Traversable wormholes via a Double Trace Deformation

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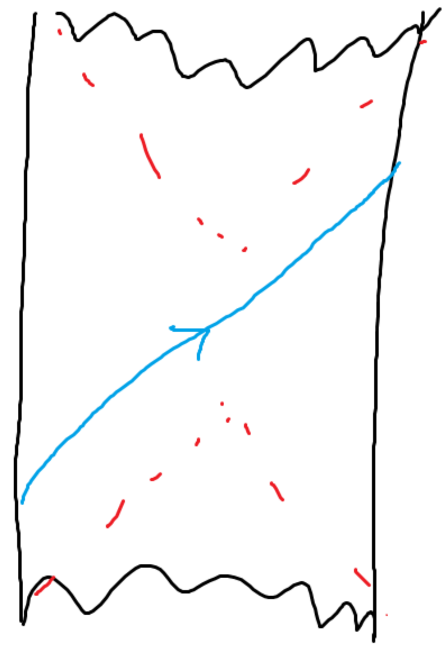
Introduction

- Find the first example of a traversable wormhole consistently embedded in quantum gravity.
- Turning on a direct boundary-boundary coupling in the eternal AdS black hole results in a negative Casimir energy that violates the ANEC along the horizon and opens the wormhole.
- Gives a method to operationally verify ER=EPR. It is a bulk analog of quantum teleportation interpreted as a dynamical quantum process.

Traversable wormholes

- A connection between distant locations. The following seems to be the first example that works in a consistent gravity theory.



Require negative ANE

- Consider a null geodesic that traverses the wormhole. On the ingoing side, there will be contraction of neighboring light rays.

- Thus traversability requires defocusing if the null ray is to reach the other boundary.

- By Rachaudhuri's equation, this requires negative null energy.

$$\int_{-\infty}^{+\infty} T_{\mu\nu} k^{\mu} k^{\nu} \, d\lambda < 0$$

Negative energy in QFT

- Although physically reasonable classical theories have positive null energy (otherwise the vacuum would be unstable), it is violated by certain states in any quantum field theory (no local operator can vanish in the vacuum and be positive in all states).

$$|\xi\rangle = \exp(\tfrac{1}{2}\xi^* a_0^2 - \tfrac{1}{2}\xi a_0^{\dagger 2})|0\rangle$$

- A typical example are squeezed states, which oscillate between positive and negative energy.

Ruled out in some contexts

- If the null geodesic is achronal, there are strong arguments that the ANEC is satisfied in QFT.

- Also, the generalized second law disallows the future horizon of a traversing worldline from having infinite area in the past.

- Moreover, there is a risk of constructing time machines by applying a relative boost.

Eternal AdS black hole

- Start with the eternal AdS black hole, dual to the thermofield double state in the decoupled product of two CFTs.

$$|\text{tfd}\rangle = \sum e^{-\beta E/2} |E_L\rangle \; |E_R\rangle$$

- The existence of the Killing symmetry implies that there is a bifurcation surface, and the spacetime is on the edge of traversability even including quantum corrections.

Non-traversable in any state

- It would contradict the duality and lack of interaction between the CFTs if the Einstein-Rosen bridge were traversable in any state.

- One can show that the bulk field vacuum is an eigenstate of the ANE with the lowest eigenvalue, 0.

$$\int_{-\infty}^{\infty} dU T_{UU} |\mathrm{tfd}\rangle = 0$$

$$\delta \mathrm{ANE} = i\langle [A, \mathrm{ANE}] \rangle = 0$$

Couple the CFTs dynamically

- Start in the eternal black hole state in the decoupled system and turn on an interaction at some time.

$$S_{\rm int} = \int dt\ d^{d-1}x\ h(t,x)\mathcal{O}_R(t,x)\mathcal{O}_L(t,x)$$

- This only affects the configuration in the future.

- Now there need not be any cancelation, so the ANE can change at leading order. Adjust the sign to make it negative.

Double trace deformations

- There change the boundary conditions for the dual scalar. The expectation value on the left acts as the source on the right, and vice versa.

