Unitary Semiclassical Black Hole Evaporation

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IAS

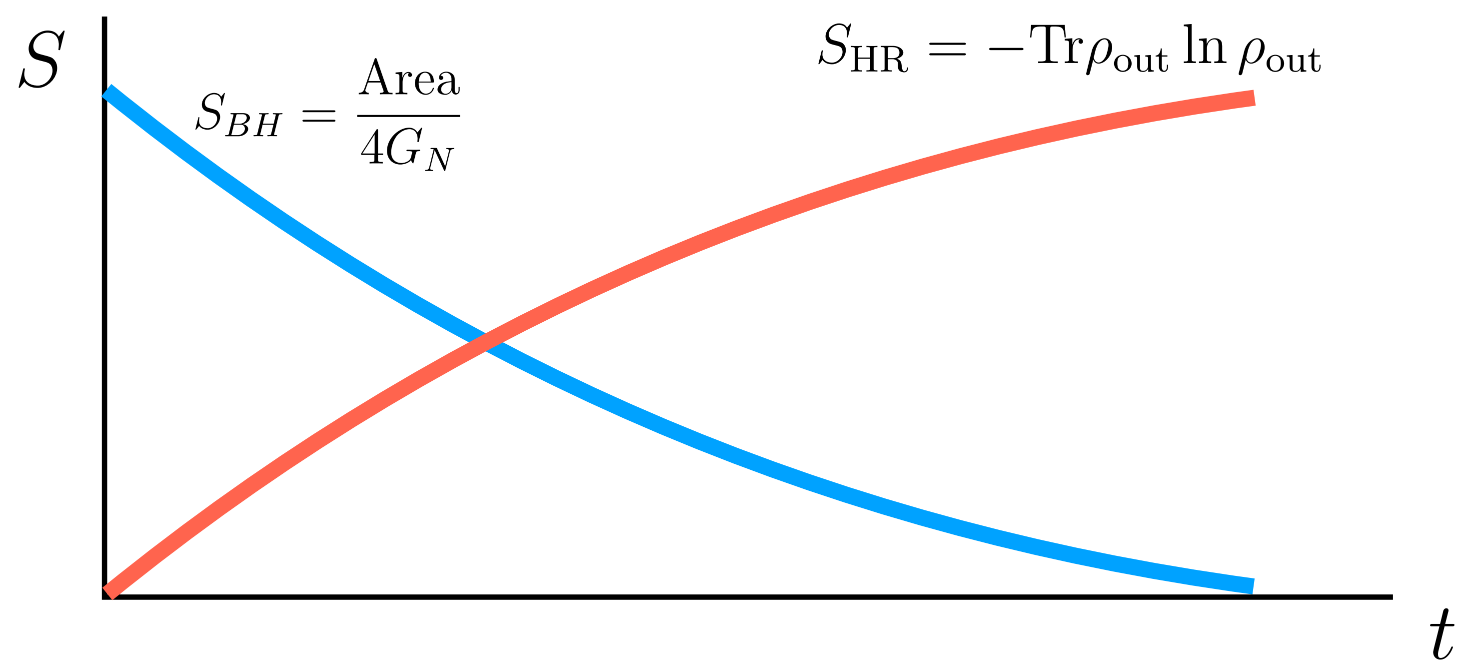
AA ’18
AA, Engelhardt, Marolf, Maxfield ’19
Penington ’19
WIP w/ Mahajan, Maldacena, Zhao

Information Paradox

Hawking

Fine-Grained Entropy of Hawking Radiation: The von Neumann entropy of the state of the Hawking radiation. **Page**

Coarse-Grained Entropy of Black hole - Bekenstein-Hawking Entropy: The area of the event horizon/4G - a measure of the dimensionality of the black hole Hilbert space.



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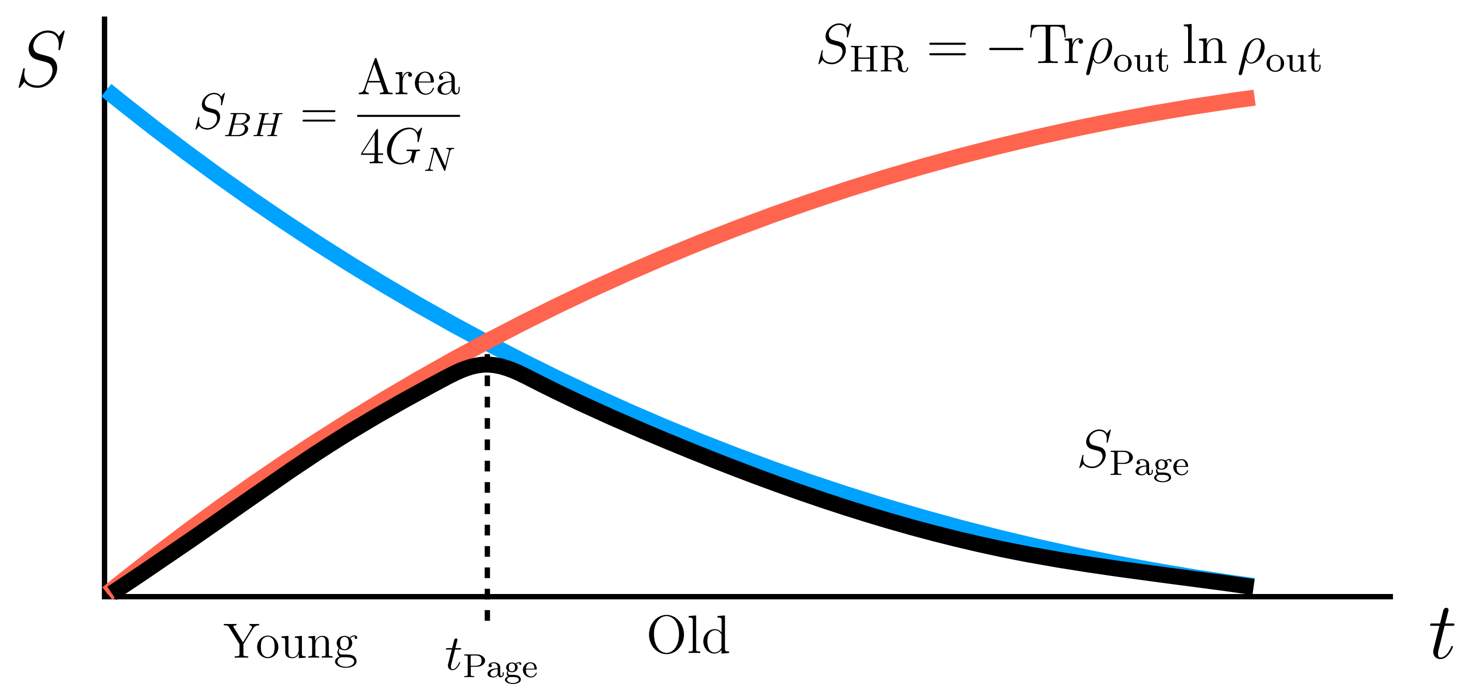

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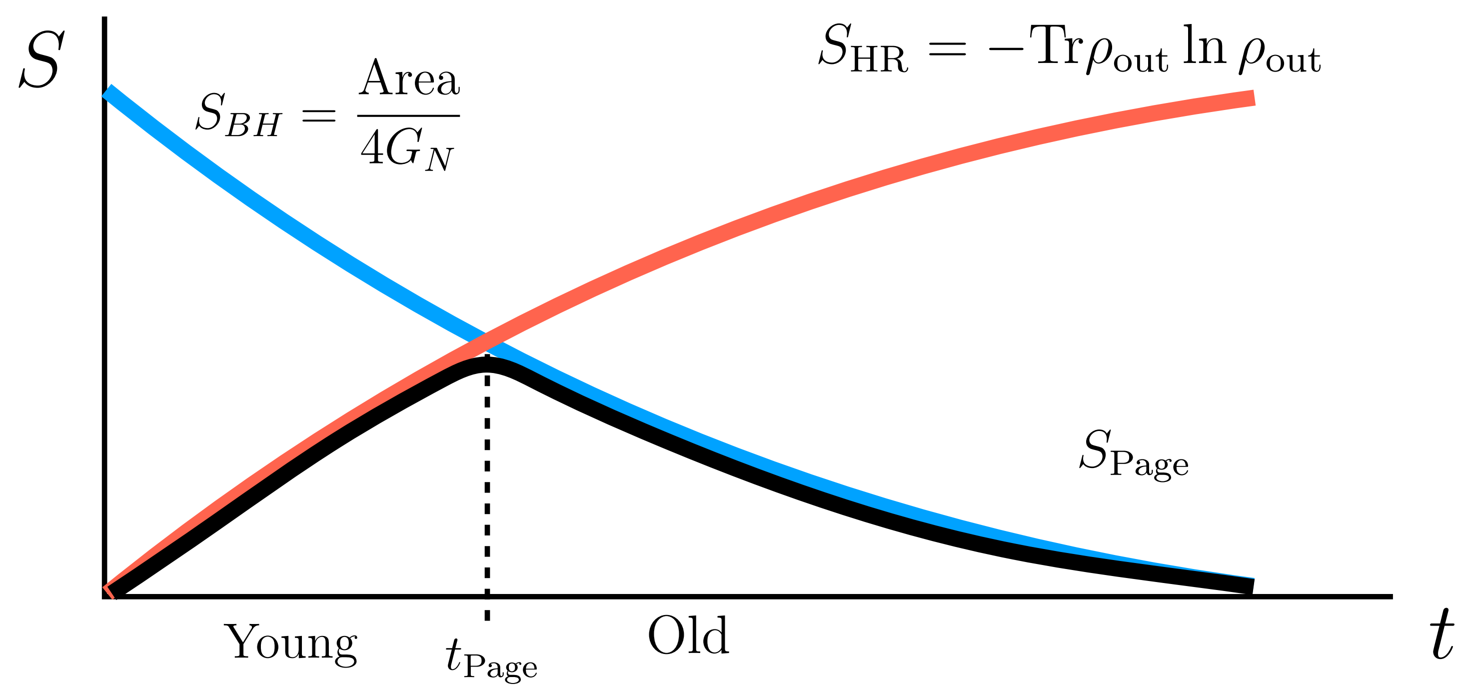


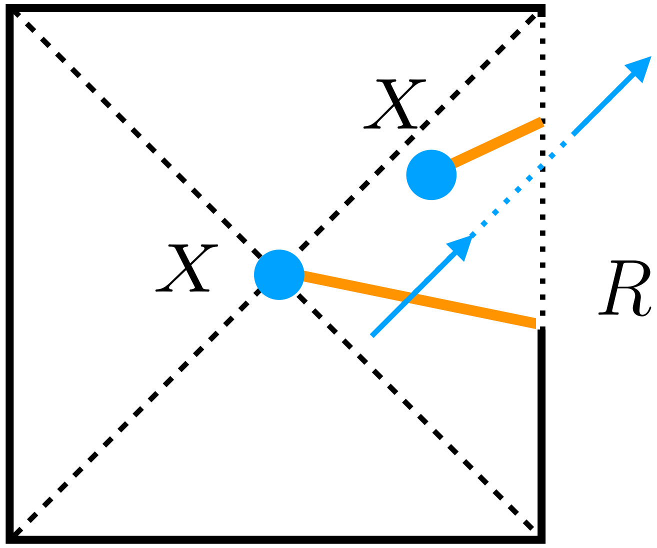
Unitary Evolution - Page Curve: Generic behavior of the fine-grained entropy in a unitary system governed by random Hamiltonian. Fine-grained entropy of either system. **Page**

<u>Reproducing the Page curve **FOR BOTH SYSTEMS** is tantamount to resolving the information paradox!</u>

Plan for this Talk

We will consider the case of evaporating one side of the eternal black hole in JT gravity coupled to an external system.

Plan: To track the evolution of the von Neumann entropy of the evaporating side, and of the extracted Hawking radiation in the external system.



$$S_R(t) = \mathrm{Min}\left[\ \mathrm{Ext}\left[\frac{\phi(X)}{4G_N} + S_{\mathrm{Bulk}}(\Sigma_X^R)\right]\ \right]$$ **Engelhardt, Wall**

Search for quantum extremal surfaces as a function of boundary time.

Goal: To reproduce the Page curve for R and for the extracted Hawking radiation.

JT Gravity + Conformal Matter

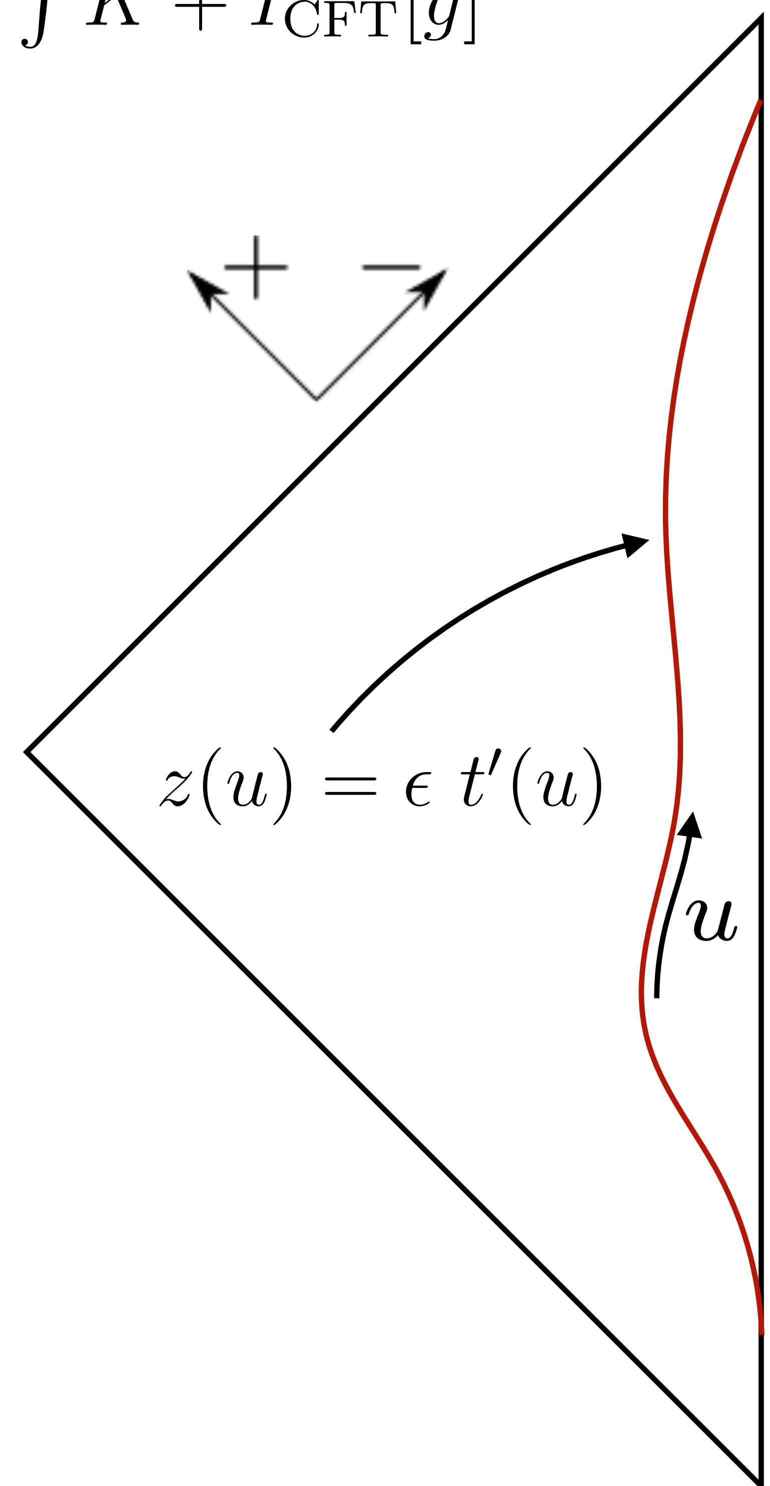
MSY
EMV
J

We study black hole evaporation in the setting of JT gravity coupled to conformal matter.

$$I = \frac{\phi_0}{G_N}\int (R+2) + \frac{1}{G_N}\int \phi(R+2) + \phi_b \int K + I_{\rm CFT}[g]$$

Integral over ϕ fixes the spacetime metric to be AdS_2

$$ds^2 = \frac{-dt^2+dz^2}{z^2} = \frac{-4dx^+dx^-}{(x^+-x^-)^2} \qquad x^\pm = t \pm z$$

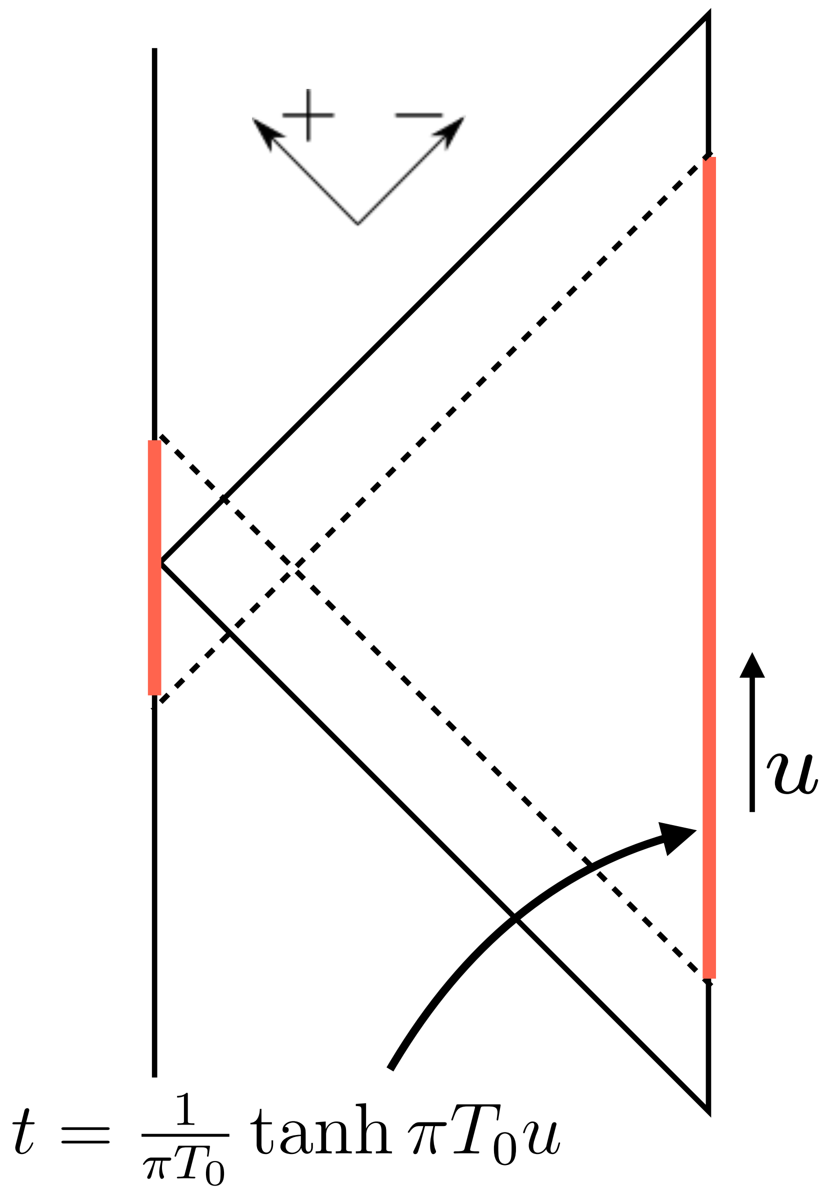


The gravitational dynamics of this theory is given entirely by that of the reparamaterization $t(u)$ where u is the physical boundary time.

Matter sector $I_{\rm CFT}[g]$ is given by a BCFT - conformal field theory with boundary @ $x^+ - x^- = 0$, with background metric being Poincare AdS_2

The Eternal Blackhole in JT Gravity

The eternal black hole is a vacuum solution: $\langle T_{x^+x^+}\rangle_{AdS_2} = \langle T_{x^-x^-}\rangle_{AdS_2} = 0$



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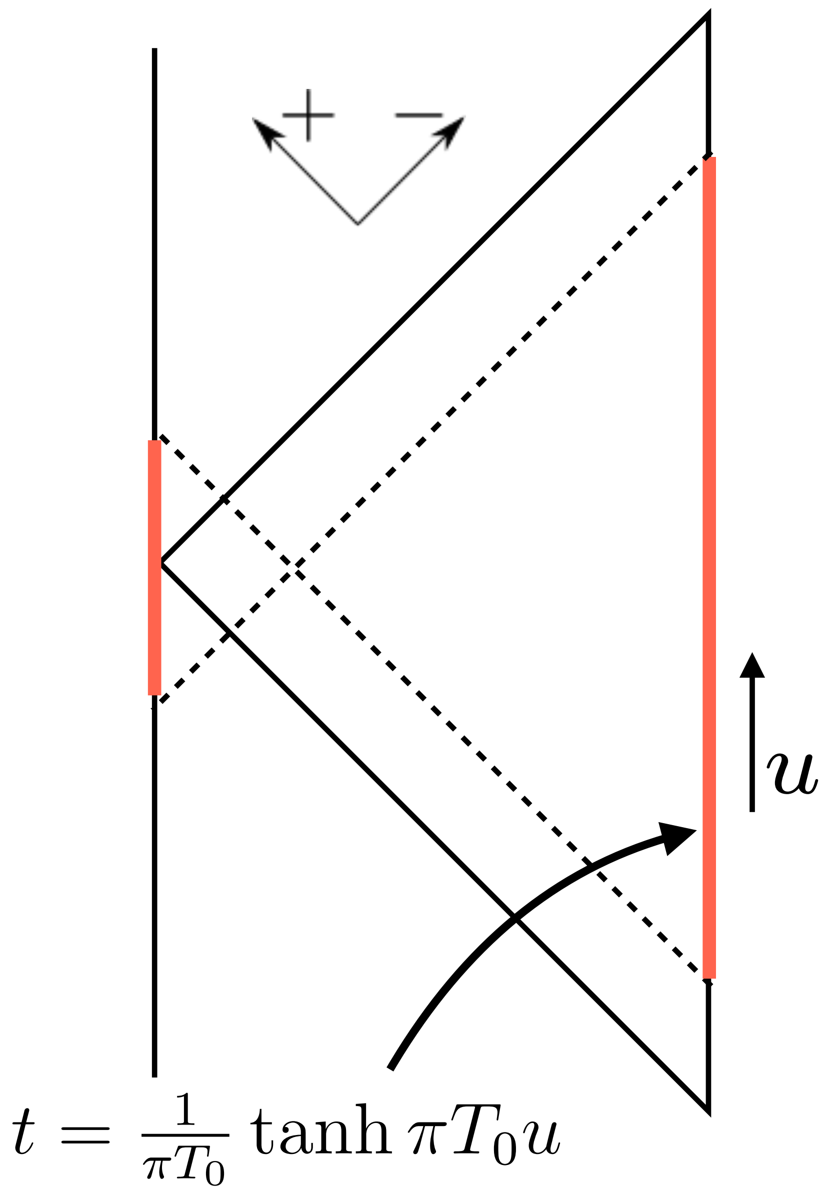
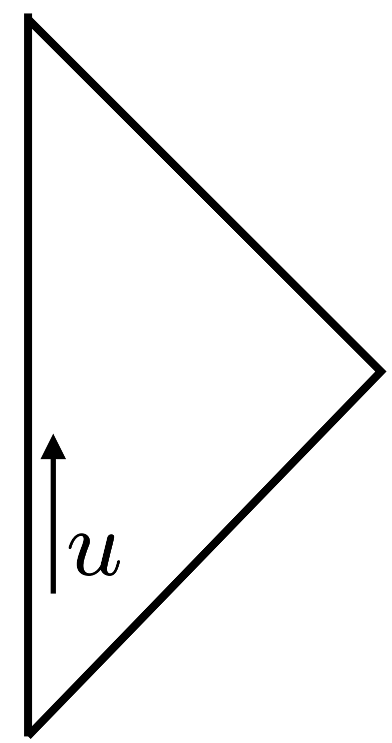


Introduce a ‘Bath’
BCFT in the vacuum



Bath

$$ds^2 = -dy^+dy^-$$
$$y^\pm = u \pm \sigma$$

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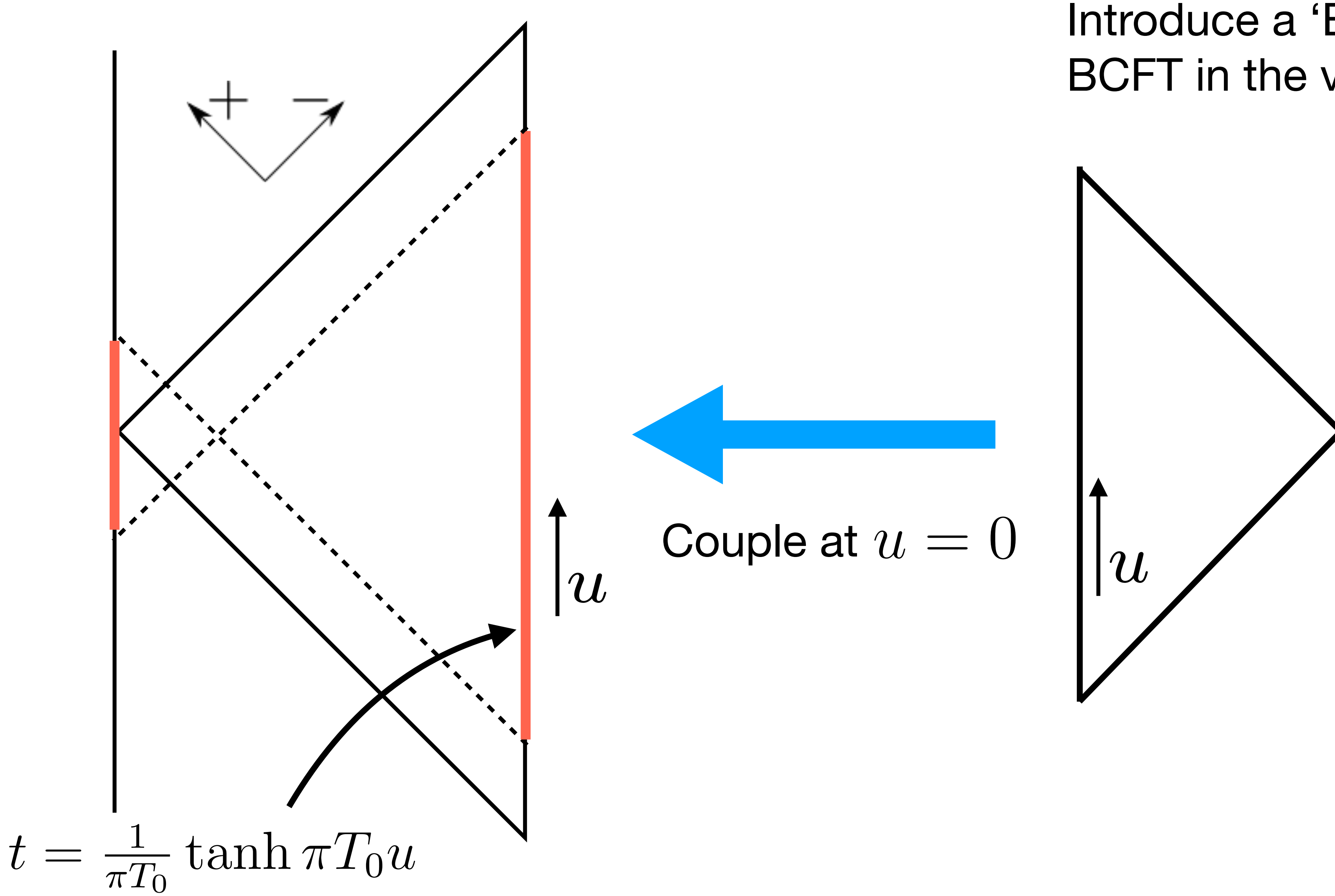

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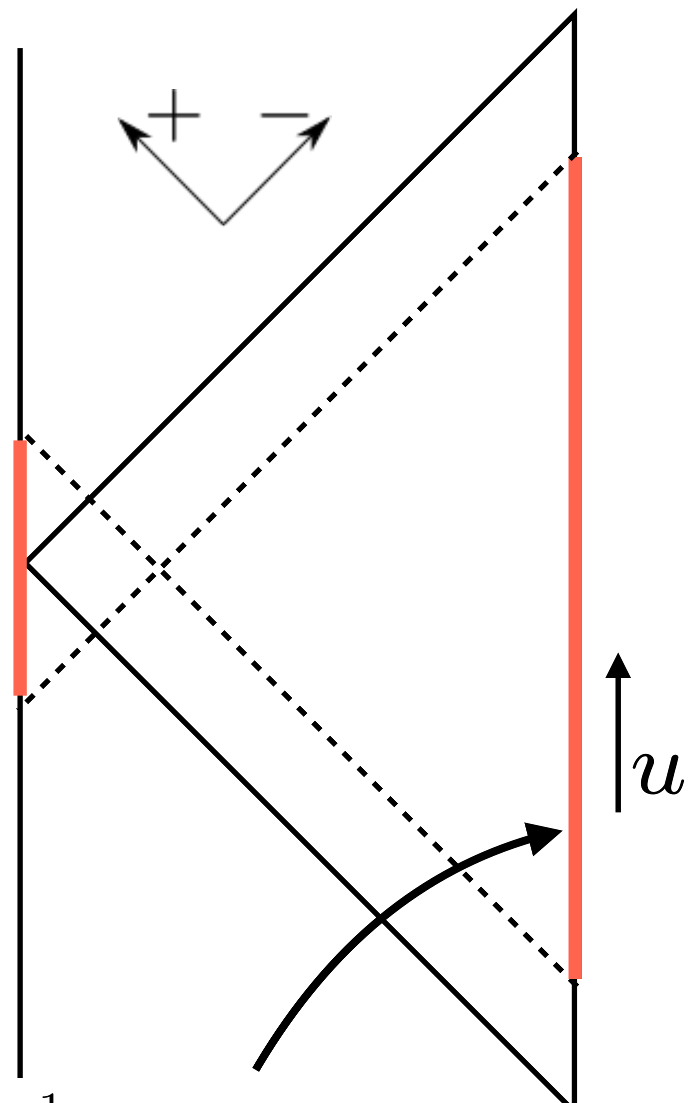

$t = \frac{1}{\pi T_0}\tanh \pi T_0 u$

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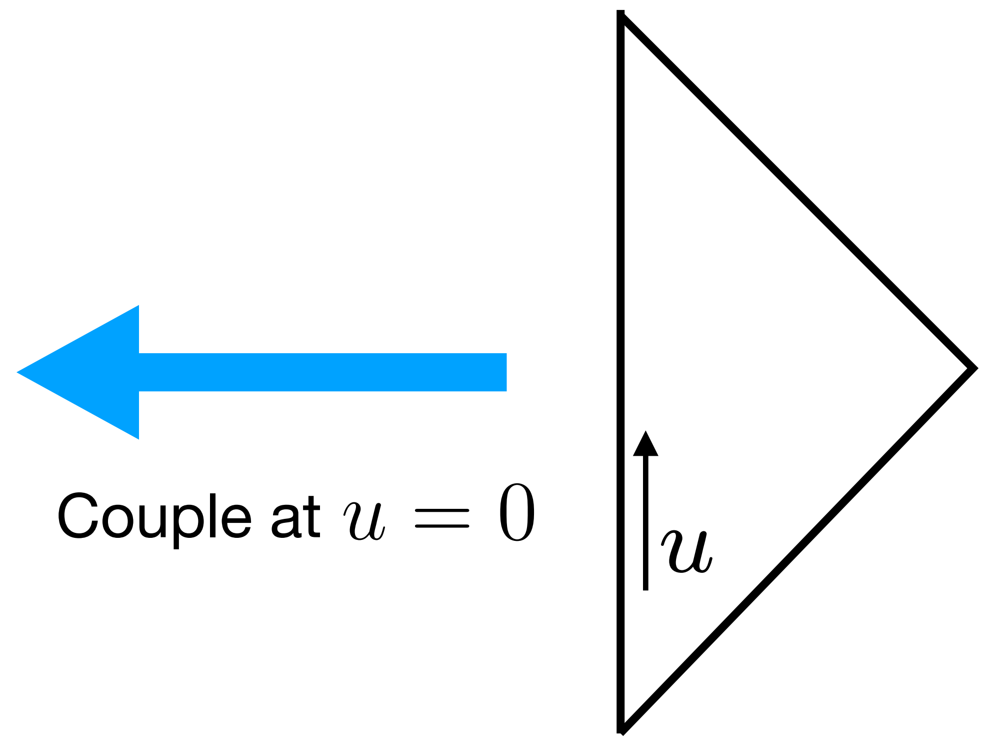

