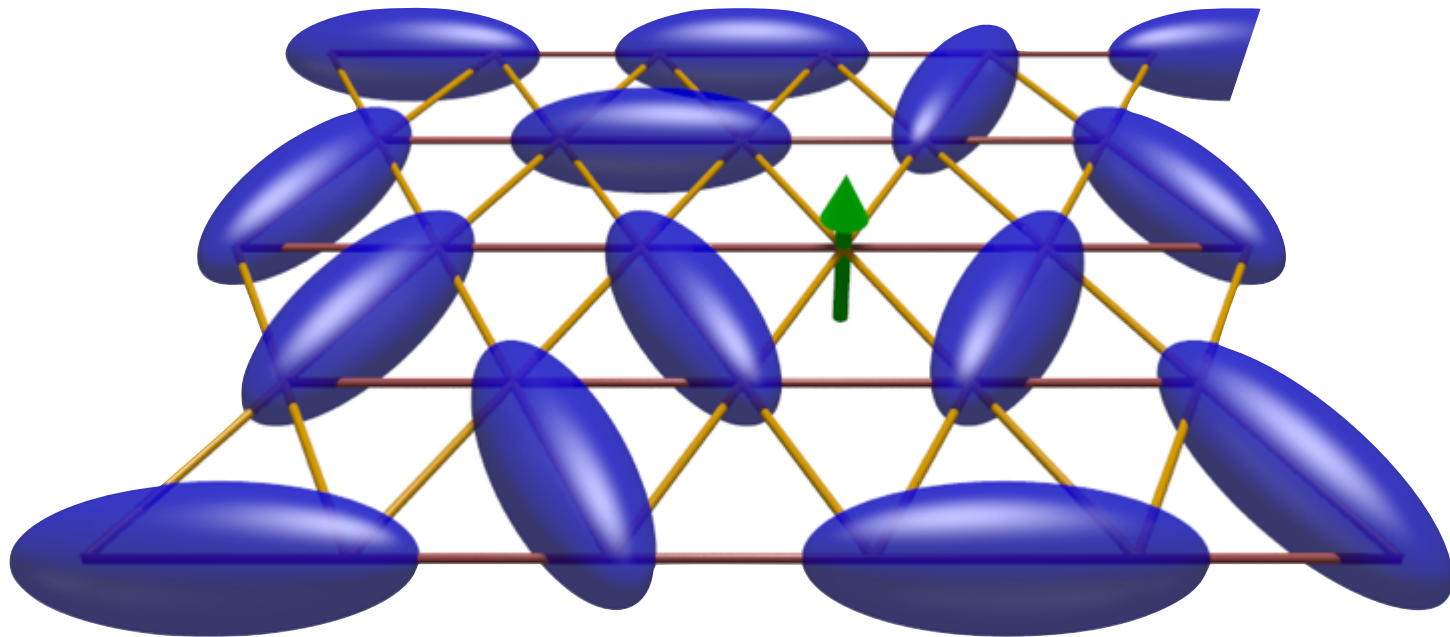
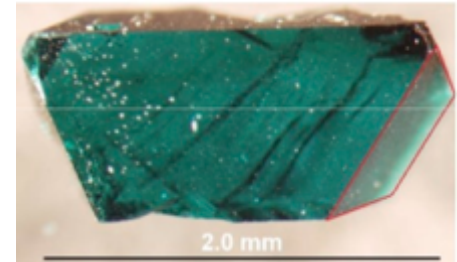
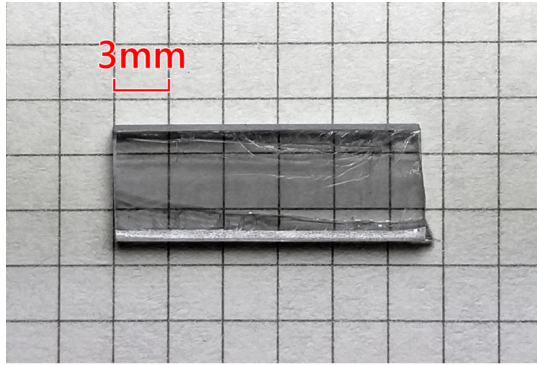


Spin Liquid



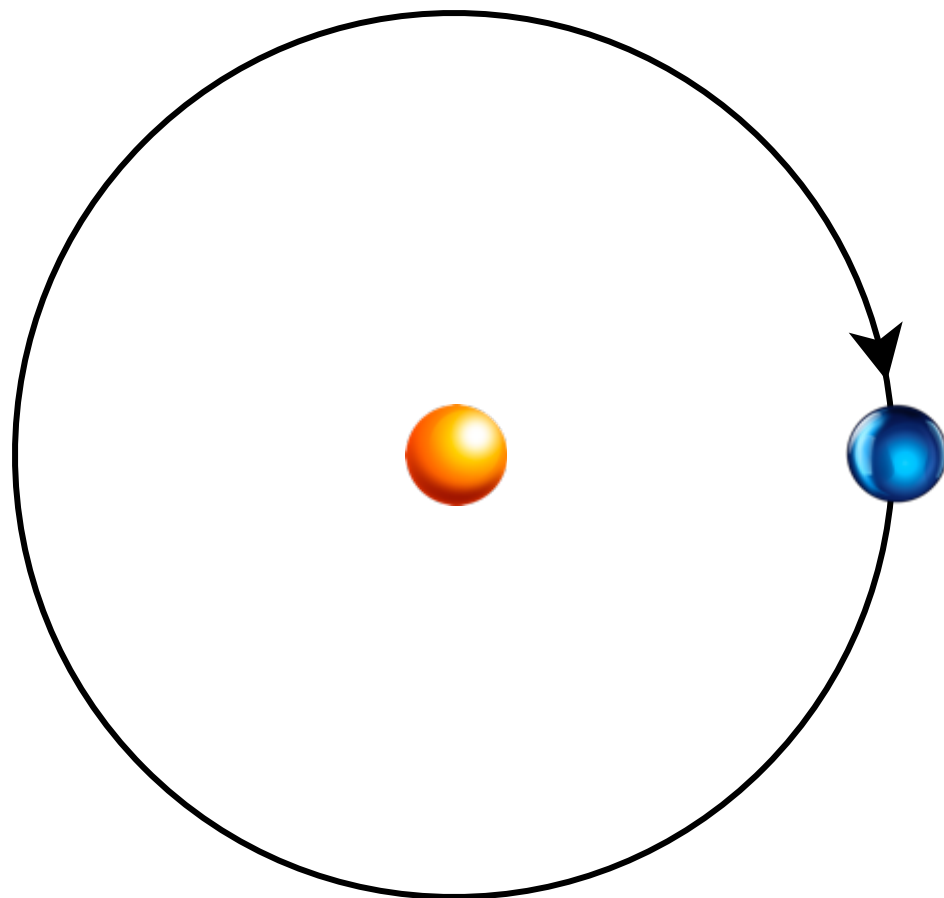
"spinon"

