Quantum Black Holes as Holograms

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ICREA + UBarcelona

Extreme Universe Online Colloquium

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Early ideas

Takahiro Tanaka gr-qc/0203082

RE+Alessandro Fabbri+Nemanja Kaloper

hep-th/0206155

Recent work with

Antonia Frassino

Raimon Luna

Juan Pedraza

Ryotaku Suzuki

Andy Svesko

Marija Tomašević

Manus Visser

Benson Way

arXiv

2007.15999

2207.03302

2301.02587

Half a century of Black Hole radiance

1974

The beginning of the era of the Quantum Era of Black Holes

Half a century of Black Hole radiance

Gravity should be the classical limit of a quantum theory

Black holes should be the classical limit of a quantum object

What is a Quantum Black Hole?

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Hawking did not have a quantum theory of gravity

He studied quantum fields in a fixed classical background

The black hole emits radiation

What is a Quantum Black Hole?

Hawking did not have a quantum theory of gravity

He studied quantum fields in a fixed classical background

The black hole emits radiation

Radiation comes out of the black hole

but the *black hole remains unaffected and classical*

What is a Quantum Black Hole?

Black hole remains unaffected and classical

- Good enough if radiation emission has a small effect on the black hole
- Fails if effects are large – because they accumulate over time, or because single quantum emission is significant

Backreaction problem

What is a Quantum Black Hole?

Hawking did not have a quantum theory of gravity

Nowadays, *we do* have good quantum theories of gravity where black holes appear in the semiclassical limit

AdS/CFT

Then, what is a Quantum Black Hole?

AdS/CFT:

Black hole = a large-N matrix, with fastly scrambling entries

But too poorly understood to deal with backreaction problem

Then, what is a Quantum Black Hole?

Simpler goal

Classical geometry of black hole modified (possibly a lot)

by quantum effects

Quantum-backreacted black hole

Much insight gained this way

Quantum backreaction

$$G_{\mu\nu}(g_{\alpha\beta}) = 8\pi G \langle T_{\mu\nu}(g_{\alpha\beta}) \rangle$$

classical Einstein tensor & metric

quantum matter renorm stress tensor (many fields)

Coupled system: metric + ⟨QFT⟩

Very hard to solve simultaneously

Perturbative backreaction: limited insight

Quantum backreaction

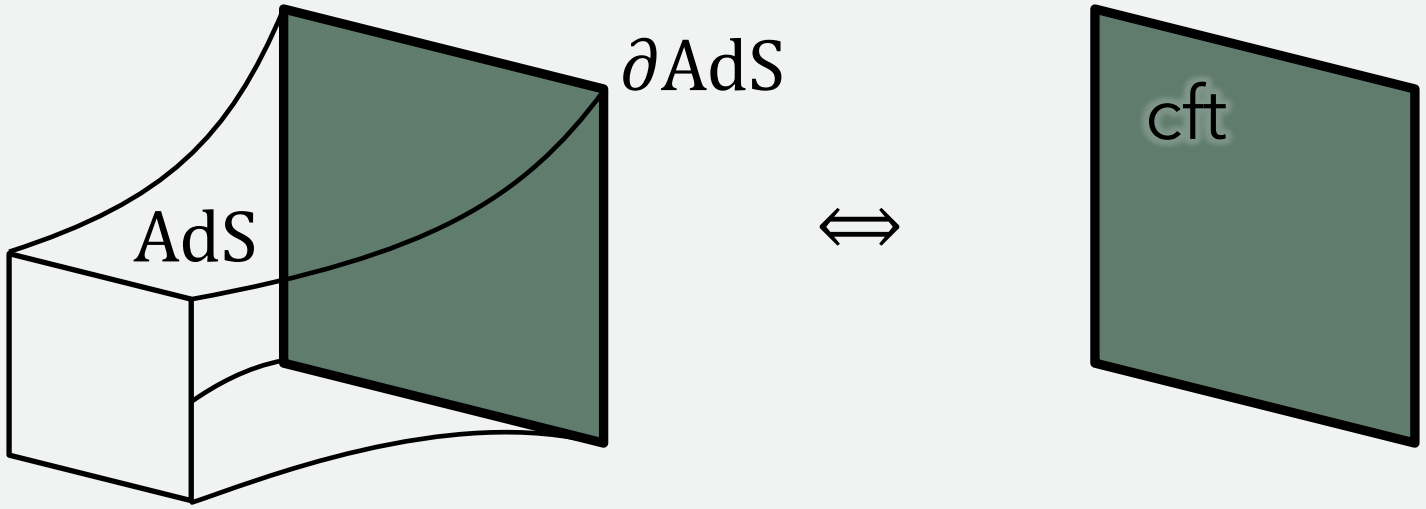
Exact backreaction:

2D models: CGHS/RST, JT+CFT

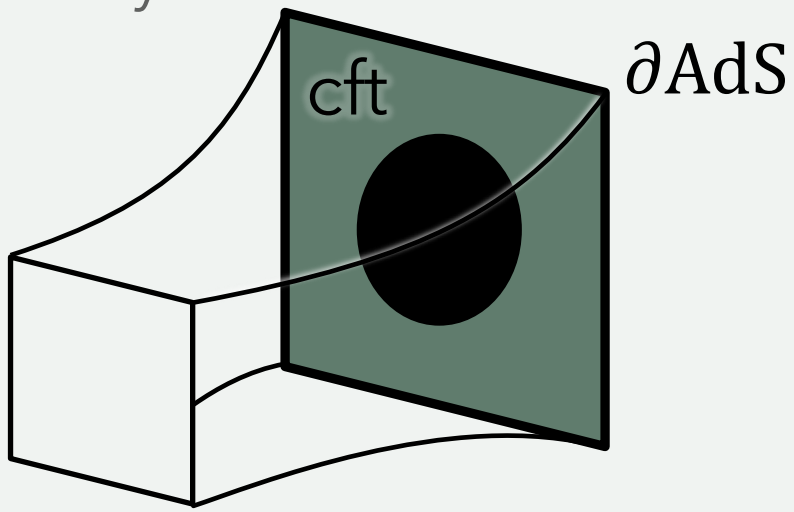
Holographic reformulation

Solving QFT with Holography

- AdS/CFT maps quantum field dynamics into classical gravitational bulk dynamics
- The AdS boundary geometry, where the CFT lives, is often flat, or spherical



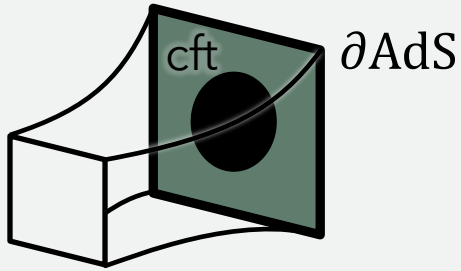
- But it can be a black hole geometry



- In this case, holographic CFT lives on black hole background (fixed)
- CFT state in the presence of black hole is dual to some classical bulk – to be found

CFT on black hole background – holographically

solve bulk ≡ solve cft in black hole



- Quantum field on a black hole background ⇒ Hawking radiation
- Quantum Hawking radiation of CFT is *dual to some classical bulk dynamics* – not trivial, but possibly easier

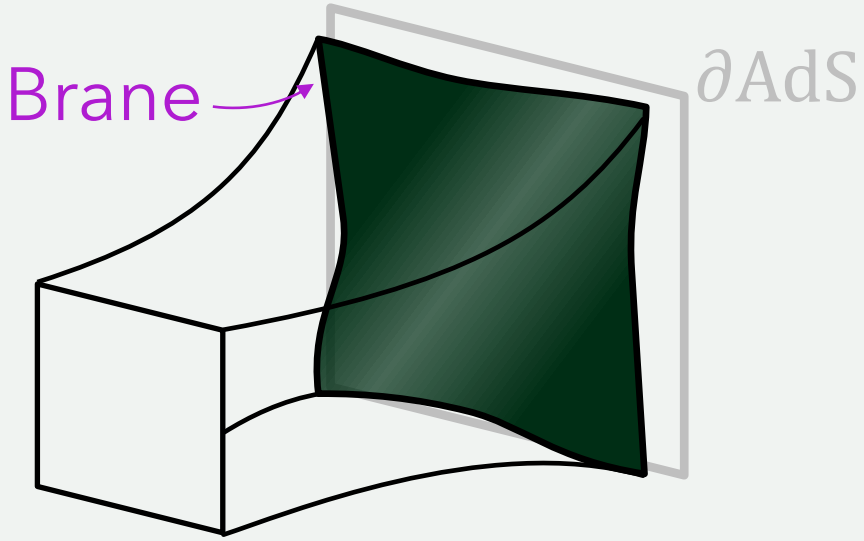
review: *Holographic thermal field theory on curved spacetimes*

Marolf+Rangamani+Wiseman 2013

CFT on *dynamical* geometry – holographically

Make gravity on boundary dynamical: *Braneworld holography*

- Gravitating brane is wall boundary that can fluctuate
- Gravity localized near AdS brane (Randall-Sundrum)



CFT on *dynamical* geometry – holographically

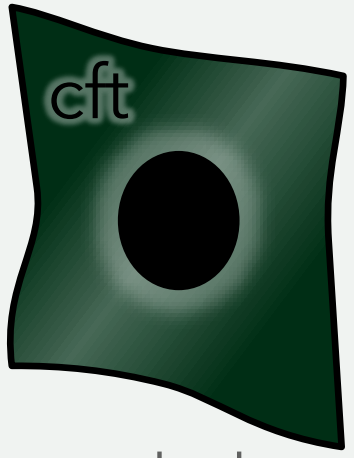
- Holographically: bulk gravity ≡ CFT
- Dynamical brane coupled to bulk gravity ≡

  Dynamical (boundary) geometry coupled to CFT – w/ backreaction

$$R_{ij} - \frac{1}{2} R g_{ij} + \cdots = 8\pi G_N \langle T_{ij} \rangle_{CFT}$$

