The Cosmic Bell Experiment

Using Ancient Photons To Test Quantum Theory

— Alan Guth —

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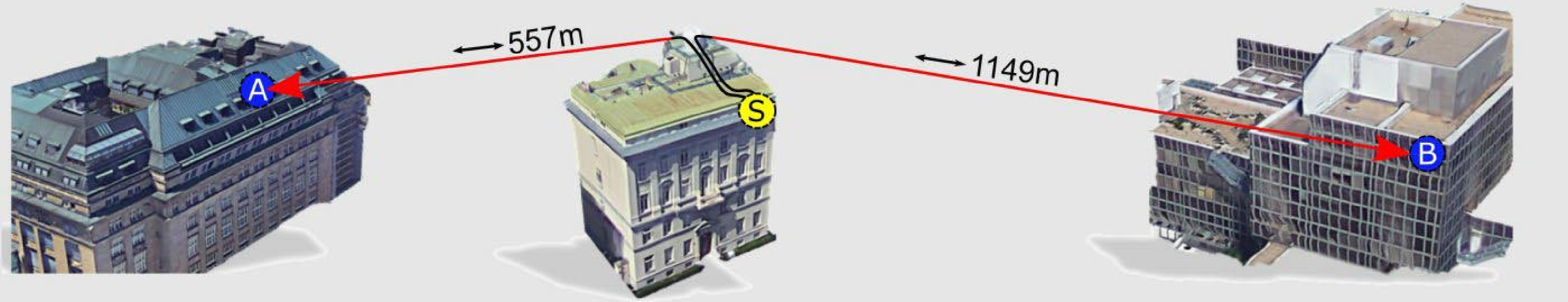

Odd Things about Quantum Mechanics: Abandoning Determinism

- In Newtonian physics, Maxwell theory, Einstein's special or general relativity, if an initial state is completely known, the future can be predicted.
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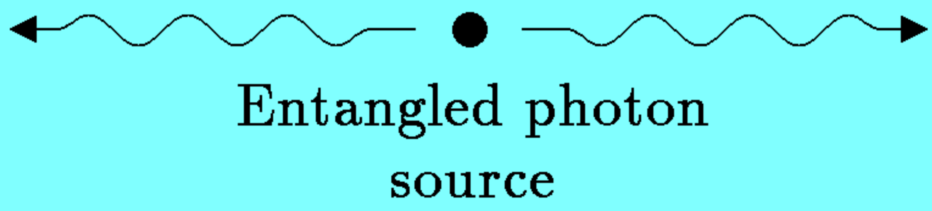
- Einstein strongly objected: "God does not throw dice," he wrote in 1926 in a letter to Max Born.

Odd Things about Quantum Mechanics: Abandoning "Realism"

- "Realism" is the proposition that the properties of a system exist independent of measurement.
- In QM, however, a system is described by a wave function, which can include multiple possibilities. The result of the measurement is not chosen until the measurement happens. As Griffiths puts it, "A particle simply does not *have* a precise position prior to measurement."

Entanglement

Two photons, sent in opposite directions, can be prepared in an *entangled* state:



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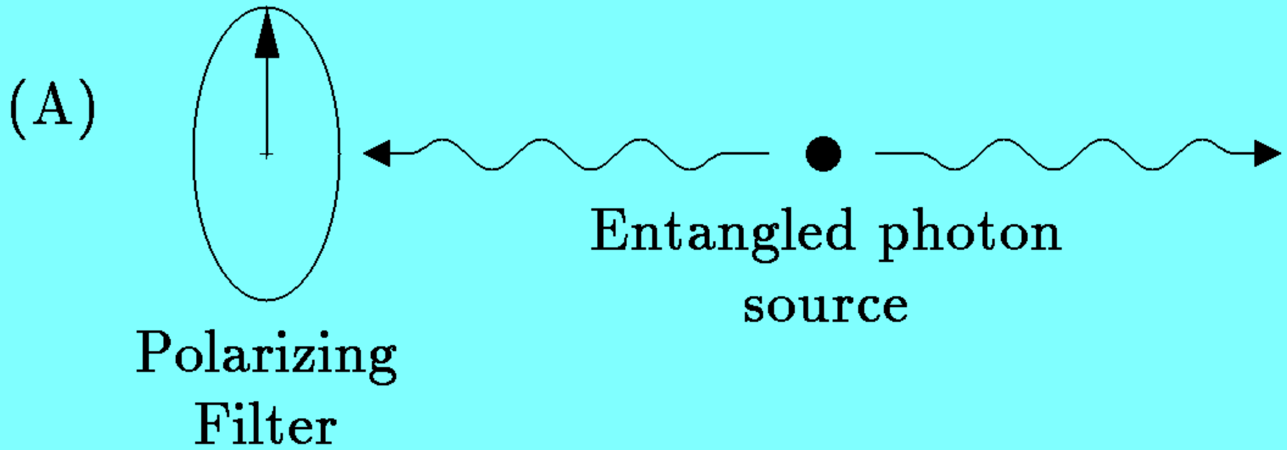

