Supersymmetry Breaking, Stringy Effects and Emergence in Microstate Geometries

The Verlinde Symposium

Thursday July 14, 2022

Nick Warner

**Research supported supported in part by:
ERC Grant number: 787320 - QBH Structure and DOE grant DE- SC0011687**

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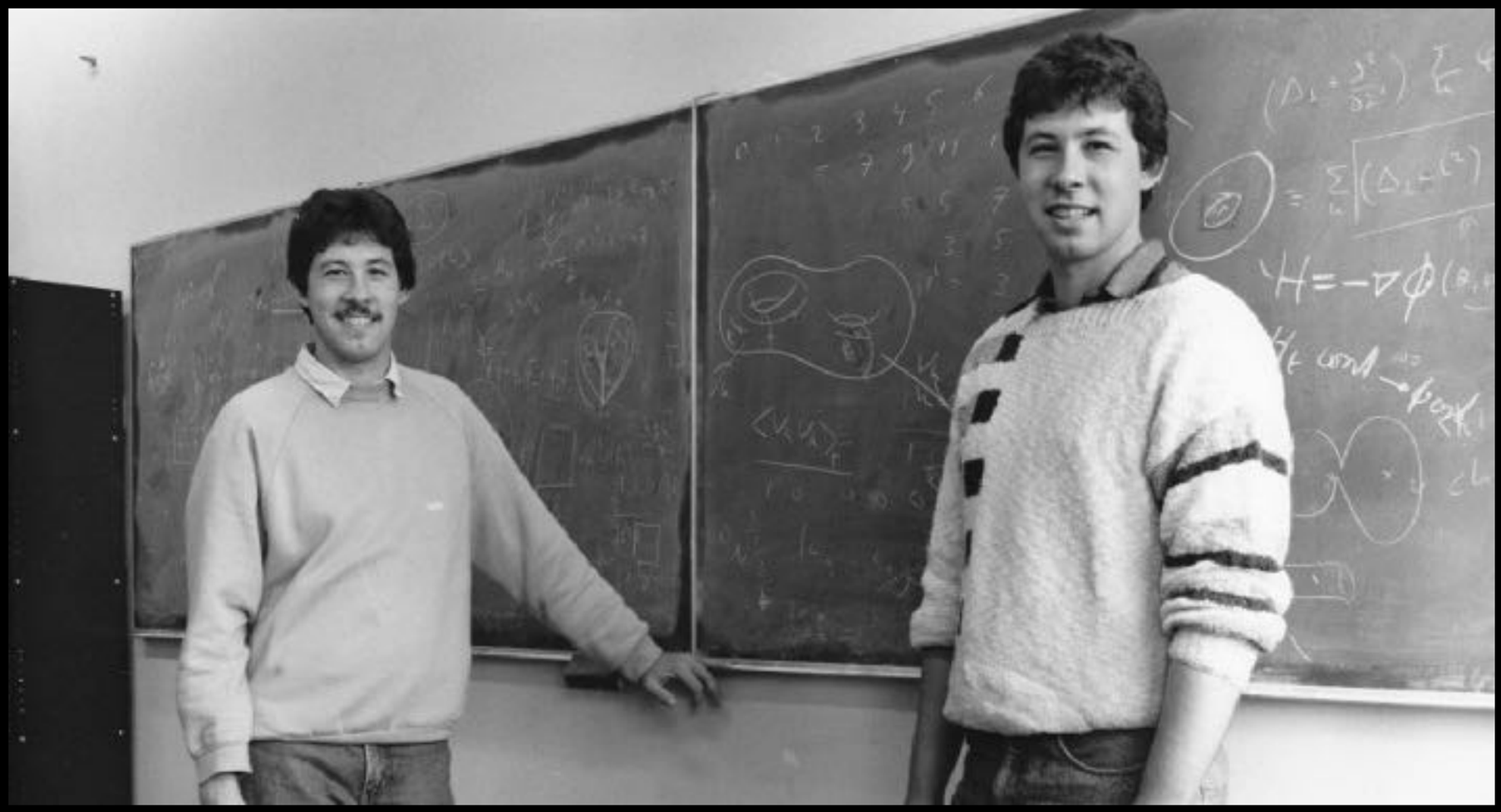

Chiral Bosonization, Determinants and the String Partition Function #36

Erik P. Verlinde (Utrecht U.), Herman L. Verlinde (Utrecht U.) (Oct, 1986)

Published in: *Nucl.Phys.B* 288 (1987) 357

DOI cite 401 citations

Perturbative strings

IASSNS-HEP-88/52
PUPT-88/1111
October 1988

Lectures on String Perturbation Theory[1]

Erik Verlinde

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and

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Fusion Rules and Modular Transformations in 2D Conformal Field Theory #103

Erik P. Verlinde (Utrecht U.) (Mar 21, 1988)

Published in: *Nucl.Phys.B* 300 (1988) 360-376

DOI cite 1,009 citations

The DVV Equations

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Computing correlators in topological sectors of $\mathcal{N}=2$ superconformal field theories …

Physics Letters B 269 (1991) 96–102
North-Holland

PHYSICS LETTERS B

Topological Landau–Ginzburg matter at $c=3$

E. Verlinde
Institute for Advanced Study, Olden Lane, Princeton, NJ 08540, USA

and

N.P. Warner
Physics Department, University of Southern California, University Park, Los Angeles, CA 90089-0484, USA

Received 23 April 1991

The topological correlation functions, their prepotential, and the Landau–Ginzburg potential are computed for the $N=2$ supersymmetric, $c=3$, matter model that is a tensor product of three $c=1$ models.

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- ★ Balanced holography and fuzzball states
- ★ Emergent geometry and D1-D5 CFT

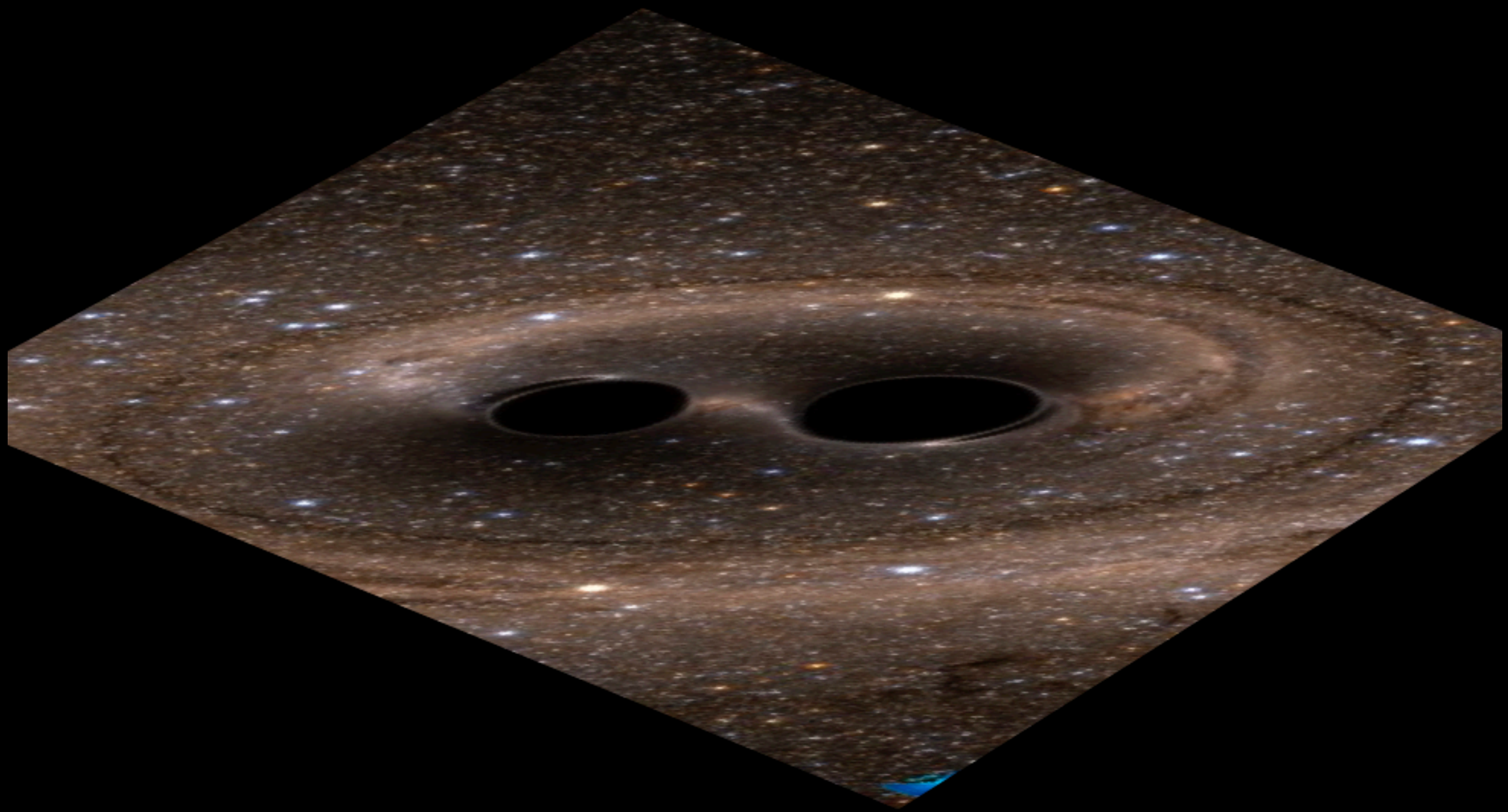
Fuzzball and Microstate Geometries

Bena, Martinec, Mathur and Warner,

2203.04981 Snowmass White Paper: Micro- and Macro-Structure of Black Holes

2204.13113 Fuzzballs and Microstate Geometries: Black-Hole Structure in String Theory

Probably the most viable solution to the information problem* (that includes gravitational back-reaction) comes from the understanding that:



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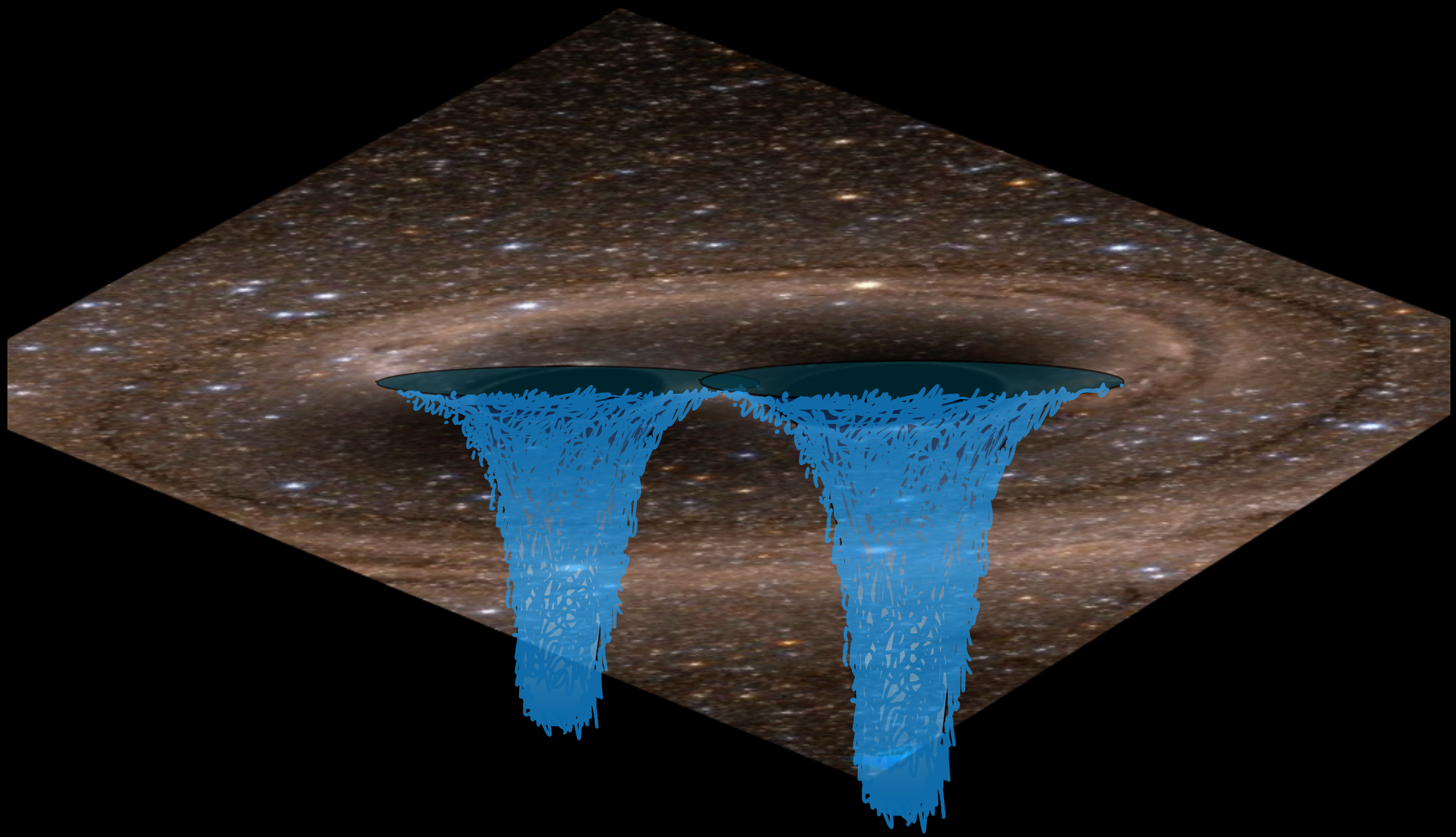
Black holes are really horizonless, strongly-quantum stringy backgrounds in more than 3+1 dimensions: *Fuzzballs*

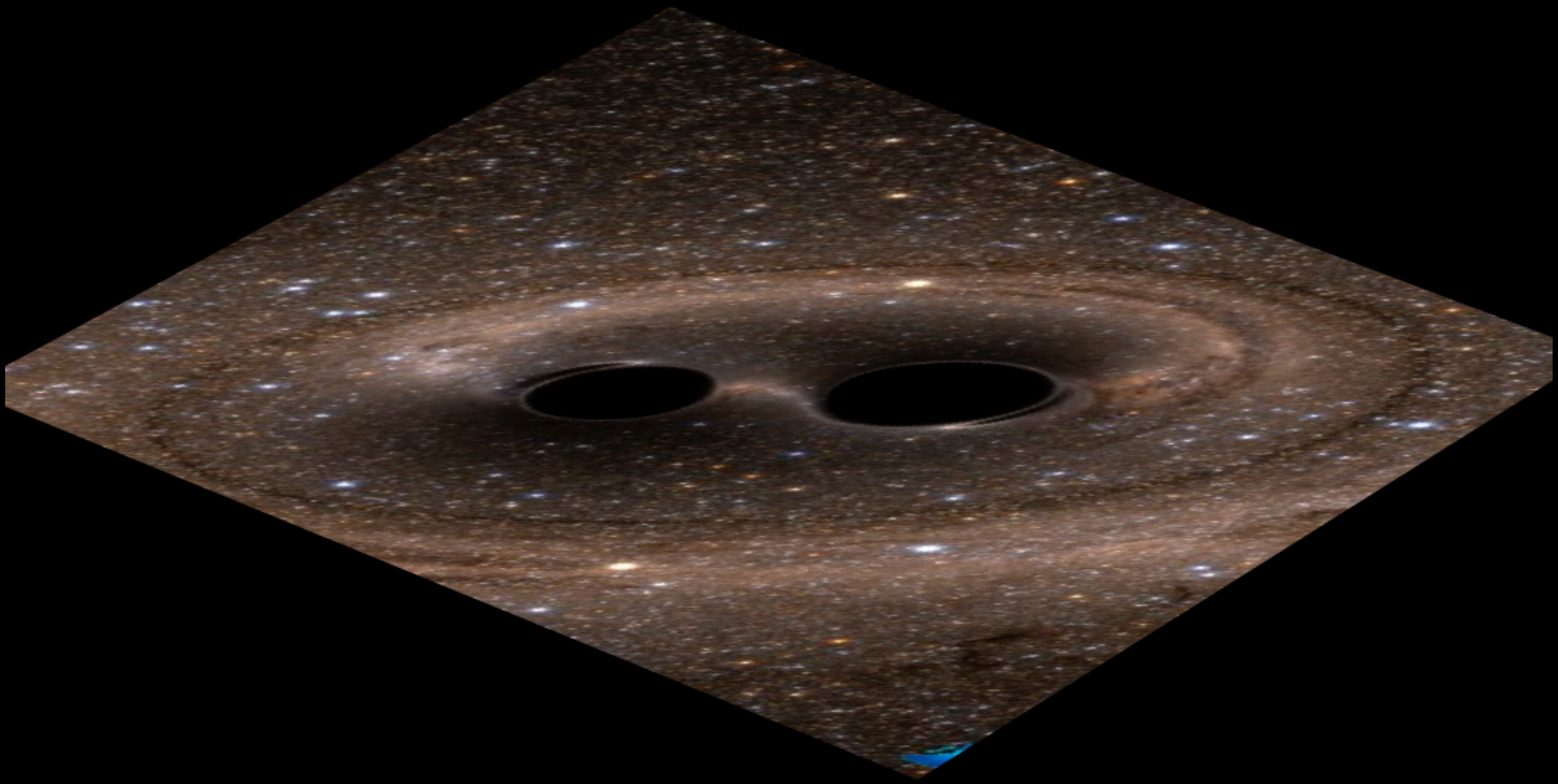


**if you want to avoid extensive, long range non-locality, or the loss of unitarity*

Microstate geometries:

Coherent expressions of fuzzballs within the supergravity limit of string theory.

⇒ *Smooth, horizonless solutions* of the supergravity equations with the same macroscopic behavior as a black-hole



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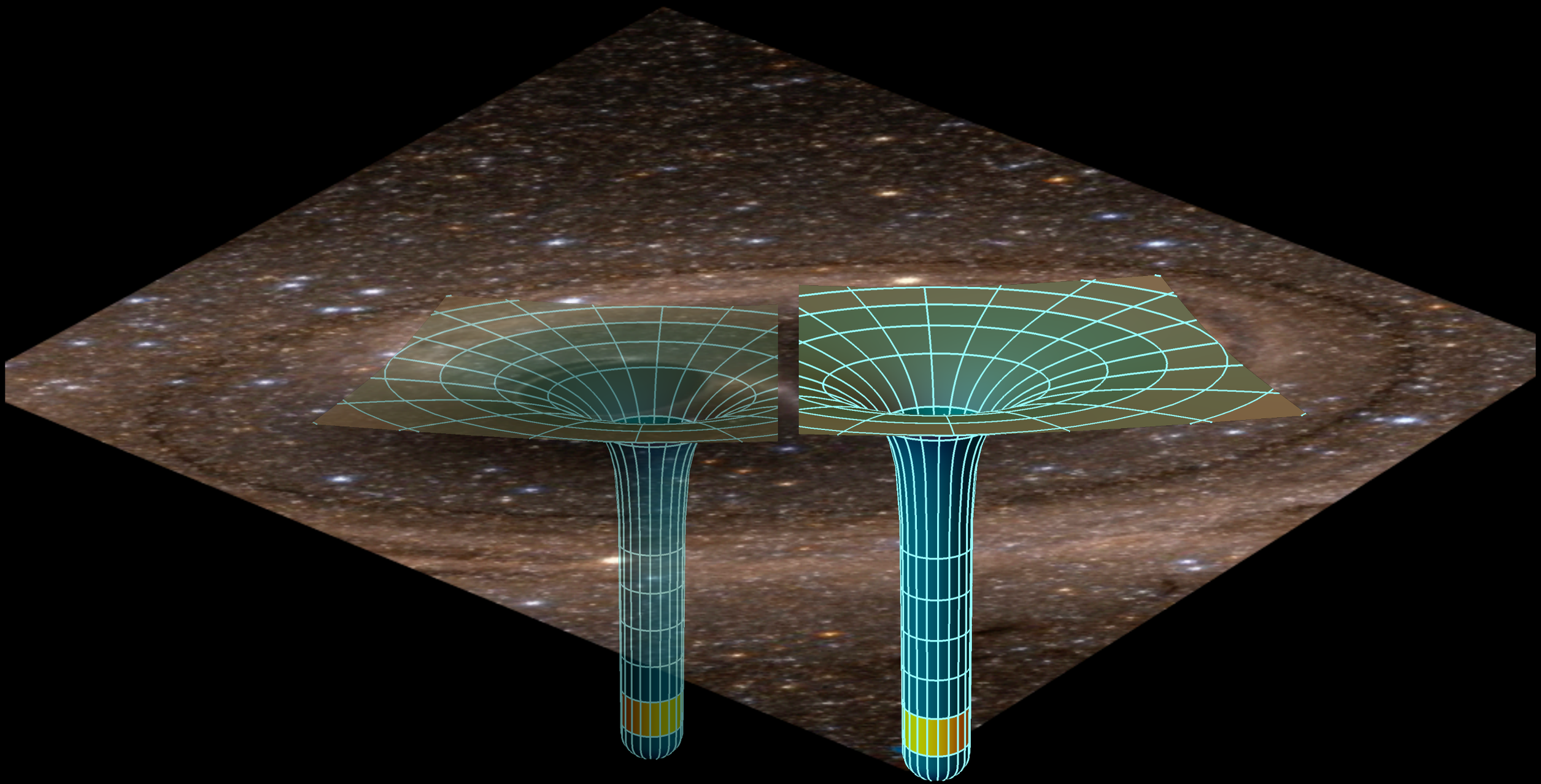

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- ★ Supergravity can also describe large-scale collective effects of strongly-coupled quantum systems: effective geometries and effective hydrodynamics of fuzzballs

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Entropy of black hole ~ Entropy of string states around superstrata?

