



Branes, Islands and Massive Gravitons

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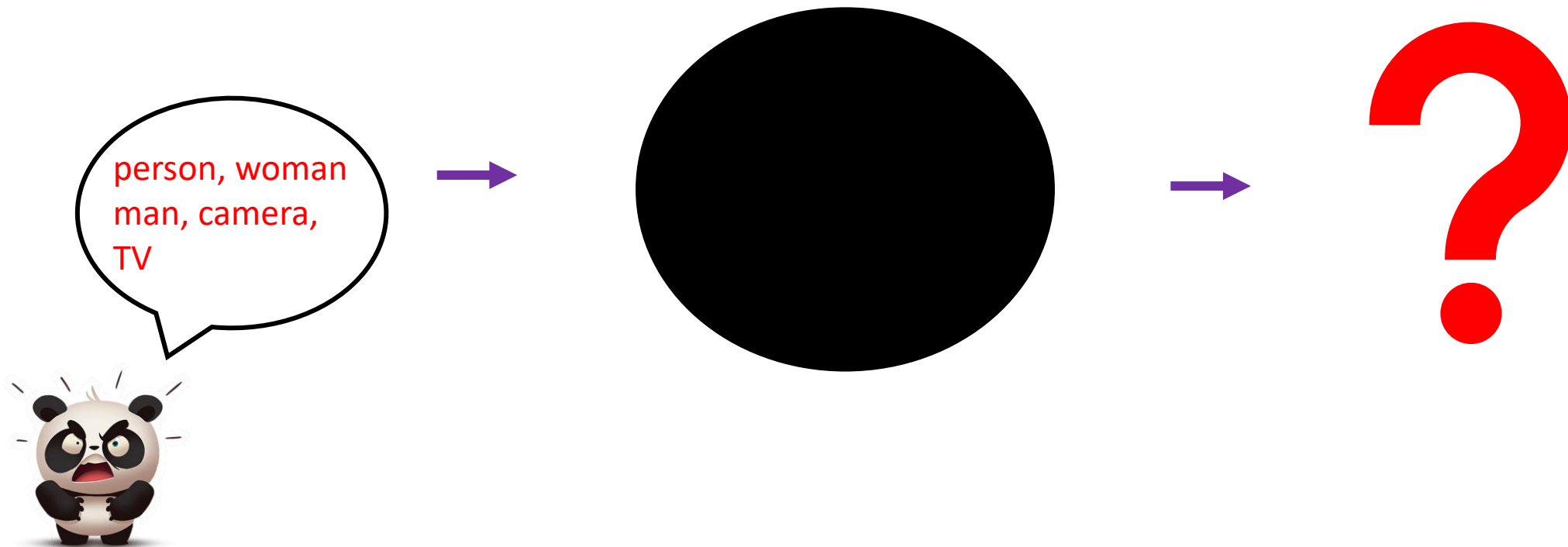
Andreas Karch (University of Texas at Austin)

Gauge/Gravity Duality 21, July 26, 2021

1. Subcritical RS branes and holography
2. Hence Mass
3. But what about Islands?

based on work with “G7”: Hao Geng, Carlos Perez, Suvrat Raju,
Lisa Randall, Marcos Riojas, and Sanjit Shashi

Do black holes lose information?



Recent Black Hole Revolution

Unitary evaporation of black holes (Page curve) from semi-classics.

yes, info
does come back!



(Pennington '19, Almheiri, Engelhardt, Marolf, Maxfield '19)

Disclaimers:

- Black holes in “box” = anti-de Sitter space
- Black holes coupled to external, non-gravitating bath

Does this matter?

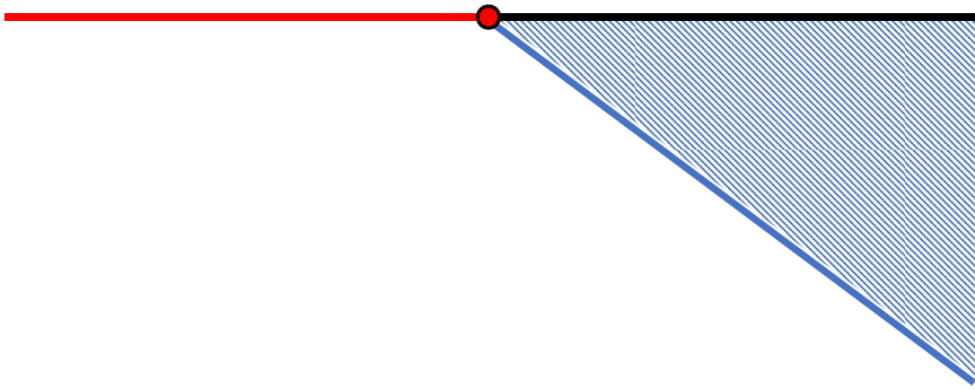
Our main tool: RS brane worlds

Subcritical RS branes give simple realization of quantum gravity coupled to bath (AK, Randall; ... '00)

Most explicit examples for Page curves are calculated for 2d bulk/ 1d boundary (JT gravity); higher dimensional examples as of now rely on RS brane constructions

Subcritical RS Holography

(AK, Randall '00)



1. Classical Gravity of bulk + brane
2. CFT + cutoff + gravity on AdS4
communicating with CFT on half-space
3. CFT with boundary (AdS/BCFT)

(see also Takayanagi '11)

Subcritical Holography

(AK, Randall '00)

Solvable



1. Classical Gravity of bulk + brane

Gravity + Bath



2. CFT + cutoff + gravity on AdS₄
communicating with CFT on half-space

**Well defined
field theory**



3. CFT with boundary (AdS/BCFT)

“double holography”

Subcritical RS -- Fluctuations

(AK, Randall '00)

Surprise: Studying small fluctuations of the bulk graviton
one finds

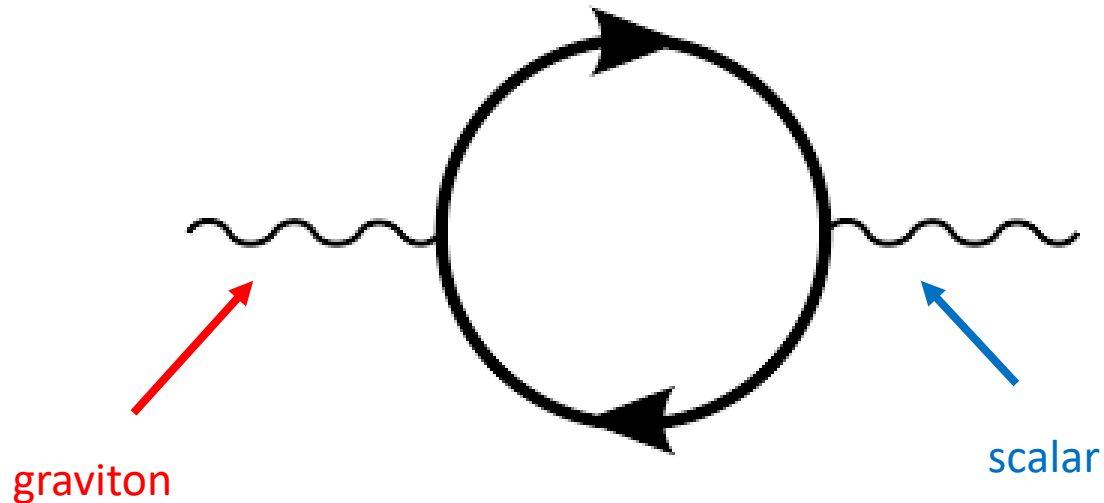
RS graviton = massive!!