- Need an operator with dimension less than d/2.

$$\Delta_{\pm} = \frac{d}{2} \pm \sqrt{(\frac{d}{2})^2 + m^2}$$

$$\varphi(r \to \infty_R) \to \alpha_R(t,\phi) r^{-\Delta} + \beta_R(t,\phi) r^{-2+\Delta}, \;\; \beta_L(t,\phi) = h(-t,\phi)\alpha_R(-t,\phi)$$

$$\varphi(r \to \infty_L) \to \alpha_L(t,\phi) r^{-\Delta} + \beta_L(t,\phi) r^{-2+\Delta}, \;\; \beta_R(t,\phi) = h(t,\phi)\alpha_L(-t,\phi)$$

An BTZ example

- For simplicity consider a scalar field in the BTZ black hole.

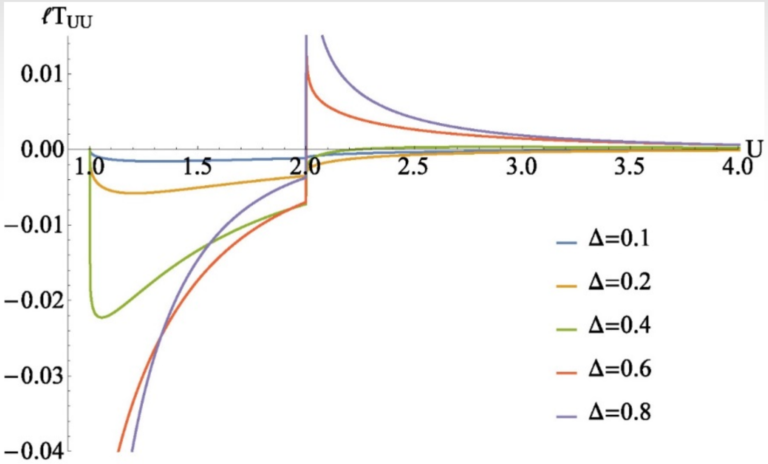
$$ds^2 = -\frac{r^2 - r_h^2}{\ell^2} dt^2 + \frac{\ell^2}{r^2 - r_h^2} dr^2 + r^2 d\phi^2$$

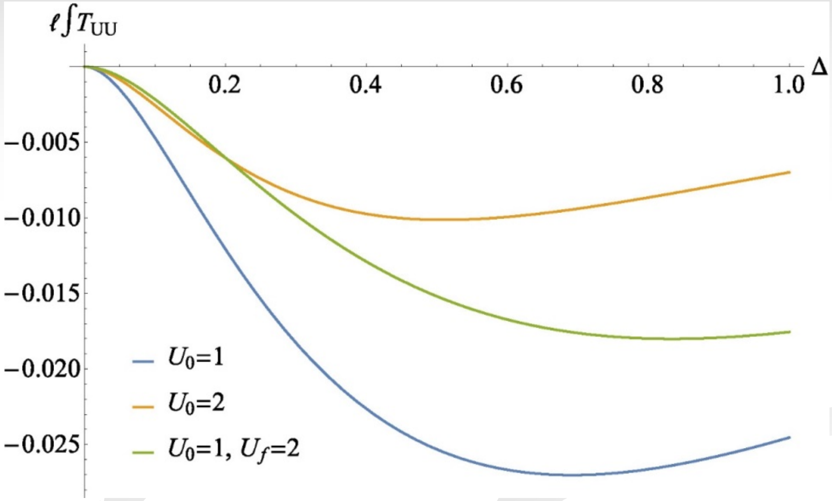
- The modified boundary conditions change the bulk 2-point function at linear order

$$G_h = 2 \sin \pi\Delta \int dt_1 h(t_1) K_\Delta(t' + t_1 - i\beta/2) K_\Delta^r(t - t_1) + (t \leftrightarrow t')$$

$$K_\Delta(r, \phi, t) = \langle \varphi(r, \phi, t) \mathcal{O}(0,0) \rangle = \frac{r_h^\Delta}{2^{\Delta+1}\pi} \left(-\frac{(r^2 - r_h^2)^{1/2}}{r_h} \cosh r_h t + \frac{r}{r_h} \cosh r_h \phi \right)^{-\Delta}$$

The result





$$\int_{U_0}^{\infty} dU T_{UU} = -\frac{h\Gamma(2\Delta+1)^2}{2^{4\Delta}(2\Delta+1)\Gamma(\Delta)^2\Gamma(\Delta+1)^2\ell} \times \frac{{}_2F_1(\frac{1}{2}+\Delta, \frac{1}{2}-\Delta; \frac{3}{2}+\Delta; \frac{1}{1+U_0^2})}{(1+U_0^2)^{\Delta+1/2}}$$

