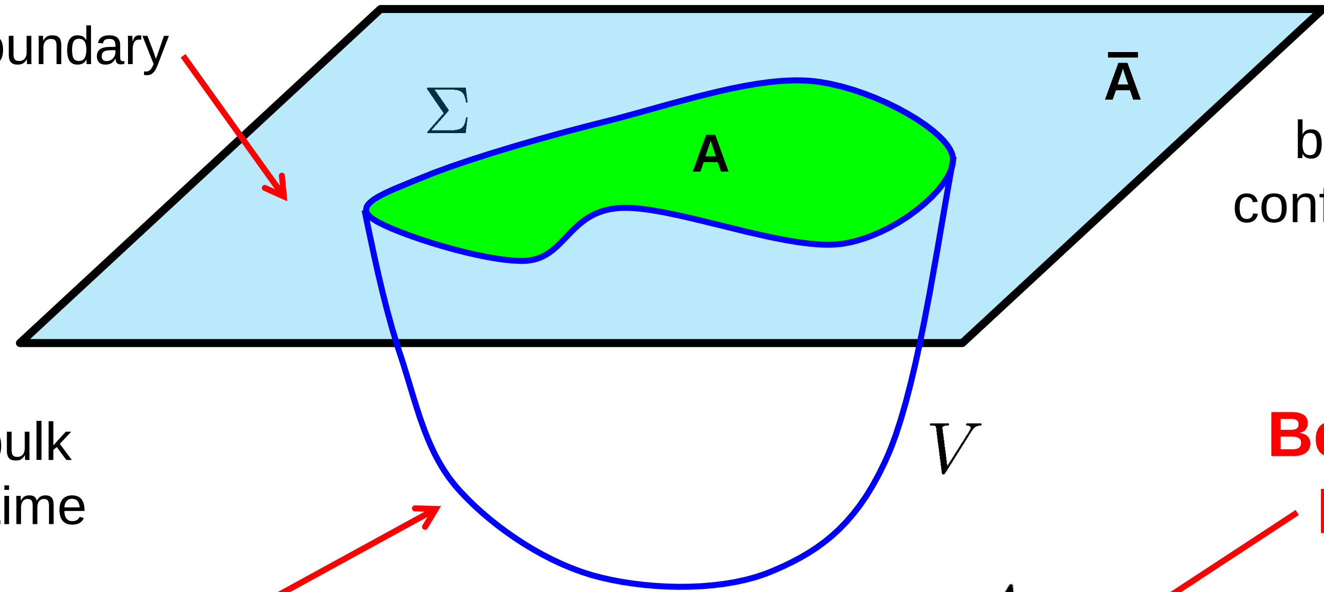
Quantum Extremal Islands Made Easy

with Chen, Neuenfeld, Reyes & Sandor; Hernandez & Ruan
(2006.04851 & 2010.00018; 2010.16398)

Holographic Entanglement Entropy:

(Ryu & Takayanagi `06)

AdS boundary



boundary conformal field theory

AdS bulk spacetime

Extremal Surface

Bekenstein-Hawking formula

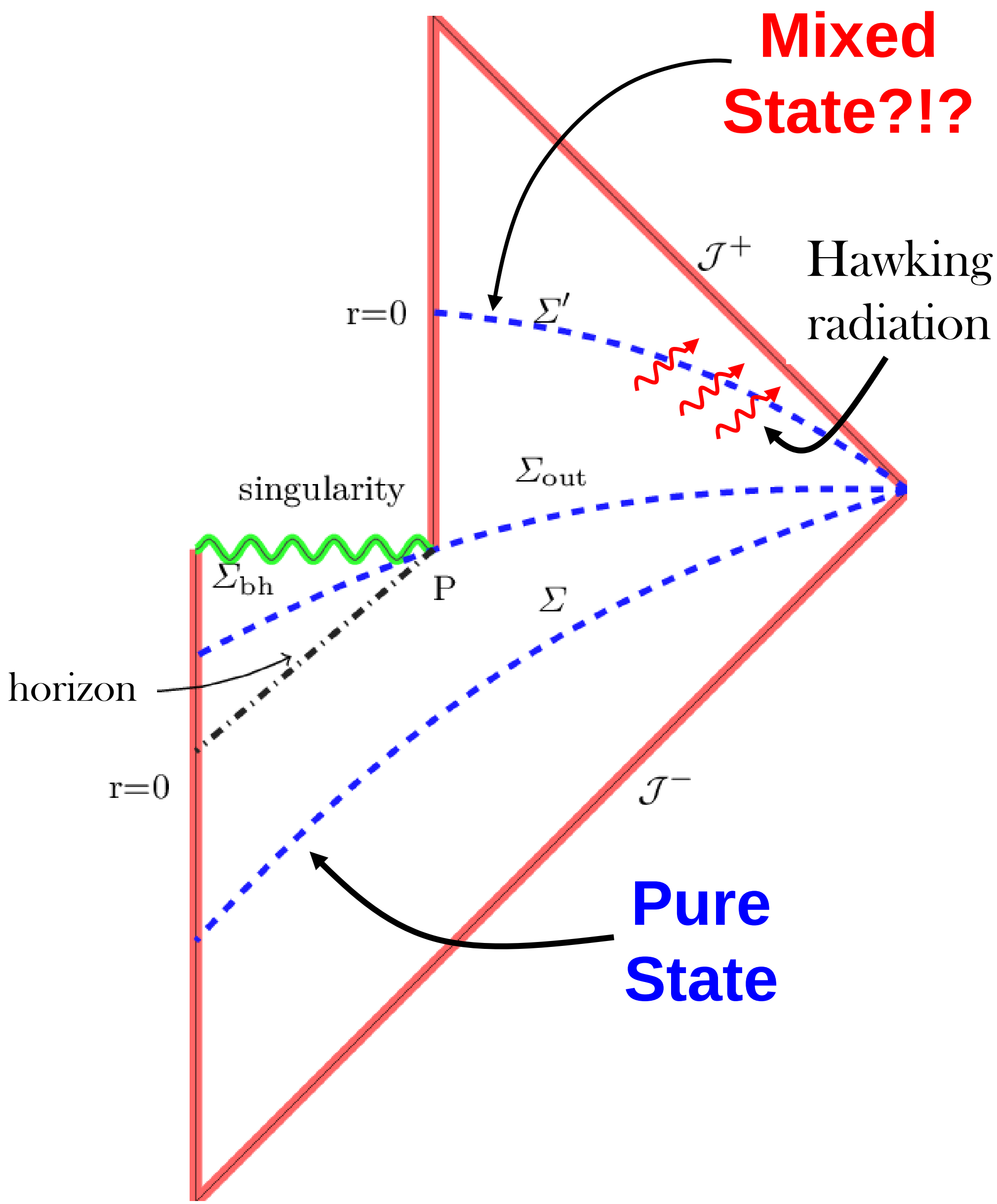
$$S(A) = \min_{\partial V \sim \Sigma} \frac{A_V}{4G_N}$$

- holographic EE is a fruitful forum for bulk-boundary dialogue:

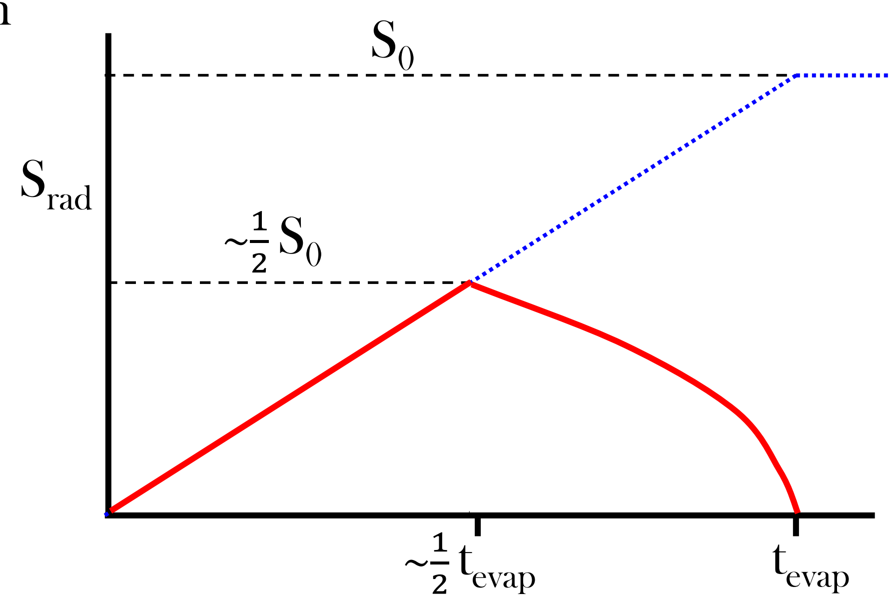
→ new lessons about quantum field theories

→ new lessons about quantum gravity

Black hole information paradox:



Page Curve



New insights from Holographic EE:

- with recent progress, it is possible to compute the Page curve in a controlled manner!

Penington [arXiv:1905.08255]
Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]
* Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]

➡ Island Rule:

- black hole coupled to an auxiliary non-gravitational reservoir (the “bath”), which captures the Hawking radiation
- entropy of the Hawking radiation is given by

$$S_{EE}(\mathbf{R}) = \min \left\{ \underset{\text{islands}}{\text{ext}} \left(S_{QFT}(\mathbf{R} \cup \text{islands}) + \frac{A(\partial(\text{islands}))}{4G_N} \right) \right\}$$

- evaluate the (semiclassical) entanglement entropy of quantum fields in the bath region **R** combined with various space-like subregions in the gravitating region, ie, islands, which also contribute the usual Bekenstein-Hawking entropy

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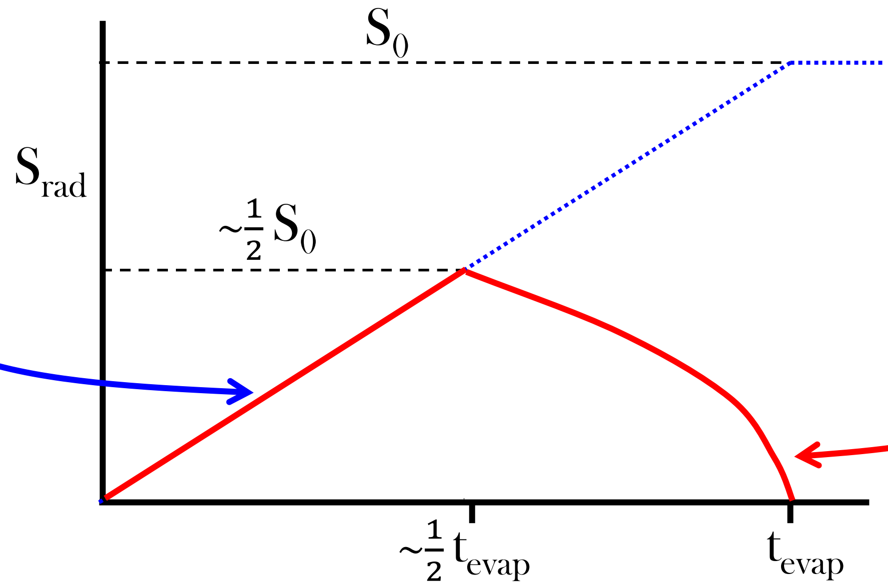
<u>Early</u>: island is the empty set; agrees with Hawking's calculation

<u>Late</u>: large entanglement between radiation and region behind horizon; **new saddle** with nontrivial island



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Key ingredients of early calculations:

$\longrightarrow$ AdS/CFT **but** absorbing or transparent b.c.

