Title: Traversable wormhole dynamics on a quantum processor

Speakers: Maria Spiropulu

Collection: Quantum Simulators of Fundamental Physics

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Abstract: I will discuss our work ("Traversable wormhole dynamics on a quantum processor", Nature) on interrogating a two-dimensional gravity dual quantum system on-chip, and implications on future exploration of this type. I will also address comments/objections raised recently in the literature (https://arxiv.org/abs/2303.15423)

Traversable wormhole dynamics on a quantum processor

or, entanglement, spacetime and quantum gravity

M . Spiropulu, Caltech

Perimeter Institute, **Quantum Simulators of Fundamental Physics**

06-06-2023

Daniel Jafferis (Harvard)
Alex Zlokapa (Caltech→ MIT)
Joseph Lykken (Fermilab)
David Kolchmeyer (Harvard→MIT)
Samantha Davis (Caltech)
Nicolai Lauk (Caltech)
Hartmut Neven (Google Quantum AI)
MS

https://www.nature.com/articles/s41586-022-05424-3

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Traversable wormhole dynamics on a quantum processor

Daniel Jafferis, Alexander Zlokapa, Joseph D. Lykken, David K. Kolchmeyer, Samantha I. Davis, Nikolai Lauk, Hartmut Neven & Maria Spiropulu

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Comment on "Comment on 'Traversable wormhole dynamics on a quantum processor'"

Daniel Jafferis,[1,*] Alexander Zlokapa,[2,3,4,5,*] Joseph D. Lykken,[6] David K. Kolchmeyer,[1]
Samantha I. Davis,[3,4] Nikolai Lauk,[3,4] Hartmut Neven,[5] and Maria Spiropulu[3,4]

[1] *Center for the Fundamental Laws of Nature, Harvard University, Cambridge, MA, USA*
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA, USA*
[3] *Division of Physics, Mathematics and Astronomy, Caltech, Pasadena, CA, USA*
[4] *Alliance for Quantum Technologies (AQT), California Institute of Technology, Pasadena, CA, USA*
[5] *Google Quantum AI, Venice, CA, USA*
[6] *Fermilab Quantum Institute, Fermi National Accelerator Laboratory, Batavia, IL, USA*

https://doi.org/10.48550/arXiv.2303.15423

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Teleportation, and ER=EPR

Leonard Susskind

Quantum gravity may have as much to tell us about the foundations and interpretation of quantum mechanics as it does about gravity. The Copenhagen interpretation of quantum mechanics and Everett's Relative State Formulation are complementary descriptions which in a sense are dual to one another. My purpose here is to discuss this duality in the light of the of ER=EPR conjecture.

Comments: Lecture
Subjects: **High Energy Physics - Theory (hep-th)**; General Relativity and Quantum Cosmology (gr-qc); Quantum Physics (quant-ph)
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(or arXiv:1604.02589v2 **[hep-th]** for this version)
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Related DOI: https://doi.org/10.1002/prop.201600036

[Submitted on 1 Jul 2022 (v1), last revised 9 Aug 2022 (this version, v2)]

Holography for people with no time

Henry W. Lin, Juan Maldacena, Liza Rozenberg, Jieru Shan

We study the gravitational description of extremal supersymmetric black holes. We point out that the AdS_2 near horizon geometry can be used to compute interesting observables, such as correlation functions of operators. In this limit, the Hamiltonian is zero and correlation functions are time independent. We discuss some possible implications for the gravity description of black hole microstates. We also compare with numerical results in a supersymmetric version of SYK. These results can also be interpreted as providing a construction of wormholes joining two extremal black holes. This is the short version of a longer and more technical companion paper arXiv:2207.00408.

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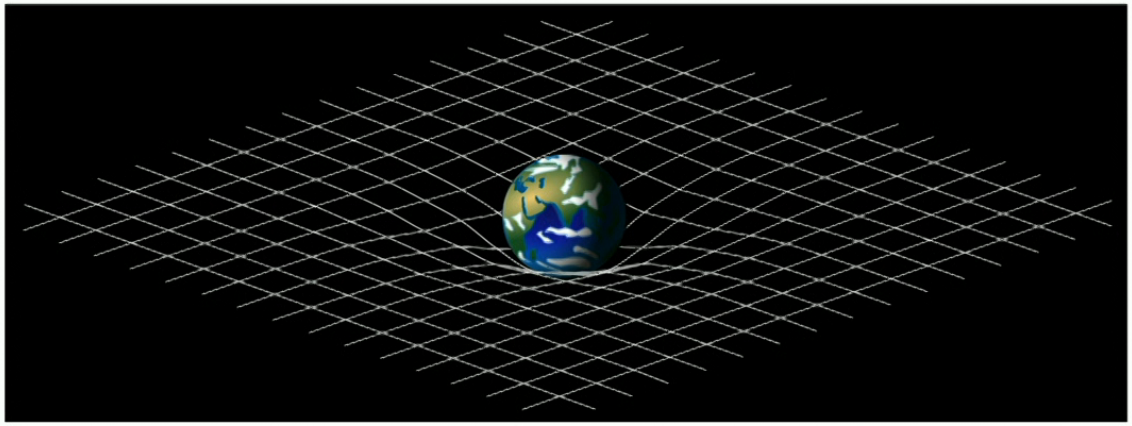
Part 1: something about quantum gravity

It’s hard

- Einstein told us that gravity is curvature in the fabric of spacetime
- But what is the fabric itself?
- What is space from the quantum point of view?



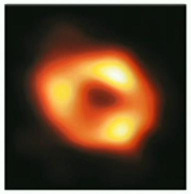
$$\ell_{\text{Planck}} \equiv \sqrt{\frac{\hbar G}{c^3}} \simeq 10^{-33}\ \text{cm}$$

Gravity is very weak on the scales where we can do experiments

Almost all progress on quantum gravity in the past 50 years has come from using "theoretical laboratories":

Black holes:

- large black holes are basically thermodynamical systems
- some of their quantum properties are well-established from semiclassical arguments, e.g. Hawking radiation
- and perhaps you can get actual data about them from gravity wave observatories



Anti-de Sitter/Conformal Field Theory holographic **duality** (AdS/CFT):

- discovered in the context of string theory in 1997 by Juan Maldacena
- **not the real world** but gives a concrete framework for talking about quantum gravity

Pic: Megadeth

N.B. Unruh & Wald (arXiv:1703.02140)

The **AdS/CFT** correspondence is a conjecture. Our difficulty in assessing the validity of the AdS/CFT argument against information loss is not so much that this conjecture has not been proven, but rather that it has not been formulated in sufficient detail and with sufficient precision to make a clear argument. In particular, relatively little is explicitly known about the conjectured “dictionary” between the “bulk observables” in the asymptotically AdS spacetime and the CFT observables defined in the boundary theory

Duality

Duality is also a fundamental property of the Standard Model of particle physics:

- Gauge symmetry is not a symmetry of the S-matrix, but rather a redundancy (i.e. a duality) in the description of the system
- This duality was exploited by Higgs et al. in 1964 to explain the Higgs mechanism:
  - In a covariant Lorenz gauge description, Goldstone's theorem applies and there are Goldstone modes
  - In the dual Coulomb gauge description, there are no Goldstones
  - Both descriptions are correct

Can we learn anything about quantum gravity by studying the quantum dynamics of entangled systems?

