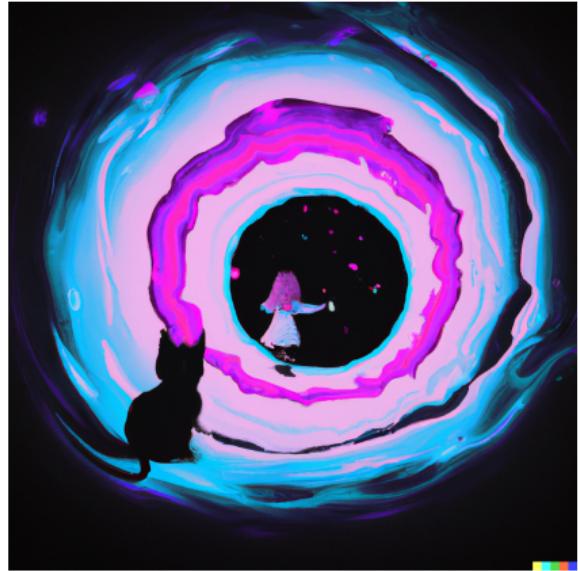


Did physicists create a wormhole in the lab?

*AdS/CFT, SYK, wormholes, ER = EPR,
Sycamore, AI, and all that*



DALL-E "Alice and the cat from Alice in Wonderland going down a blackhole in synthwave style"

Antoine Tilloy

November 28th, 2022
Christmas TLS



A recent breakthrough?

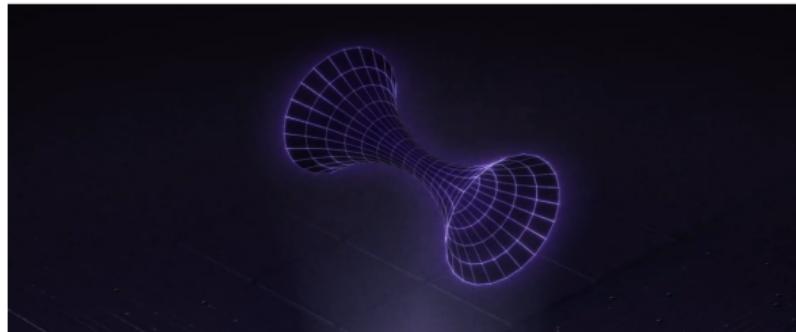


QUANTUM GRAVITY

Physicists Create a Holographic Wormhole Using a Quantum Computer

52 | ■

The unprecedented experiment explores the possibility that space-time somehow emerges from quantum information, even as the work's interpretation remains disputed.



A recent breakthrough?

- ▶ **Quanta magazine:**

The unprecedented experiment explores the possibility that space-time somehow emerges from quantum information

A recent breakthrough?

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- ▶ **Nature article:**

This work is a successful attempt at observing traversable wormhole dynamics in an experimental setting.

A recent breakthrough?

- ▶ **Quanta magazine:**

The unprecedented experiment explores the possibility that space-time somehow emerges from quantum information

- ▶ **Nature article:**

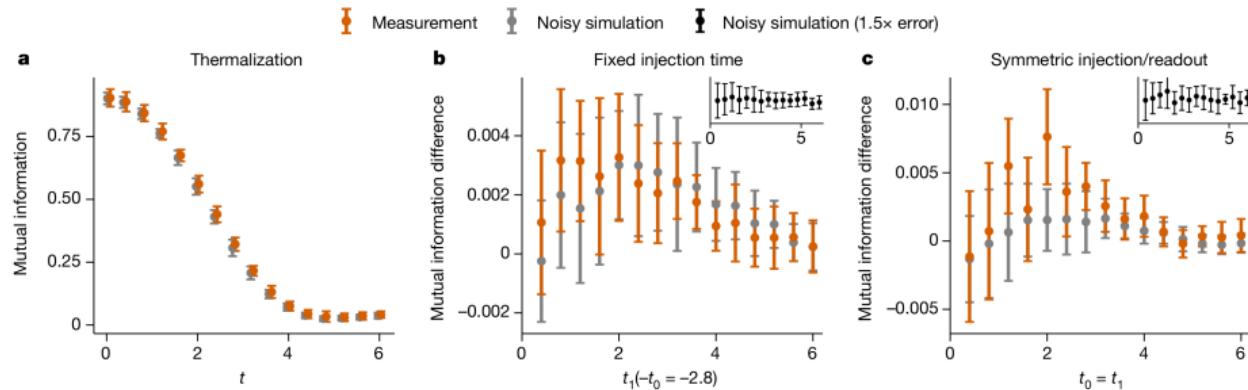
This work is a successful attempt at observing traversable wormhole dynamics in an experimental setting.

