Title: An SYK model with a scaling similarity.

Speakers: Juan Maldacena

Collection: It from Qubit 2023

Date: July 31, 2023 - 1:00 PM

URL: https://pirsa.org/23070008

Abstract: We describe supersymmetric SYK models which display a scaling similarity at low temperatures, rather than the usual conformal behavior. We discuss the large N equations, which were studied previously as uncontrolled approximations to other models. We also present a picture for the physics of the model which suggest that the relevant low energy degrees of freedom are almost free. We also searched for a spin glass phase but we found no replica symmetry breaking solutions.

An SYK model with a Scaling Similarity
+
Comments on Qubit themes

Juan Maldacena

It from Qubit

Perimeter Institute, July 2023

Based on work in progress with

Anna Biggs

Vladimir Narovlansky

We will discuss a supersymmetric SYK model which has peculiar properties.

The model

- $\mathcal{N}=2$ supersymmetric quantum mechanics with a random qth order superpotential.

$$I = \int dt d^2\theta [D\phi^i \bar{D}\phi^i + W(\phi)] \,, \qquad W = \sum C_{ijk}\phi^i \phi^j \phi^k$$

ϕ is real

$$I = \int \dot{\phi}_i^2 + \psi_{1i}\dot{\psi}_{1i} + \psi_{2i}\dot{\psi}_{2i} + (\partial_i W)^2 + \psi_{1i}\psi_{2j}\partial_i\partial_j W$$

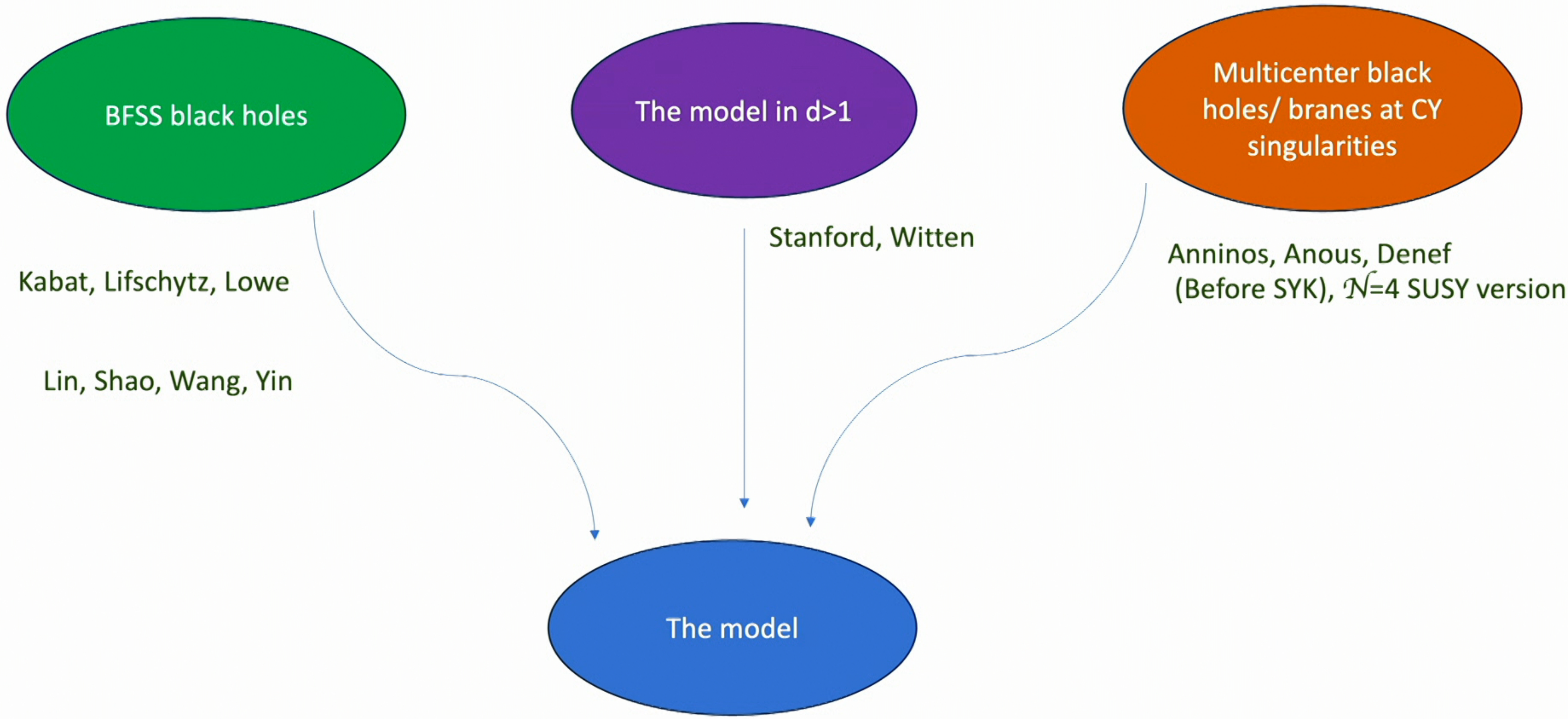
$$I = \int \dot{\phi}_i^2 + \psi_{1i}\dot{\psi}_{1i} + \psi_{2i}\dot{\psi}_{2i} + F_i^2 + C_{ijk}F_i\phi^j\phi^k + C_{ijk}\psi_{1i}\psi_{2j}\phi^k$$

(different than than the $\mathcal{N}=2$ model considered by Fu, Gaiotto, JM, Sachdev)

Dynamical bosons + fermions

(We wrote explicitly the q=3 version)

There is also an $\mathcal{N} = 4$ version → complex bosons and fermions.


