Many-body physics and gravity: an opportunity for quantum simulation

Julian Sonner

Searching for New Physics
at the Quantum Technologies Frontier

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Holographic duality ↔ quantum technologies

This talk is meant to be an introduction to how we can think about gravity in a specific emergent framework: AdS/CFT

Some older work on quantum simulation of AdS/CFT with
[Solano group (Bilbao) and A. Del Campo]

I especially want to acknowledge crucial and inspiring discussions with
[Jean-Philippe Brantut & EPFL group]
[Tillman Esslinger & ETH group]
[Philipp Hauke & Trento group]

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What is a duality?

Some countries have (more than) two official languages

“Genève” **“Genf”**

A **duality** in theoretical physics involves two (or more) different mathematical descriptions of the same phenomena

“metric” **“state”**

Like in the linguistic analogy there exists a **dictionary** to help translate from one side to the other

AdS/CFT

Dualities are found in many areas of physics and mathematics
(e.g. particle - vortex duality in condensed matter)

What is special about AdS/CFT duality is that it involves **gravity**

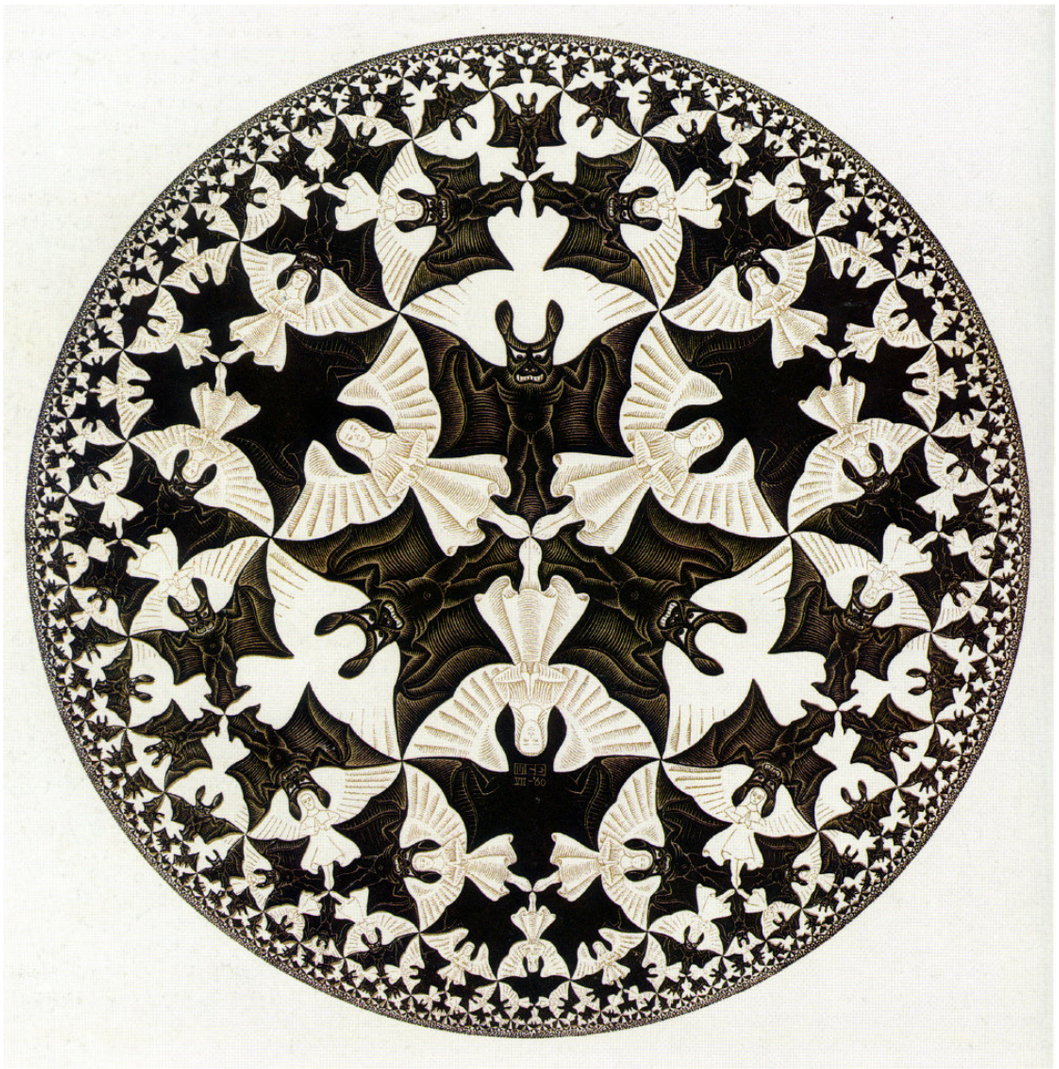
Duality:

quantum gravity in aAdS $\quad=\!=\quad$ quantum field theory on fixed background

