The Price of Curiosity:

Information Recovery in de Sitter Space

Based on upcoming work with Watse Sybesma

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Cosmological horizons

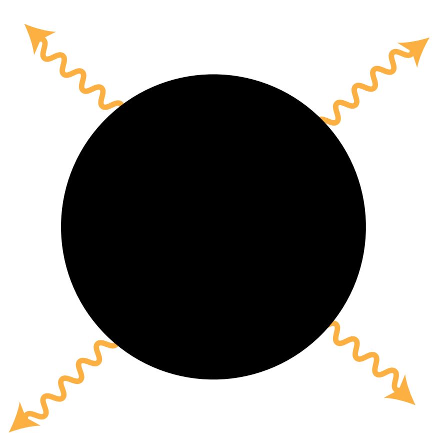
A static observer in de Sitter is surrounded by a cosmological horizon.

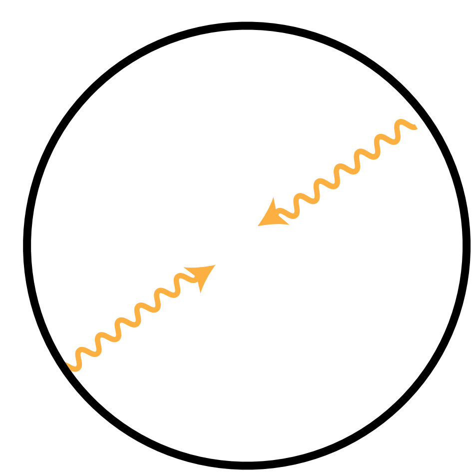
The horizon..

[Gibbons, Hawking '77]

- Has a temperature: $T_{\rm dS} = \dfrac{1}{2\pi\ell}$
- And an entropy: $S_{\rm dS} = \dfrac{\text{Area}}{4G_N}$

And shares many similarities with a black hole horizon.

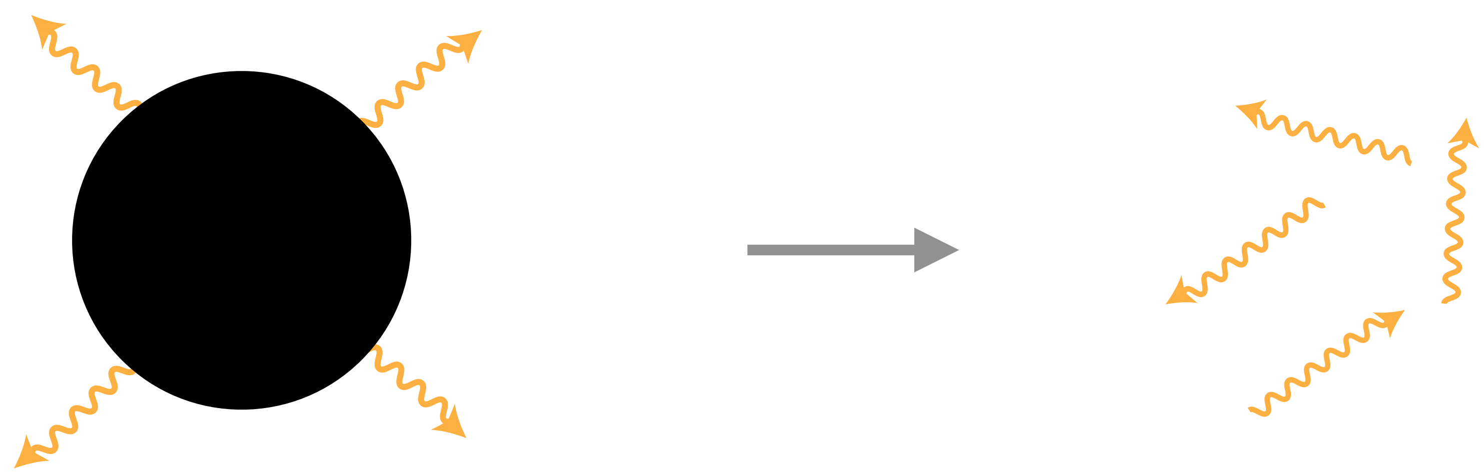




Entropy constraints

The finite black hole entropy can be associated to microstates. Is there a similar interpretation for the de Sitter entropy?

Together with unitarity, finiteness of the entropy places constraints on black hole evaporation.



To resolve the black hole information paradox, new effects should correct the EFT describing Hawking radiation.

Corrections to BHs and dS

In last ~2 years, it has been realised what new effects should be included to resolve the information paradox.

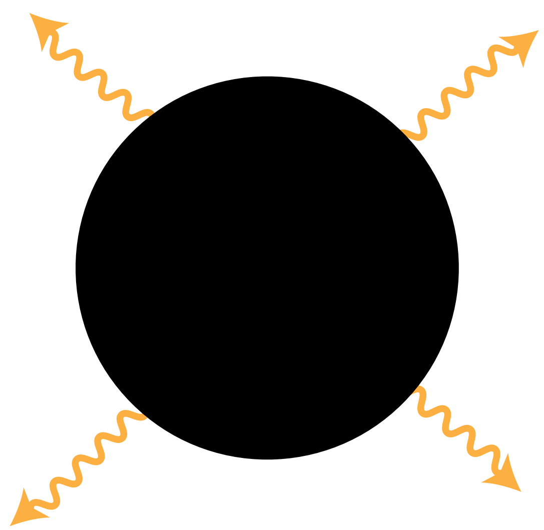
These new contributions do not rely on the specific background. Can similar effects occur in de Sitter space?

