Quantum Matter and Quantum Information with Holography

based on 2006.11717

Entanglement Islands (and Janus Black Holes)

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August 27, 2020

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imagine the impossible
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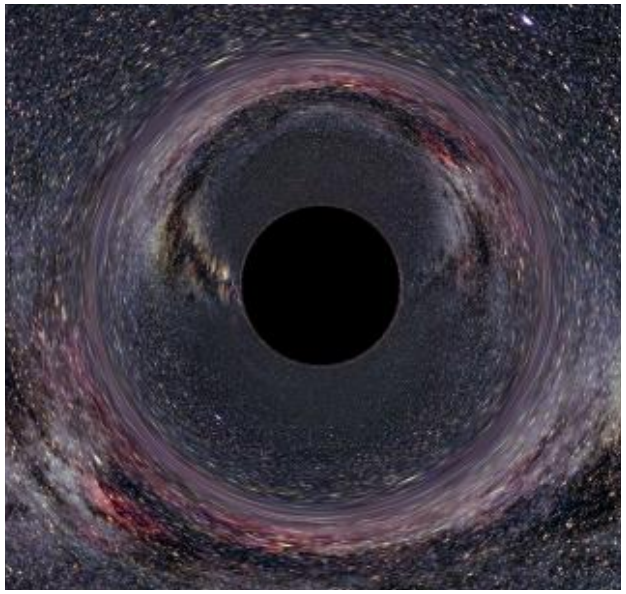
What is the state of black hole?

Is it pure or thermal (mixed)?

Black Hole Information Paradox



- Black hole seems to be thermal object
- Bekenstein-Hawking entropy of black hole:

$$S = \frac{A}{4G}$$

A: Area of horizon

✓ 1st law of thermodynamics: $dM = \frac{\kappa}{2\pi} d\left(\frac{A}{4G}\right)$

⇕

$$dE = TdS$$

- Is Black hole in mixed state?

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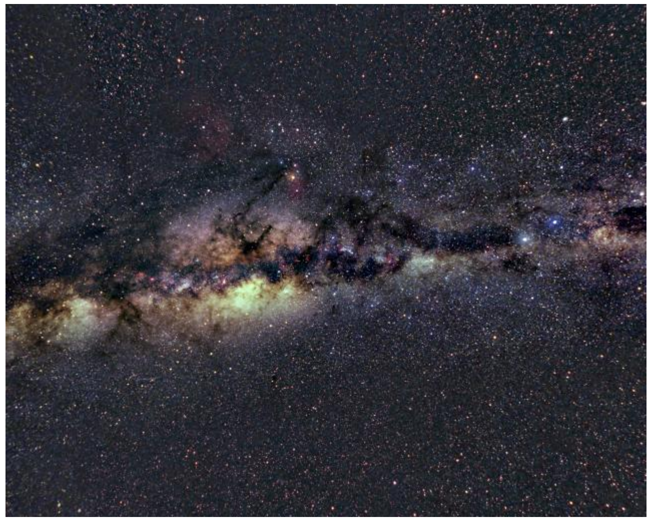
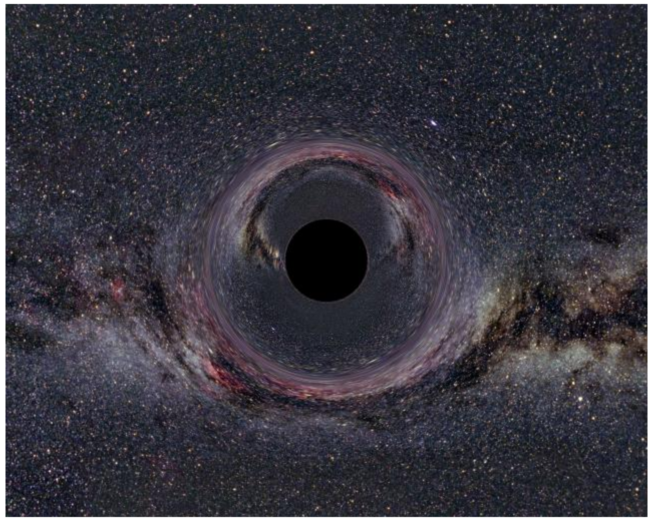
Black Hole Information Paradox

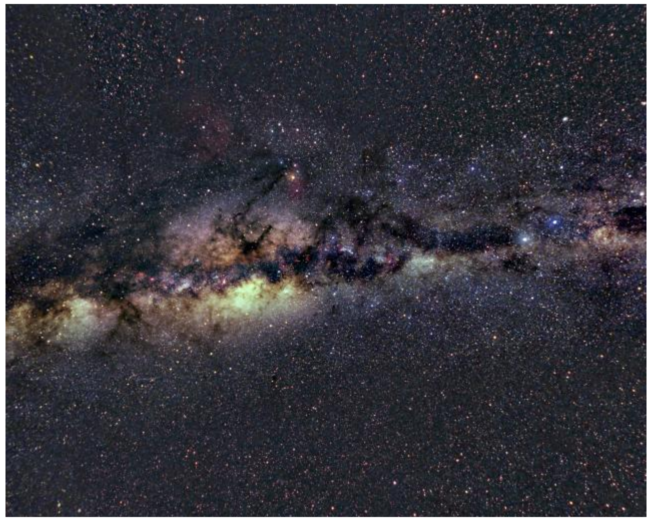
- Try Gedanken experiment for black hole formation and evaporation
  - Assumption
    - ✓ Initial state (before black hole is formed): pure state
    - ✓ Unitary evolution



Before formation
pure state



Black hole



evaporated

- The final state should be pure if the time evolution is unitary

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Black Hole Information Paradox

* When BH is in pure state, how does pure state look like thermal state?