- ▶ **France Info:**

Alors, les trous de ver existent ? En un sens, oui : l'ordinateur quantique a reproduit toutes les caractéristiques du trou de ver : deux paquets de particules séparées ont été connectées, via une sorte de tunnel, une particule supplémentaire a été ajoutée d'un côté. Et elle est ressortie de l'autre. Ça donne corps à cette vieille idée de la physique, qui avait été posée en 1935 par Einstein, comme une solution possible de sa théorie de la relativité.

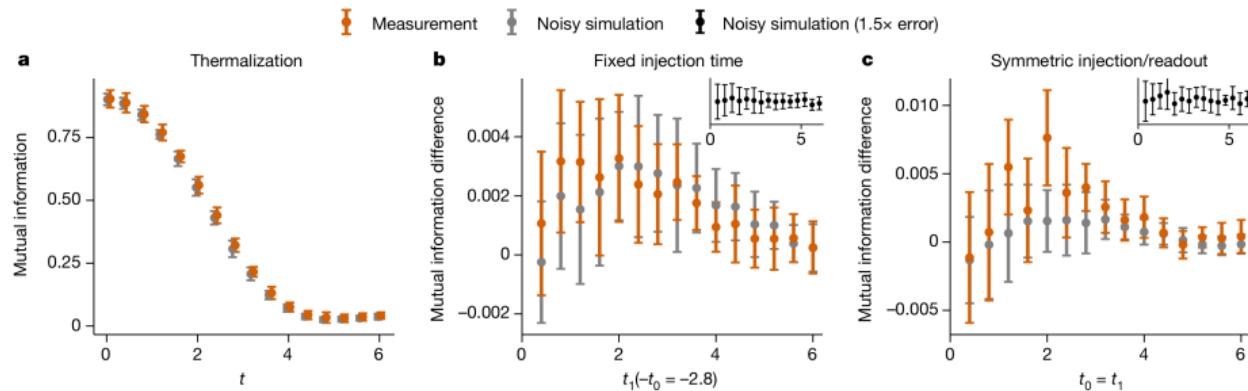
Actually

An experiment on 9 qubits with 164 two-qubit gates:



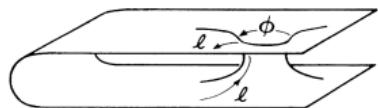
Actually

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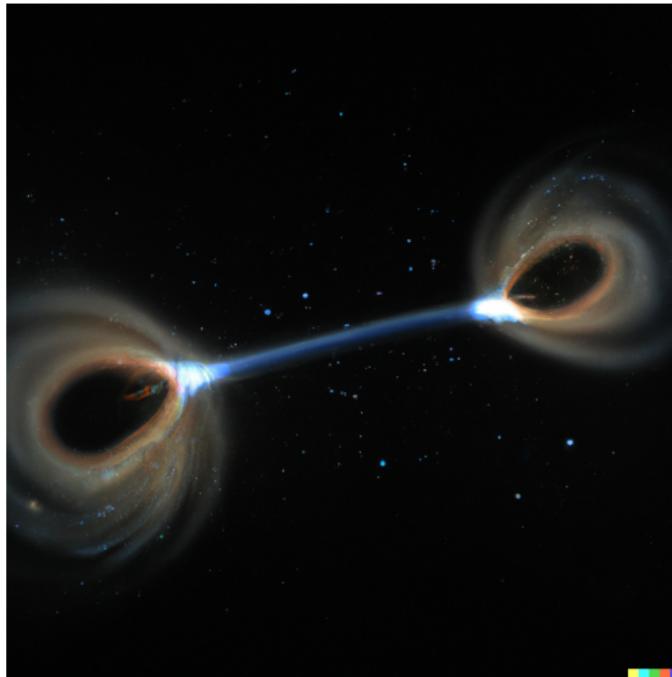
Objective

Debunk the claims while understanding a bit more of the jargon



1. General relativity and Einstein-Rosen bridges
2. Holography
3. Sachdev-Ye-Kitaev model
4. The experiment (AI sparsification)

General Relativity, Black holes, and Einstein-Rosen bridges



DALL-E "Two astrophysical blackholes connected by a thin tube"

General relativity

- ▶ Matter follows geodesics in space-time $\partial_\mu \rightarrow D_\mu$
- ▶ Space-time is curved by matter

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Black holes I

Über das Gravitationsfeld eines Massenpunktes
nach der EINSTEINSchen Theorie.

Von K. SCHWARZSCHILD.

(Vorgelegt am 13. Januar 1916 [s. oben S. 42].)

