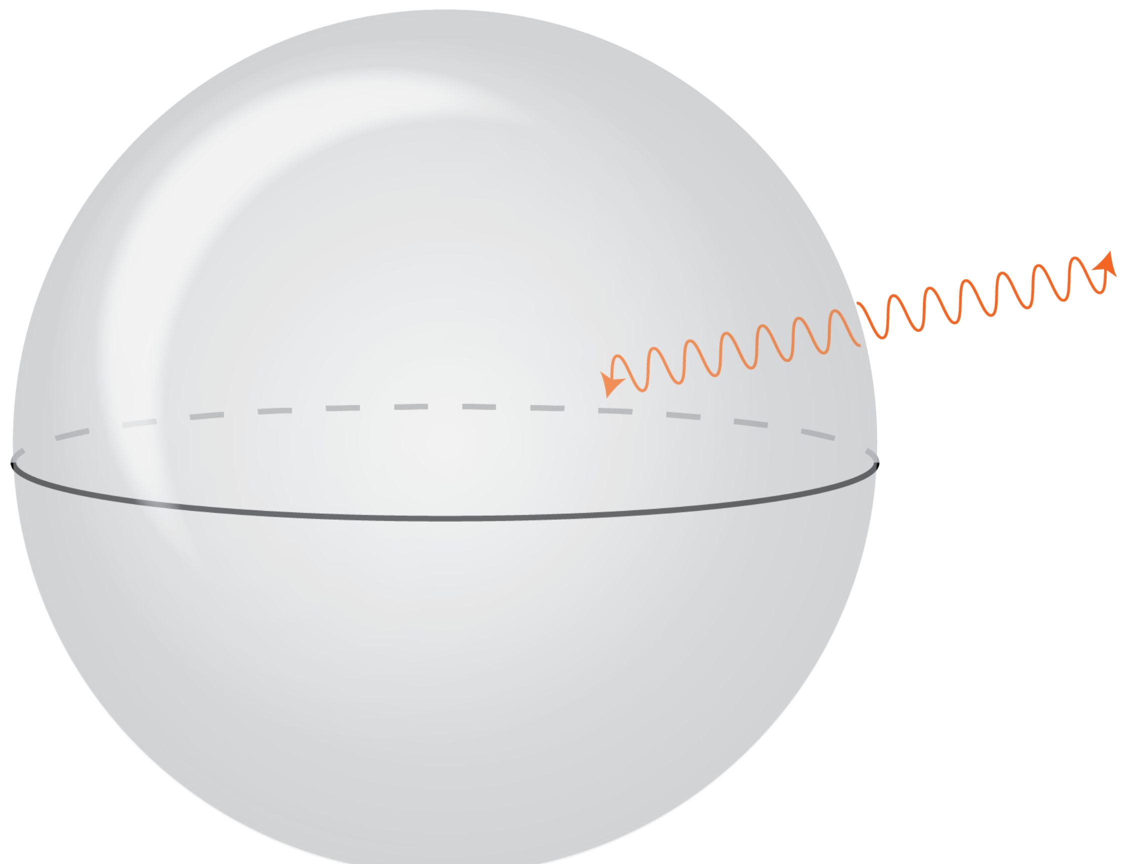
The Price of Curiosity:

Information Recovery in de Sitter Space



Based on arXiv:2104.00006 *(accepted in JHEP)* with W. Sybesma

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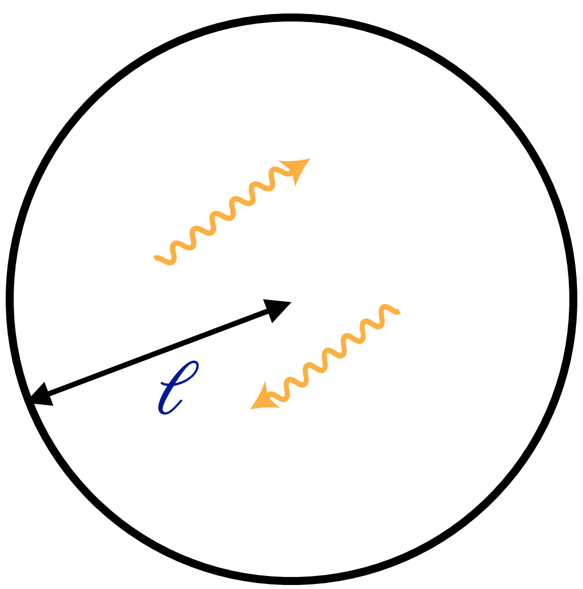
De Sitter Space

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.



