Love and Regret in a de Sitter Universe

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String Phenomenology 2020

Based on arXiv: 2002.01326 and work in progress.

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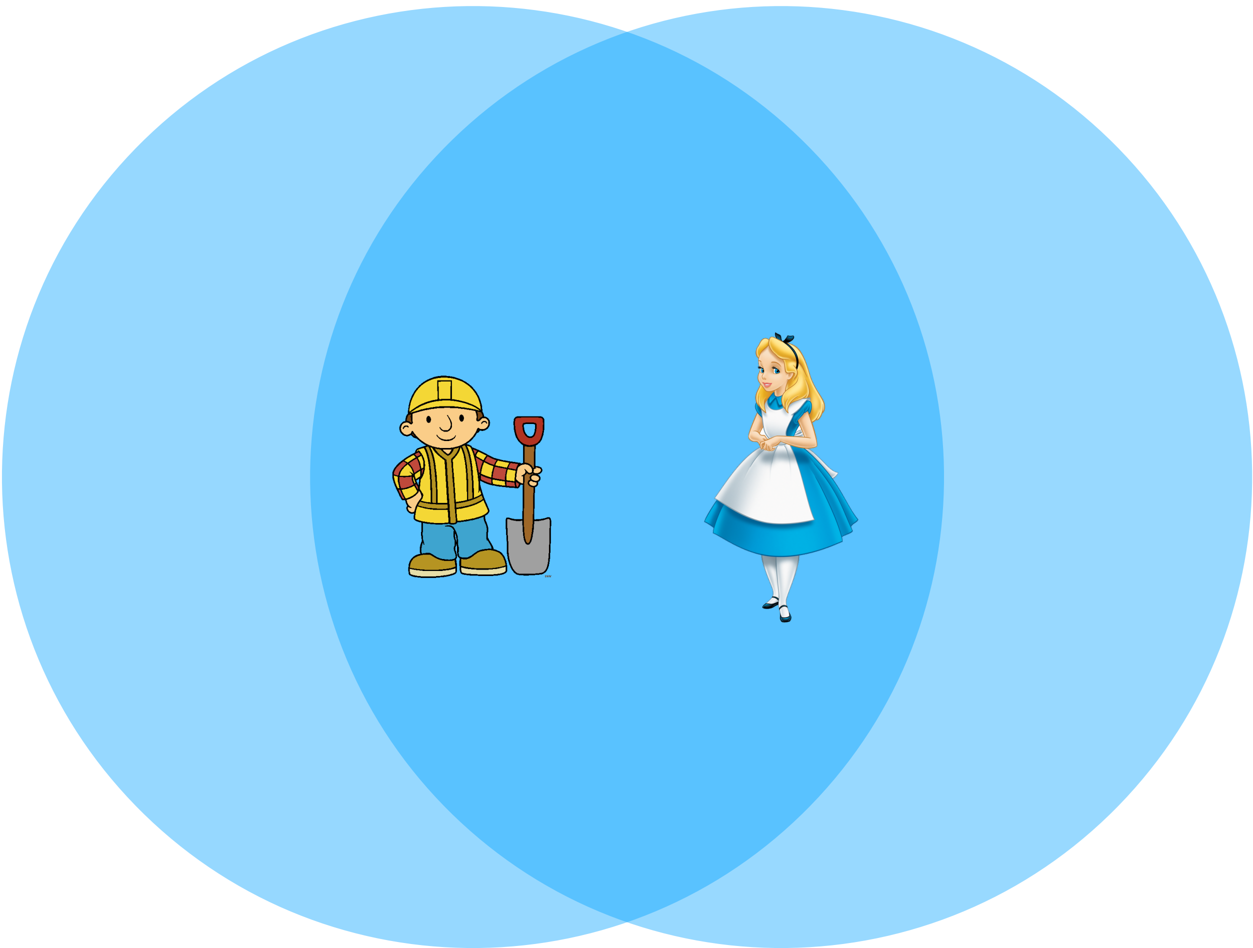
Love..

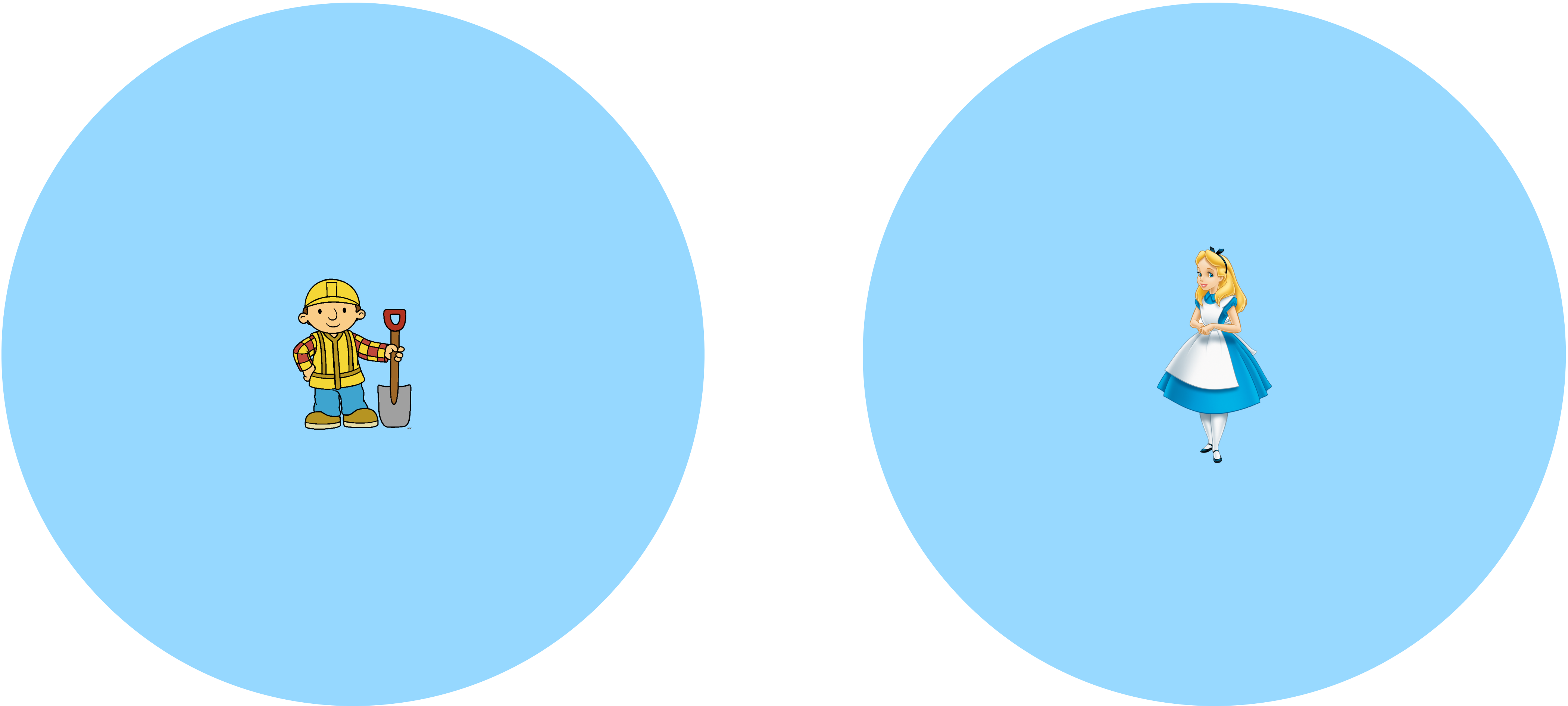
- Alice and Bob are two lovers, living in a de Sitter universe.