Bath

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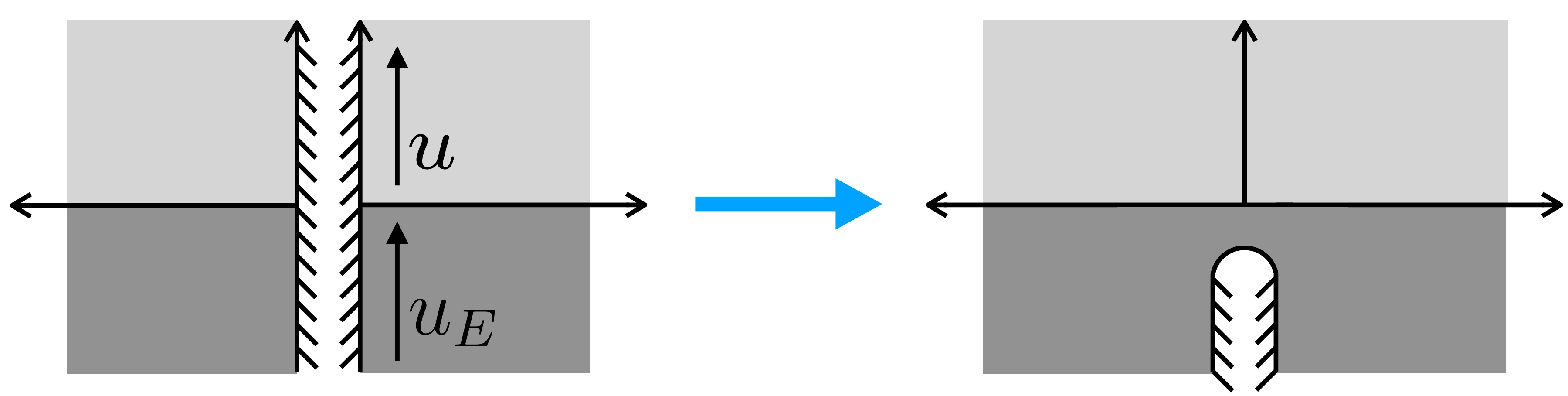
$y^\pm = u \pm \sigma$

We model this as a quantum quench of two BCFTs:

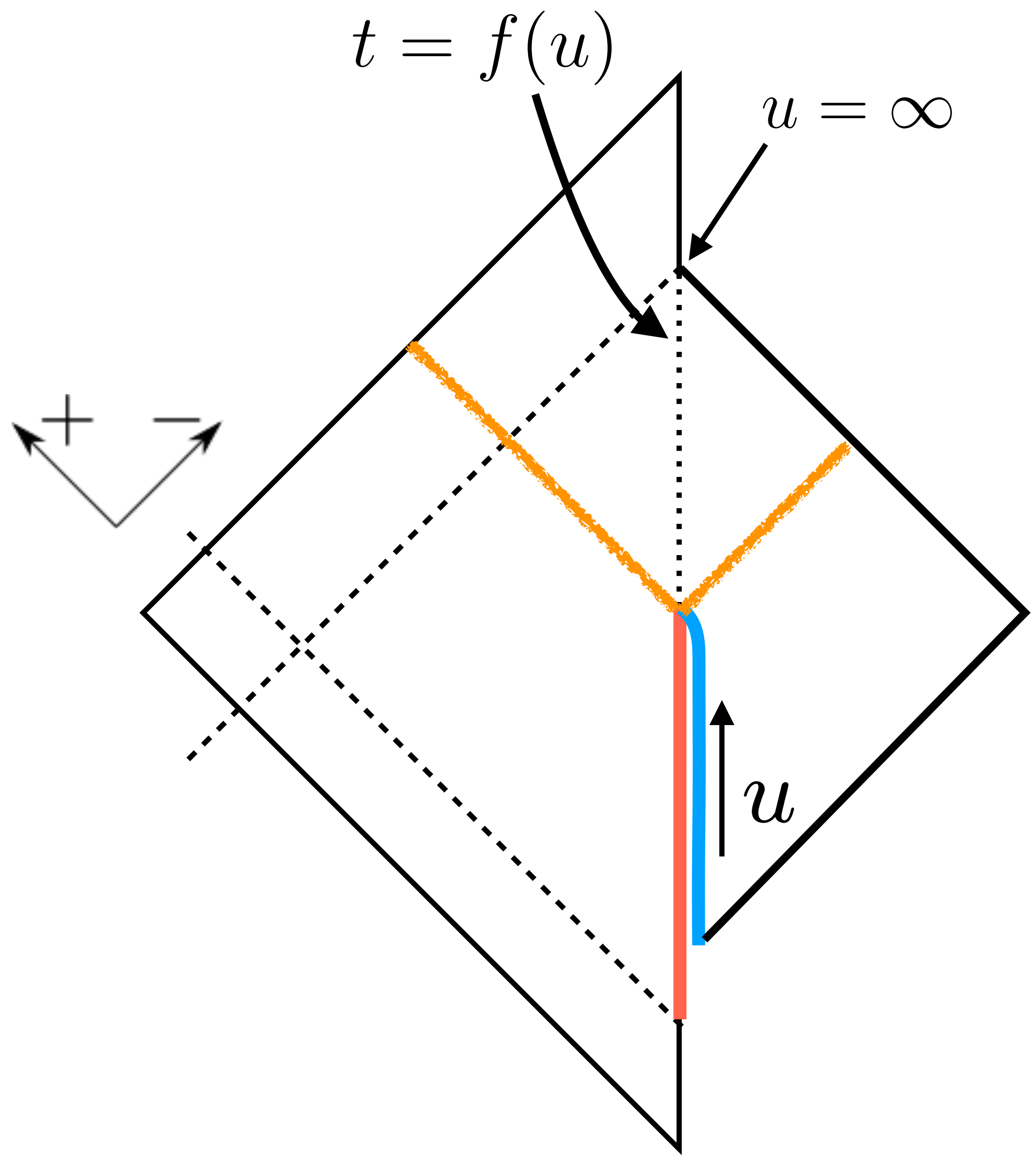
Cardy, Calabrese
Asplund, Bernamonti



Evaporating One Side of the Eternal Black hole

The Bath CFT is glued to the AdS_2 bulk along the physical boundary, identifying the physical time on the boundary with that of the bath.

Englesoy, Mertens, Verlinde



Bulk

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$$x^\pm = t \pm z$$

Bath

$$ds^2 = -dy^+dy^-$$
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$$x^\pm = f(y^\pm)$$

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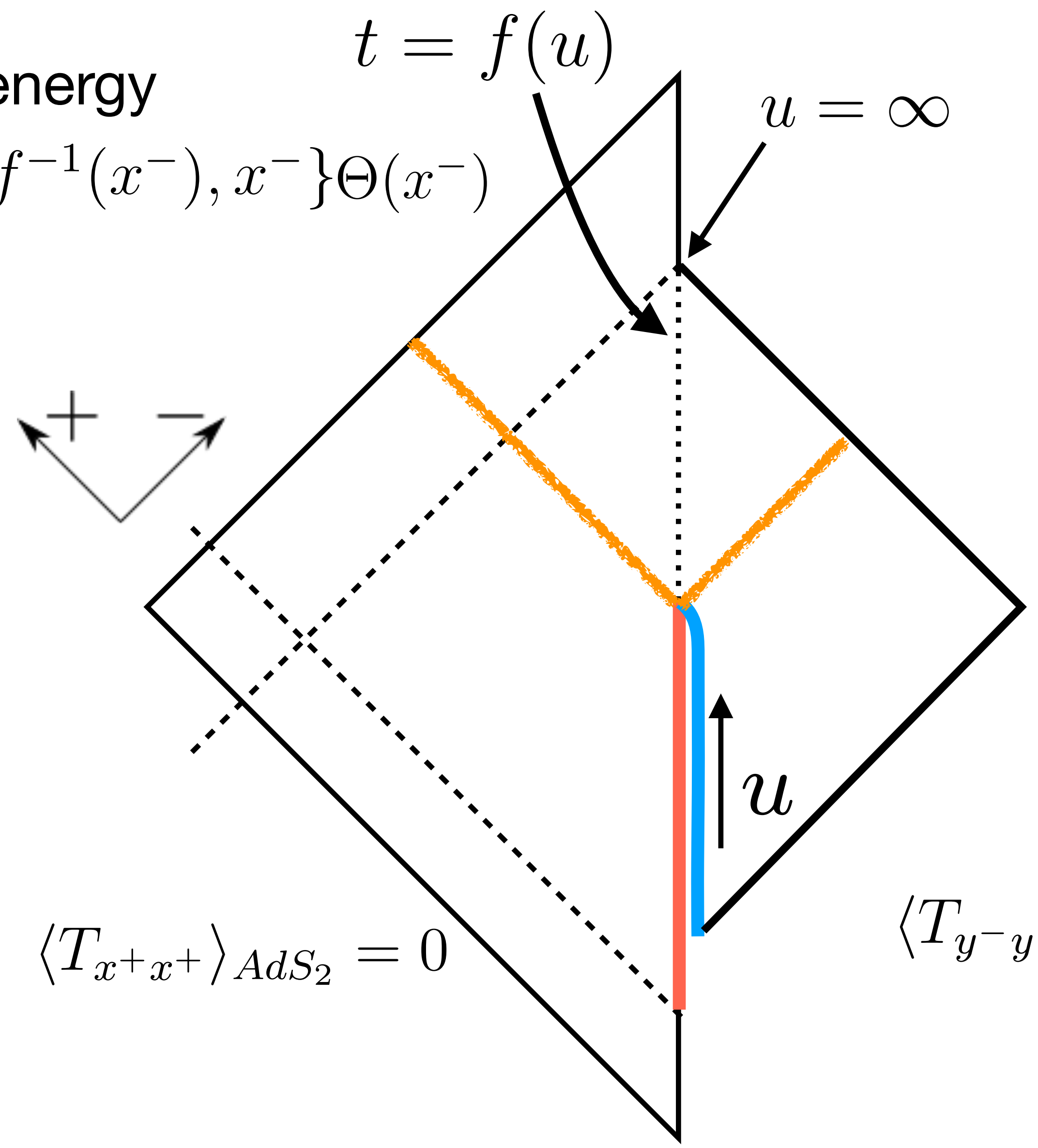
Infalling negative energy

$$\langle T_{x^-x^-}\rangle_{AdS_2} = -\frac{c}{24\pi}\{f^{-1}(x^-), x^-\}\Theta(x^-)$$



<u>Bulk</u>

$$ds^2 = \frac{-4dx^+dx^-}{(x^+-x^-)^2}$$
$$x^\pm = t \pm z$$

$$\langle T_{x^+x^+}\rangle_{AdS_2} = 0$$

$$\langle T_{y^-y^-}\rangle_{\text{Flat}} = 0$$

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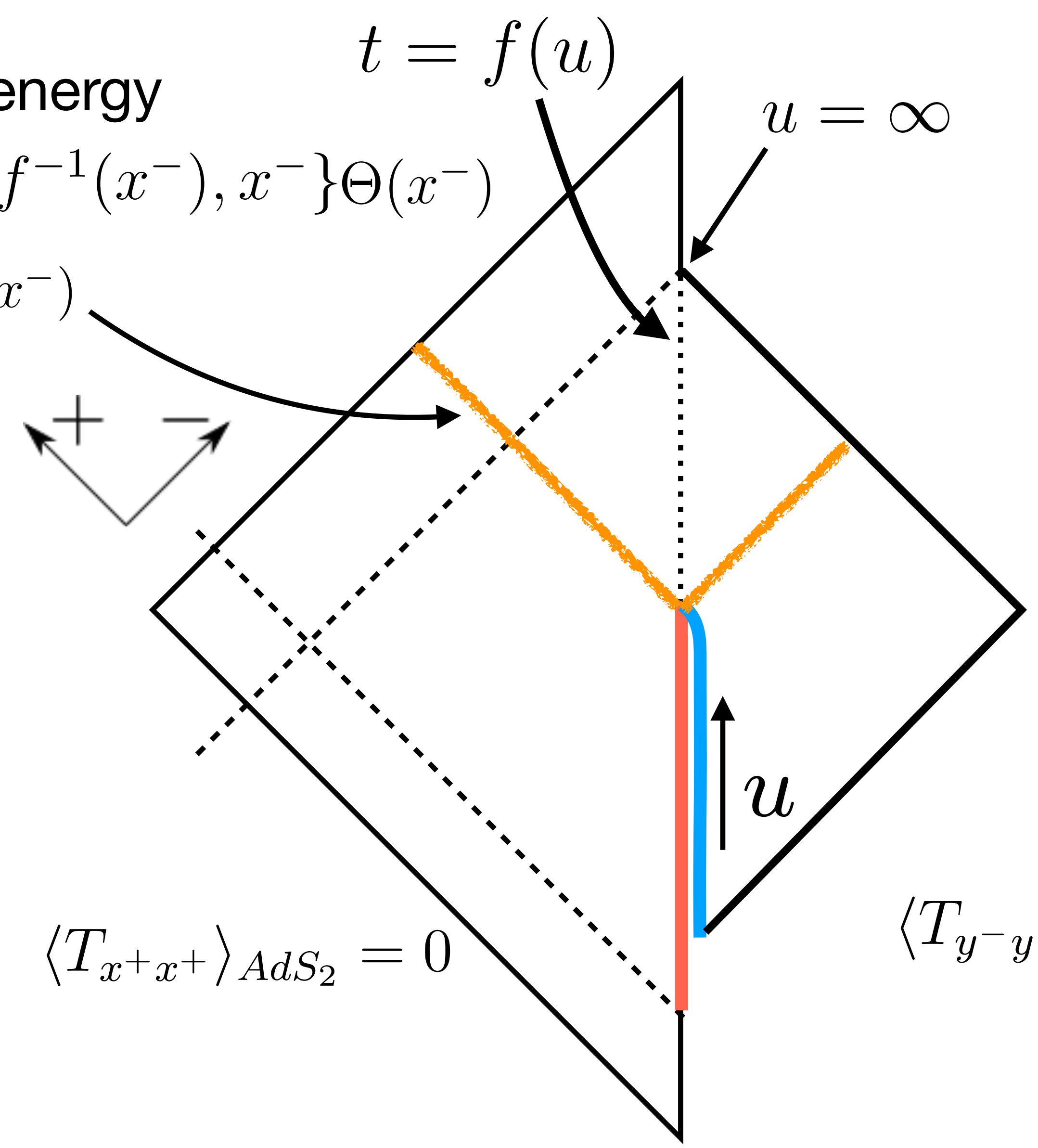

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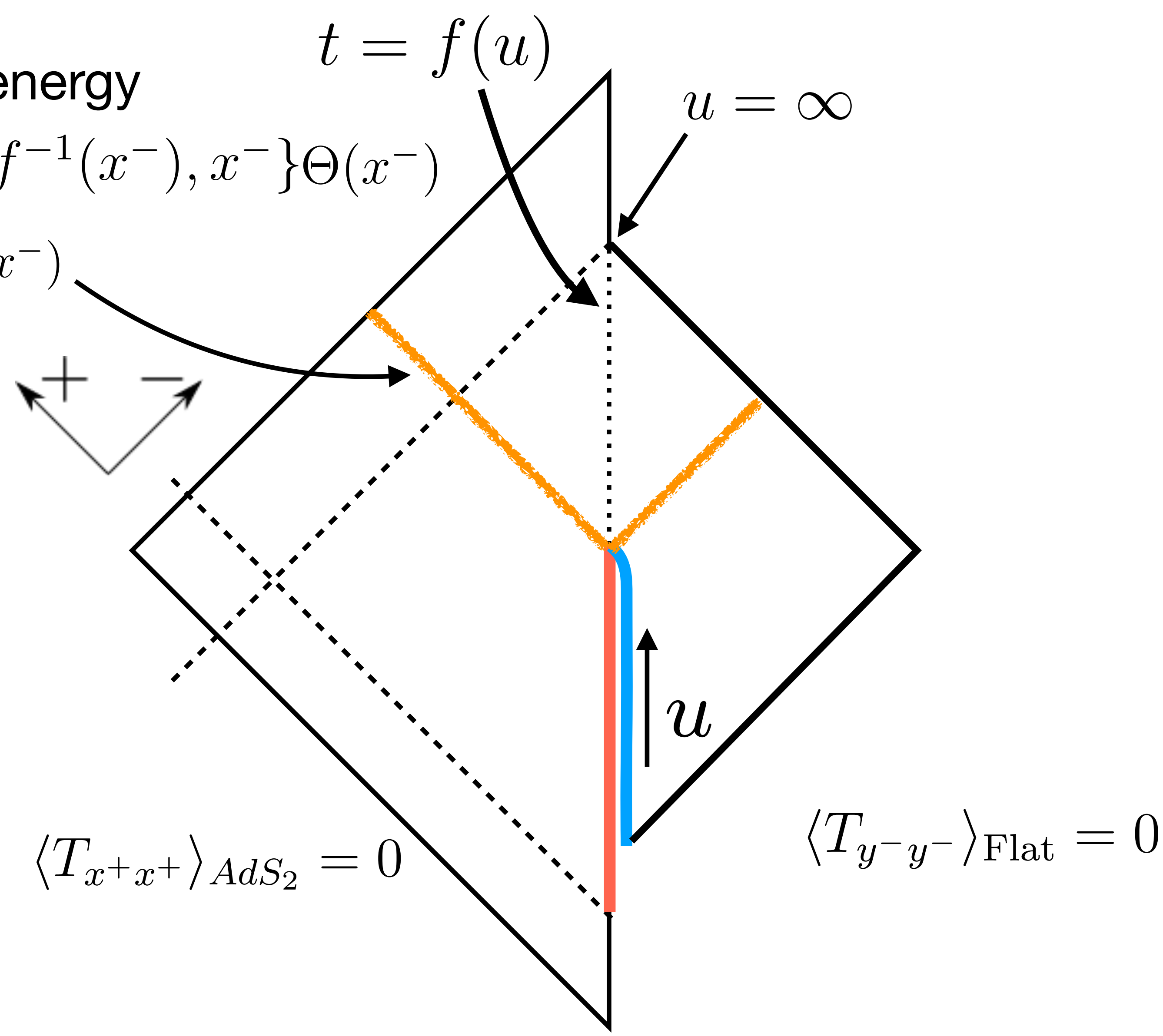

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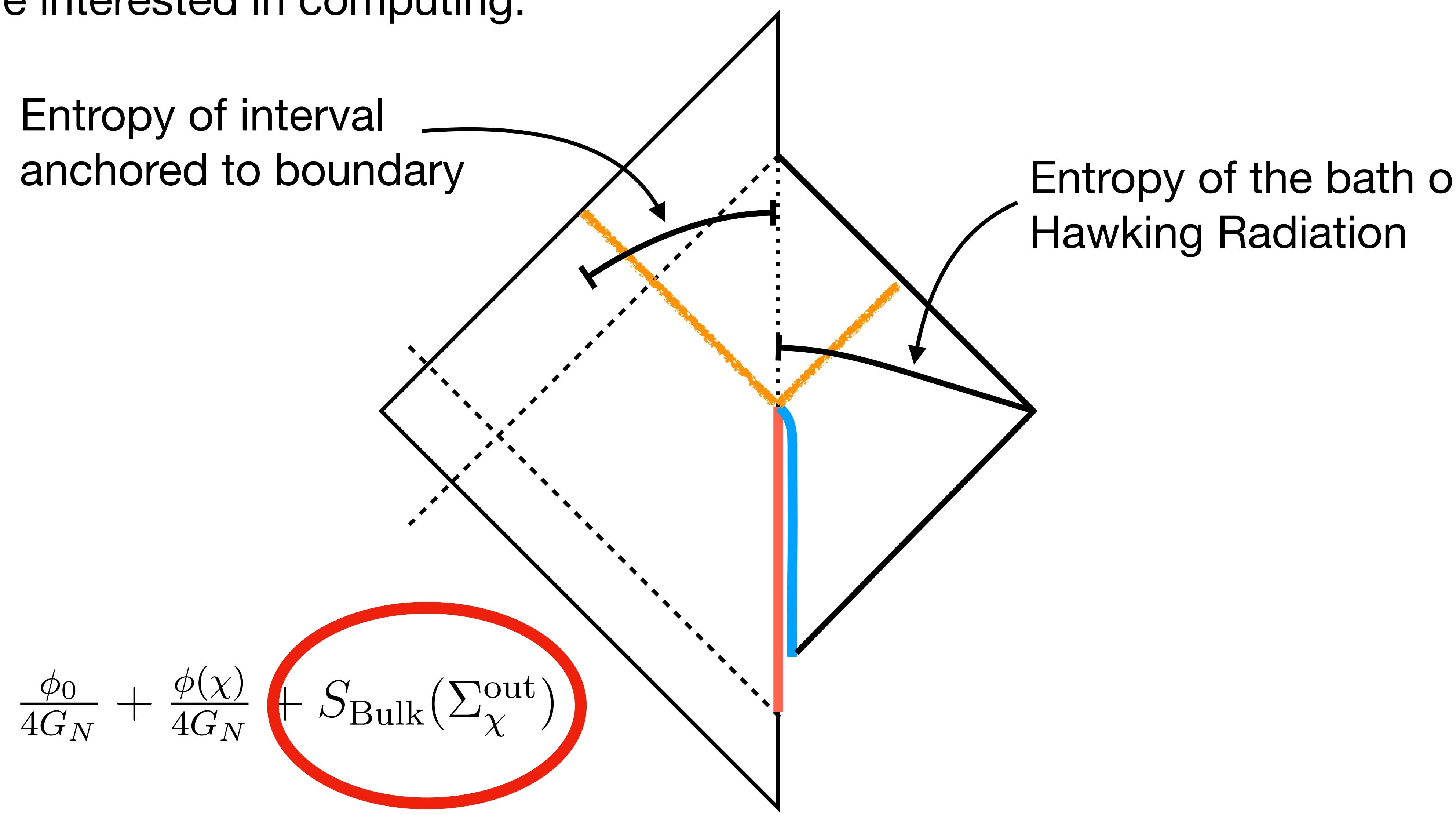
Semiclassical Limit: We source the JT equations with $\langle T_{ab}\rangle_{AdS_2}$ to determine ϕ and $f(u)$

Bulk Entanglement Entropy

We are interested in computing:



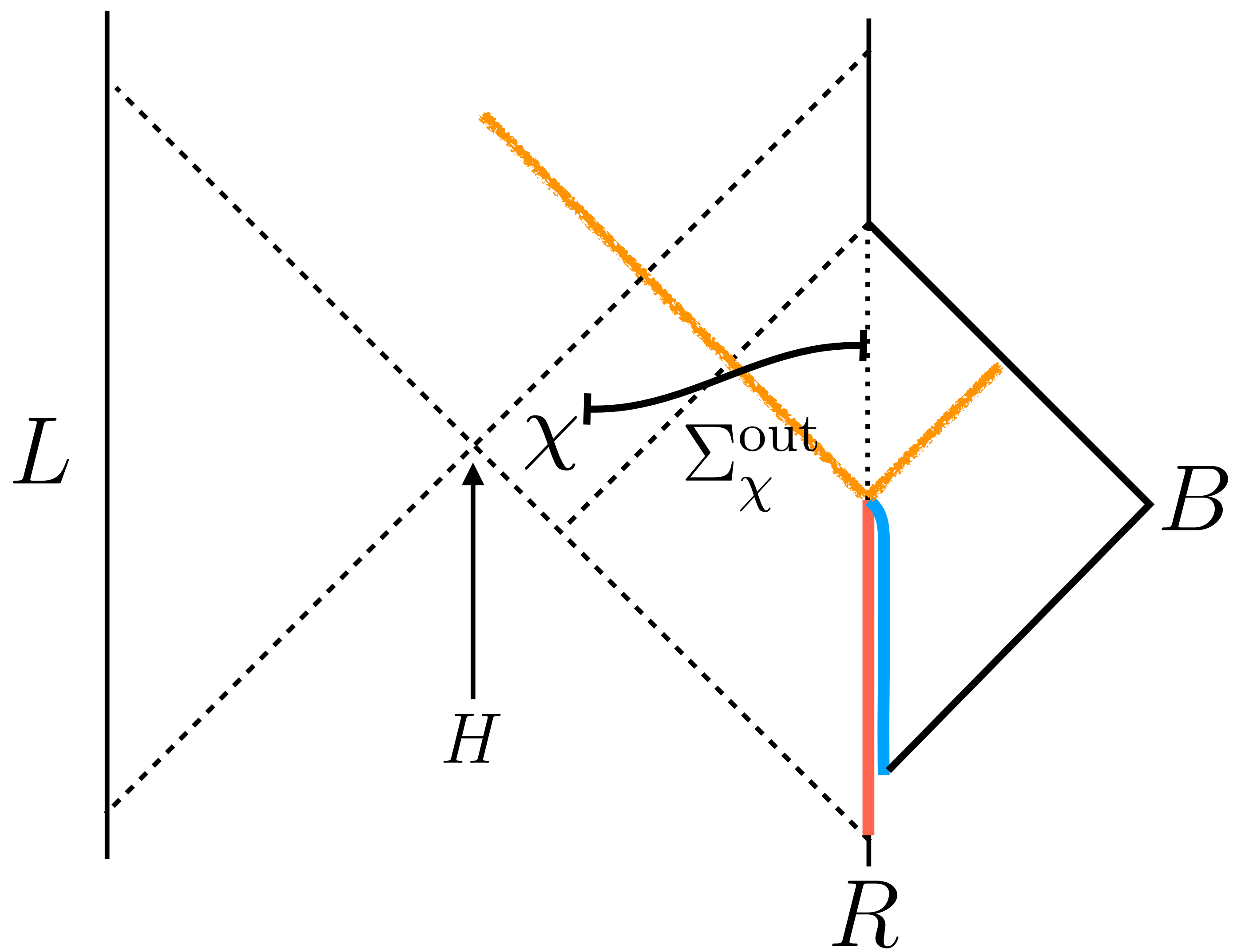
$$S_{gen} = \frac{\phi_0}{4G_N} + \frac{\phi(\chi)}{4G_N} + S_{\text{Bulk}}(\Sigma_\chi^{\text{out}})$$

1. Transformation to a coordinate system where stress tensor is trivial
2. Compute Entropy in that coordinate system
3. Transform back to physical coordinates and cutoffs

Finding the Quantum Extremal Surfaces

Generalized Entanglement Entropy $S_{gen} = \frac{\phi_0}{4G_N} + \frac{\phi(\chi)}{4G_N} + S_{\mathrm{Bulk}}(\Sigma_\chi^{\mathrm{out}})$

Extremize: $\partial_\pm S_{gen} = \frac{1}{4G_N}\partial_\pm \phi(\chi) + \partial_\pm S_{\mathrm{Bulk}}(\Sigma_\chi^{\mathrm{out}}) = 0$



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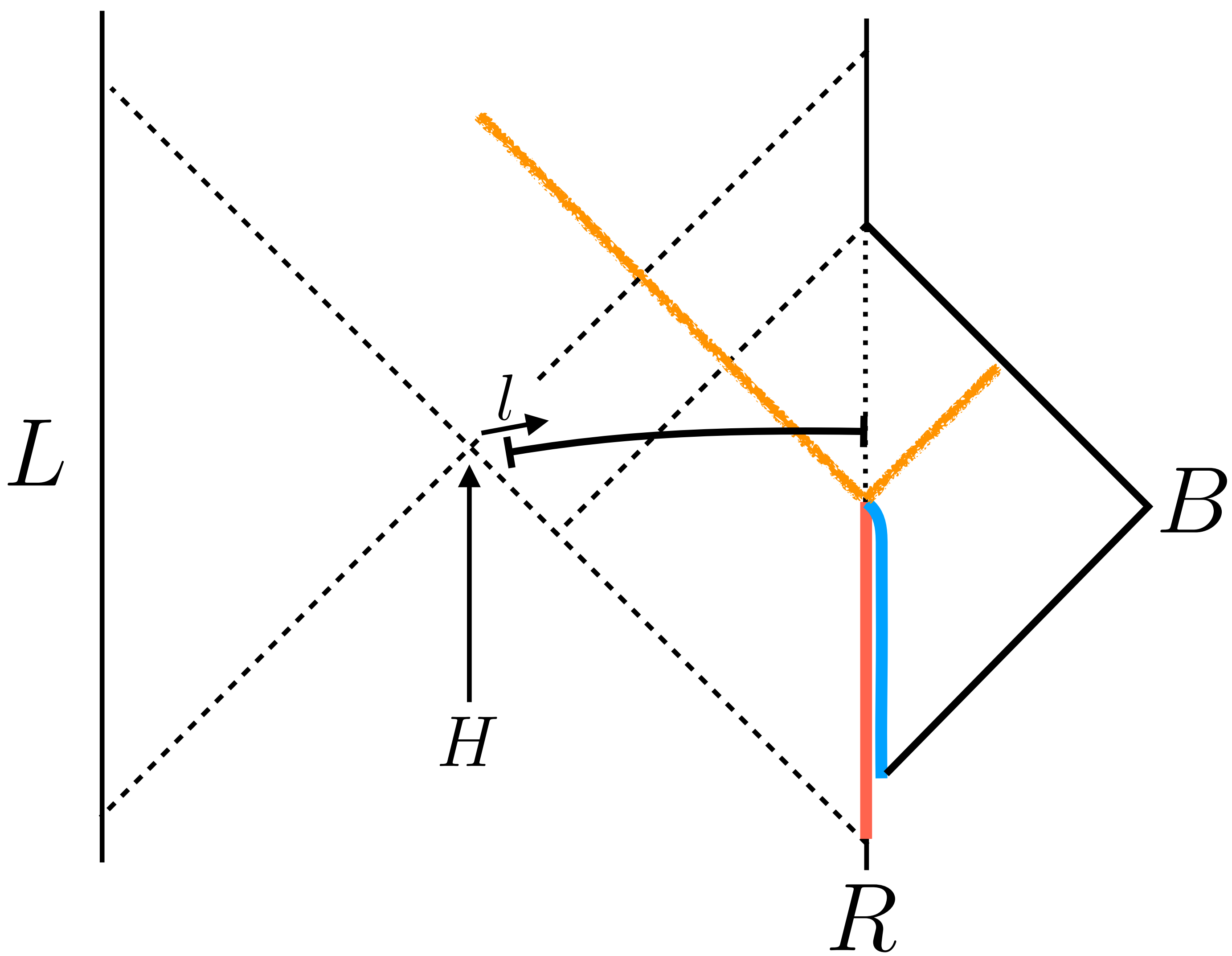