How is this consistent with the other two dual descriptions?

Graviton mass, dual interpretation:

(Porrati '02)

2. CFT + cutoff + gravity on AdS₄ communicating with CFT on half-space



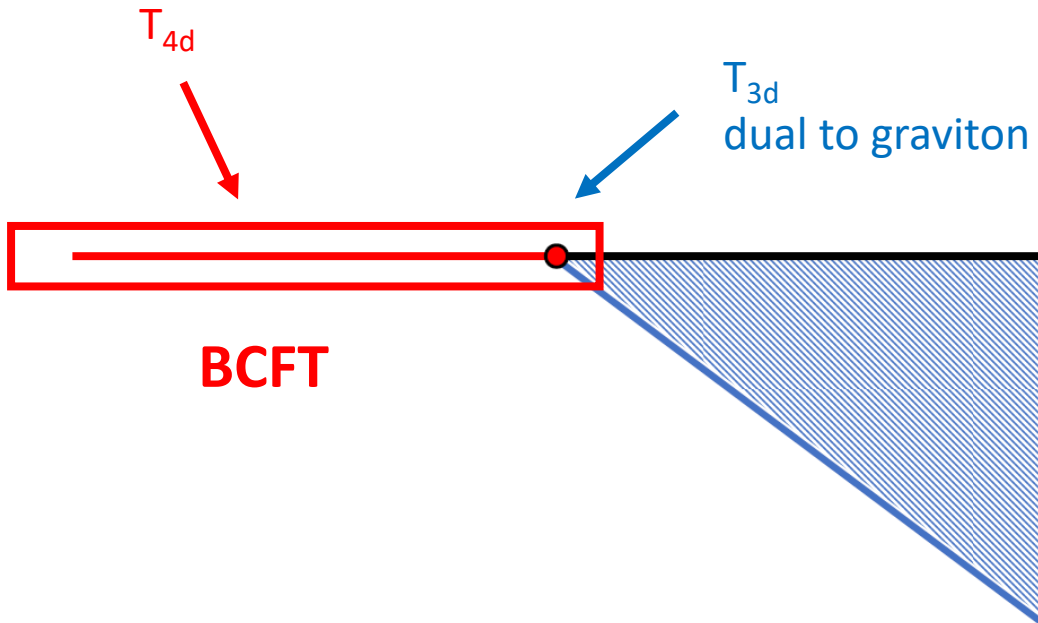
- Answer depends on bc for scalar
- Standard (reflecting) bc: no mass
- Any other bc (non-zero Transmission): graviton gets a mass!

In this setup, graviton mass direct consequence of coupling to **bath**.

Graviton mass, dual interpretation:

(Aharony, DeWolfe, Freedman, AK '03)

3. CFT with boundary (AdS/BCFT)



- $T_{4d} + T_{3d}$ conserved
- T_{3d} alone not conserved
- anomalous dimension for T_{3d}
= graviton mass

verified by explicit calculations in string theoretic D3/D5 model

Mass/Bath beyond AdS/BCFT

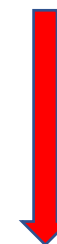
(Aharony, Clark, AK '06; Kiritsis '06)

Massless Graviton
in AdS

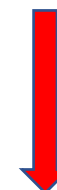
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Conserved Stress Tensor

coupling to bath



non-conservation



can't have one without the other



Massive Graviton

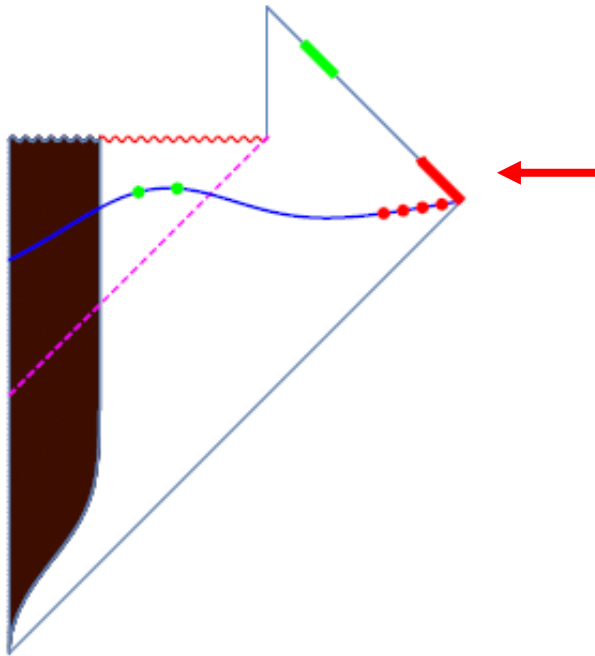
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anomalous dimension

Does the graviton mass matter?

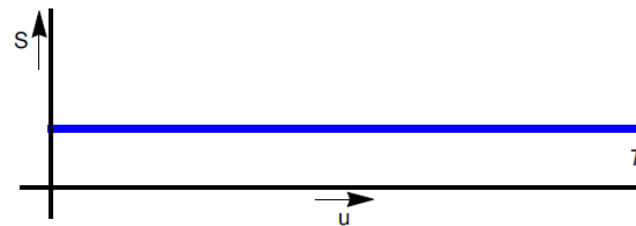
What does the Page curve look like without non-gravitating bath?
Example: asymptotically flat black hole?

(Laddha, Prabhu, Raju, Shrivastava '20)



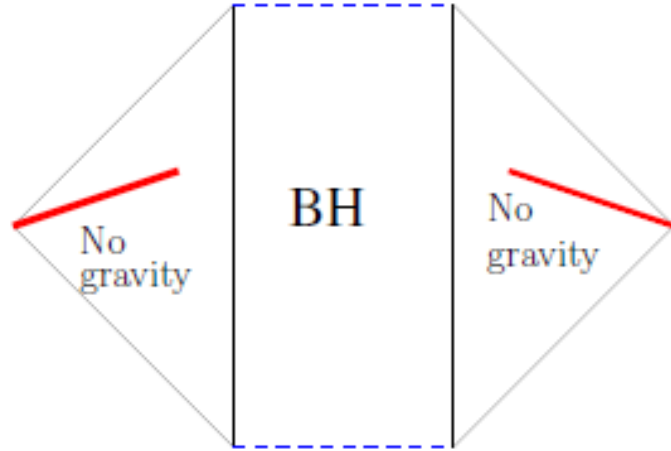
**Claim: entire information
available outside black hole
always.**

This picture would suggest that “Page curve”
is trivial:

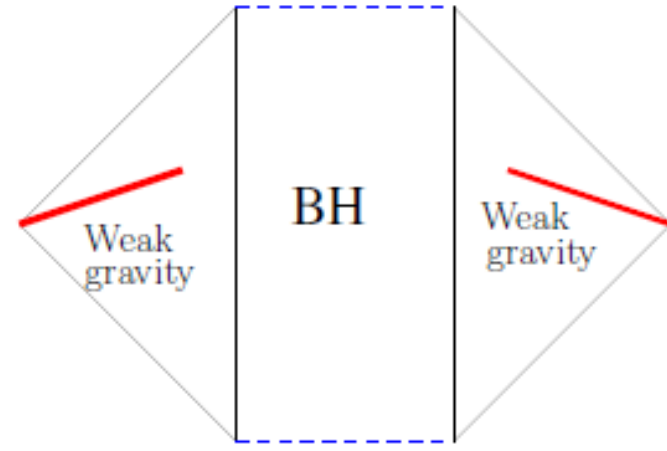


Gravitating Bath

(Laddha, Prabhu, Raju, Shrivastava '20)



Standard Page curve



Trivial Page curve

This can easily be tested using RS branes!

Double holographic islands in 4d

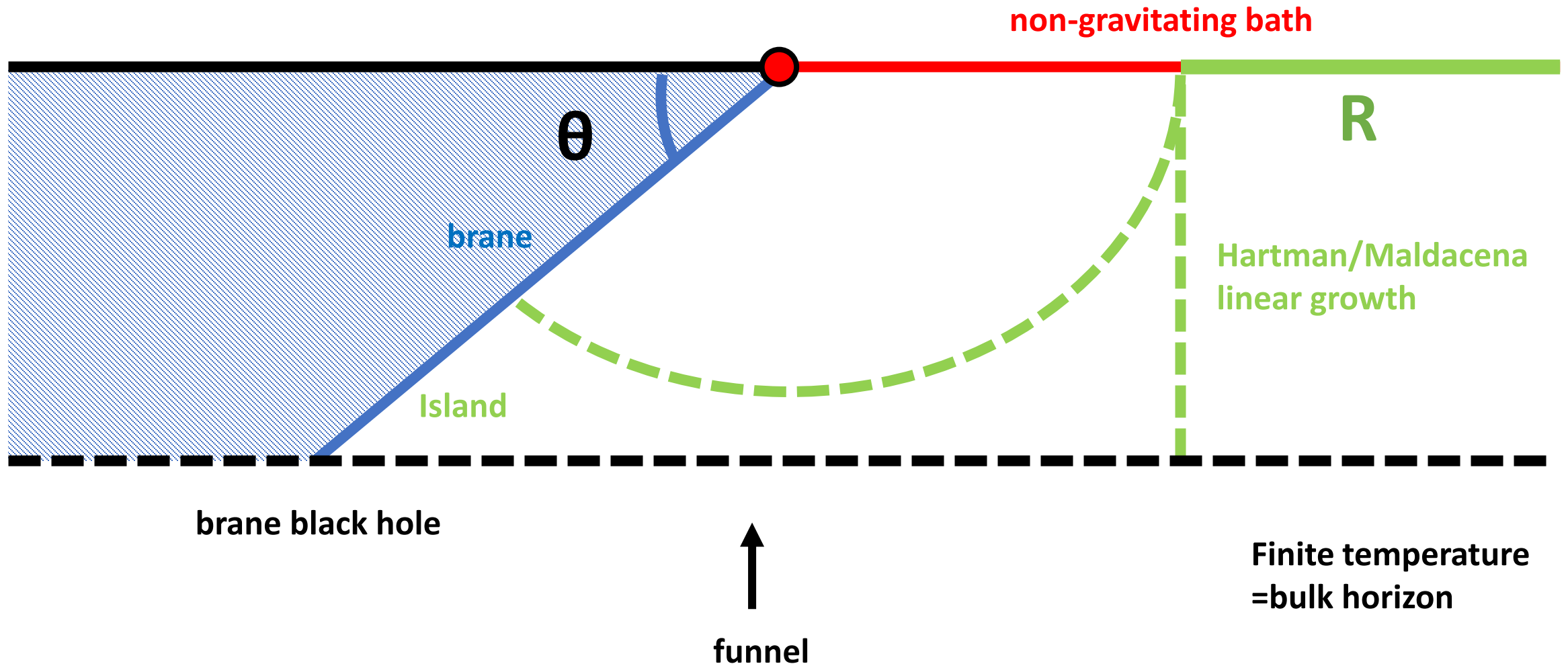
(Almheiri, Mahajan, Santos '19)

Instead of studying evaporating black hole, simplify the problem:

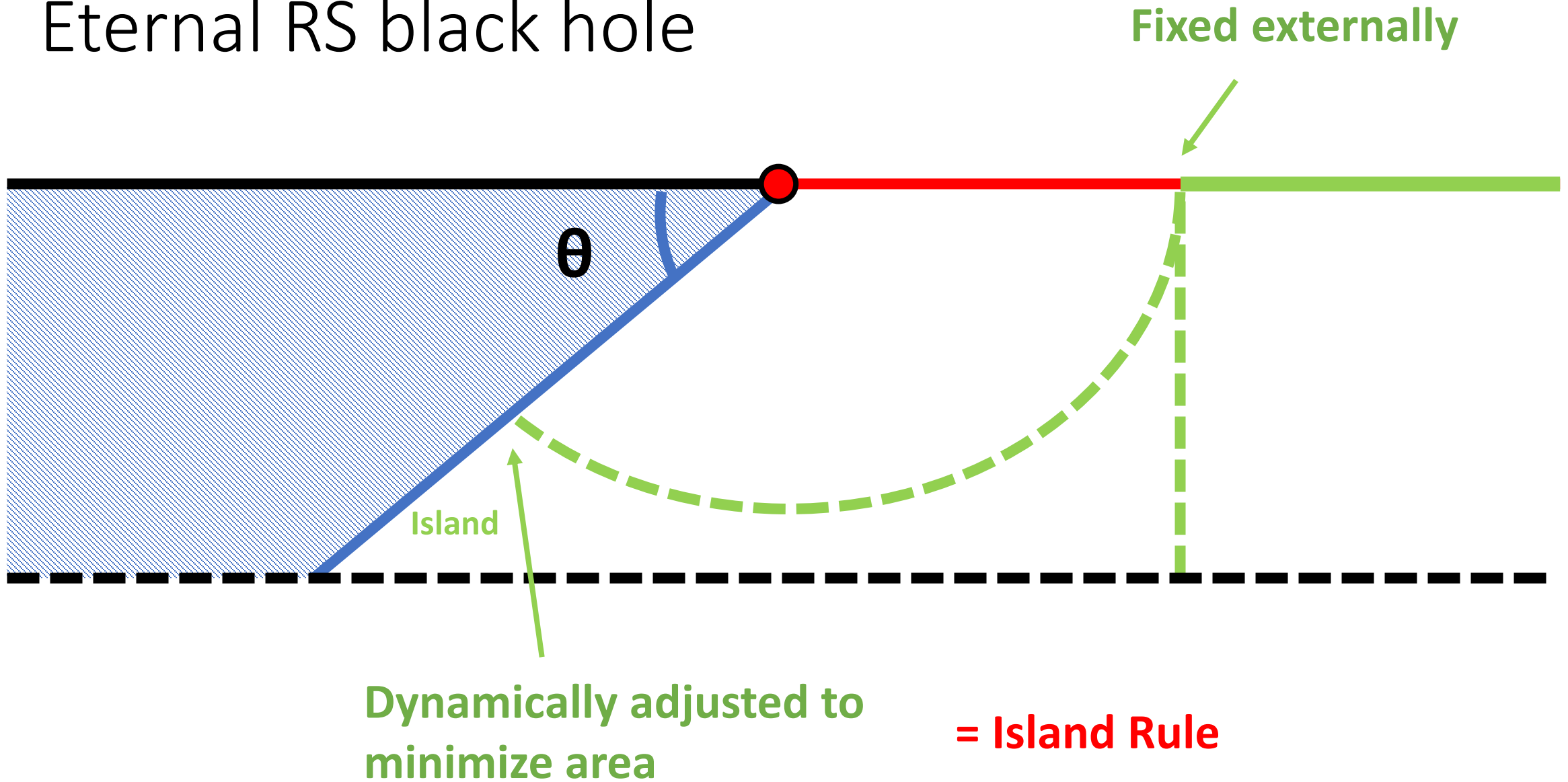
- Couple AdS gravity to non-gravitating bath
- heat up bath to finite temperature $T=T_H$
- Eternal black hole remains eternal even with bath
- Resolve the (simpler) information paradox in this case

