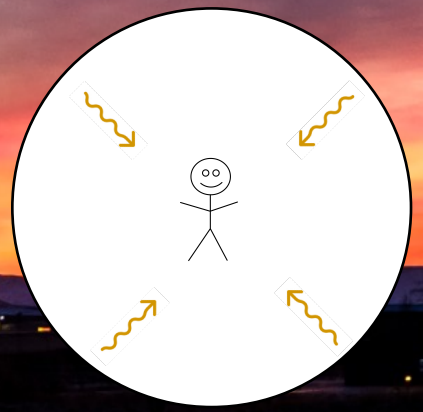
# The price of curiosity: information recovery in de Sitter space

based on 2104.00006 with Lars Aalsma



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30th Nordic Network Meeting on “Strings, Fields, and Branes”

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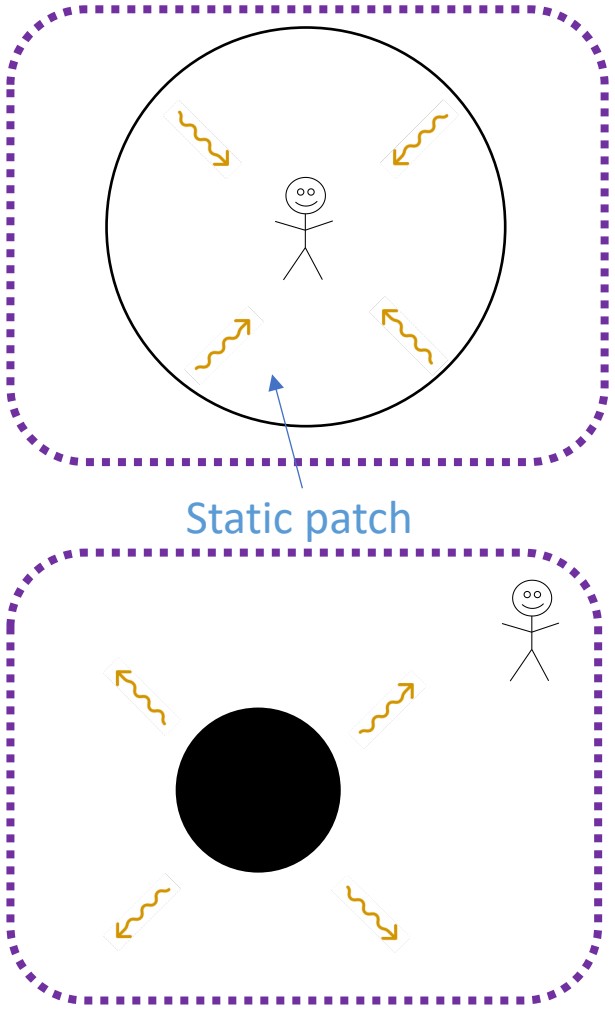
# The cosmological horizon of de Sitter

de Sitter space can describe stages of the universe where positive vacuum energy dominates




enigmatic feature is the cosmological horizon due to expanding space

[Gibbons, Hawking '77]

Some similarities with BH horizon

- ★ Surface of no return
- ★ $T_{\rm dS} = \dfrac{1}{2\pi\ell}$
- ★ $S_{\rm dS} = \dfrac{\rm Area}{4G_N}$

Some differences with BH horizon

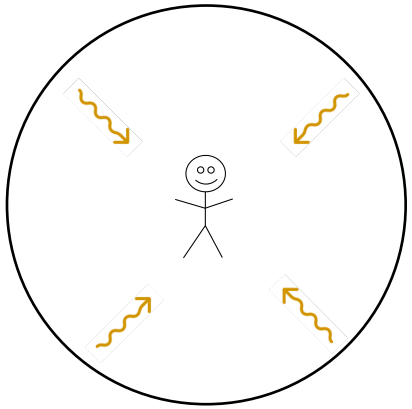
- ★ Observer dependent
- ★ $\delta E = -T\delta S$

Adding energy to static patch makes horizon shrink and vice versa

# Can we peek beyond the cosmological horizon?

Main question:

Can a static observer use Gibbons-Hawking radiation to recover info from beyond the cosmological horizon?



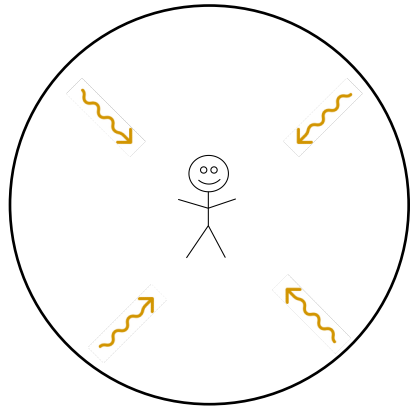
Method to answer question:

We'll apply QES or island prescription to 2d semi-classical gravity, which has been successful in answering similar questions for BH's

Due to no access to a scri+ type heat bath, back-reaction is expected to play a crucial role. The static patch will shrink as radiation piles up.

# Outline

- ~~introduction~~
- 2d backreaction
- Black holes and the Page curve
- island in de Sitter



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# Jackiw-Teitelboim action

2d gravity allows one to have analytic control over semi-classical corrections and backreaction.