- But one day, they decide to separate..

Love..

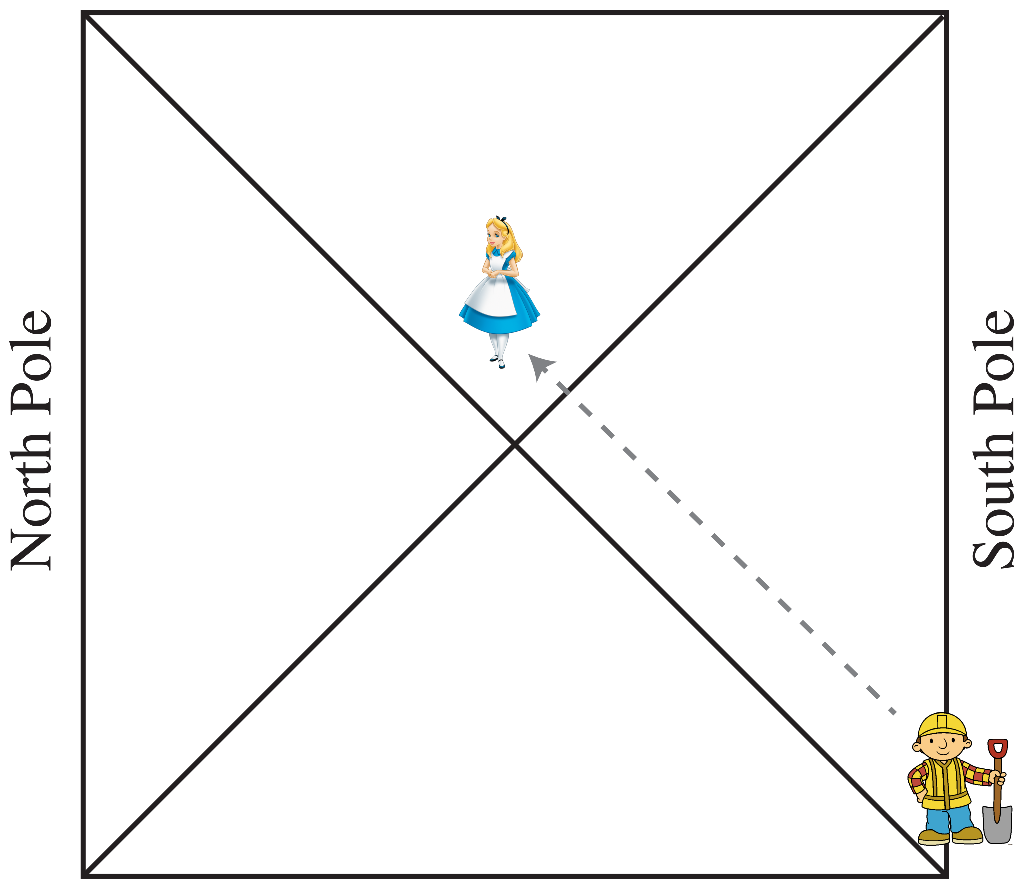
- Alice and Bob are two lovers, living in a de Sitter universe.



- But one day, they decide to separate..

and regret..

- Quickly after separating, they both regret their decision.
- But now, a cosmological horizon separates them.



Can Bob and Alice rejoin?

or

In a de Sitter universe can you retrieve information when it has left your horizon?

Why is this interesting?

- For black holes, information recovery experiments lead to paradoxes (e.g. information paradox, no-cloning paradox).

- In essence, they tells us about the validity of EFT in quantum gravitational systems.

- We'd like to use the lessons learned from black holes and apply them to de Sitter space.

- Can we use tools from quantum information to put bounds on de Sitter space?

