Event Horizon Telescope

- Distance: 17 Mpc = 55 Mly
- Mass: 6*10^9 Ms
- Size: ~ 500 AU

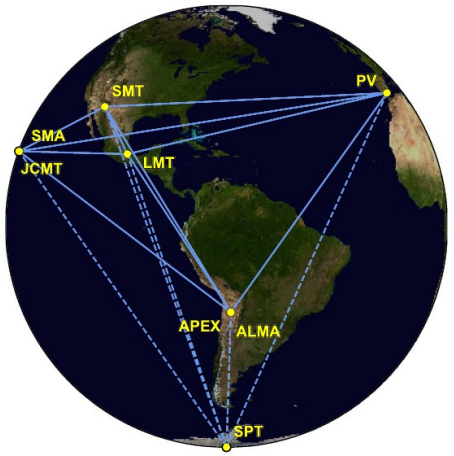
$$50\mu\text{as} = 50 \times \frac{1}{60 \times 60 \times 60 \times 1000000} = 2 \times 10^{-10}\text{rad}$$

$$\theta_{\text{res}} = 1.22\frac{\lambda}{D}$$

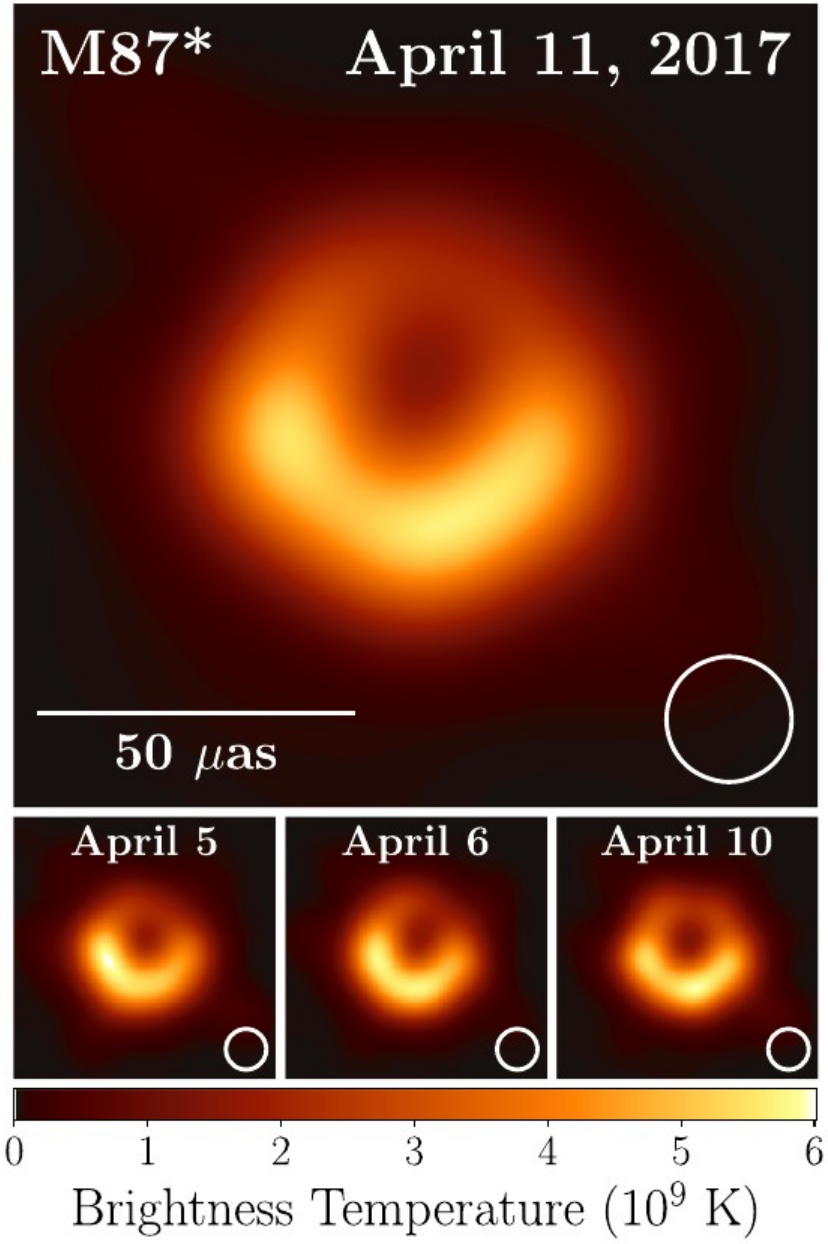
Hubble: $\theta_{\text{res}} = 1.22\frac{0.5 \times 10^{-6}\text{m}}{2.4\text{m}} \sim 0.05\text{as}$

EHT: $\theta_{\text{res}} = 1.22\frac{10^{-3}\text{m}}{13000 \times 10^{3}\text{m}} \sim 20\mu\text{as}$