[Maldacena , GKP, Witten]

What is “AdS”?

A highly ("maximally”) symmetric solution of Einstein’s equations with negative cosmological constant in d+1 dimensions — “Anti de-Sitter space”



[Escher, Circle Limit IV]

- Lorentzian version of hyperbolic space
- Gravity: geometry is dynamical
- Quantum gravity: string theory of aAdS spacetime
- Symmetry: group of isometries is

$$\mathrm{SO}(2,d)$$

What is “CFT”?

A quantum field theory in d dimensions equipped with ‘conformal’ symmetry

Conformal transformation (of flat space): $x \to x'$ such that

$$g \to g' = \Omega^2 g$$ “angles preserved”

Group of all such transformations: $\mathrm{SO}(2,d)$

First entry in the dictionary:

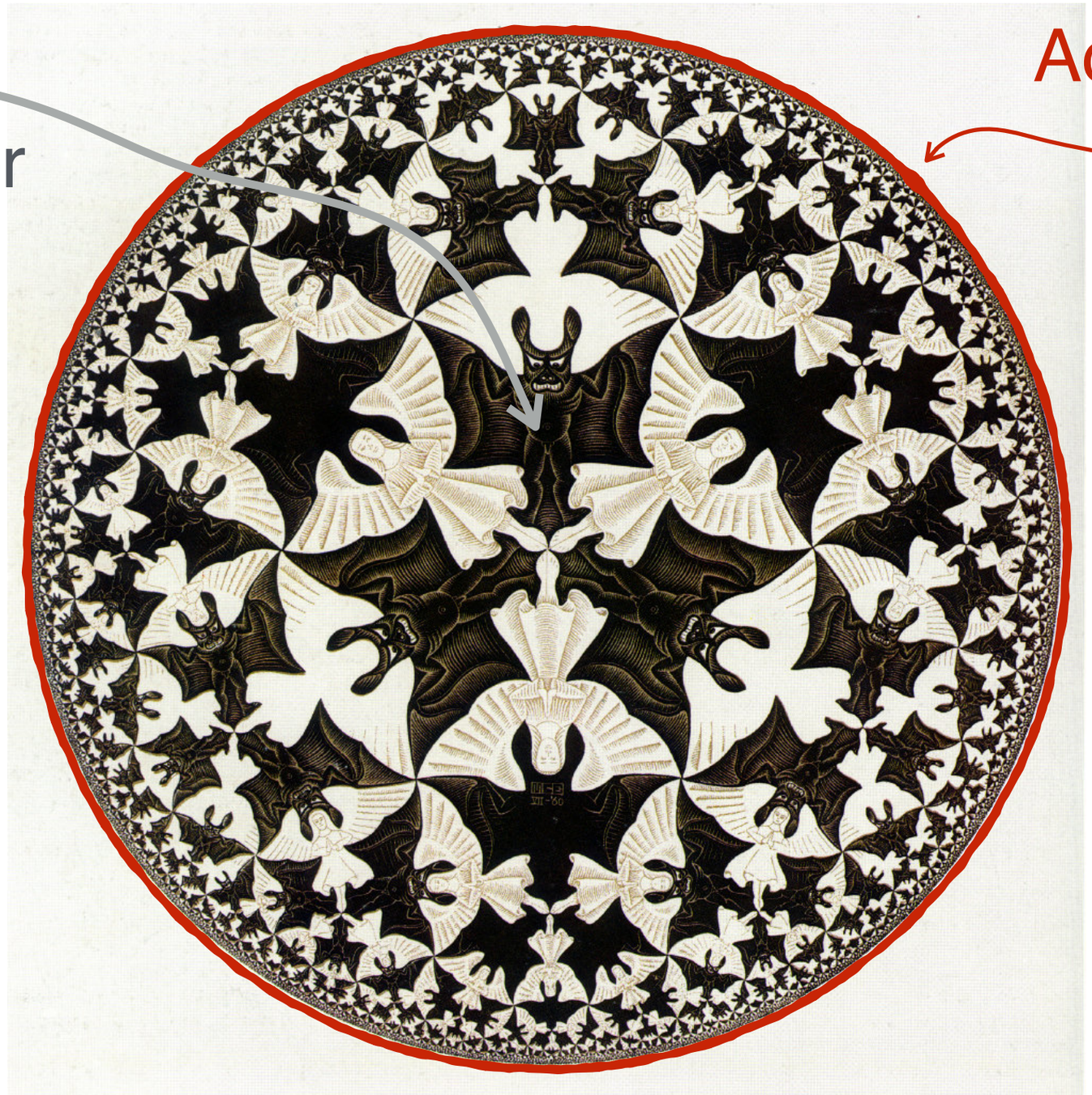
“AdS isometries” $\mathrm{SO}(2,d)$ **“conformal symmetry”**