* The pure density matrix is very close to the thermal density matrix

  ✓ Difficult to distinguish density matrix of pure state and thermal state

$$\rho_{\text{pure}} = \frac{1}{Z} e^{-\beta H} + e^{-S}\delta$$

exponentially suppressed
non-perturbative

* At early time, semi-classical perturbative calculation is valid

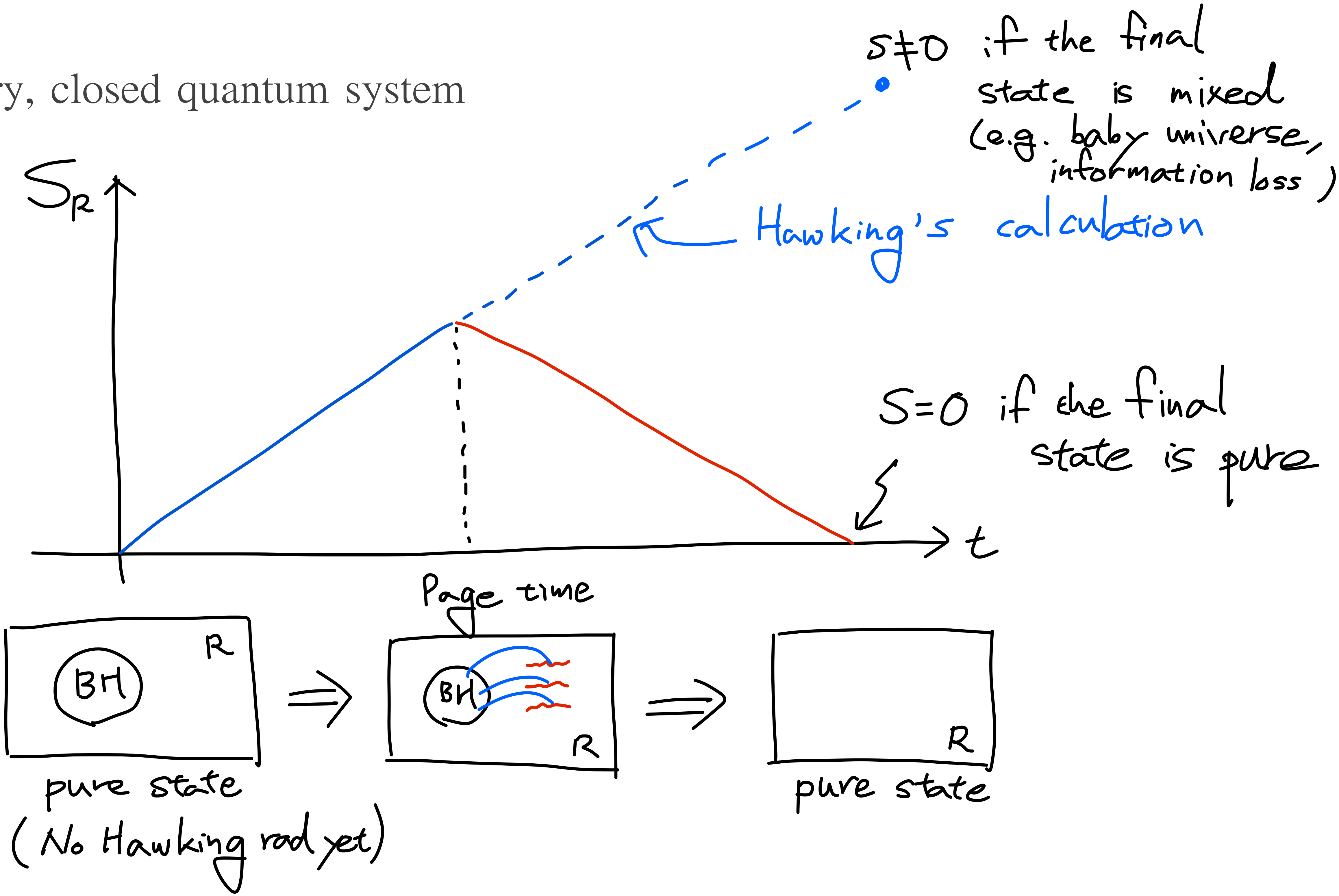
  ✓ e.g. Hawking's calculation

* In a long time later, one cannot ignore the difference $e^{-S}\delta$

  ✓ non-perturbative

Page Curve

- Unitary, closed quantum system



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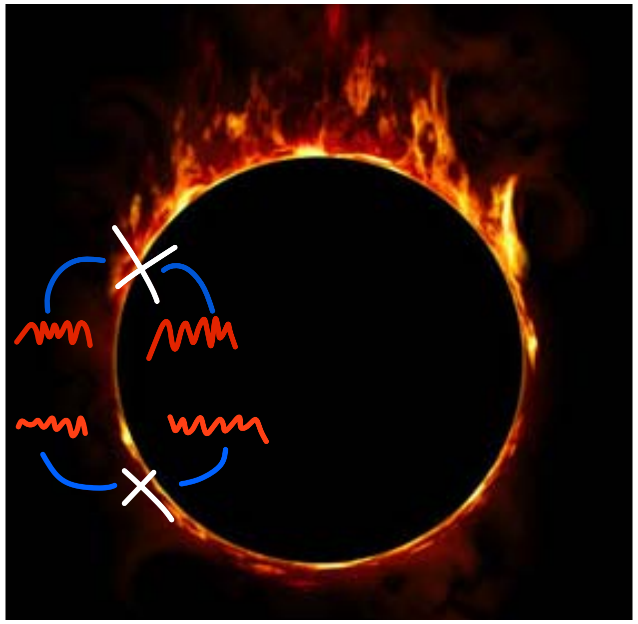
Proposed Resolutions

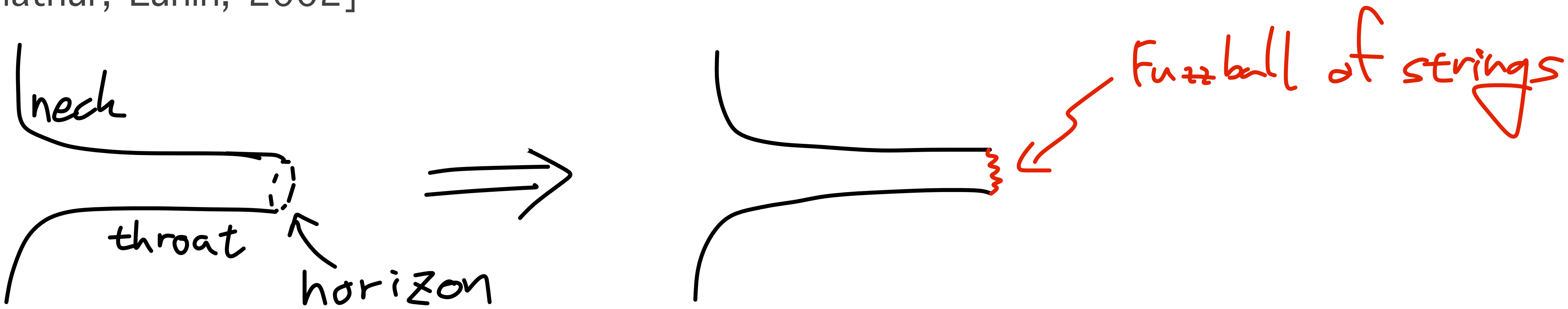
✳ Firewall at horizon [AMPS, 2012]



✓ proposed to resolve strong subadditivity (SSA) paradox of black hole

✓ non-unitarity (by firewall)

✳ Fuzzball [Mathur, Lunin, 2002]



✓ No inside of black hole, no singularity

✳ Black hole complementarity (next slide)

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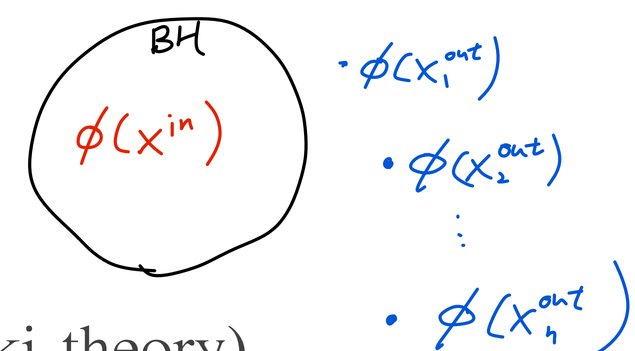
Black Hole Complementarity

- Several versions of black hole complementarity
- Susskind, Thorlacius, 1993
  - Two alternative descriptions of black hole
    - ✓ observer outside of horizon vs infalling observer
- d.o.f inside of horizon is not independent of d.o.f outside of horizon

$$\phi(x^{\text{inside}}) = F[\phi(x_1^{\text{outside}}), \cdots, \phi(x_n^{\text{outside}})]$$

$$n \sim e^S$$

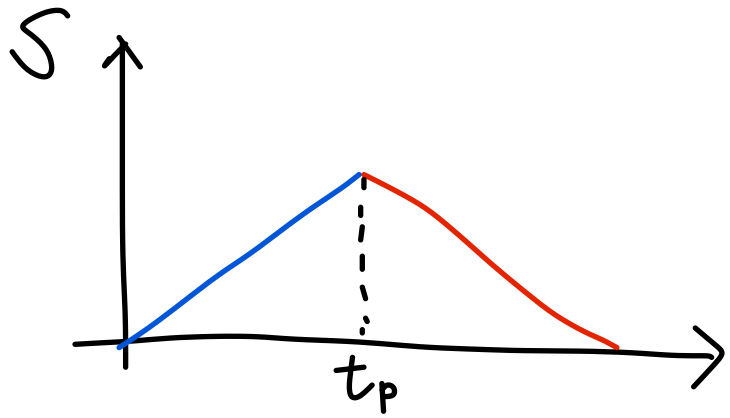


- ✓ In math, this is modular automorphism (Tomita-Takesaki theory).
- ✓ In physics, we need a separation of simple operators from complicated operators. [Raju, Papadodimas, 2012]
- ✓ Within effective field theory, they are independent d.o.f.
- ✓ Interesting development related to locality, causality using "state-dependence".

After Page Time

after Page time t_p

* To explain the decrease of the entanglement entropy, we need to distinguish pure state from mixed state.



$$\rho_{\text{pure}} = \frac{1}{Z} e^{-\beta H} + e^{-S} \delta$$

non-perturbative

* This requires quantum gravity as well as non-perturbative effects.
* But, our technique is not enough to calculate them.
  - ✓ In gravity, we could mostly calculate semi-classically (perturbatively) in fixed background. ($T \neq 0$)
* Until recently, no way to calculate S_{EE} semi-classically after Page time.

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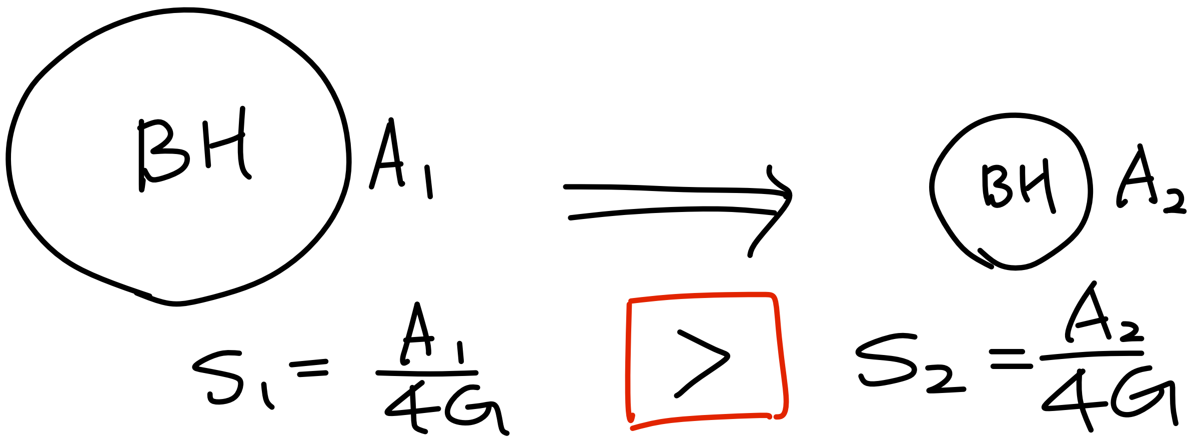
A prediction is often made in order to be disproved in future.