- This means approaching quantum gravity starting from the extreme quantum regime, and identifying features emergent from entanglement that map into recognizable features of the semi-classical gravity regime
- This requires finding appropriate quantum systems amenable for study, e.g. the SYK model
- And corresponding systems in the semi-classical gravity regime that have distinctive features, e.g. black holes and wormholes

the physical value of the Planck length is irrelevant to this approach, since **the gravity effects are emergent from quantum dynamics**

SYK model

- SYK is a quantum mechanical model of **N** interacting Majorana fermions $\psi^{\mathbf{j}}$, interacting **q** at a time with random couplings scaled by an overall strong coupling **J**
- Quantum mechanical Majorana fermion operators are the same thing as appropriately chosen strings of Pauli operators (Jordan-Wigner transformation)
- This means we can try to realize the quantum dynamics of the SYK model on a quantum computer
- For N <~ 30, we can also simulate it on a classical computer

A. Kitaev, "A simple model of quantum holography." Talks at KITP, April 7 and May 27, 2015

S. Sachdev and J.-w. Ye, Phys. Rev. Lett. 70 (1993) 3339

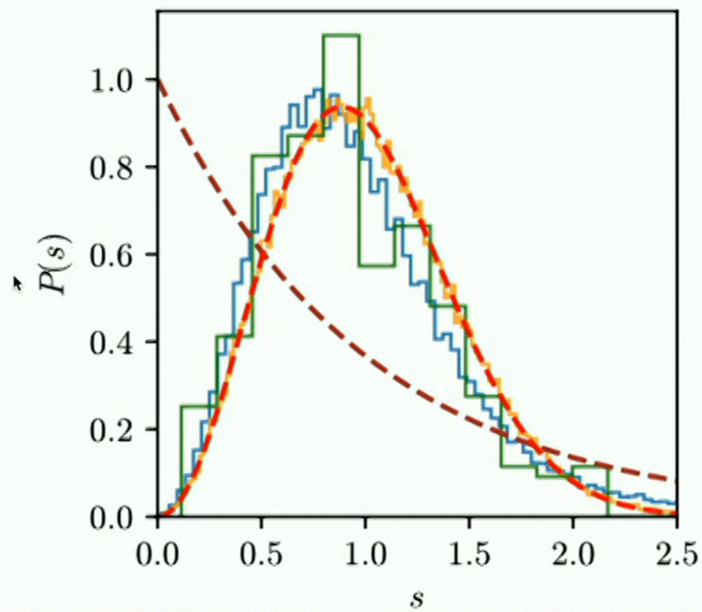
J. Maldacena and D. Stanford, arXiv:1604.07818

$$H_{\mathrm{SYK}} = \sum_{1\leq j_1<\ldots<j_q\leq N} J_{j_1\ldots j_q}\,\psi^{j_1}\cdots\psi^{j_q}$$

random couplings sampled with mean zero and variance = $J^2(q-1)!/N^{q-1}$

SYK model: features

- Hamiltonian is strongly coupled but nonlocal (no spatial dependence)
- The eigenvalue spectrum exhibits level repulsion
- Averaged over an ensemble of random instantiations, the distribution of eigenvalue spacings converges with those of random matrix theory for large N
- For large enough N, SYK model is “self-averaging”, so a single instantiation is enough



N=18 q=4 SYK model: level spacing distribution P(s) versus the separation of the eigenvalues s

Blue histogram is averaging over 400 instantiations of the SYK Hamiltonian; orange histogram is “unfolded” by rescaling the spectrum such that the mean level spacing is the same for all energies.

Green histogram is taken from a single instantiation of the SYK Hamiltonian.

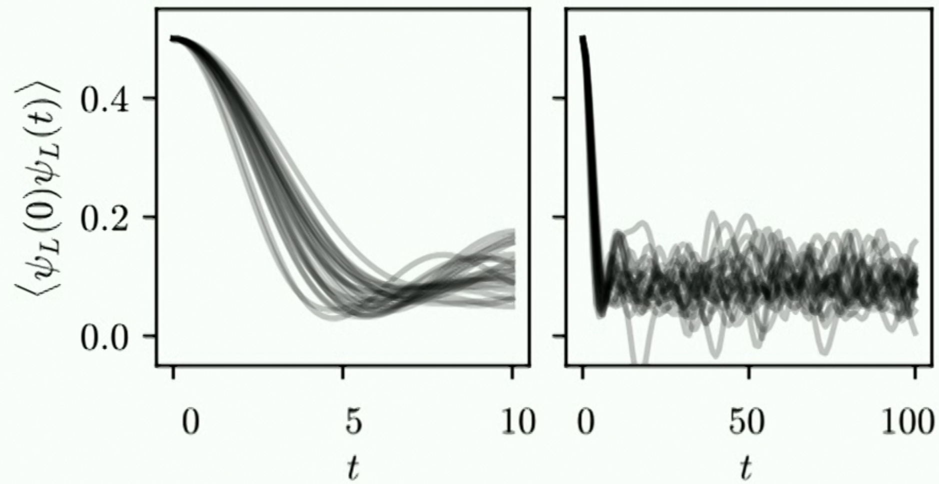
Red dashed line is the distribution expected in the large-N limit for random matrices from the Gaussian Unitary Ensemble.

SYK model and quantum chaos

The SYK model exhibits many-body quantum chaos, as embodied in two effects:

1. Exponential decay of two-point thermal correlators between any fermion at time t=0 and the same fermion at a later time t

The characteristic time is called the “dissipation” or “thermalization” time



Chaotic dynamics of the N=10 q=4 SYK model:
Two-point thermal correlator shows the dissipation time
Shown here are individual instantiations

J. Maldacena, S. Shenker, D. Stanford, arXiv:1503.01409

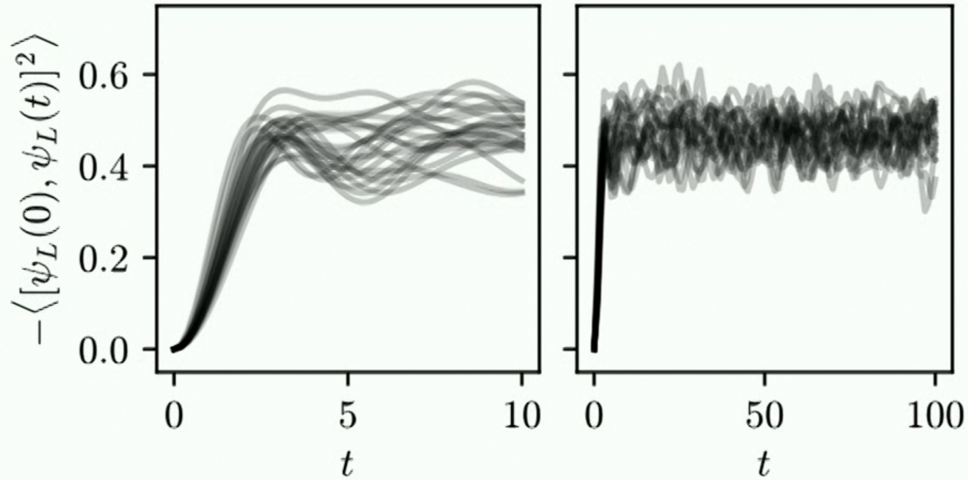
SYK model and quantum chaos

The SYK model exhibits many-body quantum chaos, as embodied in two effects:

2. Exponential growth of the out of time order (OTOC) thermal correlators showing, for example, operator growth of a fermion over time

The characteristic time is called the "scrambling" time

The exponential growth is parameterized by the Lyapunov exponent λ_L



Chaotic dynamics of the N=10 q=4 SYK model: OTOC measuring the operator growth of a fermion Shown here are individual instantiations

J. Maldacena, S. Shenker, D. Stanford, arXiv:1503.01409

SYK model and black holes

- Fast scrambling of quantum information is a characteristic feature of black hole dynamics
- This is why, when Alice throws her diary into a black hole, Bob can decode its contents in the emitted Hawking radiation (after suitable unscrambling)