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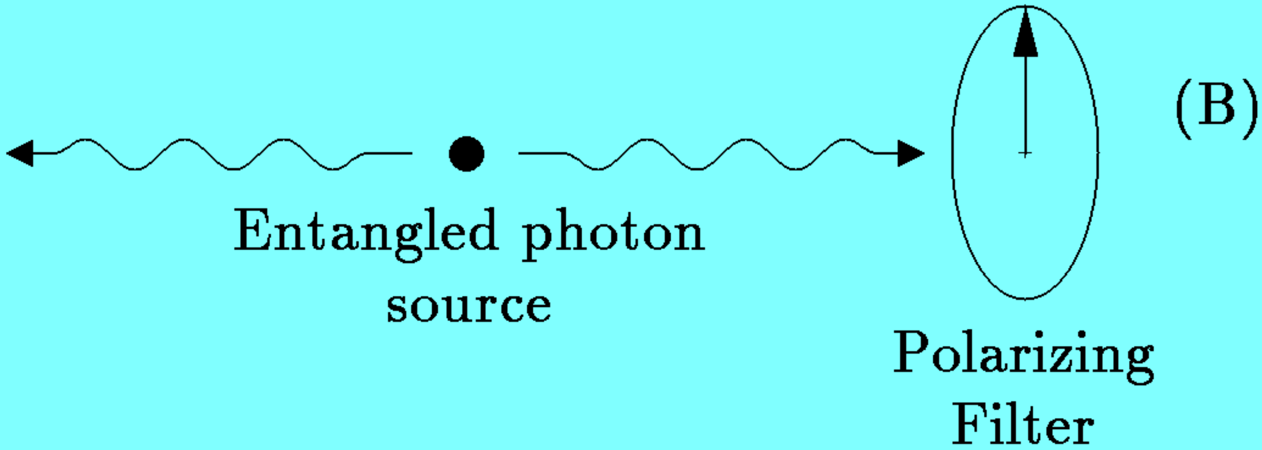

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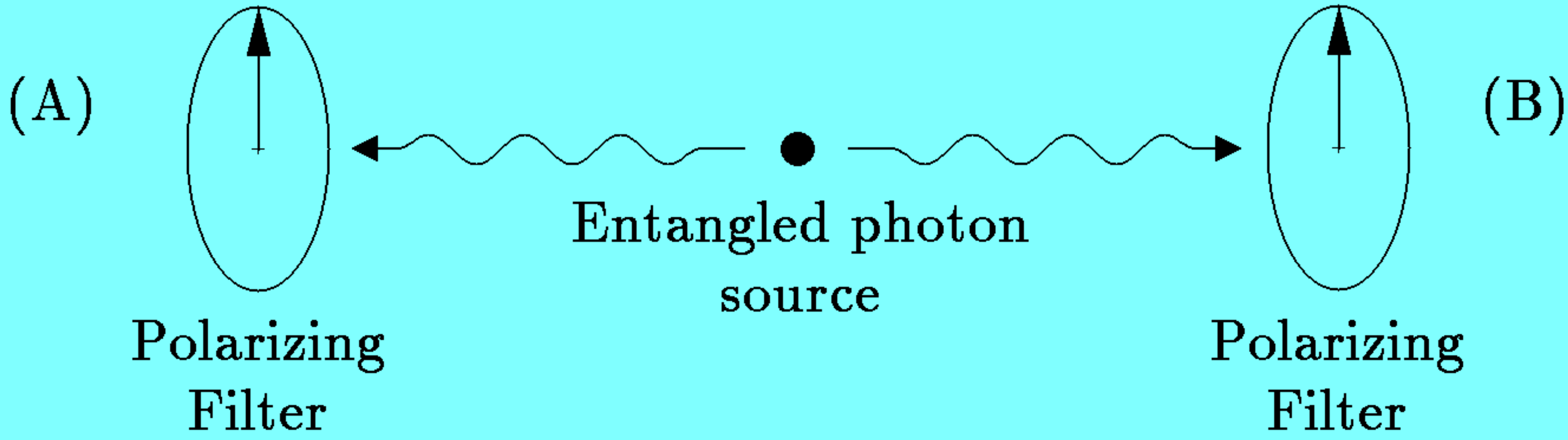