Generalized Entropy

- ✳ Bekenstein-Hawking entropy: $S = \dfrac{A}{4G}$
- ✳ 2nd law of thermodynamics of evaporating black hole



- ✳ Need to include matter (radiation) contribution

- ✳ Generalized Entropy: $S_{\text{gen}} = \dfrac{A}{4G} + S_{\text{outside}}$

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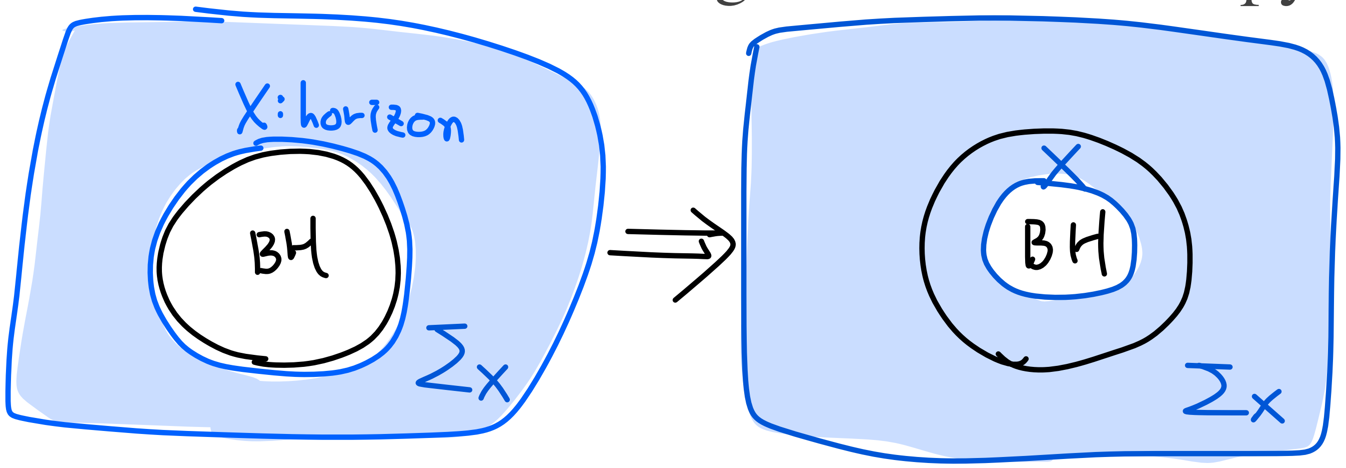
Quantum Extremal Surface

* One can consider generalized entropy for other (codim-2) surface

(Recall RT surface)



$$S_{\rm gen}(X) = \frac{A(X)}{4G} + S_{\text{semi-cl}}(\Sigma_X)$$

BH — matter (radiation) in Σ_X

* Quantum Extremal Surface: Extremize the generalized entropy

$$S_{QES} = \min_X \left[\text{Ext}_X \left(\frac{A(X)}{4G} + S_{\text{semi-cl}}(\Sigma_X) \right) \right]$$

Extremize w.r.t X
⟹ local extremum

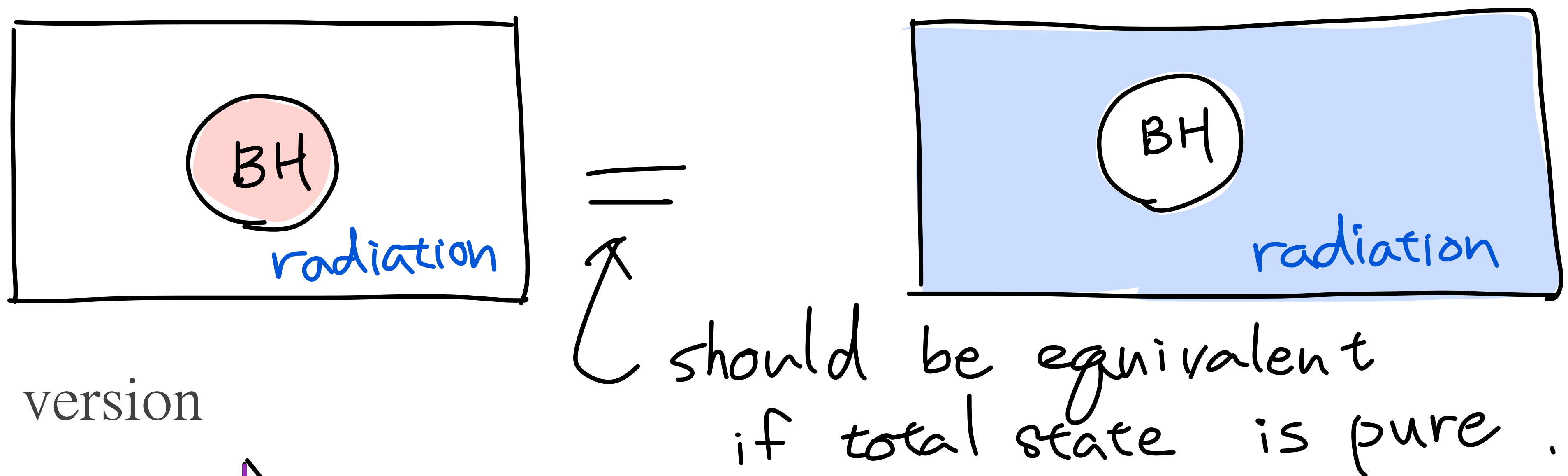
Among local extremum, choose global min
⟹ lead to transition.

*

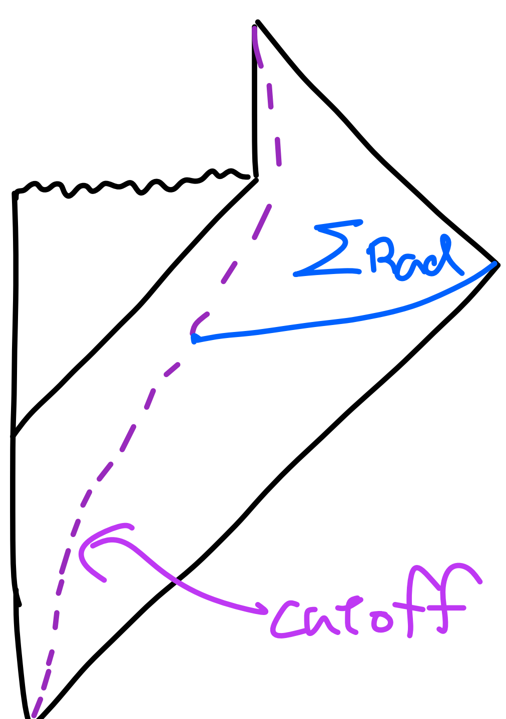
Island Conjecture

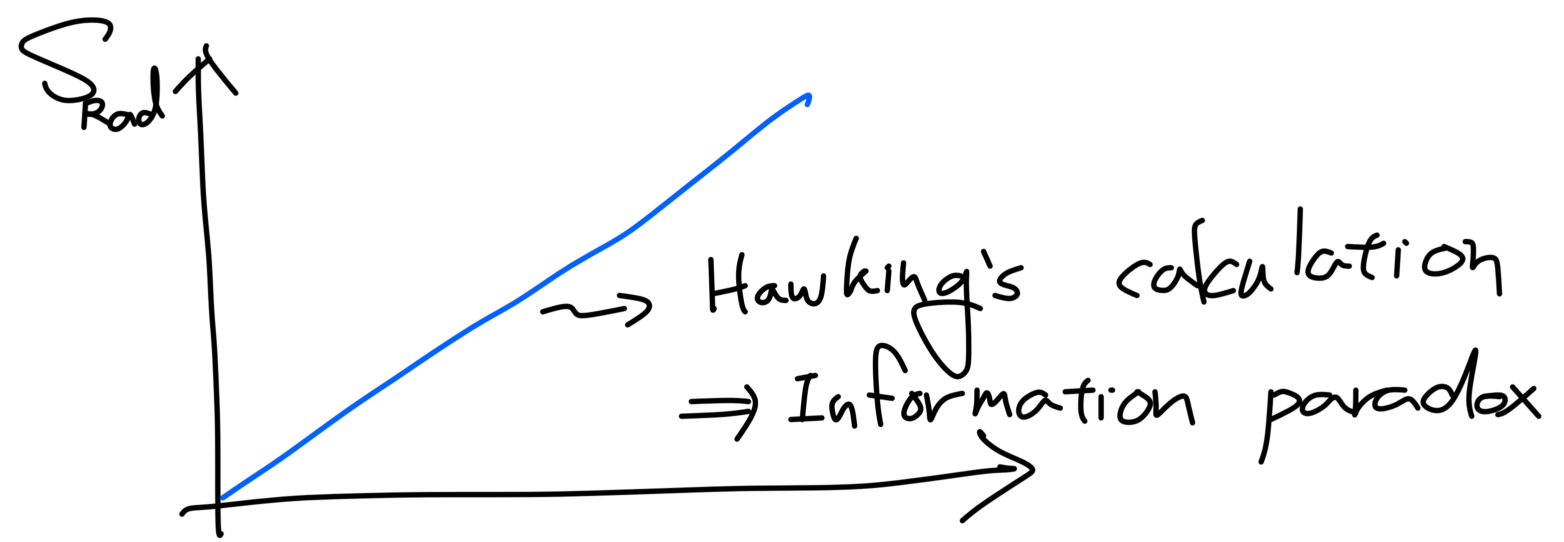
[Almheiri, Engelhardt, Marolf, Maxfield, 2019] [Almheiri, Mahajan, Maldacena, Zhao, 2019]

