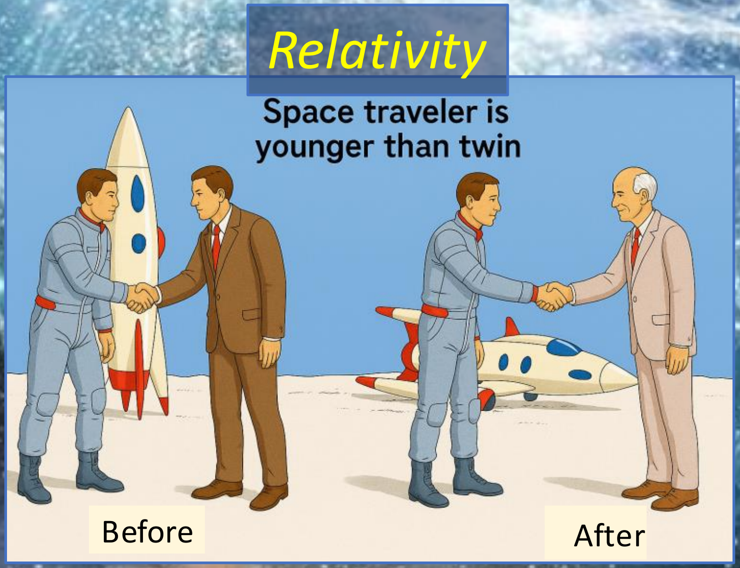
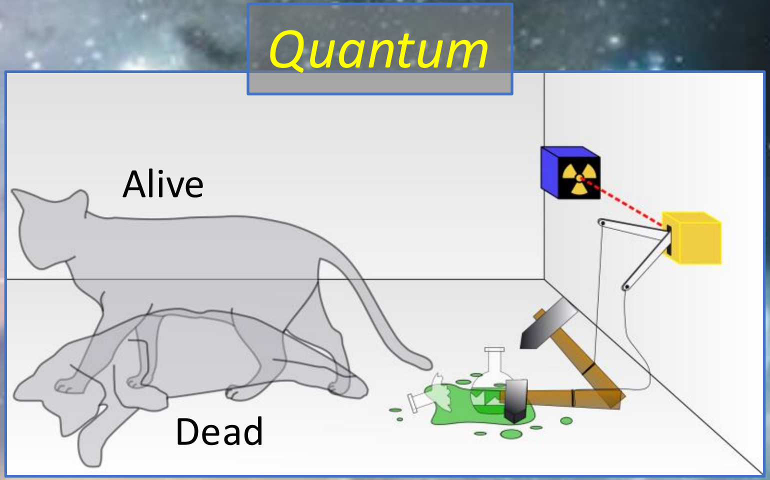
The Relativistic Quantum World

A lecture series on
Relativity Theory and Quantum Mechanics





Marcel Merk
Studium Generale Maastricht
Sep 10 – Oct 8, 2025

The Relativistic Quantum World

Relativity

Sep. 10: Lecture 1: The Principle of Relativity and the Speed of Light
Lecture 2: Time Dilation and Lorentz Contraction

Sep. 17: Lecture 3: The Lorentz Transformation and Paradoxes
Lecture 4: General Relativity and Gravitational Waves

Quantum Mechanics

Sep. 24: Lecture 5: The Early Quantum Theory
Lecture 6: Feynman's Double Slit Experiment

Oct. 1 : Lecture 7: Wheeler's Delayed Choice and Schrodinger's Cat
Lecture 8: Quantum Reality and the EPR Paradox

Standard Model

Oct. 8: Lecture 9: The Standard Model and Antimatter
Lecture 10: Why is there something rather than nothing?

Lecture notes, written for this course, are available: www.nikhef.nl/~i93/Teaching/
Prerequisite for the course: High school level physics & mathematics.

Lecture 8

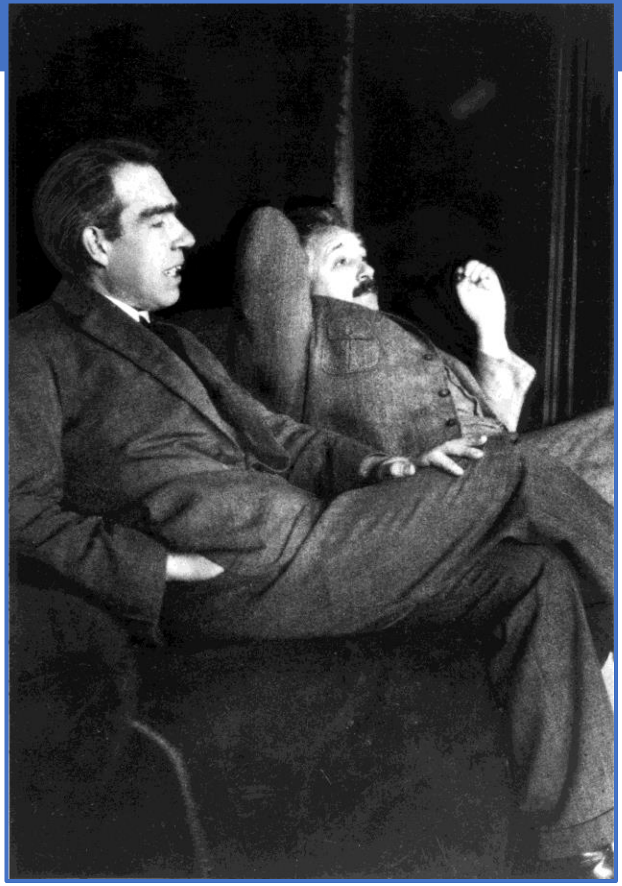
Quantum Reality and EPR Paradox

"When we measure something we are forcing an undetermined, undefined world to assume an experimental value. We are not measuring the world, we are creating it."
- Niels Bohr

"If all of this is true, it means the end of physics."
- Albert Einstein, in discussion with Niels Bohr

"Bohr was inconsistent, unclear, wilfully obscure, and right."
"Einstein was consistent, clear, down-to-earth, and wrong."
- John Bell

Einstein’s Final Objection



Principle of locality:

- An object is only directly influenced by its immediate surroundings.
- An action on a system at one point ***cannot*** have an ***instantaneous*** effect on another point.
- To have effect at a distance a field or particle (“signal”) must travel between the two points.
- Limit: the speed of light.
  - Otherwise trouble with causality (see relativity: “Bob dies before Alice actually shoots him?!”).

Einstein: Quantum Mechanics is ***not a local*** theory, therefore: it is unreasonable!

The EPR discussion is the last of the Bohr – Einstein discussions. After receiving Bohr’s reply Einstein commented that QM is too much in contradiction with his scientific instinct.

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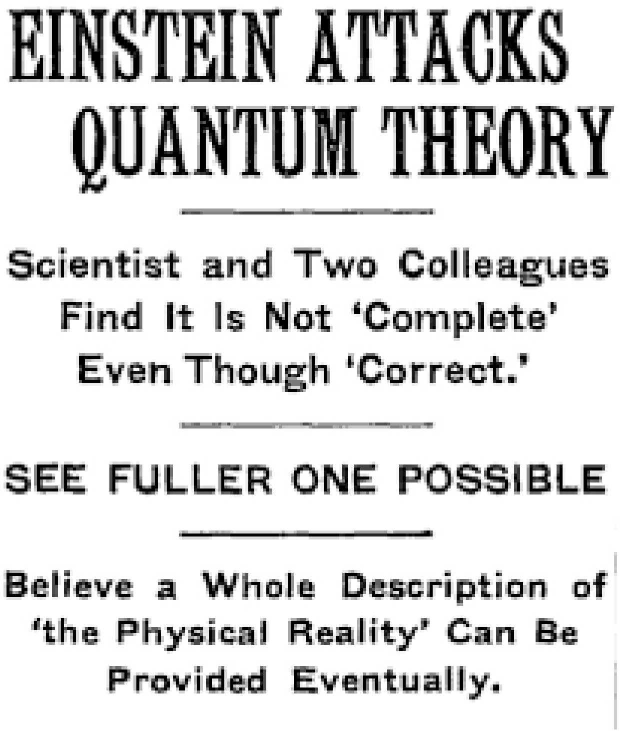

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

(New York Times, 4 May, 1935)

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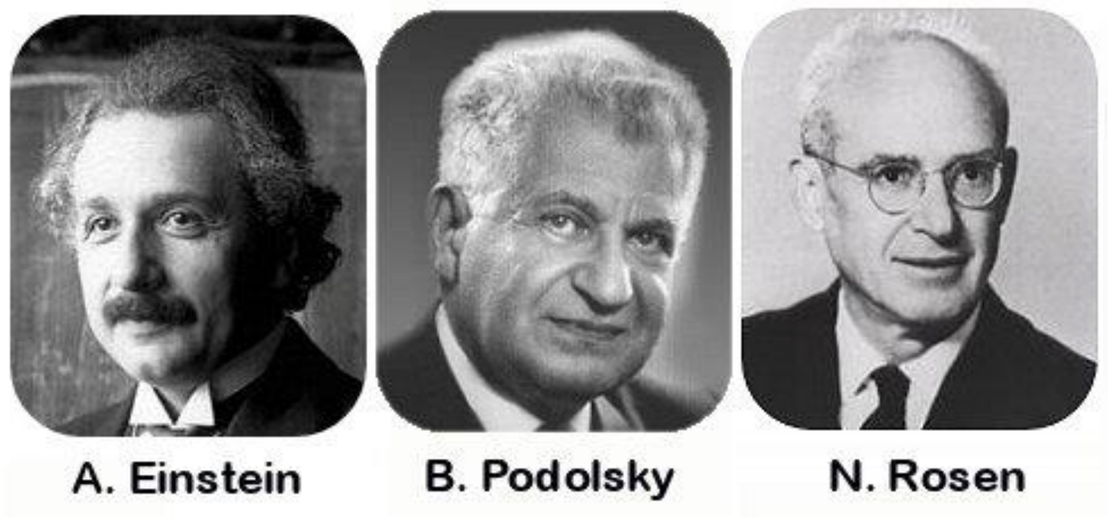
The EPR Paradox

The EPR Paradox (1935)

EPR = Albert Einstein,
Boris Podolsky,
Nathan Rosen



Bohr *et al.*: Quantum Mechanics:

The wave function can be precisely calculated, but a measurement of ***mutually exclusive quantities*** is driven by pure chance.

Einstein *et al.*: Local Reality:

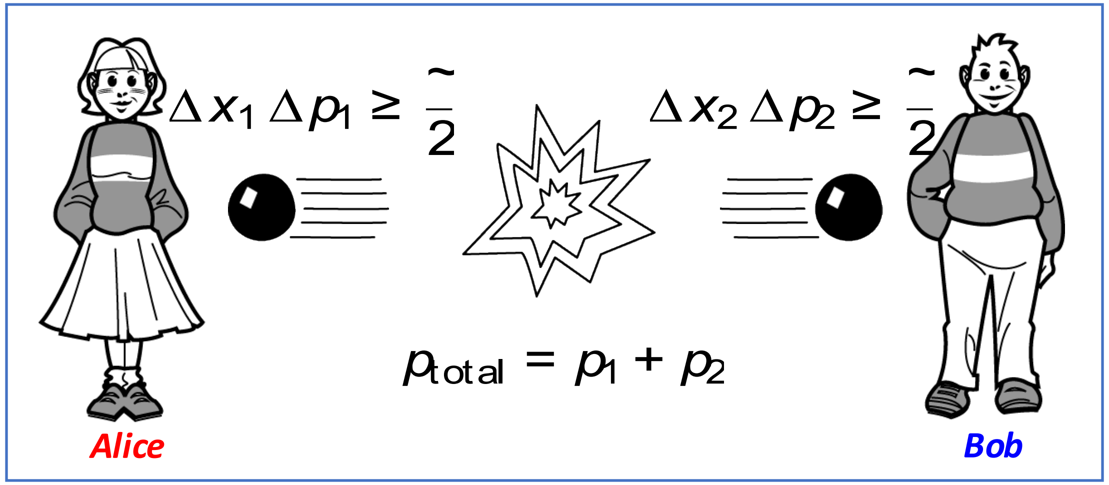
There must exist ***hidden variables*** (hidden to us) in which the outcome of the measurement is encoded such that effectively ***it only looks as*** if it is driven by chance.

Local Realism vs Quantum Entanglement:

EPR: What if the wave function is very large and a measurement at one end can influence the other end via some "***unreasonable spooky interaction***".
Propose a measurement to test ***quantum entanglement*** of particles.

The EPR Paradox – the idea

Two particles produced with known total momentum P_{total}, and fly far away.
Alice ***can not*** measure at the same time position (x_1) and momentum (p_1) of particle 1.
Bob ***can not*** measure at the same time position (x_2) and momentum (p_2) of particle 2.

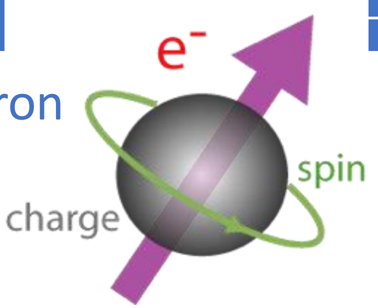


But:

If *Alice* measures p_1, then automatically p_2 is ***known***, since $p_1+p_2= p_{total}$
If *Alice* measures x_1, then p_1 is unknown and therefore also p_2 is ***unknown***.

How can a decision of Alice to measure x_1 or p_1 affect the quantum state of Bob's particle (x_2 or p_2) at the same time over a long distance?
Communication with speed faster than the speed of light? Contradiction with causality?
Is there "local realism" or "spooky action at a distance"?

