Diving into traversable wormholes

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IAS

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Based on 1704.05333 with Juan Maldacena and Zhenbin Yang, following up on 1608.05687 by Ping Gao, Daniel Jafferis, and Aron Wall.

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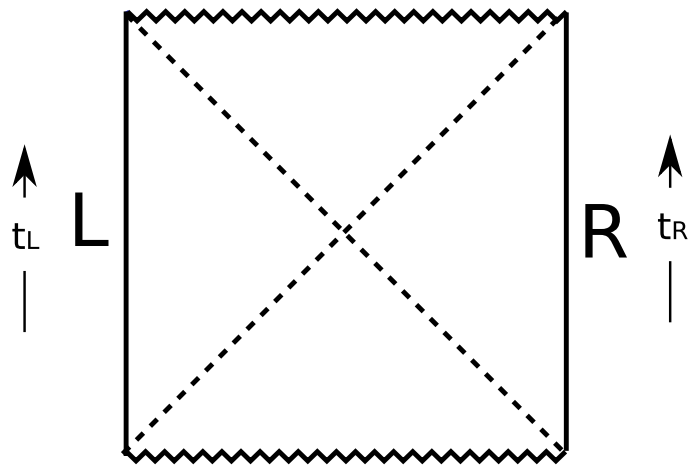
Plan:

- The thermofield double
- Negative energy in QFT
- Making wormholes traversable
- A limited application to the BHIP

The thermofield double


L
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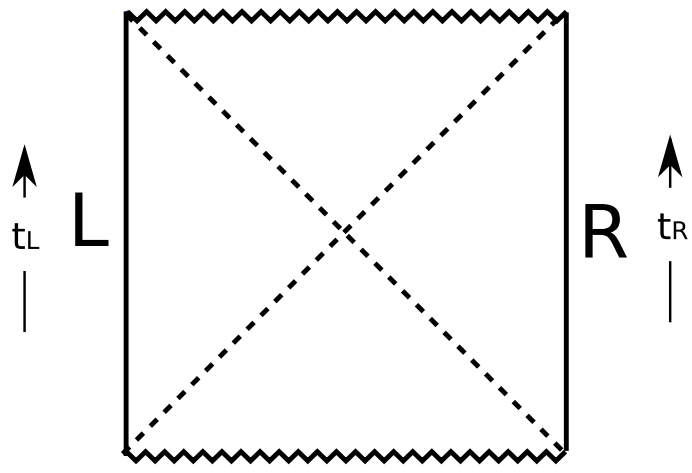
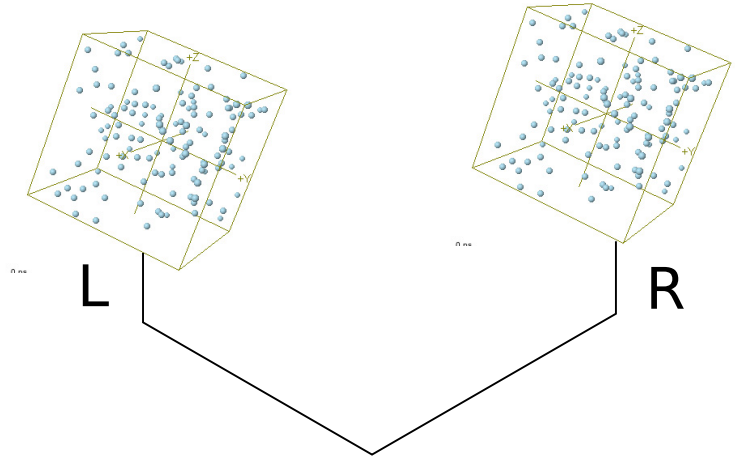
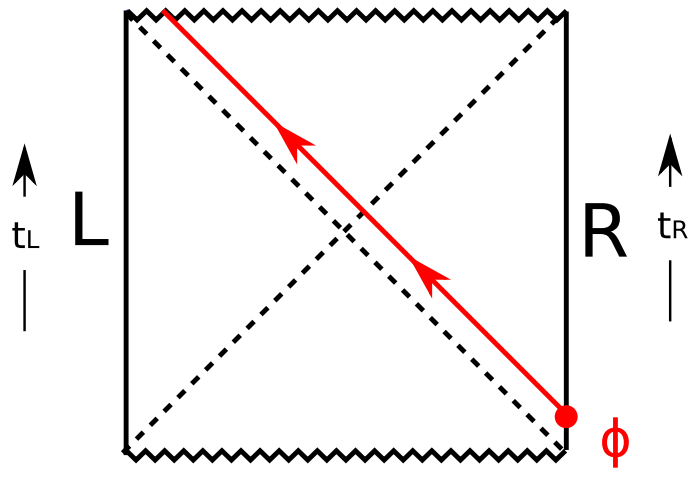
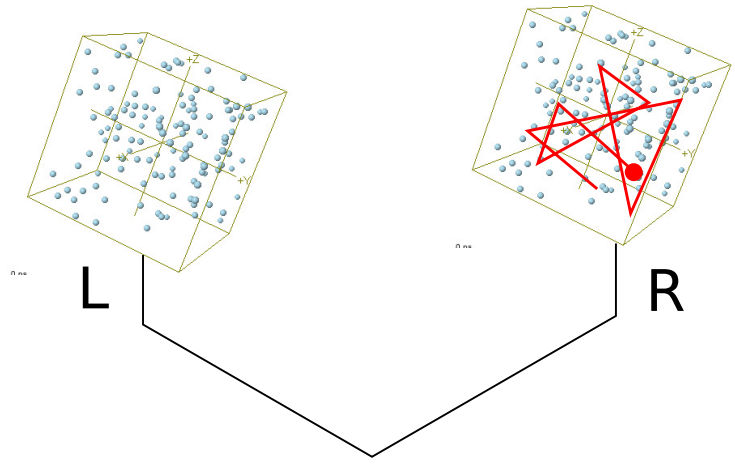




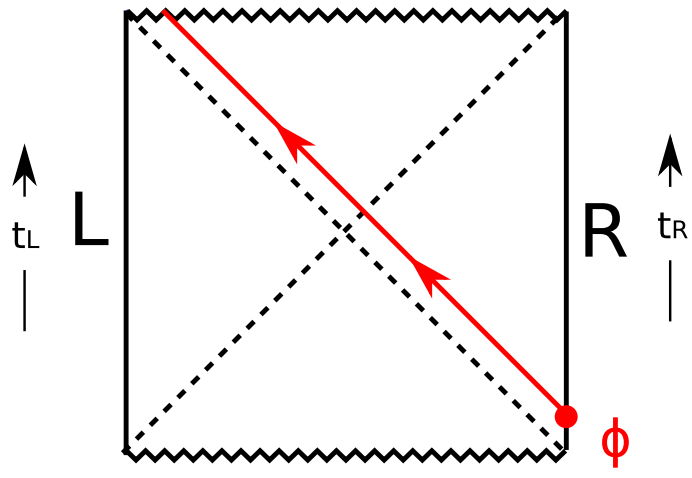
$$|TFD\rangle = \sum_n e^{-\beta E_n/2} |E_n\rangle_L |E_n\rangle_R$$

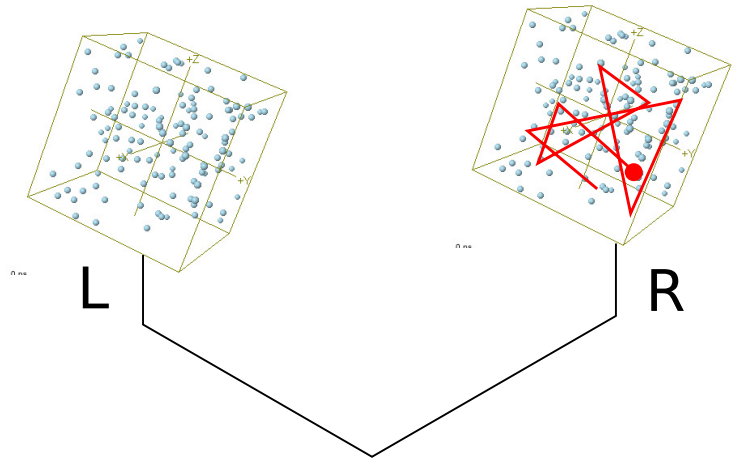
[Israel,Maldacena]





$$\phi_R|TFD\rangle = \sum_n e^{-\beta E_n/2}|E_n\rangle_L \phi |E_n\rangle_R$$

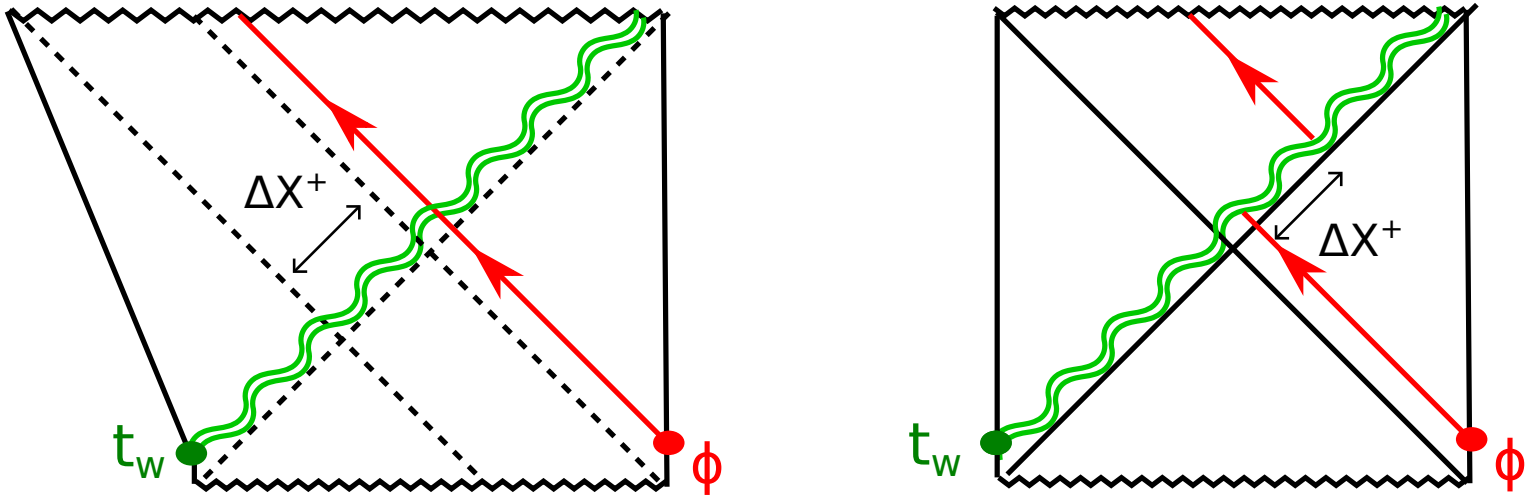




$$\phi_R|TFD\rangle = \sum_n e^{-\beta E_n/2}|E_n\rangle_L \phi |E_n\rangle_R$$

Non-traversability looks robust on QM side but delicate in gravity?

