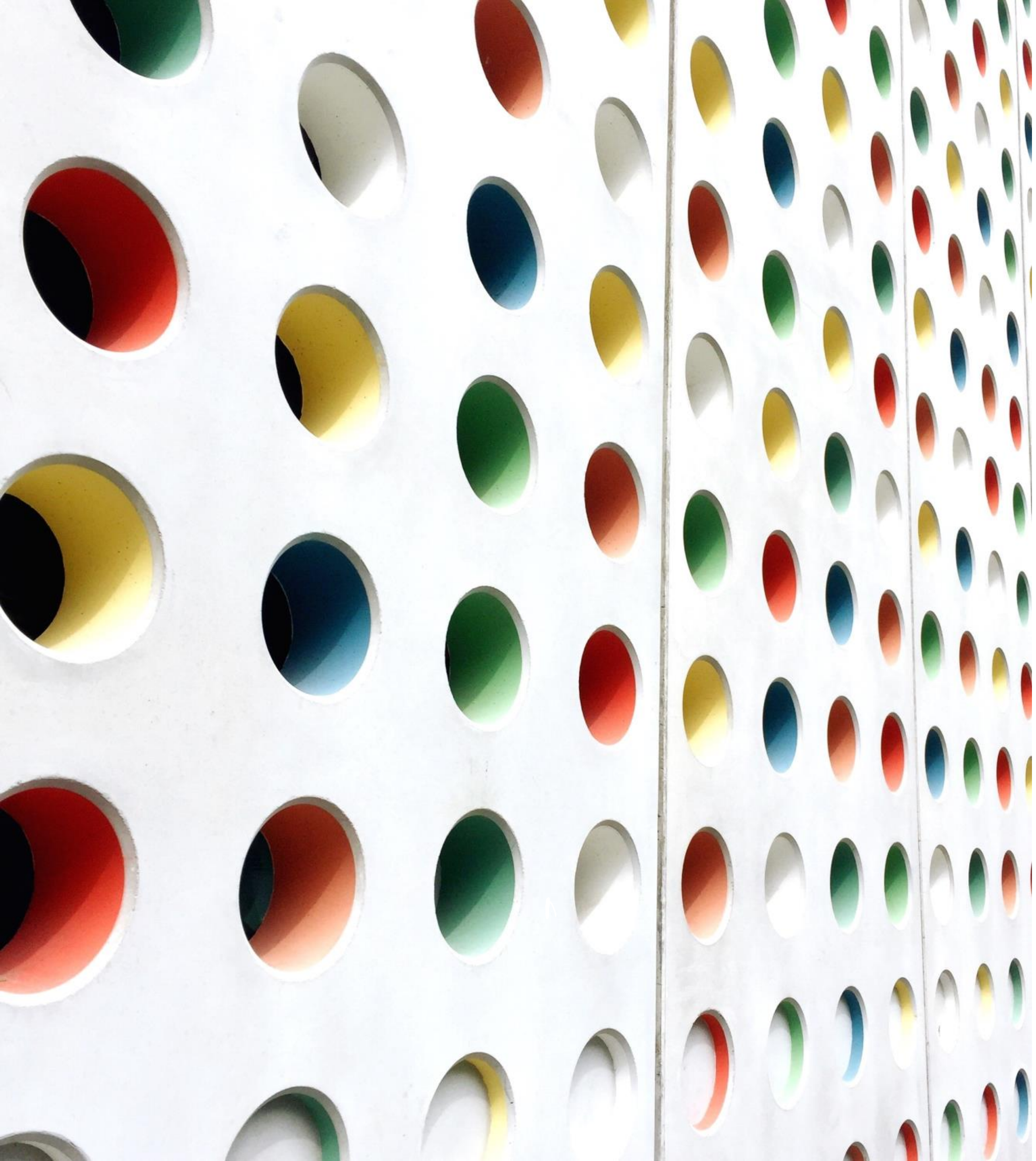

Multi-mouth traversable wormholes

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W/ EMPARAN, GRADO-WHITE AND MAROLF

Outline

HISTORY OF WORMHOLES

TWO-SIDED TRAVERSABLE WORMHOLES.