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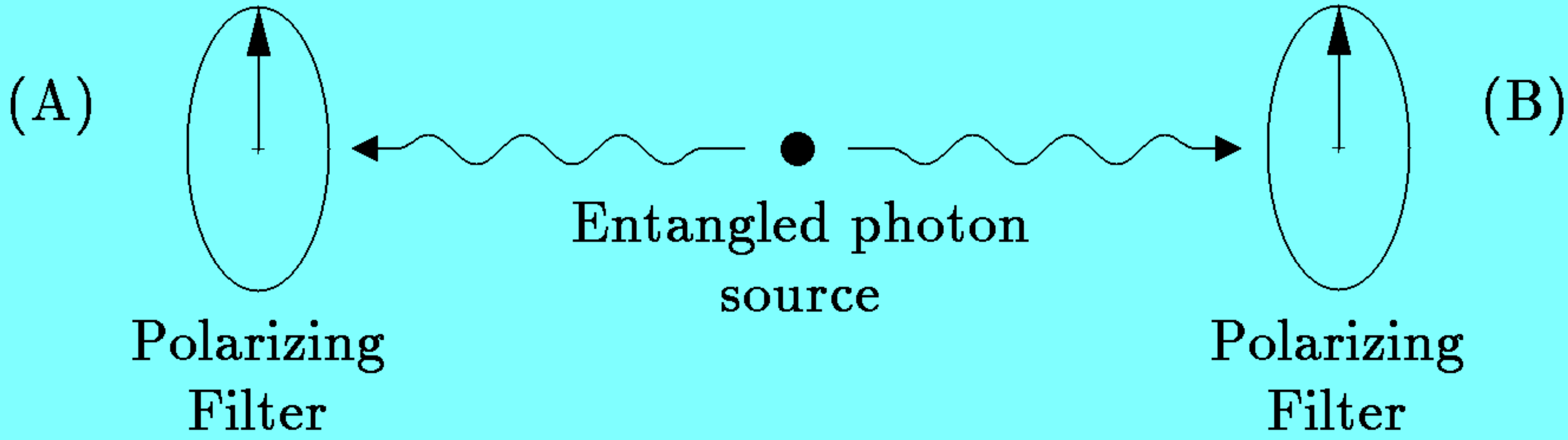

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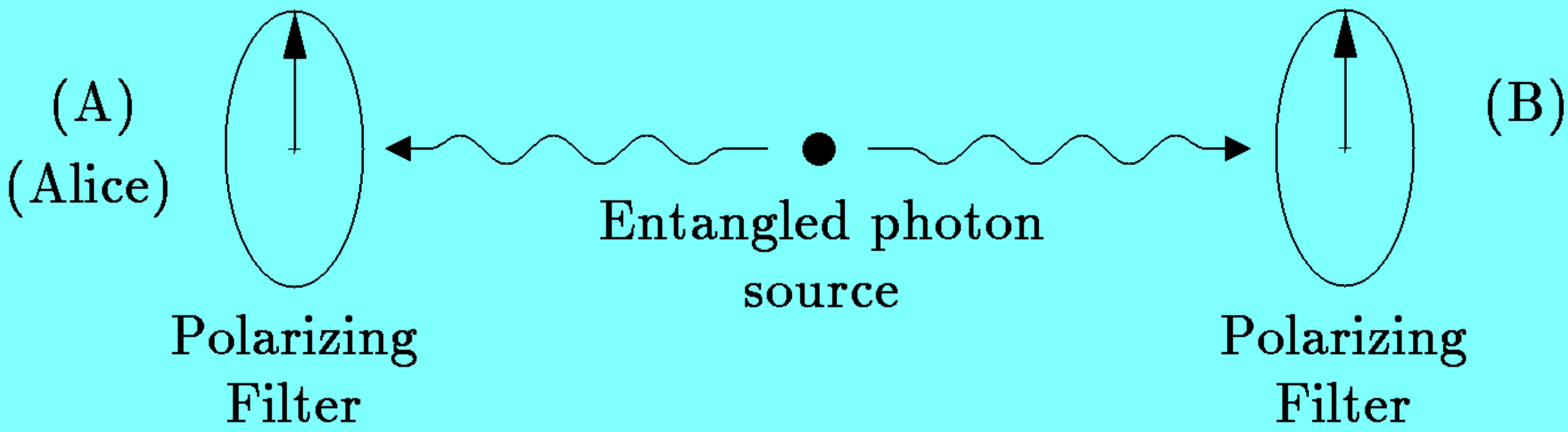

