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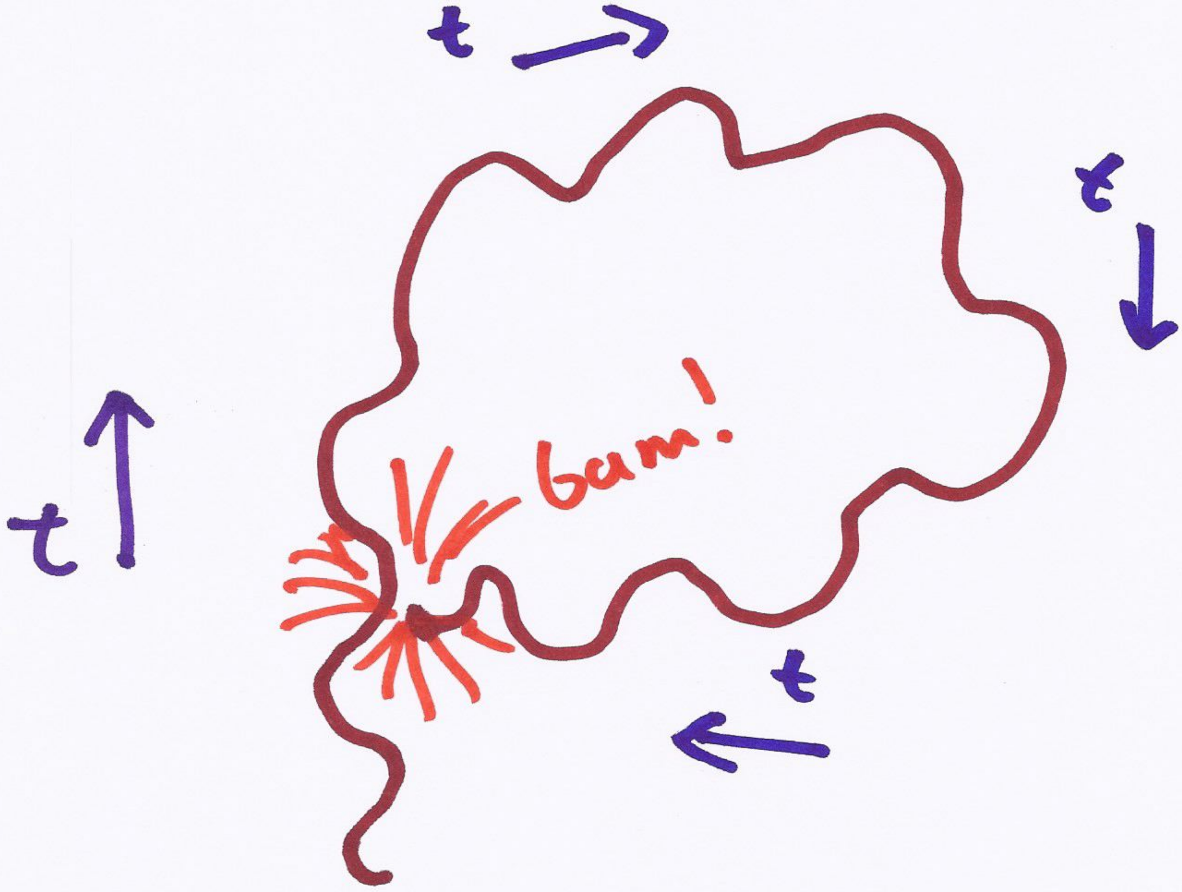
BANCHIERI · MERCANTI · NEGOZIANTI ·