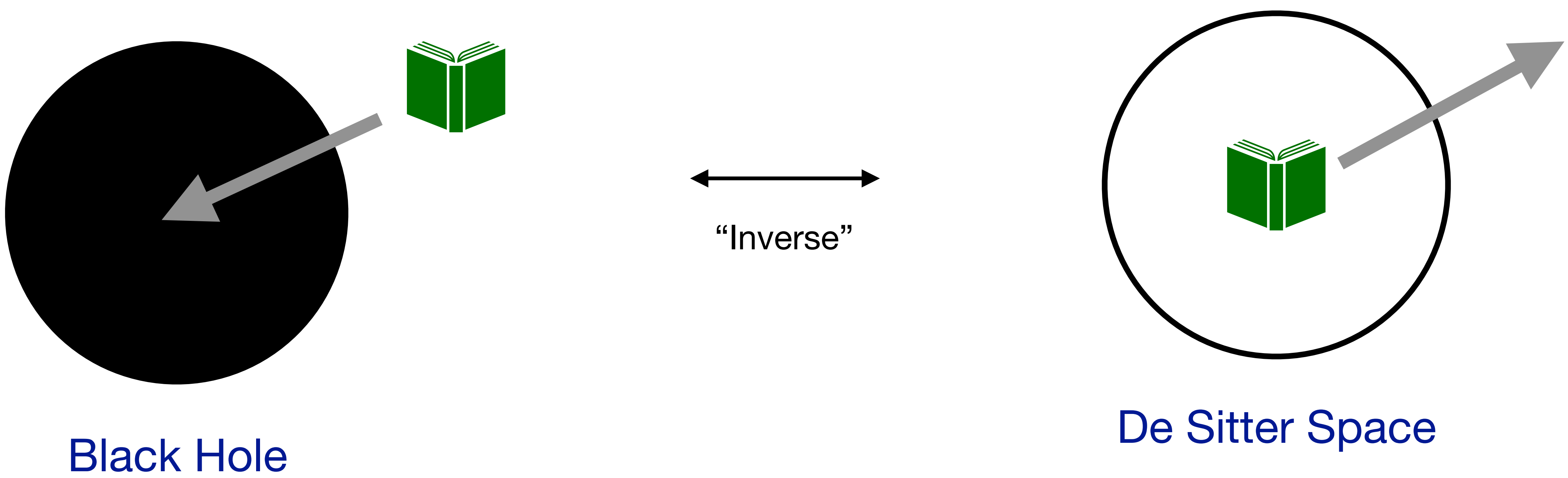
Taking into account (small) quantum effects, the horizon has thermodynamic properties.