Eternal RS black hole

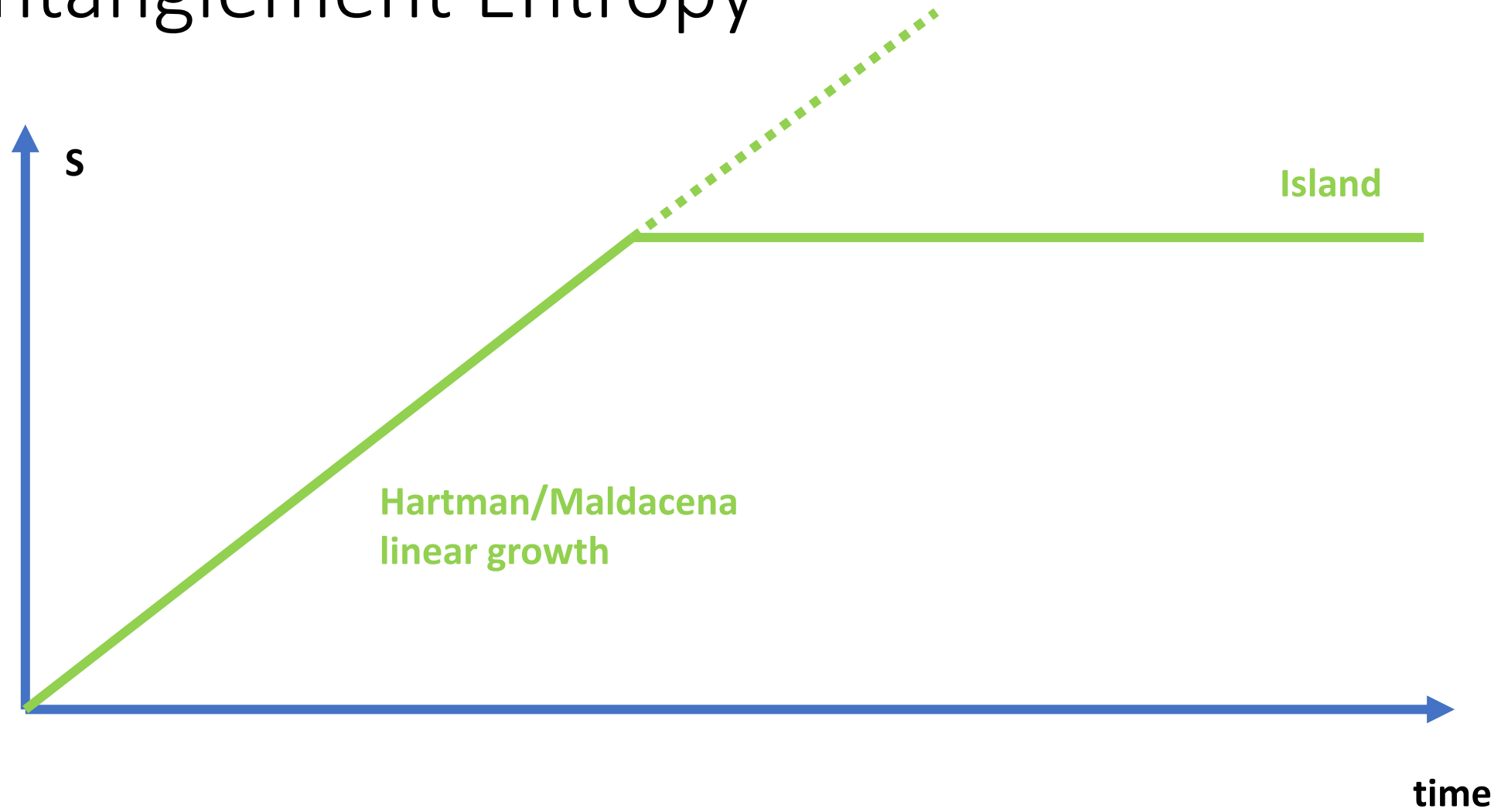
(Almheiri, Mahajan, Santos '19)



