

Broken Bridges: A Counter-example of the ER=EPR Conjecture

LeCosPA Mini-workshop

New Perspectives of Cosmology and Quantum Gravity

NTU Physics Department

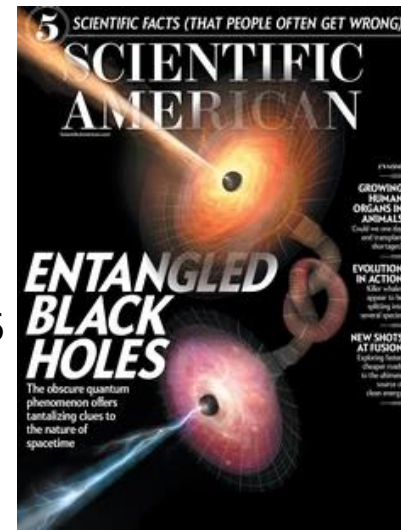
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Outline

- I. Spacetime Locality and ER=EPR Conjecture
- II. Construction of the Counter-example
- III. Debate with Professor J. Maldacena

J. Maldacena and L. Susskind, “Cool horizon for entangled black holes”,
Fortsch. Phys. 61 (2013) 781-811 arXiv:1306.0533

Pisin Chen, Chih-Hung Wu, Dong-han Yeom. “Broken bridges:
A counter-example of the ER=EPR conjecture”, arXiv:1608.08695, Aug 30, 2016

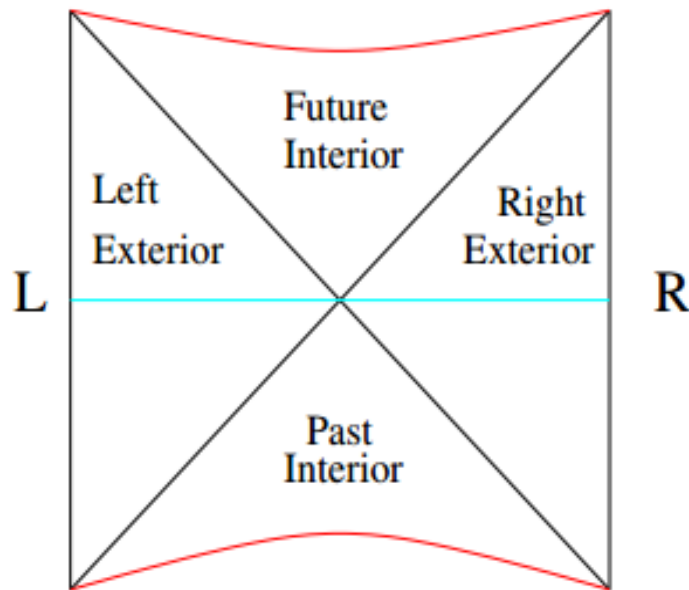


Space-time Locality

- **Locality**(Impossibility of superluminal signal)
- 1.Quantum Theory-**EPR entanglement**
- 2.General Relativity-**ER bridge**
- **Violation of Locality?---NO!**
- ER bridge should remain **un-traversable** even in the quantum theory.

AdS Black Holes

- In AdS/CFT framework, an eternal AdS-Schwarzschild BH and the Penrose diagram:



$$|\psi\rangle = \sum_n e^{-\beta E_n/2} |n_L\rangle \otimes |m_R\rangle$$

Maximally entangled

J. Maldacena, “**Eternal black hole in AdS**”
JHEP 0304 (2003) 021 ,arXiv:0106112

ER=EPR

- Consider such a scenario:
- A large number of particles, **entangled into separate Bell pairs**, and separate them when we **collapse each side to form two distant black holes**, the two black holes will be entangled.
- Now they make a **conjecture** that they will also be connected by an Einstein-Rosen bridge.