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- ★ "(Hawking) radiation" from decays of microstate geometries

Anti-branes and supersymmetry breaking

Supersymmetry breaking with anti-branes

S. Kachru, J. Pearson and H. Verlinde: *Brane/Flux Annihilation and the String Dual of a Non-Supersymmetric Field Theory* (*0112197*)

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In late 2021, early 2022: A very significant breakthrough by Bah, Heidmann, Weck …

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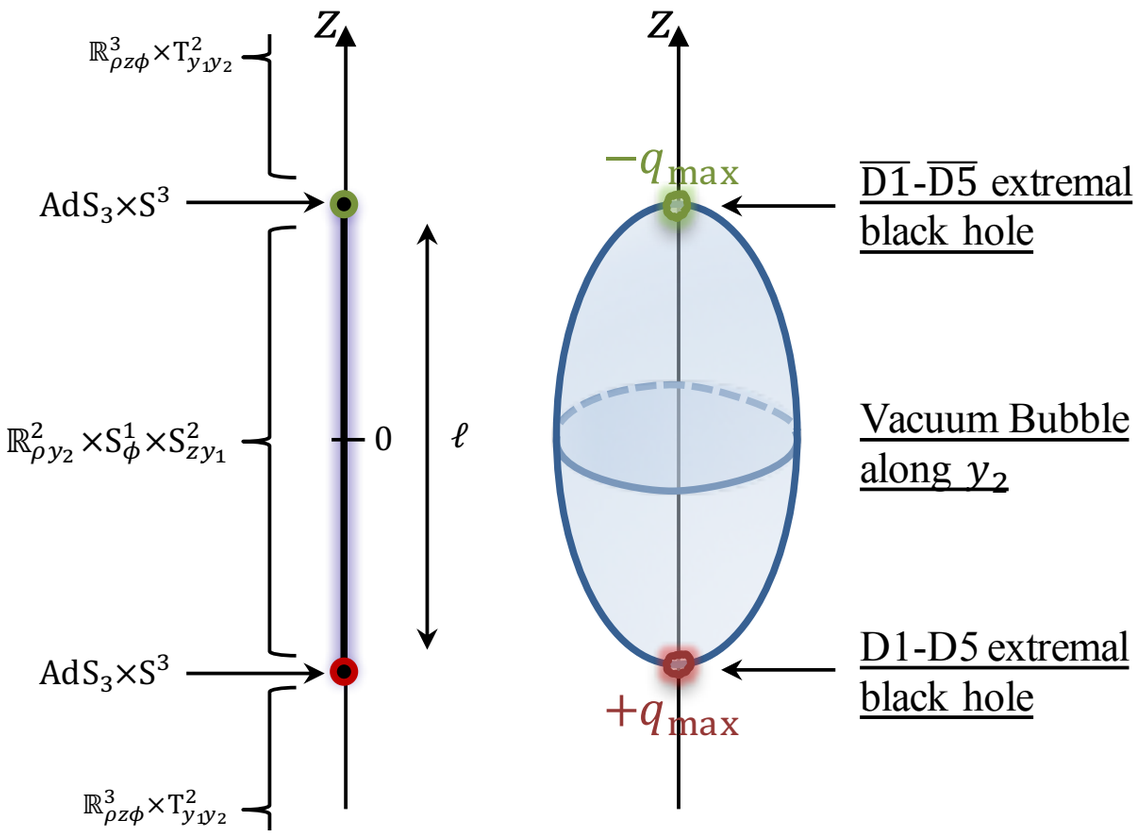

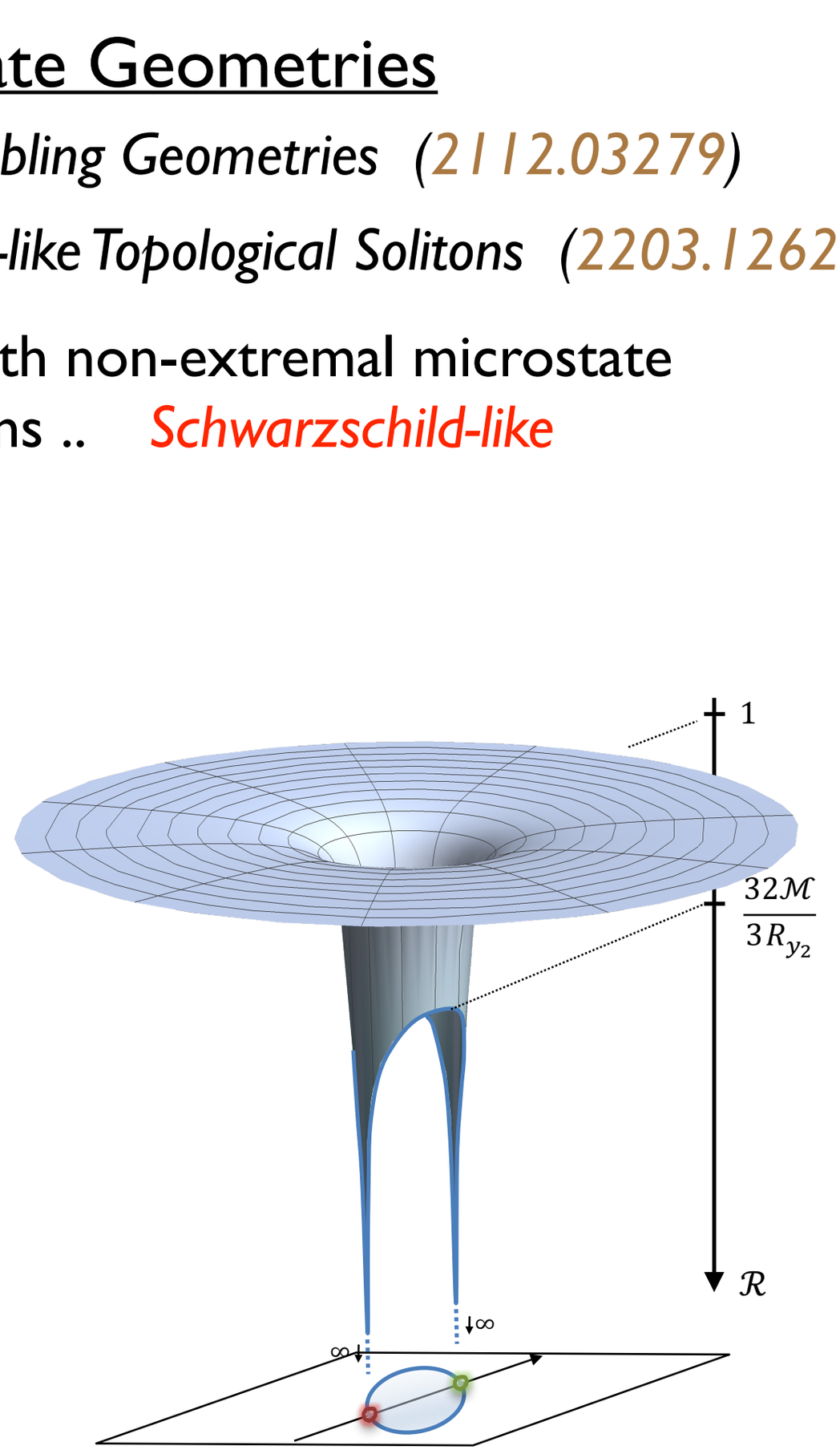

Balanced holography, fuzzball states and black-hole interior geometry

Balanced Holography

Passing through the Firewall

Erik Verlinde[1] and Herman Verlinde[2]

cal Physics, University of Amsterdam, Amster
f Physics, Princeton University, Princeton, N

(Dated: June 5, 2013)

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Double the degrees of freedom:

Black hole (interior) + *Entanglement environment (exterior)*

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Describe entanglement, various choices of basis, young and old black holes, observers and firewalls …

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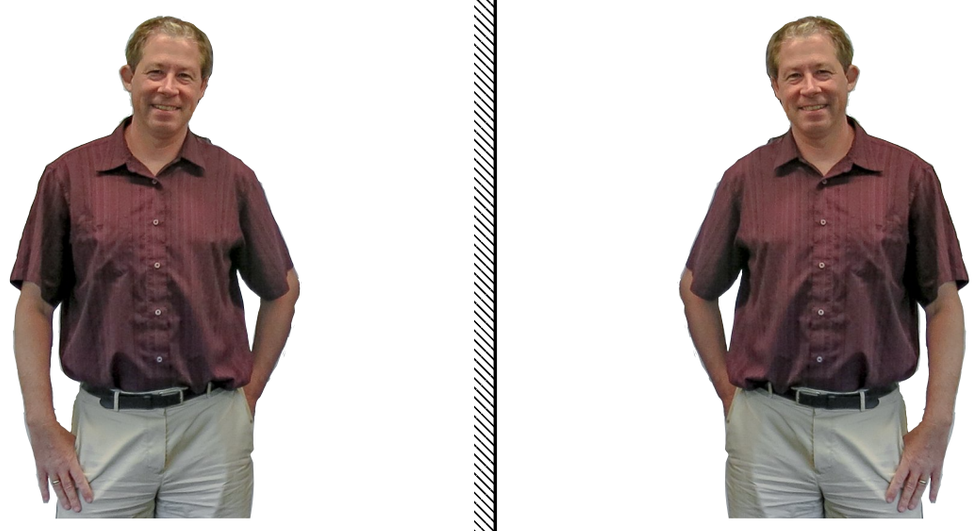

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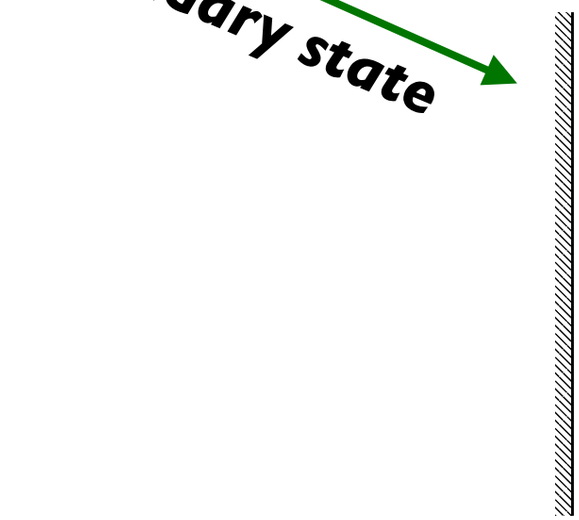
Boundary state



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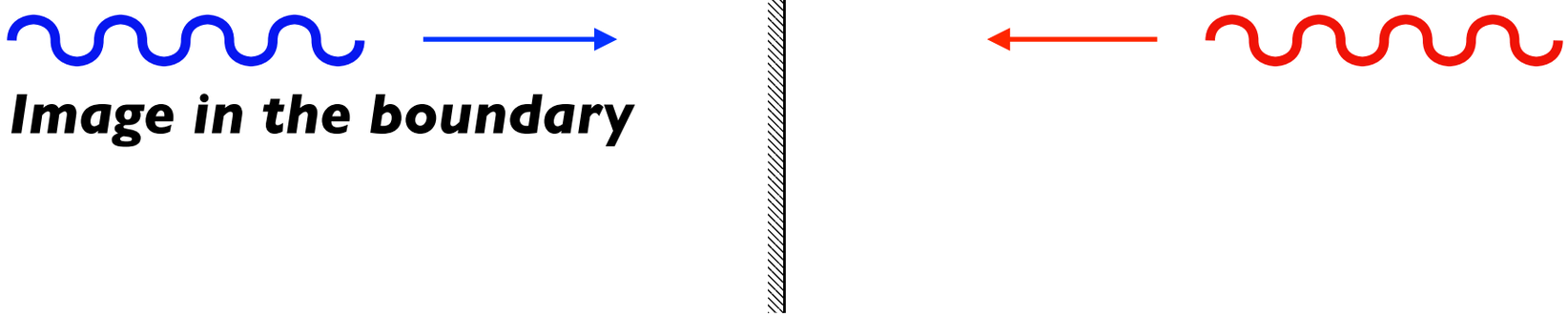

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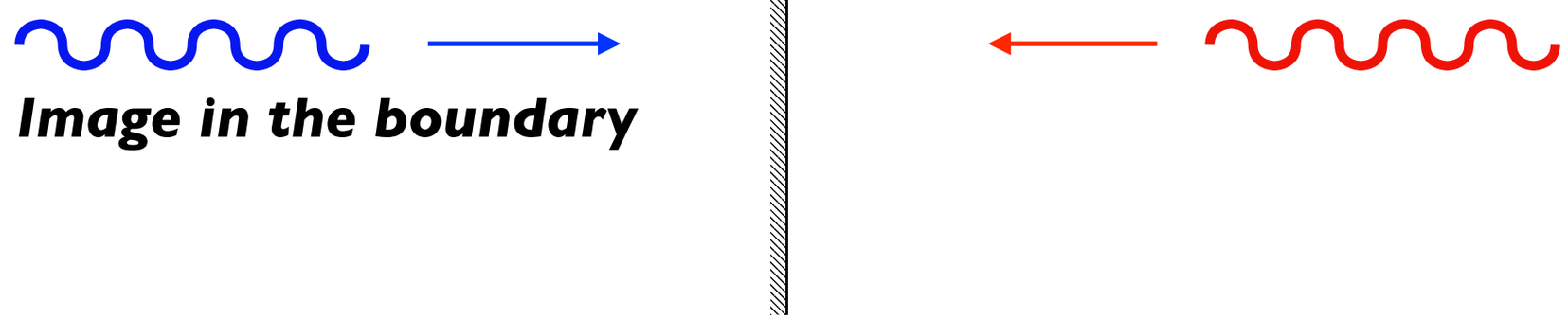
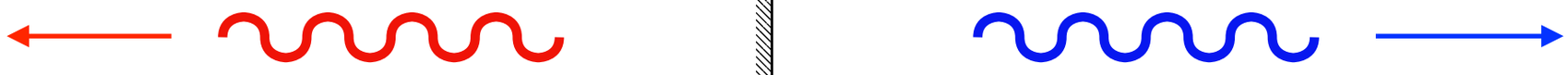


Correlations replicate reflection at the boundary



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"Ishibashi" states in one-to-one correspondence with *conformal blocks*

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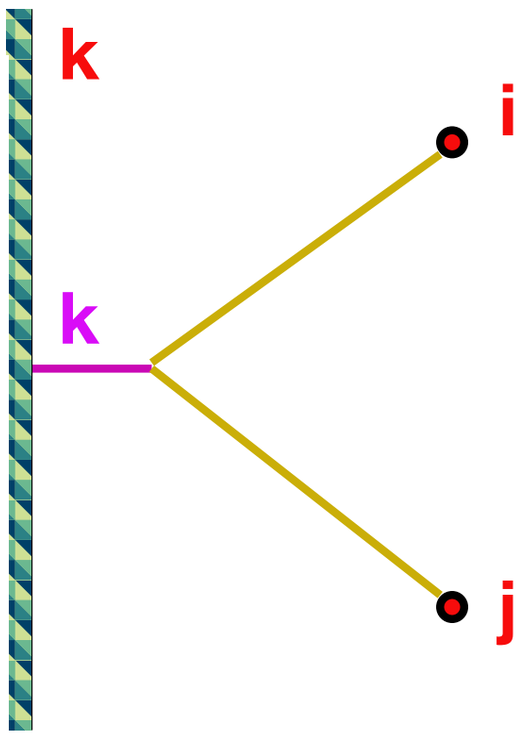

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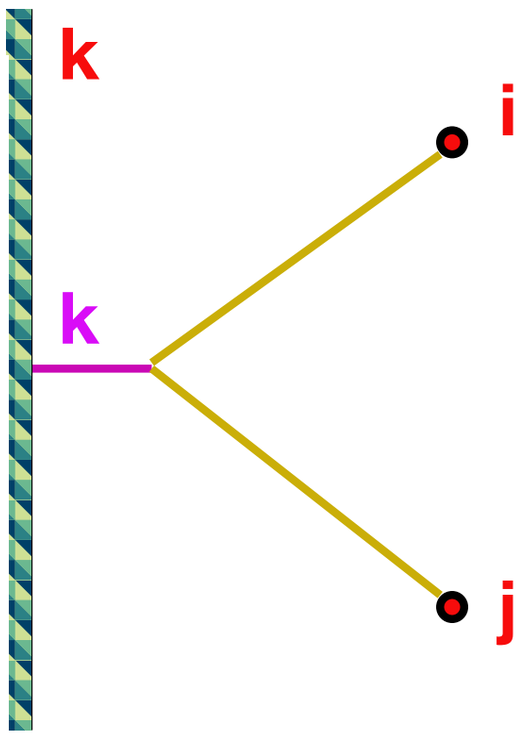

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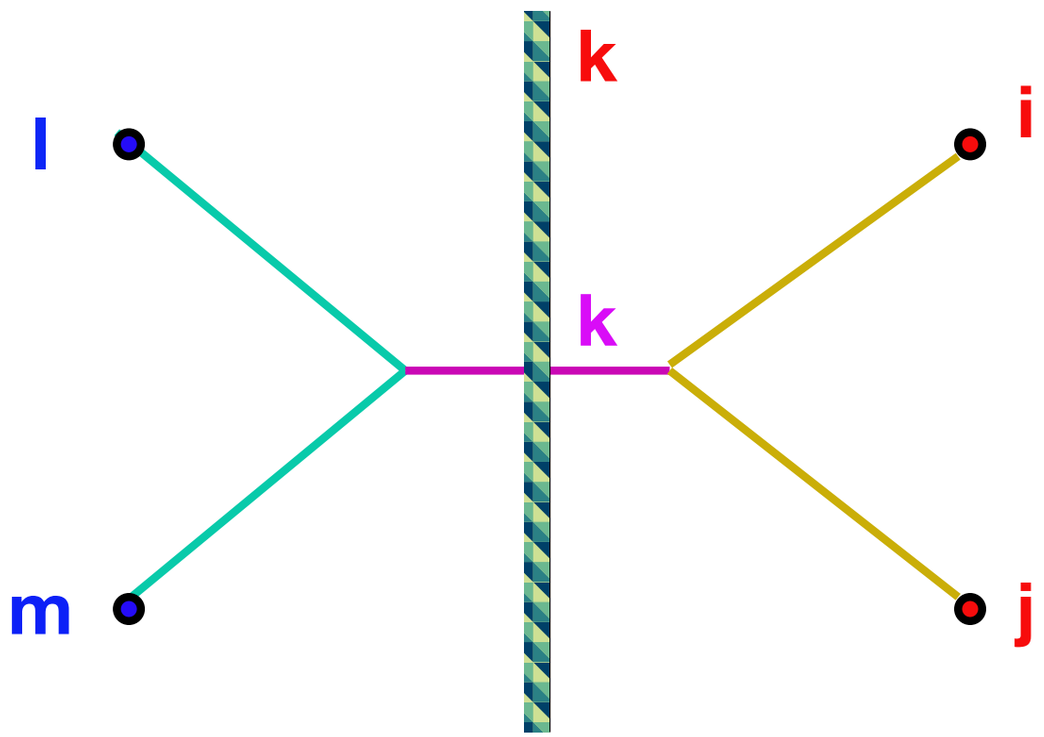

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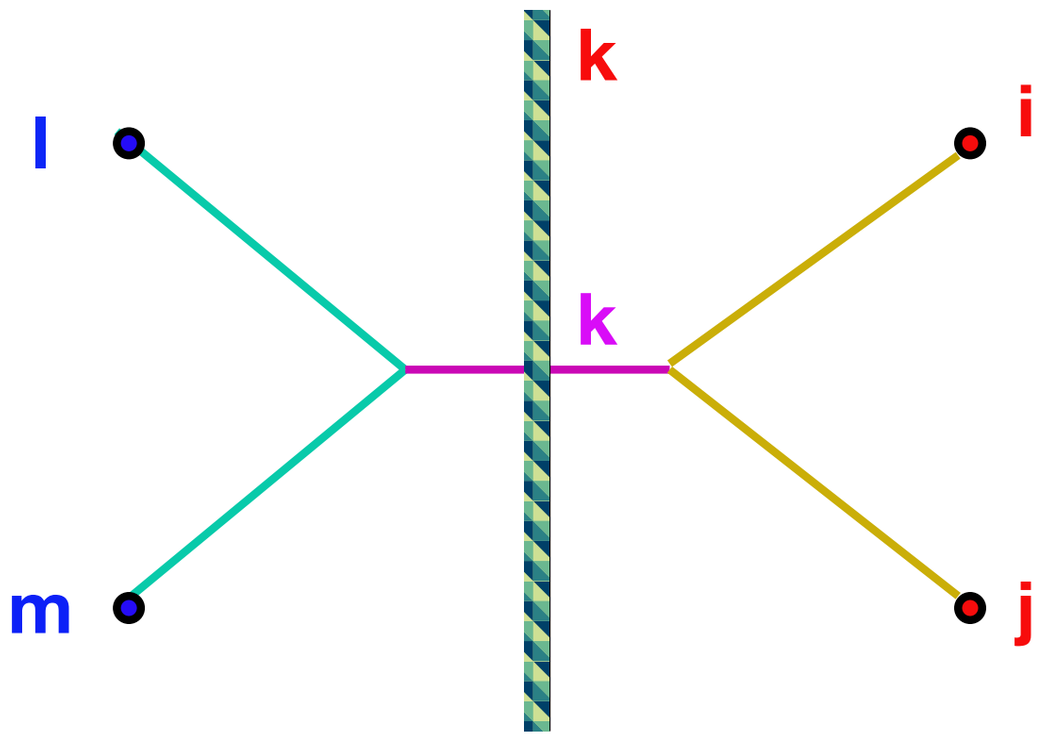

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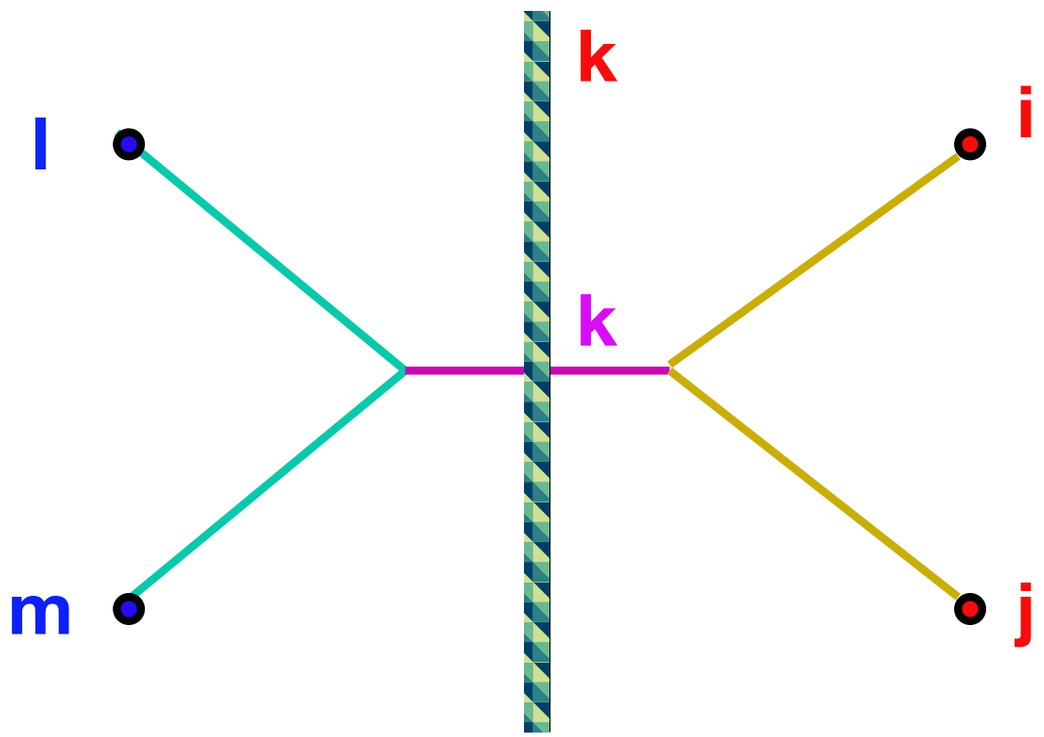