200 GHz ~ 1mm



Footprint on the Moon



https://www.nature.com/articles/d41586-019-01155-0

$0.5\,\text{MeV}$

Quantum reality

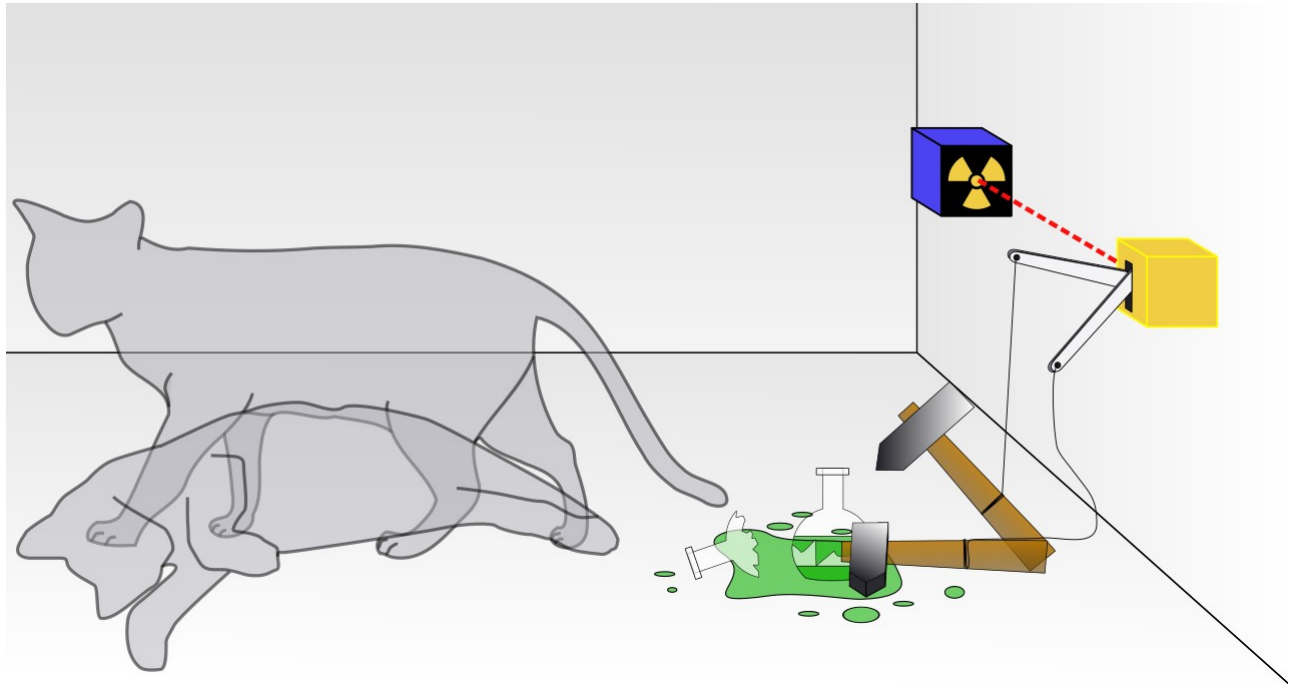
Radek Žlebčík

Tuesday,
2019, 4/23

Huttenstrasse 9, Zurich,
figure of cat,
place of Sch. 1921-1926
https://en.wikipedia.org/wiki/Schr%C3%B6dinger%27s_cat

Schrödinger's cat

The destiny of macroscopic object depends determined by quantum process



$$|\phi\rangle = \frac{1}{\sqrt{2}}(|h\rangle|\text{alive}\rangle + i|v\rangle|\text{dead}\rangle)$$

Quantum entanglement between the cat-state and polarisation of the gamma-photon
→ Tensor product to describe multiple dimensions

Schrödinger's cat – Copenhagen interpretation

- 1925-1927 by Bohr&Heisenberg
- Still commonly taught interpretation

- **U-evolution:** By Schrodinger equation, deterministic $$|\phi\rangle = \exp\left(-\frac{i}{h}H(t-t_0)\right)|\phi_0\rangle$$
- **R-evolution:** By wave function collapse to eigenvector (measurement), random

Before spin measurement:

$$|\phi\rangle = a|+\rangle + b|-\rangle$$

After spin measurement only 2 possibilities $|+\rangle, |-\rangle$

$$s_z|+\rangle = +1|+\rangle$$
$$s_z|-\rangle = -1|-\rangle$$

Schrödinger's cat – Many worlds interpretation

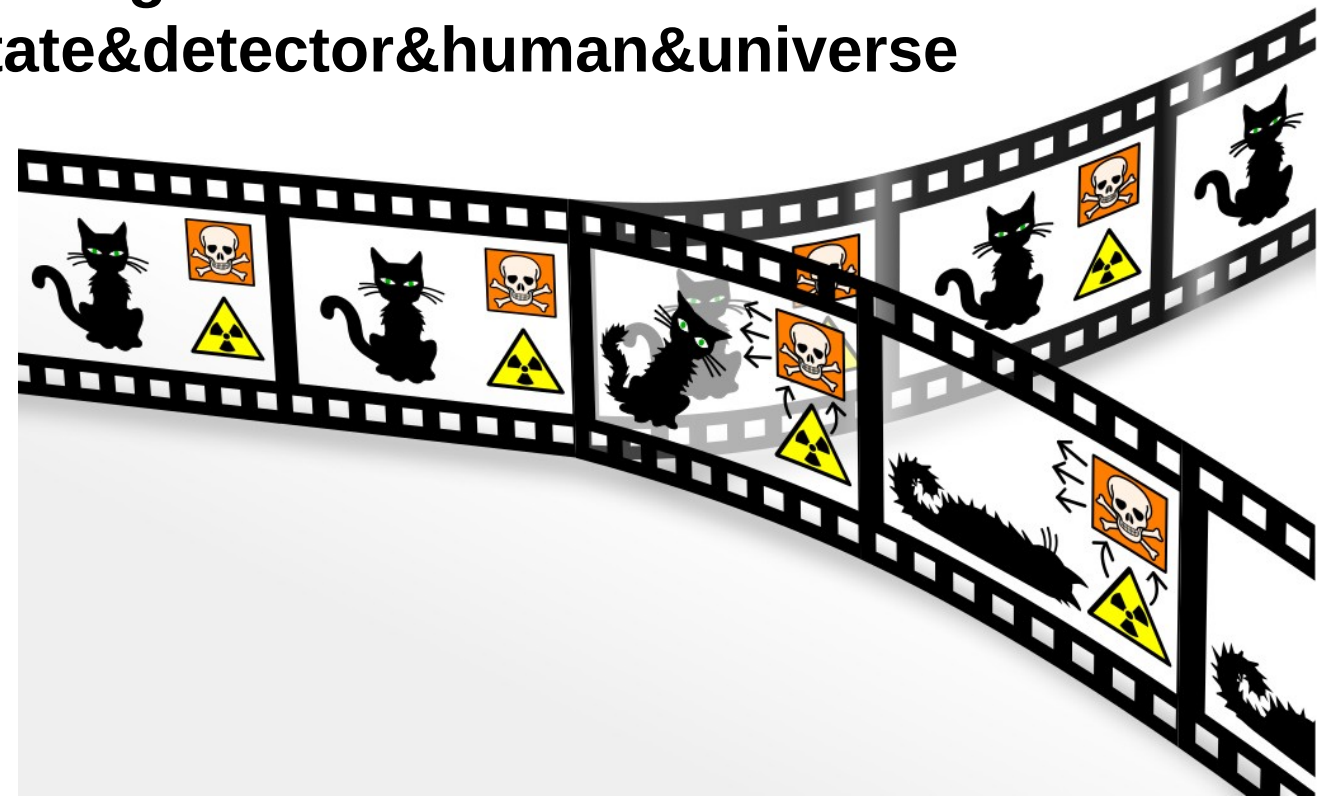
- 1957-1970s by Everett&DeWitt
- Today, the mainstream

- **U-evolution:** By Schrodinger equation, deterministic

$$|\phi\rangle = \exp(-\frac{i}{h}H(t-t_0))|\phi_0\rangle$$

- **R-evolution removed**
  → Single wave function to describe the state&detector&human&universe

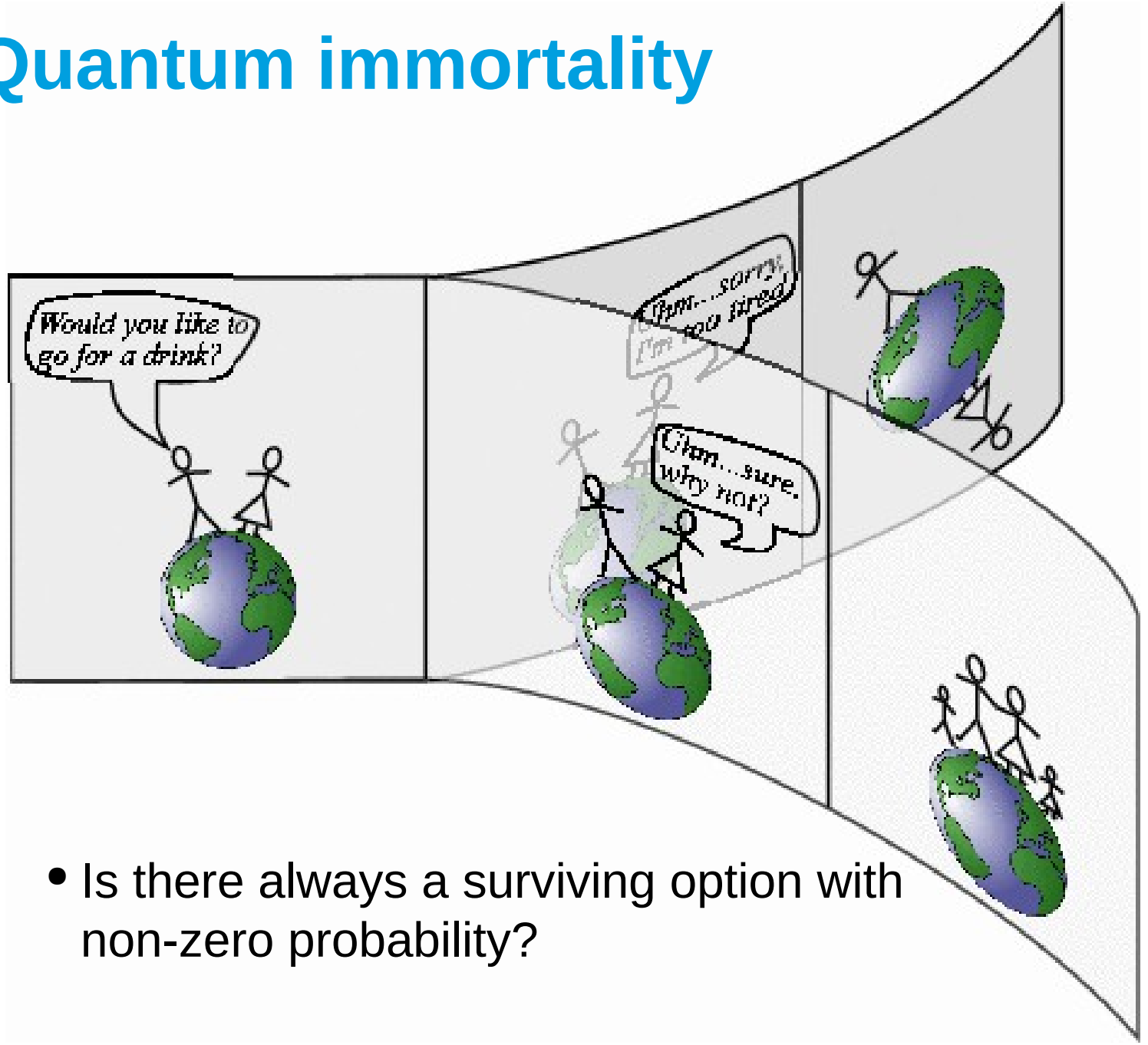
$$|\phi\rangle = |\text{photon}\rangle|\text{cat}\rangle|\text{observer}\rangle$$