BFSS black holes
The model in d>1
Multicenter black holes/ branes at CY singularities
Kabat, Lifschytz, Lowe
Lin, Shao, Wang, Yin
Stanford, Witten
Anninos, Anous, Denef
(Before SYK), $\mathcal{N}$=4 SUSY version
The model

The BFSS black hole

Banks, Fischler, Shenker, Susskind

Itzhaki, JM, Sonnenschein, Yankielowicz

1990s

Matrix Quantum Mechanics, at large N, at finite temperature

=

Black hole in 10d, with SO(9) symmetry

Matrix Quantum Mechanics, at large N, at finite temperature

=

Black hole in 10d, with SO(9) symmetry

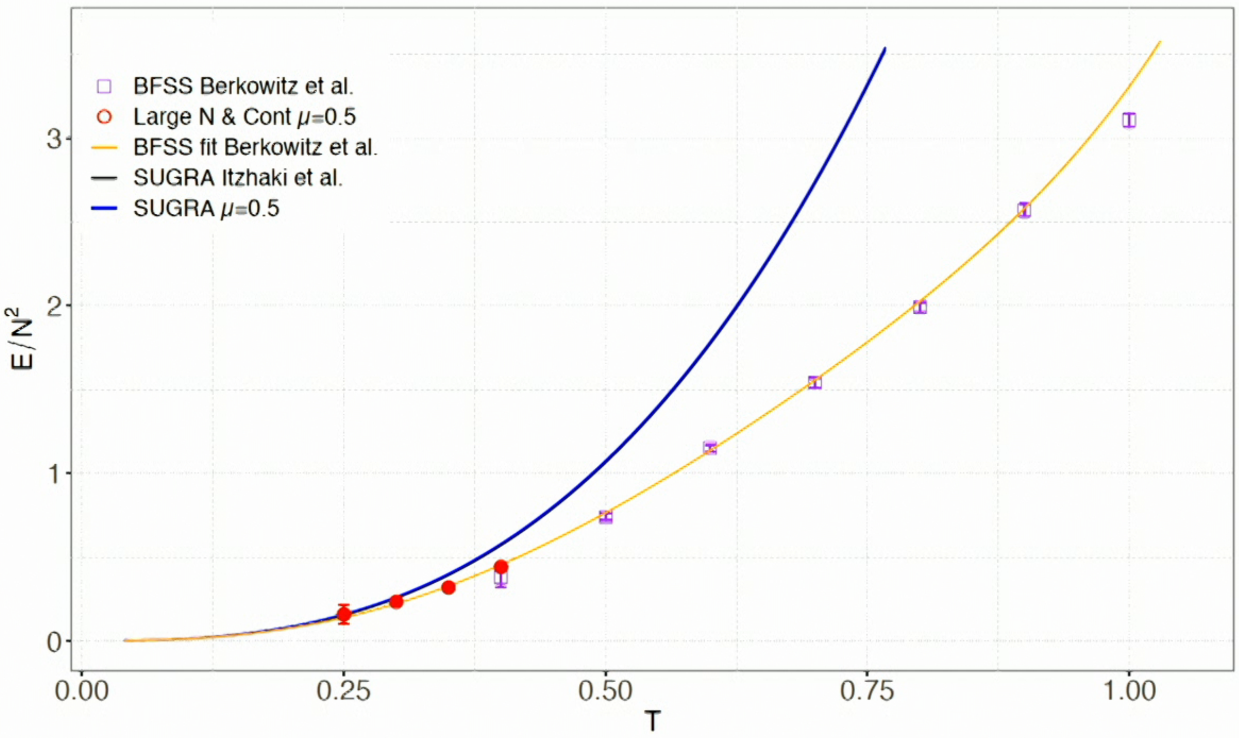
It is the simplest quantum mechanical theory* that has a bulk Einstein gravity dual†.

*as opposed to QFT

† as opposed to higher spin gravity theories

Why are we returning to this topic?

Latest lattice Montecarlo simulations



Monte Carlo String/M-theory Collaboration (MCSMC)
- Pateloudis, Bergner, Hanada, Rinaldi, Schaefer, Vranas, Watanabe, Bodendorfer

- Berkowitz, Rinaldi, Hanada, Ishiki, Shimasaki, Vranas

They have computed a certain higher derivative correction which has not been yet reproduced analytically.

They are more advanced than analytic computations!