Spin Liquid

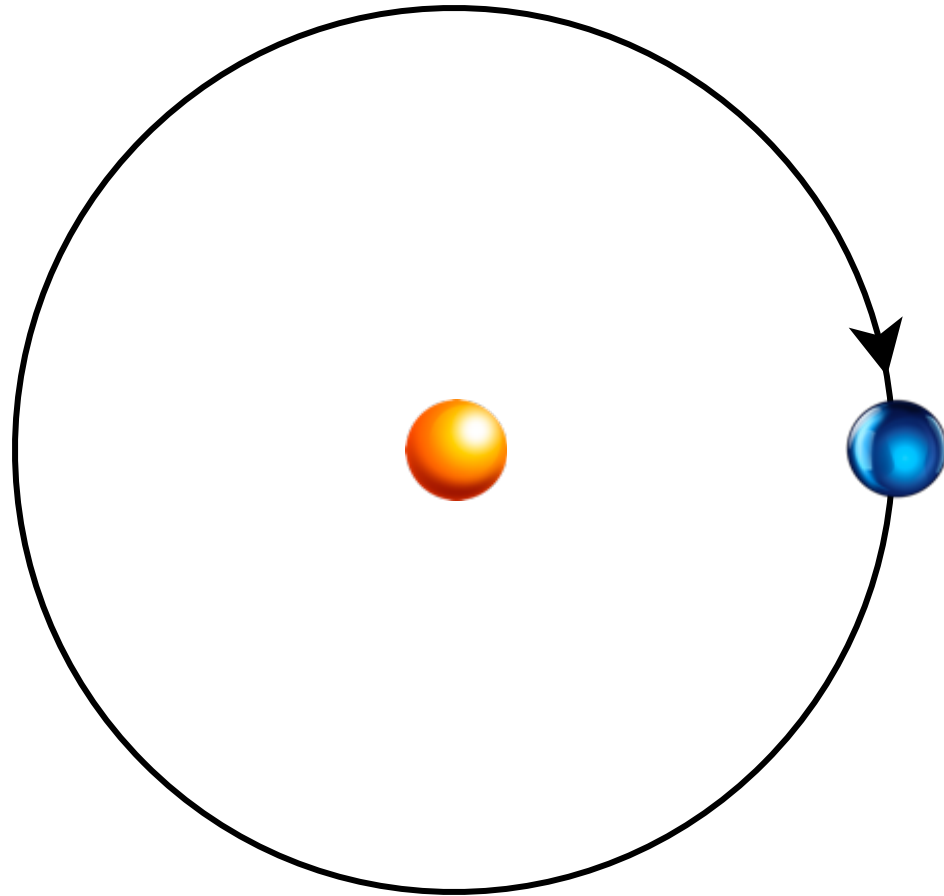


"spinon"

Anyons



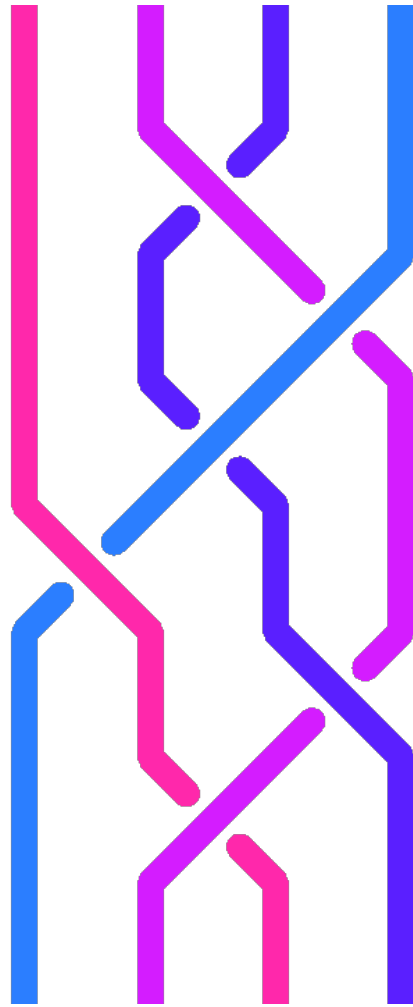
Anyons



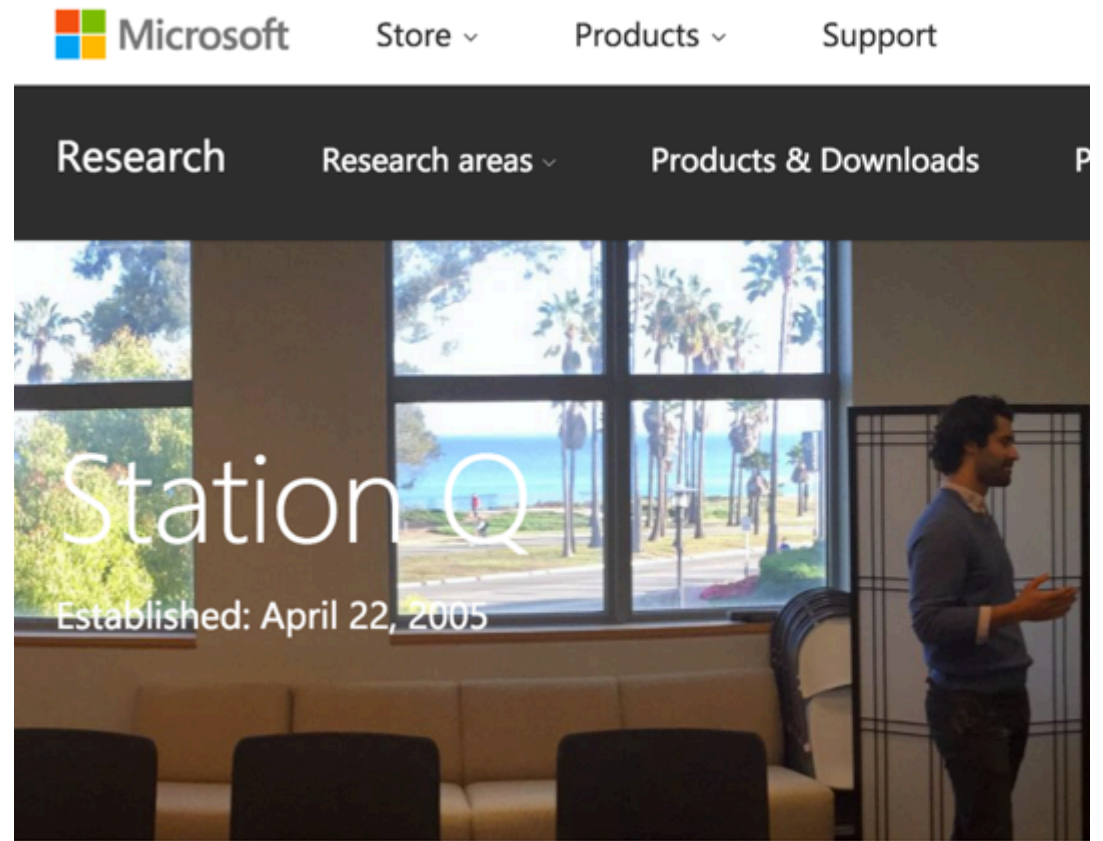
Amplitudes in entangled superposition are
changed!