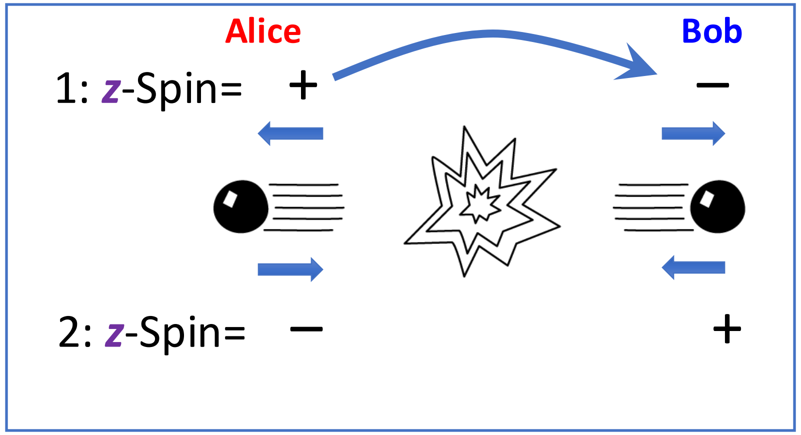
An EPR Experiment with particle "Spin"

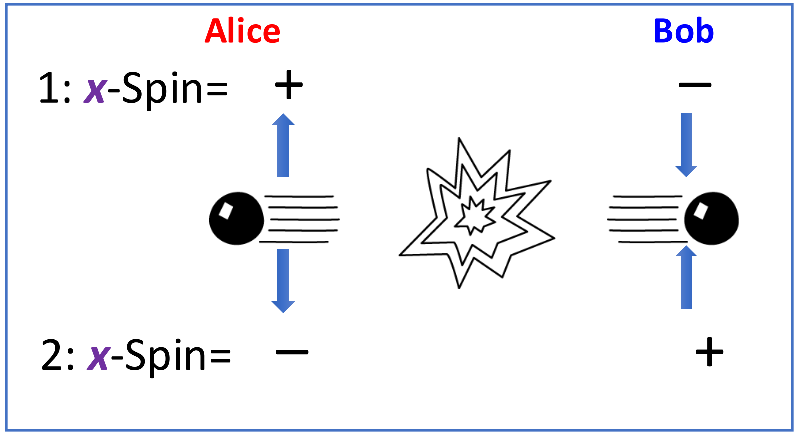


Produce two particles with an opposite ***spin quantum state.*** Heisenberg uncertainty: an electron ***cannot*** have well defined ***spin*** at same time along two different directions, eg. **z** and **x**

spin is quantized and can only have values " + " or " – "

Total spin=0





Total spin=0

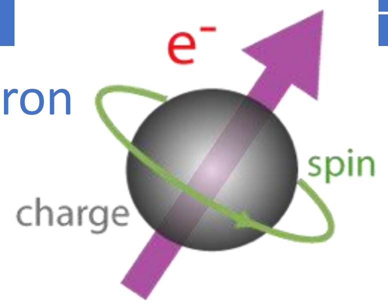
Quantum:

After first measuring ***z***, then the probability of ***+x*** vs ***–x*** = 50%-50%.

After subsequently measuring eg. **+x**, the probability of **+z** vs **–z** = 50%-50% etc.!

Quantum wave function: total spin = 0.
If Alice measures spin of her particle along the **z**-direction,
Then also Bob's particle's spin points (oppositely) along the **z**-direction!

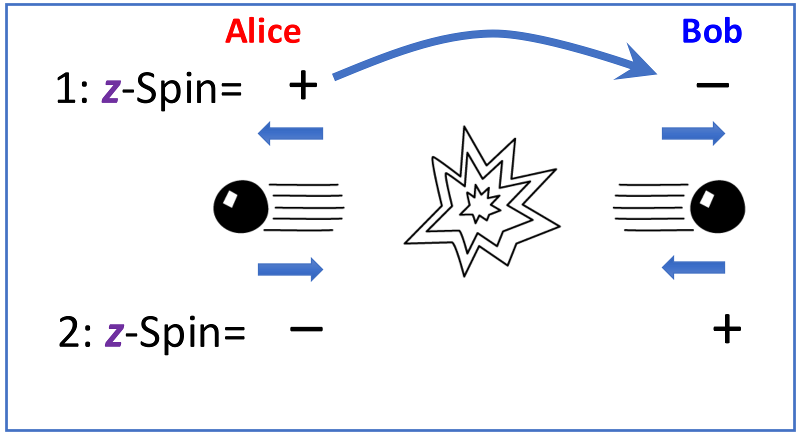
An EPR Experiment with particle "Spin"

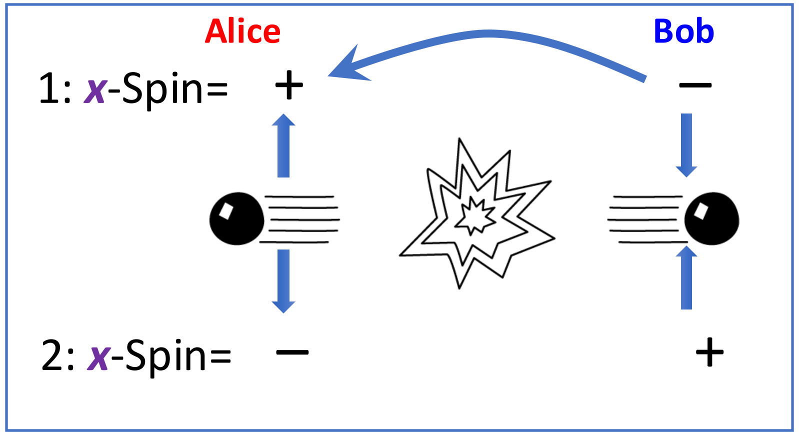


Produce two particles with an opposite ***spin quantum state.*** Heisenberg uncertainty: an electron ***cannot*** have well defined ***spin*** at same time along two different directions, eg. **z** and **x**

But how does Bob's particle know that Alice measures **x**-spin or **z**-spin?

Total spin=0



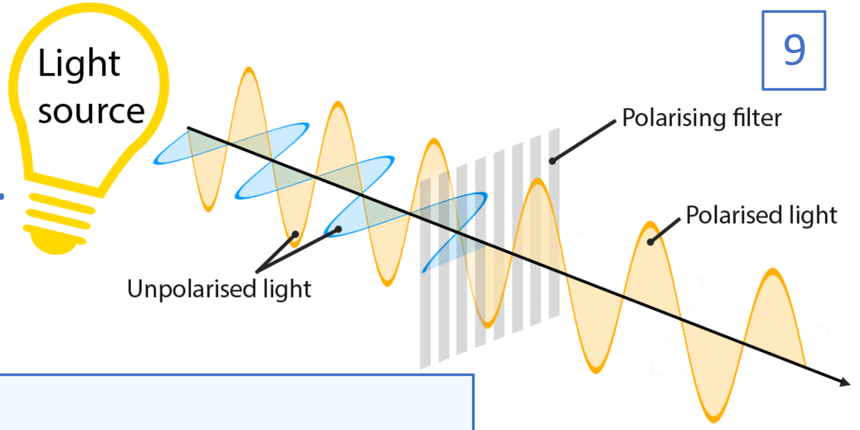


Total spin=0

Trick: if A_z^+ implies B_z^- , then alternatively: B_x^- implies A_x^+
Does the measurement $A_z^+B_x^-$ means that we have determined ***both*** **x** and **z** spin according to $A_z^+A_x^+$?!
(Note that **A** and **B** could have lightyears distance!)
➔Local realism: ***yes!*** ➔QM: ***No!*** (The first measurement "collapses" the wave function: coherence is lost.)

Either the particles are linked because of some ***hidden variable*** (local reality) ***or*** they are QM ***"entangled"*** until a measurement "collapses" the wave function.

Bell inequality – EPR with photons!

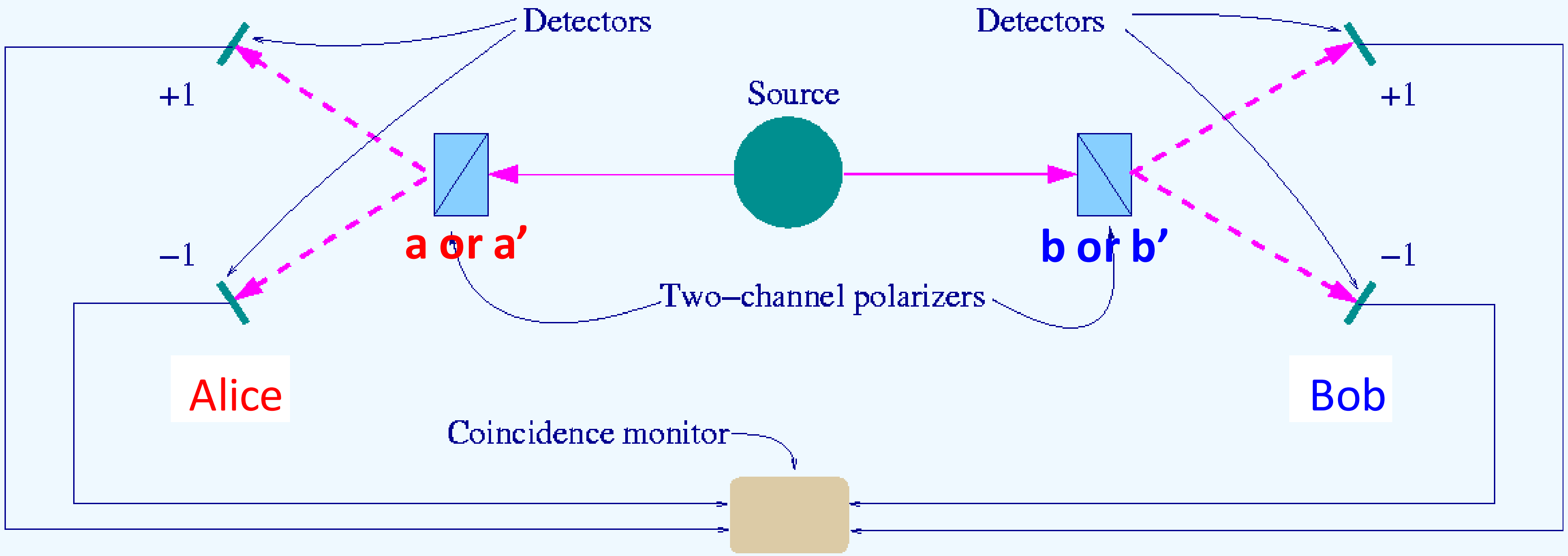


EPR experiment with photons. The ***Bell inequality*** (1964).

Correlation test, count: $E(a,b) = \dfrac{N(+,+) + N(-,-) - N(+,-) - N(-,+)}{N(+,+) + N(-,-) + N(+,-) + N(-,+)}$

"CHSH"

Polarizer settings: a=0° or a'= 45°, b=22.5° or b'= 67.5°



Determine: **S** = E(a,b) – E(a,b') + E(a',b) + E(a',b')

(quantum correlations)

- Local reality (hidden var's) : **S ≤ 2.0**
- Quantum Mechanics : **S = 2.7**

Alain Aspect 1982 – EPR with photons!

$$E(a,b) = \int \underline{A}(a,\lambda)\underline{B}(b,\lambda)\rho(\lambda)d\lambda$$

Alice: $A(a,\lambda) = \pm 1$, Bob: $B(b,\lambda) = \pm 1$ hidden variable: $\rho(\lambda)$

where $\underline{A}$ and $\underline{B}$ are the average values of the outcomes. Since the possible values of A and B are −1, 0 and +1, it follows that:

$$|\underline{A}| \le 1 \quad |\underline{B}| \le 1$$

Then, if a, a', b and b' are alternative settings for the detectors,

$$E(a,b) - E(a,b') = \int [\underline{A}(a,\lambda)\underline{B}(b,\lambda) - \underline{A}(a,\lambda)\underline{B}(b',\lambda)]\,\rho(\lambda)d\lambda$$

$$= \int \underline{A}(a,\lambda)\underline{B}(b,\lambda)\,[1 \pm \underline{A}(a',\lambda)\underline{B}(b',\lambda)]\,\rho(\lambda)d\lambda - \int \underline{A}(a,\lambda)\underline{B}(b',\lambda)\,[1 \pm \underline{A}(a',\lambda)\underline{B}(b,\lambda)]\,\rho(\lambda)d\lambda$$

Taking absolute values of both sides, and applying the triangle inequality to the right-hand side, we obtain

$$|E(a,b) - E(a,b')| \le \left|\int \underline{A}(a,\lambda)\underline{B}(b,\lambda)\,[1 \pm \underline{A}(a',\lambda)\underline{B}(b',\lambda)]\,\rho(\lambda)d\lambda\right| + \left|\int \underline{A}(a,\lambda)\underline{B}(b',\lambda)\,[1 \pm \underline{A}(a',\lambda)\underline{B}(b,\lambda)]\,\rho(\lambda)d\lambda\right|$$

We use the fact that $[1 \pm \underline{A}(a',\lambda)\underline{B}(b',\lambda)]\,\rho(\lambda)$ and $[1 \pm \underline{A}(a',\lambda)\underline{B}(b,\lambda)]\,\rho(\lambda)$ are both non-negative to rewrite the right-hand side of this as

$$\int |\underline{A}(a,\lambda)\underline{B}(b,\lambda)|\,|[1 \pm \underline{A}(a',\lambda)\underline{B}(b',\lambda)]\,\rho(\lambda)d\lambda| + \int |\underline{A}(a,\lambda)\underline{B}(b',\lambda)|\,|[1 \pm \underline{A}(a',\lambda)\underline{B}(b,\lambda)]\,\rho(\lambda)d\lambda|$$

By (4), this must be less than or equal to

$$\int [1 \pm \underline{A}(a',\lambda)\underline{B}(b',\lambda)]\,\rho(\lambda)d\lambda + \int [1 \pm \underline{A}(a',\lambda)\underline{B}(b,\lambda)]\,\rho(\lambda)d\lambda$$

which, using the fact that the integral of ρ(λ) is 1, is equal to

$$2 \pm \left[\int \underline{A}(a',\lambda)\underline{B}(b',\lambda)\rho(\lambda)d\lambda + \int \underline{A}(a',\lambda)\underline{B}(b,\lambda)\rho(\lambda)d\lambda\right]$$

which is equal to $2 \pm [E(a',b') + E(a',b)]$.

Putting this together with the left-hand side, we have:

$$|E(a,b) - E(a,b')| \le 2 \pm [E(a',b') + E(a',b)]$$

which means that the left-hand side is less than or equal to both $2 + [E(a',b') + E(a',b)]$ and $2 - [E(a',b') + E(a',b)]$. That is:

$$|E(a,b) - E(a,b')| \le 2 - |E(a',b') + E(a',b)|$$

from which we obtain

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(by the triangle inequality again), which is the CHSH inequality.

