Wormholes and black hole microstates in AdS/CFT

Kristan Jensen (Victoria)

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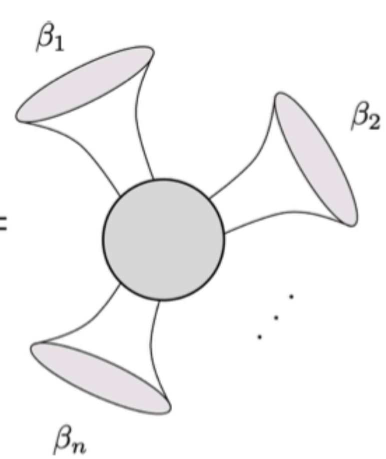
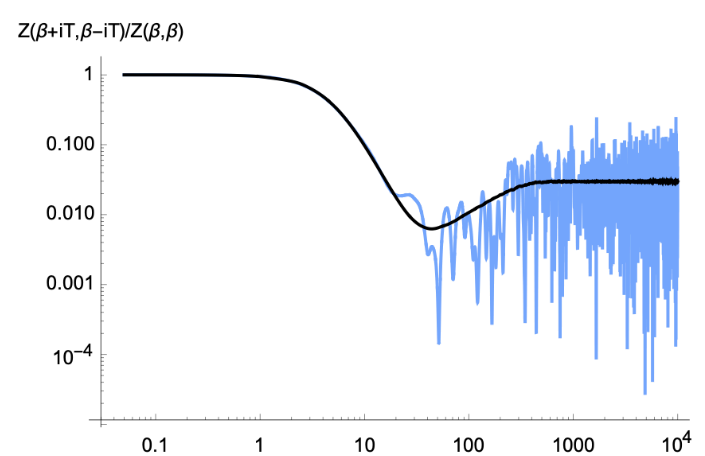
see joint work with Jordan Cotler:
arXiv:2006.08648 (JHEP 04 (2021) 033)
arXiv:2010.02241
arXiv:2104.00601 (accepted by JHEP)

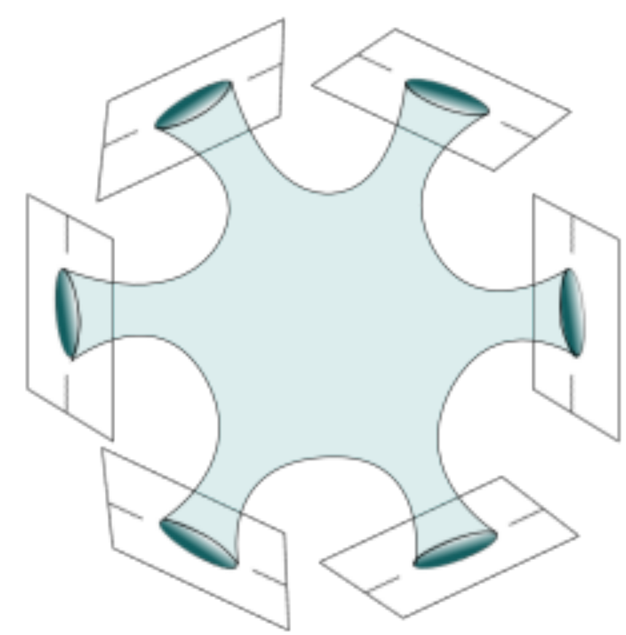
Wormholes are a central player in recent work on soluble models of two-dimensional gravity.

- Tractable non-perturbative corrections in G_N.
- Probe fluctuation statistics of dual ensemble, like level statistics of JT black holes. [Saad, Shenker, Stanford] '19
- Unitarize BH evaporation in models with replica wormholes. [Penington, et al], [Almheiri, et al] '19
- Blessing and a curse (lead to factorization paradox, suggesting that gravity is generally dual to an ensemble average). [Maldacena, Maoz] '04
- And more.

$$\langle \mathrm{tr}(e^{-\beta_1 H}) \cdots \mathrm{tr}(e^{-\beta_n H}) \rangle_{\text{ensemble}} =$$