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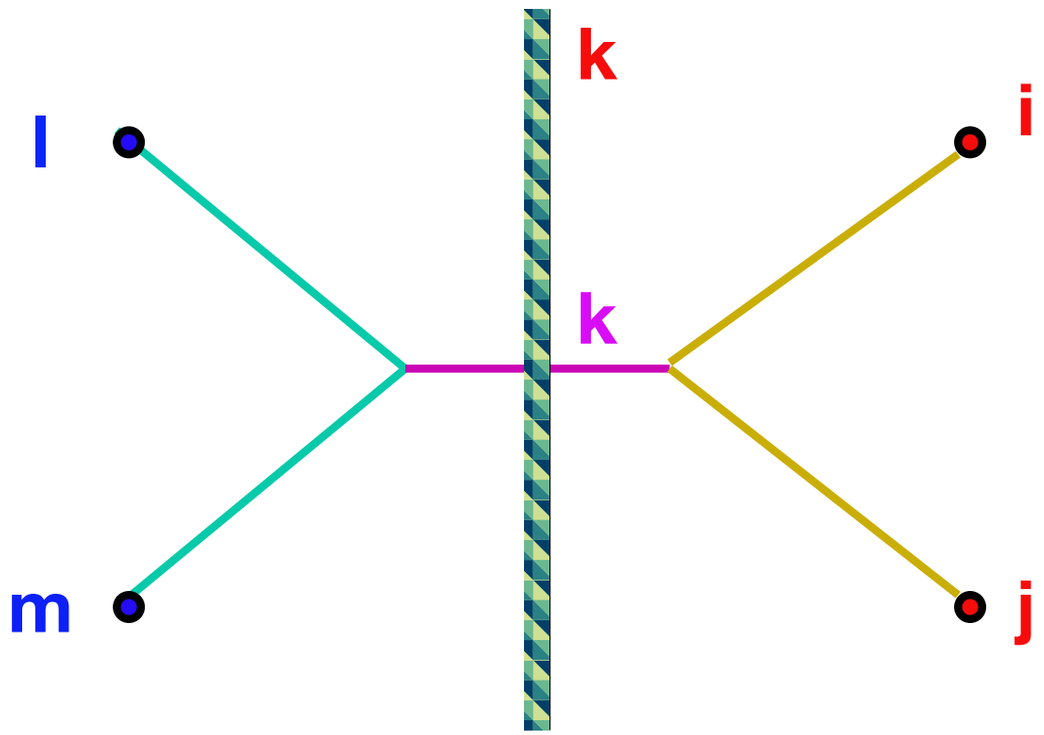

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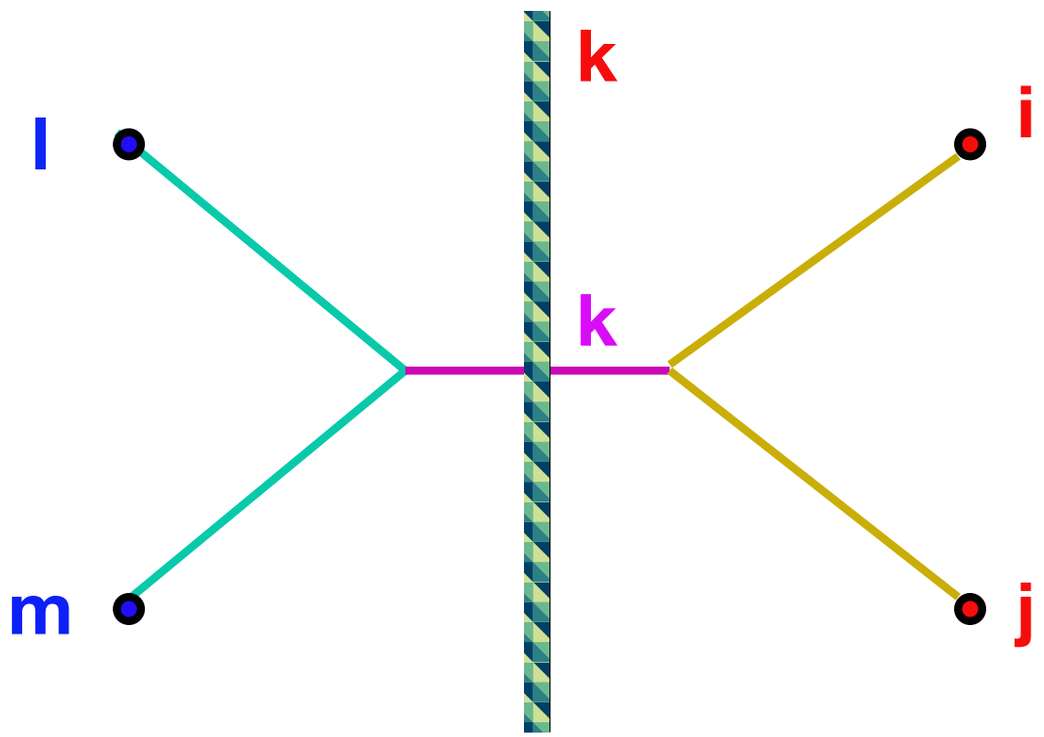

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Applying balanced Holography for BTZ black holes using Liouville gravity

L. McGough , H.Verlinde

*Bekenstein-Hawking Entropy as Topological Entanglement Entropy (*1308.2342*)*

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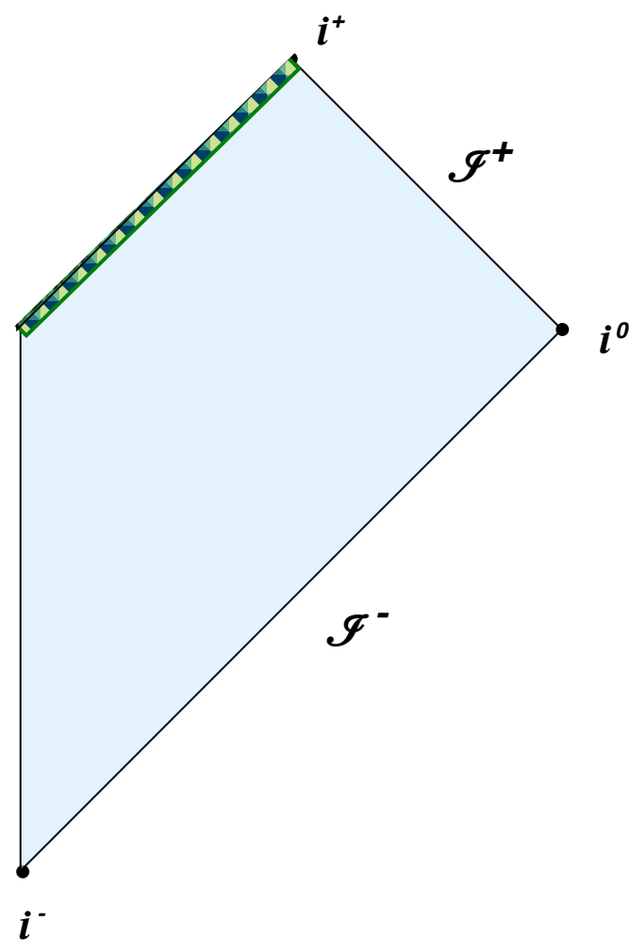

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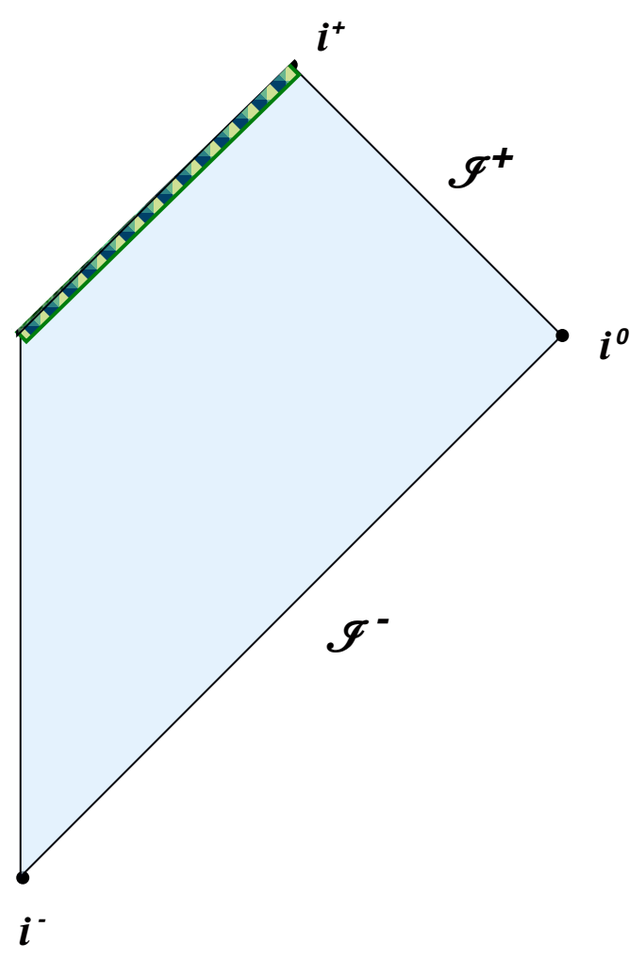

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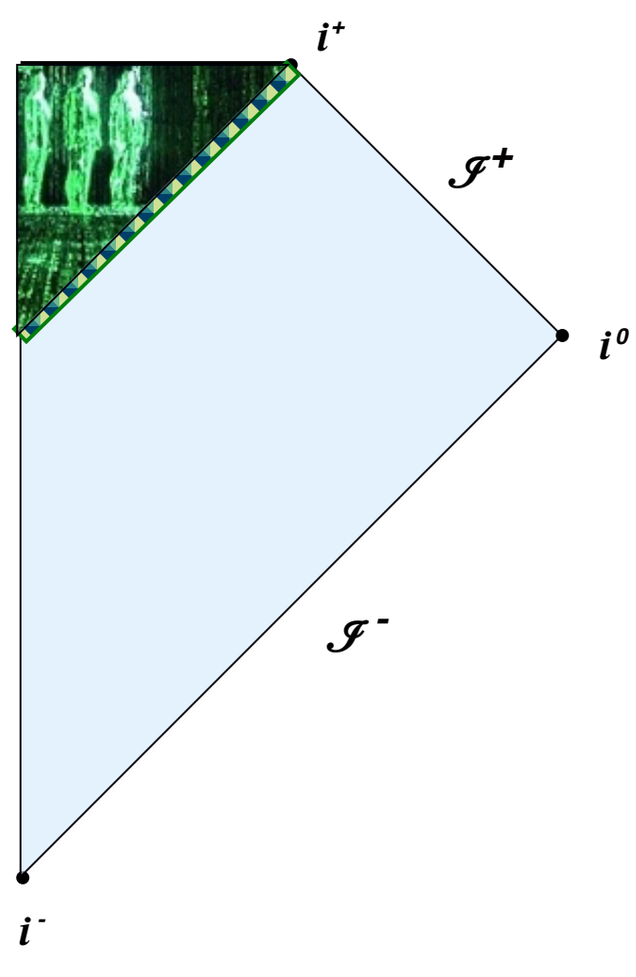

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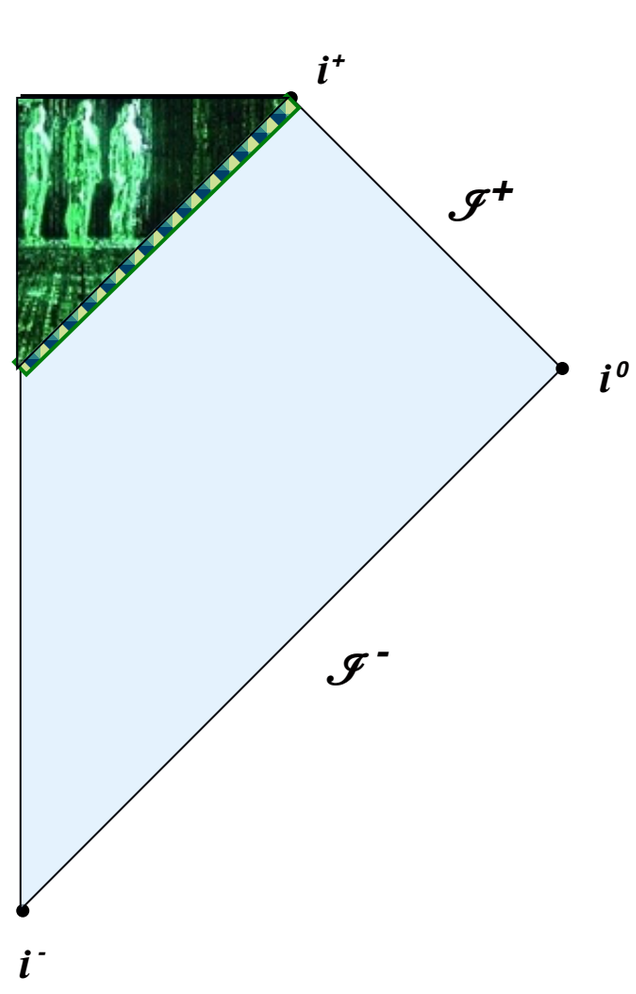
The fuzzball

Morpheus: [The black-hole interior] is the world that has been pulled over your eyes to blind you from the truth.



Emergent geometry in the D1-D5 CFT?

E. Verlinde, On the Origin of Gravity and the Laws of Newton, (1001.0785)

Superstrata

Superstrata are the fully back-reacted microstate geometries obtained from momentum excitations of the D1-D5 system. *Holographic dictionary is well understood … and extensively mapped out.*

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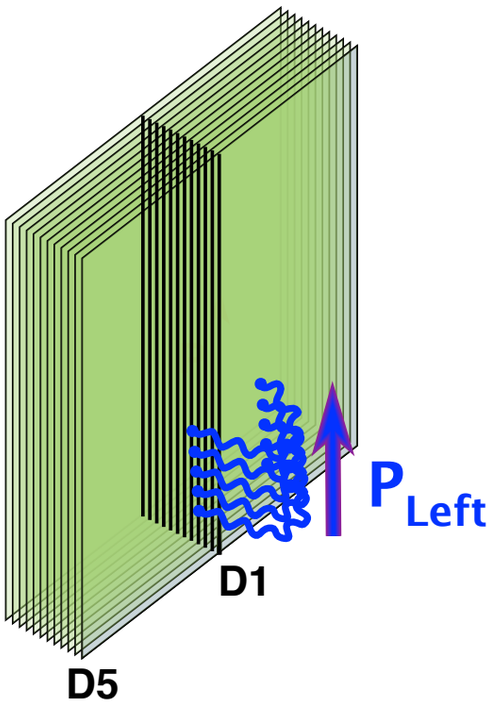
Purely left-moving momenta; ⅛ BPS states of the "Supergraviton gas"



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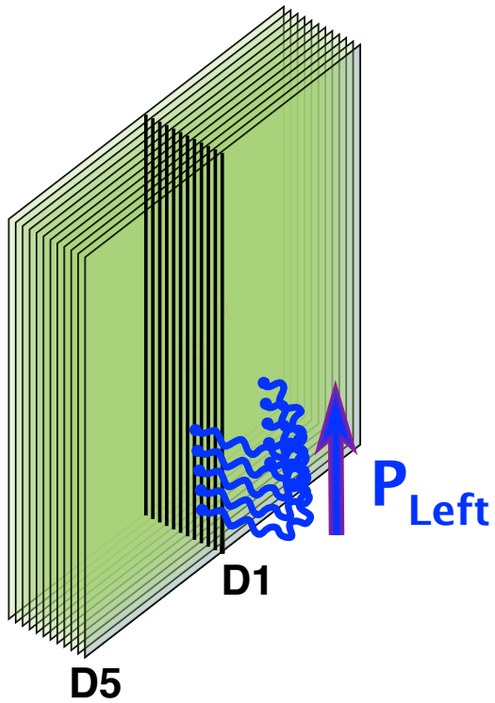

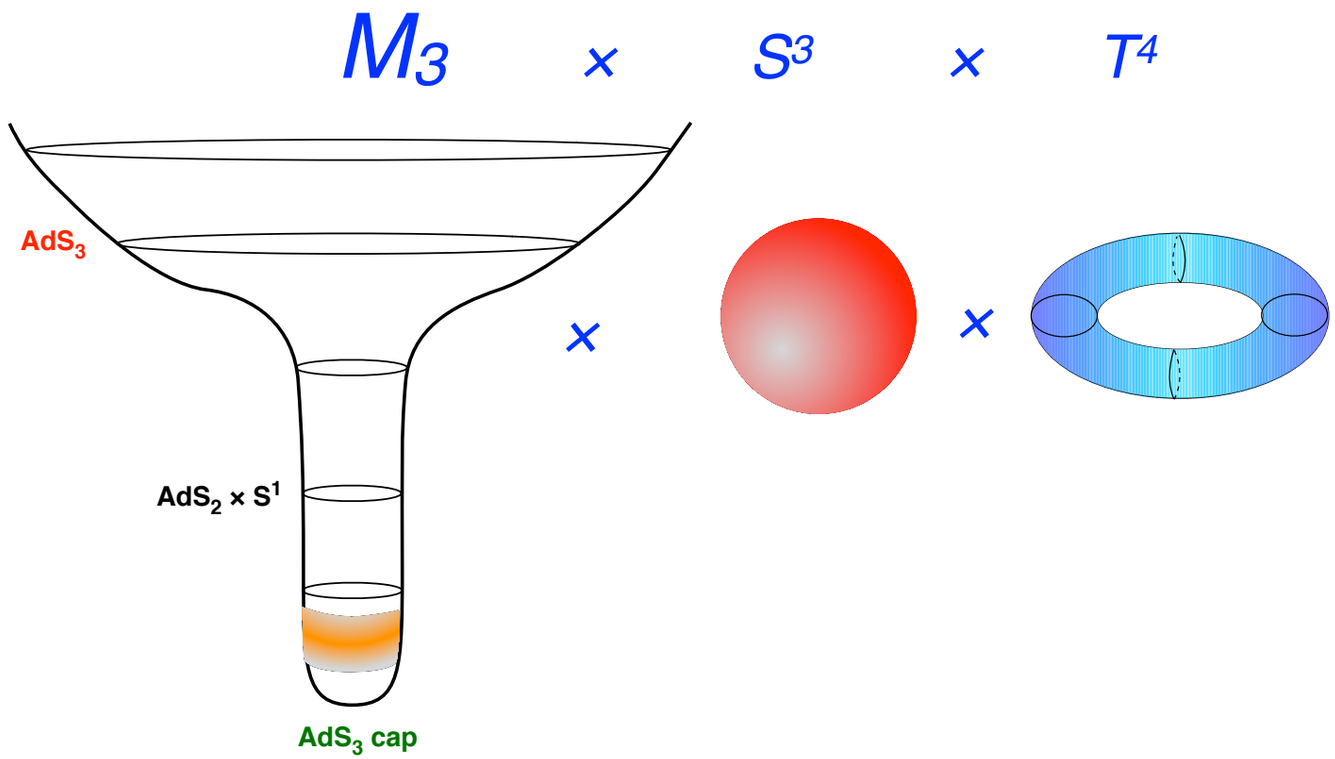

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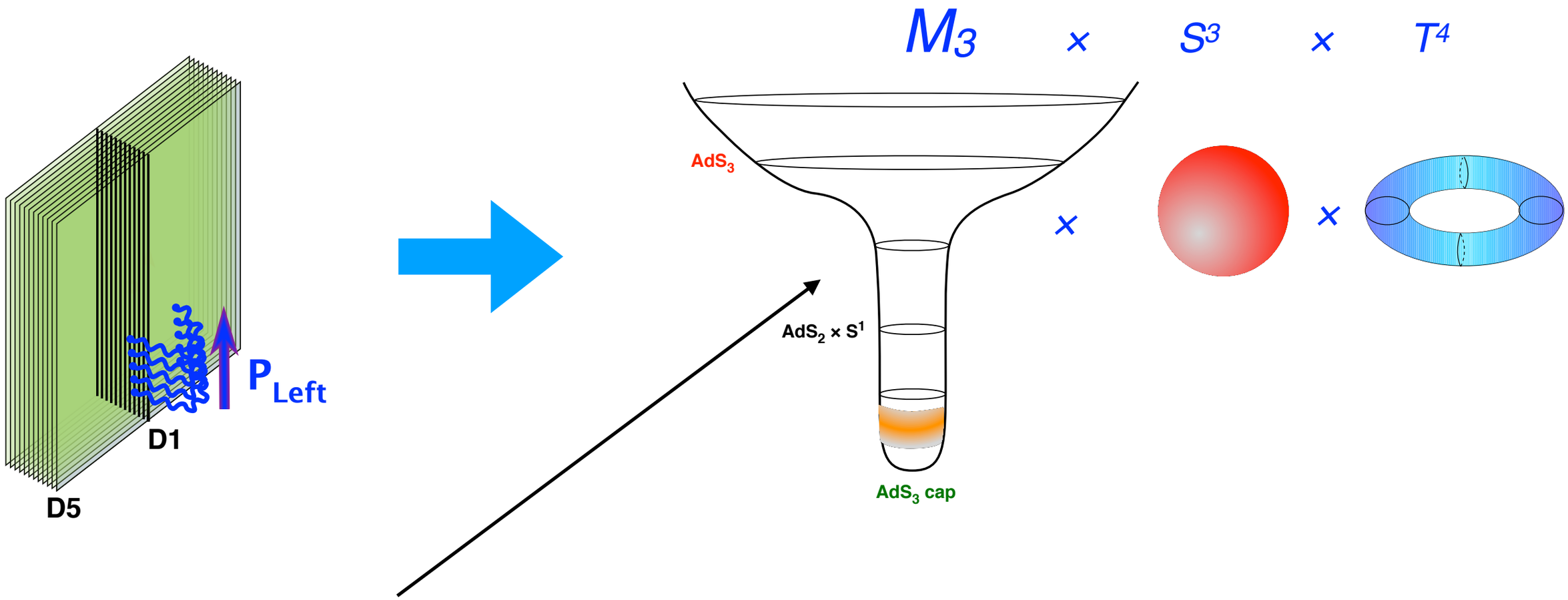

The black-hole-like throat looks like a capped BTZ geometry

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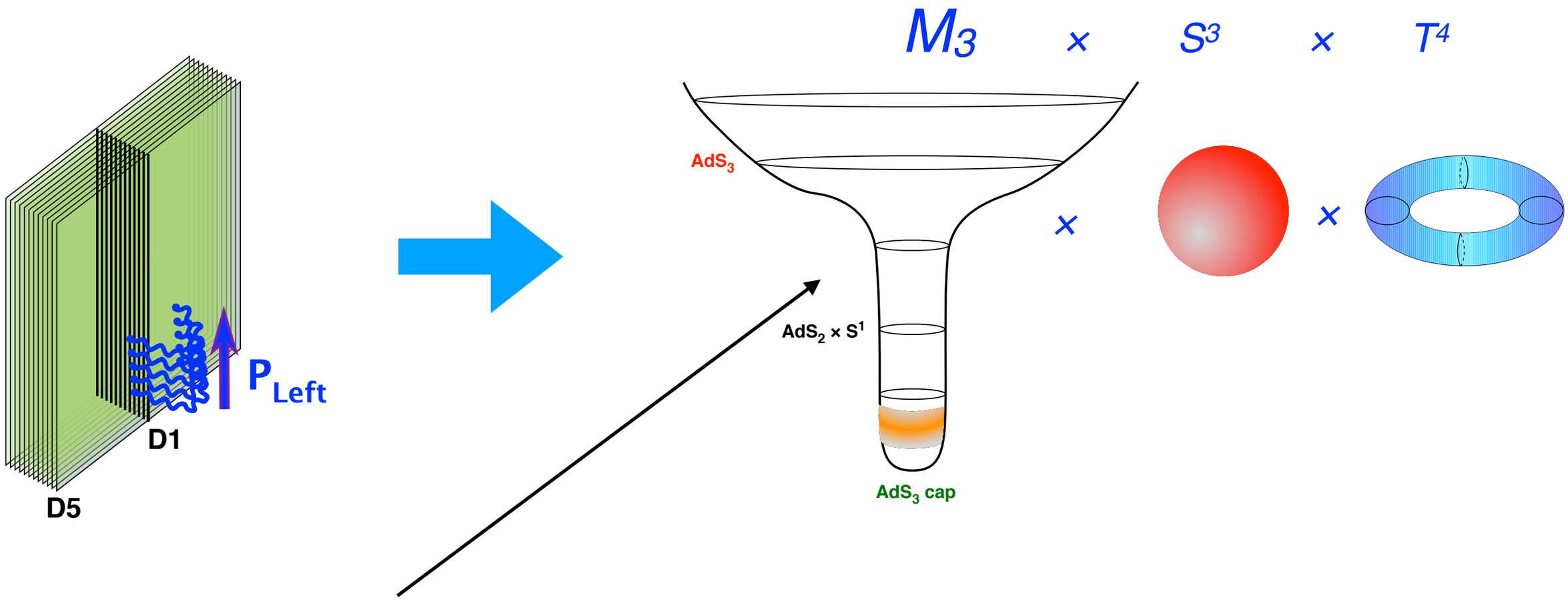