[Belavin, Polyakov, Zamolodchikov;…..]

The holographic principle

AdS_{d+1}

AdS interior



AdS boundary

$(\partial \mathrm{AdS})_d$

The CFT ‘lives’ here

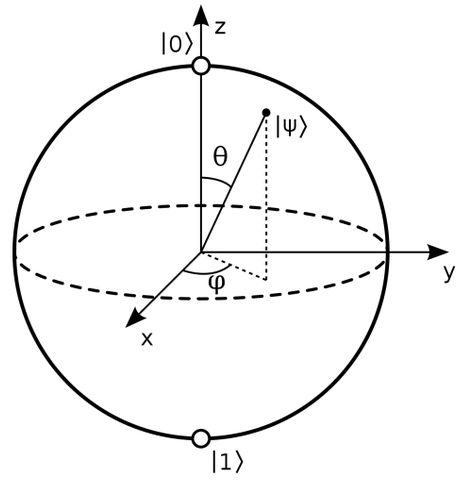
$$S_{\mathrm{BH}} = \frac{A}{4G_N}$$

[Bekenstein; Hawking]

Gravitational physics emerges from a lower-dimensional ‘hologram’

[’t Hooft; Susskind]

More entries in the dictionary

"AdS isometries"	$\mathrm{SO}(2,d)$	"conformal symmetry"
"metric"		"energy-momentum"
"ripples" (perturbations)	$W\,[J]$	"correlation functions"
"extremal surfaces"		"entanglement"

Entanglement & geometry

What is hard to express in one language may be easy in another
(extract from index of Landau & Lifshitz, Vol.3)

