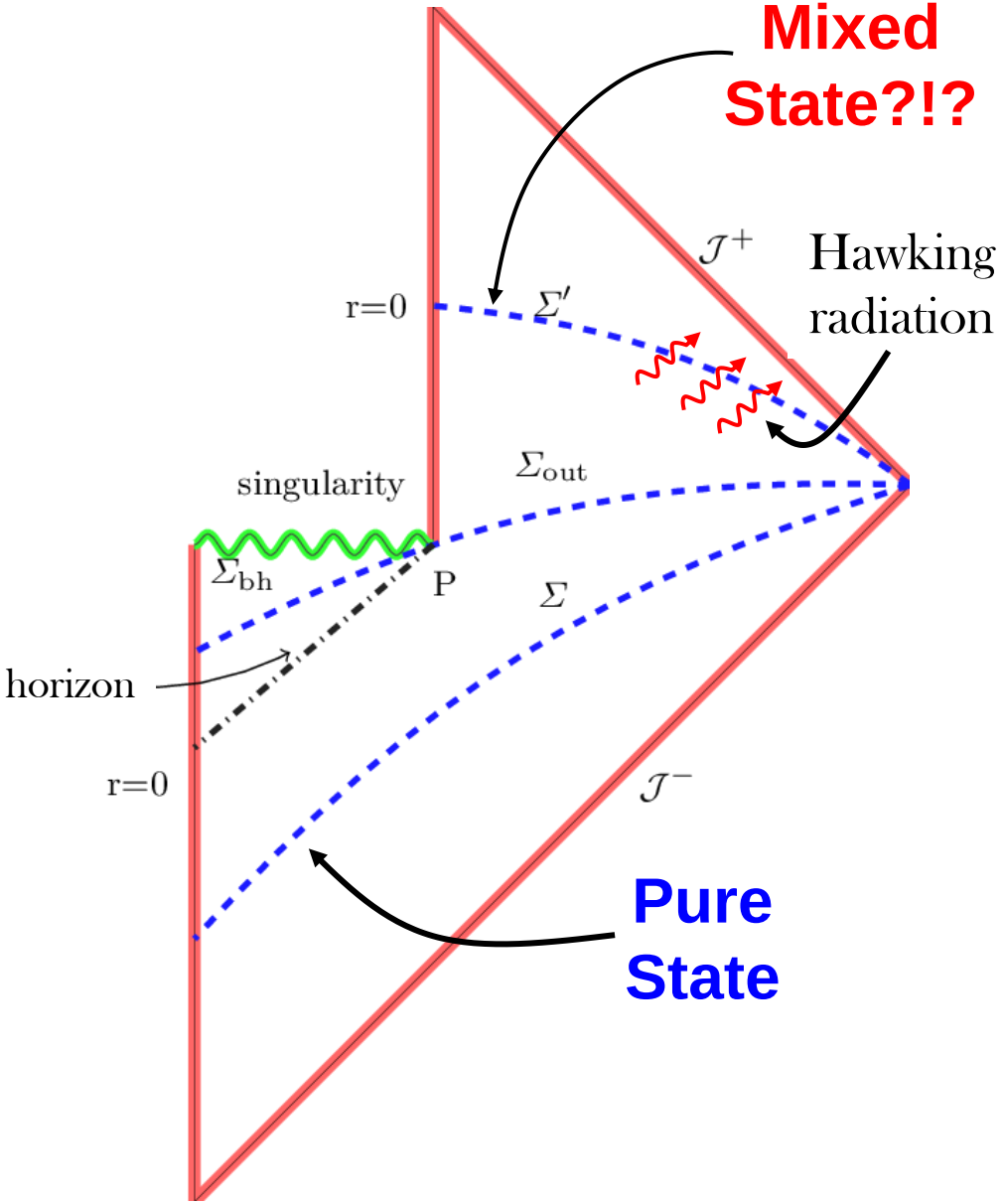
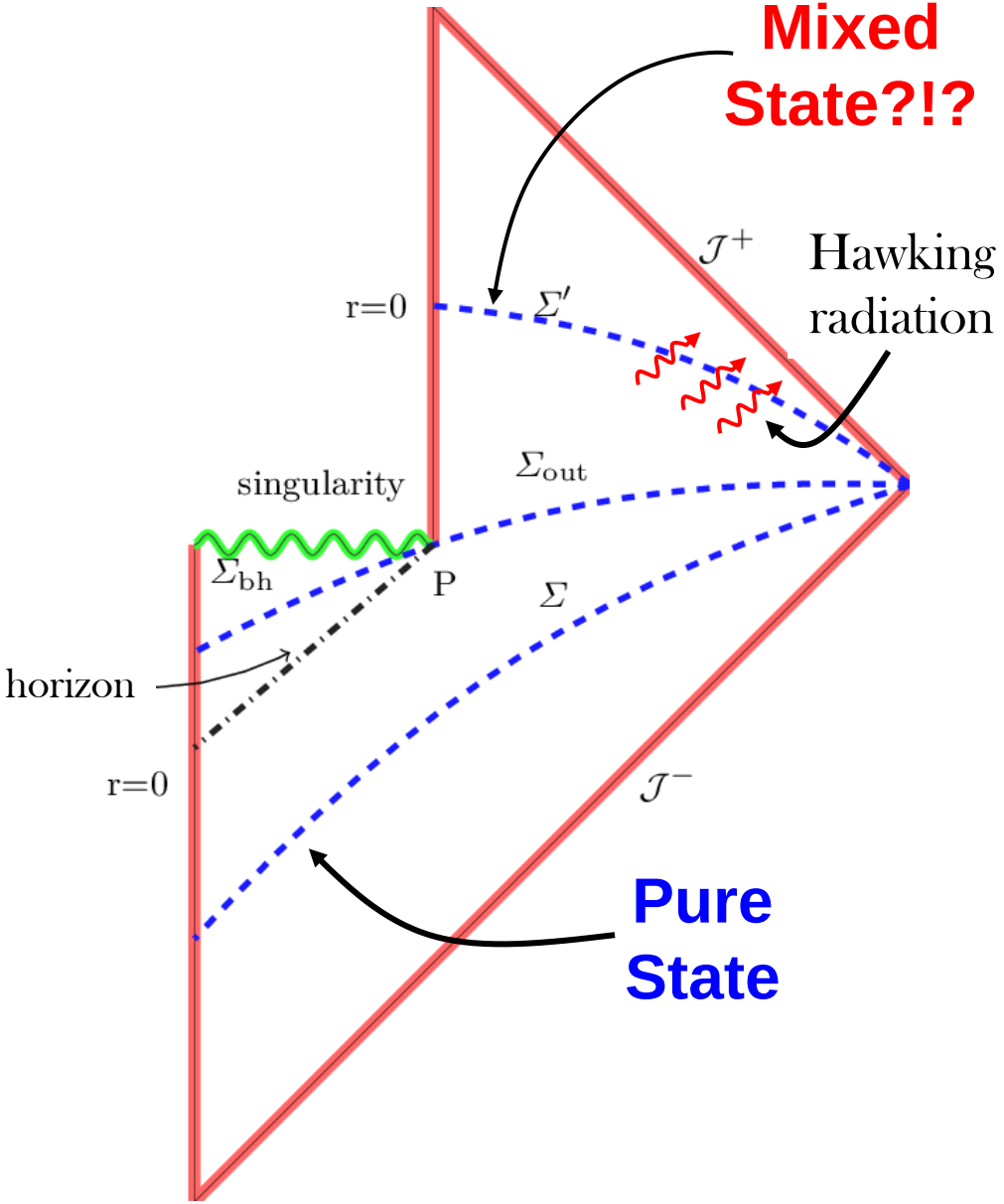
Quantum Extremal Islands Made Easy

with Chen, Neuenfeld, Reyes & Sandor

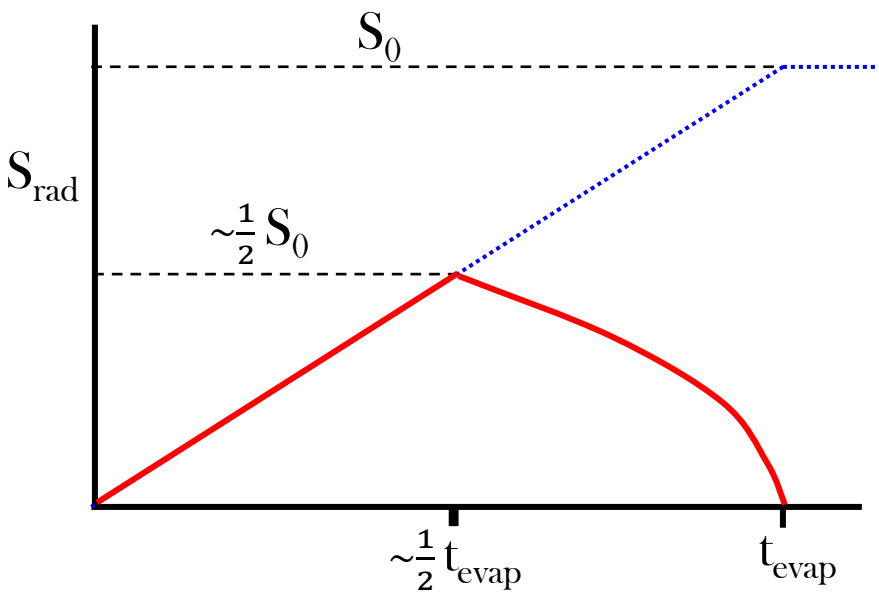
Black hole information paradox:



Black hole information paradox:



Page Curve



New insights from Holographic EE:

Penington [arXiv:1905.08255]

Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]

Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]

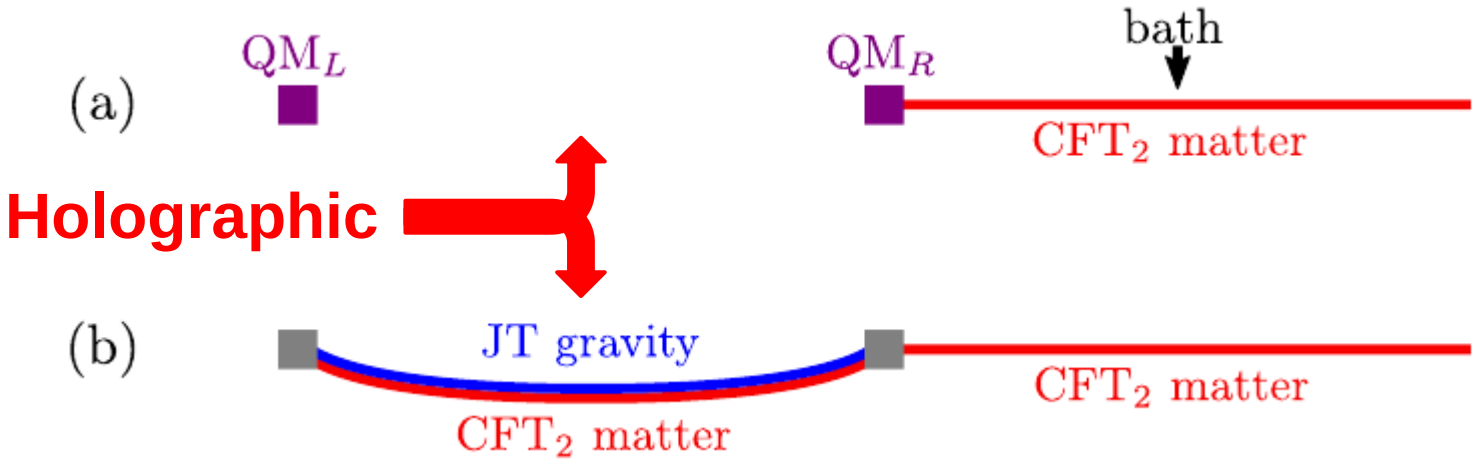
(Akers, Harlow, Rozali, van Raamsdonk, Sully, Wadell, Wakeham, Chen, Fisher, Hernadez, Ruan, Bousso, Tomasevic, Santos, Shenker, Stanford, Yang, Hartman, Shaghoulian, Tajdini, . . .)

New insights from Holographic EE:

Penington [arXiv:1905.08255]

* Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]

Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]



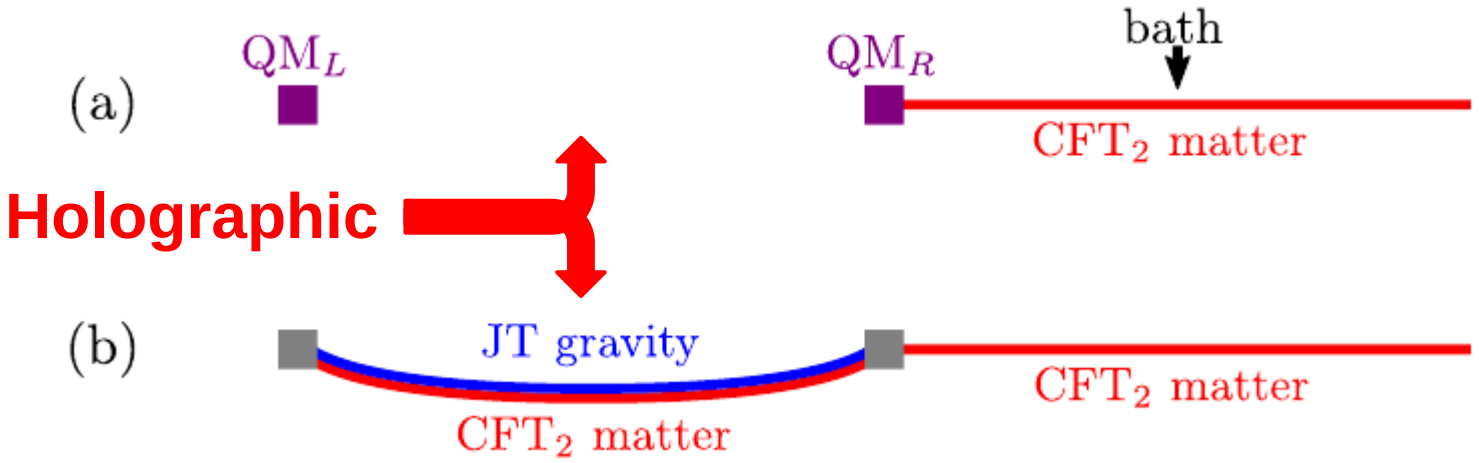
- simple holographic model: 2d gravity = 1d quantum mech's

New insights from Holographic EE:

Penington [arXiv:1905.08255]

* Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]

Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]



- simple holographic model: 2d gravity = 1d quantum mech's
- allow Hawking radiation to leak into bath (2d CFT on half-line)
- consider **Quantum Extremal Surfaces**: extremize gravitational entropy plus contributions of quantum fields (Faulkner, Lewkowycz & Maldacena; Engelhardt & Wall)

→ reproduce Page Curve

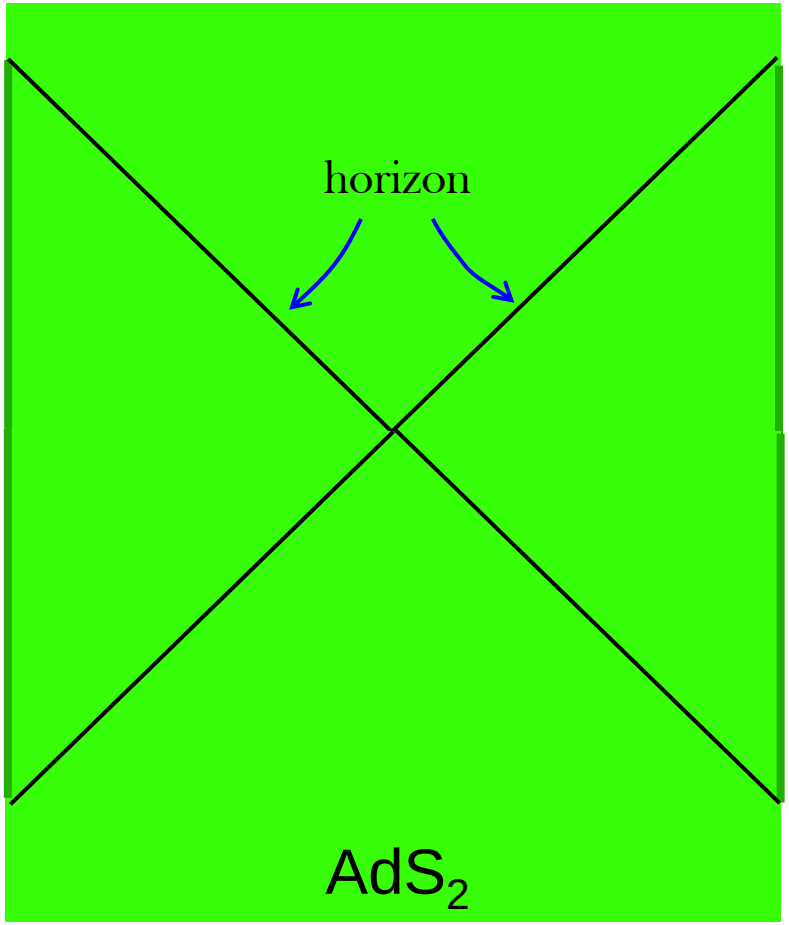
Aside:

- JT black holes:

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} \quad \text{with} \quad f(r) \equiv \frac{r^2 - \mu^2}{L_2^2} \,.$$

AdS_2 geometry

and $\Phi = \Phi_b \frac{r}{r_c}$



- Jackiw-Teitelboim gravity:

$$I = \frac{1}{16\pi G_N} \int d^2x \sqrt{-\tilde{g}}\, \Phi \left(\mathcal{R} + \frac{2}{L_2^2} \right) + \cdots$$

Aside:

- JT black holes:

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} \quad \text{with} \quad f(r) \equiv \frac{r^2 - \mu^2}{L_2^2}\,.$$

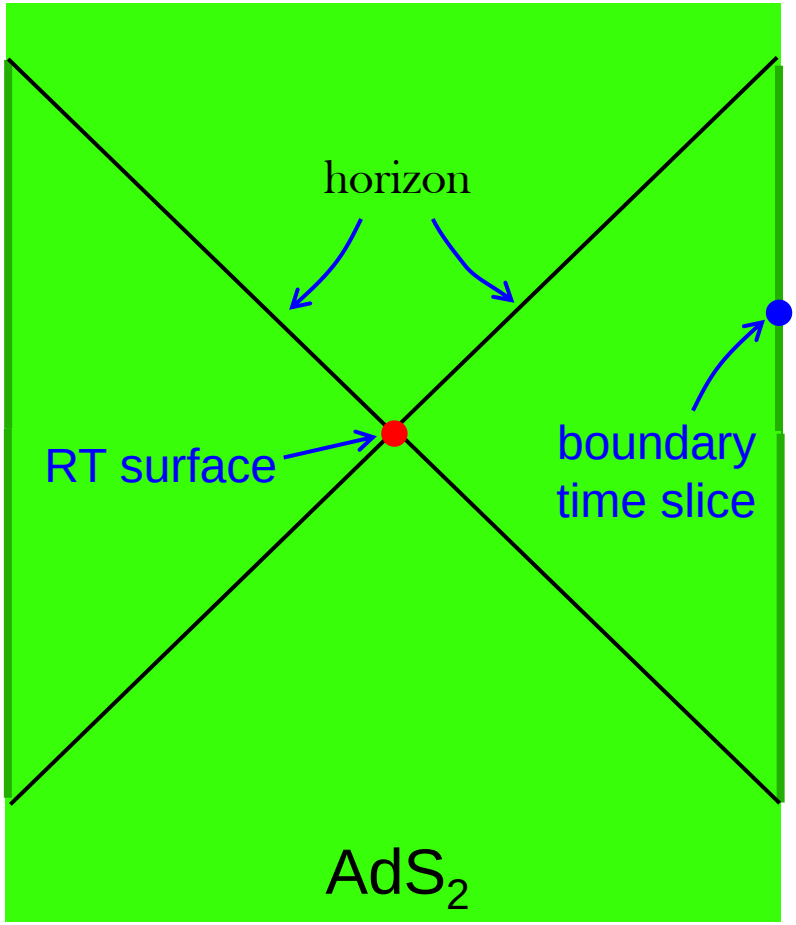
AdS_2 geometry

and $\Phi = \Phi_b \dfrac{r}{r_c}$

- RT surface: simply a point in bulk extremizing $\Phi(x)/4G_N$

- Jackiw-Teitelboim gravity:

$$I = \frac{1}{16\pi G_N}\int d^2x\sqrt{-\tilde{g}}\;\Phi\left(\mathcal{R} + \frac{2}{L_2^2}\right) + \cdots$$



Aside:

- JT black holes:

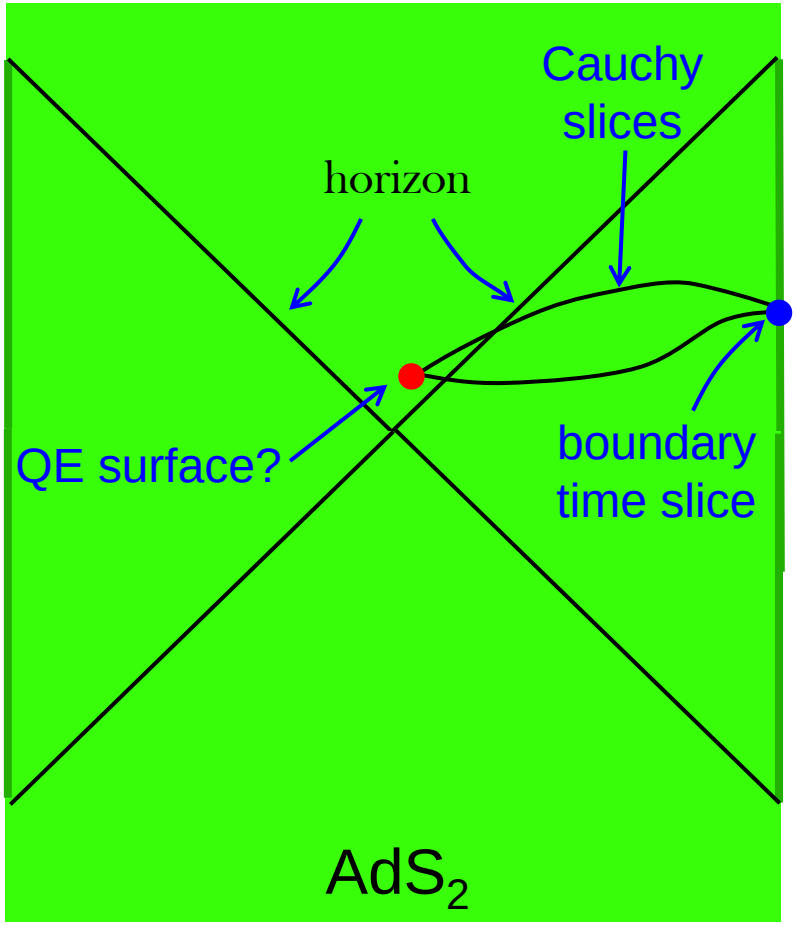
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} \quad \text{with} \quad f(r) \equiv \frac{r^2 - \mu^2}{L_2^2}\,.$$

AdS_2 geometry

and $\Phi = \Phi_b \frac{r}{r_c}$

- RT surface: simply a point in bulk extremizing $\Phi(x)/4G_N$

- Quantum Extremal surface: extremizes $\Phi(x)/4G_N$ plus quantum S_{EE} of matter fields (need Cauchy slice connecting to boundary time slice)



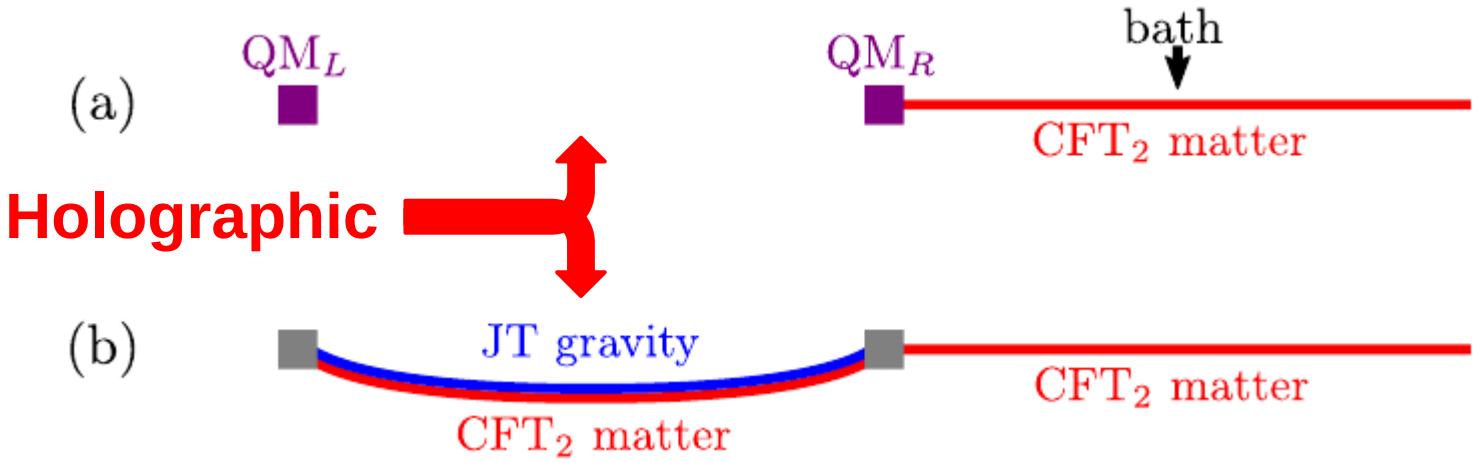
(Faulkner, Lewkowycz & Maldacena; Engelhardt & Wall)