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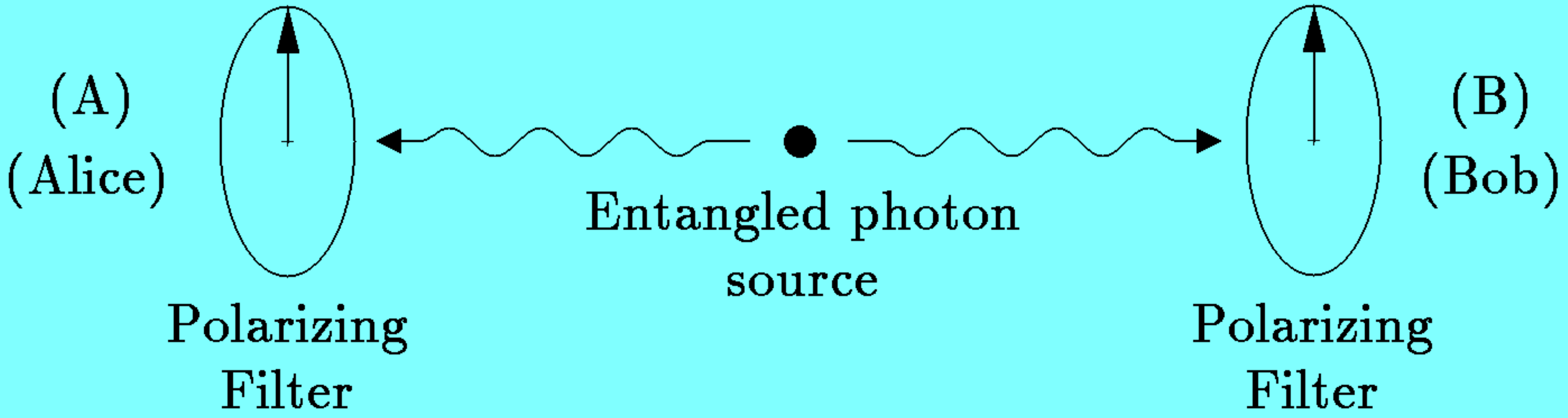

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If Alice measures her photon, she can predict the result of Bob's measurement. But Alice cannot control whether her photon will go through the polarizer or not, so she cannot control Bob's measurement.

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Niels Bohr: "Anyone who is not shocked by quantum theory has not understood it."

Richard Feynman: " I think I can safely say that nobody understands quantum mechanics. . . . Nobody knows how it can be like that."

Nagging Question: Is Quantum Mechanics Complete?

1935: Einstein, Podolsky, & Rosen (EPR): "Can Quantum-Mechanical Description of Reality Be Considered Complete?"

Can reality be governed by some underlying "hidden variable" theory, as yet undiscovered, which would simulate quantum theory, but would be realistic and deterministic?

Gerard 't Hooft (Nobel 1999): "I claim that we can attribute the fact that our predictions come with probability distributions to the fact that not all relevant data for the predictions are known to us, in particular important features of the initial state." (*Physics Today*, July 2017)

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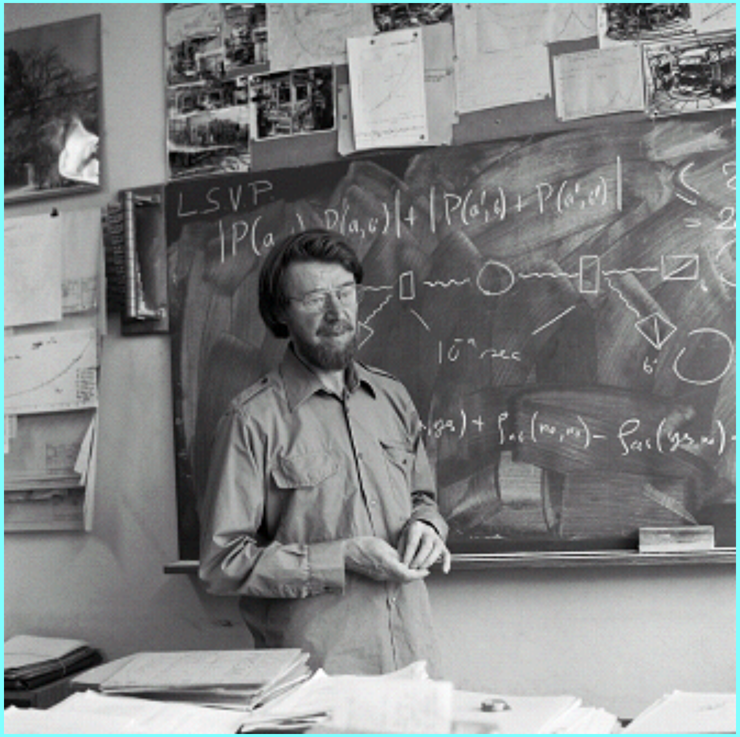
In general, one cannot tell. Reality could, for example, be like a movie being played, with all details determined by the screenplay, designed to give the illusion of quantum behavior. (This is sometimes called *superdeterminism*.)