Outline

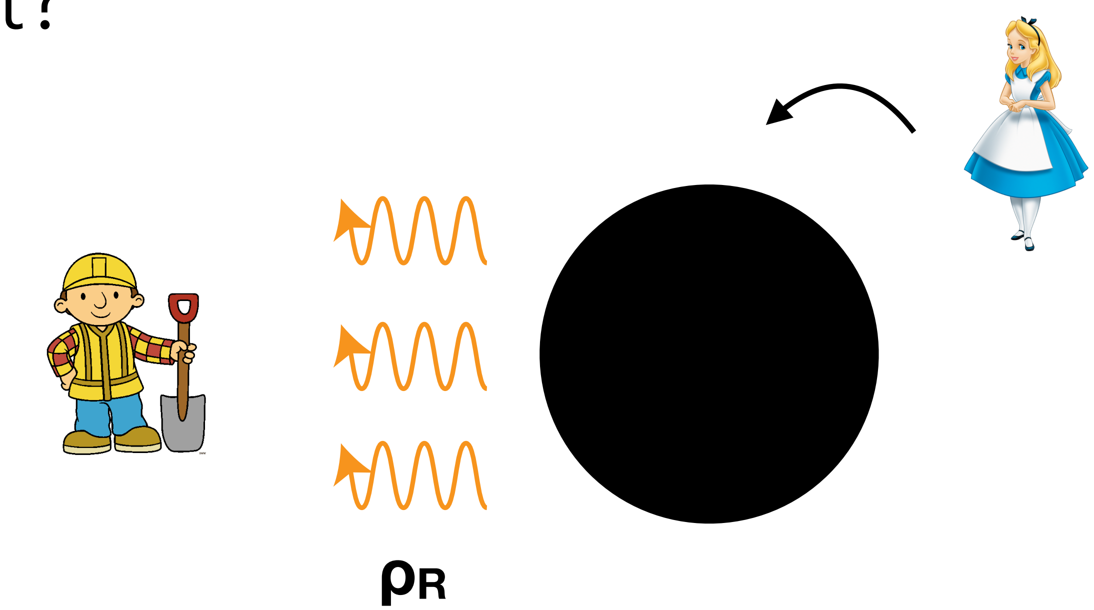
- Information recovery in black holes.
- Shockwaves and scrambling in de Sitter space.
- Information recovery in de Sitter space.
- Possible phenomenological consequences.

Information Recovery in Black Holes

Black Hole Information

- Alice jumps into an evaporating black hole, how long does it take before she gets out?

1) Alice jumps in right away, Bob starts collecting.



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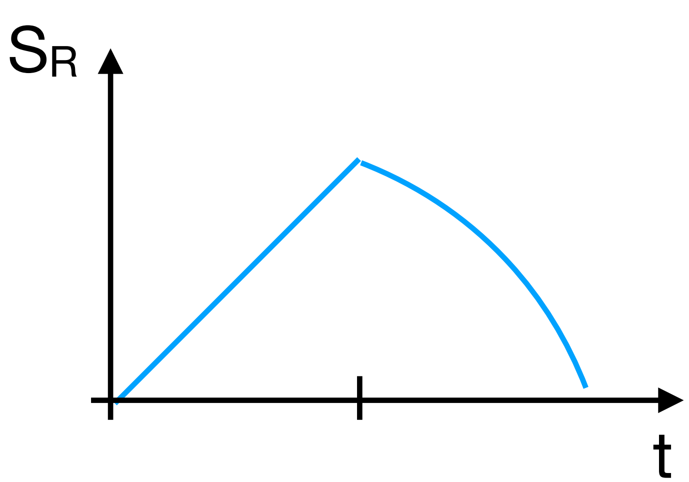


$t_{Page} \sim r_s S_{BH}$

2) After the Page time, a new qubit can be recovered much faster. [Hayden and Preskill '07]

Scrambling time:

$t_s \sim r_s \log(S_{BH})$

Information scrambling

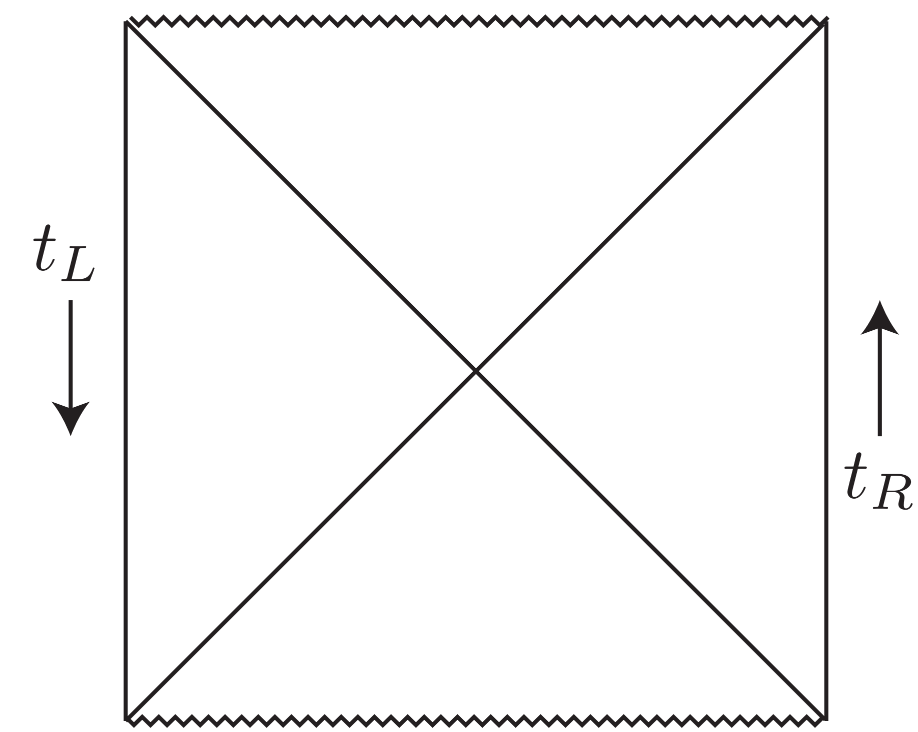
- The recovery time is bounded by the time it takes the horizon to absorb the qubit, i.e. the scrambling time.