CFT on *dynamical* black hole – holographically

$$R_{ij} - \frac{1}{2} R g_{ij} + \cdots = 8\pi G_N \langle T_{ij} \rangle_{CFT}$$



- Black hole on brane = Black hole + Hawking radiation, coupled

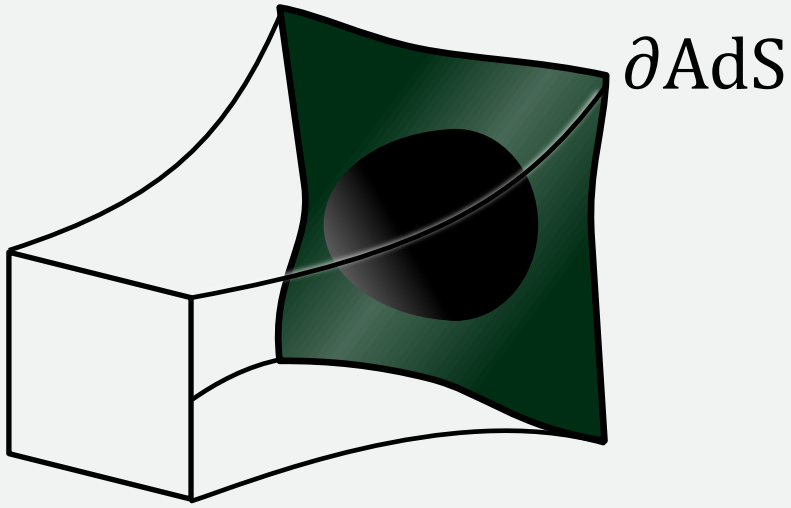
- Dynamics of black hole evaporation = Classical dynamics in bulk

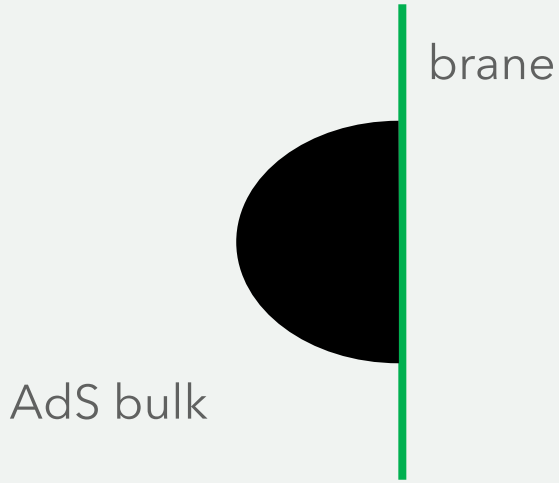
Tanaka 2002

RE+Fabbri+Kaloper 2002

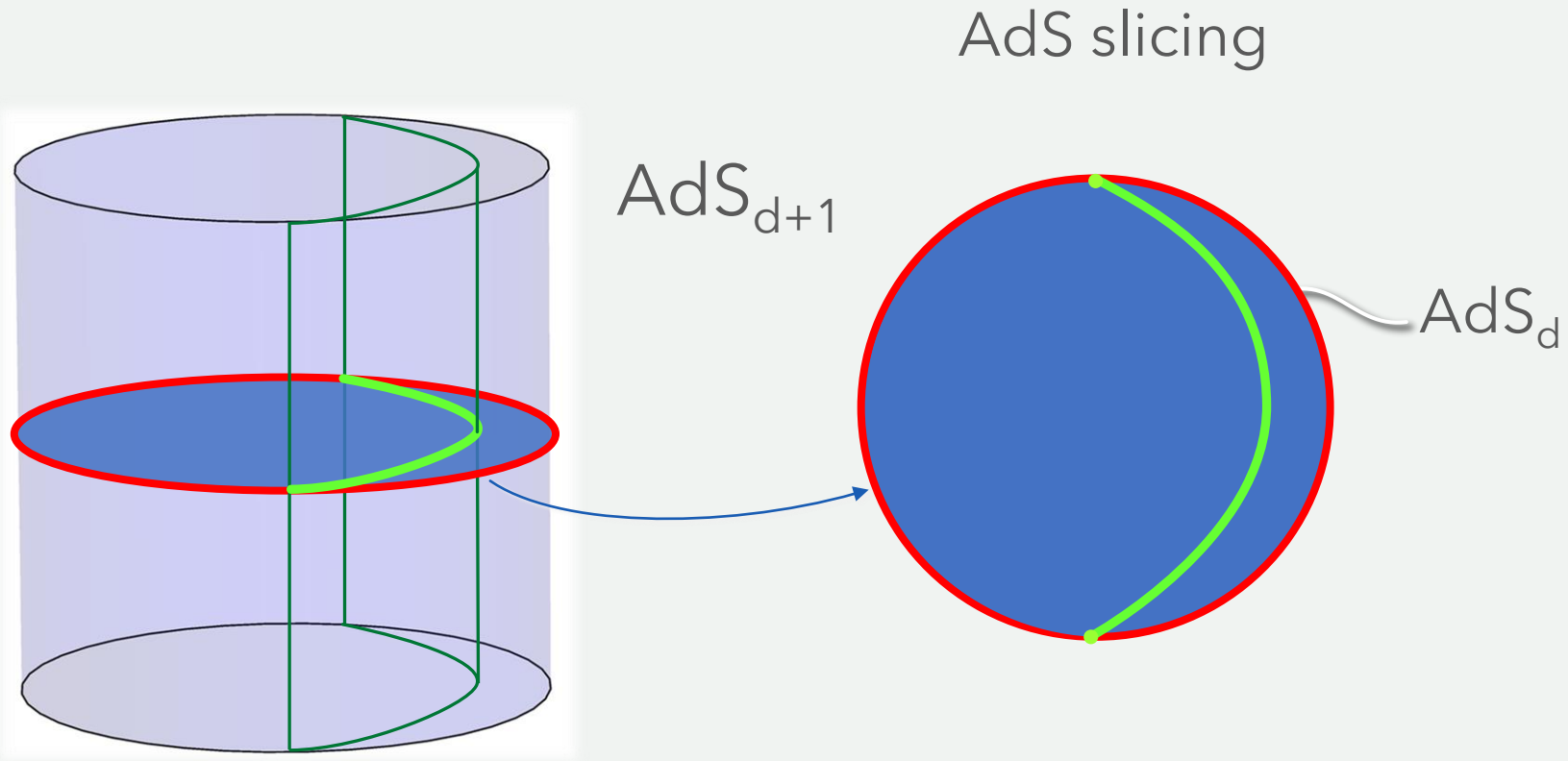
Black droplets on a brane

- Black hole coupled to CFT_d = black droplet on a brane in AdS_{d+1}



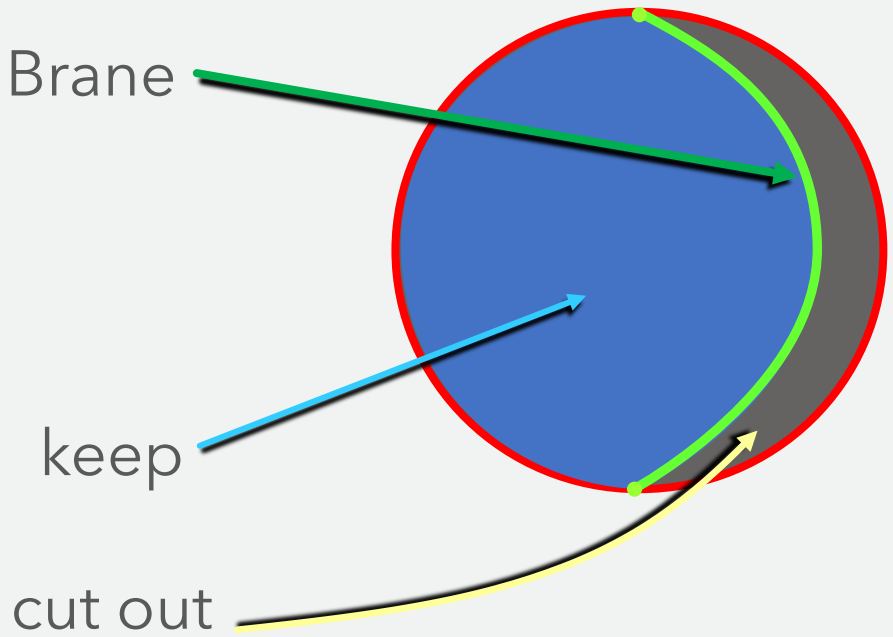


Slicing AdS



Braneworlds

Karch-Randall: AdS branes

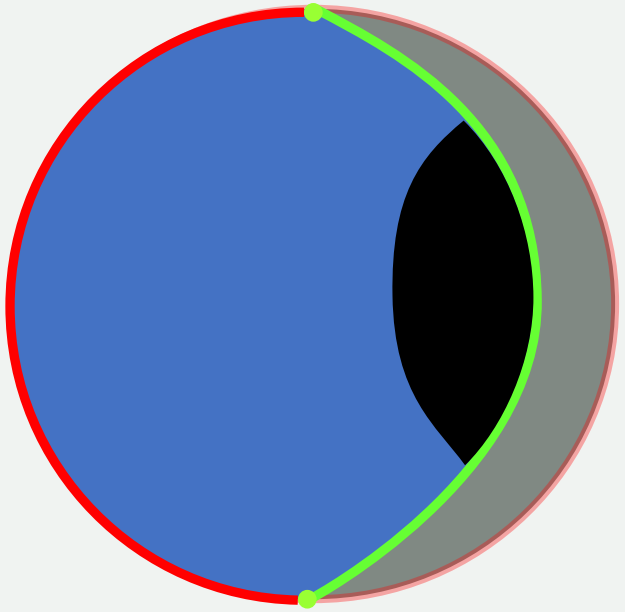


Randall+Sundrum 1999

Karch+Randall 2000

& paste to copy: 2-sided brane, $\mathbb{Z}_2$ orbifold

Black hole on a brane



- Exact solutions in AdS_4
- Numerical solutions in AdS_5 (hard)