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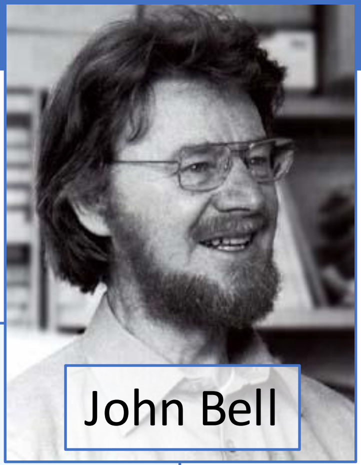
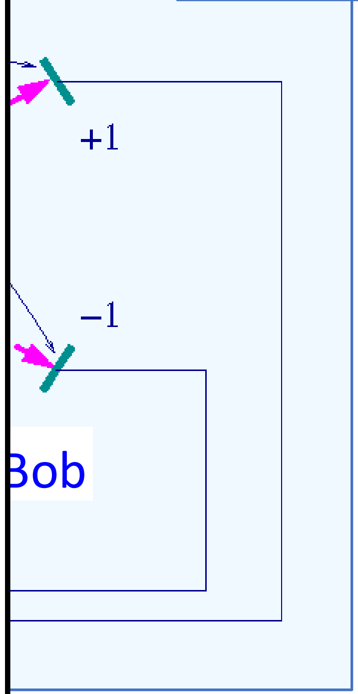


1964



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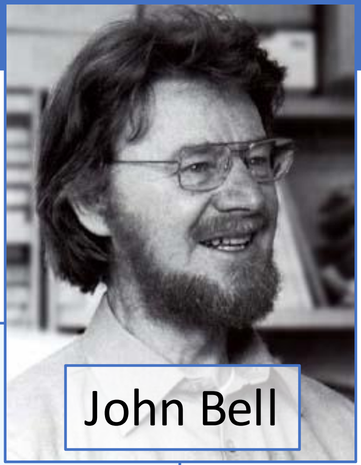

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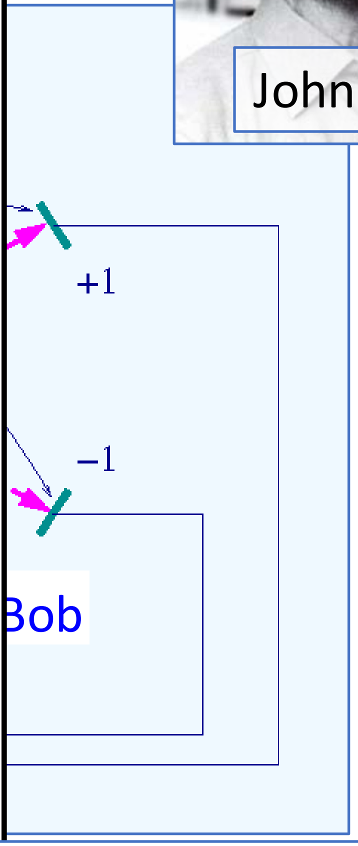

- Local reality (hidden var's) : **S ≤ 2.0**
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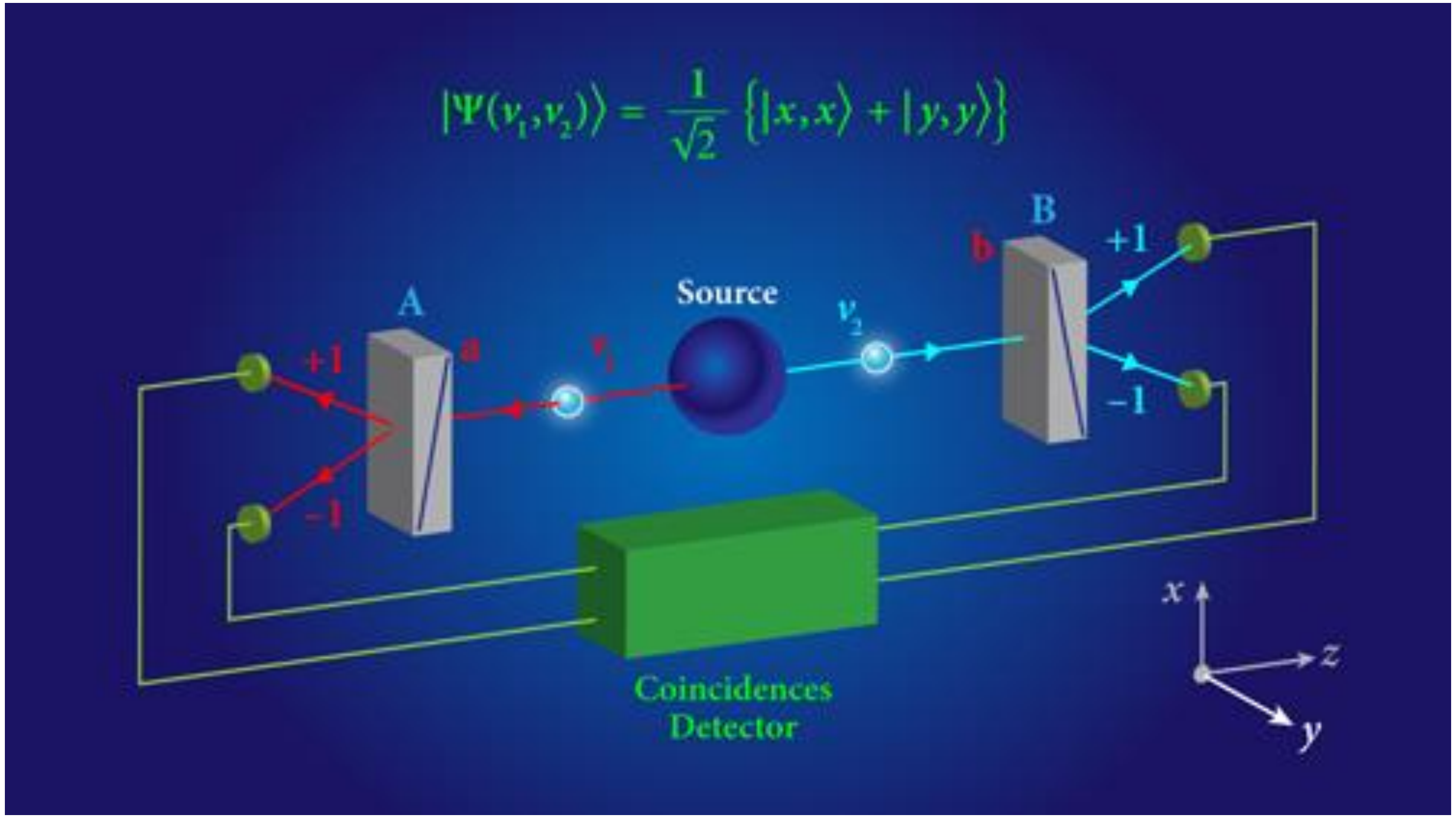
Alain Aspect 1982 – EPR with photons!

EPR experiment with photons. Testing the ***Bell inequality***.

Correlation test, count: $E(a,b) = \dfrac{N(+,+) + N(-,-) - N(+,-) - N(-,+)}{N(+,+) + N(-,-) + N(+,-) + N(-,+)}$



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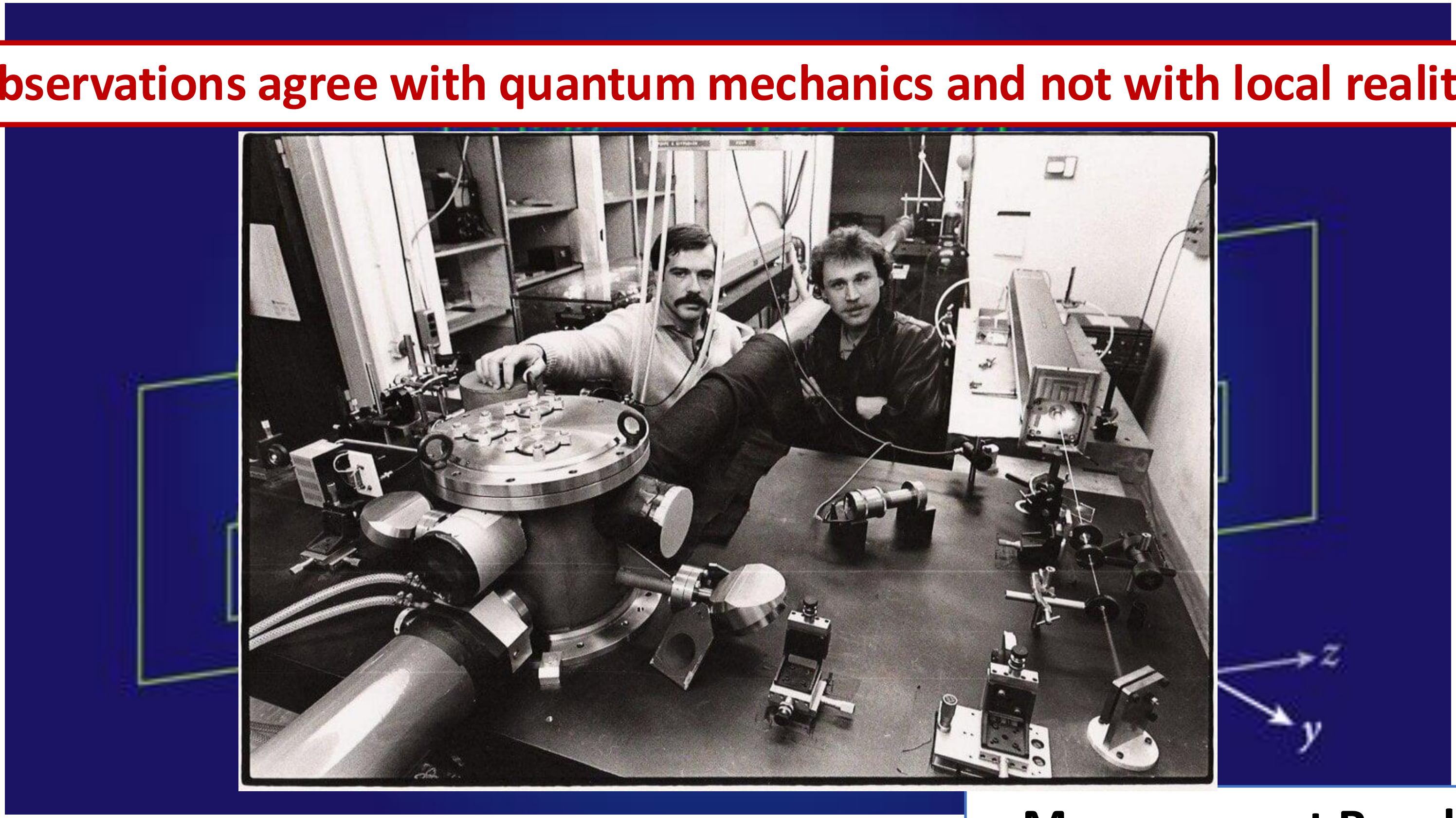
Observations agree with quantum mechanics and not with local reality!



Determine: $\mathbf{S} = E(a,b) - E(a,b') + E(a',b) + E(a',b')$

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- **Measurement Result** : **S = 2.697 +- 0.015**
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Observations agree with quantum mechanics and not with local reality!

There were two “loopholes” (comments of critics):

1. Locality loophole:
   The particles and detectors were so close to each other that *in principle* they could have communicated with each other during the Bell test.

2. “Detection loophole”:
   The detectors only measured *some* of the entangled particles, and they could be a *non-representative* selection of all.

Determine: $S = E(a,b) - E(a,b') + E(a',b) + E(a',b')$
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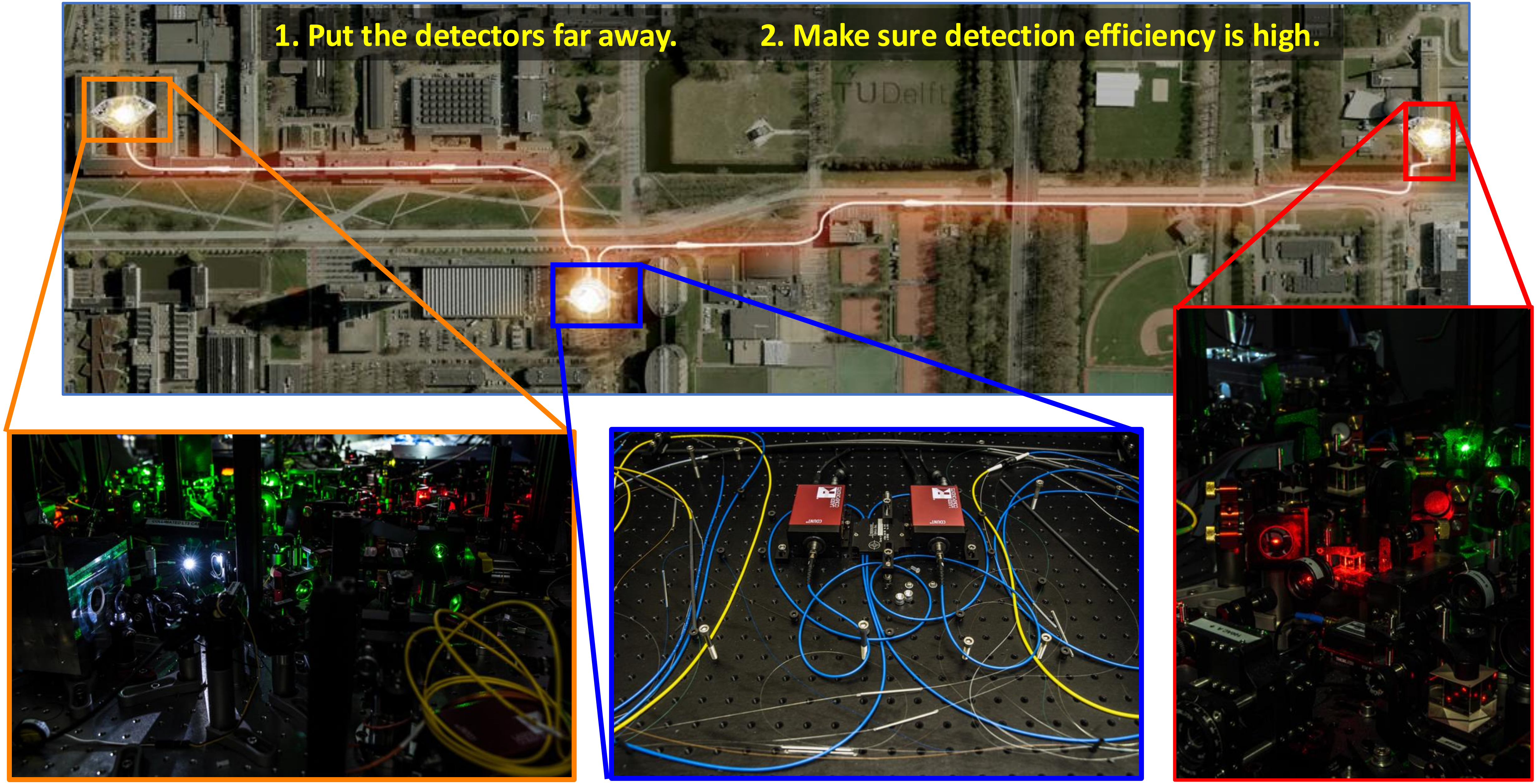
Closing the loopholes: Delft 2015



