Boundary state black holes

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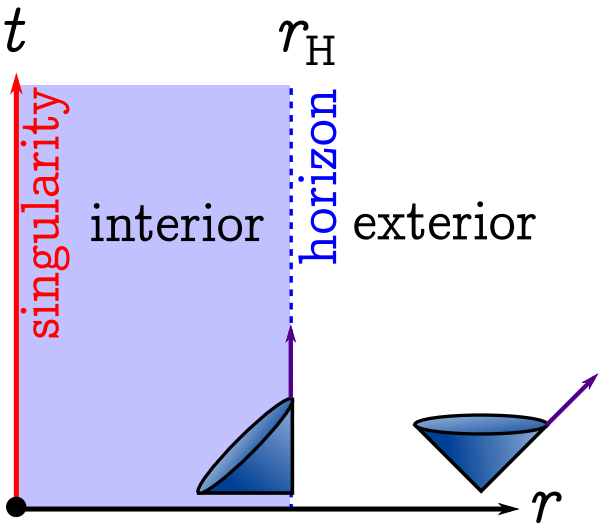
Dec 14, 2018

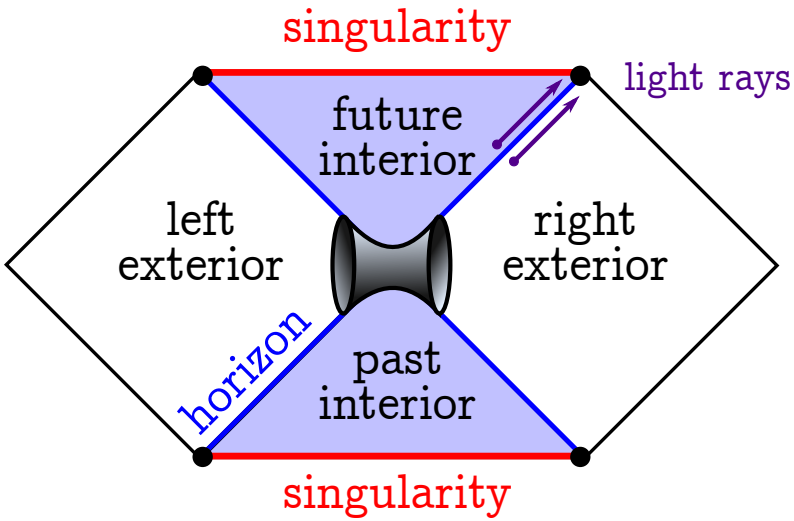
Based on 1810.10601 w/ Mark Van Raamsdonk, Moshe Rozali, Sean Cooper, Chris Waddell (UBC), and Brian Swingle (UMD)

I. Black holes

Classical black holes

- Black hole: region you can enter but can't leave.†
- Light cone of infalling observer tips over at horizon.



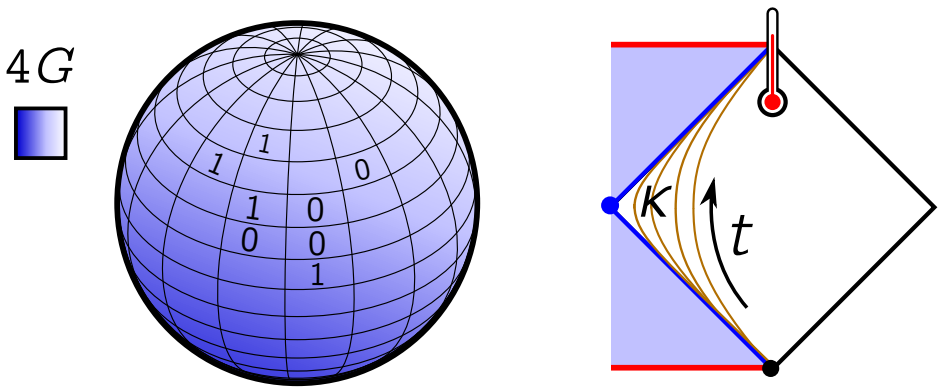


- Penrose diagram captures global structure.‡ For spherically symmetric BH, get two exteriors joined by wormhole.

†Schwarzschild 1916. ‡Penrose 1964; Carter 1966.