Early Time Branch

Bifurcation surface is *classically* extremal but not *quantum* extremal

$$\delta \frac{\phi}{4G_N} \sim \frac{l^2}{G_N}$$

$$\delta S_{\text{Bulk}} \sim cl$$

There is QES near the horizon at a distance

$$l \sim cG_N$$

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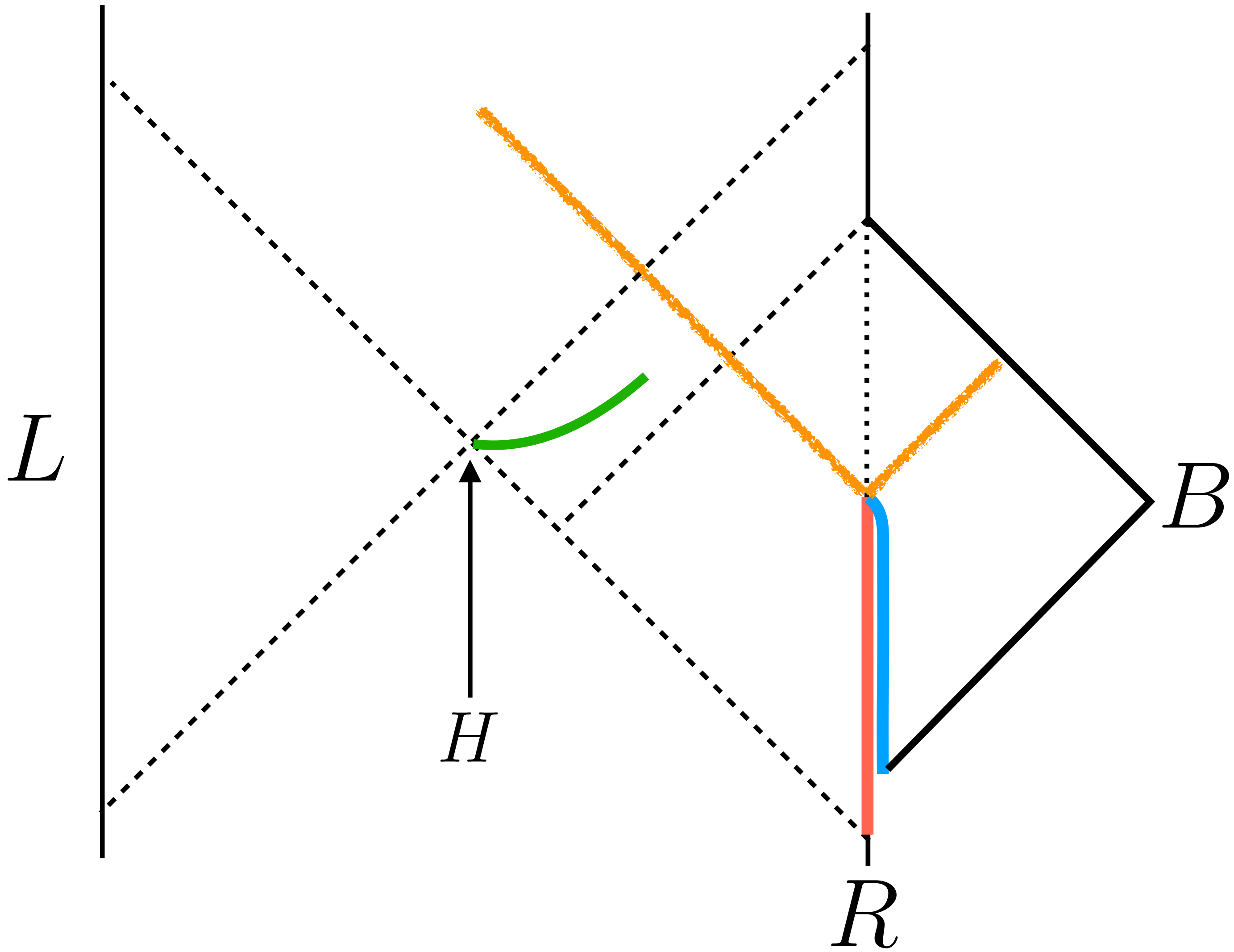

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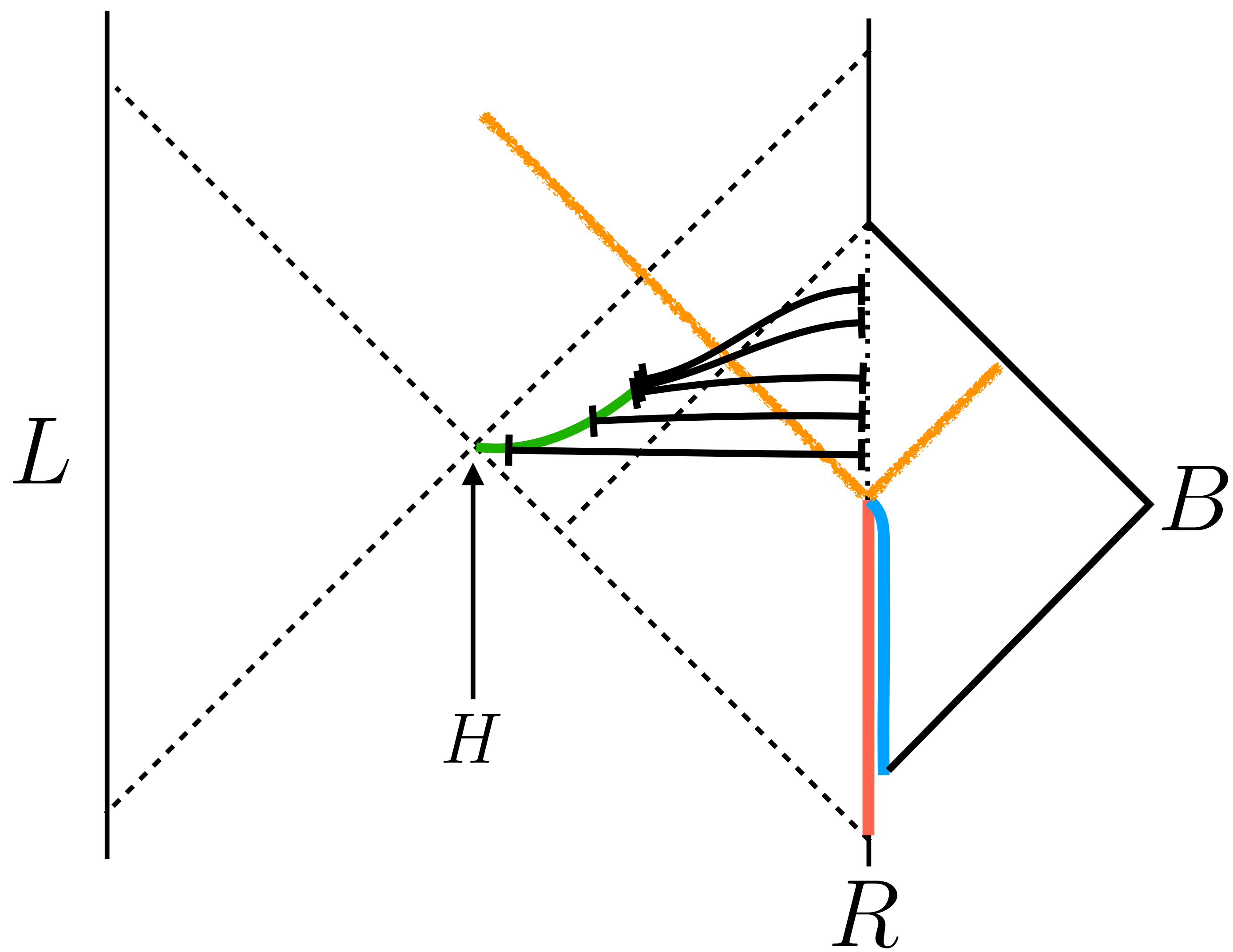

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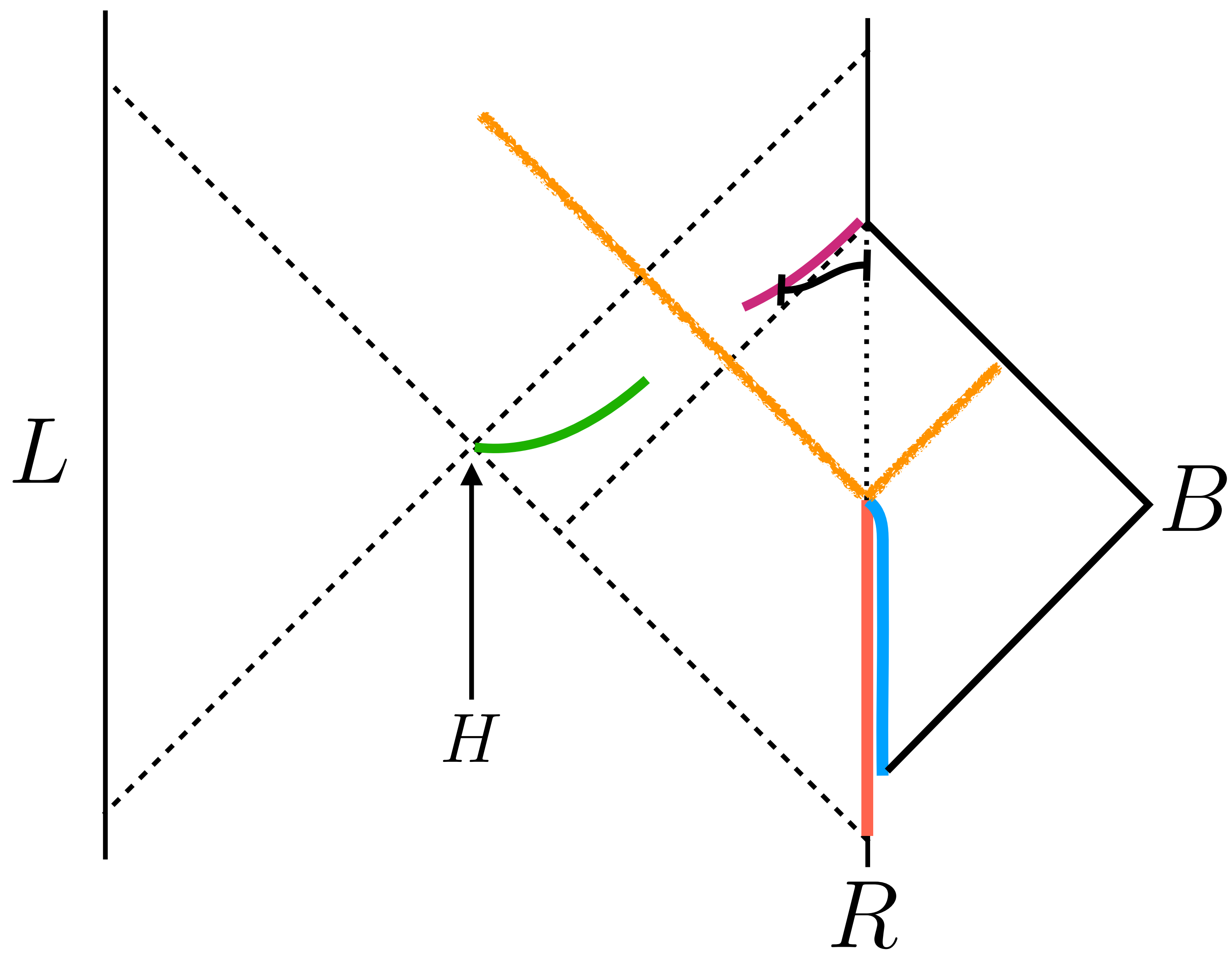


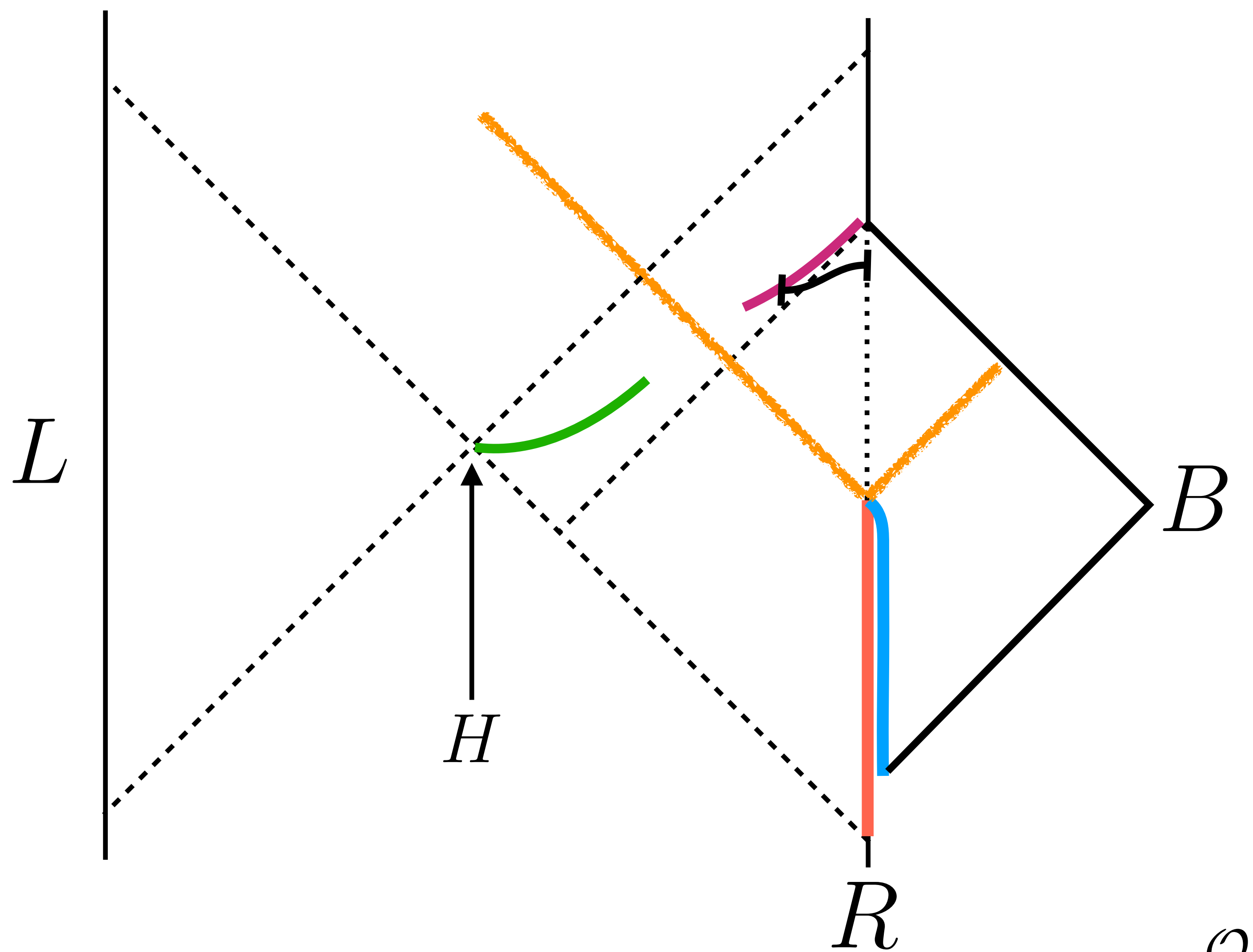
Late Time Branch

Outgoing:

$$\partial_- S_{Gen} = \frac{1}{4G_N}\partial_-\phi + \partial_- S_{\text{Bulk}} = 0$$

Search near the apparent horizon

Finding the Quantum Extremal Surfaces



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<u>Outgoing</u>:

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Search near the apparent horizon

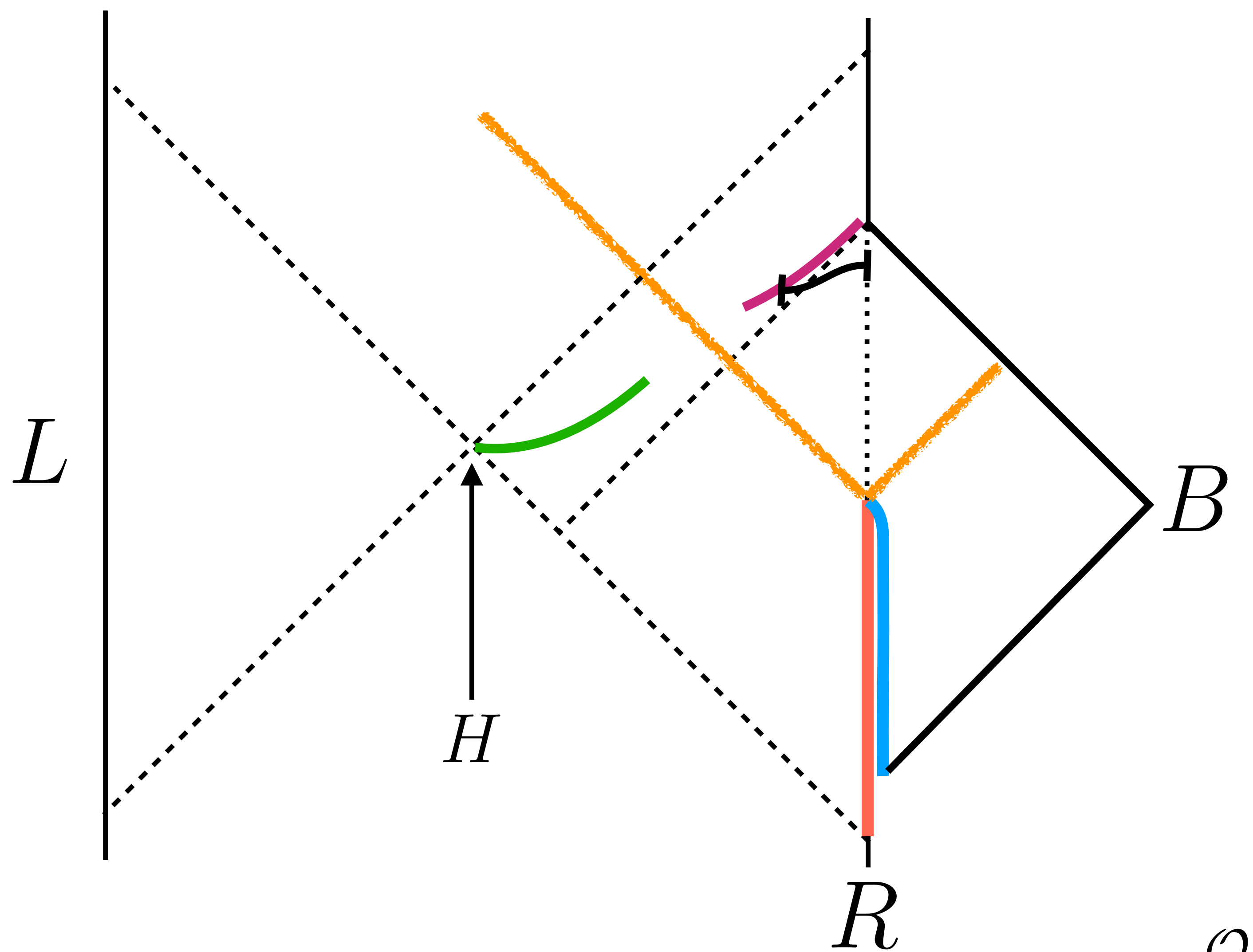
<u>Ingoing</u>:

$$\partial_+ S_{Gen} = \frac{1}{4G_N}\partial_+\phi + \partial_+ S_{\text{Bulk}} = 0$$

$\mathcal{O}(1) < 0$

Must be compensated by large

Finding the Quantum Extremal Surfaces



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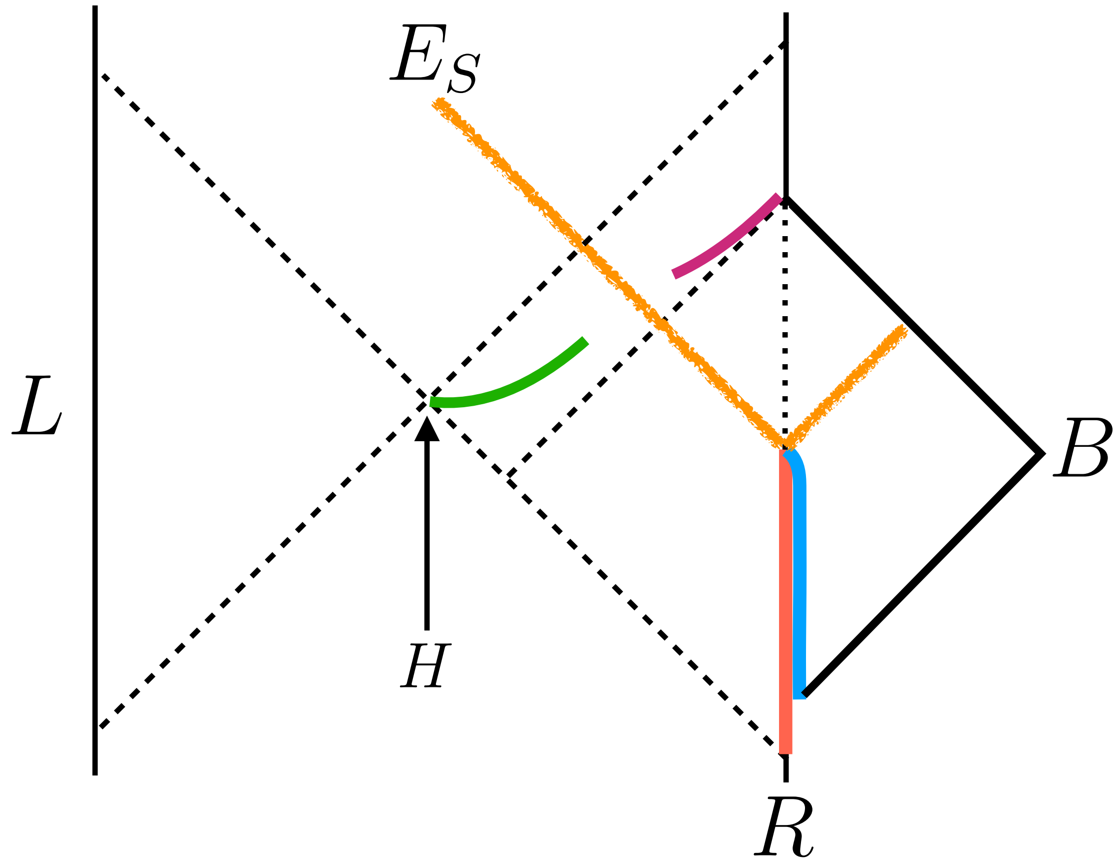
$\mathcal{O}(1) < 0$

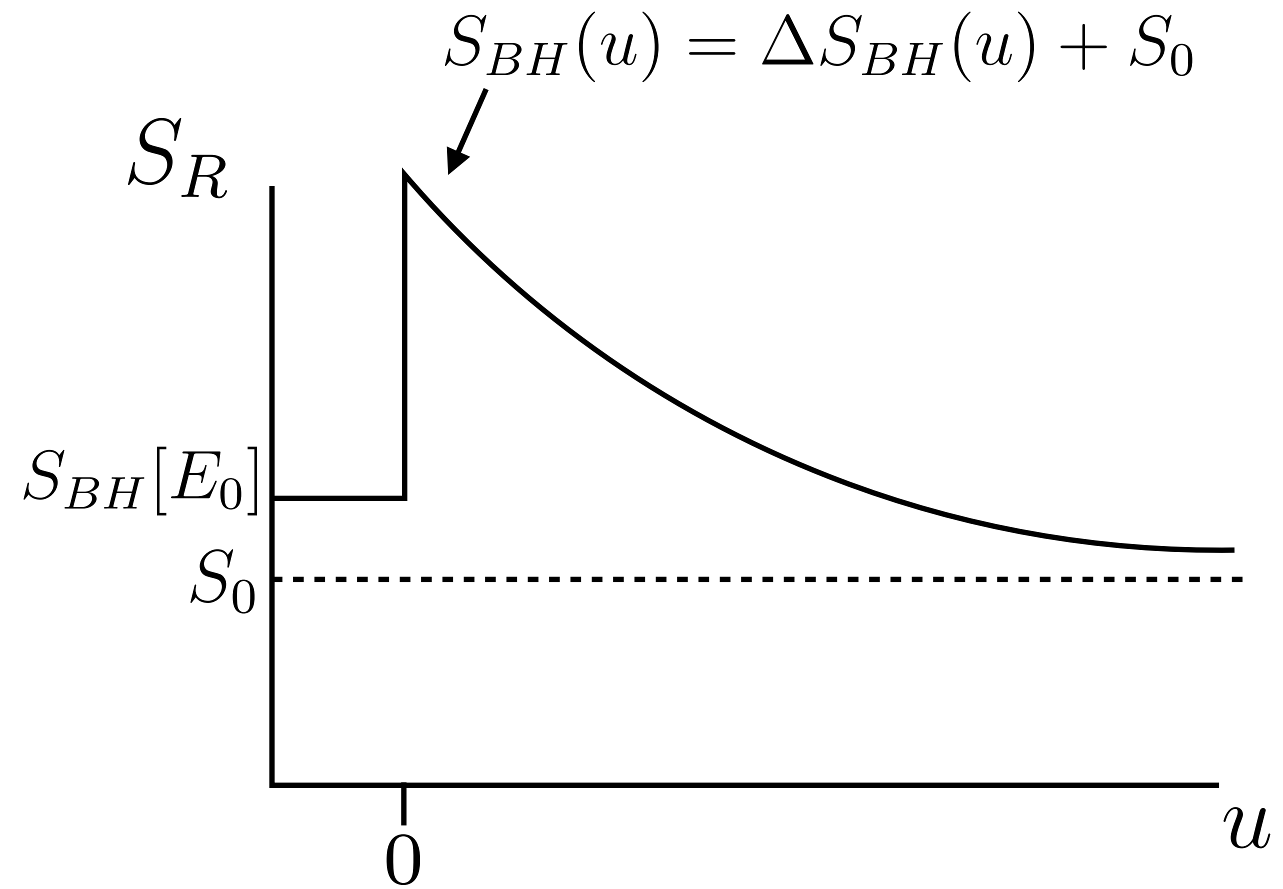
Must be compensated by large

Entropy (roughly): $S_{\text{Bulk}} \sim c \log[\text{Length}]$

Achieved in the null interval limit: $\partial_+ S_{\text{Bulk}} \sim \frac{c}{\text{Length}} \implies \text{Length} \sim cG_N$

Evolution of the Entropy





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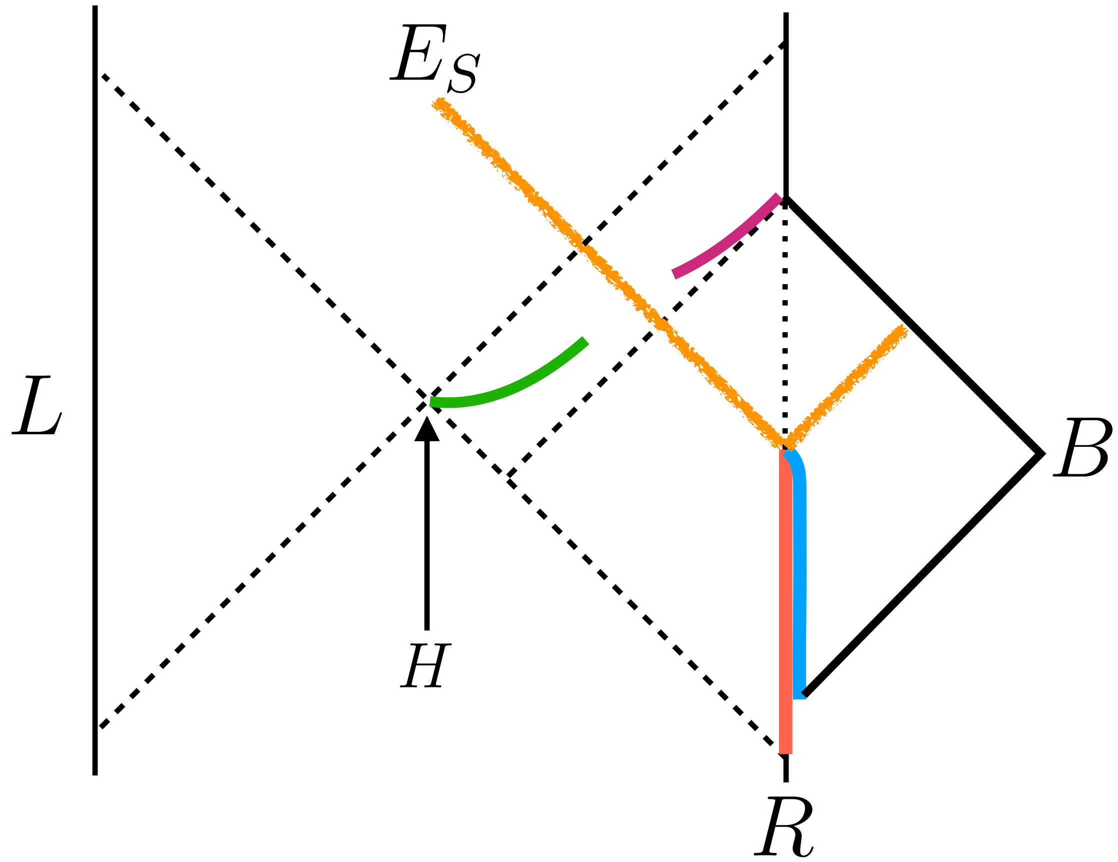
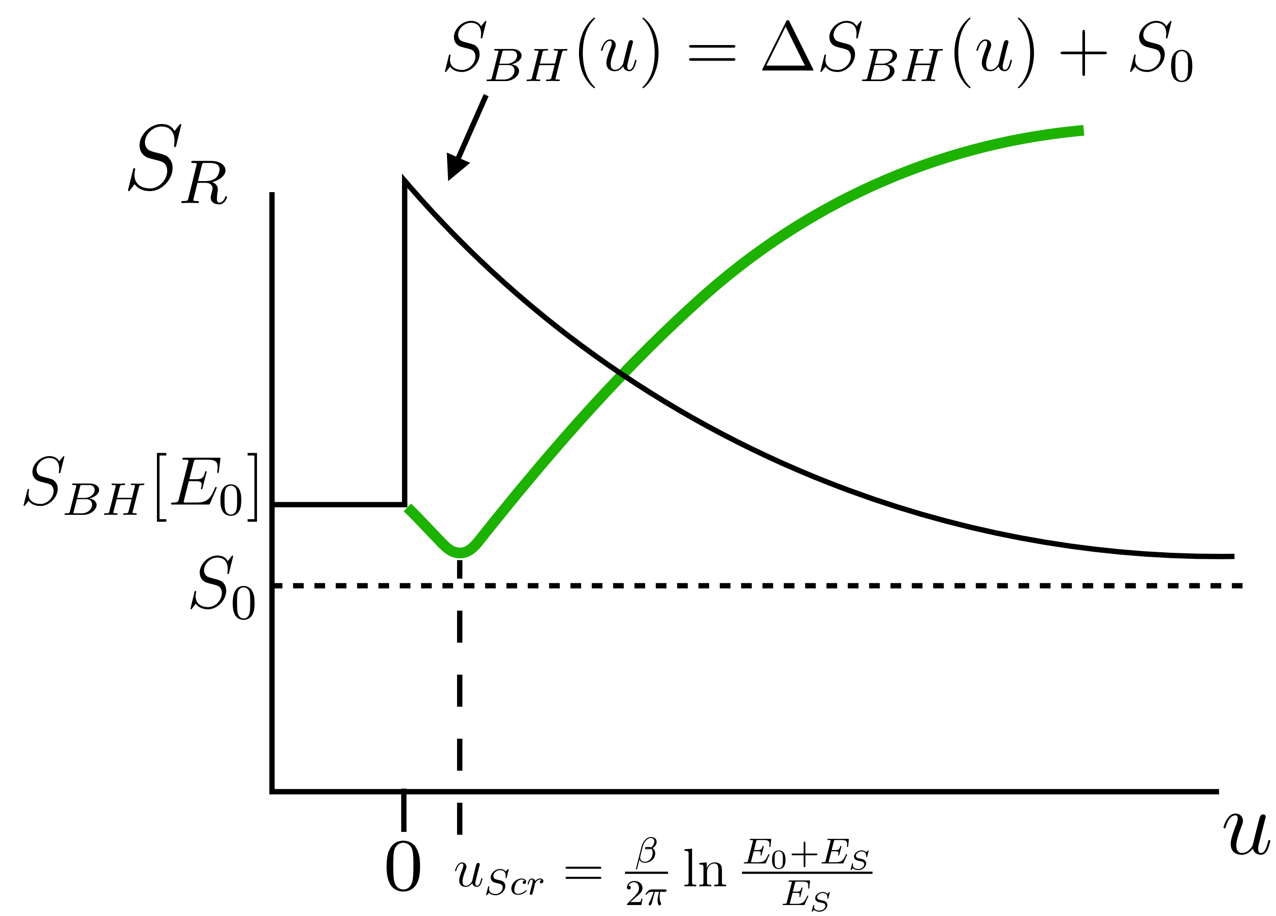