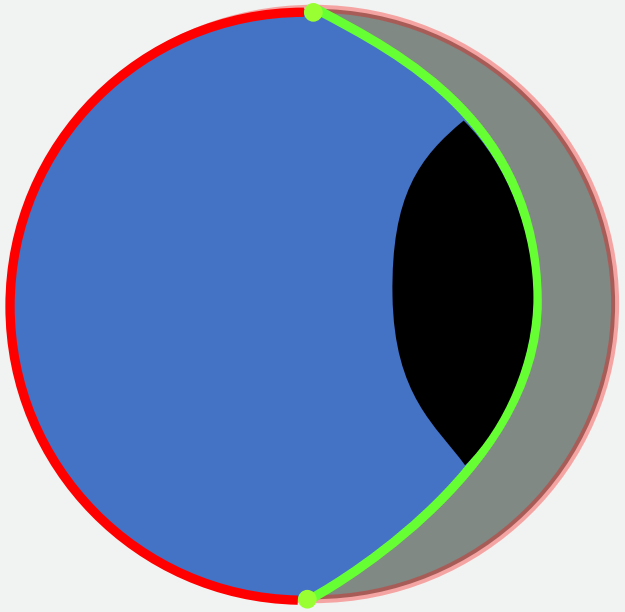
} time-independent

Figueras+Lucietti+Wiseman

- Analytical/easy numerics in large-D limit $AdS_{D>>1}$

& with time evolution

Black hole on a brane



- **Exact solutions in AdS_4**
- Numerical solutions in AdS_5 (hard)

} time-independent

Figueras+Lucietti+Wiseman

- Analytical/easy numerics **in large-D limit** $AdS_{D>>}1$

& with time evolution

Exact Holographic 3D Quantum Black Holes

Black hole on the brane from AdS C-metric

Plebański + Demiański 1976

$$ds^2 = \frac{\ell^2}{(\ell + xr)^2}\left(-H(r)dt^2 + \frac{dr^2}{H(r)} + r^2\left(\frac{dx^2}{G(x)} + G(x)d\phi^2\right)\right)$$

$$H(r) = \frac{r^2}{\ell_3^2} + \kappa - \frac{\mu\ell}{r}$$

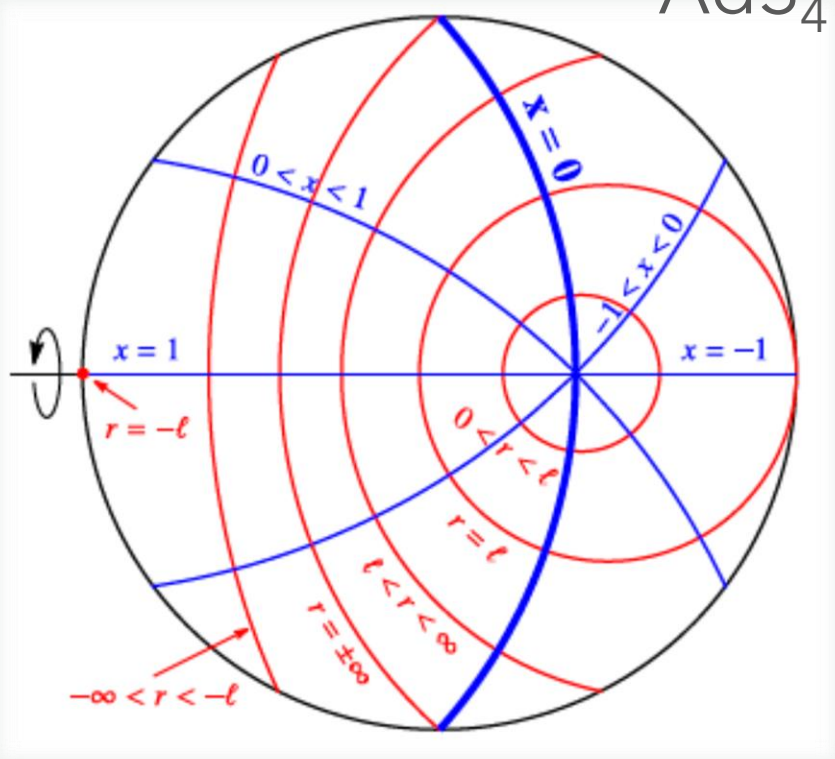
$$G(x) = 1 - \kappa x^2 - \mu x^3$$

RE+Horowitz+Myers 1999

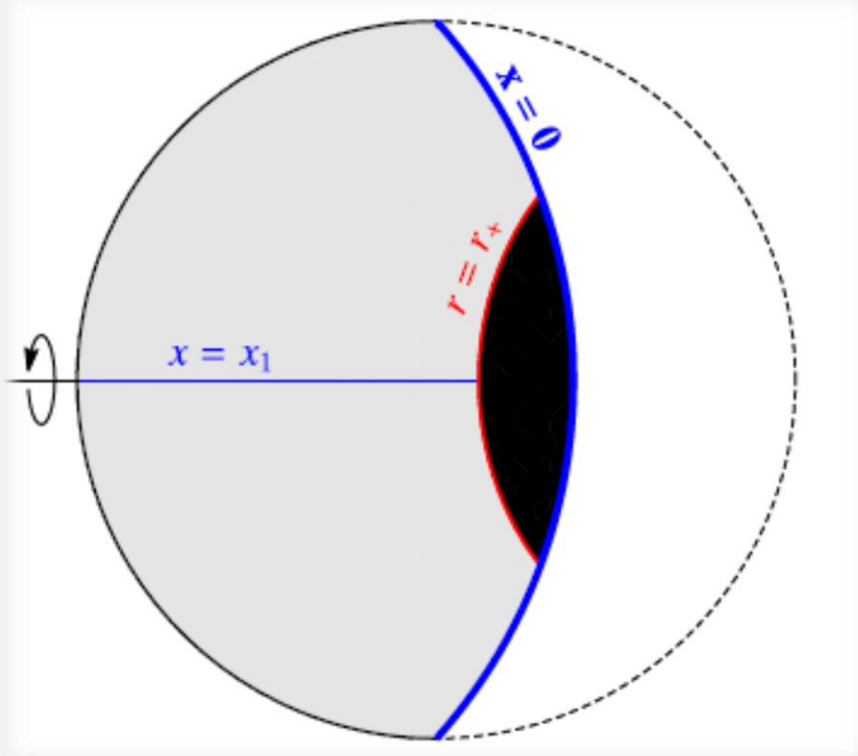
Adapted coordinates

$$ds^2 = \frac{\ell^2}{(\ell + xr)^2}\left(-H(r)dt^2 + \frac{dr^2}{H(r)} + r^2\left(\frac{dx^2}{G(x)} + G(x)d\phi^2\right)\right)$$

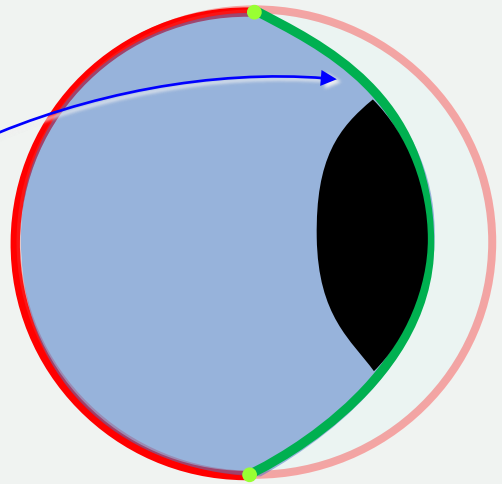
AdS_4



brane at $x = 0$



Quantum BTZ metric



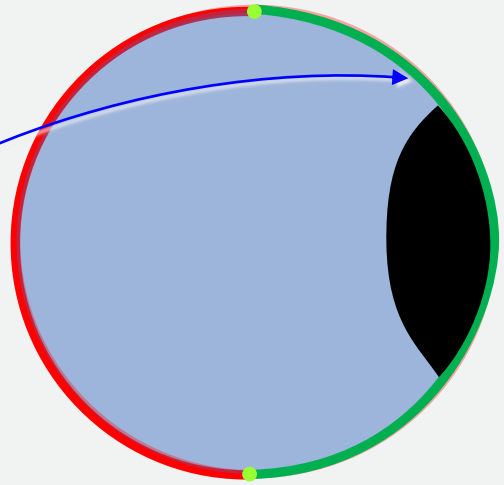
3D metric induced on brane at $\boldsymbol{x = 0}$

$$ds^2\Big|_b = -\left(\frac{r^2}{\ell_3^2} - 8\mathcal{G}_3 M - \ell\frac{F(M)}{r}\right)dt^2 + \frac{dr^2}{\frac{r^2}{\ell_3^2} - 8\mathcal{G}_3 M - \ell\frac{F(M)}{r}} + r^2 d\phi^2$$

RE+Fabbri+Kaloper 2002

RE+Frassino+Way 2020

Quantum BTZ metric



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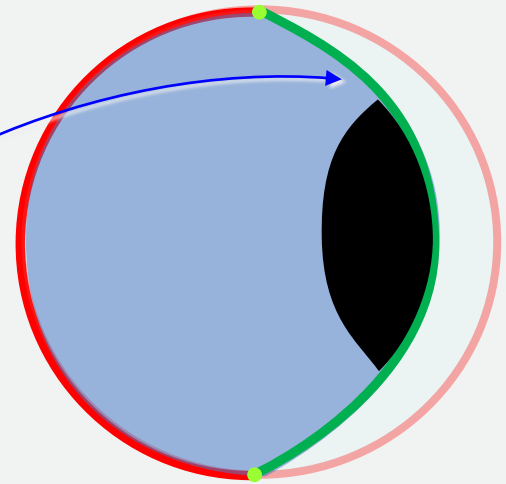
$\ell = 0$: BTZ black hole

