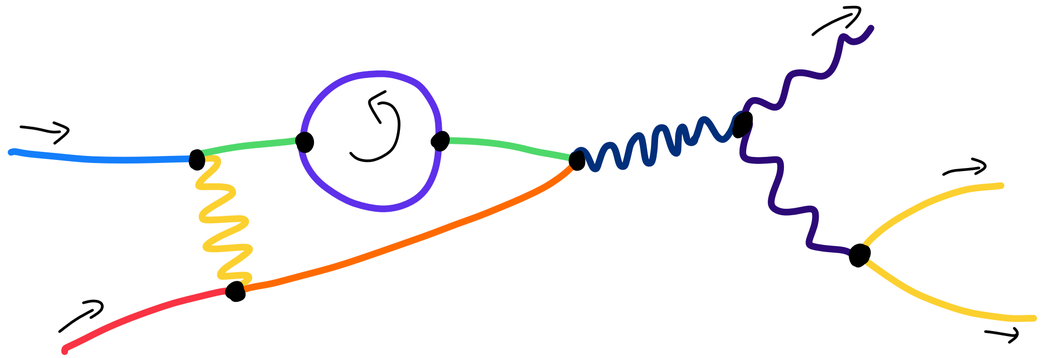
Gravity and Information

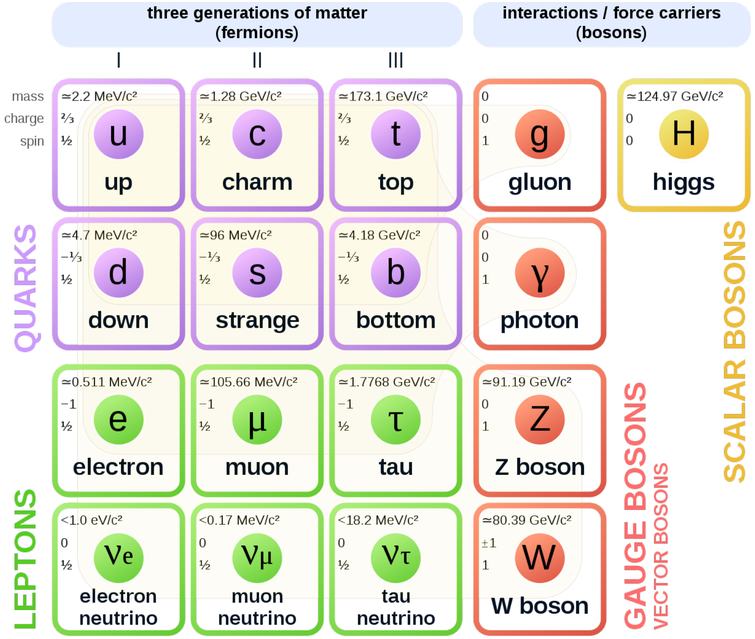
Ahmed Almheiri (IAS/NYUAD) — ICHEP 22

The problem with gravity

Local Quantum field theory

- Locality $\Longrightarrow$ fields $\Longrightarrow$ d.o.f. at every spacetime point
- Particles interacting locally in spacetime



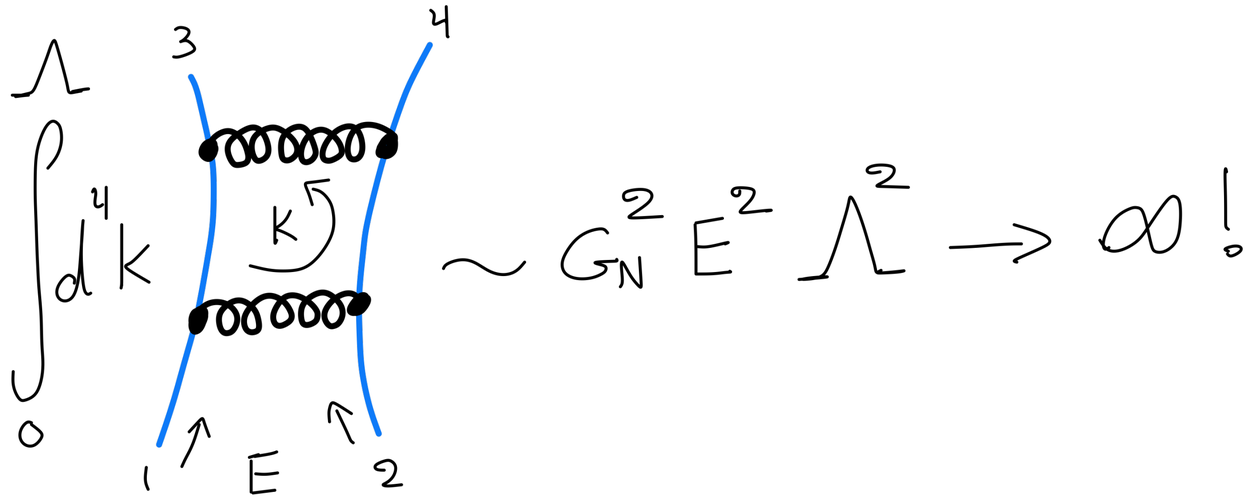


- Extremely successful!

Gravity as a Quantum field theory

- However, gravity doesn't fit into the framework of local QFT
- As a quantum field theory, it is non-renormalizable:

$$\langle p_3, p_4 | p_1, p_2 \rangle =$$

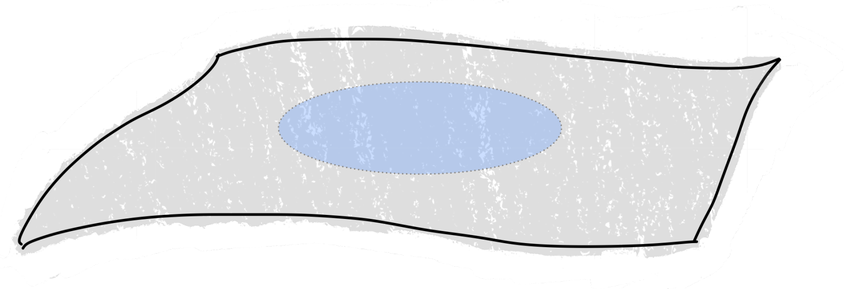


$$\sim G_N^2 E^2 \Lambda^2 \to \infty !$$

- Gravity as a QFT is not UV-complete. It's an effective field theory.
- Is the UV-completion just another local QFT?