- This timescale can be deduced by perturbing the thermofield double (TFD) state.

$$\langle V(0)W(t)V(0)W(t)\rangle \simeq 1 - \frac{1}{S_{bh}} e^{\frac{2\pi}{\beta}t}$$

Out-of-time-order correlator

$$\longrightarrow \quad t_* = \frac{\beta}{2\pi}\log(S_{bh})$$



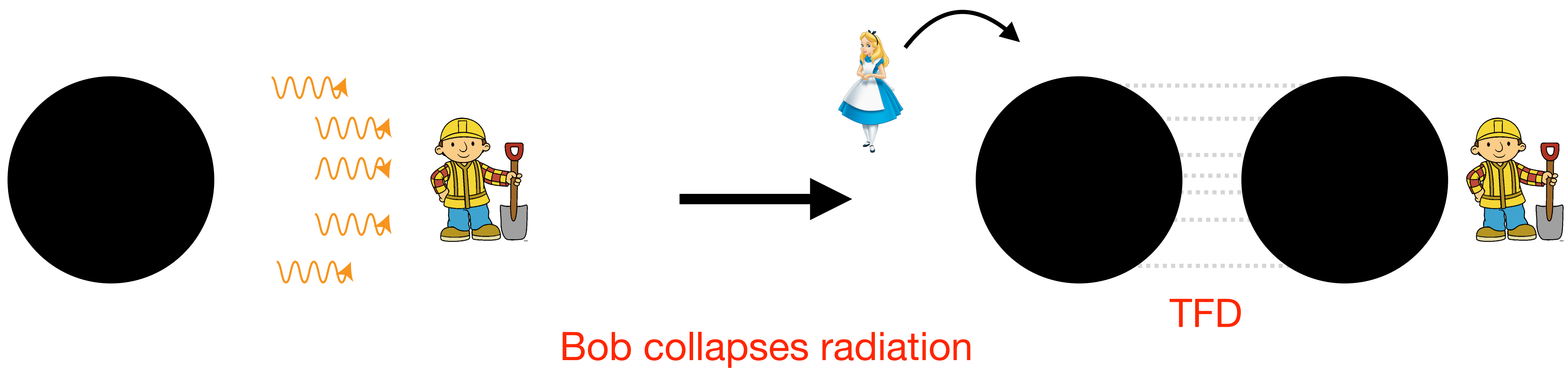
$$|\mathrm{TFD}\rangle = \frac{1}{\sqrt{Z}}\sum_n e^{-\beta E_n/2}\,|n\rangle_L \otimes |n\rangle_R$$

- Black holes are “fast scramblers”.

  [Sekino, Susskind ’08] [Shenker, Stanford ‘ 13] [Stanford, Shenker, Maldacena ’16]

Information recovery in TFD

- Information recovery can be modelled by the TFD. [Maldacena, Stanford, Yang '17]



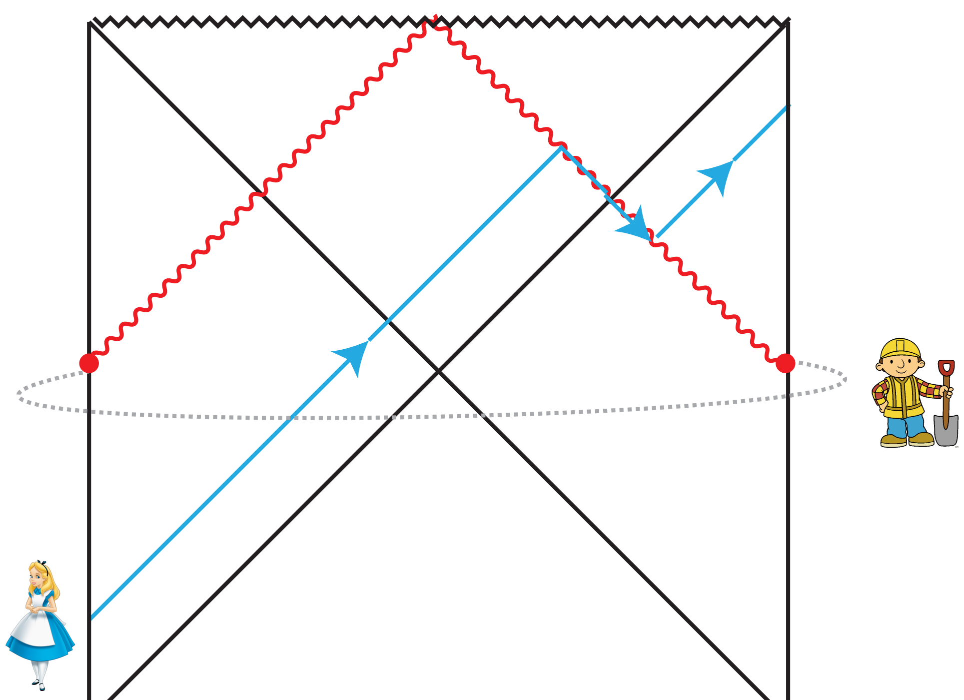
- Successful recovery is the exchange between the two boundaries of the TFD.

- This gives a bulk interpretation of recovering information.

Traversable wormholes

- By turning on an interaction between the boundaries, a negative energy shockwave is created. [Gao, Jafferis, Wall '16] [Maldacena, Stanford, Yang '17]

- This allows Alice to return to Bob!



This is a gravitational interpretation of the Hayden-Preskill decoding protocol.