Anyons



↑
time



Future computers may be very strange indeed!

Fundamental applications?

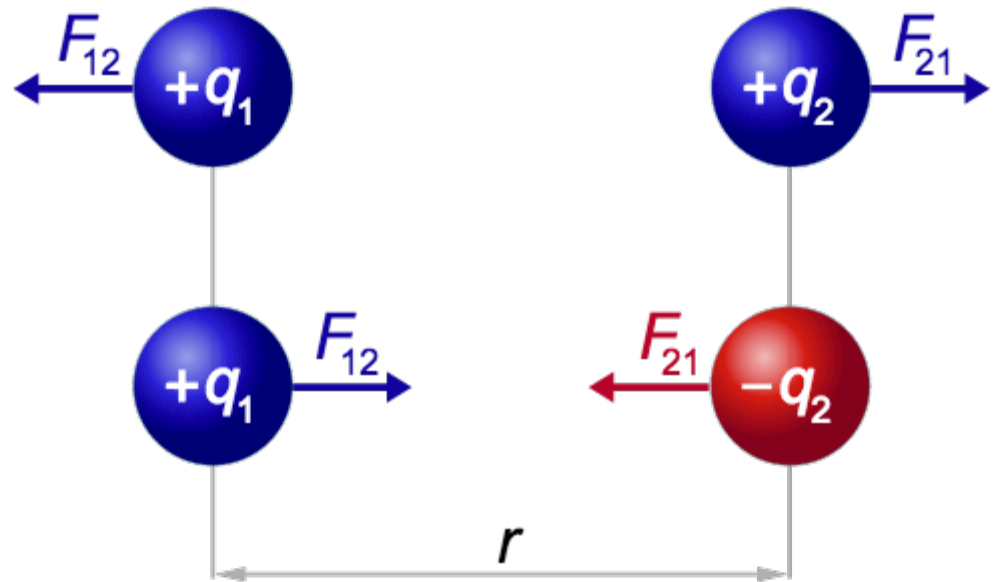
Can elementary particles and forces
of our world emerge from
entanglement?



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.