Locality is part of the issue…

- In local QFT, there is a degree of freedom per spacetime point

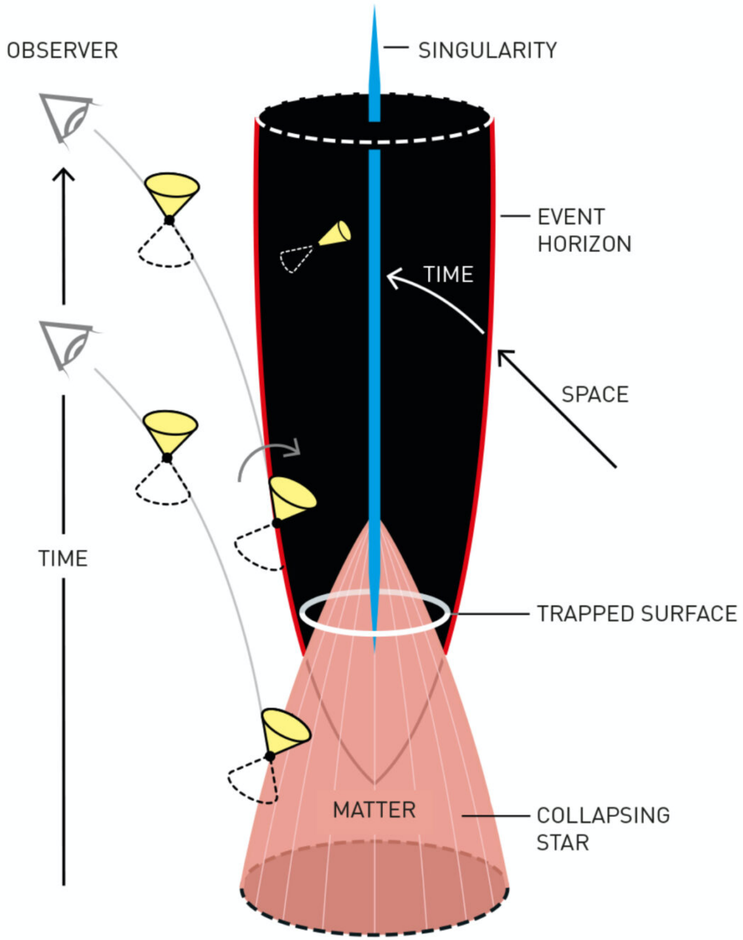


- Infinite # degrees of freedom inside any region!

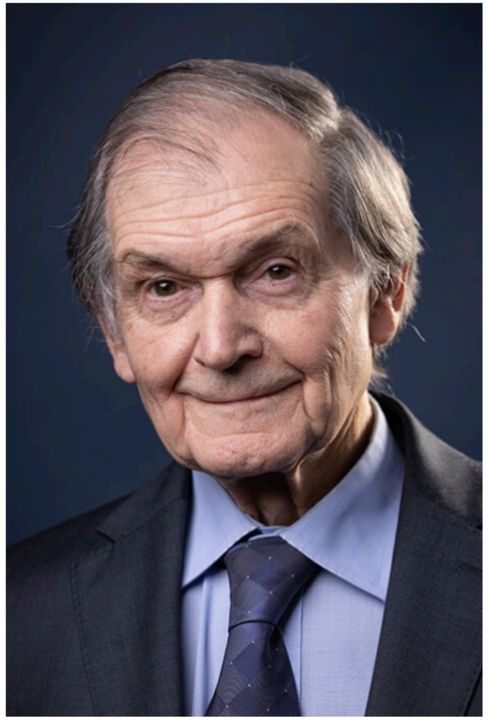
- As we'll see, this doesn't appear to be a property of gravity…

Gravity is different

Gravity has black holes



[Johan Jarnestad/The Royal Swedish Academy of Sciences]



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- **Inevitability of black holes: 2020 Physics Nobel Prize**

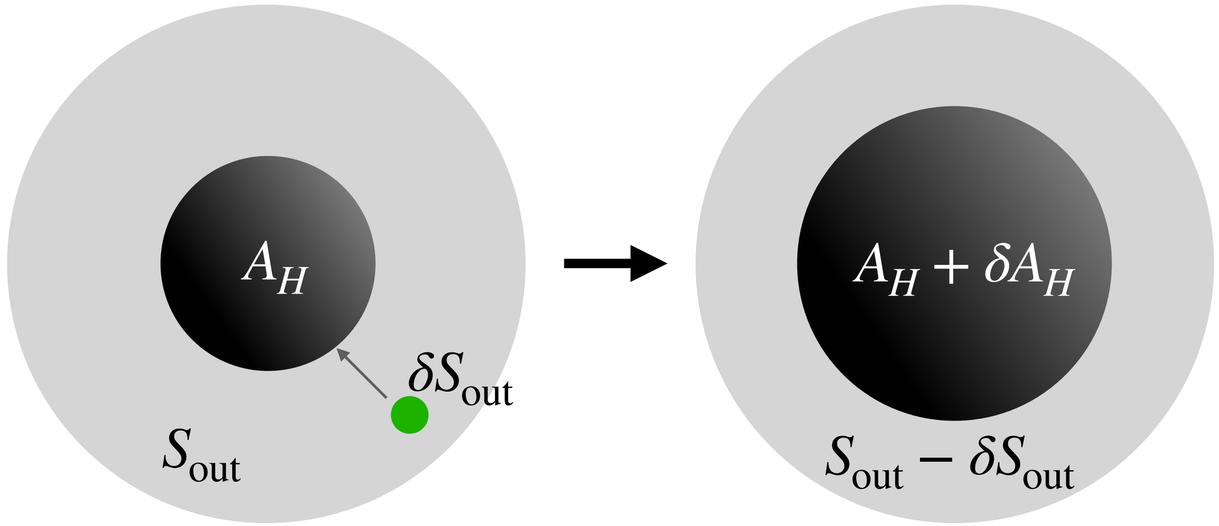
Laws of Black Hole Thermodynamics

[Bardeen, Carter, Hawking; Bekenstein]