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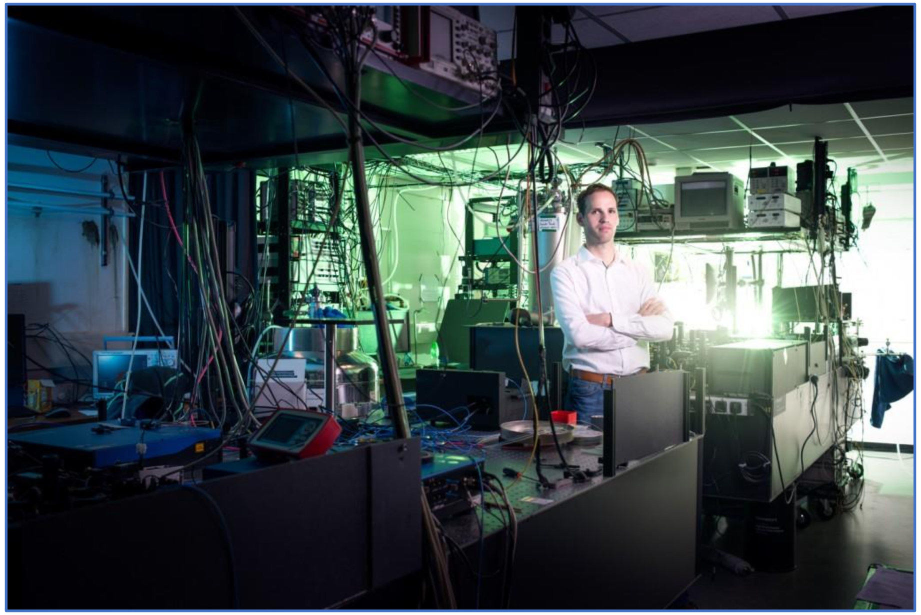
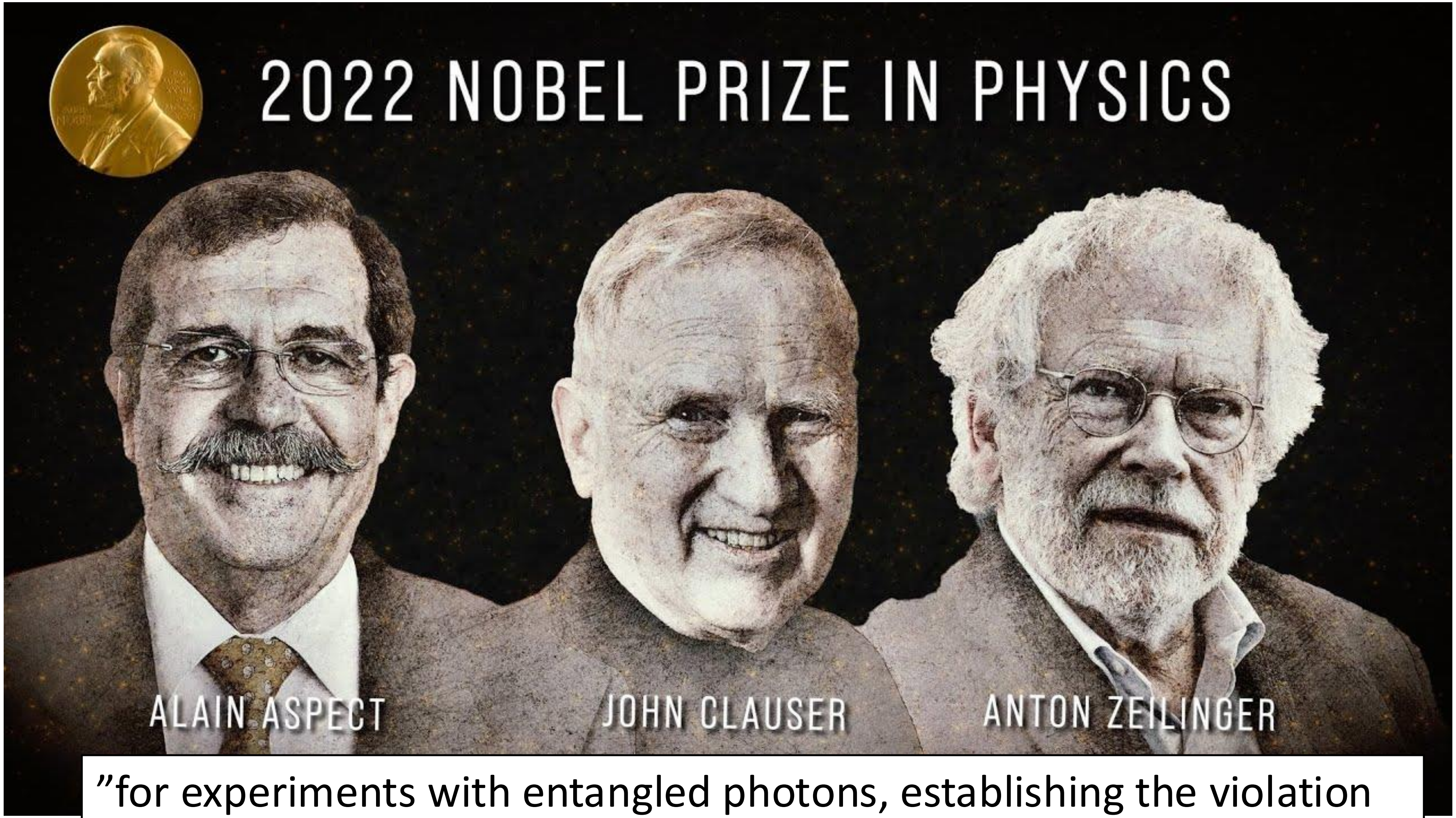


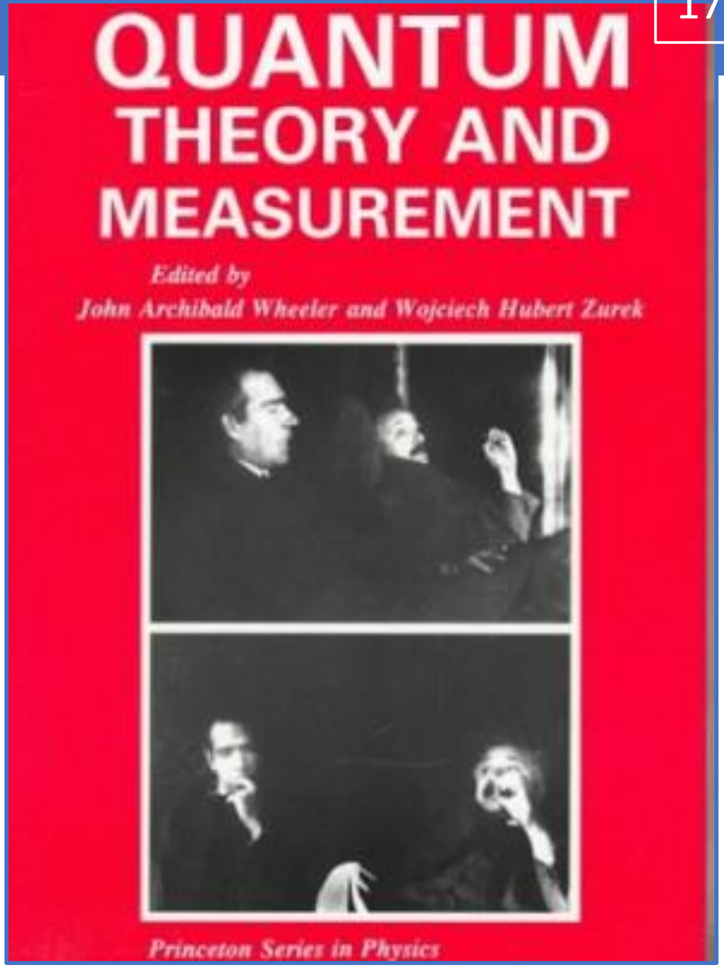
- Ronald Hanson and his group performed the first EPR experiment without loopholes.
- Measurement of photons that are entangled with electron spins.
- **Quantum entanglement again passes the test.**
- ➔ ***No hidden variables!***

2022 Nobel Prize



”for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”

Interpretations of Quantum Mechanics



The Wave function.

- ***ψ(x,t)*** contains all information of a system (eg. electron).
- Wave function includes the fundamental laws of physics and describes all types of matter particles and their interactions

Copenhagen Interpretation.

- There is ***no physical interpretation*** for the wave function.
- As long as ***no measurement*** is done the ***wave-function includes all possible outcomes***. **"Nature tries everything".**
- When a measurement is done, nature realizes one of the possibilities by the ***collapse of the wavefunction*** (particle or wave, ***x*** or ***p***, $\boldsymbol{\sigma_x}$ or $\boldsymbol{\sigma_z}$) according to probabilistic laws. **"Nothing exists until it is measured".**

The Measurement Problem.

- ***But what is a measurement?*** Is it an irreversible process? Does it require consciousness?
- There are many interpretations apart from the Copenhagen Interpretation.
  - Objective collapse theory, consciousness causes collapse, Bohm's pilot-wave, QBism, many worlds, many minds, participatory anthropic principle, quantum information ("it from bit"), …

Quantum Interpretations

Is the wave function physical?
Does is collapse?
What is a measurement?

Copenhagen (Bohr): “pragmatic”, but perhaps incomplete? Not deterministic.

Many worlds (Everett III) : universal wave function exists, but no collapse. Local theory. Deterministic.

Pilot waves (Bohm): wave function exists and guides particles. Hidden variables. Non-local. Deterministic.

Objective collapse (Penrose): wave function is real and testable. Not deterministic.

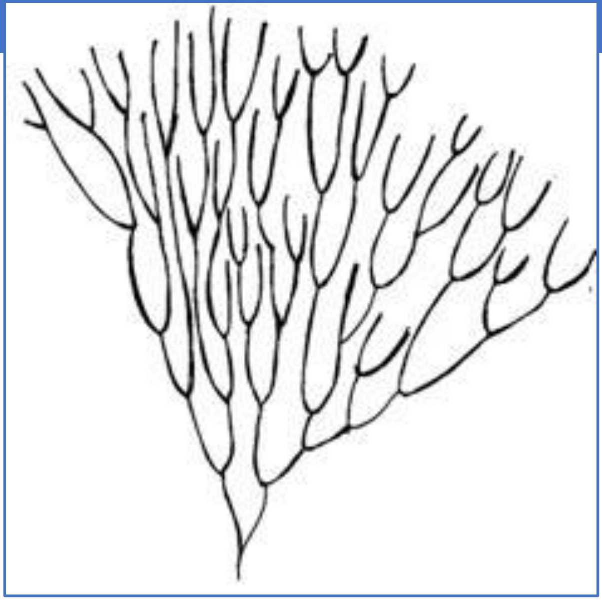
Qbism (Fuchs, Schack): wave function not physical. Encodes subjective believe (“Baysianism”). Not deterministic.

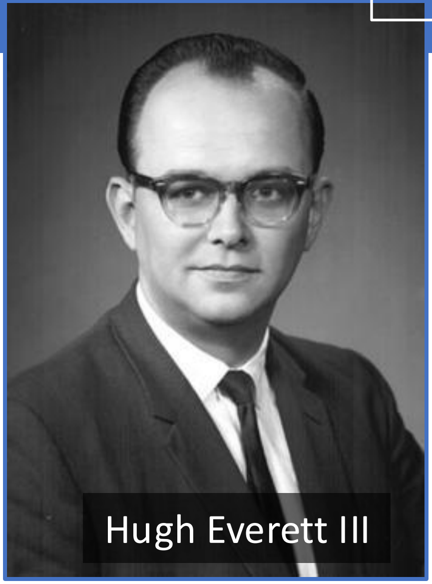
Relational Quantum Mechanics (Rovelli) Quantum state not absolute but relative to observer. Not deterministic.