OUR CONSTRUCTION

DISCUSSION

Wormhole timeline

1916	1957	1973	2010	2016/8	2018/9
• Flamm finds the **first solution**: the ER bridge (1935)	• Wheeler coins the term ***wormhole*** before: one-dimensional tubes	• Independent work by Ellis and Bronnikov on (exotic) **traversable** possibilities today: Morris-Thorne wormholes (1988)	• Wall **rules out short wormholes** using GSL AANEC established by Graham and Olum (2007)	• Gao, Jafferis and Wall: first non-exotic traversable wormhole (**short-lived**) Maldacena *et al*: first non-exotic traversable wormhole (**long-lived**)	• Grado-White *et al*: **perturbative construction** of traversable wormholes Maldacena *et al*: **non-perturbative construction** of traversable wormholes

Wormholes 101

General relativity allows any smooth Lorentzian manifold to be a spacetime: given a spacetime geometry, one simply solves Einstein's equations in order to determine the stress-energy tensor needed to produce it.

Any restrictions on non-trivial phenomena, such as wormholes, must be given in terms of **energy conditions** that constrain the set of possible stress-energy tensors.

Energy conditions

Classical physics:

Null Energy Condition

energy has to be positive at every point

Quantum physics:

Achronal Average Null Energy Condition

average energy along the fastest* null geodesic has to be positive

*no points along the null geodesic are connected by a timelike curve

Current status

What is the set of all allowed wormholes?

Classical physics: only non-traversable wormholes

(Einstein-Rosen bridge)

Quantum physics: allows traversable wormholes, but

only if they are *long* + supported by *negative energy*

Traversable wormholes in 4D

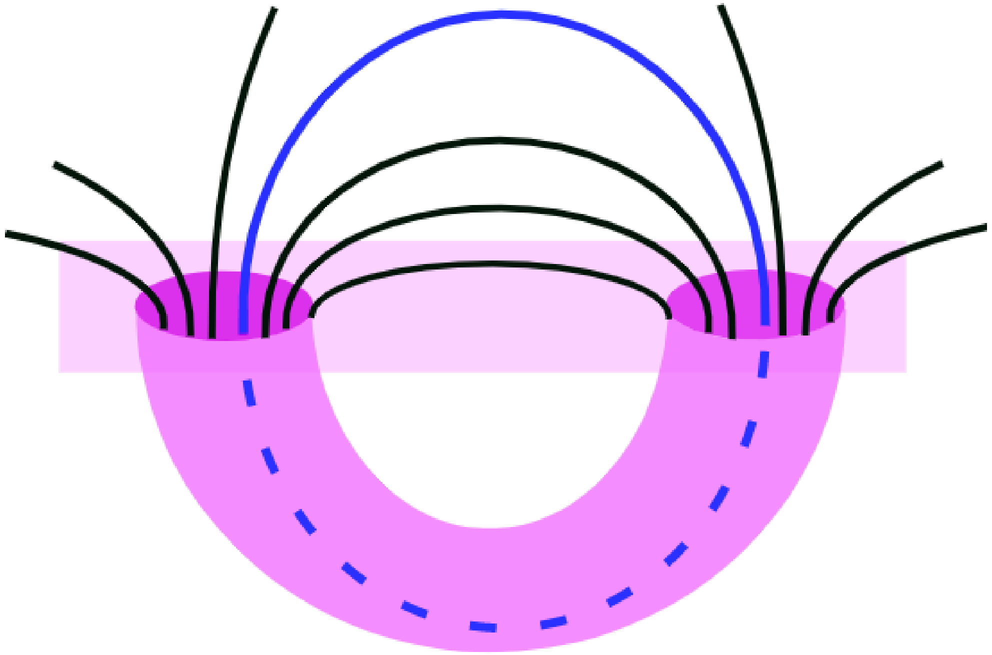
Review of Maldacena, Milekhin and Popov 1807.04726

Key features: it must have a **long throat** and supporting **negative energy**

Long throat: for example, near-extremal RN black holes have long throats

Negative energy: Casimir, but it's a tiny quantum effect

However, if we could amplify the effect in some way, the wormhole mouth could be bigger



Magnetic traversable wormholes

So, put together two near-extremal RN black holes – connect their throats

Throat needs to be longer than the distance between the mouths in ambient space

Black holes are magnetically charged – magnetic field lines go in and out of mouths

Fermions on a loop give Casimir energy – put N>>1 of them

→ Traversable wormhole!