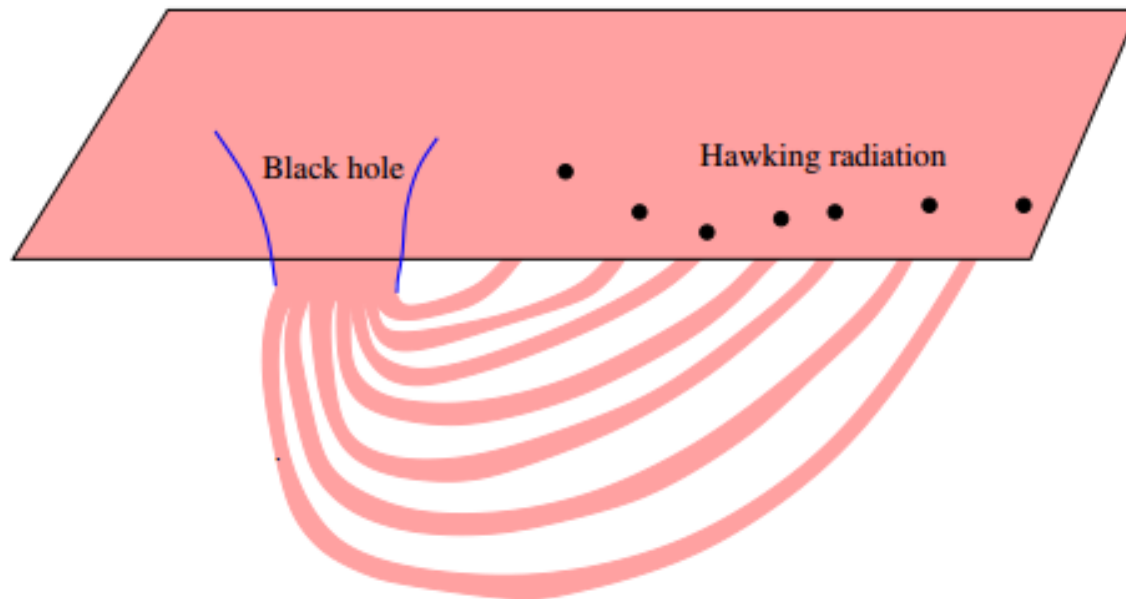
$$\text{ER}=\text{EPR}$$

Known: $\text{ER} \rightarrow \text{EPR}$

Conjecture: $\text{EPR} \rightarrow \text{ER}$

The ER=EPR Conjecture

- How to realize in the usual Hawking radiation scenario?
- **Second black hole= early half of HR.**



The Broken Bridges

- Step 1: Generate an entangled system
- Step 2: Formation of the ER bridge
- Step 3: Collapsing of the bubble
- Step 4: Evaporation of the black hole
- **Step 5: Communication via ER bridge**

Generate an entangled system

- **Assumption:** GR with N massless scalar fields

$$S = \int \sqrt{-g} d^4x \left[\mathfrak{R} - \frac{1}{2} (\nabla \phi)^2 - U(\phi) - \sum_{i=1}^N \frac{1}{2} (\nabla f_i)^2 \right]$$

- The potential has **two minima**: (AdS space)

$$\Lambda_+$$

Background (false vacuum)

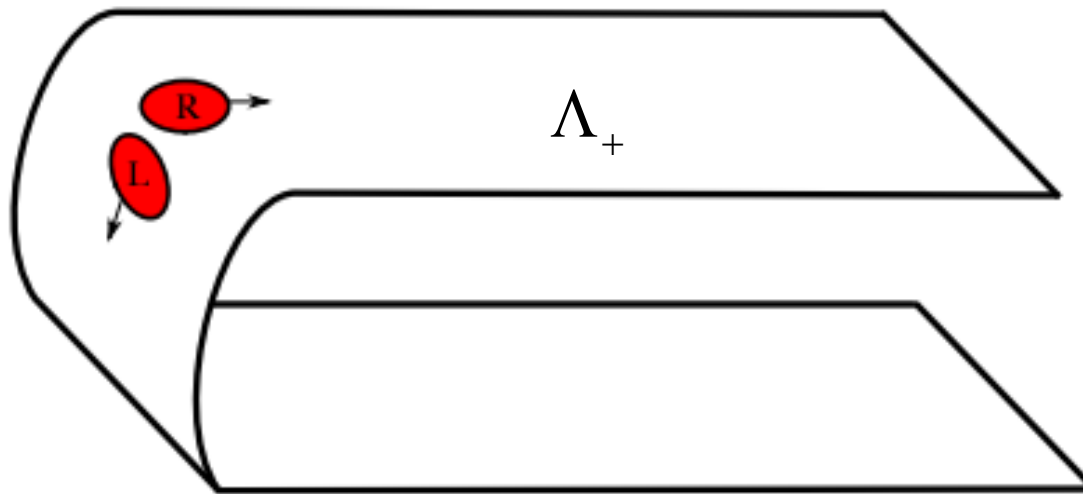
$$\Lambda_-$$

True vacuum

$$\Lambda_- < \Lambda_+ < 0$$

Generate an entangled system

- Prepared in advance (e.g. by a third observer)