The perturbed thermofield double



$$\Delta X^+ = G_N P^+ = G_N \int_{-\infty}^{\infty} dx^- \, T_{--} > 0$$

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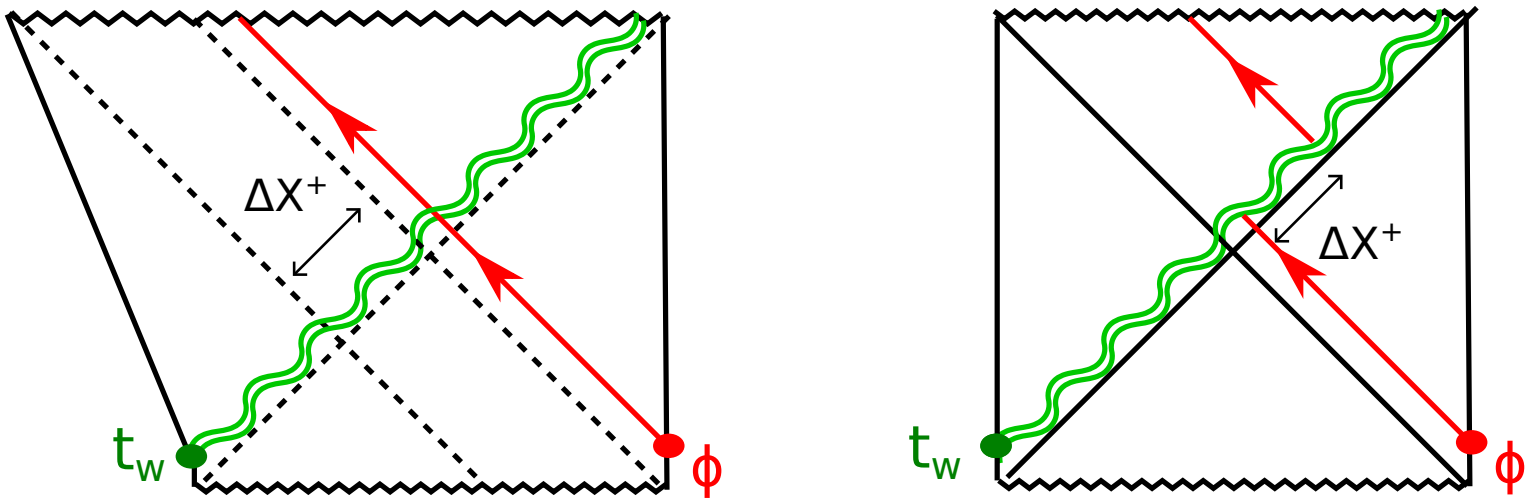

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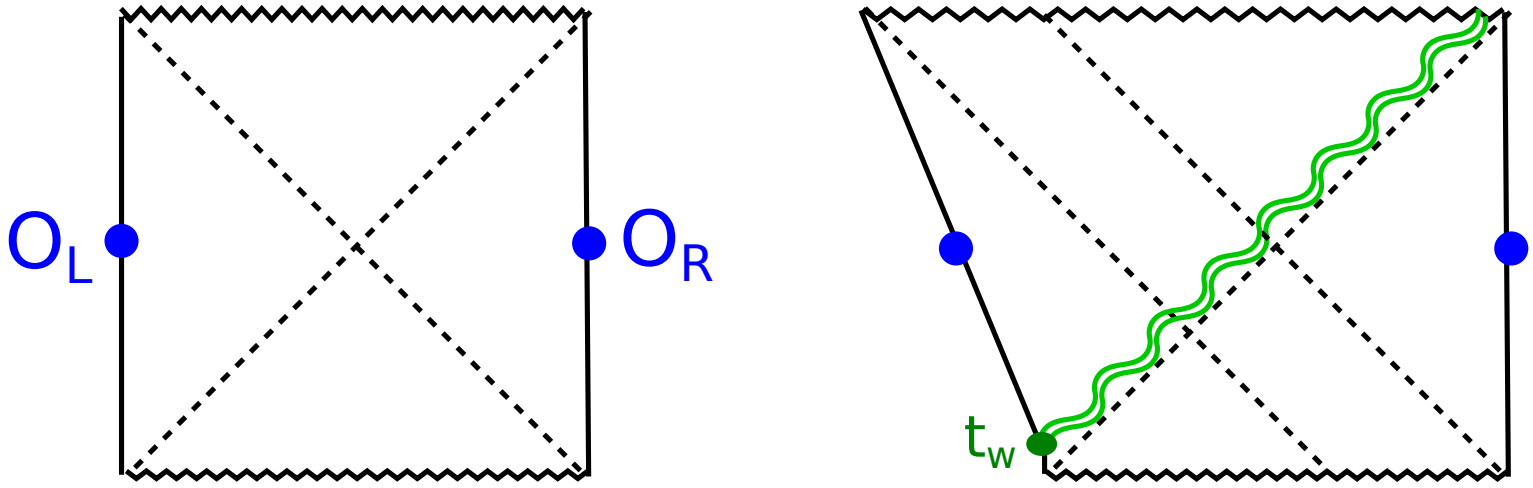
Averaged null energy condition (ANEC) makes non-traversability robust on gravity side too. [Morris,Thorne,Yurtsever]

Recent ANEC proofs: [Faulkner,Leigh,Parrikar,Wang][Hartman,Kundu,Tajdini]

Correlations and chaos



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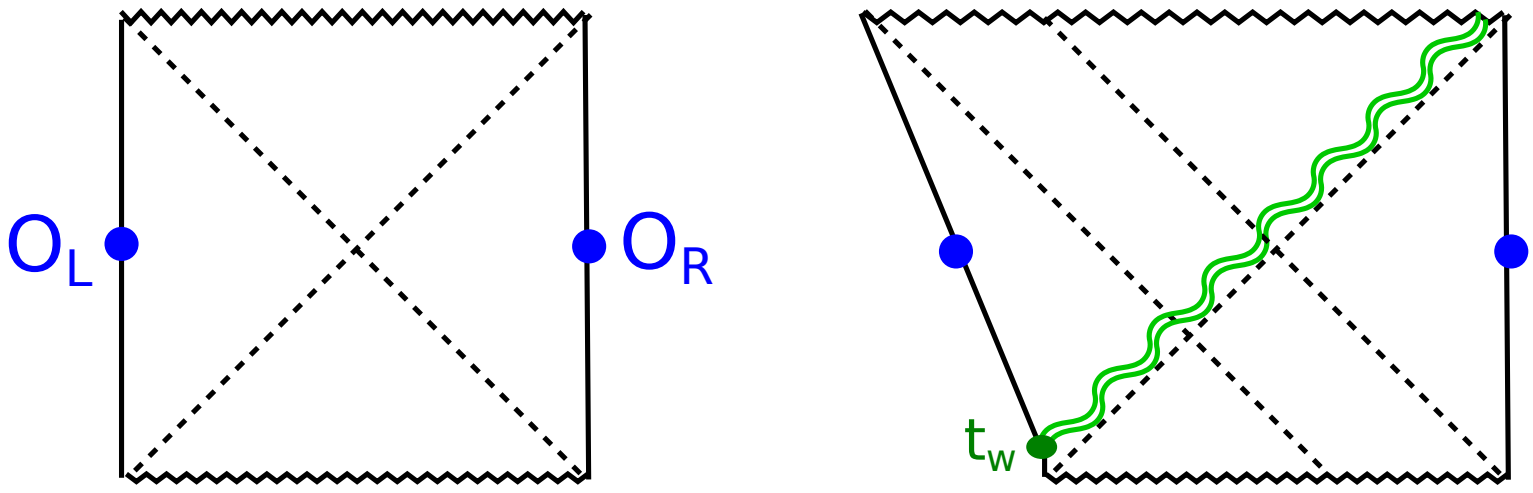

$$\frac{\langle O_L O_R \rangle}{\langle TFD | O_L O_R | TFD \rangle} = 1 - G_N e^{\frac{2\pi}{\beta}|t_w|} + \ldots$$

Becomes small around the "scrambling time" $t_* \sim \frac{\beta}{2\pi} \log \frac{1}{G_N}$.

[Hayden,Preskill][Sekino,Susskind][Shenker, DS][Kitaev][Maldacena,Shenker,DS]

Negative energy in QFT

$$S = -\frac{1}{2}\int d^2x(\partial O)^2,$$

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$$\langle\Psi|T_{00}(x)|\Psi\rangle = -ig\langle 0|[O_L O_R, T_{00}(x)]|\Psi\rangle + O(g^2).$$

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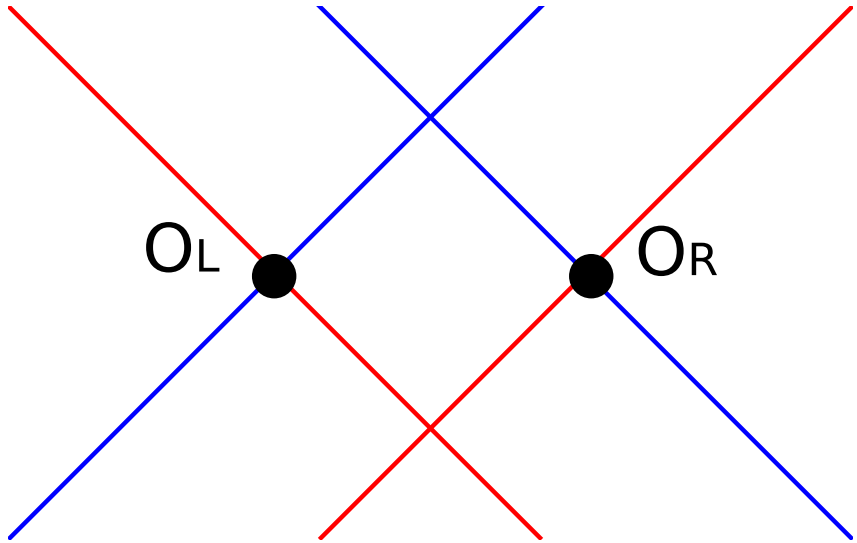