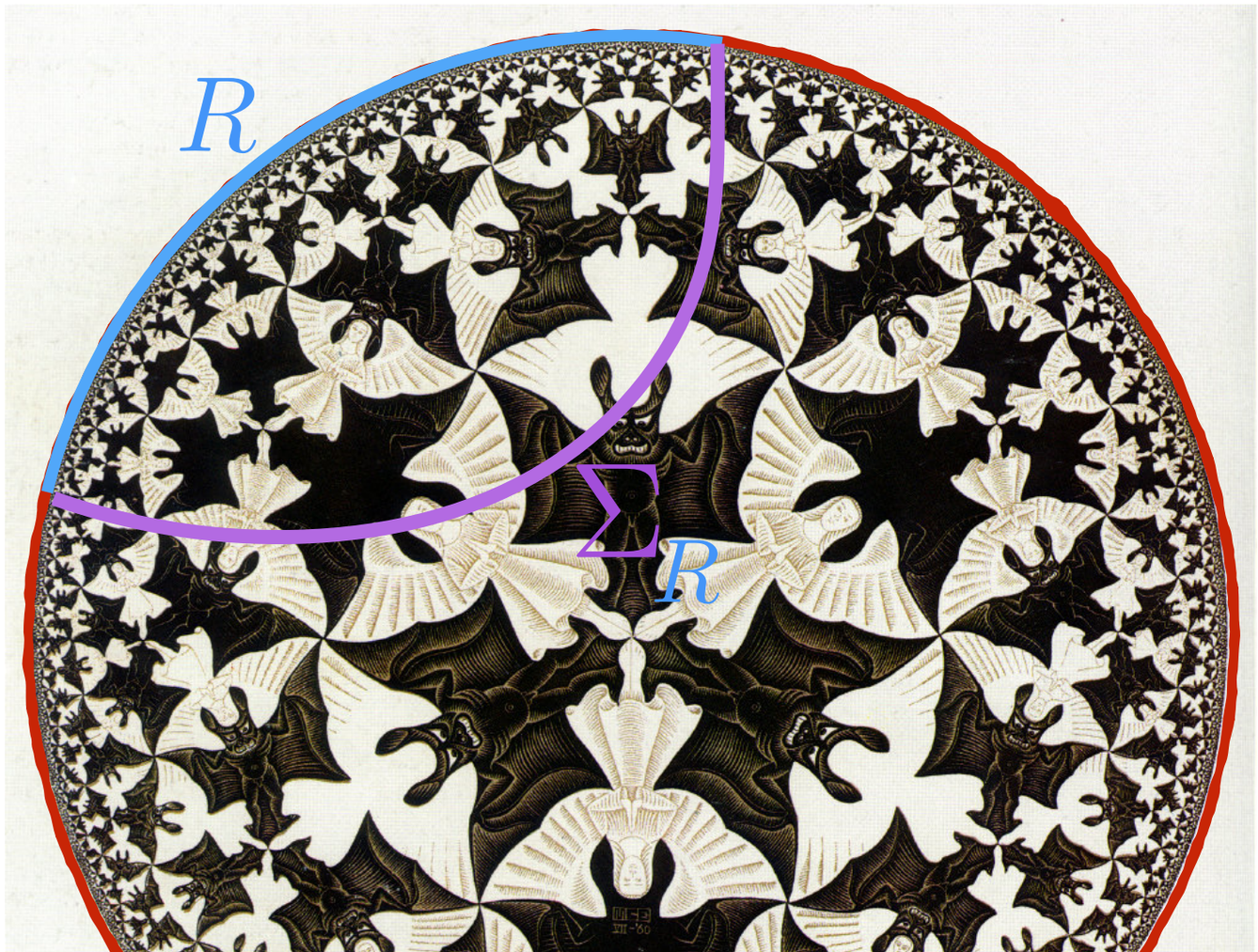
“Drehimpulswahrscheinlichkeitsdichteverteilungsfunktion”

AdS/CFT allows computations that seem impossible otherwise:

R : a subregion

$$S(R) = \frac{\text{area}(\Sigma)}{4G_N}$$

[Ryu & Takayanagi]



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Many-body approach to holography

The most well-known holographic pair:

N=4 SU(N) SYM $\cong$ IIB string theory in $AdS_5 x S^5$

(Cf QCD…. but not the best starting point for our purpose)

➙ in recent years, simple(r) many-body Hamiltonians have emerged:

$$H = \sum_{i_1 \leq \cdots \leq i_q} J_{i_1 \cdots i_q} \psi_{i_1} \cdots \psi_{i_q} \qquad \{\psi_i, \psi_j\} = \delta_{ij}$$