Black hole thermodynamics

- Remarkable fact: black holes are thermodynamic systems.[†]
- The entropy is proportional to the horizon area, $S = A/4G$.[‡]

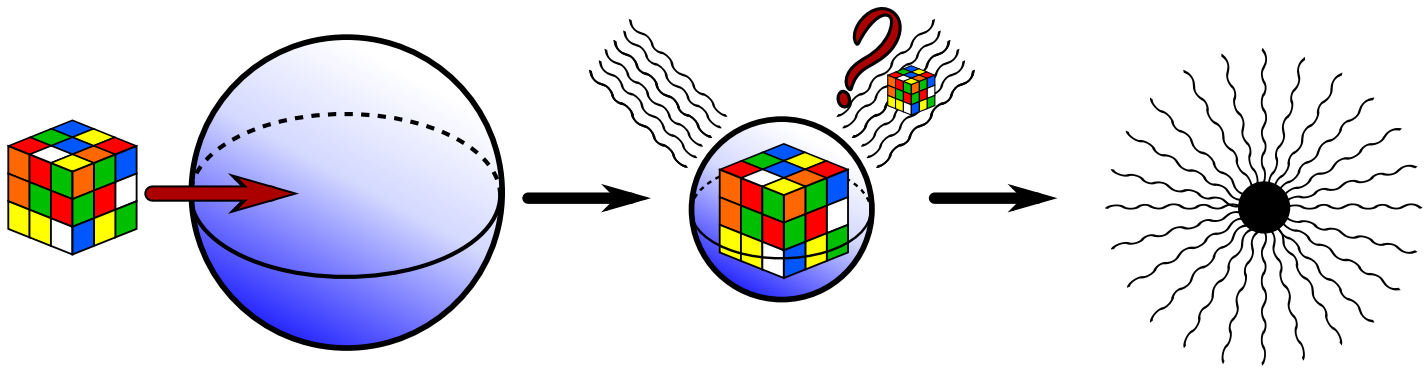


- BHs emit Hawking radiation at $T = \kappa/2\pi$, where κ is the surface gravity (proper acceleration at horizon).

[†]Bardeen, Carter and Hawking 1973. [‡]Hawking 1971; Bekenstein 1972. [§]Hawking 1974.

The information problem

- Radiation leads to a paradox: BHs evaporate into thermal noise. They destroy information about what fell in![†]

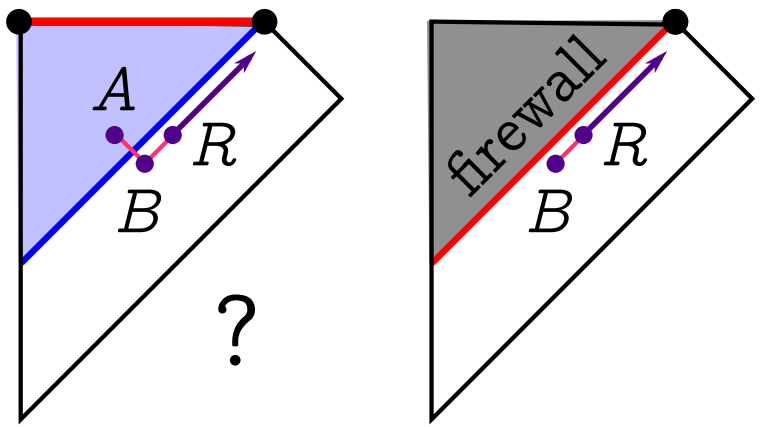


- Process is irreversible, like the second law. But second law comes from ignoring microscopic details.
- Suggests that information is encoded in microscopic details of radiation.[‡] Acts like a xerox machine on things falling in!

[†]Hawking 1975. [‡]Susskind, Thorlacius and Uglum 1993; Susskind and Thorlacius 1993.

Firewalls

- If radiation copies things falling in, we get a paradox. First, copying entangles the black hole with radiation.[†]
- Second, having smooth fields across the horizon requires the horizon and interior to be entangled.[‡]

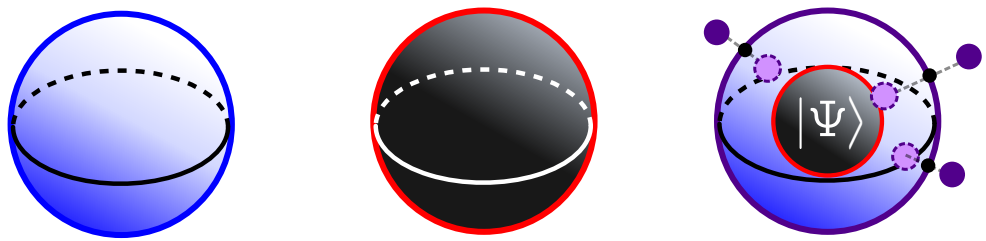


- Paradox: only one can hold![§] "Monogamy" of entanglement. If horizon not smooth, replaced by a high-energy "firewall".[♭]