- **Area of the event horizon behaves like an entropy**

First Law of Thermodynamics: $dE = \frac{\kappa}{8\pi} dA_H = T\, dS$

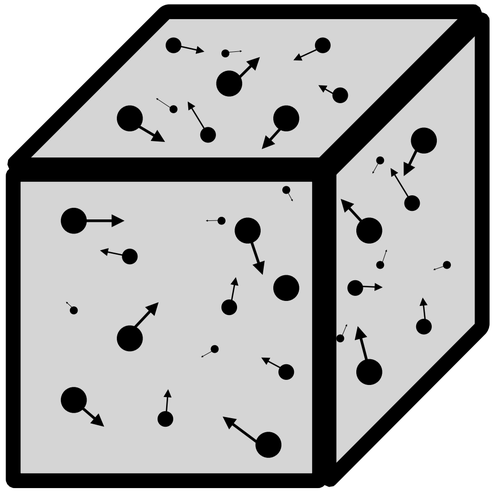
Generalized Second Law of Thermodynamics: $S_{\text{gen}} = \frac{A_H}{4G_N} + S_{\text{out}} \implies \delta S_{\text{gen}} = \frac{\delta A_H}{4G_N} + \delta S_{\text{out}} \geq 0$

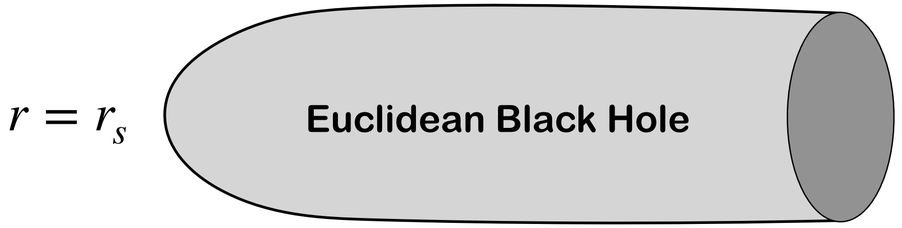


- **Entropy of the black hole (Bekenstein-Hawking entropy):** $S_{\text{BH}} = \frac{\text{Area of Horizon}}{4G_N}$

Is it really entropy?

Thermodynamic Entropy





$$ds^2 = \left(1 - \frac{r_s}{r}\right) d\tau^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

- **A measure of the size of phase space of a system**

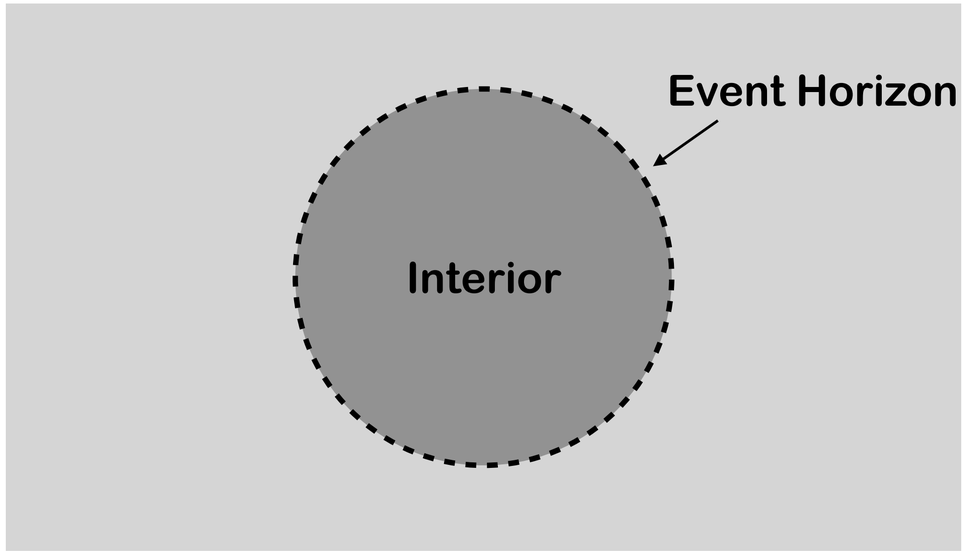
$$Z[\beta] = \mathrm{Tr}[e^{-\beta H}] = \int D g_{\mu\nu} e^{-I[g]} \times Z_{\mathrm{m}}[g]$$ [Gibbons, Hawking]

$$S_{\mathrm{Th}} = (1 - \beta\partial_\beta) \ln Z[\beta] \sim \log \Omega = \frac{\text{Area of Horizon}}{4G_N}$$

- **Reproduced in String Theory** [Strominger, Vafa]

Gravity is holographic

- # of degrees of freedom scales with area rather than volume!