P. Hayden and J. Preskill, arXiv:0708.4025

- Maldacena, Shenker, and Stanford have argued that in fact black holes saturate an upper bound on the Lyapunov exponent
- The SYK model, in the large N limit, also saturates this upper bound

J. Maldacena, S. Shenker, D. Stanford, arXiv:1503.01409

SYK model and wormholes

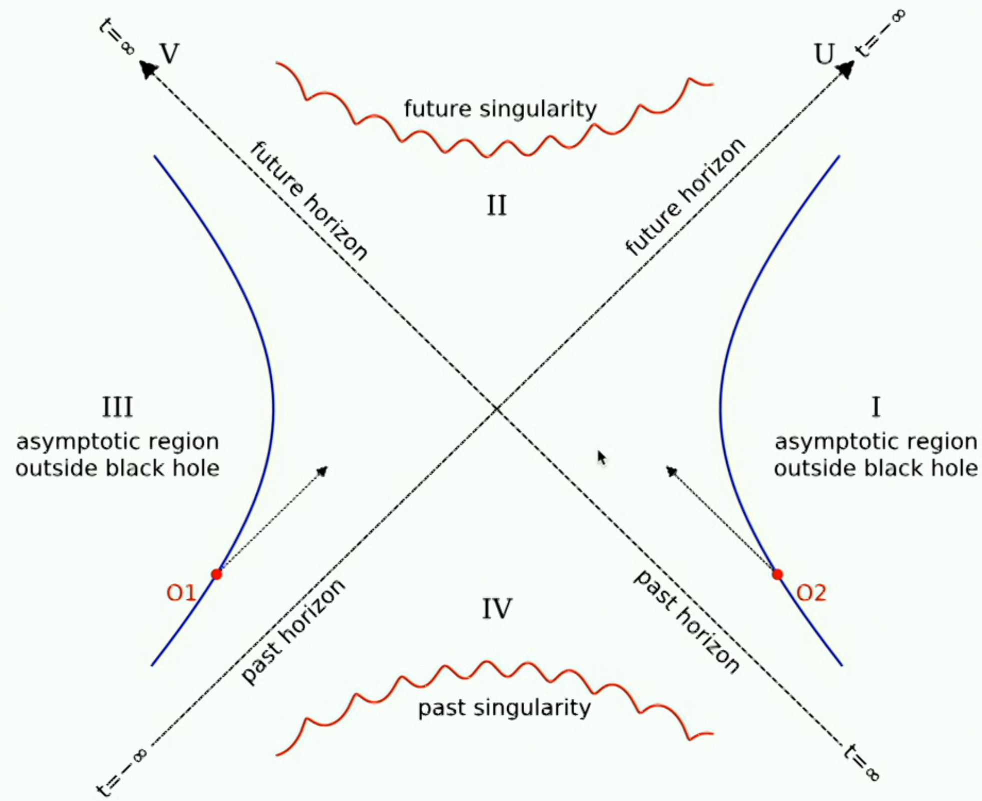
J. Maldacena, D. Stanford, and Z. Yang, arXiv:1704.05333

P. Gao and D. Jafferis, arXiv:1911.07416

- So simulating the SYK model is as close as you can get to black hole quantum dynamics
- We can be even more ambitious by looking at the dynamics of two entangled copies of the SYK model
- This can be related to the dynamics of traversable wormholes

Wormholes in AdS/CFT

- **In the theoretical laboratory of AdS/CFT there is rigorous connection between quantum entanglement and wormholes**
- One makes an ER bridge from two AdS black holes
- Now the two asymptotic regions are actually the boundaries of the anti-de Sitter spaces



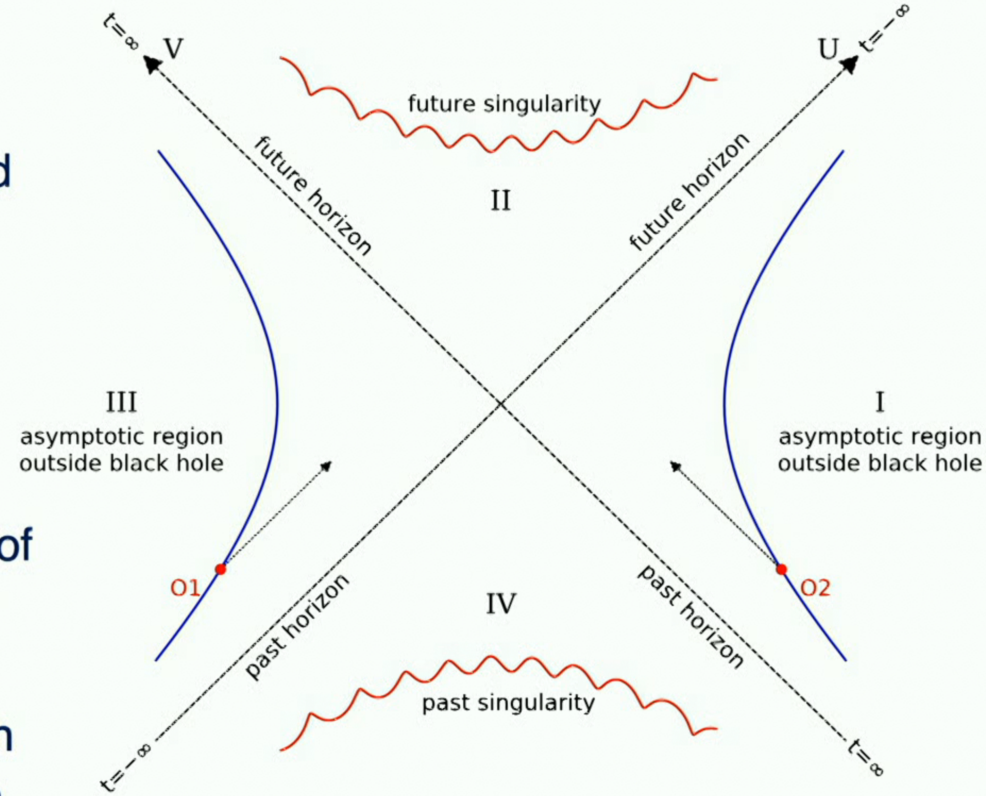
J. Maldacena, hep-th/0106112

Wormholes from entanglement

- The AdS/CFT duality then says that the ER bridge is an entangled state of two quantum field theories living on the boundaries, written as a "thermofield double state":

$$|\mathrm{TFD}(\beta)\rangle = \frac{1}{Z(\beta)} \sum_n \mathrm{e}^{-\beta E_n/2} |n\rangle_L |n'\rangle_R$$

- Since the two black hole exterior regions are causally disconnected, if you want a description of either one you should trace out the states of the other one in the TFD
- This gives a thermal state density matrix for each individual black hole at the Hawking temperature, with entanglement entropy = the Bekenstein-Hawking entropy