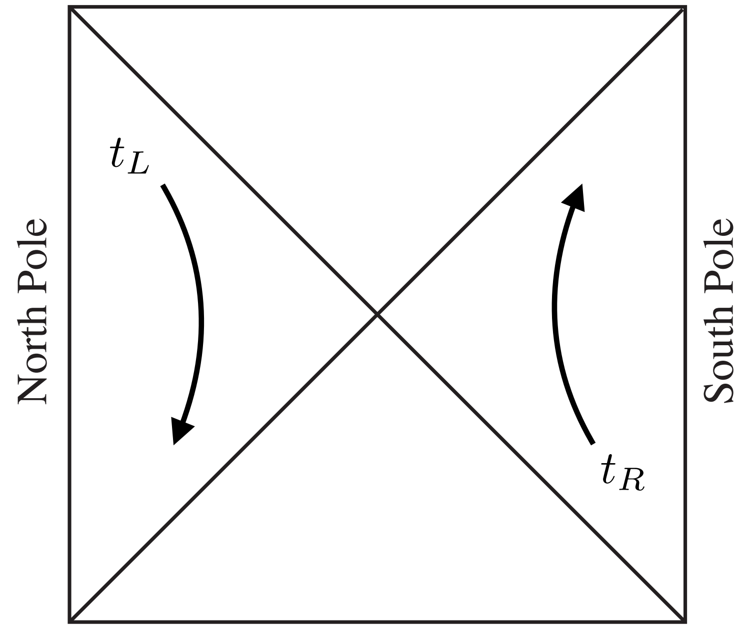
Information Recovery in de Sitter Space

Bunch-Davies vacuum

- In de Sitter space, the thermofield double state is the Bunch-Davies vacuum.

- This vacuum state maximally entangles two static patches of observers at the North and South pole.

- The Bunch-Davies state is an attractor.

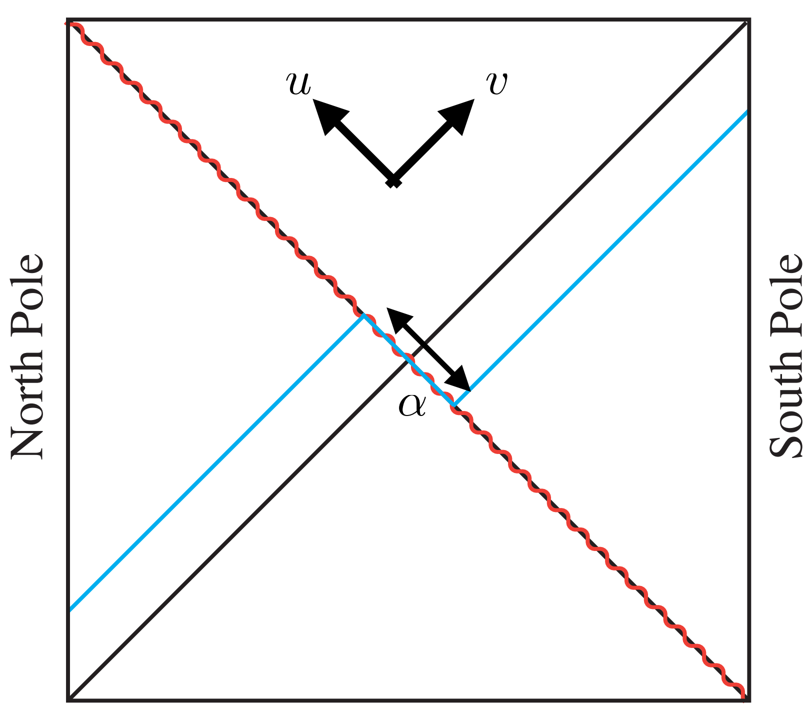


To compute the scrambling time, we need the OTOC.

$$|\mathrm{TFD}\rangle = \frac{1}{\sqrt{Z}} \sum_n e^{-\beta E_n/2} \, |n\rangle_L \otimes |n\rangle_R$$

Shockwaves in de Sitter

- Shockwaves in de Sitter are given by the infinite boost limit of Schwarzschild-de Sitter. In d=3 dimensions:



Lightcone coordinates:

$$u = -\ell e^{-t/\ell}\sqrt{\frac{\ell - r}{\ell + r}} \qquad v = \ell e^{t/\ell}\sqrt{\frac{\ell - r}{\ell + r}}$$

$$ds^2 = \frac{4\ell^4}{(\ell^2 - uv)^2}(-du dv) - 4\alpha\delta(v)dv^2 + \ell^2\left(\frac{\ell^2 + uv}{\ell^2 - uv}\right)^2 d\phi^2$$

Effect of shockwave

$$T_{vv} = \frac{\alpha}{4\pi G_N \ell^2}\delta(v)$$

NEC: $\alpha \geq 0$

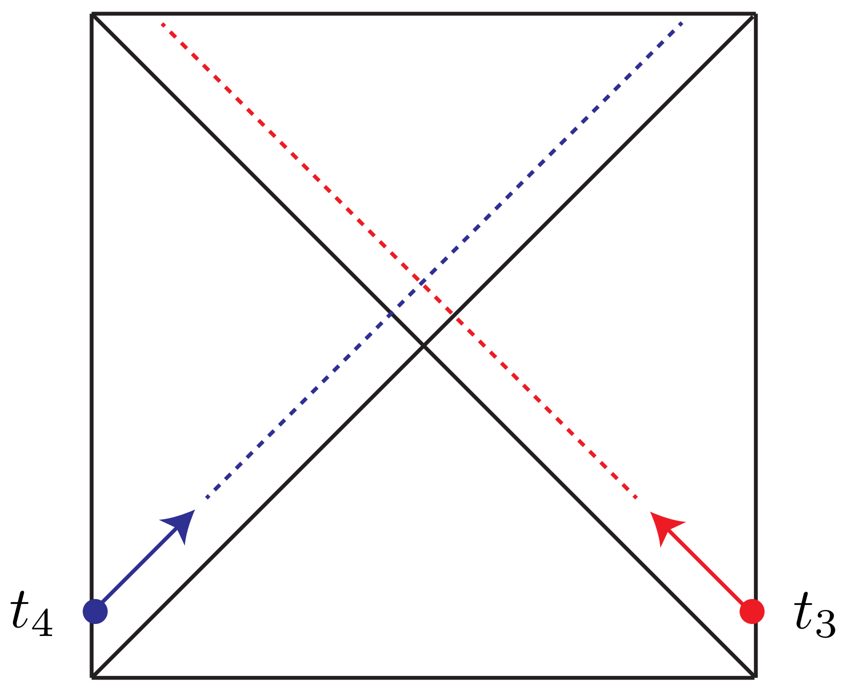
- Positive energy perturbations generate a time advance!