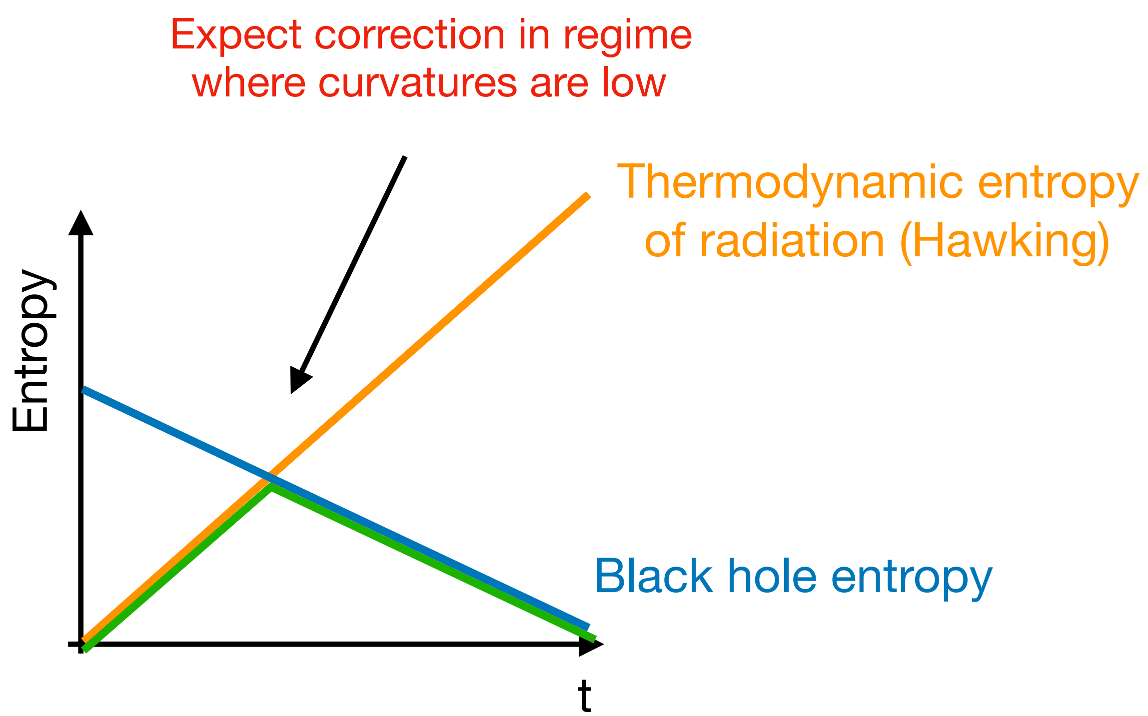
Today we'll see:

- A review of recent developments resolving the info paradox.
- How these results can be applied to JT gravity in dS_2.
- This implies information can be recovered behind the cosmological horizon.
- This experiment does not end well for a static observer.

BH information paradox

The fact that Hawking radiation is thermal, leads to a paradox.



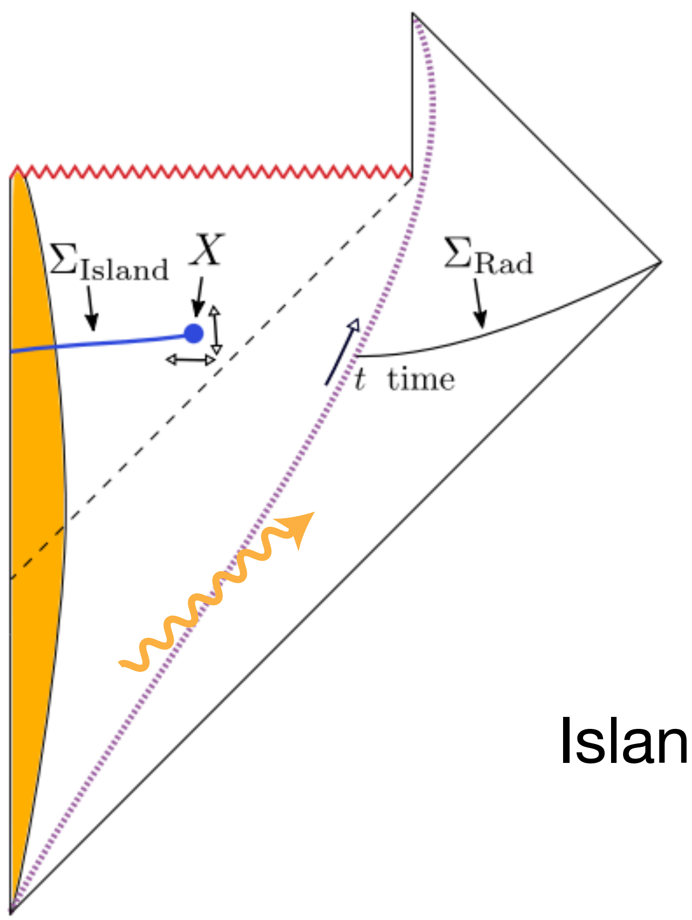


- Unitary evolution requires the radiation entropy to follow the green (Page) curve. [Page '93]

- Recently, a new "island" contribution has been found that reproduces the Page curve. [Almheiri, Hartman, Engelhardt, Maldacena, Marolf, Maxfield, Penington, Shaghoulian, Tajdini + many more works]

The island formula

They key insight is that a disconnected (island) region can contribute to the entropy of radiation.



$$S_{\text{Rad}} = \textbf{min ext}_X \left[\frac{\textbf{Area}(X)}{4G_N} + S_{\text{vN}}(\Sigma_{\text{Rad}} \cup \Sigma_{\text{Island}}) \right]$$

Extremize X to find a quantum extremal surface and pick minimum entropy

Island contribution appears as a new saddle in the Euclidean path integral

1) At early times, trivial island dominates: $S_{\text{Rad}} \simeq S_{\text{vN}}(\Sigma_{\text{Rad}})$