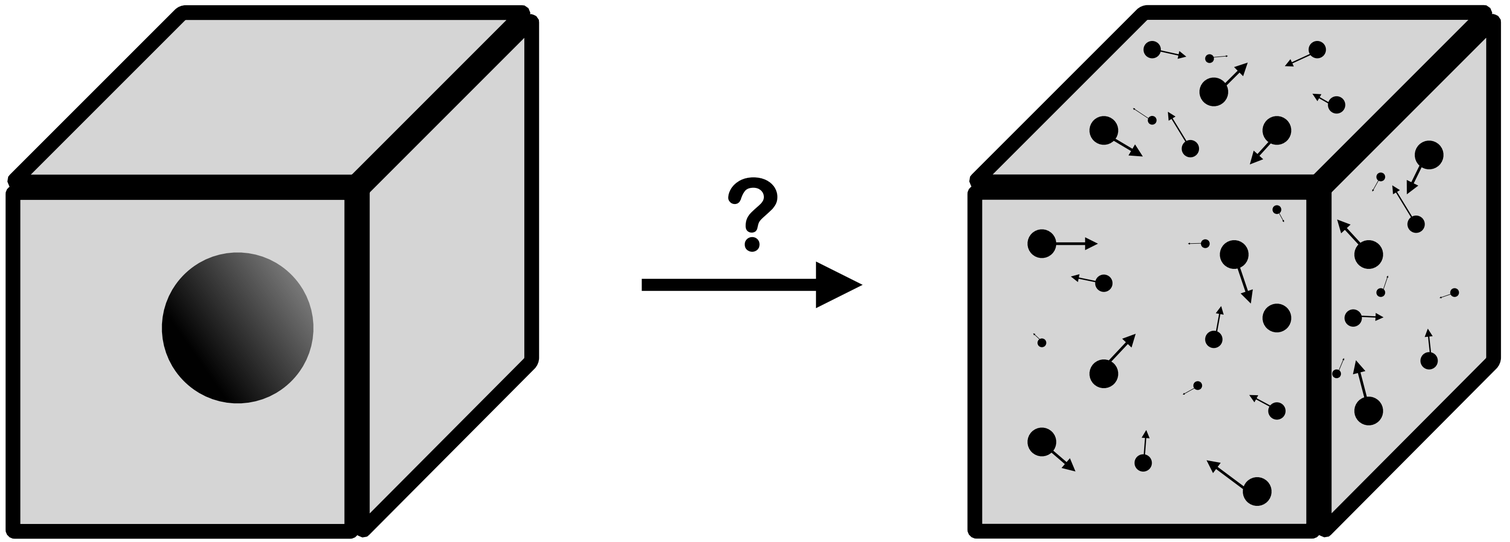


$$S_{\mathrm{BH}} = \frac{\text{Area of Horizon}}{4G_N}$$

- QFT would predict ~ volume of the interior
- Holographic principle ['t Hooft; Susskind]
- AdS/CFT [Maldacena]

Gravity is normal

Thermodynamic puzzle



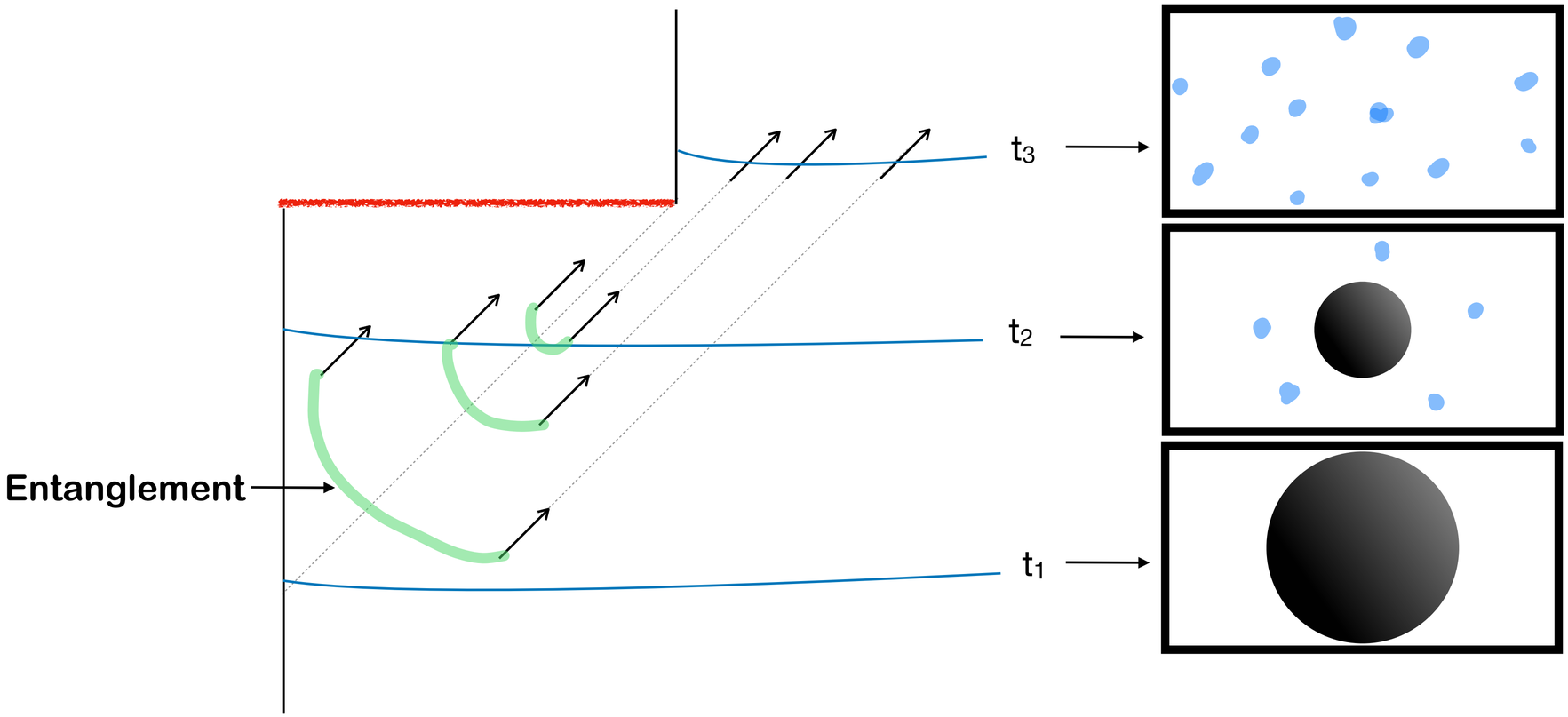
(A) (B)

$$S_{\text{Box}}(A) = \frac{\text{Area}_H}{4G_N} \ll S_{\text{Box}}(B) \sim \text{Volume(Box)}$$

- At large volume, the black hole is thermodynamically disfavored
- There must be a process that takes (A) to (B)
- Classically, there isn't. But there is quantum mechanically…