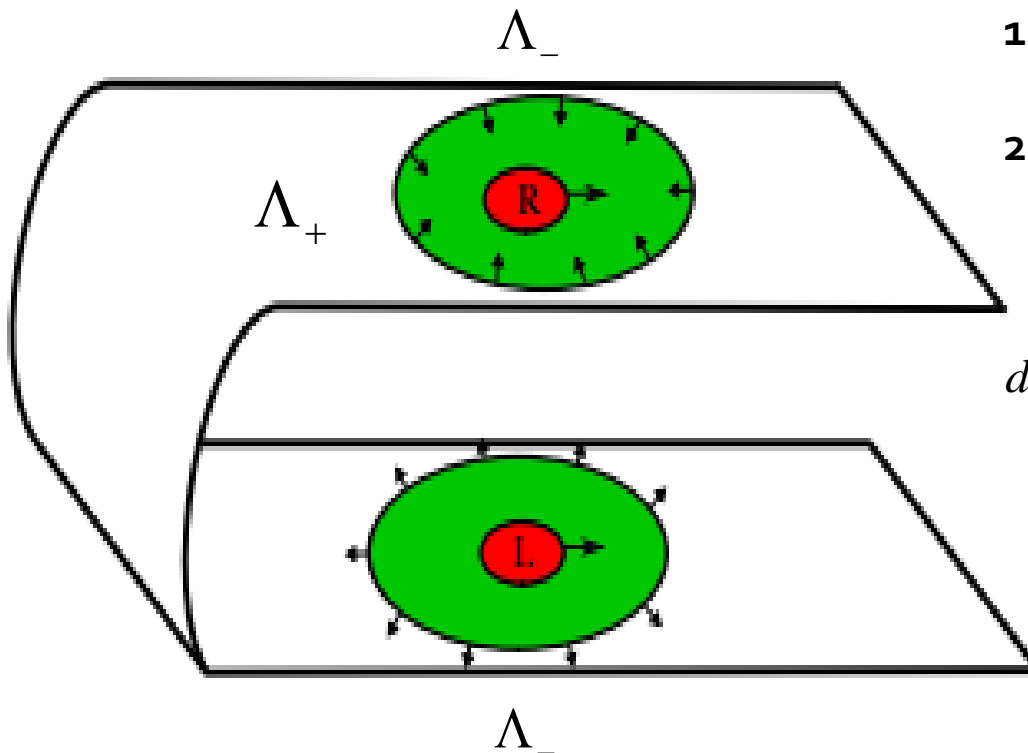


Trapping by Bubbles

- Two true vacuum bubbles are created and trap the L and R.

Conditions:

1. One bubble is contracting, the other expanding
2. Spherically-sym thin-shell



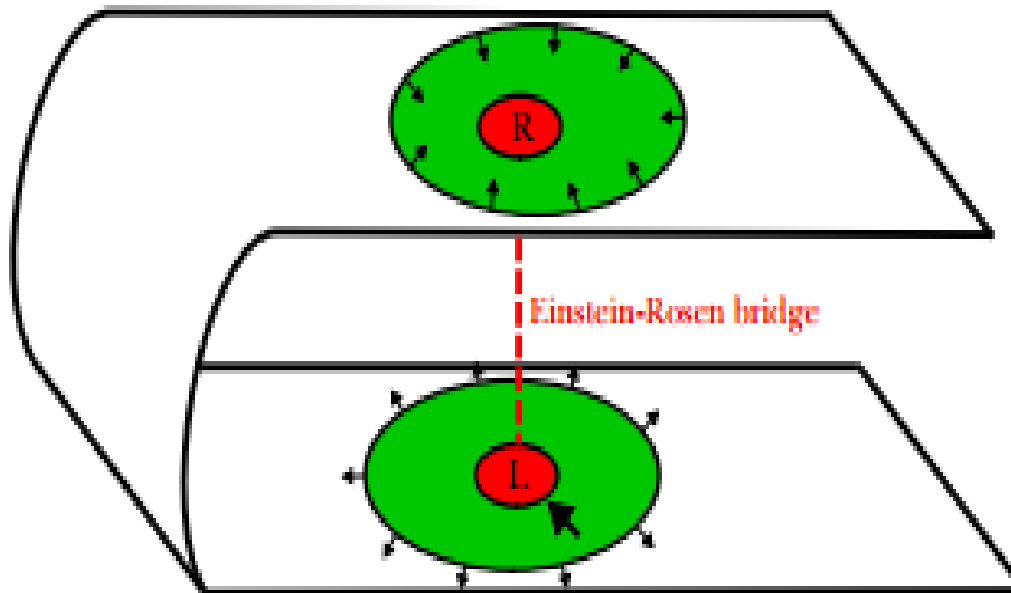
$$ds^2 = -f_{\pm}(R)dT^2 + \frac{1}{f_{\pm}(R)}dR^2 + R^2d\Omega^2$$

$$f_{\pm} = 1 - \frac{2M_{\pm}}{R} + \frac{R^2}{\ell_{\pm}^2}$$

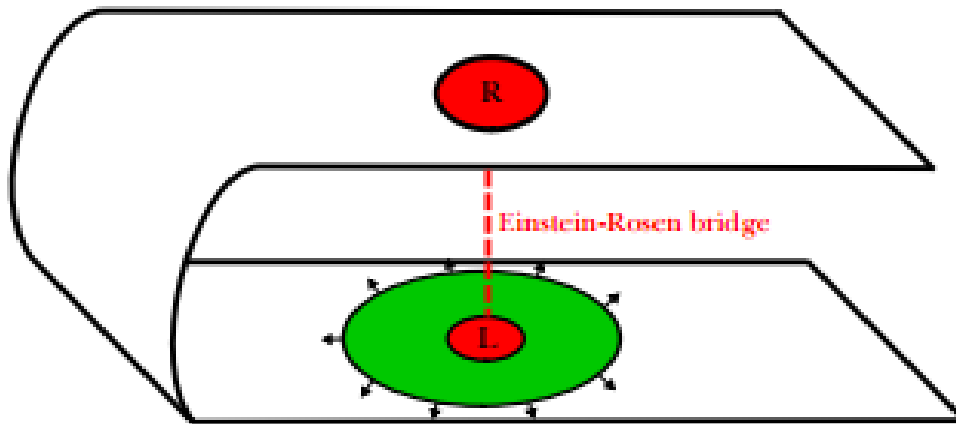
$$\ell_{\pm}^2 = 3/8\pi|\Lambda_{\pm}|$$

Formation of the ER Bridge

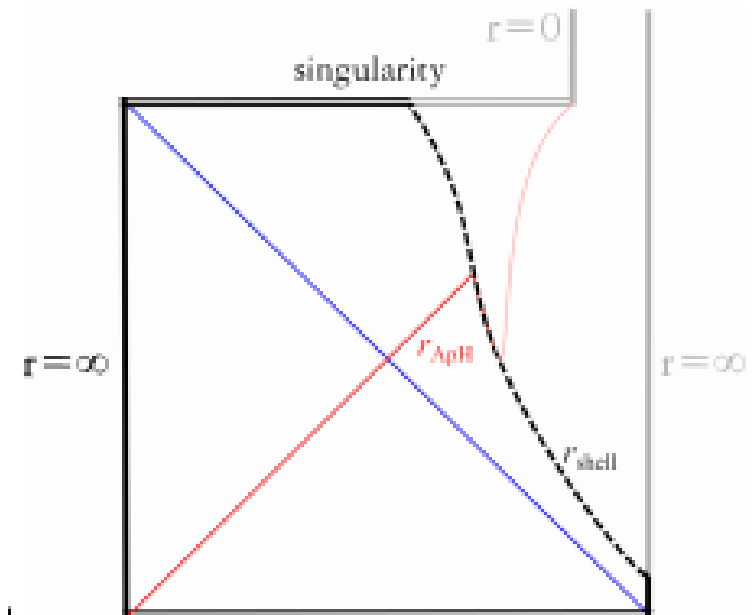
- According to $ER=EPR$, we induce the ER bridge.
(by scrambling-the two are **maximally entangled**)