Quantum BTZ metric



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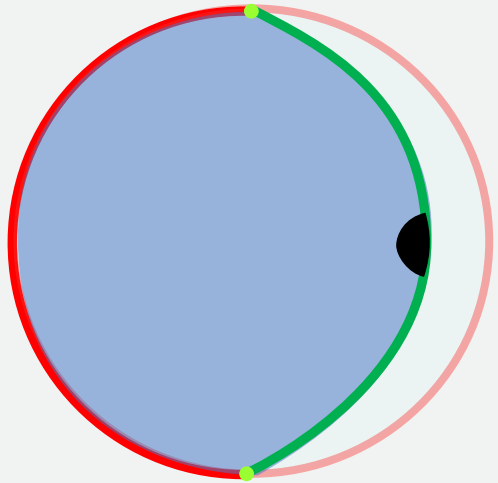
$\ell = 0$: BTZ black hole

$\ell > 0$: quantum-corrected BTZ

Small AdS_3 quantum black holes



$$ds^2 = -\left(\frac{r^2}{\ell_3^2} - 8G_3M - \ell\frac{F(M)}{r}\right)dt^2 + \frac{dr^2}{\frac{r^2}{\ell_3^2} - 8G_3M - \ell\frac{F(M)}{r}} + r^2 d\phi^2$$

$$-\frac{1}{8G_3} < M < 0$$

$\ell = 0$: conical defect

$\ell > 0$: small black hole = dressed cone

Casimir energy on a cone dresses conical singularity

Quantum Cosmic Censorship

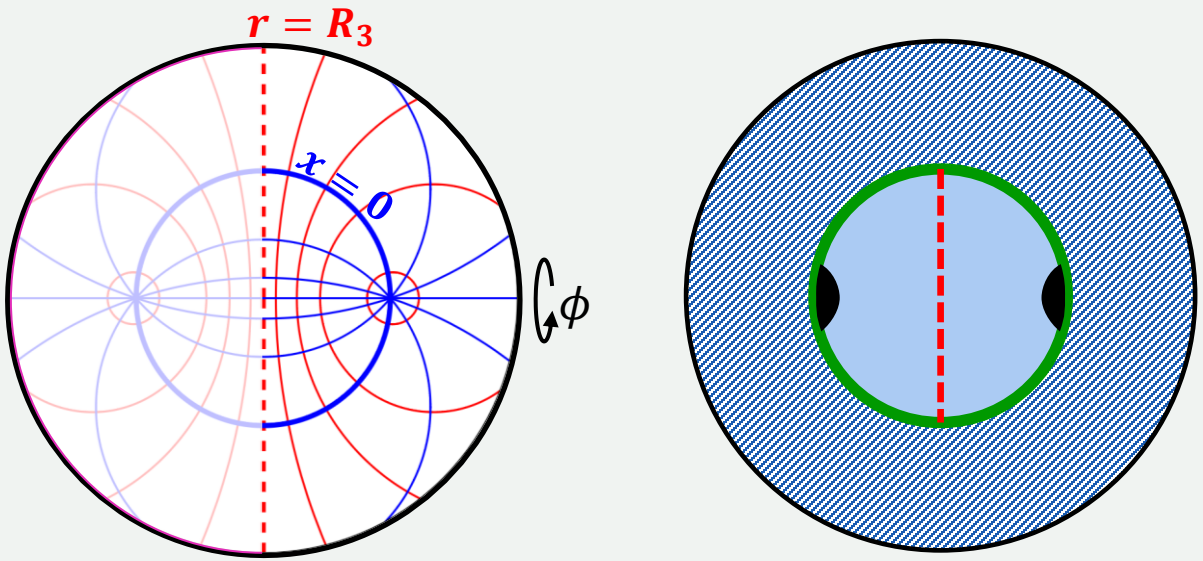
dS_3 quantum black holes

RE+Pedraza+Svesko+Tomašević+Visser 2022

$$ds^2 = -\left(1 - \frac{r^2}{\ell_3^2} - \ell\frac{\mu}{r}\right)dt^2 + \frac{dr^2}{1 - \frac{r^2}{\ell_3^2} - \ell\frac{\mu}{r}} + r^2 d\phi^2$$

$\ell = 0$: (conical defect in) dS_3

$\ell > 0$: black hole in dS_3



The take away (1): Holographic backreaction works

Quantum-backreacted black hole and CFT stress tensor

can be described *exactly* and *in detail*

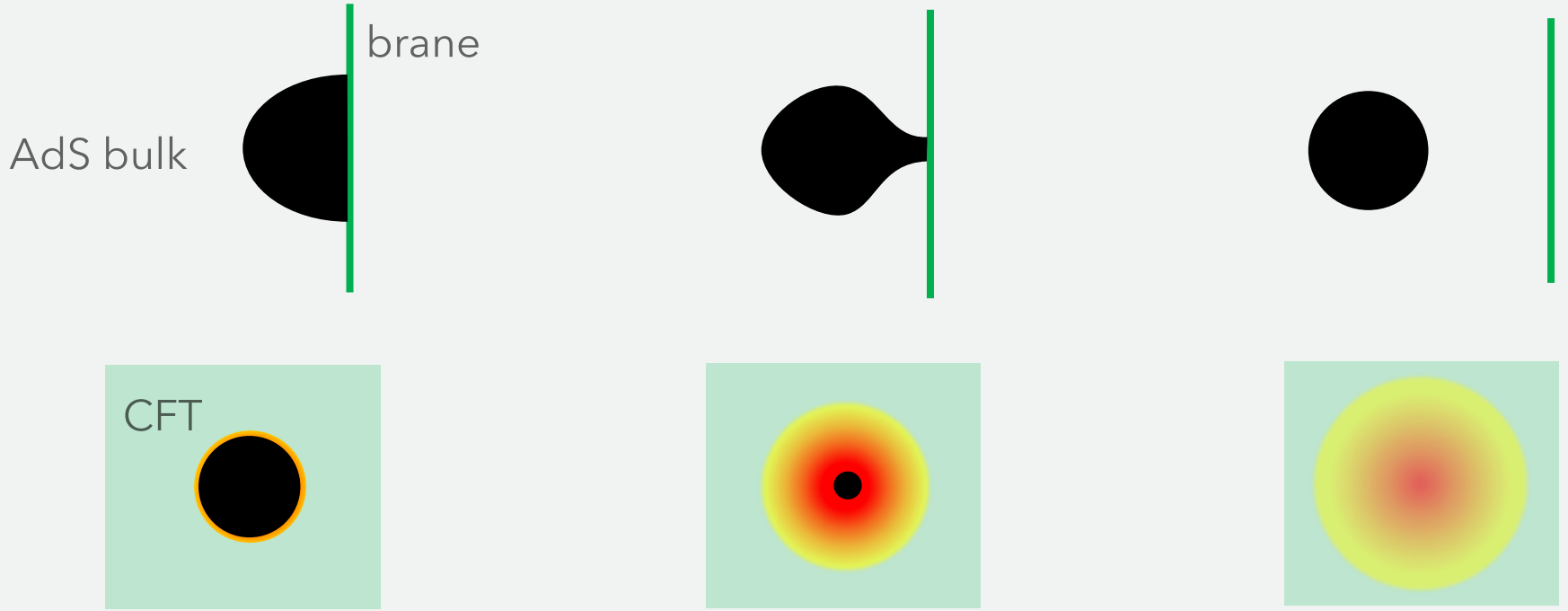
Efficient use of holography to solve a hard quantum problem

Holographic duals of evaporating black holes

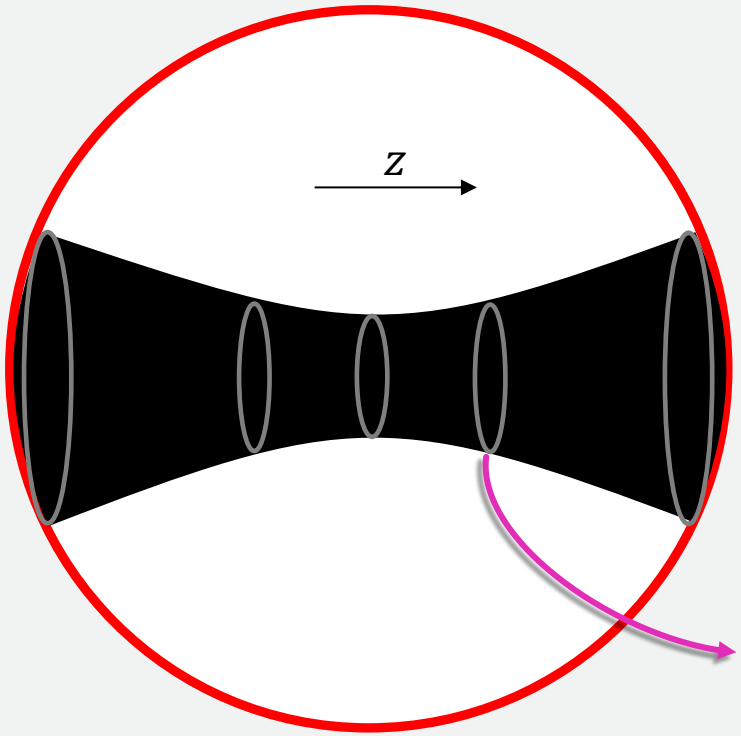
RE+Luna+Suzuki+Tomašević+Way 2023

Black hole coupled to CFT radiation – holographically

- Black hole = bulk horizon intersecting brane
- Thermal CFT radiation = horizon in bulk