Schrödinger's cat & Quantum immortality

- Imagine periodically repeated Schrodinger's cat experiment with period 1minute

- There is always a universe branch where the cat is alive
  → Immortality

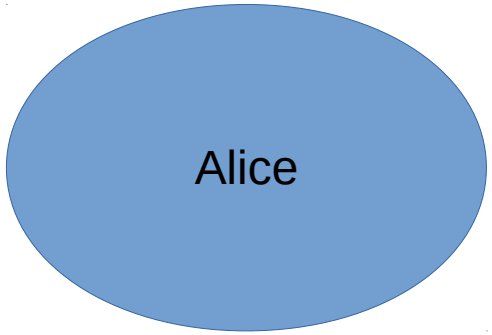


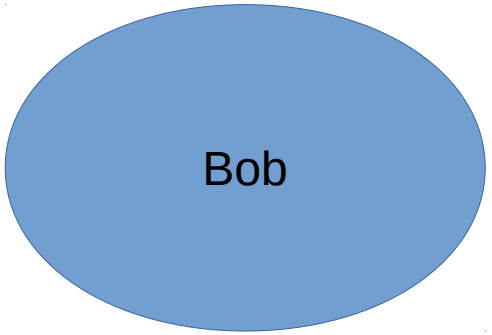
- Is there always a surviving option with non-zero probability?

Quantum cryptography

- Using wave-function collapse to prevent Eve listen...

- Man(woman)-in-the-middle attack proof, if:
  - → Nature obeys quantum laws
  - → **Eve is not able to impersonate Bob**





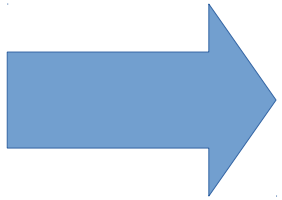
After the secure communication between Alice & Bob(or Eve) is established:

Alice is asking Ave:
What is our secret?
(answer in form
hash:135433password)

Eve cannot send the right answer

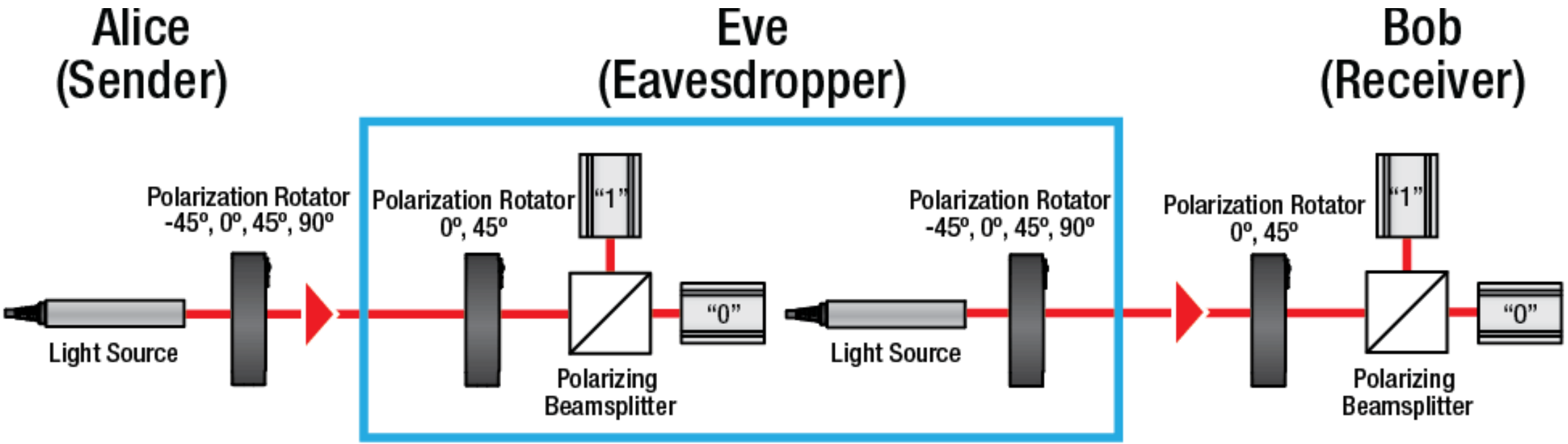
Eve is asking Alice:
What is our secret?
(answer in form
hash:452454password)