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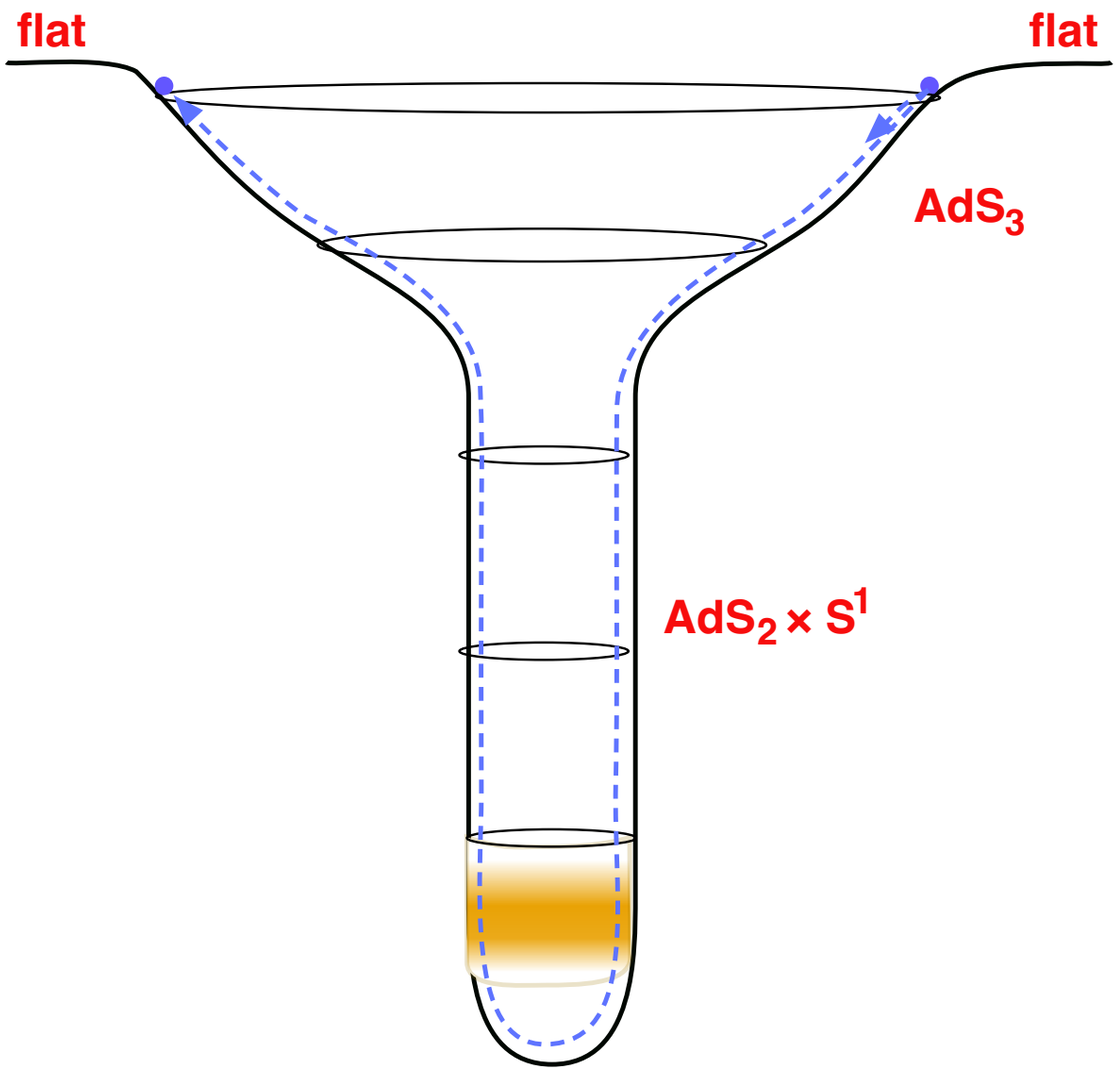
Extensively probed in both CFT and in gravity

Simplest, naive probes

For the deepest superstrata, particle/geodesic *return time* is ~ $N_1 N_5 R_y$



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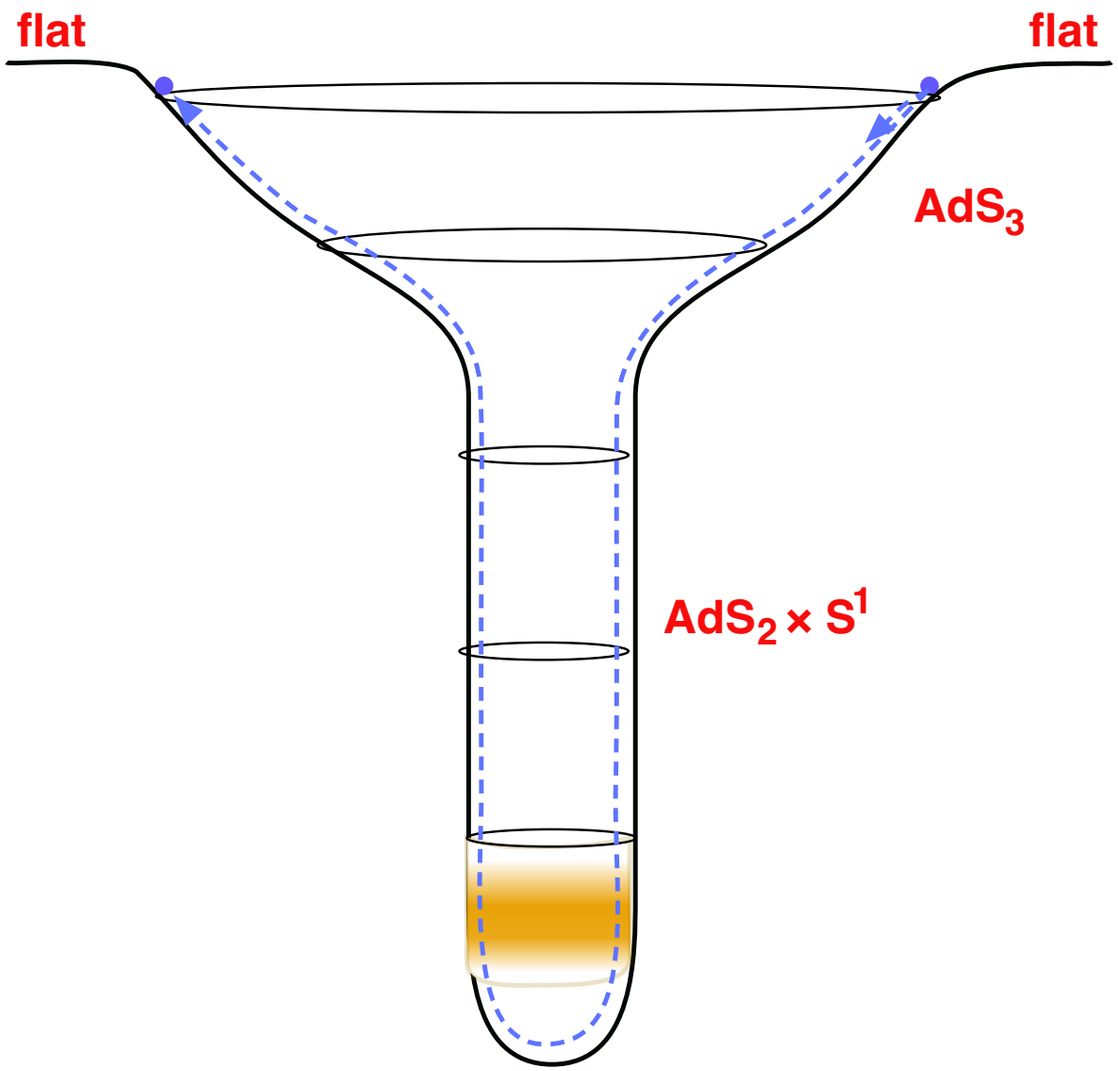

Scattering of waves into the throat:
Initial Thermal decay + *Echo after* $N_1\, N_5\, R_y$
but the return signal is attenuated and deformed by the geometry

I. Bena, P. Heidmann, R. Monten, N.P. Warner: 1905.05194

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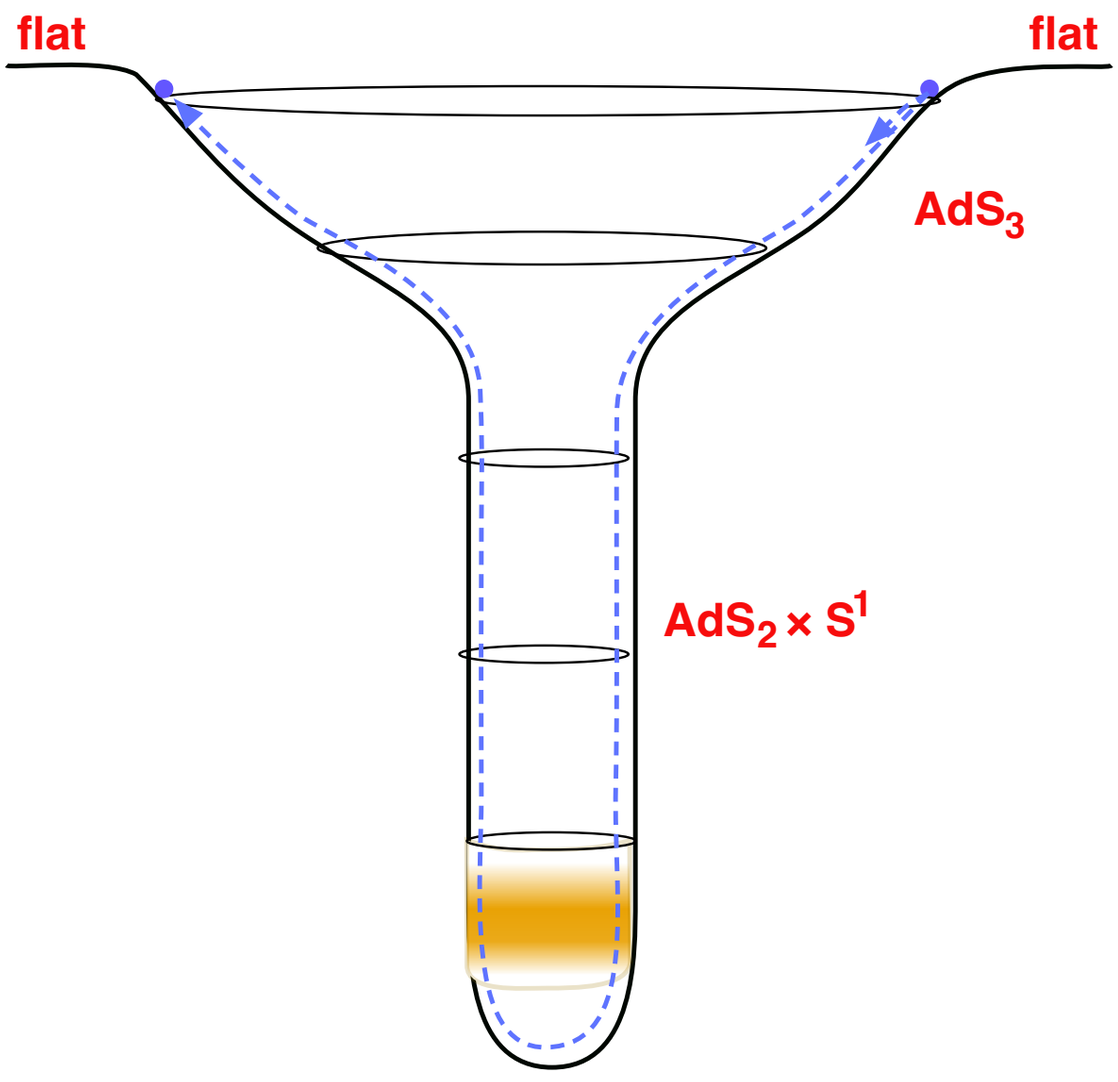

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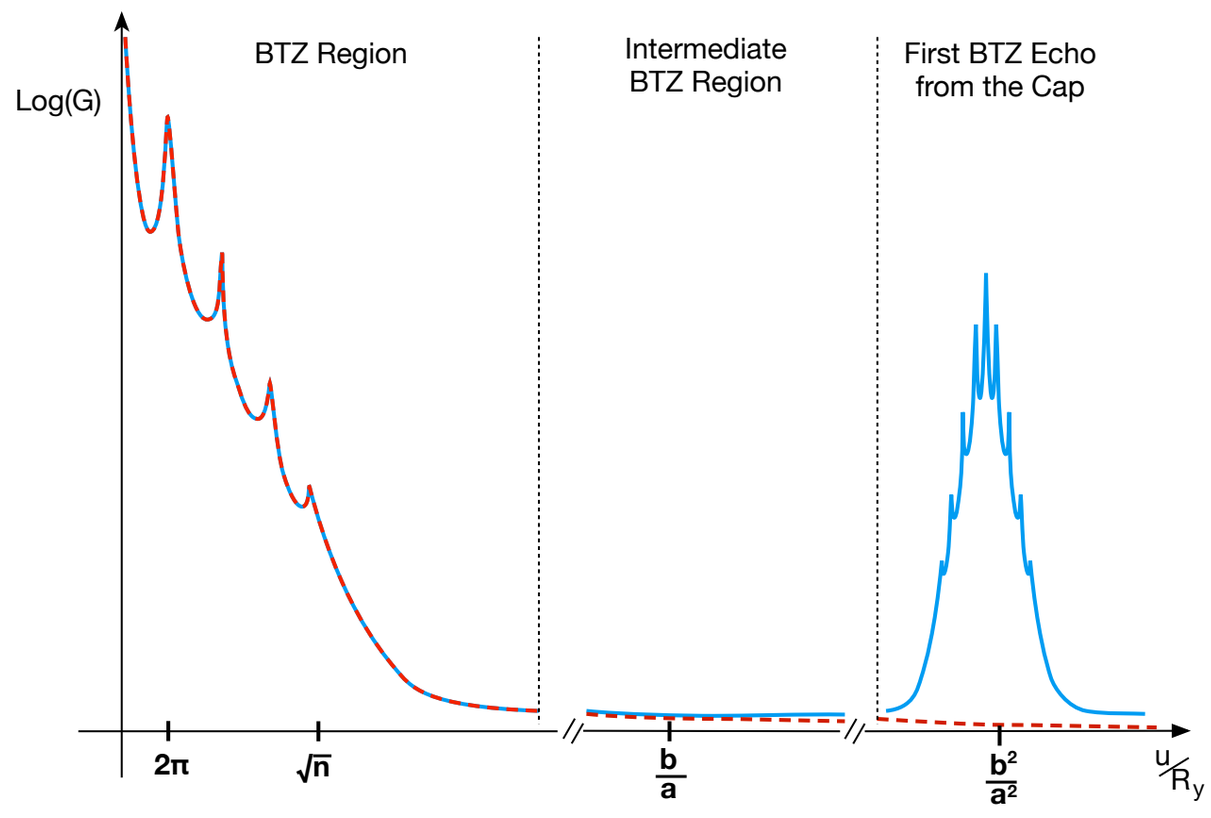

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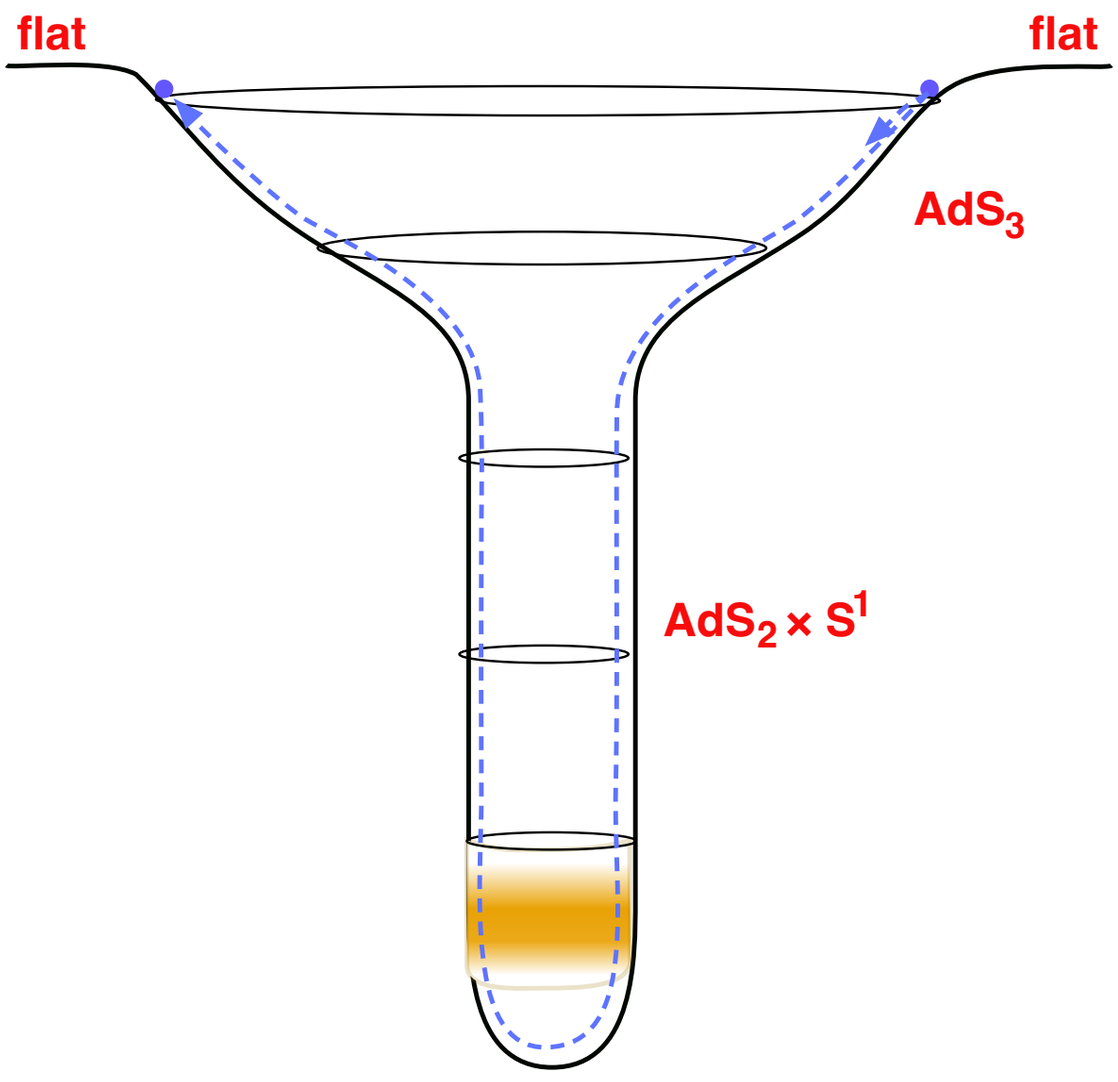

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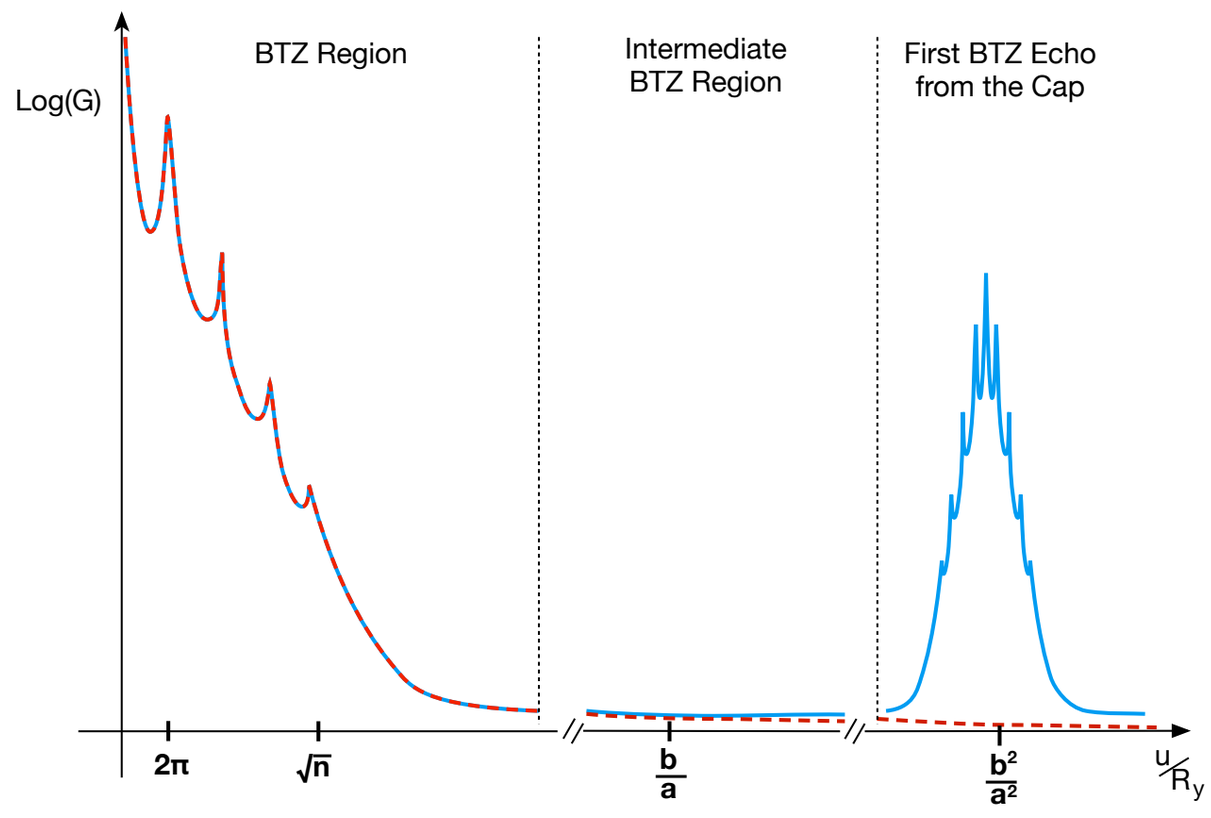
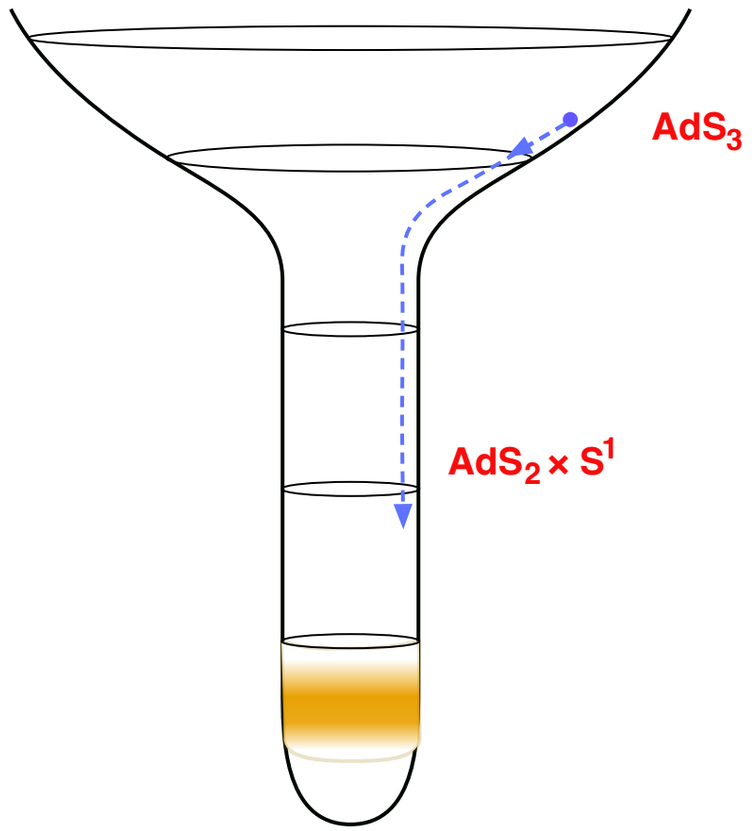


String theory tells a very different story …

Stringy effects on probes



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Tidal forces reach string scale in the throat:

small deviations (multipole moments) amplified by ultra-relativistic speeds.