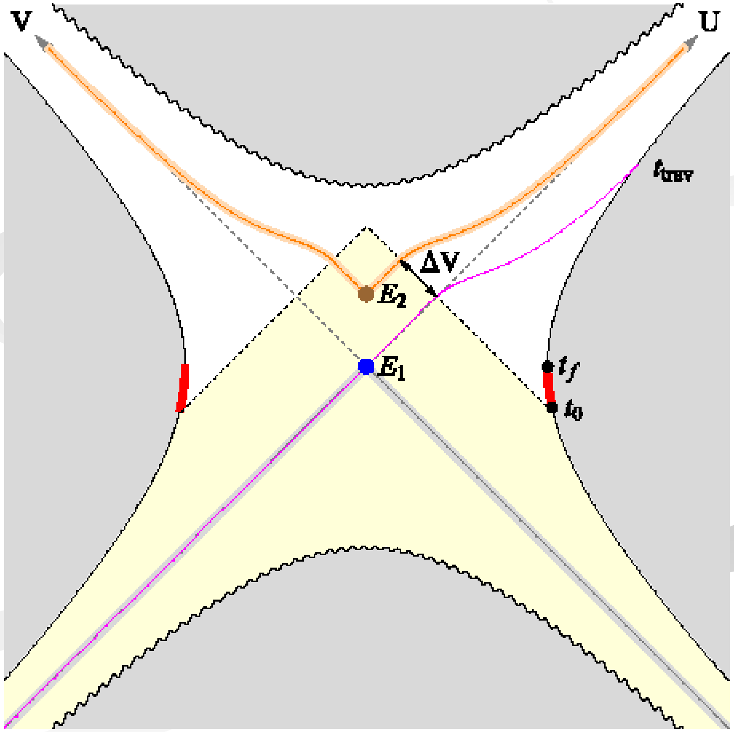
Features of the wormhole

- The perturbation reduces the energy of the state, hence the horizon shrinks.

$$\Delta V \sim \frac{hG_N}{R^{D-2}}$$

- One must jump in early enough.

- For a non-test particle, there is a collision with the negative energy squeezed state $\sqrt{s} \sim \sqrt{\frac{R^{D-4}}{hG_N}}$, but it has very small cross section.



- Maybe a Bousso-like bound on how much information can get through.

Connecting two black holes in a single spacetime

- There will be a tiny Casimir energy associated to the cycle that threads the wormhole. This can be negative and result in traversability.
- Stronger if Hawking radiation from one maximally entangled black hole is actively sent into the other.
- The GSL implies that no speed up can occur over asymptotically long distances.

ER=EPR

- Entangled systems can be described as being connected by a non-traversable wormhole.
- The most novel feature is that if observers jump into each of the entangled systems, they can meet in the connected interior.
- However, there fate then appears sealed and they die in the singularity.

Verification in the bulk semiclassical regime

- One might have argued that this interior geometry is impossible to probe from the outside or the CFT.
- In particular, it is not obvious how to determine if the meeting indeed took place.
- Now we see that by coupling the two systems after the observers jump in, they can be seen.

Quantum information interpretation

- Suppose that a qubit Q is sent from the left to right boundary. Although the boundaries are coupled, Q is not being sent directly via the coupling. For example, by bulk causality, it commutes with the interaction Hamiltonian to exponential accuracy.

- The initial entanglement is crucial to the transmission. Similar to teleportation and Hayden-Preskill mirrors:

- If a black hole is maximally entangled with another system, only a few Hawking are needed to reconstruct a qubit that is thrown in (in principle).

Quantum teleportation

- Suppose Alice and Bob shared an entangled pair of qubits, A and B. Alice wants to sent another qubit, Q, to Bob, but they are connected only by a classical channel.

- By making a combined measurement on QA, and sending the resulting 2 bits to Bob, the pattern of Q is transferred to B, after application of a unitary by Bob.

As a dynamical process

- Thought of as a strict projection, B had the pattern of Q from the beginning after Alice's measurement.

- But resolving the measurement process in a fully quantum way, this looks like a unitary operation

$$V = \sum_i P_i^{QA} U_i^B$$

- This is exactly of the type that can open the wormhole.

Summary

- Traversable wormholes can exist in consistent gravity theories. But they cannot be used to violate causality.
- Provides a way to operationally detect the connected interior in ER=EPR.
- Interesting to understand the bounds on information passing through the throat.
- What are the implications for bulk reconstruction and linearity of quantum mechanics?