[†] Page 1993. [‡] Unruh and Wald 1984. [§] Coffman, Kundu, and Wootters 1999; Mathur 2009. [♭] Almheiri, Marolf, Polchinski and Sully 2012.

Simulating the interior

- Second option: "simulate" interior with stuff outside black hole.[†] Avoids monogamy issue.
- Use state $|\Psi\rangle$ outside BH as computational resource, giving state-dependent[‡] simulation.



classical firewall simulation

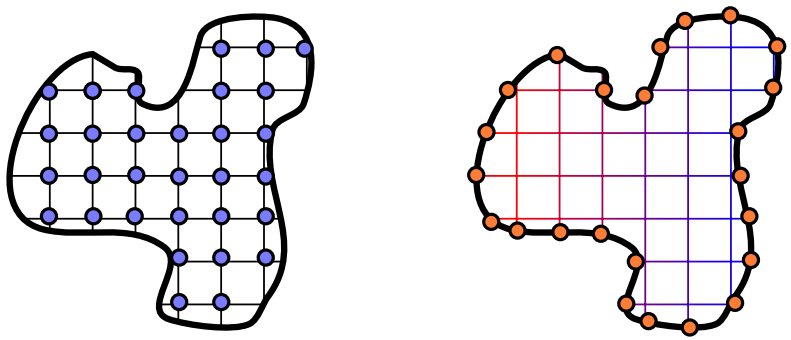
- Can't simulate everything behind horizon, so we expect a state-dependent amount of interior.[§]
- We will give precise realisation in AdS/CFT!

[†]Papadodimas and Raju 2014; Maldacena and Susskind 2013. [‡]Papadodimas and Raju 2015. [§]Shenker and Stanford 2013; de Boer, van Breukelen, Lokhande, Papadodimas and Verlinde 2018.

II. AdS/CFT

Gravity is holographic

- AdS/CFT is a theory of quantum gravity.
- Motivation: quantum gravity is holographic.[†] Unlike local theory, entropy in gravity scales with area rather than volume.



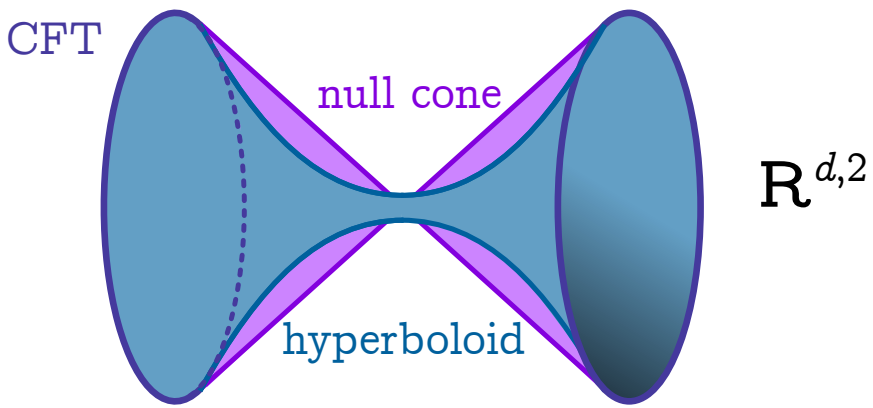
local QFT quantum gravity

- Simple argument: BHs maximise entropy density. Otherwise, you can collapse a system into a BH and violate second law.

[†] 't Hooft 1993; Susskind 1995.

Matching symmetries

- AdS/CFT realises holography, with (AdS) gravity in $d+1$ dimensions equal to (CFT) quantum theory in d dimensions.[†]
- AdS = anti-de Sitter space (constant negative curvature).
  CFT = conformal field theory (conformally invariant QFT).