Consistent truncation of near Nariai 4d BH is governed by

$$I = \frac{\Phi_0}{2\pi}\int d^2x\sqrt{-g}R + \frac{1}{2\pi}\int d^2x\sqrt{-g}\Phi\left(R - \frac{2}{\ell^2}\right) + I_{\rm CFT}$$

propto Nariai entropy

deviation from Nariai

matter sector with central charge c

$$\Phi_0 \gg \Phi|_{\rm Horizon} \gg c \gg 1$$

consistency

$\Phi_0 + \Phi$ mediates the size of inverse Newton's constant/size transverse space

The equations of motion read:

$$R - 2/\ell^2 = 0$$
$$\Phi g_{\mu\nu} - \ell^2\nabla_\mu\nabla_\nu + \ell^2 g_{\mu\nu}\Phi = \pi\ell^2\langle T^{\rm CFT}_{\mu\nu}\rangle$$

[Teitelboim'83][Jackiw'85]
[Callan, Giddings, Harvey, Strominger'92]

# Classical solutions

Classical solutions in conformal gauge:

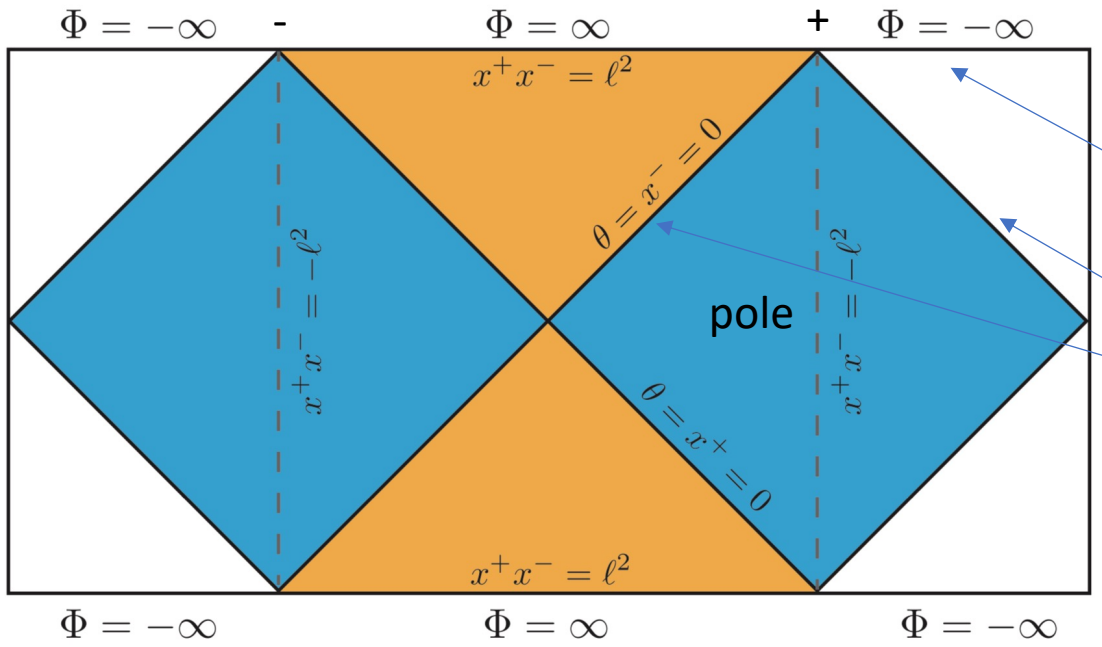
$$e^{2\rho(x^+,x^-)} = \frac{4\ell^2}{(\ell^2 - x^+x^-)^2} \qquad \Phi(x^+,x^-) = \frac{\Phi_s}{24}\frac{\ell^2 + x^+x^-}{\ell^2 - x^+x^-}$$

relation between static and Kruskal coords

$$ds^2 = -e^{2\rho(x^+,x^-)}dx^+dx^-$$

$$x^\pm = \pm\ell e^{\pm\sigma^\pm/\ell} = \pm\ell e^{\pm t/\ell}\sqrt{\frac{\ell - r}{\ell + r}}$$

$$\sigma^\pm = t \pm r_* \qquad \frac{r}{\ell} = \frac{\ell^2 + x^+x^-}{\ell^2 - x^+x^-}$$




BH singularity

(Wald) entropy:

$$S = 2\Phi_{\rm H} = 2\Phi_0 \pm 2\Phi|_{\rm Horizon}$$

see e.g. [Maldacena, Turiaci, Yang '19]

# Backreaction on the dilaton

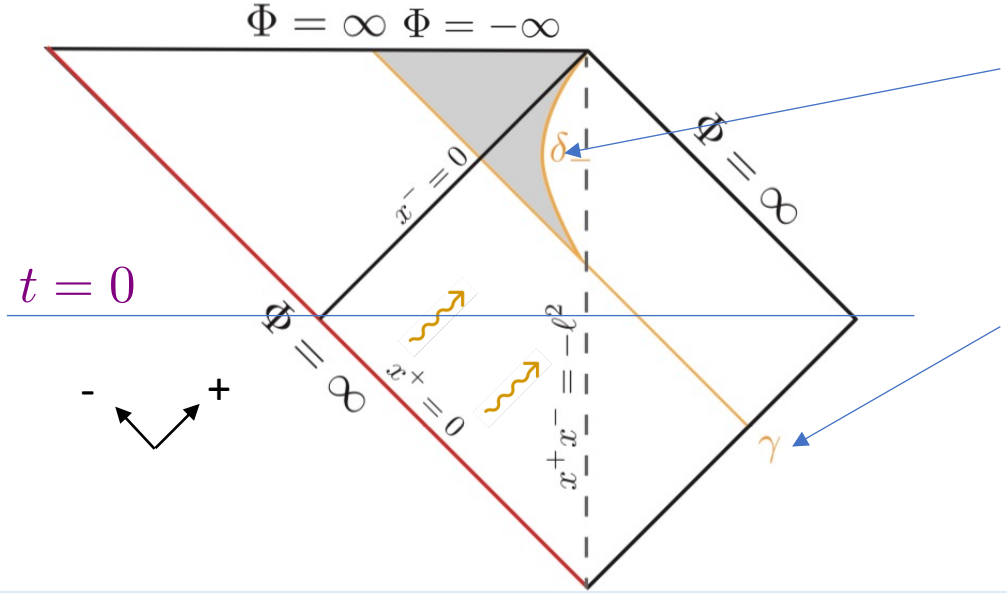
interpolate between Bunch-Davies (t_{+}=0, equilibrium) and Unruh-de Sitter (t_{+}=1, out-of-equilibrium)

$$\langle : T_{++}(x^+) : \rangle = -\frac{c}{48\pi (x^+)^2}(1-t_+^2) \qquad \langle : T_{--}(x^-) : \rangle = 0$$