Tyukov, Walker and Warner 1710.09006

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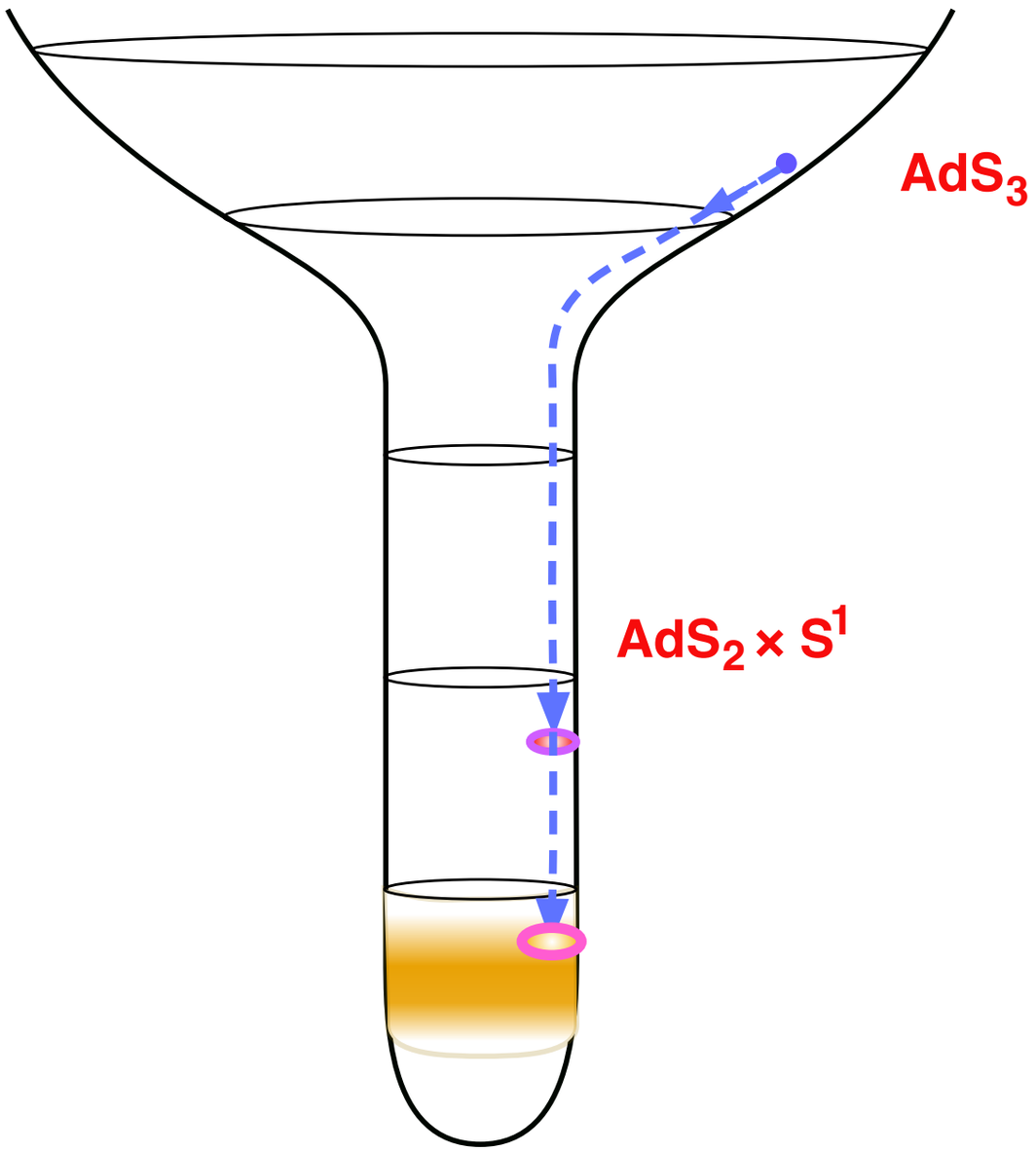

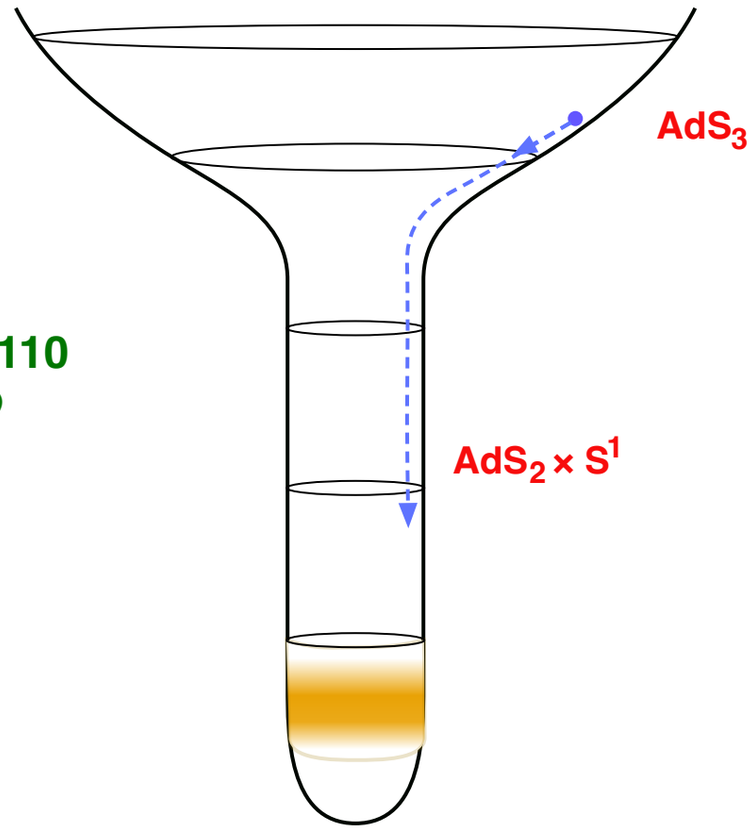

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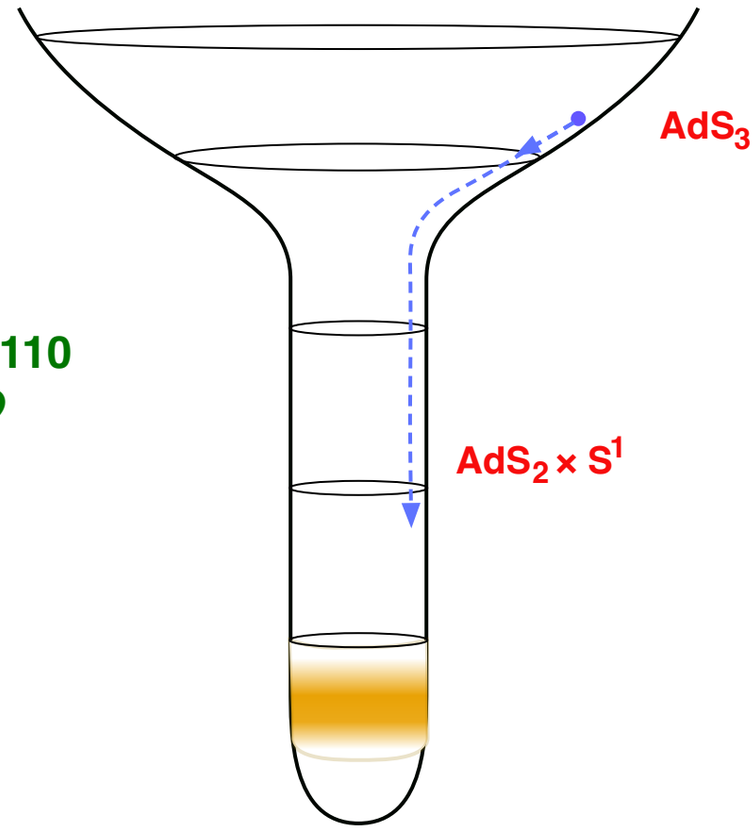

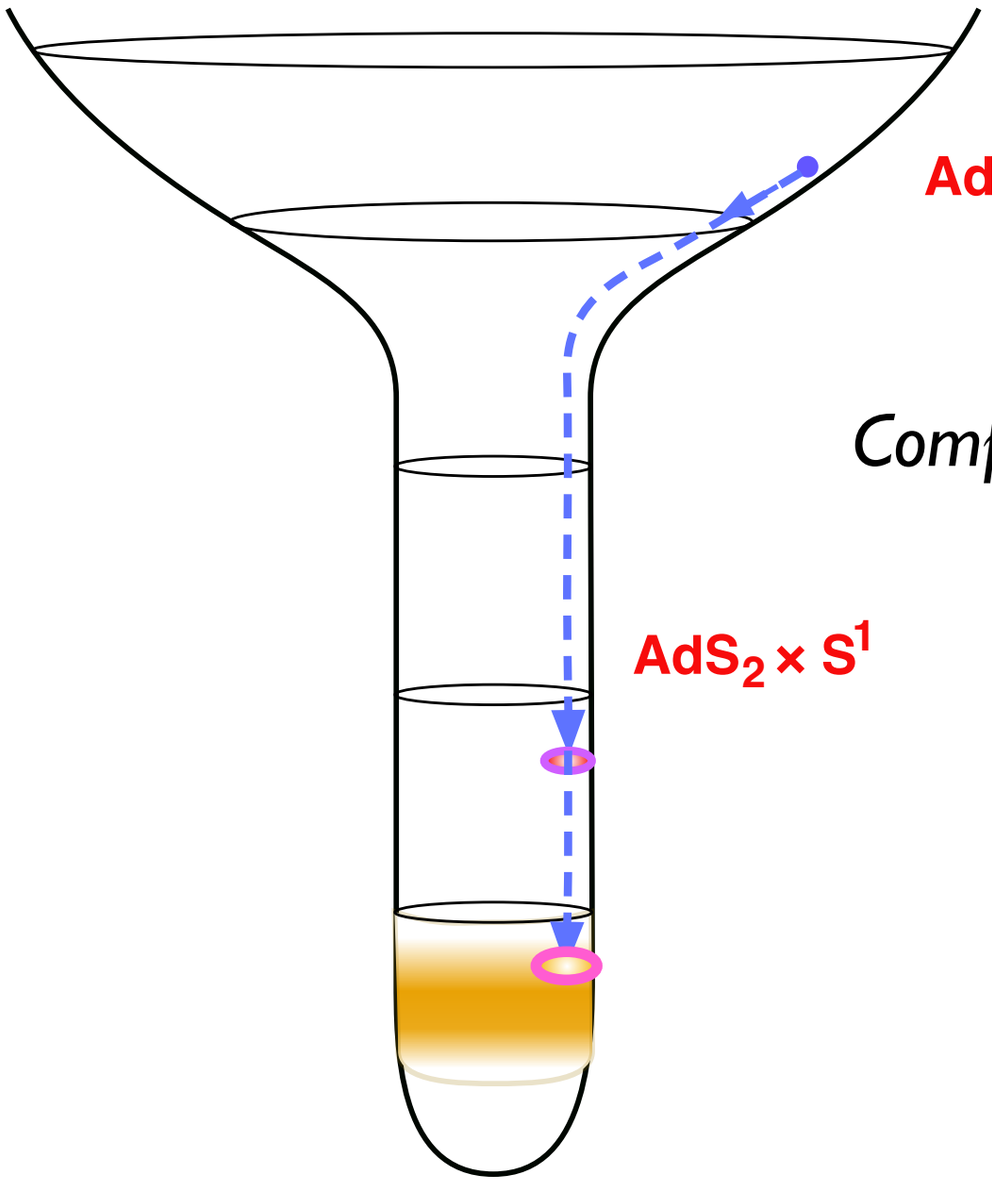

Compute the tidal excitations of the string

Martinec and Warner 2009.07847

Ceplak, Hampton and Lxi 2106.03841

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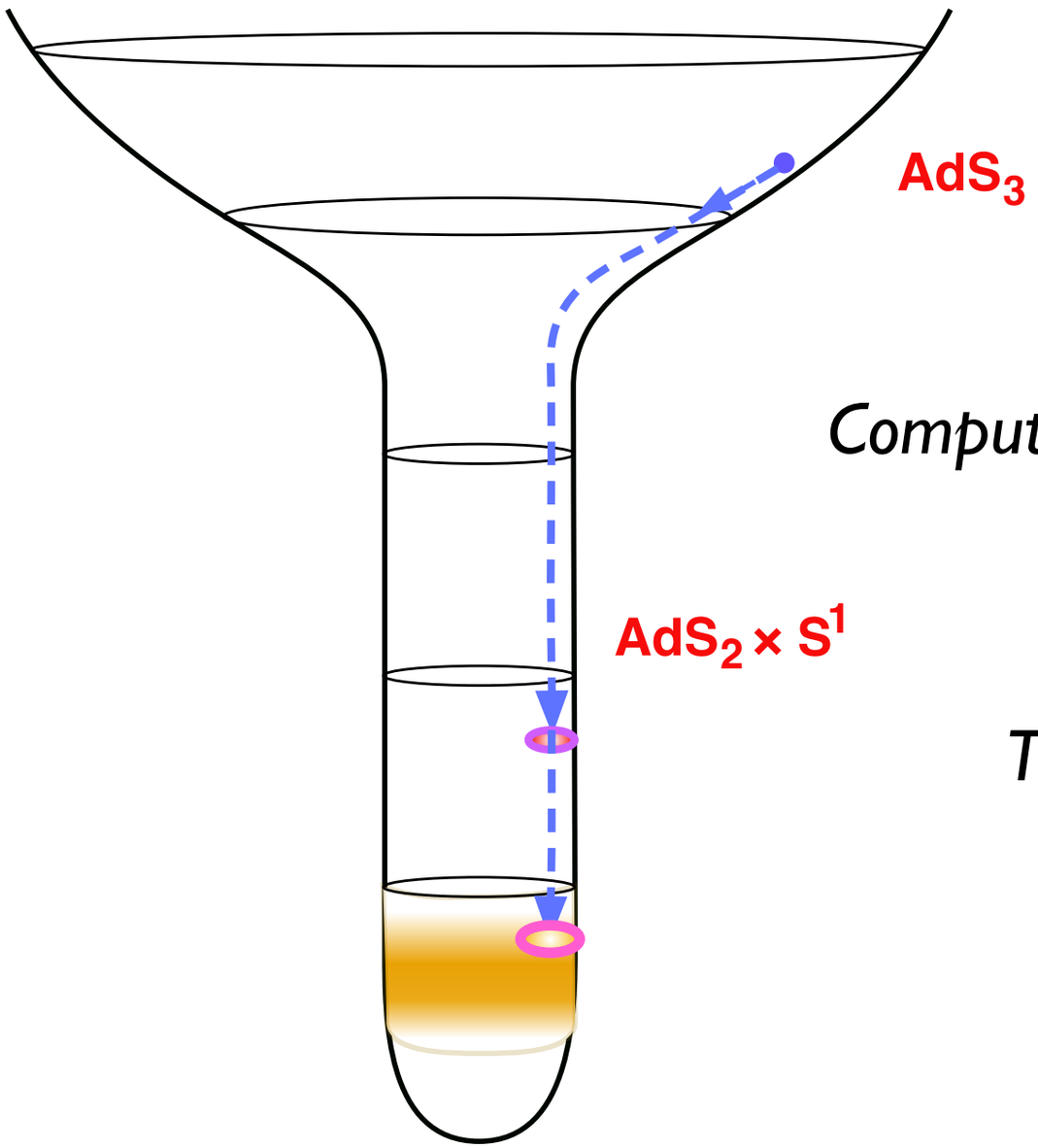

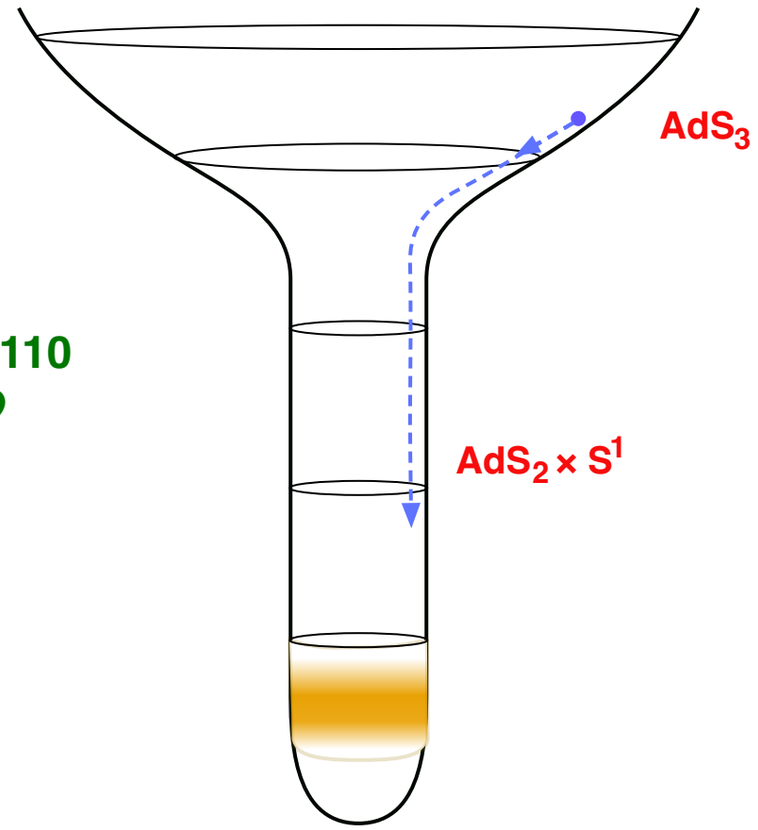

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The probe becomes massive:

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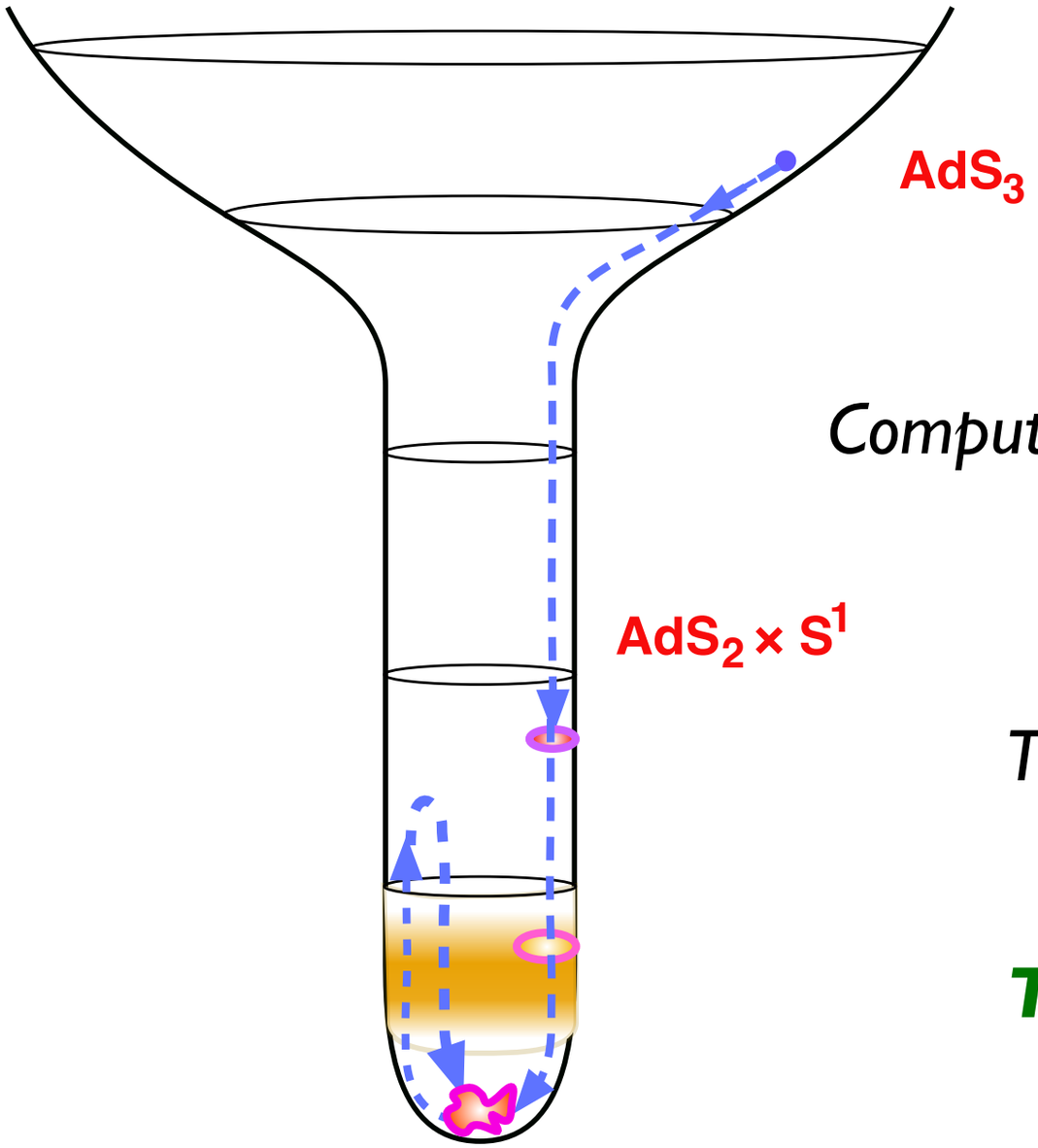