Eternal RS black hole

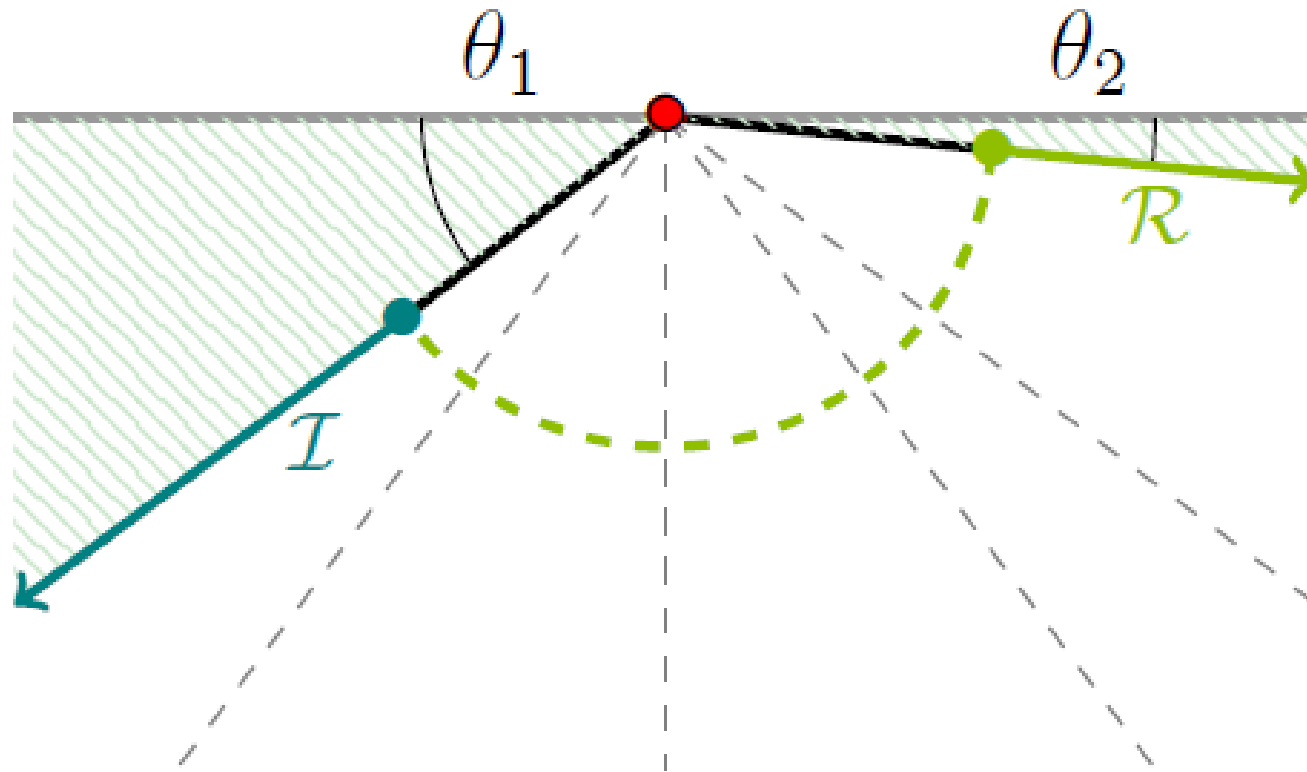


Entanglement Entropy



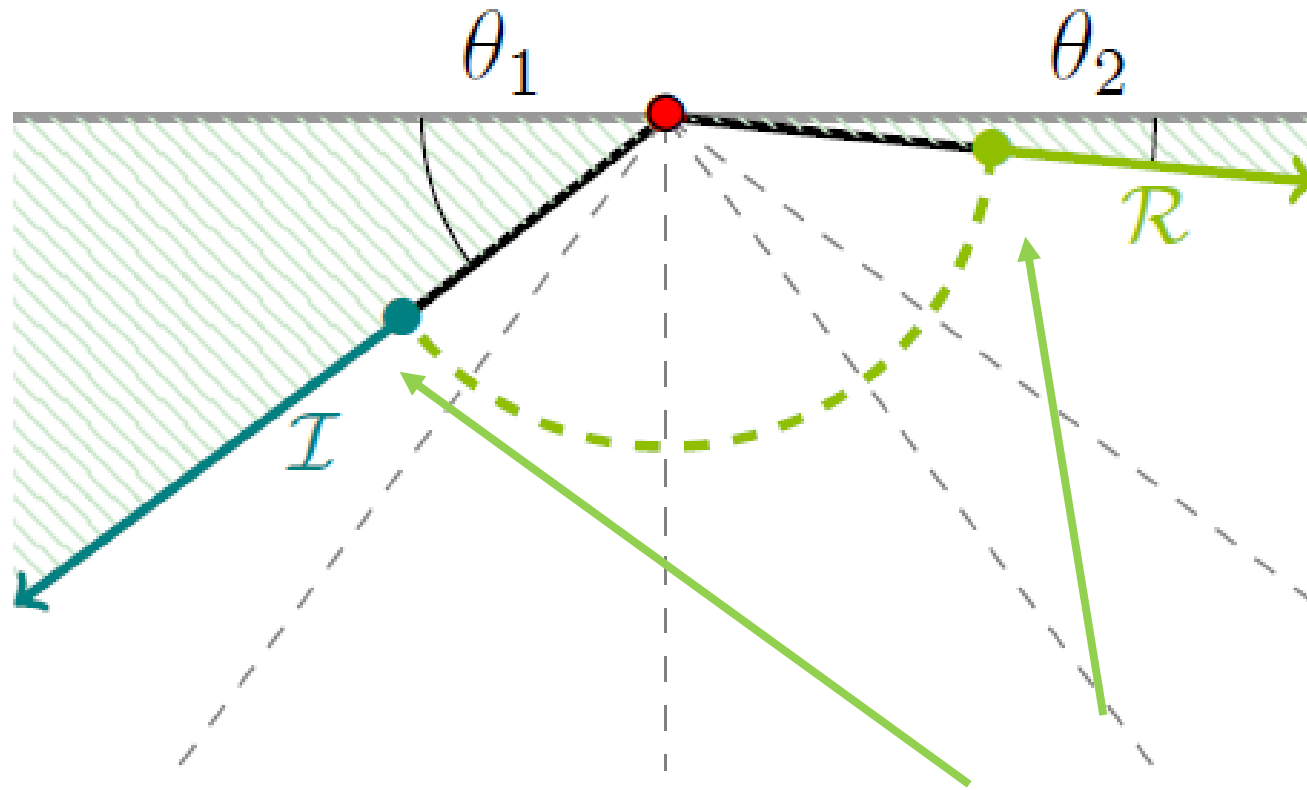
RS branes for gravitating bath.

(G7, '20)



- Simply add 2nd brane
- One massless, one massive graviton
- Smaller angle = weaker Newton's constant