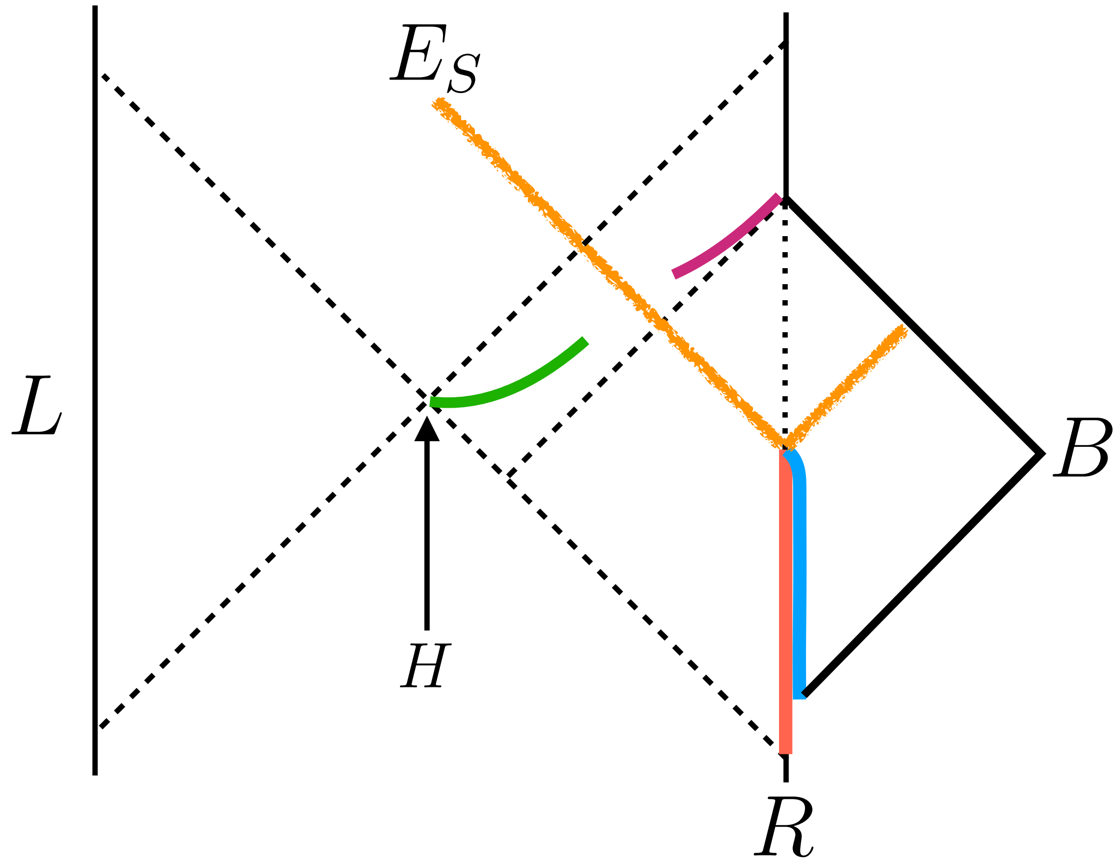


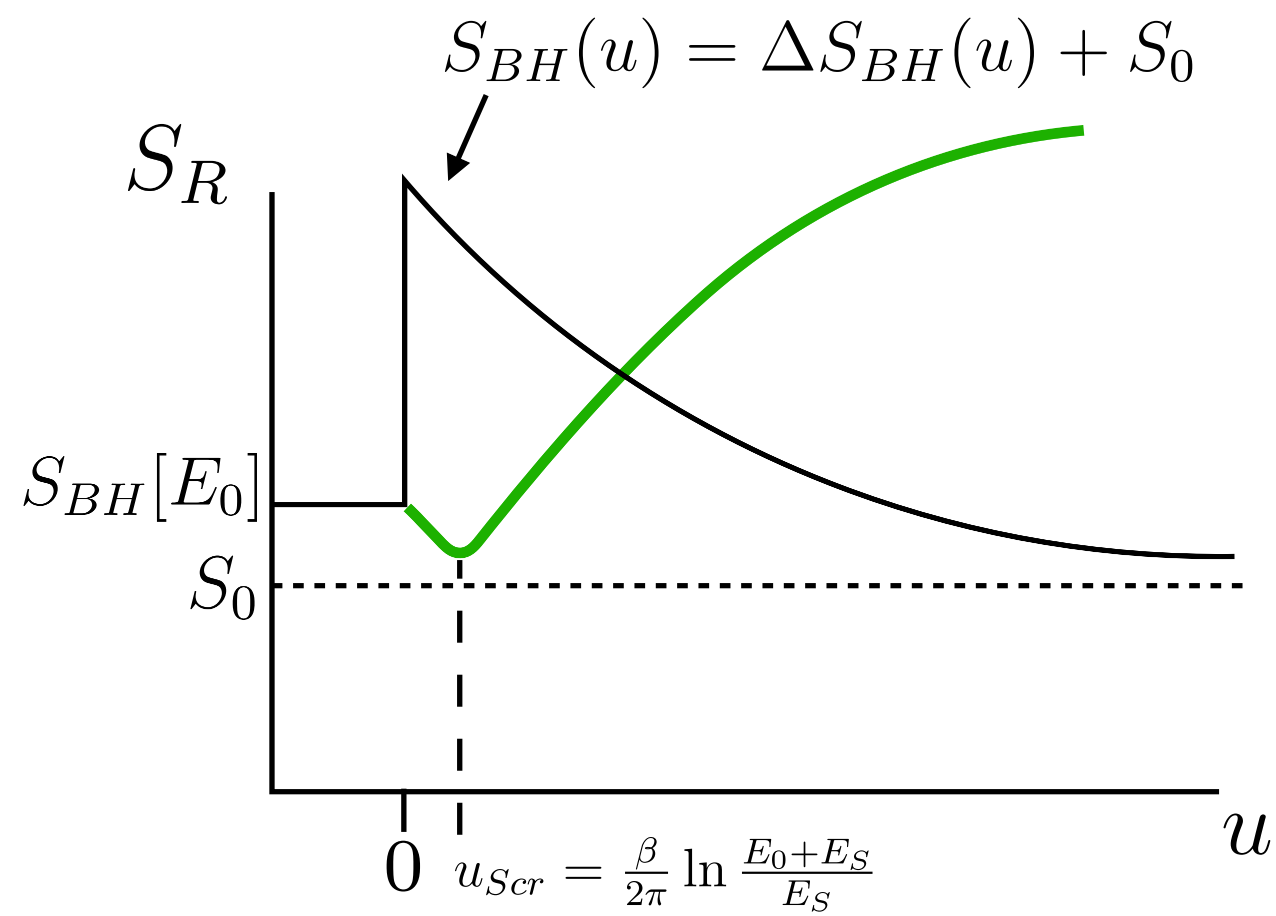
Early time branch: QES near original bifurcate horizon

$$S^R_{Gen} \approx \frac{\phi_0}{4G_N} + \frac{\phi(H)}{4G_N} + S_{\text{Bulk}}(u)$$

where $S_{\text{Bulk}} \xrightarrow{\text{Late}} 2\Delta S_{BH}[E_0 + E_S] \times (1 - e^{-cG_N u/2})$

Evolution of the Entropy





Leichenauer

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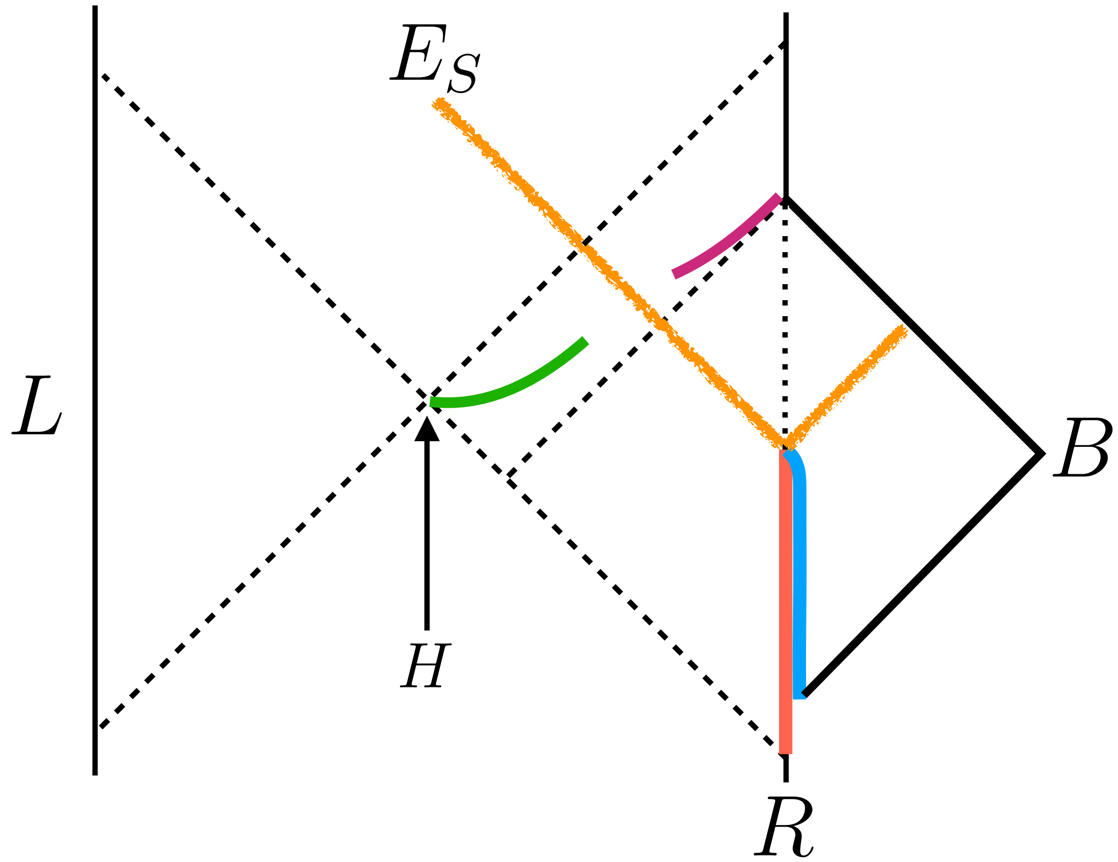

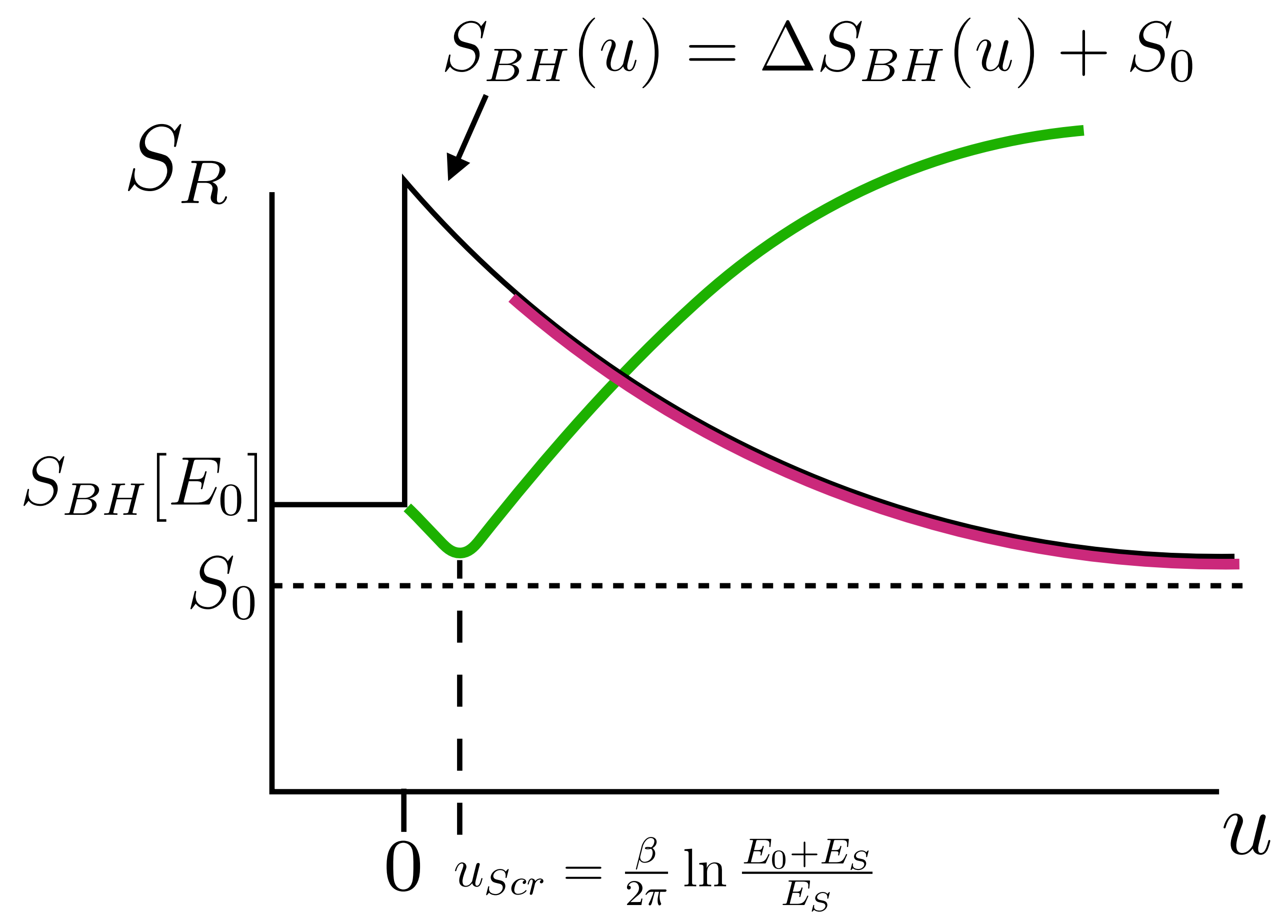

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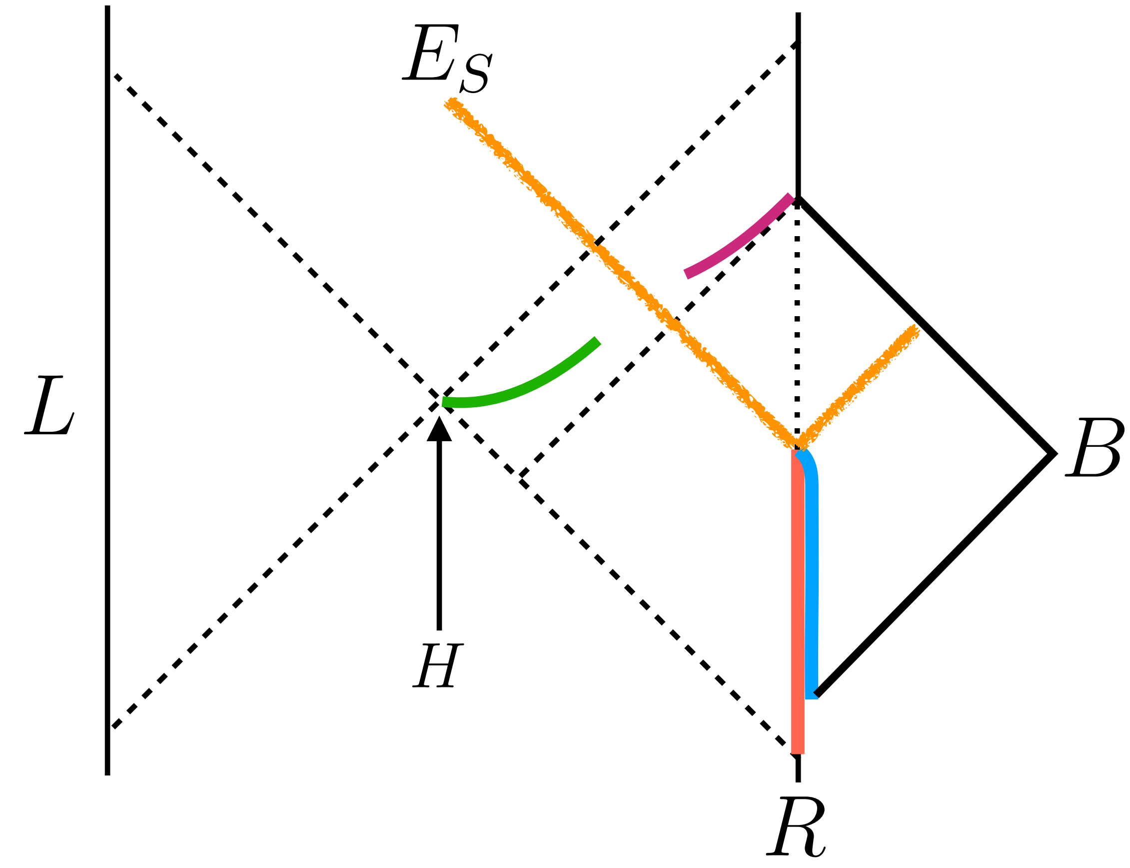
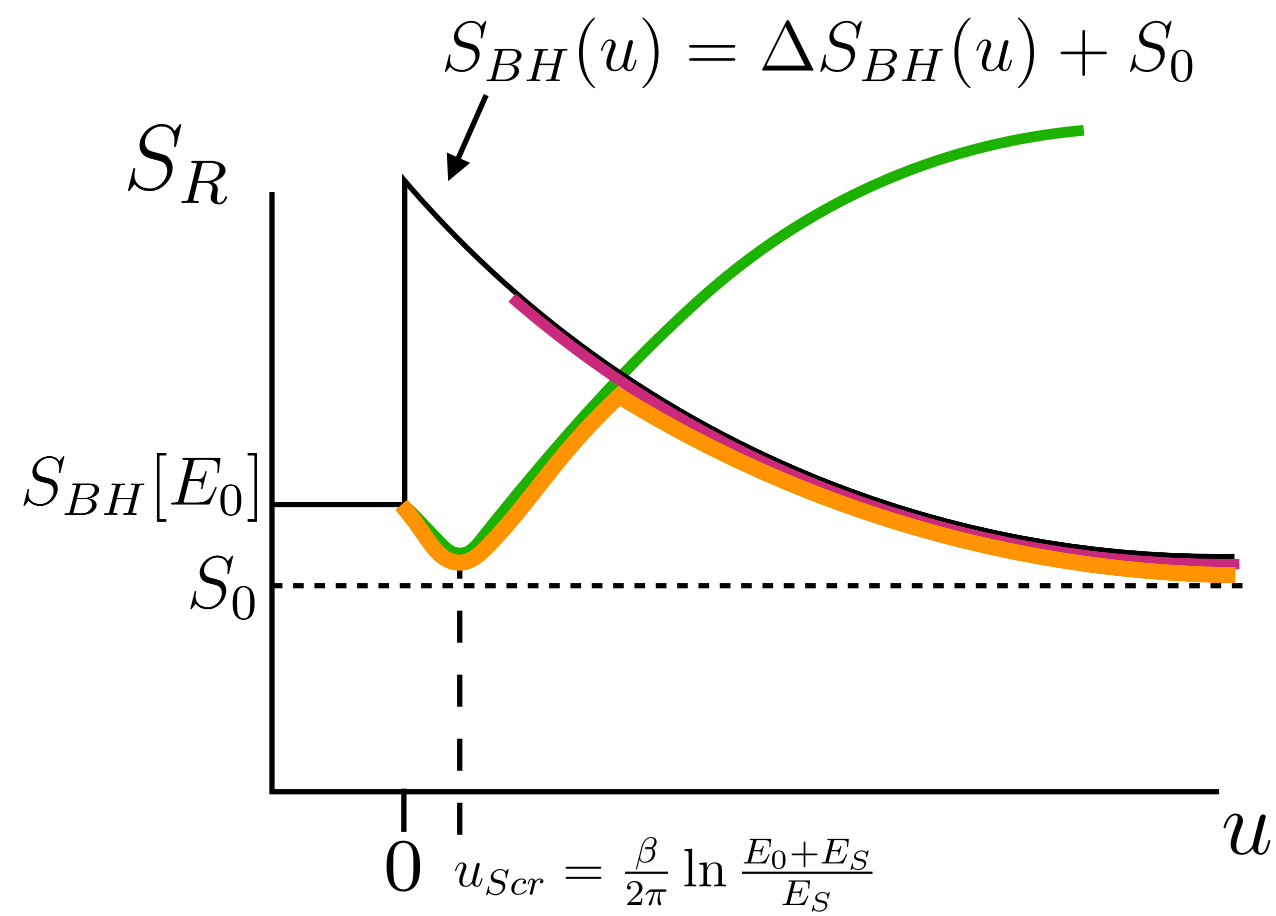
Late time branch: QES near the apparent horizon

$$S^R_{Gen} \approx S_{BH}[E_{ADM}(u)] - c \ln cG_N$$

$$\approx S_{BH}[E_0 + E_S] e^{-cG_N u/2} - c \ln cG_N$$

Evolution of the Entropy





Leichenauer

$S_R(u) = \text{Min}$

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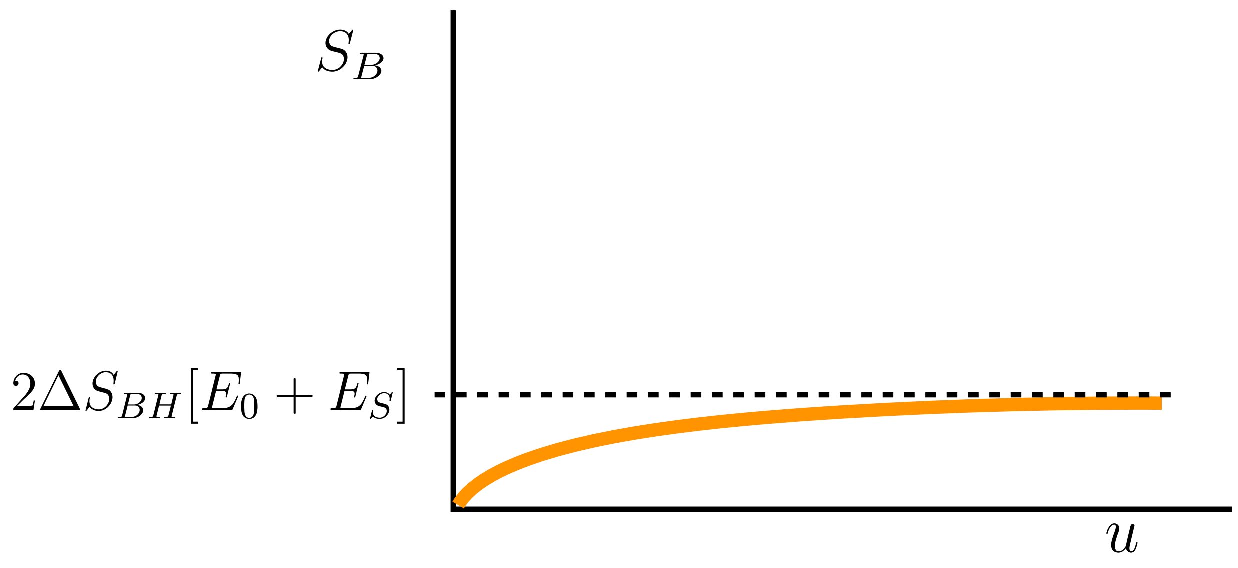
Does this resolve the Information Paradox?

What about the entropy of the bath?



The Araki-Lieb inequality provides an upper bound on the bath entropy:

$$S_L = S_{RB} \geq |S_R - S_B| \implies S_B \leq S_L + S_R$$

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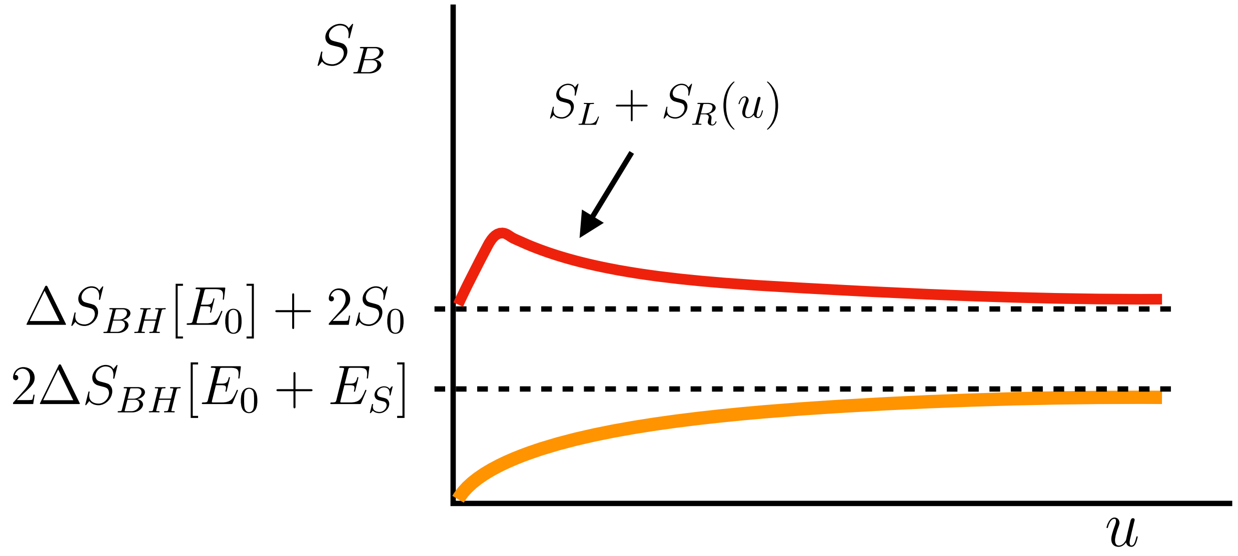

Not a problem when S_0 is large!

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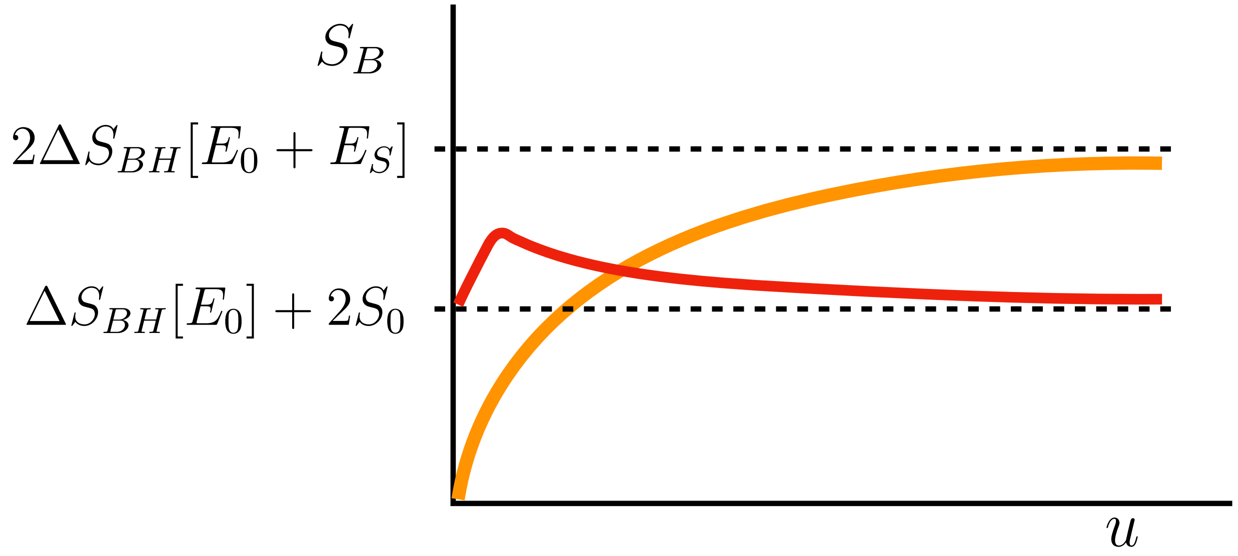
Does this resolve the Information Paradox?

What about the entropy of the bath?

Increase E_S !



Araki-Lieb is violated!
Information Loss!!

The Araki-Lieb inequality provides an upper bound on the bath entropy:

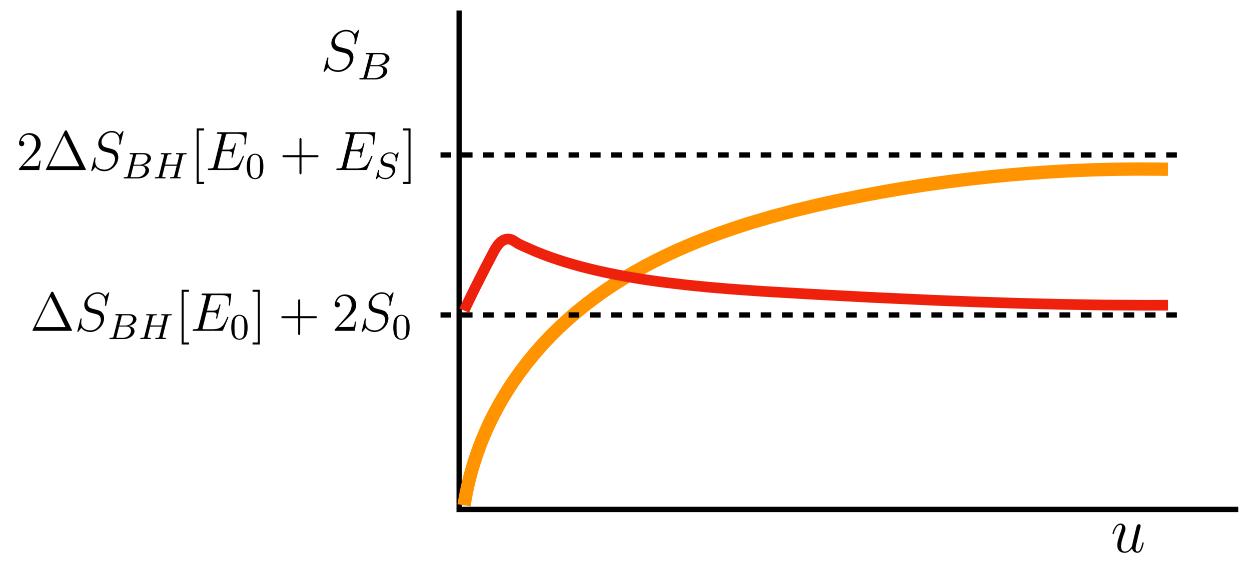
$$S_L = S_{RB} \geq |S_R - S_B| \implies S_B \leq S_L + S_R$$

We didn't find a Page curve for the bath! This is the standard Hawking result…
This does not resolve the information paradox!

Does this resolve the Information Paradox?

What about the entropy of the bath?

Increase E_S !



Araki-Lieb is violated!
Information Loss!!