Which yields the back-reacted dilaton

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

No change in BD. Diagram of Unruh-de Sitter in full model:




Roughly equal size BH and CH

(Quantum) trapped surfaces

$$t_{\rm trap} = \frac{2\Phi_s \ell}{c(1-t_+^2)}$$

[Aalsma, WS'21]

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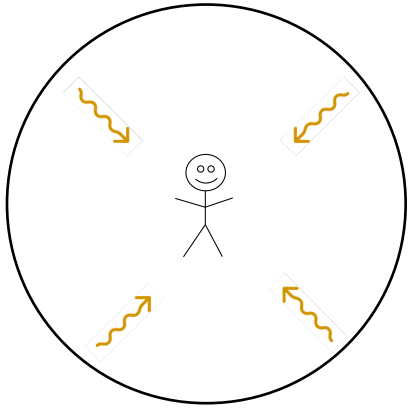

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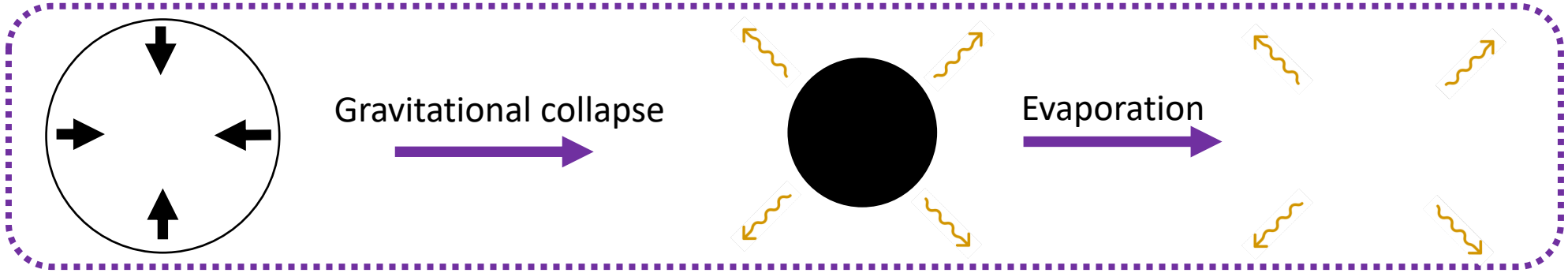
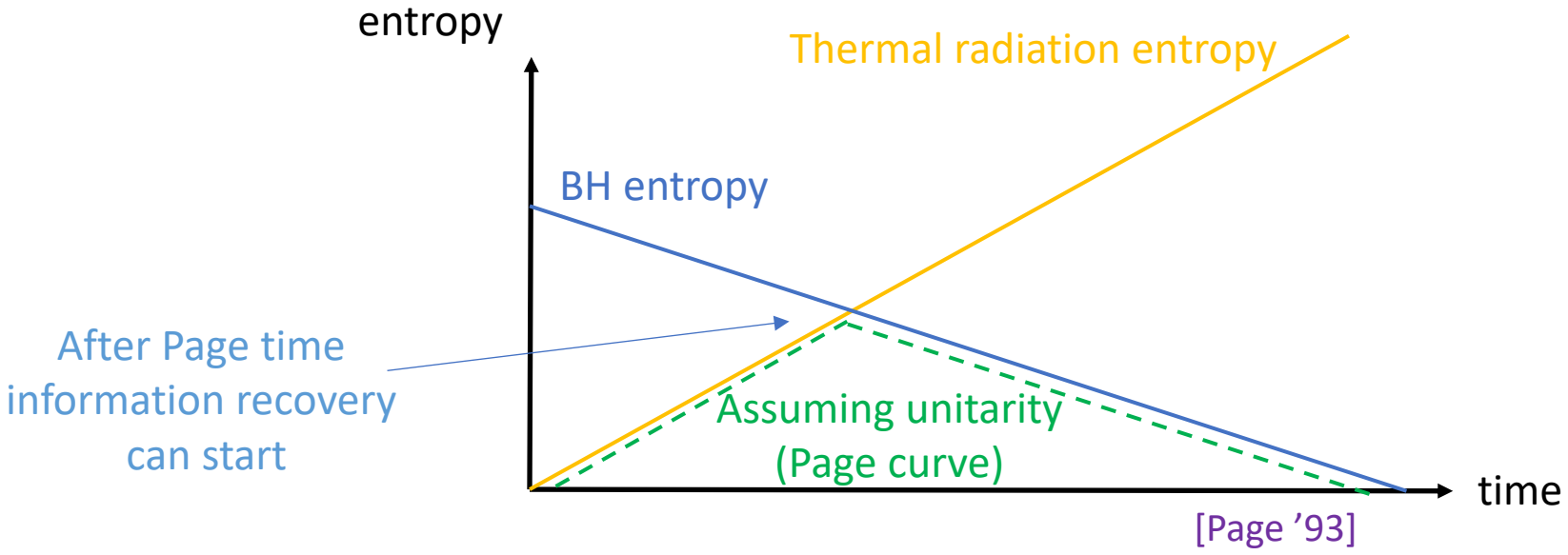
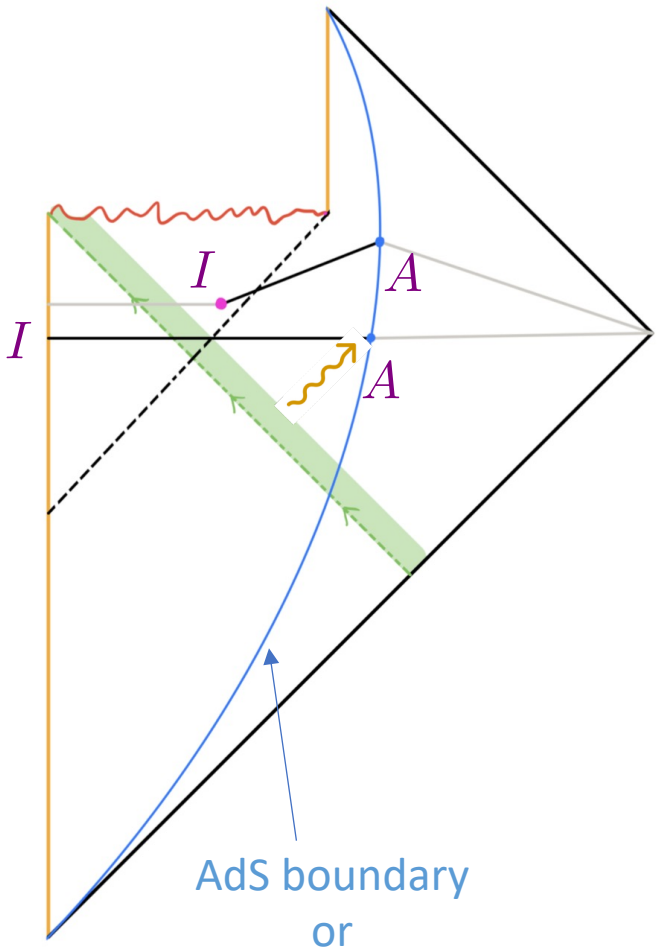
# Page curve: unitarity and information recovery