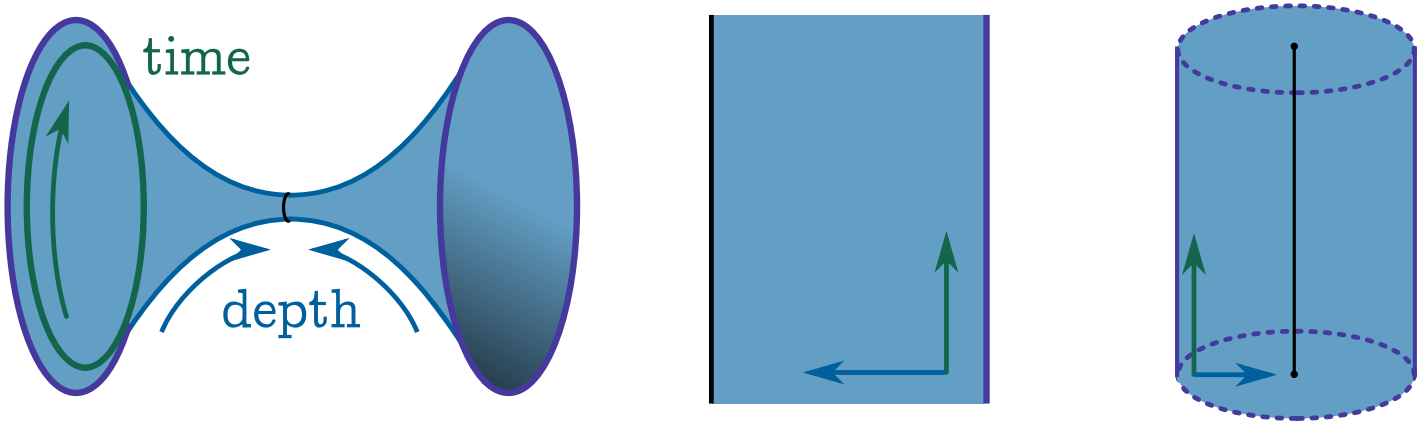


- We can embed AdS as hyperboloid $X^2 = L^2$ in $\mathbb{R}^{d,2}$. CFT lives on projective null cone $X^2 = 0$ in $\mathbb{R}^{d,2}$.[§]
- Symmetry group $SO(d,2)$ on both sides matches!

[†]Maldacena 1997; Gubser, Klebanov and Polyakov 1998; Witten 1998. [§]Dirac 1935.

Pictures of AdS/CFT

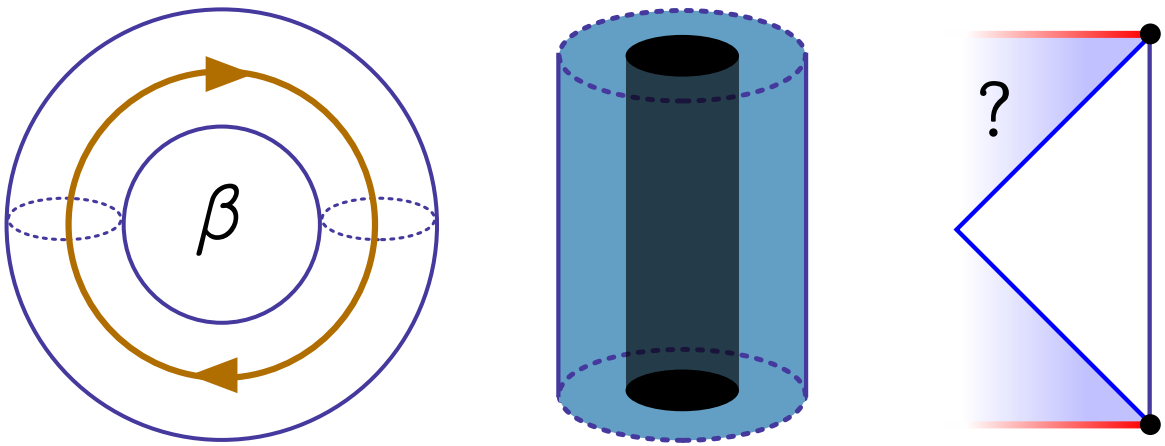
- Two important directions: time on the hyperboloid is periodic, so we unwrap it. Depth is distance from purple boundary.
- In time/depth coordinates, Penrose diagram is a rectangle.



- CFT lives in flat space $\mathbb{R}^{d-1} \times \mathbb{R}$. We can make space compact so that CFT lives on a cylinder $\mathbb{S}^{d-1} \times \mathbb{R}$.