Alice send the correct answer,
but Eve cannot reveal the password



Both Alice & Bob need to ask such questions to verify the second party

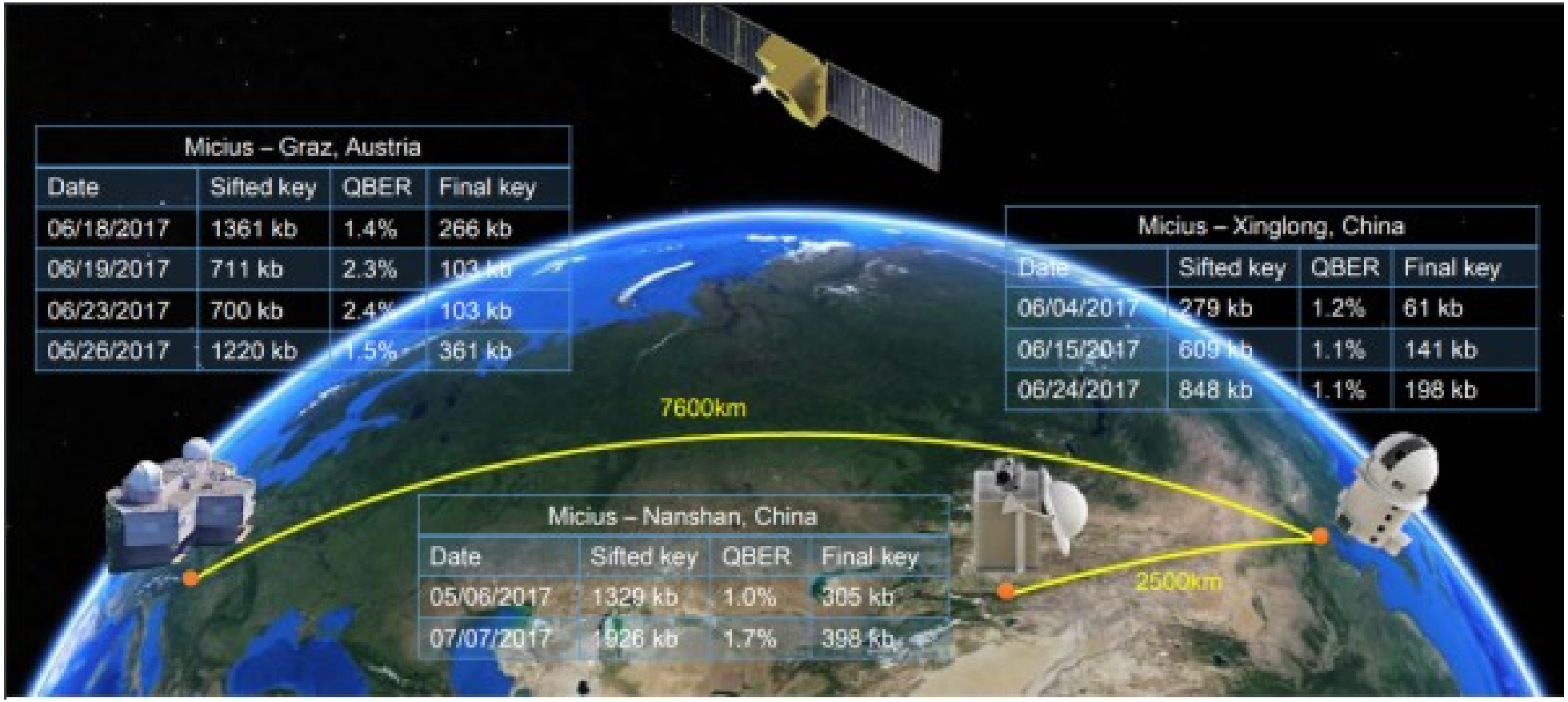
Alice's random bit	0	1	1	0	1	0	0	1
Alice's random sending basis	+	+	×	+	×	×	×	+
Photon polarization Alice sends	↑	→	↘	↑	↘	↗	↗	→
Bob's random measuring basis	+	×	×	×	+	×	+	+
Photon polarization Bob measures	↑	↗	↘	↗	→	↗	→	→
PUBLIC DISCUSSION OF BASIS								
Shared secret key	0		1			0		1