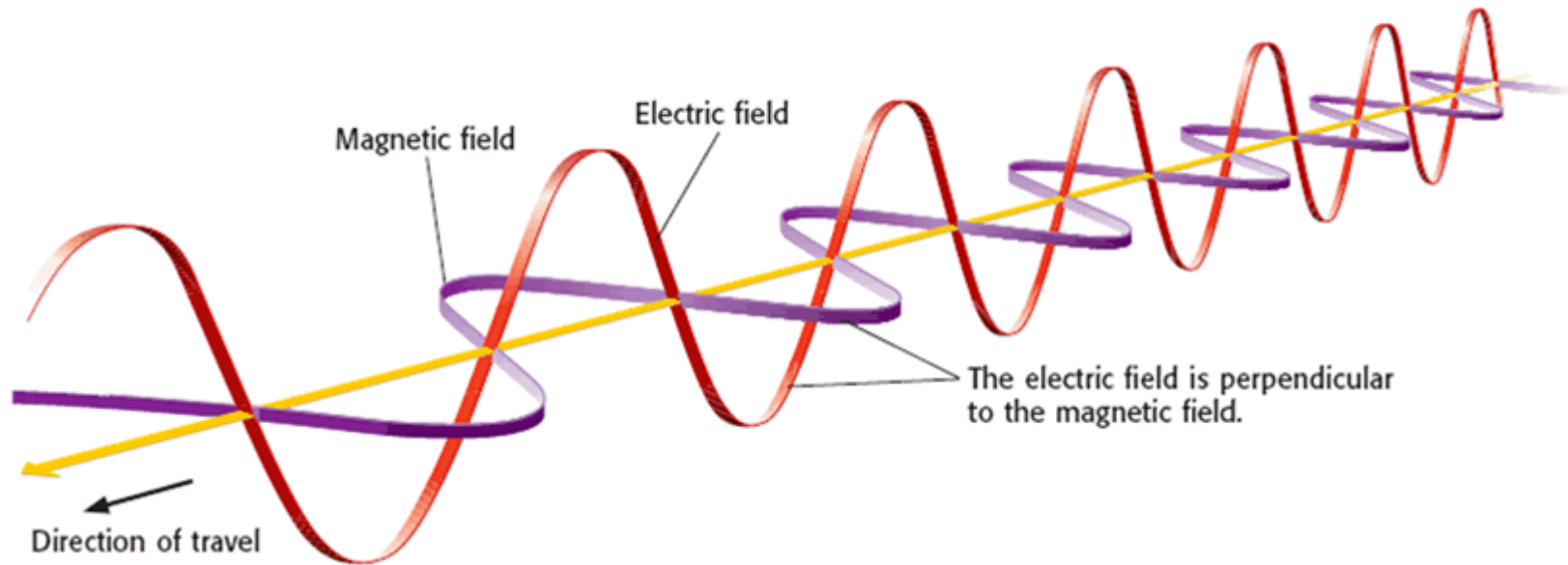


$$F_{12} = F_{21} = k \frac{q_1 q_2}{r^2}$$

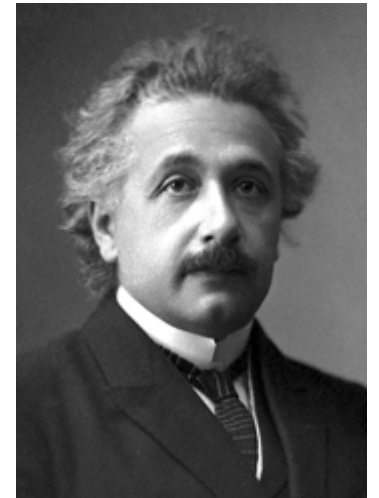
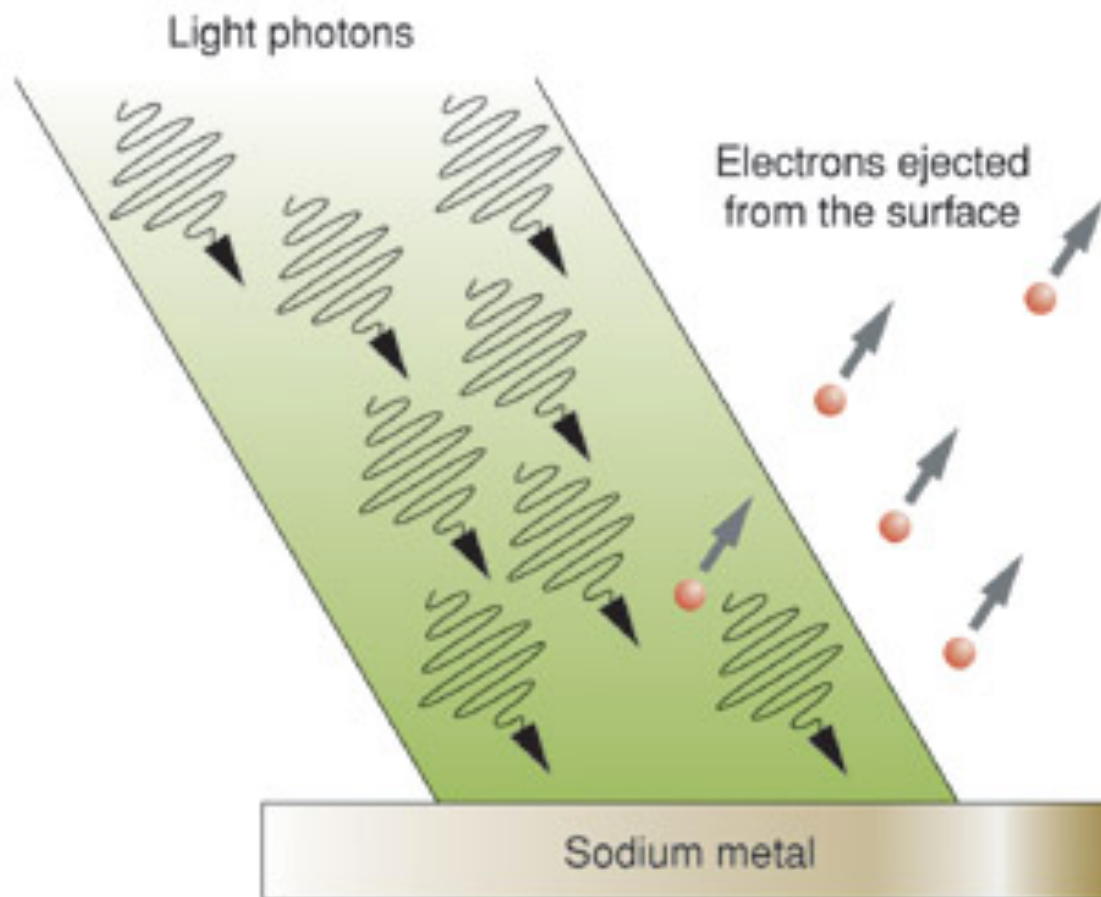
Electromagnetism