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

$$\beta = 2\pi\ell \qquad S = \frac{\textbf{Area}}{4G_N}$$

Quantum Information

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



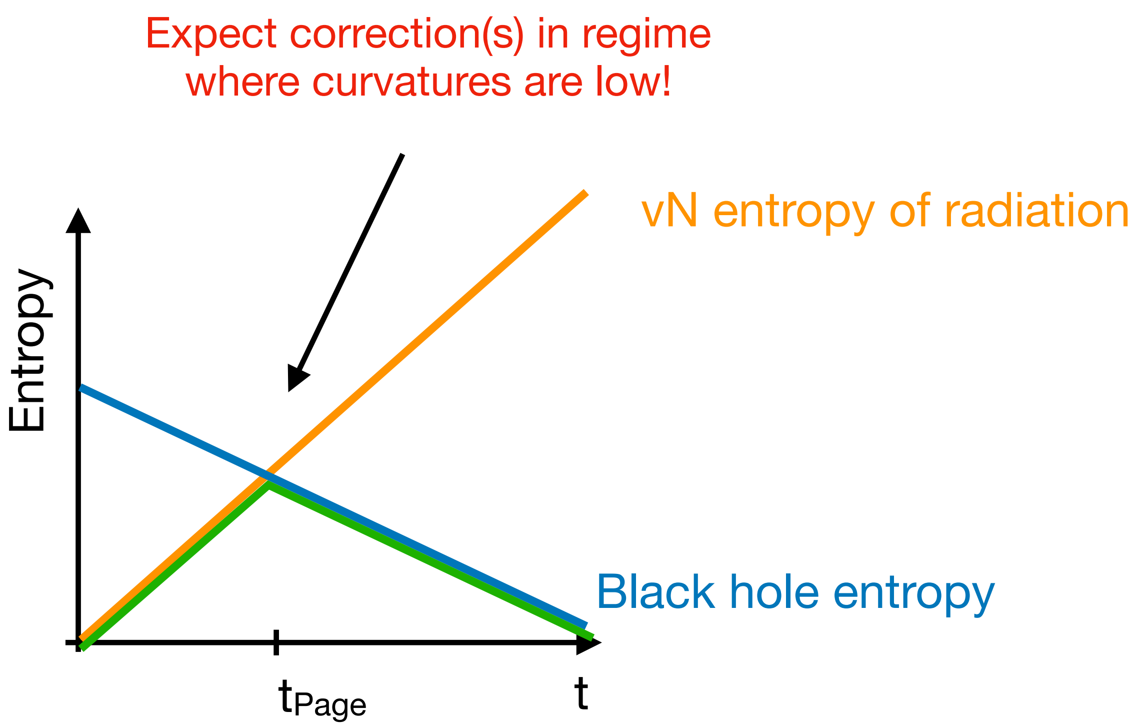
Quantum mechanically, unitary evolution implies that information is preserved. It should be encoded in the Hawking radiation. [Page '93]

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:
$S_{\text{Rad}}(t) \leq S_{\text{BH}}(t)$



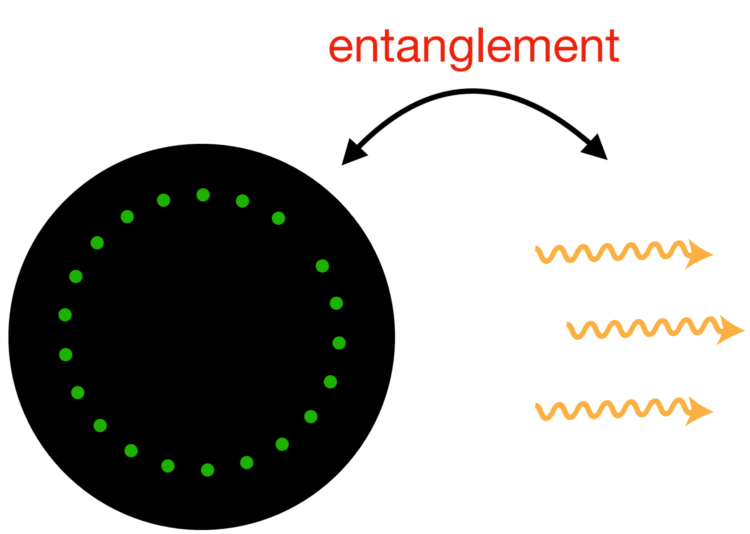
Recently, the required corrections have been found resulting in a unitary Page curve . [Almheiri, Hartman, Engelhardt, Maldacena, Marolf, Maxfield, Penington, Shaghoulian, Tajdini + many more works '19-'21]