Interpre-tation	Year pub-lished	Author(s)	Determ-inistic?	Ontic wave-function?	Unique history?	Hidden variables?	Collapsing wave-functions?	Observer role?	Local dyna-mics?	Counter-factually definite?	Extant universal wave-function?
Ensemble interpretation	1926	Max Born	Agnostic	No	Yes	Agnostic	No	No	No	No	No
Copenhagen interpretation	1927	Niels Bohr, Werner Heisenberg	No	Some[59]	Yes	No	Some[60]	No[61][62]	Yes	No	No
De Broglie–Bohm theory	1927–1952	Louis de Broglie, David Bohm	Yes	Yes[a]	Yes[b]	Yes	Phenomen-ological	No	No	Yes	Yes
Quantum logic	1936	Garrett Birkhoff	Agnostic	Agnostic	Yes[c]	No	No	Interpre-tational[d]	Agnostic	No	No
Time-symmetric theories	1955	Satosi Watanabe	Yes	No	Yes	Yes	No	No	No[63]	No	Yes
Many-worlds interpretation	1957	Hugh Everett	Yes	Yes	No	No	No	No	Yes	Ill-posed	Yes
Consciousness causes collapse	1961–1993	John von Neumann, Eugene Wigner, Henry Stapp	No	Yes	Yes	No	Yes	Causal	No	No	Yes
Many-minds interpretation	1970	H. Dieter Zeh	Yes	Yes	No	No	No	Interpre-tational[e]	Yes	Ill-posed	Yes
Consistent histories	1984	Robert B. Griffiths	No	No	No	No	No[f]	No[g]	Yes	No	Yes
Transactional interpretation	1986	John G. Cramer	No	Yes	Yes	No	Yes[h]	No	No[i]	Yes	No
Objective-collapse theories	1986–1989	Ghirardi–Rimini–Weber, Roger Penrose	No	Yes	Yes	No	Yes	No	No	No	No
Relational interpretation	1994	Carlo Rovelli	No[64]	No	Agnostic[j]	No	Yes[k]	Intrinsic[l]	Possibly[m]	No	No
QBism	2010	Christopher Fuchs, Rüdiger Schack	No	No[n]	Agnostic[o]	No	Yes[p]	Intrinsic[q]	Yes	No	No

Many Worlds Interpretation

Hugh Everett III (PhD Student of John Wheeler) formulated the Many Worlds Interpretation of quantum mechanics in 1957





Multiverse:

Very large tree of quantum worlds for each quantum decision.

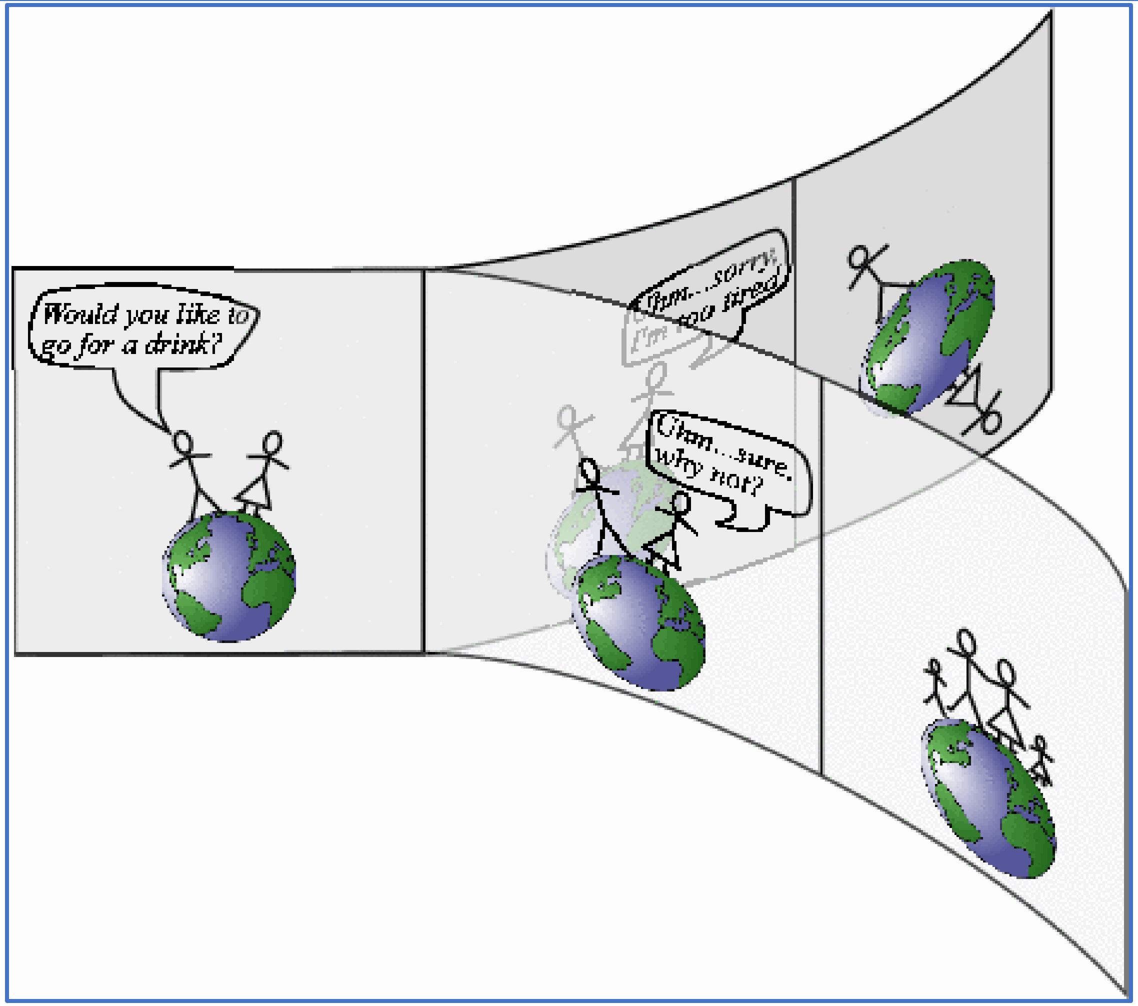
The total wave function of complete multiverse is deterministic.

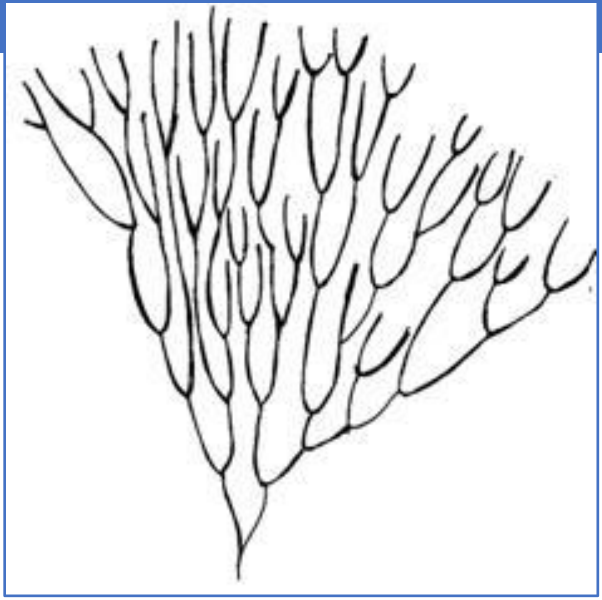
Probability rule $P = |\psi^2|$ follows automatically.

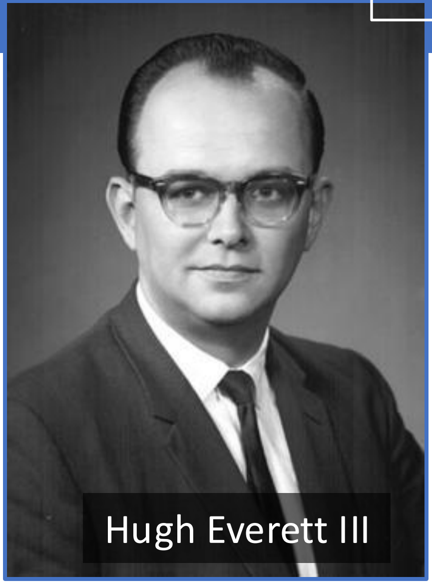
Minimalistic approach: the wave function does ***not*** collapse, but at each quantum measurement ***both states continue to exist in a decoupled world***.

Triggered science fiction stories with “parallel universes”.

Many Worlds Interpretation







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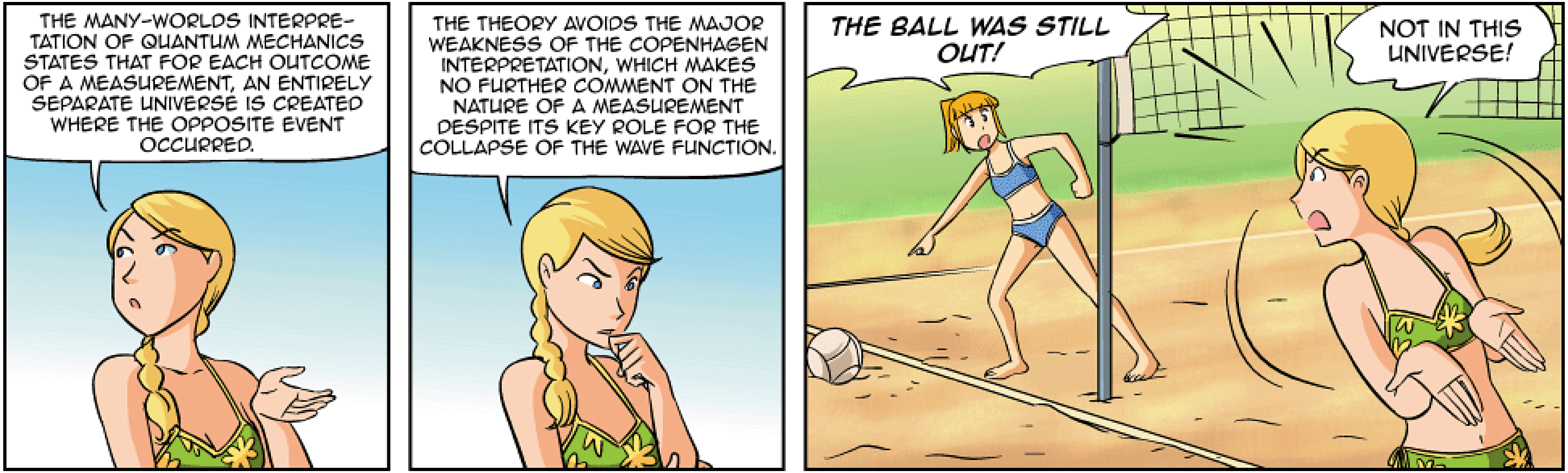
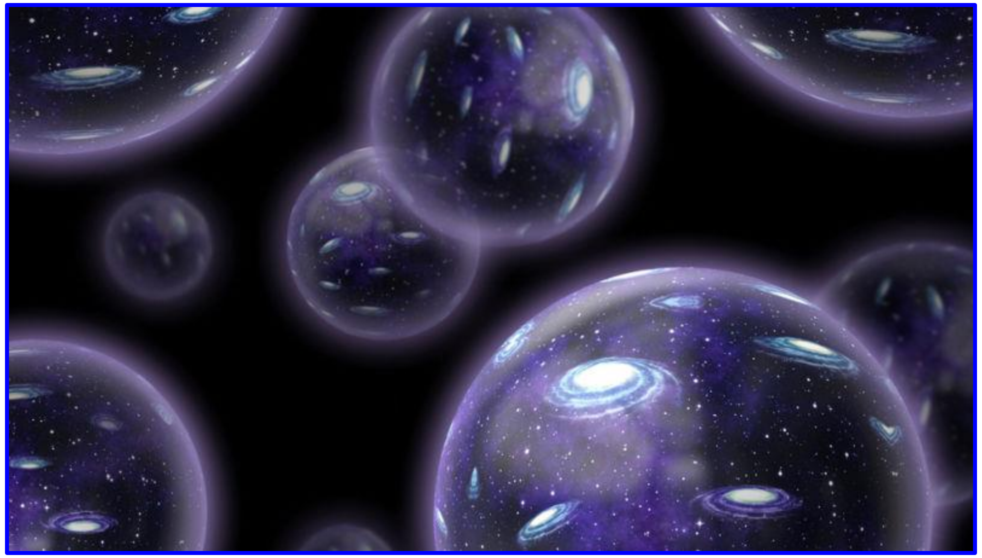


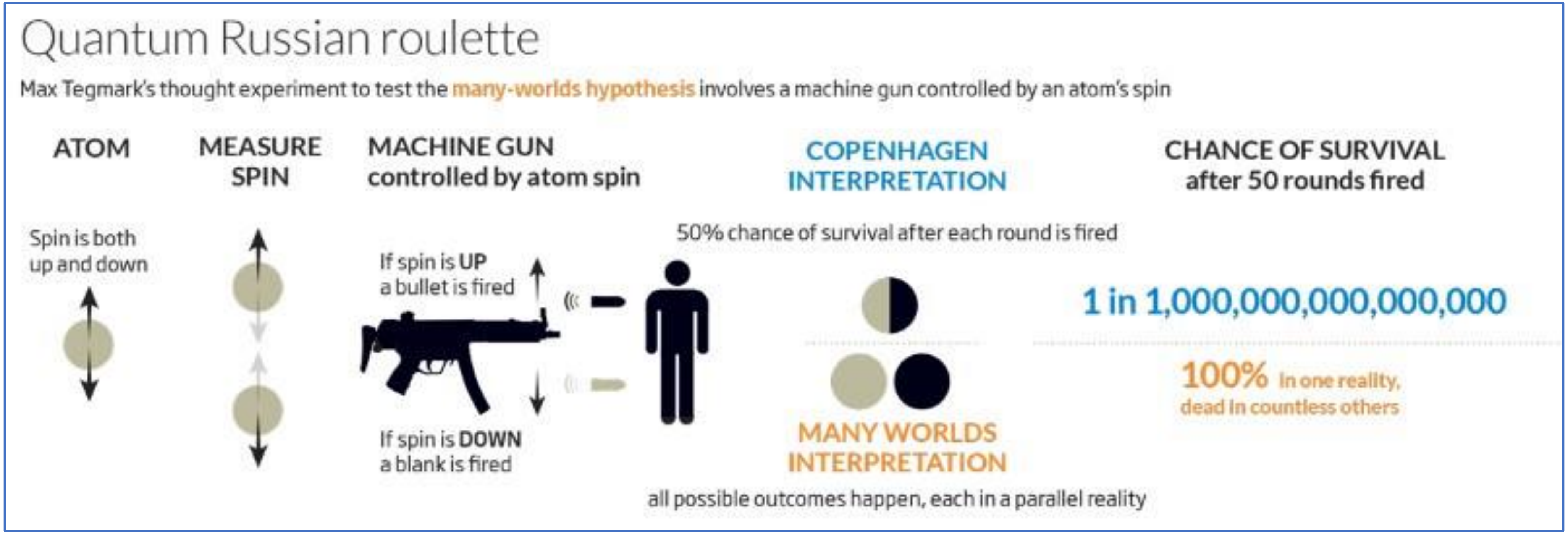
Sandra and Woo by Oliver Knörzer (writer), Powree (artist) and Lisa Moore (colorist) - www.sandraandwoo.com

Many Worlds test

Thought Experiment!!!