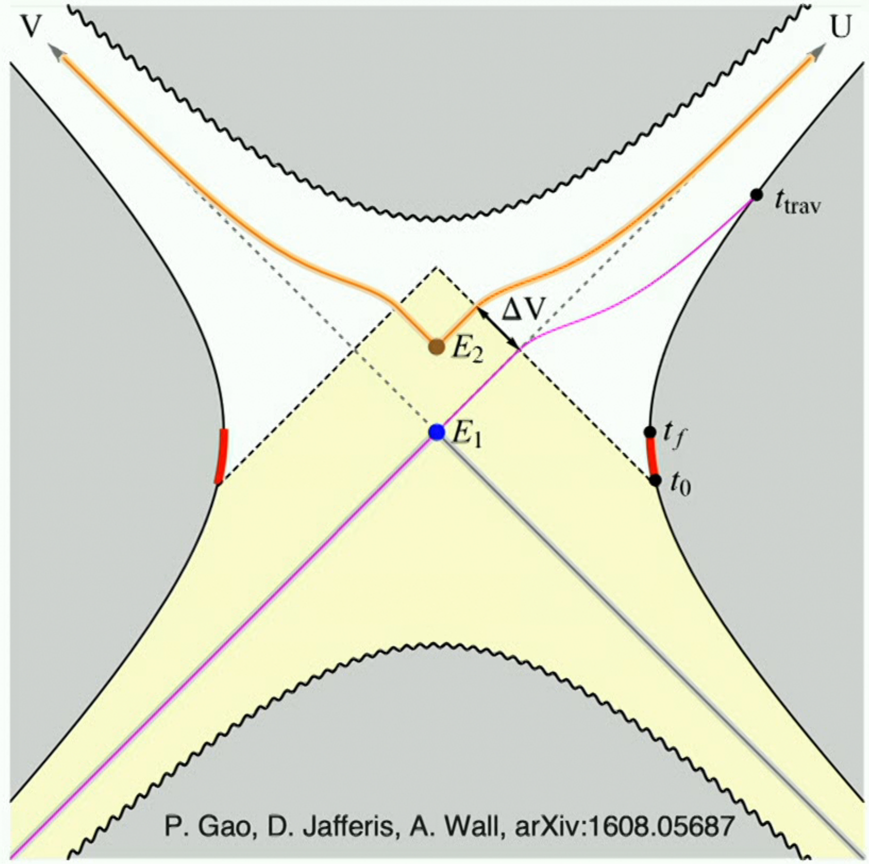


J. Maldacena, hep-th/0106112

Traversable wormholes

P. Gao, D. Jafferis, A. Wall, arXiv:1608.05687

- In 2016 Gao, Jafferis, and Wall showed how to make traversable wormholes
- This requires a quantum effect acting as a negative energy flux that shrinks the horizon
- This will open up a route that is traversable for some period of time
- A similar quantum effect is responsible for Hawking radiation from black holes



W. Unruh, Phys. Rev. D14 (1976) 870

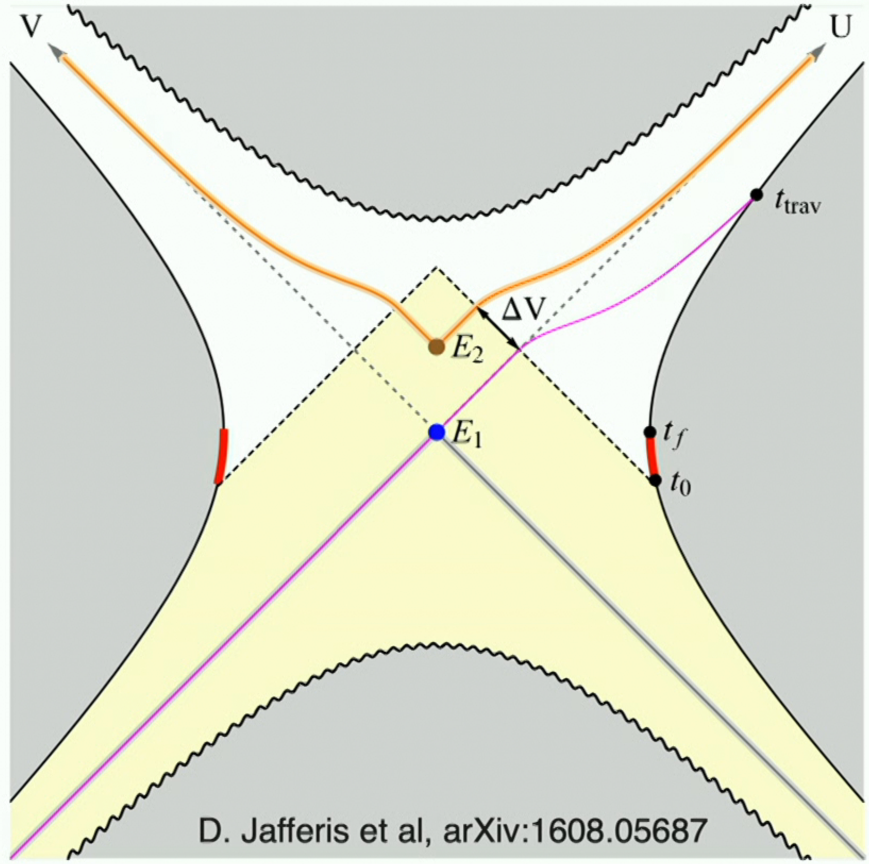
N.B. Unruh's effect and insights on HR vs st curvature and entanglement

- The Unruh effect is a property of quantum entanglement as applied to the vacuum of 4D Minkowski space $ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$

Wormhole teleportation

D. Jafferis et al, arXiv:1608.05687

- To make this happen, I need some operator that explicitly couples the two sides
- In terms of operators in the L/R asymptotic regions, I can write: $H_L + H_R + \mu O_L O_R$
- Where O_L, O_R are operators in the L/R asymptotic regions, and it is understood that I only use them in the time evolution starting at some time t_0 and ending at t_f
- You have to choose the sign of μ correctly to get a negative energy pulse



ER = EPR hypothesis

A. Einstein and N. Rosen, Phys. Rev. 48, 73 (1935)

A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47, 777 (1935)

J. Maldacena and L. Susskind, arXiv:1306.0533

J. Maldacena, arXiv:hep-th/0106112

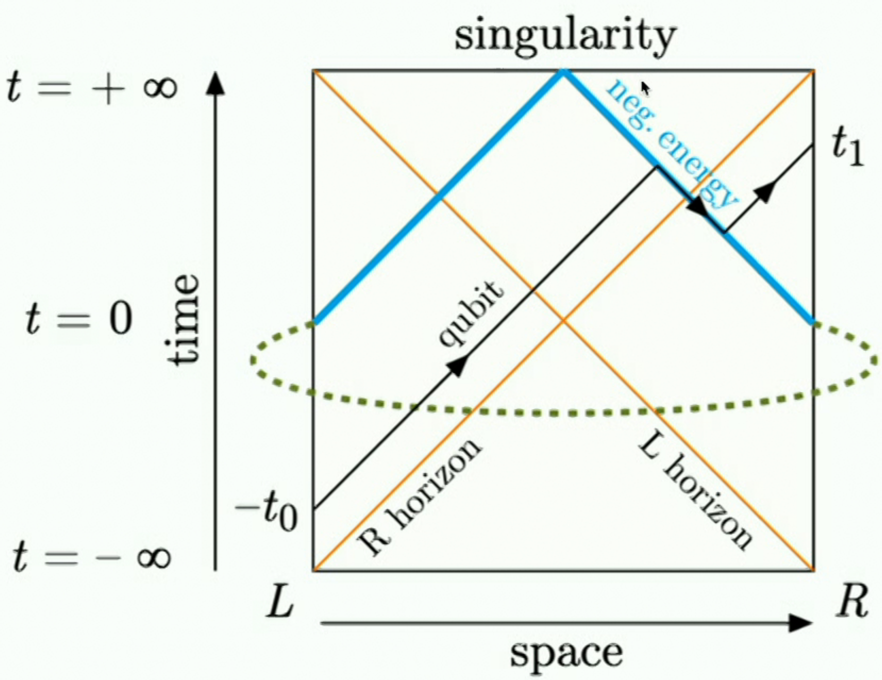
Maldacena and Susskind in 2013 argued that the 1935 ER paper on wormholes and the 1935 EPR paper on entanglement are actually talking about the same thing