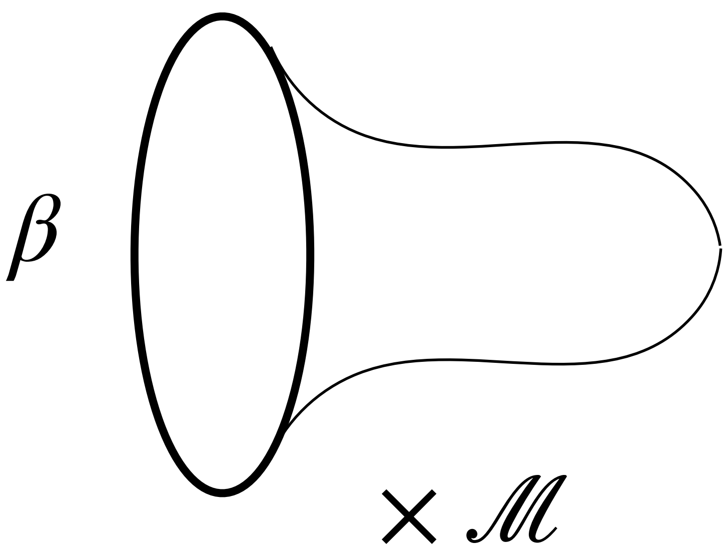


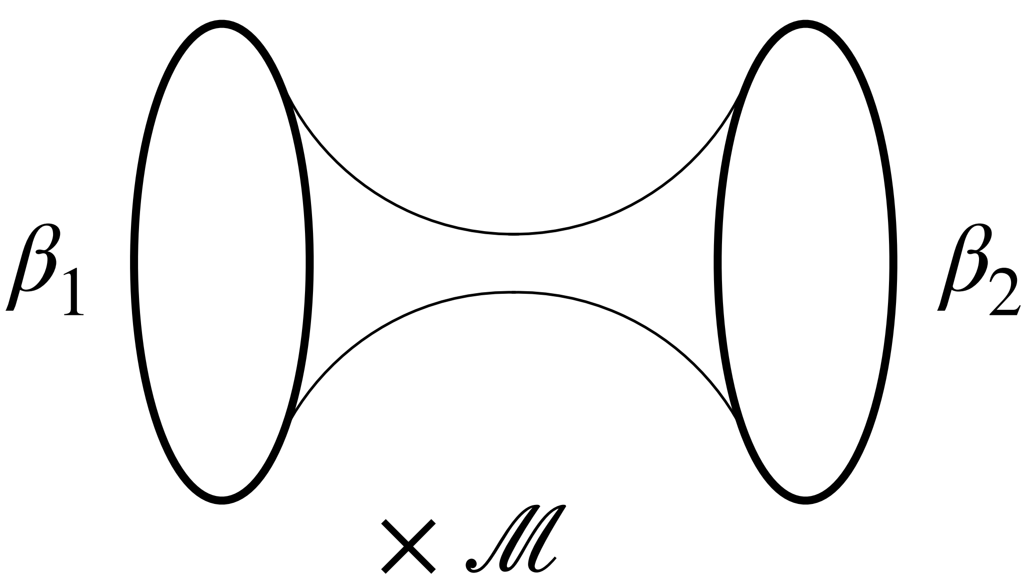




What do we hope to learn?

In gravity we look for Euclidean wormholes with two asymptotically (Euclidean) AdS regions with $\mathbb{S}^1 \times \mathscr{M}$ boundary.





<u>Punchline:</u>

Euclidean BH amplitude (one boundary) encodes coarse-grained approximation to the black hole density of states.

Euclidean wormhole amplitude (two bdys) encodes coarse-grained approximation to the two-point level statistics of black hole microstates, in particular, <u>long-range</u> repulsion.

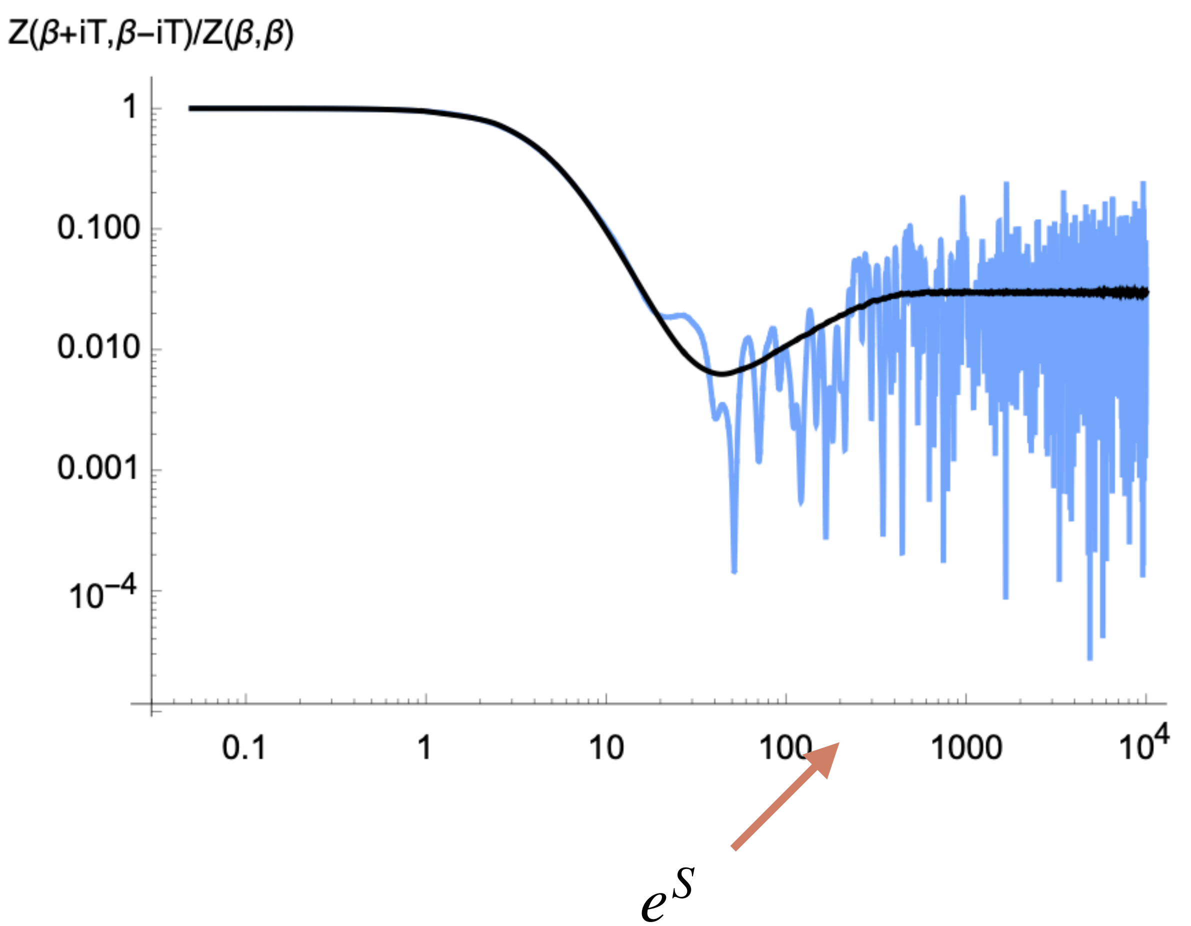
What do we hope to learn?