Bell's Inequality

In 1964, John Bell discovered that there are some predictions of quantum mechanics that cannot be simulated by *any* local, realistic, hidden variable theory.



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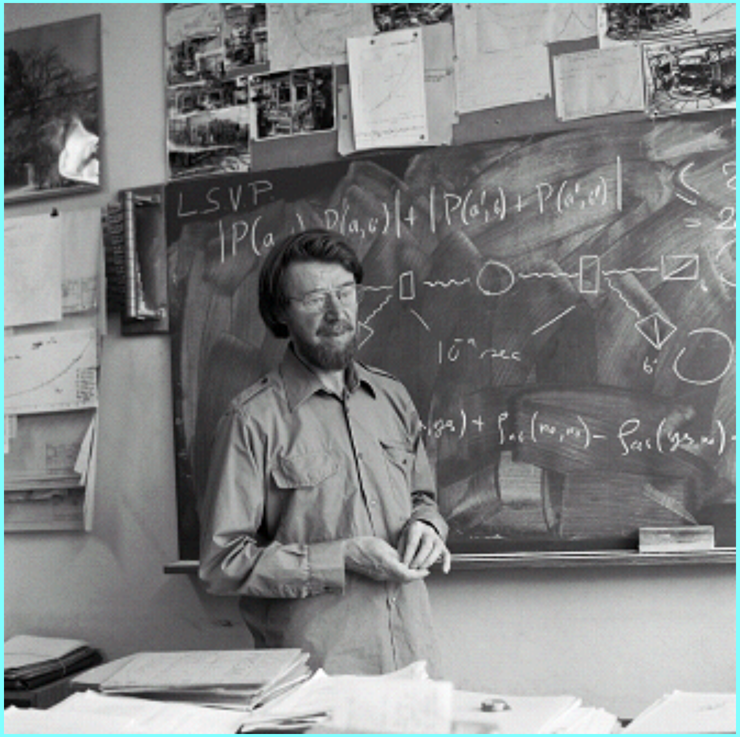

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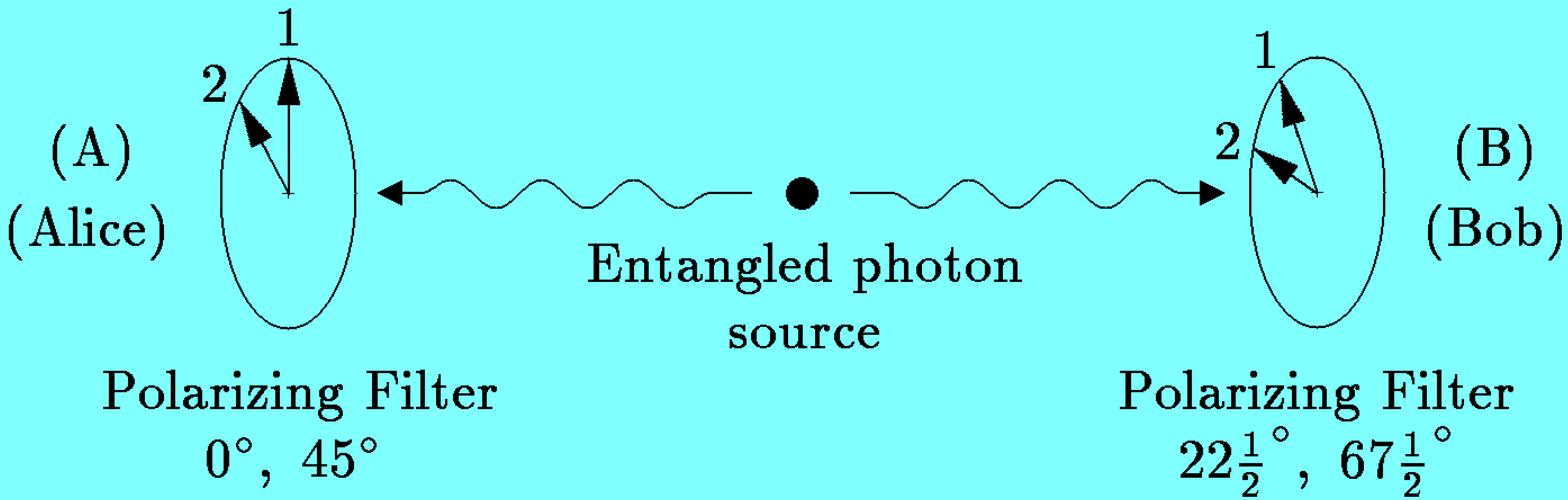
The Challenge: does nature follow the predictions of quantum mechanics for this case?