Hawking radiation being thermal leads to a paradox when assuming evaporation to be unitarity



# The island of an evaporating black hole




[Gautason, Schneiderbauer, WS, Thorlacius '20]

The island (or QES) prescription can give you Page curve

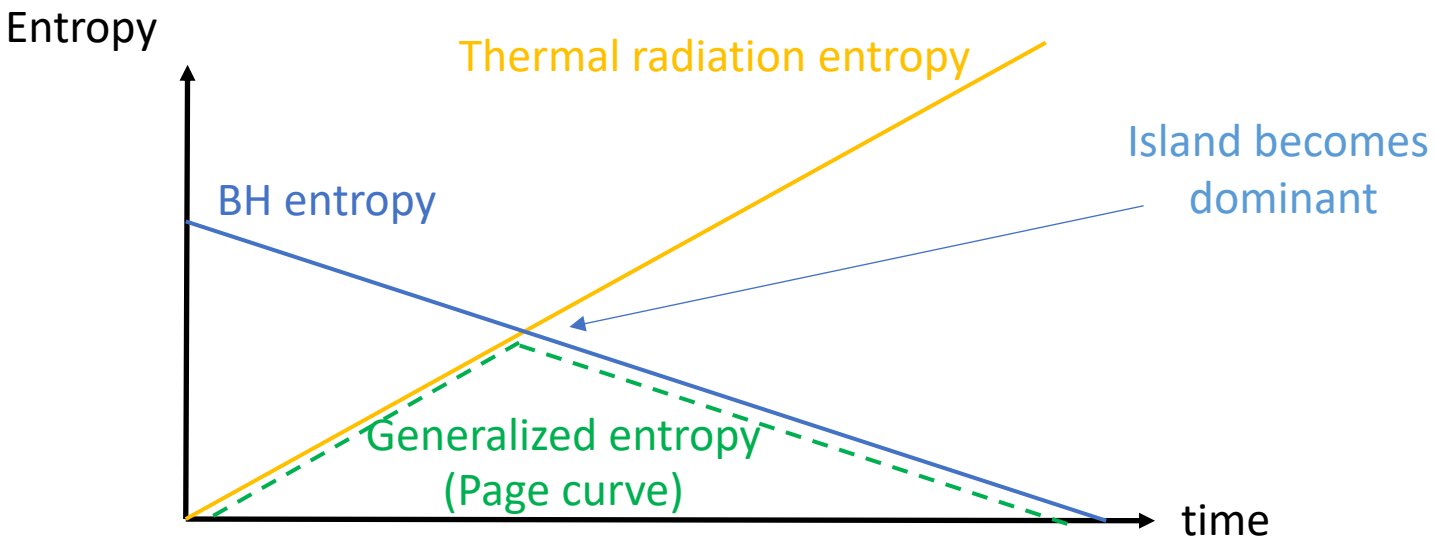
[Ryu, Takayanagi'06][Hubeny, Rangamani, Takayanagi'07][Faulkner, Lewkowycz, Maldacena'09]
[Engelhardt, Wall'15][Penington '19][Almheiri, Engelhardt, Marolf, Maxfield '19]

prescription instructs to extremize and take the minimum of the generalized entropy