There is good reason to expect a holographic CFT on $\mathbb{S}^{d-1}$ to have a chaotic spectrum of energy eigenstates. Such a spectrum has short-range and long-range repulsion between energy eigenvalues. Both are well-diagnosed by "spectral form factor."
[many papers], [CGHPS⁴T] '16

$$Z(\beta + iT, \beta - iT) = \mathrm{tr}(e^{-(\beta+iT)H})\mathrm{tr}(e^{-(\beta-iT)H})$$

β_1 β_2

SFF of a single theory has a wildly fluctuating form at late times, but ensemble (or time) average is smooth.



Existing computations

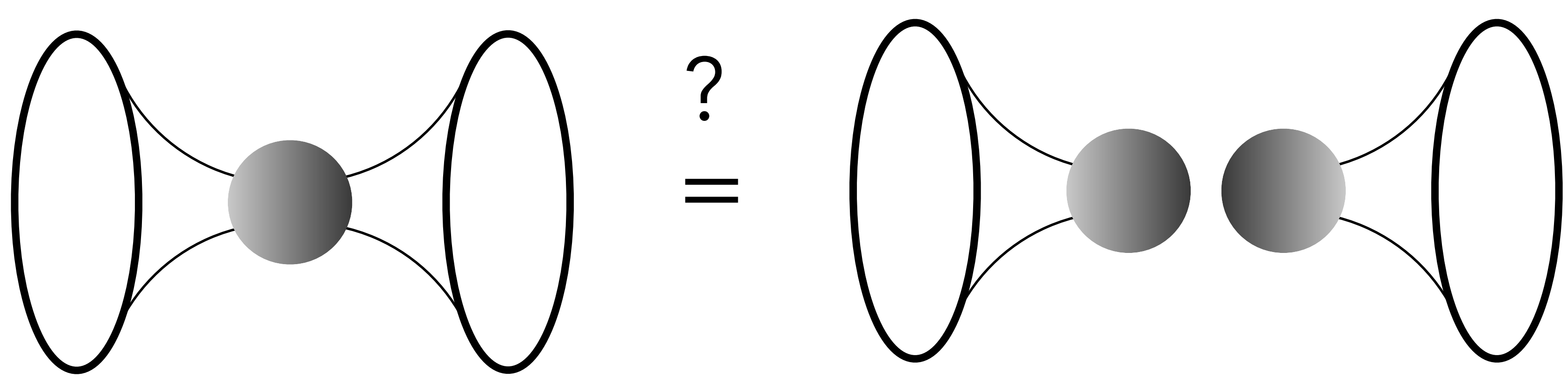
1. Jackiw-Teitelboim gravity [Saad, Shenker, Stanford] ’19
2. Variants of JT gravity [Stanford, Witten] ’19, [Maxfield, Turiaci] ’20, [Witten] ’20
3. Pure gravity in 3d [Cotler, KJ], arXiv:2006.08648
4. Einstein gravity in d>2 [Cotler, KJ] ’20, ’21, related to [Saad, Shenker, Stanford] ’18

In all cases, the wormhole amplitude is a non-perturbatively suppressed contribution, with no saddle-point approximation.

Open questions

Euclidean wormholes suggest that gravity describes an ensemble of Hamiltonians.
But, in conventional AdS/CFT, gravity is dual to a single boundary Hamiltonian.

This leads to a factorization paradox whose resolution is currently unclear.
Our non-perturbative knowledge of UV-complete models of gravity, like IIB strings, is yet not refined enough to resolve this paradox.



The "plateau" is also robust. Is it described by a non-perturbative, "IR-safe" effect in gravity?

Thank you!