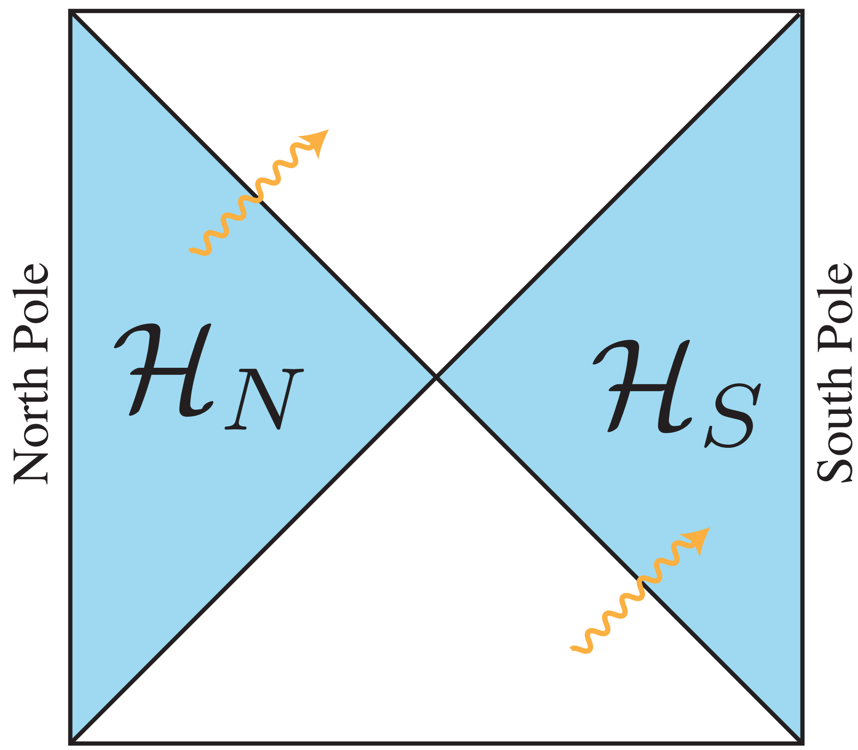
2) After Page time, island starts dominating: $S_{\text{Rad}} \simeq \dfrac{\textbf{Area(X)}}{4G_N}$

$\Longrightarrow$ **Results in Page curve**

[Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini '20]

Entanglement in de Sitter space

The natural vacuum state in de Sitter space is the Bunch-Davies state.



$\beta = 2\pi\ell$

$$\rho = \frac{1}{Z}\sum_i e^{-\beta E_i} |E_i\rangle_N |E_i\rangle_S \ \langle E_i|_N \langle E_i|_S$$

Pure state.

Tracing over NP:

$$\rho_S = \mathbf{tr}_N(\rho) = \frac{1}{Z}\sum_i e^{-\beta E_i} |E_i\rangle_S \ \langle E_i|_S$$

Maximally entangled state.

Side remark: $\langle \mathcal{O} \rangle = \mathbf{tr}_S(\mathcal{O}\rho_S)$

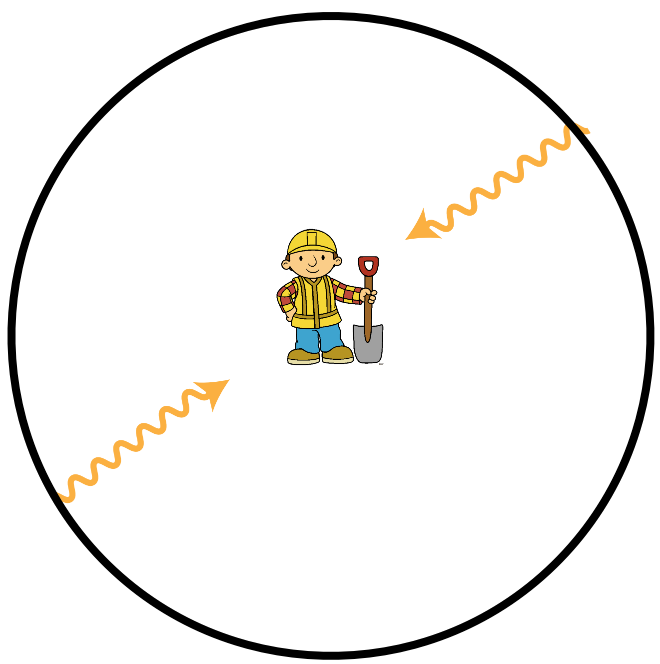
Tracing does <u>not</u> break the de Sitter isometries.

Large entanglement entropy suggests possibility of information recovery.

Islands in de Sitter space?

To decode, islands should contribute to the entropy in de Sitter space.

[Hartman, Jiang, Shaghoulian '20] [Chen, Gorbenko, Maldacena '20] [Chen, Gorbenko, Maldacena '20] [Balasubramanian, Kar, Ugajin '20][Sybesma '20][Geng, Nomura, Sun '21]



Decoding information requires radiation to be stored in the static patch.

Positive energy shrinks the horizon, breaking the thermal equilibrium!

We will go beyond the thermal equilibrium studied so far and compute backreaction in JT gravity.

JT Gravity in dS_2

[Maldacena, Turiaci, Yang '19]

JT gravity can be obtained as the $dS_2 \times S^2$ near-horizon limit of a near-Nariai black hole.