- Incredibly many alternative versions of us exist in the multiverse.
- To prove validity of the multiverse:
  - Shoot yourself with 50%-50% quantum probability in russian roulette.
  - Repeat it 50 times.
  - In many worlds survival will ***always*** happen.
  - You will never have the luck to survive in single universe



Many Worlds test

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universe

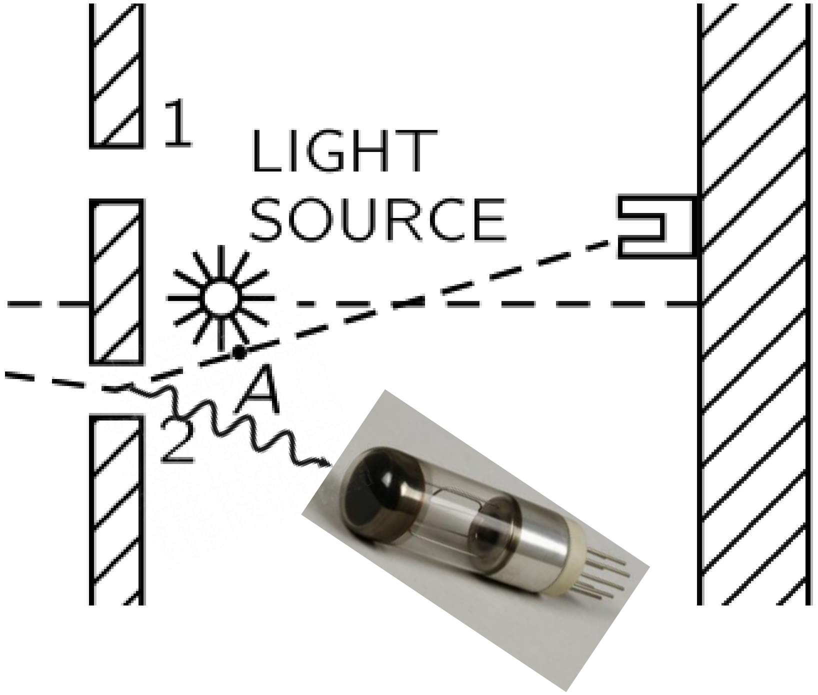
The Many World Interpretation seems a far-fetched view of our existence.
But I think it is one of the simpler and more elegant interpretations!

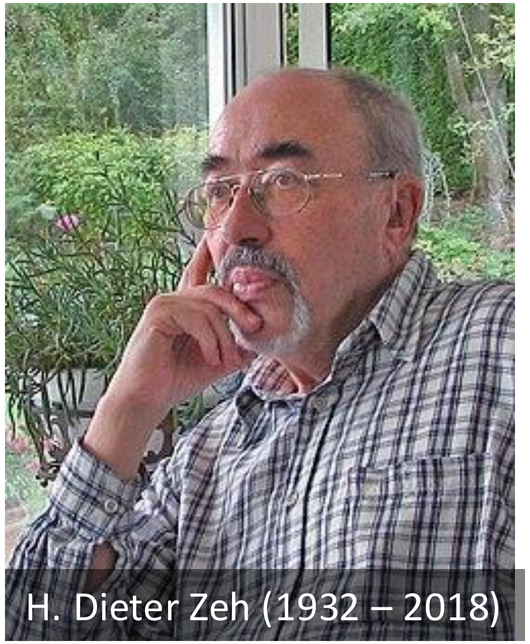
→ It avoids the collapse of the wave function
→ It explains Born's probability rule: $P = |\psi|^2$

Many physicists consider such interpretations outside physics.

Modern view of Measurement: Decoherence

Heinz Dieter Zeh (1970) and Wojciech Zurek (1981):
Decoherence explains how quantum systems evolve into classical systems by interactions with the environment.




H. Dieter Zeh (1932 – 2018)


Wojciech Zurek (1951)

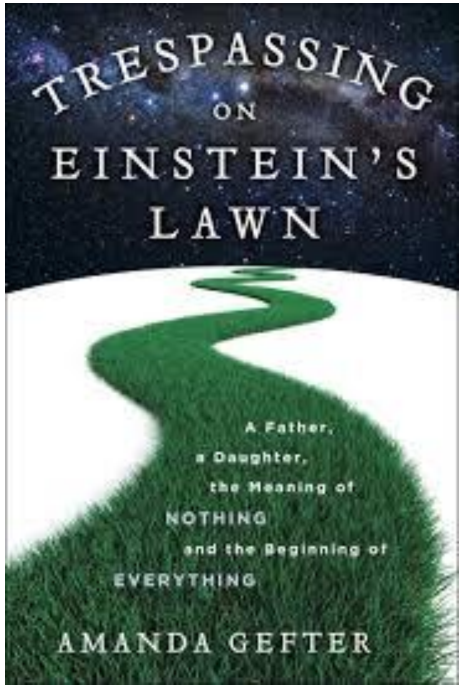
Measurement: interaction of electron with macroscopic object is an *irreversible* act. Information is dispersed in the environment and cannot be reversed.

Double slit experiment: the electron is not allowed to interact during its flight. For example, if the volume is not high vacuum, the interference pattern will disappear.

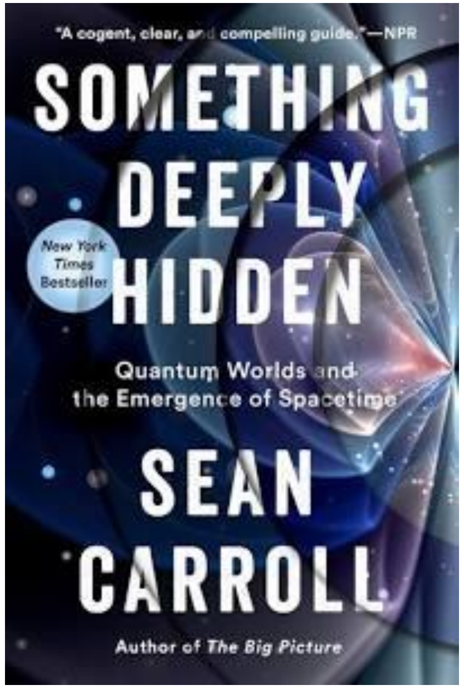
Decoherence does not explain the probability aspect of a measurement nor wave function collapse.
Eg. In many worlds: decoherence provides the *mechanism* of the branching.

Further Reading

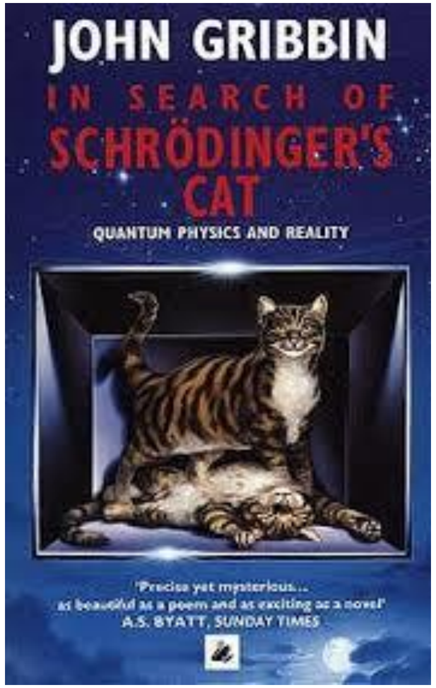
Excellent (in my view) books explaining deep physics without mathematics:



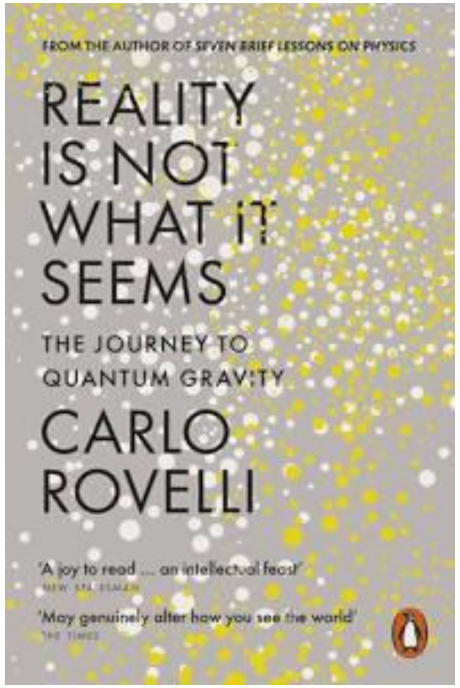
A very well written book from self-made science journalist hunting the "big questions" in fundamental physics physics through discussions with renown scientists.



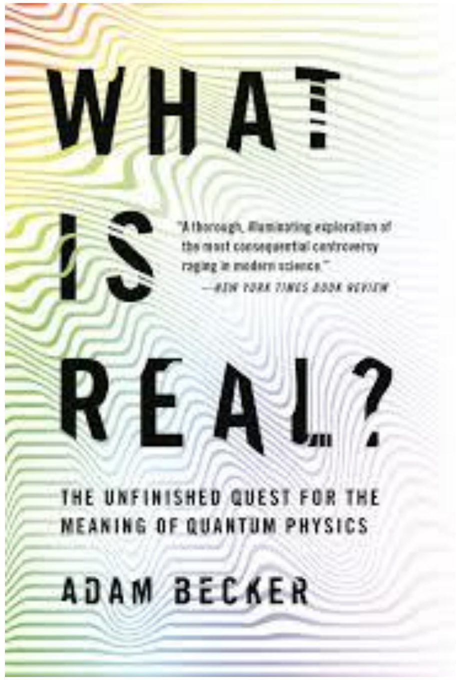
On the interpretation of quantum mechanics: Carrol advocates many worlds interpretation. The text is scientifically precise but still accessible for non-specialists.



A classic reference introducing the world of quantum physics. A bit older book but good overview of the strange aspects of the quantum world.



A somewhat more philosophical view of humanity's quest to understand the universe from relativity, quantum, up to loop quantum gravity.

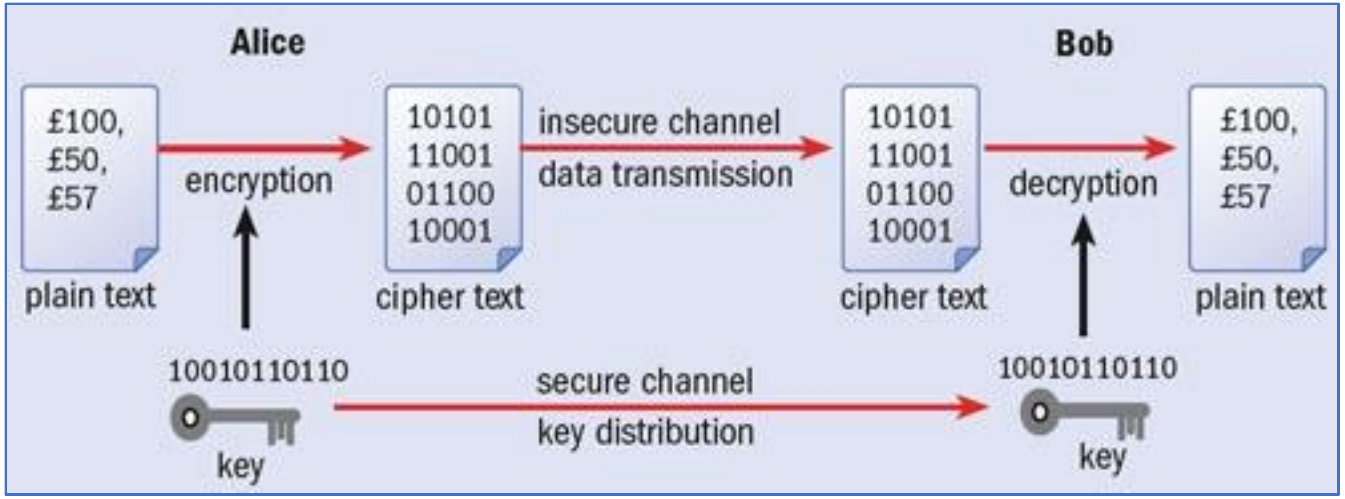


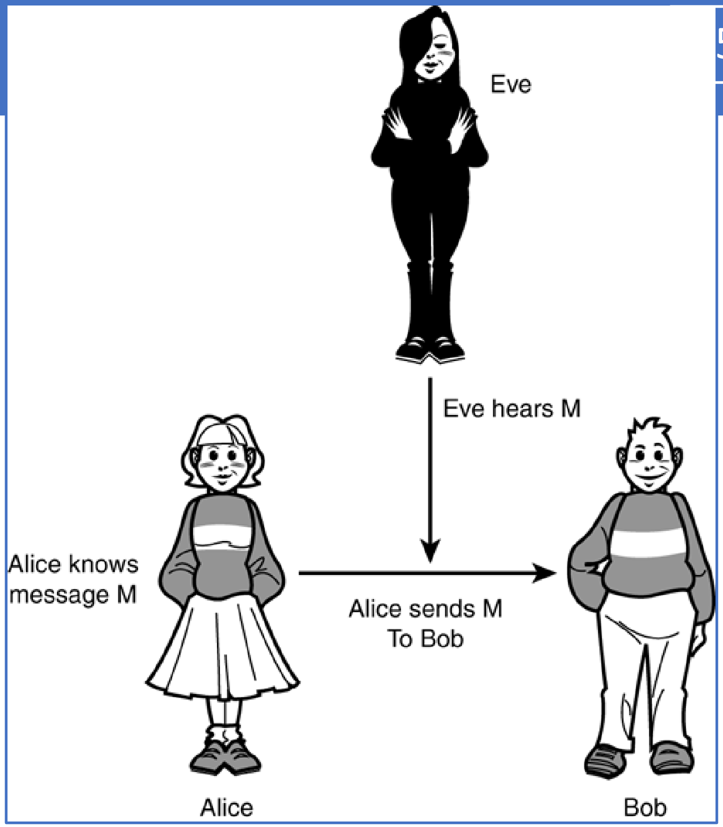
Addressing the debates on quantum inter-pretation challenging the Copenhagen view. A mix of history, philosophy and science communication.