Schwarzschild's metric

$$ds^2 = -\frac{1}{1-2m/r}dr^2 - r^2(d\theta^2 + \sin(\theta)^2d\phi^2) + (1-2m/r)dt^2$$

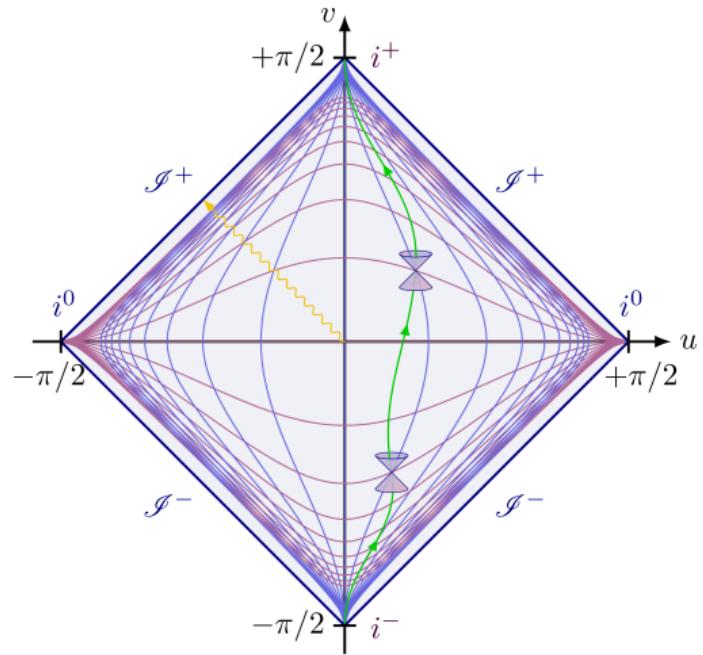
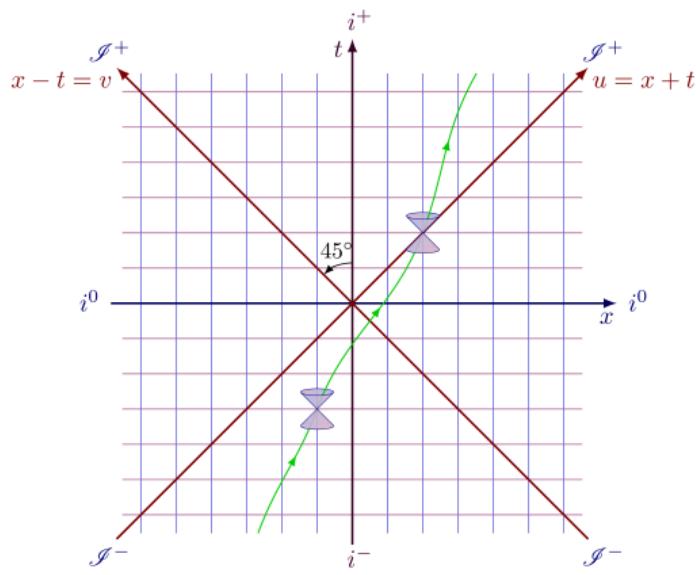
Spherically symmetric solution without matter, i.e. $T_{\mu\nu} = 0$
→ weird at $r = 2m$

Intermezzo: Penrose's conformal coordinates

Minkowsky space-time

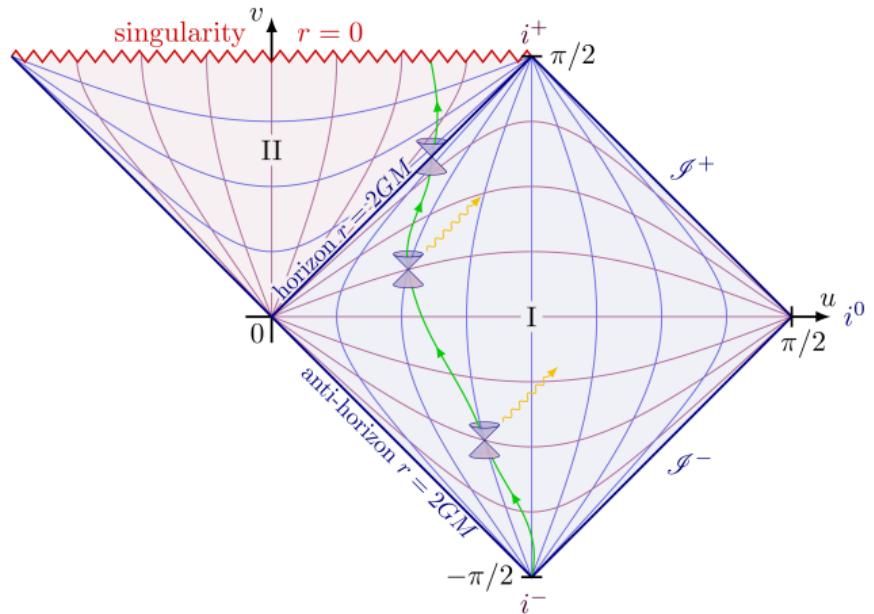
$$x + t = \tan(u + v) \text{ and } x - t = \tan(u - v)$$

perserves local lightcones!