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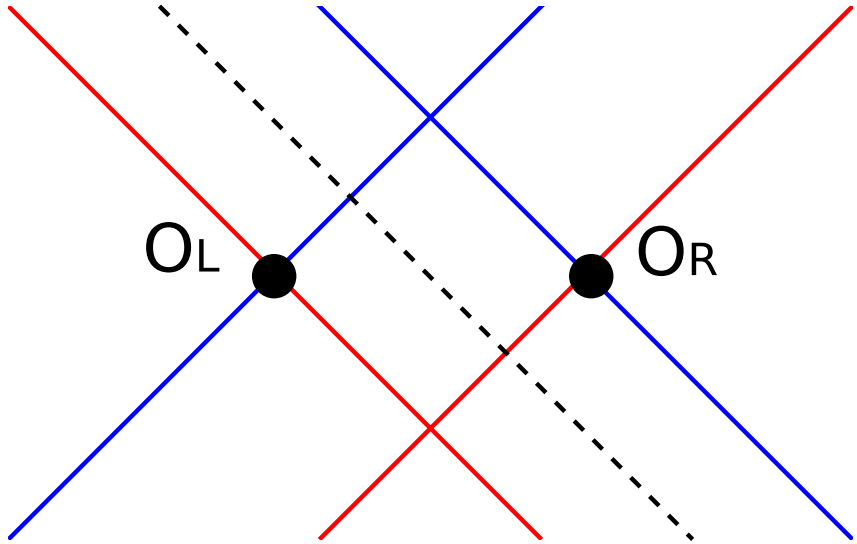
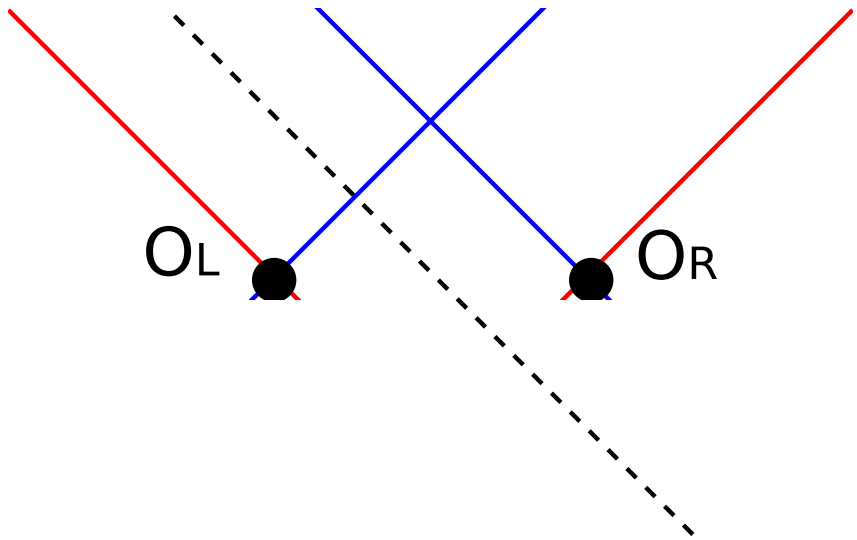


$$P^+ = \int \langle T_{--}\rangle dx^- = 0$$

Can instead think of a history with time-dependent Hamiltonian: start with vacuum, then at $t = 0$ act with $e^{igO_L O_R}$:

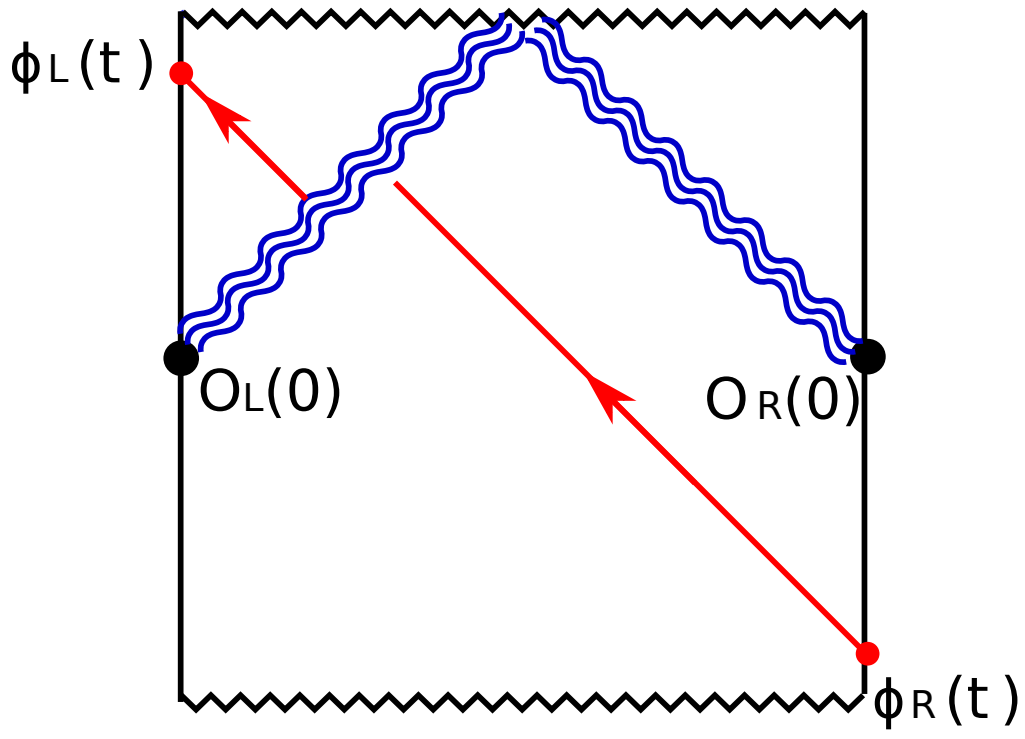


$$P^+ = \int \langle T_{--} \rangle dx^- < 0$$

Making wormholes traversable

Gao-Jafferis-Wall

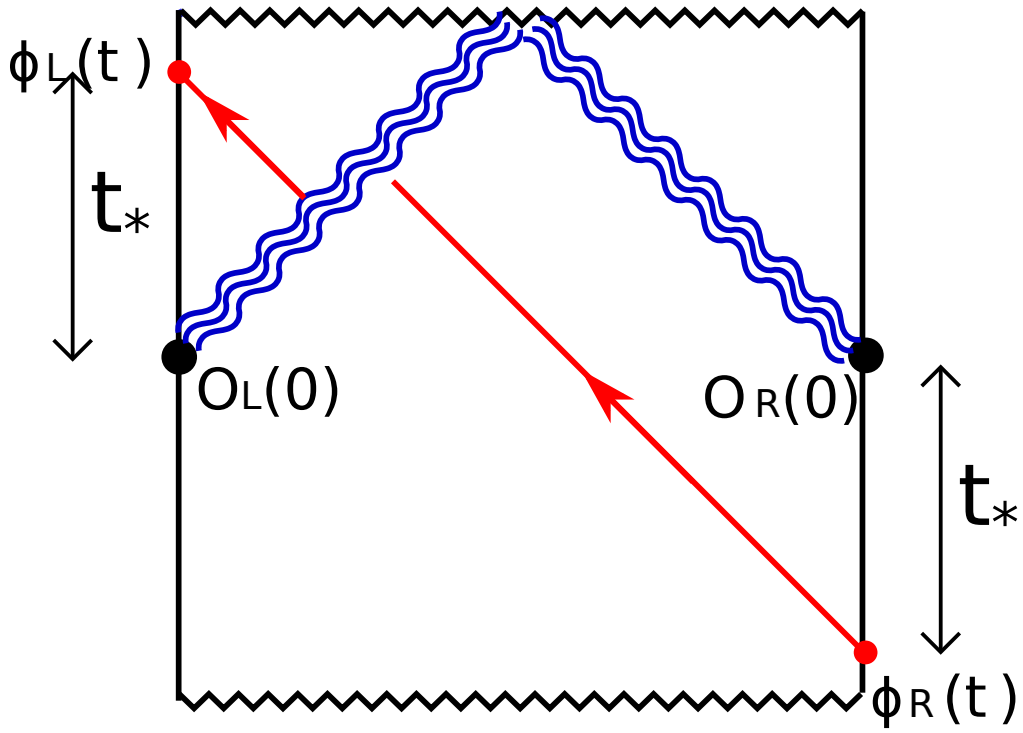
Start with TFD state where we have added a signal from R. Then at $t = 0$, apply $e^{igO_L O_R}$ (more precise version: $e^{i\frac{g}{K}\sum_{j=1}^{K} O_L^{(j)} O_R^{(j)}}$):



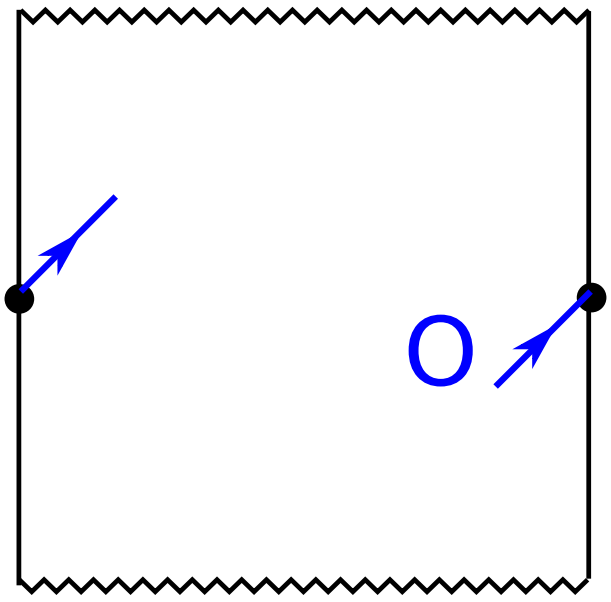
Wormhole becomes traversable.

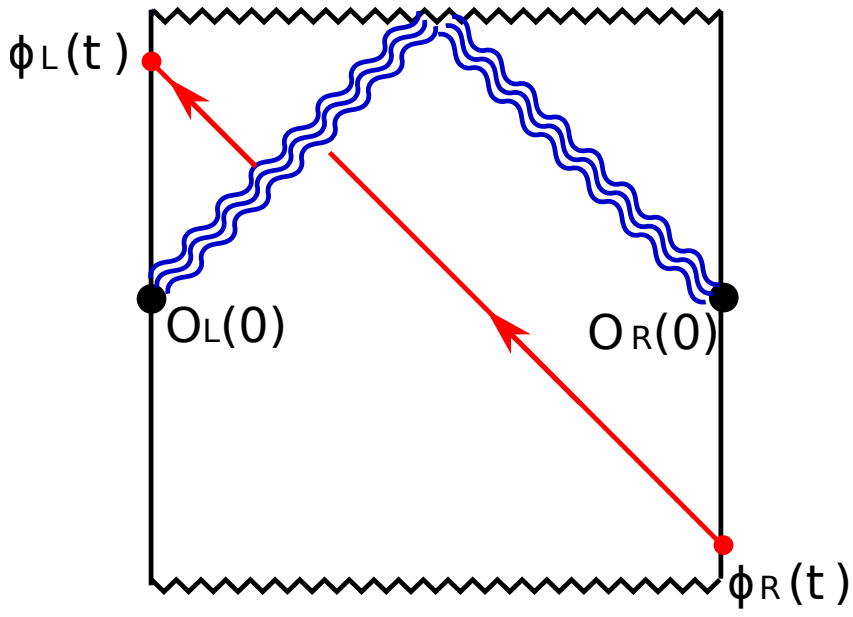
Amplification by chaos

Traversability happens when $G_N e^{\frac{2\pi}{\beta}|t|}$ becomes order one, $|t| \sim t_*$



Is it surprising?