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

Topological term

Deviation from Nariai limit

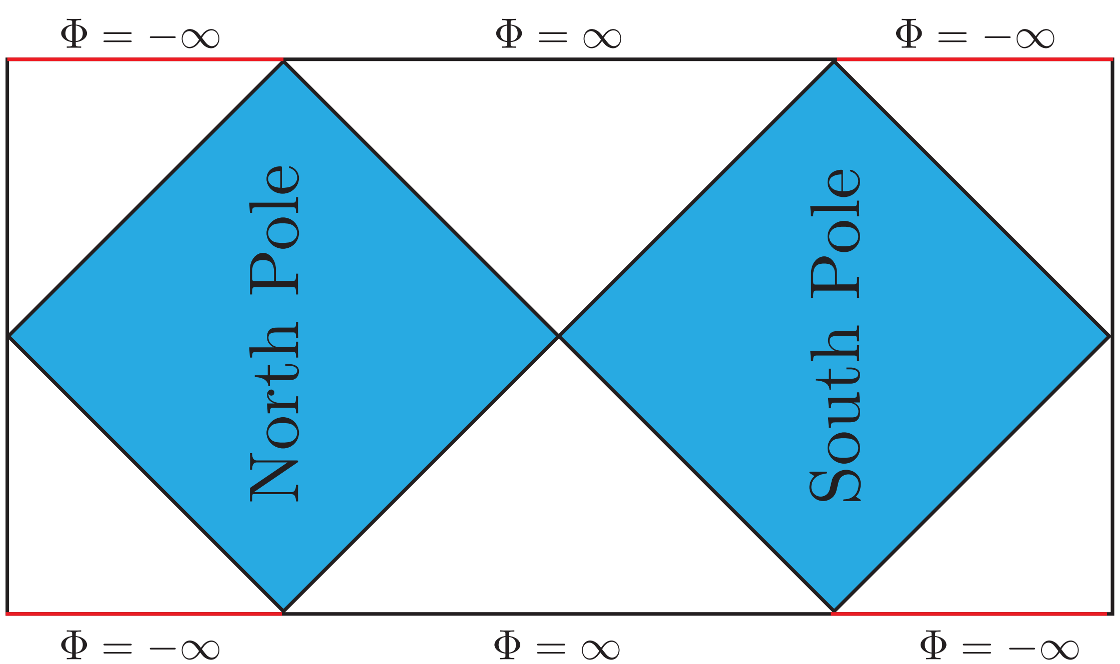
Large c matter sector

Picking coordinates that cover the static patch: $ds^2 = -\sin^2\theta dt^2 + \ell^2 d\theta^2$

$$\Phi = \frac{\Phi_s}{24}\cos\theta$$

$$S_{\rm dS} = 2\Phi_0 + 2\Phi(\theta = 0)$$

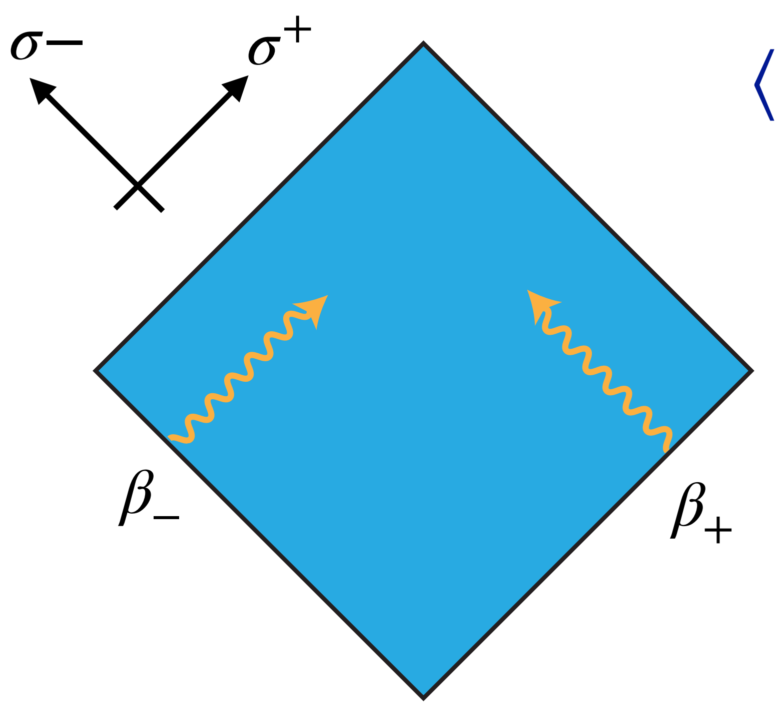
Large dilaton corresponds
to weak gravitational coupling



Including matter

Including conformal matter, we can compute the quantum-corrected geometry.

Using null coordinates $\sigma^{\pm} = t \pm r_*$, we find in the Bunch-Davies state:



$$\langle T_{\pm\pm}(\sigma^{\pm})\rangle = \mathbf{tr}_S\left(T_{\pm\pm}(\sigma^{\pm})\rho_S\right) = \frac{\pi c}{12\beta_{\pm}^2}$$

$\beta_{\pm} = 2\pi\ell$

$$\Phi = \frac{\Phi_s}{24}\cos\theta + \frac{c}{24}$$

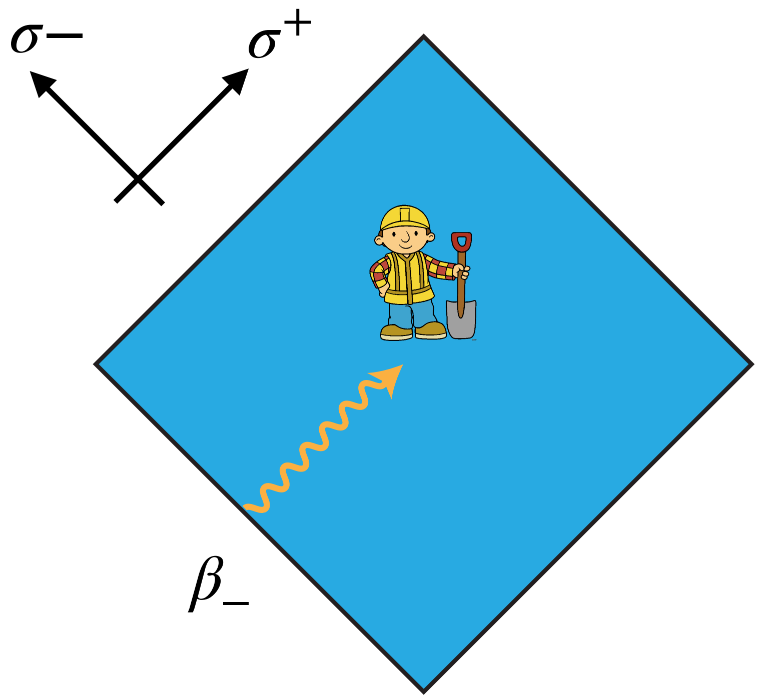
This describes a thermal equilibrium with no backreaction.