Sending a photon backwards in time

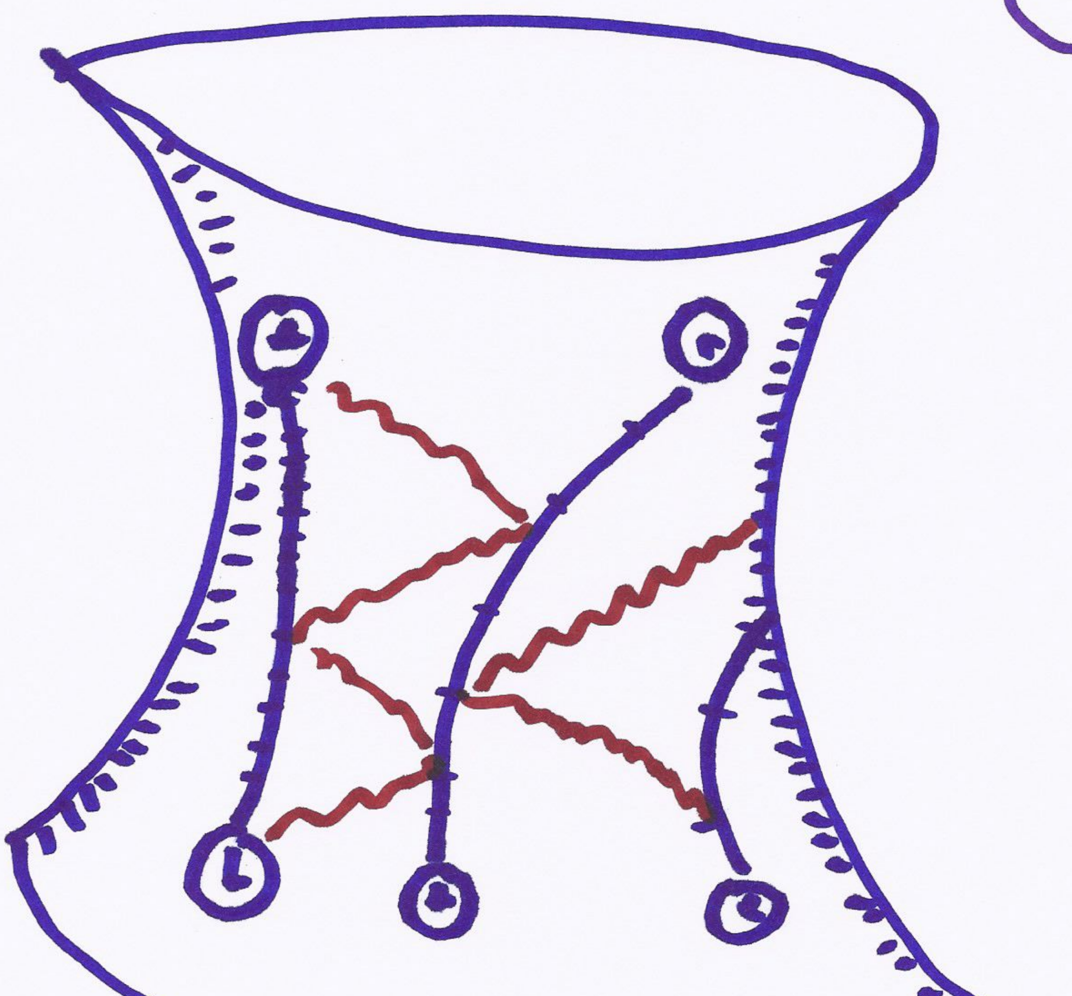
Seth Lloyd, MIT




H.G. Wells
The time machine.
t

Einstein

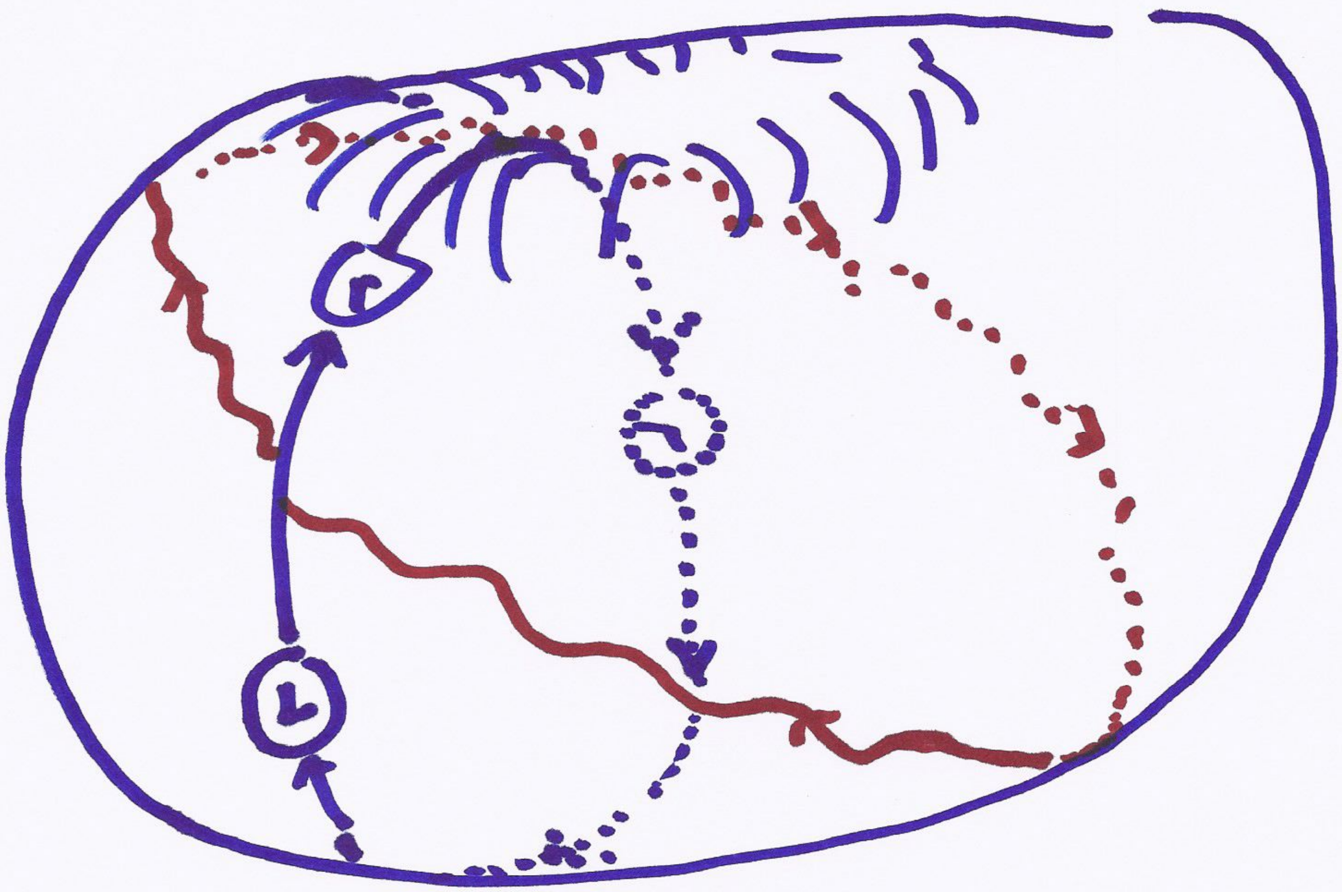
Gravity
= Geometry

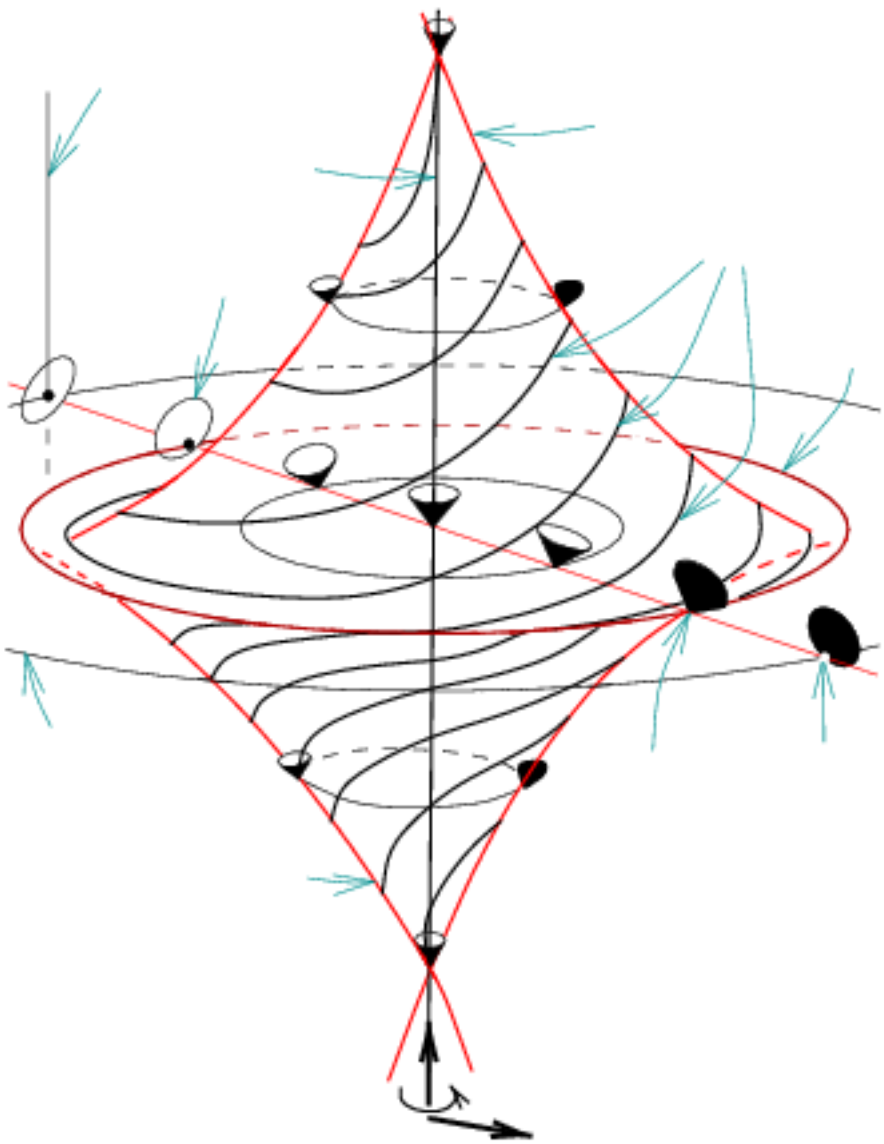


E.g. GPS

Gödel

Space time with closed timelike curves





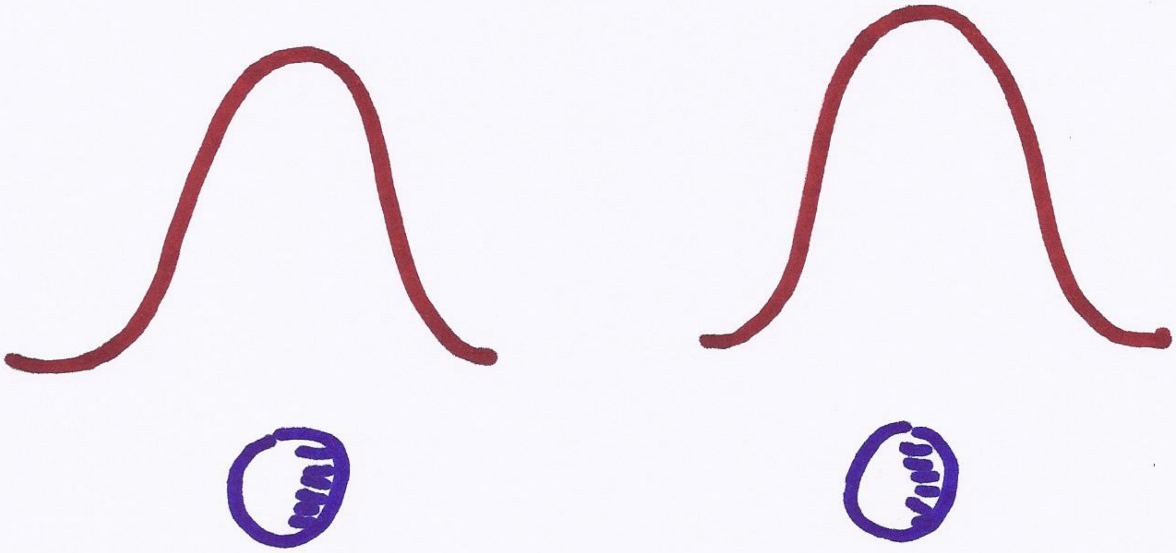
Deutsch

How can we make sense of closed timelike curves at the quantum mechanical level?