The Araki-Lieb inequality provides an upper bound on the bath entropy:

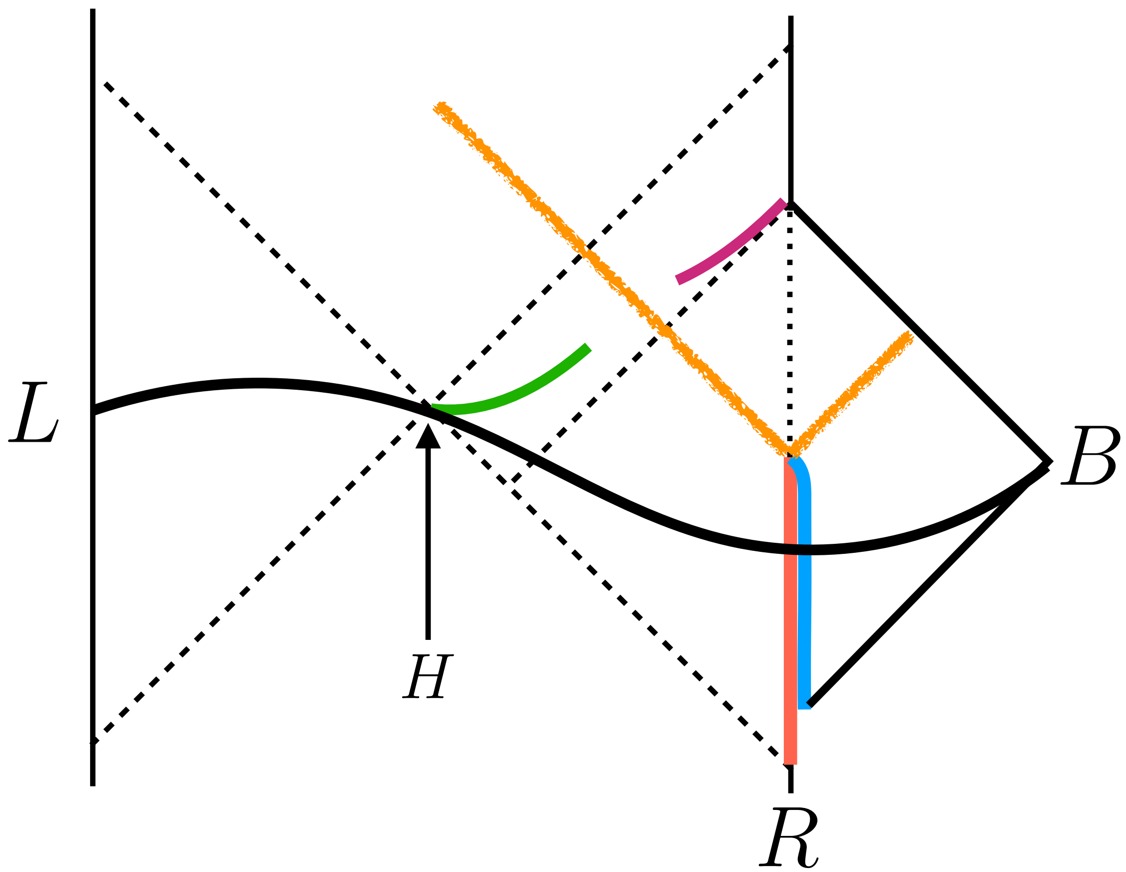
$$S_L = S_{RB} \geq |S_R - S_B| \implies S_B \leq S_L + S_R$$

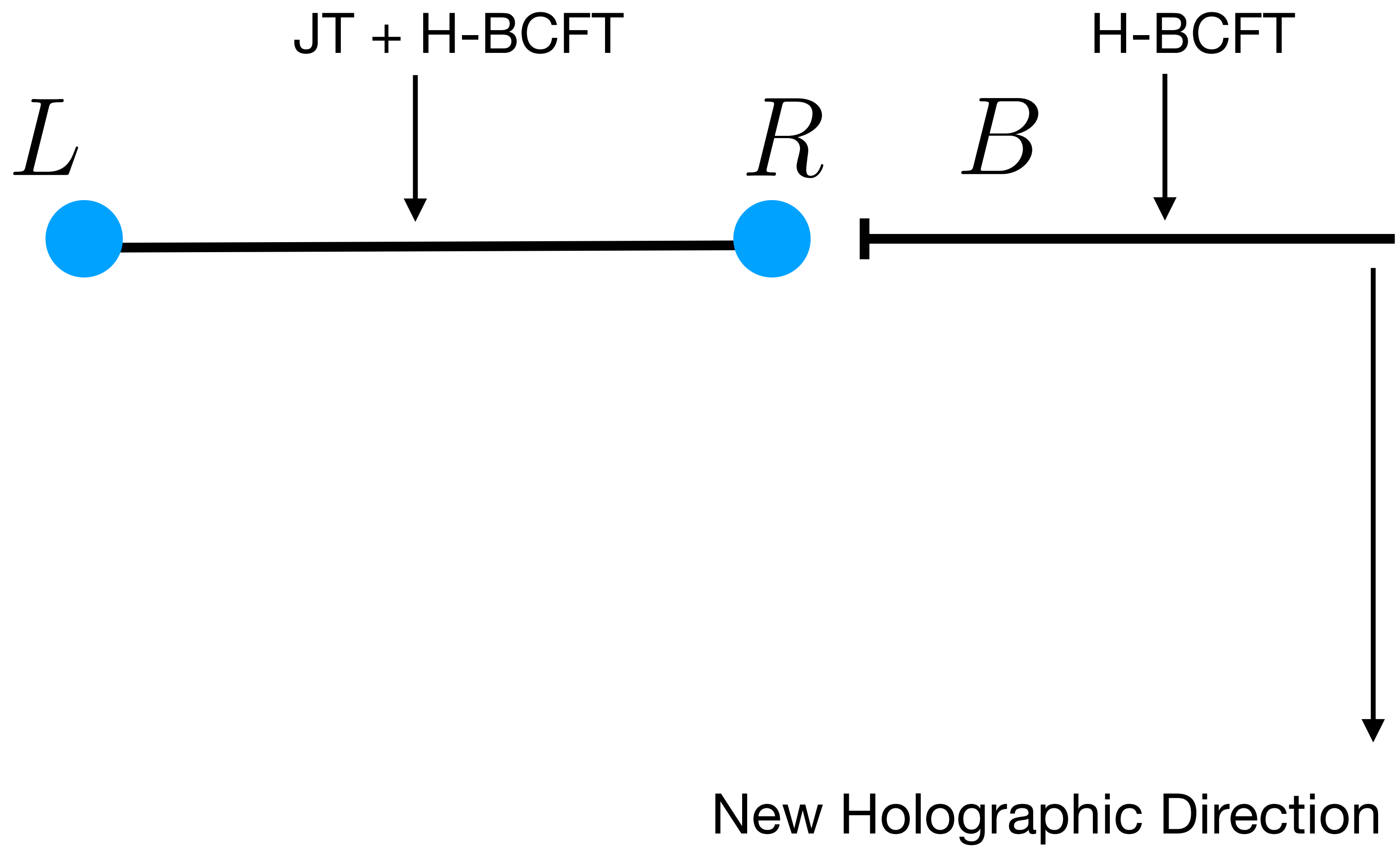
We didn't find a Page curve for the bath! This is the standard Hawking result…
This does not resolve the information paradox!

Ok, now let me tell you how to resolve it…

What if the bulk/bath BCFT was holographic?

The 1+1d system will be dual to a 2+1d bulk!





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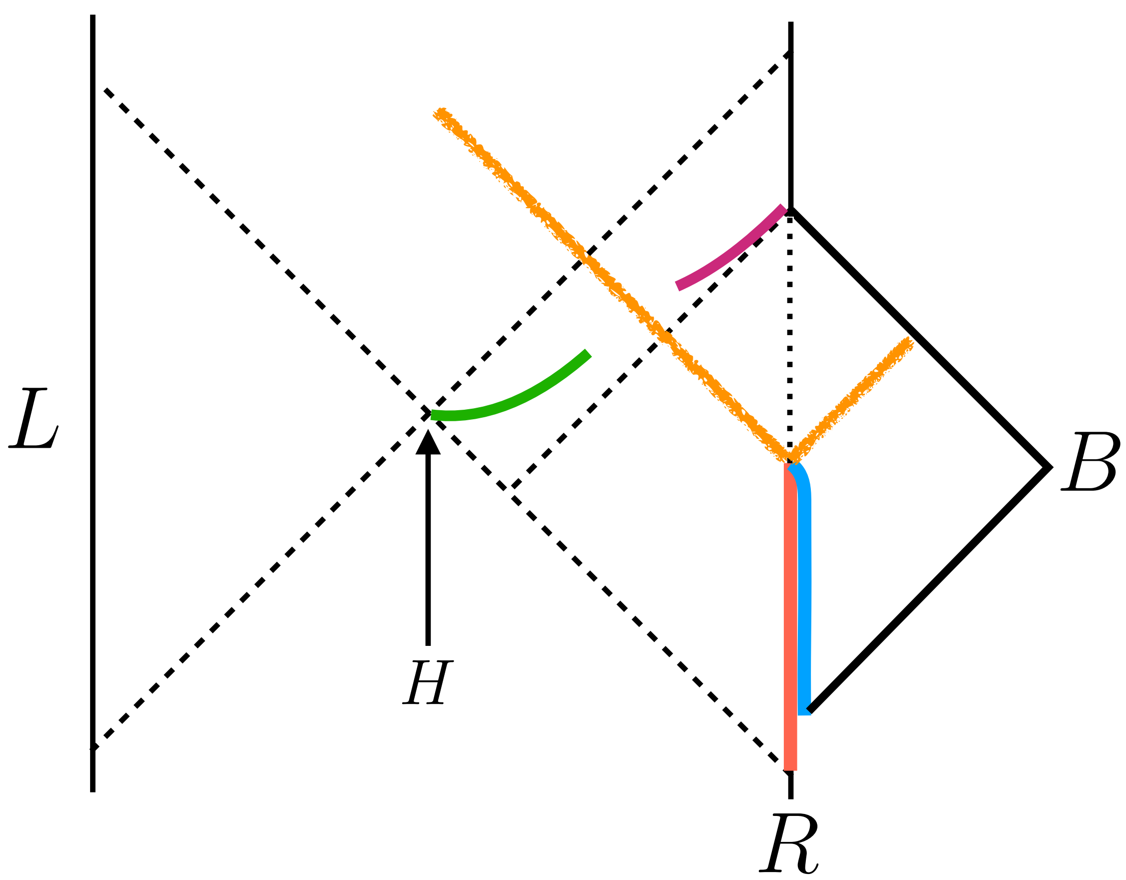

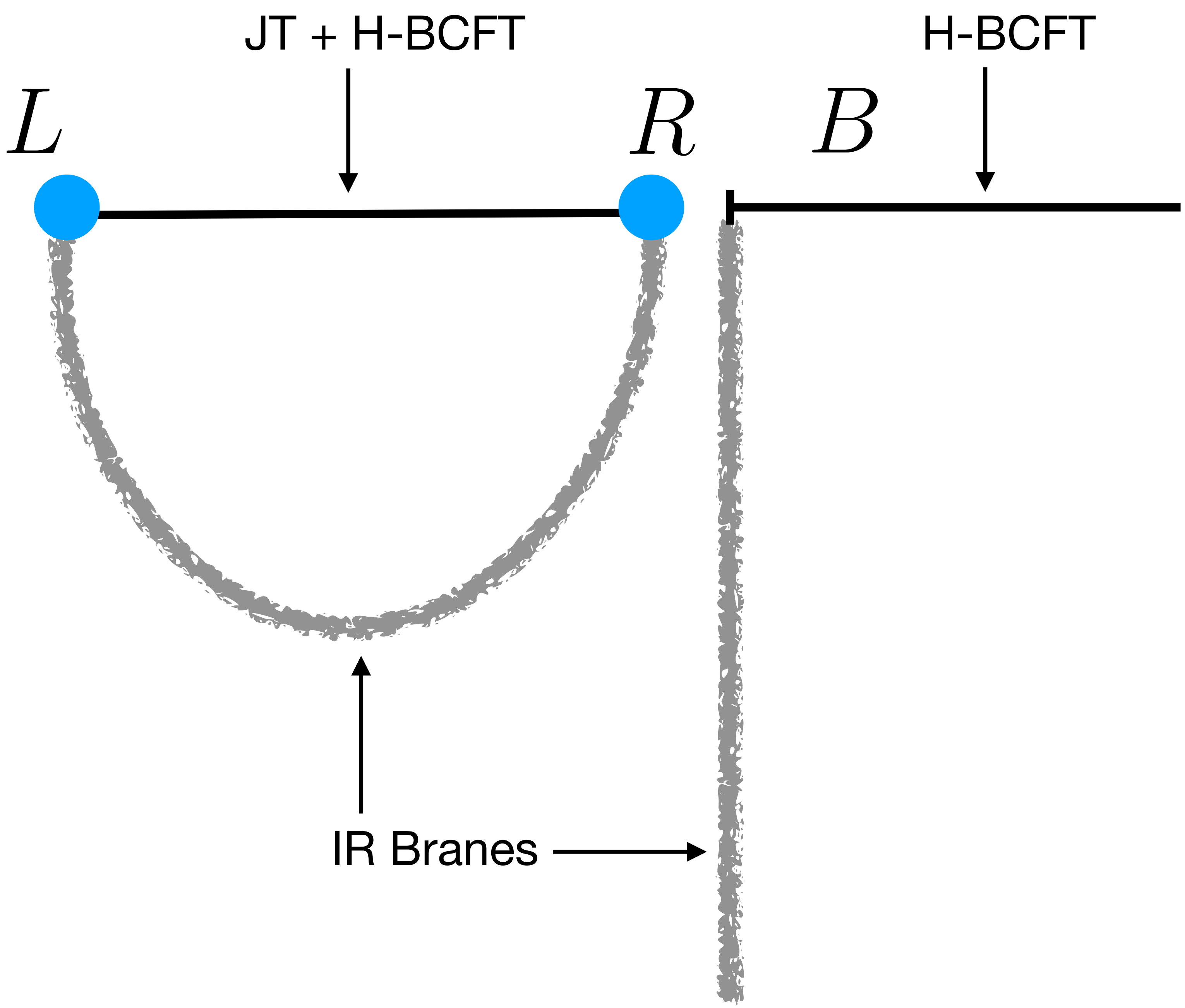

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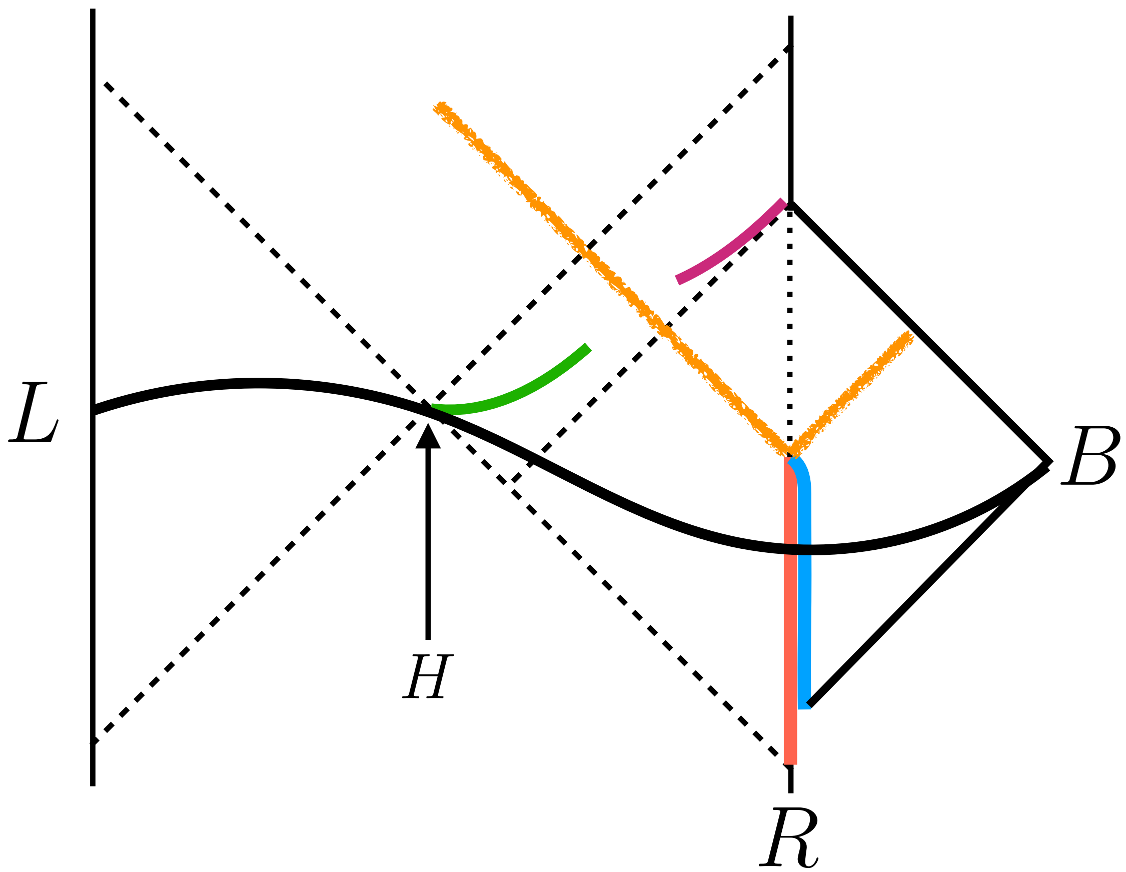
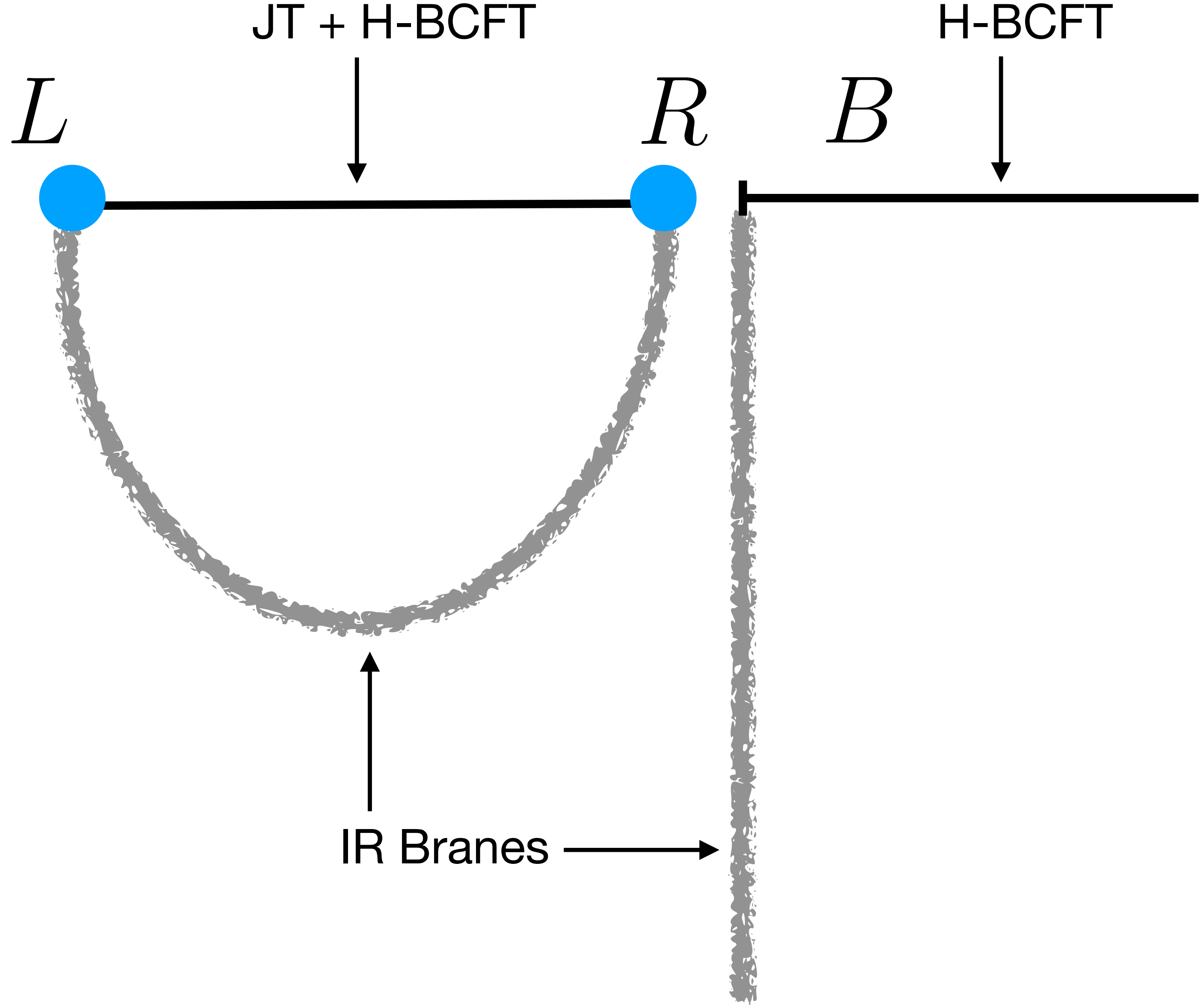
Fujita, Takayanagi, Tonni





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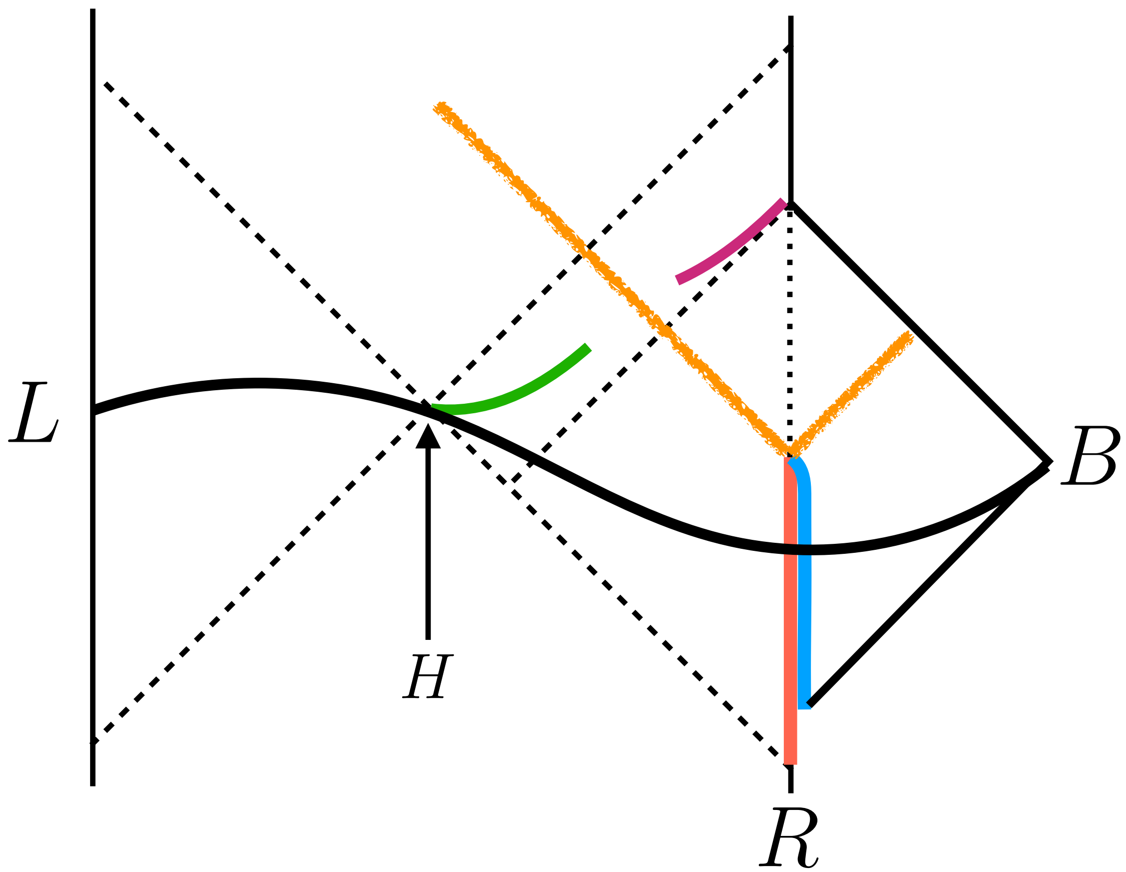

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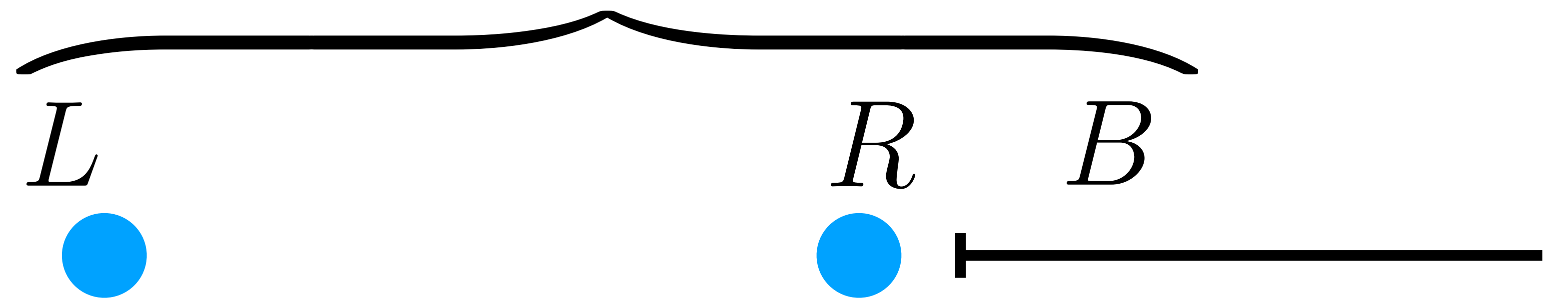

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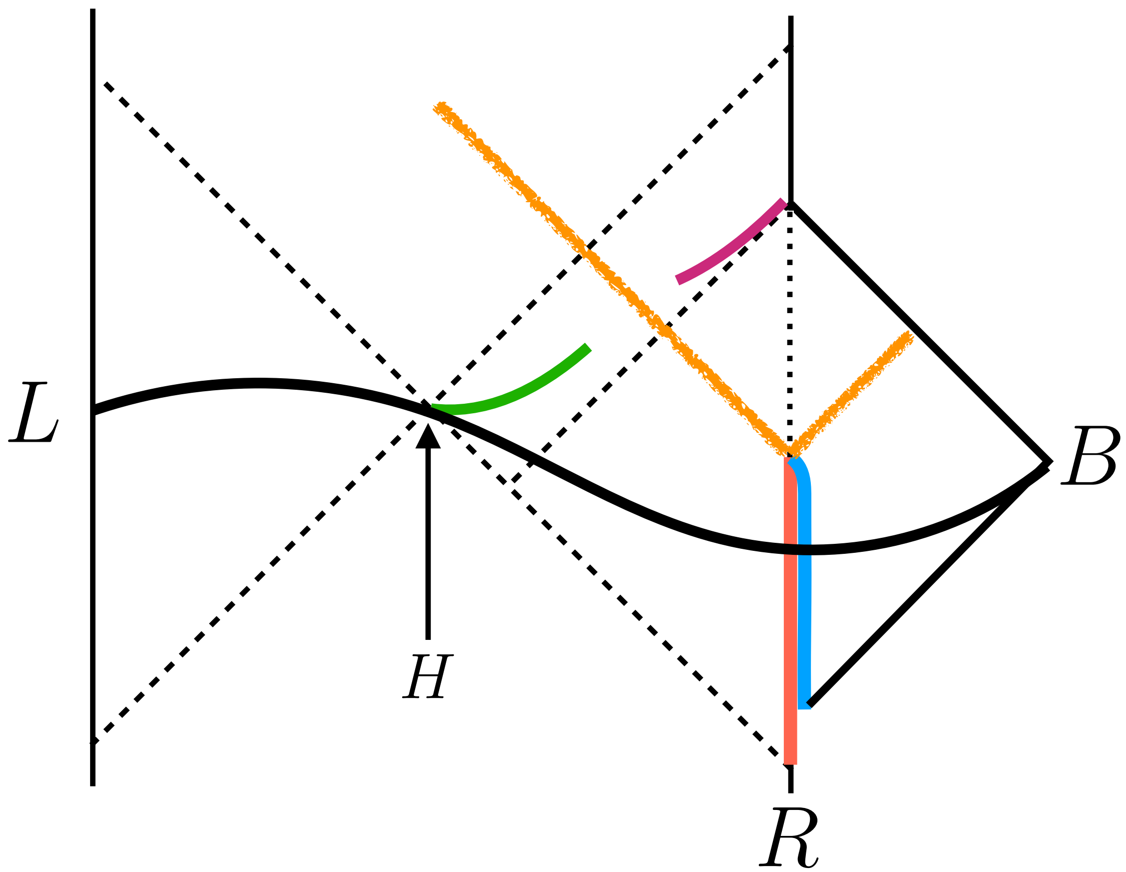

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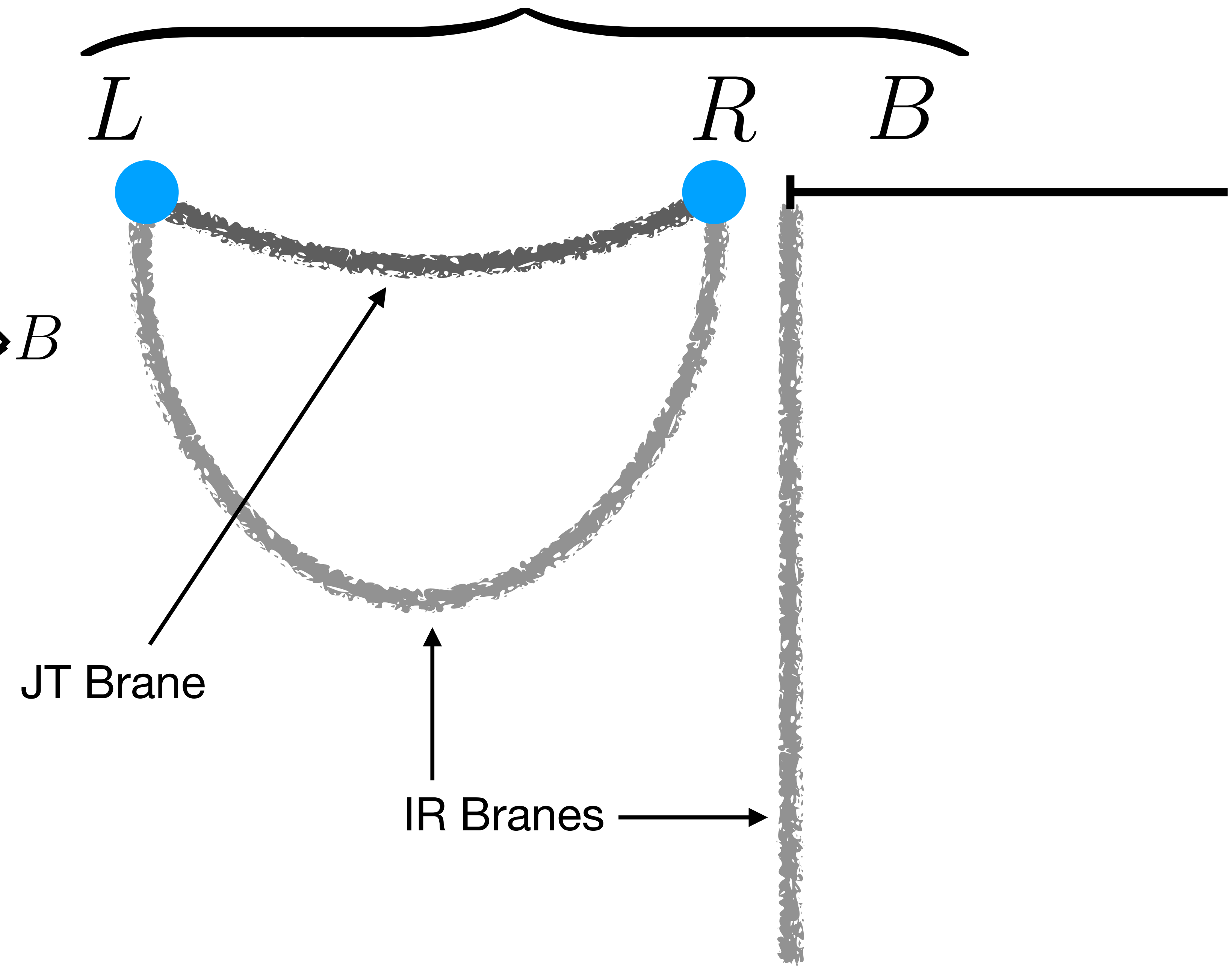