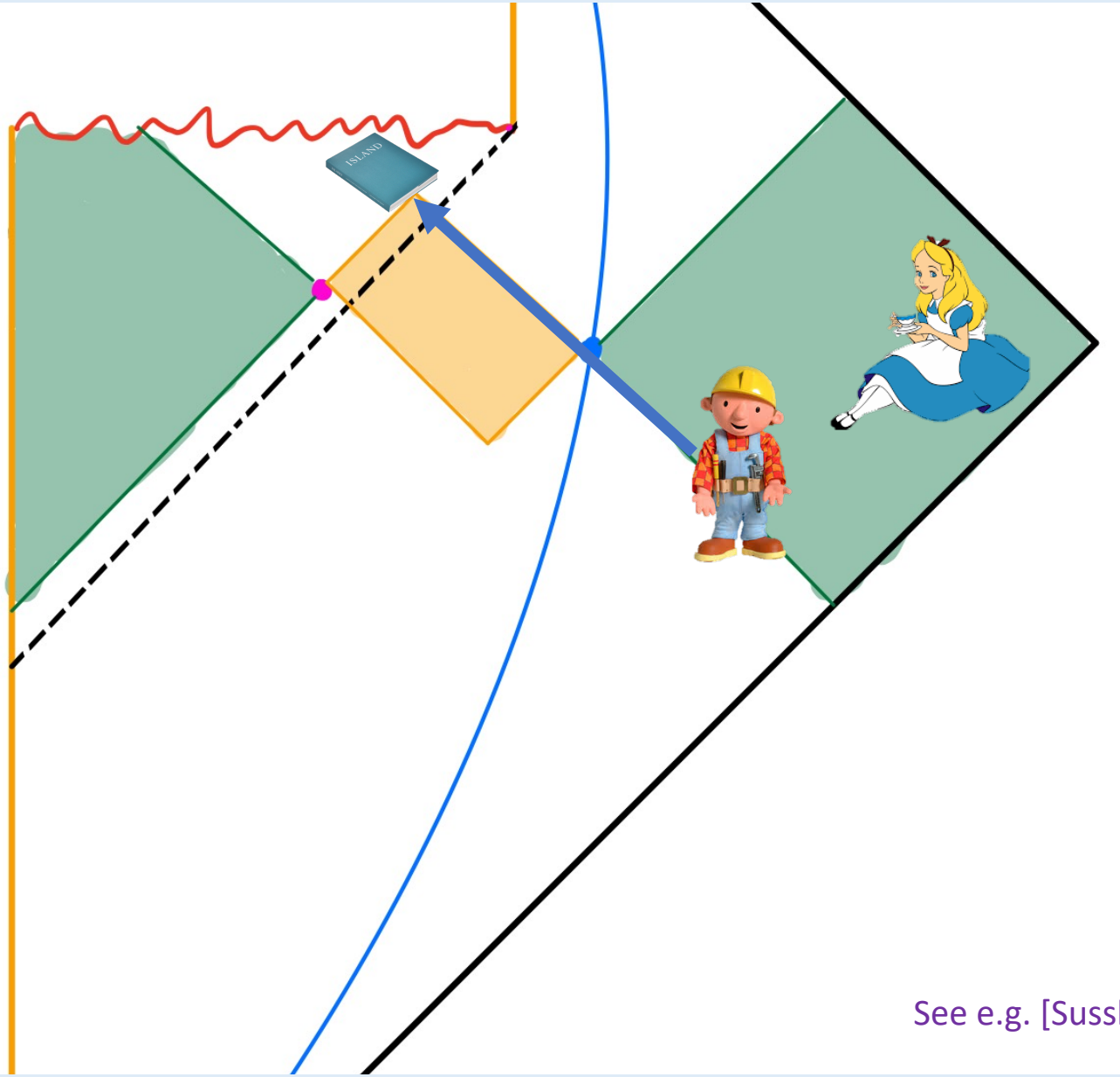
$$S_{\text{gen}} = \frac{\text{Area}(I)}{4G_N} + S_{\text{vN}}[IA]$$

$2\Phi_{\text{H}}(I)$

$$\frac{c}{12}\log\left[\frac{d(A,I)^2}{e^{-2\rho_A}e^{-2\rho_I}}\right]\Bigg|_{t_\pm=0}$$



# Recovery through the island: Page and Scrambling time




Island formula: wait until
Page time for decoding

Scrambling time needed to evade paradoxes is also reproduced:

$$t_s = \log(S)$$

See e.g. [Susskind, Thorlacius'93][hayden, preskill'07][Sekino, Susskind'08]

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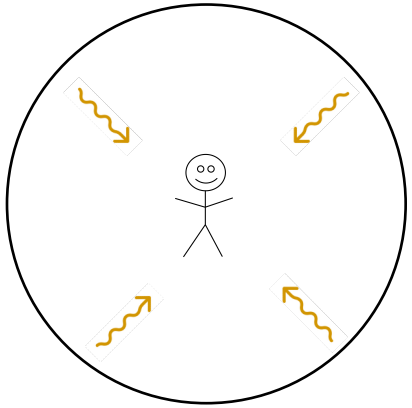

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# Islands in de Sitter: Thermodynamical guess

Islands in de Sitter have been studied in many setups, often involving future skri+ as heat bath

[Hartman, Jiang, Shaghoulian '20] [Chen, Gorbenko, Maldacena '20] [Chen, Gorbenko, Maldacena '20]
[Balasubramanian, Kar, Ugajin '20][Sybesma '20][Geng, Nomura, Sun '21] [Aalsma, WS'21][King-Kames, Verheijden, Verlinde'21]