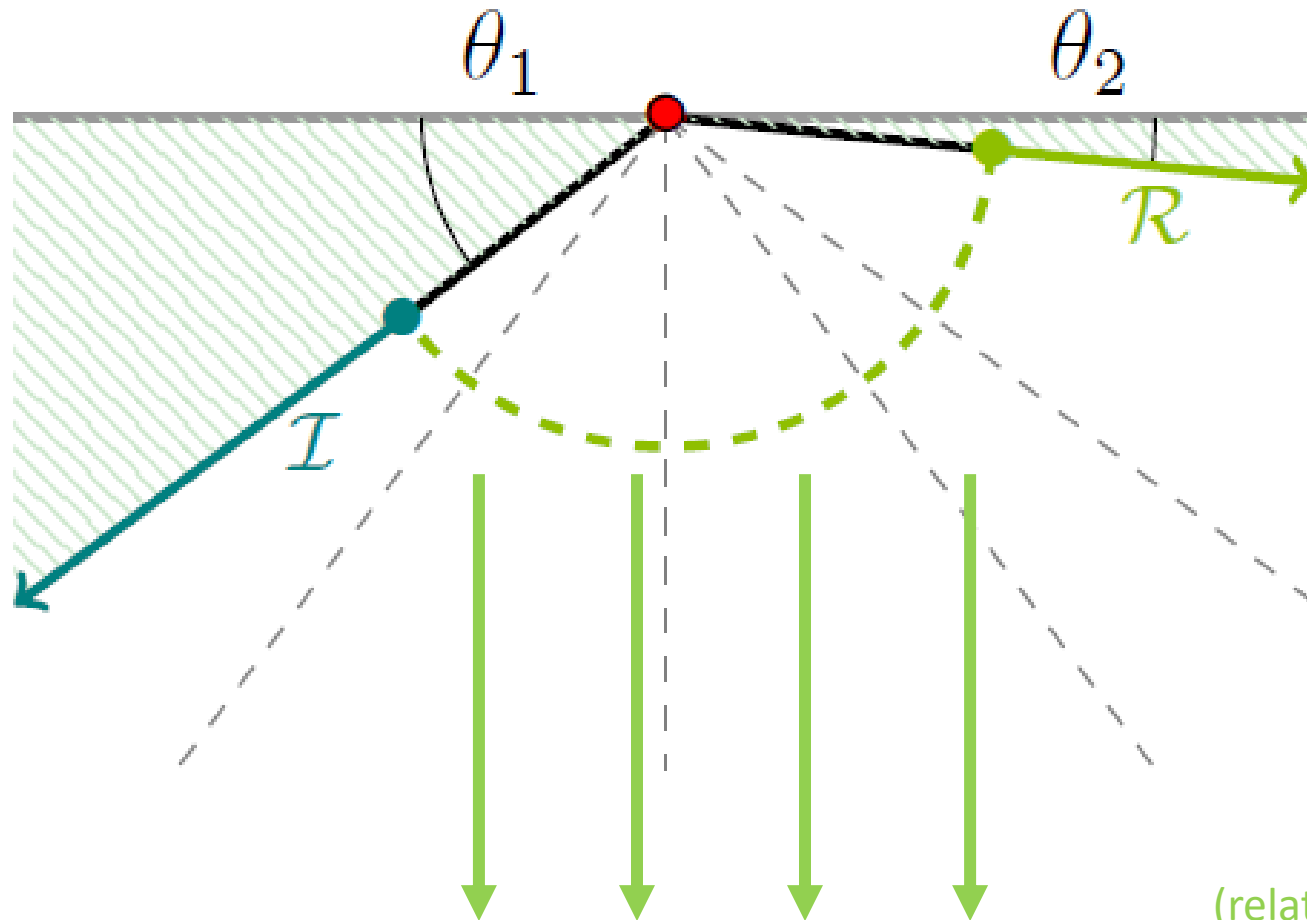
RS branes for gravitating bath.



**Radiation Region
obeys island rule!**

**Both endpoints dynamically
adjusted!!**

RS branes for gravitating bath.



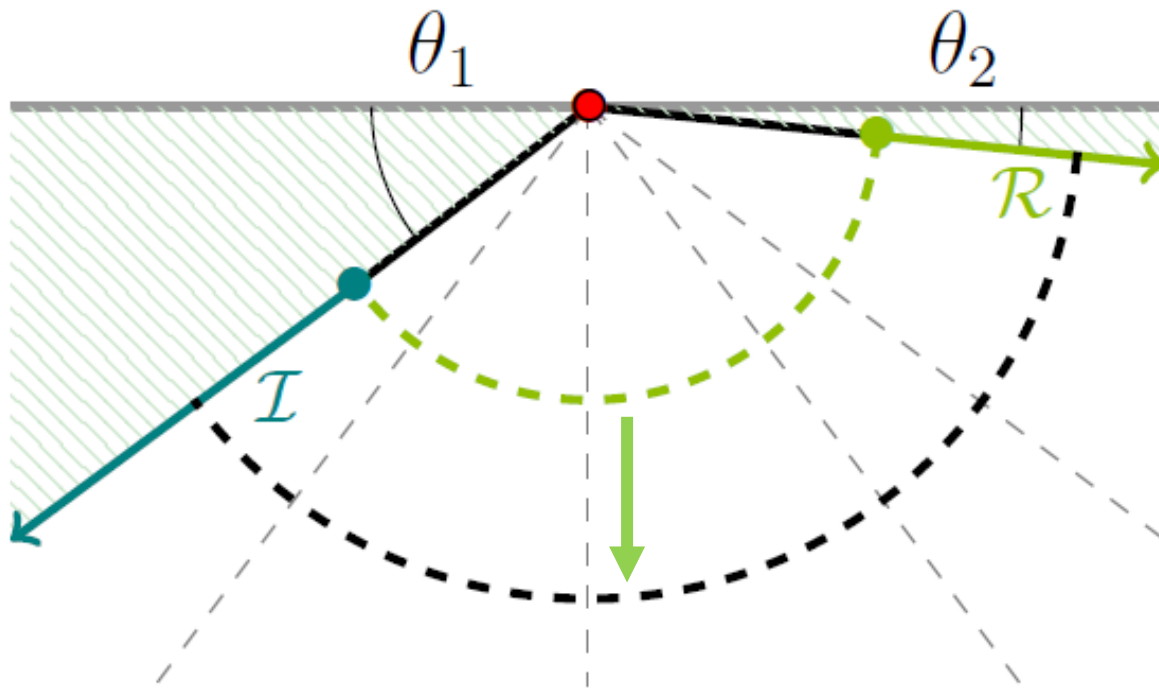
RT surface falls into bulk

$$S=0$$

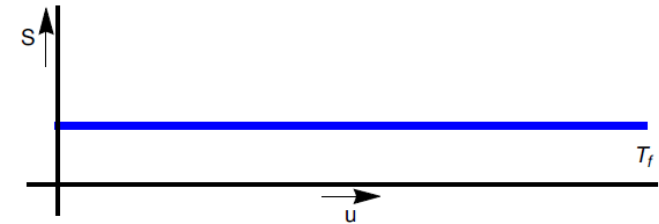
obvious from CFT: pure state

(related work by Akal, Kusuki, Takayanagi, Wei '20)

Gravitating Bath with black hole



RT-surface = horizon



Flat Page Curve

RS story -- Two options:

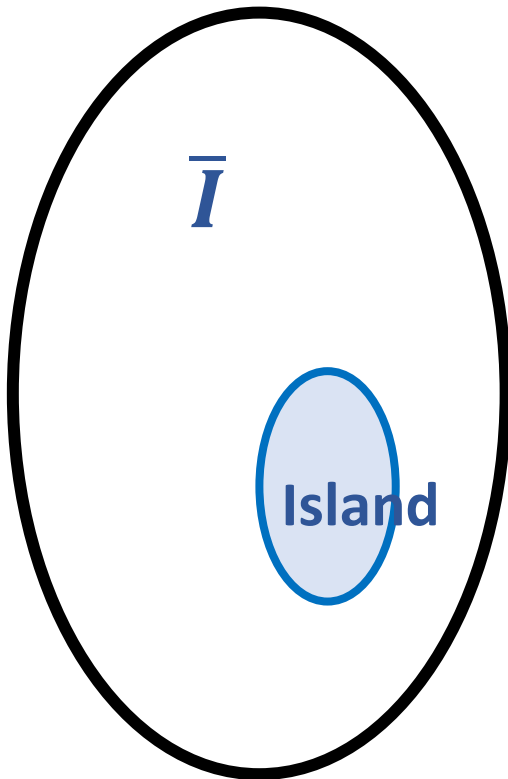
1. **Massive Graviton:** Islands, non-trivial Page curve
2. **Massless Gravitons:** no islands, flat Page curve

Does this hold more generally?