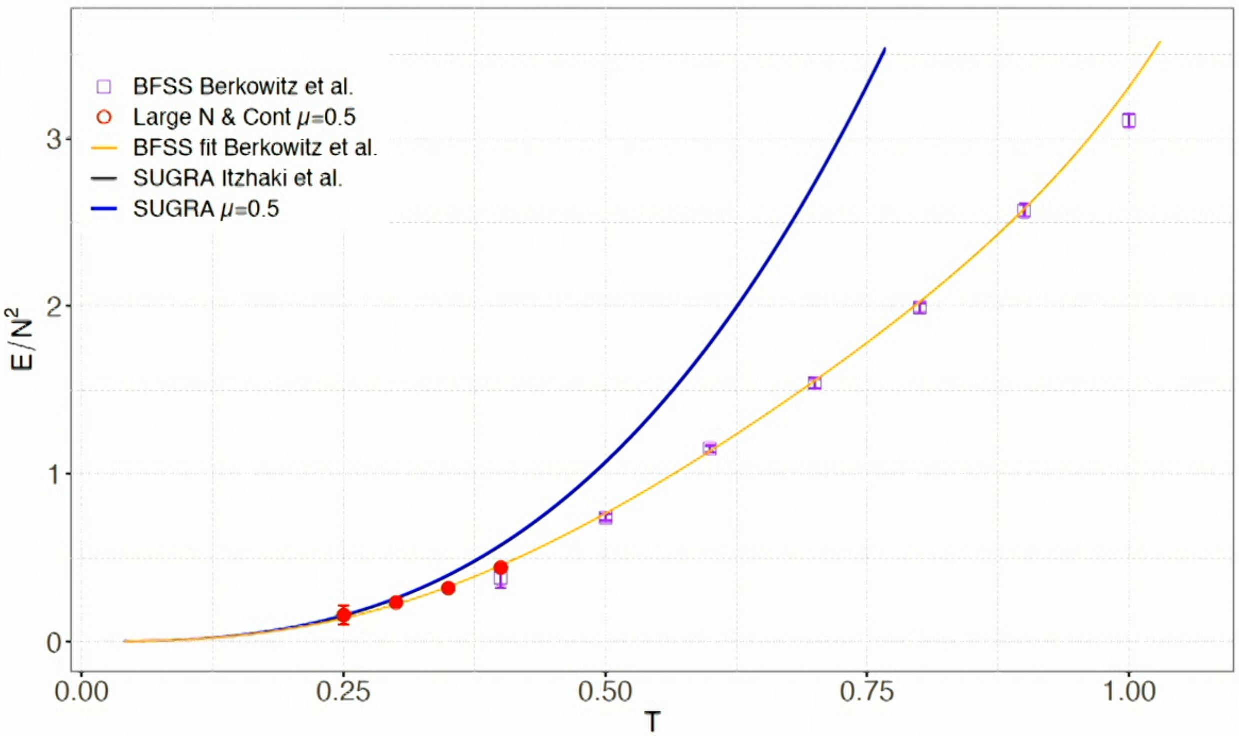
The low temperature entropy goes as

$$\log Z \propto S \propto N^2 T^{9/5}$$

As opposed to $$\log Z \propto S \propto S_0 + CT \propto N + NcT$$

For SYK (almost conformal symmetry)
or near extremal black holes.

Latest lattice Montecarlo simulations



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For SYK (almost conformal symmetry) or near extremal black holes.

This power law is governed by a ``scaling similarity''

=

A scaling transformation that rescales the action

$\rightarrow$ symmetry of equations of motion.

This motivated us to look for simpler models with this realization of scaling.

Kabat, Lifschytz, Lowe, and Lin, Shao, Wang, Yin , had considered a matrix model and truncated their planar diagrams to melon diagrams.

We reinterpreted their equations as the large N equations of the SYK- model we introduced above.

They did numerical and analytic analysis showing that the free energy is

$$\log Z \propto \text{constant} + T^{6/5}$$

Anninos, Anous, Denef , had suggested that this model would have a spin glass phase.

We failed to find such a phase.

End of the long motivation.

The large N equations can be derived as in the usual SYK model case.

Integrate the disorder $\rightarrow$ bilocal term in the action.

Introduce G and Σ variables, etc.

We need to consider the following two point functions

$$G_\phi(t,t') = \frac{1}{N}\langle \phi^i(t)\phi^i(t')\rangle \ , \qquad G_\psi = \frac{1}{N}\langle \psi^i\psi^i\rangle \ , \qquad G_F = \frac{1}{N}\langle F^i F^i\rangle$$

Auxiliary fields

Finite temperature: $t \sim t + \beta$

$$G_\phi(t,t') \to G_\phi(t-t') \ , \qquad \text{etc.}$$

An aside

$$G_{\phi F} = \frac{1}{N}\langle \phi^i(t) F^i(t') \rangle \qquad ?$$

For odd q, → the model has a Z_2 symmetry that forbids it, as long as the symmetry is not spontaneously broken.

We found that the solutions we will describe are locally stable under turning on a vev for this variable.

So we will set it to zero.

The large N equations

Definitions of the self energies:

$$G_\phi(\omega)[\omega^2 - \Sigma_\phi(\omega)] = 1 \ , \qquad G_\psi(\omega)[-i\omega - \Sigma_\psi(\omega)] = 1 \ , \qquad G_F(\omega)[1 - \Sigma_F(\omega)] = 1$$

Self energies in terms of G (melon approximation) :

$$\Sigma_\phi = -2G_F G_\phi + 2G_\psi^2$$
$$\Sigma_\psi = 2G_\psi G_\phi$$
$$\Sigma_F = -G_\phi^2$$

Both sides are functions of (t,t'), or really t-t'.