where the couplings are drawn from a Gaussian with variance

$$\overline{J^2_{i_1 \cdots i_q}} = \frac{J^2 (q-1)!}{N^{q-1}}$$

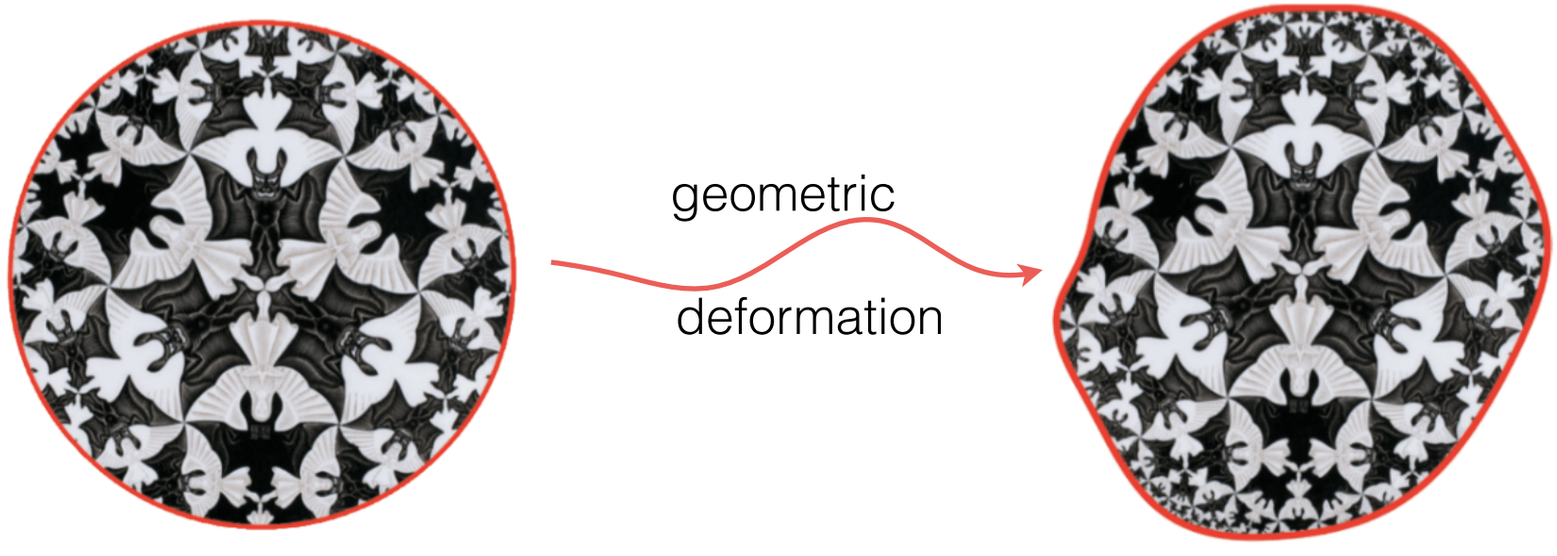
~ spin glass models!

[Sachdev, Ye; Kitaev]

Infrared-SYK & Schwarzian

At strong coupling (J ≫ T), this model “flows” to a (-n almost) CFT, the so-called Schwarzian theory [Maldacena, Stanford; Jensen; Alexeev, Shatashvili]

This theory can be directly related to the physics of 2D gravity, so-called “JT gravity”

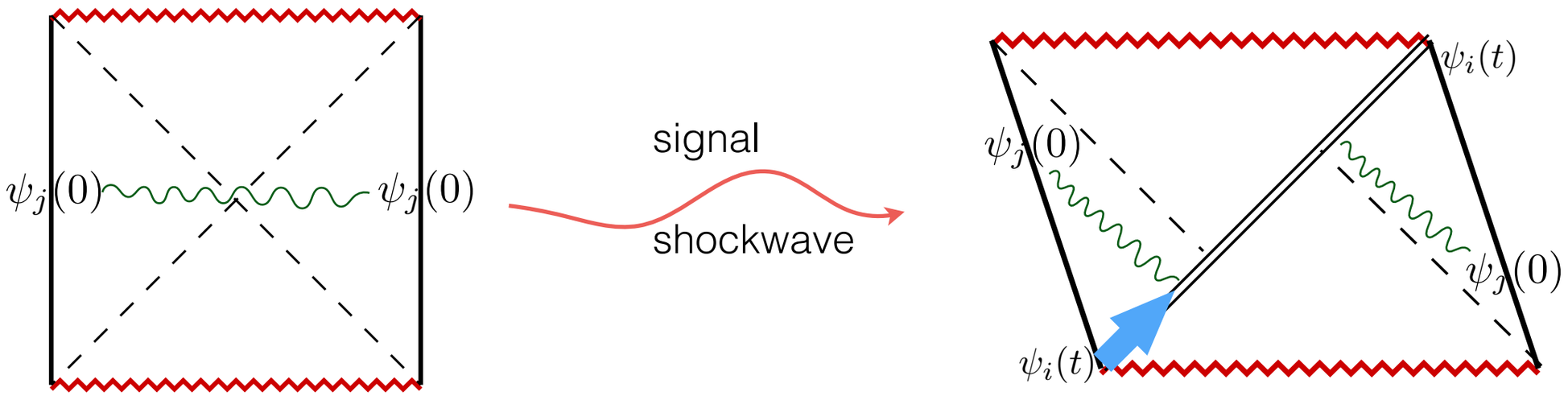


Includes black holes, whose entropy is understood in SYK language: extensive ground state degeneracy S_0

Leading fluctuations are again described by the Schwarzian!