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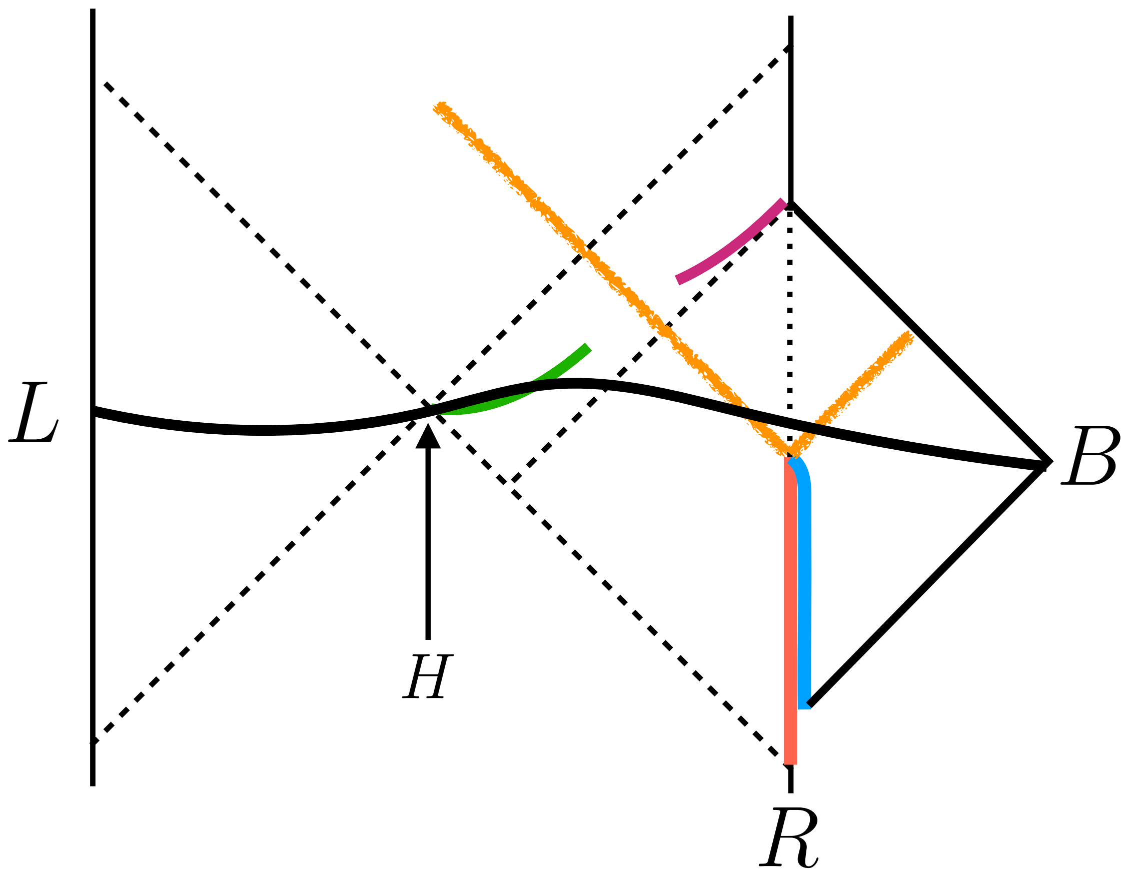
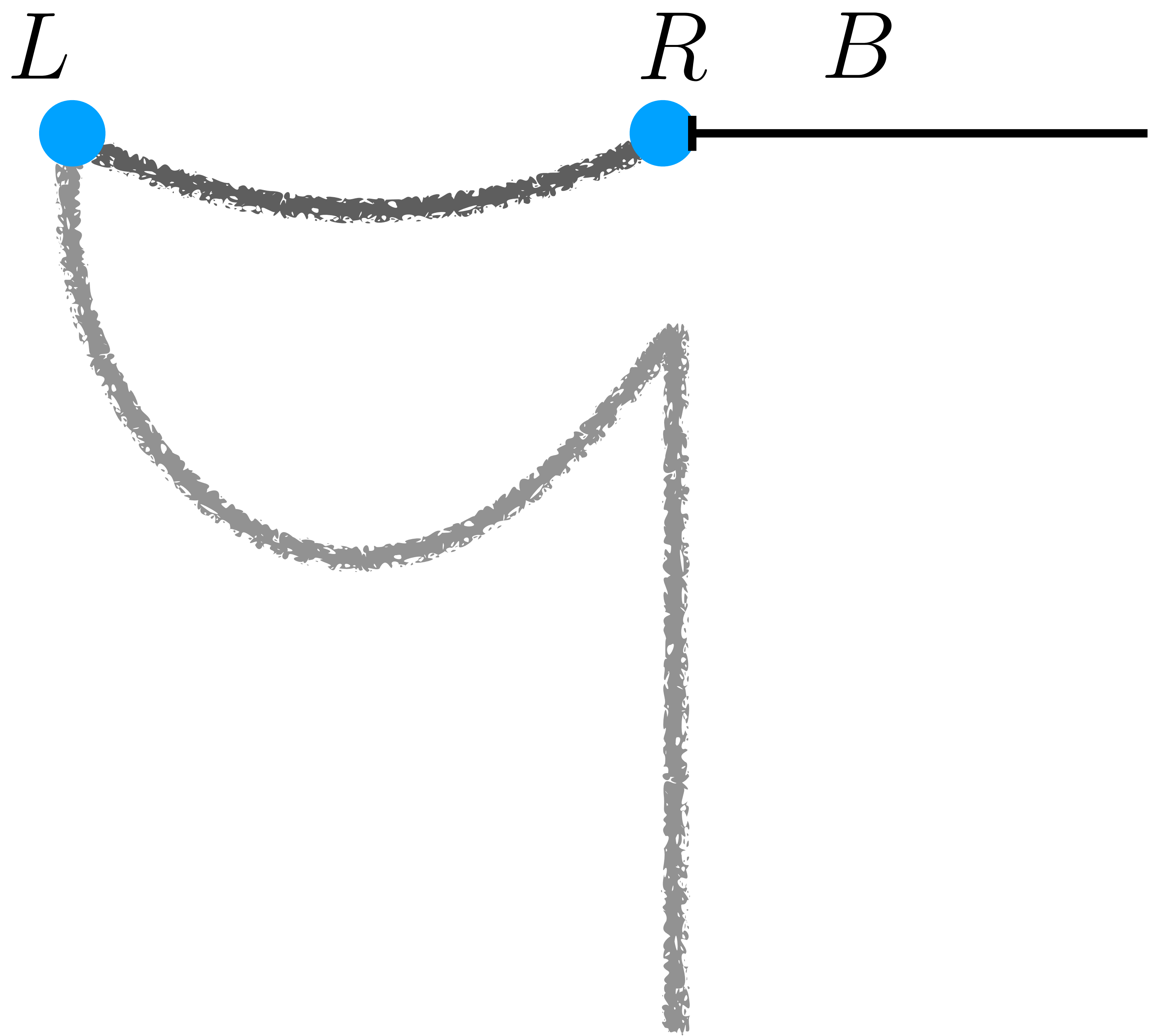
Entropy is given by the RT surface in 2+1d bulk





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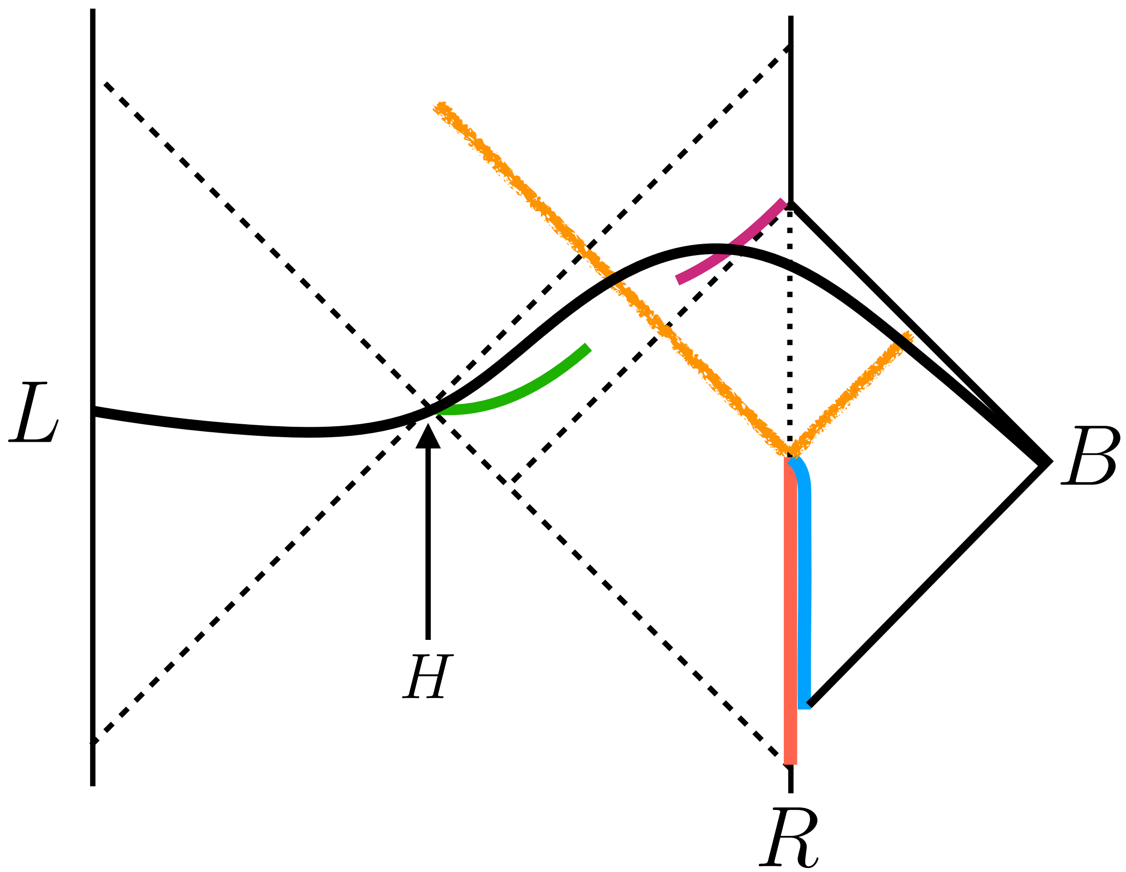

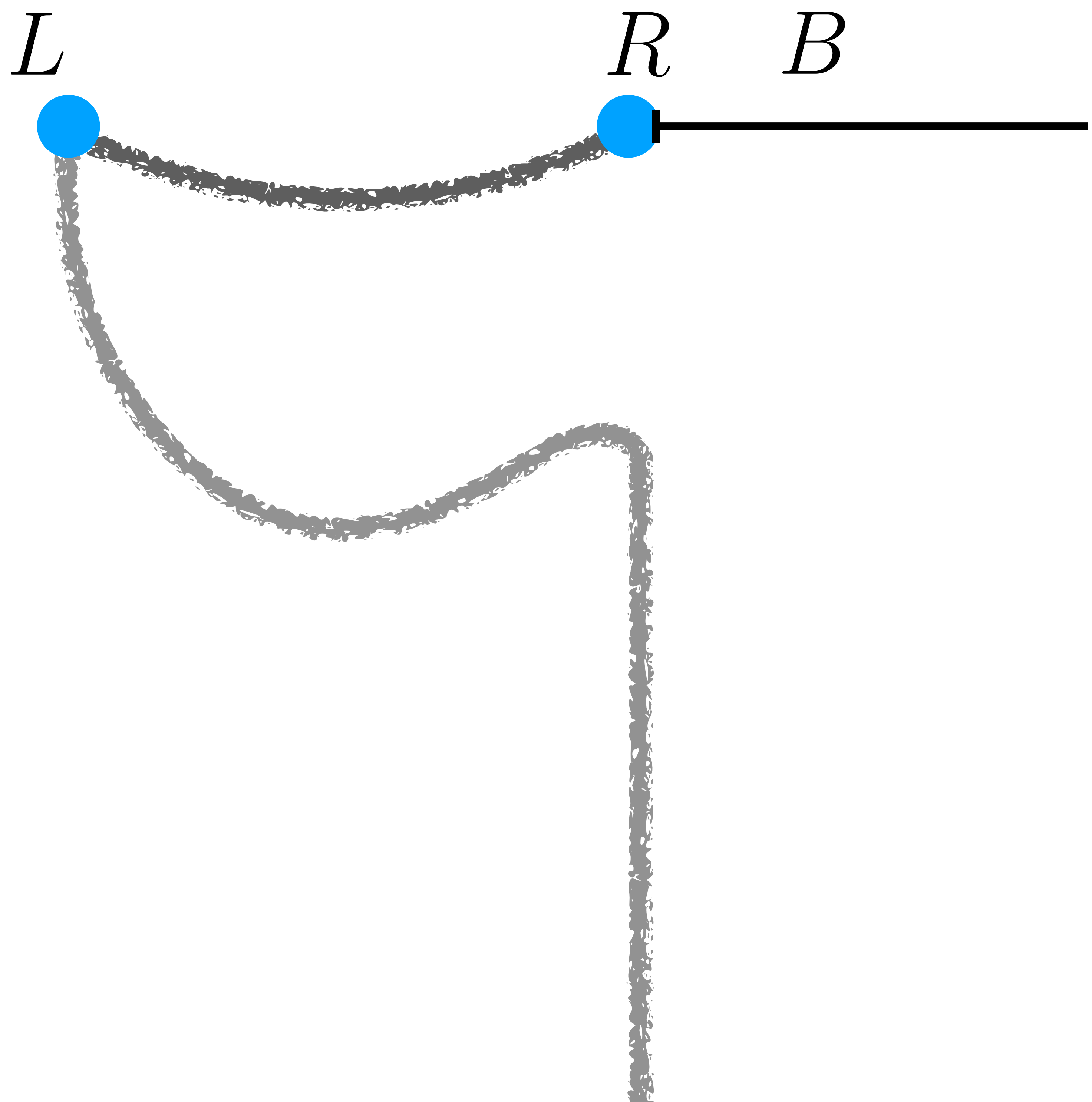

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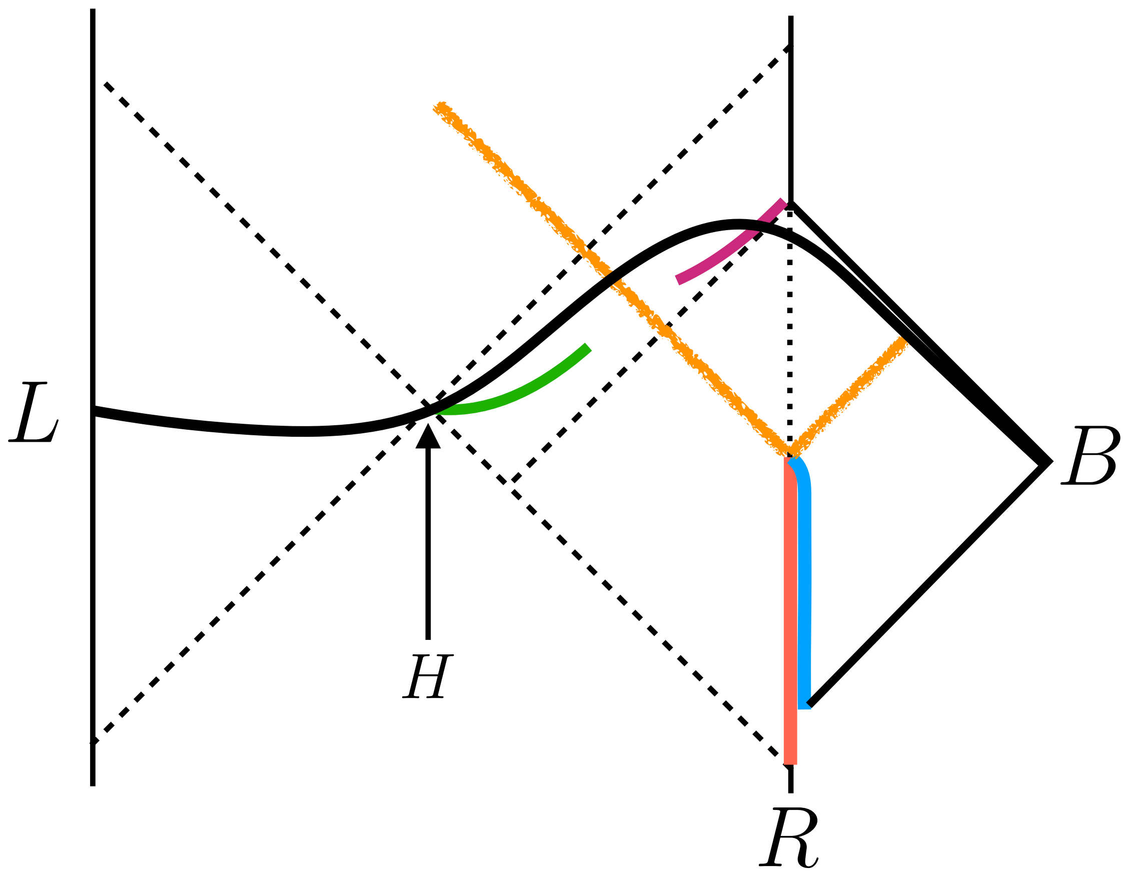

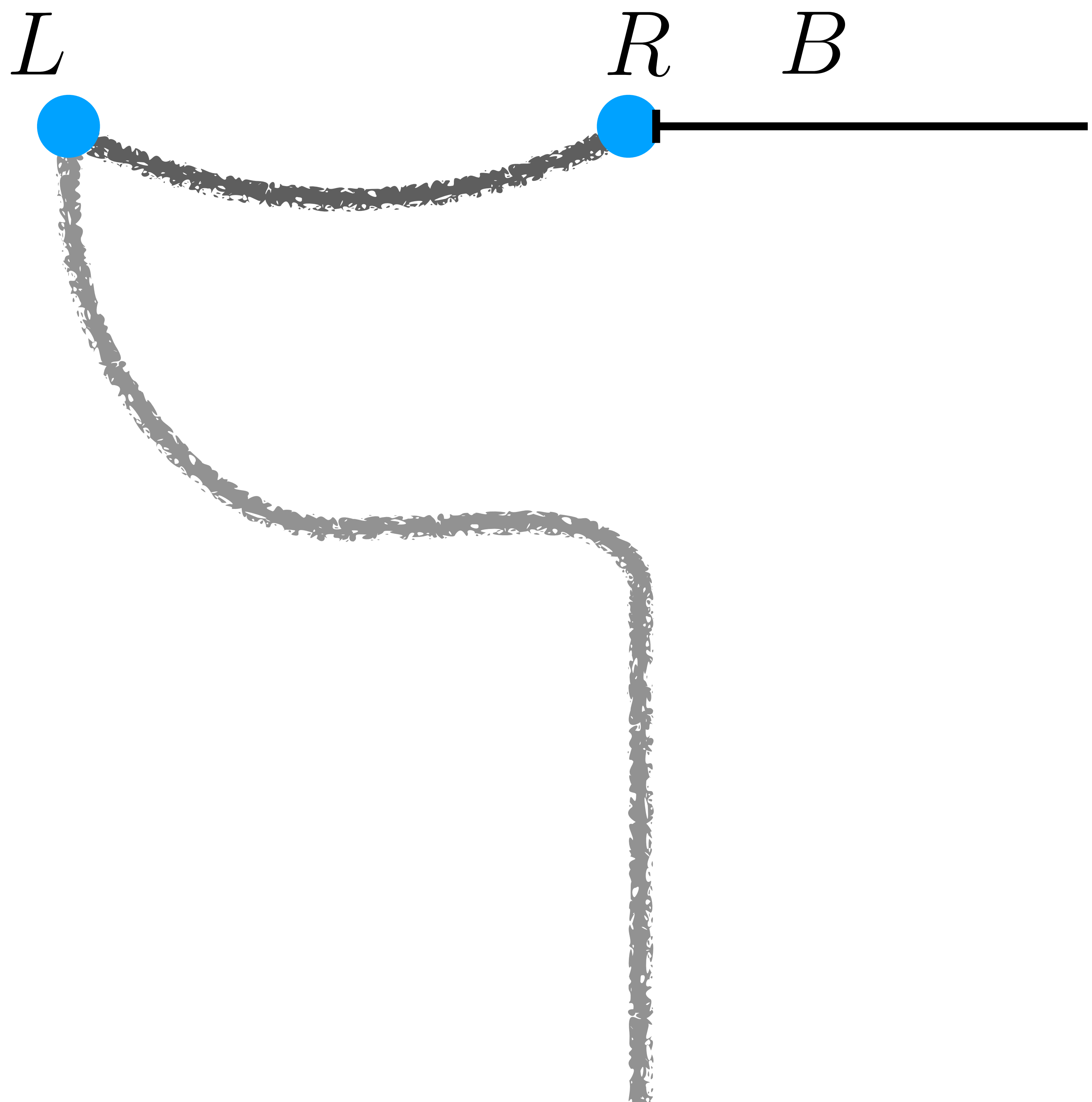

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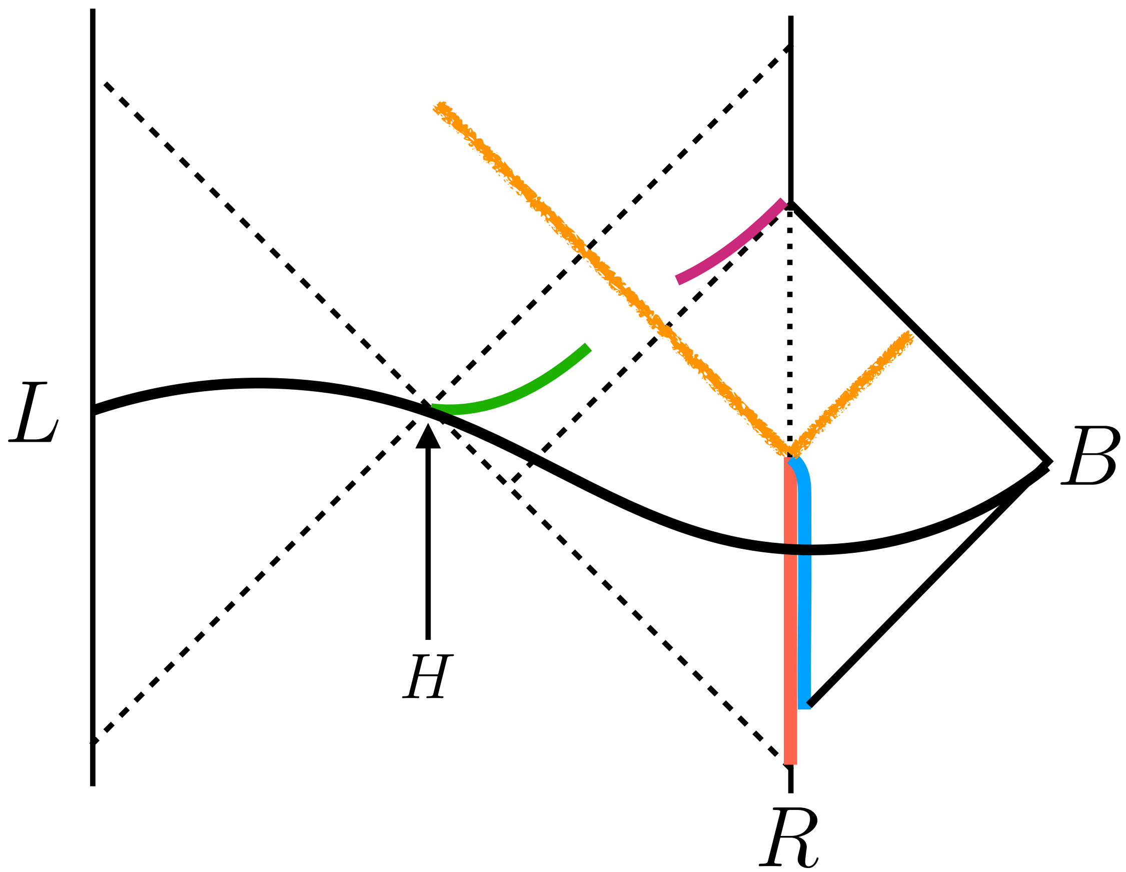

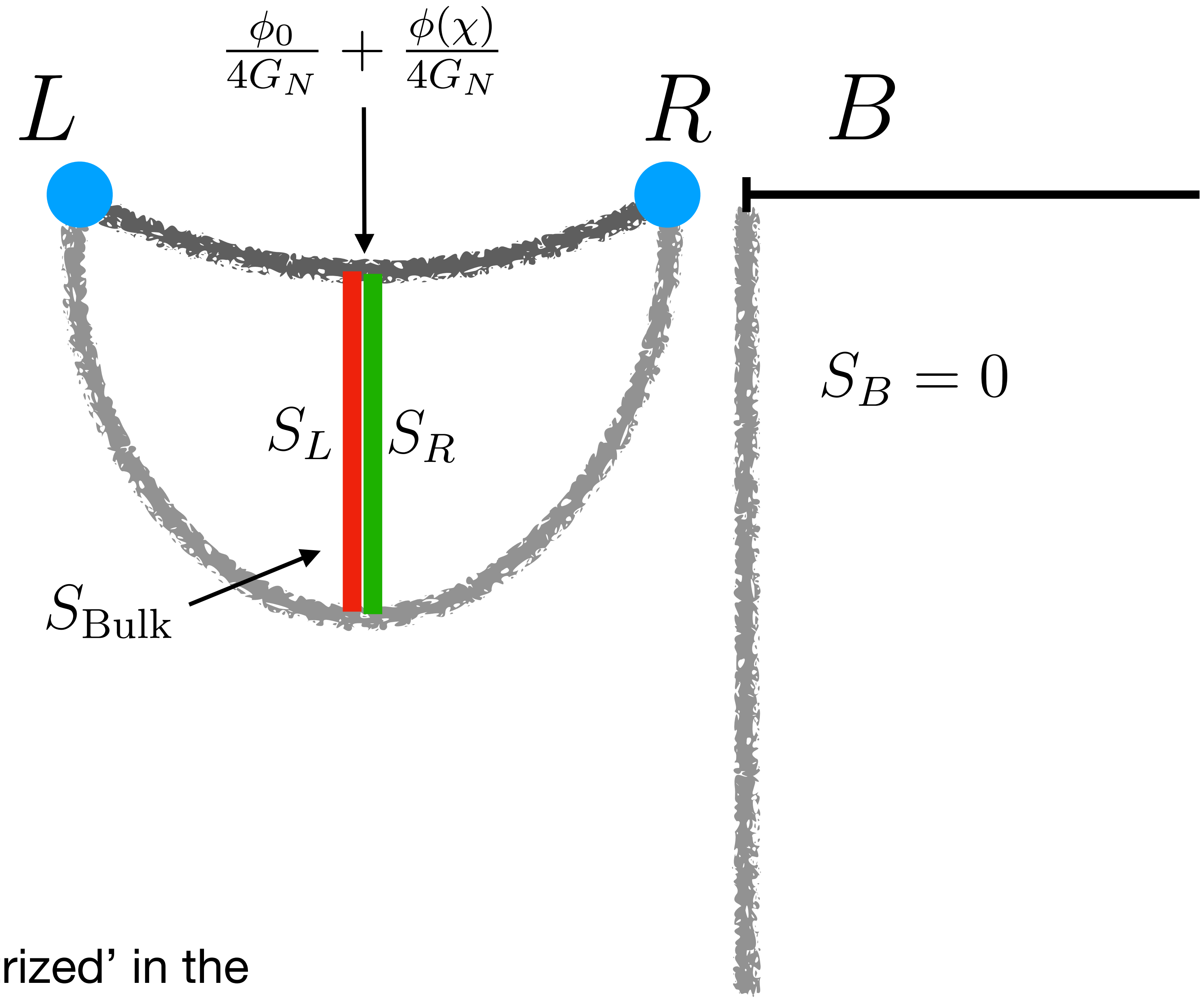

$$S_{gen} = \frac{\phi_0}{4G_N} + \frac{\phi(\chi)}{4G_N} + S_{\rm Bulk}$$

The $S_{\rm Bulk}$ contribution is 'geometrized' in the new bulk. Apply regular RT.

What if the bulk/bath BCFT was holographic?