Thermal states and black holes

- Empty AdS corresponds to CFT vacuum state. Now consider thermal state with temperature $T = 1/\beta$.
- System has period β in imaginary time,[†] so CFT cylinder is wrapped into a donut. In AdS, corresponds to a black hole![‡]

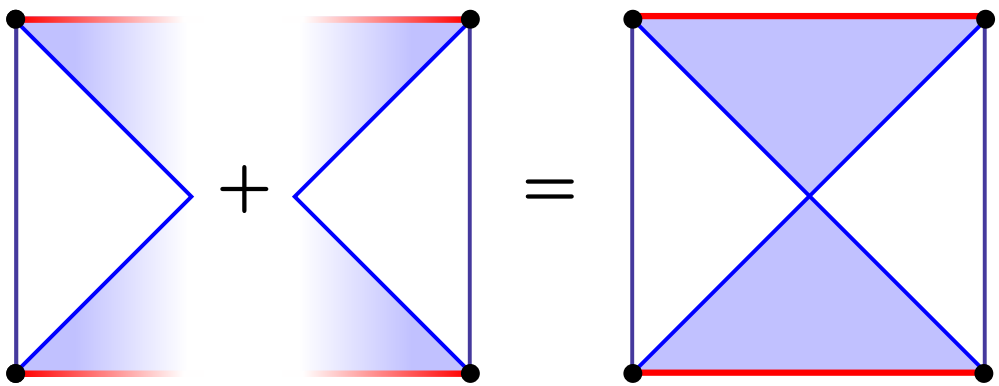


- Information problem: we don't know what's inside BH!

[†]Matsubara 1955. [‡]Hawking and Page 1983; Witten 1998.

Purification and wormholes

- Ignorance of BH interior corresponds to fact that quantum state ρ is mixed. What happens if we purify the state?
- Recipe for purifying ρ: copy system, entangle copies, and apply $\sqrt{\rho}$. Construction gives thermofield double (TFD).

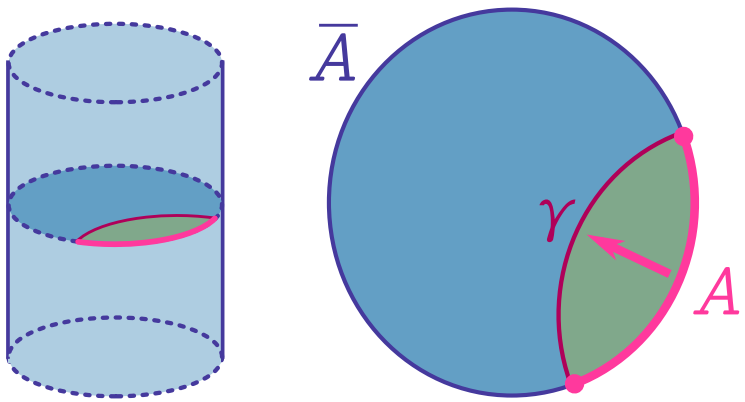


- Each copy has BH exterior. Natural to expect that TFD is dual to a wormhole with Schwarzschild AdS ends.[‡]

[†] Israel 1976. [‡] Maldacena 2001.

Entanglement and geometry

- Geometry and entanglement connected.[†] Ryu-Takayanagi (RT) formula gives similar connection.[‡]
- Pick a subsystem A of the CFT. "Push" A into bulk surface γ of minimal area.



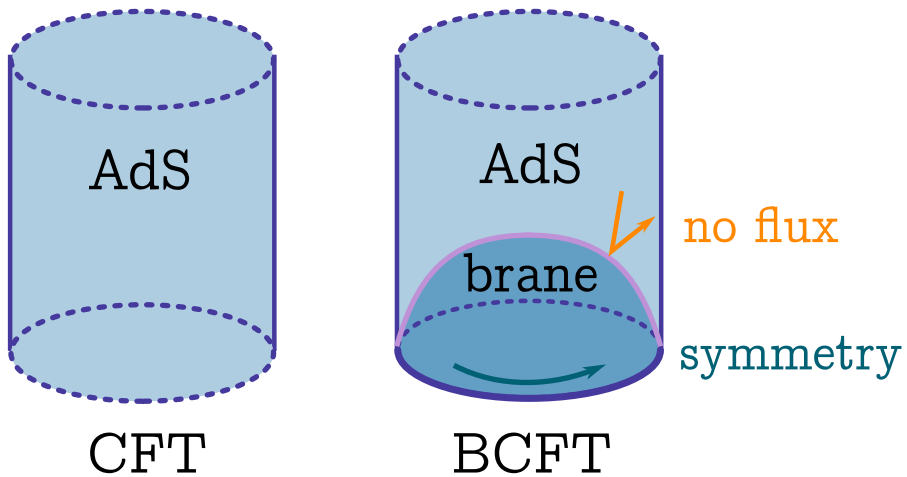
- RT formula states that entanglement between A and complement $\bar{A}$ is Area$(\gamma)/4G$. Similar to black hole entropy!