The CHSH Bell Test

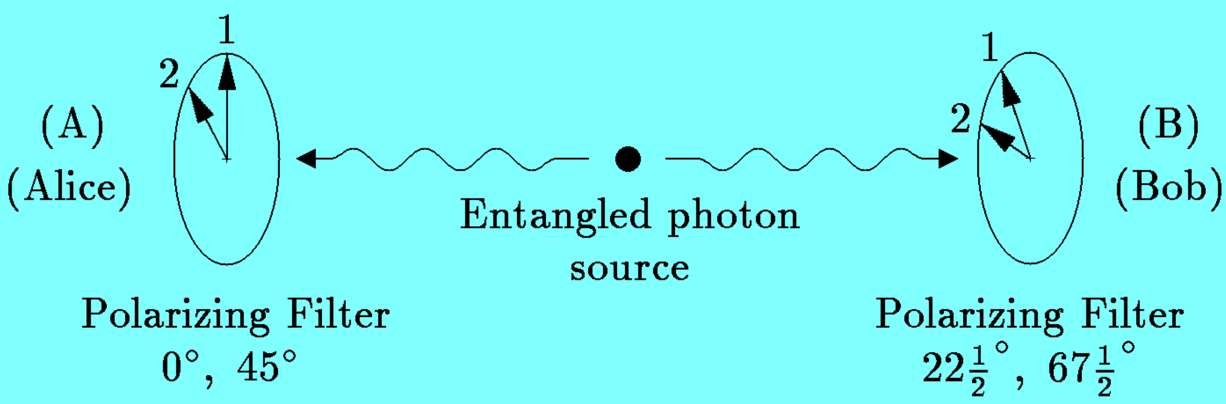
CHSH = Clauser-Horne-Shimony-Holt (1969).



Detectors A and B are switched randomly between settings 1 and 2.

Locality: when photon B reaches detector B, there is no possible knowledge of the setting or outcome at A. And vice-versa.

Rules of the game: For setting combinations (A1,B1), (A1,B2), or (A2,B1) the photons "win" if they match—both go through, or neither goes through. But, for (A2,B2), they win if they do not match.



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Bell's inequality: no classical strategy can win more than 75% of the time (on average).

What is a strategy? It is a plan for what each photon will do for each setting of its detector. Example:

Photon A: A1 $\rightarrow$ yes, A2 $\rightarrow$ yes.

Photon B: B1 $\rightarrow$ yes, B2 $\rightarrow$ yes.

Results: (A1,B1)=win, (A1,B2)=win, (A2,B1)=win, (A2,B2)=loss.

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Is there a better strategy? No.

How do we know that? There are just 16 possible strategies: look at them and see.

Alternatively, notice that any change yes$\leftrightarrow$no reverses the result in 2 cases. Hence the number of wins (of the 4 settings combinations) must always be odd.

So, no classical (local, realistic) strategy can win more than 75% of the time.

But, quantum mechanics wins 85.4% of the time!

So, if the experiment finds more than 75% wins, then local realistic hidden variable theories are ruled out.

(Note: in the literature, results are quantified by $S \equiv 4(2W - 1)$, where W is the fraction of wins. Bell inequality is $S \leq 2$, while quantum mechanics predicts $S = 2\sqrt{2}$.)