[Gao, Wald '00]

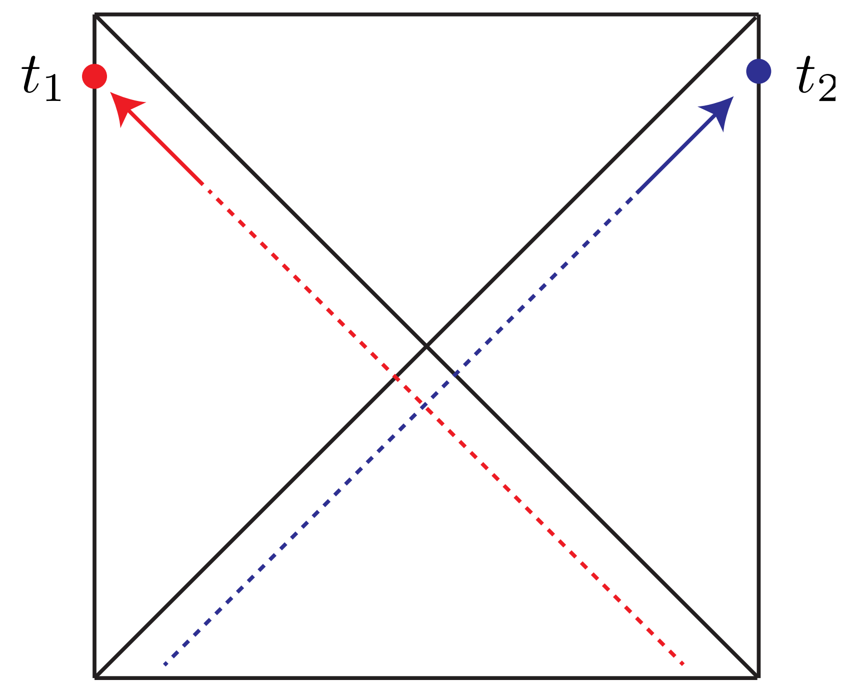
Computing the OTOC

- Before Bob can recover Alice, he has to know she's gone.

Following [Shenker, Stanford '14] we can compute OTOC by scattering "in" and "out" states.



$$|\Psi\rangle = V_R(t_3) W_L(t_4) \, |\mathrm{TFD}\rangle$$



$$|\Psi'\rangle = W_R(t_2)^\dagger V_L(t_1)^\dagger \, |\mathrm{TFD}\rangle$$

$$\longrightarrow \quad \langle V_L(t_1) W_R(t_2) V_R(t_3) W_L(t_4) \rangle = \langle \Psi' \Psi \rangle$$

Results

- Using these ingredients, the OTOC can be computed analytically for conformally coupled fields.

- This gives a result in terms of special functions, expanding we find:

$$\langle V(0)W(t)V(0)W(t)\rangle = 1 - \left(\frac{G_N \pi}{8\ell} e^{t/\ell}\right)^2 + \mathcal{O}\left(\frac{G_N}{\ell} e^{t/\ell}\right)^4$$

[LA, Shiu '20]

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

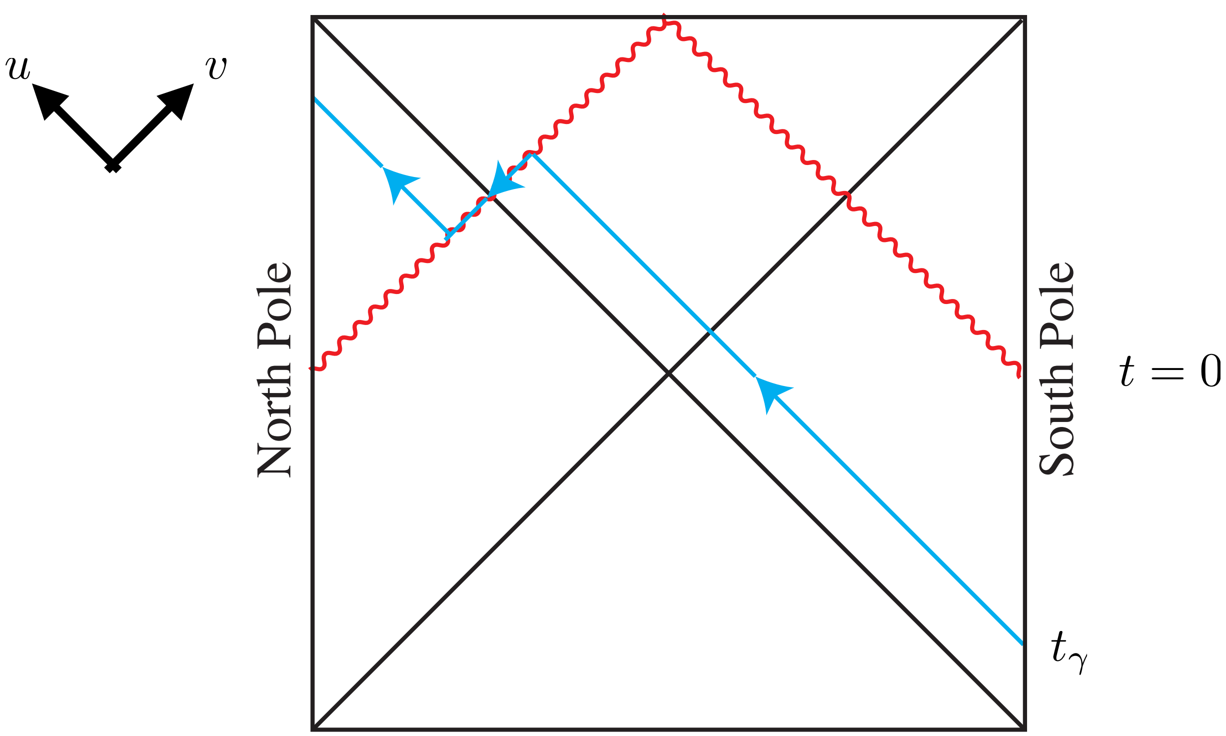
De Sitter is also a fast scrambler!