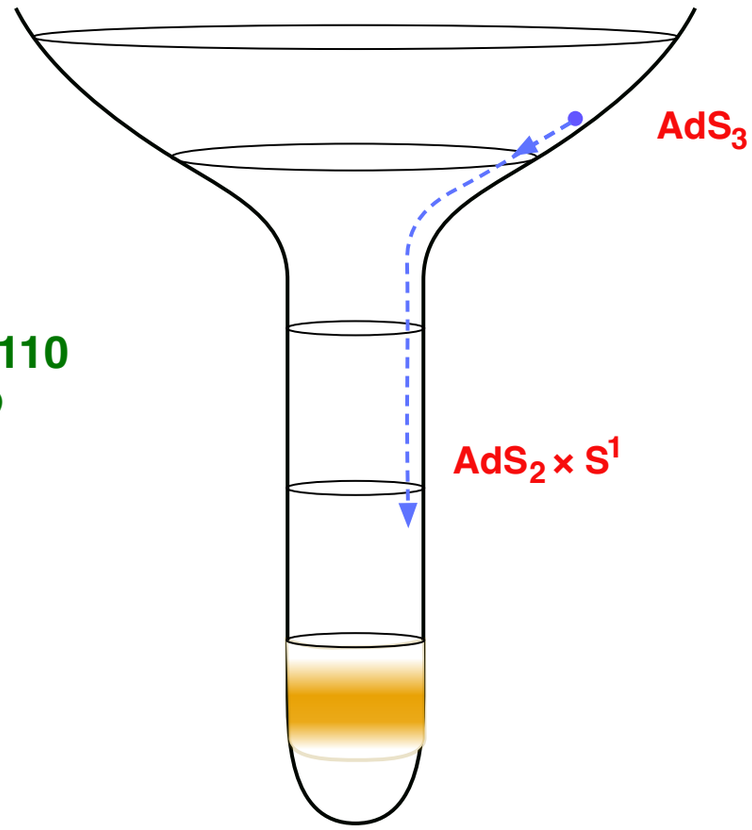

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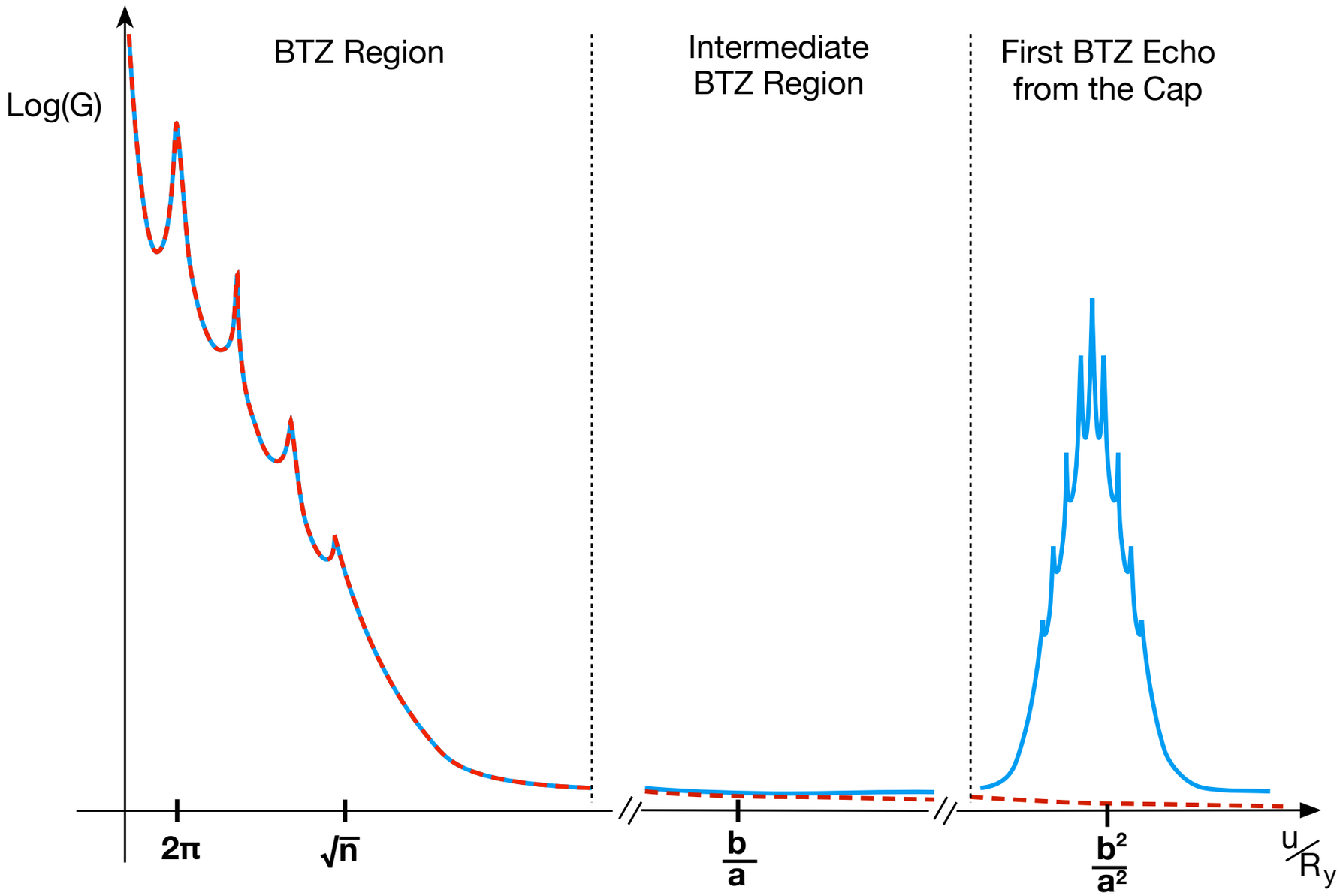
Log(G)
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2π
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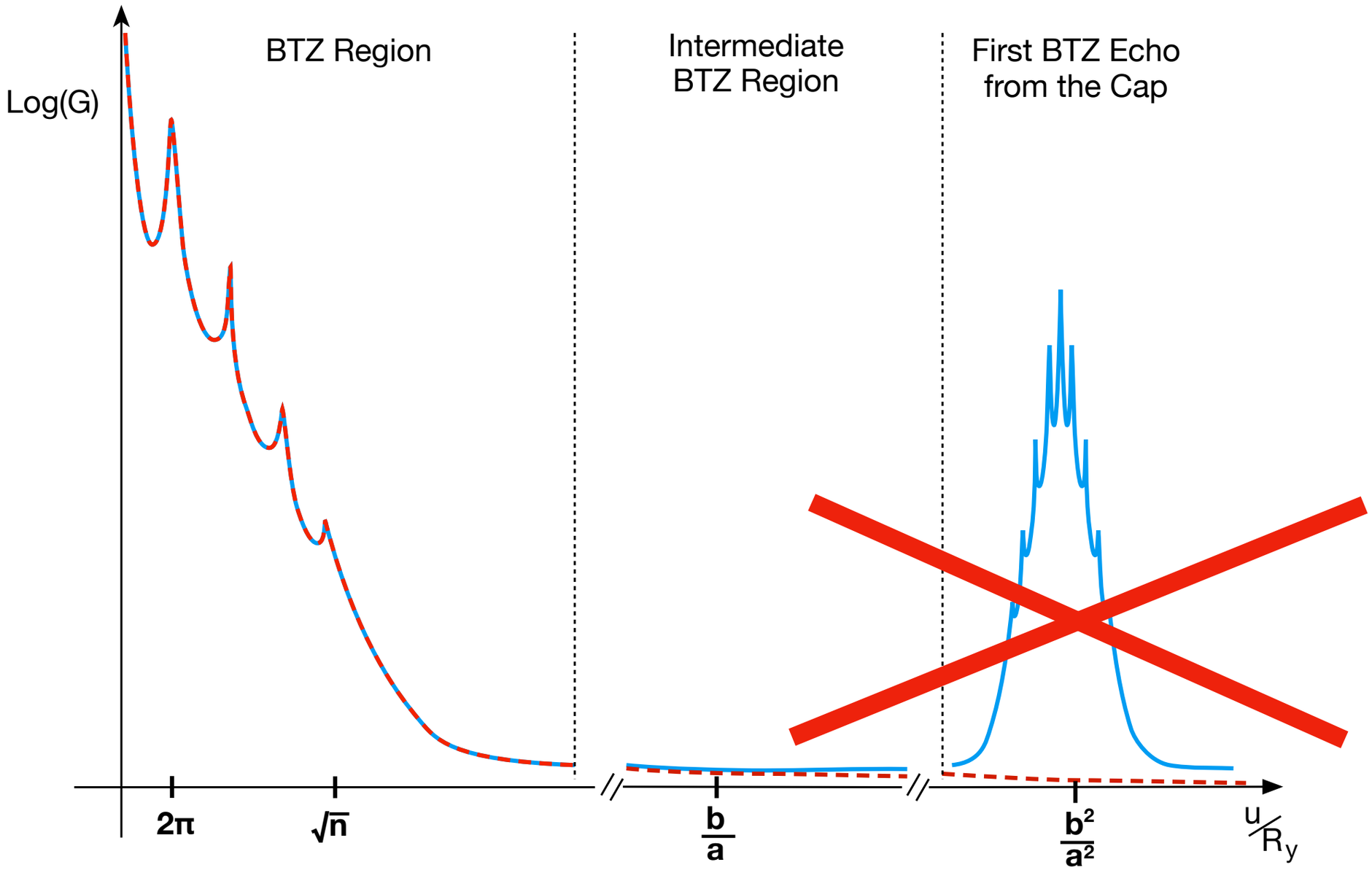
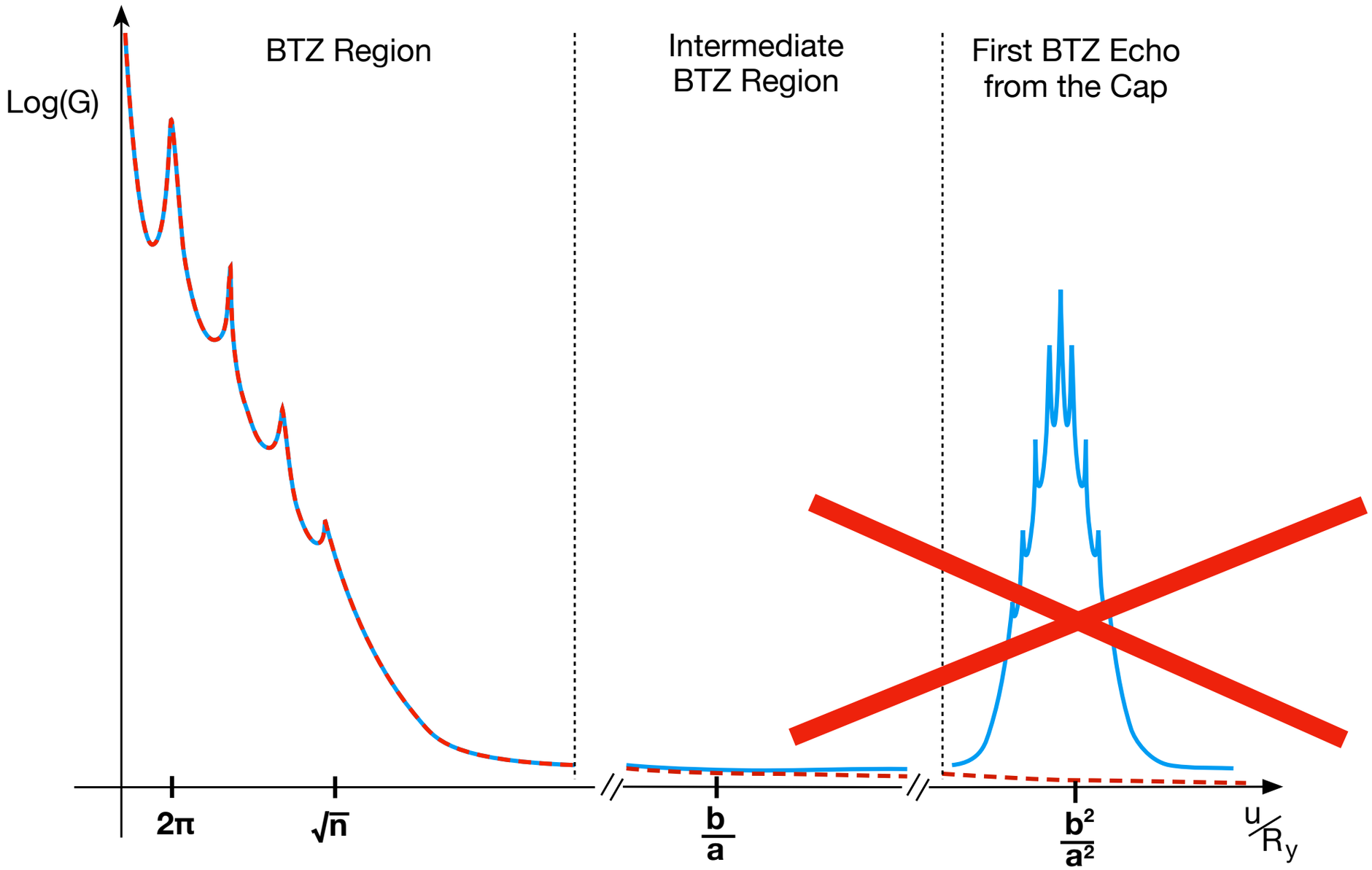


String theory ⇒ No Echoes



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Microstate geometries exhibit truly black-hole-like behaviour

Stringy effects on probes

Tidal forces reach string scale in the throat:

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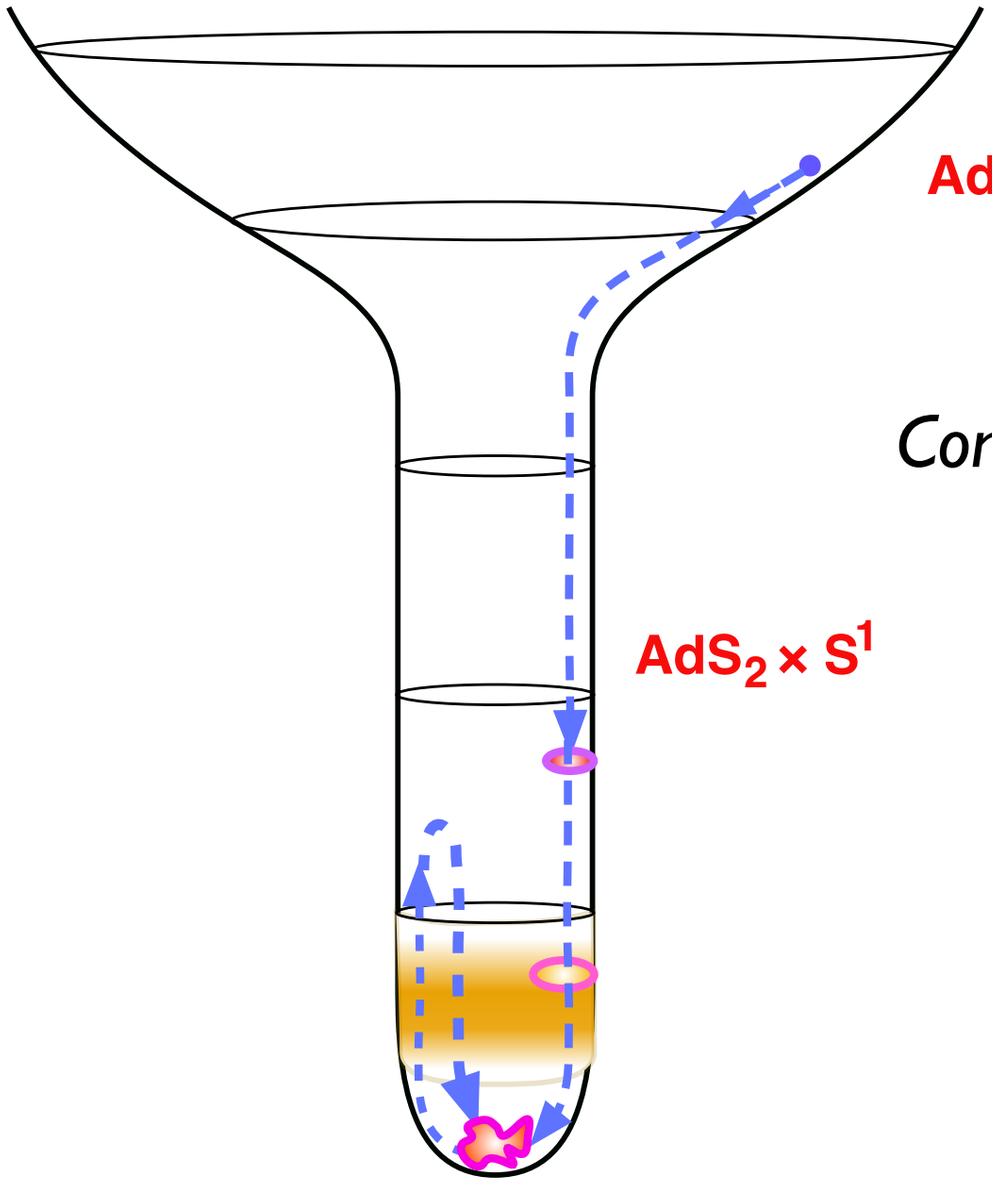

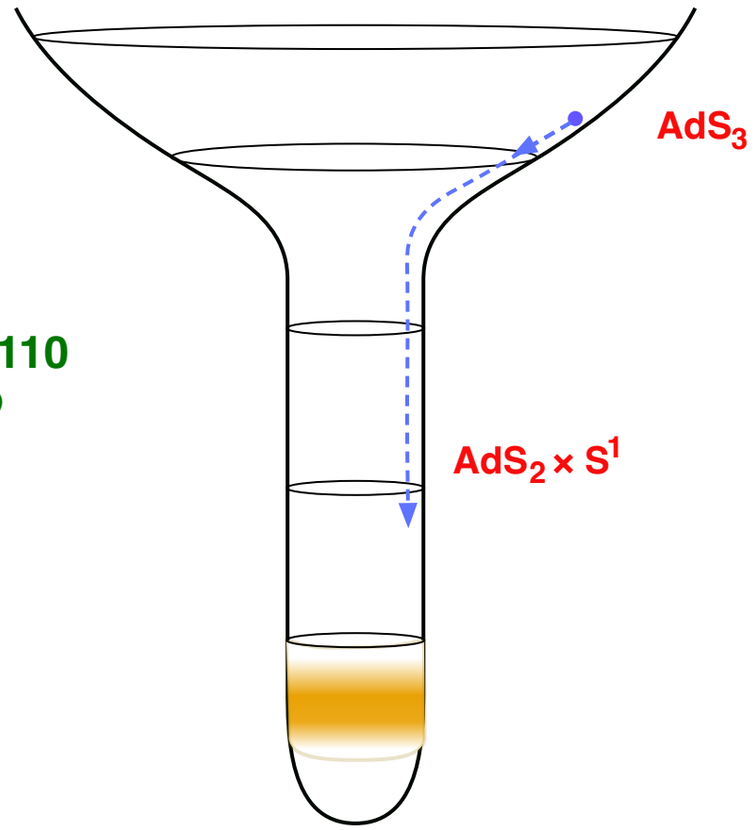

Compute the tidal excitations of the string

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The probe becomes massive:

Kinetic Energy → *Mass*

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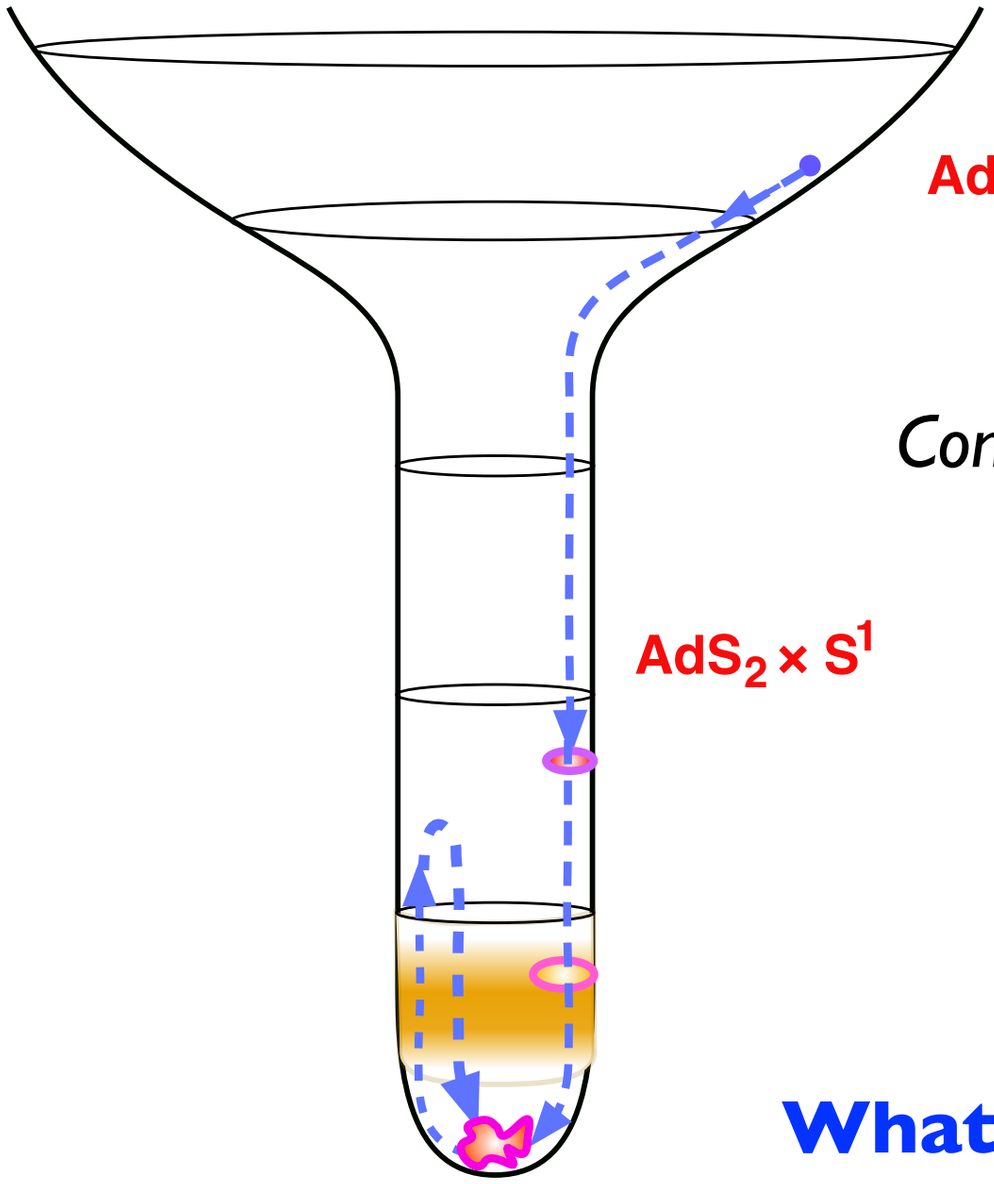