Application 1: Quantum Cryptography

Alice sends a secret message to Bob and prevents Eve to eavesdrop.

First idea by Stephen Wiesner (1970s), worked out by Bennet (IBM) and Brassard (1980s)
→ BB84 protocol





Quantum Key Distribution (QKD):

1. Public Channel (Internet, email):
   send an encrypted message.
2. Quantum Channel (Laser + fiber optics)
   send key to decode the public message
3. Eve cannot secretly eavesdrop. She destroys quantum information and is detected.

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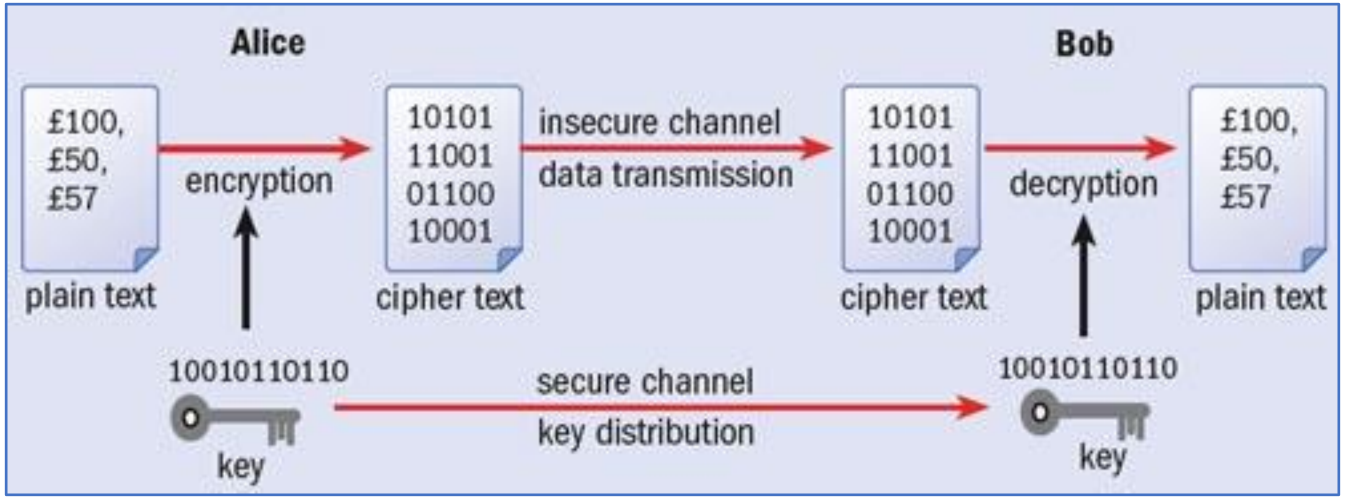

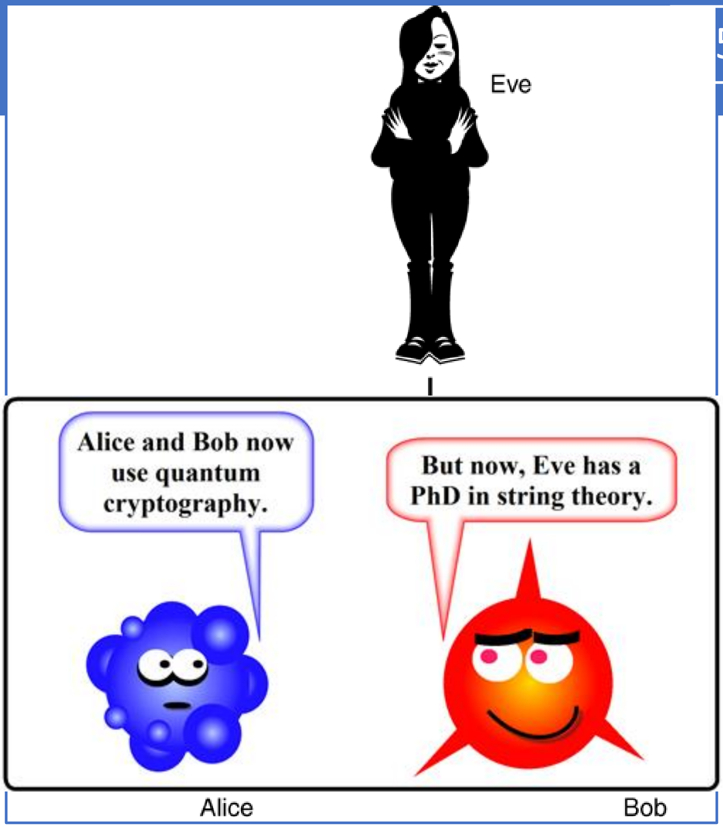

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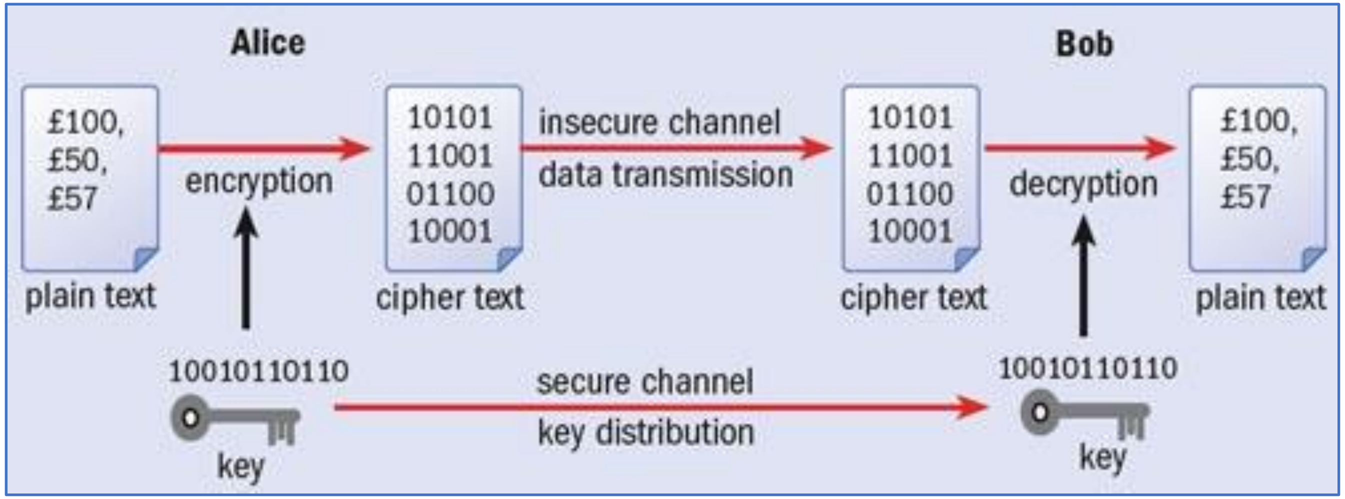

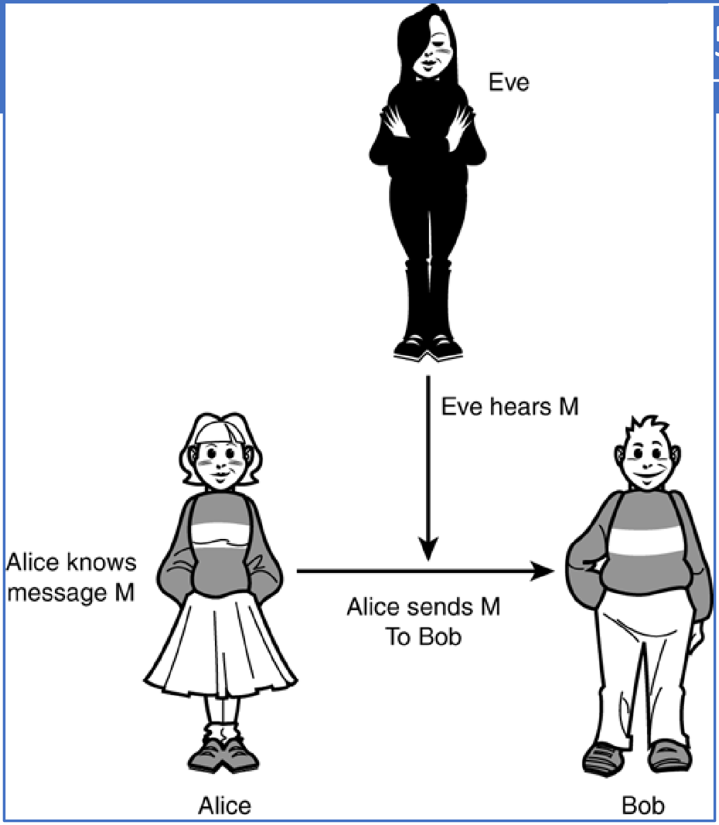

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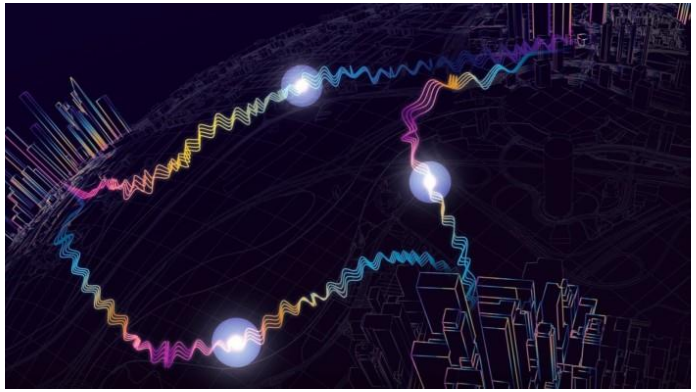
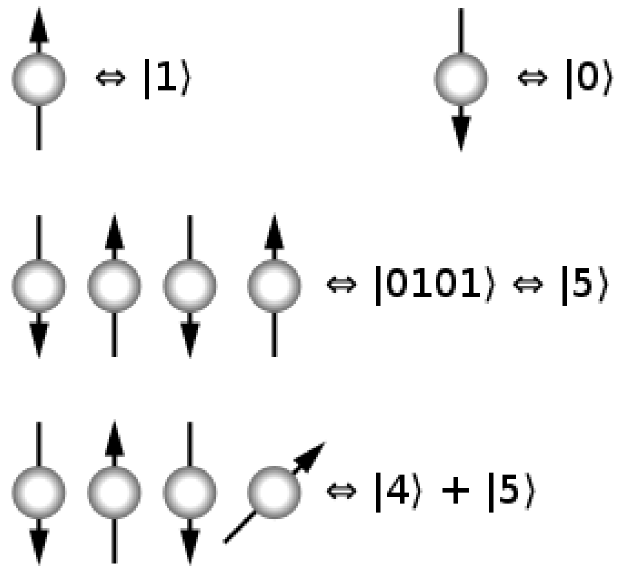
QKD over thousands of kilometers



Application 2: Quantum Computer

<u>Idea</u>: Yuri Manin and Richard Feynman: use superposition and entanglement of quantum states to make a super-fast computer.

Normal computer : bits are either 0 or 1
Quantum computer: qubits are coherent super-positions of states 0 and 1 at the same time.
(Eg. Electron spin up and spin down)



qubits can be in a superposition of all the clasically allowed states

Compute with quantum logic.
With 2 bits it can do 4 calculations simultaneously.
With 3 bits 8 calculations, with n bits 2^n !

Qubit Technologies:

- Josephson circuit: IBM, Google, Rigetti
- Trapped Ion: IonQ, Quantinuum
- Spin Qubits: Intel, Delft/QuTech
- Photonic Qubits: Xanadu, PsiQuantum,
- Neutral Rydberg Atoms: Pascal, QuEra, Eindhoven

Difficulty: prevent "decoherence".

Application 2: Quantum Computer

"Hardware" technological difficulty:

- Prevent "decoherence"
- IBM, Google, Microsoft competing for the largest quantum computers
- Quantinuum has cleanest qubits
- More and more devices publicly available in the cloud

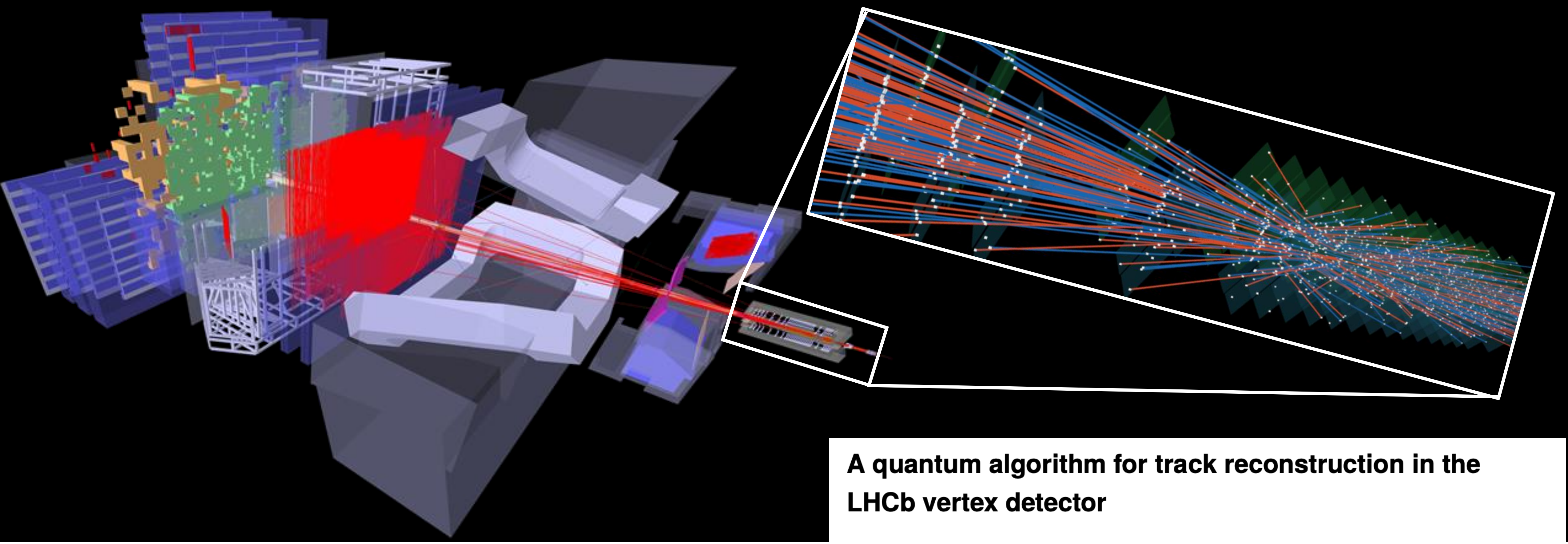
IBM condor:
1121 qubits

Aim for 100,000 qubits in 2033

Software technological difficulty:

- Prepare system in known state
- Let it evolve according to the algorithm into large simultaneous state.
- Correct solution results from constructive interference of states (→ think double slit)
- Only few algorithms recently existed:
  – Shor factorization, Grover's search
- Now a fast developing science in itself!