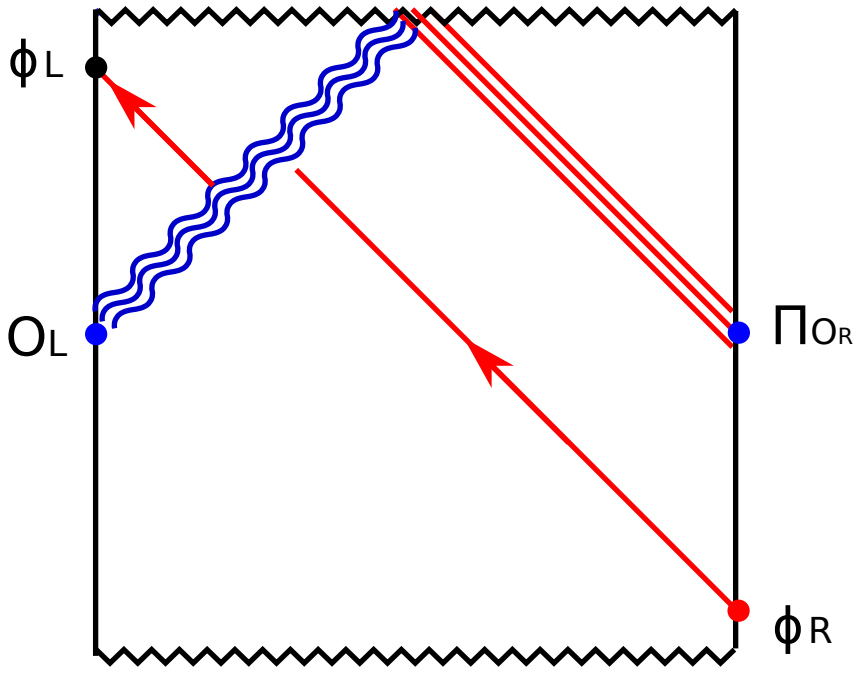




Teleportation interpretation

Teleportation interpretation

Instead of applying $e^{igO_L O_R}$, can measure O_R, get result o_R and then apply $e^{igO_L o_R}$ on the L system. This has the same effect:



Comfortable quantum teleportation!

A limited application to the BHIP

Simplified gravity in AdS_2

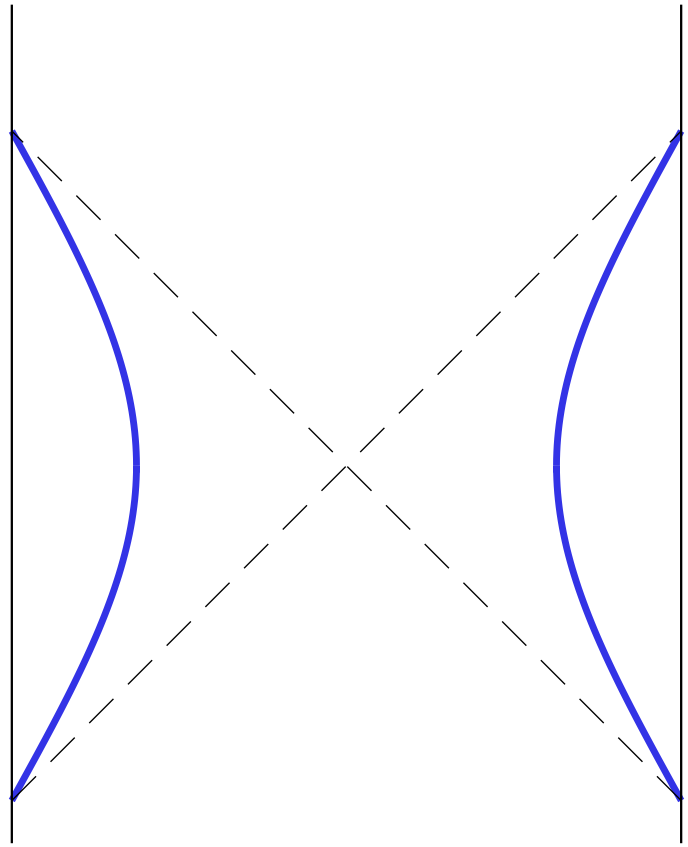
Jackiw-Teitelboim gravity:

$$S = \frac{1}{G_N}\int d^2x\sqrt{-g}\,\Phi\,(R+2) + \frac{2}{G_N}\int_{bdry}\Phi K$$

After integrating over Φ we set $R+2=0$ so geometry is rigid AdS_2. Only degree of freedom is the location of the boundary. The dynamics for this is equivalent to a particle in an electric field in AdS_2.

The thermofield double

$|TFD\rangle =$ uniformly accelerated R, L trajectories:



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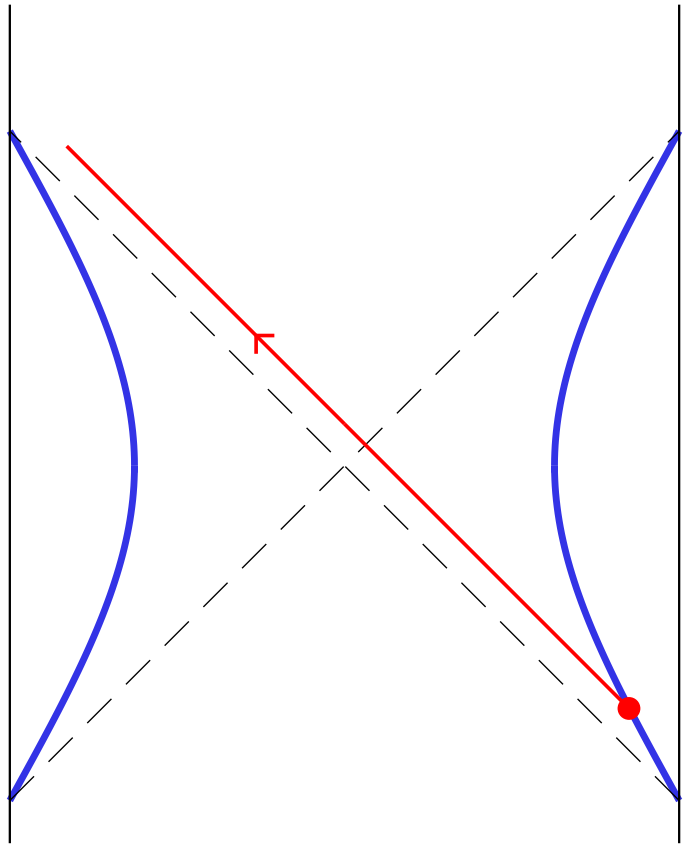
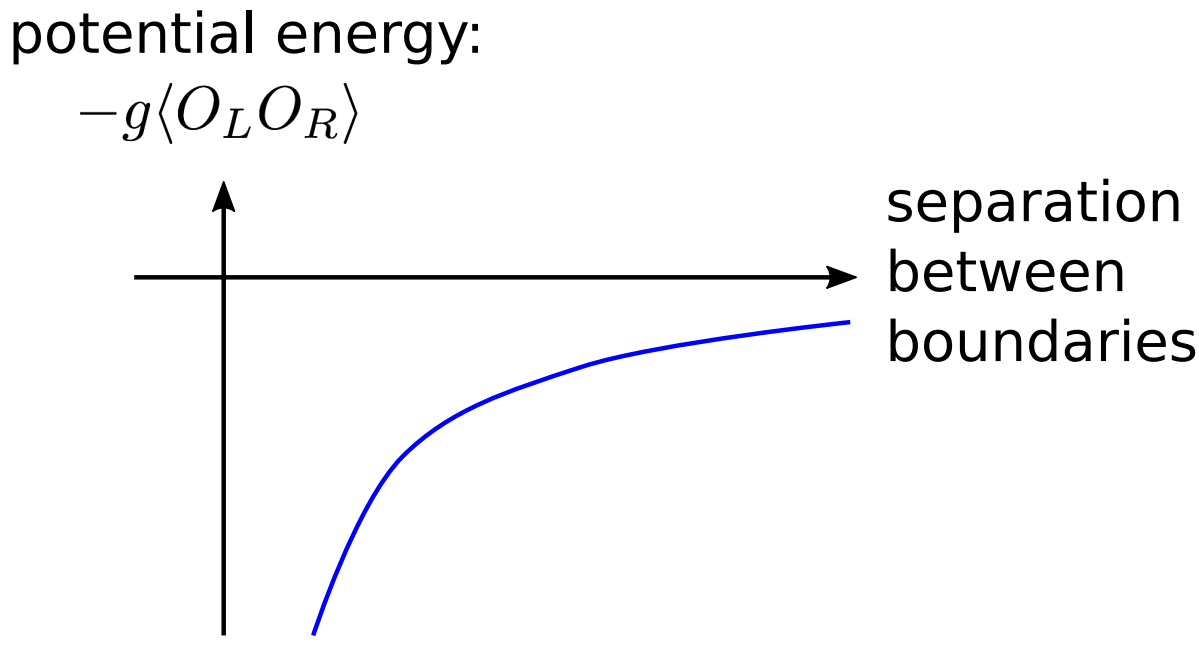


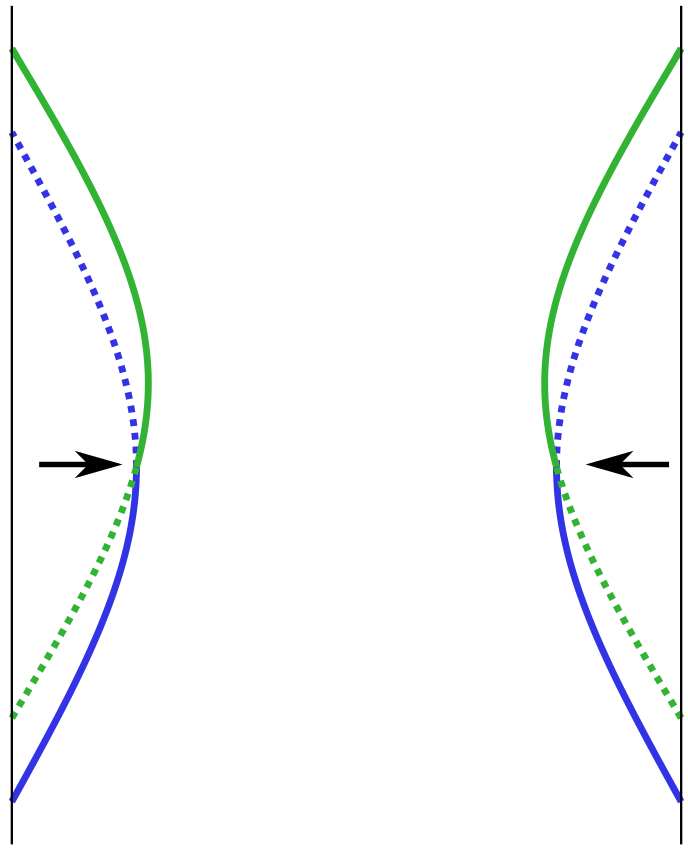
The traversable wormhole protocol

Acting with $e^{igO_LO_R}$ can be approximated by adding $-g\langle O_LO_R\rangle$ to the potential energy. This is an attractive potential



so turning it on briefly gives an impulsive force.