Black string in AdS_D

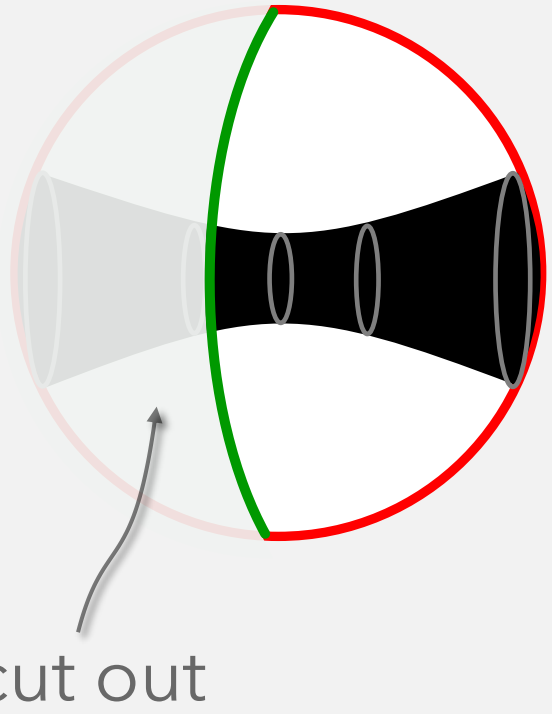


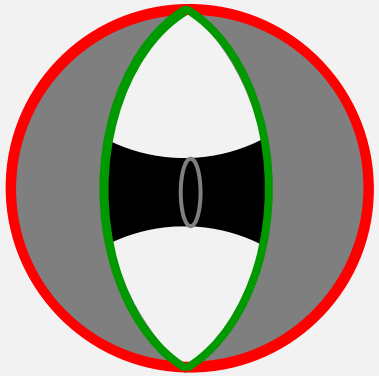
$$ds^2 = \frac{L^2}{\cos^2 z}\left(dz^2 + ds^2(\text{Schw}-\text{AdS}_{D-1})\right)$$

Boundary geometry:

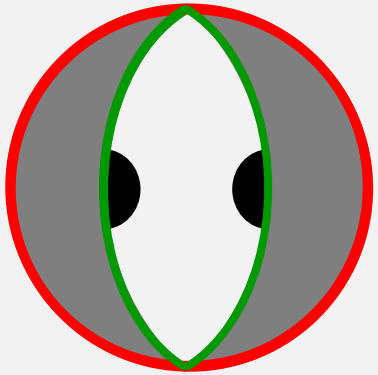
Sphere with two black holes at antipodes

Braneworld

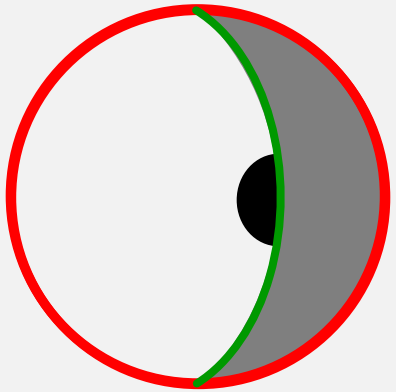




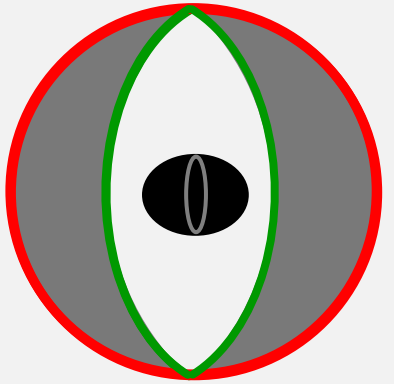
Black string/Funnel



Double droplet



Single droplet



Bulk black hole

Large D help

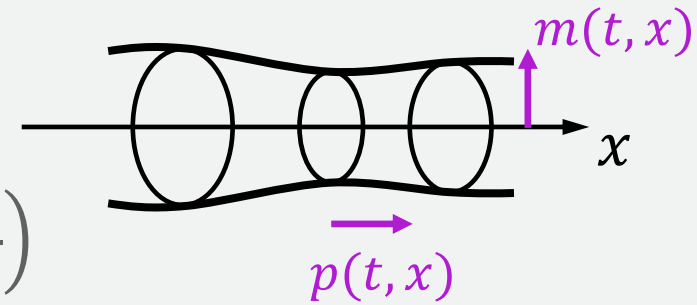
RE+Suzuki+Tanabe 2013, 2015

- $D \gg 1$: gravitational dynamics localized near horizon
- Radiation is suppressed $\sim e^{-D}$
- Effective theory for horizon dynamics

E.g., for AF black strings:

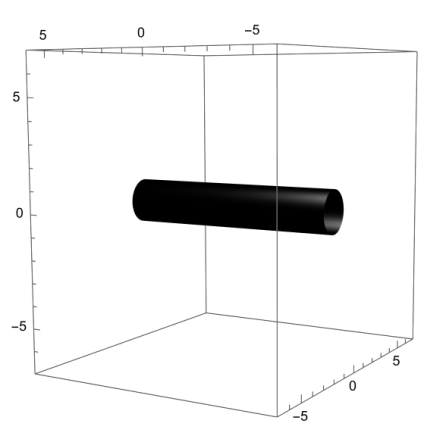
$$\partial_t m - \partial_x^2 m = -\partial_x p$$

$$\partial_t p_i - \partial_x^2 p_i = \partial_x m - \partial_x \left(\frac{p^2}{m}\right)$$



Some static phases

Black string/Uniform funnel



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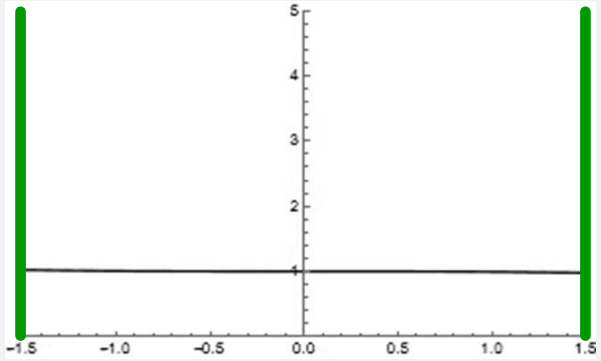

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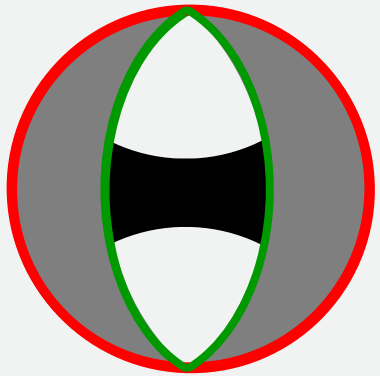
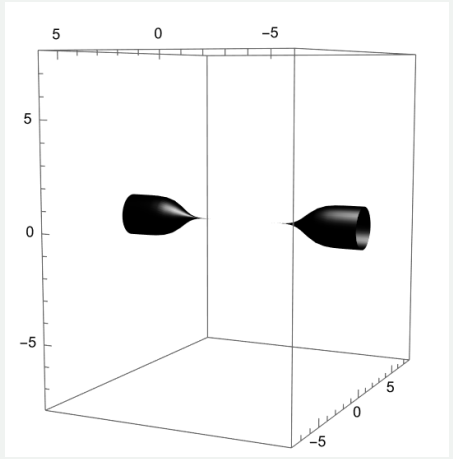


Black holes @ large D = gaussian blobs



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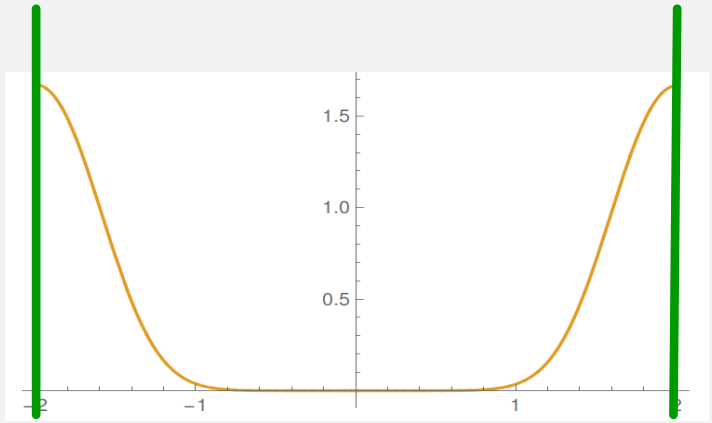

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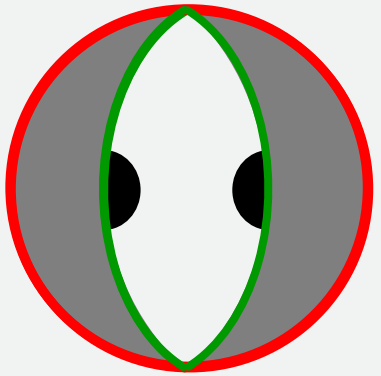
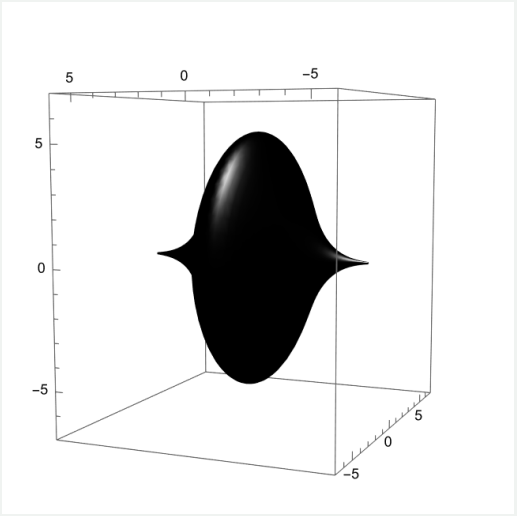
Double droplet