(we specialized to q=3 and J=1 to avoid clutter)

$$\langle C_{ijk}^2 \rangle \propto \frac{J^3}{N^2}$$

Naïve low energy analysis

Anninos, Anous, Denef

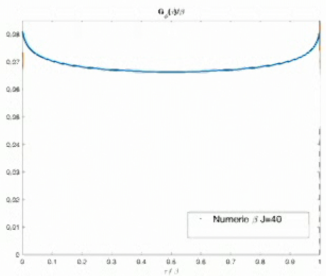
Set all functions to be power laws, $G_\phi \sim t^{-2\Delta}$, and similarly for the others.
Assume SUSY at short times.

$$G_\phi \propto \frac{1}{t^{2\Delta}} \ , \qquad G_\psi \propto \frac{1}{t^{2\Delta+1}} \ , \qquad G_F \propto \frac{1}{t^{2\Delta+2}}$$

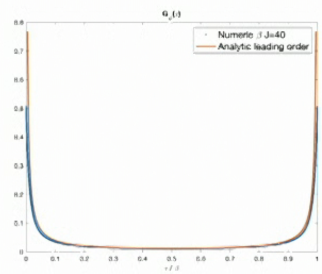
Insert in equations → Find $\Delta = 0$.

Not really a solution, some coefficients diverge as $\Delta \to 0$

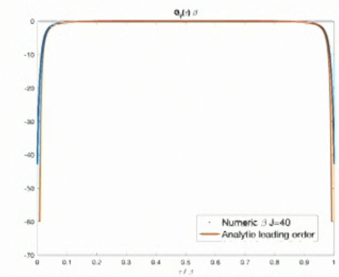
One can solve them numerically



G_ϕ



G_ψ



G_F

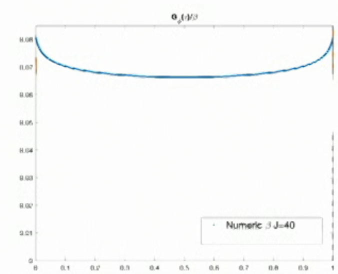
The solution for at a low temperature

We will now discuss an approximate scheme to solve the model at low temperatures.

Start with the full large N action:

$$\frac{\log Z}{N} = \sum_{\omega_n} \left[\log[-i\omega - 2\Sigma_\psi(\omega)] - \frac{1}{2}\log(w^2 - 2\Sigma_\phi) - \frac{1}{2}\log(1 - 2\Sigma_f) \right] +$$
$$+ \int_0^\beta dt dt' \left(-G_\phi \Sigma_\phi - G_f \Sigma_f - 2G_\psi \Sigma_\psi - \frac{1}{2} G_f G_\phi^{q-1} + \frac{(q-1)}{2} G_\psi^2 G_\phi^{q-2} \right)$$

Expand



$$G_\phi = \bar{G}_\phi + \delta G_\phi \ , \qquad \delta G_\phi \ll \bar{G}_\phi$$

Independent of Euclidean time

Non-zero Matsubara frequencies.

For example: $G_f G_\phi^2 \to \delta G_f \delta G_\phi \bar{G}_\phi + \delta G_f \delta G_\phi^2$

$$I = \text{const} + I_2 + I_3 + I_4 + \cdots$$

Solve exactly up to the quadratic terms

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \frac{\pi}{\sqrt{8}\beta \bar{G}_\phi^{1/2}}$$

(for q=3, other values of q are similar)

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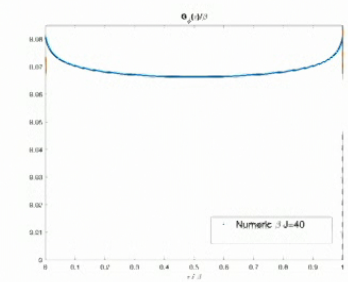
$$+\int_0^\beta dt dt'\left(-G_\phi\Sigma_\phi - G_f\Sigma_f - 2G_\psi\Sigma_\psi \underbrace{- \frac{1}{2}G_f G_\phi^{q-1} + \frac{(q-1)}{2}G_\psi^2 G_\phi^{q-2}}\right)$$

Expand

$$G_\phi = \bar{G}_\phi + \delta G_\phi \ , \qquad \delta G_\phi \ll \bar{G}_\phi$$



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(for q=3, other values of q are similar)

Add the higher order terms perturbatively

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \frac{\pi}{\sqrt{8}\beta \bar{G}_\phi^{1/2}} - \frac{1}{32\bar{G}_\phi^3}$$

Ground state entropy

Quadratic terms

Cubic terms (and quartic, for q>3)

Minimize with respect to $\bar{G}_\phi$ → determine $\bar{G}_\phi$ → find power $\log Z \propto T^{\frac{6}{5}}$

Scaling similarity

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \underbrace{\frac{\pi}{\sqrt{8}\beta\bar{G}_{\phi}^{1/2}} - \frac{1}{32\bar{G}_{\phi}^{3}}}_{\text{Has a simple scaling similarity} \rightarrow \text{extends to the approximate solution}}$$

An irrelevant comment

For generic q :

$$\log Z \propto NT^{\frac{2q}{q+2}} \;, \qquad \text{for} \quad q = 18 \qquad \log Z \propto NT^{\frac{9}{5}}$$

Coincidence.

We will see that the physics is rather different.

Is the ground state entropy arising from BPS states?

The Witten index and the ground state entropy.

$$I_W = Tr[(-1)^F e^{-\beta H}]$$

$I_W = 0.$ (Proved for odd q and odd N).

We expect no exact susy zero energy states.

The solution obeys the supersymmetric relations at short times.

$$G_F \propto \partial_\tau G_\psi \propto \partial_\tau^2 G_\phi \ , \qquad \tau \ll \beta$$

No SUSY breaking (other than the temperature) at large N.
The ground state energy vanishes at large N

→ SUSY breaking is probably very small (perhaps non-perturbative, e^{-N}).

