Ensemble Averages and Wormholes

Discussion Session Strings 2021

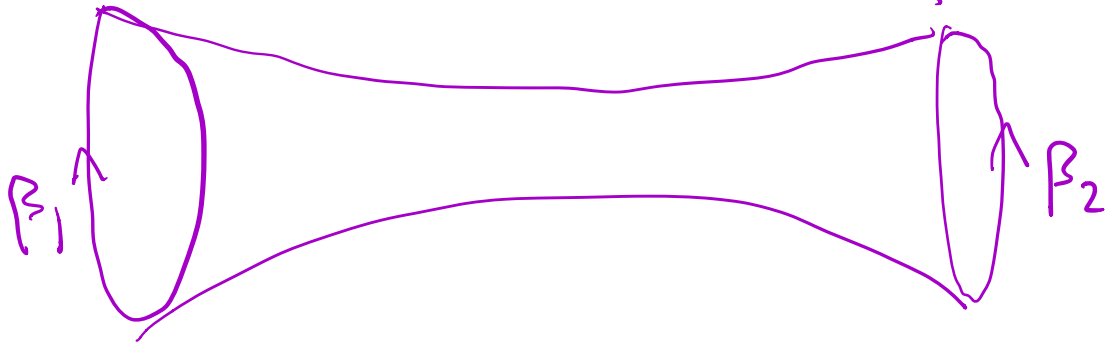
See also talks by: Shenker, Johnson, Jensen, Mertens,…

References: see Steve's talk…..

Thanks to collaborators: Alex Belin, Julian Sonner, Pranjal Nayak, Diego Liska, Tarek Anous, Igal Arav and Shira Chapman…

Wormholes seem to spoil factorization

$\langle Z(\beta_1) Z(\beta_2) \rangle_c \neq 0$



One way out: gravity is dual to ensemble averages. But what about good old AdS/CFT?

55% says gravity $\neq$ ensemble $\nabla \neq 0$

One perspective:

Ensemble averaging is approximately the same as coarse graining as far as low-energy observers/low-energy effective field theory is concerned.

in the bulk

Both the averaging and the coarse graining should affect only physics above the cutoff scale Λ

$$\int d\rho dJ\, \delta\left(\rho - \frac{e^{-\beta H[J]}}{Z[J]}\right) \simeq \int d\rho dU\, \delta\left(\rho - U^\dagger e^{-\beta H} U\right)$$

In LEEFT we do not have access to $\rho(E) = \sum \delta(E - E_i)$ but only to a coarse grained version via e.g. black hole entropy. (LEEFT = bulk/gravitational LEEFT ≠ boundary LEEFT)

"State averages" (Schrödinger picture) or "operator averages" (Heisenberg picture) can capture many aspects of wormhole physics.

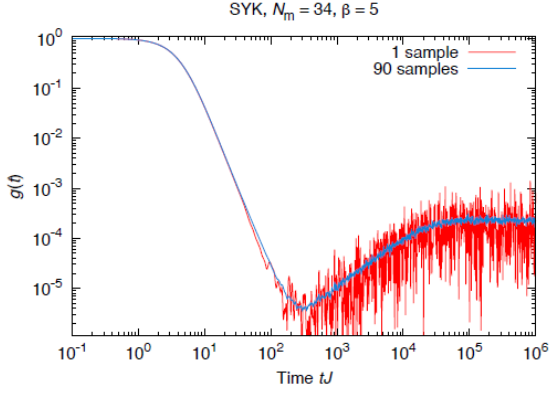
as in ETH

$$\overline{\rho \otimes \rho} \neq \bar{\rho} \otimes \bar{\rho}$$

QUESTION: is there a simple low-energy diagnostic to distinguish ensemble averaging from "coarse graining" in a single theory? And what do we precisely mean by "coarse graining"?

In both perspectives, wormholes compute statistical fluctuations or moments of the relevant probability distributions.

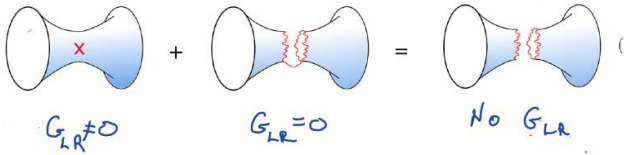
Single sample noise



QUESTION: where does the noise come from?

Presumably need the individual microstates. If not accessible in LEEFT will not be able to capture the noise (cf microstate discussion session).