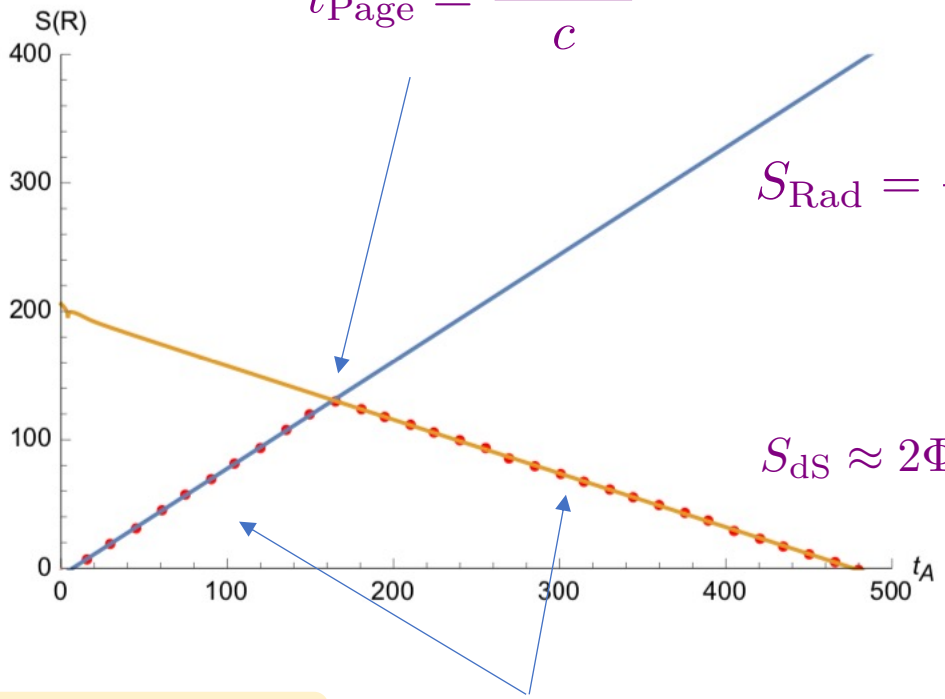
Thermodynamics implies:

2d CFT radiation $\Delta S_{\rm Rad} = \frac{c}{12\ell} t$

First Law $\Delta S_{\rm dS} = -\frac{c}{24\ell} t$

Decoding after Page time

$t_{\rm Page} = \frac{16\ell\Phi_0}{c}$




$t_{\rm trap} \sim \Phi_s \ll t_{\rm Page}$

Page curve, consistent with unitarity

# islands in de Sitter

The island formula for in the Unruh-de Sitter vacuum
Extremize and take minimal saddle

$$S_{\text{gen}} = \frac{\text{Area}(I)}{4G_N} + S_{\text{vN}}[IA]$$

[Ryu, Takayanagi'06]
[Hubeny, Rangamani, Takayanagi'07]
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[Engelhardt, Wall'15][Penington '19]
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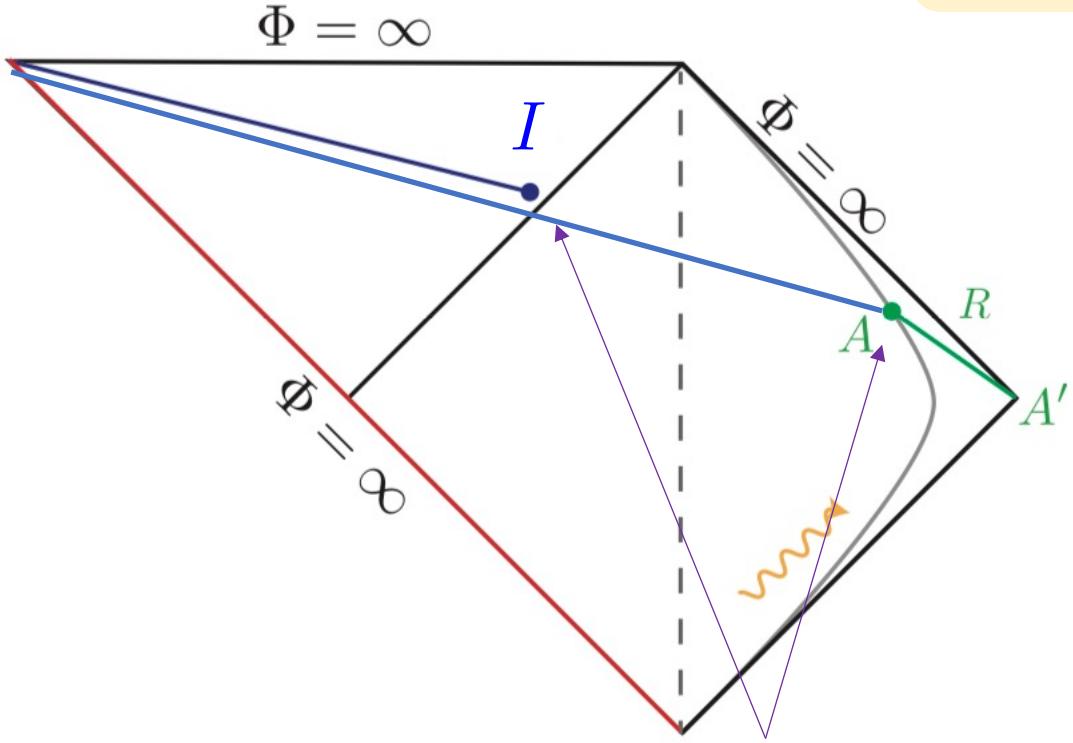
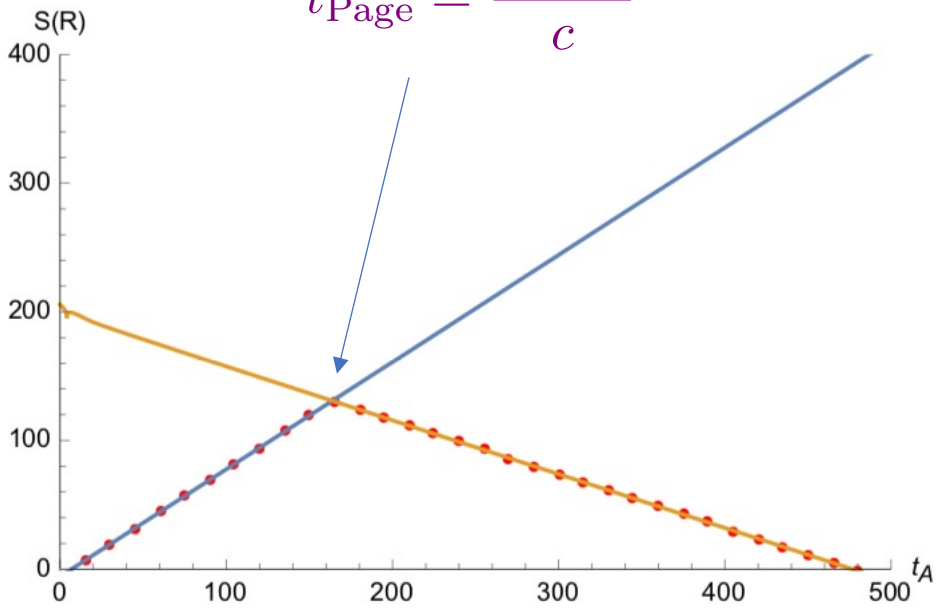