An aside

There is an $\mathcal{N}$=4 model which is very similar.
Real fields → complex fields.

Same large N equations. In the final action N → 2 N.

The index is non-zero $I_W = 2^N$

Entropy:

$$\left.\frac{\log Z}{N}\right|_{\mathcal{N}=2} = \frac{1}{2}\log 2 + \cdots \ , \qquad \left.\frac{\log Z}{N}\right|_{\mathcal{N}=4} = \log 2 + \cdots$$

Now we look at the next term of the free energy

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \frac{\pi}{\sqrt{8}\beta \bar{G}_\phi^{1/2}} - \frac{1}{32\bar{G}_\phi^3}$$

Comes from the quadratic approximation

Essentially the same as a q=2 model.

$$G_f G_\phi^2 \to \delta G_f \delta G_\phi \bar{G}_\phi + \delta G_f \delta G_\phi^2$$

Similar to a model with

$$\tilde{W}_2 = \tilde{C}_{ij}\phi_i\phi_j \ , \qquad \langle C_{ij}^2 \rangle \propto \frac{m^2}{N} \ , \qquad m^2 \propto \bar{G}^{q-2}$$

The effective q=2 model

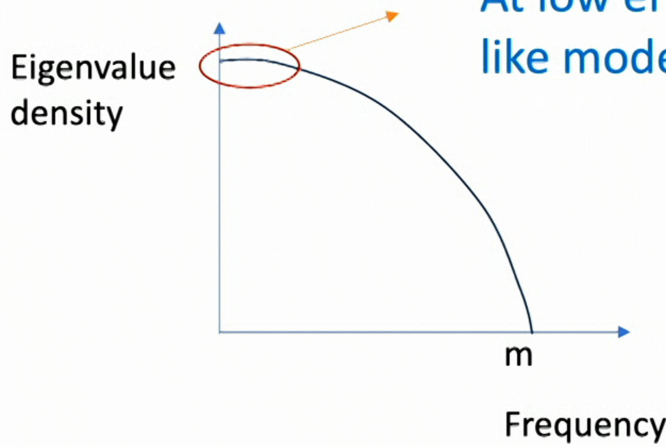
$$\tilde{W}_2 = \tilde{C}_{ij}\phi_i\phi_j \ , \qquad \langle C_{ij}^2 \rangle \propto \frac{m^2}{N} \ , \qquad m^2 \propto \bar{G}^{q-2}$$

Diagonalize the matrix $\widetilde{C_{ij}}$.

Each eigenvalue → leads to a bosonic + fermionic oscillator. → ground state energies cancel.

There is a temperature dependent contribution to the free energy.

The effective q=2 model.



At low energies, constant density →
like modes of a 1+1 dimensional field.

m = typical eigenvalue.
1/L ~ spacing between them

Free energy $\log Z \propto TL \propto N\frac{T}{m}, \qquad L \propto N/m$

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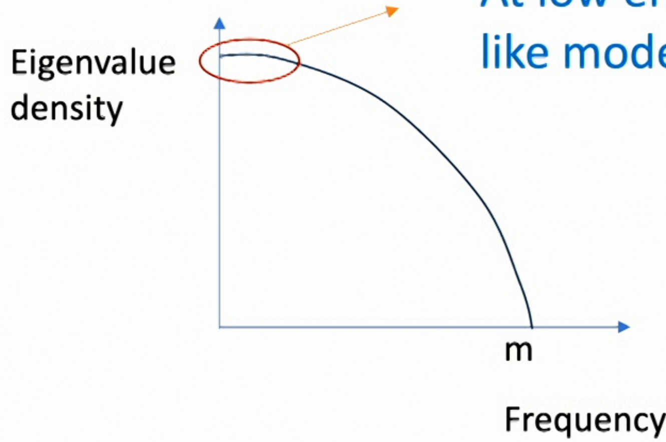

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Finally

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \frac{\pi}{\sqrt{8}\beta \bar{G}_{\phi}^{1/2}} - \frac{1}{32\bar{G}_{\phi}^{3}}$$

Comes from the quadratic approximation

Finally

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Comes from the quadratic approximation

Just this term wants to drive G_ϕ to zero.