- The Einstein-Rosen bridge occurs because the two black holes are entangled

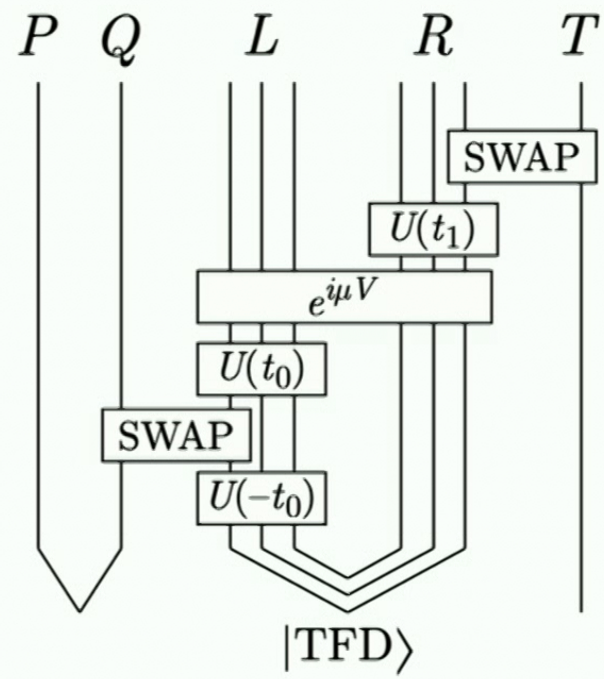
- More generally, wormholes are a result of entanglement between certain kinds of quantum systems

The ER=EPR hypothesis asserts that traversable wormholes always have an equivalent physical description as some form of quantum teleportation

Dual descriptions of the same physical process

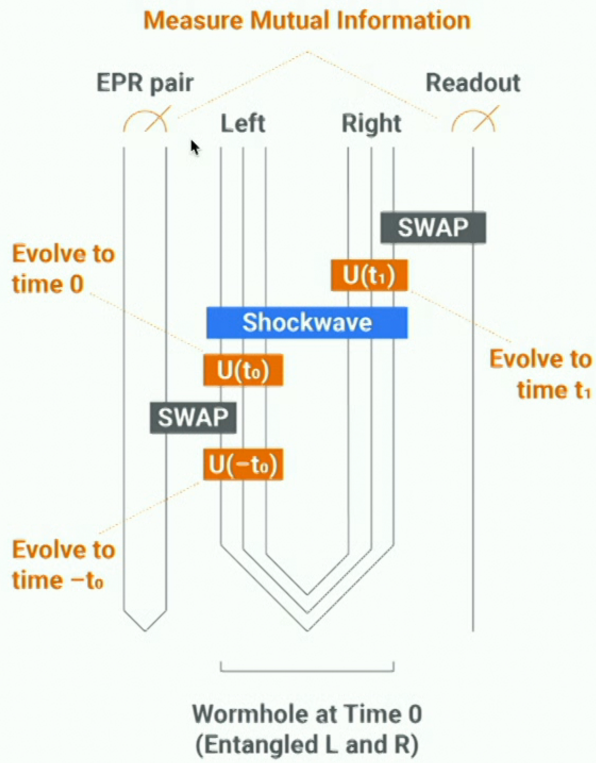


Traversable wormhole (gravity)



Many-body teleportation (quantum)

The protocol



Left: *Quantum circuit describing a traversable wormhole. A maximally entangled pair of qubits ("EPR pair") are used as an entanglement probe to send a qubit through the wormhole. The qubit is swapped into the left side of the wormhole at time $-t_0$; the energy shockwave is applied at time 0; and the right side of the wormhole is measured at time t_1.* ***Right****: Photograph of the Google Sycamore quantum processor.*

SYK wormholes

J. Maldacena, D. Stanford, and Z. Yang, arXiv:1704.05333

P. Gao and D. Jafferis, arXiv:1911.07416

In a certain regime of parameters: $N \gg q \gg J\beta \gg 1$

it has been shown explicitly that a thermofield double state (i.e. entangled state) of two SYK systems exhibits holographic duality:

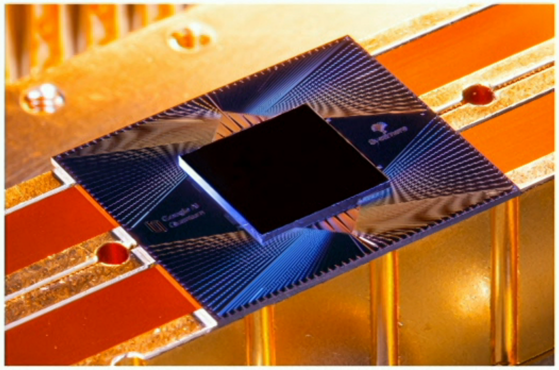
- In one description you see a new kind of many-body quantum teleportation between the two systems, where a message qubit gets swapped into one SYK system, then later appears in the other SYK system
- In the physically equivalent dual description, the quantum information of the message qubit propagates through a wormhole

$$G_N \sim \frac{qJ\beta}{N}$$

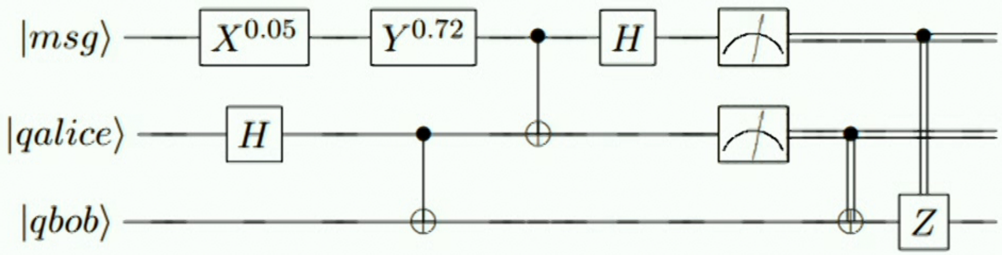
So the ER = EPR hypothesis is correct in this regime

Quantum teleportation in the laboratory

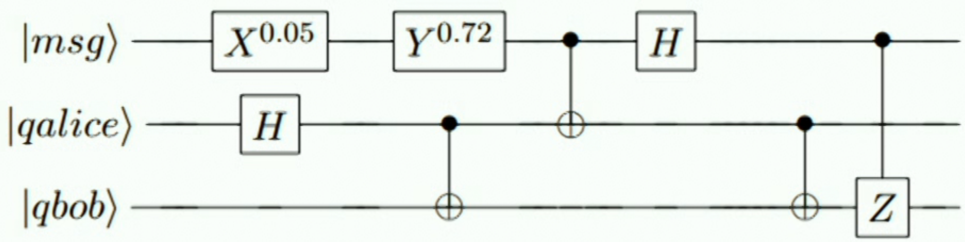
Quantum teleportation can be performed as a quantum circuit on a quantum processor



Google Sycamore
quantum processor



Example of a quantum circuit that performs
(short-range) quantum teleportation



Can we do through-the-wormhole teleportation on a quantum processor?

If you are using the SYK model with N Majoranas, then you need a quantum processor with at least N qubits to realize two copies of it

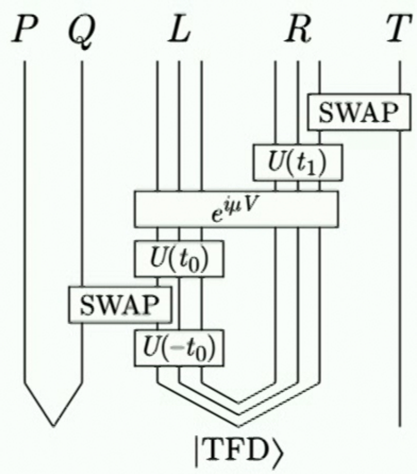
Furthermore, for, e.g., N=50 and q=8, the SYK Hamiltonian has 536 million terms

So the real challenge is circuit depth

SYK wormhole for smaller N?