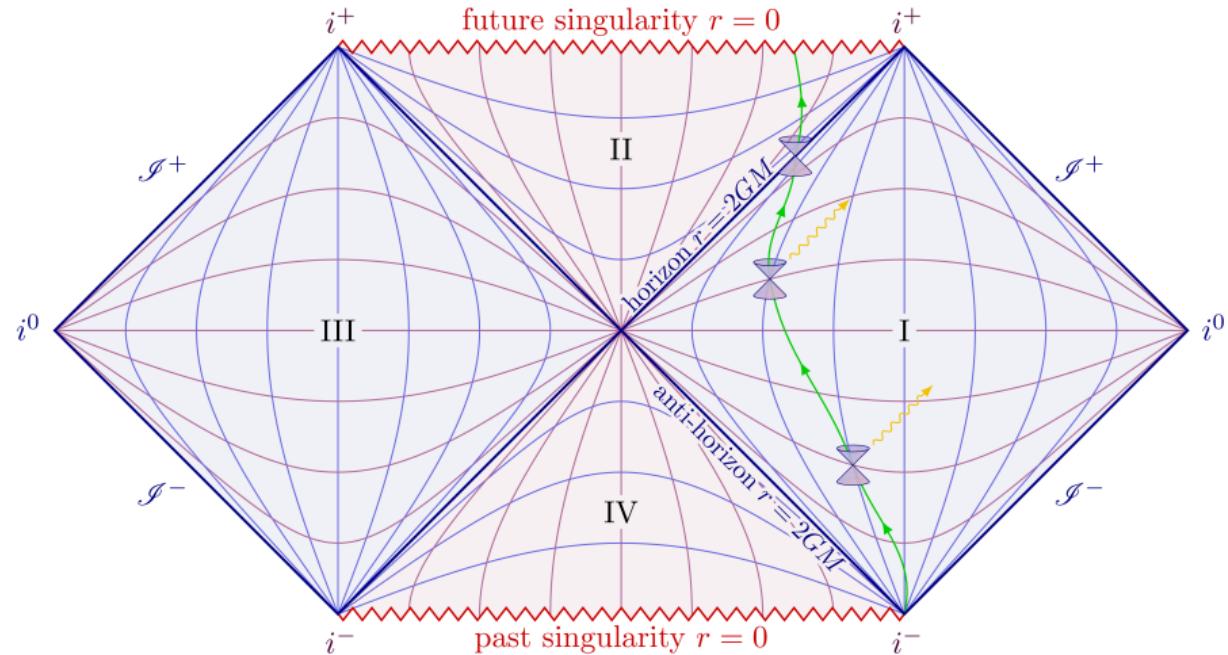
Black holes II: Penrose coordinates

Schwarzschild's space-time in spherical coordinates (r, t) \rightarrow Kruskal coordinates (U, V) \rightarrow Penrose conformal coordinates (u, v)



credit Izaak Neutelings

Black holes III: Maximally extended solution

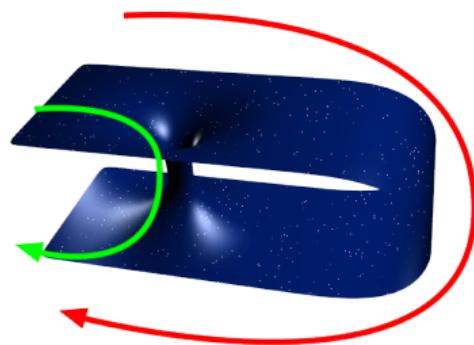
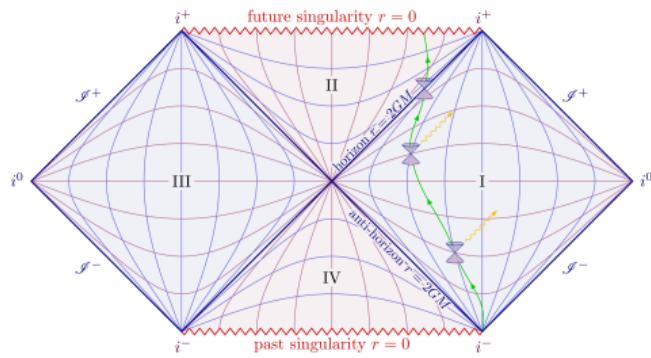


credit Izaak Neutelings

A (non-traversable) wormhole or Einstein-Rosen bridge

A (non-traversable) wormhole

Interesting if I and III are two patches of the same space-time

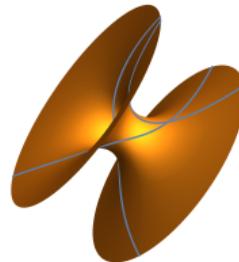


Falling into two different black holes, you could fall into the same interior

A traversable wormhole?