$\longrightarrow$ two-dimensional JT gravity

$\longrightarrow$ quantum extremal surfaces

extremize geometric/grav. entropy plus quantum S_{EE} of matter fields (Faulkner, Lewkowycz & Maldacena; Engelhardt & Wall)

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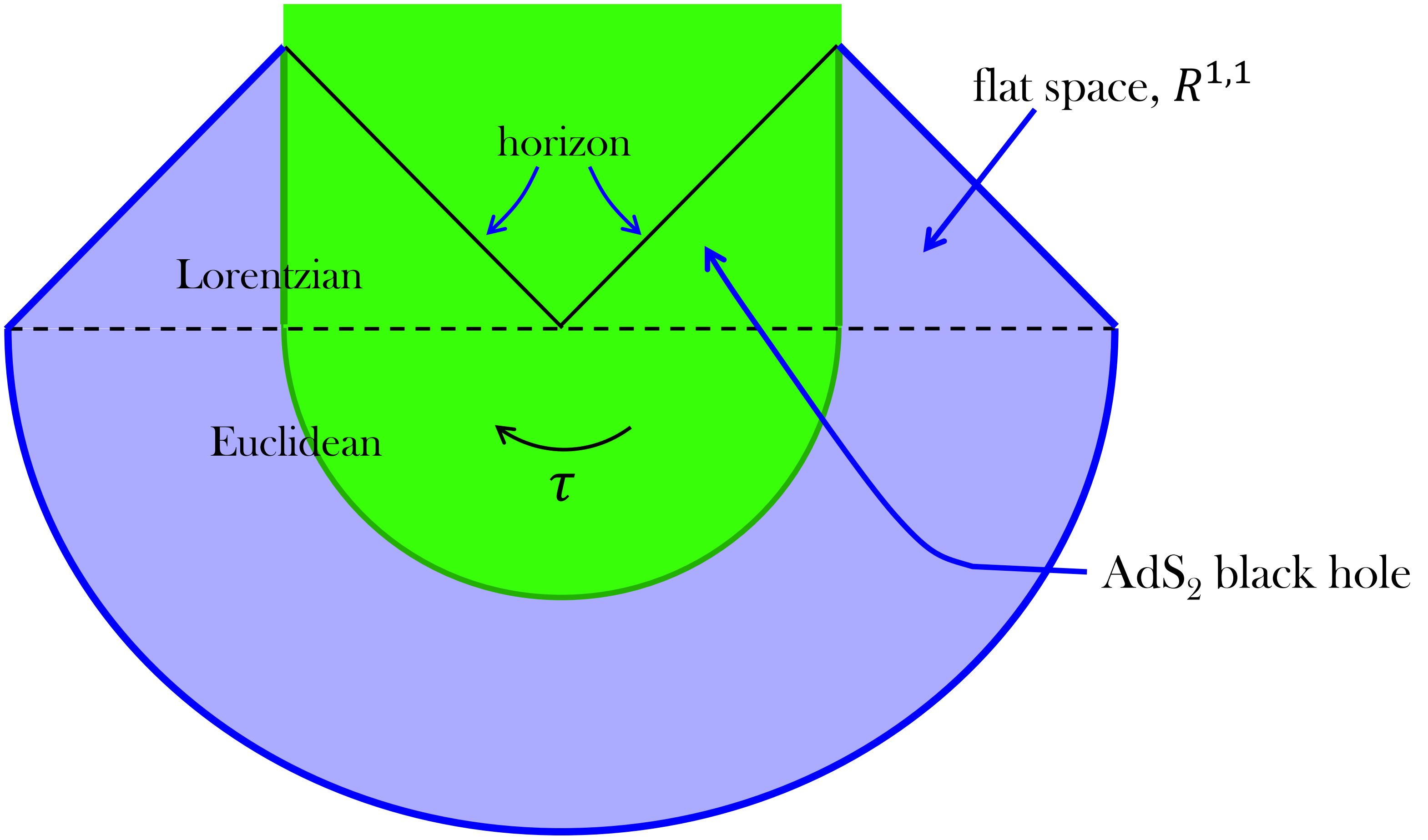
Example: Not Evaporating Black Holes!

Black Holes in Thermal Equilibrium:

Almheiri, Mahajan & Maldacena
(see also: Rozali, Van Raamsdonk, Waddell & Wakeham)

- simple holographic model: 2d JT gravity + CFT = 1d quantum mech's
- prepare state with 2d black hole & bath in thermal equilibrium



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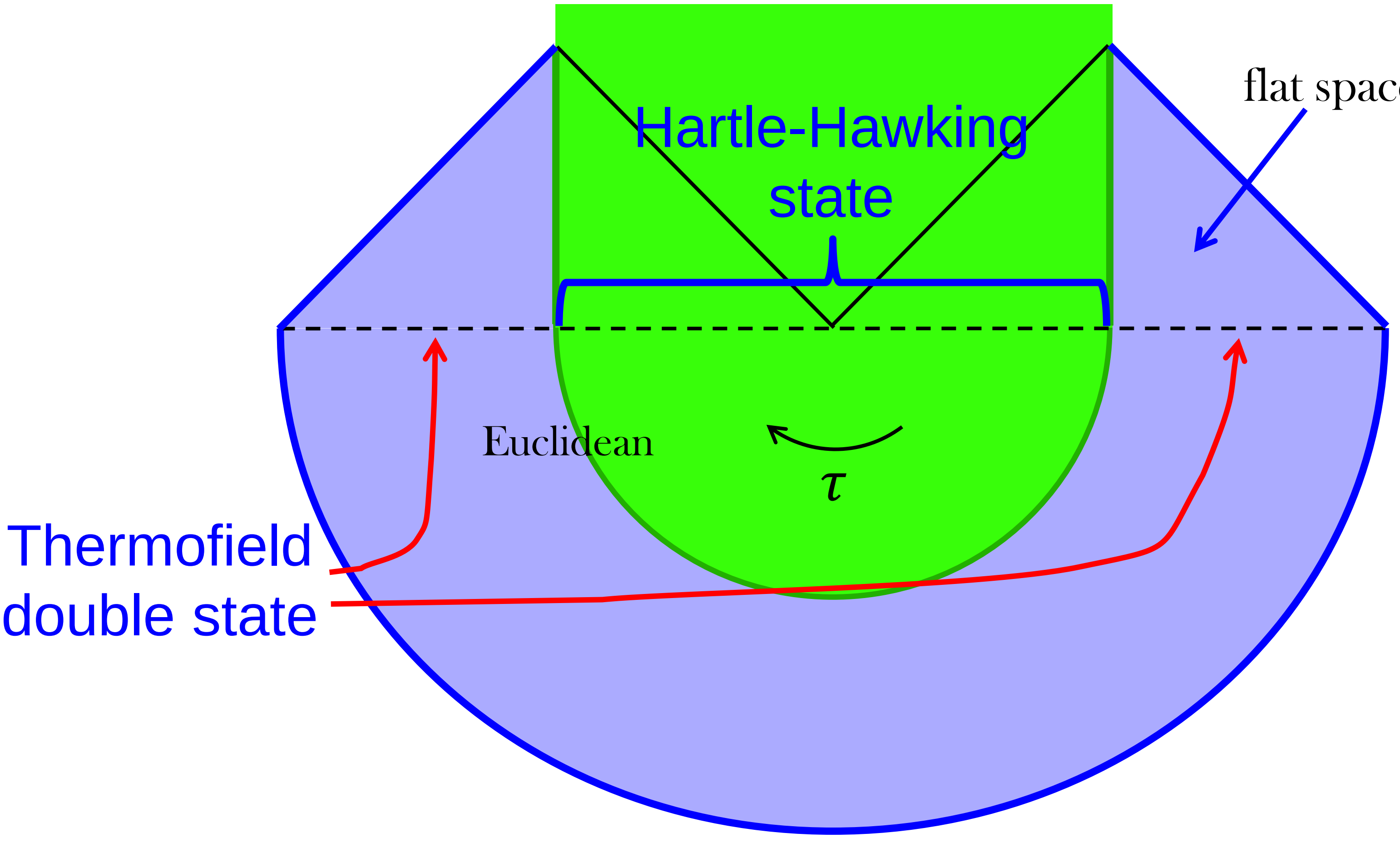

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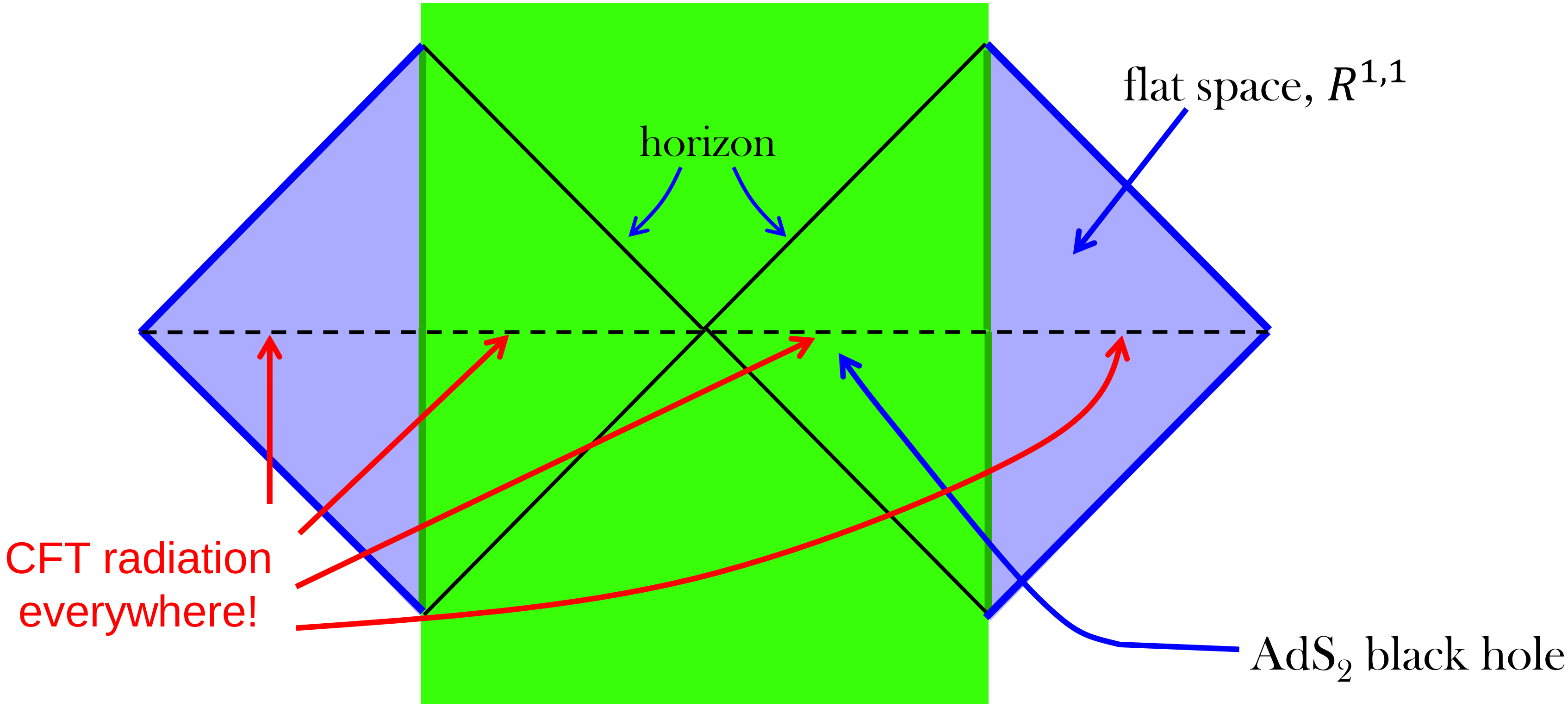

Thermal equilibrium? No information paradox?