We showed, using a simulation on a classical computer, that you can exhibit through-the-wormhole teleportation using two copies of the N=10, q=4 SYK model

For N=10 and q=4, the SYK Hamiltonian has 210 terms



For the L-R interaction we use

$$V = \frac{1}{qN}\sum_{j=1}^{N} \psi_L^j \psi_R^j$$

This is small enough to simulate on a classical computer, but still much to complicated to run on Google Sycamore

How do you know it is through-the-wormhole teleportation?

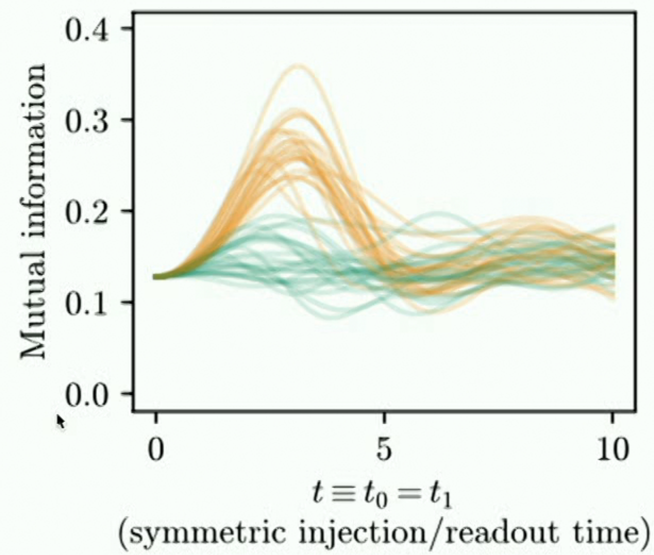
By simulating on a classical computer, we can exhibit several distinctive physical properties of through-the-wormhole teleportation:

The teleportation has a characteristic time scale:

- the "door" is only open for a finite time, and it takes time to traverse the wormhole
- implies that the mutual information between the initial and final qubits peaks at a characteristic time

The teleportation requires negative sign of the coupling μ corresponding to a negative energy pulse

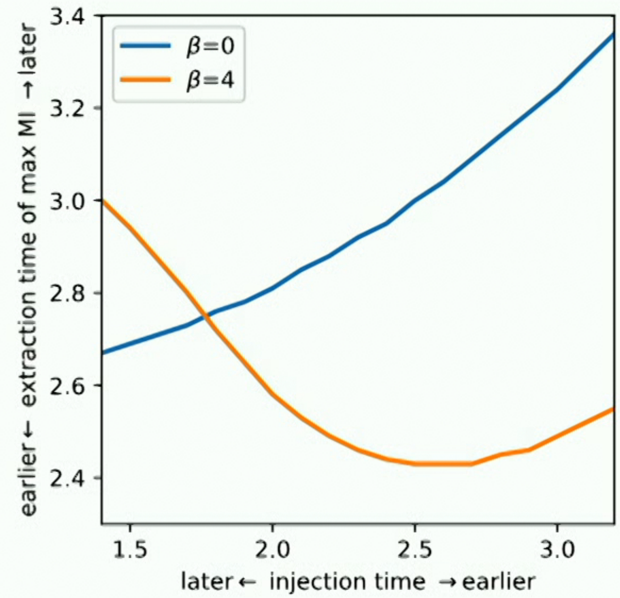
Note that there is also some non-wormhole many-body teleportation going on, as expected



Teleportation for two copies of N=10, q=4 SYK single instantiations.
orange = negative energy pulse
green = positive energy pulse

Causal time ordering for successive teleports:

- In our simulation we see the “first in, first out” time ordering characteristic of through-the-wormhole teleportation (orange curve)
- We can also exhibit the “first in, last out” time ordering characteristic of non-wormhole many-body teleportation, by looking at infinite temperature, where the wormhole teleportation is not expected to occur (blue curve)
- Note that the orange curve also turns up at later times, since after the wormhole “door closes” the non-wormhole teleportation always dominates

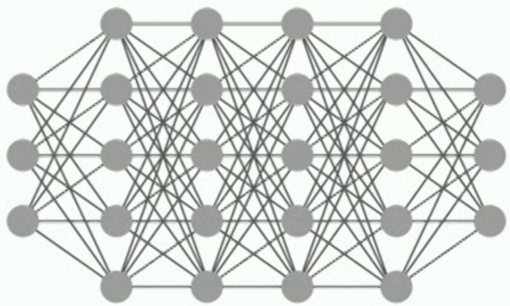


injection time vs optimal extraction time for two copies of N=10, q=4 SYK, a single instantiation
orange = low temperature
blue = infinite temperature

Learned sparsification of coupled copies of the SYK model

We developed a method, using tools from AI, to sparsify the SYK Hamiltonian while preserving the traversable wormhole-like dynamics

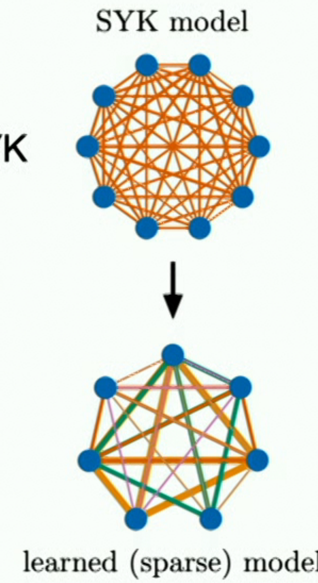
Analogue to neural network:



Dataset $\Leftrightarrow I_{PT}(t)$ for $N = 10$ SYK

Weights $\Leftrightarrow$ SYK coefficients

Train via backpropagation
with regularization to sparsify H



$$\mathcal{L} = \sum_{\pm\mu} \left[\int_0^T \left(I_{PT}^{\mathrm{SYK}}(t;\mu) - I_{PT}^{\mathrm{sparse}}(t;\mu)\right)^2 \mathrm{d}t + \lambda \sum \left|J_{ijkl}^{\mathrm{sparse}}\right|\right], t \equiv t_0 = t_1$$