- What does this imply for the recovery time?

Traversable wormholes

- In de Sitter, positive energy makes the wormhole connecting the two poles traversable.

- No negative energy needed!



$$v_\gamma = \ell e^{t_\gamma/\ell}$$

Traversable when: $v_\gamma - \alpha < 0$

α is related to shockwave energy: $\alpha = \ell \ell_p E$

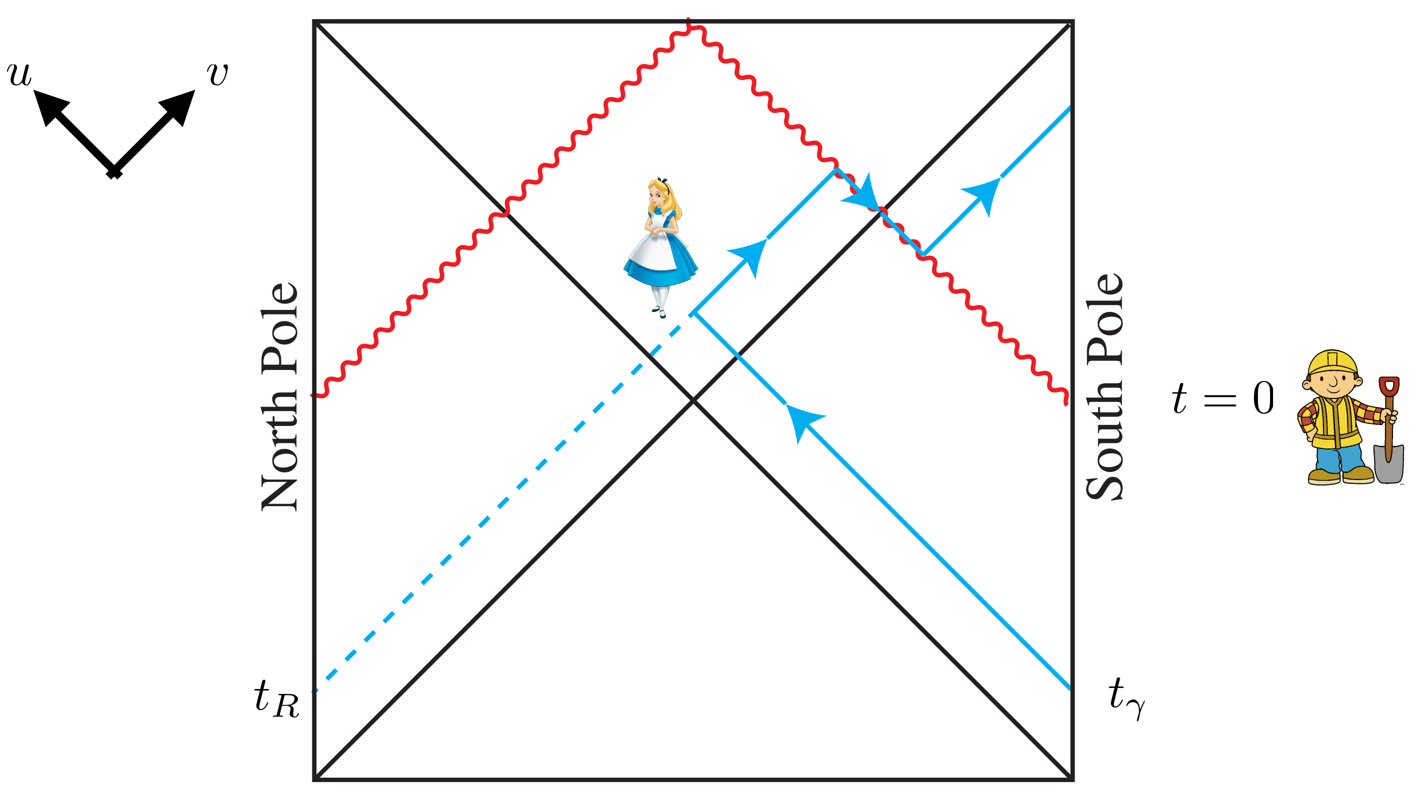
Bob only has access to modes with: $E \simeq 1/\ell$

$$\longrightarrow \quad -t_\gamma > \ell \log(\ell/\ell_p)$$

After a scrambling time, information can be exchanged.

Single-sided protocol

- Now consider a single-sided protocol.



$$u_R = \ell e^{-t_R/\ell}$$

After Alice leaves, Bob has N_γ e-folds to absorb radiation:

$$\longrightarrow \quad \alpha = \ell_p N_\gamma$$

Traversable when: $\quad u_R - \alpha < 0$

Alice returns after:

$$t_{\text{tot}} = N_\gamma \ell - \ell \log\left(N_\gamma \frac{\ell_p}{\ell} - e^{-t_R/\ell}\right)$$