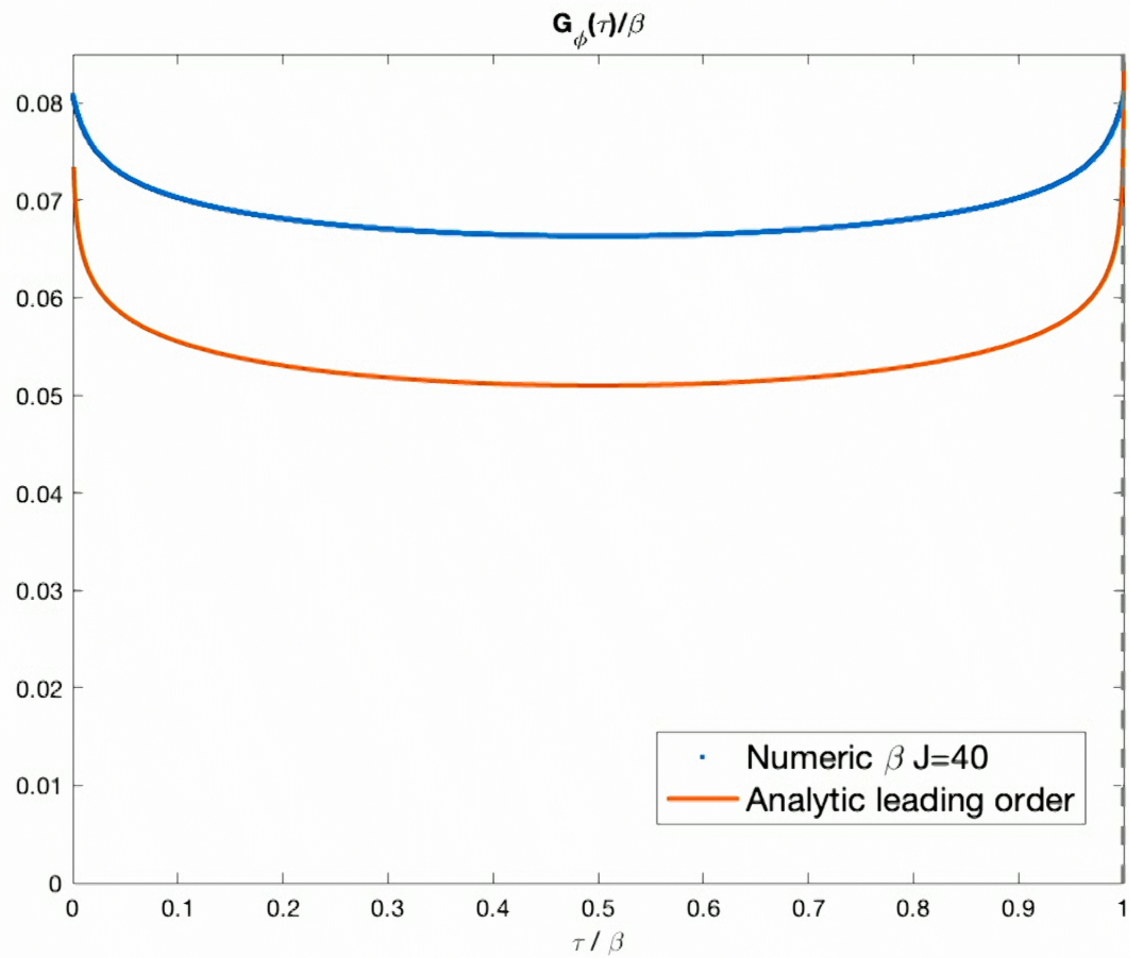
To decrease the typical frequency of the oscillators → increases the entropy of the bosonic oscillators.

The quadratic solution more explicitly

$$\delta G_\phi \propto -\frac{1}{m}\log\left[2\sin\frac{\varphi}{2}\right] \qquad \Delta \sim 0$$

$$\delta G_\psi \propto \frac{1}{m\beta}\frac{1}{\sin\frac{\varphi}{2}} \qquad \Delta = \frac{1}{2}$$

$$\delta G_F \propto \frac{1}{m\beta^2}\frac{1}{\sin^2\frac{\varphi}{2}}\,, \qquad \varphi = 2\pi\frac{\tau}{\beta}\,, \qquad m^2 = \bar{G}_\phi^{q-2} \qquad \Delta = 1$$



$G_\phi(\tau)/\beta$
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
τ / β
Numeric β J=40
Analytic leading order

Finally

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \frac{\pi}{\sqrt{8}\beta \bar{G}_\phi^{1/2}} - \frac{1}{32\bar{G}_\phi^3}$$

Comes from the cubic (and quartic) interactions, wants to increase the value of $\overline{G_\phi}$

Minimizing with respect to $\bar{G}_\phi$ → $\bar{G}_\phi \propto \beta^{\frac{2}{5}}$, $\frac{\log Z}{N} \propto T^{\frac{6}{5}}$

A puzzle

The expectation value of ϕ^2 grows as we lower the temperature

$$\langle \phi^2 \rangle \propto \beta^{\frac{2}{5}} \ , \qquad \beta J \gg 1$$

Finally

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \frac{\pi}{\sqrt{8}\beta\bar{G}_{\phi}^{1/2}} - \frac{1}{32\bar{G}_{\phi}^{3}}$$