* Two ways to consider the entanglement entropy: black hole vs radiation



* Old version





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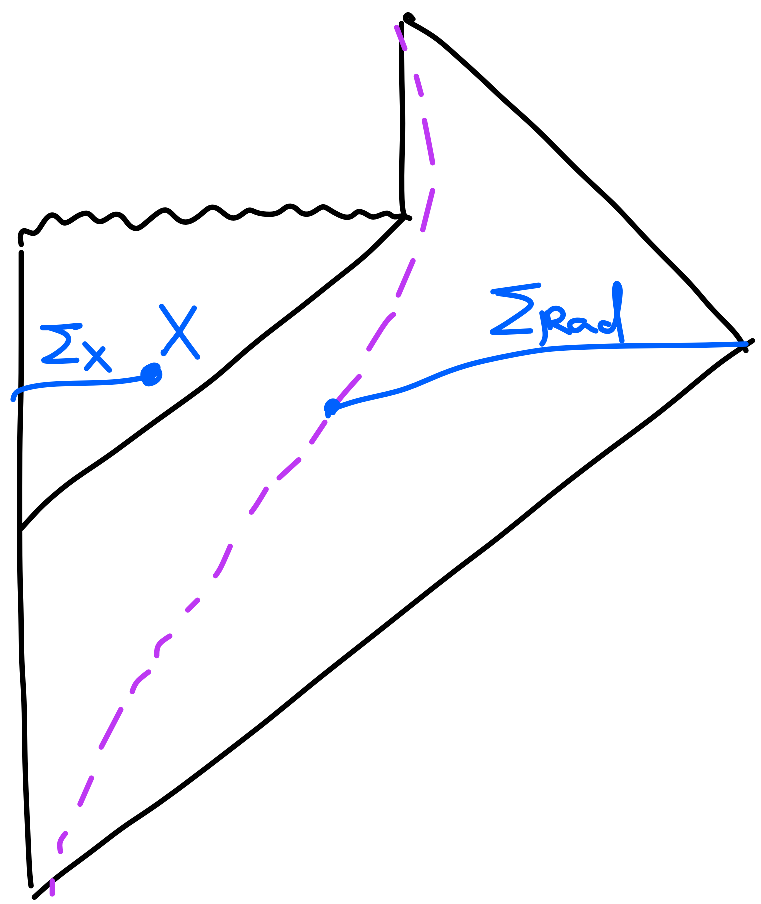
Island Conjecture

based on [Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, 2006.06872]

* New version: introduce an island inside of horizon



Island : new ingredient.

$$S_{\text{radiation}} = \min_X \left[\text{Ext}_X \left(\frac{A(X)}{4G} + S_{\text{semi-cl}}(\Sigma_X \cup \Sigma_{\text{rad}}) \right) \right]$$

→ Two possible minima.

*

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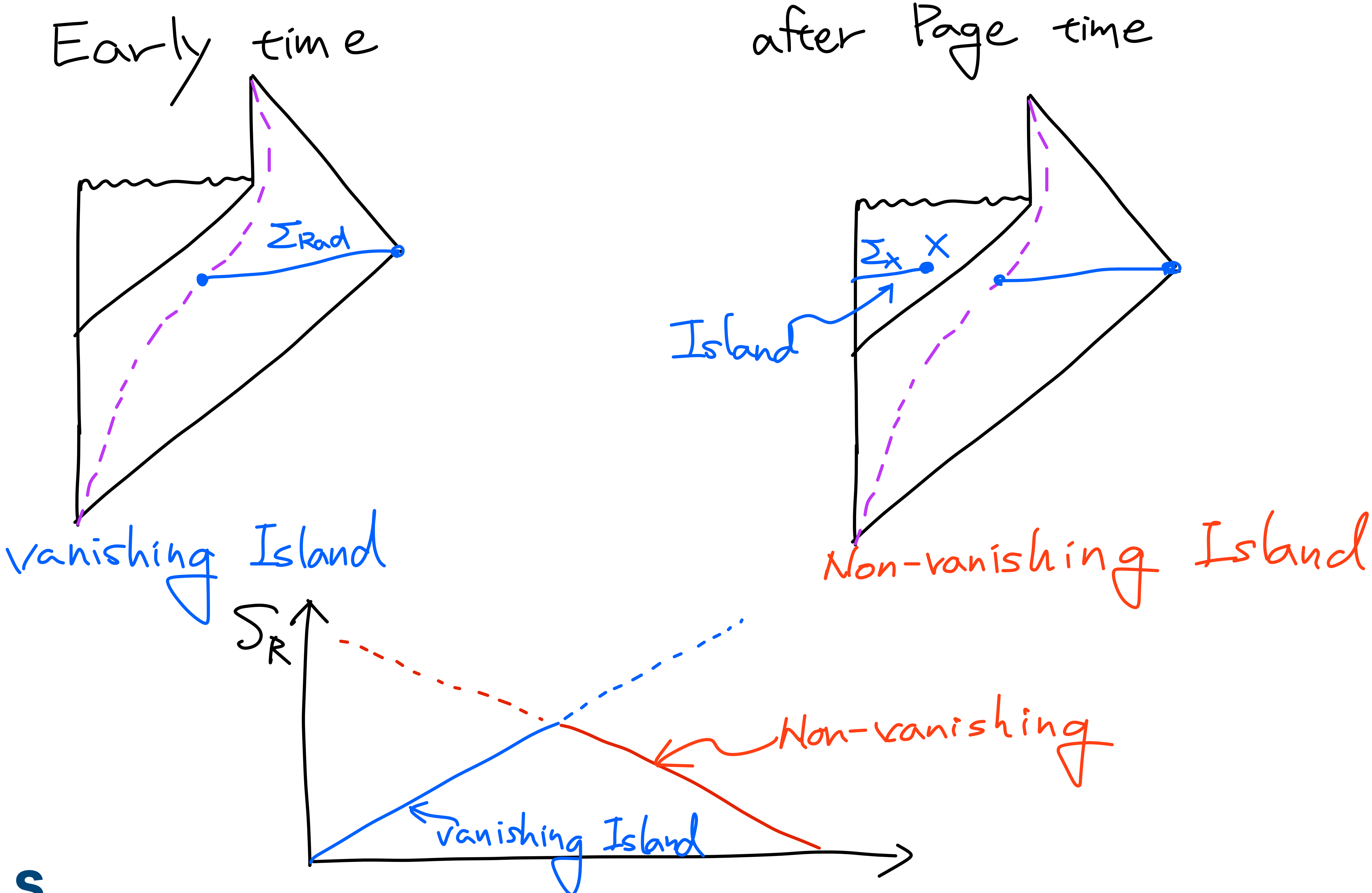
Island Conjecture

based on [Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, 2006.06872]



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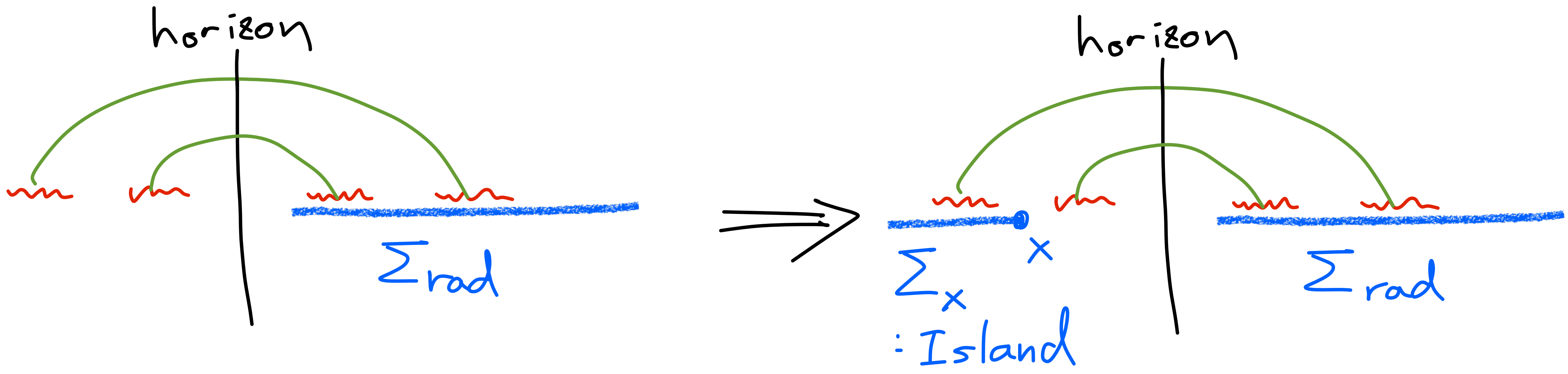
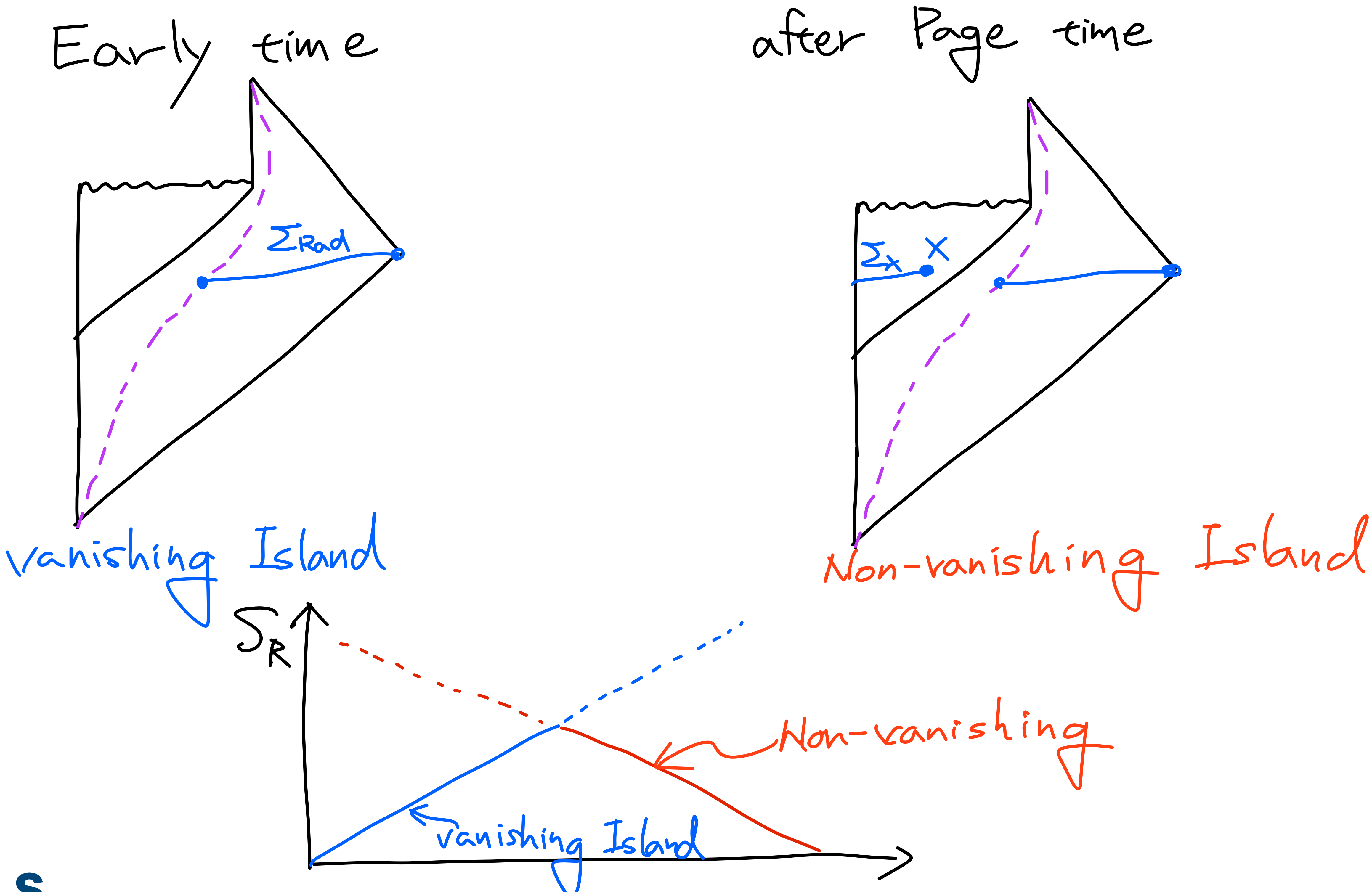