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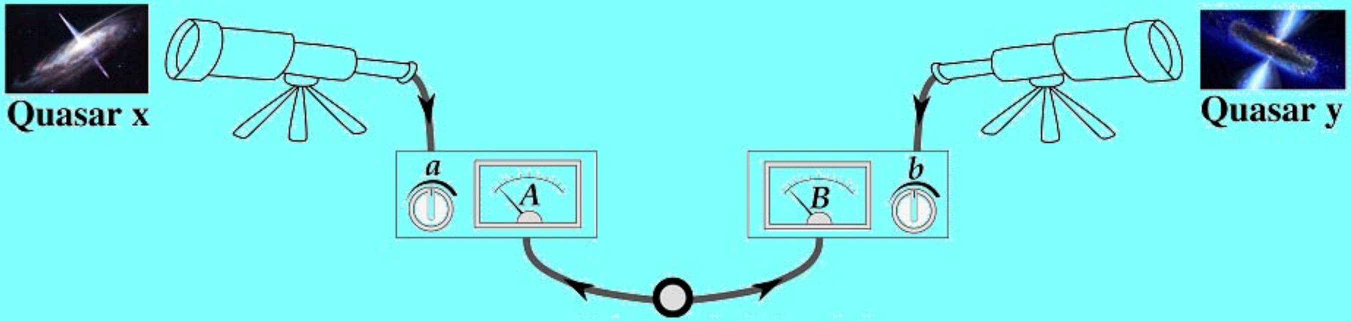
The fair sampling loophole: if not all photons are detected, is it possible that the hidden variable theory is controlling which ones are detected, thereby biasing the results? This loophole was not closed (for photons) until 2013. Simultaneous closure of locality and fair-sampling loopholes was not achieved until 2015.

The Settings-Independence Loophole

Is it possible that the settings of the two detectors are not really being set randomly, but maybe some hidden variable theory is controlling our choices, without our knowing it?

The most recent experiments use quantum random number generators, but since we are trying to test quantum mechanics, we shouldn't rely on quantum random number generation.

The Cosmic Bell Experiment



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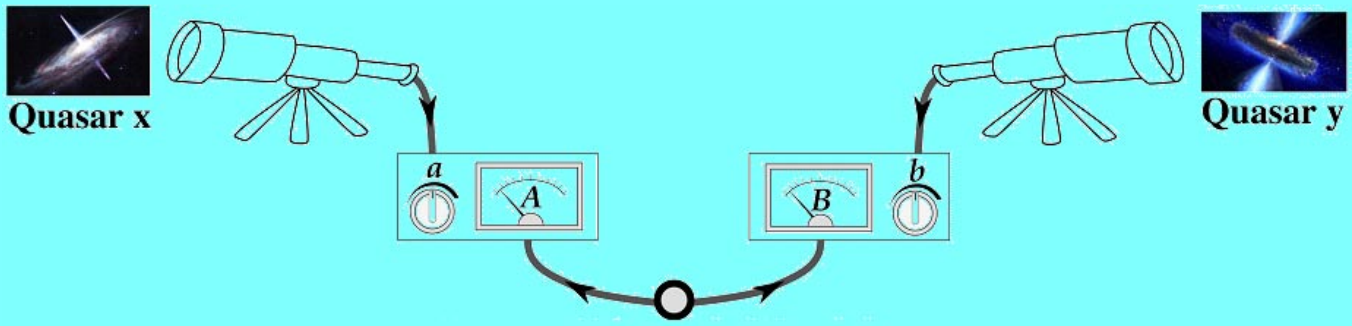

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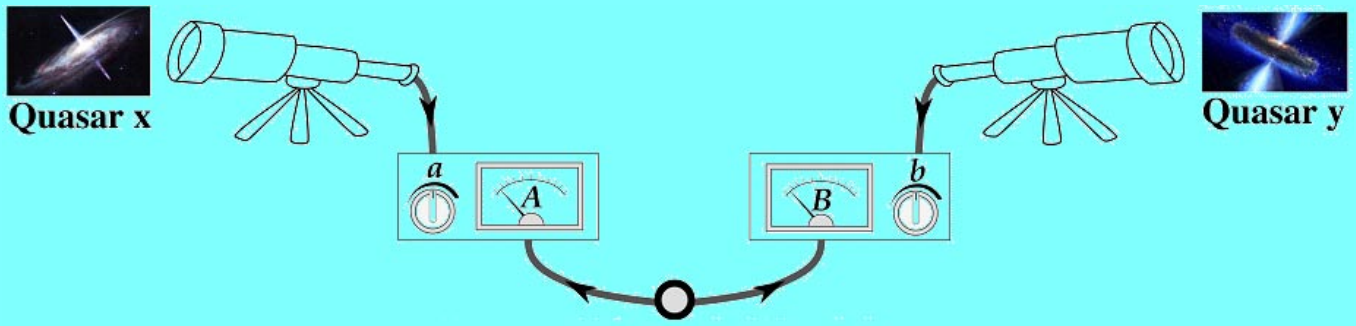