[†]Van Raamsdonk 2009; Swingle 2009; Maldacena and Susskind 2013. [‡]Ryu and Takayanagi 2006; Hubeny, Rangamani, and Takayanagi 2007.

III. Boundary states

AdS/BCFT

- If we cut CFT in half, get a boundary CFT (BCFT).[†] Each half has symmetry group $SO(d,1)$ and leaks no energy.
- Gravity dual is a brane with same symmetry group and no flux (Neumann) boundary conditions.[‡]

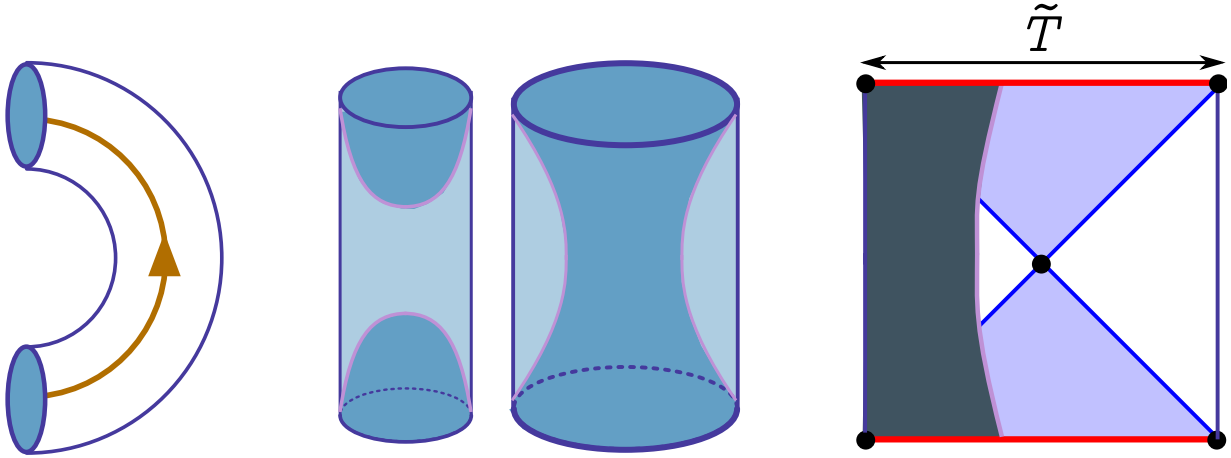


- $SO(d,1)$-symmetric BCFT configurations are called boundary (B) states $|B\rangle$.[§] Model different $|B\rangle$ with brane tension $\tilde{T}$.

[†] Cardy 1984. [‡] Karch and Randall 2001; Takayanagi 2011. [§] Cardy 1989.

Boundary state black holes

- Now consider BCFT at finite temperature. We cut the donut in half and get finite cylinder with two boundary components.
- Two brane topologies: disconnected and connected.