Single magnetically charged black hole

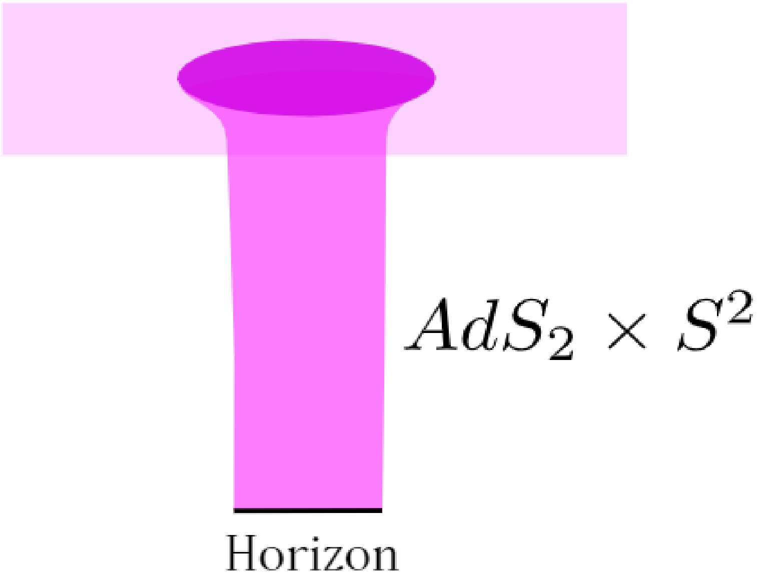
The theory is Einstein-Maxwell + Dirac fermions

$$ds^2 = -\left(1 - \frac{2MG_N}{r} + \frac{r_e^2}{r^2}\right) dt^2 + \left(1 - \frac{2MG_N}{r} + \frac{r_e^2}{r^2}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$A = \frac{q}{2}\cos\theta d\phi \,, \qquad r_e^2 \equiv \frac{\pi q^2 l_p^2}{g^2} \,, \qquad l_p \equiv \sqrt{G_N}$$

Near horizon geometry of a near-extremal bh

$$ds^2 = r_e^2 \left[-d\tau_r^2(\rho_r^2 - 1) + \frac{d\rho_r^2}{\rho_r^2 - 1} + (d\theta^2 + \sin^2\theta d\phi^2)\right]$$

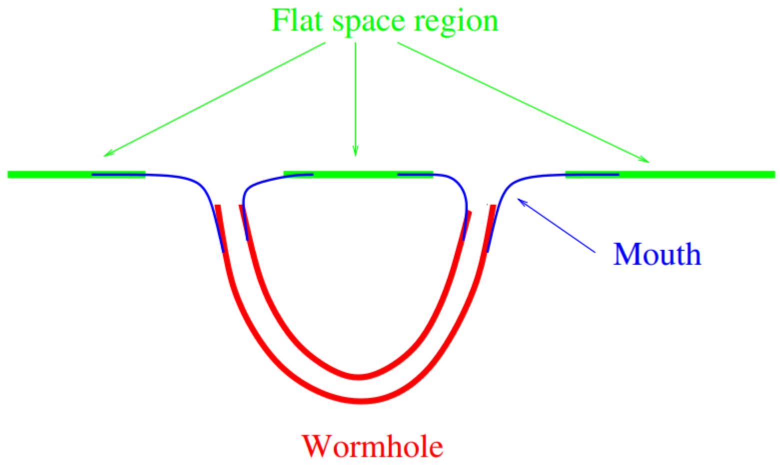


Two-sided traversable wormhole

The wormhole metric

$$ds^2 = r_e^2[-(1+\rho^2+\gamma)d\tau^2 + \frac{d\rho^2}{1+\rho^2+\gamma} + (1+\varphi)(d\theta^2 + \sin^2\theta d\phi^2)]$$

We replaced *Rindler*-AdS_2 with a *global* AdS_2 metric



Properties

They are in **4D, asymptotically flat spacetime**

The physics used is entirely contained within the **Standard Model**

These wormholes are **small** – only low energy particles can traverse it (unless we deviate from SM)

(size of the systems smaller than electroweak scale)

They are **fragile**: quantum fluctuations can destroy the wormhole if it becomes too long!

They are **long-lived**: we can put them into a binary orbit, and they will radiate EM and gravitational waves, leading to a collision (can be made far in the future)

Can we generalize them?

Yes! And in the simplest way possible

Consider a small black hole deep in the throat – that's it

The small black hole should have similar structure as the original bhs, so as to develop a throat on its own and connect to the same ambient spacetime

Construction manual

Small black hole as a perturbation of the throat – no backreaction needed at the lowest order

Stability and traversability: several options, depending on the toolbox

- can charge the mouths with a different U(1)
- stabilize with cosmic strings which also provide negative energies
- hybrid of the above two options
- maybe one can utilize the 5D dark sector [2008.06618]

How big can the small black hole be?

The bigger it is, the less negative energy we have in the throat – need defocusing to exit the tube

There's an upper bound on M_{sbh}: it cannot exceed the binding energy of the wormhole

$$m < \frac{N_f Q}{8\pi r_e} \qquad E_{bh} < |E_{min}|$$

Nor can it be bigger than the throat itself: $G_N m < r_e$

Signals

Traversable wormholes are also discussed in the context of quantum teleportation

How does adding a third mouth change the protocol, if at all?