No cloning theorem

Quantum communication

- First intercontinental secure quantum video call (2016, Vienna & Beiging)



Quantum entanglement – non-locality

- The **E**instein **P**odolsky **R**osen Paradox
- Imagine $\pi^0 \rightarrow e^+e^-$

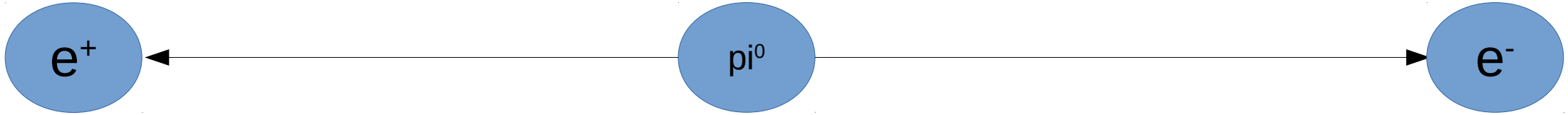
$$|e^+e^-\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle|-\rangle - |-\rangle|+\rangle\right)$$

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.



- When the spin of e^+ is measured, the wave function of whole entangled system collapses → the result of e^- spin measurement is known
- Notice that when measurements space-time points are space-like the causality is **relative**

Quantum entanglement – Hidden parameters

Bell: No physical theory of local hidden variables can ever reproduce all of the predictions of quantum mechanics.

Alice's pol. vec.

Bob's pol. vec.

$$C_e(a,b) = \frac{(N_{++} + N_{--}) - (N_{-+} + N_{+-})}{(N_{++} + N_{--}) + (N_{-+} + N_{+-})}$$

Between (-1, 1)

Quantum prediction:

$$C_q(a,b) = -a \cdot b$$

From Hidden Parameters:

$$C_h(a,b) = \int A(a,\lambda)B(b,\lambda)p(\lambda)d\lambda$$

Bell inequality

$$C_h(a,c) - C_h(b,a) - C_h(b,c) \leq 1$$

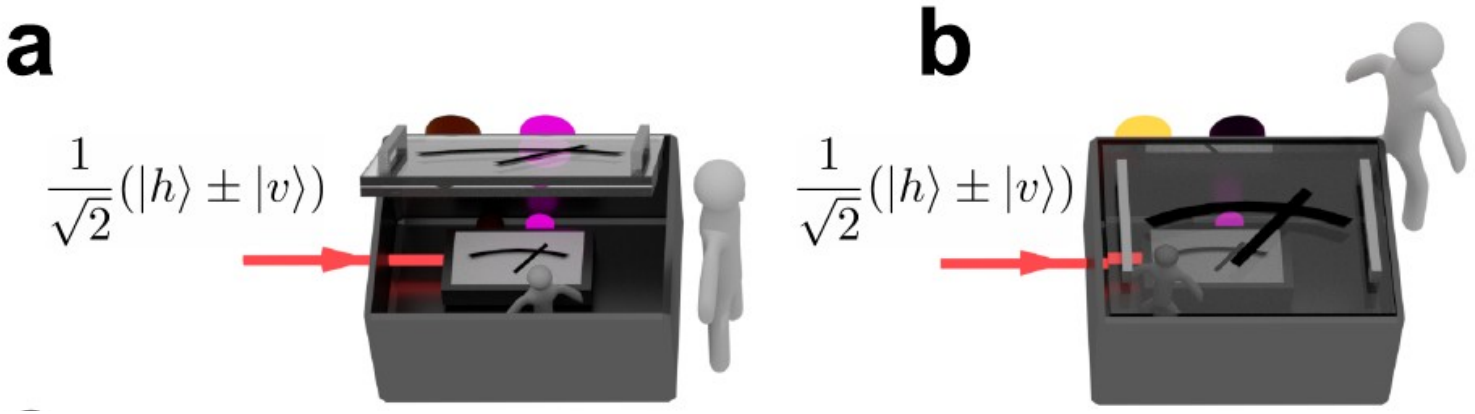
Wiegner's Friend experiment

Is the wave function collapse relative, depending on the observer?

- **From inside** the lab the wave-function collapsed
- **From outside** the photon+stored result in entangled state (no collapse)

Wave function of the whole laboratory

$$|\Phi_0^{\pm}\rangle = \frac{1}{\sqrt{2}}(|h\rangle|\text{photon is "h"}\rangle \pm |v\rangle|\text{photon is "v"}\rangle)$$