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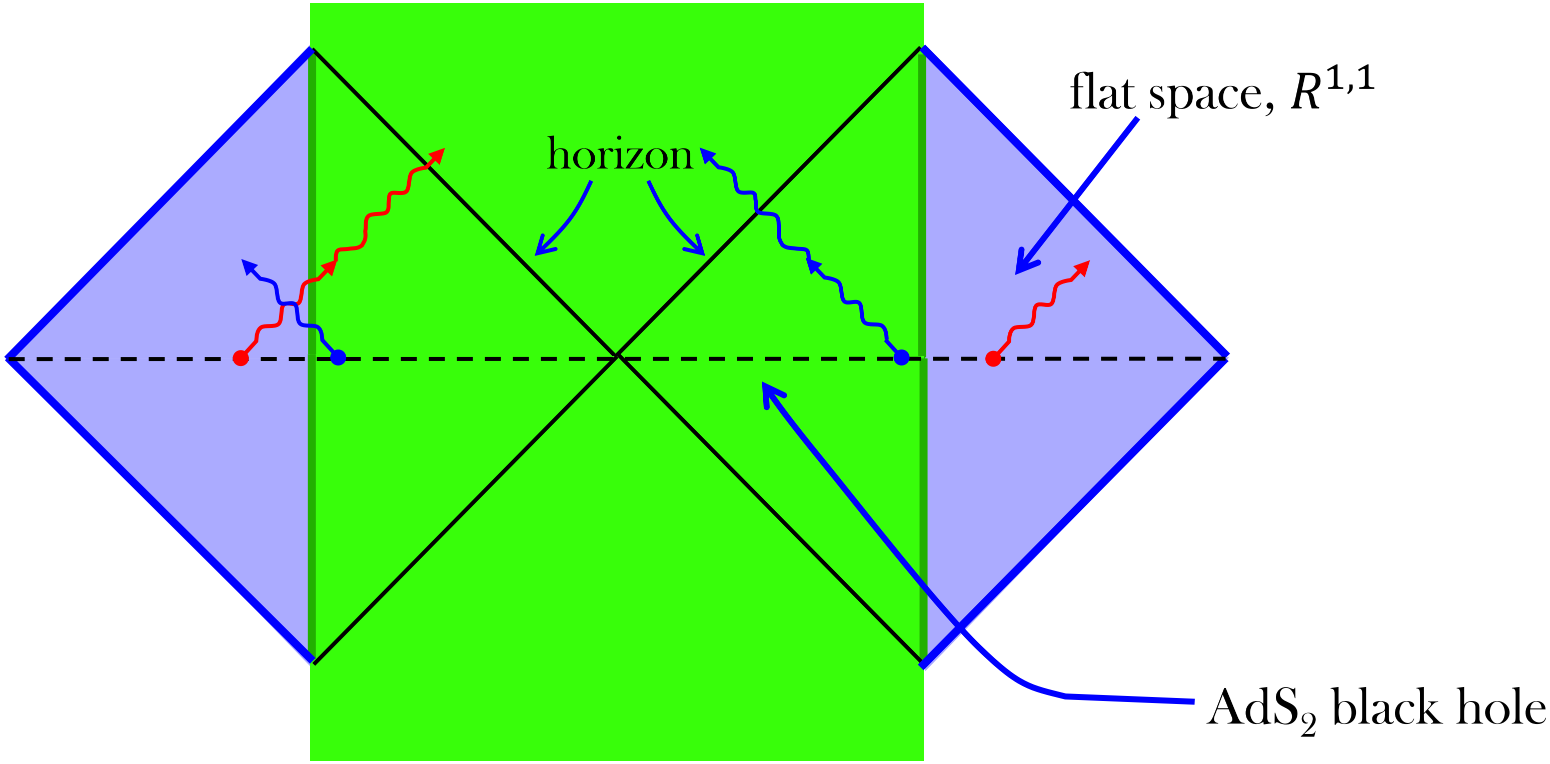

- eternal BH and bath are continuously exchanging radiation

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+ CFT
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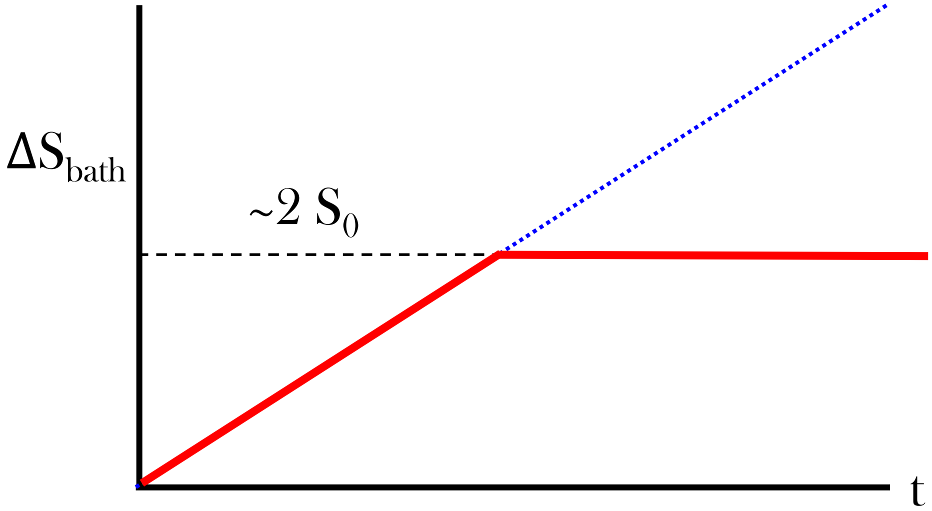
What does Page curve look like for eternal black hole?

- eternal BH and bath are continuously exchanging radiation



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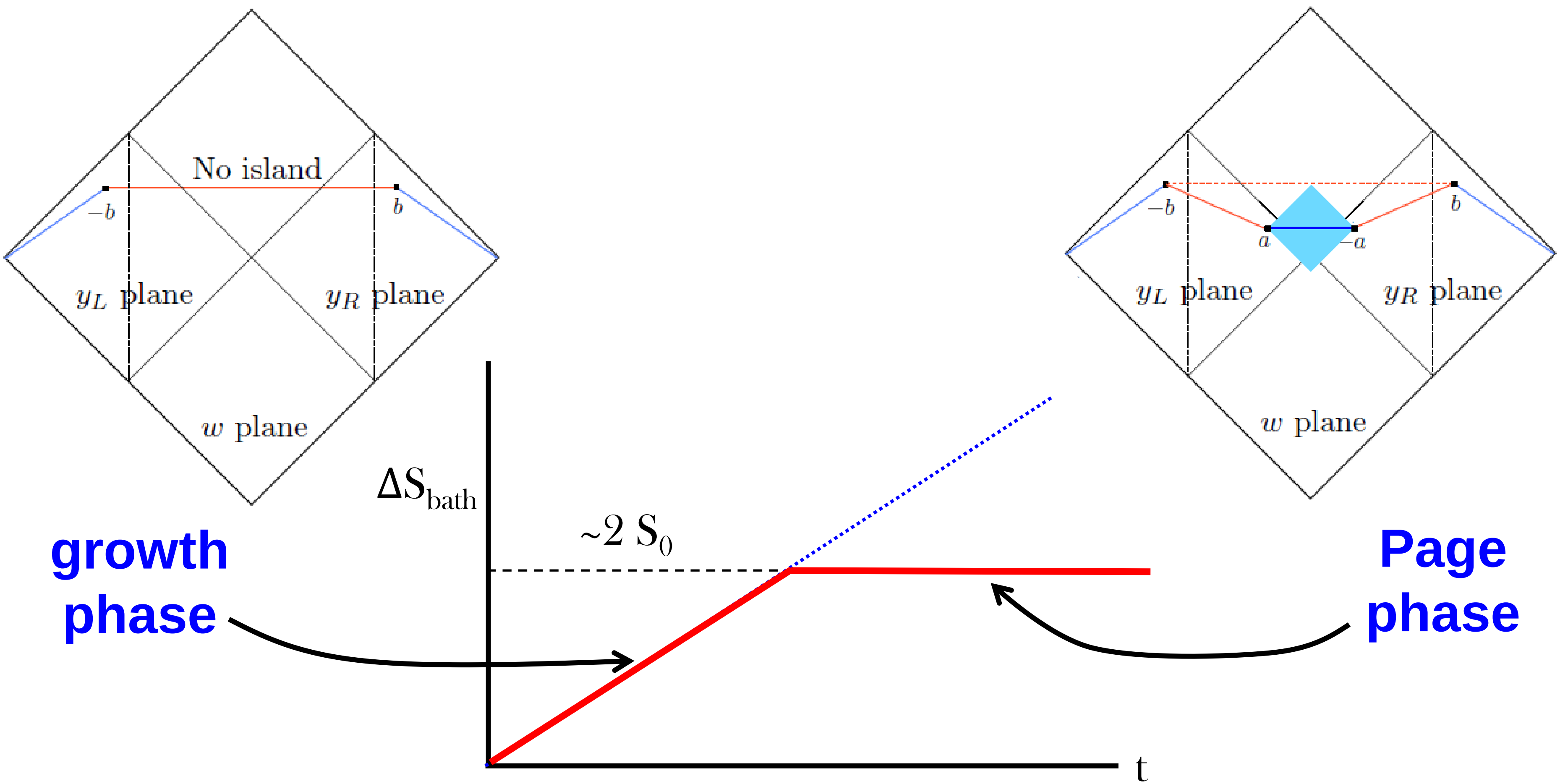

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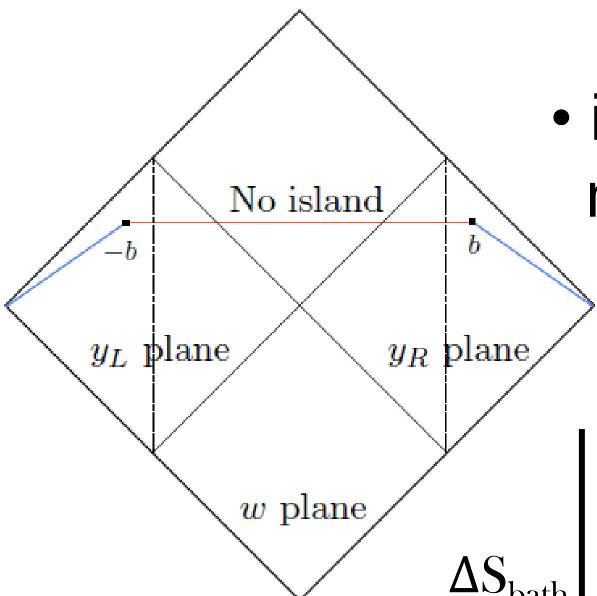
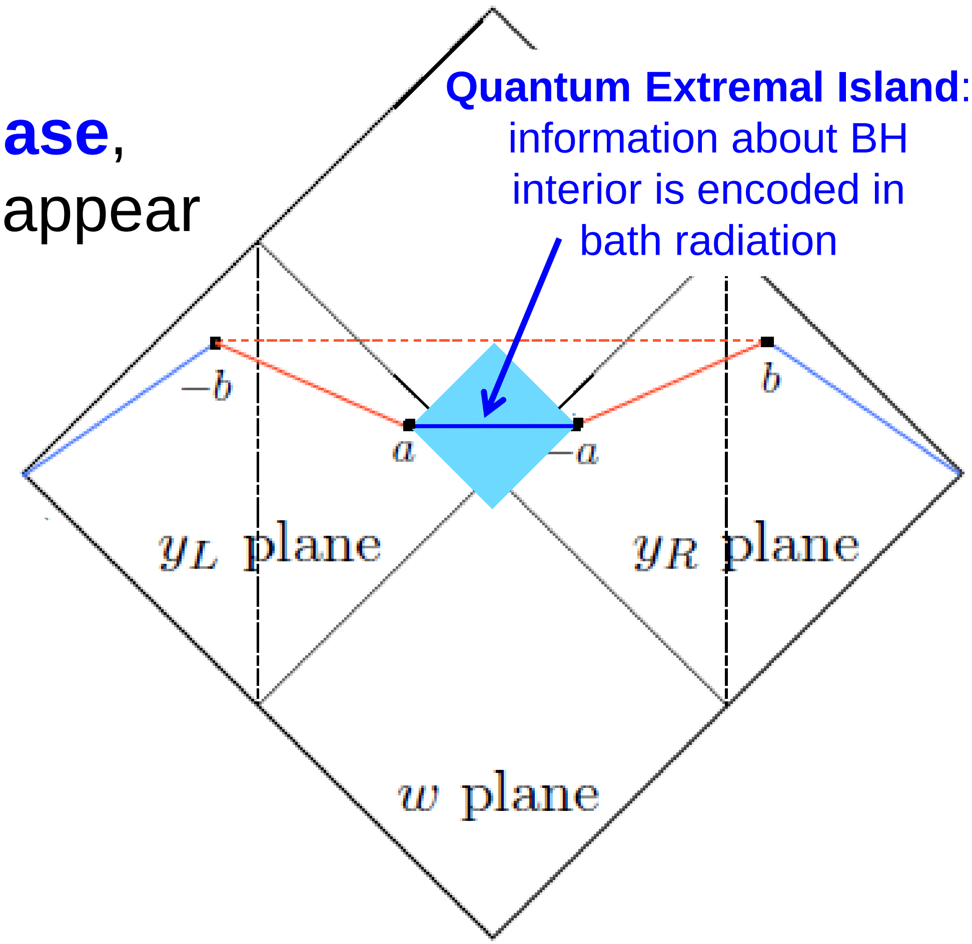
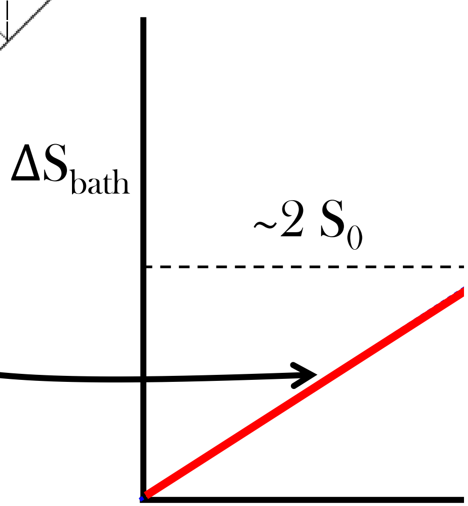


- in **Page phase**, new QESs appear



growth phase



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Questions, Questions, Questions:

- how important is two dimensions?
- are dof on Planck brane part of boundary or bulk?
- was JT gravity important?
- was ensemble average of SYK model important?
- how was information encoded in Hawking radiation?