In general, there are two effects:

- Leaky pipeline: information goes down the C drain
- Shapiro time delay: takes longer to traverse the throat

Leaky pipeline

Area of C and angular position important

These effects will have counterparts in a qudit toy model of the three-mouth wormhole.

Area prop to # of dofs, but what does angular position correspond to?

Having information about this angular position is essential for A and B if they intend to communicate efficiently with C

Need better understanding!

Shapiro time delay

Signals passing near a massive object take slightly longer to travel

Same happens with our small black hole

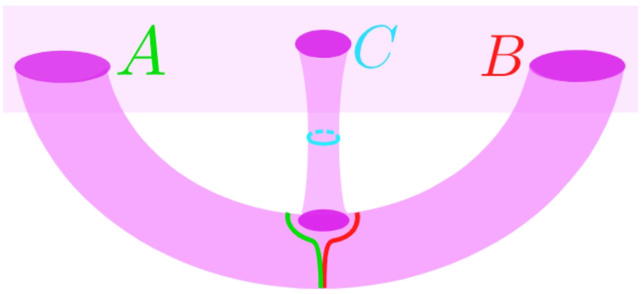
What is the dual of Shapiro time delay?

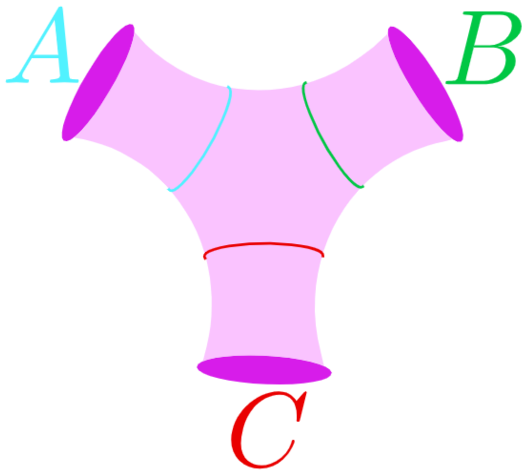
Conjecture: the increased travel-time can be correlated with an increased *complexity* in decoding the teleported message

ER+ε = EPR+ε?

While two-mouth traversable wormholes are associated with **Bell-pair-like entanglement**, our three-mouth wormholes will require a **new entanglement structure** – a concept that can be made precise by embedding our construction in the AdS/CFT context*

*still in progress





How can we see the entanglement structure?

One way of telling is by looking at the *positions of extremal surfaces* [1406.2663, 1506.04128]

If the separation between two surfaces is small w.r.t. the 3rd – mostly *bipartite* entanglement

If the separation between two surfaces is similar in size of the 3rd – *tripartite* entanglement

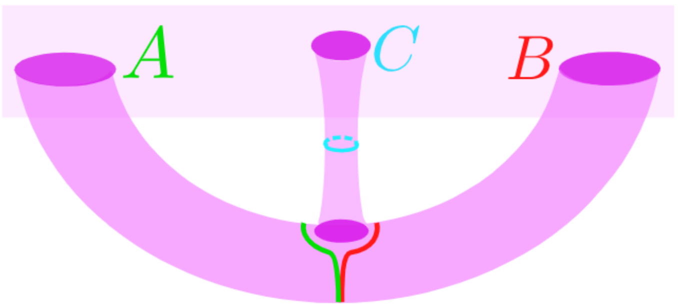
Our case

Recall that we have a small black hole in a big throat

Before we add the small bh C, A and B extremal surfaces coincide and lie at the bottom of the throat

When C is really small, its effect is also very small on the A and B surfaces – mostly bipartite

The large bipartite entanglement between A and B is consistent with the idea that C has little effect on signals being sent between A and B