Collapsing of the Bubble



By changing boundary conditions of R ,
We can induce the shrink of the black hole.
(through Hawking radiation)



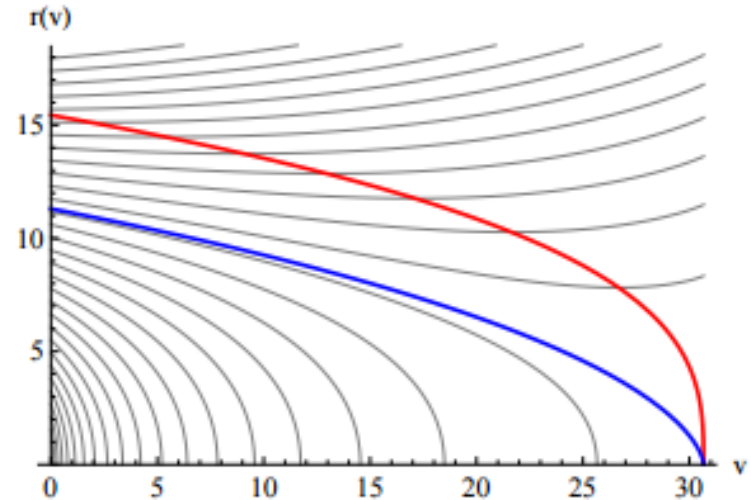
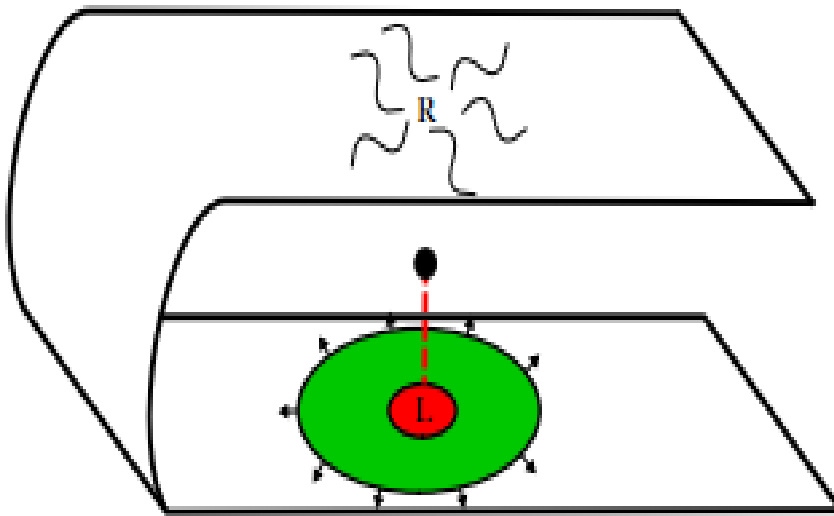
Evaporation of the Black Hole