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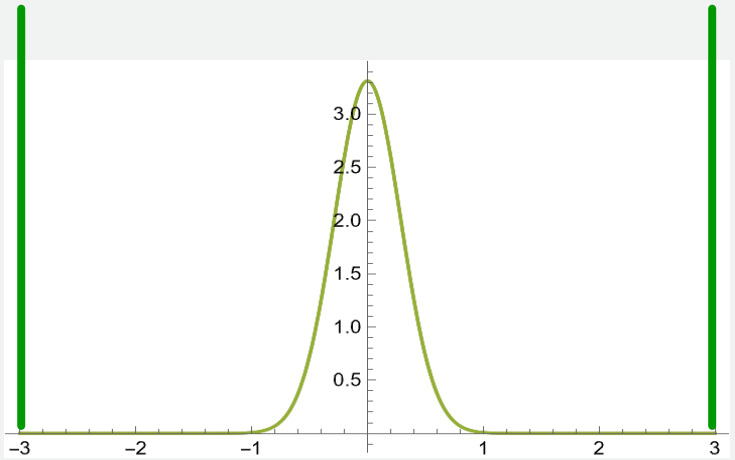

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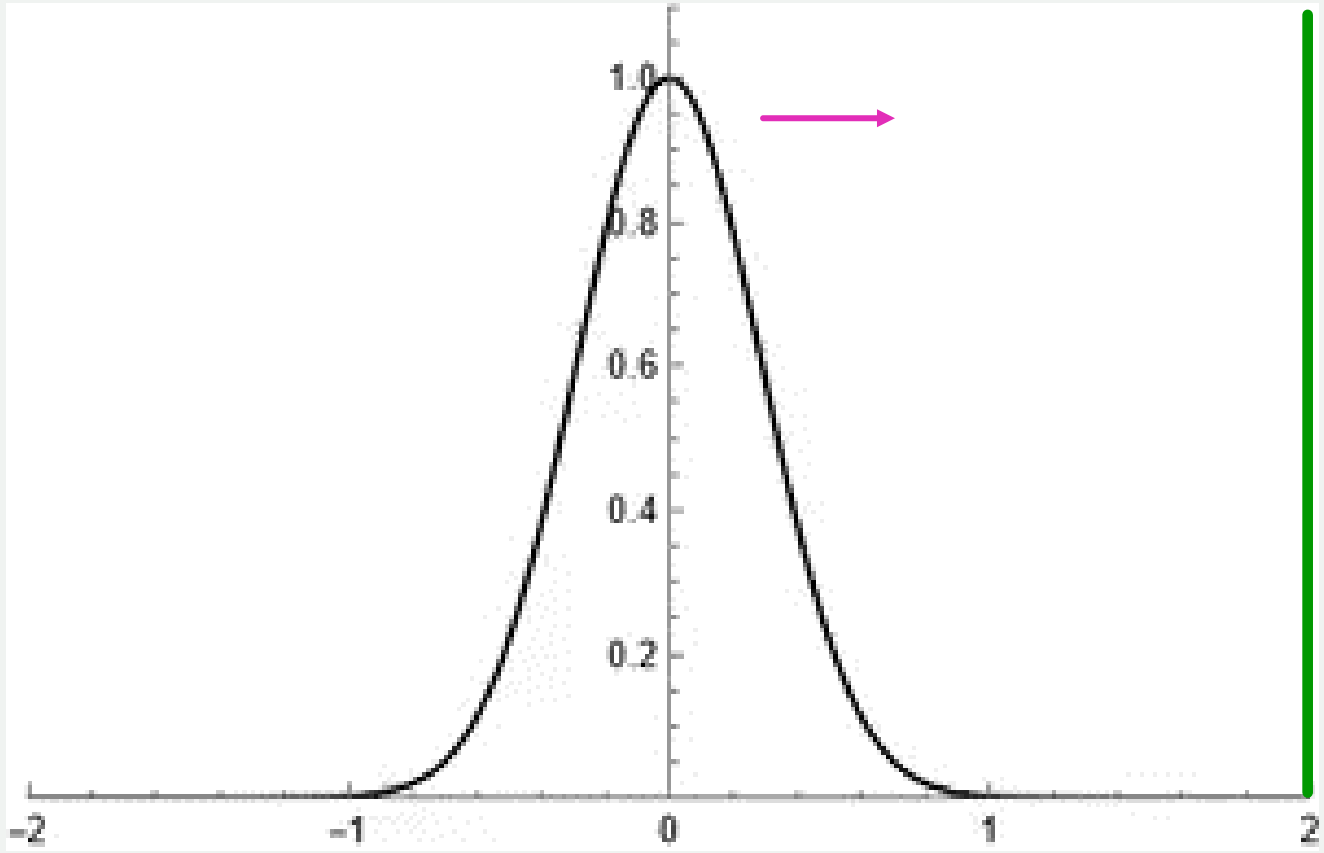
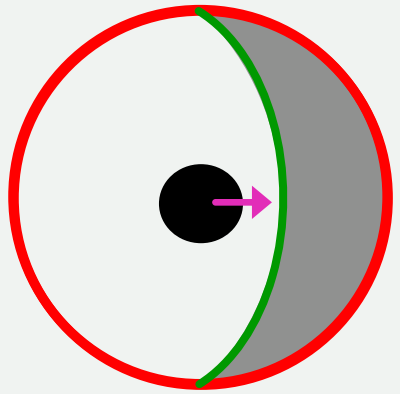
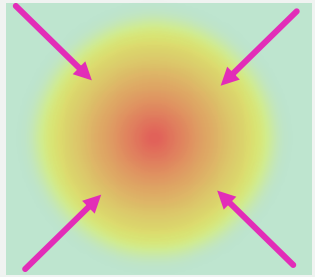
Bulk black hole