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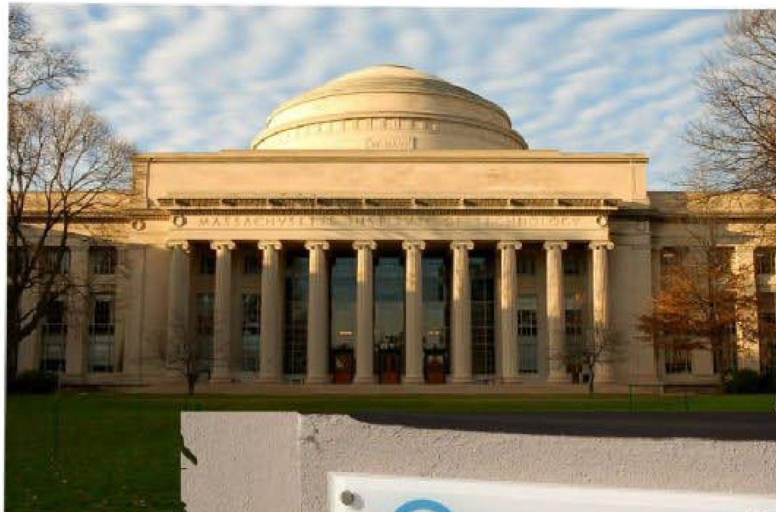
Does this really guarantee randomness?

No, but it makes it very implausible. Assuming that our apparatus is working properly, implementing the settings based on the astronomical photons, it means that any hidden variable mechanism that is enabling our experiment to duplicate the results of quantum mechanics would have to have begun its operations before the photons from the closer source were emitted.

New Collaboration



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Cosmic Bell Test: Measurement Settings from Milky Way Stars

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Anthony Mark,[2] Hien T. Nguyen,[6] Isabella Sanders,[2] Fabian Steinlechner,[1] Rupert Ursin,[1,7]
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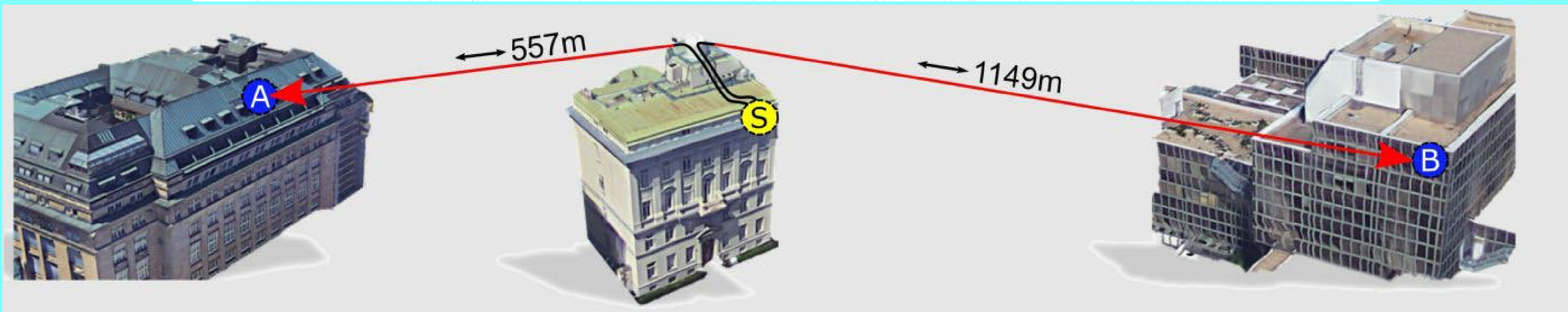

A = Austrian National Bank

S = Source = Institute for Quantum Optics and Quantum Information

B = University of Natural Resources and Life Sciences

Results of Pilot Run in Vienna

Run 1:

Number of events: 136,332 (in about 3 minutes).
Percent "wins": 80.3.
Nearest star: 604 ± 35 light-years.
Probability that a theory obeying Bell's inequality could have achieved this result by chance: 1.8×10^{-13}.

Run 2:

Number of events: 88,779 (in about 3 minutes)
Percent "wins": 81.3.
Nearest star: 577 ± 40 light-years.
Probability that a theory obeying Bell's inequality could have achieved this result by chance: 4.0×10^{-33}.

Conclusions

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- Next up: repeat the experiment with quasars, which would push back the time by which a hidden variable theory would have to plan ahead to billions of years.
- Testing the fundamentals of quantum mechanics is not easy, but it is a lot of fun. (Special thanks to Dave Kaiser for getting me involved in this.)