$$ds^2 = -\left(1 - \frac{2M(v)}{r}\right)dv^2 + 2dvdr$$

Consider semi-classical metric
Vaidya metric approximation

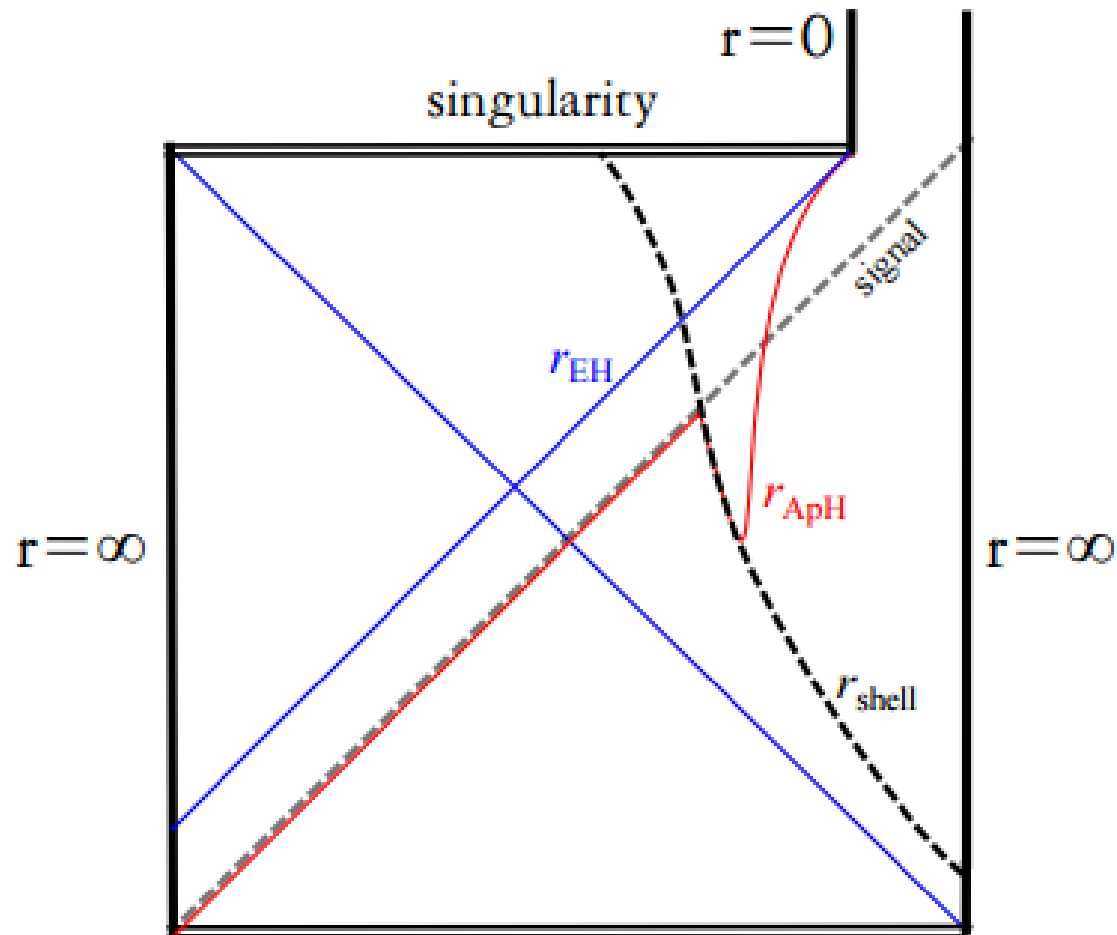
$$\frac{dM}{dv} = -\frac{\alpha N}{M^2}$$

$$\frac{|r_{ApH} - r_{EH}|}{2M_+} \approx \frac{4\alpha N}{M_+^2} + O(M_+^{-4})$$



Pisin Chen et al, **"Naked Black Hole Firewalls"**,
Phys.Rev.Lett. 116 (2016) no.16, 161304,
arXiv: 1511.0569

Communication via ER Bridge



Conclusions

- **A counter-example of $ER=EPR$**
- 1.If the thought experiment and $ER=EPR$ are true---**violate locality of EPR .**
- 2. **$ER=EPR$ is not generic.**
- Perhaps quantum gravity do not respect locality??

What is a counter-example?

- One possible way:
- ER=EPR respects locality.
- Violation of locality through traversable ERB.
- Violation of ANEC is a prerequisite.

$$\int \langle T_{\mu\nu} \rangle d\lambda < 0$$

Criticism from Prof. Maldacena

- Prof. Maldacena's counter-arguments:
 - 1. By changing the boundary conditions, there would be **positive energy contribution** from the collapsing shell.
 - 2. Positive energy would **dominate over the negative energy** of Hawking radiation.