State of a curious observer

[LA, Sybesma]

[LA, Parikh, van der Schaar '19]

Now consider an observer at the South Pole that collects right-moving radiation with the aim of decoding information.



$$\langle T_{--}(\sigma^-)\rangle = \frac{\pi c}{12\beta_-^2}$$

$$\langle T_{++}(\sigma^+)\rangle = 0$$

Effectively sets left-moving temperature to zero.

Working in $x^\pm$ (Kruskal) coordinates, the backreacted solution is:

$$x^\pm = \pm\,\ell\, e^{\pm\sigma^\pm/\ell}$$

$$\Phi = \frac{c}{48}\left[1 + \frac{2\Phi_s}{c\ell} r - \frac{r}{\ell}\log(x^+/\ell)\right]$$

Explicit time dependence.

dS information paradox

The entropy of the collected radiation increases, while the horizon entropy decreases.

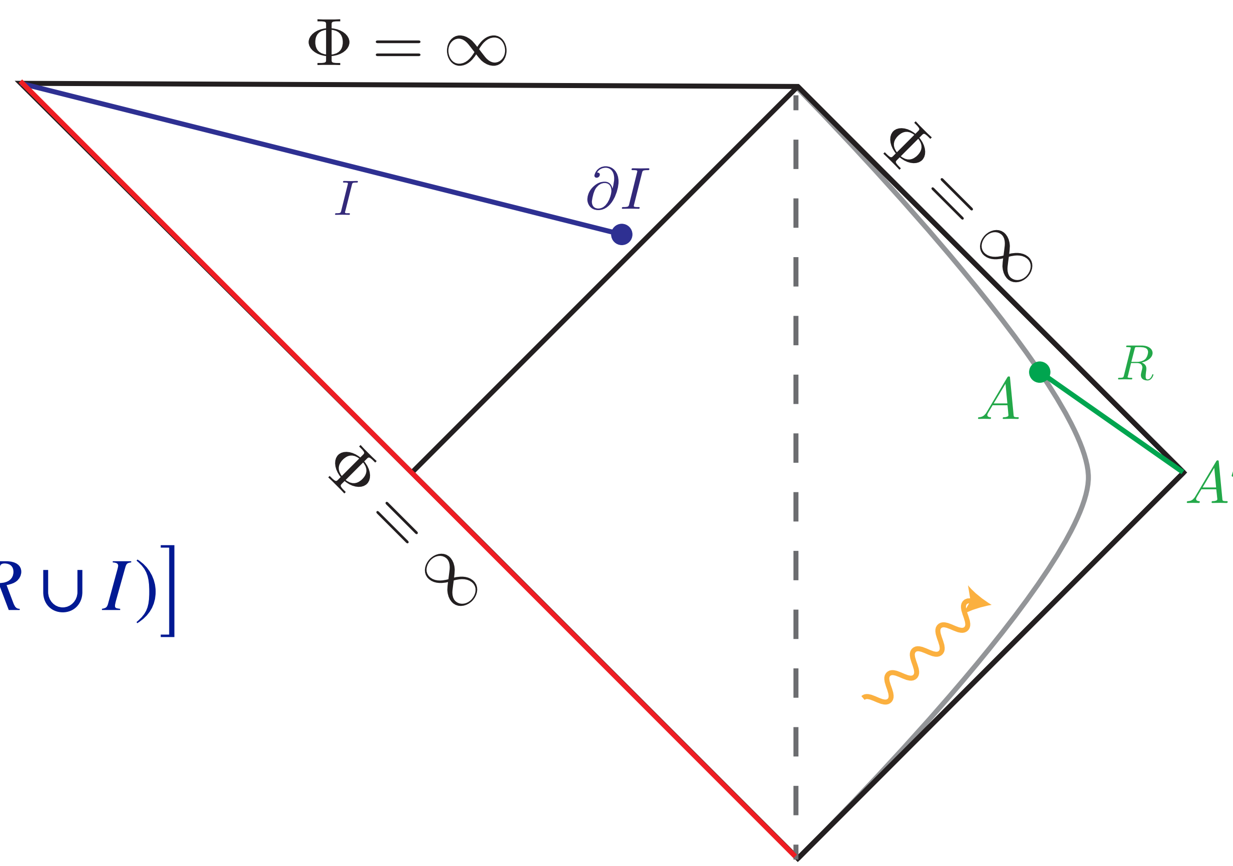
1st law: $dS_{\rm dS} = -\frac{c}{24\ell}dt$

CFT: $dS_{\rm Rad} = \frac{c}{12\ell}dt$

$\Rightarrow$ Without island contribution, violates unitarity.

We now allow for the contribution of an island.

$$S(R) = \textbf{min}\,\textbf{ext}_{\partial I}\left[2\Phi_0 + 2\Phi(\partial I) + S_{\rm vN}(R \cup I)\right]$$