wave

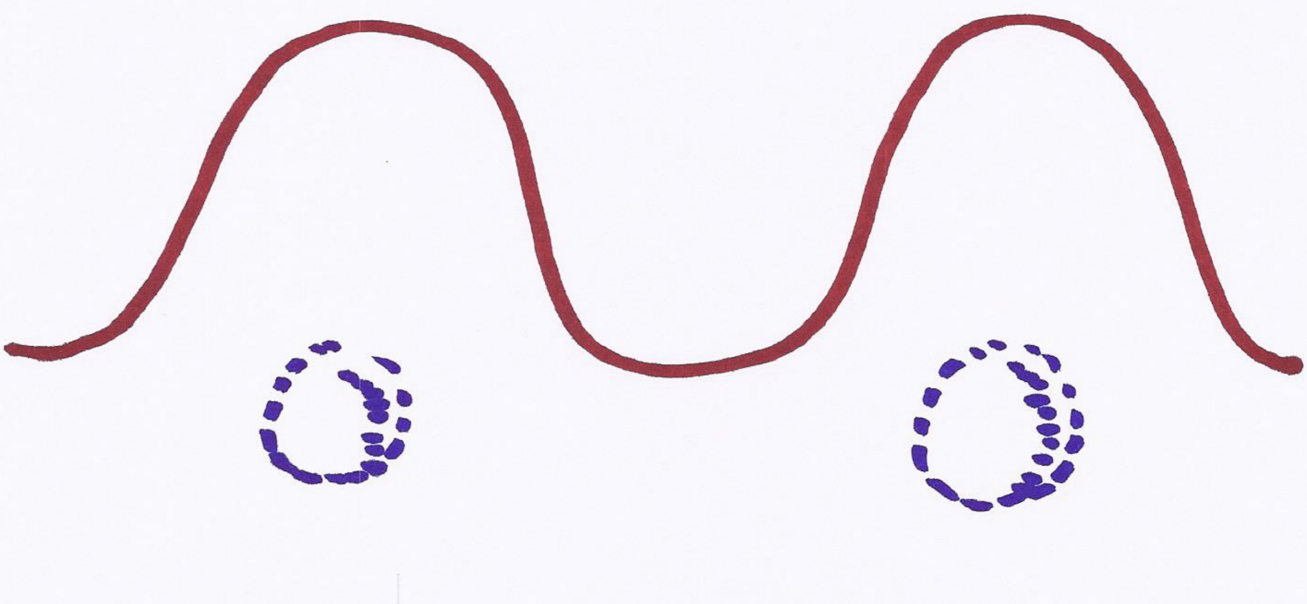
particle

Wave particle duality

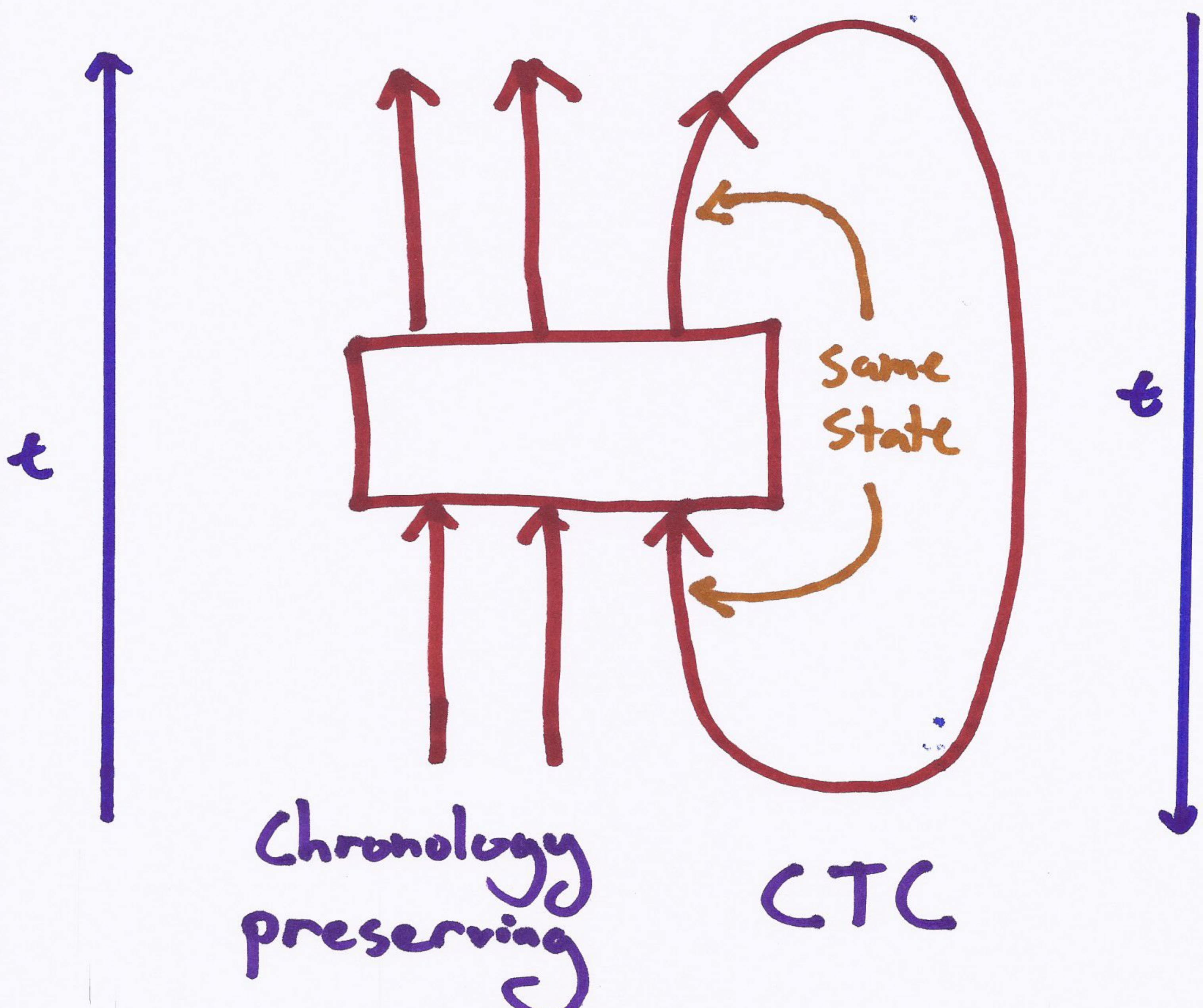


wave here
particle here
0

wave there
particle there
1



Deutsch's closed timelike curves



Alternative theory

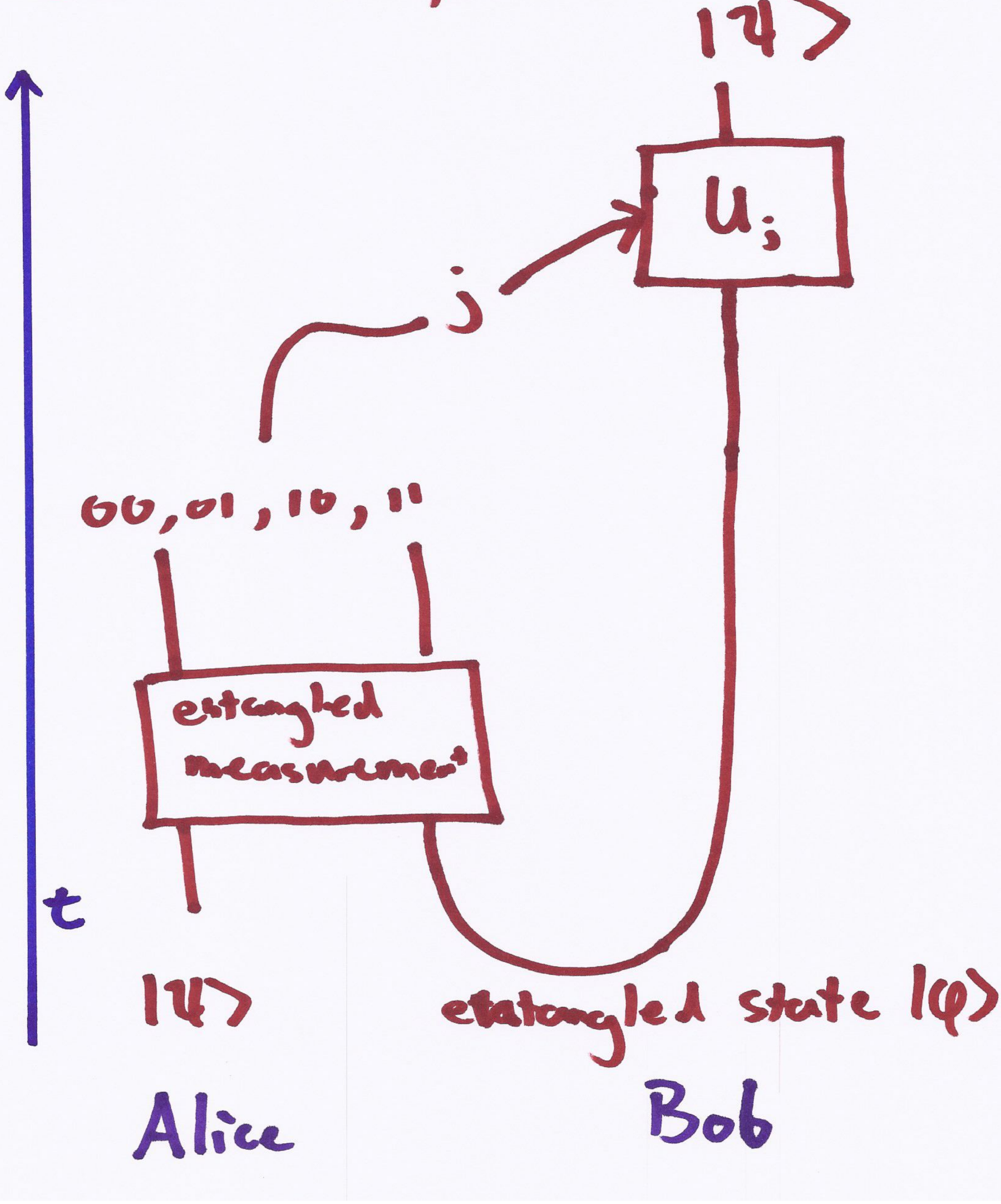