Island purifies the EPR pair of Hawking radiation

$\Longrightarrow$ decreases the entanglement entropy

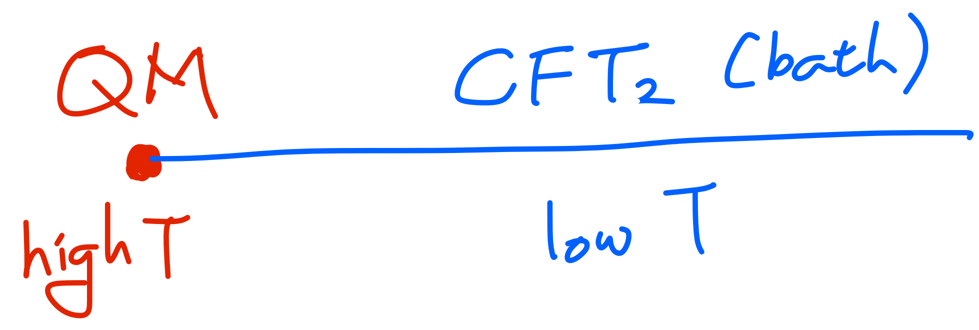
Island Conjecture

based on [Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, 2006.06872]



Low-Dimensional Model (Bottom-up)

- ✳ AdS_3 (1+2 dim)
- ✳ AdS2 (1+1 dim)
  + CFT_2 (1+1 dim)
- ✳ QM (0+1 dim)
  + CFT_2 (1+1 dim)



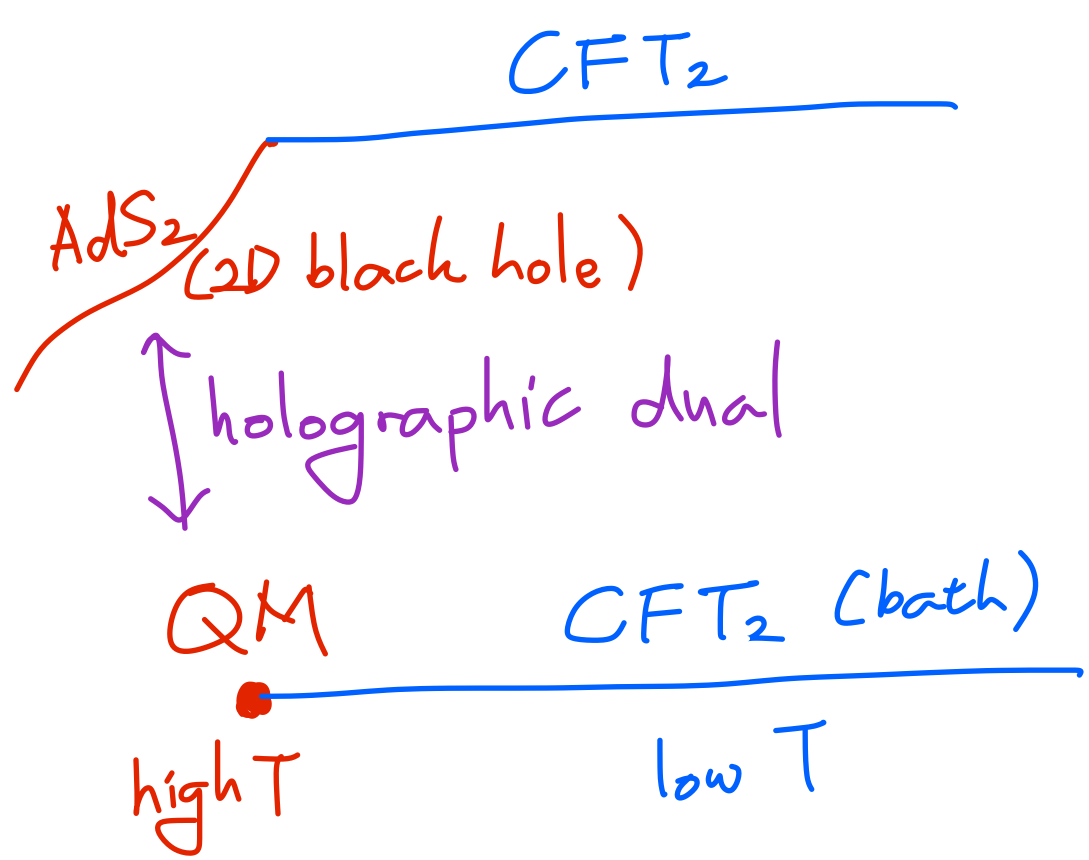
Low-Dimensional Model (Bottom-up)

- ✴ AdS_3 (1+2 dim)

- ✴ AdS2 (1+1 dim)
  + CFT_2 (1+1 dim)

  [Almheiri, Engelhardt, Marolf, Maxfield, 2019]

- ✴ QM (0+1 dim)
  + CFT_2 (1+1 dim)



Low-Dimensional Model (Bottom-up)

- ✴ AdS_3 (1+2 dim)

[Almheiri, Mahajan, Maldacena, Zhao, 2019]

- ✴ AdS2 (1+1 dim)
  + CFT_2 (1+1 dim)

[Almheiri, Engelhardt, Marolf, Maxfield, 2019]

- ✴ QM (0+1 dim)
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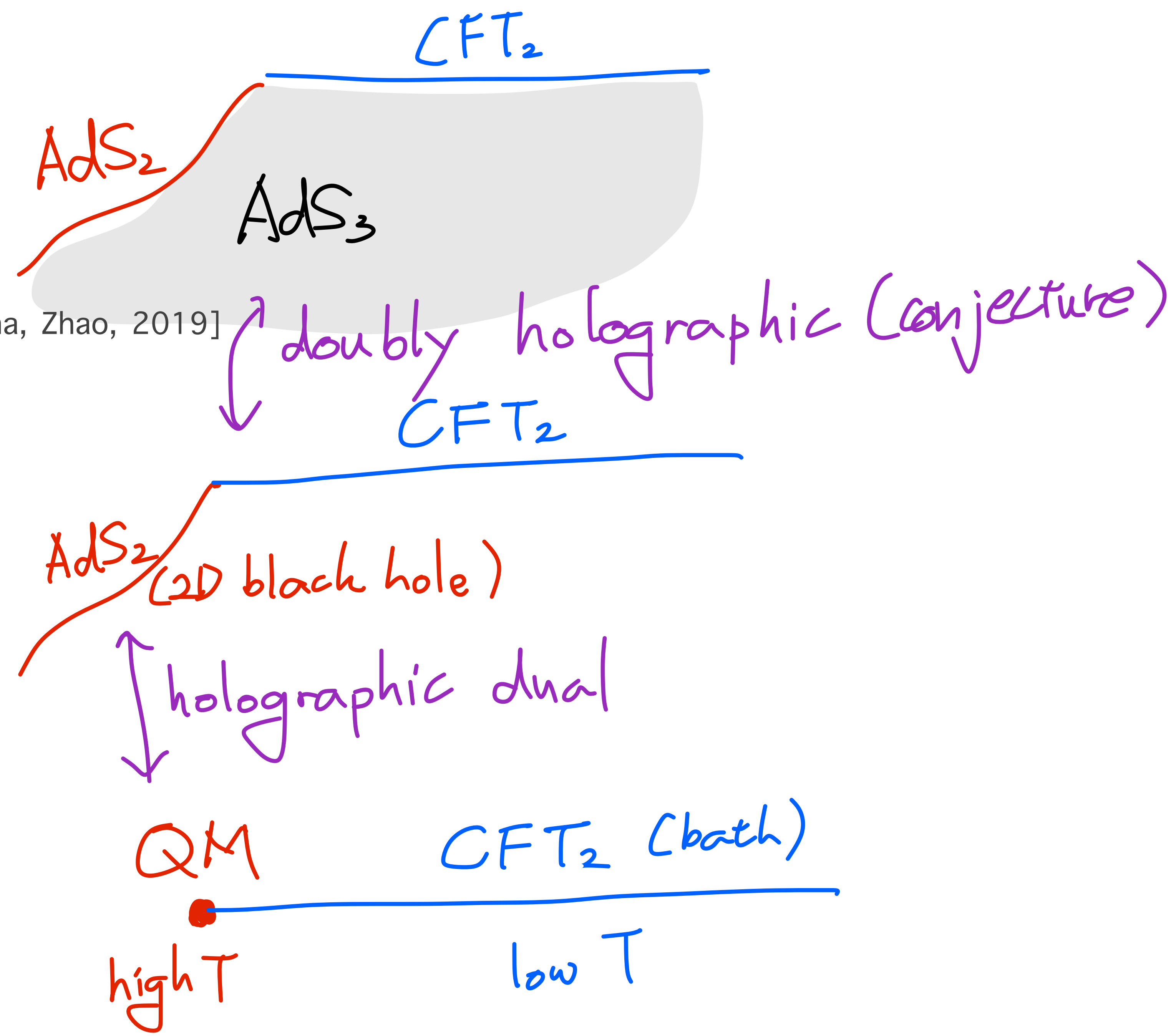