QUESTION: how is factorization restored? Toy model:



$$\sum_{i=j} 1 + \sum_{i \neq j} e^{i(\phi_i - \phi_j)} = \left(\sum e^{i\phi_i}\right)\left(\sum e^{i\phi_i}\right)^*$$

What happens in the UV? Possibilities:

- The relevant gravitational solution (eg wormhole) is unstable and factorization is restored (but solution remains as off-shell configuration)
- UV physics adds the fluctuating contributions $\sum_{i \neq j} e^{i(\phi_i - \phi_j)}$ and factorization is restored (*what are these? Cf half wormholes*)
- The UV theory is an average of theories, averaging makes the fluctuating term exactly zero, and factorization is not restored

D=2: JT gravity and its cousins.

Viewed as exact UV complete gravitational theories these are described by suitable matrix models.

QUESTION: Single SYK sample/single matrix is dual to what?

D=3:

Can study off-shell wormhole contributions using “constrained instantons” (genus 1 boundaries)

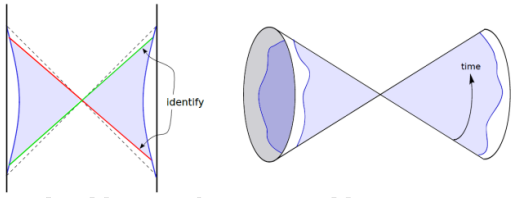
Can study on-shell wormholes with higher genus boundaries.

Can study explicitly ensemble averages of certain families of 2d CFTs and their dual description (typically a Chern-Simons like theory).

QUESTION: what is the dual of pure 3d gravity (and what do we even mean by the latter)?

QUESTION: are there other more general/natural ensembles of holographic 2d CFTs?

D>3



Double cone exists as complex solution (negative modes?)
Suggests level repulsion is universal in strongly coupled holographic CFTs

QUESTION: is very long timescale physics part of LEEFT?

Stable Euclidean wormhole solutions exist but are always subleading.

QUESTION: is there a general argument that this must happen? If there is a counterexample what would be the implication? Requirement for UV completions?

QUESTION: does it make sense to average N=4 SYM over the complex coupling constant?

Connection to the swampland program

QUESTION: Can gravitational duals of averaged theories violate some of the swampland conjectures? (e.g. can have ungauged global symmetries?)

QUESTION: How does one test for unitarity in duals of averaged theories (i.e. unitarity of the individual theories in the ensemble)?

Connection to the bootstrap program

Wormholes yield statistical information about the high-energy sector of the theory.

The bootstrap program does that as well (e.g. sum rules).

QUESTION: Is there a more precise connection? Can one bootstrap averages of theories?

Connection to the information paradox.

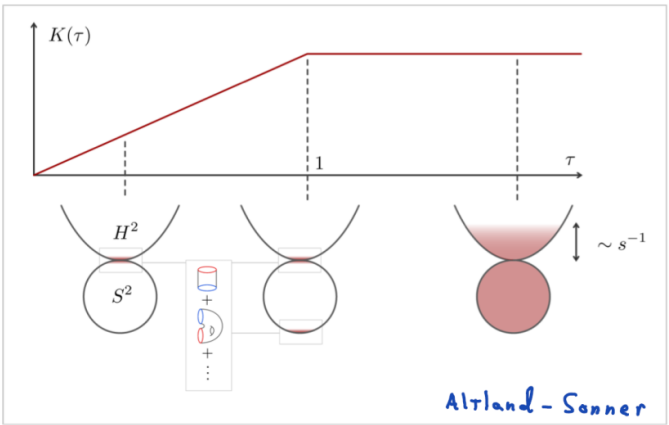
Replica wormholes are important in getting the page curve.

QUESTION: is unitarity $SS^\dagger = \mathbb{I}$ an example of a quantity that does not fluctuate and therefore had to come out correctly in a LEEFT approximation with wormholes?

The plateau

QUESTION: Is there a gravitational argument for universality of the plateau in the SSF in higher dimensional theories?

Altland-Sonner proposed a non-linear sigma model of Goldstone modes, what is the gravitational interpretation of this description?



Euclidean vs Lorentzian wormholes

QUESTION: what is the role of Lorentzian wormholes in all of this?

Baby universes, alpha vacua and all that

QUESTION: can we reliably establish/rule out that this is a reliable picture in full-fledged solutions of string theory, like in AdS/CFT? Or does it only apply to averaged theories? Or only to low-dimensional topological examples? What would be the relevant smoking gun computation?