$\longrightarrow$

Extremizing over N_γ

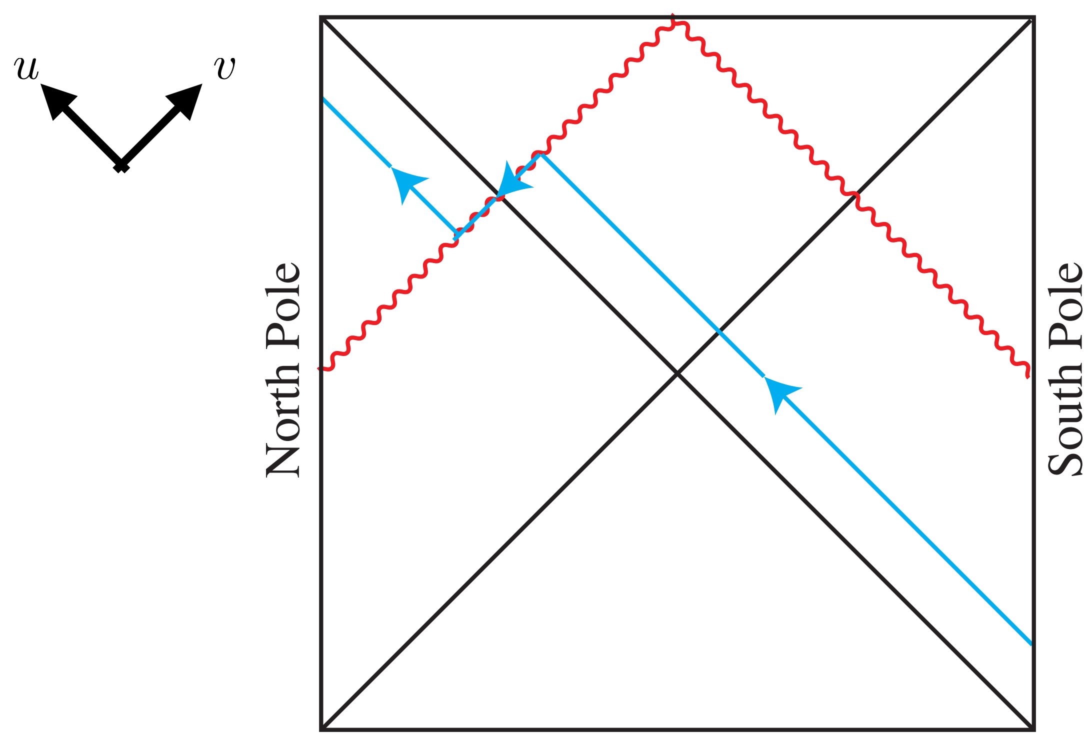
$$\boxed{t_{\text{tot}} = \ell + \ell \log\left(\frac{\ell}{\ell_p}\right) \simeq \ell \log\left(S_{dS}\right)}$$

[LA, Cole, Morvan, van der Schaar, Shiu]

Phenomenological consequences

Information bounds

- There is a bound on the amount of information that can be send/recovered. [Freivogel, Galante, Nikolakopoulou, Rotundo '19]



To avoid black hole formation by shockwave:

$$E_{\text{shock}} < S_{dS}/\ell \longrightarrow \alpha < \ell$$

Total energy of message:

$$E_{\text{message}} = N_{\text{bit}} E_{\text{bit}} < 1/\ell_p$$

For the message to "fit" through the wormhole"

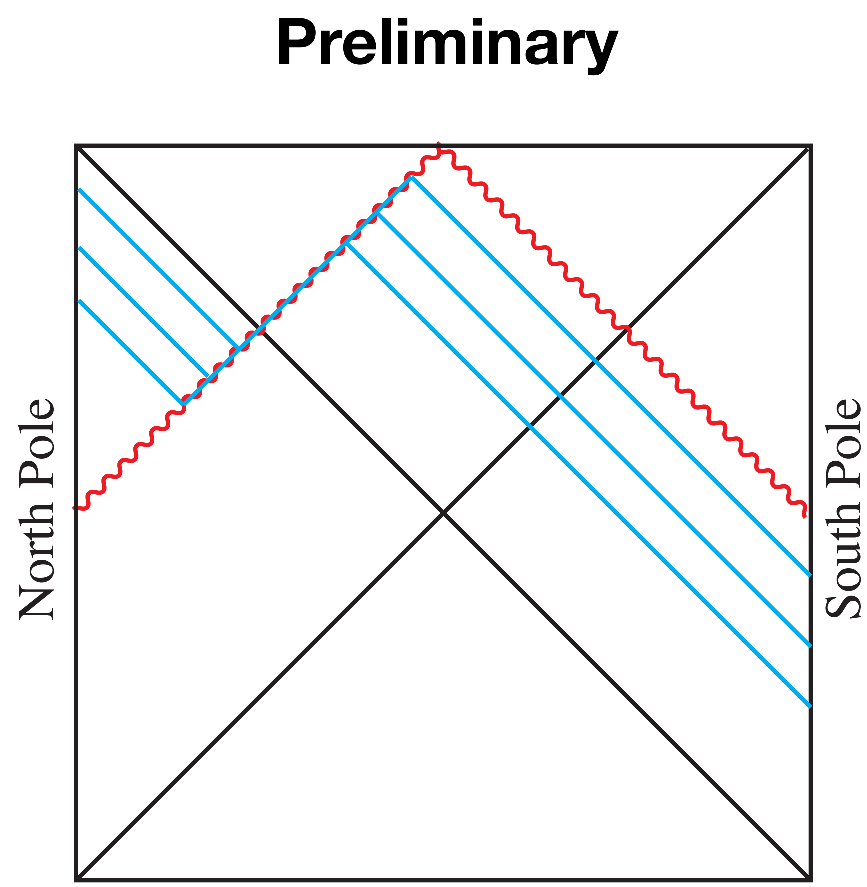
$$E_{\text{bit}} > 1/\alpha$$

Combining these bounds: $N_{\text{bit}} < S_{\text{dS}}$

[LA, Cole, Morvan, van der Schaar, Shiu]

When is this bound saturated?

- Let's say Bob wants to update Alice about the local expansion rate and sends one bit per e-fold.



- The total number of bits is bounded by the entropy.

- Semiclassical de Sitter can be supported for $N < S_{dS}$ e-folds.

- Similar to bounds on slow-roll inflation. [Arkani-Hamed, Dubovsky, Nicolis, Trincherini, Villadoro '07]

Conclusions

- We studied information scrambling and retrieval in de Sitter space.
- By computing an OTOC, we learned that de Sitter is a "fast scrambler".
- Bob and Alice can rejoin; information can be recovered!
- Bounds on information transfer, limit the number of e-folds semiclassical de Sitter can be sustained.

Thank you!