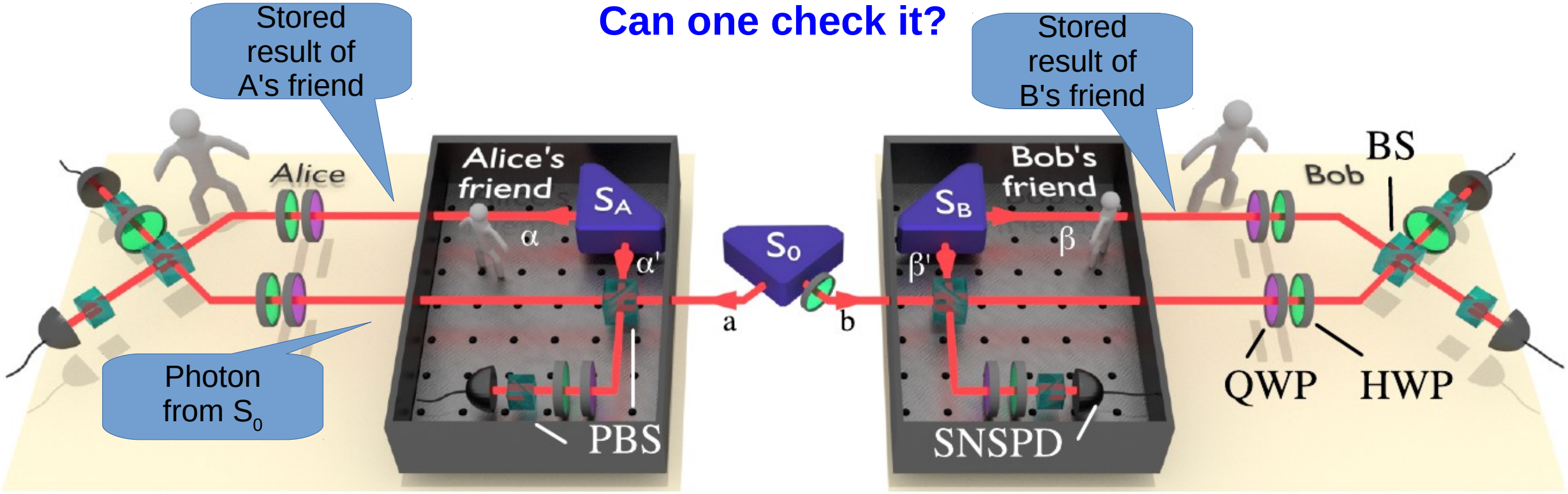
https://www.livescience.com/65029-dueling-reality-photons.html

[arXiv:1902.05080]

Wiegner's Friend experiment

- **From inside:** The polarization of the photon was measured (collapsed) and result stored
- **From outside:** Photon is still in quantum superposition (together with observer)

Can one check it?



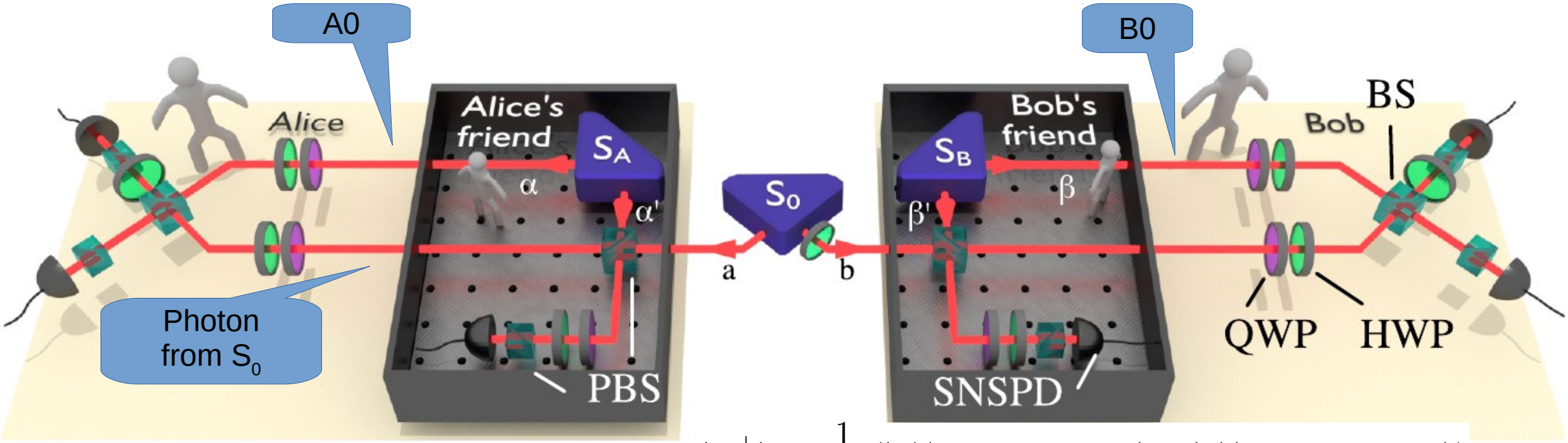
Wiegner's Friend experiment

$$A_0 = B_0 = \mathbb{1} \otimes \big(|\text{“photon is } h\text{”}\rangle\langle\text{“photon is } h\text{”}| - |\text{“photon is } v\text{”}\rangle\langle\text{“photon is } v\text{”}|\big),$$

$$A_1 = B_1 = |\Phi^+_{\text{photon/record}}\rangle\langle\Phi^+_{\text{photon/record}}| - |\Phi^-_{\text{photon/record}}\rangle\langle\Phi^-_{\text{photon/record}}|.$$