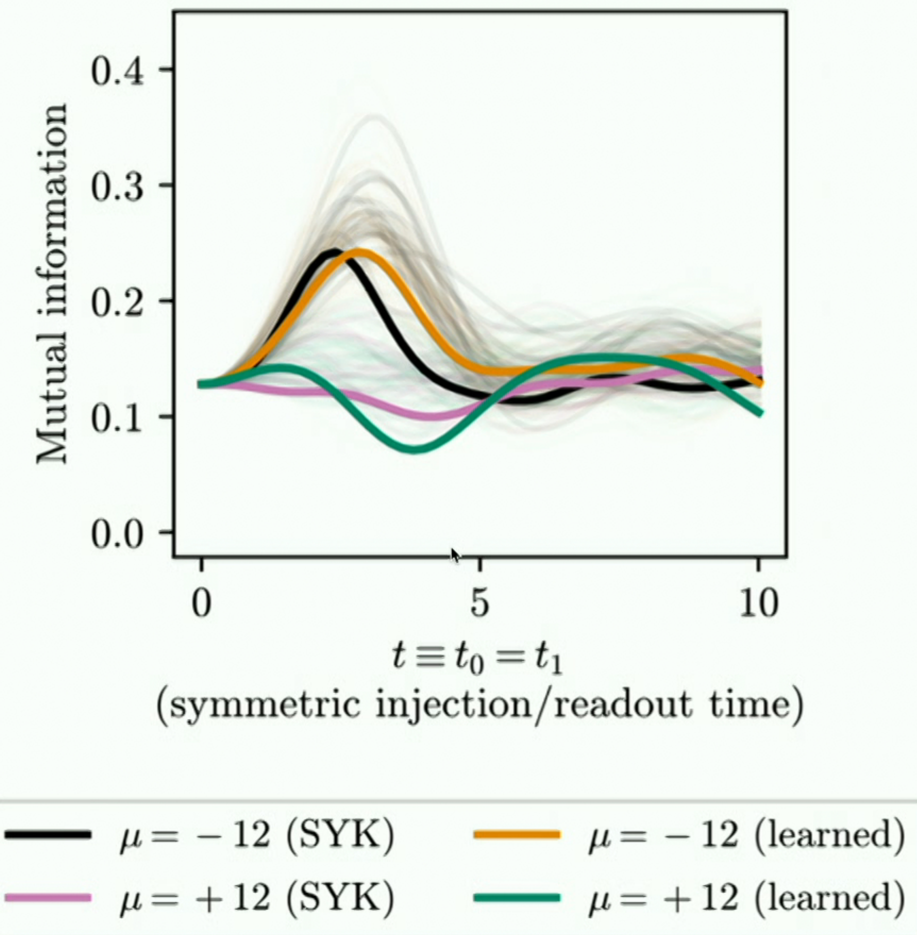
$$H = -0.36\psi^1\psi^2\psi^4\psi^5 + 0.19\psi^1\psi^3\psi^4\psi^7 - 0.71\psi^1\psi^3\psi^5\psi^6 \\ +0.22\psi^2\psi^3\psi^4\psi^6 + 0.49\psi^2\psi^3\psi^5\psi^7$$

Dynamics of sparsified model vs two copies of N=10 SYK

Shows a similar mutual information peak with correct asymmetry with respect to the sign of the interaction

Also shows the wormhole-like time ordering

As an even more rigorous check, we looked at "size winding"



Size winding for through-the-wormhole teleportation

As shown by the Stanford group, one can make a detailed mapping between the operator growth of fermions in the SYK dynamics and a fermion propagating through the wormhole:

A. Brown et al, arXiv:1911.06314
A. Brown et al, arXiv:2102.01064

Starting e.g. with $\psi^1(t=0)$, after some time t the effective thermal fermion operator becomes a sum of products of strings of fermions:

$$\rho_\beta \psi^1(t) = \sum_P c_P \psi^P$$

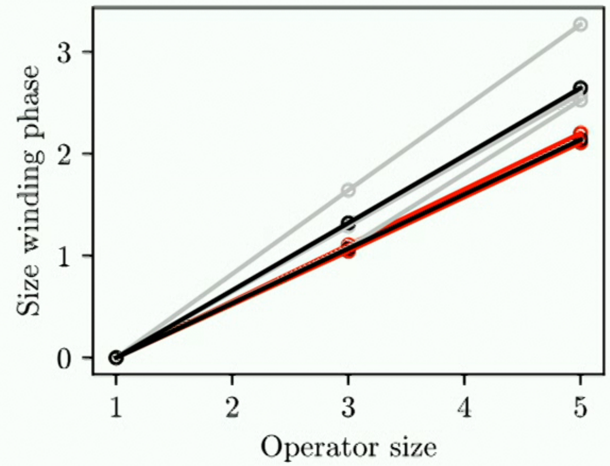
$$\rho_\beta = \mathrm{e}^{-\beta H} / \mathrm{tr}\ \mathrm{e}^{-\beta H}$$

From the coefficients c_P describing this operator growth, define a "winding size" distribution $q(\ell) = \sum_{|P|=\ell} c_P^2$

Then the Fourier transform of this distribution describes the bulk location in the wormhole, and one can see explicitly that the L-R interaction kicks the fermion to the other side of the horizon

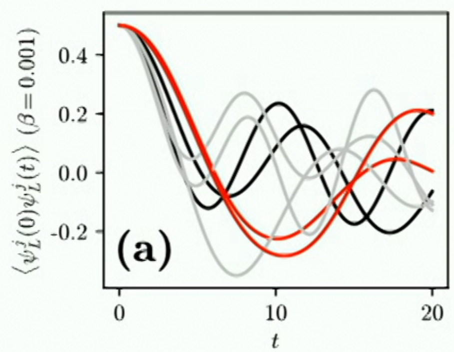
Size winding of sparsified model

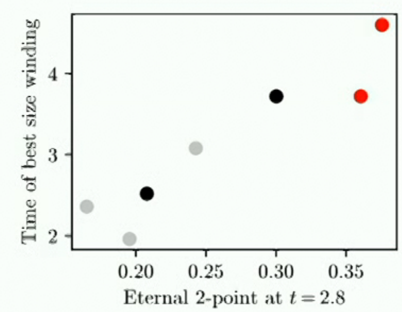
The through-the-wormhole interpretation (assuming only gravitational dynamics) requires that the size winding phase be linear in the effective thermal fermion operator size



We see this for all 7 fermions of the sparsified model

And as expected, the time of best size winding increases inversely to the mass of the fermion (as extracted from the 2-point function)