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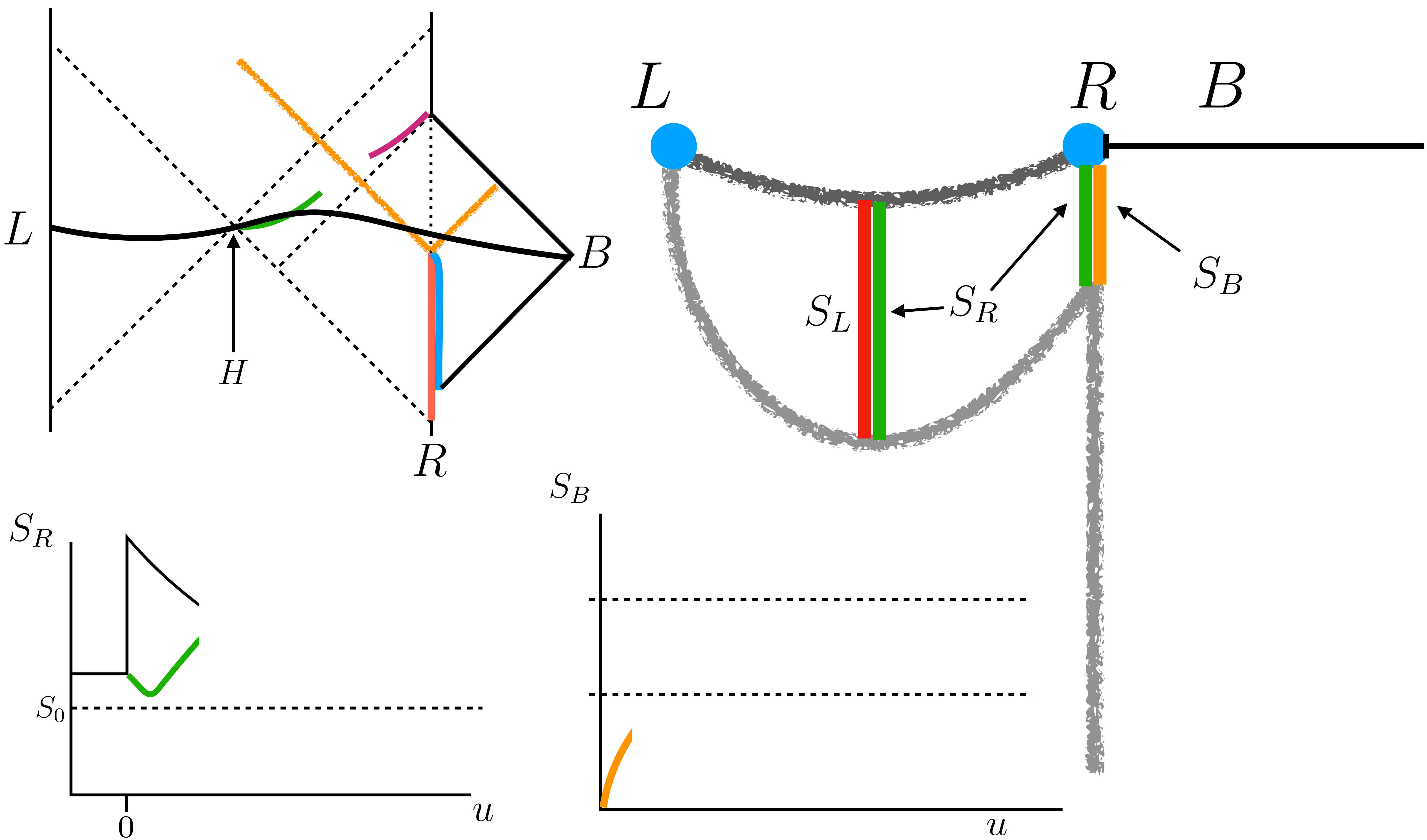

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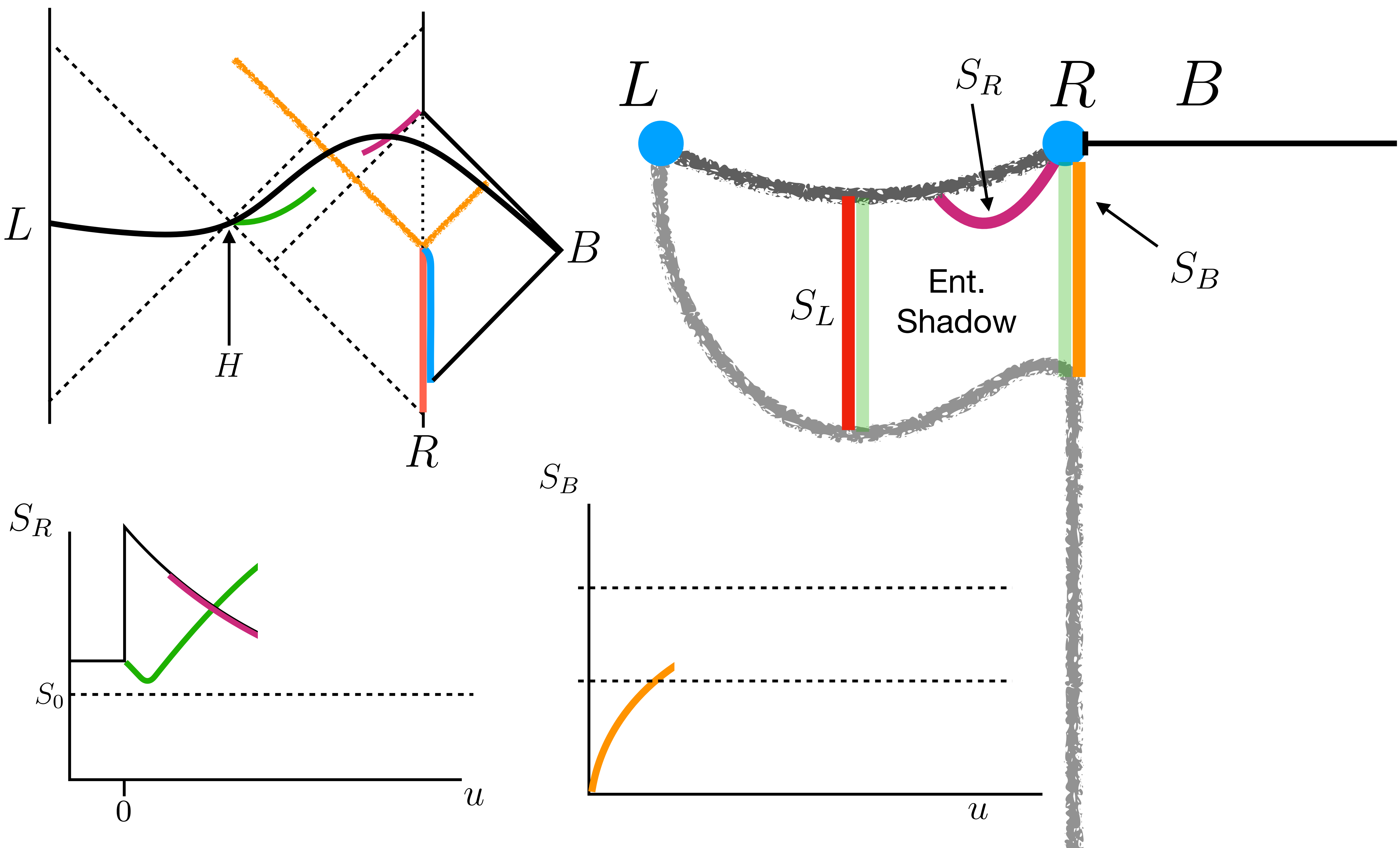

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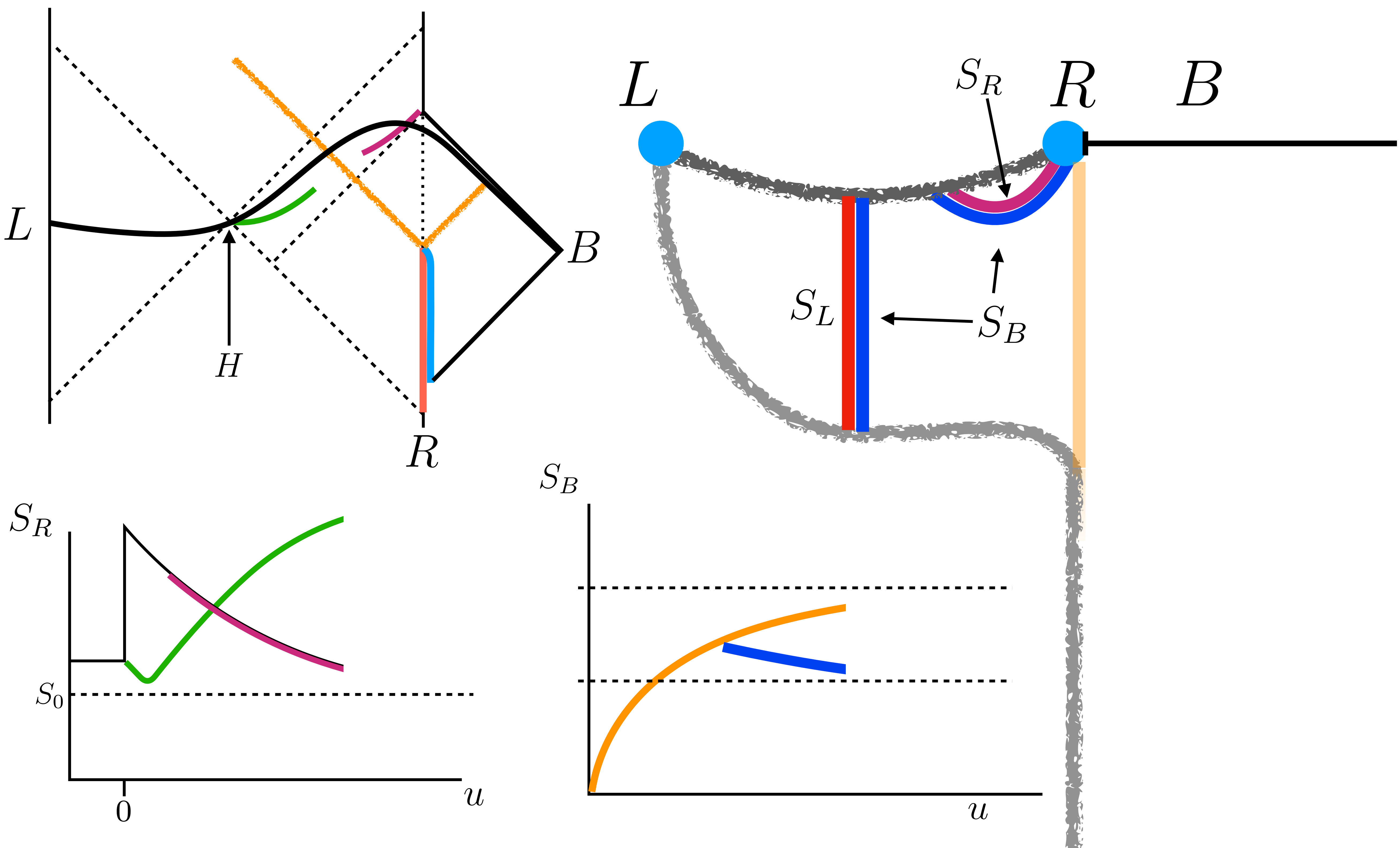

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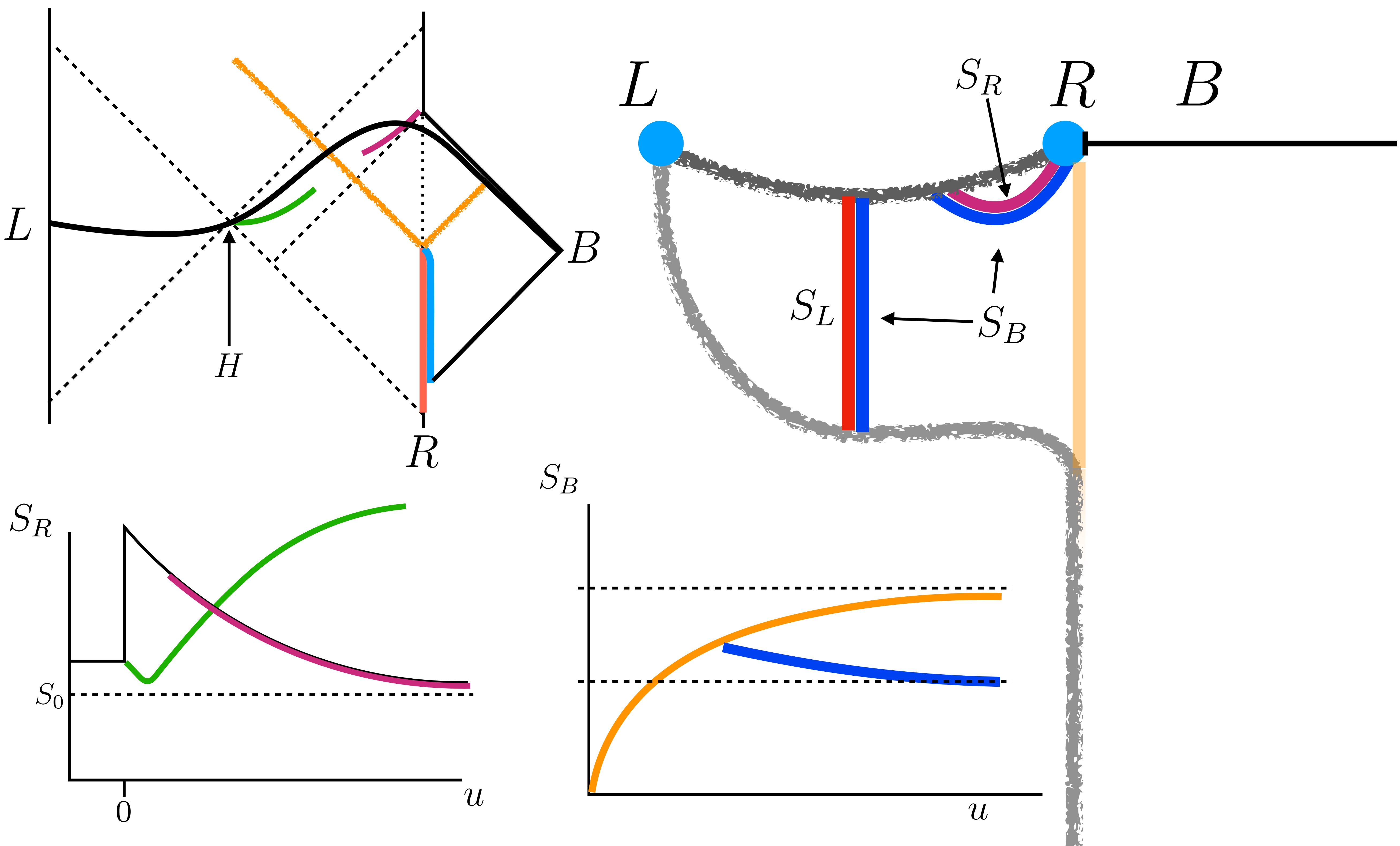

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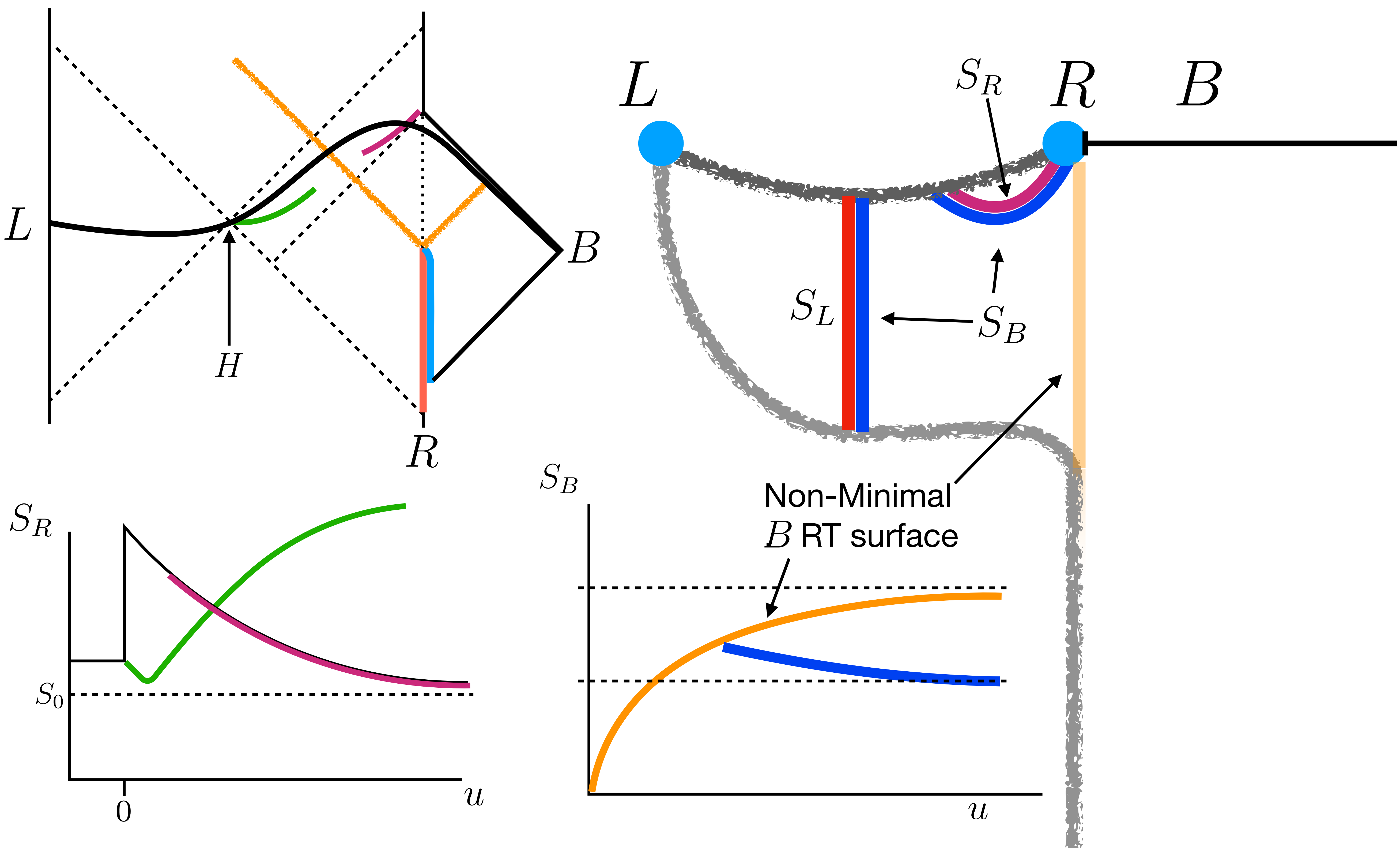

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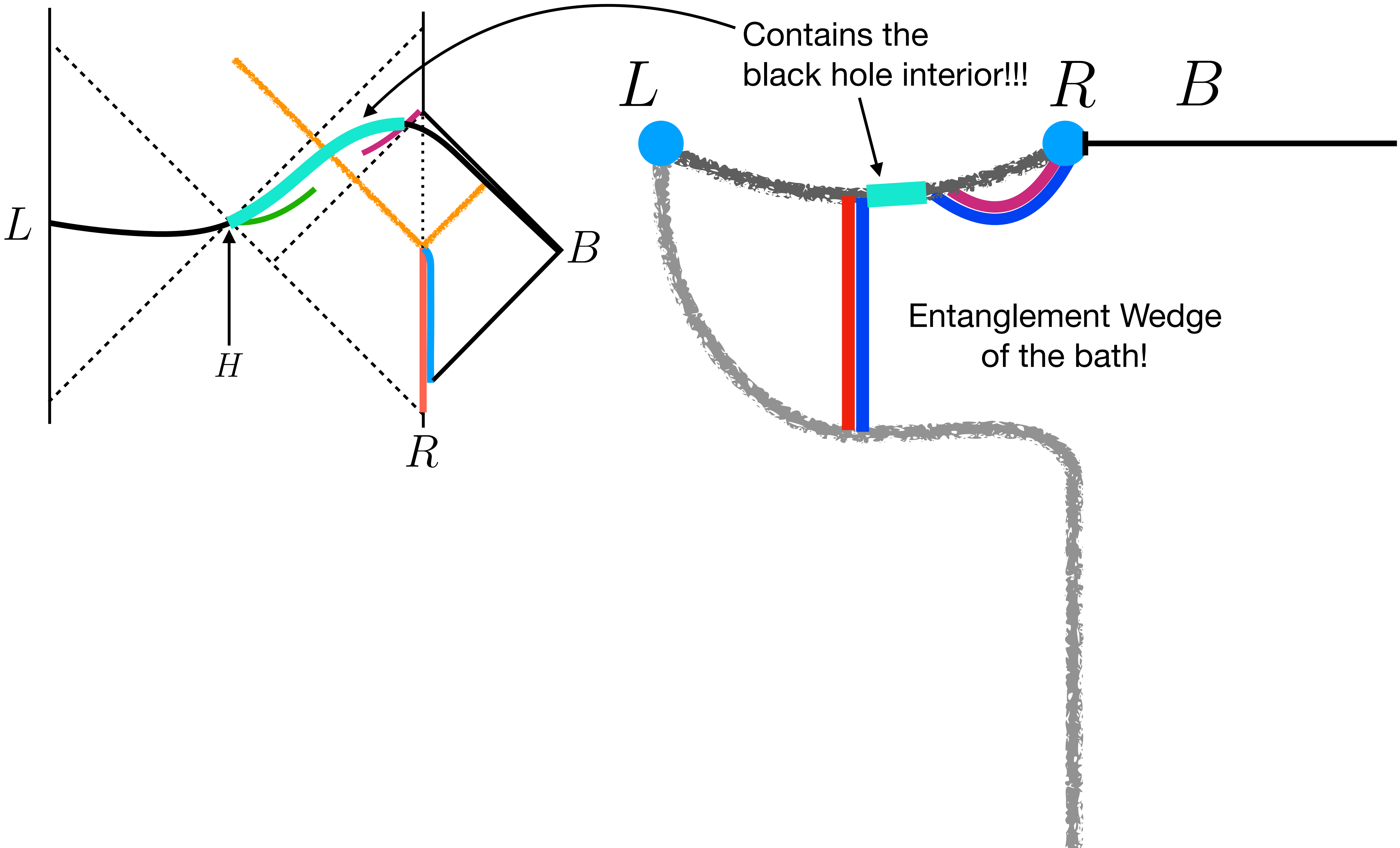

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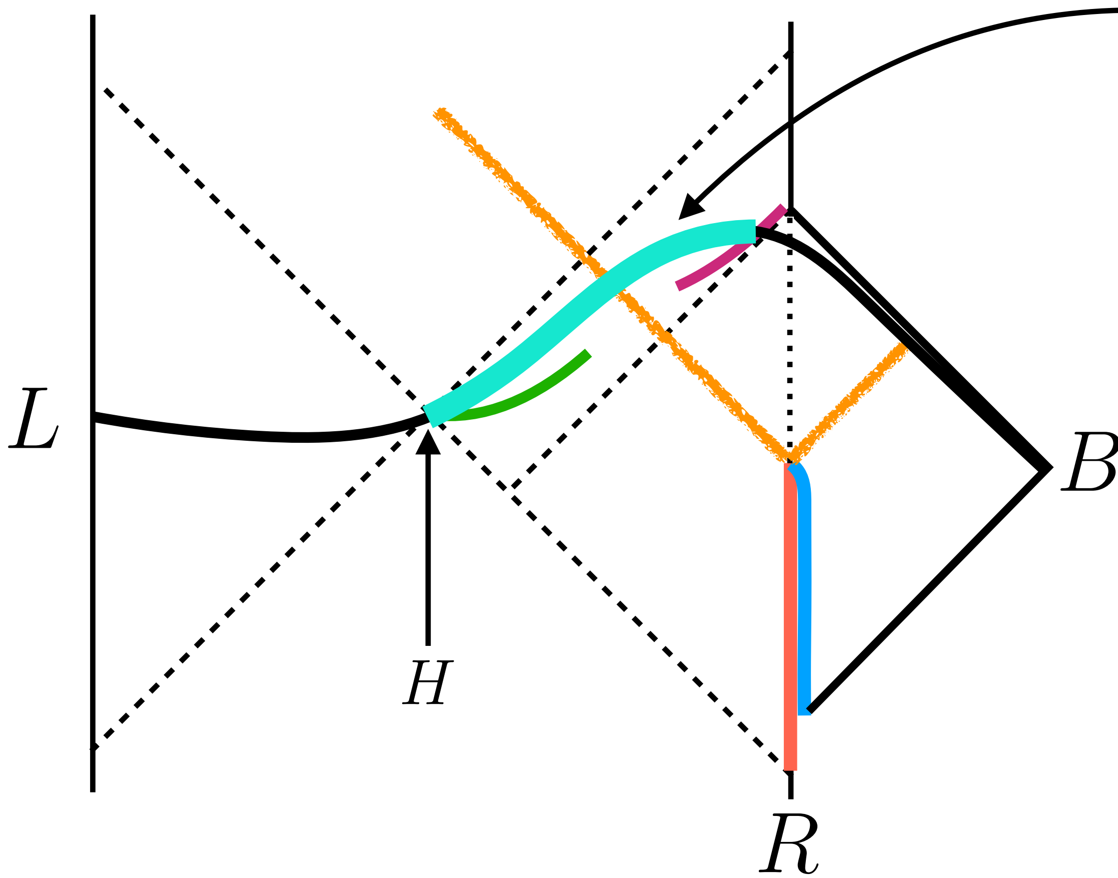

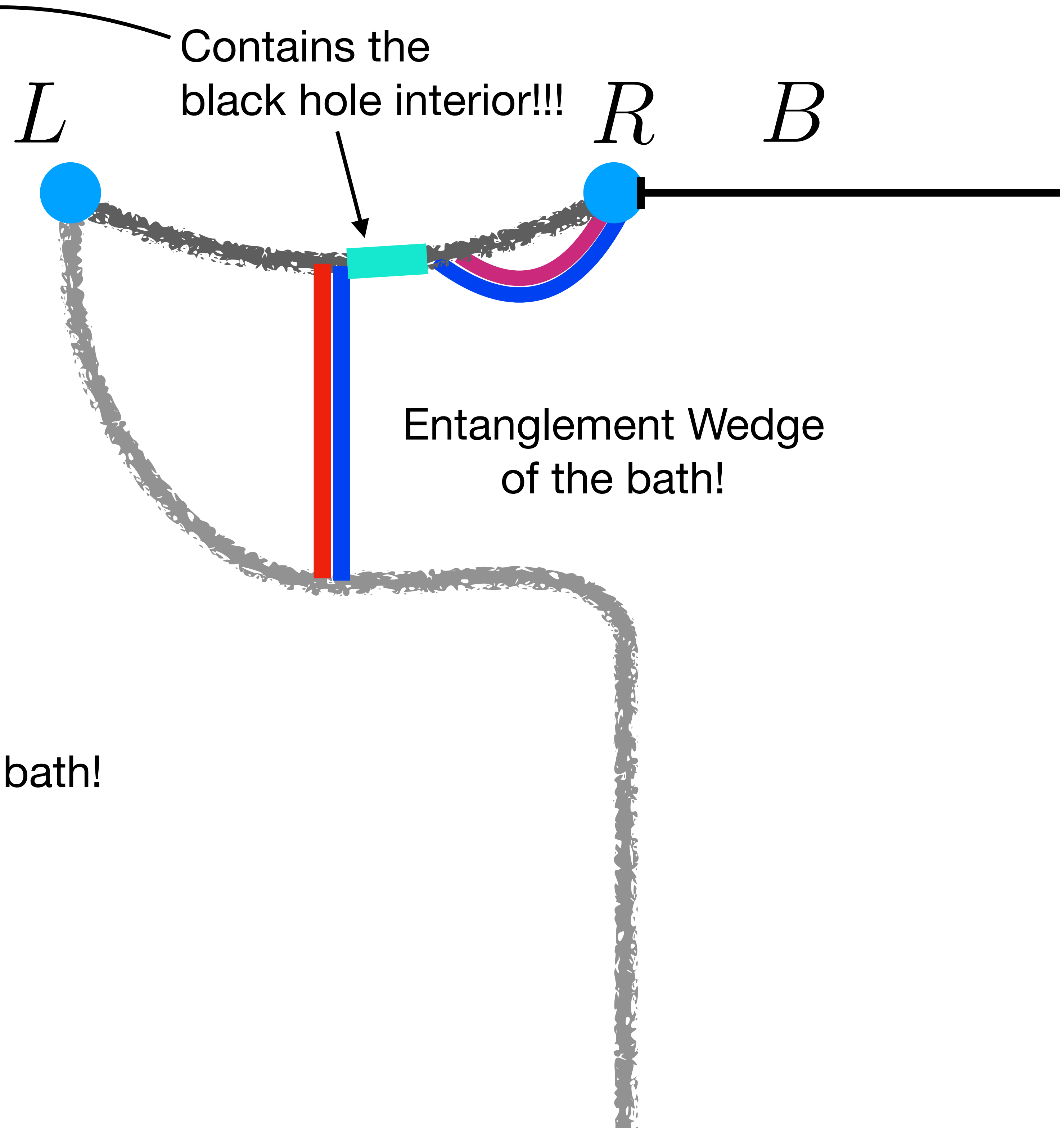

The black hole interior is dual to the bath!
This realizes ER = EPR!!

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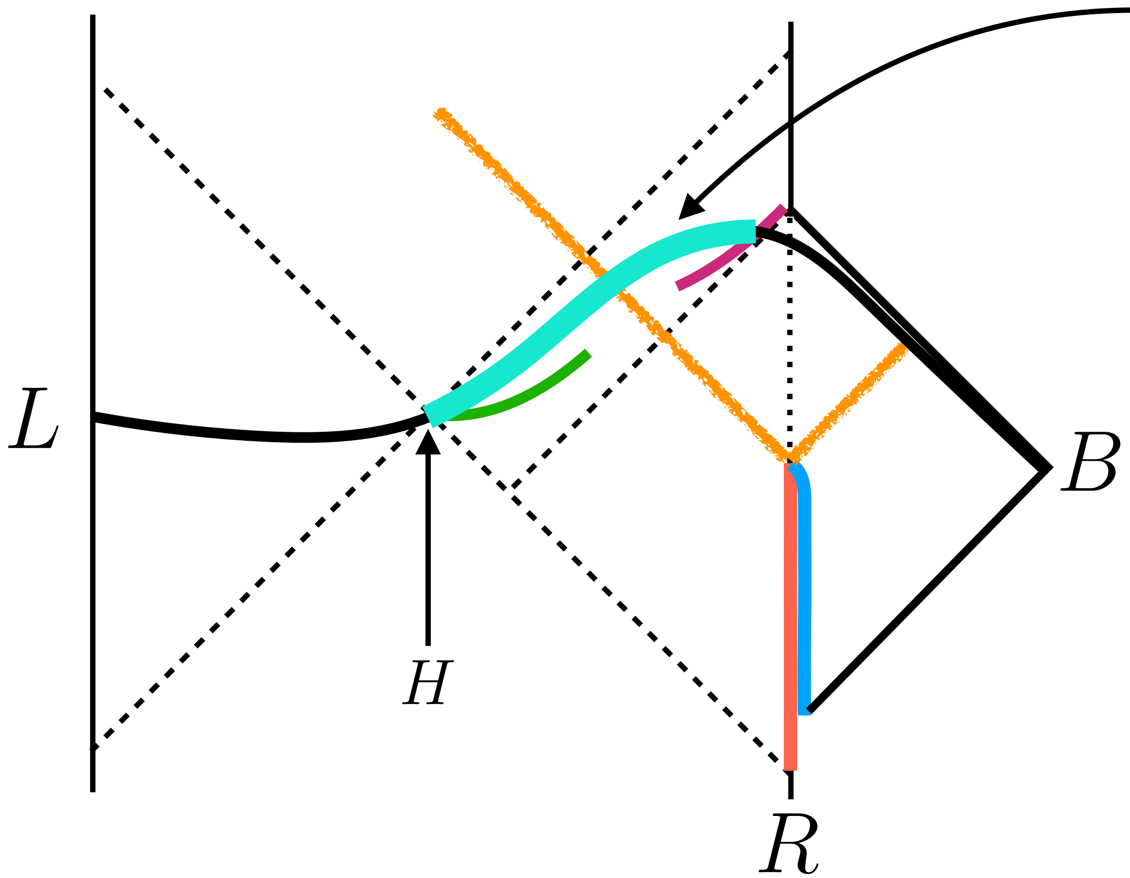
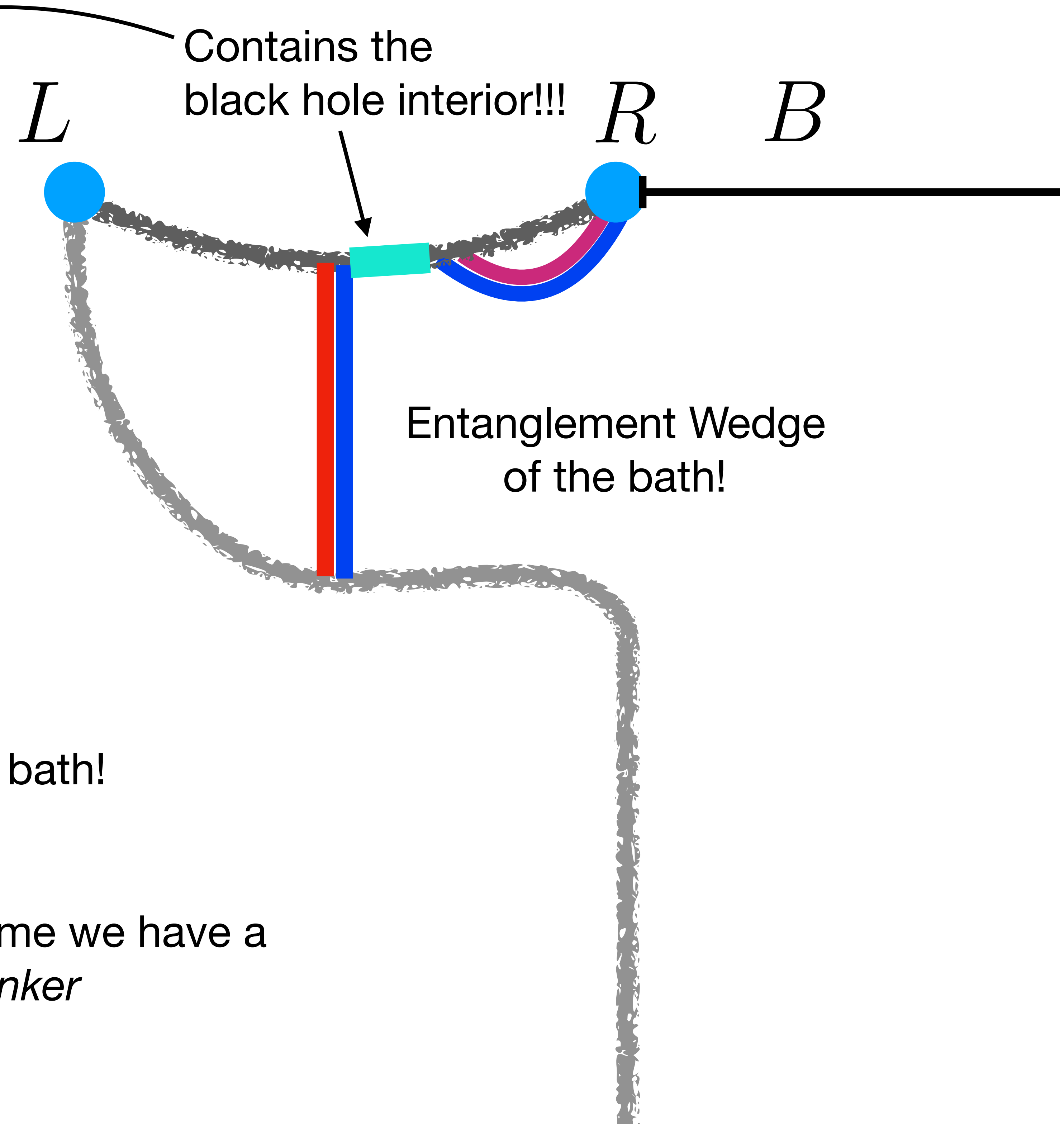


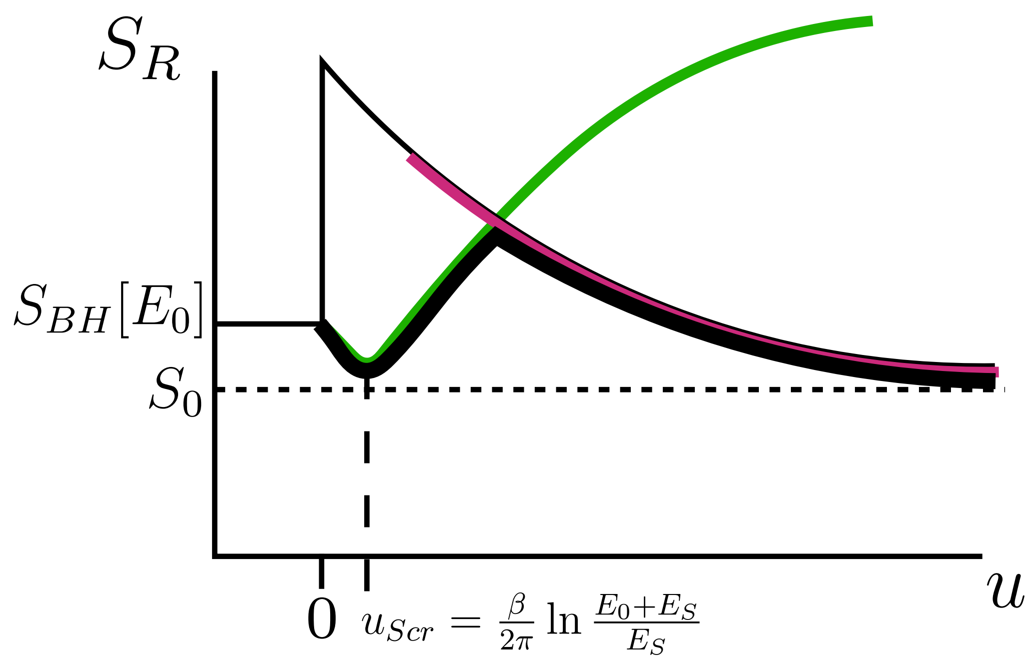


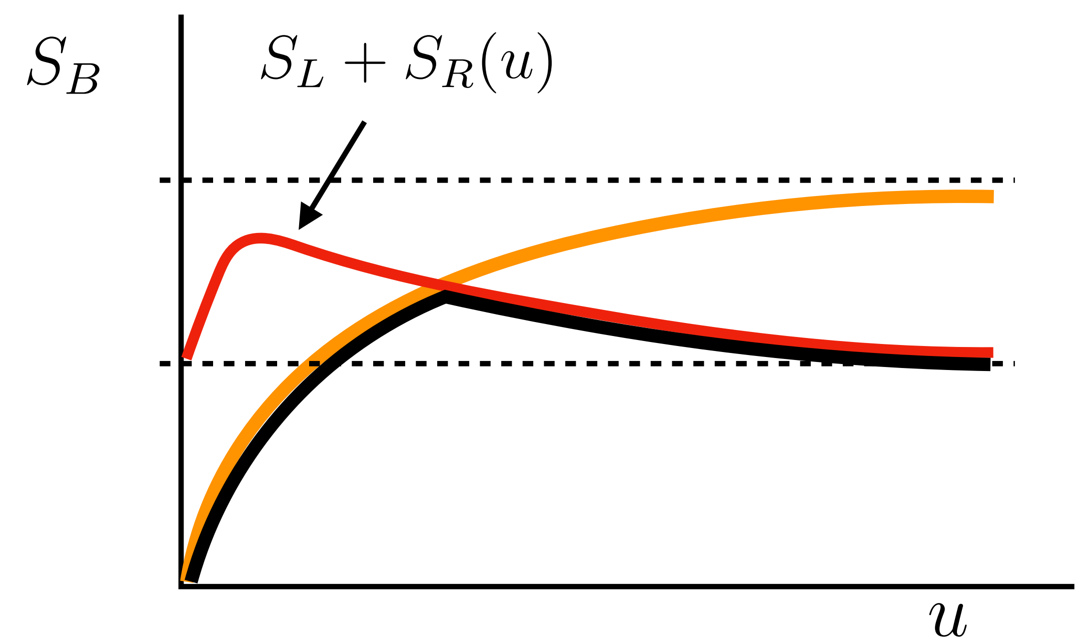
The black hole interior is dual to the bath!
This realizes ER = EPR!!