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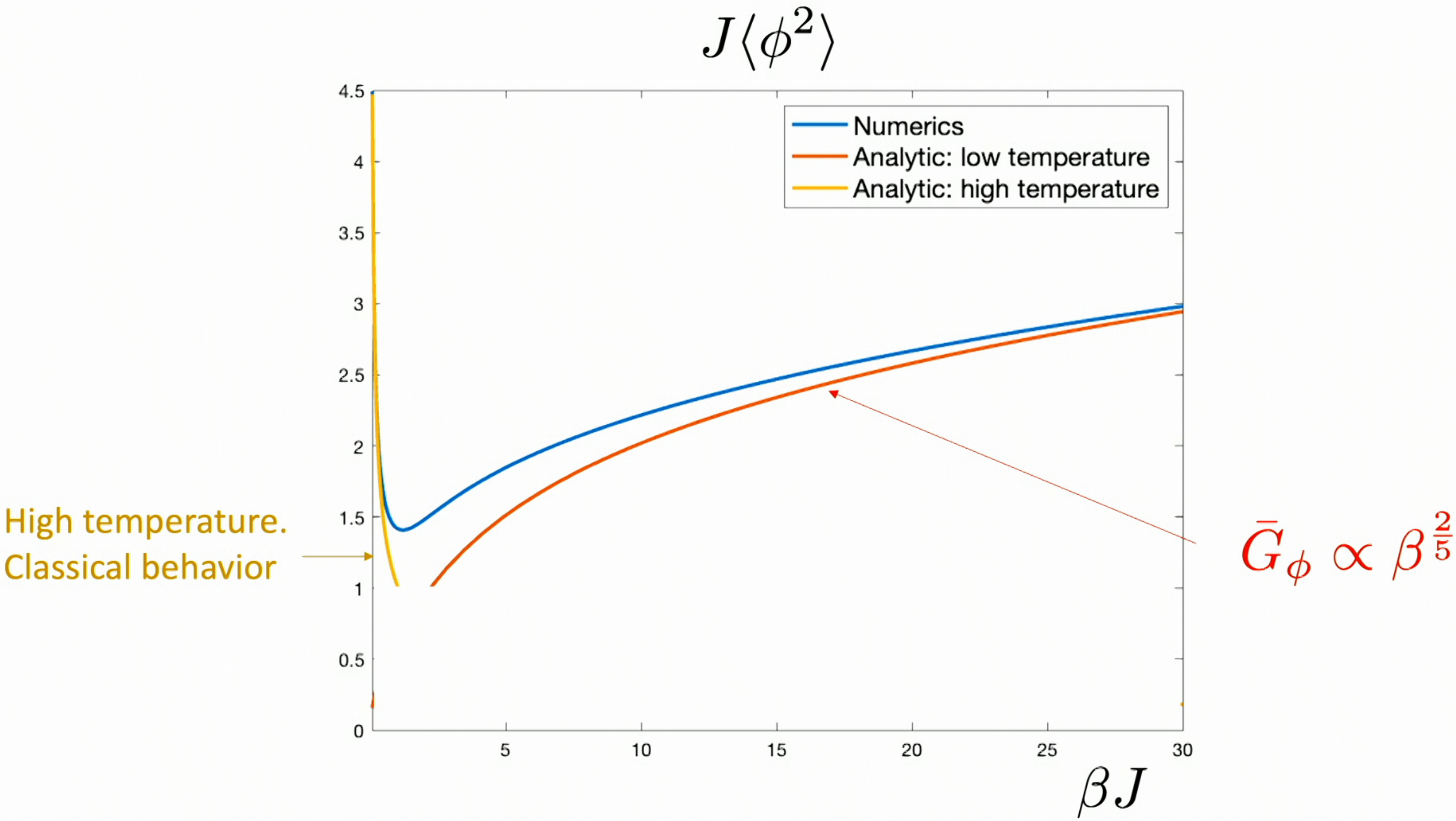
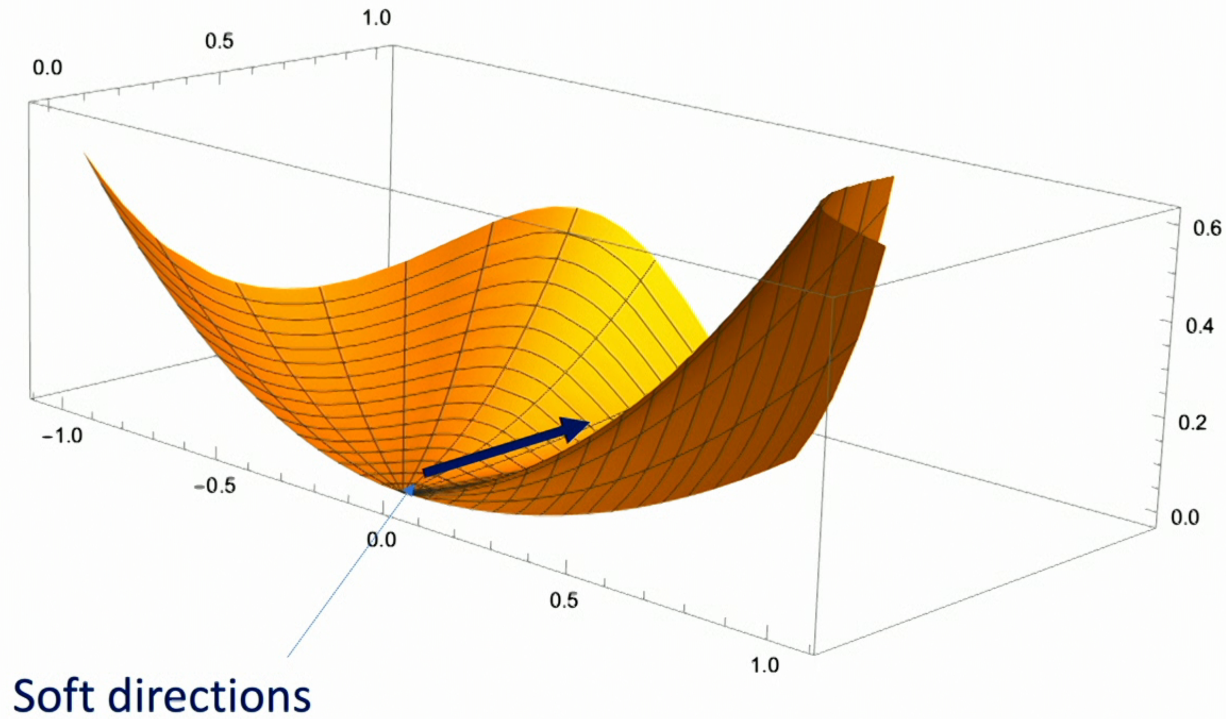

$J\langle\phi^2\rangle$
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
5
10
15
20
25
30
βJ
Numerics
Analytic: low temperature
Analytic: high temperature
High temperature.
Classical behavior
$\bar{G}_\phi \propto \beta^{\frac{2}{5}}$

What is the physical interpretation?