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Many of new insights can be understood as familiar properties of holographic entanglement entropy

- how was information encoded in Hawking radiation?

(see also: Geng & Karch)

Randall-Sundrum gravity (quick review):

- introduce d-dim. brane in (d+1)-dim. AdS geometry, backreaction creates extra d-dim. graviton mode localized on brane:

$$I_{\rm bulk} = \frac{1}{16\pi G_{\rm bulk}} \int d^{d+1}x\,\sqrt{-g}\left[\frac{d(d-1)}{L^2} + R(g)\right]$$

$$I_{\rm brane} = -T_0 \int d^d x \sqrt{-\tilde{g}}$$

(see also: Geng & Karch)

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L^2/ℓ_{eff}^4

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with $$\frac{1}{G_{\text{eff}}} = \frac{2\,L}{(d-2)\,G_{\text{bulk}}} \,; \qquad \frac{1}{\ell_{\text{eff}}^2} \simeq \frac{2}{L^2}\left(1 - \frac{4\pi\, G_{\text{bulk}}\, L\, T_0}{d-1}\right) \ll \frac{1}{L^2}$$

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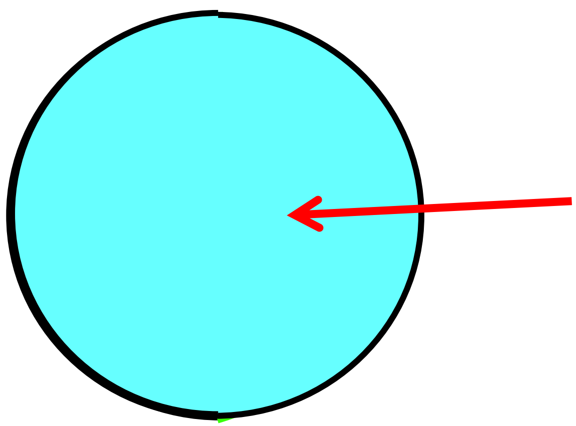
- “position” of brane can be determined by: using Israel junction conditions



cross-section of AdS_{d+1}

$$ds^2 = L^2\left[d\rho^2 + \cosh^2\!\rho\; d\Sigma_d^2\right]$$ ← AdS_d

(see also: Geng & Karch)

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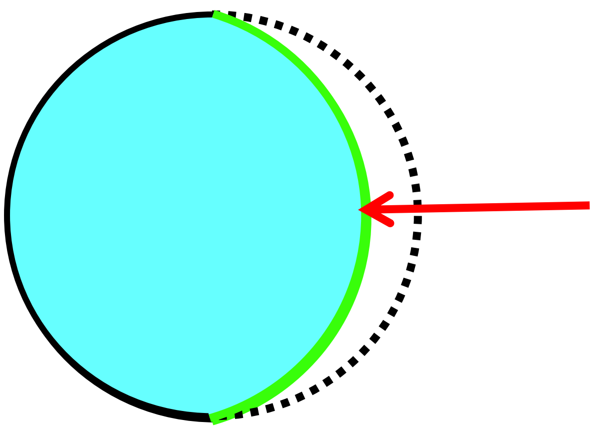

cut off at ρ_{brane}

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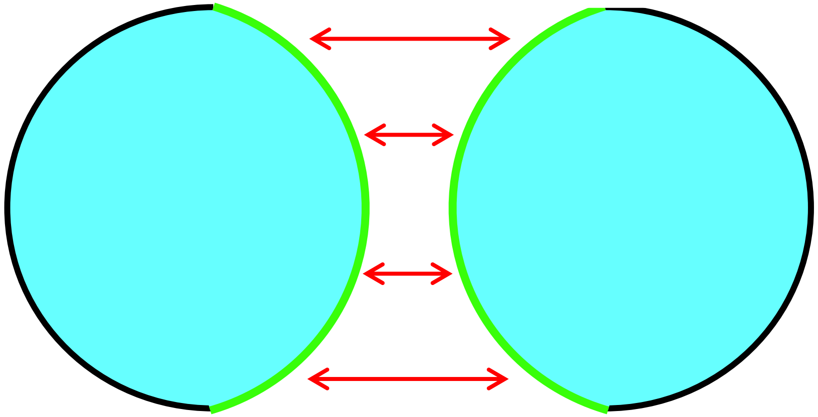

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$$\Delta K_{ij} - \tilde g_{ij}\,\Delta K^\ell{}_\ell = -8\pi G_{\rm bulk} T_0\,\tilde g_{ij}$$

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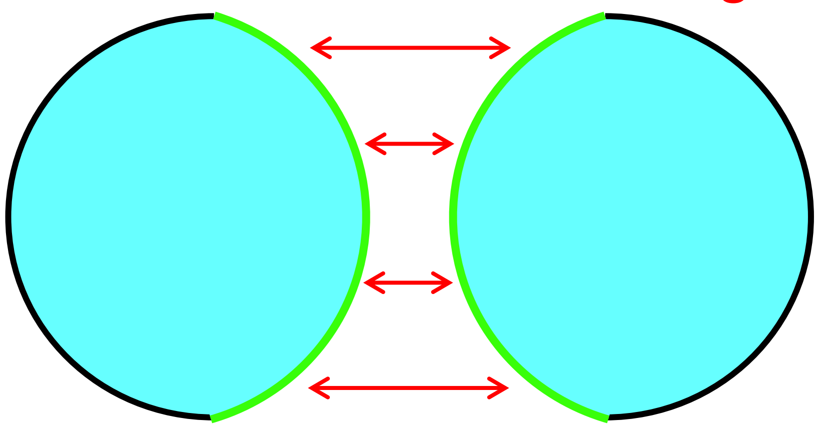
- “position” of brane can be determined by:

using Israel junction conditions or solving brane gravity eom

$$\frac{1}{\ell_{\rm eff}^2} = \frac{1}{\ell_{\rm B}^2}\left[1 + \frac{1}{4}\frac{L^2}{\ell_{\rm B}^2} + \cdots\right]$$

with $\ell_{\rm B} = L\,\cosh\rho_{\rm brane}$



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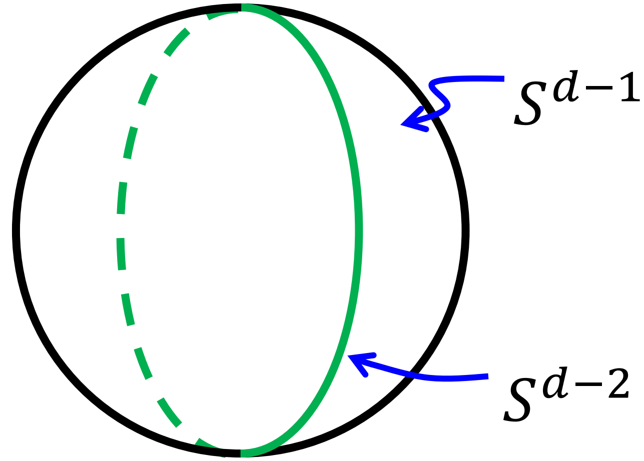
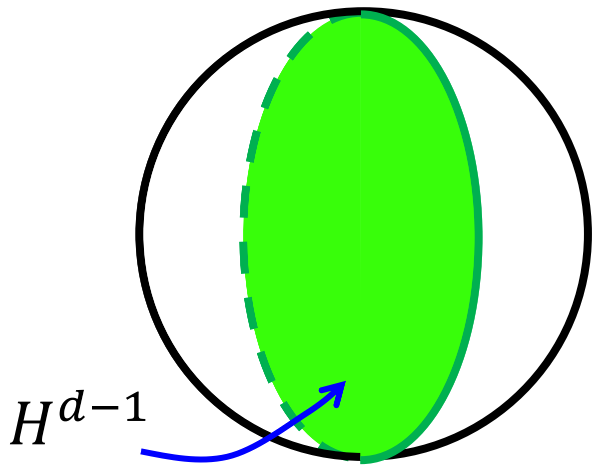
AdS_d

Randall-Sundrum gravity:

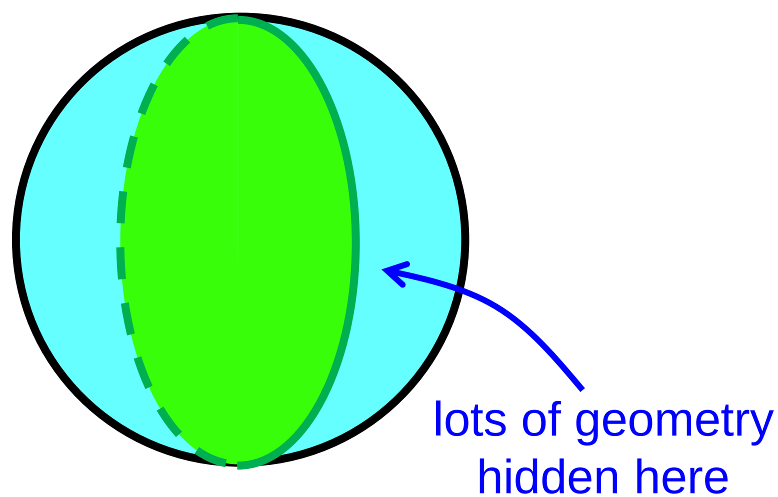
(a) boundary $\mathrm{CFT_d}$ coupled to conformal defect (ie, boundary $\mathrm{CFT_{d-1}}$)





(b) boundary $\mathrm{CFT_d}$ coupled to $\mathrm{CFT_d}$ with gravity on $\mathrm{AdS_d}$

(c) $\mathrm{AdS_{d+1}}$ gravity coupled to brane with $\mathrm{AdS_d}$ geometry

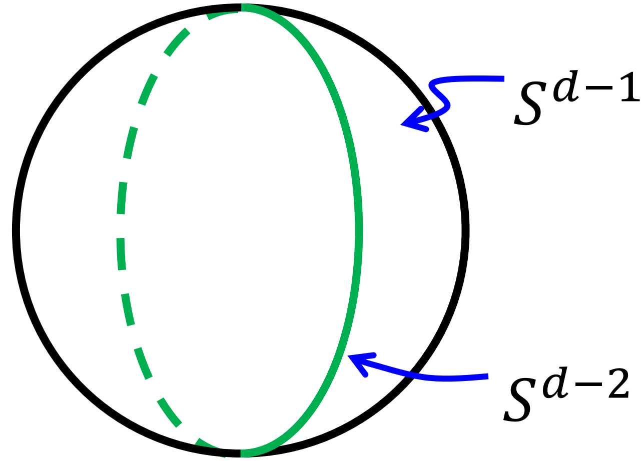


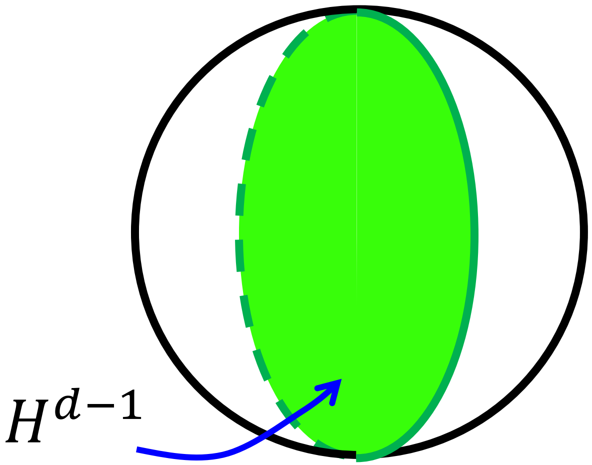
Randall-Sundrum gravity:

AdS/CFT correspondence

Boundary perspective

(a) boundary CFT_d coupled to conformal defect (ie, boundary CFT_{d-1})

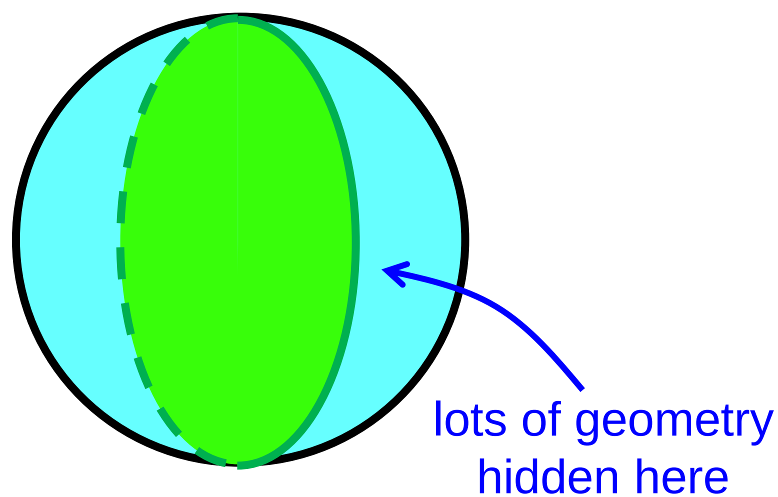




(b) boundary CFT_d coupled to CFT_d with gravity on AdS_d

Bulk perspective

(c) AdS_{d+1} gravity coupled to brane with AdS_d geometry



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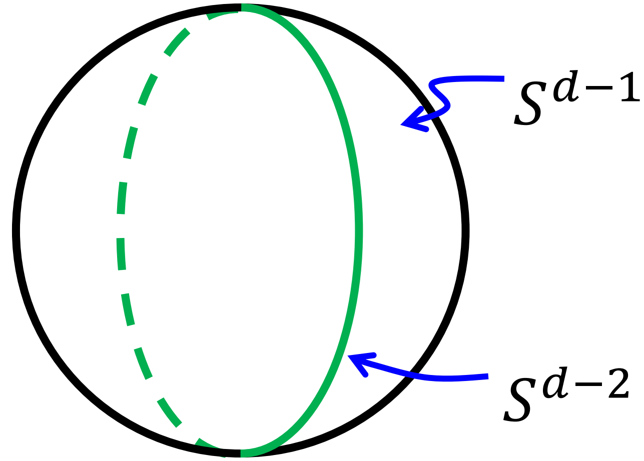
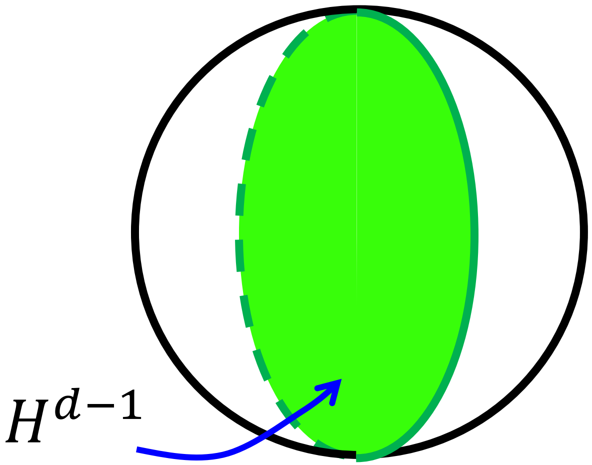


Brane perspective

(b) boundary $\mathrm{CFT_d}$ coupled to $\mathrm{CFT_d}$ with <u>gravity</u> on $\mathrm{AdS_d}$

only an effective theory!



Bulk perspective

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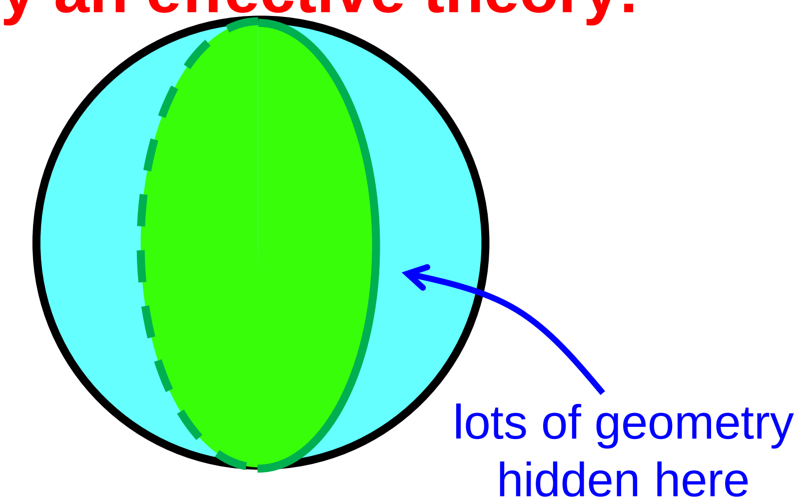
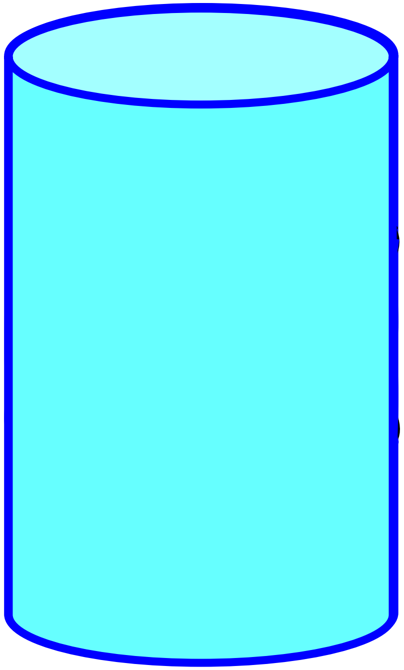


Black Holes in Thermal Equilibrium:

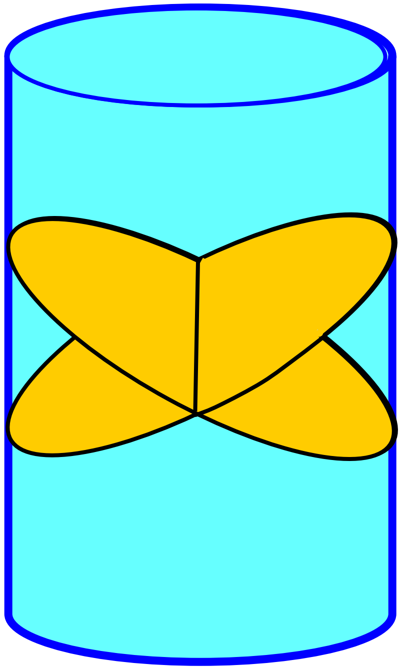
- AdS_{d+1} gravity ~~coupled to brane with AdS_d geometry~~



Black Holes in Thermal Equilibrium:

- AdS_{d+1} gravity ~~coupled to brane with AdS_d geometry~~
- empty AdS_{d+1} space can be described as “hyperbolic” black hole

$$ds^2 = \frac{L^2\, d\rho^2}{(\rho^2 - L^2)} - \frac{\rho^2 - L^2}{R^2}\, dt^2 + \rho^2\, d\Sigma_{d-1}^2$$



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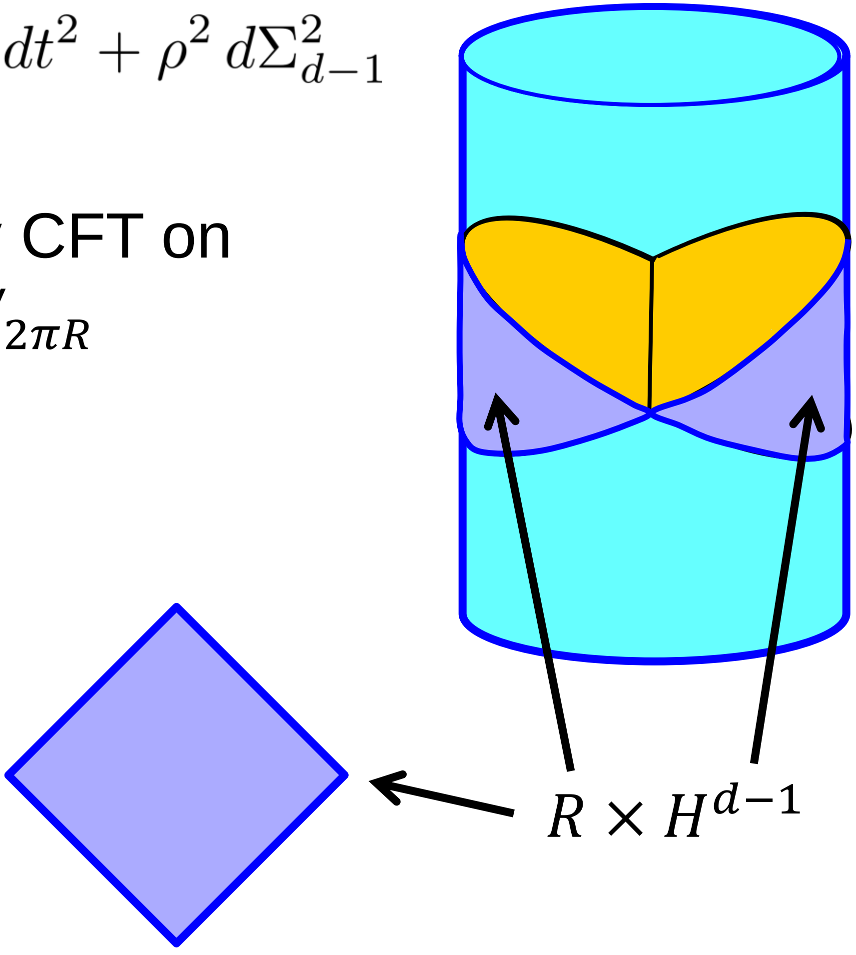

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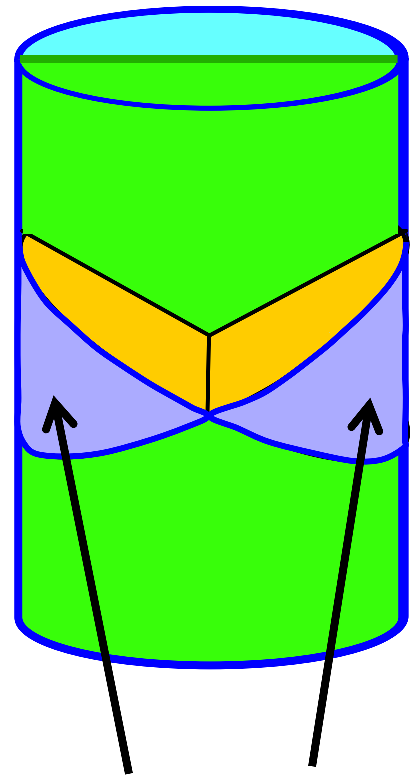
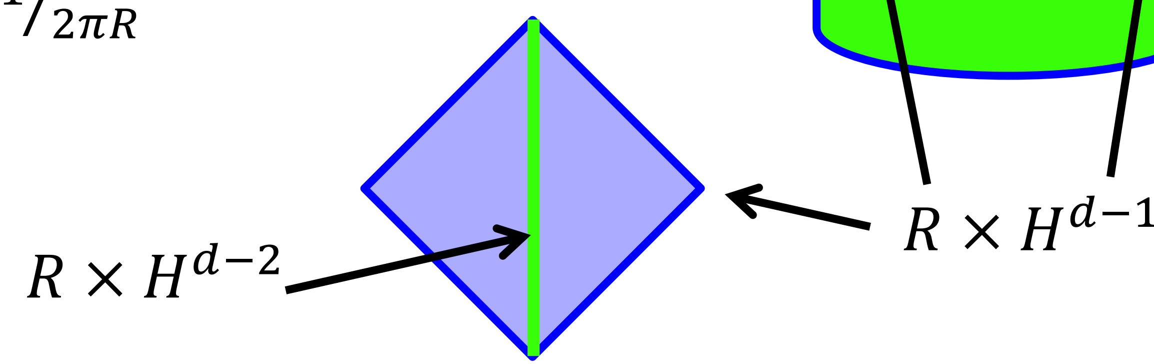