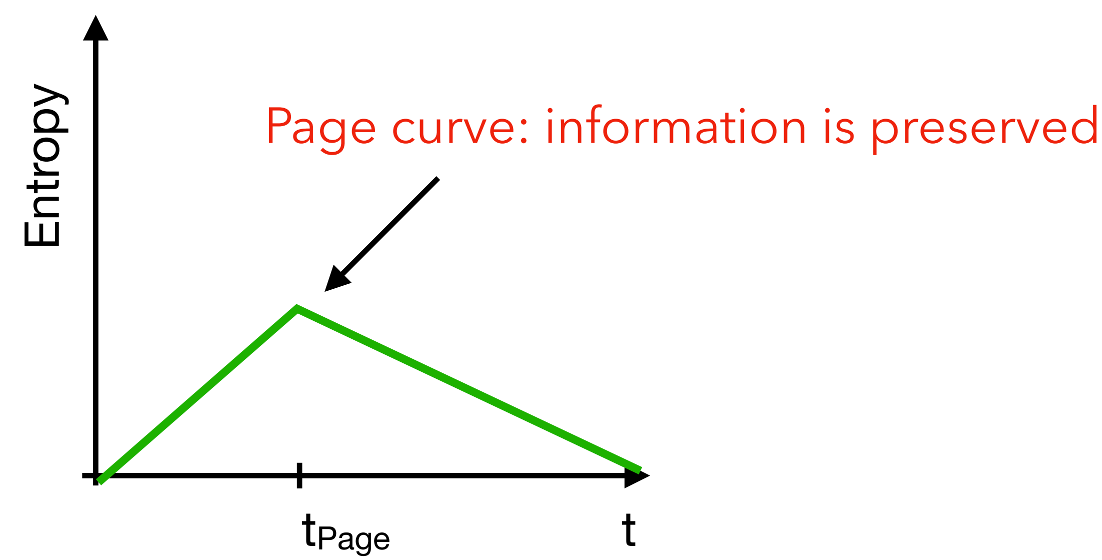
Entanglement Islands

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".





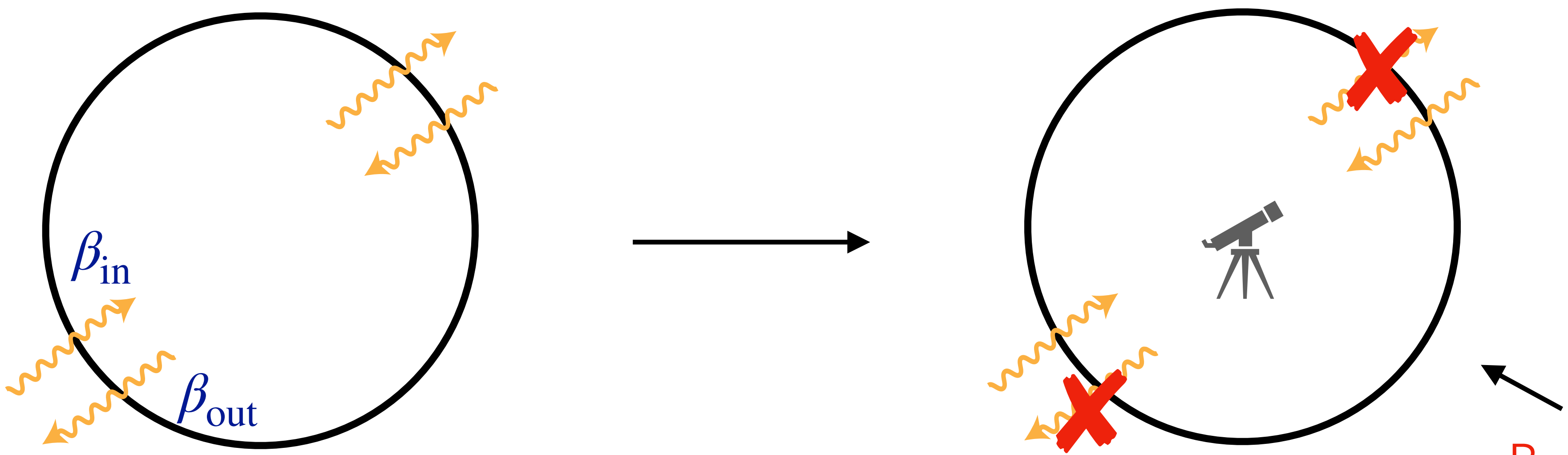
$$S_{\text{Rad}} = \frac{A_{\text{Island}}}{4G_N} + S^{\text{vN}}_{\text{Island}} + S^{\text{vN}}_{\text{Rad}}$$

island found by extremizing

Info Recovery in dS

[LA, Parikh, van der Schaar '19]

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



Breaks thermal equilibrium!

$\beta_{\text{in}} = \beta_{\text{out}} = 2\pi\ell$ $\qquad$ $\beta_{\text{out}} \to \infty$

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.