The traversable wormhole protocol



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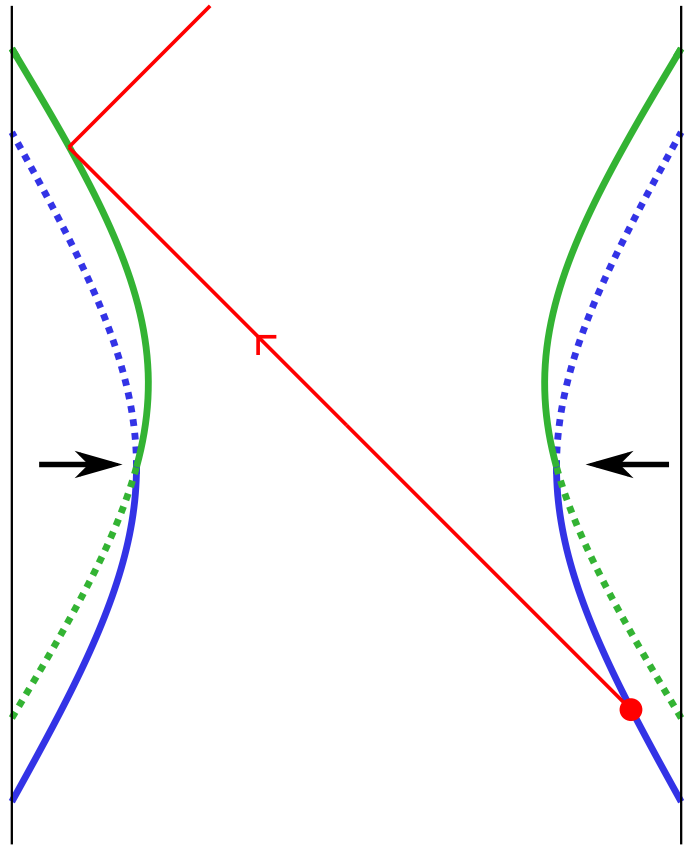
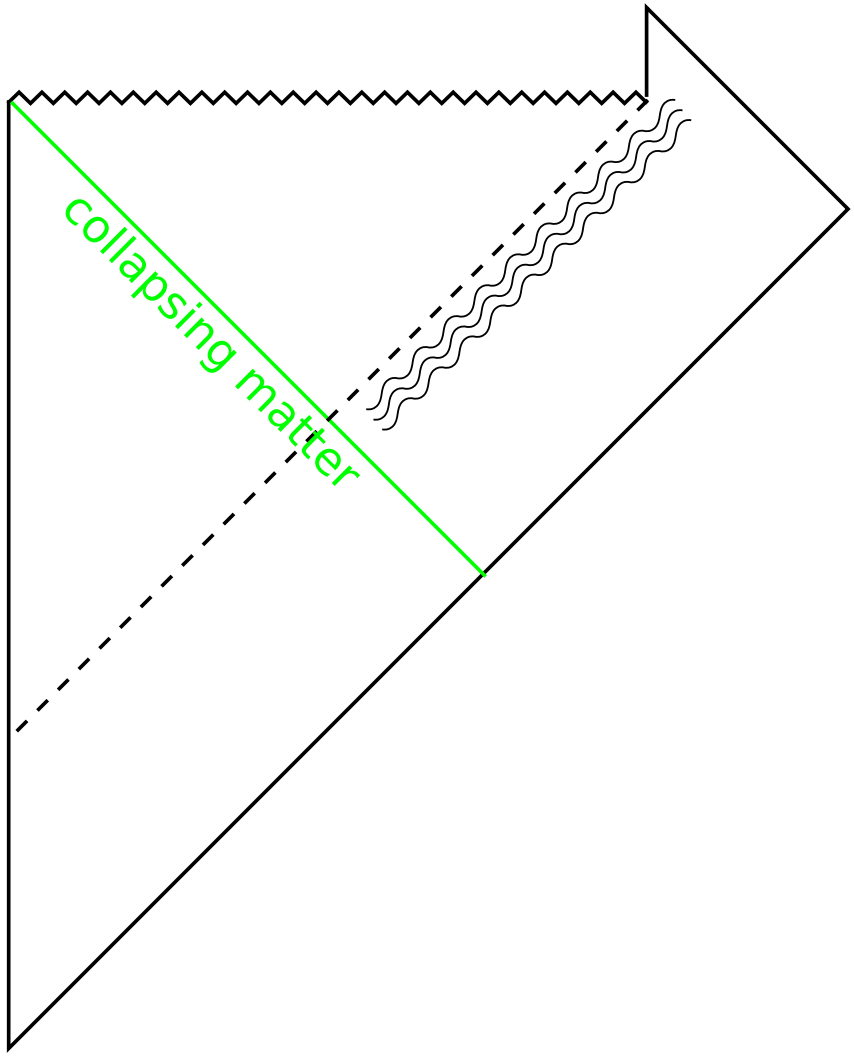
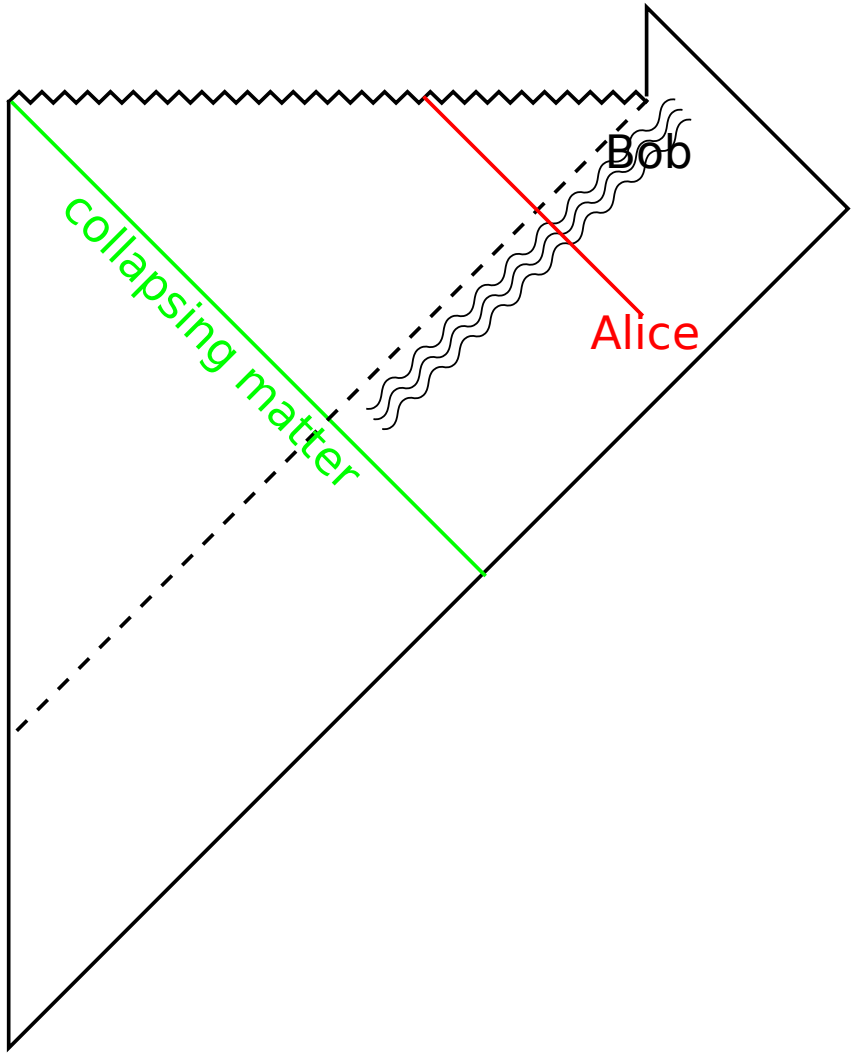


Review: Hayden-Preskill



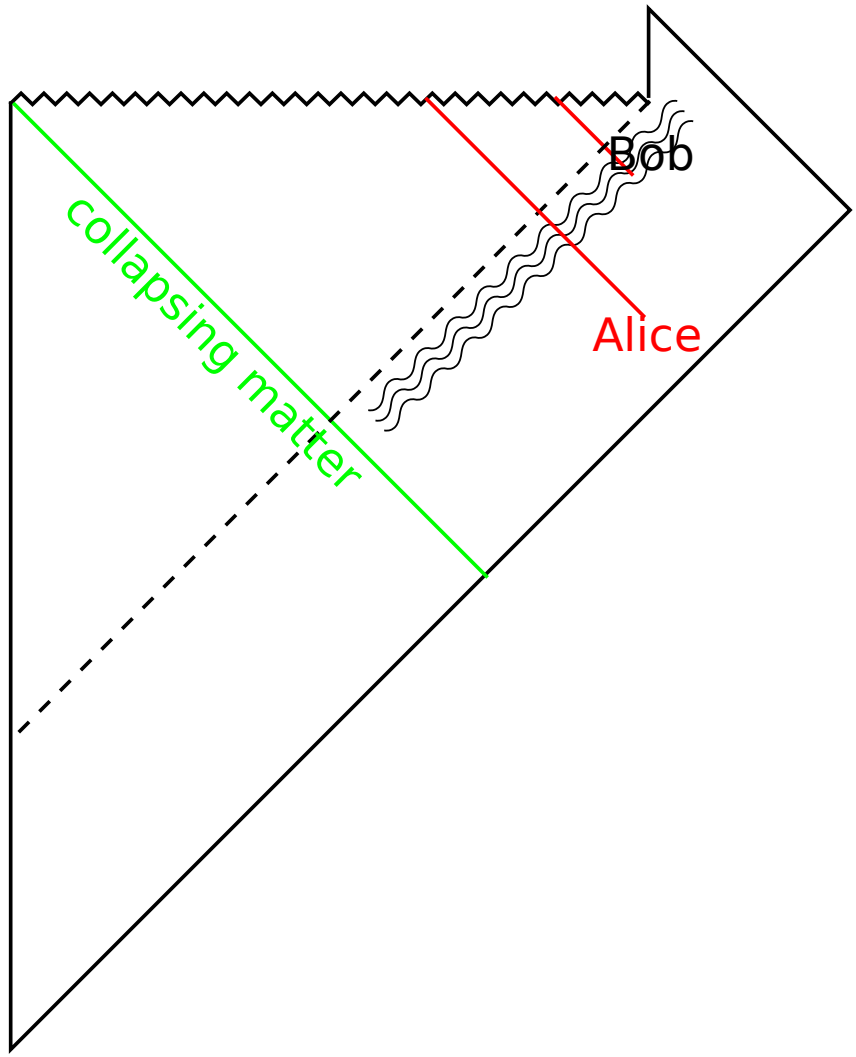
(1) A black hole forms from collapse. We wait until it evaporates halfway, becoming maximally entangled with its Hawking radiation.