Proposed by Ellis and Bronnikov in 1973

Rediscovered and popularized by Thorne in 1988



1. Has geodesics joining both sides!
2. Not a solution of Einstein's equation in a vacuum (unstable)
3. Requires negative energy to stay open

ER = EPR

MAY 15, 1935

PHYSICAL REVIEW

VOLUME 47

JULY 1, 1935

PHYSICAL REVIEW

VOLUME 48

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in

quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

The Particle Problem in the General Theory of Relativity

A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*

(Received May 8, 1935)

The writers investigate the possibility of an atomistic theory of matter and electricity which, while excluding singularities of the field, makes use of no other variables than the $g_{\mu\nu}$ of the general relativity theory and the ϕ_{μ} of the Maxwell theory. By the consideration of a simple example they are led to modify slightly the gravitational equations which then admit regular solutions for the static spherically symmetric case. These solutions involve the mathematical representation of physical space by a space of two identical sheets, a particle being represented by a "bridge" connecting these sheets. One is able to understand why no neutral particles of negative mass are to be

found. The combined system of gravitational and electromagnetic equations are treated similarly and lead to a similar interpretation. The most natural elementary charged particle is found to be one of zero mass. The many-particle system is expected to be represented by a regular solution of the field equations corresponding to a space of two identical sheets joined by many bridges. In this case, because of the absence of singularities, the field equations determine both the field and the motion of the particles. The many-particle problem, which would decide the value of the theory, has not yet been treated.

Maldacena and Susskind 2013

Black holes connected by a bridge are a lot like EPR pairs.

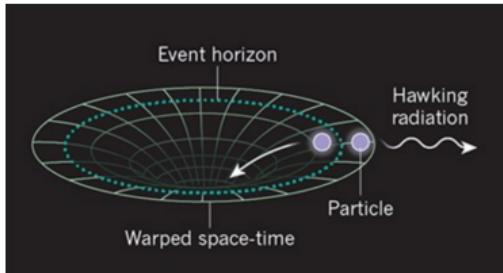
- ▶ funky non-local stuff going on
- ▶ no information transferable

What if it's the same thing?

From vague analogy to duality to equality

Holography and AdS/CFT

Holographic duality



Bekenstein-Hawking formula

A black hole with an event horizon of area A has entropy

$$S_{BH} = \frac{k_B}{4\ell_P^2} A$$

As if the “relevant” degrees of freedom lie on the surface

The original Maldacena duality

The Large- N Limit of Superconformal Field Theories and Supergravity

Juan Maldacena[†]

Received September 15, 1998

We show that the large- N limits of certain conformal field theories in various dimensions include in their Hilbert space a sector describing supergravity on the product of anti-de Sitter spacetimes, spheres, and other compact manifolds. This is shown by taking some branes in the full M/string theory and then taking a low-energy limit where the field theory on the brane decouples from the bulk. We observe that, in this limit, we can still trust the near-horizon geometry for large N . The enhanced supersymmetries of the near-horizon geometry correspond to the extra supersymmetry generators present in the superconformal group (as opposed to just the super-Poincaré group). The 't Hooft limit of $3 + 1 \times 4$ super-Yang-Mills at the conformal point is shown to contain strings: they are IIB strings. We conjecture that compactifications of M/string theory on various anti-de Sitter spacetimes are dual to various conformal field theories. This leads to a new proposal for a definition of M-theory which could be extended to include five noncompact dimensions.

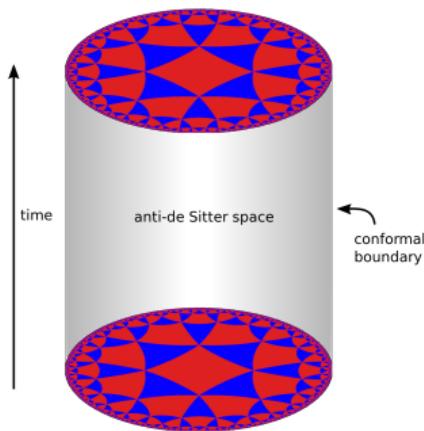
Conjecture by Maldacena, 1998

The following two theories are “dual” to each other

- ▶ Type II-B string theory on $AdS_5 \times S_5$
- ▶ $N = 4$ supersymmetric Yang-Mills quantum field theory

→ Most cited paper in high energy theory (~ 23000)