(S.L., Maccone, Giovannetti, Shikano
Garcia-Patron, Pirandola, Rozema,
Darabi, Soudagar, Shalm, Steinberg)

Closed timelike curves
via post-selection

P-CTC

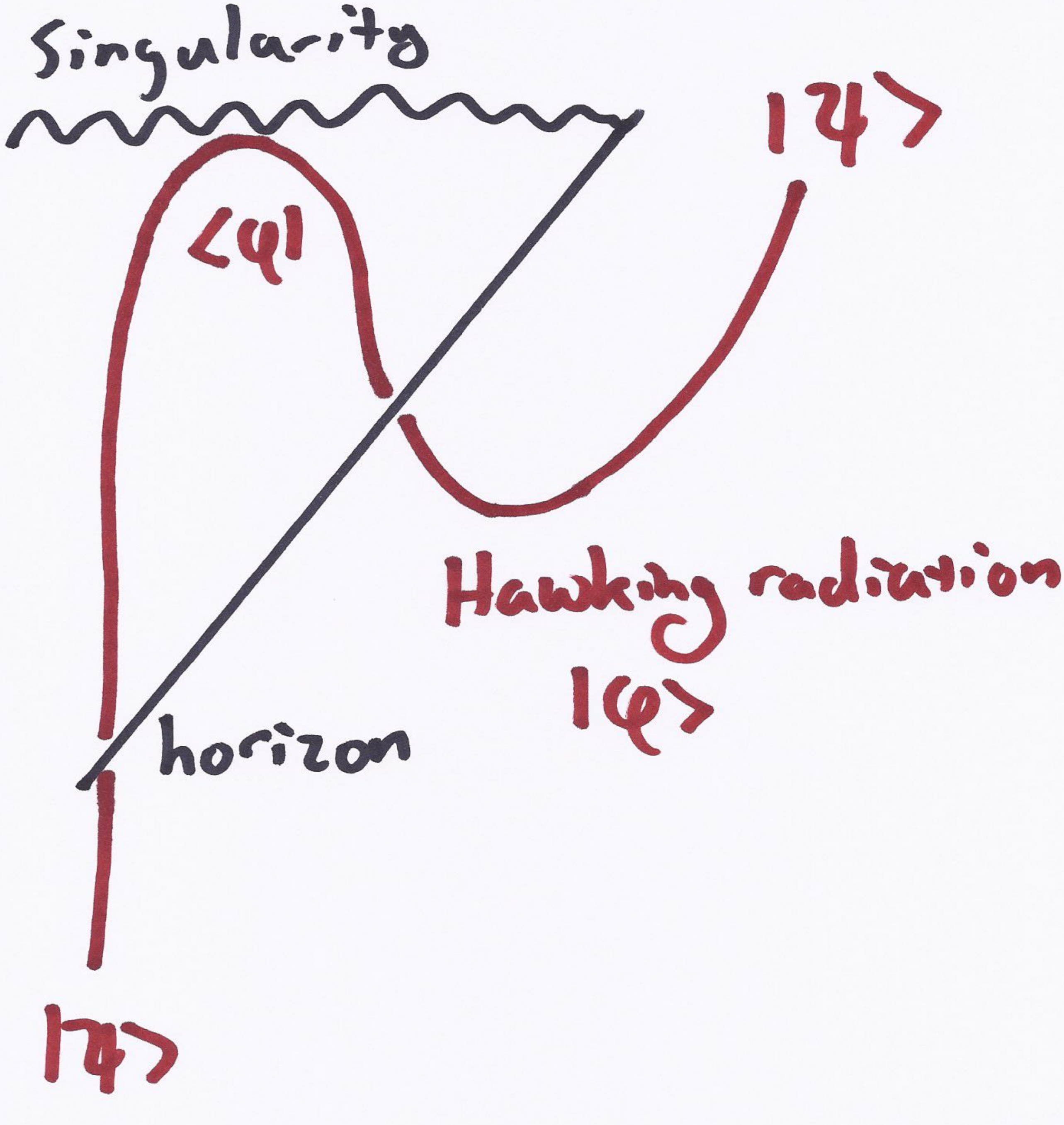
(cf. Bennett, Schumacher, Gottesman
Preskill, Horowitz, Maldacena, Svetlichny,
...)