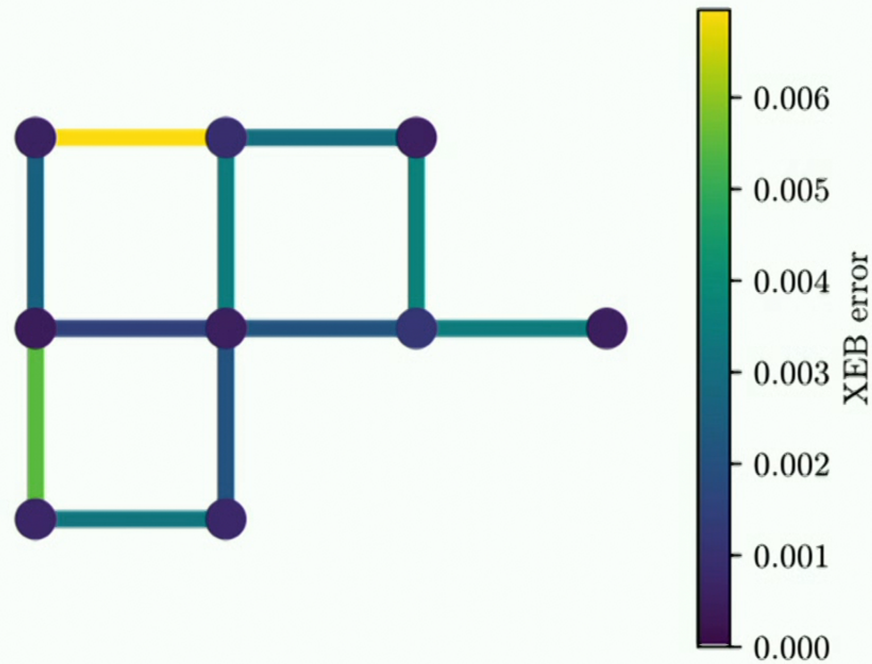


Two-qubit gate errors on Google Sycamore

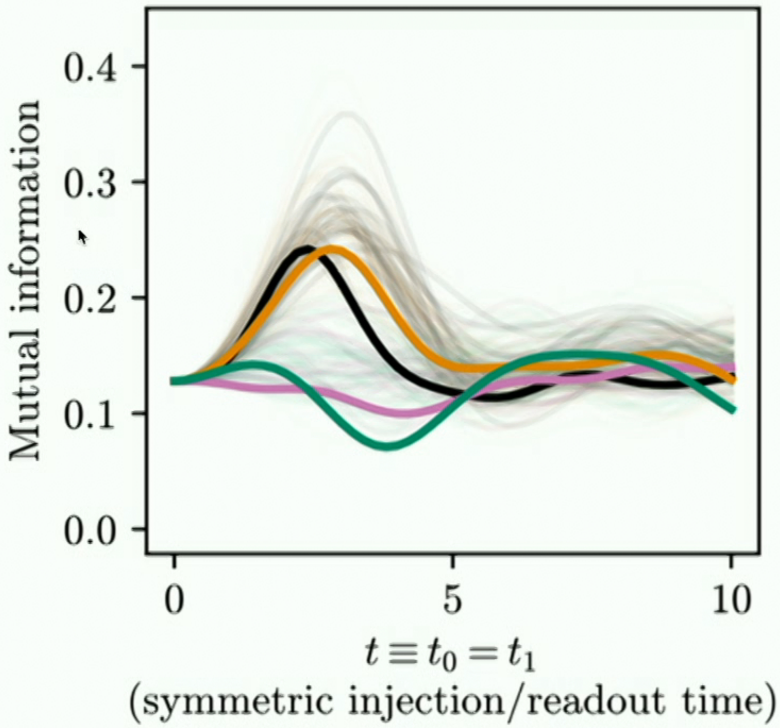
As measured on the nine qubits used for the actual experiment

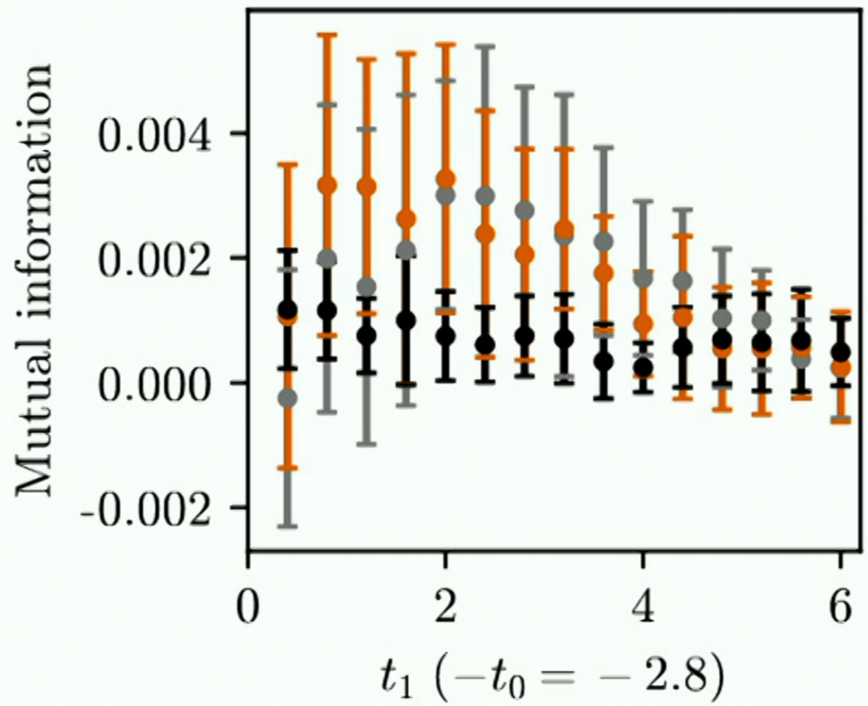
The complete circuit required only 164 two-qubit gates

In principle this should work



Quantum experiment on Google Sycamore: Results from 90,000 trials





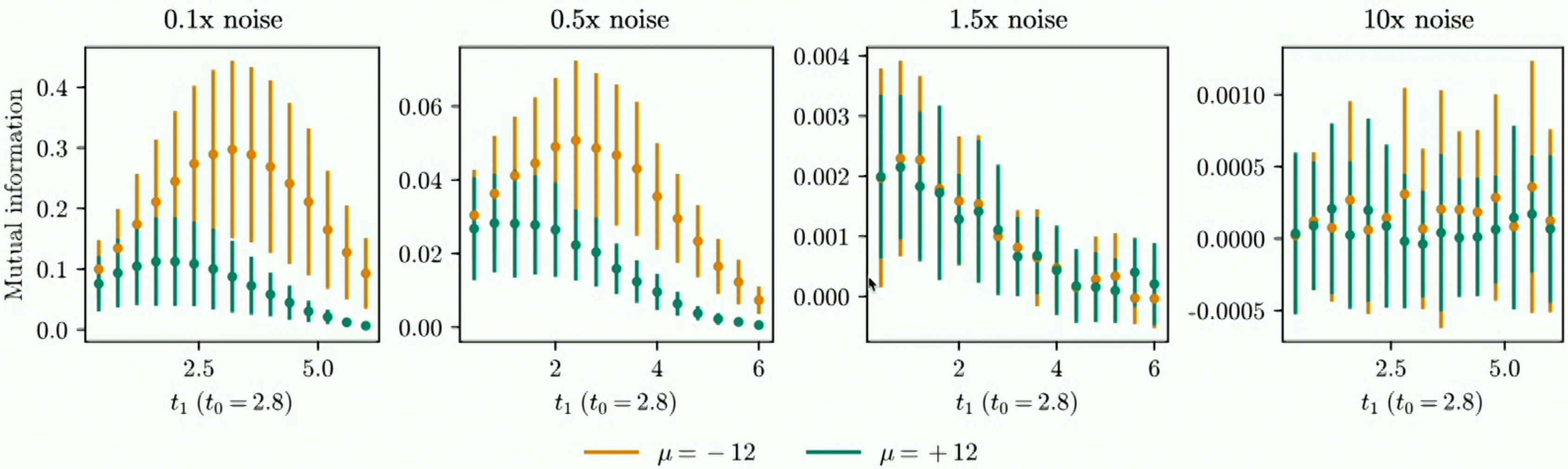
Quantum experiment on Google Sycamore: What this is and is not

This is not drilling a hole in ordinary spacetime (obviously)

This is also not just a numerical computation (obviously):

- Classical computers can only simulate quantum entanglement and quantum teleportation
- But quantum computers can actually produce quantum entanglement and perform quantum teleportation (including through-the-wormhole teleportation) as a physical event

Outlook



- Better performance of quantum computers expected in the coming years
- This will rapidly increase our ability to do these kind of experiments, e.g., reducing the noise by a factor of 2 will increase the signal by a factor of 10
- With more qubits and better performance, you get a more fine-grained system and can experimentally probe more detailed features

Outlook

- The wormhole teleportation system we discussed here, with 9 qubits is simple enough to simulate the full quantum dynamics on a classical computer
- But once we get to 50-100 qubits, it will not be possible to simulate the wormhole dynamics on a classical computer any more
- However, this regime is still not in the semiclassical limit either, so it will exhibit features difficult (if not impossible) to calculate using the analytical methods of the string theorists
- To explore this "mesoscopic" quantum gravity regime, we will need a program of experiments on suitable quantum processors

What can we learn?

- One can try to measure physical properties of the wormhole interior such as the bulk curvature
- The bulk gravity system will generically have non-gravitational modes that show up, e.g., as interactions that reduce the teleportation fidelity. In AdS/CFT these are string modes – what are they in these experiments?
- The SYK model is presumably not the only way to exhibit through-the-wormhole teleportation; what other quantum systems do this? What do they have in common?
- Does the wormhole description of teleportation imply some kind of error protection?
- How exactly does emergent space get built from quantum entanglement?