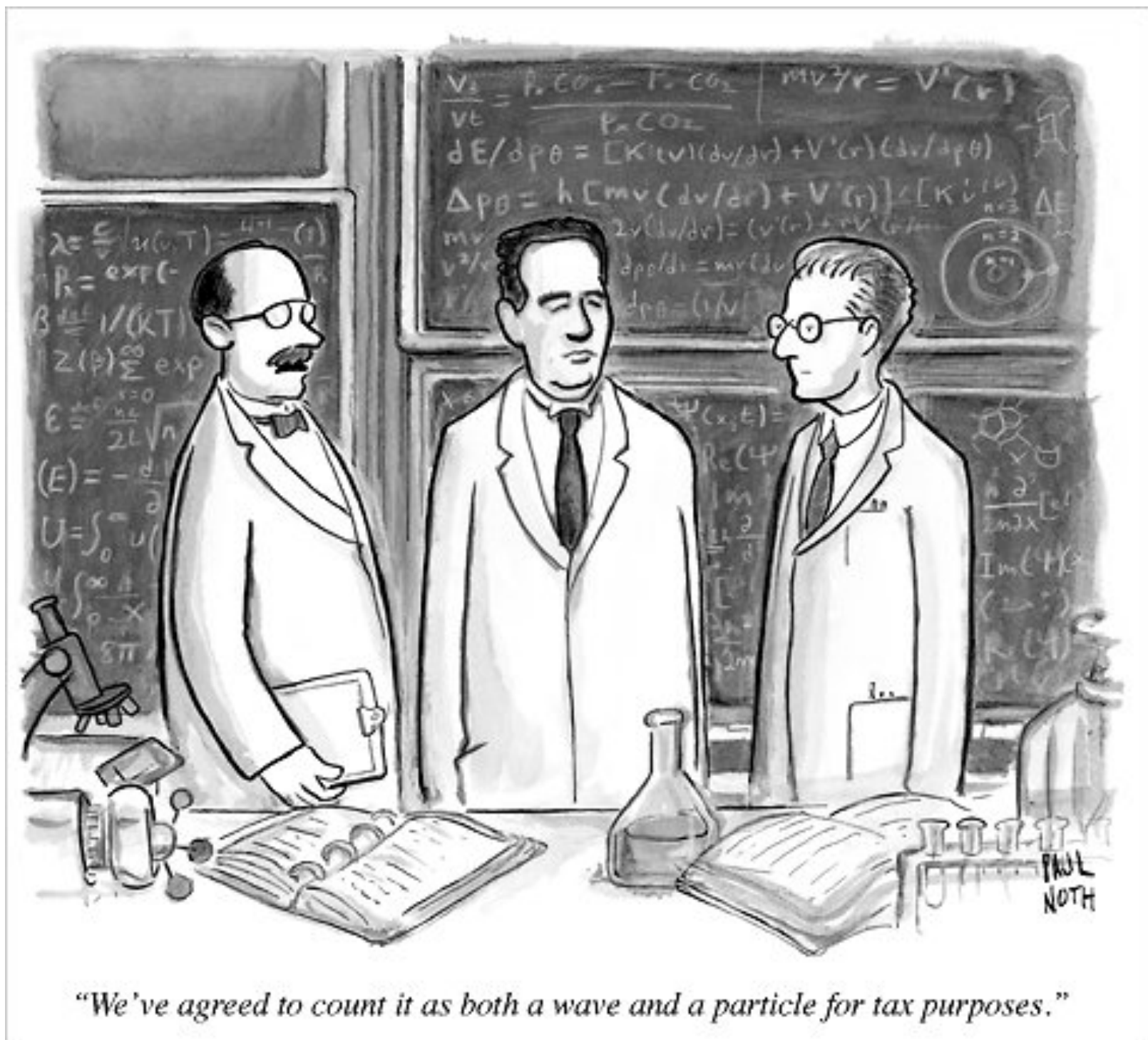


James Clerk Maxwell



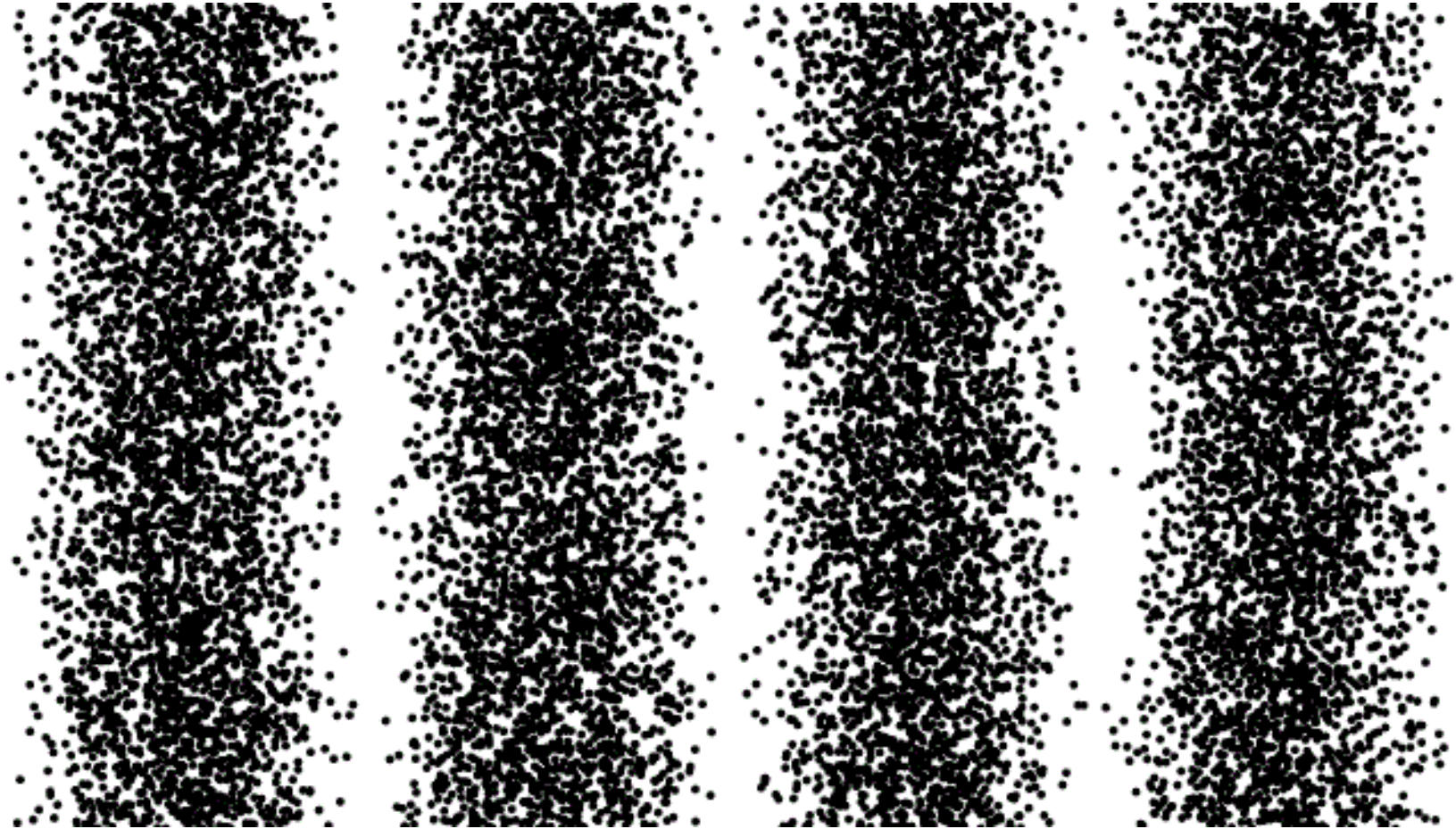
Photoelectric effect





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

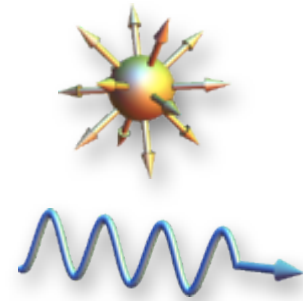
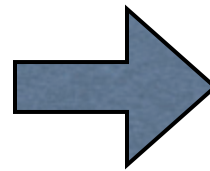
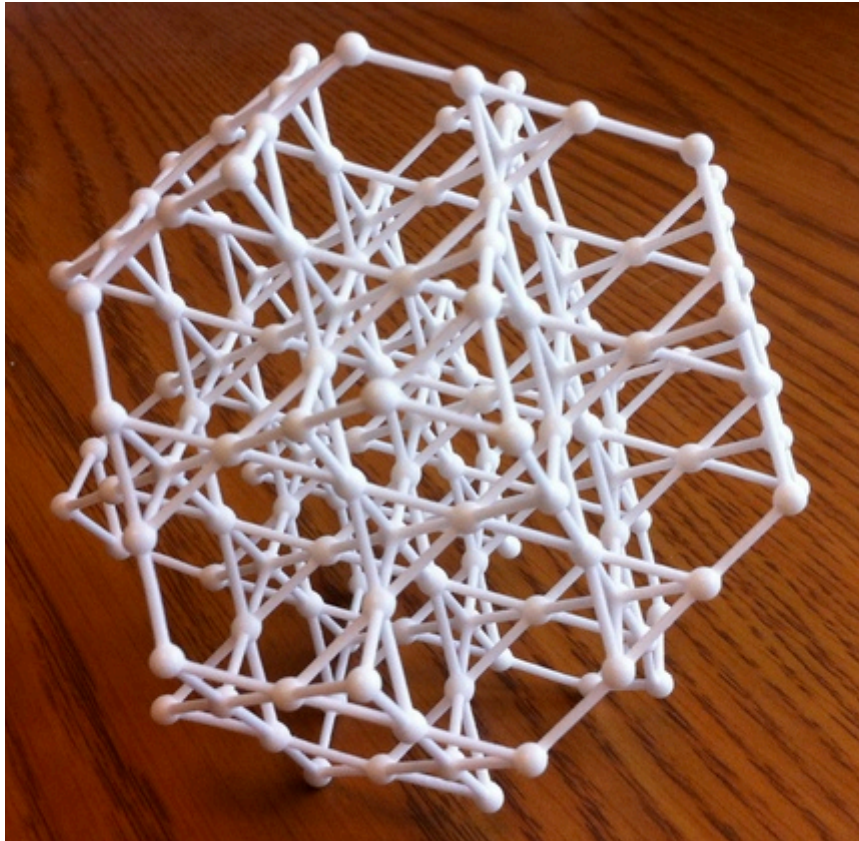
Particle-wave duality



But where does
electromagnetism come from?