Conclusions

Understanding wormholes is leading to many insights in quantum gravity

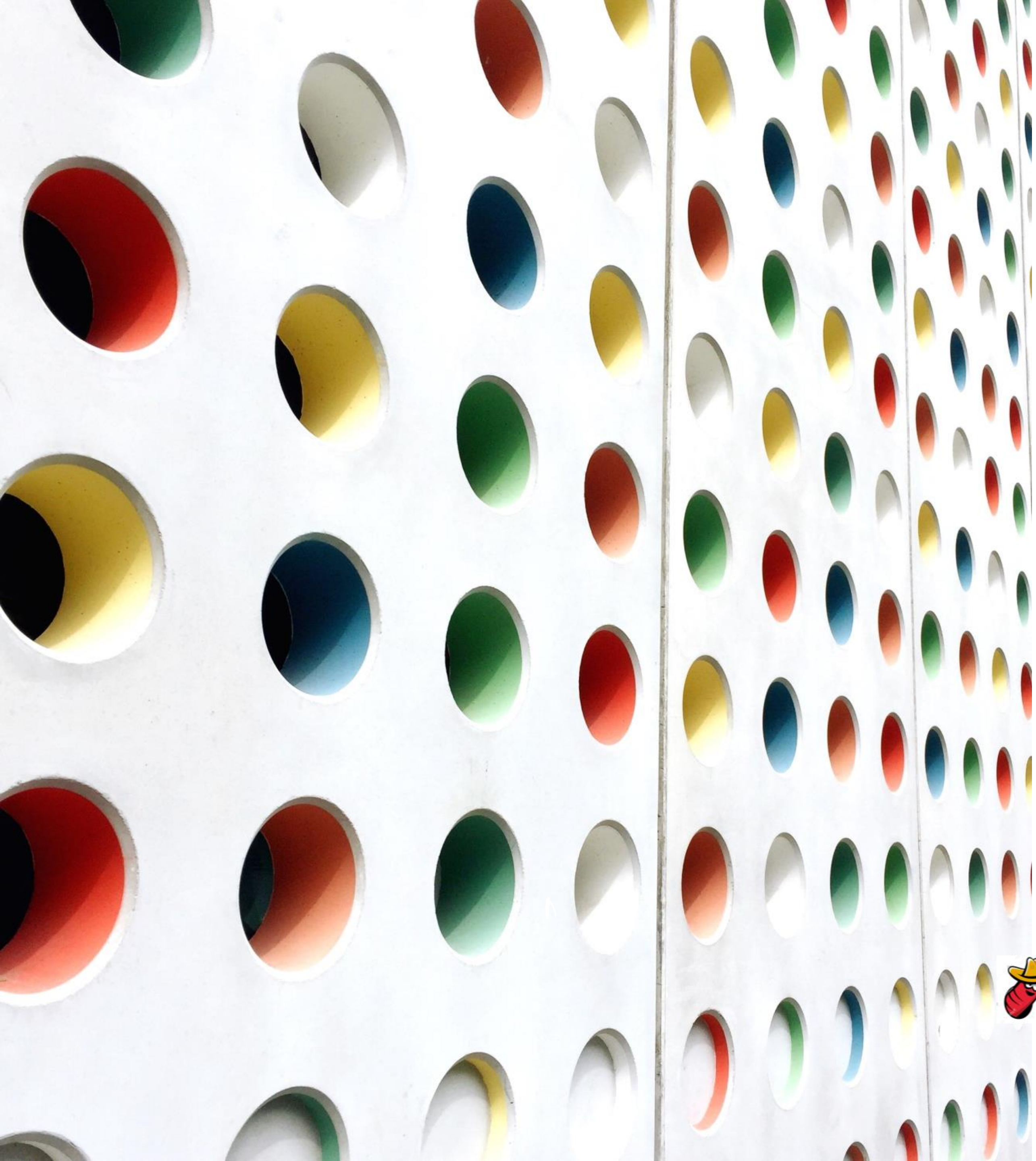
Studying their properties can shed light on the black hole interiors

And multi-mouth wormholes can shed light on the holographic dictionary

So far, we have mostly focused only on the bipartite notions in AdS/CFT

But entanglement is inherently a multipartite concept

We constructed the bulk picture – holographic dual should come next!



Thank you!

Entanglement structure

Balasubramanian ***et al*** **[1406.2663]** focused on CFT_2 states defined by the Euclidean path integral over Riemann surfaces with n asymptotic boundaries (n=2 example is the TFD state)

For some values of the moduli, the bulk solution is a connected, multiboundary wormhole (non-traversable)

When all the boundaries are connected in the bulk, one might expect multipartite entanglement to play the main role

But, what they found is more complicated: in some regions of the moduli space, the entanglement is entirely multipartite and in some others, entirely bipartite,

even though the bulk geometry is **completely connected**!

Cosmic string setup

In this construction, we start with a classical background containing a pair of charged, RN-like black holes

These black holes are held apart by the tension of a cosmic string that threads the wormhole and stretches to infinity

A second cosmic string wraps the non-contractible compact cycle through the wormhole

The quantum fluctuations of this compact string generate the negative Casimir energy needed for traversability

This wormhole will generally be strongly time-dependent and can be traversed by curves only if they leave past null infinity at sufficiently early times

This leads to a more stringent bound on the size of the smaller wormhole mouth