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

Constant entropy

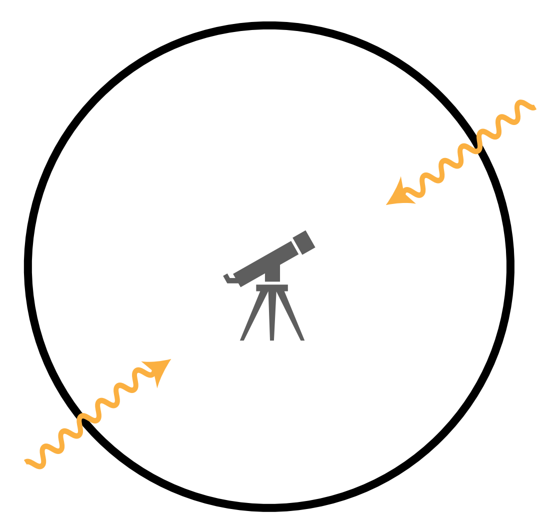
Dynamics

Large c matter sector

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

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

$$\langle T_{\mathrm{out}} \rangle = 0$$



Islands in JT Gravity

[LA, Sybesma '21]

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

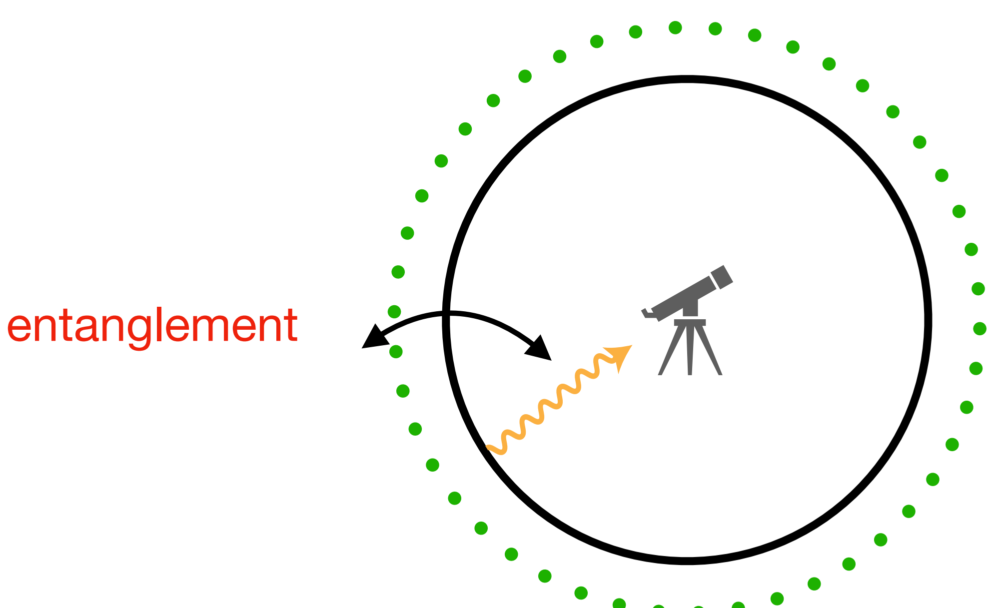
Metric:

$$ds^2 = -(1 - r^2/\ell^2)dt^2 + (1 - r^2/\ell^2)^{-1}dr^2$$

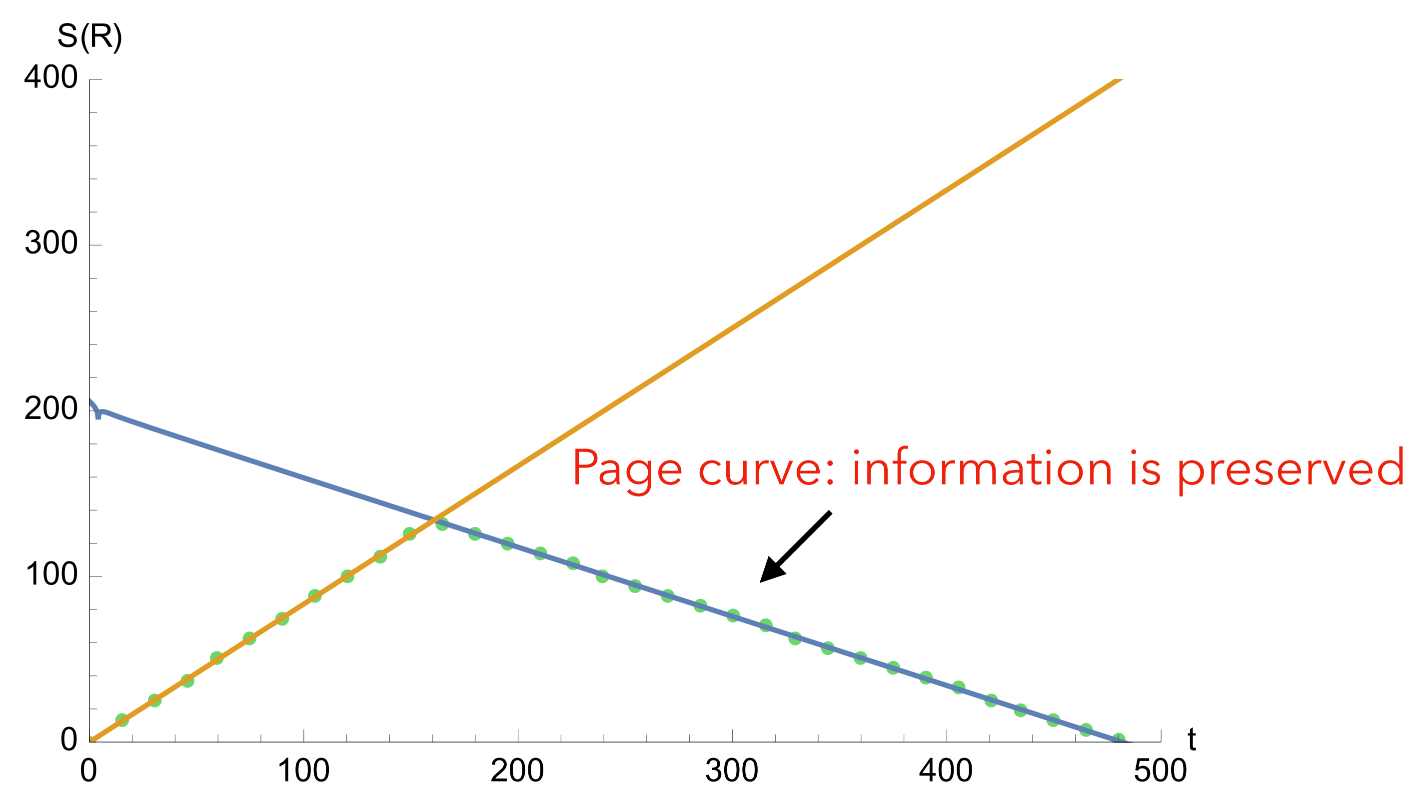
Dilaton:

$$\Phi = -\frac{cr}{\ell^2}t + \dots$$

Using the island formula, we find that islands contribute!



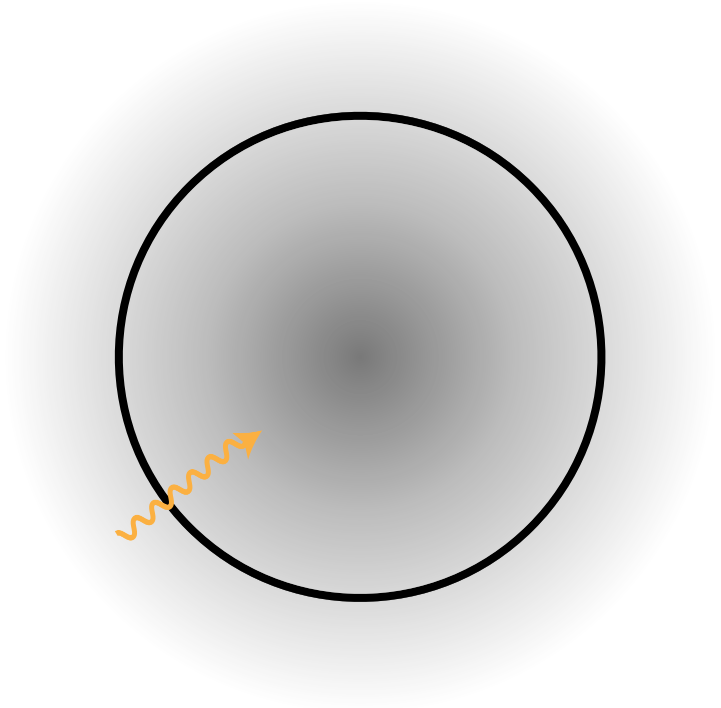
$$S_{\text{Rad}} = \frac{A_{\text{Island}}}{4G_N} + S^{\text{vN}}_{\text{Island}} + S^{\text{vN}}_{\text{Rad}}$$



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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