Island contributions

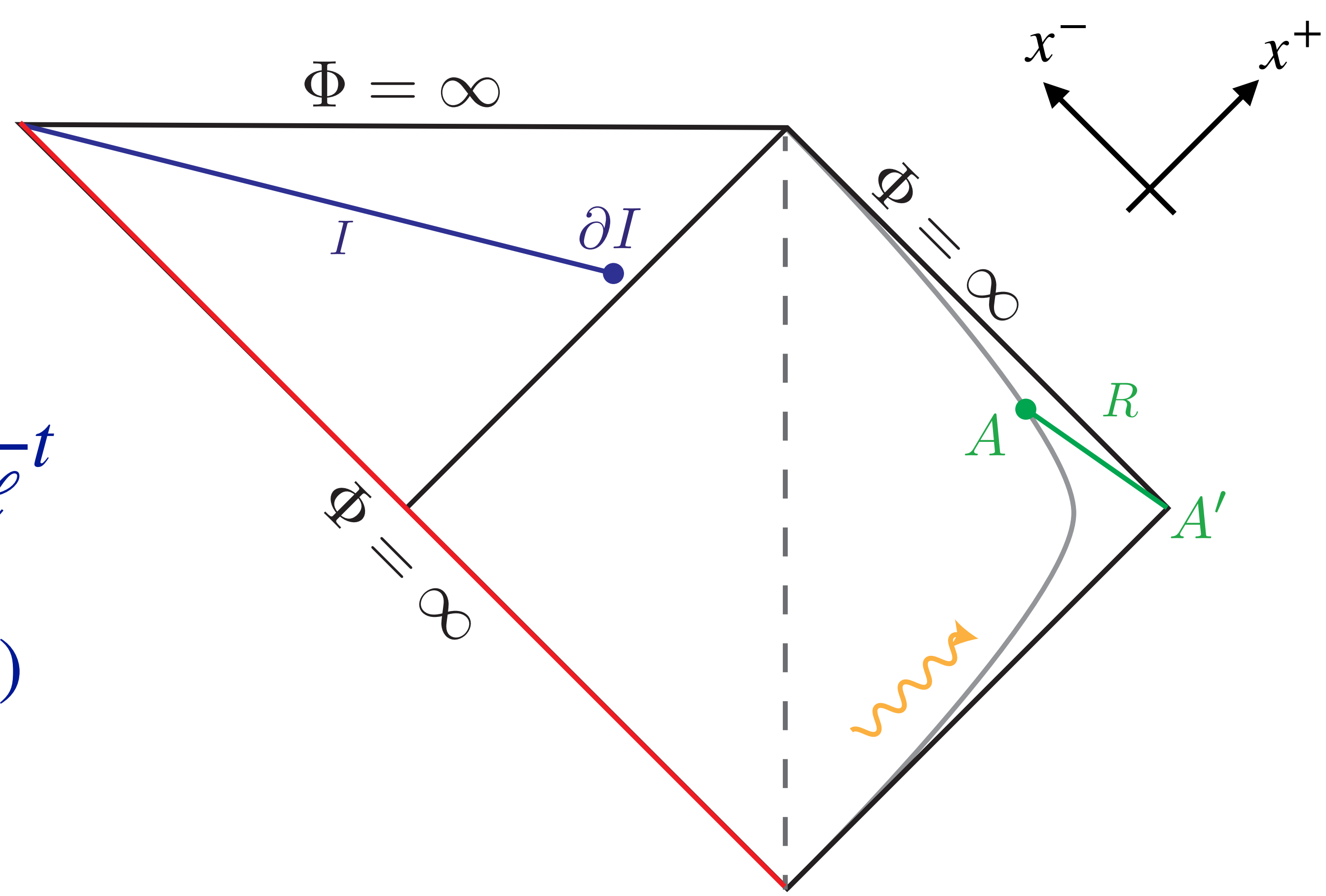
[LA, Sybesma]

Extremizing the fine-grained entropy, we find in addition to the trivial island an additional contribution:

Island location: $x^-_{\partial I} \gtrsim 0 \qquad x^+_{\partial I} \simeq \ell e^{1+2\Phi_s/c} + 2\ell e^{t/\ell}$

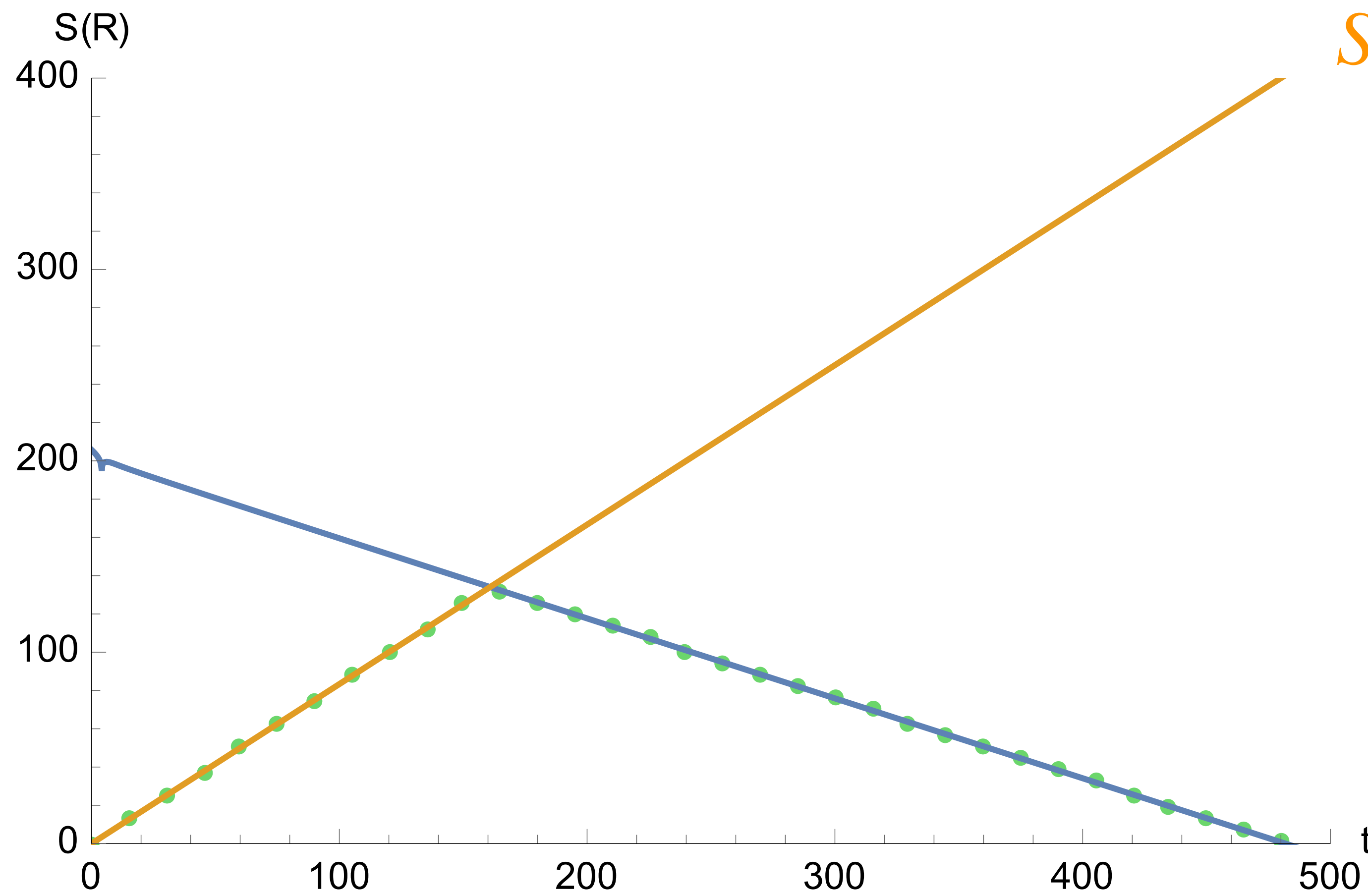
Trivial island: $S(R) \simeq S_{\rm vN}(R) = \dfrac{c}{12\ell} t$