New insights from Holographic EE:

Penington [arXiv:1905.08255]

* Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]

Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]



- simple holographic model: 2d gravity = 1d quantum mech's
- allow Hawking radiation to leak into bath (2d CFT on half-line)
- consider **Quantum Extremal Surfaces**: extremize gravitational entropy plus contributions of quantum fields (Faulkner, Lewkowycz & Maldacena; Engelhardt & Wall)

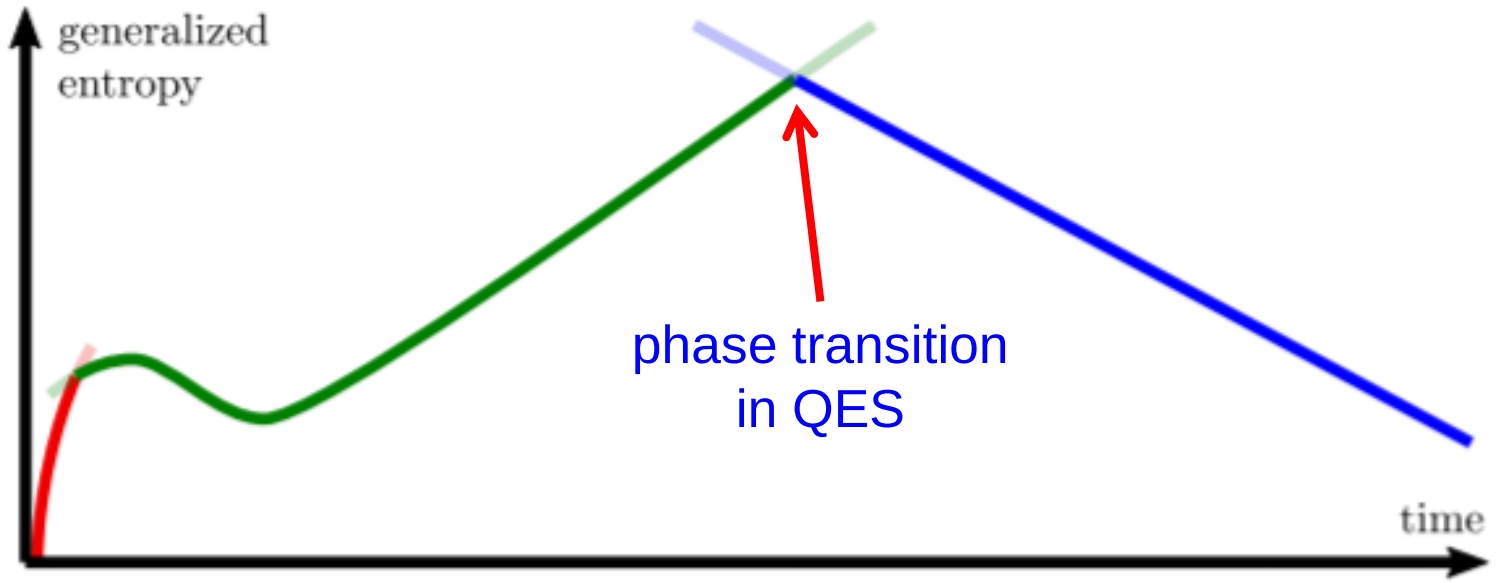
→ reproduce Page Curve

New insights from Holographic EE:

Penington [arXiv:1905.08255]

* Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]

Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]



- consider **Quantum Extremal Surfaces**: extremize gravitational entropy plus contributions of quantum fields

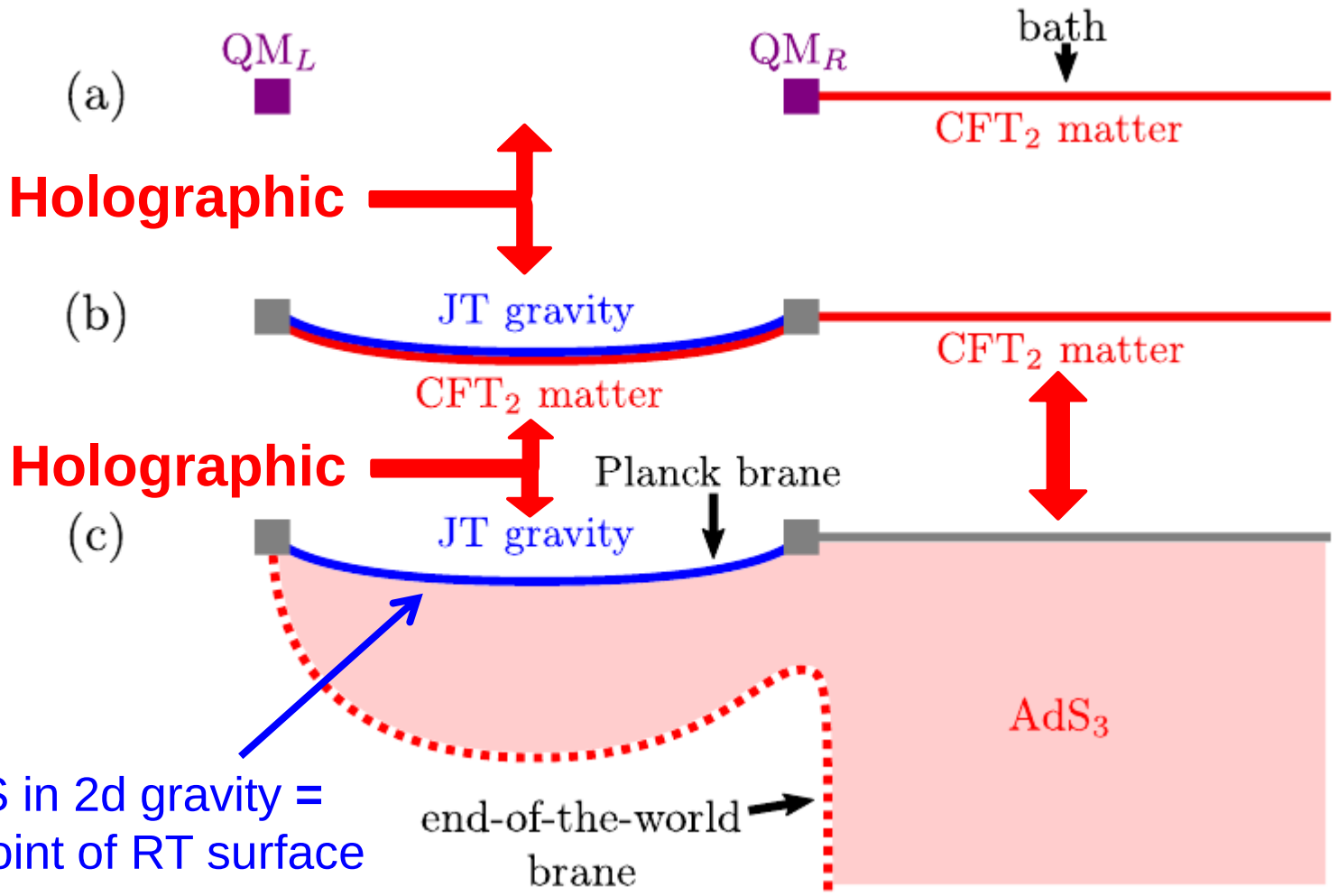
  ➡ reproduce Page Curve

- bath has information about interior: **Quantum Extremal Island**

New insights from Holographic EE:

Penington [arXiv:1905.08255]

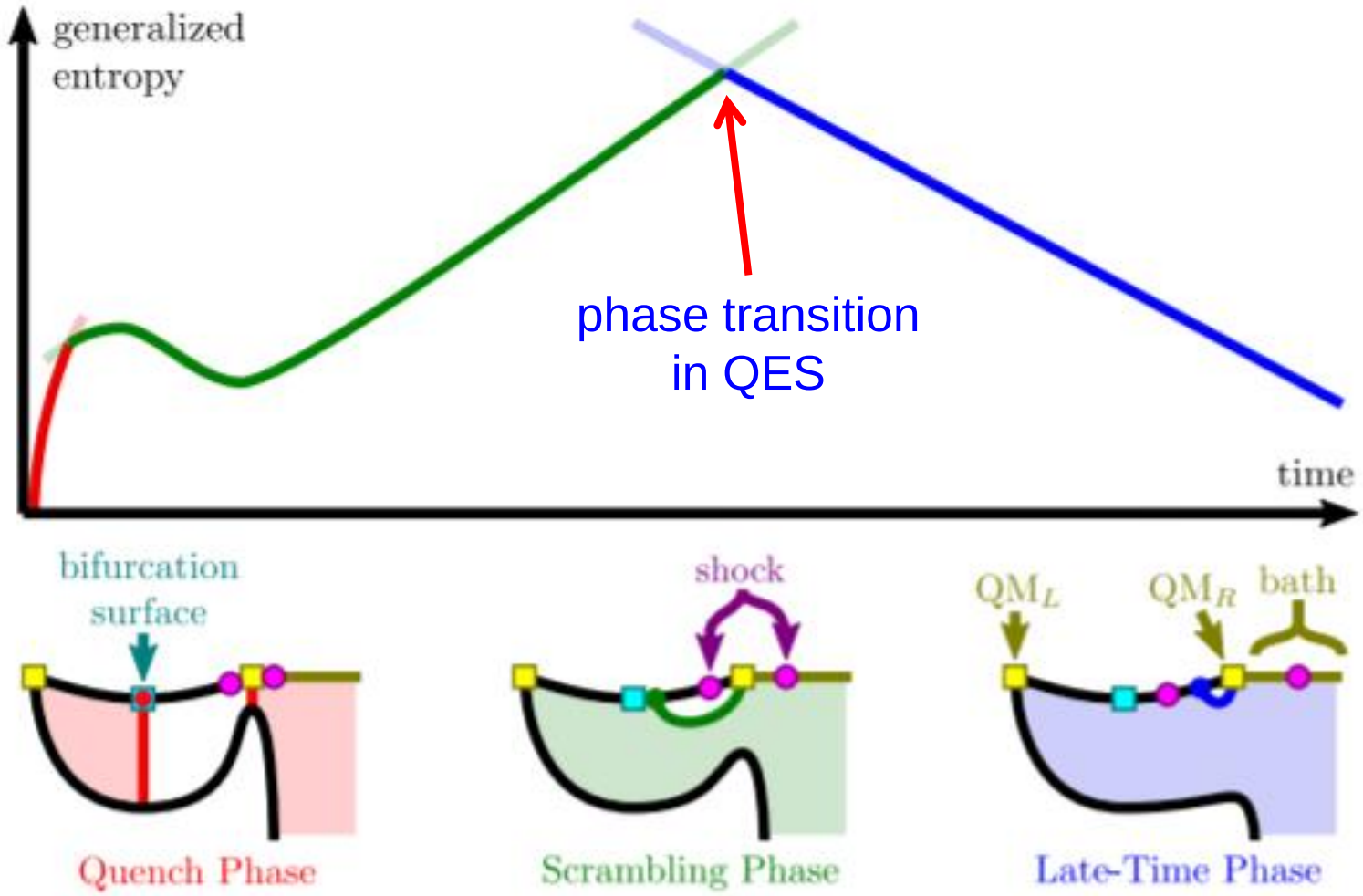
* Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]
* Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]



New insights from Holographic EE:

Penington [arXiv:1905.08255]

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



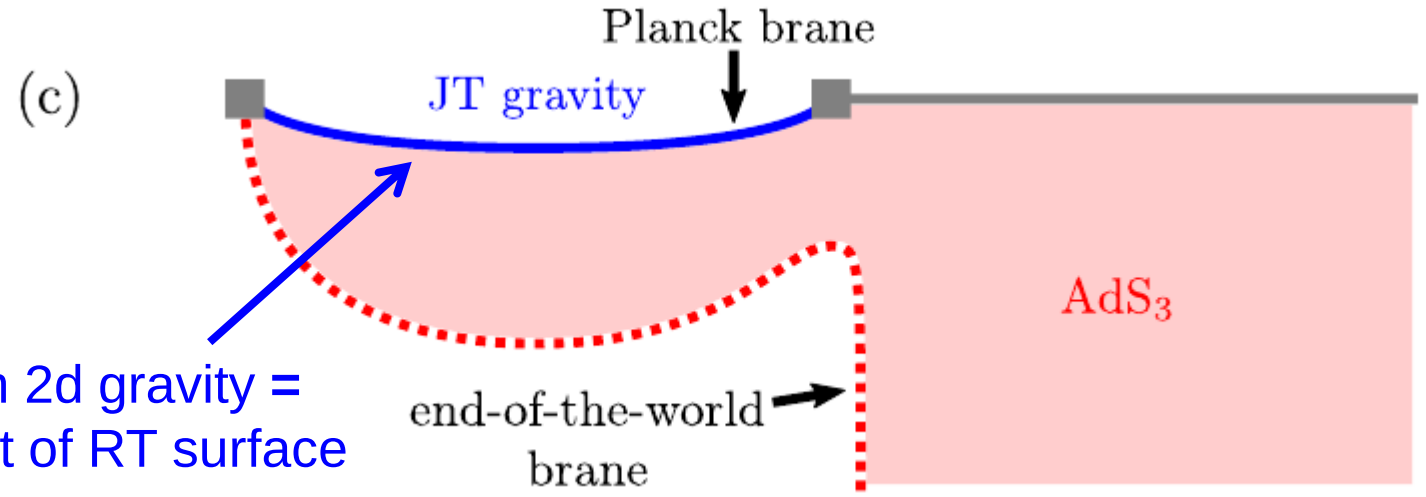
New insights from Holographic EE:

Penington [arXiv:1905.08255]

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

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?



QES in 2d gravity = endpoint of RT surface

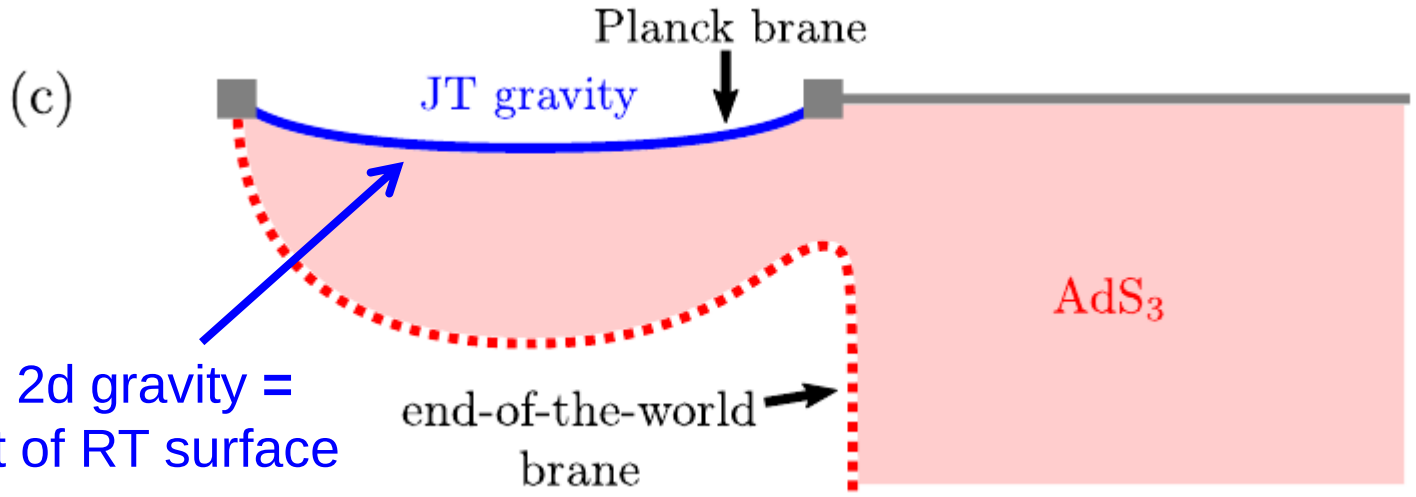
New insights from Holographic EE:

Penington [arXiv:1905.08255]

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

Questions, Questions, Questions:

- how important is two dimensions? **NOT**
- are dof on Planck brane part of boundary or bulk? **BULK**
- was JT gravity important? **NO**
- was ensemble average of SYK model important? **NO**
- how was information encoded in Hawking radiation? **????**



QES in 2d gravity = endpoint of RT surface

New insights from Holographic EE:

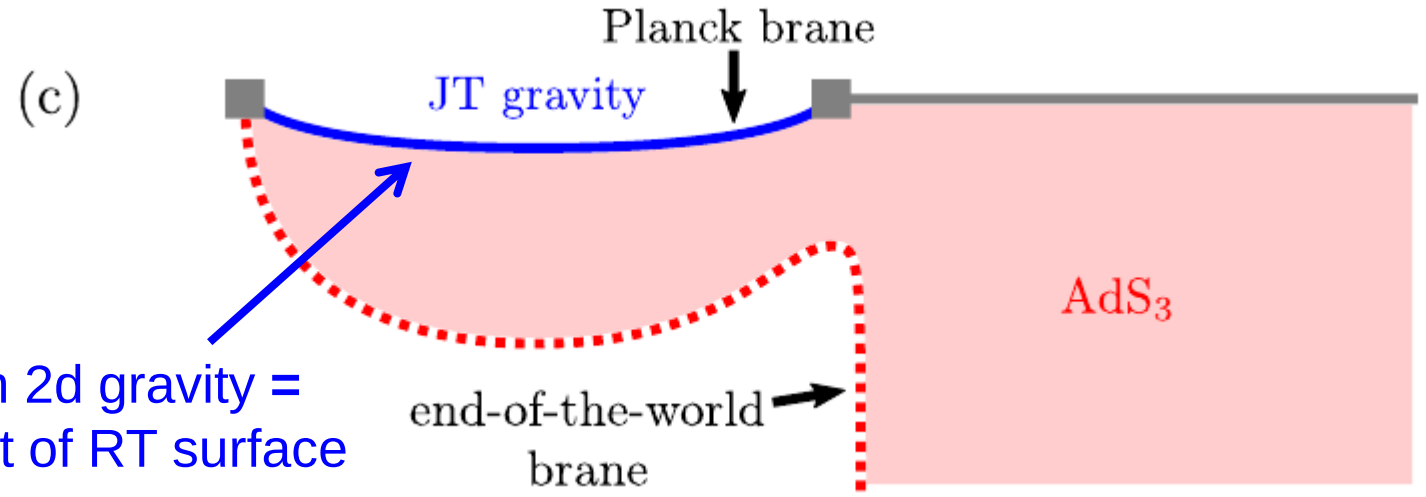
Penington [arXiv:1905.08255]

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

Questions, Questions, Questions:

- how important is two dimensions? NOT
- LK
- NO
- NO
- how was information encoded in Hawking radiation? ????

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



QES in 2d gravity = endpoint of RT surface

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:

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

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

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:

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

$$I_{\rm brane} = -T_0 \int d^d x \sqrt{-\tilde{g}} \quad + \frac{1}{16\pi G_{\rm brane}} \int d^d x \sqrt{-\tilde{g}}\, \tilde{R}(\tilde{g})$$

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:

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

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

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:

$$I_{\rm induce} = \frac{1}{16\pi G_{\rm eff}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\rm eff}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

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

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:

$$I_{\rm induce} = \frac{1}{16\pi G_{\rm eff}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\rm eff}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

$L^2/\ell_{\rm eff}^4$

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

Randall-Sundrum gravity (quick review):

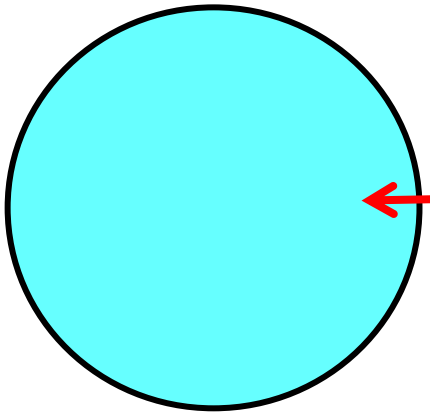
- introduce d-dim. brane in (d+1)-dim. AdS geometry, backreaction creates extra d-dim. graviton mode localized on brane:

$L^2/\ell_{\rm eff}^4$

$$I_{\rm induce} = \frac{1}{16\pi G_{\rm eff}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\rm eff}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

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

- “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

Randall-Sundrum gravity (quick review):

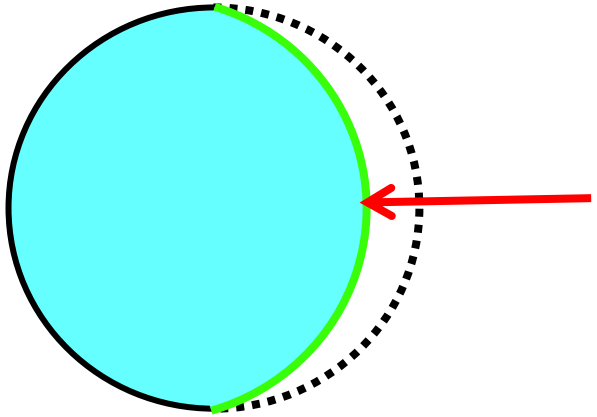
- introduce d-dim. brane in (d+1)-dim. AdS geometry, backreaction creates extra d-dim. graviton mode localized on brane:

$$I_{\text{induce}} = \frac{1}{16\pi G_{\text{eff}}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\text{eff}}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

L^2/ℓ_{eff}^4

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

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



cut off
at ρ_{brane}

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

Randall-Sundrum gravity (quick review):

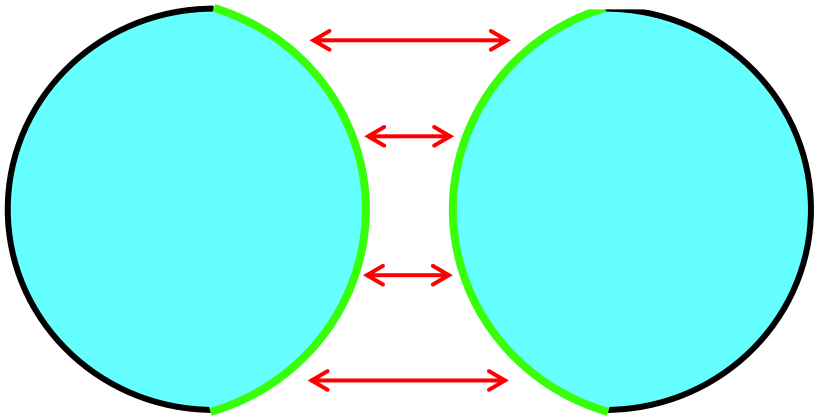
- introduce d-dim. brane in (d+1)-dim. AdS geometry, backreaction creates extra d-dim. graviton mode localized on brane:

$L^2/\ell_{\rm eff}^4$

$$I_{\rm induce} = \frac{1}{16\pi G_{\rm eff}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\rm eff}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

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

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



paste to 2nd copy

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

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

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:

$L^2/\ell_{\rm eff}^4$

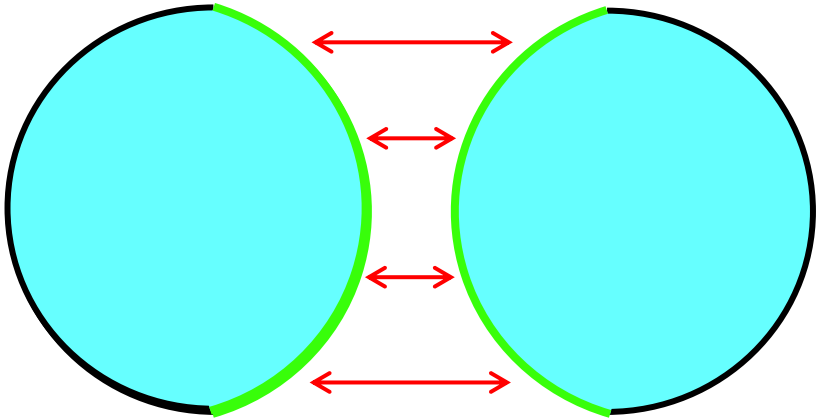
$$I_{\rm induce} = \frac{1}{16\pi G_{\rm eff}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\rm eff}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

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

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



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

Randall-Sundrum gravity (quick review):

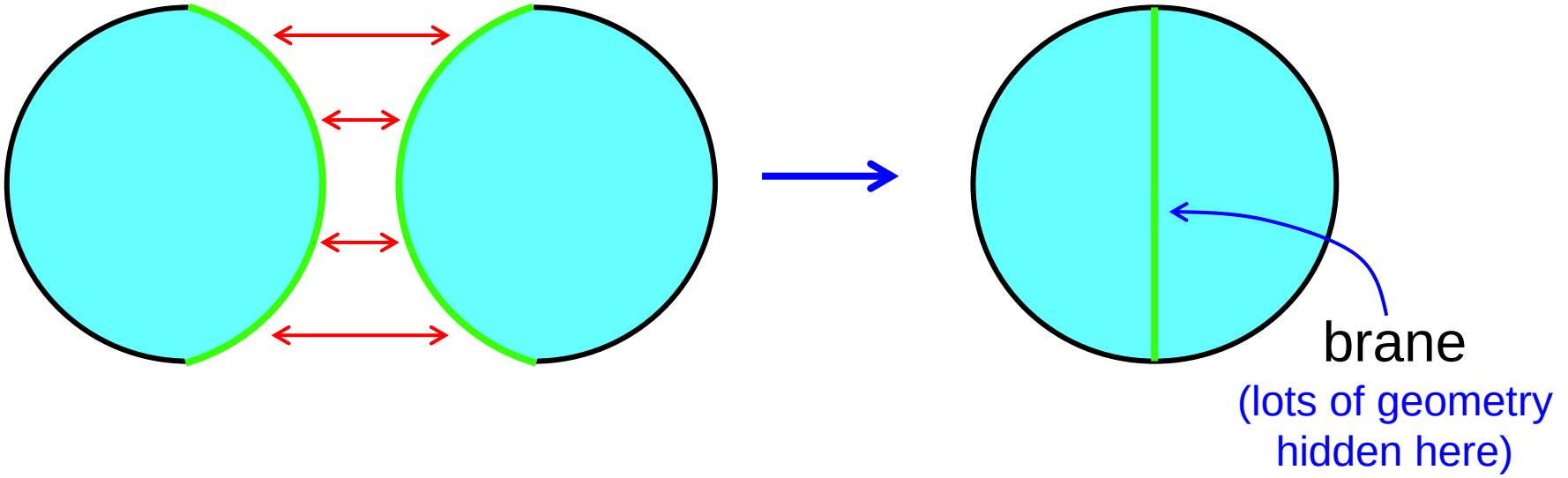
- introduce d-dim. brane in (d+1)-dim. AdS geometry, backreaction creates extra d-dim. graviton mode localized on brane:

$$I_{\rm induce} = \frac{1}{16\pi G_{\rm eff}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\rm eff}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