Review: Hayden-Preskill



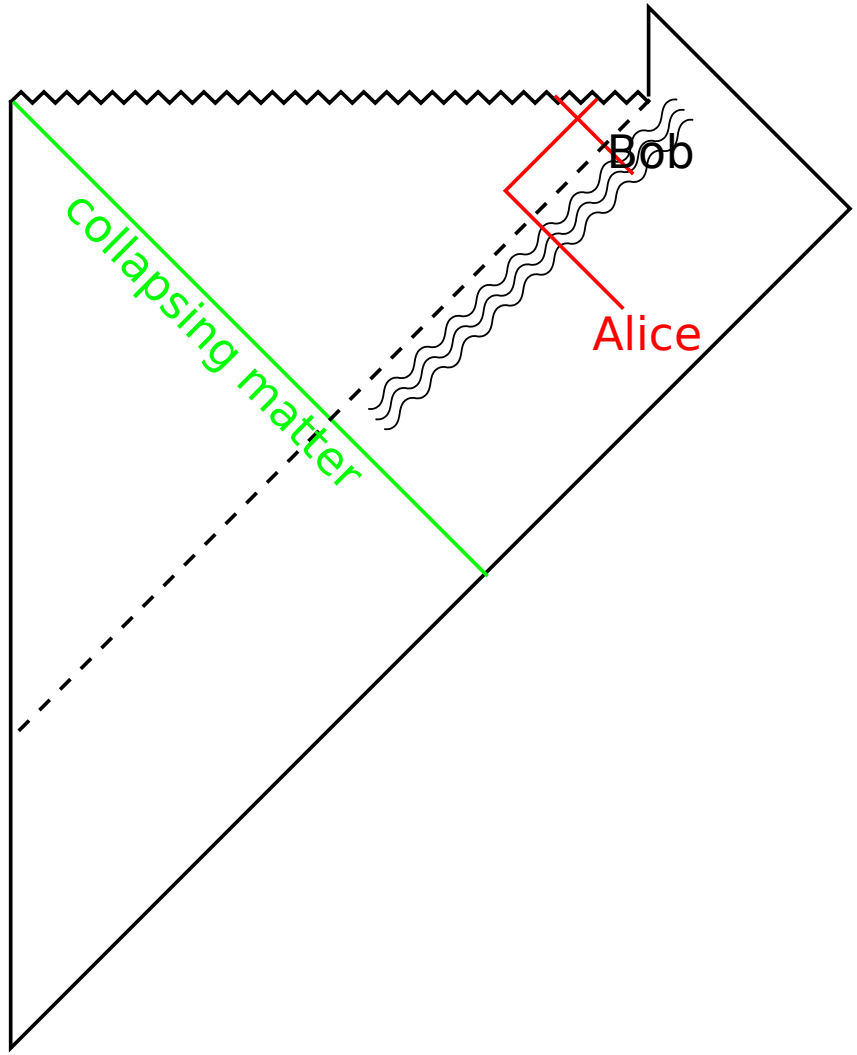
(2) Alice throws a bit into the black hole.

Review: Hayden-Preskill

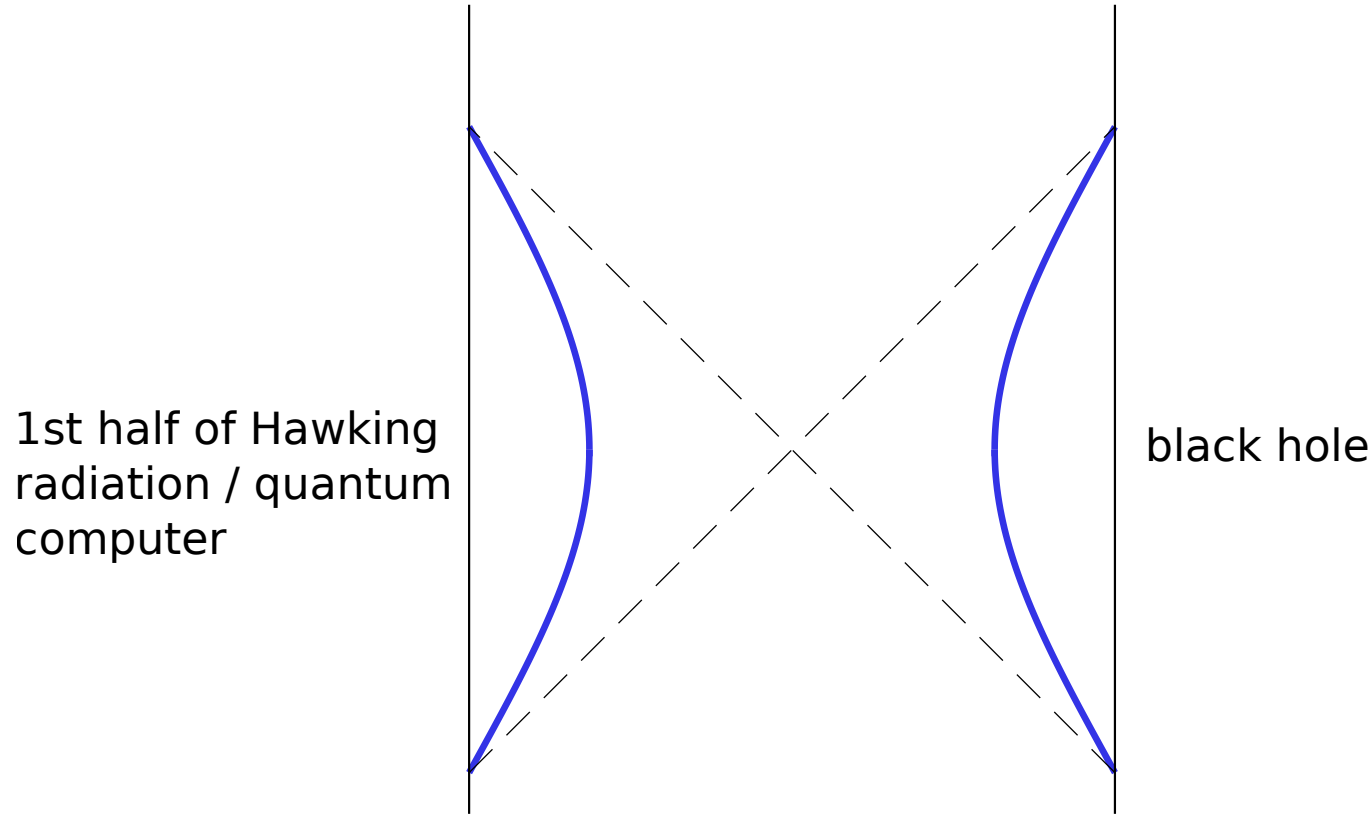


(3) Bob grabs a couple more quanta after Alice's bit falls in. Feeding this plus the first half of the radiation into a quantum computer, he can decode Alice's bit!

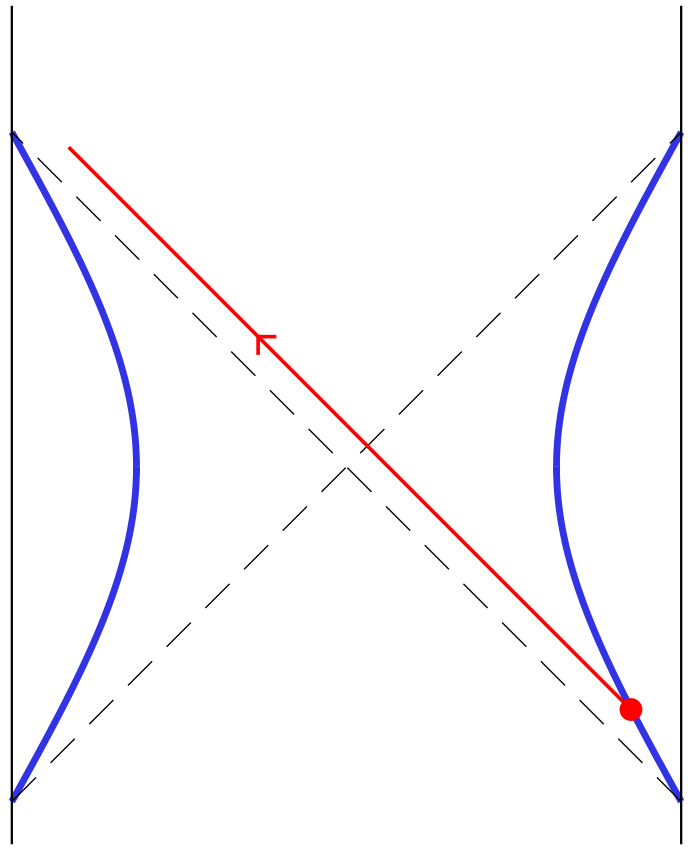
Review: Hayden-Preskill



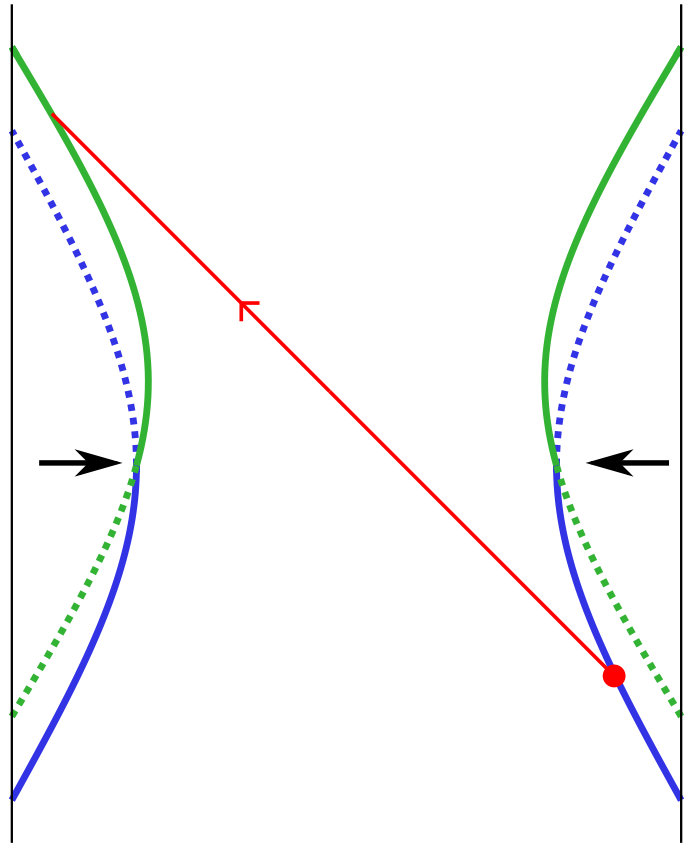
(4) If he then jumps in with his copy, it looks like there is quantum cloning. :(



(1) Half evaporated black hole (R) is maximally entangled with radiation, which our quantum computer is storing as a simulated black hole (L).