Hawking radiation

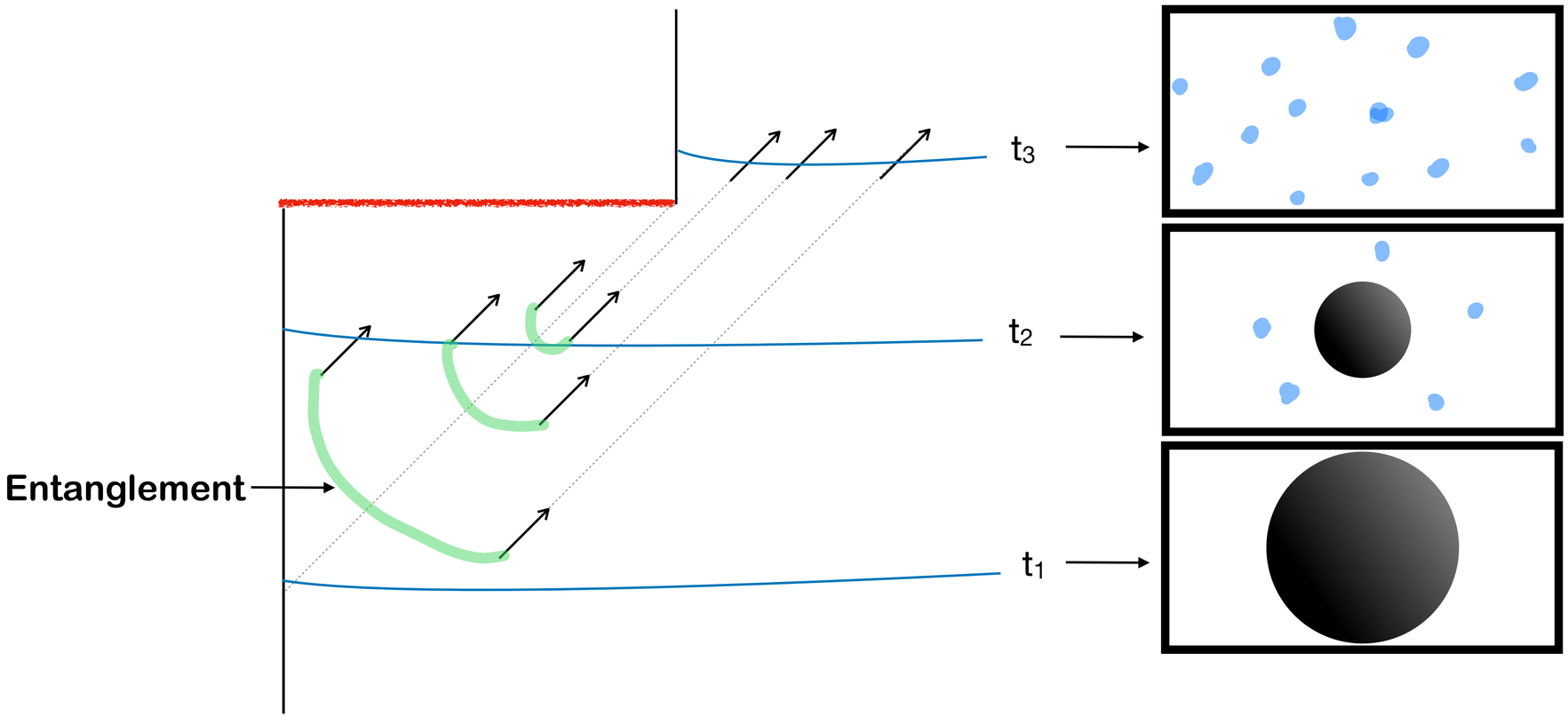
- Pair-creation at the event horizon [Hawking]



- Vacuum at the horizon = entangled state in Hawking mode basis

Information Loss

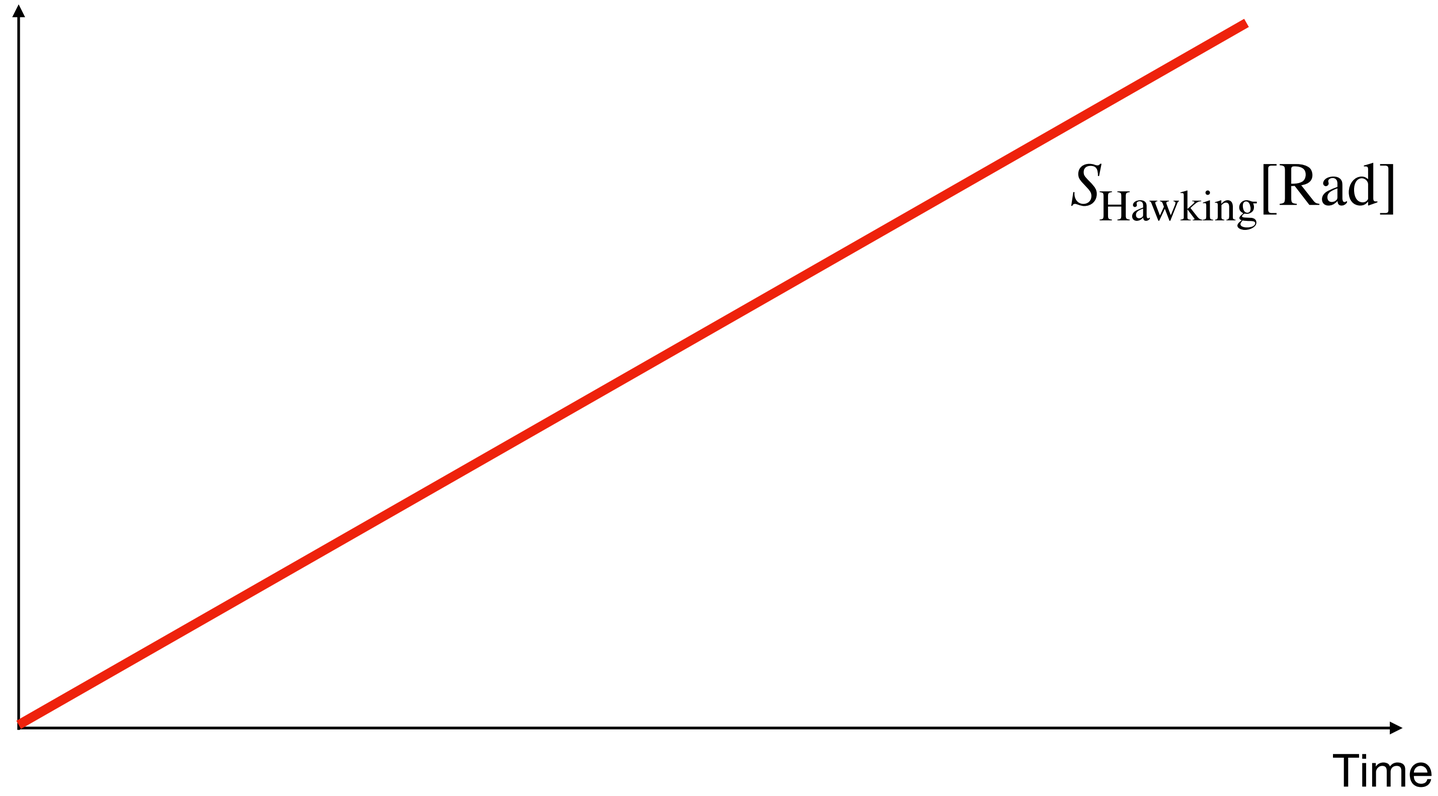
- Outside radiation is in a <u>Random Thermal State</u> [Hawking]