$L^2/\ell_{\rm eff}^4$

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

- “position” of brane can be determined by:
  using Israel junction conditions or solving brane gravity eom



Randall-Sundrum gravity (quick review):

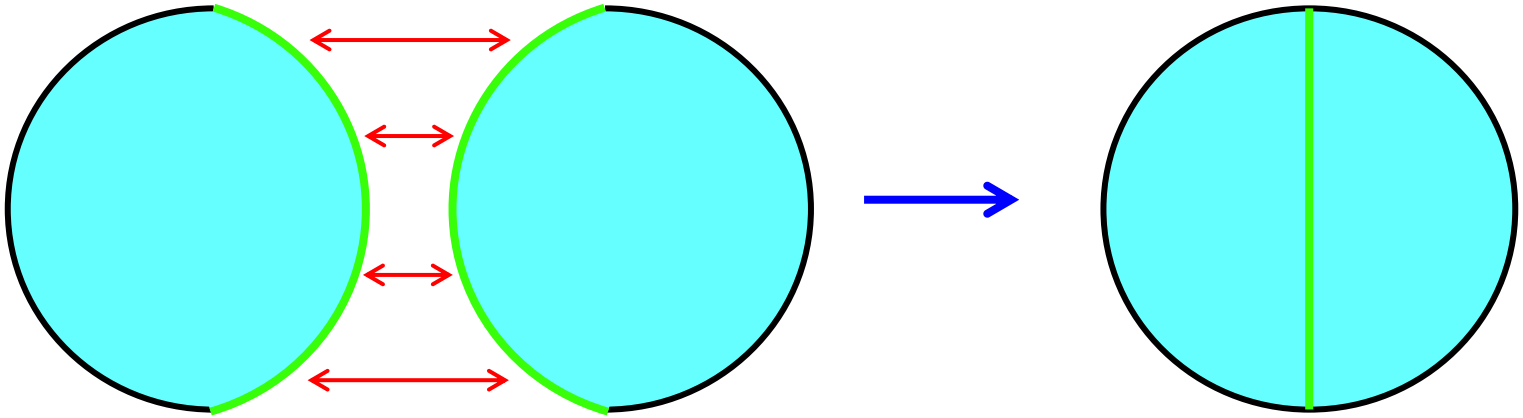
- introduce d-dim. brane in (d+1)-dim. AdS geometry, backreaction creates extra d-dim. graviton mode localized on brane:

$$I_{\rm induce} = \frac{1}{16\pi G_{\rm eff}} \int d^d x \sqrt{-\tilde{g}} \left[\frac{(d-1)(d-2)}{\ell_{\rm eff}^2} + \tilde{R}(\tilde{g}) + L^2(\text{“}\tilde{R}^2\text{”}) + \cdots \right]$$

$L^2/\ell_{\rm eff}^4$

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

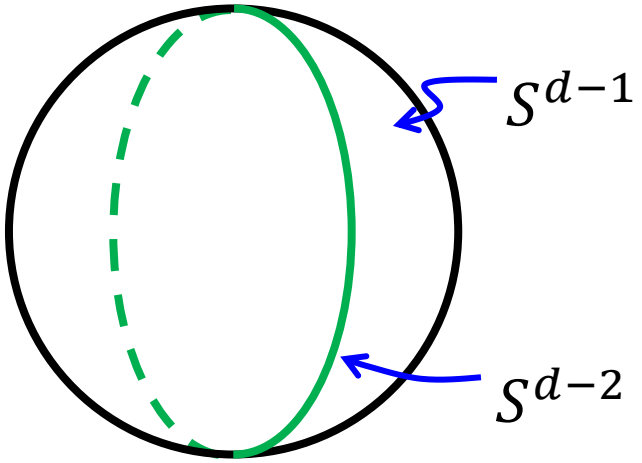
- “position” of brane can be determined by:
  using Israel junction conditions or solving brane gravity eom

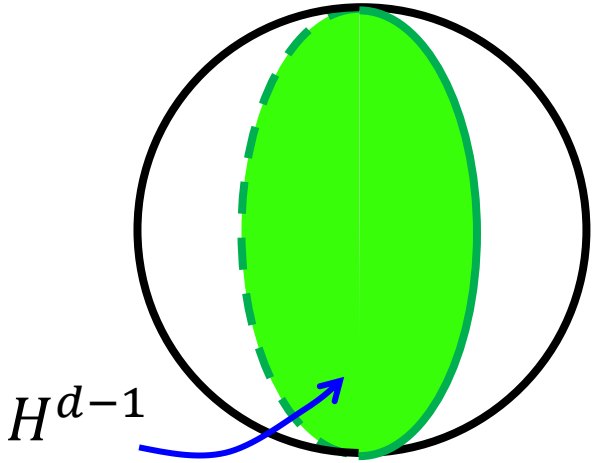


- when RT surface crosses brane, leading term: $S_{\rm EE} \sim \frac{A(\tilde{g})}{4G_{\rm eff}} + \cdots$

Randall-Sundrum gravity:

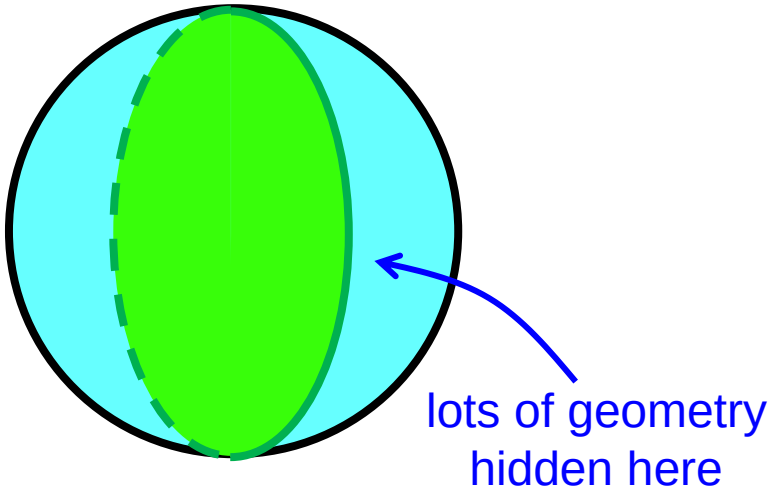
(a) holographic CFT_d coupled to conformal defect (ie, boundary CFT_{d-1})





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

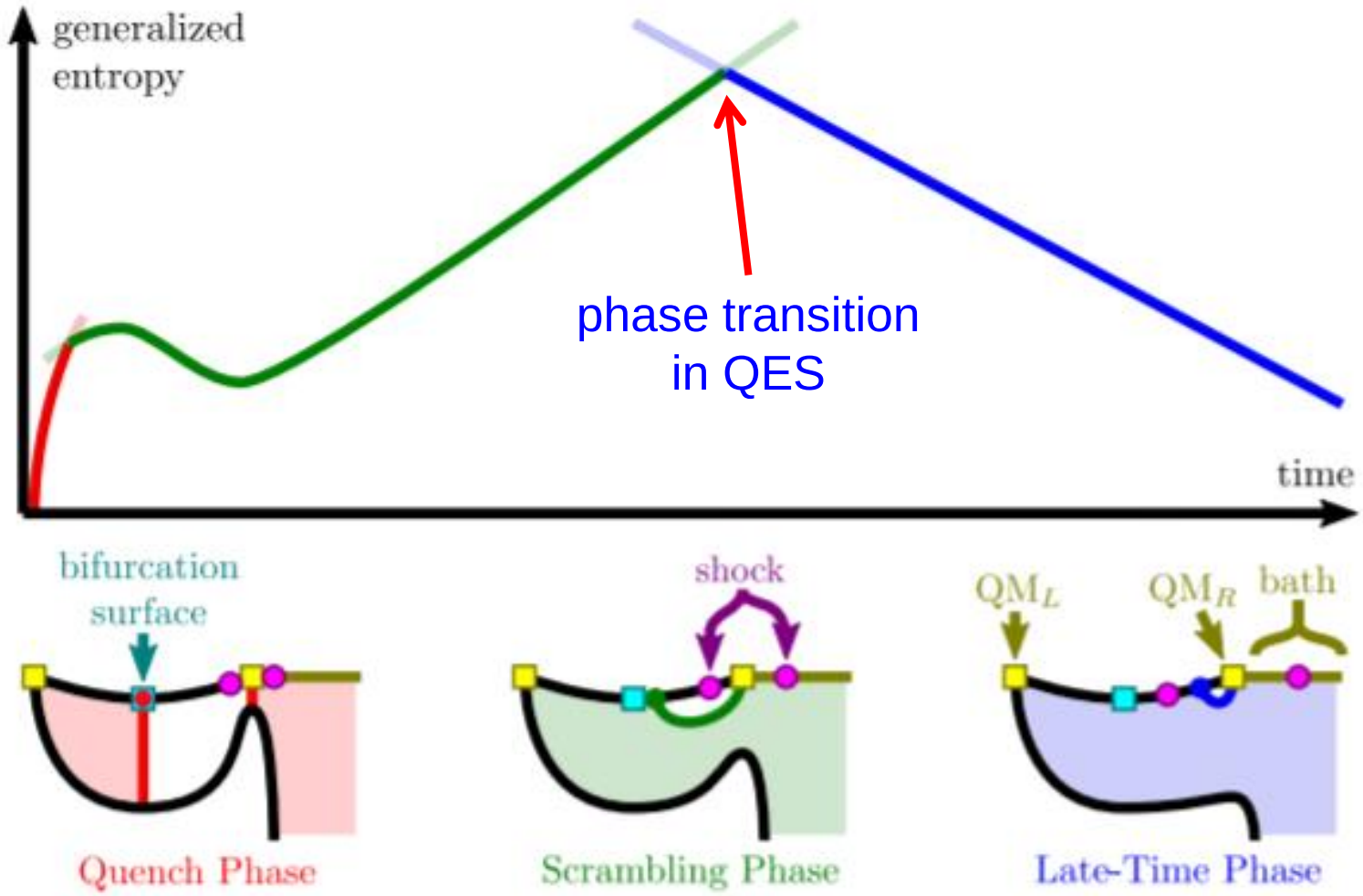
(c) AdS_{d+1} gravity coupled to brane with AdS_d geometry



New insights from Holographic EE:

Penington [arXiv:1905.08255]

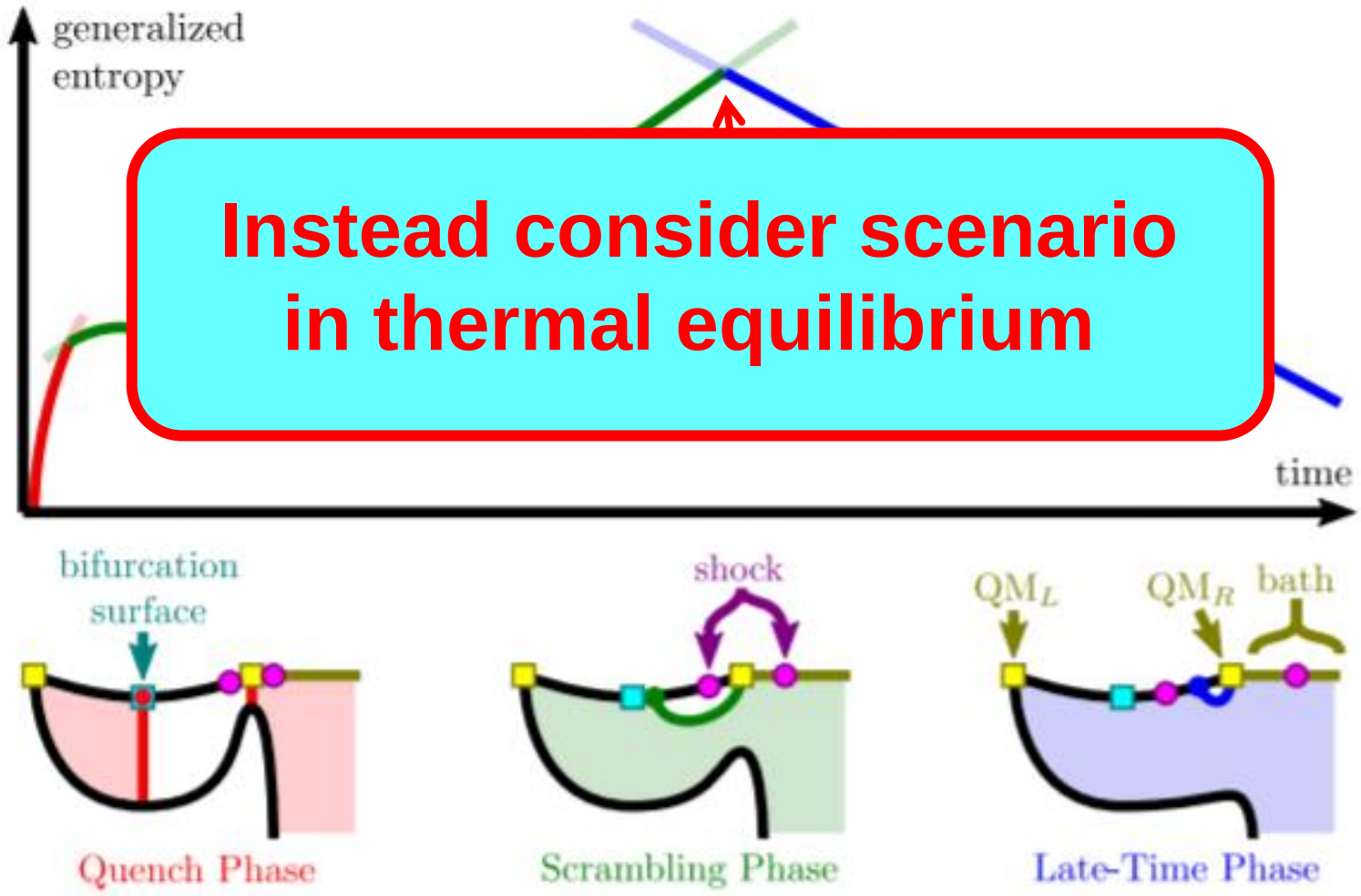
* Almheiri, Engelhardt, Marolf & Maxfield [arXiv:1905.08762]
* Almheiri, Mahajan, Maldacena & Zhao [arXiv:1908.10996]



New insights from Holographic EE:

Penington [arXiv:1905.08255]

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



Instead consider scenario in thermal equilibrium

Black Holes in Thermal Equilibrium:

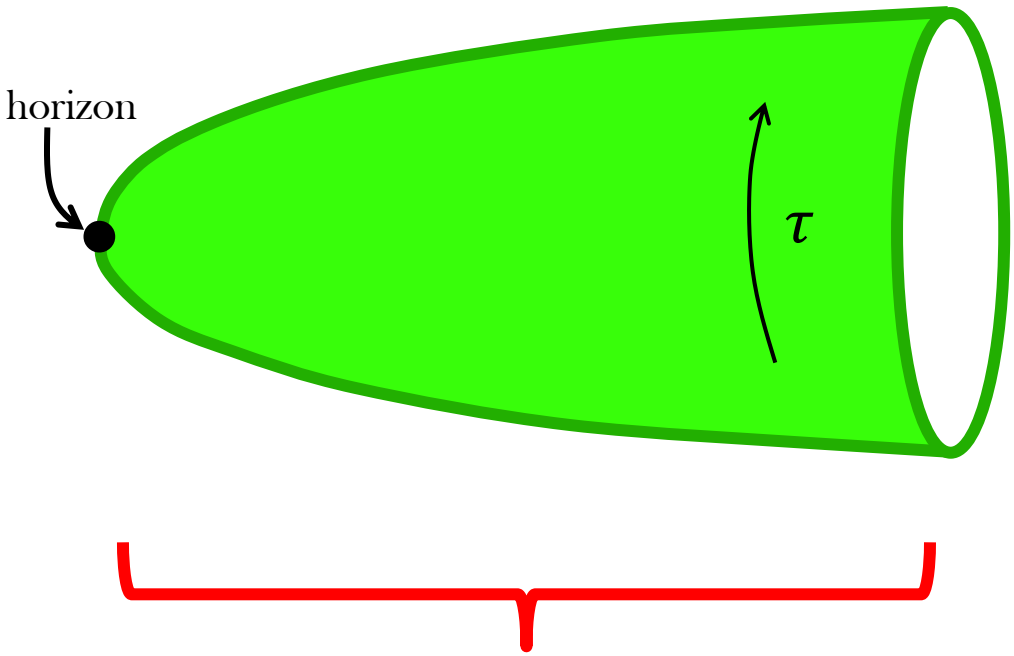
Almheiri, Mahajan & Maldacena

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

same

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

→ Hartle-Hawking state



2d Euclidean BH

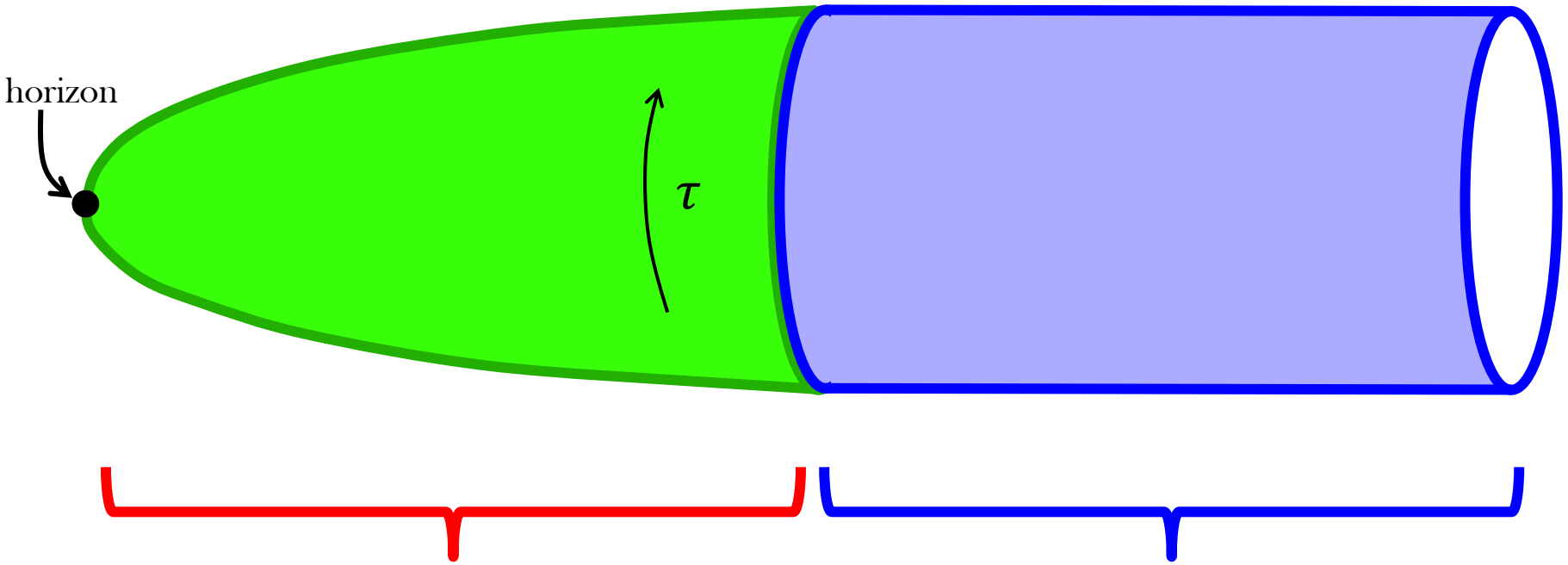
Black Holes in Thermal Equilibrium:

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

same

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

→ Hartle-Hawking state



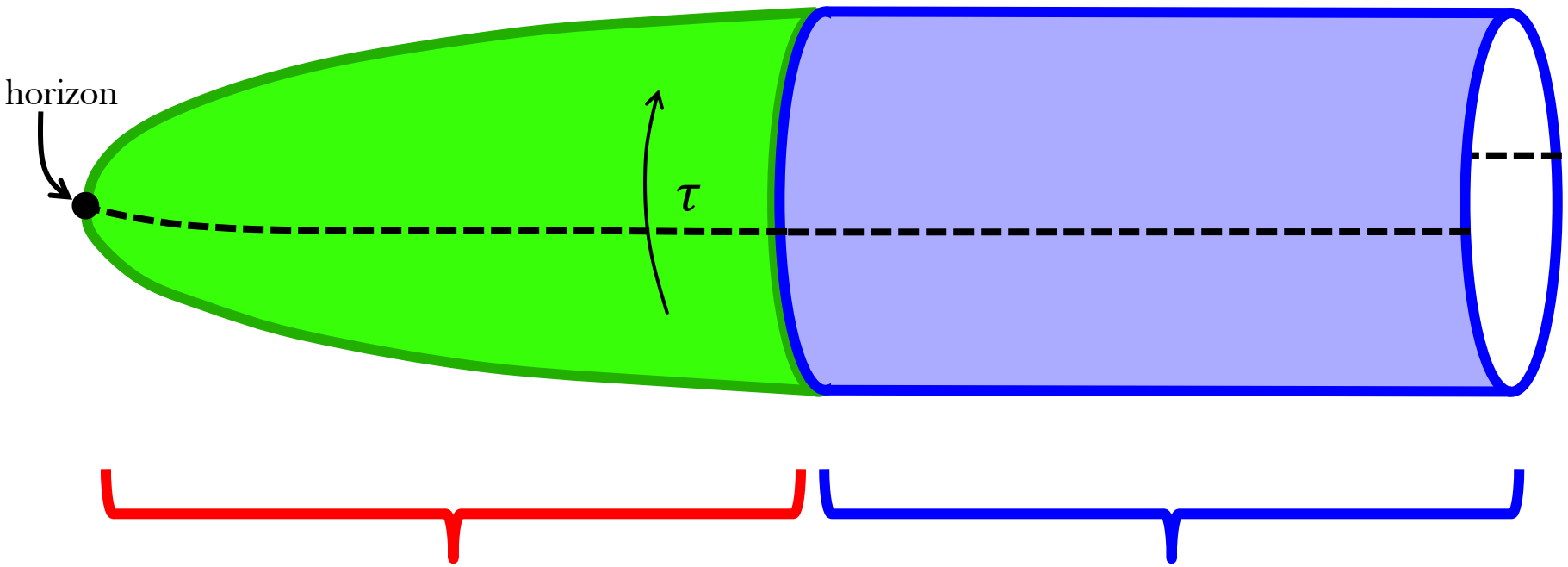
Black Holes in Thermal Equilibrium:

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

same

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

→ Hartle-Hawking state



2d Euclidean BH

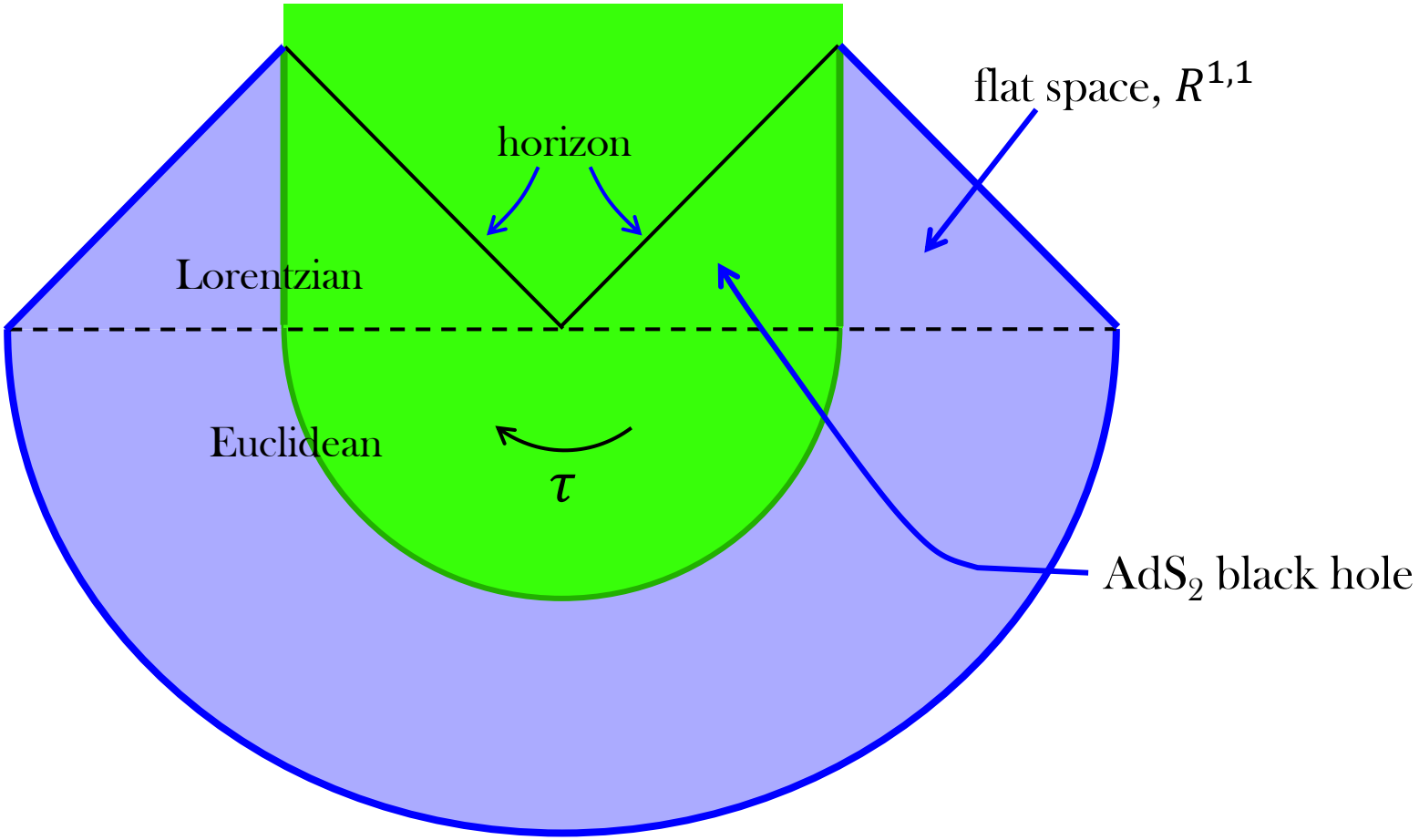
CFT_2 on thermal cylinder

Black Holes in Thermal Equilibrium:

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

same

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

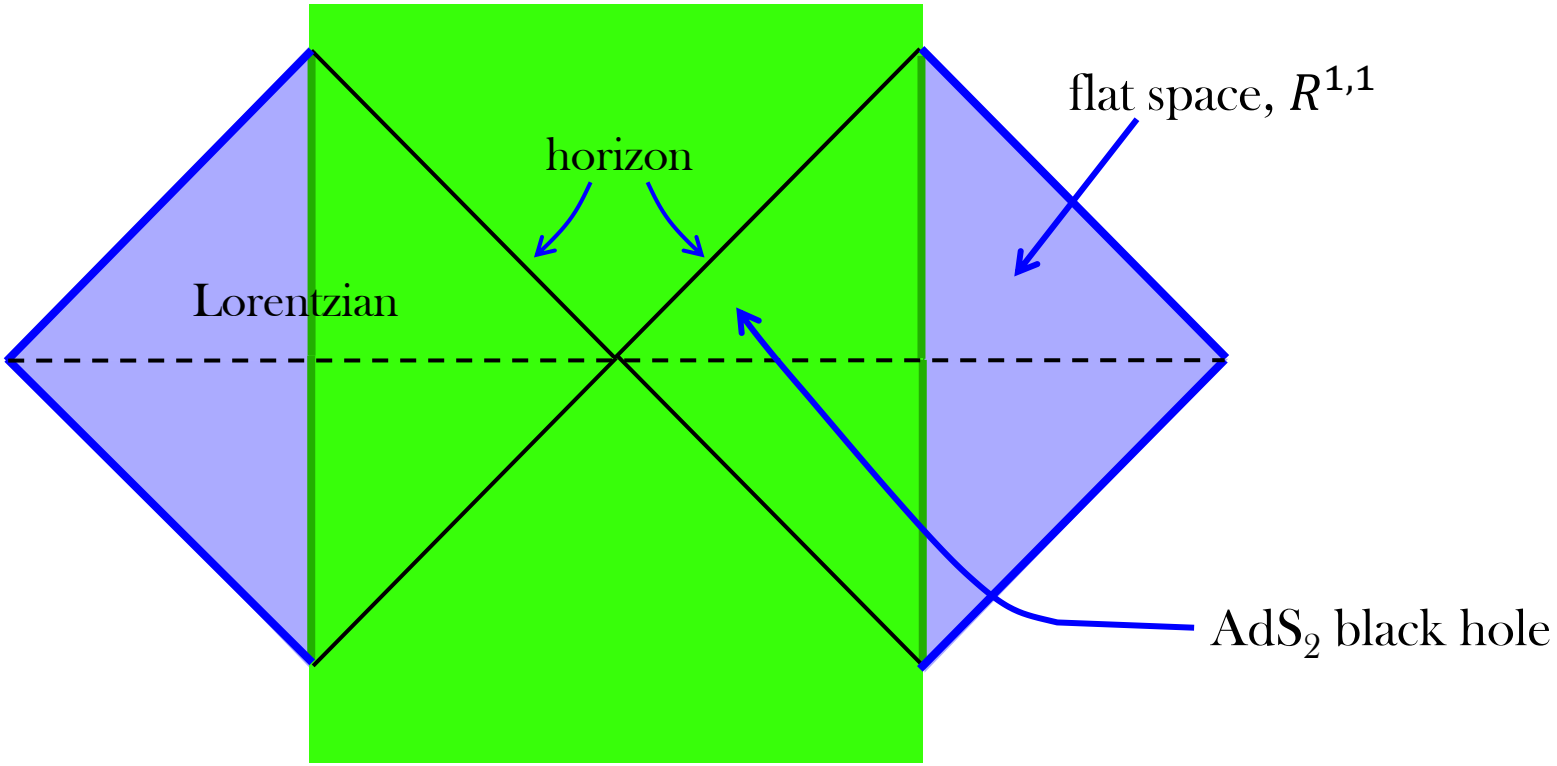


Black Holes in Thermal Equilibrium:

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

same

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



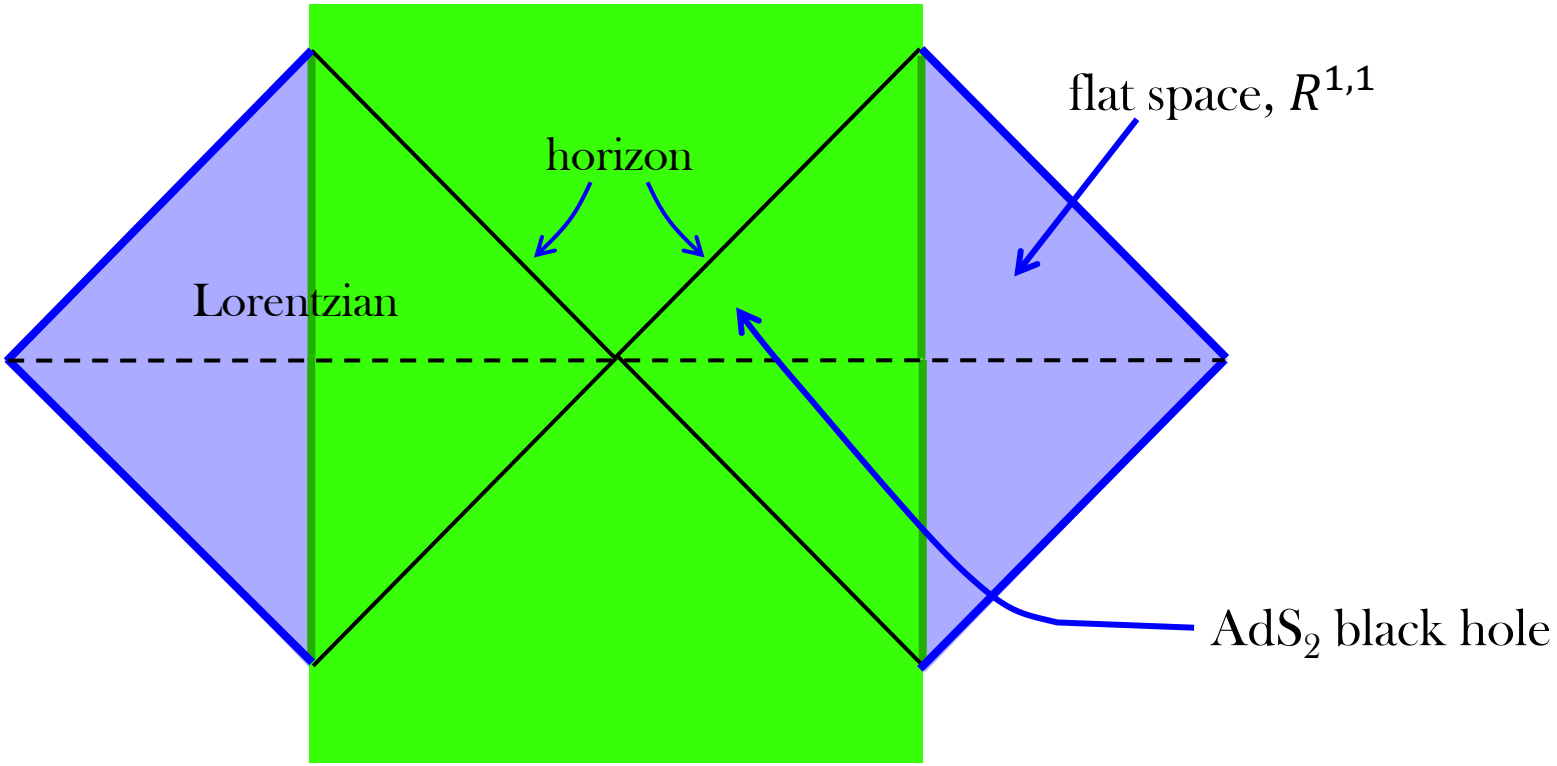
Thermal equilibrium? No information paradox?

Black Holes in Thermal Equilibrium:

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

same

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



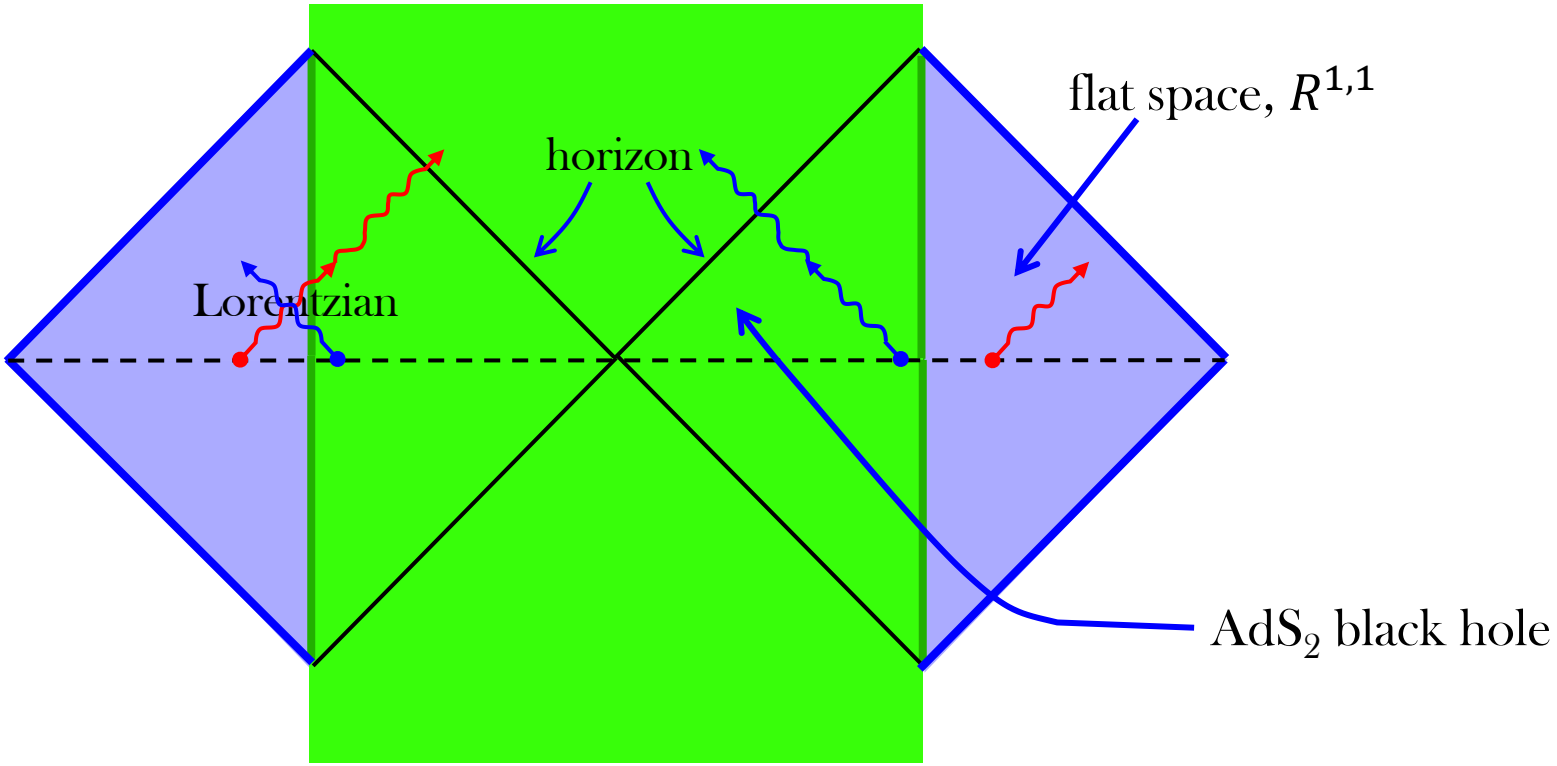
- eternal BH and bath are continuously exchanging radiation

Black Holes in Thermal Equilibrium:

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

same

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



- eternal BH and bath are continuously exchanging radiation

Black Holes in Thermal Equilibrium:

Almheiri, Mahajan & Maldacena

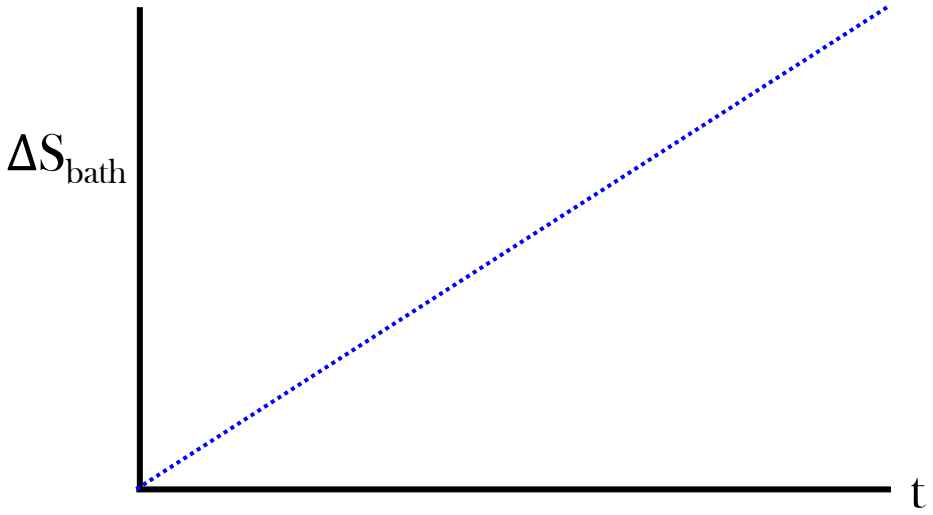
(see also: Rozali, Van Raamsdonk, Waddell & Wakeham)

same

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

What does Page curve look like for eternal black hole?

- eternal BH and bath are continuously exchanging radiation



Black Holes in Thermal Equilibrium:

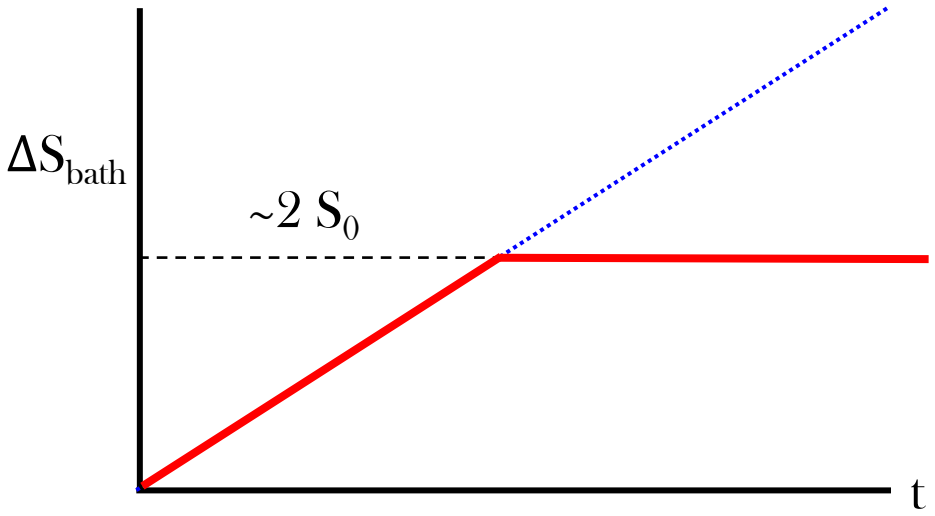
Almheiri, Mahajan & Maldacena
(see also: Rozali, Van Raamsdonk, Waddell & Wakeham)

same

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

What does Page curve look like for eternal black hole?

- eternal BH and bath are continuously exchanging radiation but BH can only store a finite amount of information



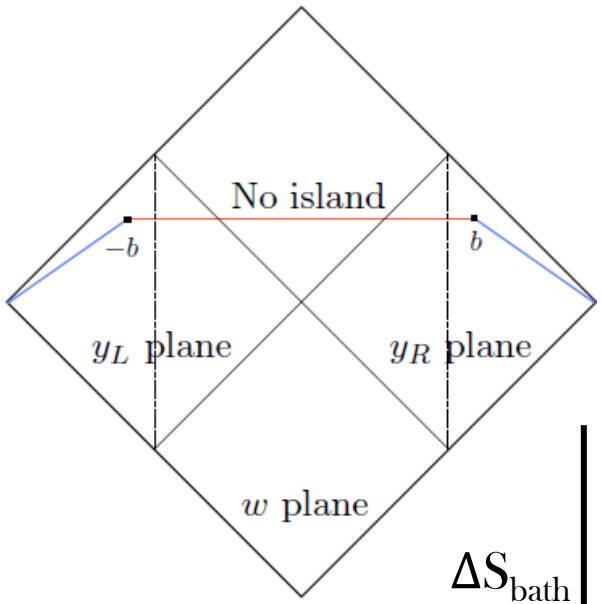
Black Holes in Thermal Equilibrium:

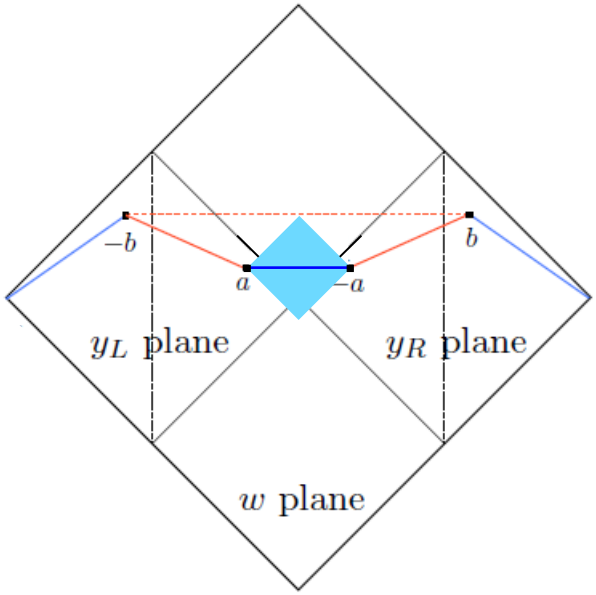
Almheiri, Mahajan & Maldacena

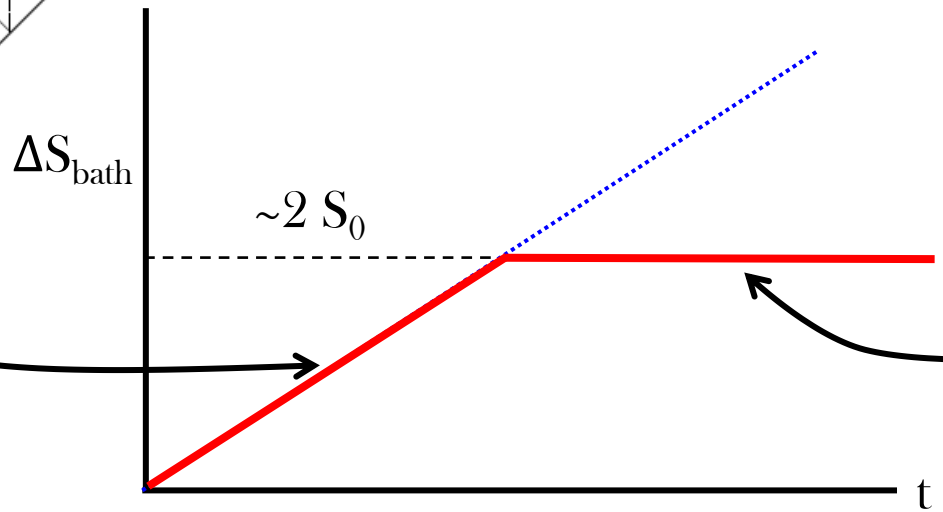
(see also: Rozali, Van Raamsdonk, Waddell & Wakeham)

same

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







growth phase

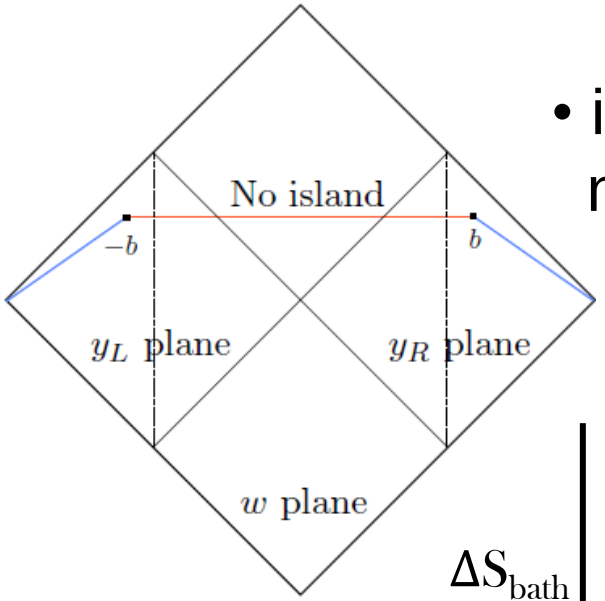
Page phase

Black Holes in Thermal Equilibrium:

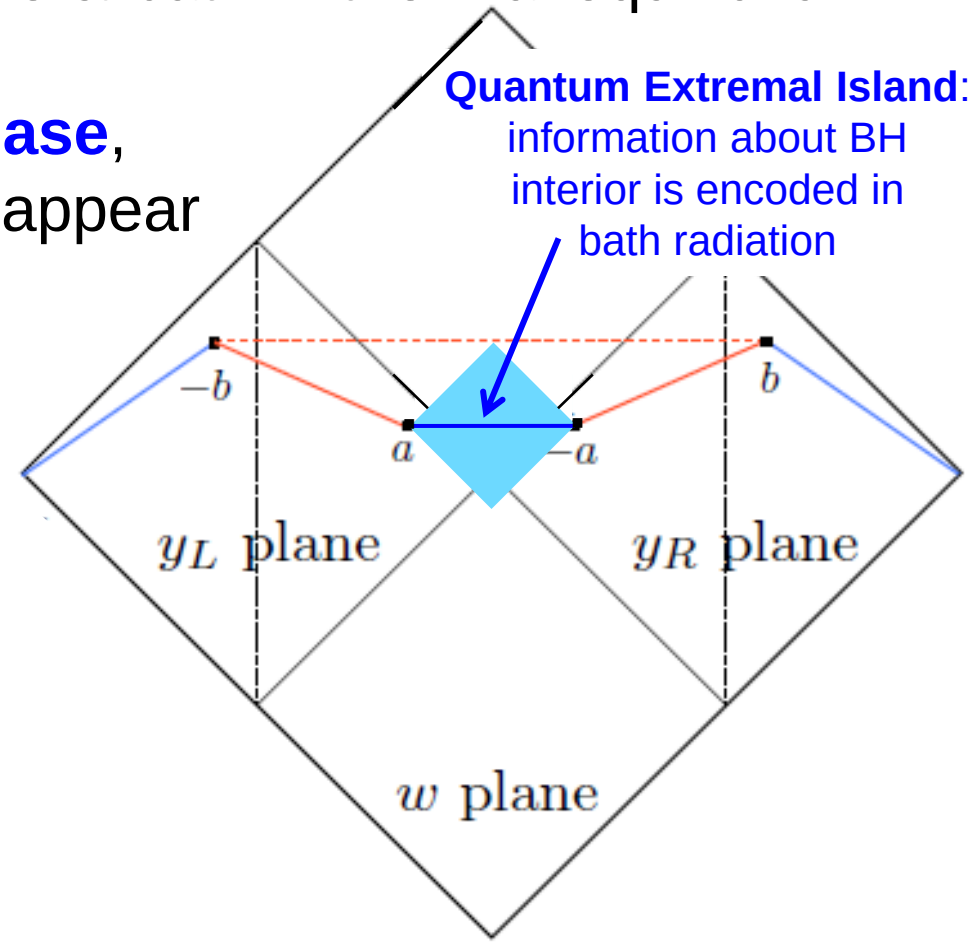
Almheiri, Mahajan & Maldacena
(see also: Rozali, Van Raamsdonk, Waddell & Wakeham)

same

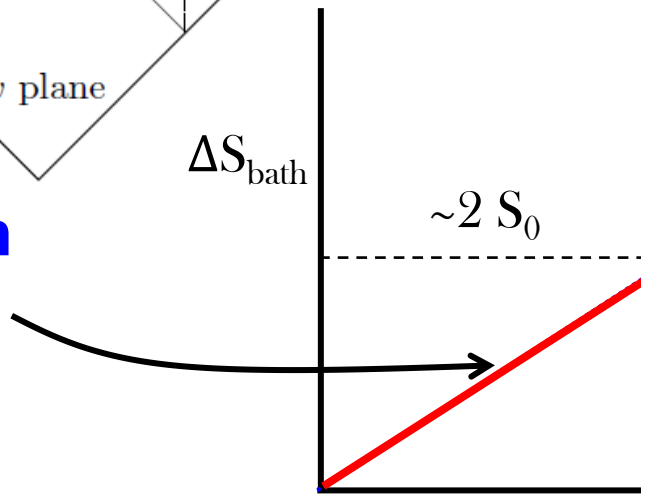
- simple holographic model: 2d gravity = 1d quantum mech's
- prepare state with 2d black hole & bath in thermal equilibrium