Personal Involvement at UM



In 2020 started project developing a quantum algorithm for particle reconstruction in colliders

Currently first tests on quantum computers

A quantum algorithm for track reconstruction in the LHCb vertex detector

D. Nicotra,[a] M. Lucio Martinez,[a] J. A. de Vries,[a] M. Merk,[a,b] K. Driessens,[a] R. L. Westra,[a] D. Dibenedetto[a] and D. H. Cámpora Pérez[a]

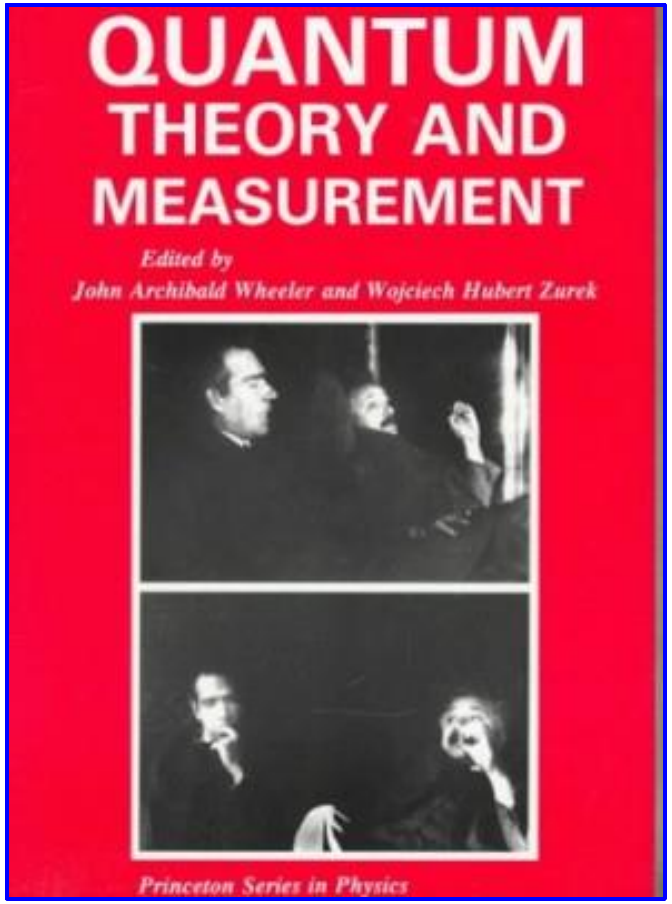
[a] *Universiteit Maastricht, Maastricht, The Netherlands*

[b] *Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands*

E-mail: d.nicotra@maastrichtuniversity.nl

Summary: Quantum Reality and the Measurement Problem

- Quantum reality differs from the classical world.
- Einstein brought a revolutionary way of thinking with relativity theory, but could not accept the revolution of quantum mechanics.
- Bohr never managed to convince Einstein.
- Einstein's objections have been disproven in many tests while the quantum view is always confirmed.
- The Copenhagen interpretation does not provide a meaning for what the wave function is and what the role of the observer (i.e. a measurement) is.



Philosophical:
Would the universe exist if there would be no "observers" to see it?
Is the universe perhaps created by acts of observation?

Summary of the lectures sofar

Relativity theory:

The finite speed of light means that there is no sharp separation between space and time. (Think of different observers)

Universal constant: c = 300 000 km/s

Quantum Mechanics:

The finite value of the quantum of action means that there is no sharp separation between a system and an observer

Universal constant: $\hbar = 6.6262 \times 10^{-34}$ Js

John Wheeler:

“Bohr’s principle of complementarity is the most revolutionary scientific concept of the century.”

Next Week

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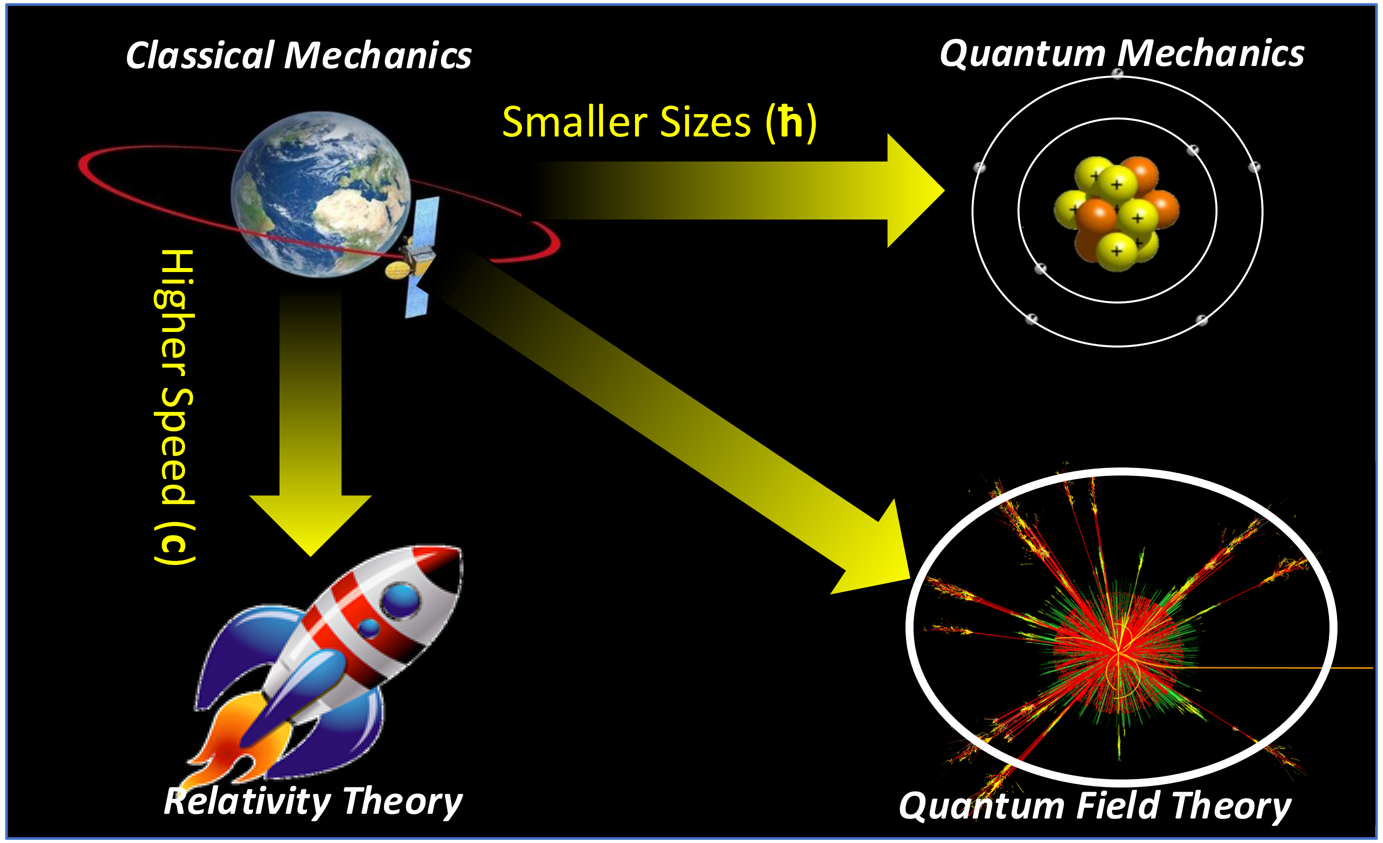
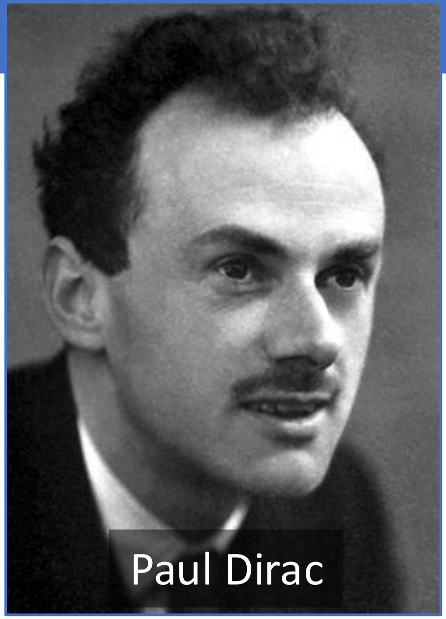
- Matter and Antimatter particles
- Forces and the The Standard Model
- The Large Hadron Collider:
    - Higgs and possible new force?





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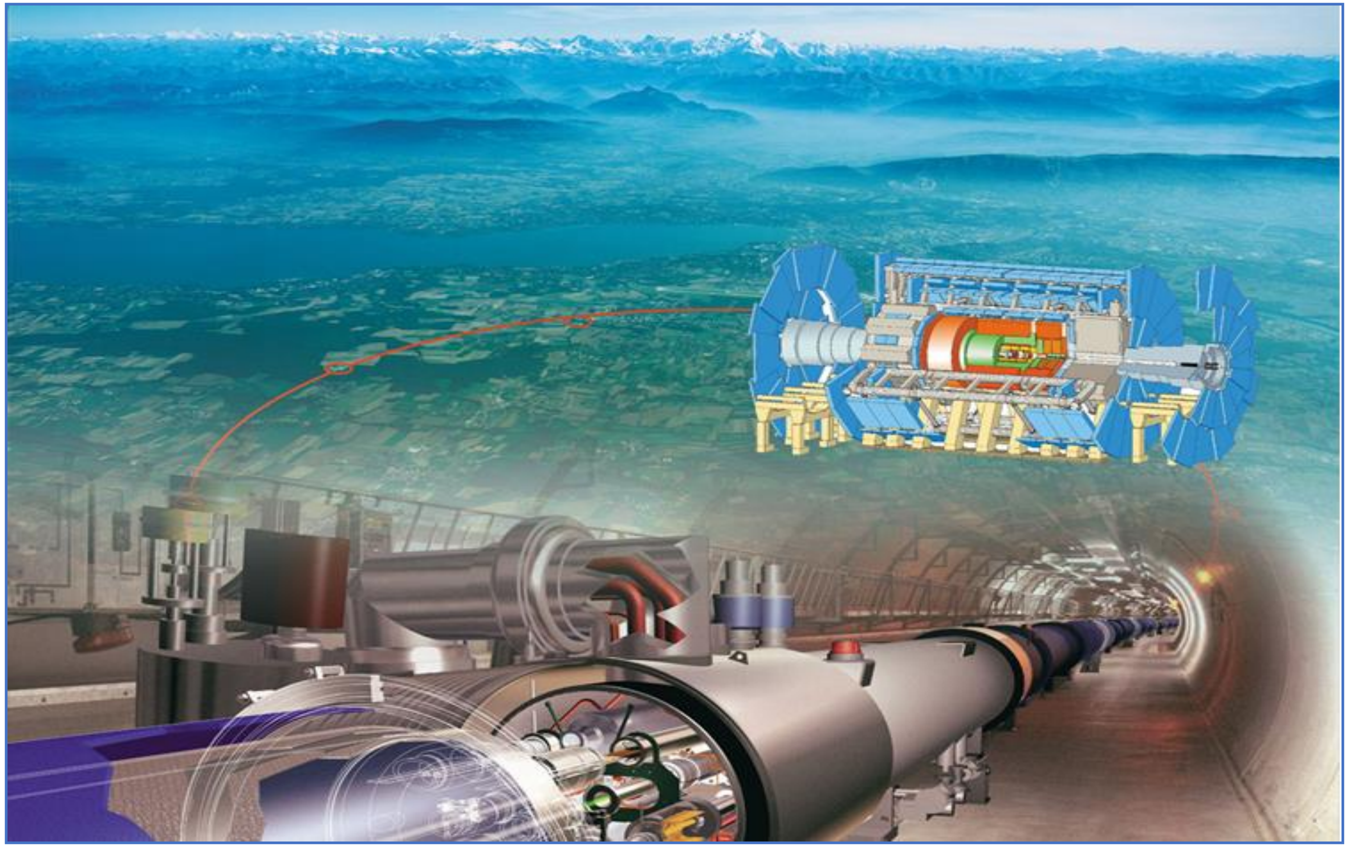

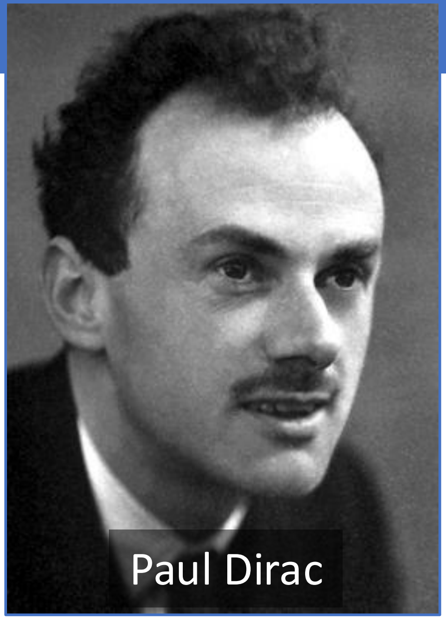
Paul Dirac


Richard Feynman


Francois Englert


Peter Higgs

Perhaps time for…