Information scrambling

The black-hole horizon rapidly blueshifts an in-falling signal



Gravity analog of the butterfly effect with $\lambda_L = 2\pi T$

On the many-body side this is diagnosed by a 4-pt function

$$\left\langle [\psi_i(t), \psi_j(0)]^2 \right\rangle_\beta \sim e^{2\lambda_L t}$$

The Lyapunov exponent takes the maximal allowed value in both SYK and the 2D black hole (↛ this is an example of Planckian dissipation)

[Maldacena, Stanford, Shenker]

Transport without quasiparticles

SYK excitations decay on at a Planckian rate

$$\tau_d \sim \frac{\hbar}{k_B T}$$

↠ quasiparticle description is inapplicable: “Planckian dissipation”

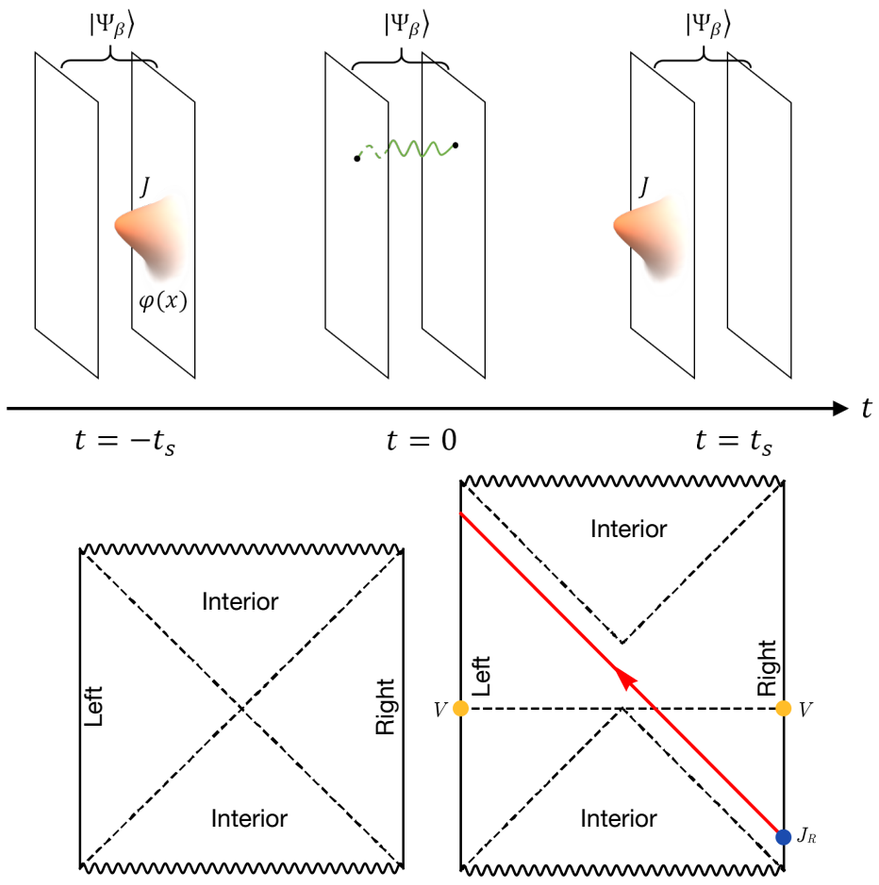
- maximal scrambling $\lambda_L = 2\pi T$

- minimal viscosity $\frac{\eta}{s} \sim \frac{\hbar}{4\pi k_B}$

- strange-metal like transport (other bounds?)

[e.g. SYK chains]

Quantum informational aspects



Prepare two copies of the system

Entangle in TFD state

A signal introduced on the right rapidly dissipates

By judicial coupling of left and right, the signal reappears

cf: quantum teleportation. In bulk, signal goes through wormhole!

[Gao, Jafferis, Wall; Gao, Liu,…]

- idea: spatial connectivity is due to entanglement

- idea: bulk reconstruction is quantum error correction

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1. Introduction

   the connection between N-body and gravity

2. Simple holographic models and their properties

   SYK/Schwarzian, transport without quasiparticles

3. Quantum simulations

   (i) platforms; (ii) probes

Quantum Gravity in the Lab?