Non-trivial island: $S(R) \simeq 2\Phi_0 + 2\Phi(\partial I)$



Page curve for dS

Taking the minimum of both contributions, we find a Page curve for the radiation in de Sitter space.



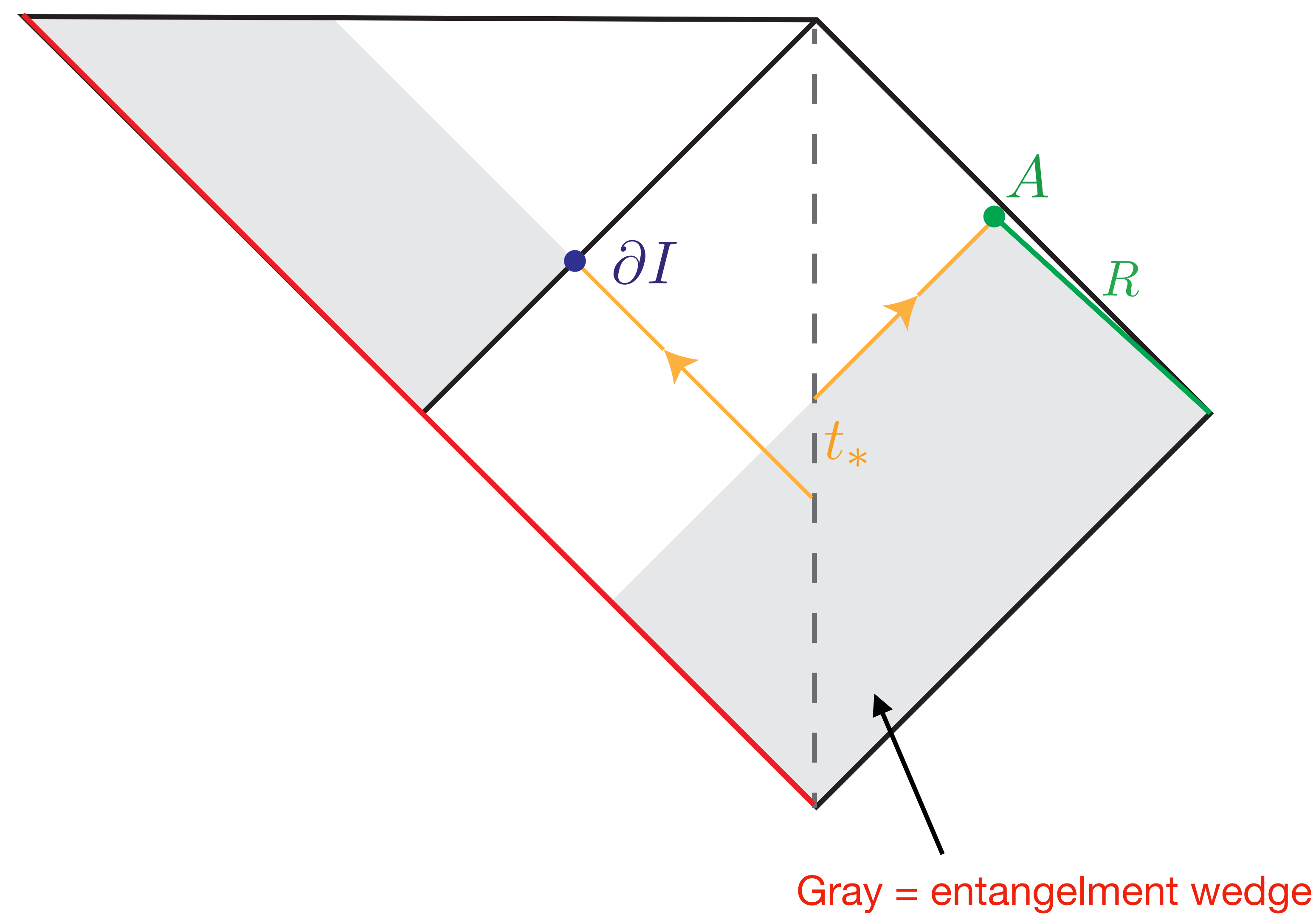
$$S_{\mathrm{Rad}} = \frac{c}{12\ell} t$$

$$S_{\mathrm{dS}} = 2\Phi_0 + 2\Phi(\partial I)$$

The Page time is given by: $t_{\mathrm{Page}} = \dfrac{16\ell\Phi_0}{c}$.

Information recovery in dS

After the Page time, information recovery becomes possible in a scrambling time.



Compute time difference between a lightray reaching the island and arrival in R:

$$t_* = \ell \log(S_{\mathrm{dS}})$$

Agrees with computation using OTOCs [LA, Shiu '20] [Blommaert '20] .