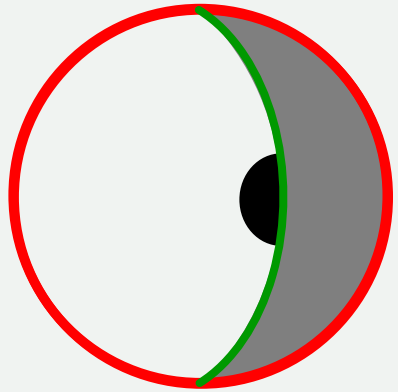
Dynamic play

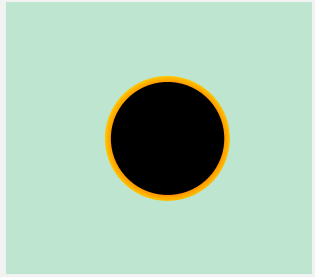
Collapse on the brane



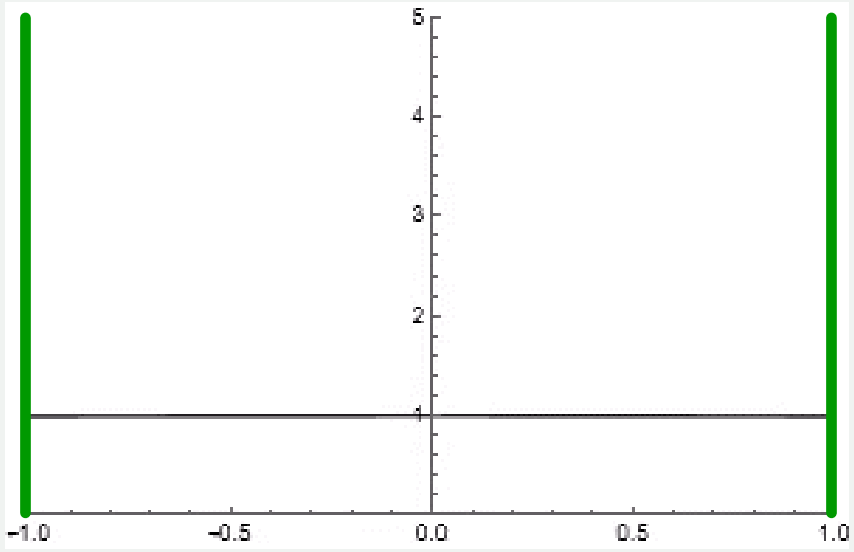




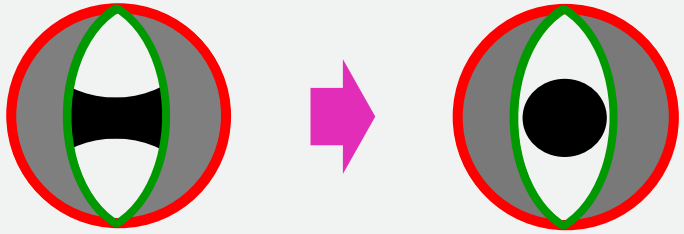




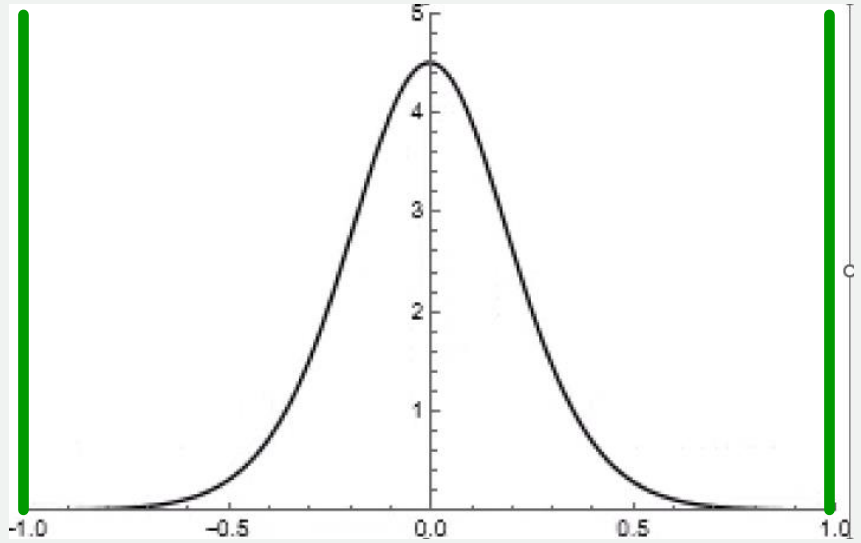
Evaporation



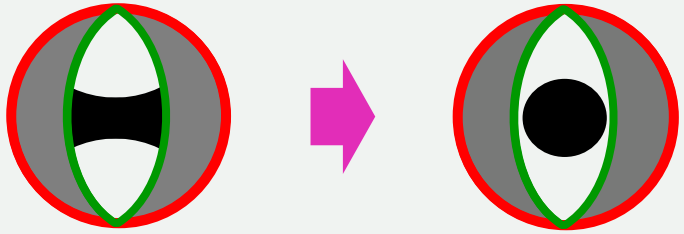
Evaporation as flow into bulk

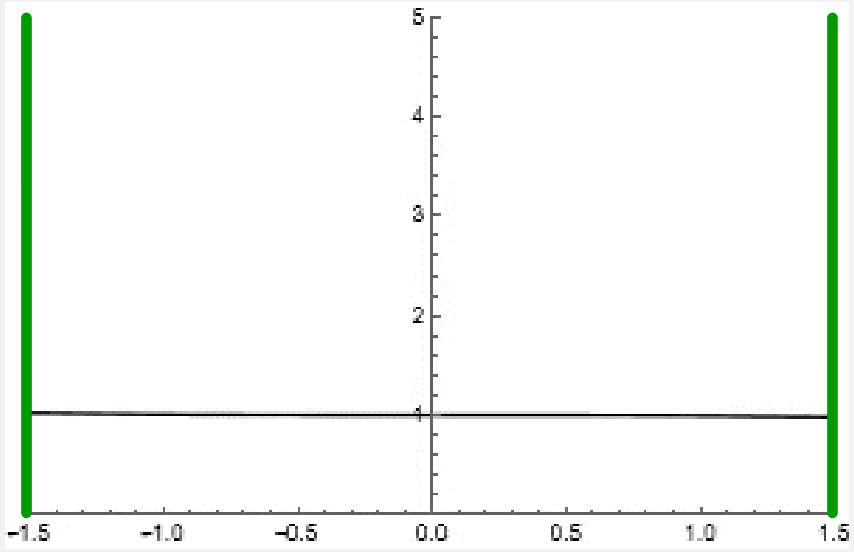


Evaporation

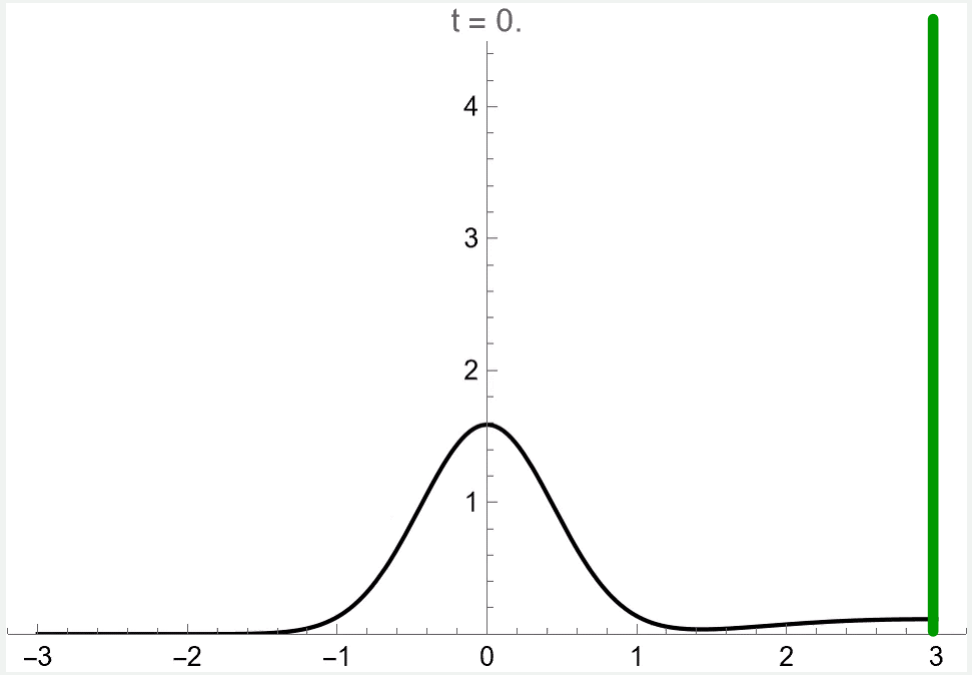


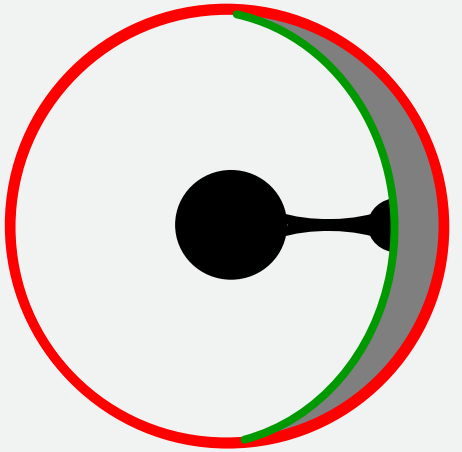
Evaporation as flow into bulk

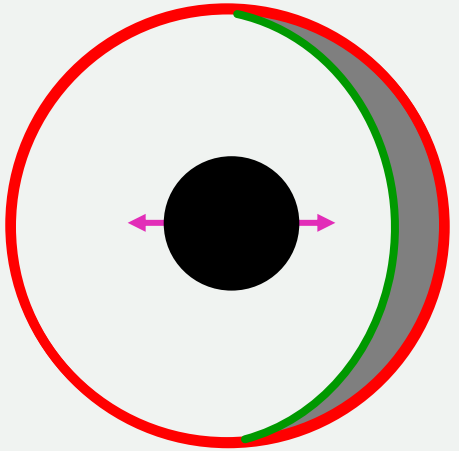




Evaporation as flow between black holes







Evaporation into a bulk black hole

Holographic black hole evaporation

How and Why

What makes holographic dual evaporation possible?

- Black hole on brane evaporates by funneling radiation into a colder horizon—in the bulk, on another brane, or at a boundary

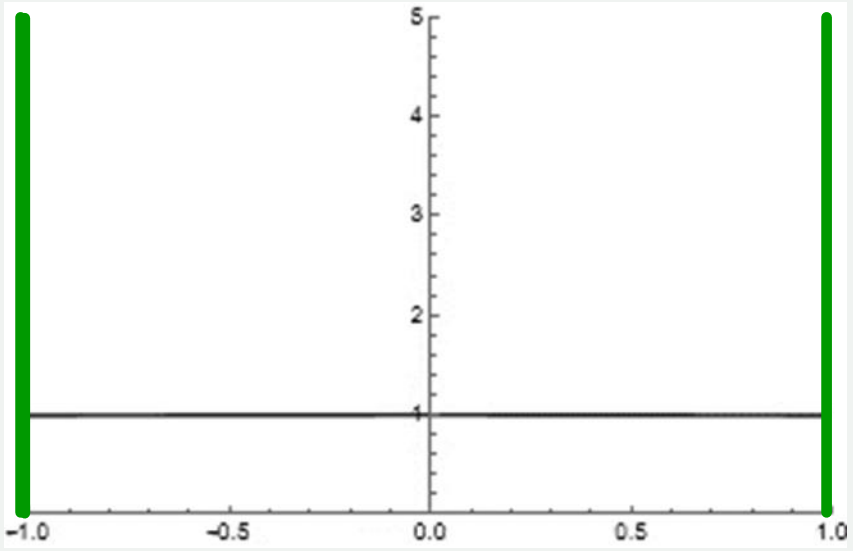
  “Heat (radiation) flows from the hotter system to the colder one"

- Requires access to thermalized degrees of freedom
- Requires entanglement channel in bulk: black funnel

Twin black holes evaporating into colder bulk

$r_0 < L_{AdS}$

small AdS black hole
hotter when smaller



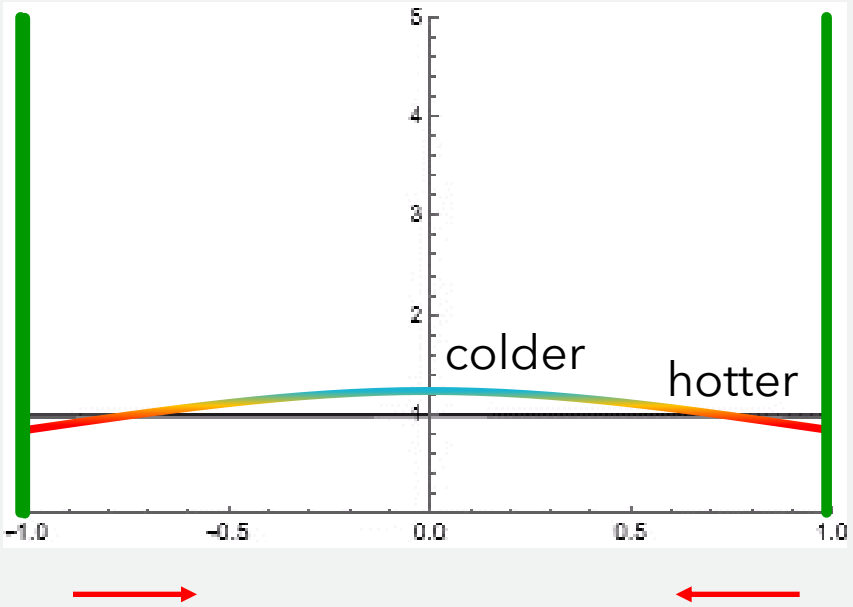
Twin black holes evaporating into colder bulk