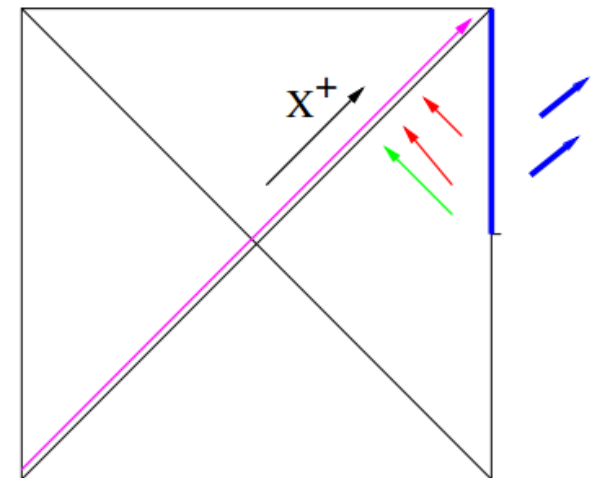
Criticism from Prof. Maldacena

- 3. **Even in large-N fields**, the effect will not only enhance the Hawking radiation but **also the positive energy.**

$$\frac{dM}{dv} = -\frac{\alpha N}{M^2}$$

- 4. The ER bridge would still be un-traversable **since ANEC is not violated.**

- 5. Also, there are many proofs regarding the ANEC.



Our Counter-counter-arguments

- 1. We indeed find a parameter space that includes both the **positive contribution** of the shell and **negative contribution** from HR.
- 2. Those **theorems for ANEC are limited**.
(e.g. only for free or super-renormalizable theories by imposing generalized second law; or ANEC for Minkowski spacetime)

Tunneling: Sum over Histories

- Usually, the bubbles are created by **non-perturbative effects**.
- Those theorems do not include possible non-perturbative effects.

$$\langle T_{\mu\nu} \rangle \approx \langle T_{\mu\nu}^{(1)} \rangle + e^{-s} \langle T_{\mu\nu}^{(2)} \rangle + \dots$$

- Overall history may not violate ANEC, but the **specific non-perturbative one may violate it.**

The End!

Thank you very much!

Rings of Fire

- 2012, Almheiri, Marolf, Polchinski and Sully proposed the so-called

AMPS Firewall

- Monogamy of entanglement---**Give up GR?**

$$|\psi\rangle = |HRat\ early\ time\rangle \otimes |HRat\ late\ time\rangle$$

$$blue - shift \sim \frac{1}{\sqrt{1 - \frac{2M}{r}}}$$



Setup

- **Alice** lives on the left boundary
---send message into the bulk
- **Bob** lives in the bulk--- starts out on the right exterior region and **may or may not cross the horizon**
- **Q:Does Bob's BH have a firewall?**

Does Bob's BH have a firewall?

- The answer depends on what Alice does.

Why?

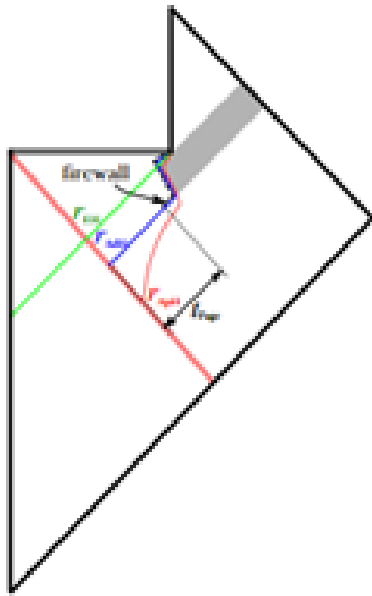
- **If Bob does cross the horizon**---receive a message from Alice if Alice sends it early enough.
- **She can send a firewall** that will propagate upward to the right very close to Bob's horizon.

Teleological Nature of Black Hole

- The location of Firewalls dep on the **past history** of Hawking evaporating black hole.
- Event horizon dep on the **future history**.
- Later **quantum fluctuation** would cause the event horizon to migrate to the inside of the firewall.---Naked Firewalls

Naked Firewalls

- **How to realize?**
- Consider the backreaction---Vaidya metric (2d approximation, semi-classical Einstein eq)



$$ds^2 = -\left(1 - \frac{2M(v)}{r}\right)dv^2 + 2dvdr$$

More refined version of firewall paradox.

Conclusions

- Furthermore, if **ER=EPR is not true** and **there is a firewall---****firewall should still be naked**
- Firewall can be naked not only for one-sided black holes, **but also two-sided!**

Outlook

- **Possible Criticisms?**(black hole chaos?)
- Holographic dual of this communicating two boundary systems?
- Corresponding AdS/CFT dictionary?
- **More clarification is needed!**