Low-Dimensional Model (Bottom-up)

✳ AdS_3 (1+2 dim)

S_{EE} can be evaluated via Ryu-Takayanagi formula.
Classical calculation!

[Almheiri, Mahajan, Maldacena, Zhao, 2019]

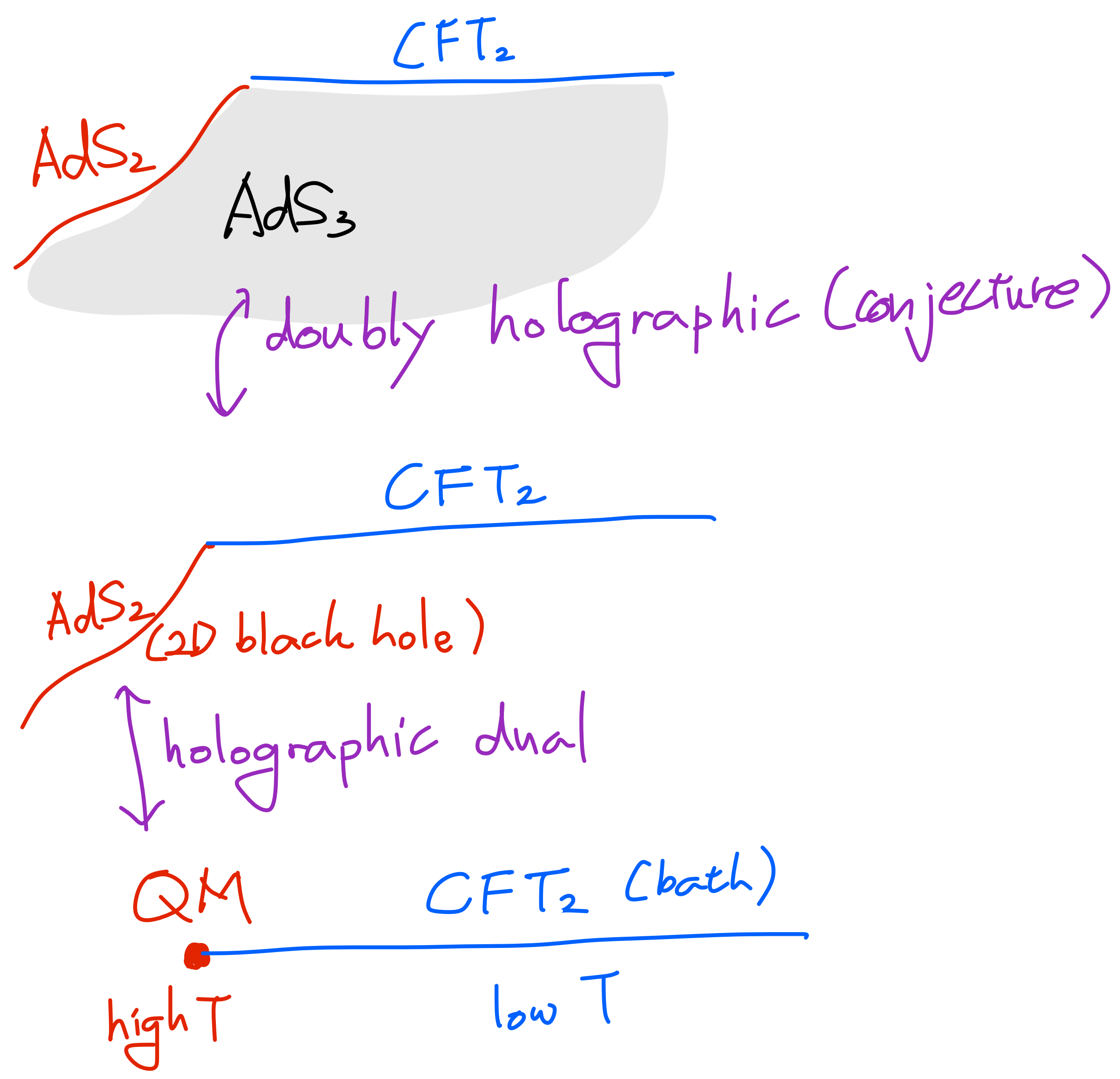
✳ AdS_2 (1+1 dim)
+ CFT_2 (1+1 dim)

S_{EE} can be calculated using conformal symmetry for conformal matter.

[Almheiri, Engelhardt, Marolf, Maxfield, 2019]

✳ QM (0+1 dim)
+ CFT_2 (1+1 dim)

S_{EE} : quantum calculation



Unitarity of Entanglement and Islands in Two-sided Janus Black Holes

D. Bak, C. Kim, S. Yi and JY
arXiv: 2006.11717

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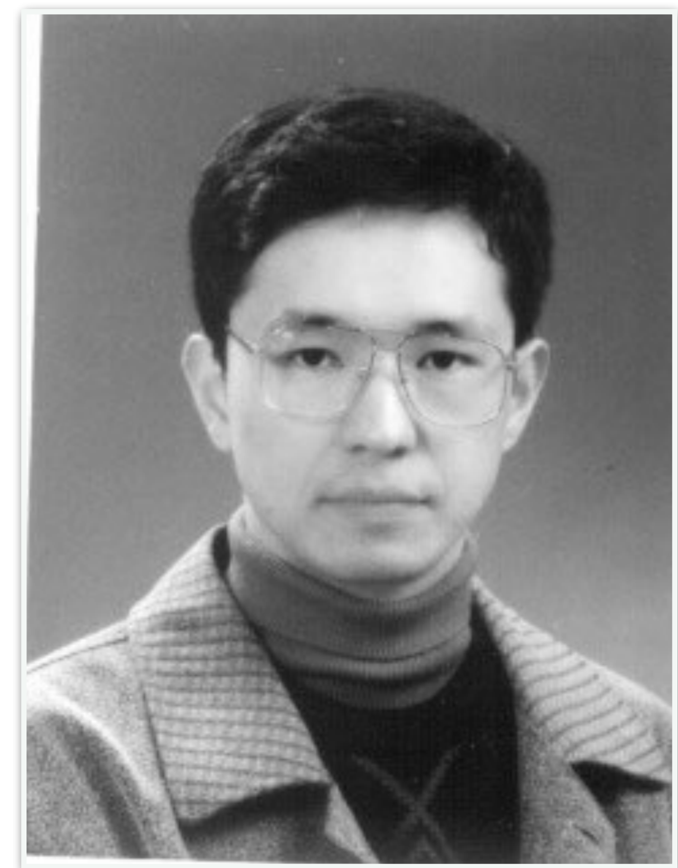

Sang-Heon Yi
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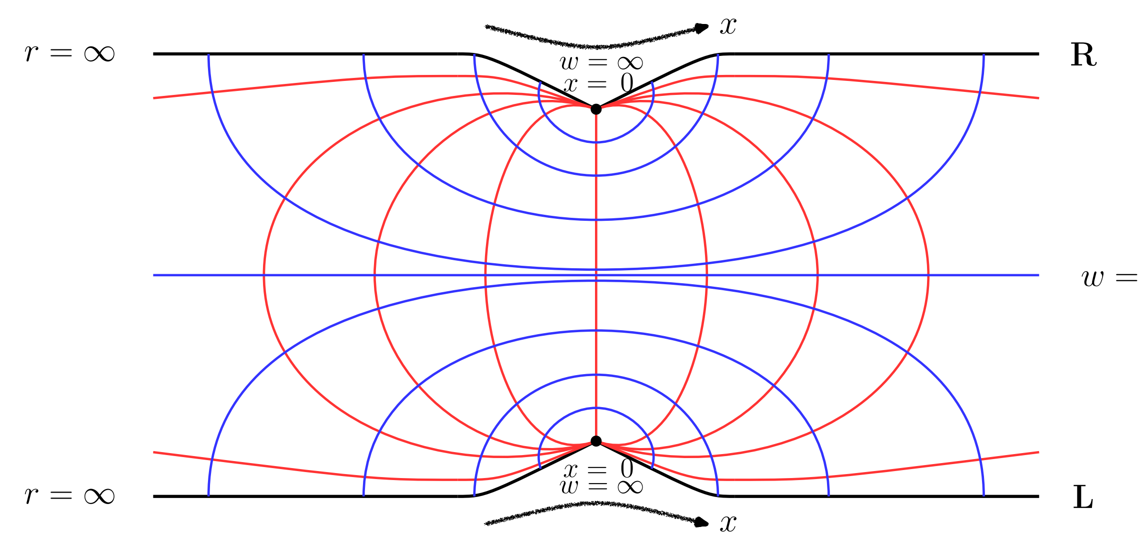
Janus Black Hole

