The Price of Curiosity:
Information Recovery in de Sitter Space

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De Sitter Space

Observations suggest that the accelerated expansion of the universe is driven by a positive cosmological constant.

The corresponding solution to the vacuum Einstein’s equations is de Sitter space.

In de Sitter space, there is a cosmological horizon.

Taking into account (small) quantum effects, the horizon has thermodynamic properties.

Shares similarities with a black hole horizon, such as temperature and entropy.

\[ \beta = 2\pi \ell \quad S = \frac{\text{Area}}{4G_N} \]
Quantum Information

Information that falls through a horizon is lost (classically).

Quantum mechanically, unitary evolution implies that information is preserved. It should be encoded in the Hawking radiation. [Page '93]
Information Paradox

Precisely how information can be recovered was unknown until recently, this is the information paradox.

Quantum information is captured by the von Neumann/entanglement entropy.

Unitarity:
\[ S_{\text{Rad}}(t) \leq S_{\text{BH}}(t) \]

Recently, the required corrections have been found resulting in a unitary Page curve. [Almheiri, Hartman, Engelhardt, Maldacena, Marolf, Maxfield, Penington, Shaghoulian, Tajdini + many more works ’19-’21]
Entanglement Islands

The entropy of a gravitational systems is given by:

\[ S_{\text{gen}} = \frac{A}{4G_N} + S_{\text{vN}} \]

When there is a large amount of entanglement, the generalized entropy is given by the "island formula".

\[ S_{\text{Rad}} = \frac{A_{\text{Island}}}{4G_N} + S_{\text{vN, Island}} + S_{\text{vN, Rad}} \]

Page curve: information is preserved!
Info Recovery in dS

De Sitter does not “evaporate”, but an observer can collect radiation to try to recover information.

\[ \beta_{\text{in}} = \beta_{\text{out}} = 2\pi \ell \]

\[ \beta_{\text{out}} \rightarrow \infty \]

Breaks thermal equilibrium!

Explicit expression for entropy and backreaction are difficult to compute in general.

We consider a simplified model: two-dimensional JT gravity. [Hartman, Jiang, Shaghoulian ’20] [Chen, Gorbenko, Maldacena ’20] [Chen, Gorbenko, Maldacena ’20] [Balasubramanian, Kar, Ugajin ’20][Sybesma ’20][Geng, Nomura, Sun ’21]
JT Gravity in $dS_2$

Jackiw-Teitelboim gravity is a two-dimensional dilaton model of gravity. Obtained as reduction of four-dimensional black hole in $dS$. 

$$I = I_0(\Phi_0) + \int d^2x \Phi \left( R - \frac{2}{\ell^2} \right) + I_{\text{CFT}}$$

**Constant entropy**  
**Dynamics**  
**Large c matter sector**

EOM:  
$$\Phi g_{ab} - \ell^2 \nabla_a \nabla_b \Phi + \ell^2 g_{ab} \Box \Phi = \pi \ell^2 \langle T_{ab} \rangle$$

$$\langle T_{\text{in}} \rangle = \frac{\pi c}{12 \beta_{\text{in}}^2}$$

$$\langle T_{\text{out}} \rangle = 0$$
Islands in JT Gravity

The solution to the EOMs in the state where an observer collects radiation is:

Metric:
\[ ds^2 = -(1 - r^2/\ell^2)dt^2 + (1 - r^2/\ell^2)^{-1}dr^2 \]

Dilaton:
\[ \Phi = -\frac{cr}{\ell^2}t + \ldots \]

Using the island formula, we find that islands contribute!

\[ S_{\text{Rad}} = \frac{A_{\text{Island}}}{4G_N} + S_{\text{Island}}^{\text{vN}} + S_{\text{Rad}}^{\text{vN}} \]
The Price of Curiosity

Contrary to a black hole, all radiation has to be stored in a finite volume. This will (eventually) lead to large backreaction.

Look for singularities using a quantum singularity theorem. [Wall ’10] (see also [Freivogel, Kontou, Krommydas ’20])

When information recovery is possible, formation of a singularity is unavoidable.

Information recovery is possible, but comes at a price!
Conclusions

• Using recent developments in black hole physics, we studied information recovery in de Sitter space.

• For analytical results, we focused on JT gravity.

• Computing the entropy of radiation, we found that information is not lost.

• Curiosity has a pricetag: a singularity forms.

• Focused on a static observer, consequences for inflation?
Thank you!

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