Quantum teleportation

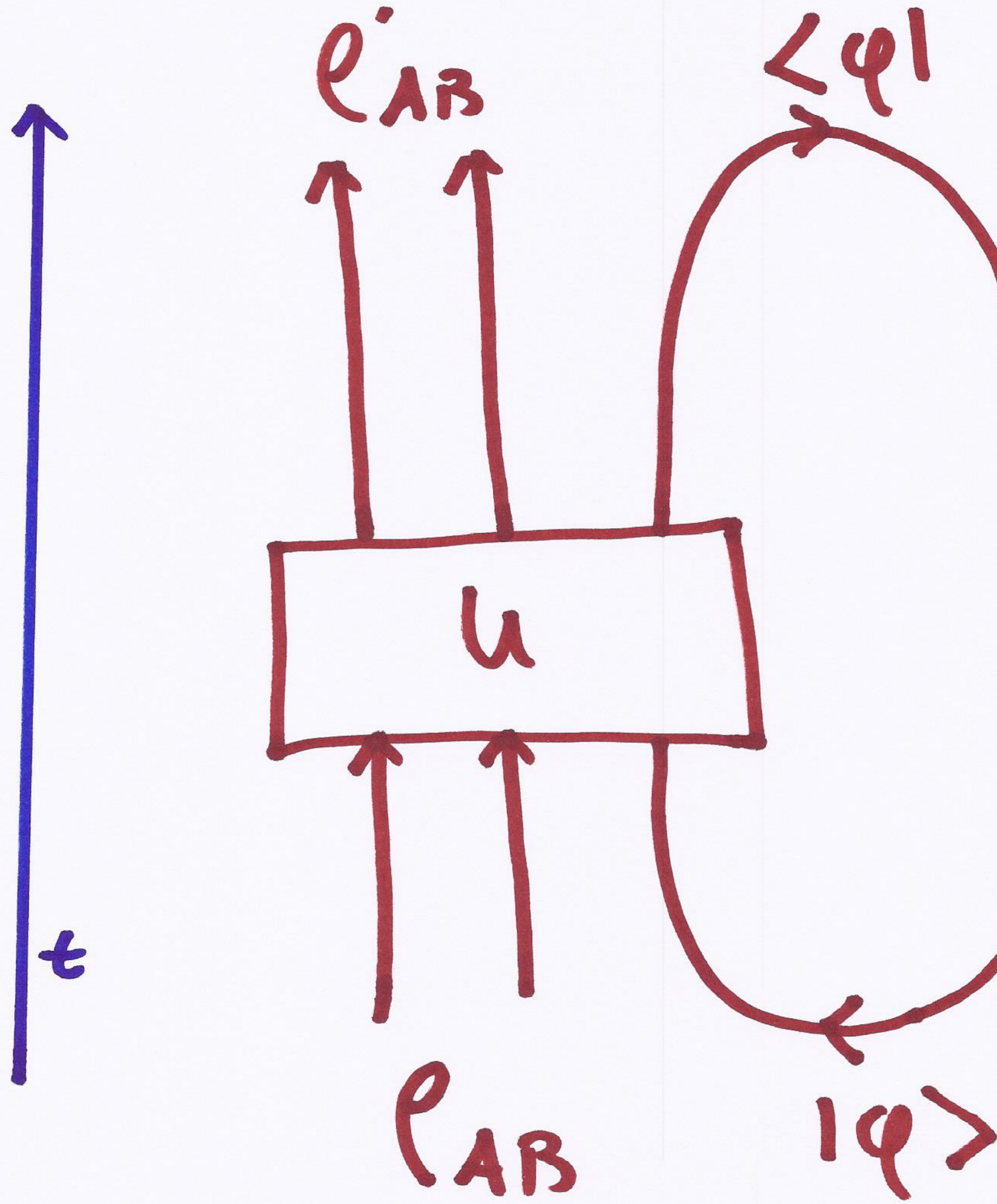


Quantum teleportation: $\bar{j} = 00$ case

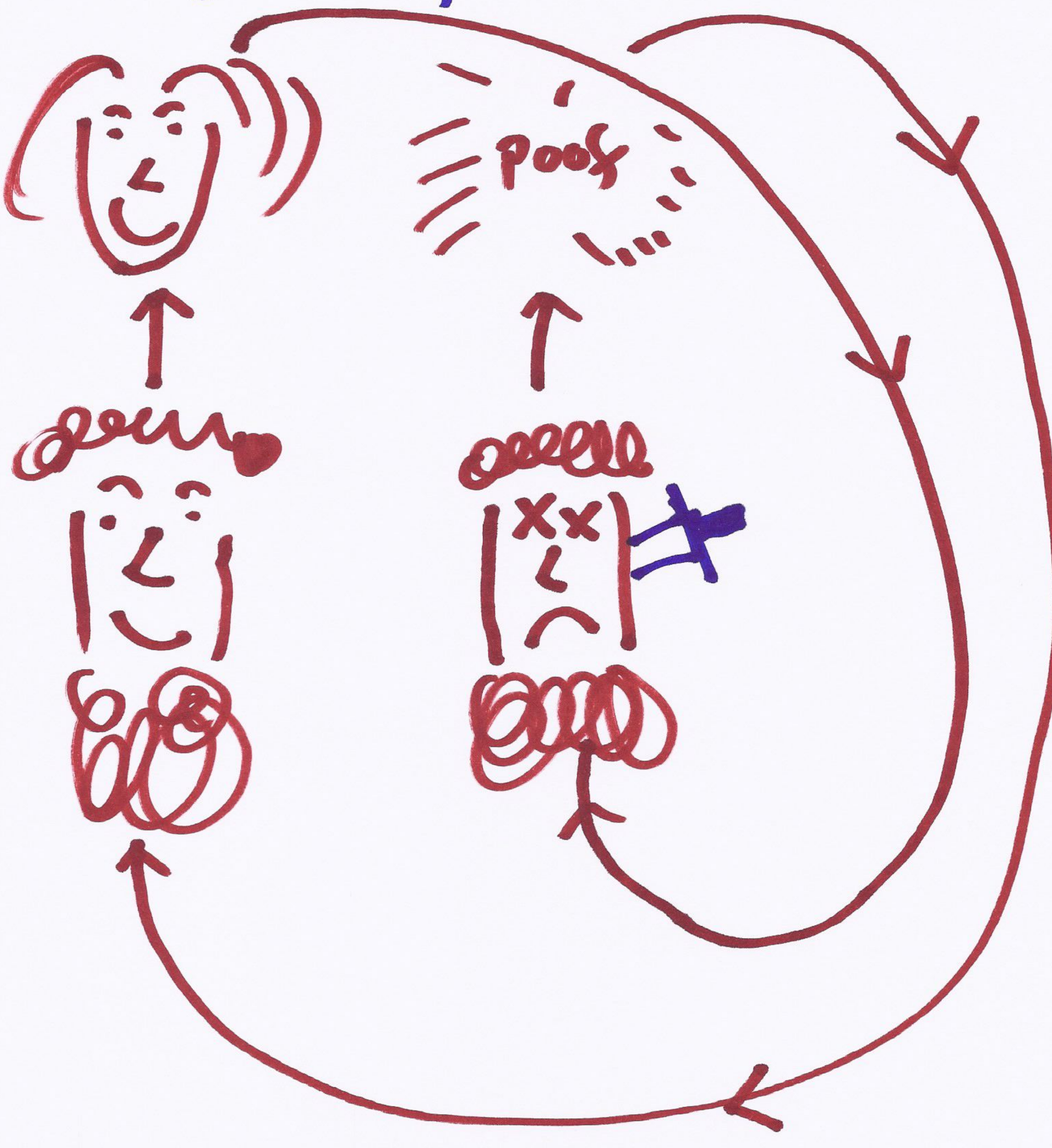
Horowitz-Maldacena mechanism for black hole evaporation:



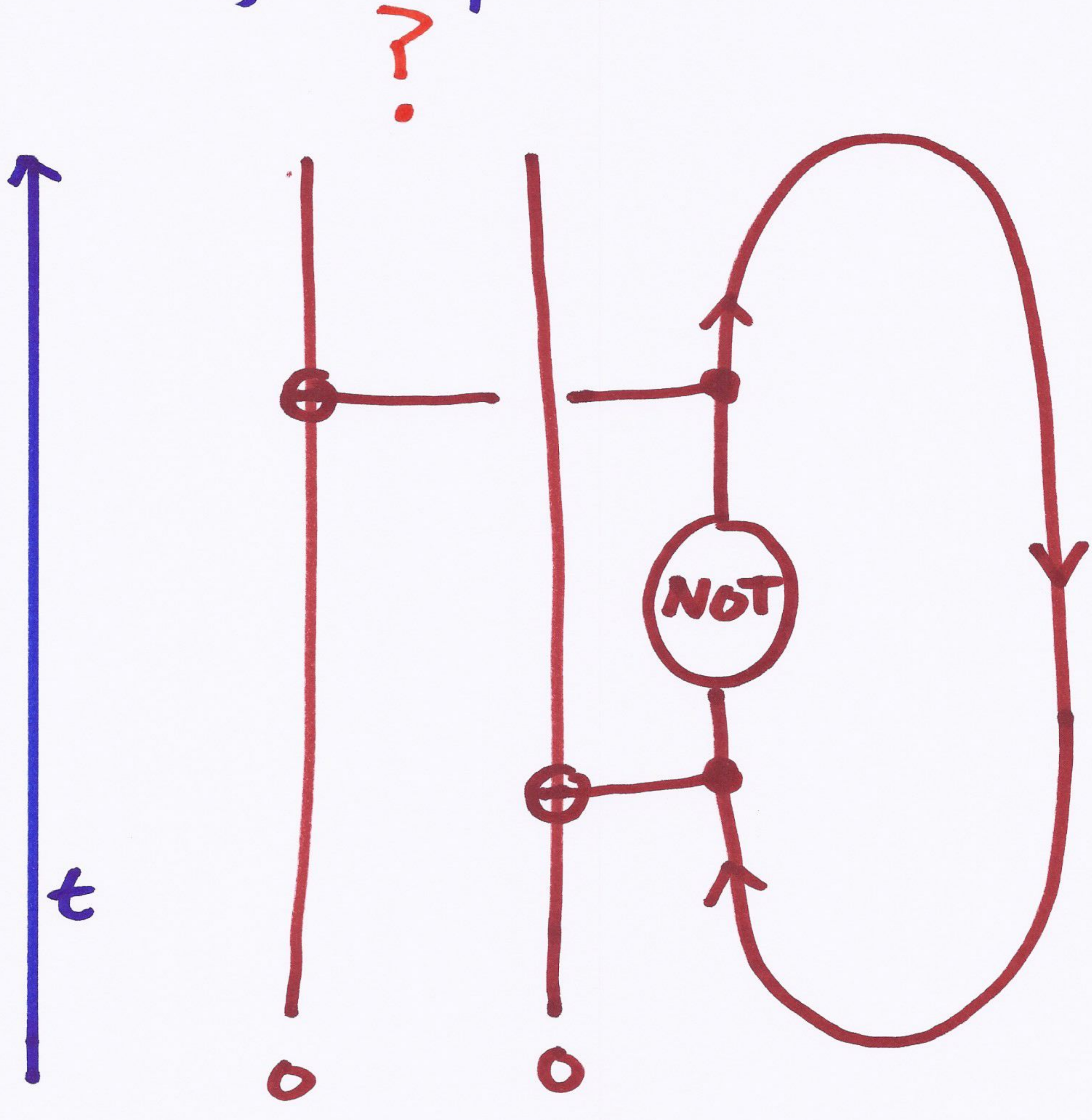
Closed timelike curves via post selection

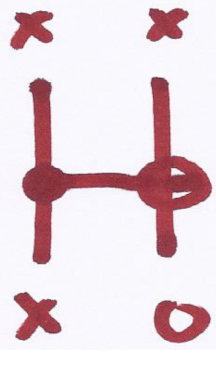


Grandfather paradox



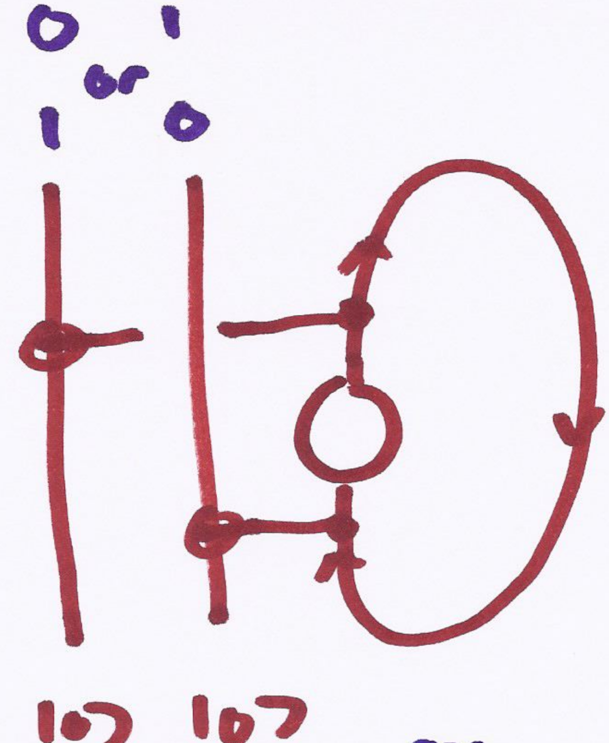
Grandfather paradox circuit 1:





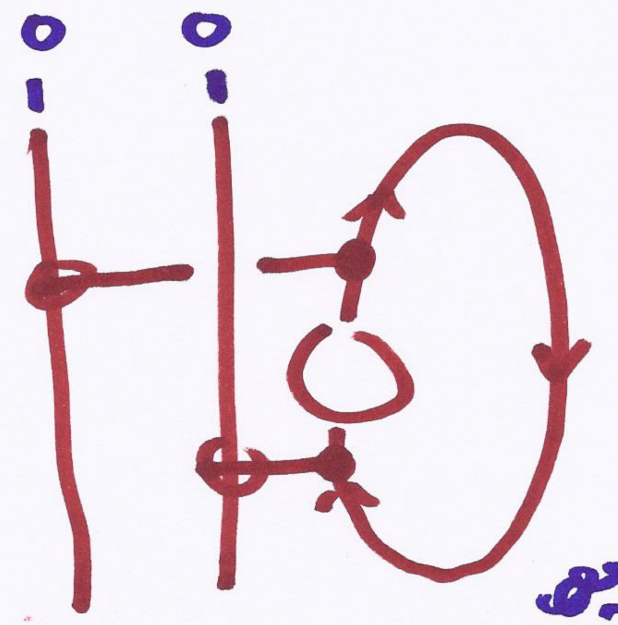
'controlled-NOT'

Deutsch:



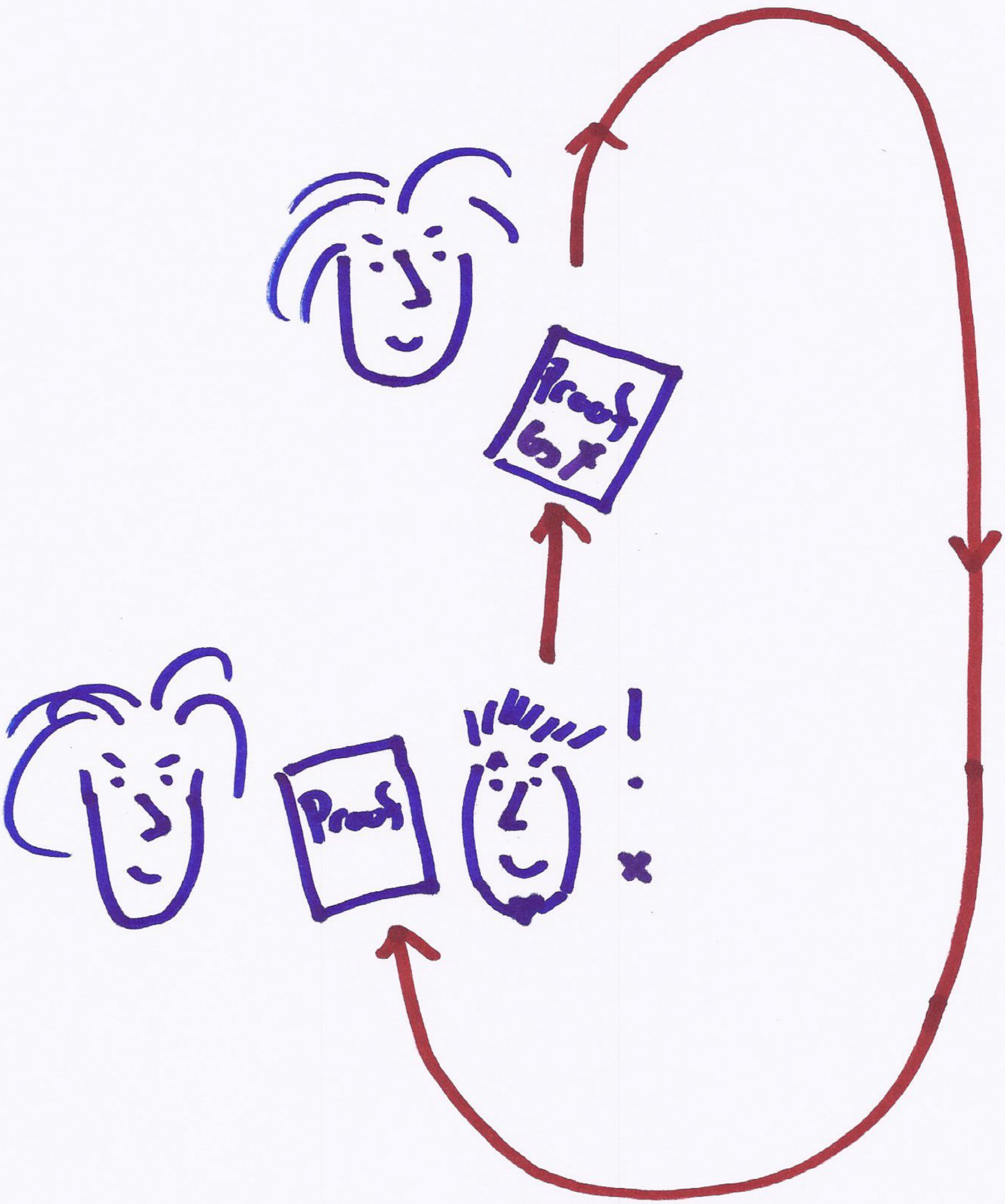
⇒  always kills 

P-CTC:



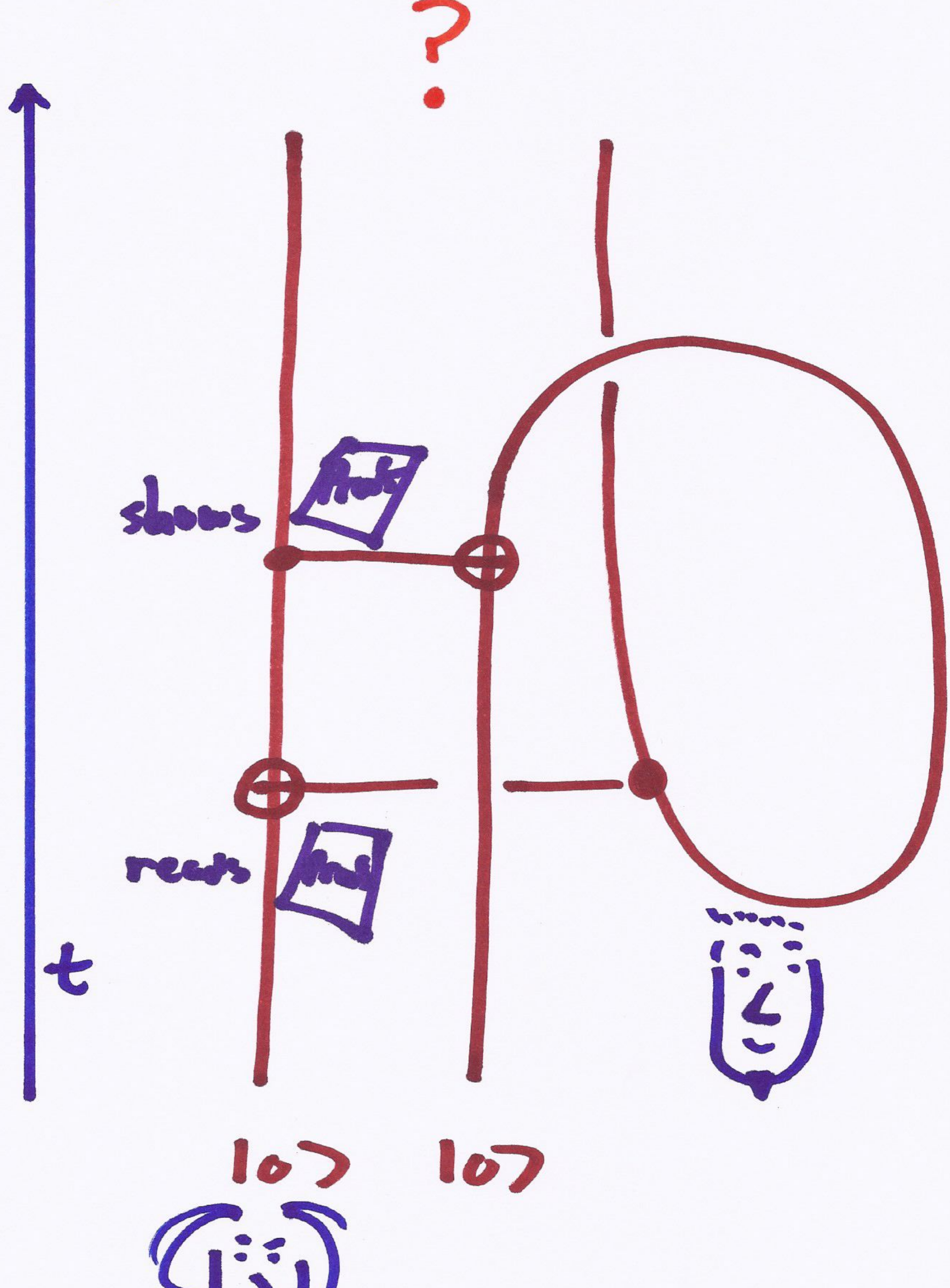
⇒  never kills 

Unproved theorem paradox:



Where did the proof come from?