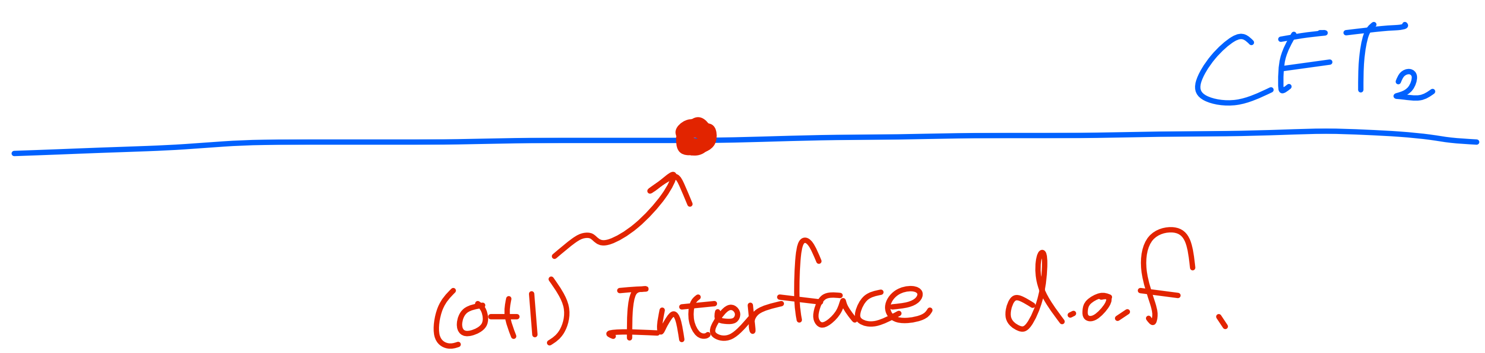
✳ Three-dimensional two-sided Janus black hole solution

$$ds^2 = \ell^2 \left[dy^2 + f(y)\, ds^2_{\mathrm{AdS}_2} \right]$$

$$\phi(y) = \frac{1}{\sqrt{2}} \ln \left(\frac{1 + \sqrt{1 - 2\gamma^2} + \sqrt{2}\gamma \tanh y}{1 + \sqrt{1 - 2\gamma^2} - \sqrt{2}\gamma \tanh y} \right)$$

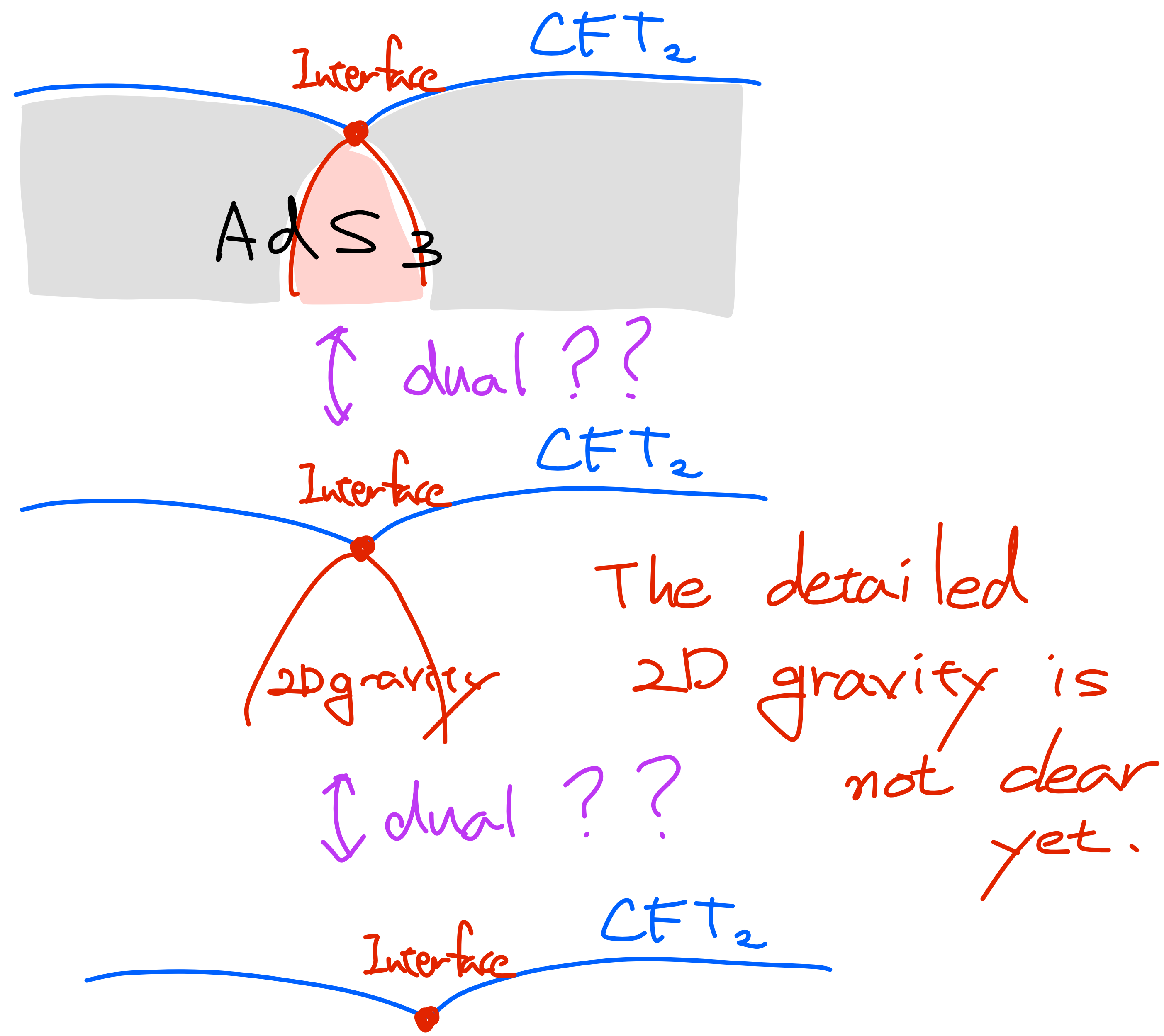


✳ Dual to Interface CFT



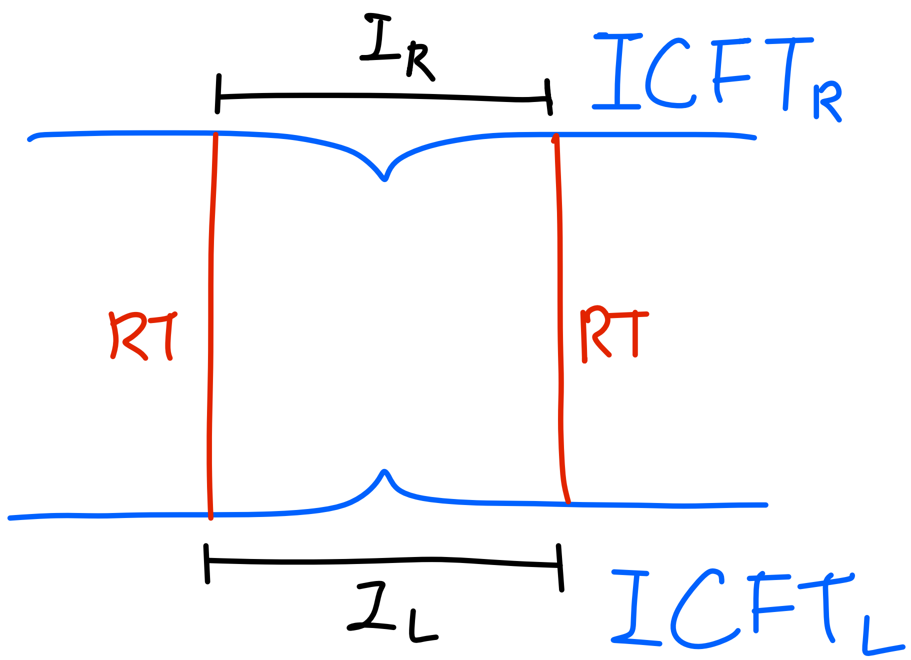
Top-down Approach

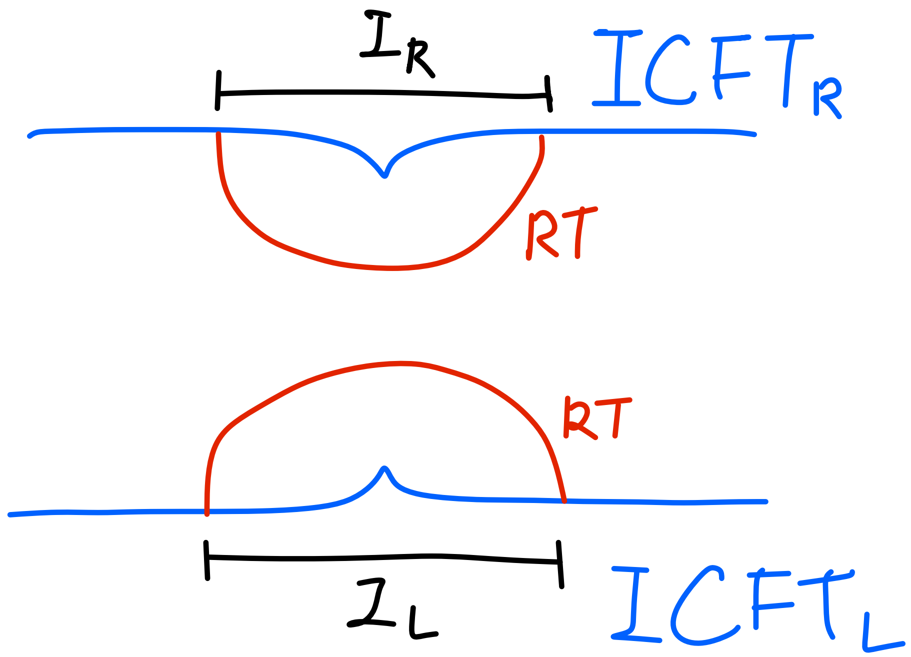
- ✶ AdS_3 (1+2 dim)
- ✶ AdS2 (1+1 dim) + CFT_2 (1+1 dim)
- ✶ QM (0+1 dim) + CFT_2 (1+1 dim)