A puzzle with Islands

(G7, '21)

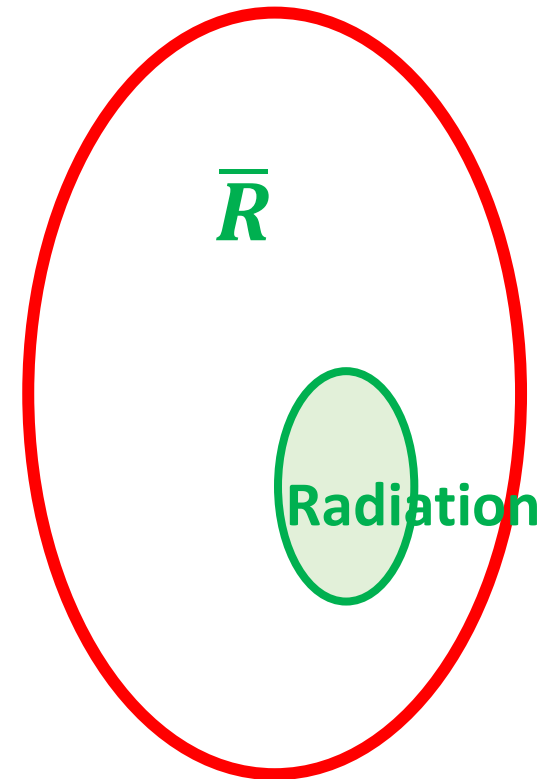
GRAVITY



Entanglement reconstruction posits that we can reconstruct an operator in R from data in I .

Similar, the complement of R can be reconstructed from the complement of I .

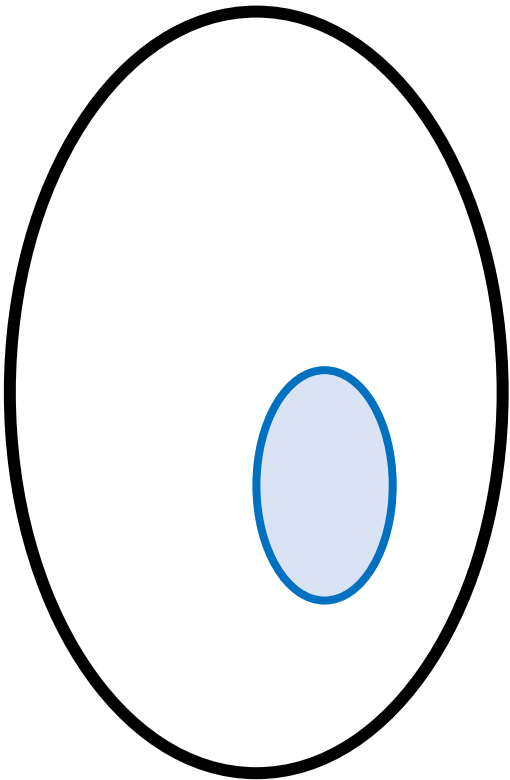
BATH



A puzzle with Islands

(G7, '21)

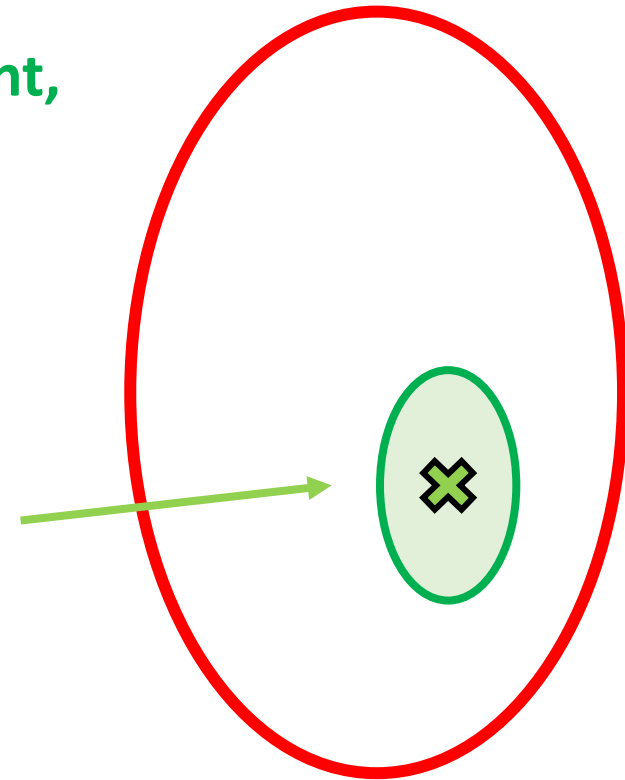
GRAVITY



In a local QFT
(non-gravitating bath)
this excitation is
invisible to the complement,
by causality.

Local Excitation
in R , carrying finite
energy E

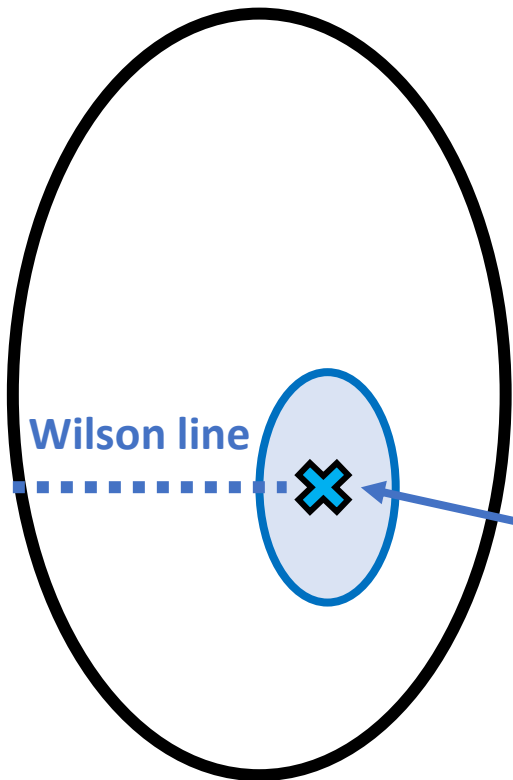
BATH



A puzzle with Islands

(G7, '21)

GRAVITY

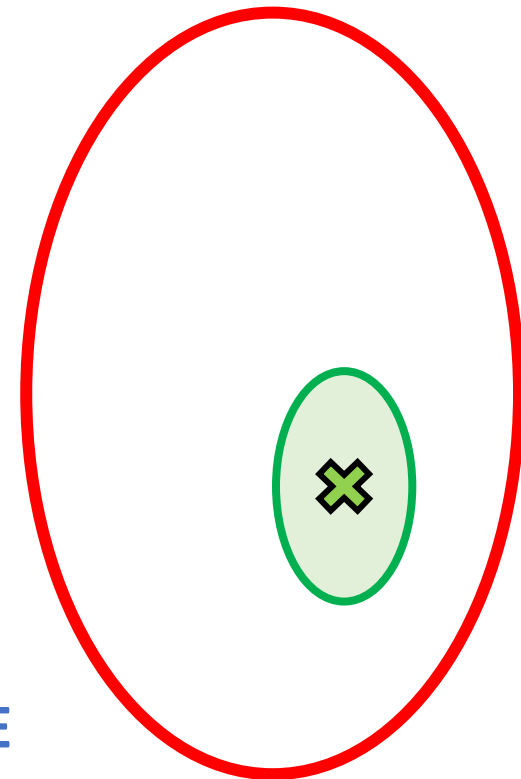


In a theory of gravity
local excitations aren't
gauge invariant. Need to
be “dressed” to boundary.