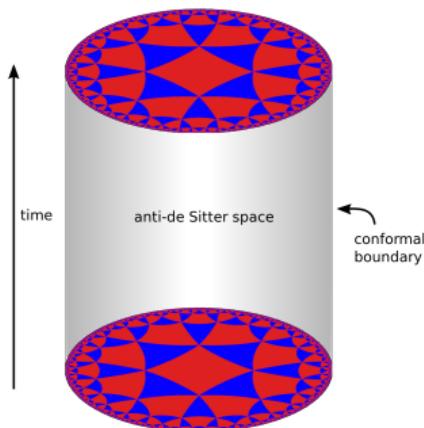
AdS / CFT correspondence



One should always be able to relate observables in

1. Conformal Field Theories **CFT** in d dimensions
2. Gravitational Theories in $d + 1$ dimensional anti de Sitter space **AdS**

AdS / CFT correspondence



One should always be able to relate observables in

1. Conformal Field Theories **CFT** in d dimensions
2. Gravitational Theories in $d + 1$ dimensional anti de Sitter space **AdS**

From conjecture to correspondence and from duality to equality

Comment: our universe is **dS**

Traversable holographic wormhole

Gao – Jafferis – Wall 2017

Add an interaction term between two *holographic* black holes L and R

$$H_{\text{CFT}} \rightarrow H_{\text{CFT}} + \mu \int \mathcal{O}_L \otimes \mathcal{O}_R$$

Information can now be sent from one BH to the other

Traversable holographic wormhole

Gao – Jafferis – Wall 2017

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$$H_{\text{CFT}} \rightarrow H_{\text{CFT}} + \mu \int \mathcal{O}_L \otimes \mathcal{O}_R$$

Information can now be sent from one BH to the other

- ▶ Sort of obvious without invoking gravity
- ▶ Fancy on the gravity side (“wormhole is held open by a negative energy pulse”)
- ▶ They call it “quantum teleportation” through the wormhole

The Sachdev-Ye-Kitaev model

Definition

It is a model of N Majorana fermions with all possible random 4-body interaction

$$H = -\frac{1}{4!} \sum_{i_1, i_2, i_3, i_4=1}^N J_{i_1 i_2 i_3 i_4} \psi_{i_1} \psi_{i_2} \psi_{i_3} \psi_{i_4}$$

- ▶ $\psi_i^\dagger = \psi_i$ and $\{\psi_i, \psi_j\} = 2\delta_{ij}$
- ▶ J_{ijkl} independent Gaussian random variables

Definition

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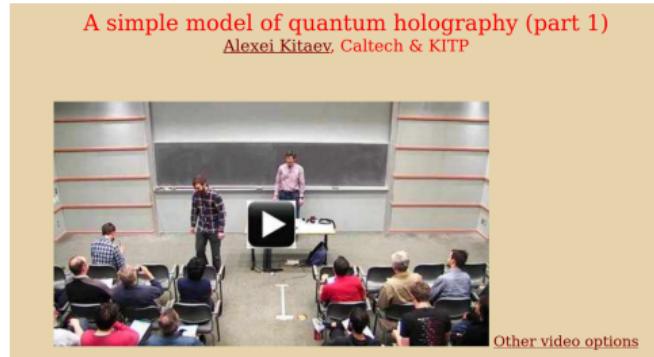
$$H = -\frac{1}{4!} \sum_{i_1, i_2, i_3, i_4=1}^N J_{i_1 i_2 i_3 i_4} \psi_{i_1} \psi_{i_2} \psi_{i_3} \psi_{i_4}$$

- ▶ $\psi_i^\dagger = \psi_i$ and $\{\psi_i, \psi_j\} = 2\delta_{ij}$
- ▶ J_{ijkl} independent Gaussian random variables

Interesting features

1. Maximally chaotic
2. Solvable at $N \rightarrow +\infty$

SYK duality



Duality to JT gravity – Kitaev 2019

SYK (0+1 dimensions) at large N is dual to Jackiw–Teitelboim gravity (toy model of gravity in $1 + 1$ dimensions)

SYK looks like it describes the point boundary of toy gravity in $1 + 1$ dimensions

SYK “traversable wormhole”

Gao - Jafferis 2021

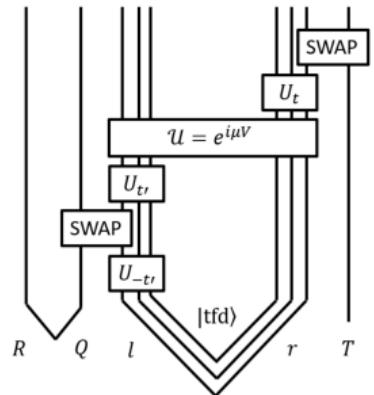
Take two SYK models,
Initialize the pair in a “thermofield double state”

$$|\psi\rangle = \sum_n e^{-\beta E_n/2} |n\rangle_L |n\rangle_R$$

couple them with

$$V = \mu \sum_i \psi_i^L \psi_i^R$$

Tuning μ you transfer information well from L to R



- ▶ Surprising? we added by hand what is needed!