$$t_s \sim \log(S_H) \ll t_{\text{Page}}$$

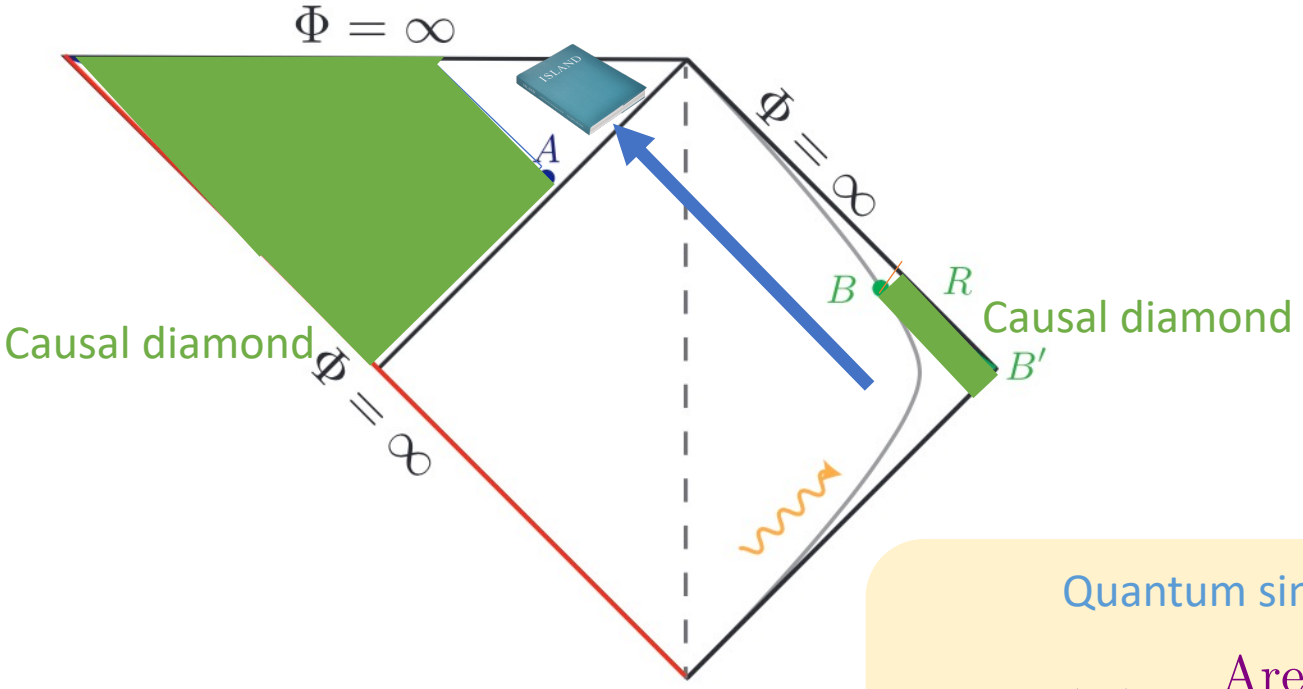
$$t_{\text{Page}} = \frac{16\ell\Phi_0}{c}$$




$$t_{\text{trap}} \sim \Phi_s \ll t_{\text{Page}}$$

# Quantum singularity theorem

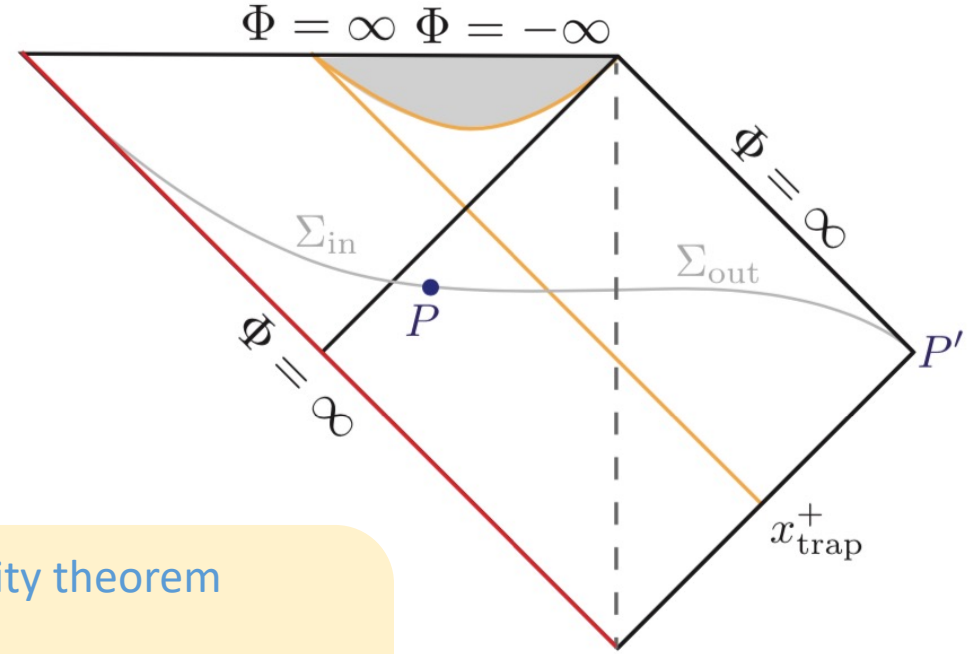
Are we able to evade no-cloning?