Entanglement Entropy

- In AdS_3, one can evaluate the EE using RT surface.
- Two phases





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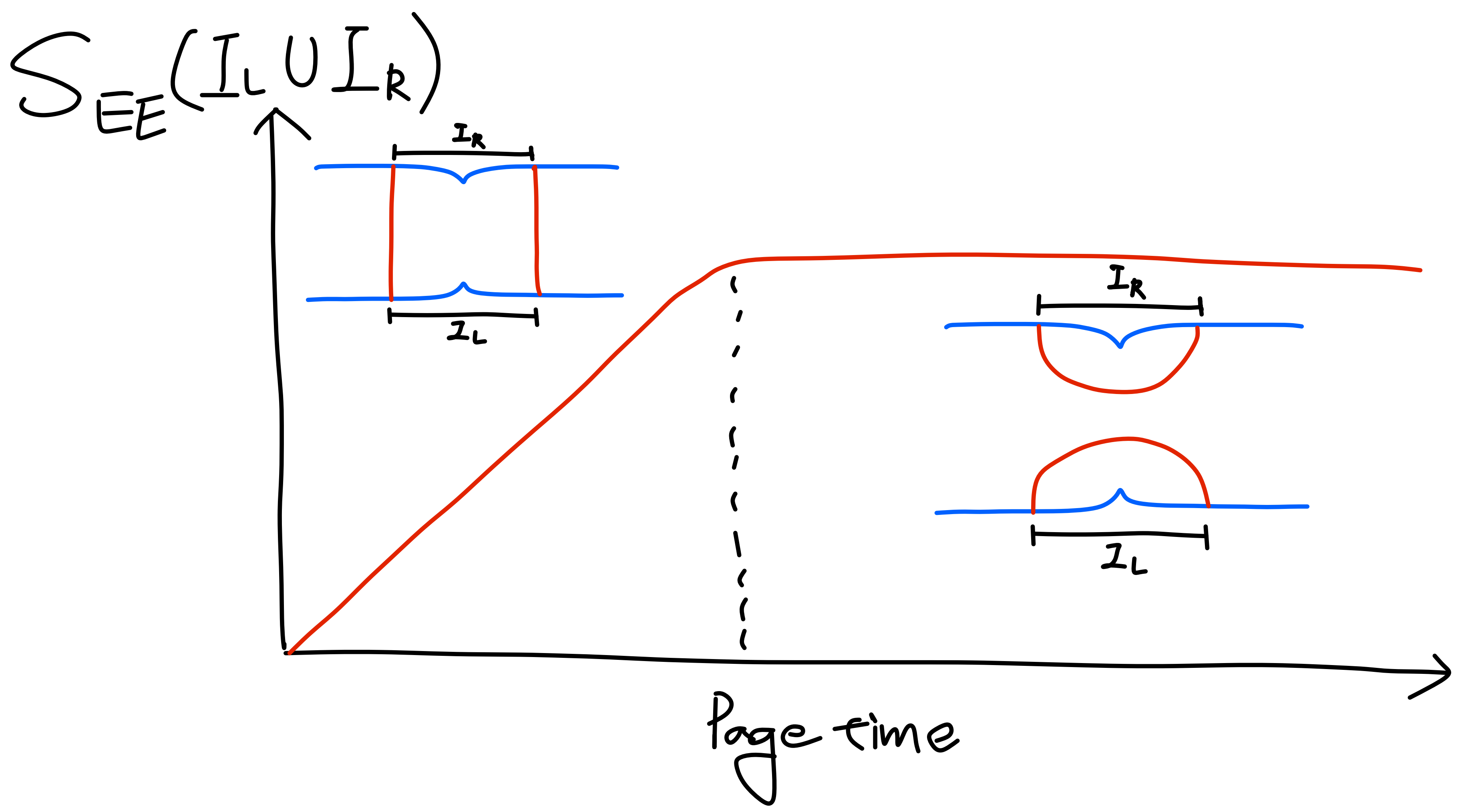
Page Curve

* We have the usual phase transition of EE.



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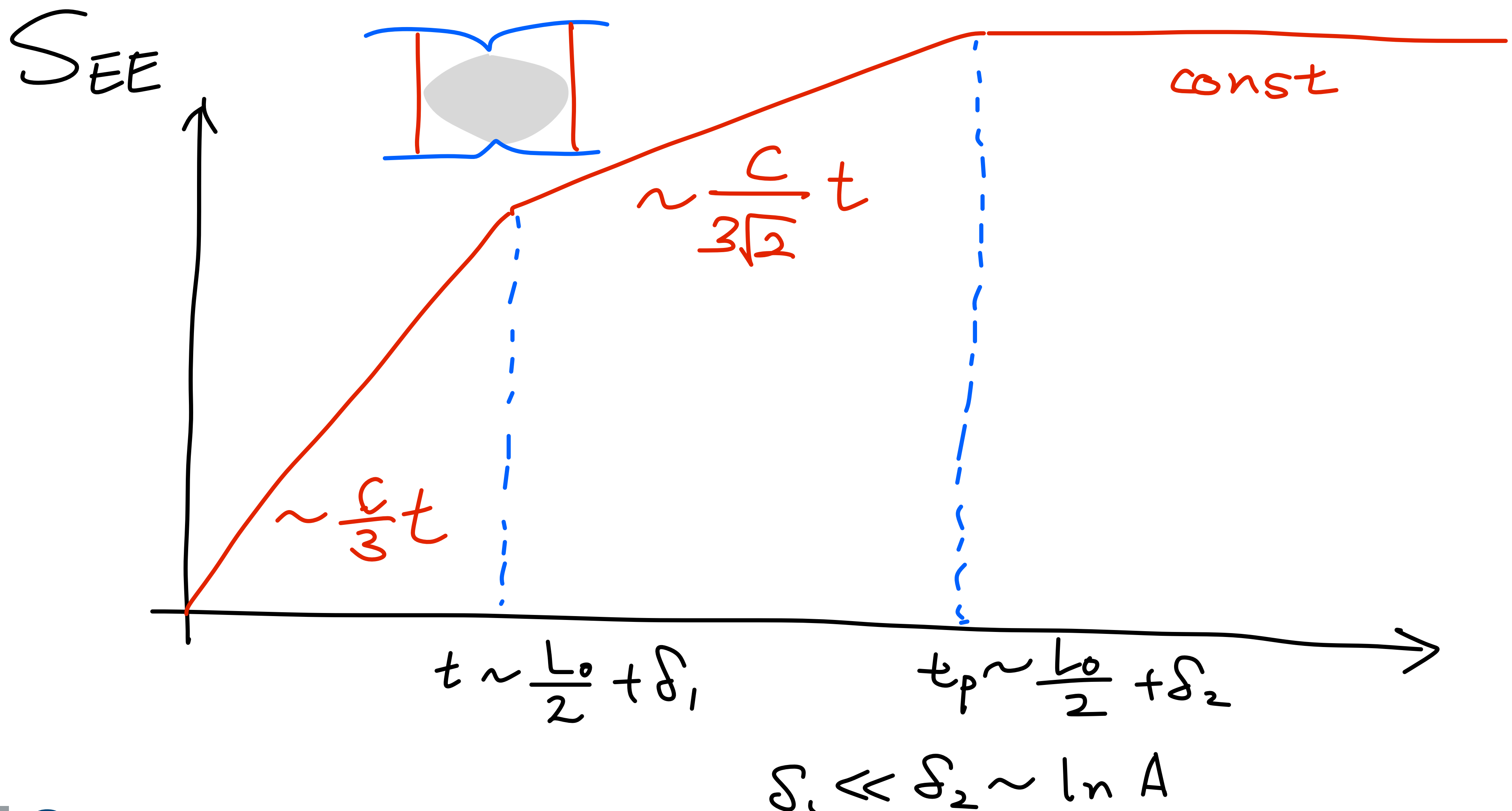
"Phase Transition"

- In the limit where the influence of the interface d.o.f. gets stronger, we have an interesting behavior of EE before Page time



Open Question

- The details description of the emergent 2D gravity of Janus black hole
- Island conjecture could be seen as a prescription to reproduce the Page curve
- What is the origin of the Island?
- Though we could reproduce the Page curve semi-classically, we still don't know the state of black hole after Page time (when Island appears)
- Can we calculate the same thing in higher dimension? e.g. SYM/AdS5

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Thank You