The experiment



Albert Einstein riding a unicorn on the surface of the moon, in the style Hergé

The paper

Traversable wormhole dynamics on a quantum processor

<https://doi.org/10.1038/s41586-022-05424-3>

Received: 22 February 2022

Accepted: 7 October 2022

 Check for updates

Daniel Jafferis^{1,7}, Alexander Zlokapa^{2,3,4,5,7}, Joseph D. Lykken⁶, David K. Colchmeyer¹, Samantha I. Davis^{3,4}, Nikolai Lauk^{3,4}, Hartmut Neven⁷ & Maria Spiropulu^{3,4,6,8}

The holographic principle, theorized to be a property of quantum gravity, postulates that the description of a volume of space can be encoded on a lower-dimensional boundary. The anti-de Sitter (AdS)/conformal field theory correspondence or duality¹ is the principal example of holography. The Sachdev–Ye–Kitaev (SYK) model of $N \gg 1$ Majorana fermions^{2,3} has features suggesting the existence of a gravitational dual in AdS₂, and is a new realization of holography^{4–6}. We invoke the holographic correspondence of the SYK many-body system and gravity to probe the conjectured ER=EPR relation between entanglement and spacetime geometry^{7,8} through the traversable wormhole mechanism as implemented in the SYK model^{9,10}. A qubit can be used to probe the SYK traversable wormhole dynamics through the corresponding teleportation protocol⁹. This can be realized as a quantum circuit, equivalent to the gravitational picture in the semiclassical limit of an infinite number of qubits⁹. Here we use learning techniques to construct a sparsified SYK model that we experimentally realize with 164 two-qubit gates on a nine-qubit circuit and observe the corresponding traversable wormhole dynamics. Despite its approximate nature, the sparsified SYK model preserves key properties of the traversable wormhole physics: perfect size winding^{11–13}, coupling on either side of the wormhole that is consistent with a negative energy shockwave¹⁴, a Shapiro time delay¹⁵, causal time-order of signals emerging from the wormhole, and scrambling and thermalization dynamics^{16,17}. Our experiment was run on the Google Sycamore processor. By interrogating a two-dimensional gravity dual system, our work represents a step towards a program for studying quantum gravity in the laboratory. Future developments will require improved hardware scalability and performance as well as theoretical developments including higher-dimensional quantum gravity duals¹⁸ and other SYK-like models¹⁹.

SYK with $N = 10$

For $N = 10$,

$$H = -\frac{1}{4!} \sum_{i_1, i_2, i_3, i_4=1}^N J_{i_1 i_2 i_3 i_4} \psi_{i_1} \psi_{i_2} \psi_{i_3} \psi_{i_4}$$

is still too deep to simulate with Sycamore

→ sparsify massively

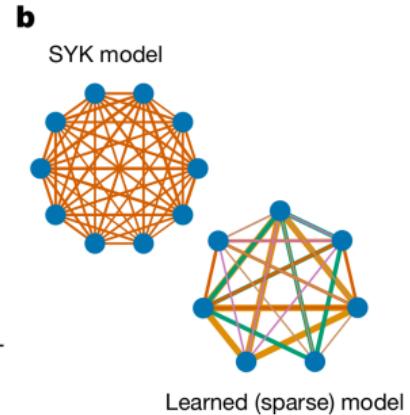
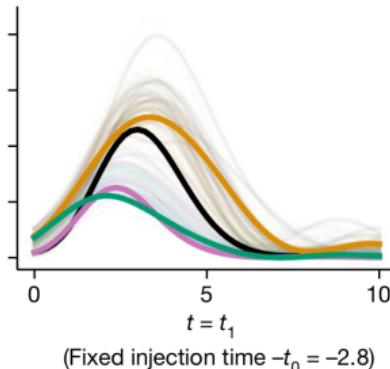
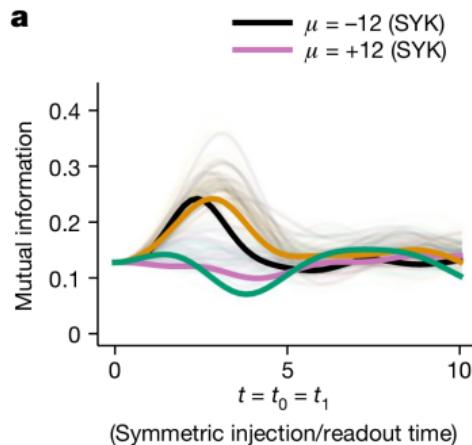
Applying the learning process, we produce a large population of sparse Hamiltonians showing the appropriate interaction sign dependence (Fig. 2a). We select the learned Hamiltonian