But instead of the ‘octopus’ spacetime we have a nice *“single filet of salmon”* - *S. Shenker*

Punch Line

We obtained the **Page curve** for both the radiation and black hole in the context of evaporating a black hole in 1+1 dimensions coupled to holographic matter.





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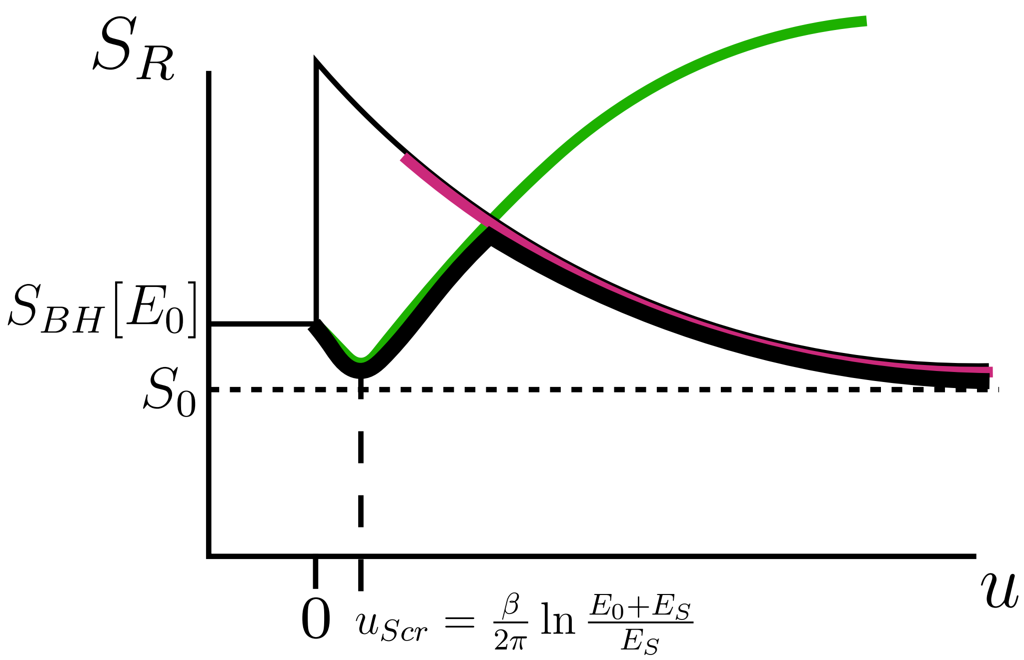

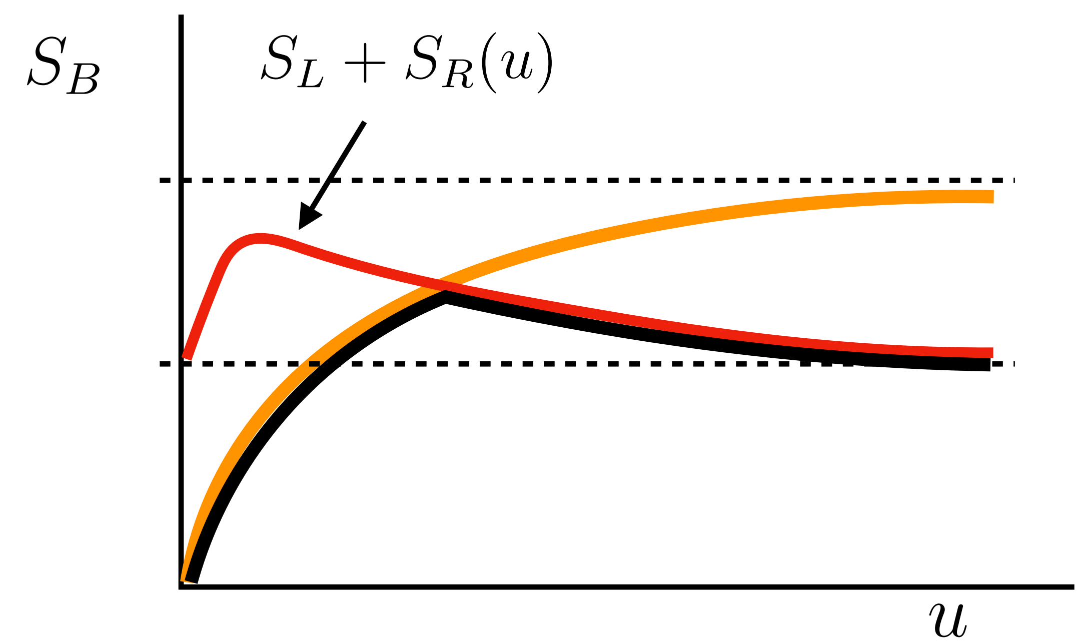

Hawking's 'mistake': He didn't know about the Minimality condition of RT formula!

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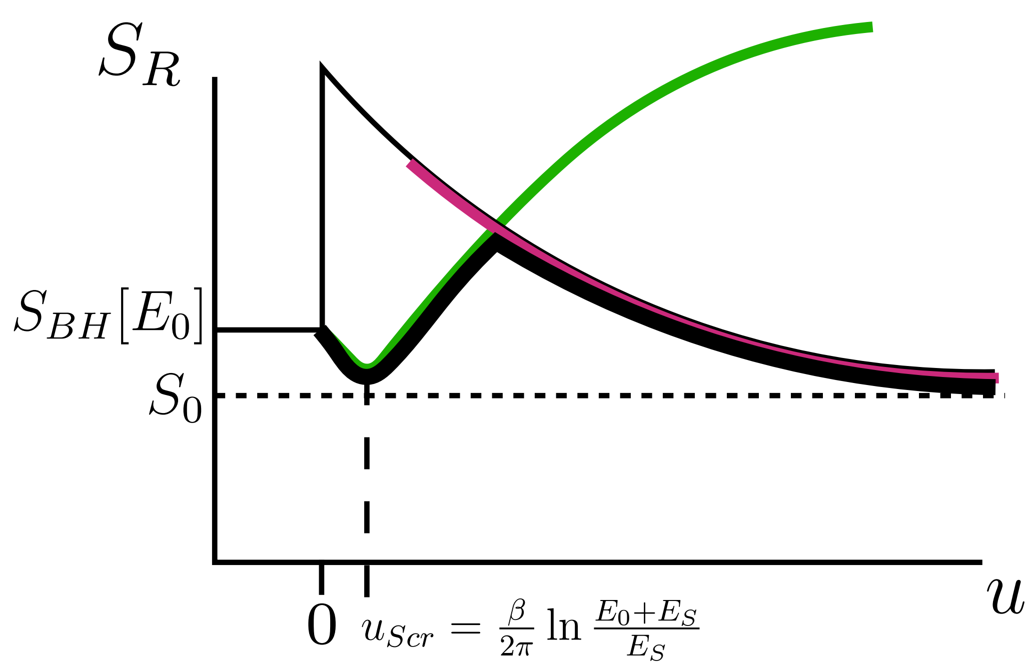

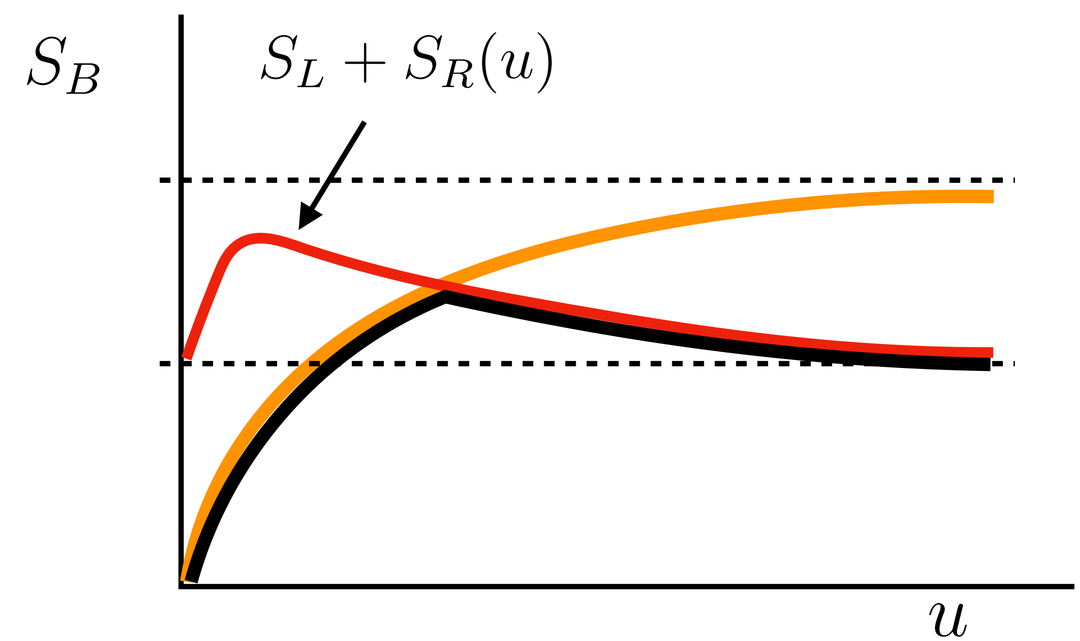

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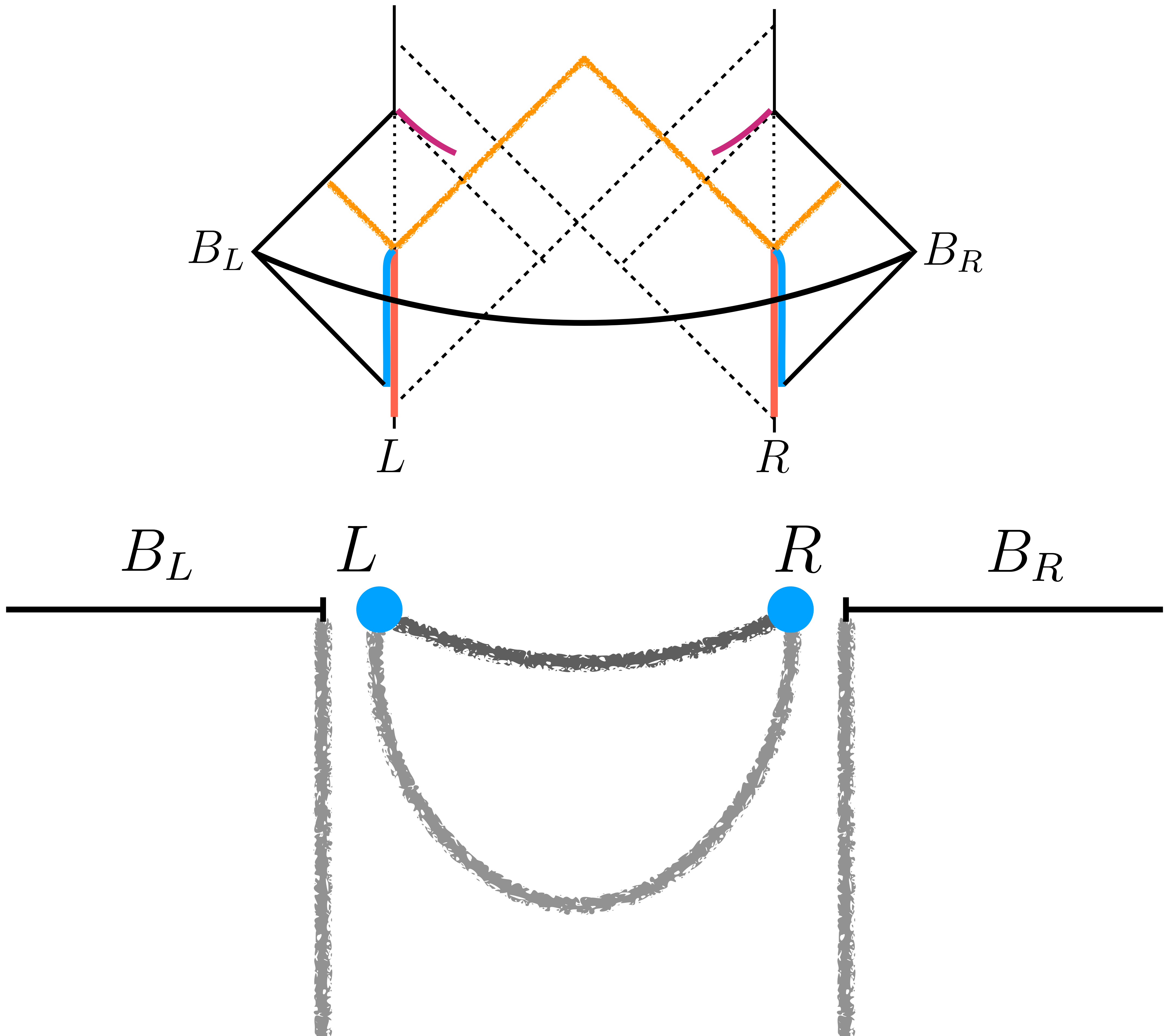
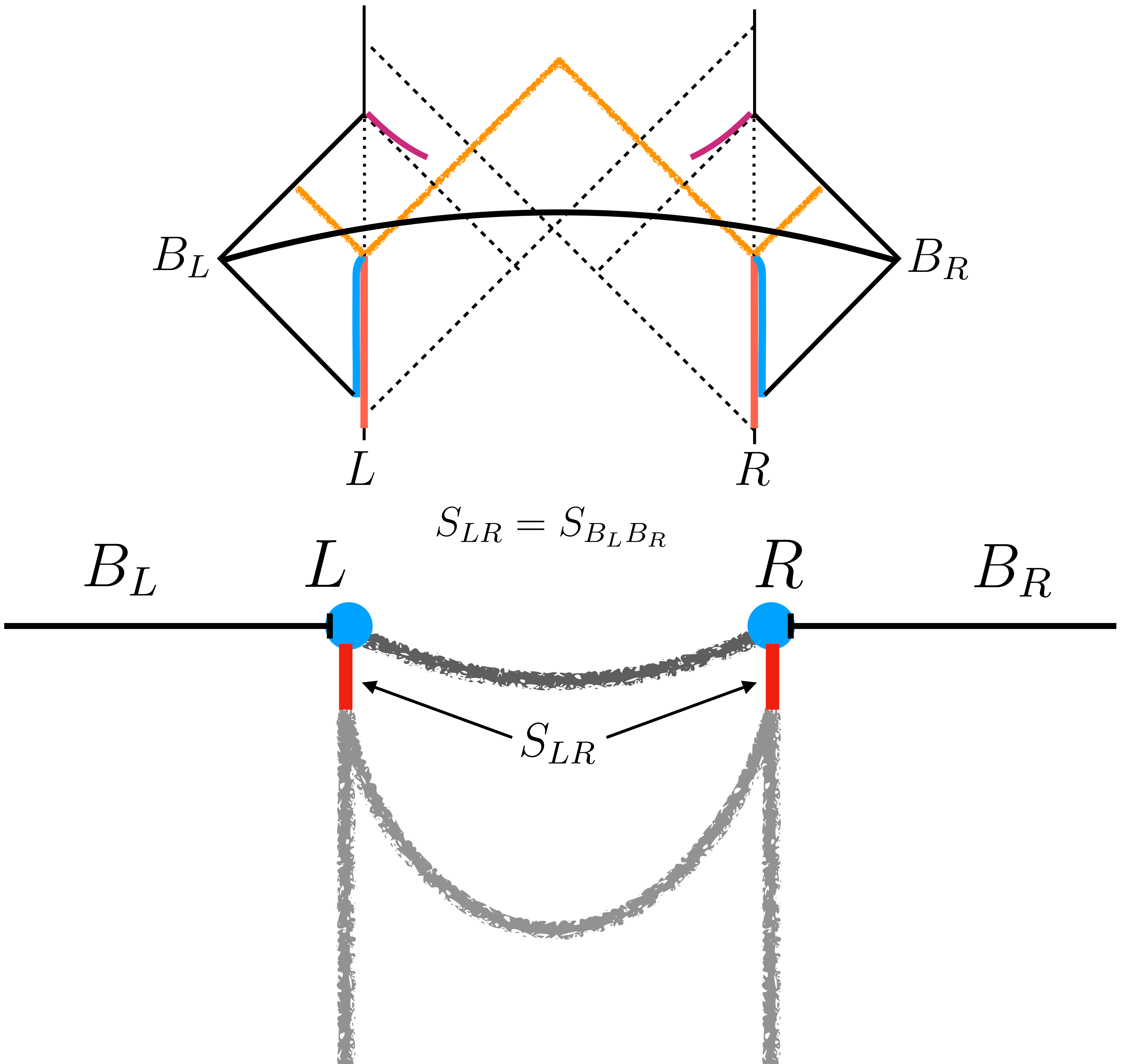
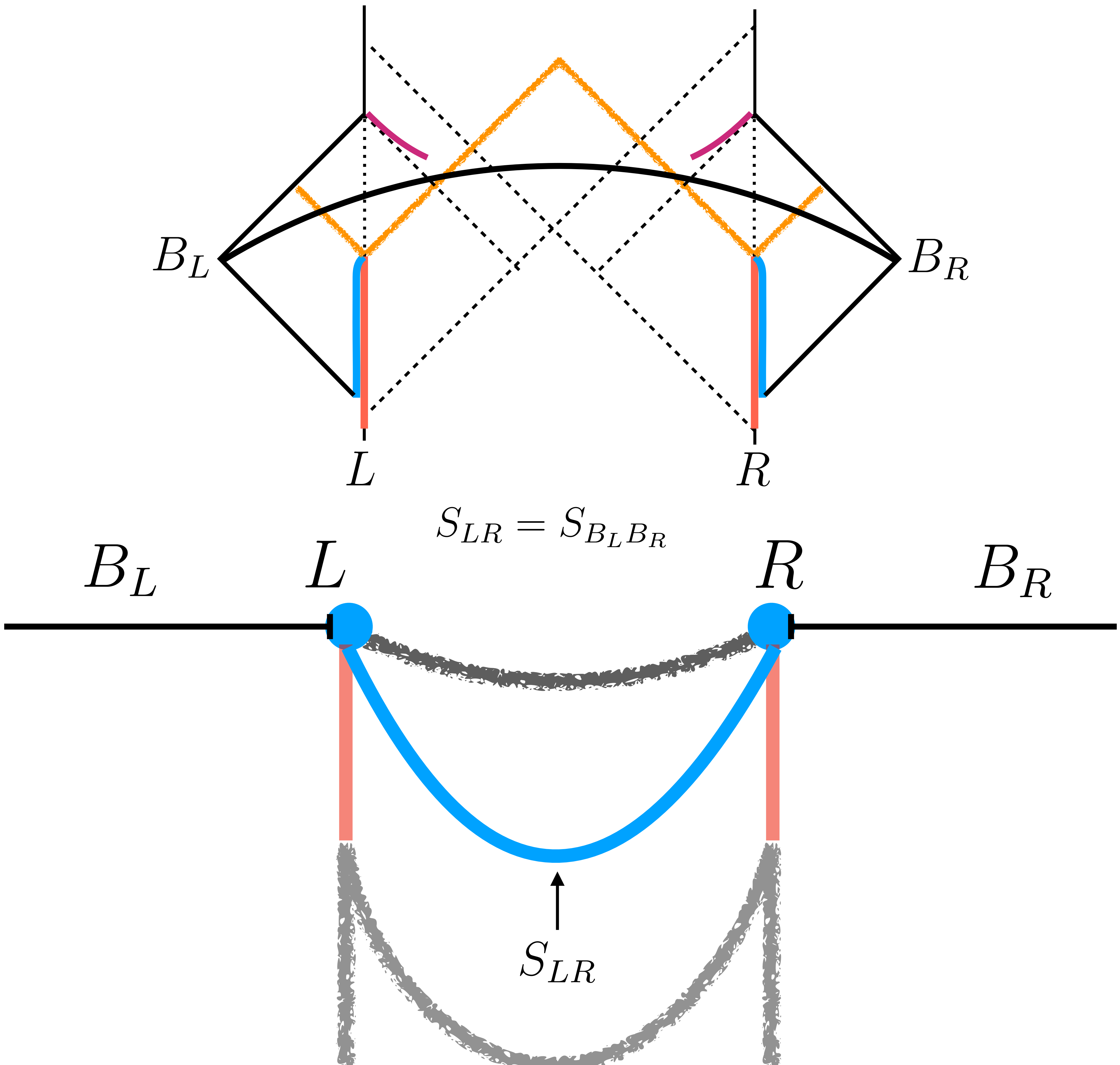
Somebody should ask me about what happens to pure states…


B_L
B_R
L
R
B_L
L
R
B_R



B_L
B_R
L
R
$S_{LR} = S_{B_L B_R}$
B_L
L
R
B_R
S_{LR}



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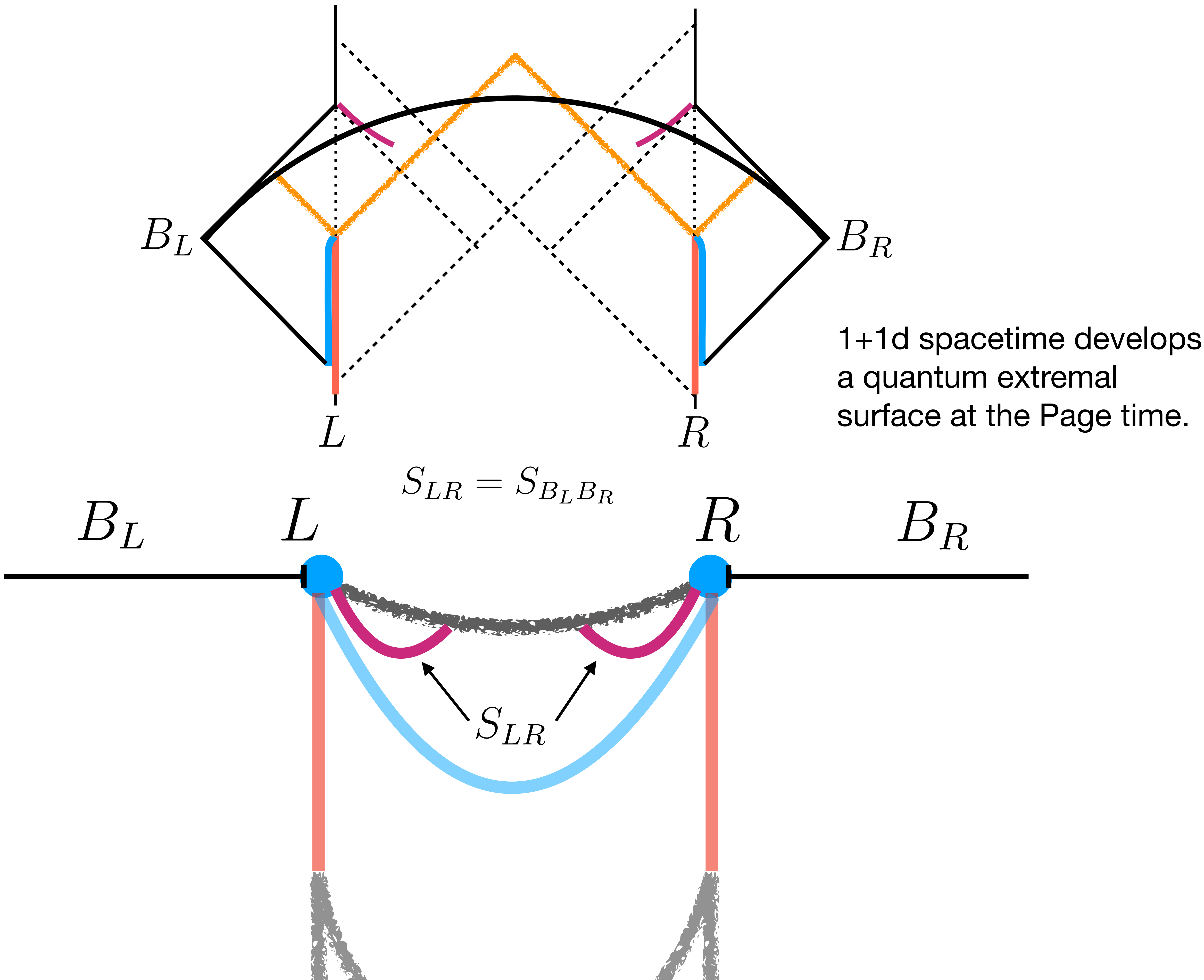

B_L
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1+1d spacetime develops
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L
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B_L
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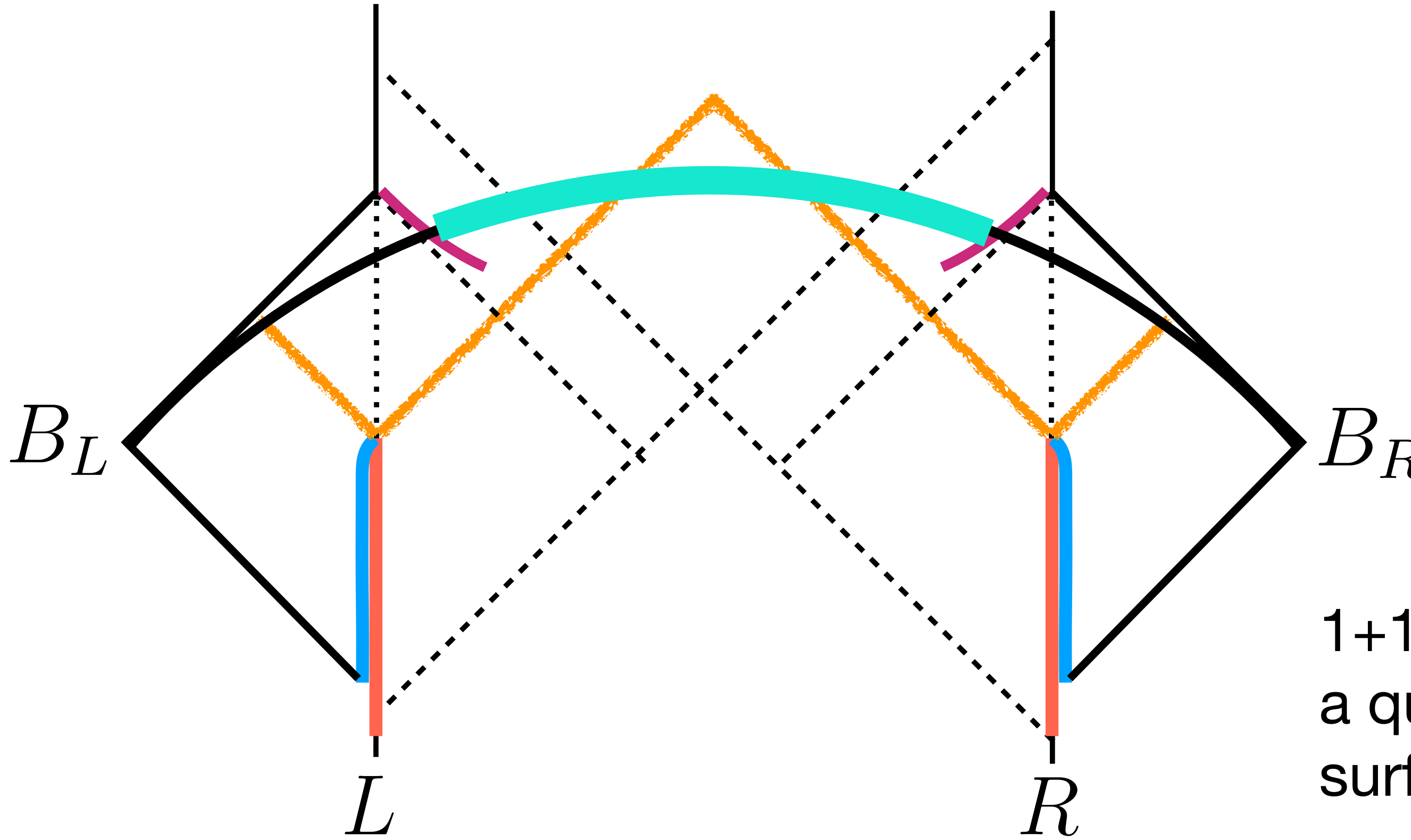

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