Up to now, quantum gravity is a purely theoretical subject:

its effects become native at the Planck scale

$$10^{19} GeV, \qquad 10^{-35} m, \qquad 10^{-44} s$$

Compare this to the scale of the LHC: $13\, TeV$

It is certainly a good idea to try and advance in directions that could change this situation: holographic quantum simulation

The Planck scale becomes a tunable parameter: “large-N”

Quantum Computers

Simplest encoding of SYK interactions: Jordan-Wigner spins
+ Suzuki-Trotter time steps

Leads to high gate complexity: $\mathcal{O}\left(N^{10}t^2/\epsilon\right)$ [Garcia-Alvarez,…]

↠ improved to $\mathcal{O}\left(N^{7/2}t + N^{5/2}t\,\mathrm{polylog}(N/\epsilon)\right)$ [Google]

NMR experiment:

nature › npj quantum information › articles › article

Article | Open Access | Published: 18 June 2019

Quantum simulation of the non-fermi-liquid state of Sachdev-Ye-Kitaev model

Zhihuang Luo, Yi-Zhuang You, Jun Li, Chao-Ming Jian, Dawei Lu ✉, Cenke Xu, Bei Zeng ✉ & Raymond Laflamme

practical protocol for measuring scrambling of quantum information

$$\exp\left(-iH_{CS}t\right)|\Psi\rangle = \alpha|e\rangle U(t)|\psi\rangle + \beta|g\rangle U(-t)|\psi\rangle$$ [Garcia-Alvarez,…]

ancilla

backward evolution [Bentsen,…]

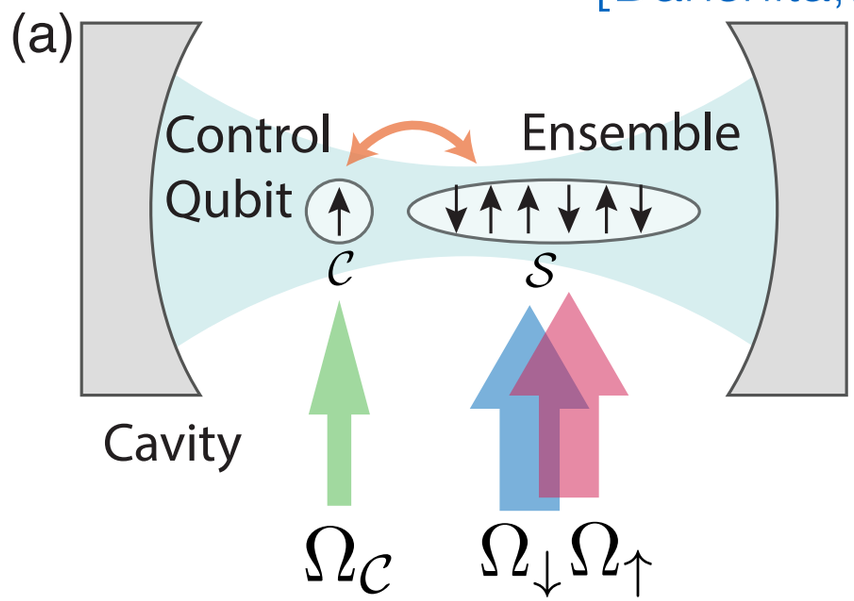
Cold atomic gases

Quantum computers are great, but high gate complexity (so far), and scaling up to large-N pose a challenge

Non-local nature of interactions seems to be challenge for cold gases

[Danshita,…]

→ Cavity - QED!



Gives a non-local (pseudo) spin model

Randomize interactions with drive fields and/or cavity couplings

[see talk by Sauerwein]

[Bentsen,…]

Distribution of couplings? What size of atomic clouds? Dissipation? … lots of interesting and concrete questions.

Can cold atoms do for QG what it has done for many-body physics?

Conclusions & Outlook

AdS/CFT or ‘holographic duality’ defines quantum gravity as an emergent phenomenon

Some examples involve (relatively) simple many-body systems and lower-D gravity theories

Interesting and rich phenomenology of non-Fermi liquid transport

Simple enough to consider experiments on quantum platforms: towards quantum gravity in the lab.

→ solid-state platforms?

thank you very much
for your attention