Fate of the observer

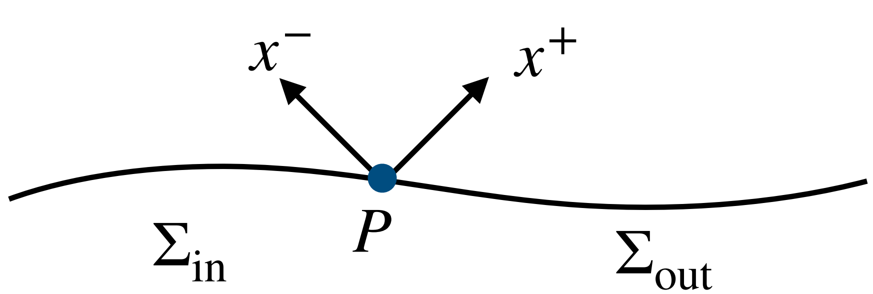
Information recovery is possible, but what is the fate of the observer?

- Because energy is continuously collected in a finite volume, backreaction eventually becomes large.

- Does a singularity form?

To assess, use quantum singularity theorem: [Wall ' 10] (see also [Freivogel, Kontou, Krommydas '20])

Quantum Singularity Theorem:
a singularity is unavoidable when a quantum trapped region forms.



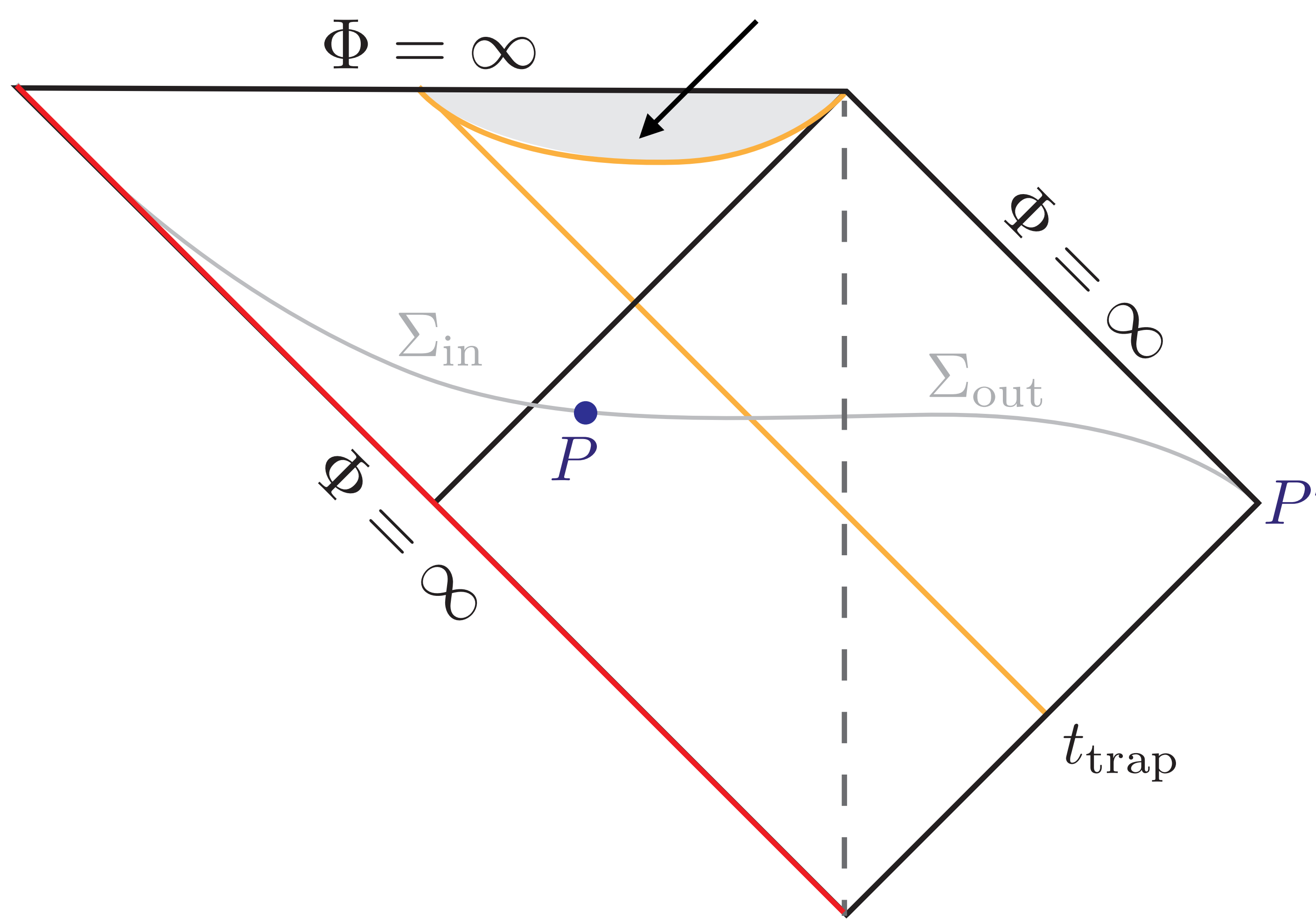
$$S(P) = \frac{\textbf{Area(P)}}{4G_N} + S_{\rm vN}(\Sigma_{\rm out})$$

Quantum Trapped: $\partial_\pm S(P) < 0$

Quantum singularity theorem

We now look for quantum trapped regions in the non-equilibrium state.

Quantum trapped region.



Solving for $\partial_\pm S = 0$ we find a quantum trapped region after:

$$t > t_{\rm trap} = \frac{2\Phi_s \ell}{c}$$

Hierarchy: $t_* \ll t_{\rm trap} \simeq t_{\rm Island} \ll t_{\rm Page}$

After $t_{\rm trap}$ the formulation of a singularity will be unavoidable.

Conclusions

- Using recent developments in quantum information, we assessed if the static patch of de Sitter exhibits an information paradox.
- In JT gravity, we found that quantum extremal islands contribute to the fine-grained entropy.
- Gives an interpretation of the de Sitter entropy with respect to a single static observer.
- In de Sitter, curiosity comes at a price: when an island appears, formation of a singularity is unavoidable.
- Relation to inflationary physics?

Thank you!

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