Unproved theorem paradox circuit



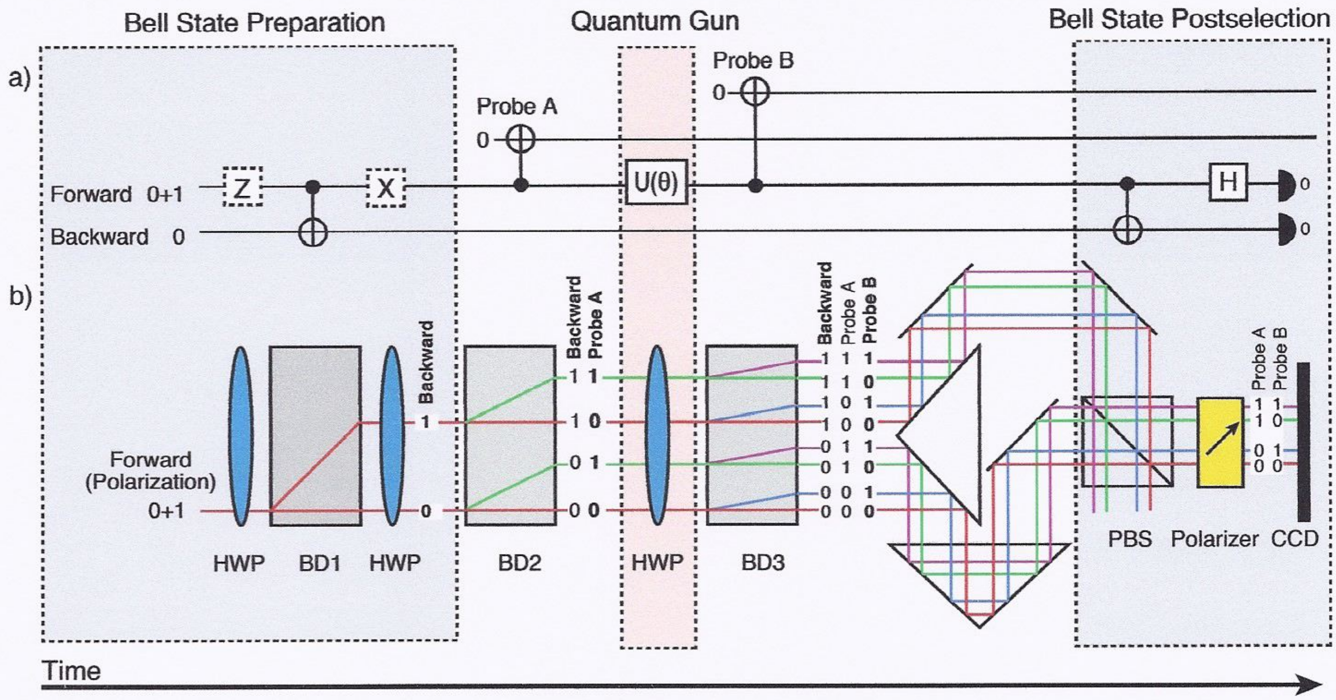


Figure 3: Experiment to implement the grandfather paradox via a post-selected CTC. a) Diagram of the quantum circuit. Using a CNOT gate sandwiched between optional Z and X gates, it is possible to prepare all of the maximally entangled Bell states. The Bell state measurement is implemented using a CNOT and a Hadamard. Each of the probe qubits is coupled to the forward qubit via a CNOT gate. b) Diagram of experimental apparatus. The polarization and path degrees of freedom of single photons from a quantum dot (see methods section) are entangled via a calcite polarization-dependent beam displacer (BD1), implementing the CNOT. Half-wave plates (HWP) before and after BD1 implement the optional Z and X gates, allowing any arbitrary Bell state to be generated. The state $|\phi^+\rangle$ is created by setting the angle of both HWPs to zero. The postselection onto $|\phi^+\rangle$ is carried out by first recombining the path degrees of freedom on a polarizing beamsplitter (performing a CNOT gate between path and polarization) and then passing the photons through a calcite polarizer set to 45°. The photons are then detected on a CCD. A rotatable HWP acts as a quantum gun, implementing the unitary $U(\theta) = e^{-i\theta\sigma_x}$. The "accuracy" θ of the quantum gun can be varied from $U(0) = \mathbf{1}$ (the gun always misses) to $U(\pi) = \sigma_x$ (the gun never misses) by rotating the HWP. Calcite beam displacers (BD2 and BD3) couple the polarization qubit to two probe qubits encoded in additional spatial degrees of freedom. To independently test the teleportation circuit, BD2 and BD3 are removed from the setup via translation stages to decouple the probe qubits from the loop. When the beam displacers are inserted into the setup, four spots appear on the CCD corresponding to the probe states 11, 10, 01, and 00.

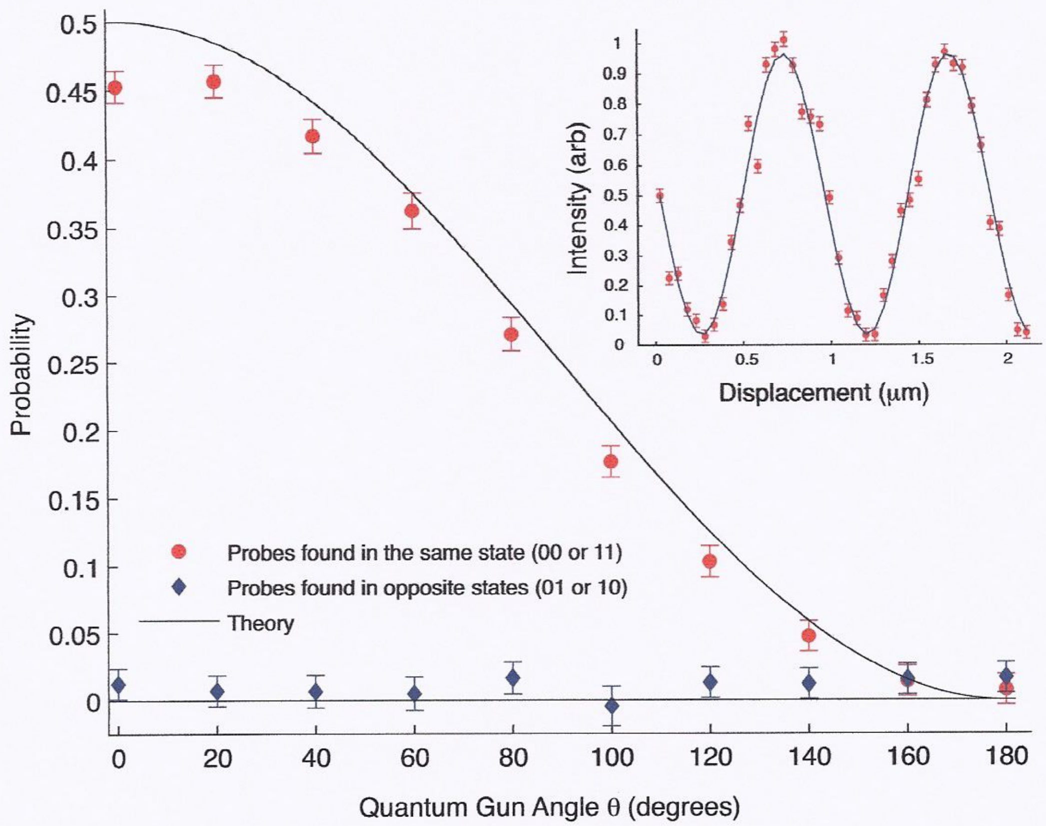


Figure 4: Probability that time travel succeeds and the probes are found in the same state (red circles) or in opposite states (blue diamonds). When the quantum gun "misfires", the polarization qubit is not flipped and the probe qubits are found in either the 00 or 11 state. As the accuracy of the quantum gun increases (θ increases from 0 to π), the probability that the teleportation succeeds decreases. When the quantum gun "kills" the photon (flips the polarization qubit), the probes record opposite values (01 or 10). The probability that the probe qubits are found in either the 10 or 01 state is 0.01 ± 0.04, indicating that the photons never succeed in travelling back in time and killing their former selves. Solid curves correspond to theoretical predictions. The discrepancy between theory and experiment when the probes are found in the same state is due to a $1.1 \pm 0.1^{\circ}$ mismatch between polarizers used in the state creation and measurement portions of the teleportation circuit. Data were collected for 6 seconds at each point. The error bars are due to photon counting statistics and background fluctuations from the cooled CCD. Inset: As explained in the methods section, the implementation of the teleportation loop constitutes a polarization interferometer. The visibility of this interferometer was measured by varying the phase (path-length difference) between the two paths, converting $|\phi^{+}\rangle$ to $(1/\sqrt{2})(|00\rangle + e^{i\phi}|11\rangle)$ before postselecting on $|\phi^{+}\rangle$. The observed visibility of $93 \pm 3\%$ confirms that the teleportation is functioning correctly.

Future work:

- computational power
- uniqueness
- more experiments
- general relativity