“Gauss law”

The local excitation
encoding this in the island
necessarily also has finite E

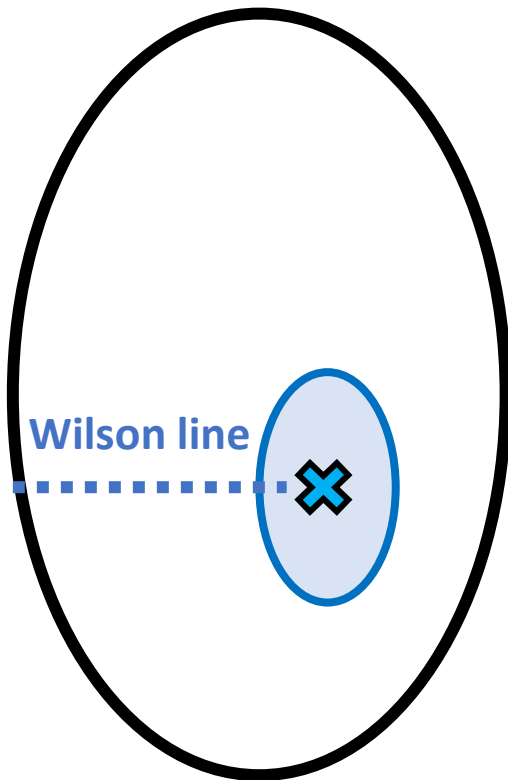
BATH



A puzzle with Islands

(G7, '21)

GRAVITY

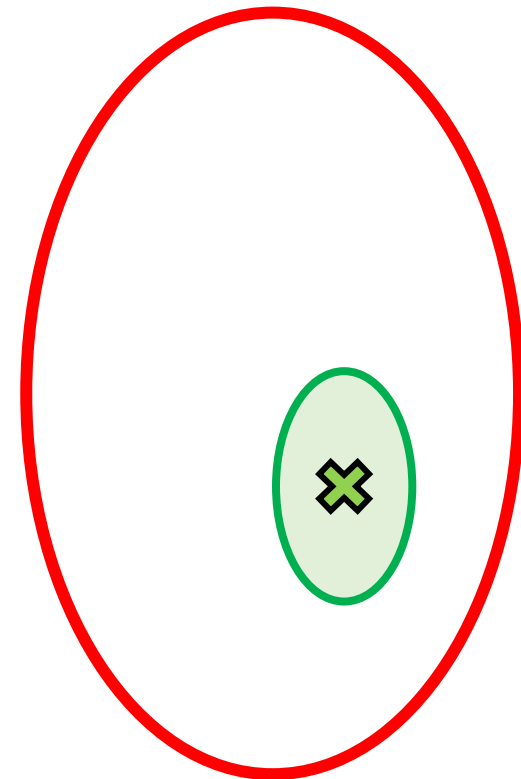


Contradiction!

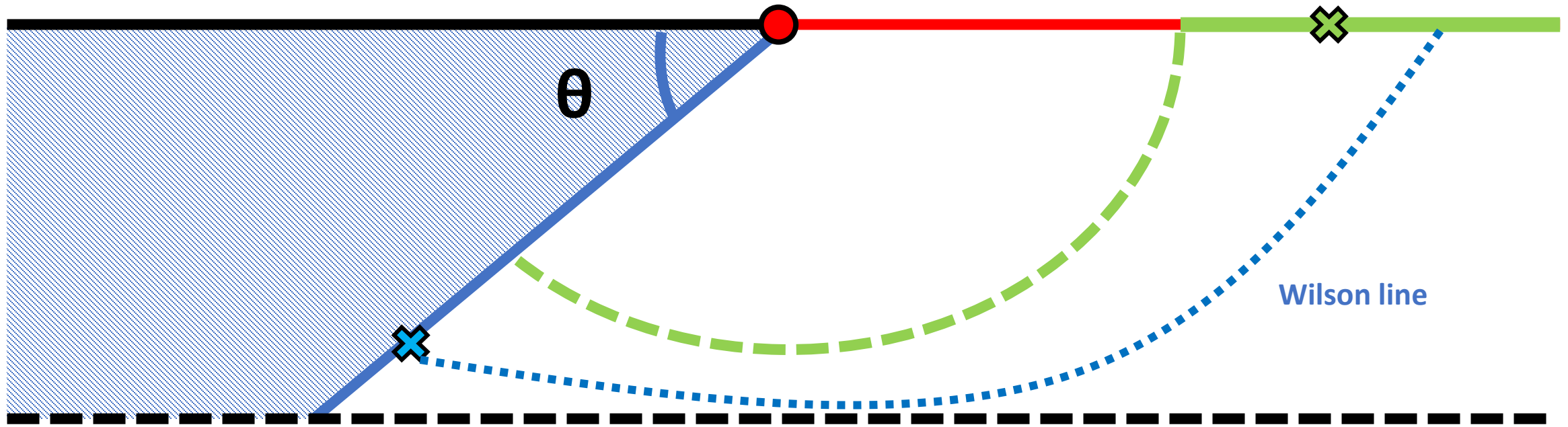
Complement of R **can not** see excitation.

Complement of I **can** see excitation

BATH



But how come islands exist in RS???



Excitation in I can be dressed to R via higher dimensional bulk!

How can this be understood from brane?

The graviton mass is what solves this puzzle on the brane.

Standard (massless) constraint equation:

$$\frac{1}{16\pi G} \sqrt{g} \nabla_i J^i = N \sqrt{g} \delta \rho$$

$$J^i \equiv N \nabla_j h^{ij} - h^{ij} \nabla_j N - N \nabla^i h_j^j + h_j^j \nabla^i N$$

$$E \equiv \frac{1}{16\pi G} \int_{S_\infty} d^{d-1}x \sqrt{g} n_i J^i$$

Also holds
in correlation
functions.

Energy of any excitation can be read off from asymptotia

How can this be understood from brane?

The graviton mass is what solves this puzzle on the brane.

Massive braneworld constraint equation:

$$m_n^2 \bar{N} \bar{h}_n + \bar{\nabla}_{\bar{i}} \bar{J}_n^{\bar{i}} = 16\pi G \bar{N} \bar{\rho}_n.$$

LHS no longer total derivative.

Energy density can be accounted for by **local** metric fluctuations. Link to asymptotia broken.

Summary

- In a massless theory of gravity the Gauss law leads to a clash between existence of islands and standard lore about entanglement wedge reconstruction.
- One way out of this clash is to give the graviton a mass; this is the solution found in RS brane worlds (or any time an island is found in a theory of gravity coupled to a bath).



Thank you