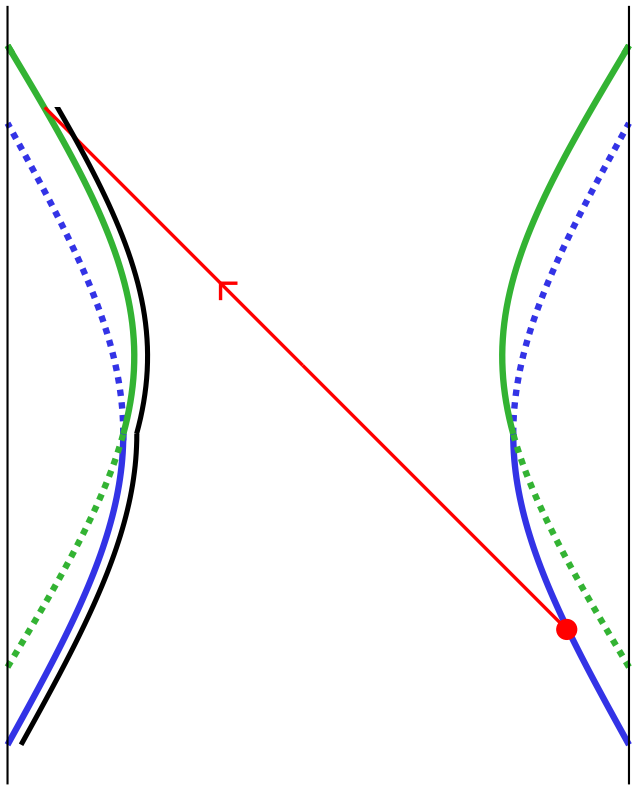


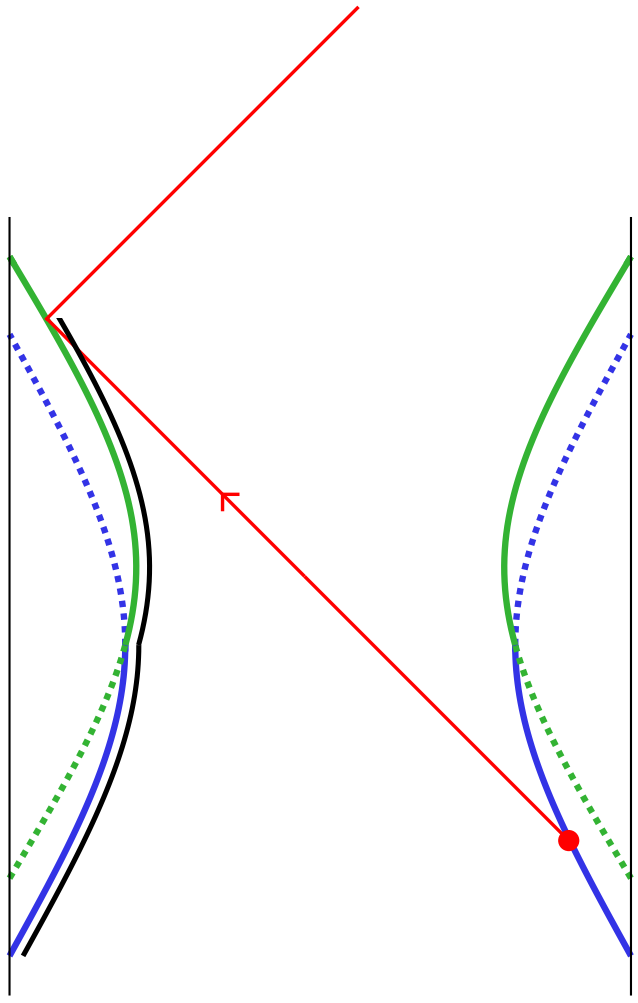
(2) Alice throws bit into BH.



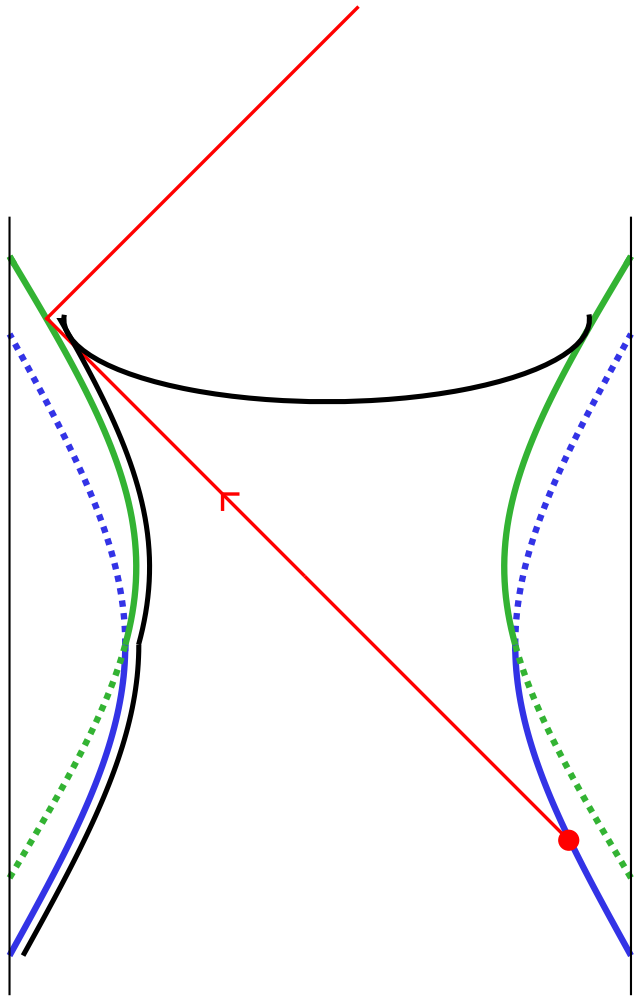
(3) Bob waits a while, then collects a few more quanta from R and acts on L with them. Wormhole becomes traversable and the bit propagates to Bob's computer.

What about cloning?

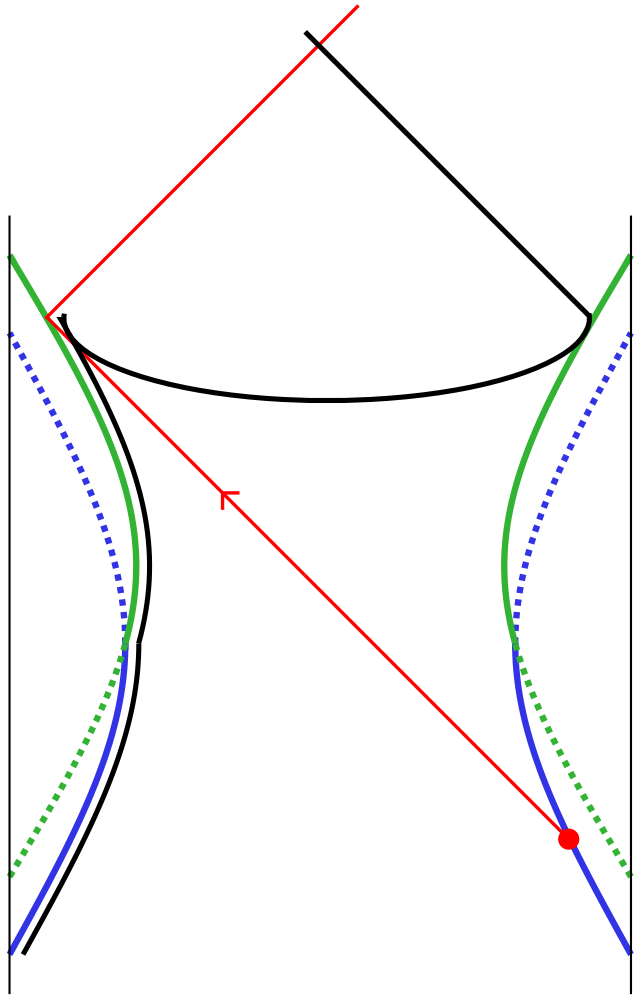




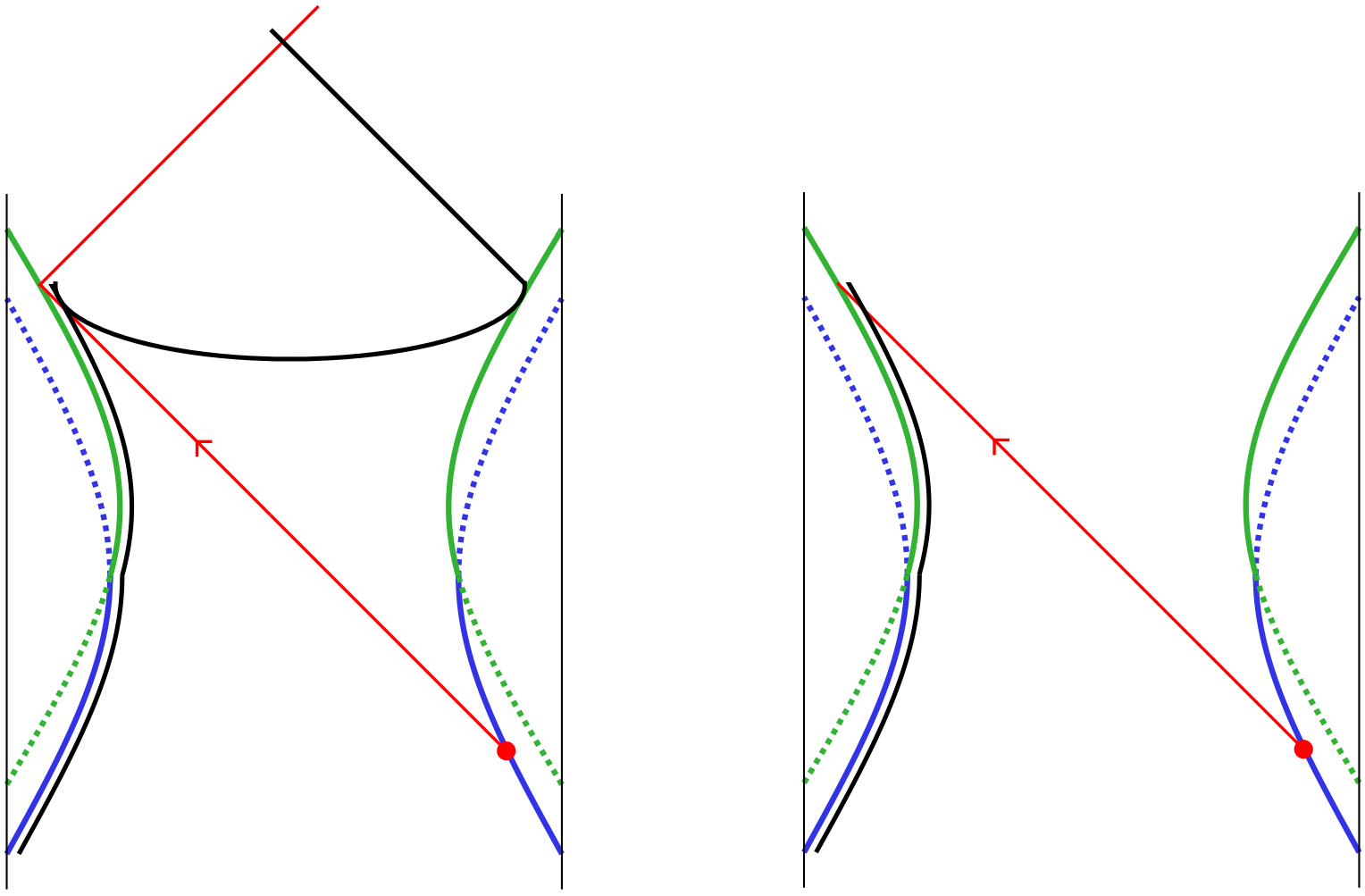
Bob doesn't extract the bit from the quantum computer. It reflects off the boundary.