- Evaporation transforms a pure state into a mixed state

Information Loss

- **Randomness of the radiation: Entanglement entropy** [Hawking]



Gravity is unreasonably smart

[**AA** 18]

[**AA**, Engelhardt, Marolf, Maxfield 19]

[Penington 19]

[**AA**, Mahajan, Maldacena, Zhao 19]

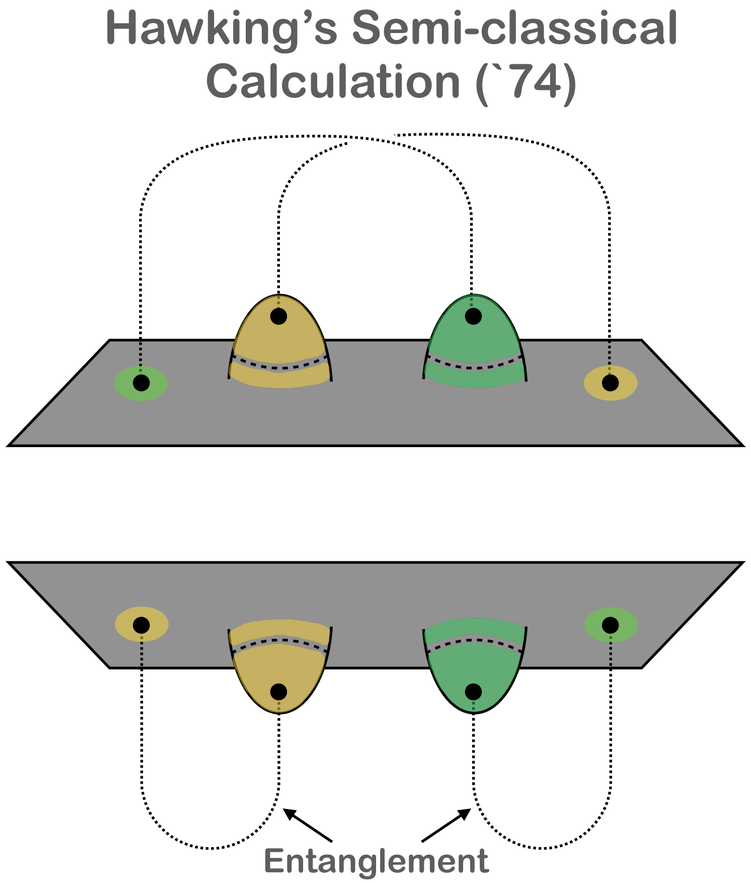
[**AA**, Mahajan, Maldacena 19]

[**AA**, Maldacena, Hartman, Shaghoulian, Tajdini 19]

[Penington, Shenker, Stanford, Yang 19]

Quantifying Randomness: Swap Test

- **Swap test: Multiple r<u>andom</u> answers are distinguishable, d<u>efinite</u> answers are not.**