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



growth phase

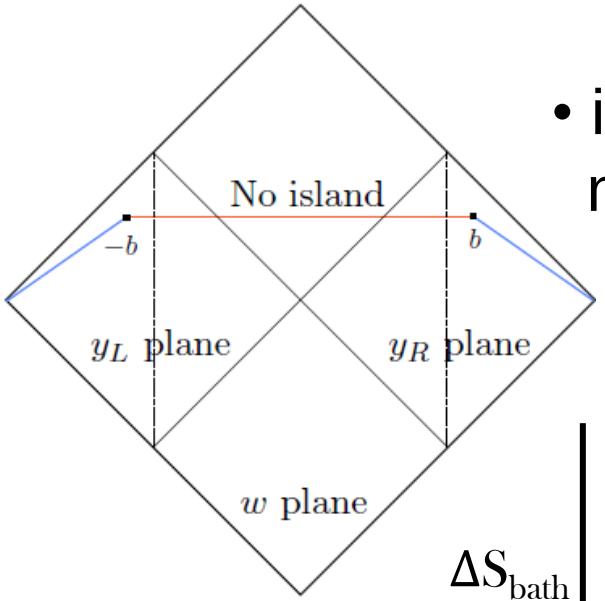


Black Holes in Thermal Equilibrium:

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

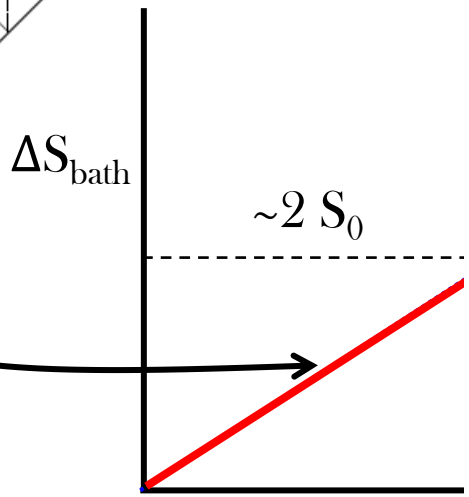
same

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

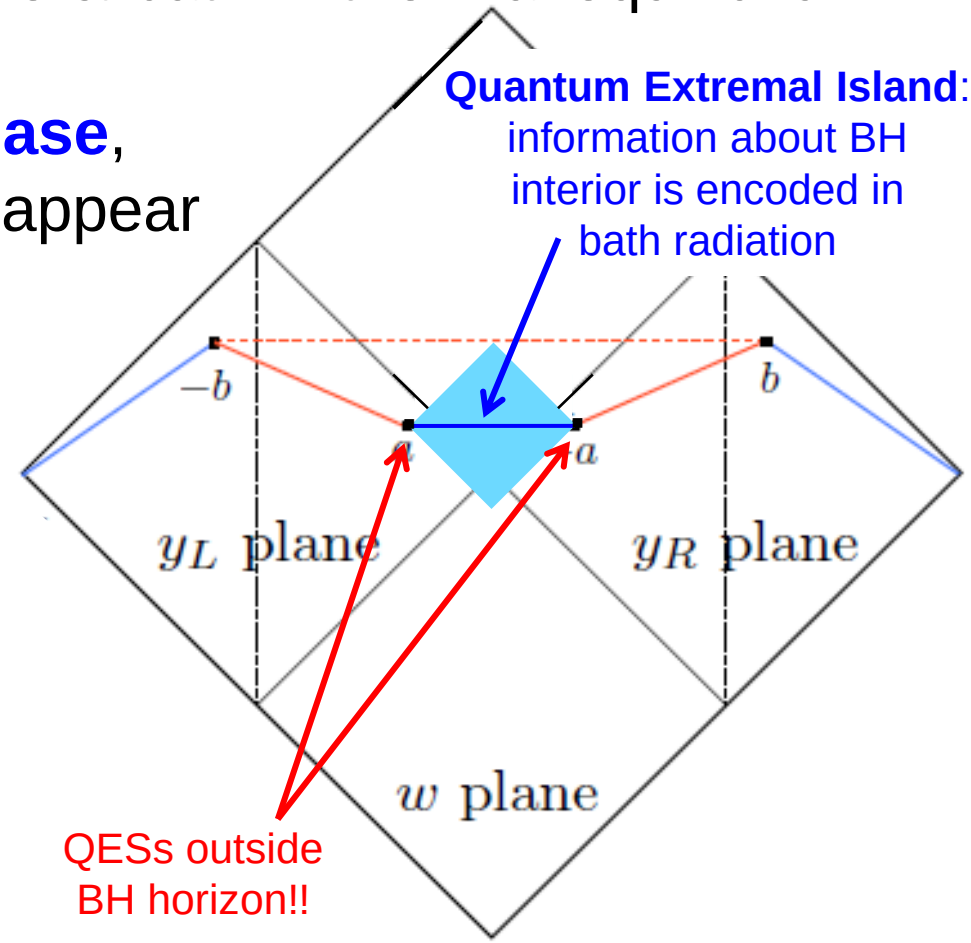


- in **Page phase**, new QESs appear

growth phase



Quantum Extremal Island: information about BH interior is encoded in bath radiation



QESs outside BH horizon!!

Black Holes in Thermal Equilibrium:

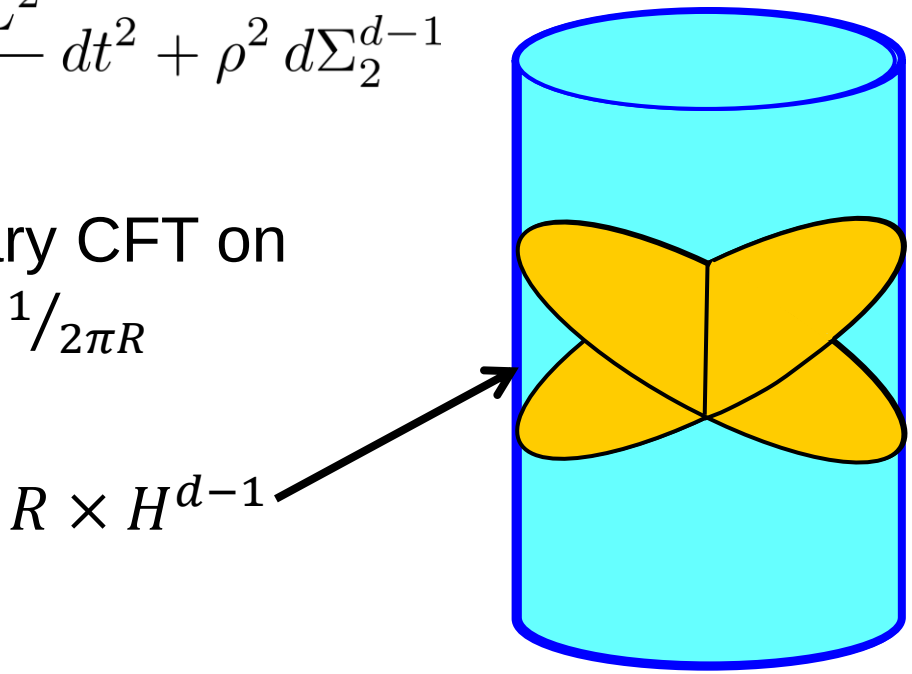
- AdS_{d+1} gravity coupled to brane with AdS_d geometry

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

$$ds^2 = \frac{L^2\, d\rho^2}{(\rho^2 - L^2)} - \frac{\rho^2 - L^2}{R^2}\, dt^2 + \rho^2\, d\Sigma_2^{d-1}$$

- describes TFD state of boundary CFT on $R \times H^{d-1}$ at temperature $T = {}^{1}/_{2\pi R}$

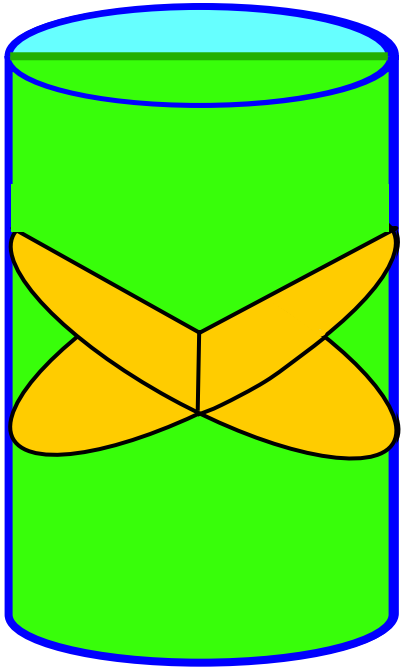


Black Holes in Thermal Equilibrium:

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

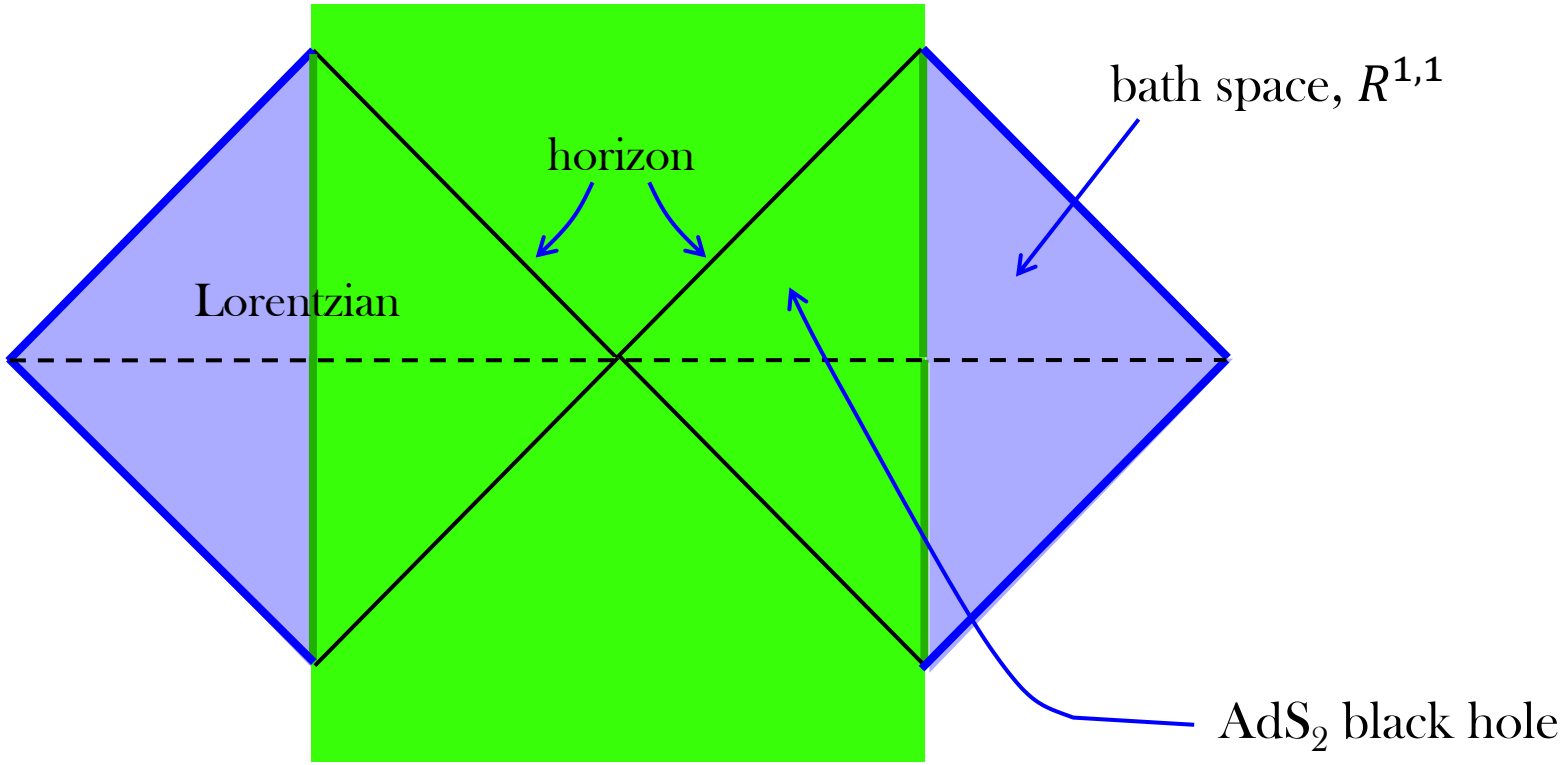
$$ds^2 = \frac{L^2\, d\rho^2}{(\rho^2 - L^2)} - \frac{\rho^2 - L^2}{R^2}\, dt^2 + \rho^2\, d\Sigma_2^{d-1}$$

- 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 $T = {}^{1}/_{2\pi R}$



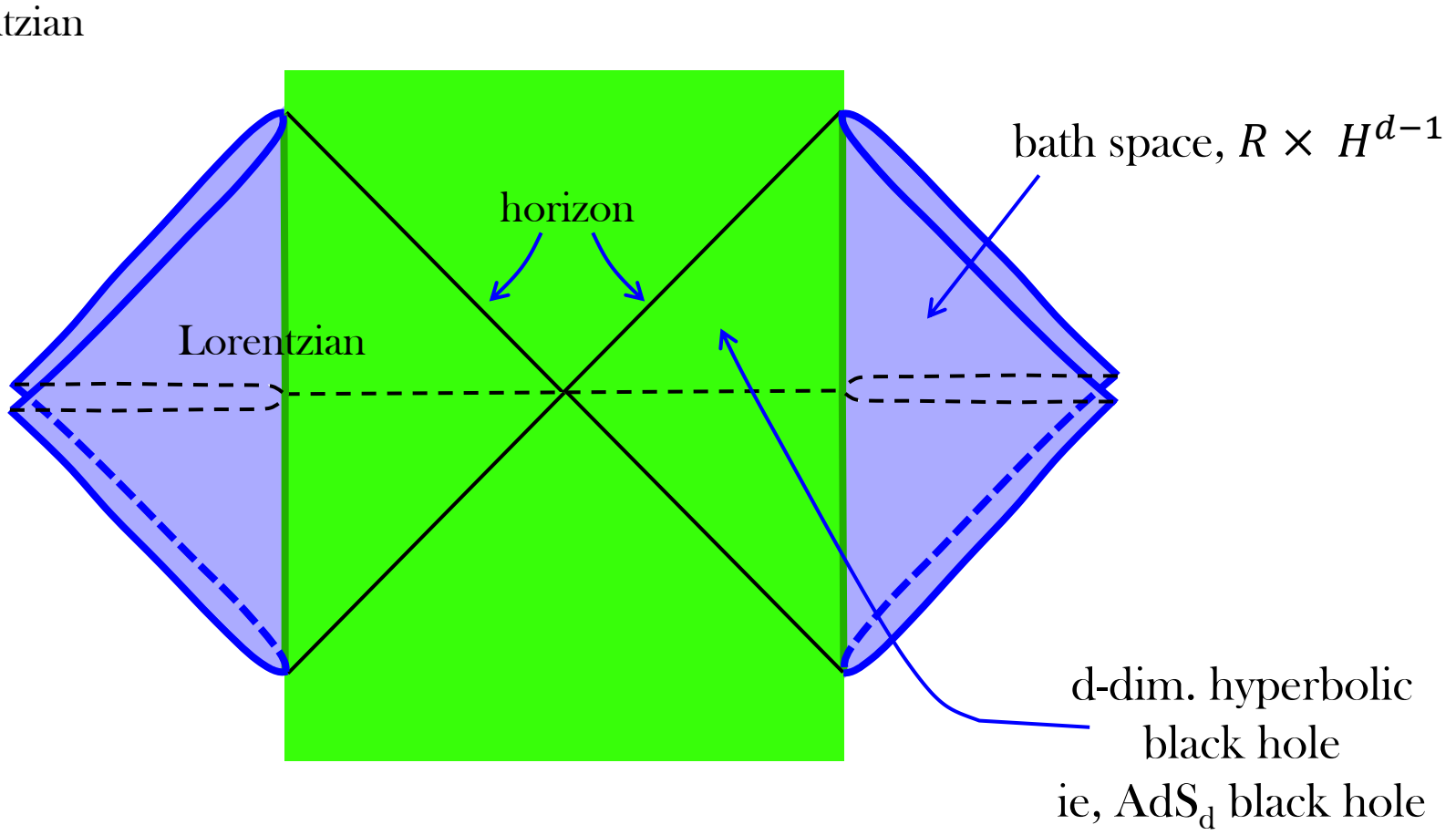
Black Holes in Thermal Equilibrium:

- previous discussion lifts to higher dim'l holographic model with d=2 JT gravity replaced by induced d-dim. Einstein gravity



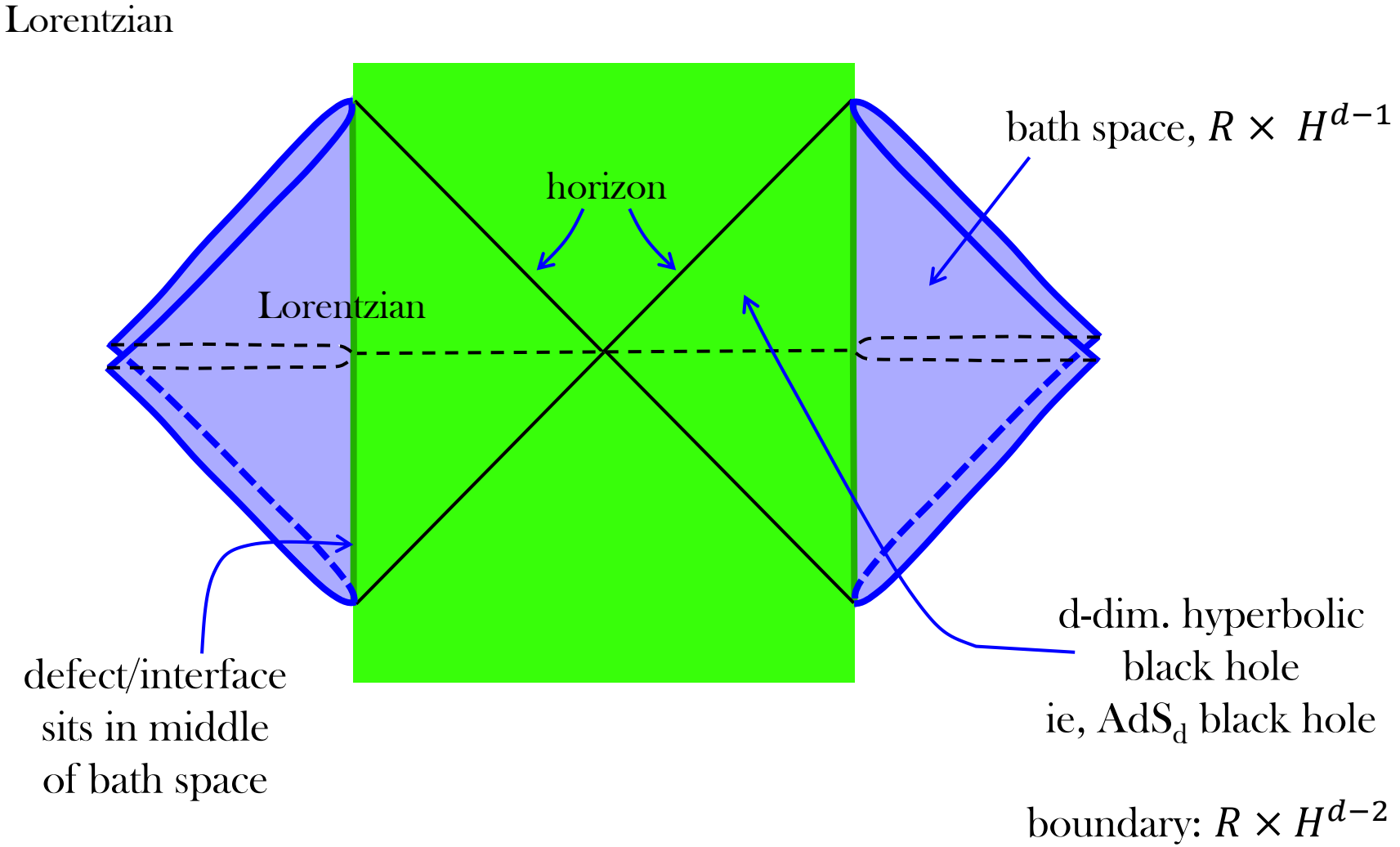
Black Holes in Thermal Equilibrium:

- previous discussion lifts to higher dim'l holographic model with d=2 JT gravity replaced by induced d-dim. Einstein gravity

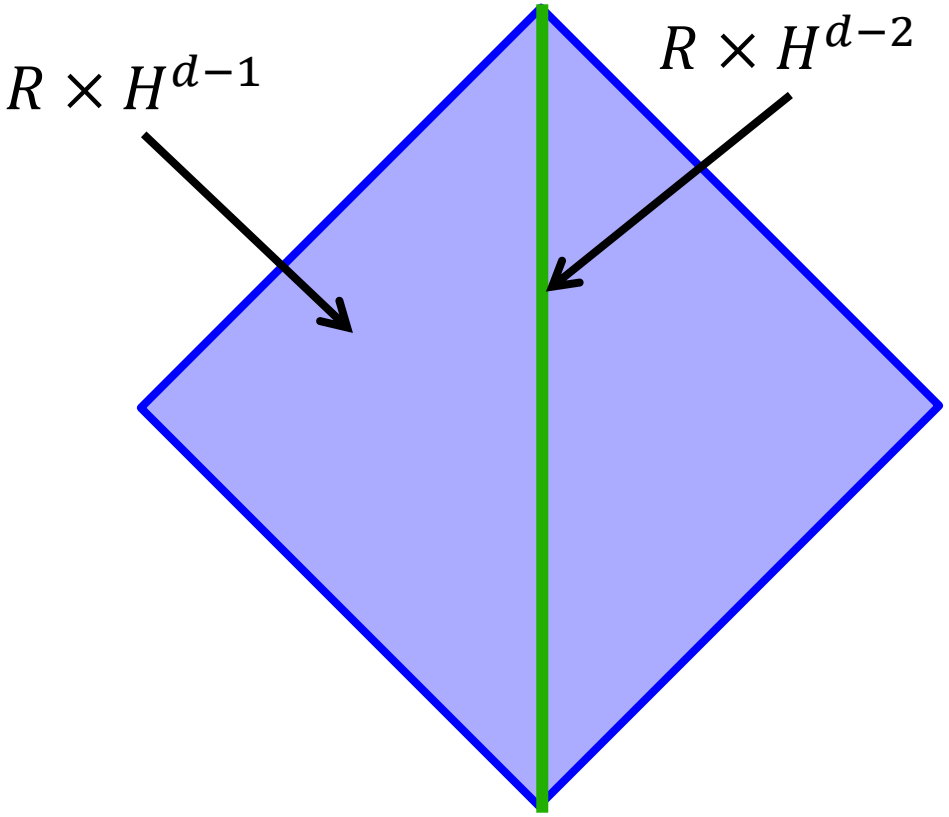


Black Holes in Thermal Equilibrium:

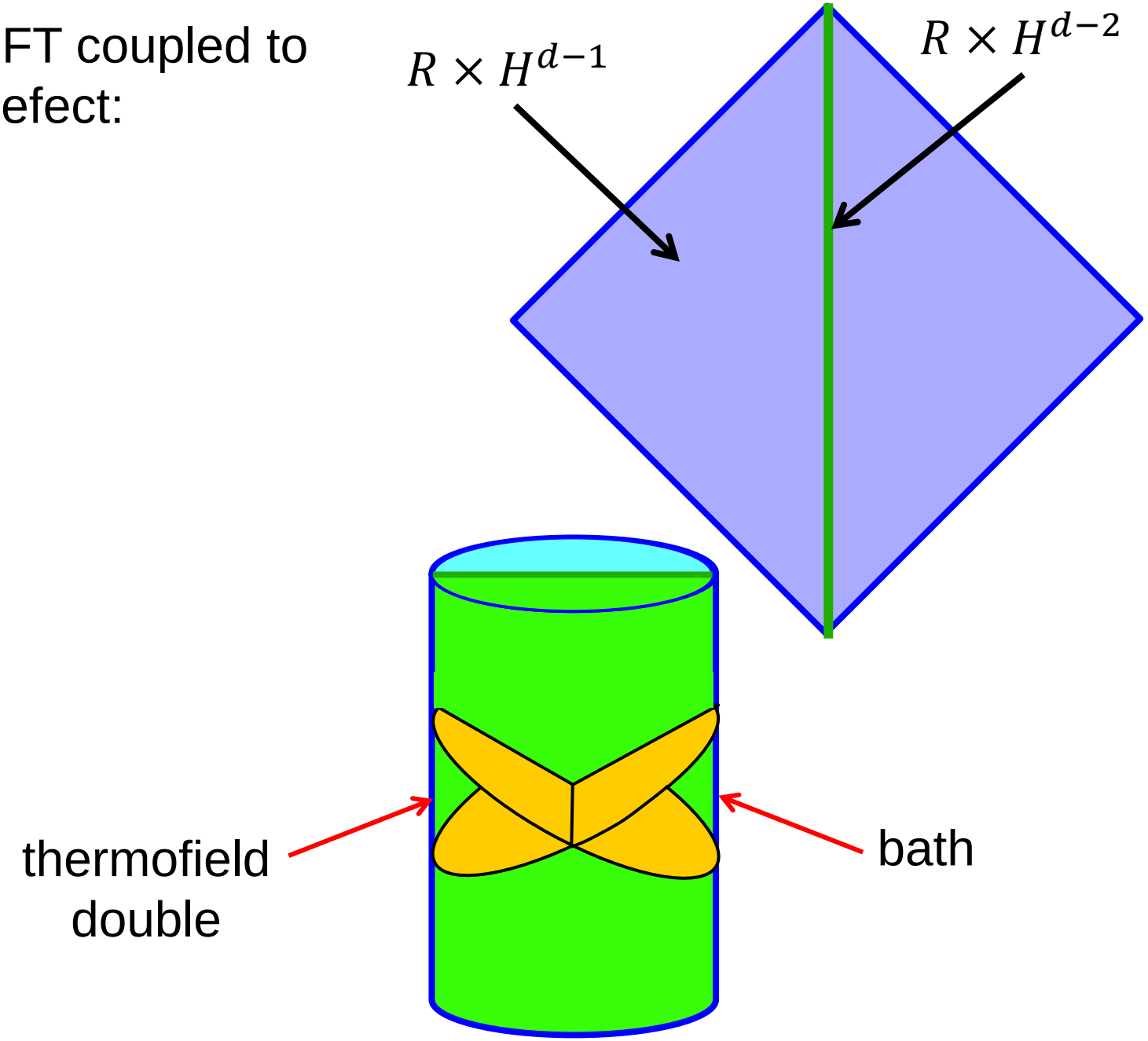
- previous discussion lifts to higher dim'l holographic model with d=2 JT gravity replaced by induced d-dim. Einstein gravity



- boundary CFT coupled to conformal defect:

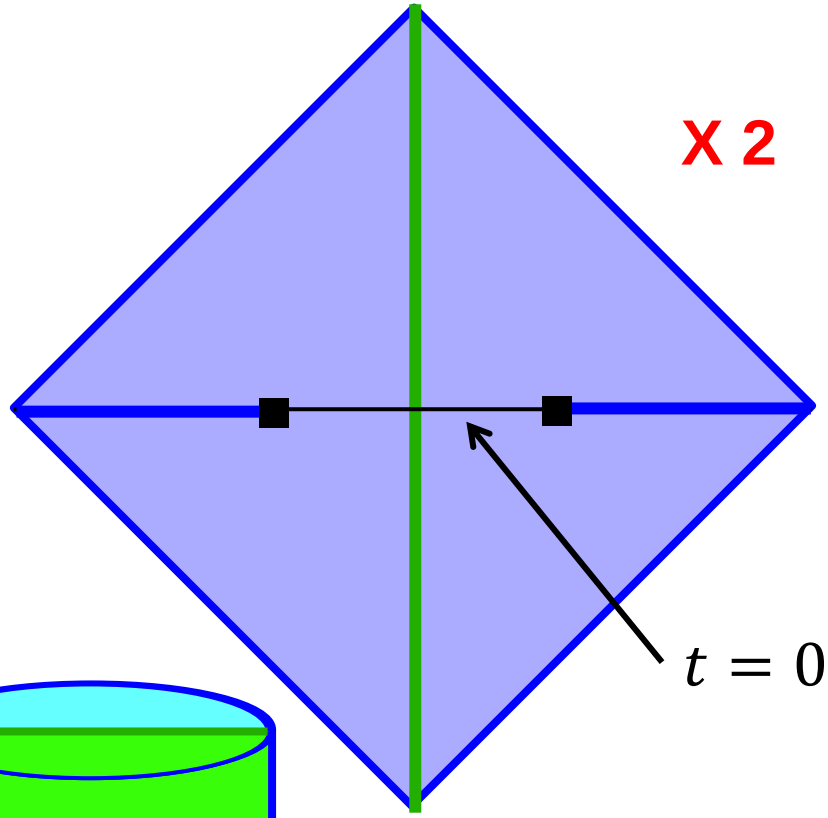


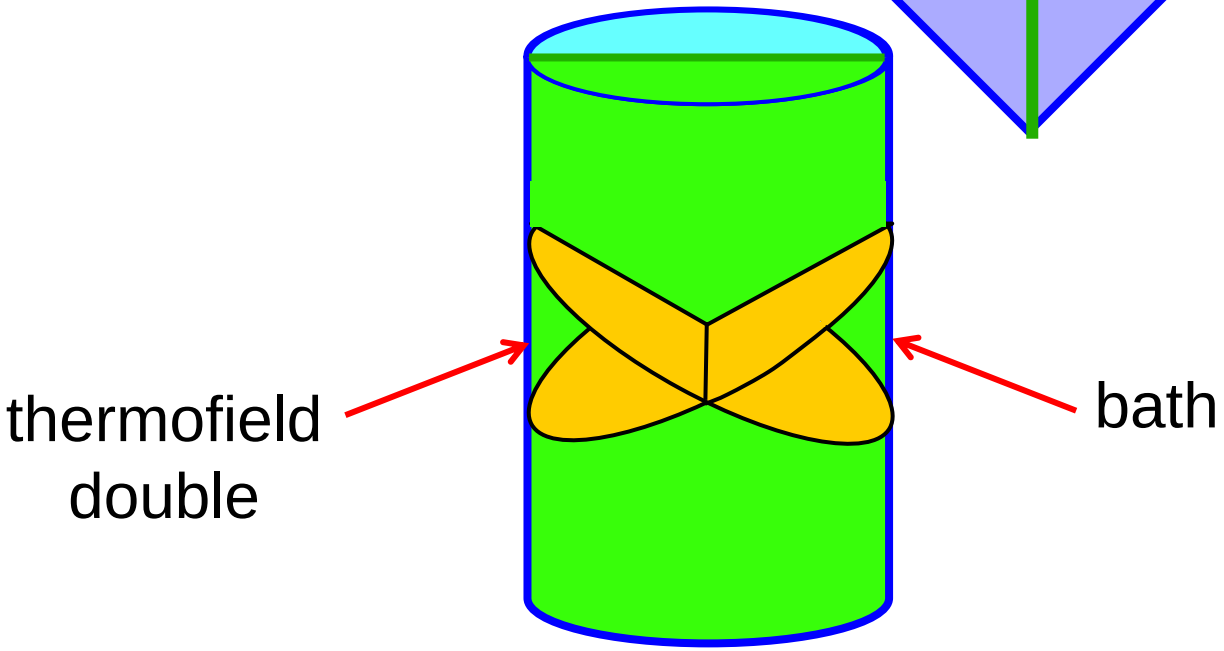
- boundary CFT coupled to conformal defect:



- boundary CFT coupled to conformal defect:

- EE of a bath (and thermal copy), some distance from defect:

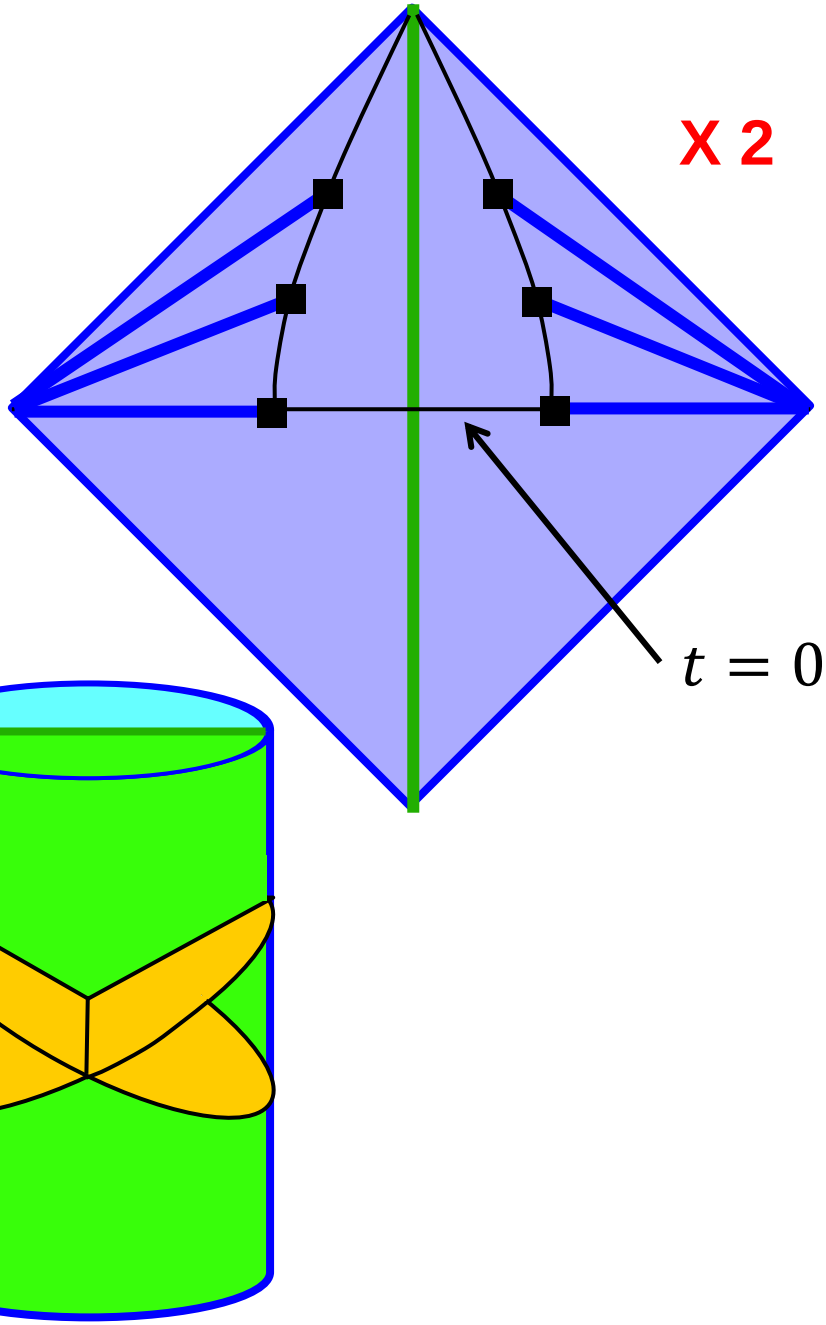




- boundary CFT coupled to conformal defect:

- EE of a bath (and thermal copy), some distance from defect:

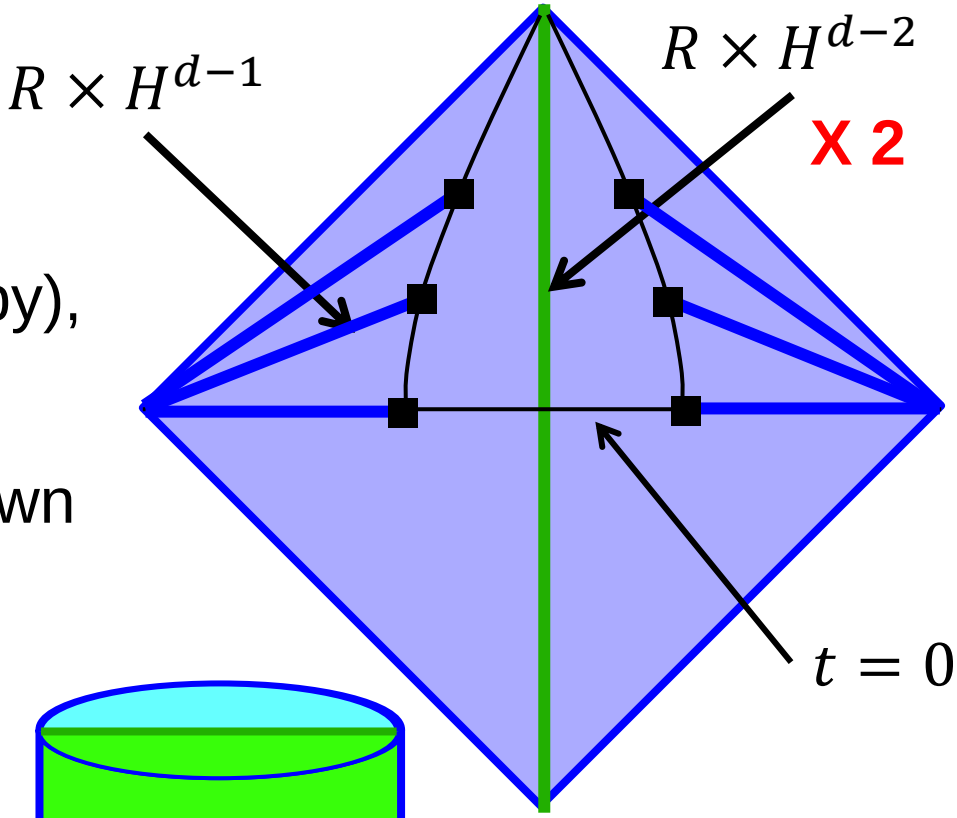
- evolve in time; end points drawn closer to the defect

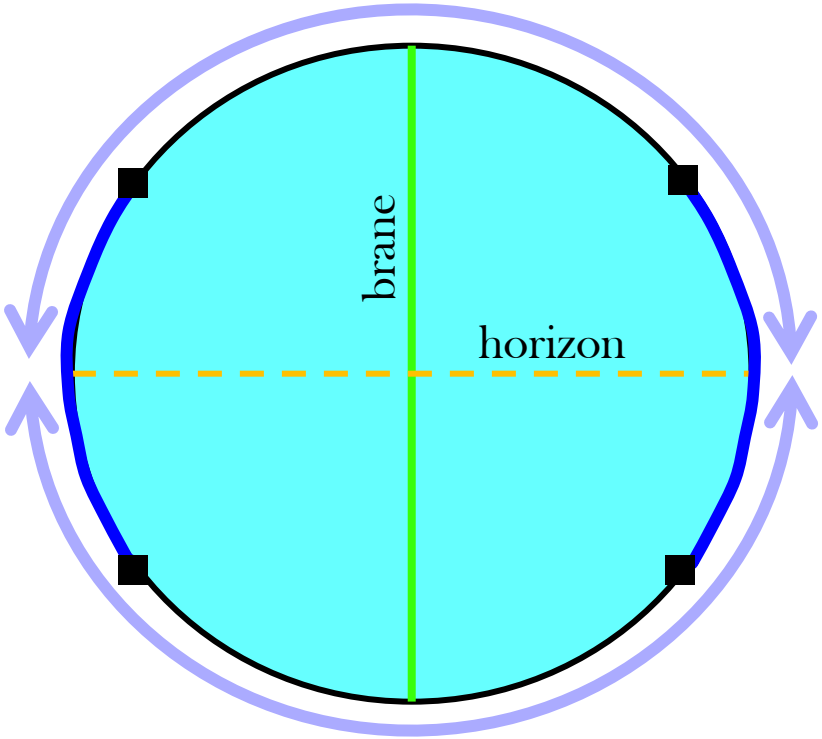


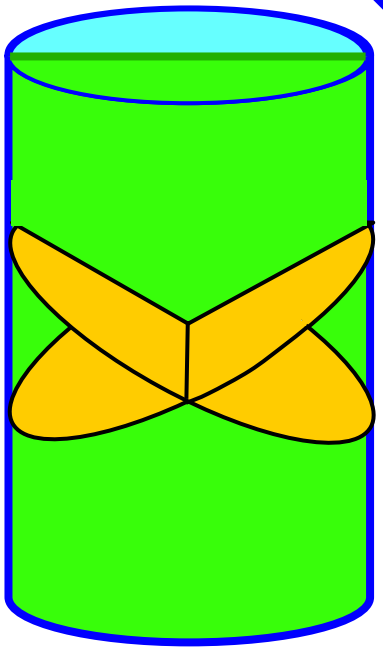
- boundary CFT coupled to conformal defect:

- EE of a bath (and thermal copy), some distance from defect:

- evolve in time; end points drawn closer to the defect



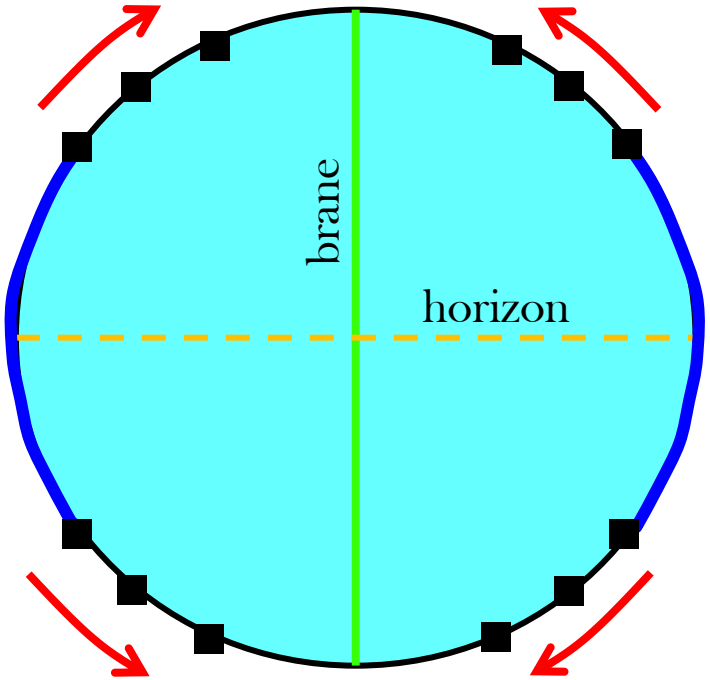


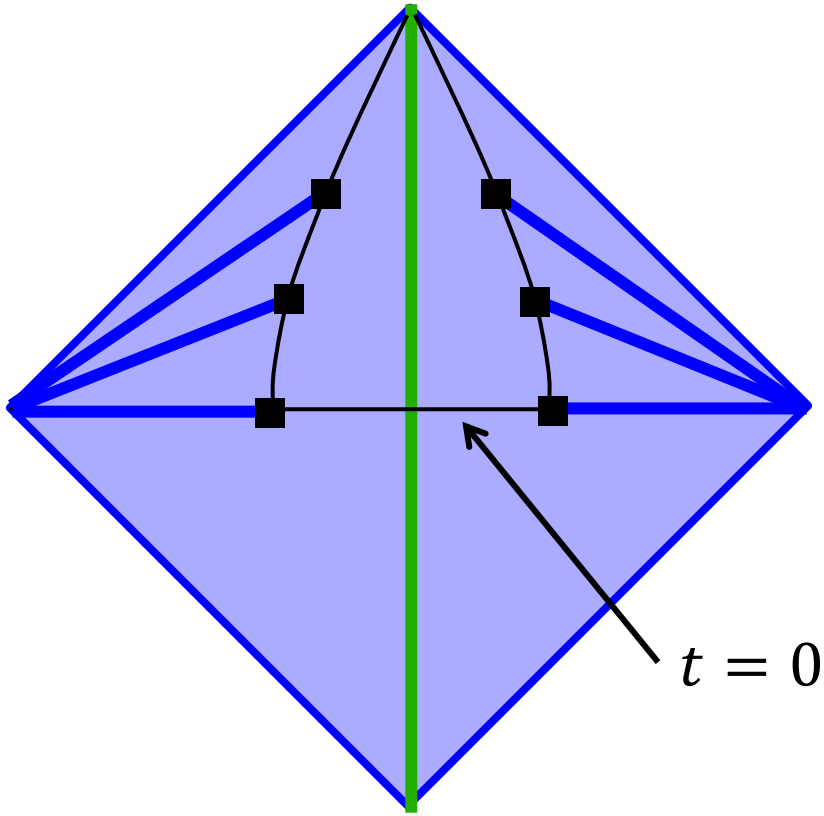


- boundary CFT coupled to conformal defect:

- EE of a bath (and thermal copy), some distance from defect:

- evolve in time; end points drawn closer to the defect



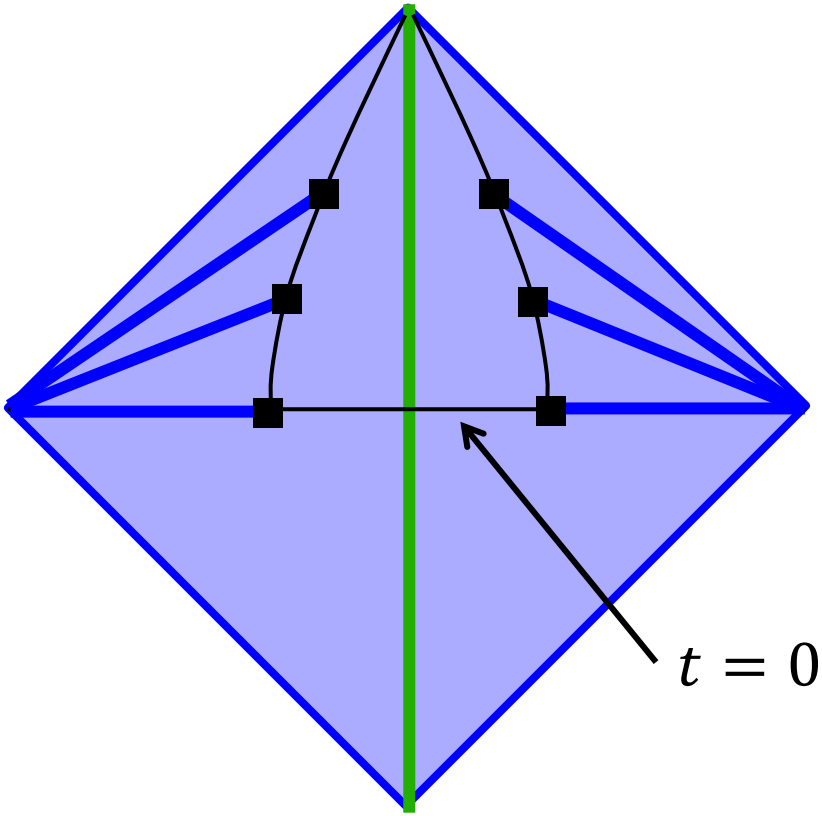


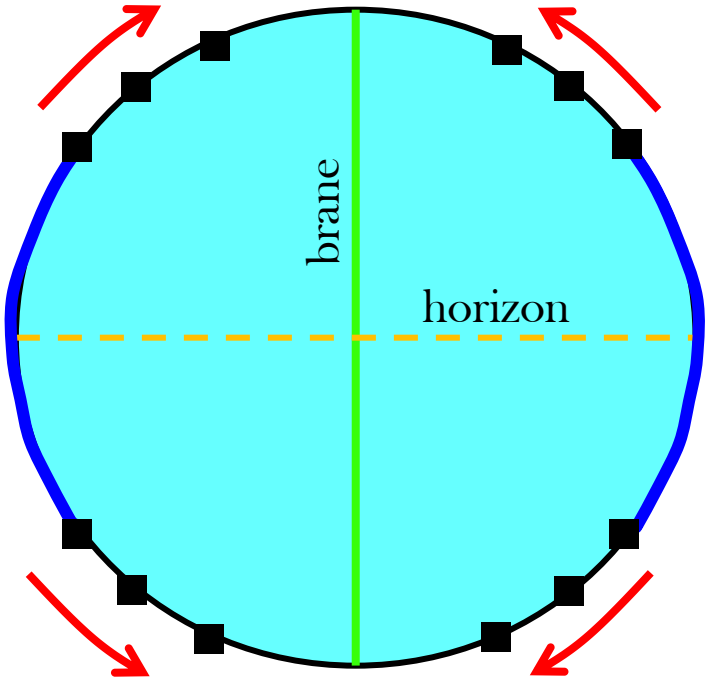
- evolution of endpoints on AdS boundary

- boundary CFT coupled to conformal defect:

- EE of a bath (and thermal copy), some distance from defect:

- evolve in time; end points drawn closer to the defect

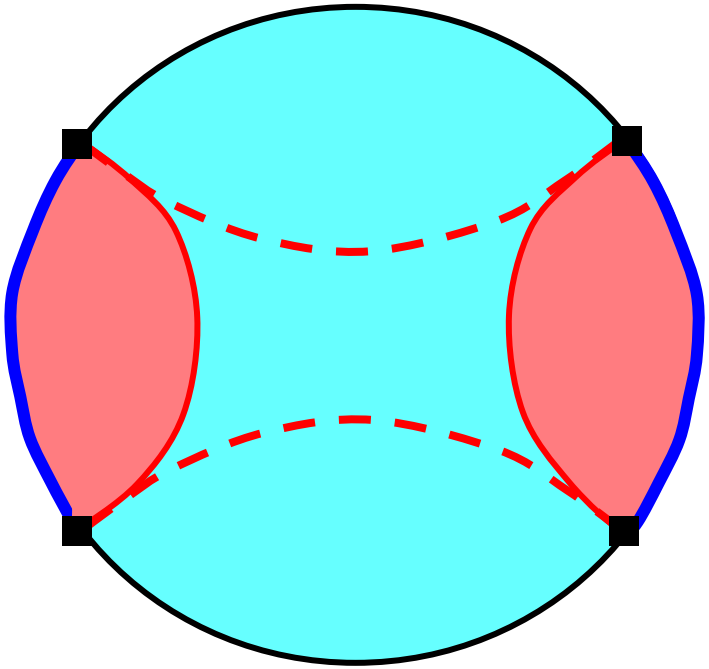


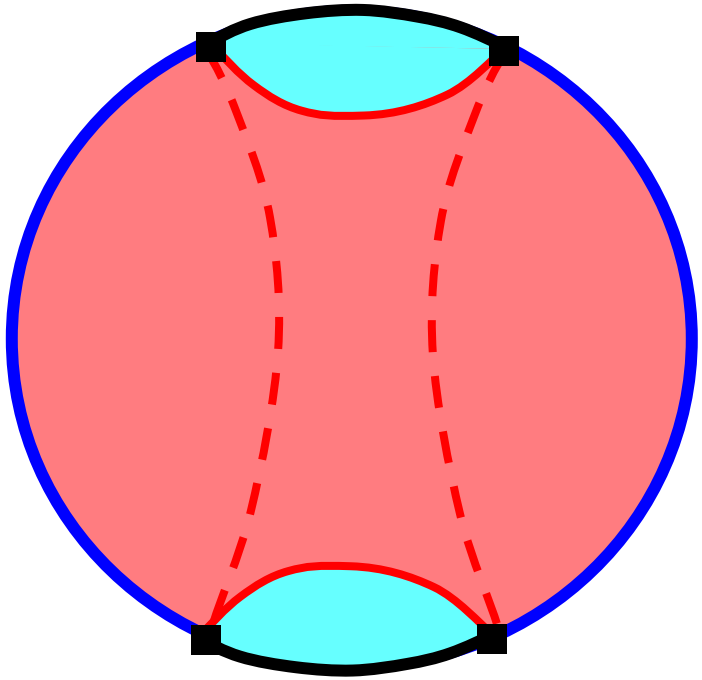


- evolution of endpoints on AdS boundary

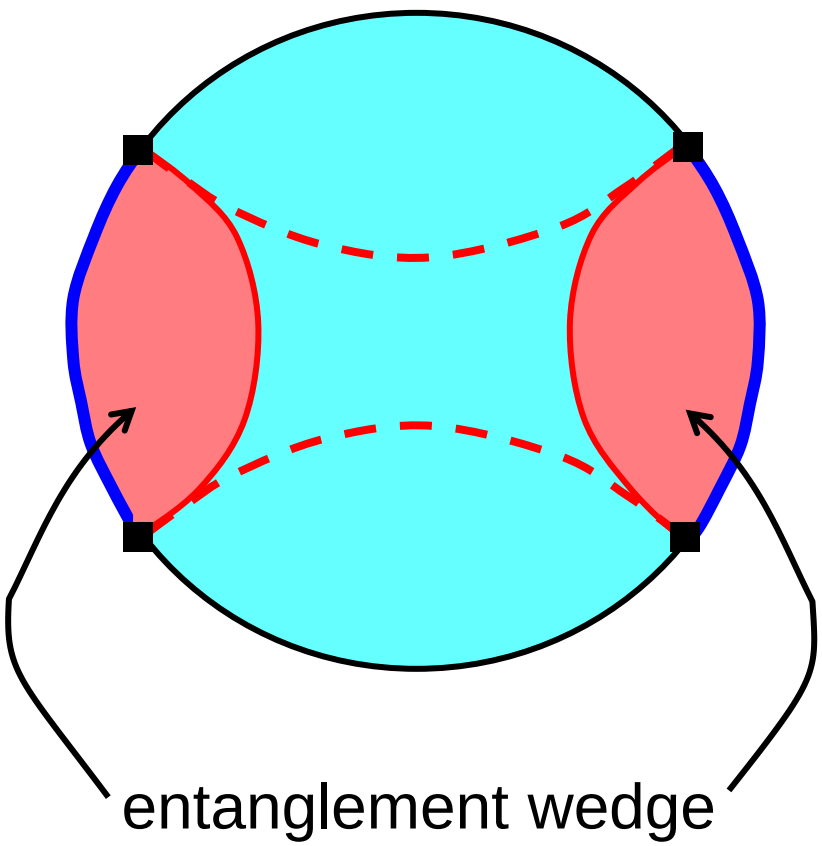
→ reminiscent of familiar holographic EE scenario

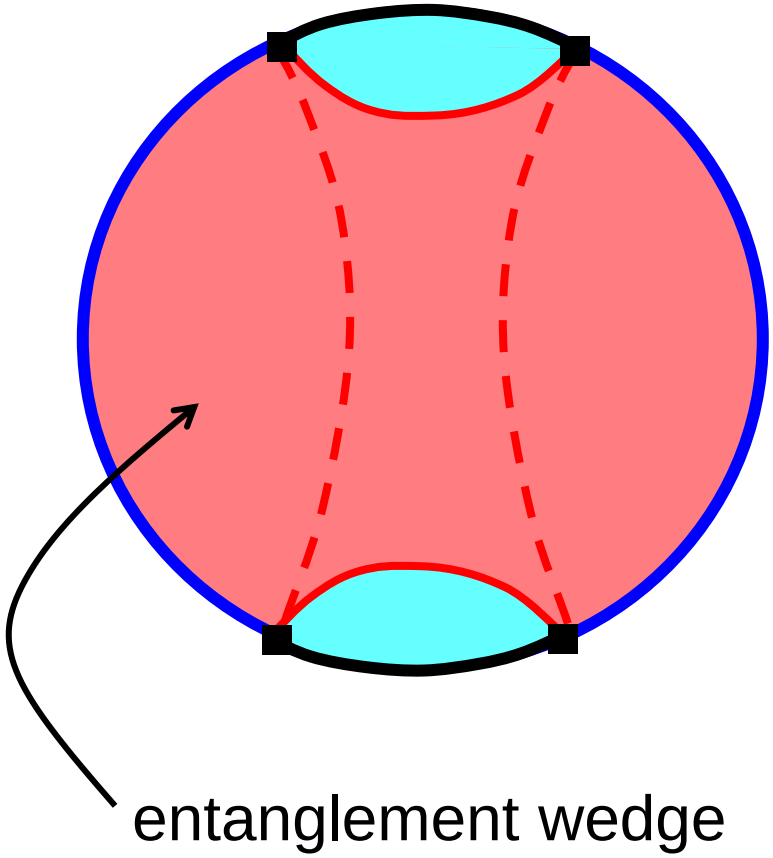
reminiscent of familiar holographic EE scenario



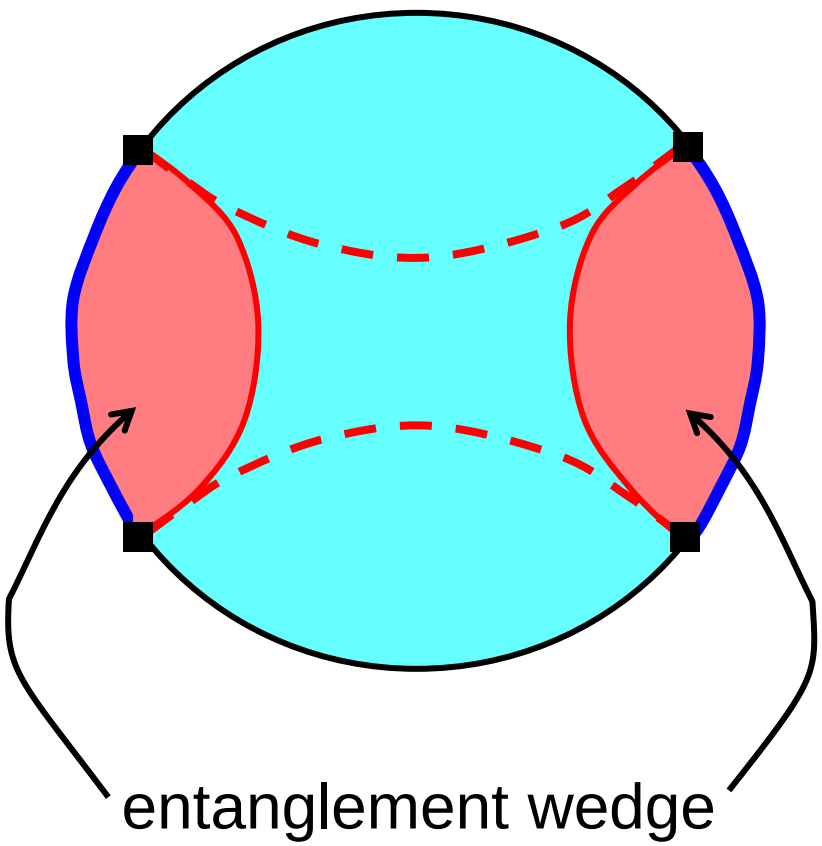


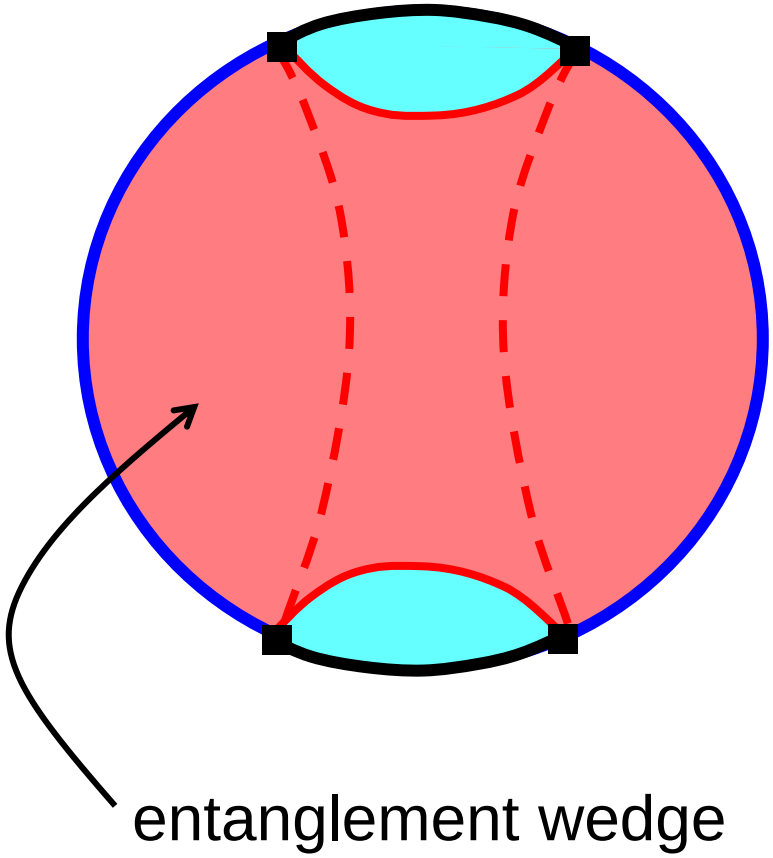
reminiscent of familiar holographic EE scenario





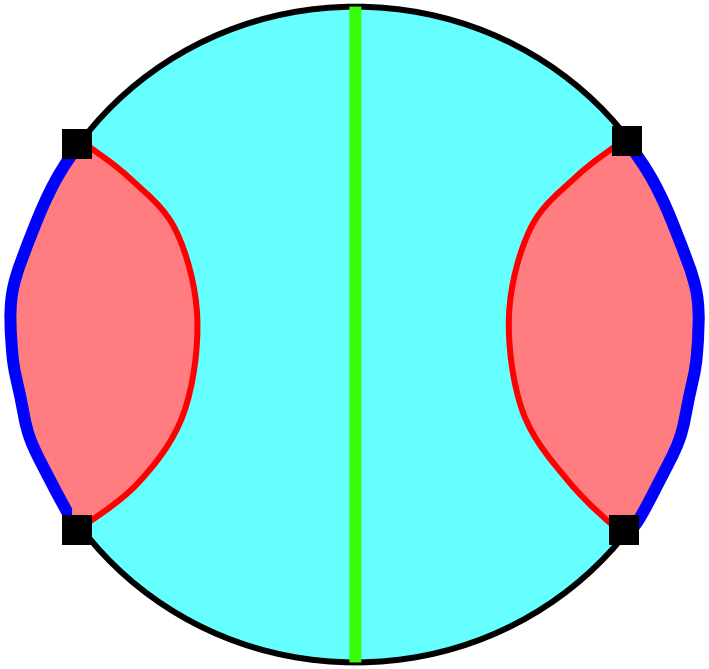
reminiscent of familiar holographic EE scenario

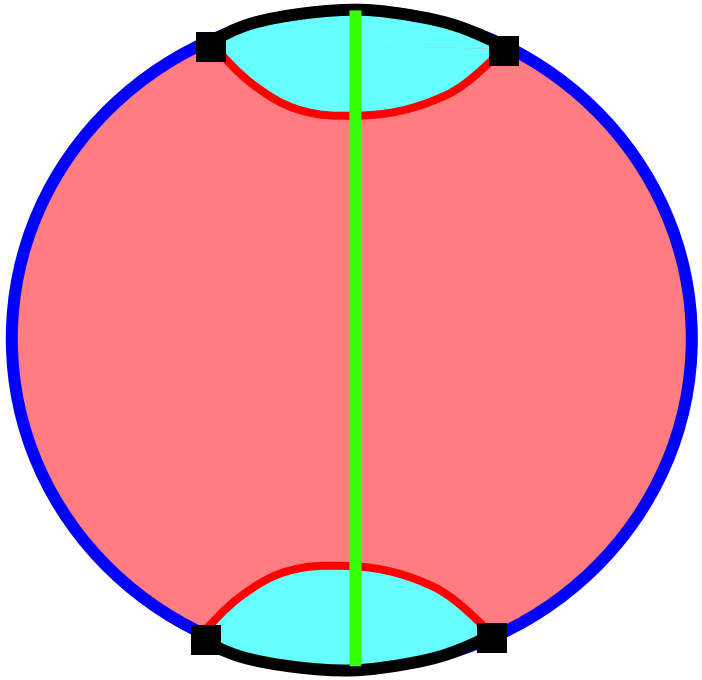




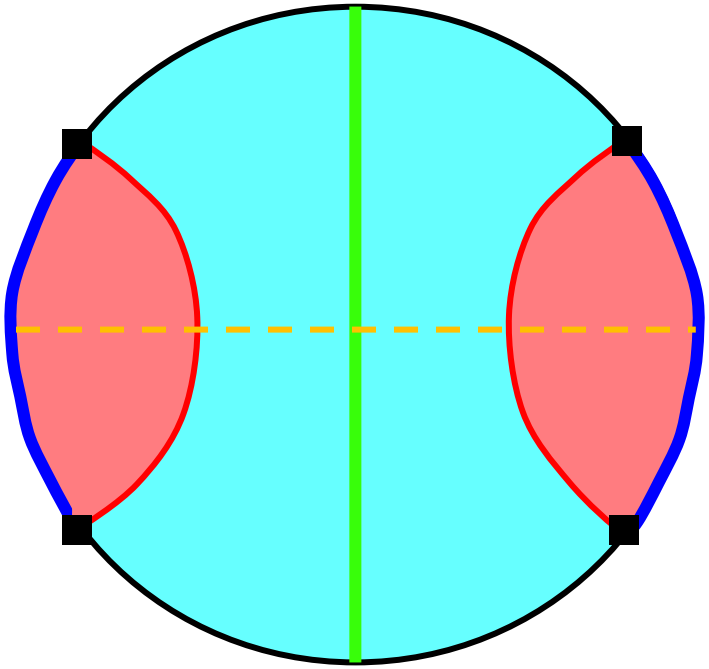
- entanglement wedge reconstruction: can recover bulk operators (within code subspace) inside entanglement wedge with boundary CFT operators in corresponding boundary subregion

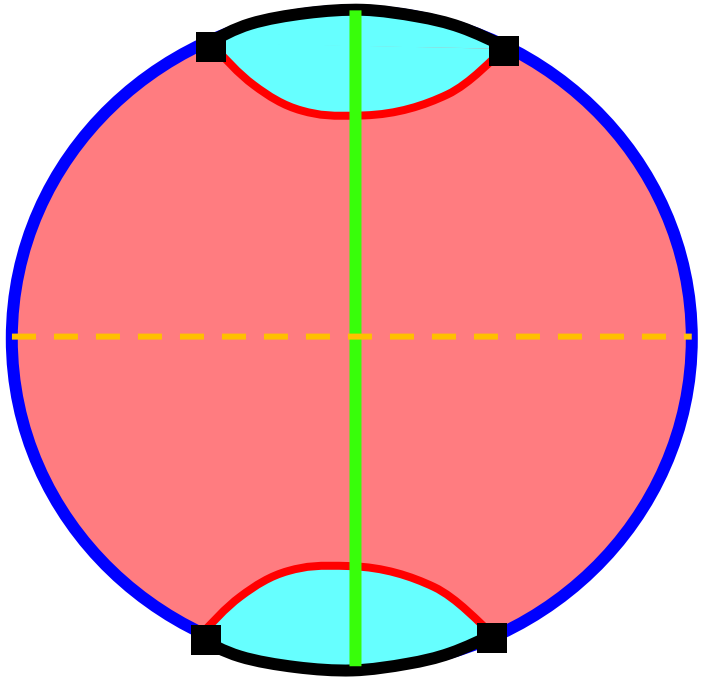
reminiscent of familiar holographic EE scenario





→ reminiscent of familiar holographic EE scenario



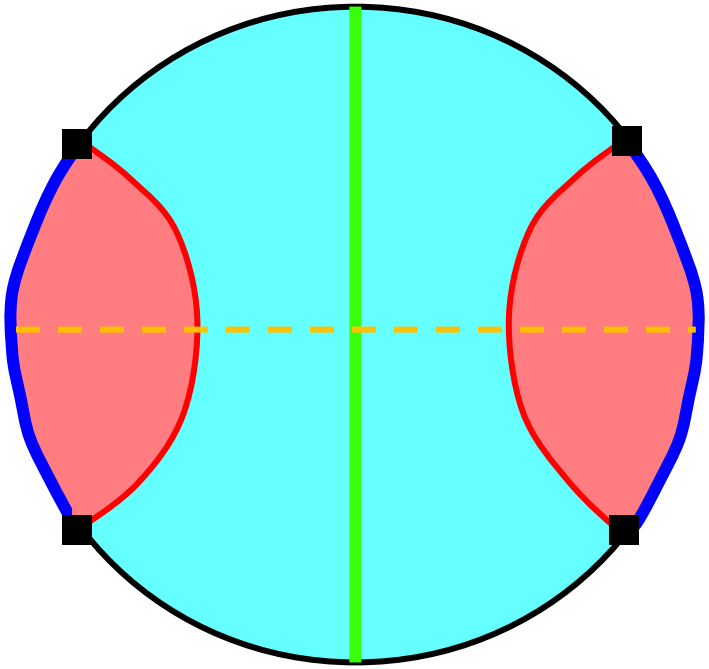


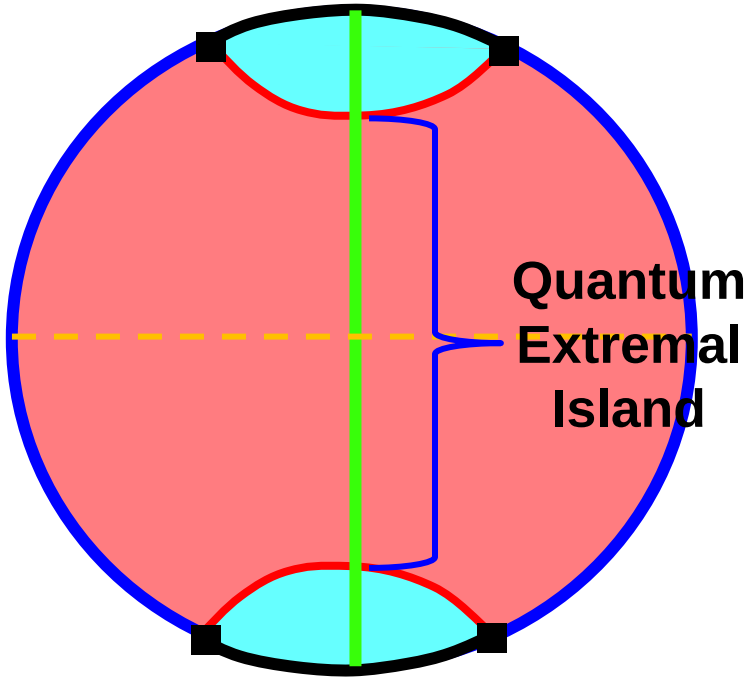
Early times:

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

→ **growth phase**

→ reminiscent of familiar holographic EE scenario





Early times:

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

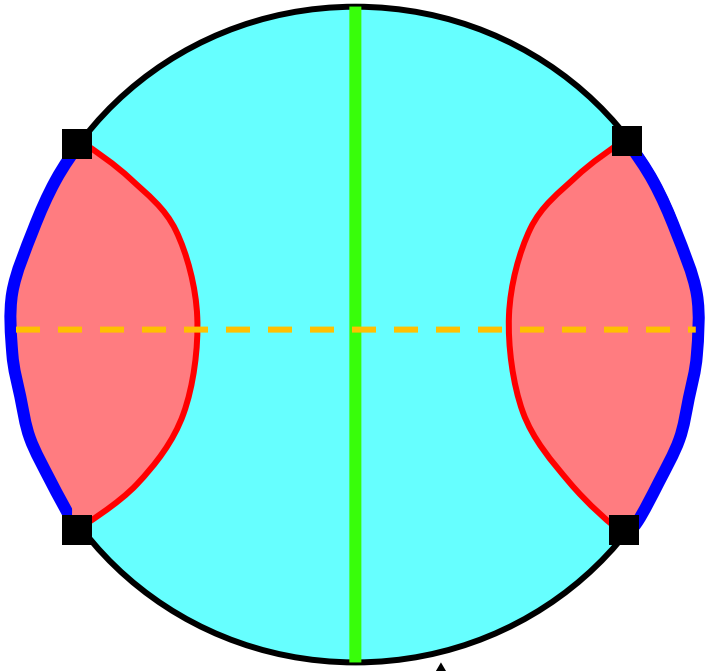
→ **growth phase**

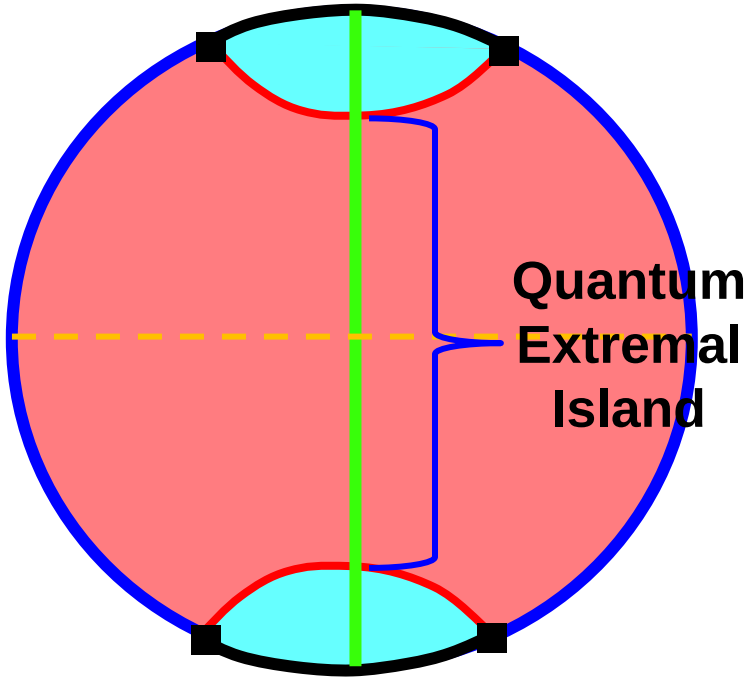
Late times:

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

→ **Page phase**

→ reminiscent of familiar holographic EE scenario





Early times:

Late times:

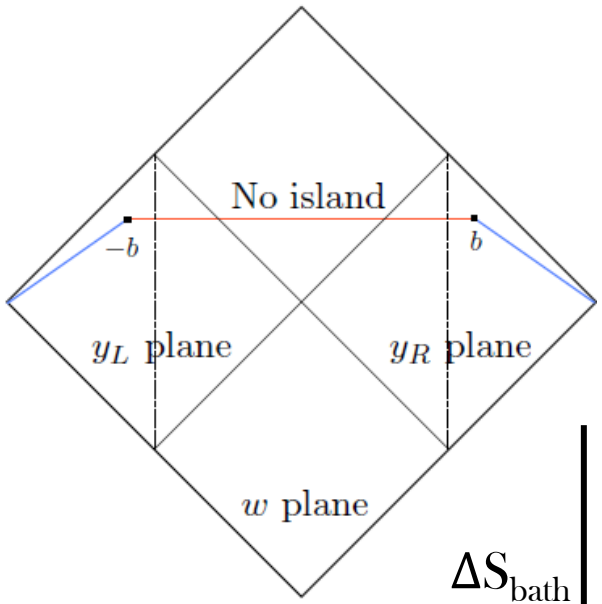
- RT surfaces … n single side of BH → EE … ked in time
- entanglemen… wedge extends boundary … → QE island