$$H_{L,R} = -0.36\psi^1\psi^2\psi^4\psi^5 + 0.19\psi^1\psi^3\psi^4\psi^7 - 0.71\psi^1\psi^3\psi^5\psi^6 + 0.22\psi^2\psi^3\psi^4\psi^6 + 0.49\psi^2\psi^3\psi^5\psi^7, \quad (3)$$

which requires seven of the original $N = 10$ SYK model fermions, where ψ^i denotes the Majorana fermions of either the left or the right systems.

Sparsified SYK

Testing theoretically the state transfer protocol suggests qualitative agreement:



- ▶ State transfer still pretty bad
- ▶ So far, pure theory

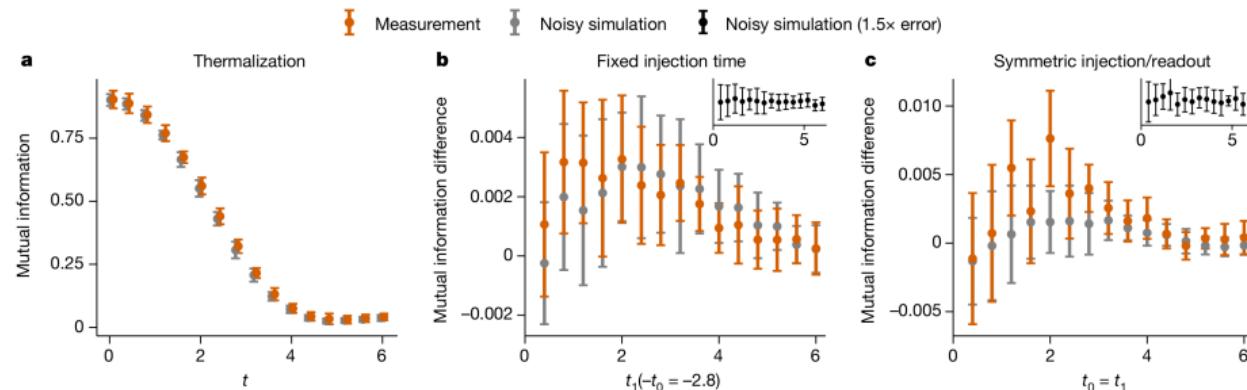
Implementation

Supplementary:

The chosen Jordan-Wigner transformation is as follows, where Z^i indicates $Z \otimes \cdots \otimes Z$ over i Paulis:

$$\begin{array}{ll} \psi_L^1 = ZX & \psi_R^1 = X \\ \psi_L^2 = ZY & \psi_R^2 = Y \\ \psi_L^3 = Z^5X & \psi_R^3 = Z^5Y \\ \psi_L^4 = Z^2X & \psi_R^4 = Z^2Y \quad (\text{S22}) \\ \psi_L^5 = Z^4X & \psi_R^5 = Z^4Y \\ \psi_L^6 = Z^3X & \psi_R^6 = Z^3Y \\ \psi_L^7 = Z^6X. & \psi_R^7 = Z^6Y. \end{array}$$

Results:



Some conclusions about the logic

- ▶ A sparsified version of a conjectured dual of an unphysical toy model of gravity was quantum simulated with an additional term in the dynamics.
- ▶ All was exactly simulable classically and experimental results were mixed
- ▶ No holography or ER=EPR stuff can be validated since they are assumed, and only one side of the duality (the trivial one) is simulated
- ▶ The link with gravity is words, a nice story

Conclusion – from the AI



If I simulate a wormhole with a quantum computer, did a real wormhole actually come into existence?



It is not possible to create a real wormhole by simulating it with a quantum computer. A wormhole is a hypothetical tunnel-like structure that connects two different points in space-time, allowing objects or information to pass through it. While the concept of a wormhole is often used in science fiction, it is not known if they actually exist in the real world.



Simulating a wormhole with a quantum computer would involve using the computer's quantum mechanical properties to model the behavior of a wormhole. However, this would not create a real, physical wormhole. Instead, it would produce a mathematical model or simulation that represents what a wormhole might look like or how it might behave.

In addition, it is not currently possible to build a quantum computer that is powerful enough to simulate a wormhole. Quantum computers are still in the early stages of development, and while they have shown great promise in certain areas, they are not yet capable of simulating complex phenomena such as wormholes.

Overall, while simulating a wormhole with a quantum computer could provide insights into the behavior of wormholes, it would not create a real, physical wormhole.