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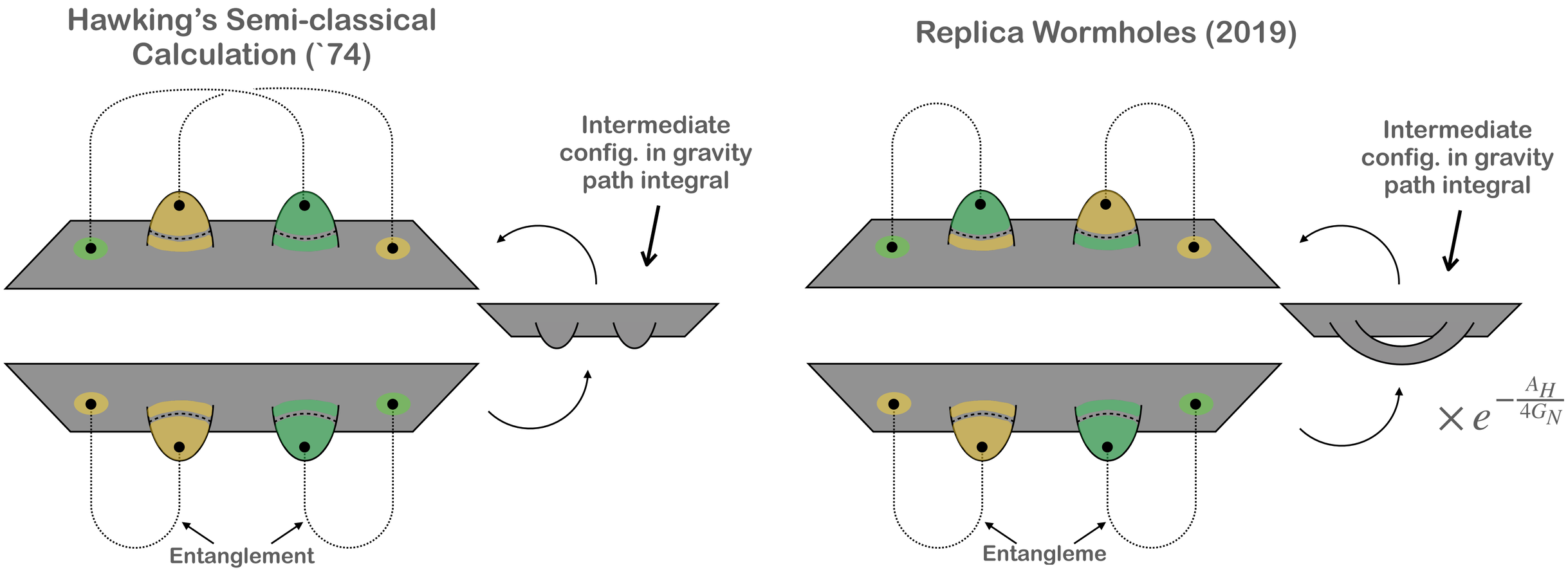
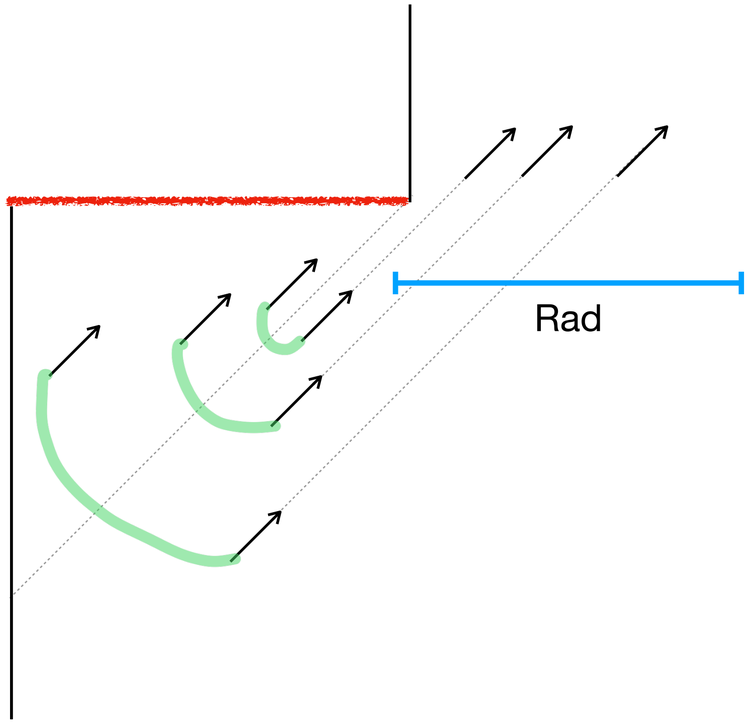


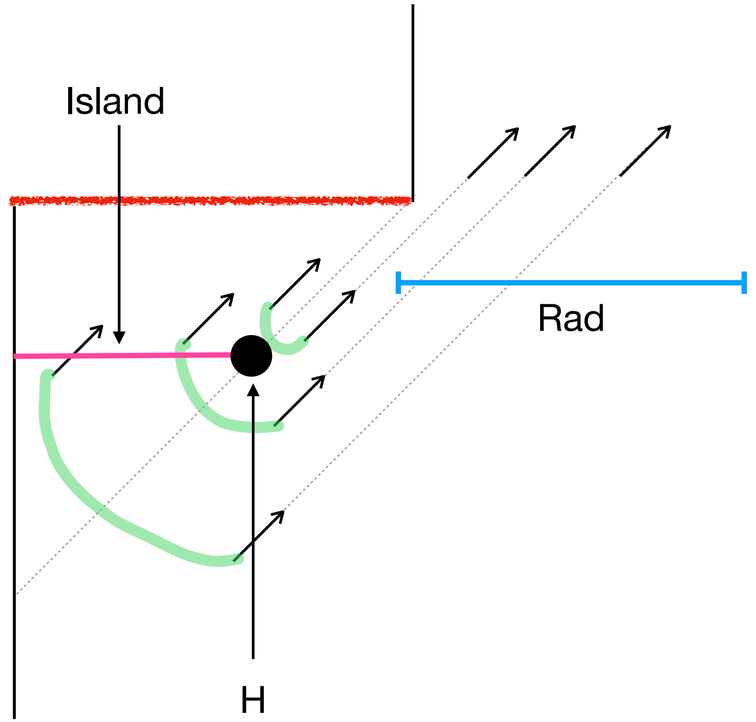
- **Wormhole swaps the interiors! The original swap is not distinguishable!**