Observer independent facts, then:

$$S = \langle A_1 B_1\rangle + \langle A_1 B_0\rangle + \langle A_0 B_1\rangle - \langle A_0 B_0\rangle \leq 2$$



$$|\Phi_0^{\pm}\rangle = \frac{1}{\sqrt{2}}(|h\rangle|\text{photon is ”h”}\rangle \pm |v\rangle|\text{photon is ”v”}\rangle)$$

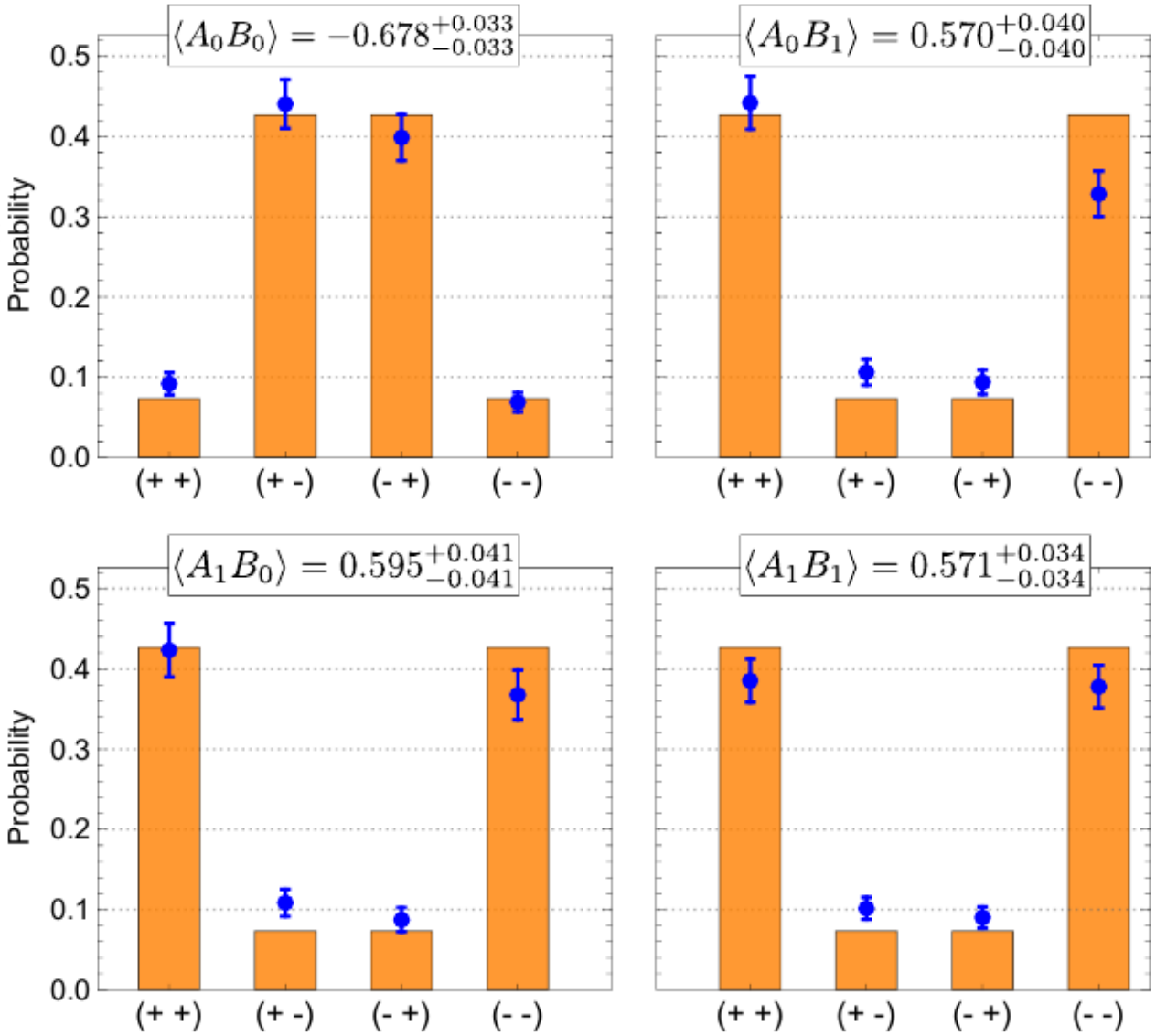
Wiegner's Friend experiment

Observer independent facts, then:

$$S = \langle A_1 B_1 \rangle + \langle A_1 B_0 \rangle + \langle A_0 B_1 \rangle - \langle A_0 B_0 \rangle \leq 2$$

0.571 0.595 0.570 -0.678

$$S_{\text{exp}} = 2.416^{+0.075}_{-0.075}$$



Interpretation

One way to accommodate our result is by proclaiming that “facts of the world” can only be established by a privileged observer—e.g., one that would have access to the “global wavefunction” in the many worlds interpretation...

Is global wavefunction meaningful?
In any case, not accessible,
→ Results relative wrt observer