Mike Hermele



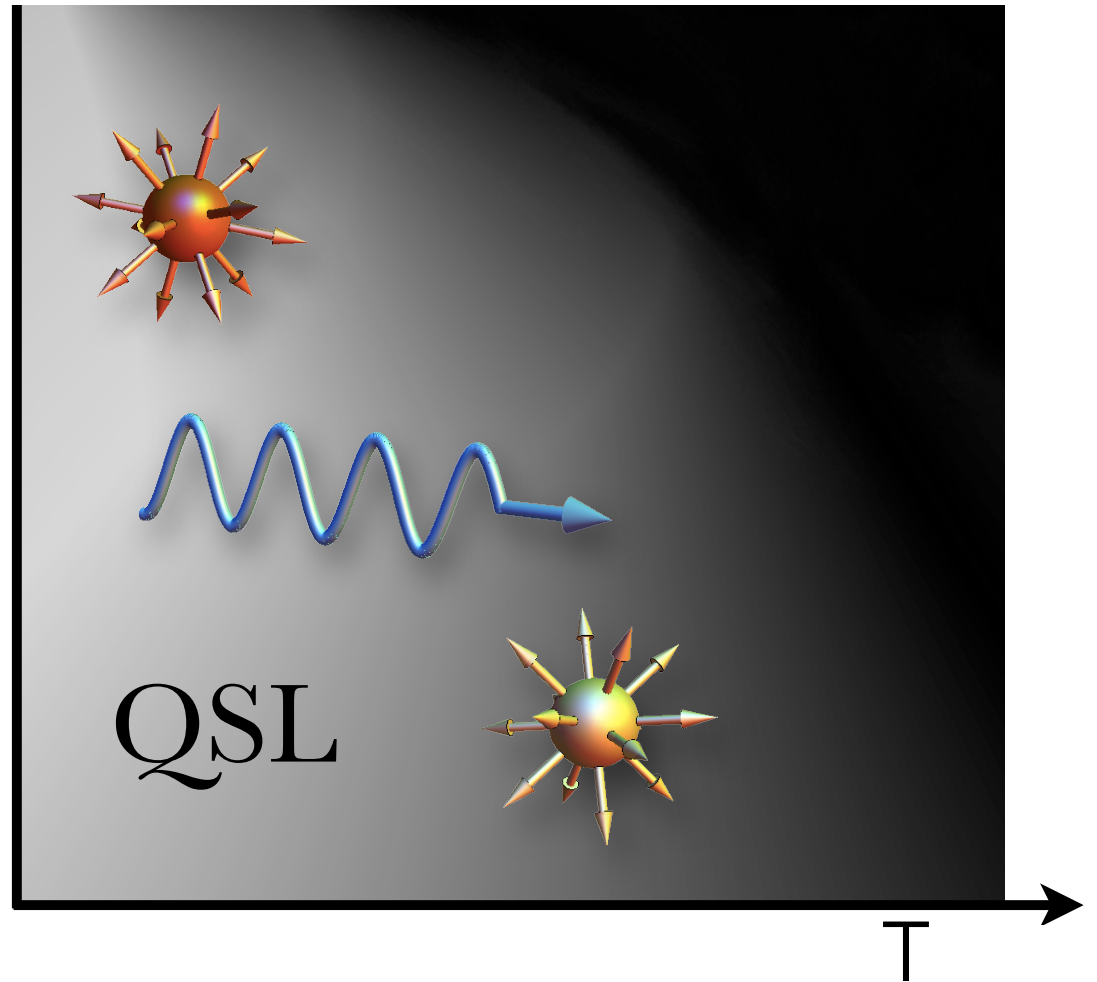


Lucile Savary



$\text{Yb}_2\text{Ti}_2\text{O}_7$

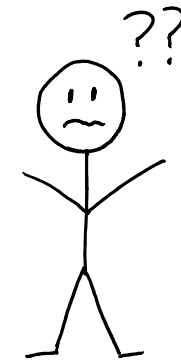
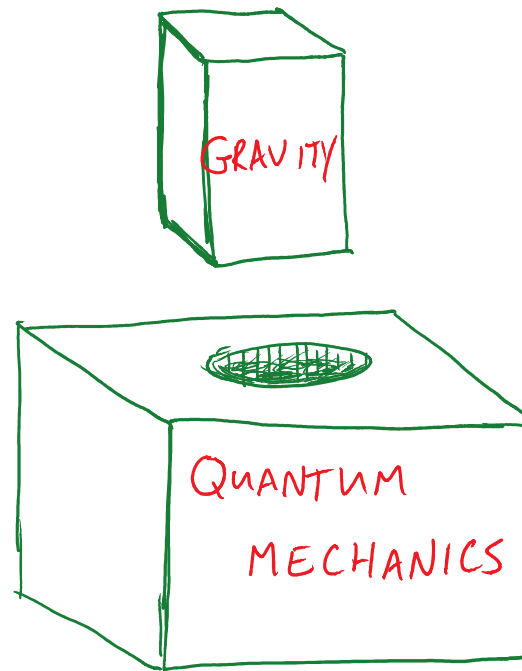
B



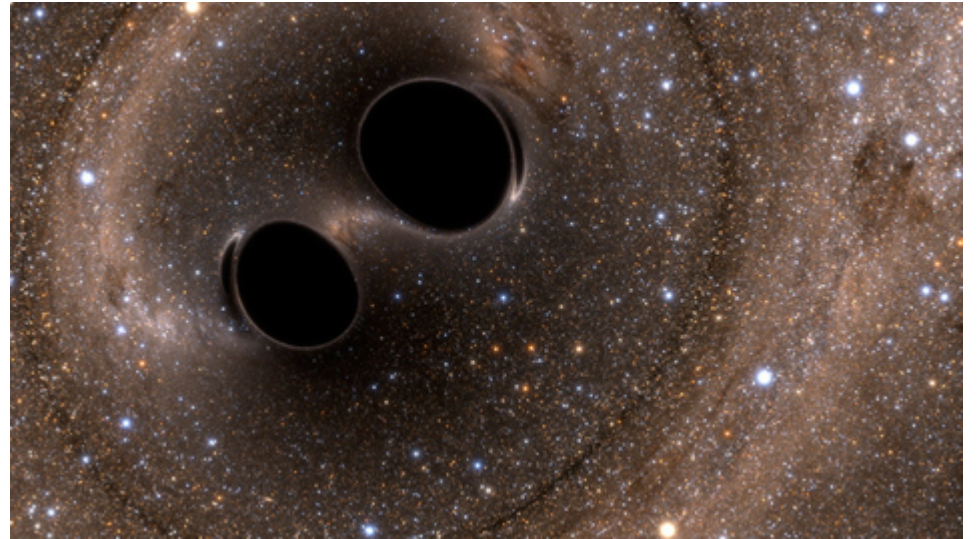
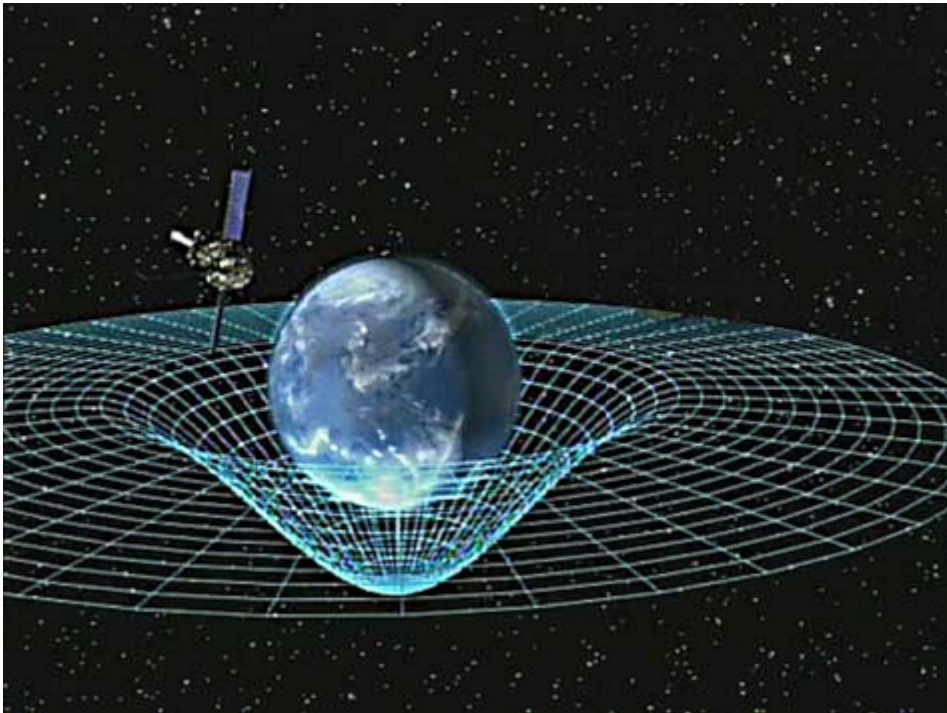
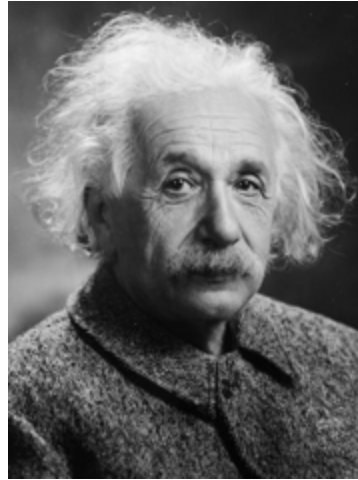
Gravity