- describes TFD state of boundary CFT on $R \times H^{d-1}$ at temperature $T = {}^{1}/_{2\pi R}$
- insert brane, describes TFD state of boundary CFT coupled to conformal defect on $R \times H^{d-1}$ at temperature $T = {}^{1}/_{2\pi R}$



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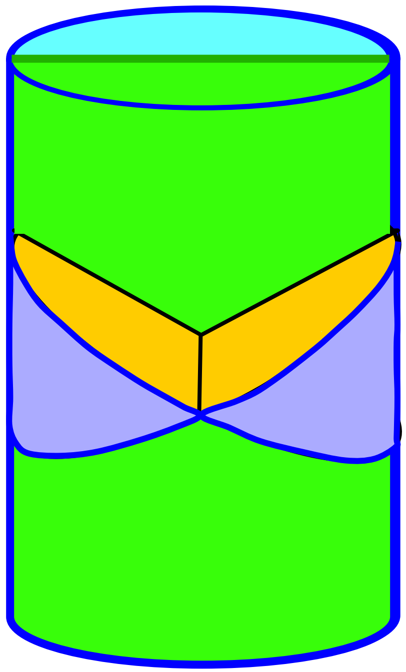
- empty AdS_{d+1} space can be described as "hyperbolic" black hole

$$ds^2 = \frac{L^2\, d\rho^2}{(\rho^2 - L^2)} - \frac{\rho^2 - L^2}{R^2}\, dt^2 + \rho^2\, d\Sigma_{d-1}^2$$



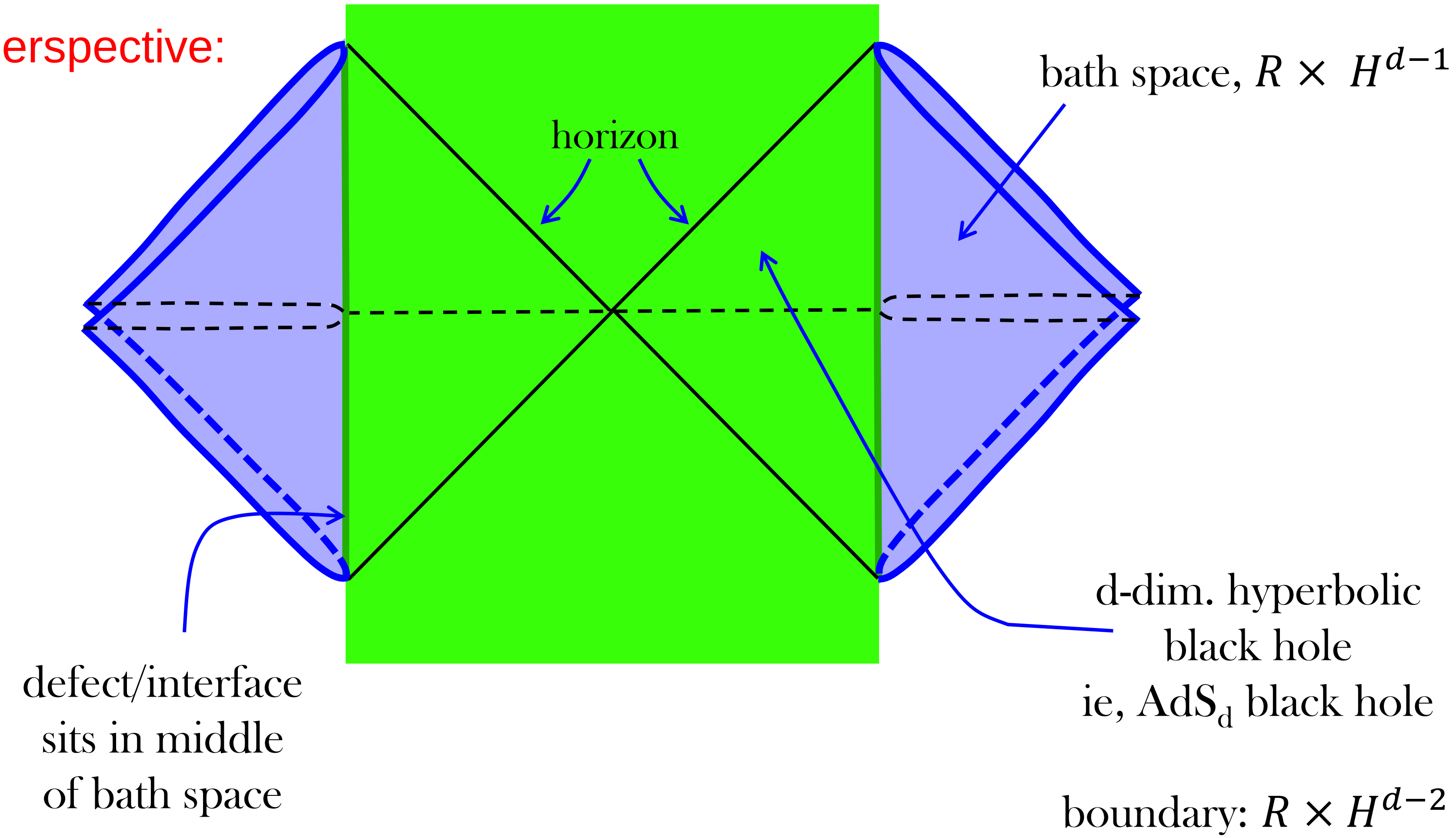
- describes TFD state of boundary CFT on $R \times H^{d-1}$ at temperature $T = {}^1/_{2\pi R}$
- insert brane, describes TFD state of boundary CFT coupled to conformal defect on $R \times H^{d-1}$ at temperature $T = {}^1/_{2\pi R}$
- induced brane metric "inherits" hyperbolic black hole geometry

$$ds^2 = \frac{\ell_B^2\, d\tilde\rho^2}{\tilde\rho^2 - \ell_B^2} - \frac{\tilde\rho^2 - \ell_B^2}{R^2}\, dt^2 + \tilde\rho^2\, d\Sigma_{d-2}^2$$

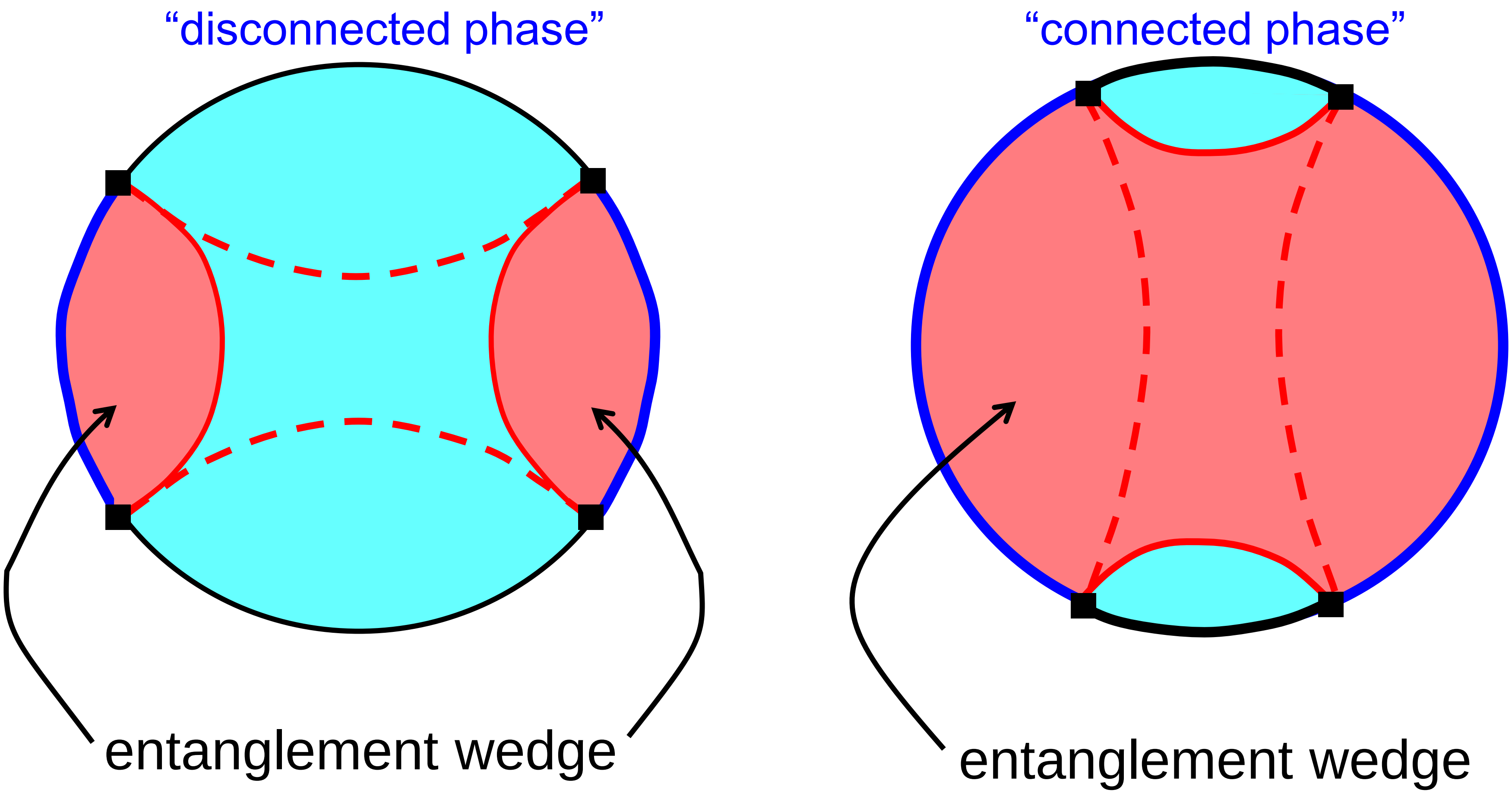
Black Holes in Thermal Equilibrium:

- previous discussion lifts to higher dim'l holographic model with d=2 JT gravity ⟶ induced d-dim. Einstein gravity (& CFT)

Brane perspective:

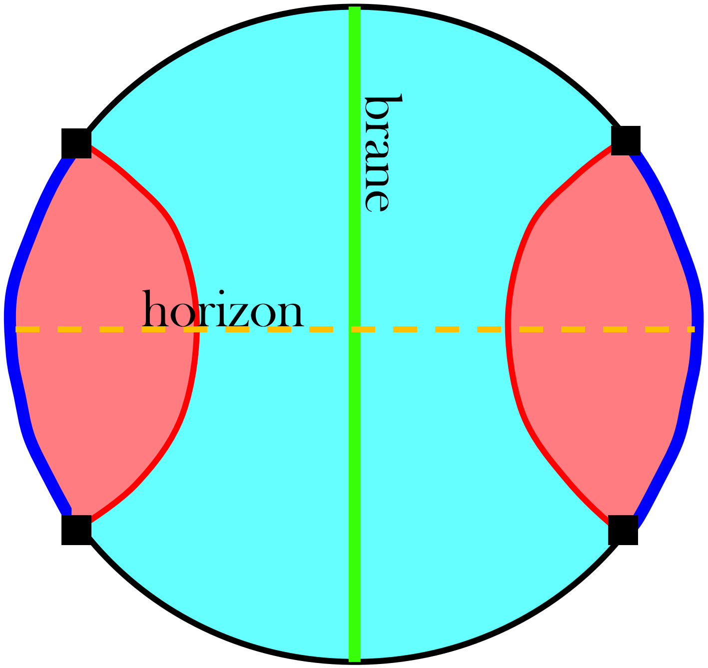


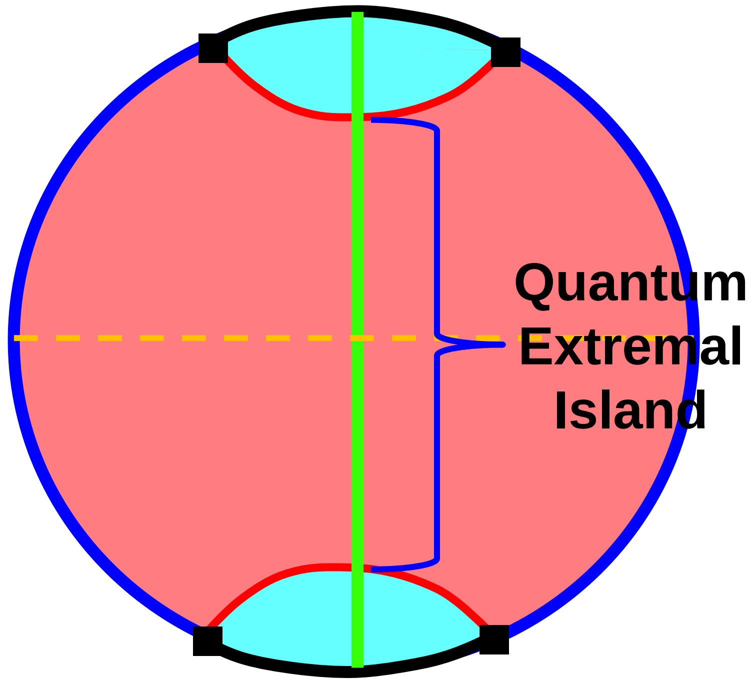
→ recall familiar holographic EE scenario:
two saddles compete to give minimal RT surface



• entanglement wedge reconstruction: can recover bulk operators (within code subspace) inside entanglement wedge with boundary CFT operators in corresponding boundary subregion

→ recall familiar holographic EE scenario:
two saddles compete to give minimal RT surface





Early times:

- RT surfaces join opposite sides of BH → EE grows with time
- entanglement wedge close to boundary

→ **growth phase**

Late times:

- RT surfaces on single side of BH → EE fixed in time
- entanglement wedge extends through brane → QE island

→ **Page phase**

Black Holes in Thermal Equilibrium:

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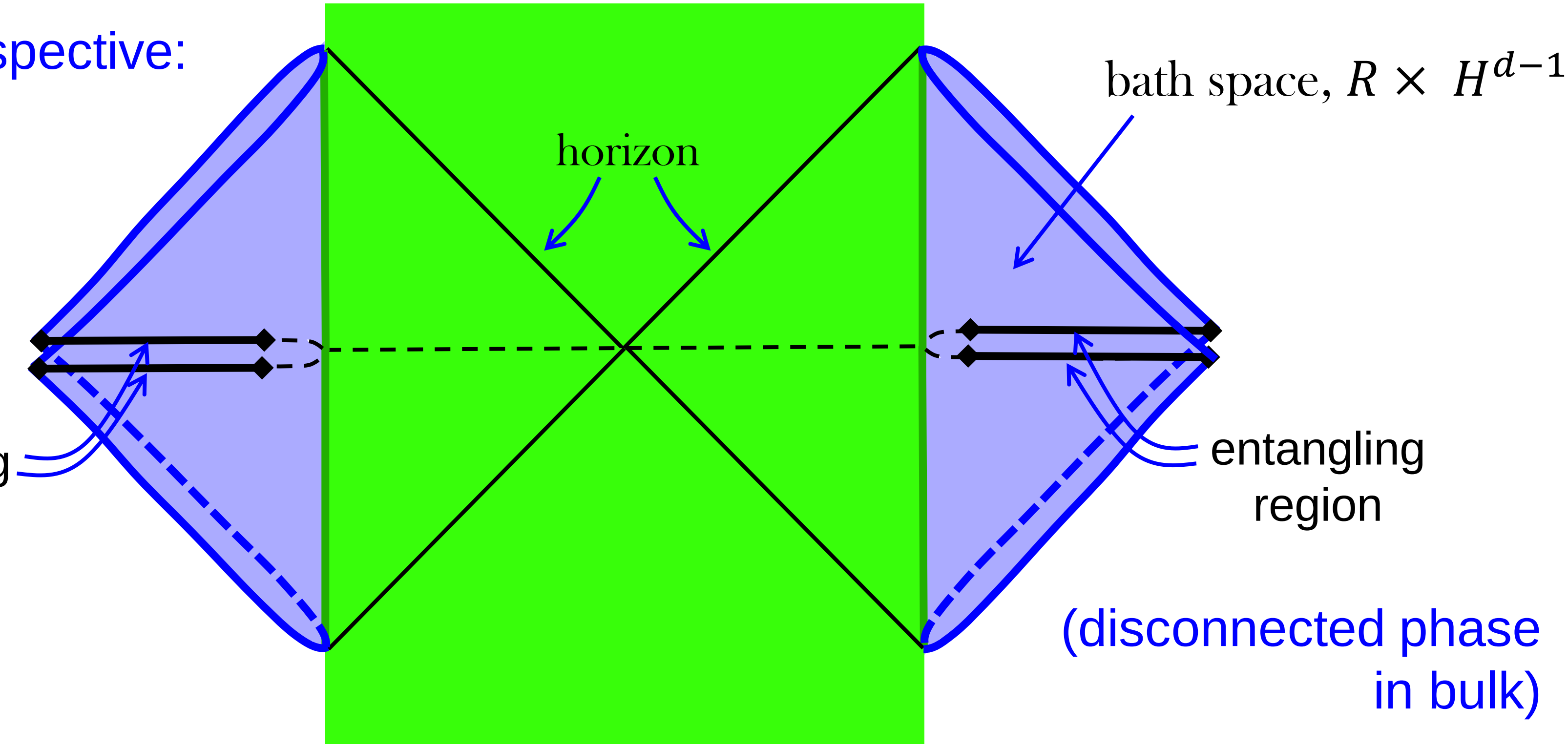
- new model reproduces the island formula:

$$S_{EE}(\mathbf{R}) = \min\left\{ \underset{\text{islands}}{\text{ext}} \left(S_{QFT}(\mathbf{R} \cup \text{islands}) + \frac{A(\partial(\text{islands}))}{4G_N} \right) \right\}$$

brane perspective:



(disconnected phase in bulk)

Early times: standard QFT rules apply (no island); EE grows

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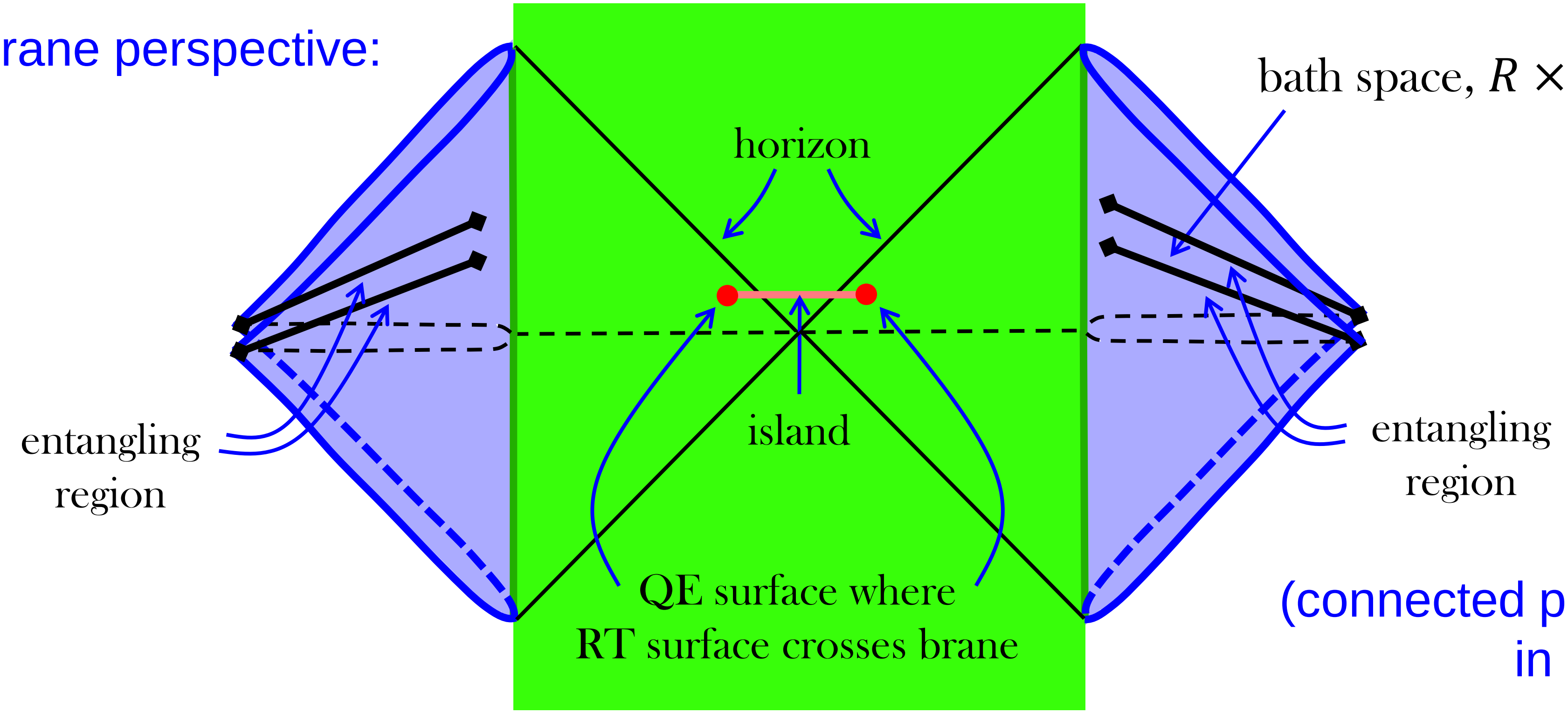

(connected phase in bulk)

Late times: quantum extremal island forms; EE saturated

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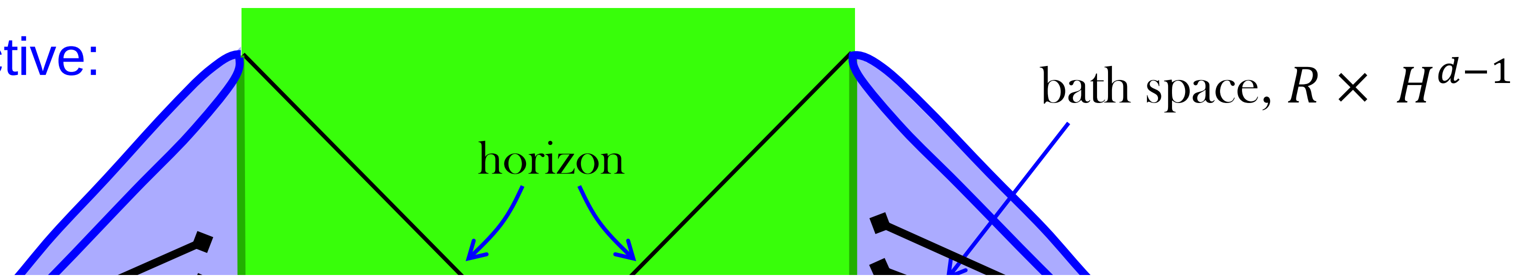
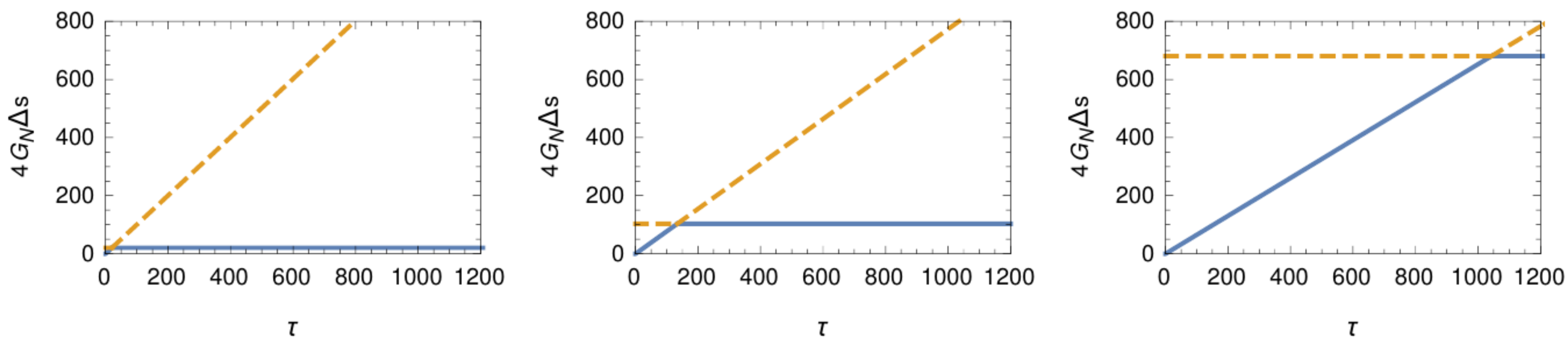




Late times: quantum extremal island forms; EE saturated

Questions, Questions, Questions:

- how important is two dimensions?