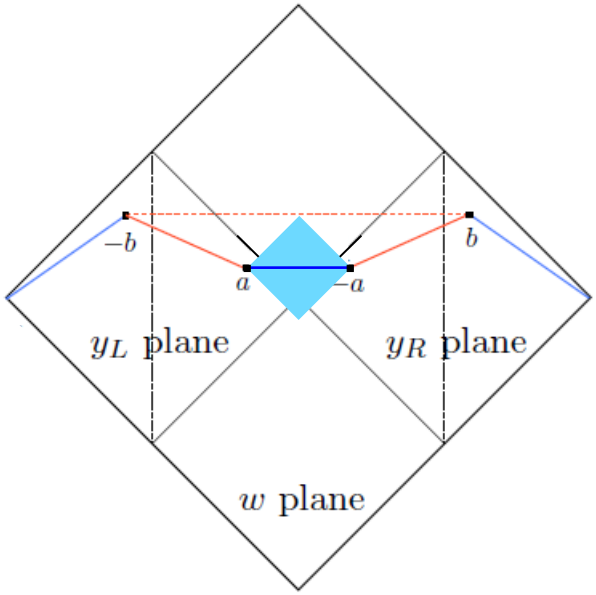
→ **g… ge phase**

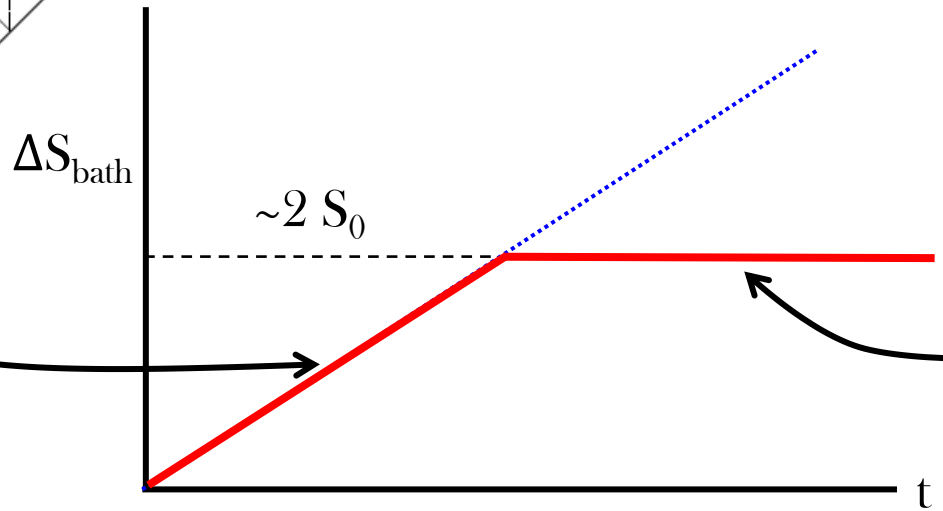
- consider **complementary** regions:
  a) compare Hartman & Maldacena
     → system rapidly thermalizes
  b) outside the horizon?
     → entanglement wedge nesting

New insights from Holographic EE:

- previous discussion lifts to higher dim'l holographic model with d=2 JT gravity replaced by induced d-dim. Einstein gravity
- new model reproduces precisely the behaviour originally seen with d=2 model from familiar properties of holographic EE





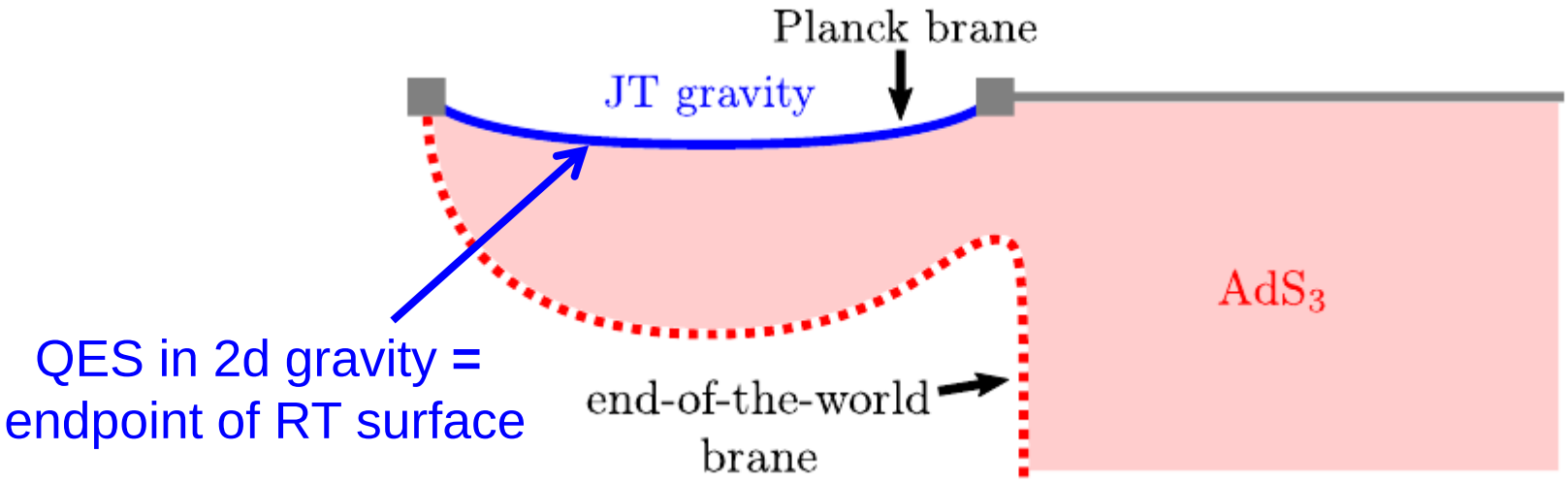


growth phase

Page phase

Questions, Questions, Questions:

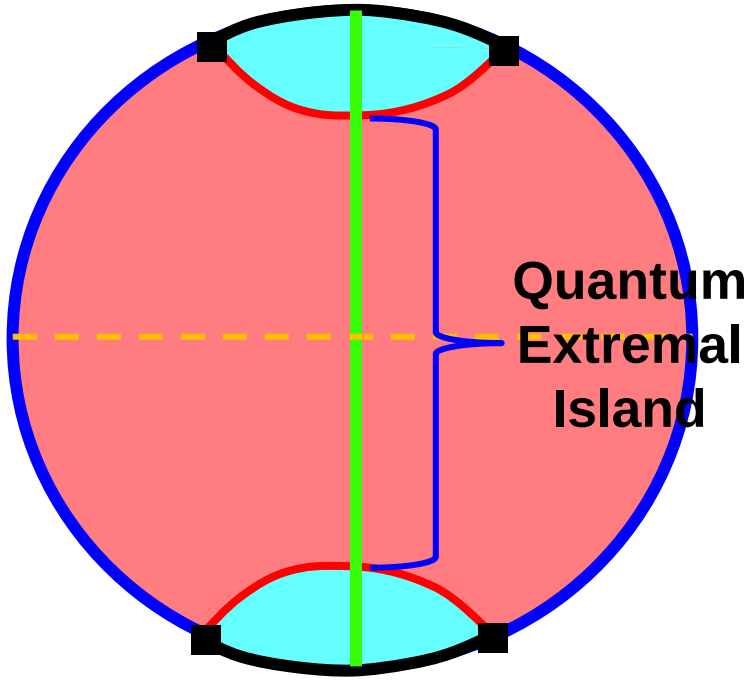
- are dof on Planck brane part of boundary or bulk?
- can RT surfaces really end on the Planck brane?
- does bath state really describe QE Island?



Questions, Questions, Questions:

- are dof on Planck brane part of boundary or bulk?
- can RT surfaces really end on the Planck brane?
- does bath state really describe QE Island?

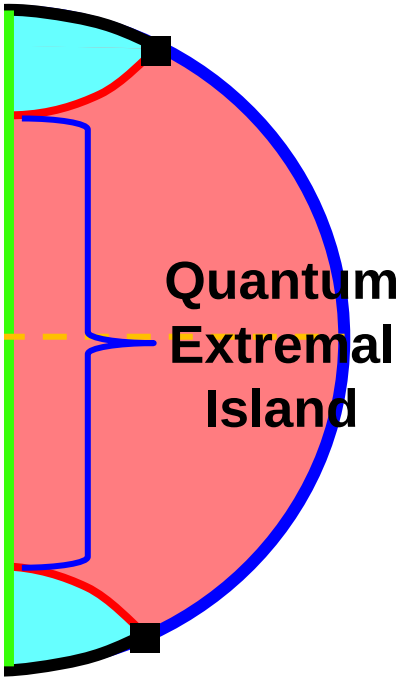
- in our construction, brane is in the middle of the bulk, ie, is part of bulk
- RT surfaces simply cross the brane
- QE Island is part of interior of entanglement wedge, ie, bath state describes QE Island



Questions, Questions, Questions:

- are dof on Planck brane part of boundary or bulk?
- can RT surfaces really end on the Planck brane?
- does bath state really describe QE Island?

- in our construction, brane is in the middle of the bulk, ie, is part of bulk
- RT surfaces simply cross the brane
- QE Island is part of interior of entanglement wedge, ie, bath state describes QE Island



- applying Z_2 orbifold on brane would yield same picture as Almheiri, Mahajan & Maldacena

Questions, Questions, Questions:

- how important is two dimensions?

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

  (see also: Almheiri, Mahajan & Santos)

- was JT gravity important?

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

- was ensemble average of SYK model important?

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

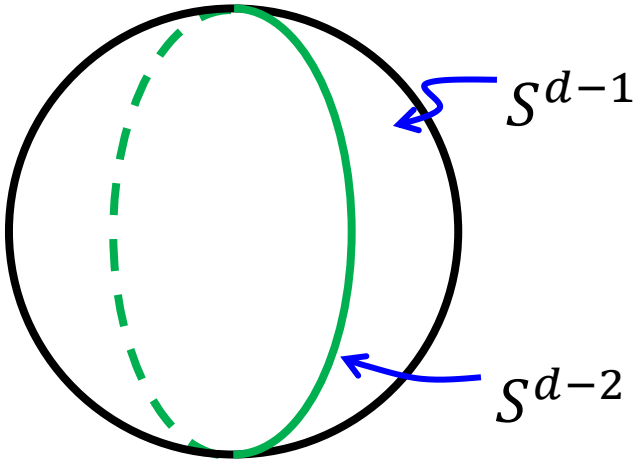
(Note top-down construction with D3 ⊥ D5 by Karch & Randall)

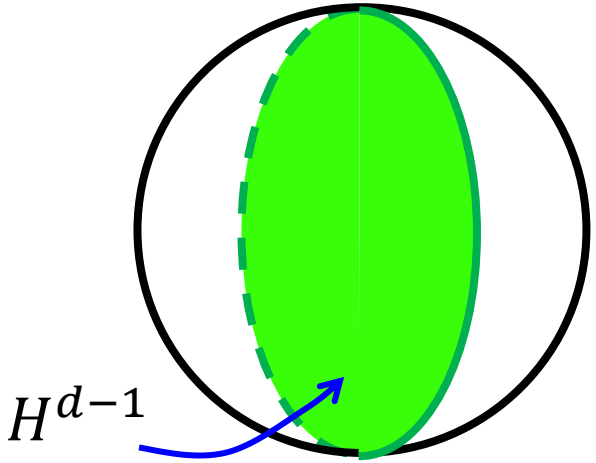
Questions, Questions, Questions:

- 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)
- what's up with that?

Randall-Sundrum gravity:

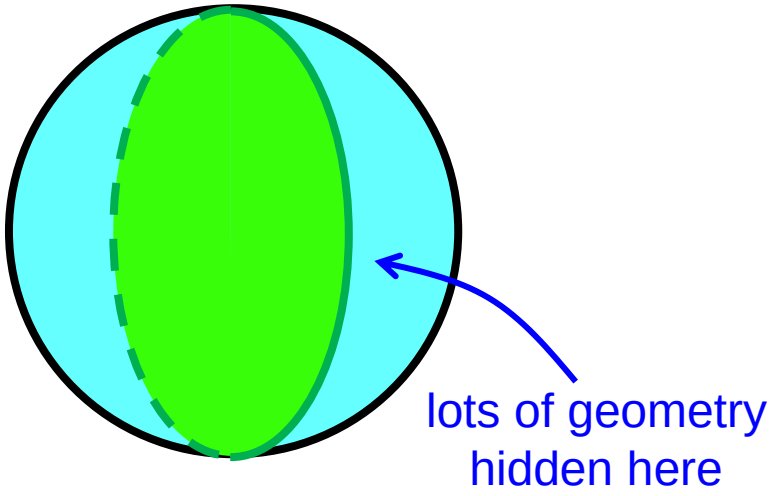
(a) holographic CFT_d coupled to conformal defect (ie, boundary CFT_{d-1})





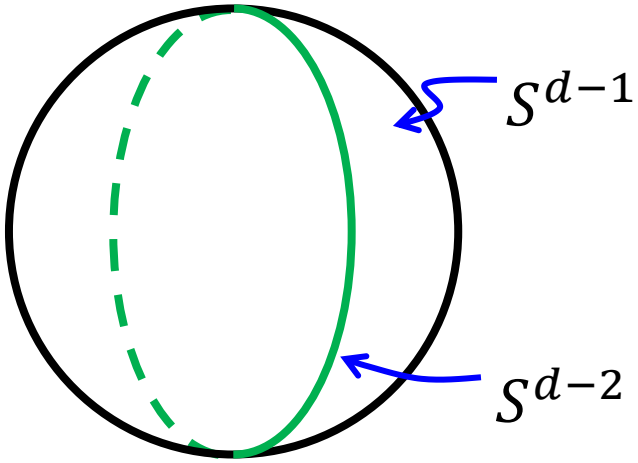
(b) holographic CFT_d coupled to CFT_d with gravity on AdS_d

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



Randall-Sundrum gravity:

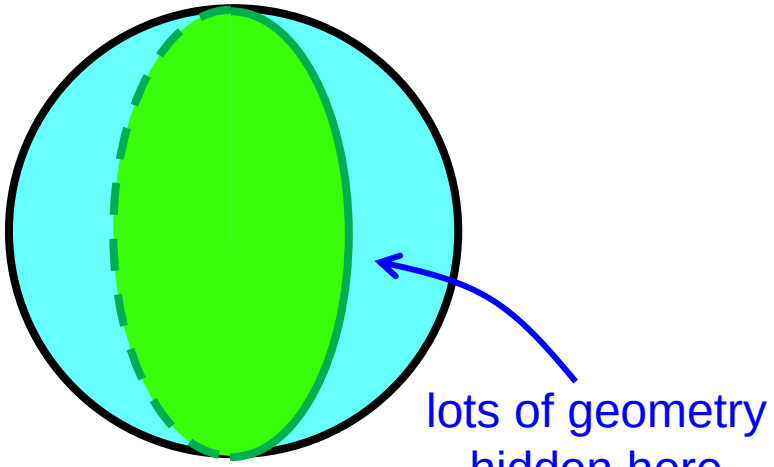
(a) holographic CFT_d coupled to conformal defect (ie, boundary CFT_{d-1})



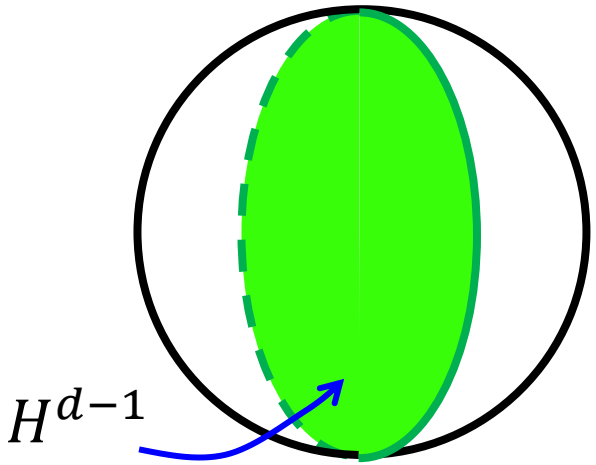
AdS/CFT correspondence

- **these descriptions provide UV complete framework; provide "full quantum description" of radiation**

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



Randall-Sundrum gravity:



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

- **this description provides effective low energy framework, eg, cut-off in CFT_d with gravity theory**
- **provides "semiclassical description" of radiation and Hawking partners**
- **framework for calculations in** Almheiri, Mahajan & Maldacena

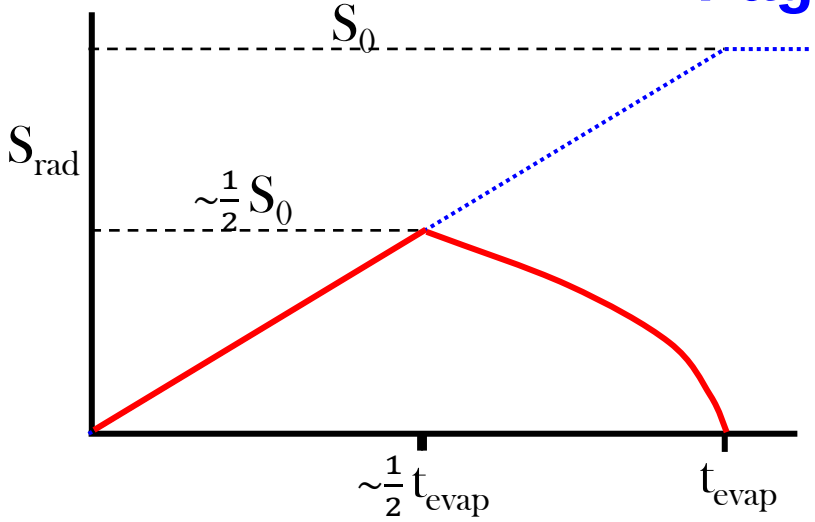
Questions, Questions, Questions:

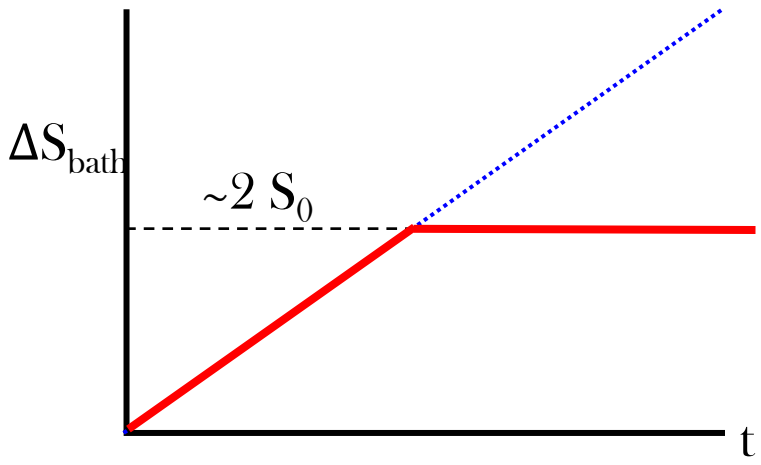
- how was information encoded in Hawking radiation?

Questions, Questions, Questions:

- how was information encoded in Hawking radiation?

Page Curves





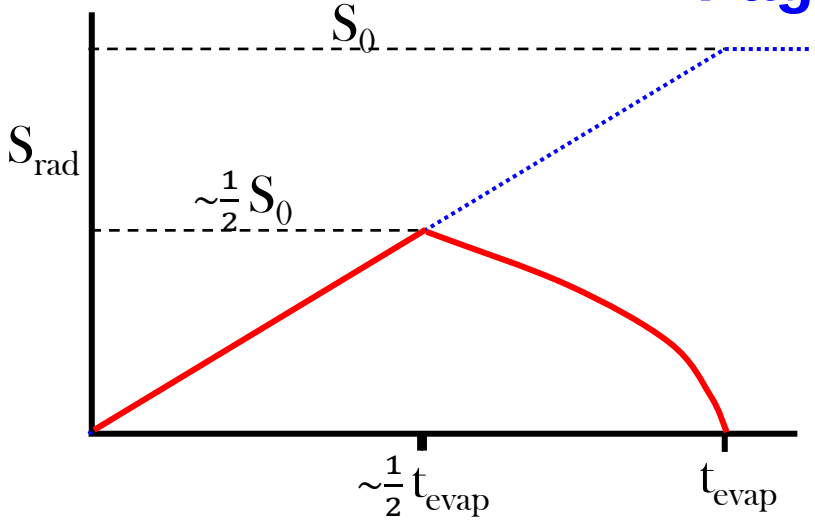
- growth phase: smooth semiclassical saddle points reveal BH entropy without revealing underlying microstates

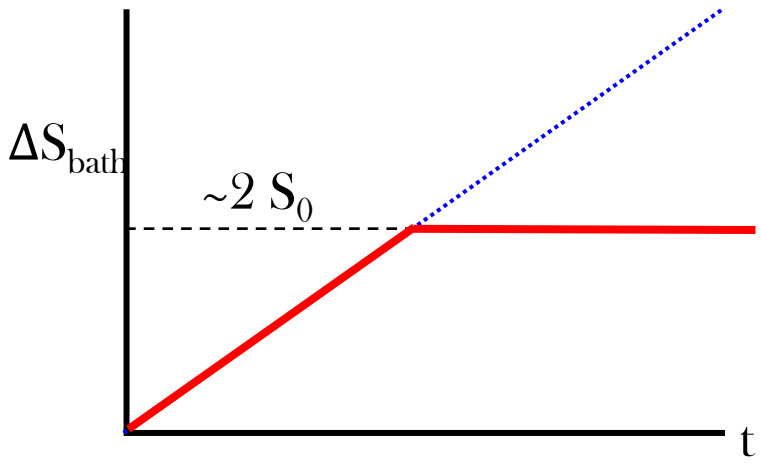
⟶ information paradox

Questions, Questions, Questions:

- how was information encoded in Hawking radiation?

Page Curves





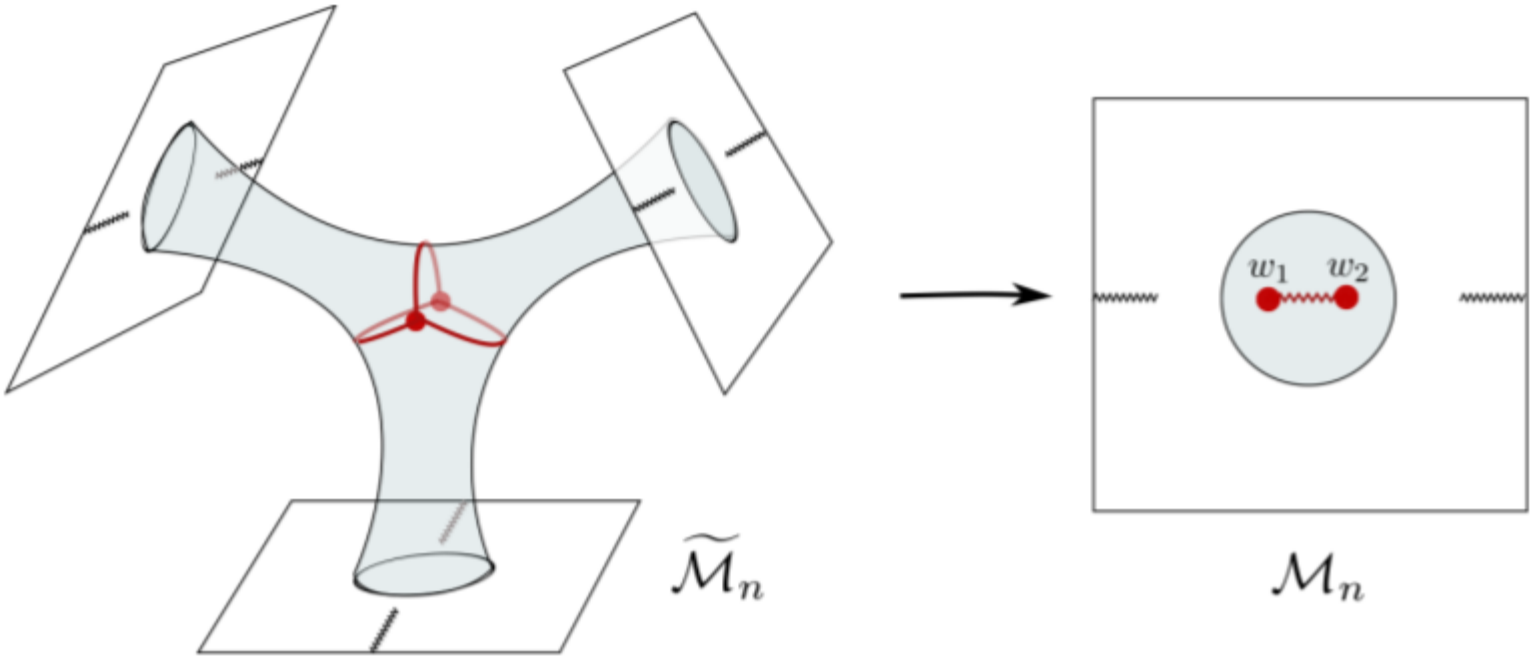
- growth phase: smooth semiclassical saddle points reveal BH entropy without revealing underlying microstates

  ⟶ information paradox

- Page phase: resolves information paradox; expected detailed understanding of BH microstates and encoding of information

Questions, Questions, Questions:

- how was information encoded in Hawking radiation?



see: Almheiri, Hartman, Maldacena, Shaghoulian & Tajdini;
(Penington, Shenker & Stanford)

- Page phase: resolves information paradox; expected detailed understanding of BH microstates and encoding of information

⟶ **Surprise:** Page phase described by saddle point(s) without revealing microscopic details!!

Conclusions:

- simple holographic model illustrates the appearance of quantum extremal islands
- new insights viewed as familiar properties of holographic EE → are insights universal??
- Page phase can be described by saddle point without revealing microscopic details with large-N!! → what/how learn about microstates and information?
- what about: evaporating BHs? massive BHs? teleportation to mine information on island? quantum focusing & isolating island? understand how information escapes horizon? . . . . .

Conclusions:

- simple holographic model illustrates the appearance of quantum extremal islands
- new insights viewed as familiar properties of holographic EE → are insights universal??
- Page phase can be described by saddle point without revealing microscopic details with large-N!! → what/how learn about microstates and information?
- what about: evaporating BHs? massive BHs? teleportation to mine information on island? quantum
  how infor

Lots to explore!