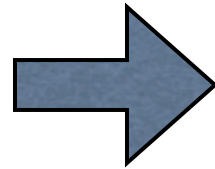
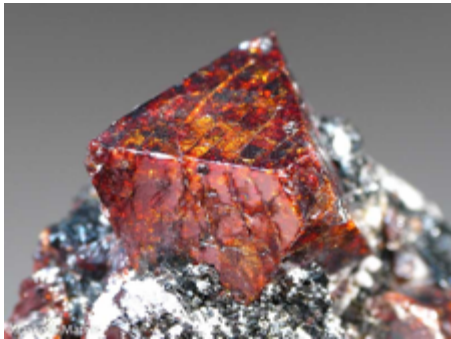
Mark Van Raamsdonk, UBC
KITP, April 2015



There is no theory of quantum gravity

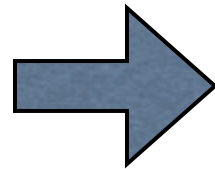


explaining gravity is explaining the emergence of
space-time itself

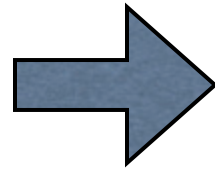
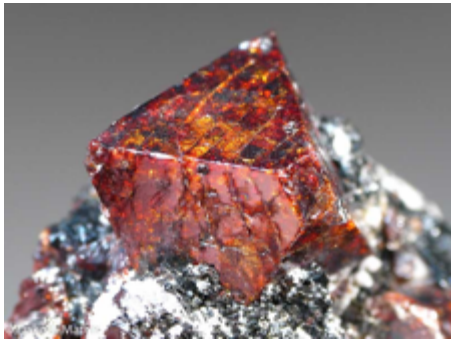


electromagnetism

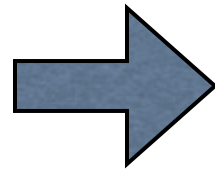
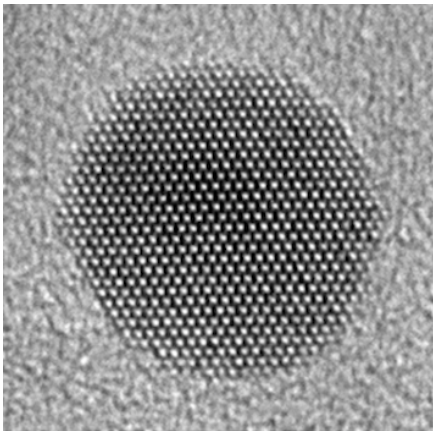
???



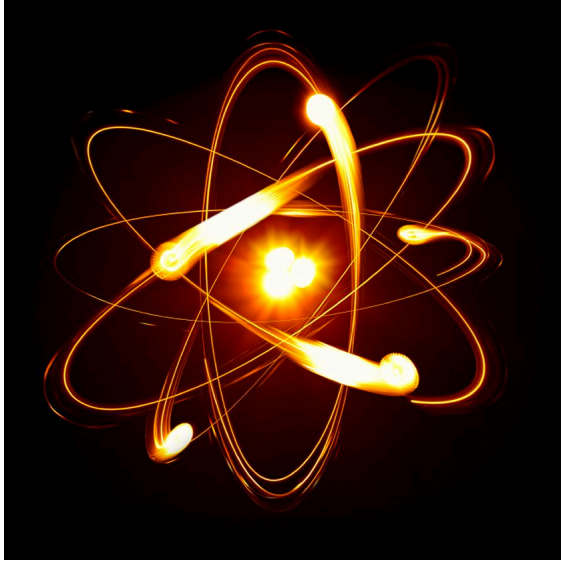
gravity?



electromagnetism



gravity?