$\longrightarrow$ **not at all**, our construction extends discussion to gravity and black holes in d dimensions

(see also: Almheiri, Mahajan & Santos)

- was JT gravity important?

$\longrightarrow$ **no**, our construction extends discussion to Einstein gravity and black holes in d dimensions

- was ensemble average of SYK model important?

$\longrightarrow$ **no**, our construction relies on standard rules of AdS/CFT correspondence, ie, do not average over couplings in boundary CFT

(Note top-down construction with D3 $\perp$ D5 by Karch & Randall)

Questions, Questions, Questions:

- Almheiri, Mahajan & Maldacena distinguish "*full quantum description*" of radiation and "*semiclassical description*" which includes outgoing radiation and purifying partners on QE island (ie, boldface notation)

Island Rule:

$$S_{EE}(\mathbf{R}) = \min\left\{\operatorname*{ext}_{\text{islands}}\left(S_{QFT}(\mathbf{R}\cup\text{islands}) + \frac{A(\partial(\text{islands}))}{4G_N}\right)\right\}$$

"*full quantum description*"

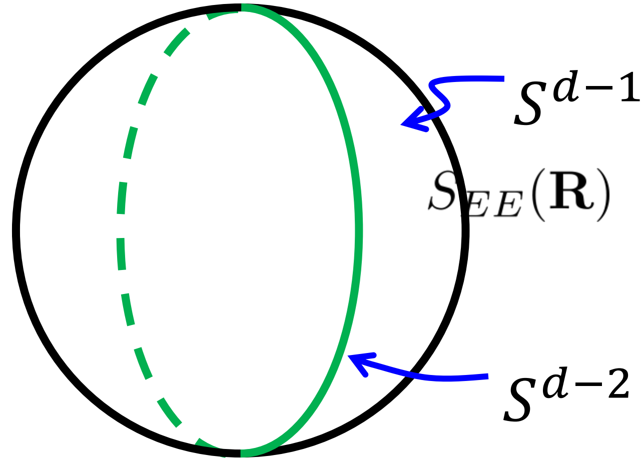
"*semiclassical description*"

- what's up with that?

Randall-Sundrum gravity:

Boundary perspective

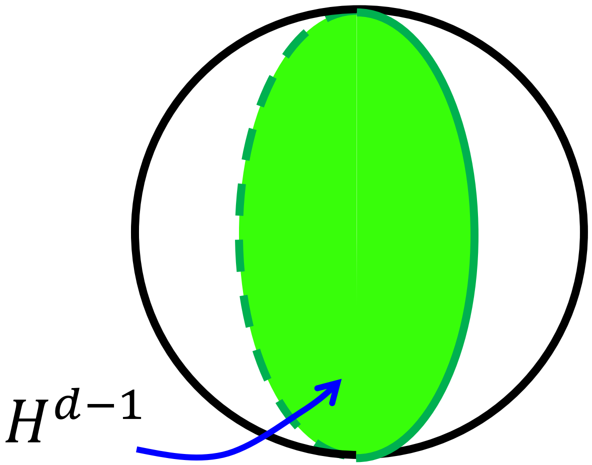
(a) boundary CFT_d coupled to conformal defect (ie, boundary CFT_{d-1})



Brane perspective

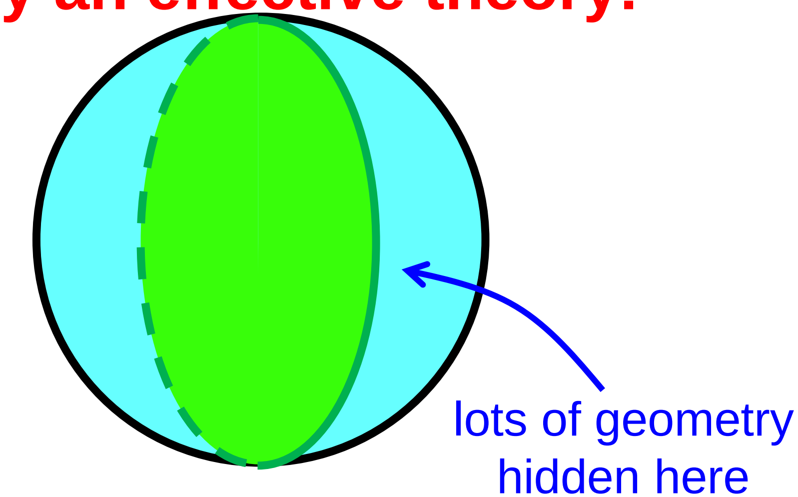
(b) boundary CFT_d coupled to CFT_d with gravity on AdS_d

only an effective theory!



Bulk perspective

(c) AdS_{d+1} gravity coupled to brane with AdS_d geometry



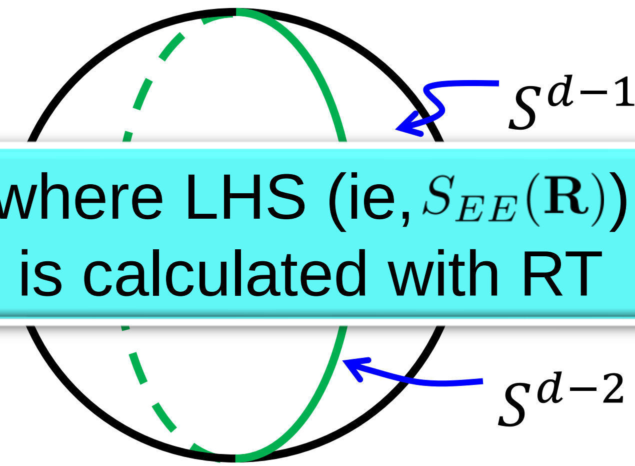
AdS/CFT correspondence

Randall-Sundrum gravity:

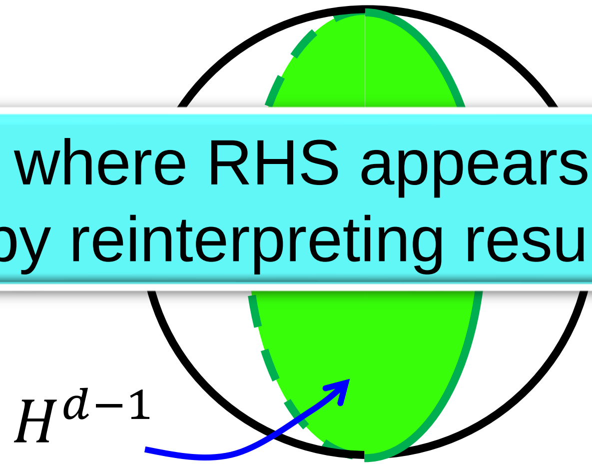
AdS/CFT correspondence

Boundary perspective

(a) boundary CFT$_d$ coupled to conformal defect (ie, boundary CFT$_{d-1}$)



where LHS (ie, $S_{EE}(\mathbf{R})$) is calculated with RT



where RHS appears by reinterpreting result

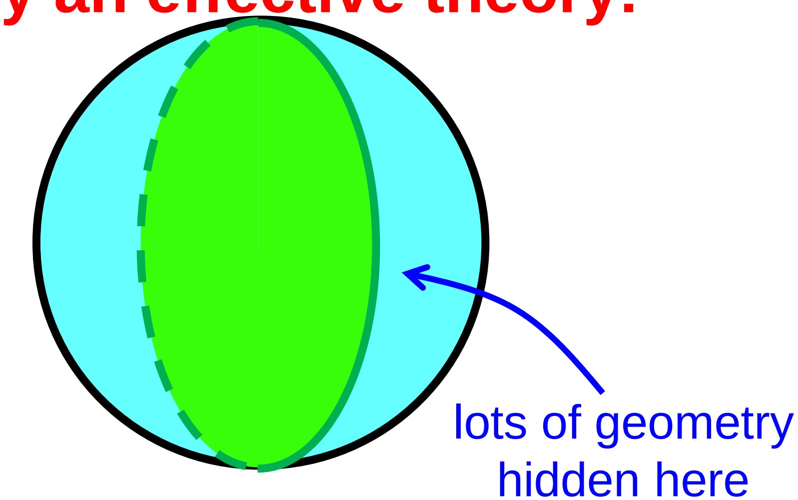
Brane perspective

(b) boundary CFT$_d$ coupled to CFT$_d$ with gravity on AdS$_d$

only an effective theory!

Bulk perspective

(c) AdS$_{d+1}$ gravity coupled to brane with AdS$_d$ geometry



Randall-Sundrum gravity:

Boundary perspective

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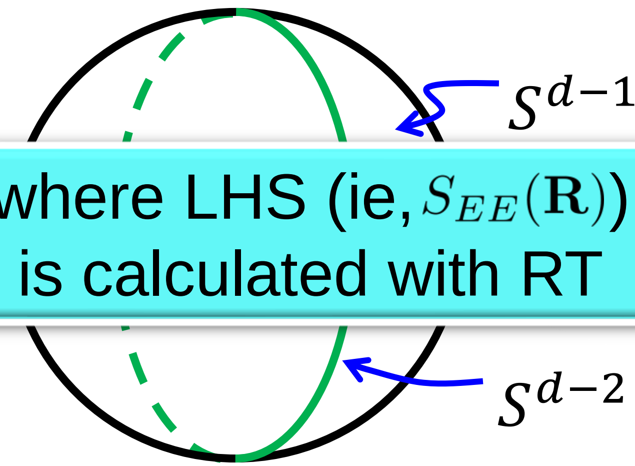

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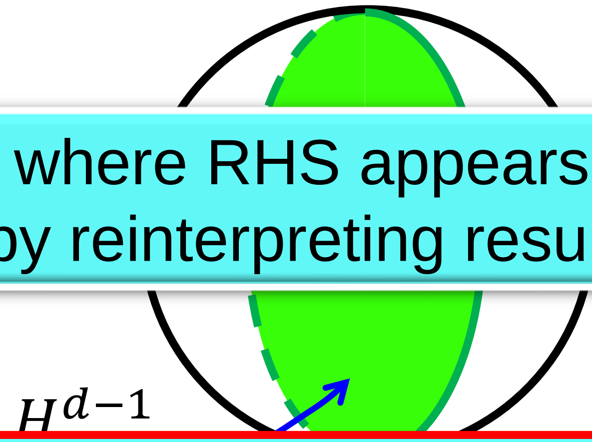
CFT correspondence

Brane perspective



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only an effective theory!

Island rule: $S_{EE}(\mathbf{R}) = \min\left\{ \underset{\text{islands}}{\text{ext}} \left(S_{QFT}(\mathbf{R} \cup \text{islands}) + \frac{A(\partial(\text{islands}))}{4G_N} \right) \right\}$

- provides mnemonic for "effective" gravitational theory
- within this framework, can not reveal "hidden"correlations

compare: Akers, Engelhardt & Harlow

hidden here

Conclusions:

- simple holographic model illustrates the appearance of quantum extremal islands
- new insights viewed as familiar properties of holographic EE
- has information paradox been solved?

NO, not yet!

- Page phase can be described by saddle point without revealing microscopic details with large-N!!

$\rightarrow$ what/how learn about microstates and information?

Still lots to explore!