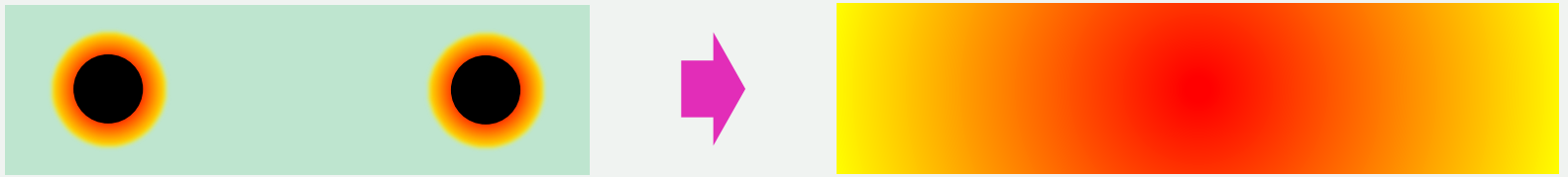
$r_0 < L_{AdS}$

small AdS black hole
hotter when smaller

Radiation flows from

hotter to colder





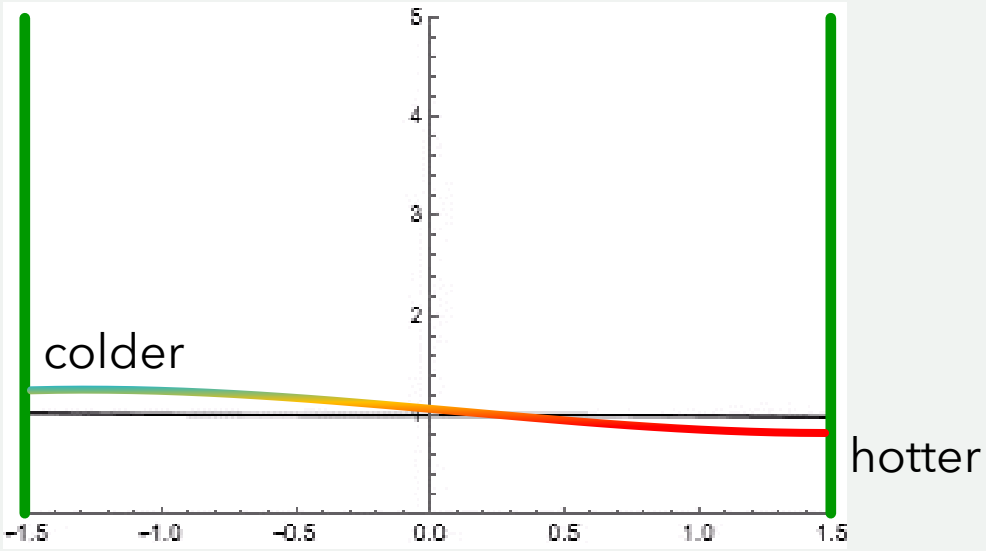
Hot black hole radiating to colder one

$r_0 < L_{AdS}$

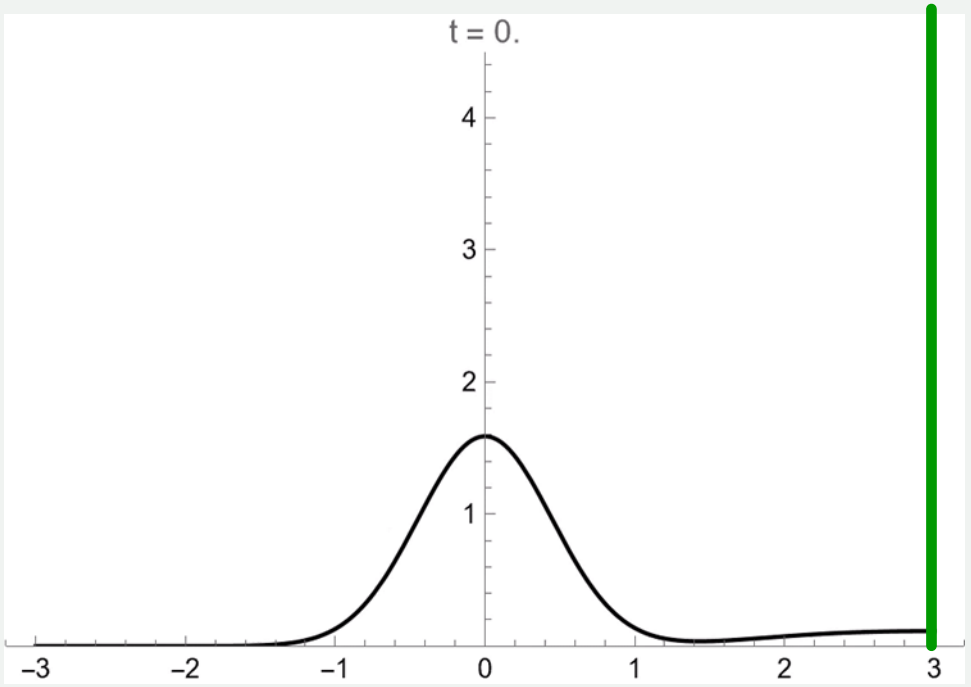
small AdS black hole hotter when smaller

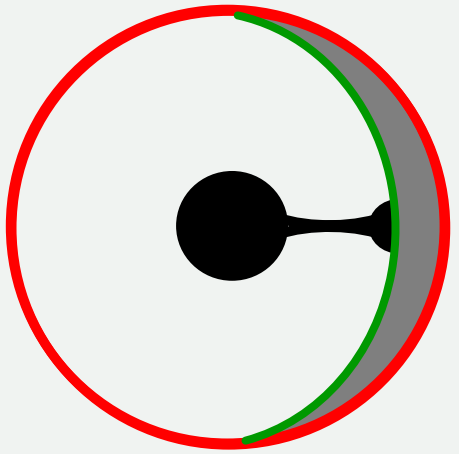
Radiation flows from

hotter to colder



Hot black hole evaporates into colder bath





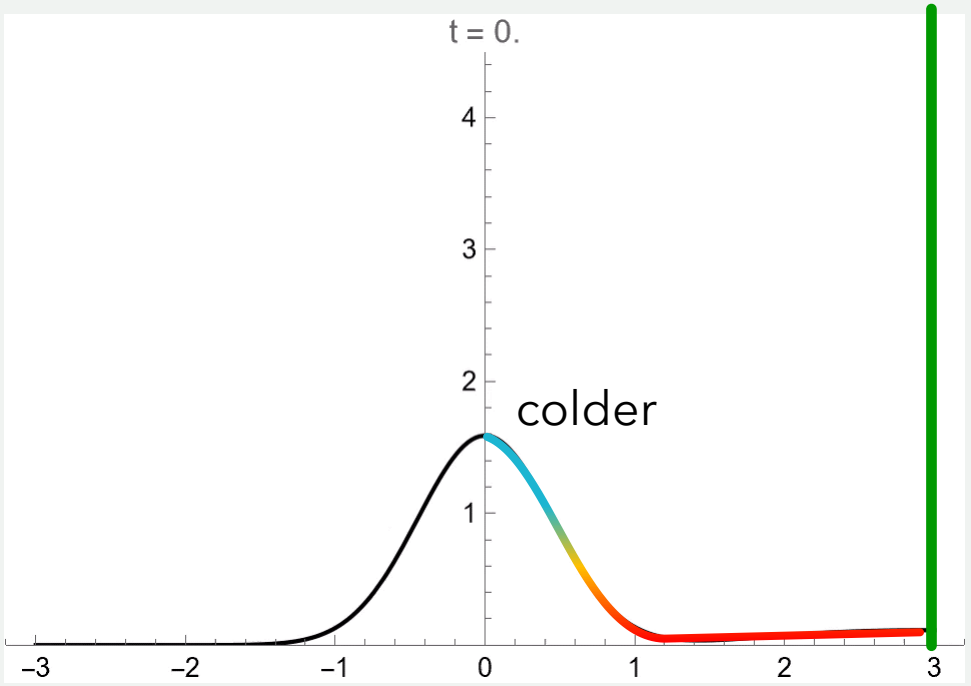
$r_0 < L_{AdS}$

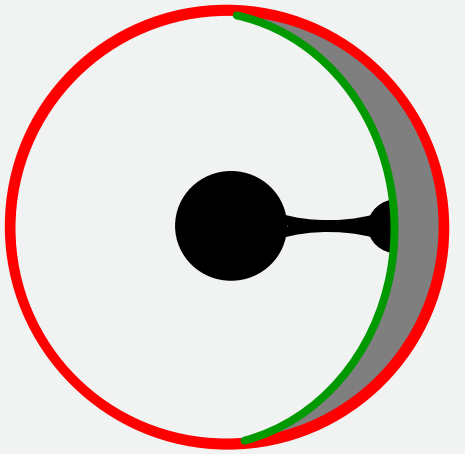
small AdS black hole
hotter when smaller

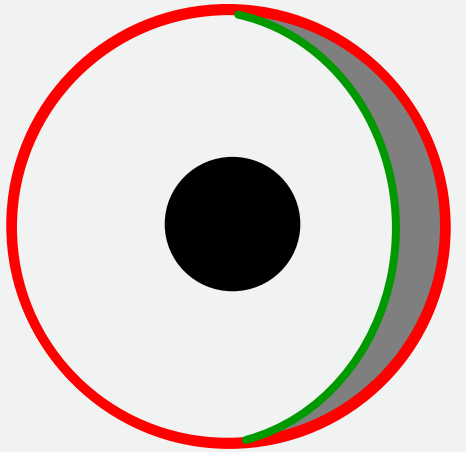
Hot black hole evaporates into colder bath

$r_0 < L_{AdS}$

small AdS black hole hotter when smaller







The take away (2): Classicalization of Hawking evaporation

- Dynamical holographic black hole evaporation through classical bulk evolution is possible – it is dual to horizon instabilities
- Hot black hole evaporates through funnel into colder thermal degrees of freedom

Conclusions

Quantum Black Holes as Braneworld Holograms

- Efficient solution of quantum backreaction = classical bulk problem in one more dimension – not easy but doable
  - New Quantum Black Hole solutions in 3D
  - Classicalization of Hawking evaporation
- Limited to infinite coupling+infinite-N QFT (with peculiarities of its own)
- Bottom-up holography: effective theory, not fully UV complete


Thank you