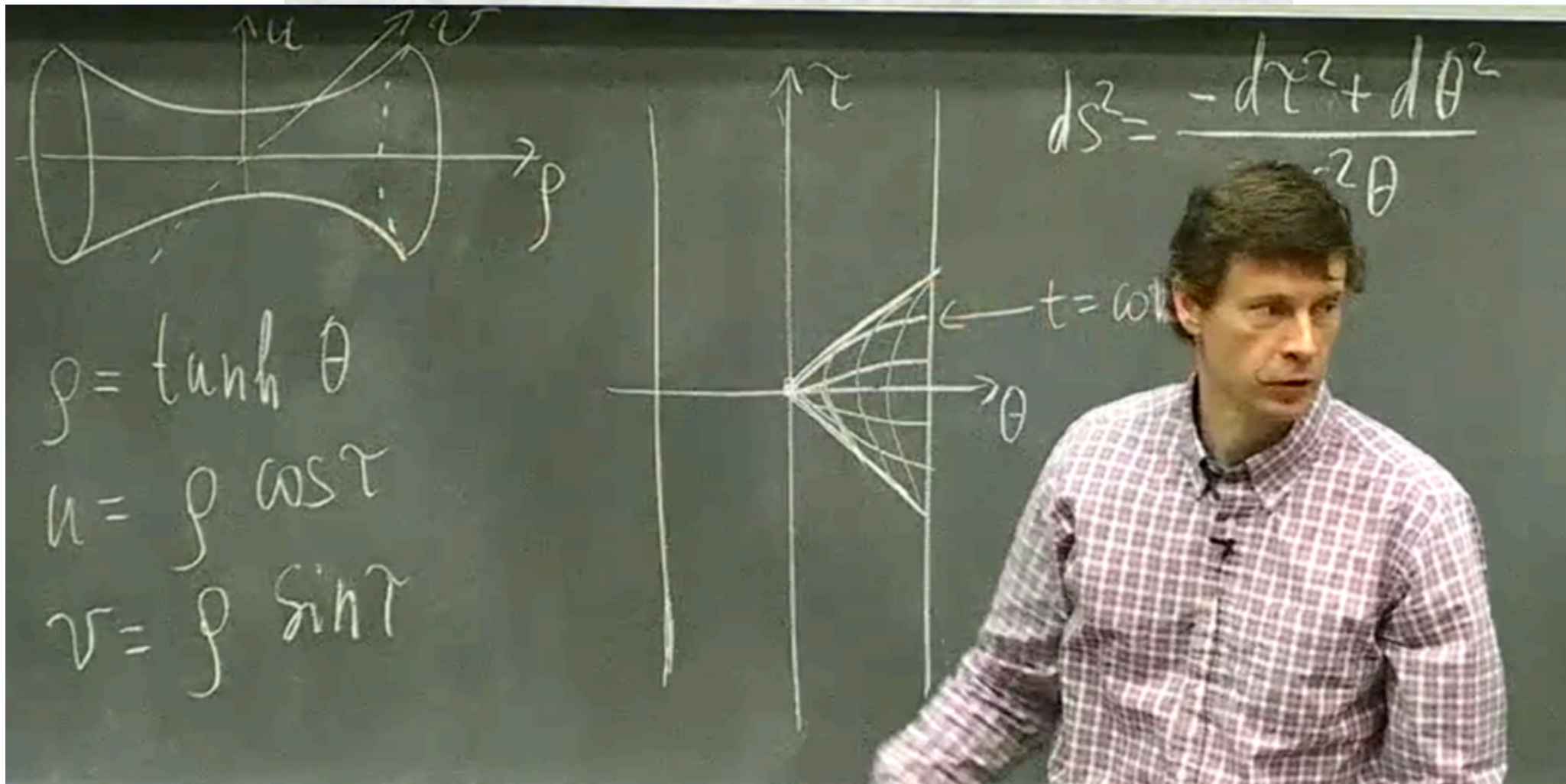


Electrons

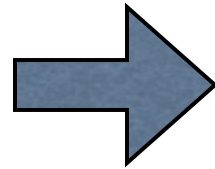
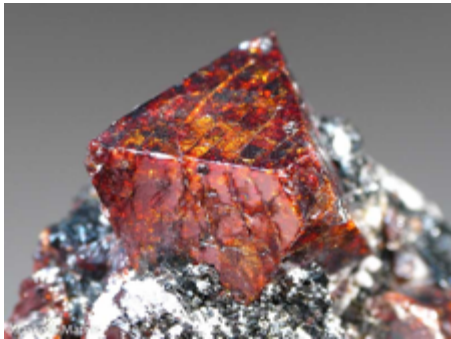


Black holes

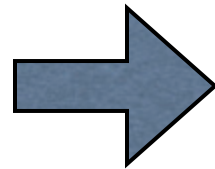
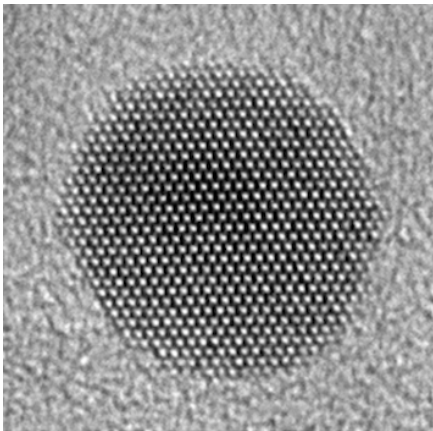
Sachdev-Ye-Kitaev Model



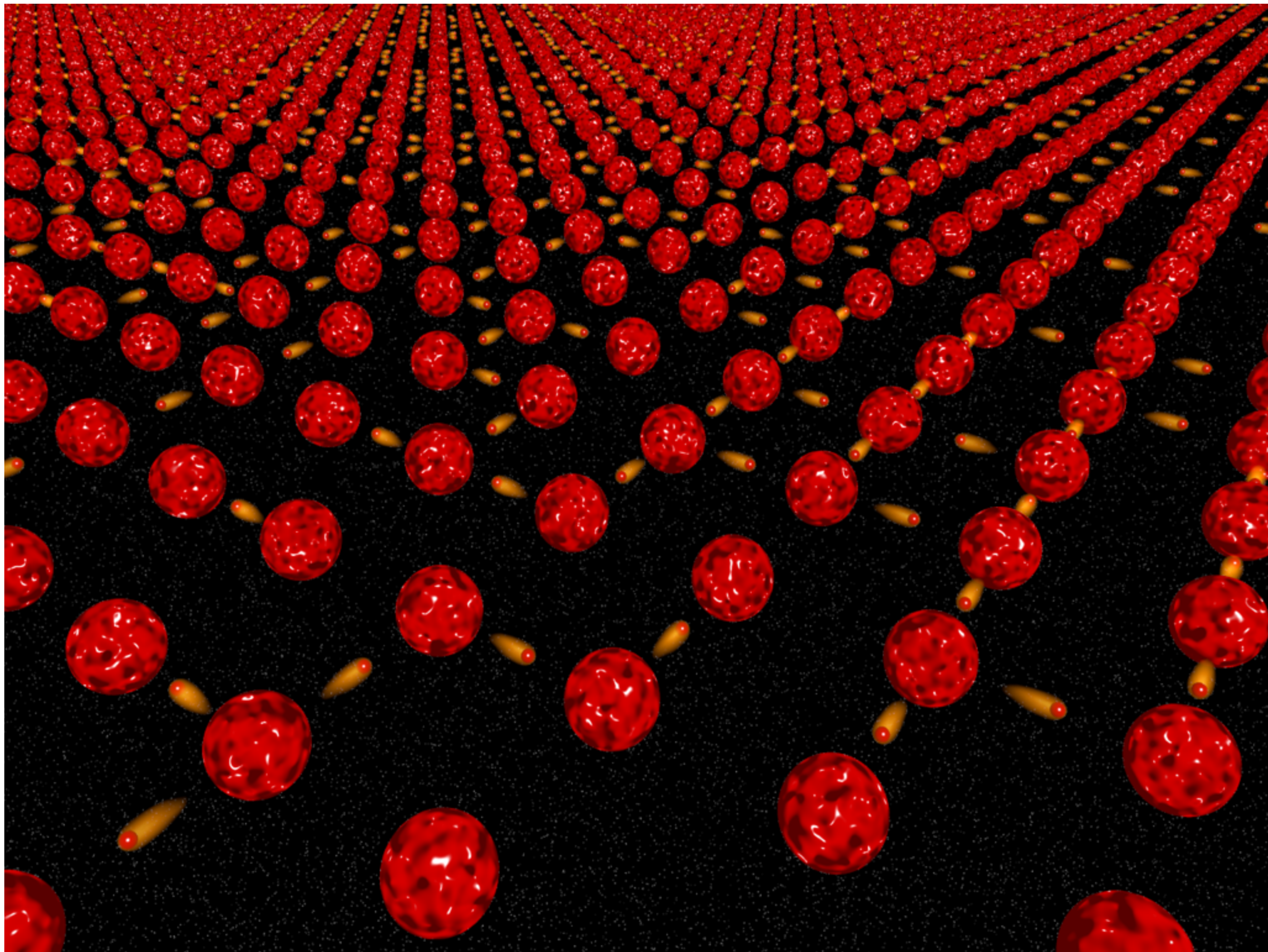
April 2015



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