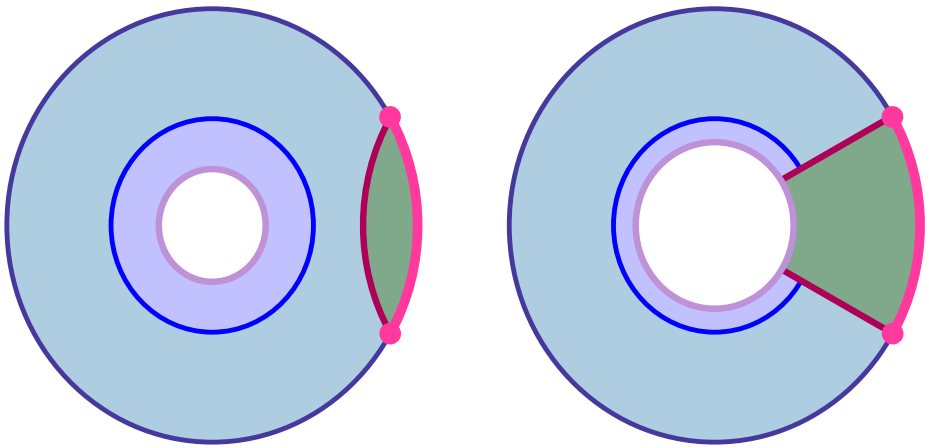


- Connected phase is boundary state BH (wormhole with brane).[†] It hits singularity at position determined by $\tilde{T}$.
- Get state-dependent amount of interior, as advertised!

[†] Fujita, Takayanagi and Tonni 2011; Almheiri, Mousatov, and Shyani 2018.

Hawking radiation and subsystem entanglement

- Can we decode Hawking radiation for boundary state BHs? Too hard! Entanglement of CFT regions is good surrogate.
- Use RT formula. Two options for minimal surface: outside horizon or onto brane[†] when the brane is close enough.

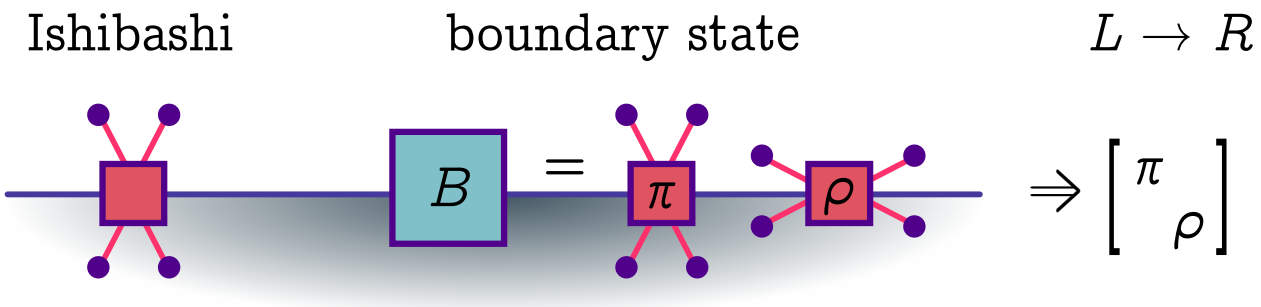


- Since brane size depends on tension $\tilde{T}$ and time t, we can decode boundary state $|B\rangle$ from subsystem entanglement.

[†] Harlow 2016.

Boundary state simulation?

- Can we use entanglement in B state to simulate interior?
- Ishibashi states[†] (entangling left and right movers on either side of boundary) satisfy no flux condition.

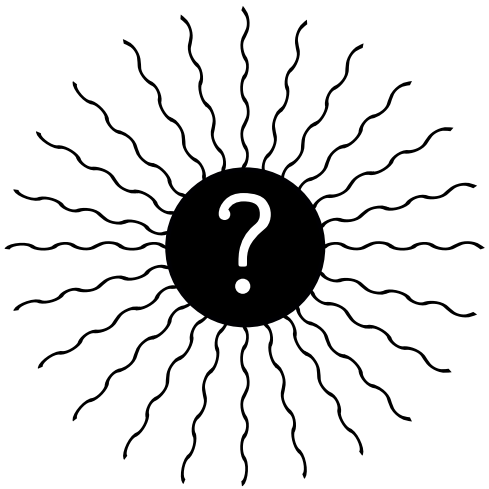


- Combining Ishibashi states to preserve symmetry gives B states. B state is twisted map between left and right sectors!
- Work in progress, but twisted map can construct interior.[‡]

[†] Ishibashi 1989. [‡] Almheiri 2018.

Loose threads

- Can we do branework cosmology?[†] Perhaps in charged BH!
- Enlarge AdS/BCFT dictionary to understand brane dynamics.
- Compare to rigorous entropy calculations in $BCFT_2$.[‡]
- Finally, see if B states give insights into BHs or AdS/CFT.[§]



Thanks for listening! Questions?

[†] Randall and Sundrum 1999; Karch and Randall 2000; Hebecker and March-Russell 2001. [‡] Cardy and Calabrese 2009. [§] Almheiri 2018.