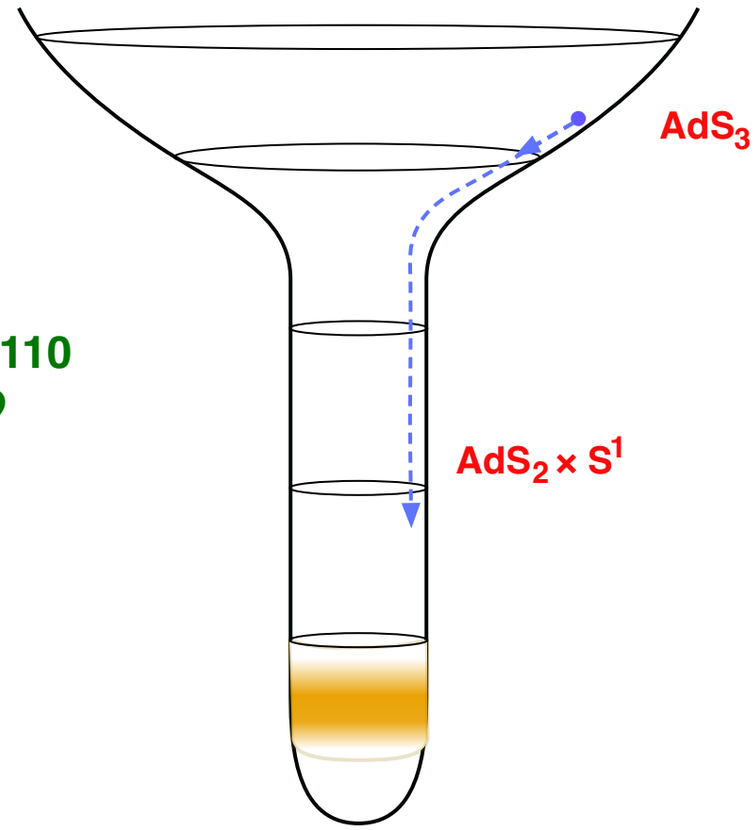

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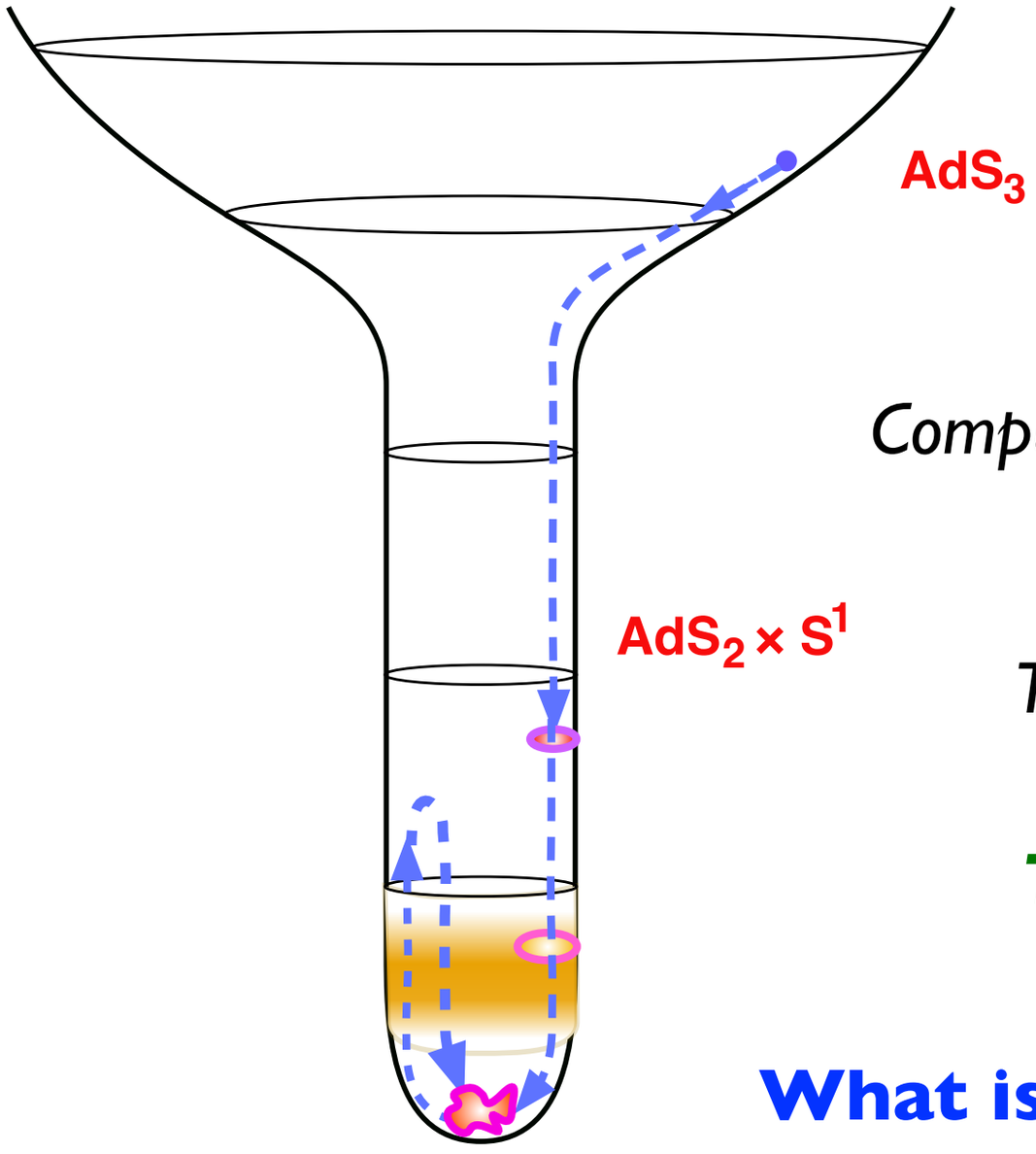

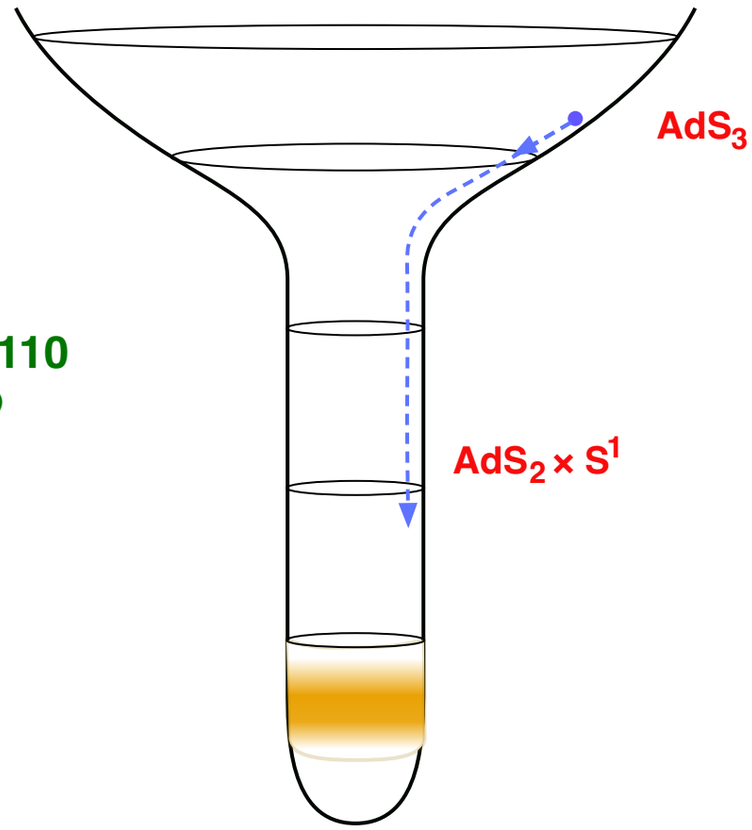

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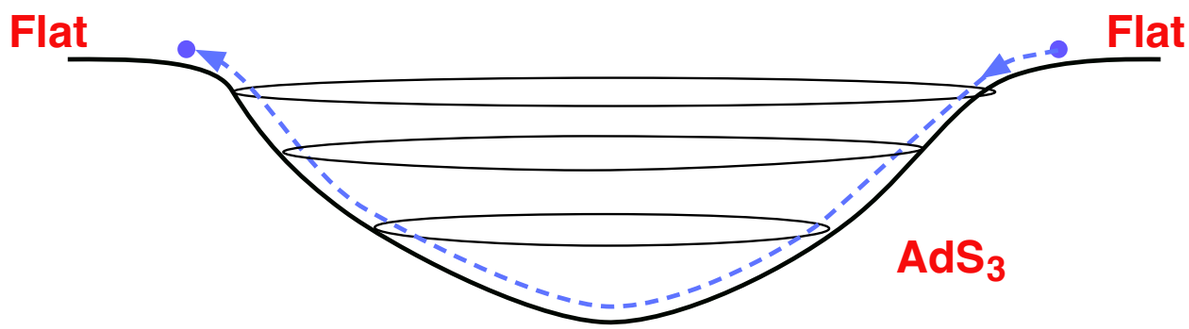

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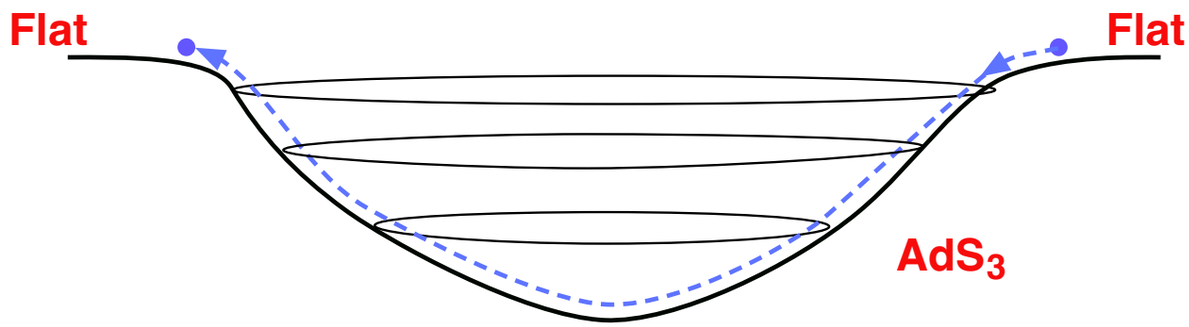
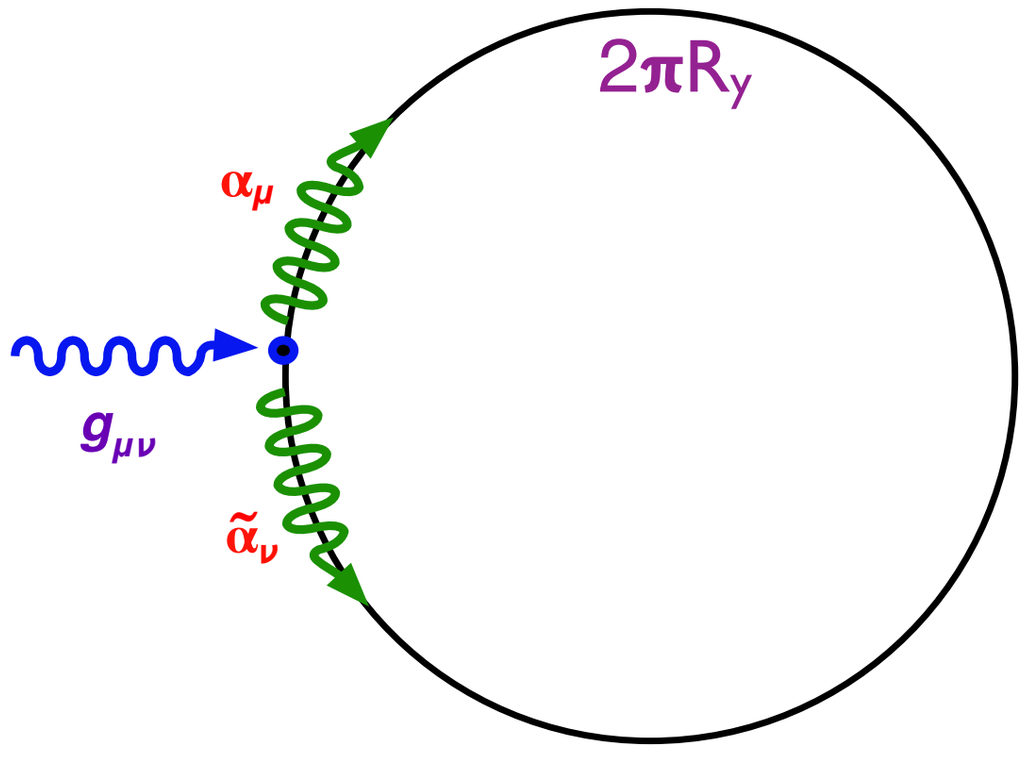


Graviton falling into AdS_3 throat of a supertube is dual to graviton hitting stack of D1-D5 branes, splitting into open string states ….



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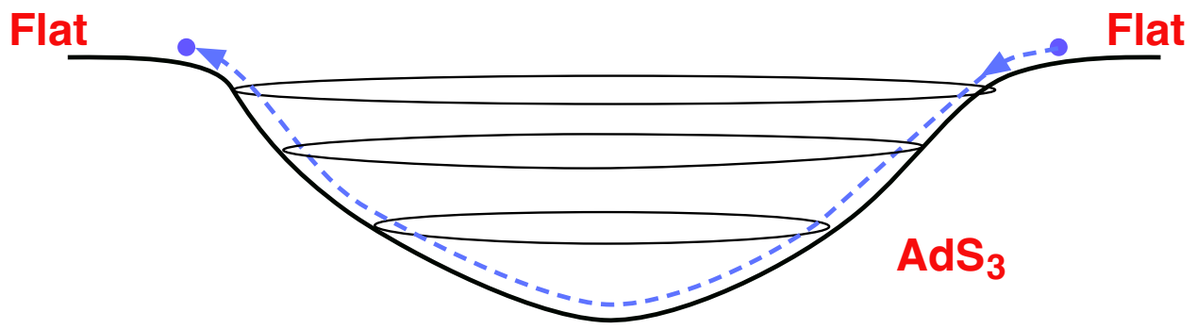

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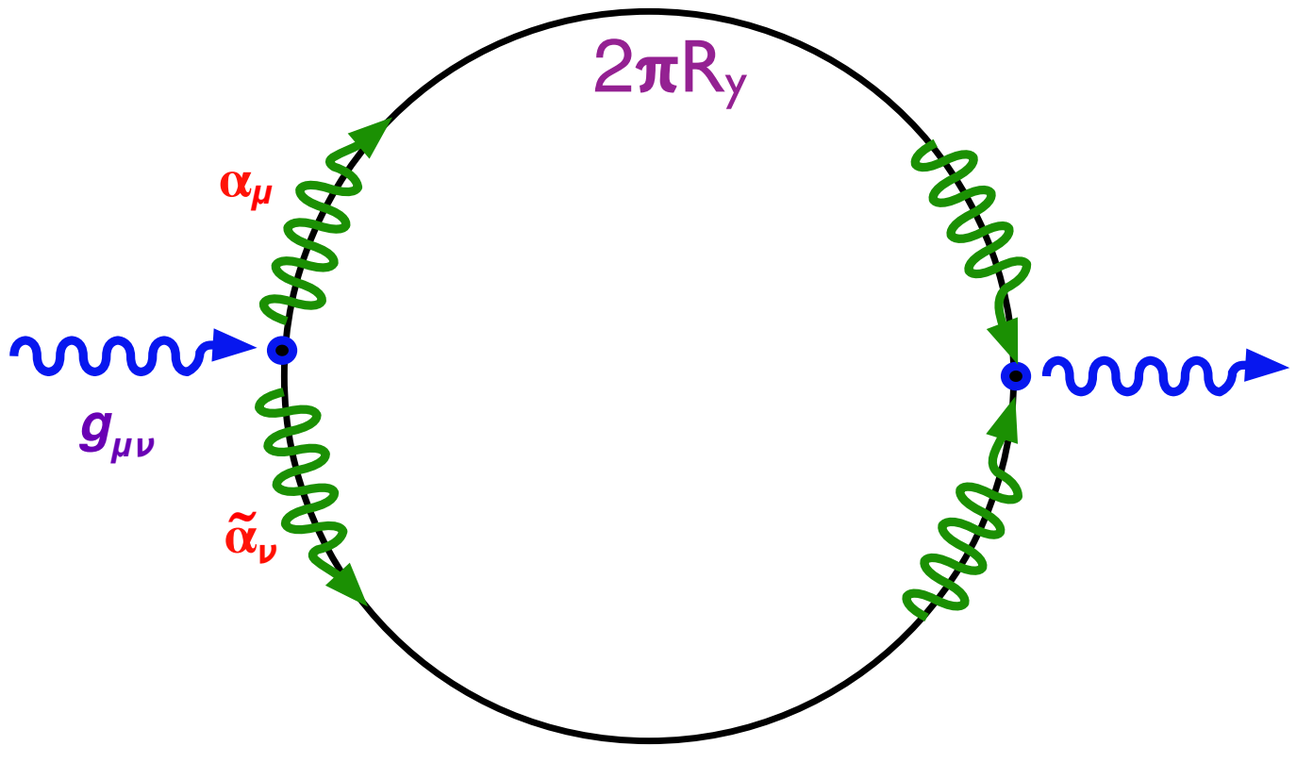

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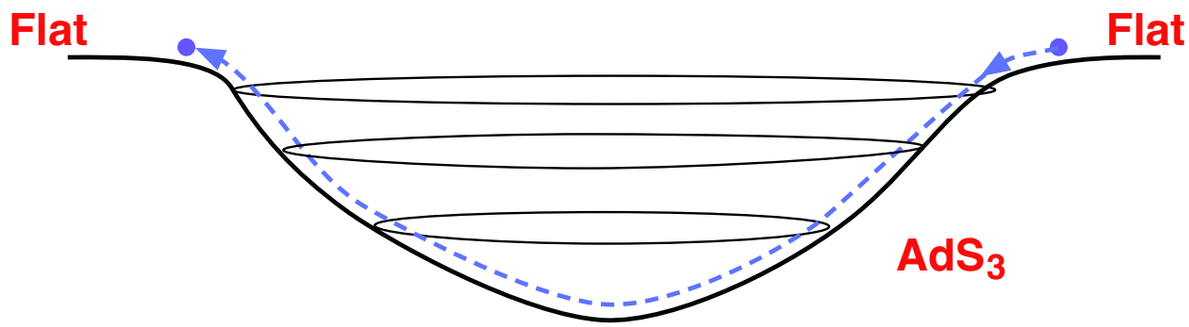

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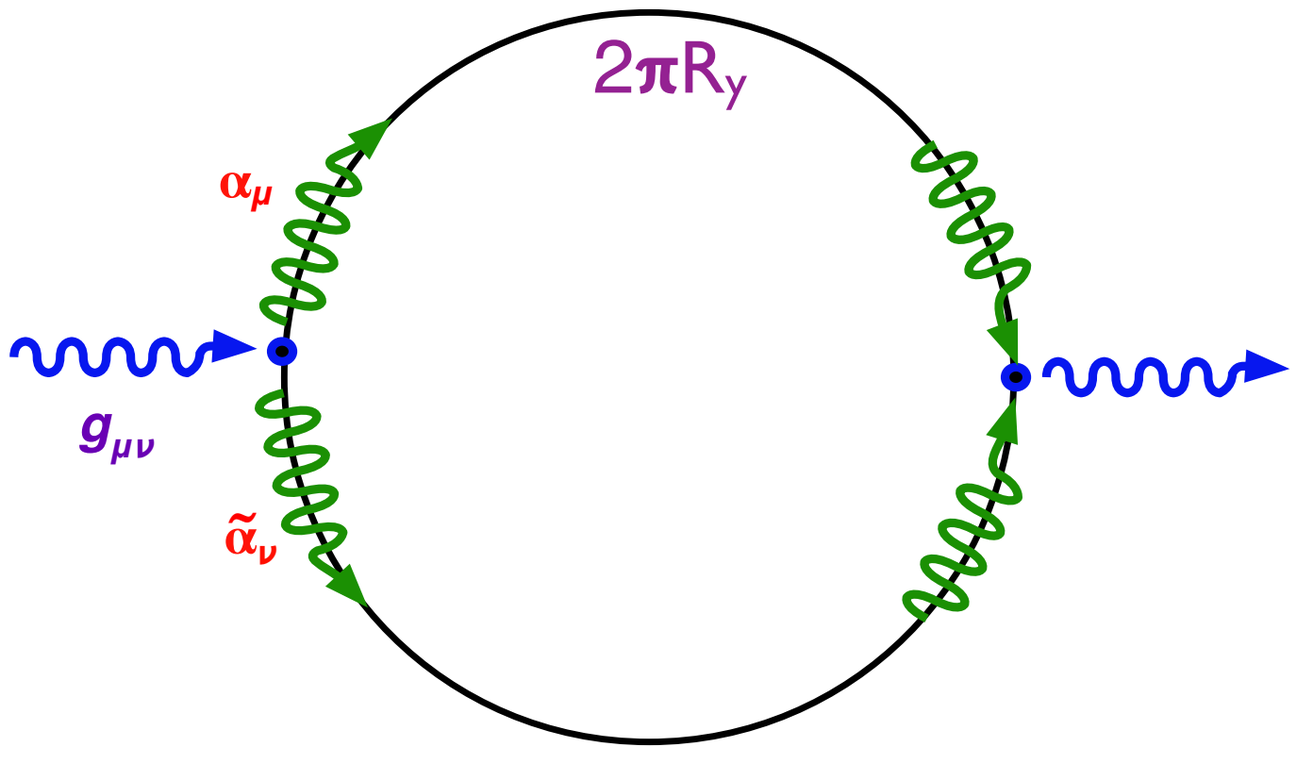
Graviton return times match between geometry and CFT



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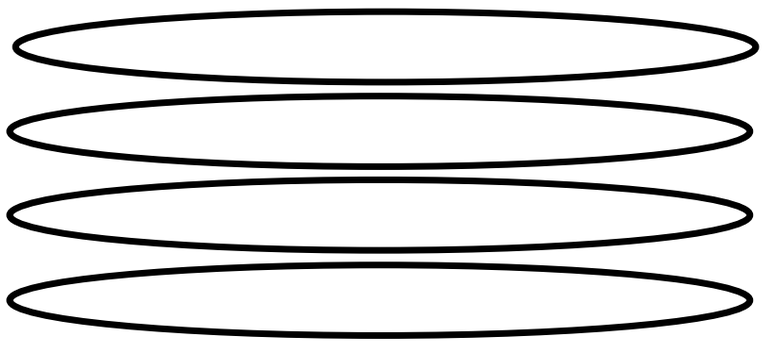