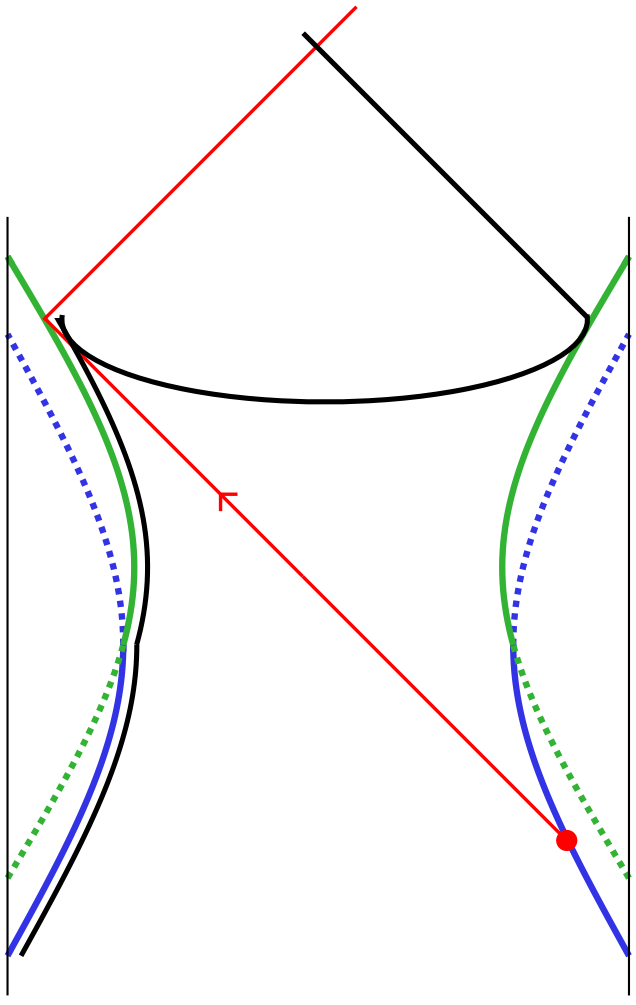
Bob disconnects form the quantum computer and jumps into the black hole.

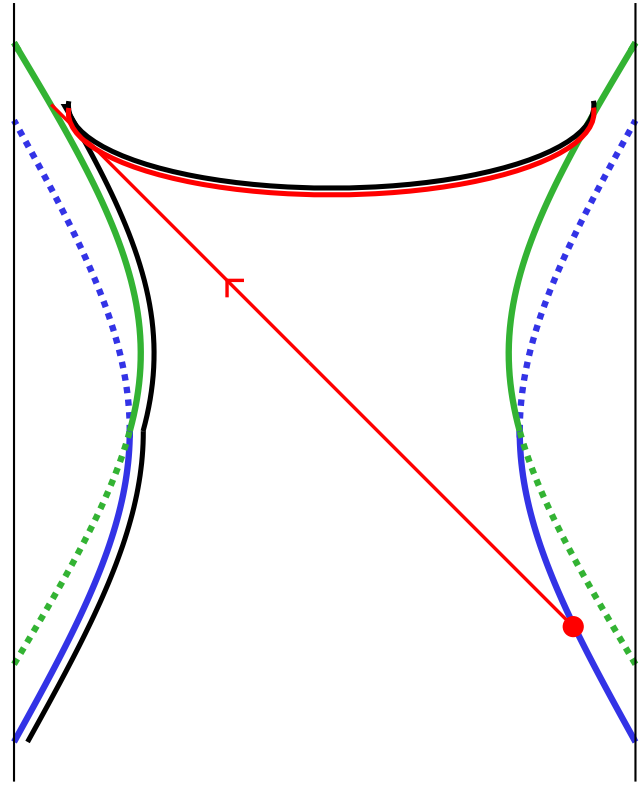


He finds the bit behind the horizon.

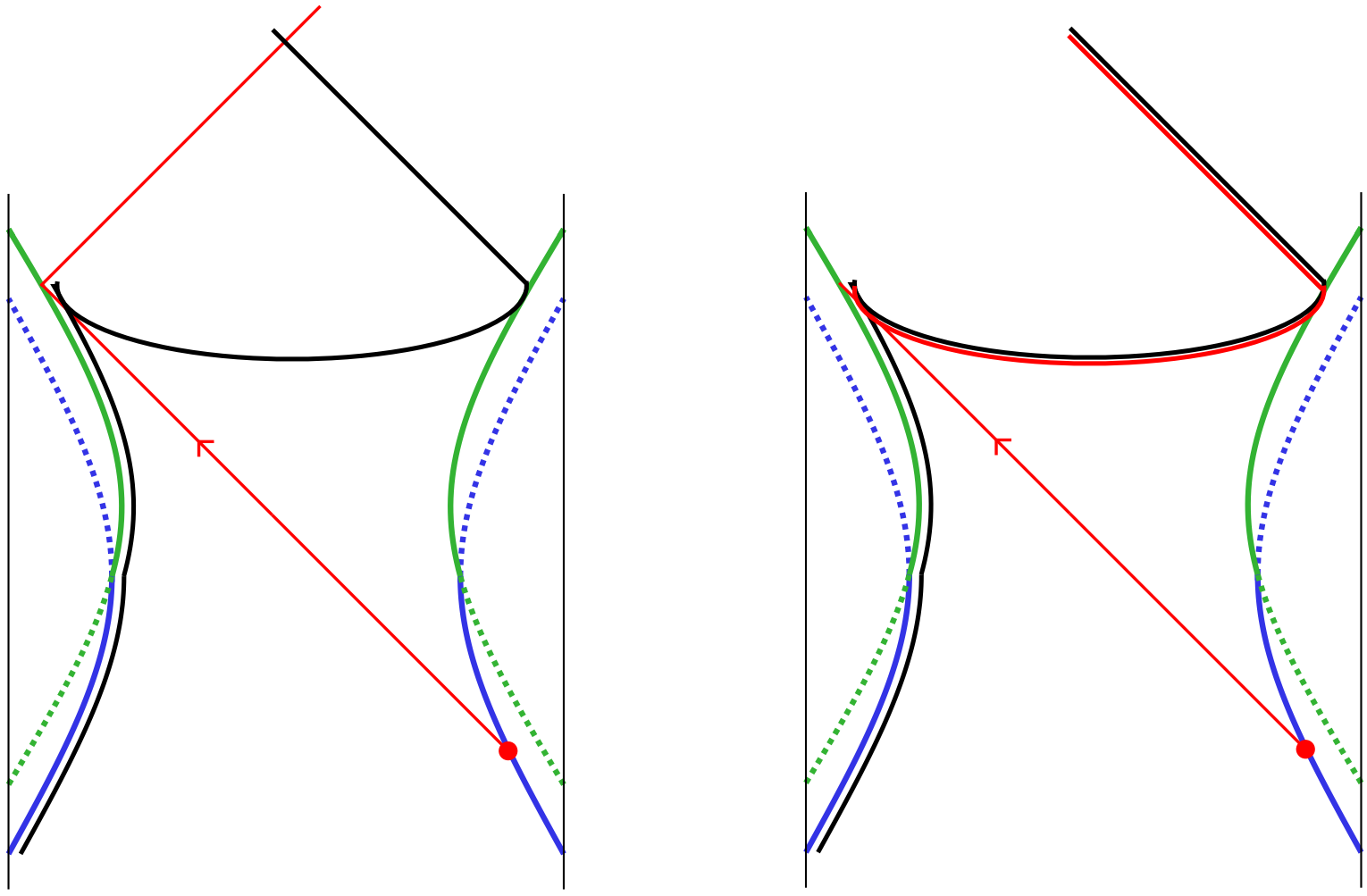


Alternatively, Bob can extract the bit from the quantum computer...



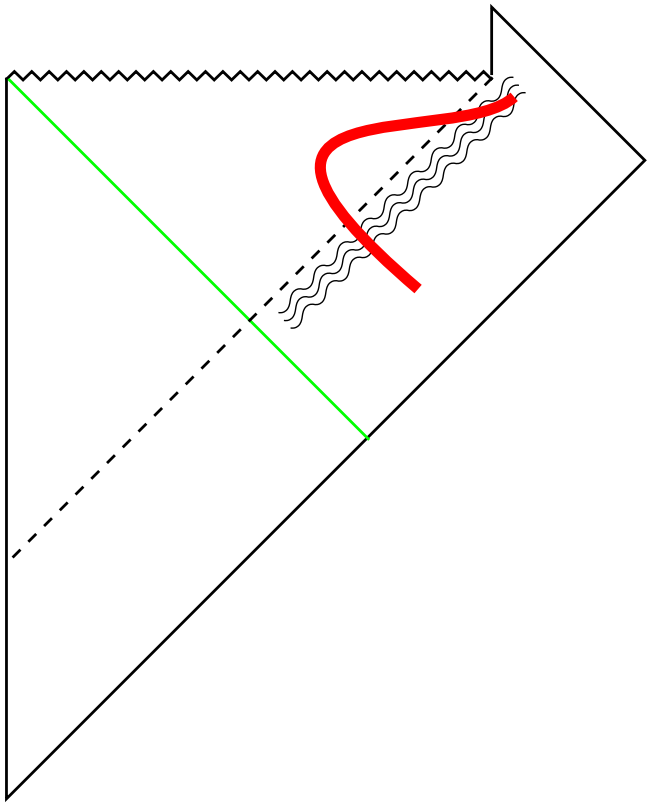


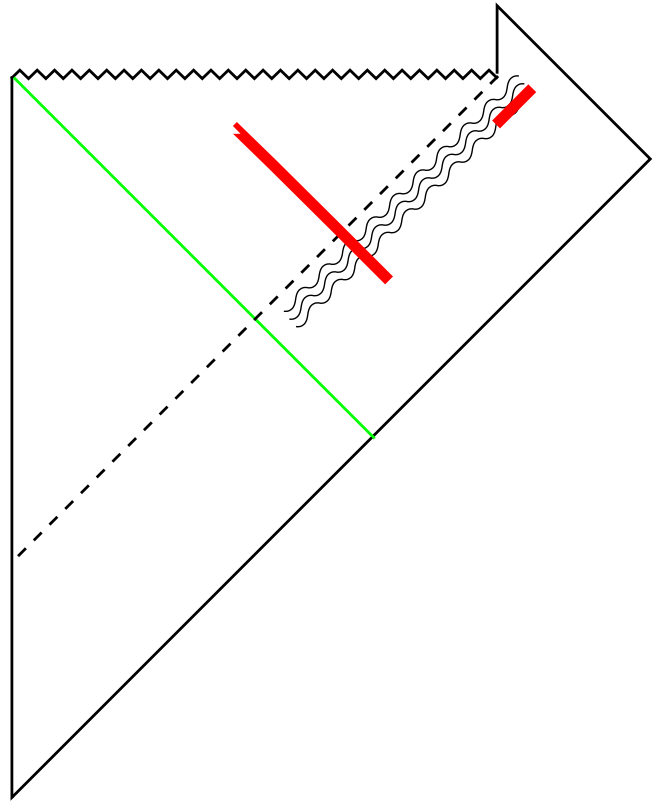
... carry it over to the black hole...



... and dive in with it. Now he is carrying a copy but there is no second copy behind the horizon.

How to apply this to general black holes?





Where is the wormhole connecting the Hawking radiation to the interior? Better understanding of ER = EPR is needed.

[Maldacena,Susskind]

Summary

- By coupling the two sides of the TFD wormhole together, we can create negative energy that makes the wormhole traversable.
- This gives a geometrical realization of the Hayden-Preskill protocol.
- It makes it clear that cloning is avoided because the operation of recovering the information removes it from the region behind the horizon.
- We don't know how to apply this to evaporating black holes but ER $=$ EPR might help.

Happy Birthday Stephen!