New Entropy Formula

- **Minimization between**



VS

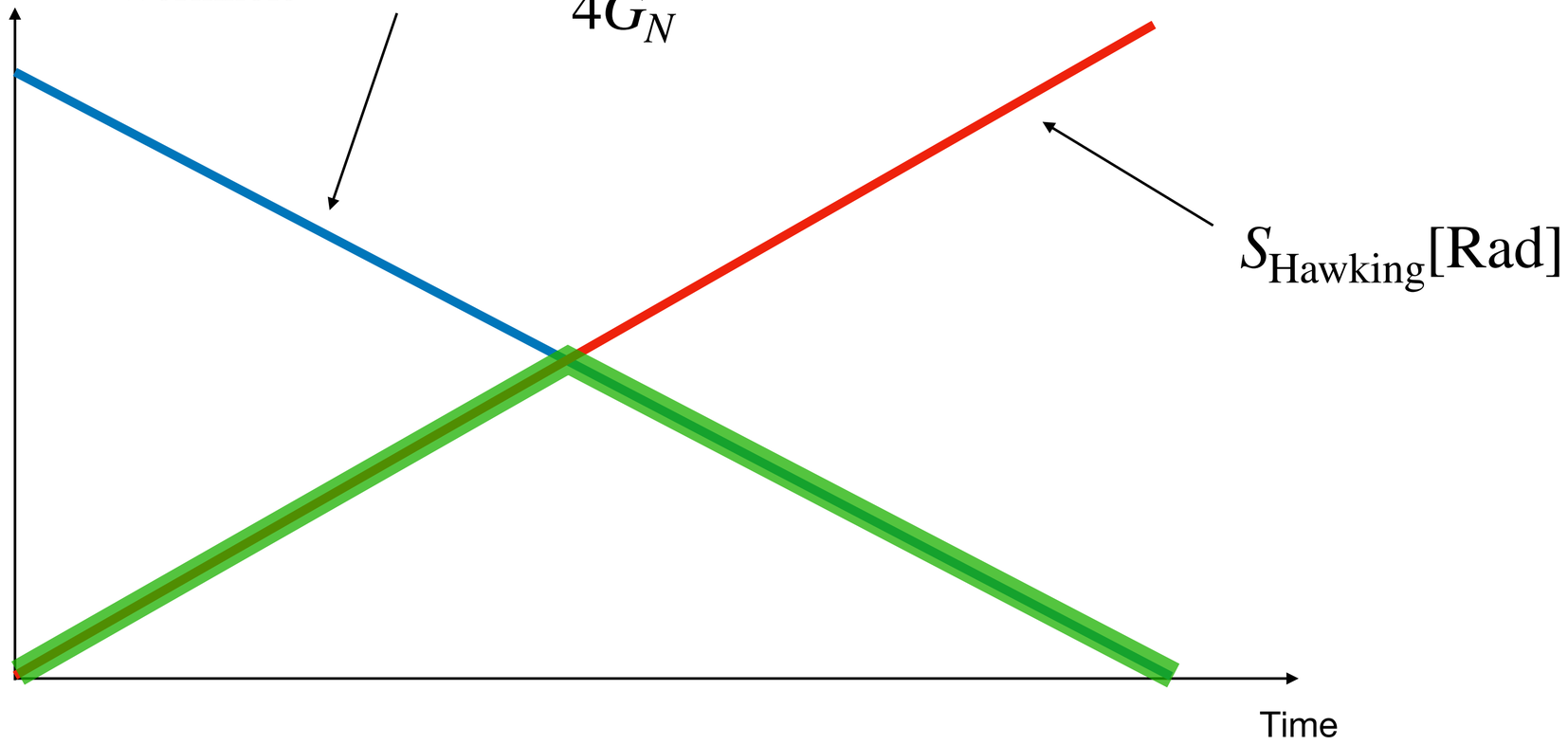


$$S_{\text{Hawking}}[\text{Rad}] = S_{\text{m}}[\text{Rad}]$$

$$S_{\text{Wormhole}}[\text{Rad}] = \frac{\text{Area}[H]}{4G_N} + S_{\text{m}}[\text{Rad} \cup \text{Island}]$$

Randomness of the radiation

$$S_{\text{Wormhole}}[\text{Rad}] = \frac{\text{Area}[H]}{4G_N} + \dots$$



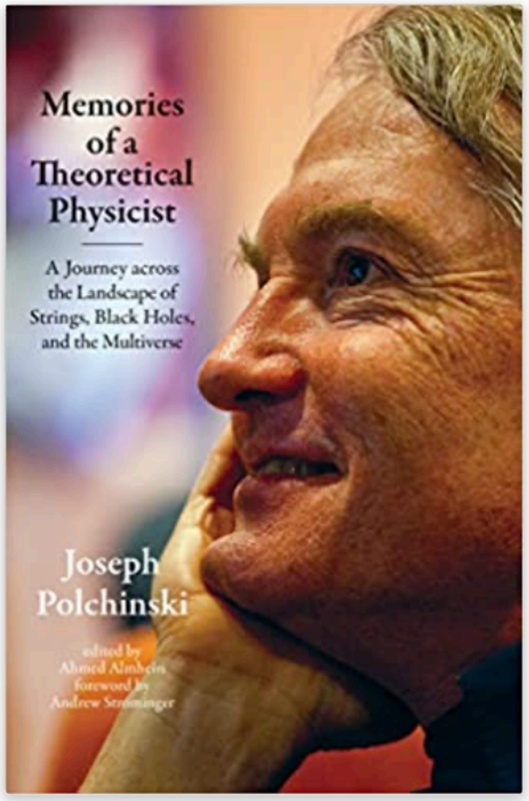
$$S_{\text{vN}}[\text{Rad}] = \min\left\{ S_{\text{Hawking}}[\text{Rad}],\ S_{\text{Wormhole}}[\text{Rad}] \right\}$$

Conclusions

- Gravity seemingly contains the right structure to be consistent with Quantum Mechanics
- Spacetime wormholes in the gravity path integral ensures purity of the Hawking radiation
- Spacetime wormholes are the missing ingredient in Hawking's original analysis

Open Problems

- Evaluate the actual state of the Hawking radiation
- Understand the experience of an infalling observer
- The nature of the Singularity



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Memories of a Theoretical Physicist: A Journey across the Landscape of Strings, Black Holes, and the Multiverse Paperback – May 24, 2022

by Joseph Polchinski (Author), Ahmed Almheiri (Editor), Andrew Strominger (Foreword)

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A groundbreaking theoretical physicist traces his career, reflecting on the successes and failures, triumphs and insecurities of a life cut short by cancer.

The groundbreaking theoretical physicist Joseph Polchinski explained the genesis of his memoir this way: "Having only two bodies of knowledge, myself and physics, I decided to write an autobiography about my development as a theoretical physicist." In this posthumously published account of his life and work, Polchinski (1954–2018) describes successes and failures, triumphs and insecurities, and the sheer persistence that led to his greatest discoveries. Writing engagingly and accessibly, with the wry humor for which he was known, Polchinski gives theoretical physics a very human face.

Polchinski, famous for his contributions to string theory, may have changed the course of modern theoretical physics, but he was a late bloomer—doing most of his important work after the age of forty. His death from brain cancer at sixty-three cut short a career at its peak. Working on the memoir after his diagnosis, using a text-to-speech algorithm because he could no longer read words on a page, he was able to recapitulate his entire career, down to the details of problems he had worked on. For Polchinski, physics went deeper than words.