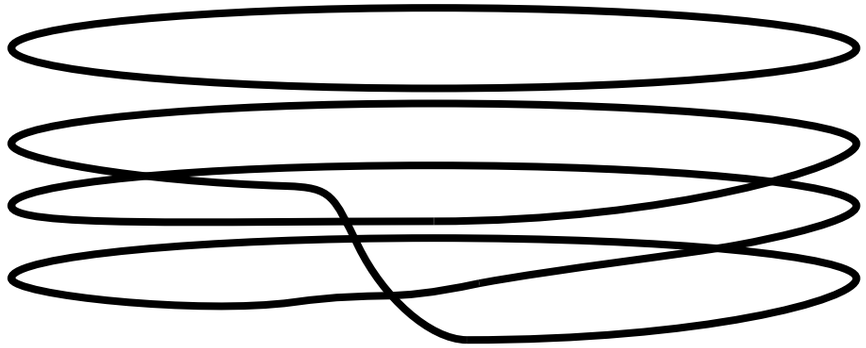

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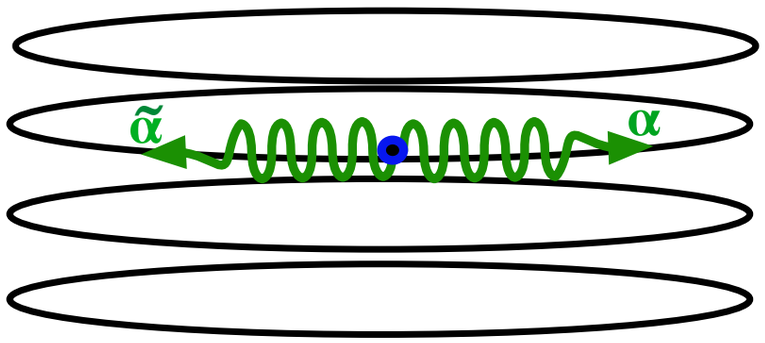

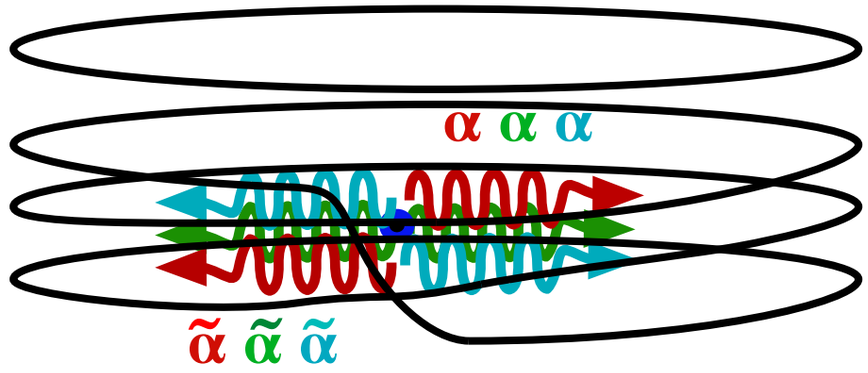

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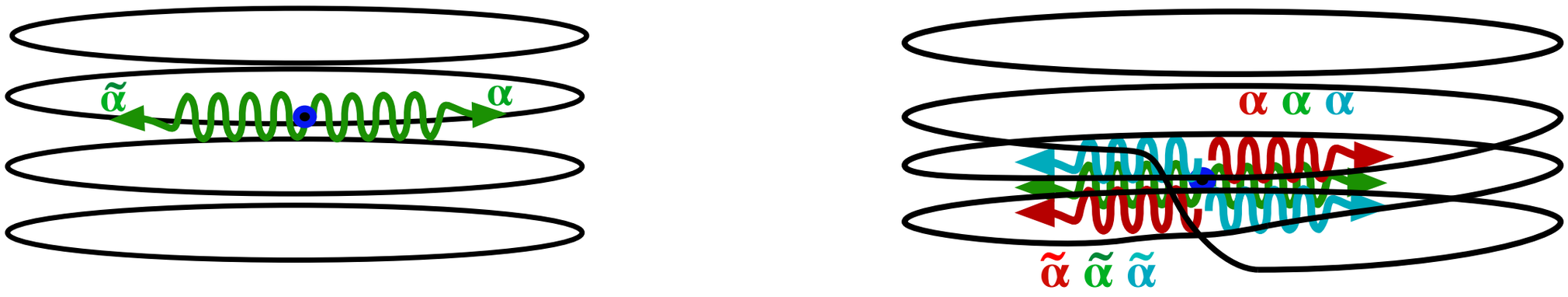

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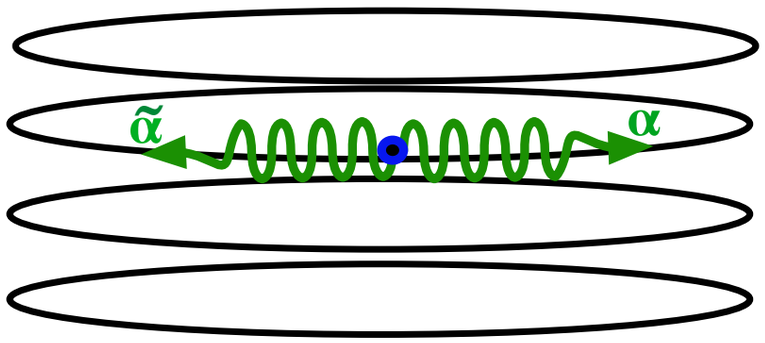

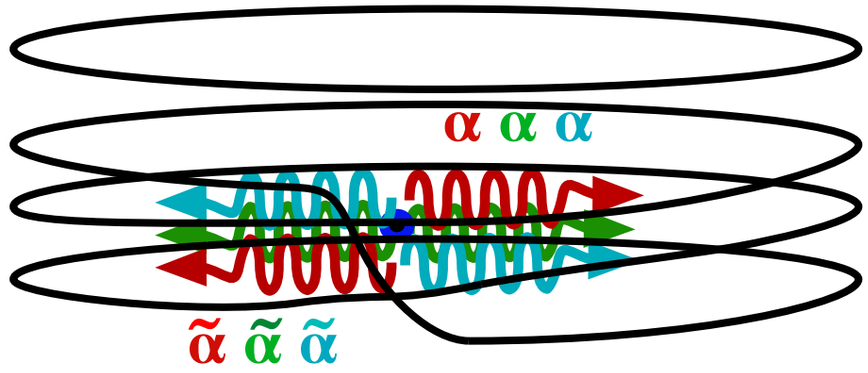

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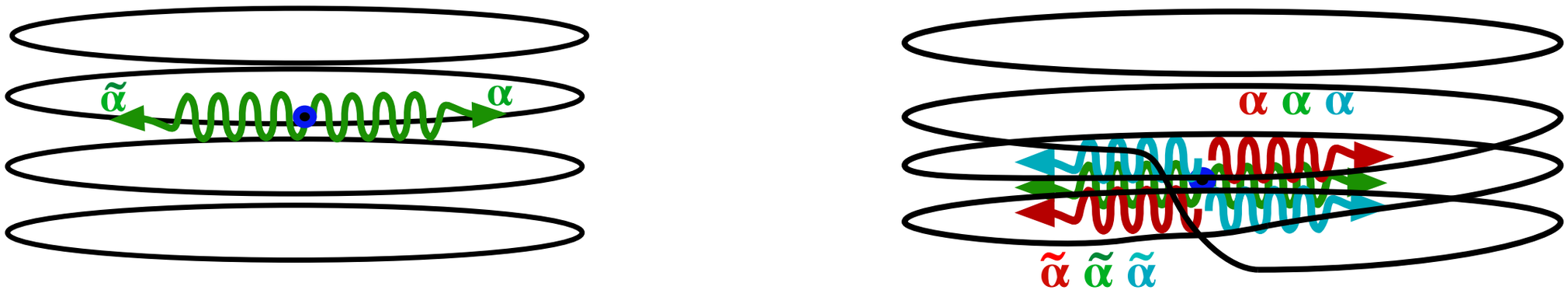

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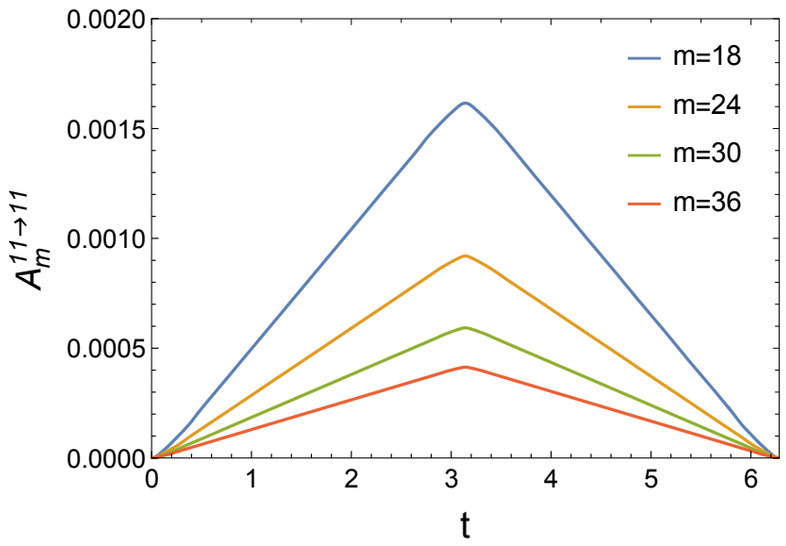

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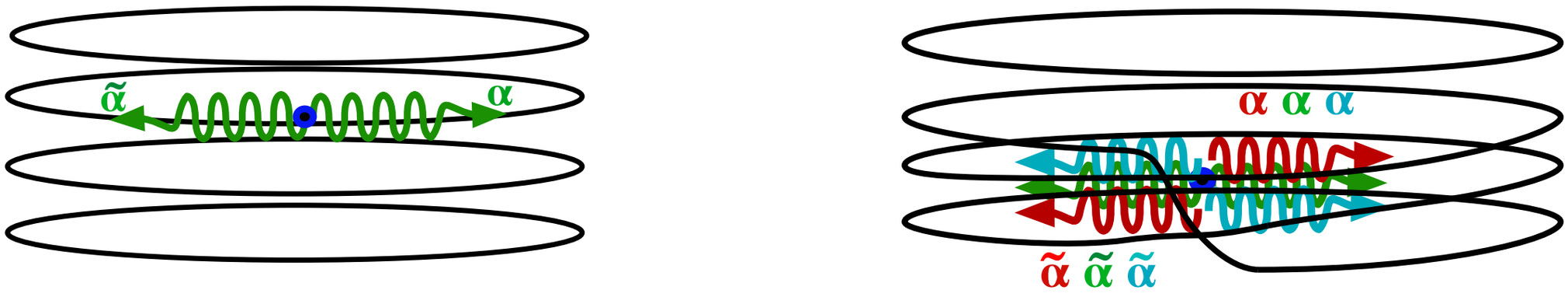

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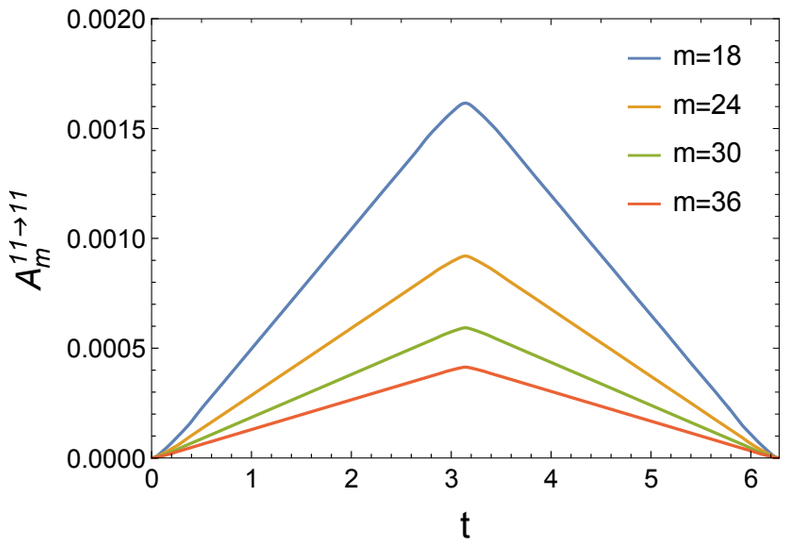

Fractionated modes recombine into single graviton again…

Stringy probes and "tides" in CFT

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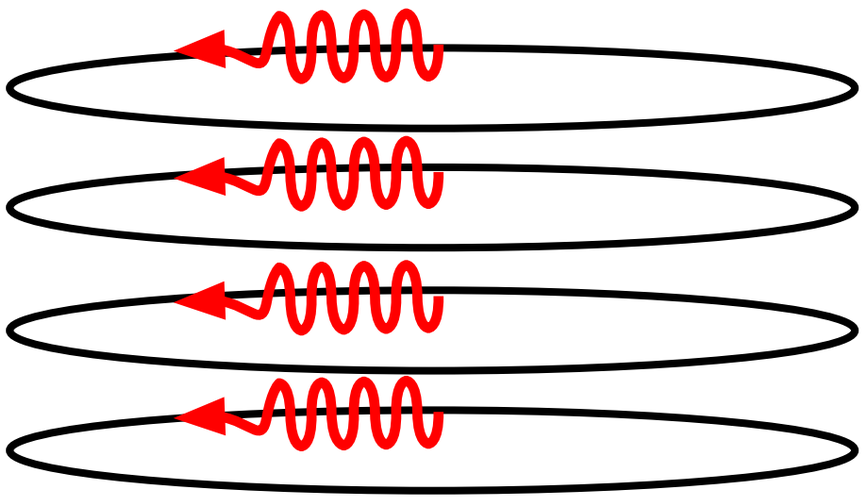

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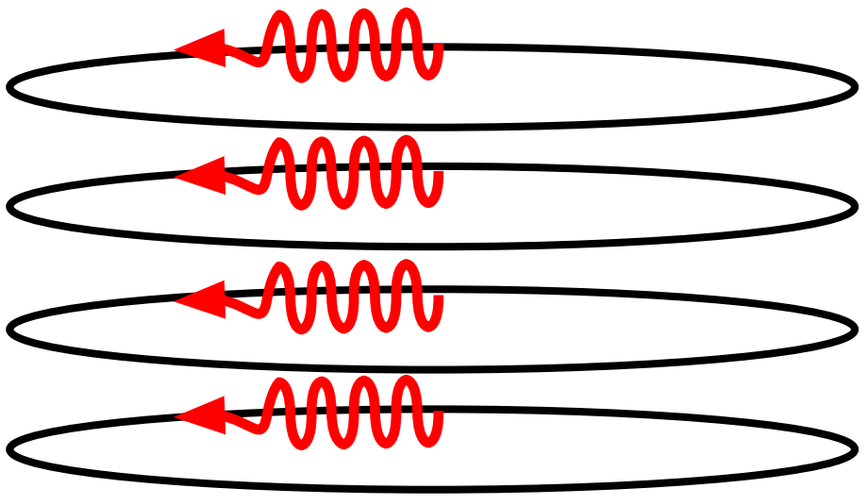

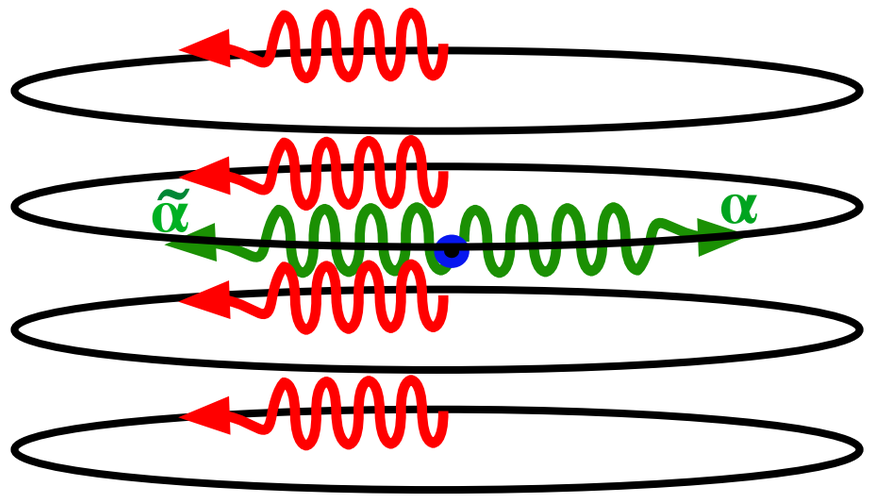

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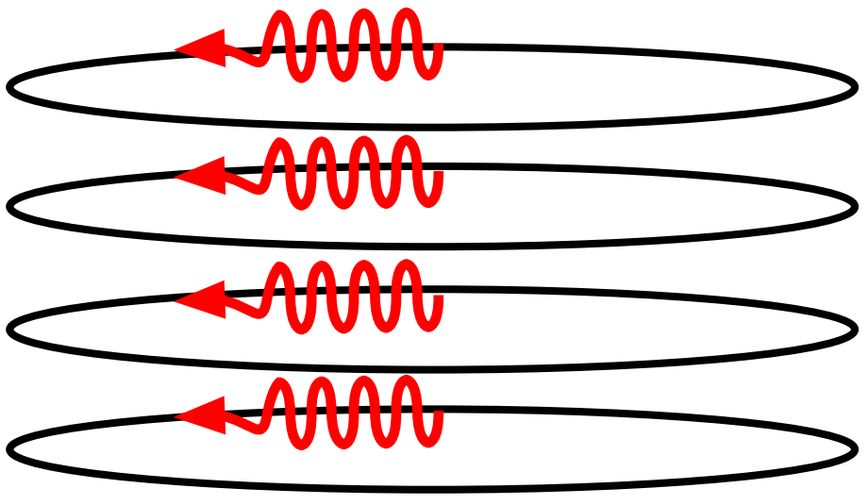

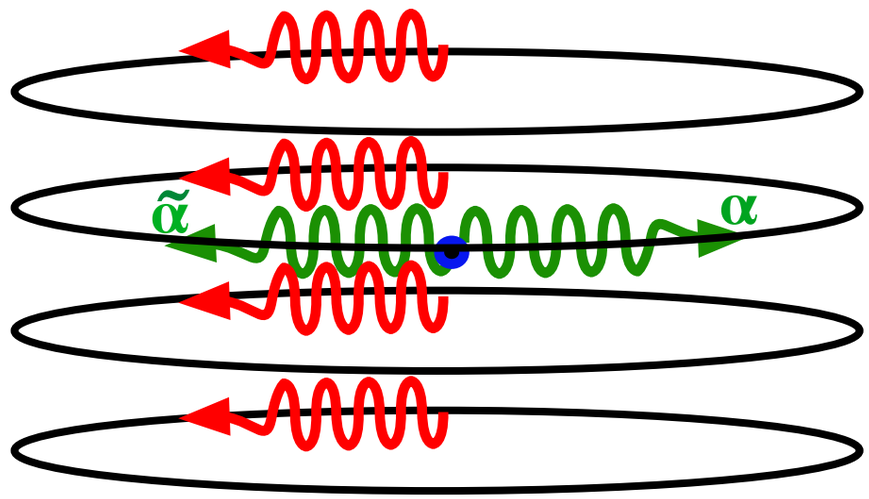

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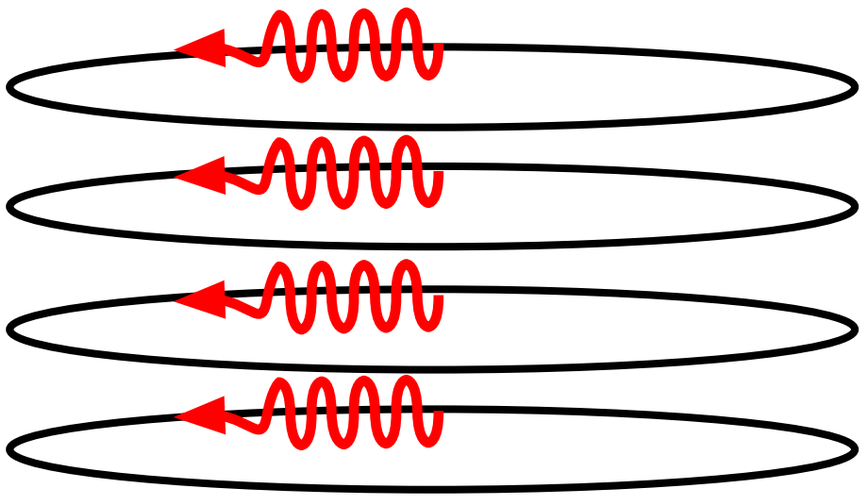

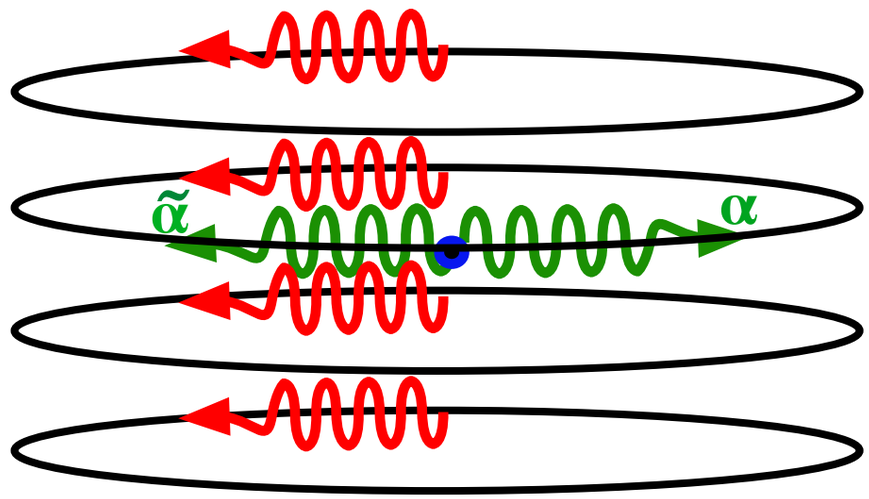

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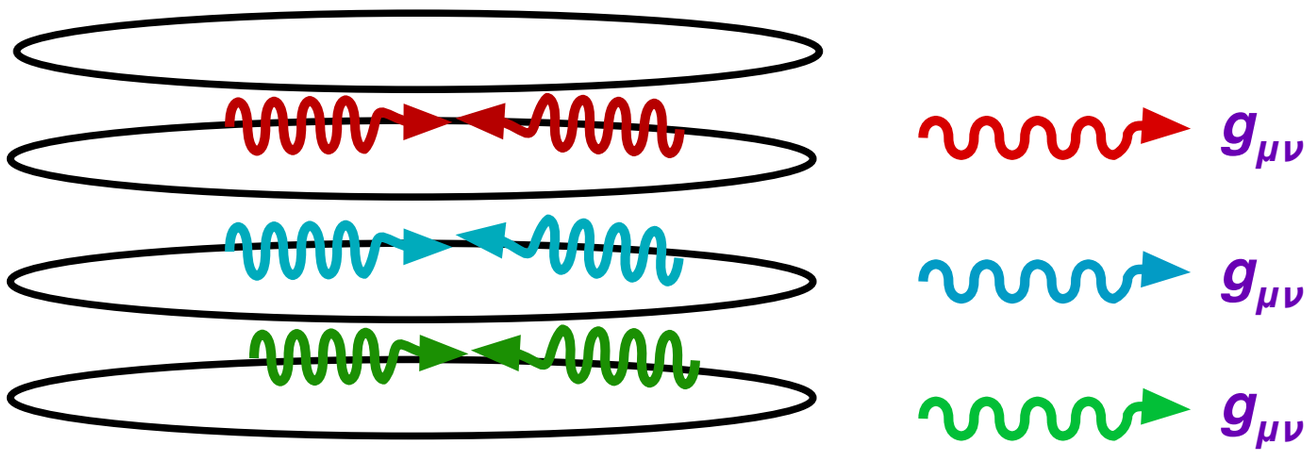

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Answering these questions will be an essential part of emergent space-time at strong gravitational coupling…

Happy Birthday
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It has been a great pleasure to talk and interact with you over the last > 35 years