No decoding before Page time

Scrambling time

Most obvious if genuine singularity is around.




Quantum singularity theorem

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

Quantum trapped if $\partial_{\pm} S(P) < 0$

[Wall'10]

Thus, after trapped time scale a singularity is unavoidable

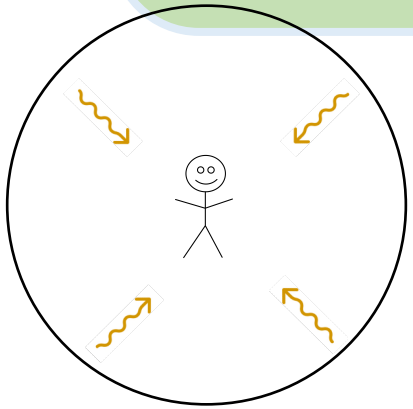
# Conclusion: Fate of the observer

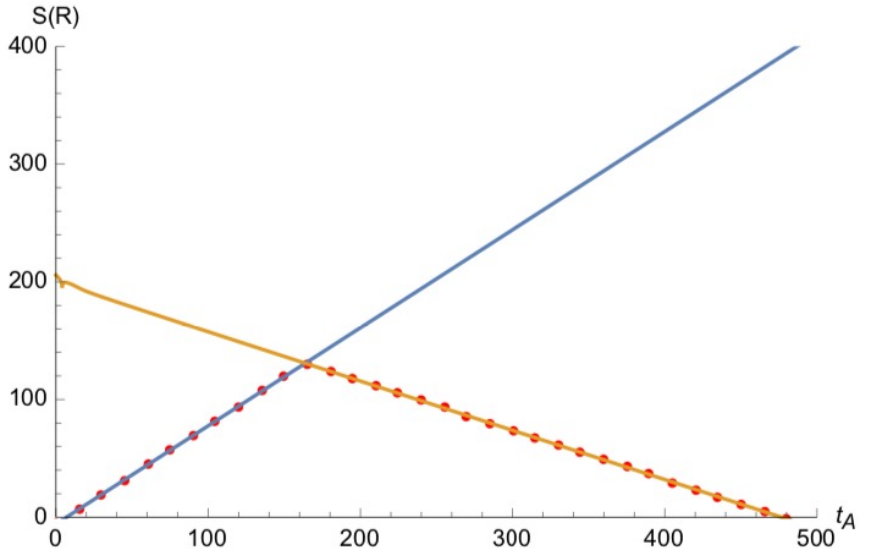
Can a static observer use Gibbons-Hawking radiation to recover info from beyond their cosmological horizon?

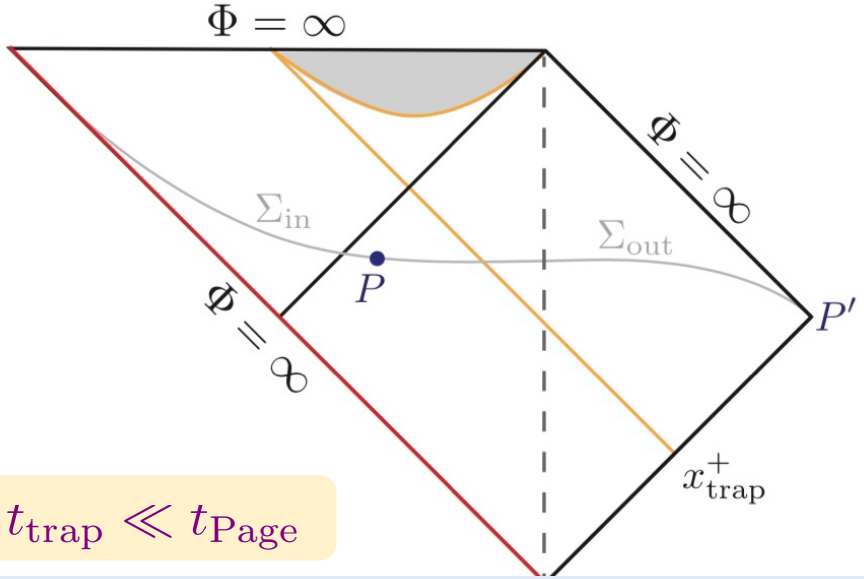
2d Unruh-de Sitter vacuum
yields a Page curve using island prescription

After the trapped time, long time before Page time,
a singularity forms.

After trapped time all timelike curves end in a singularity.
Curiosity comes at a price

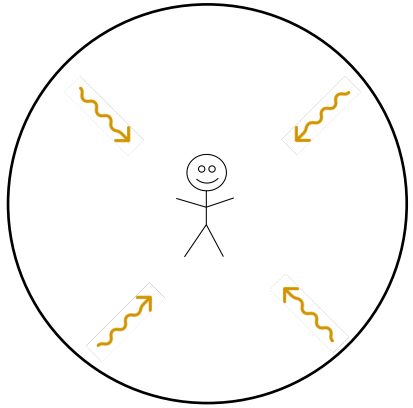





$t_{\text{trap}} \ll t_{\text{Page}}$

# Some follow up directions



Formation from collapse

BH evaporation in dS; can you store the information?

Other 2d setups

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