We are exploring the soft directions of the potential

Exploring the potential

``Eigenvalues'' of the tensor

Qi; Cartwright, Strumfels

$$C_{ijk}\bar{\phi}_j\bar{\phi}_k = \lambda\bar{\phi}_i\sqrt{\bar{\phi}_l^2}$$

Look for low values of the ``Eigenvalues'' λ.

How many solutions ?

Exponentially many solutions.

$2^{\frac{N}{2}}$ real solutions.

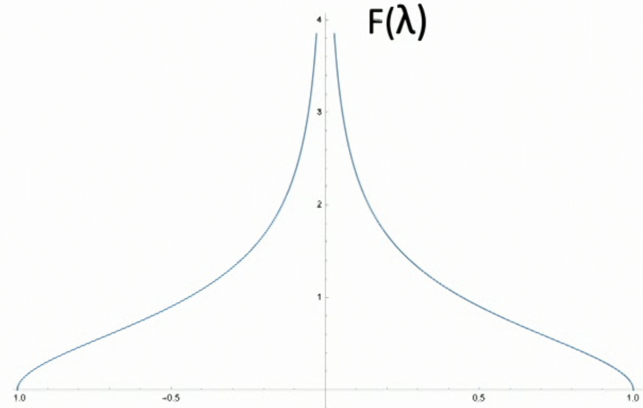
Breiding (2019)

Eigenvalue distribution for the tensor

$$\rho(\lambda) = e^{S_0} F(\lambda)$$

$$2^{\frac{N}{2}}$$

Order one function.



(Is integrable at zero).

Exponentially many low lying eigenvalues

Zero temperature entropy

$$\frac{\log Z}{N} = \frac{1}{2}\log 2 + \cdots$$

Gurau

Fluctuations around the soft directions

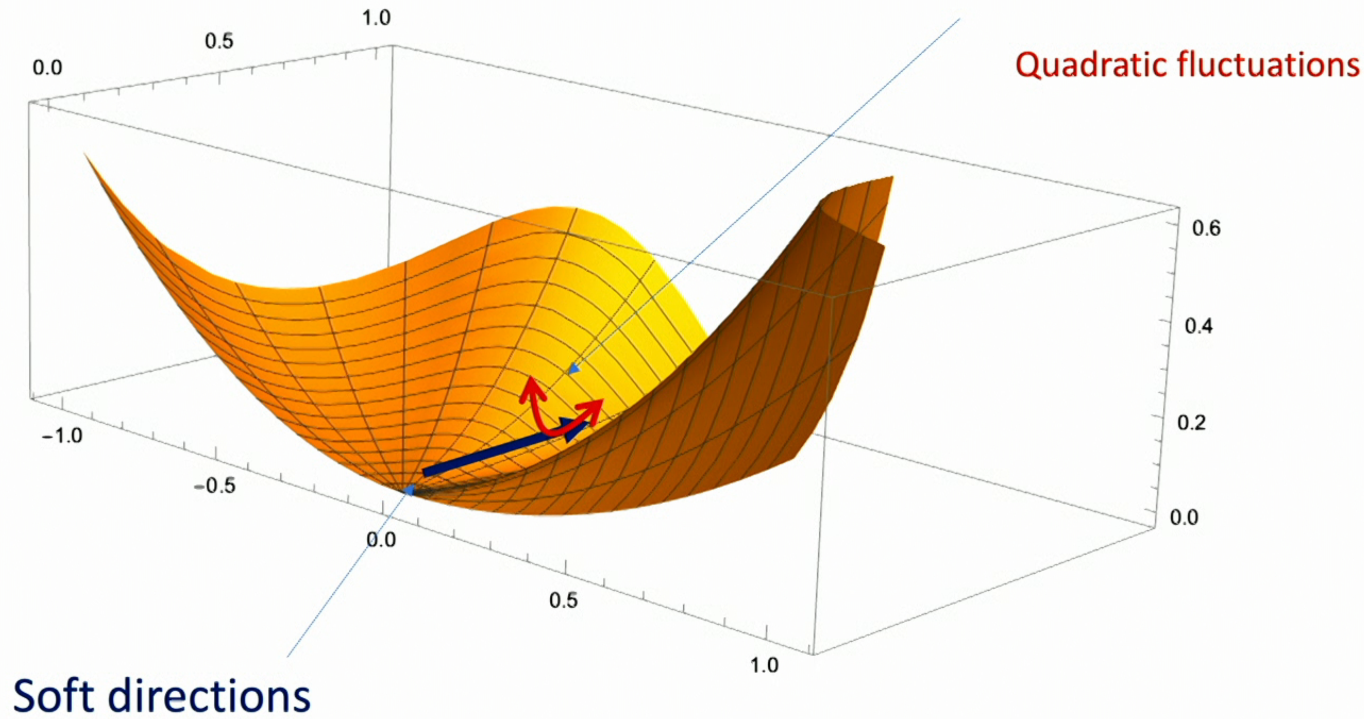
$$\phi_i = \bar{\phi}_i + \delta\phi^i$$

General fluctuations

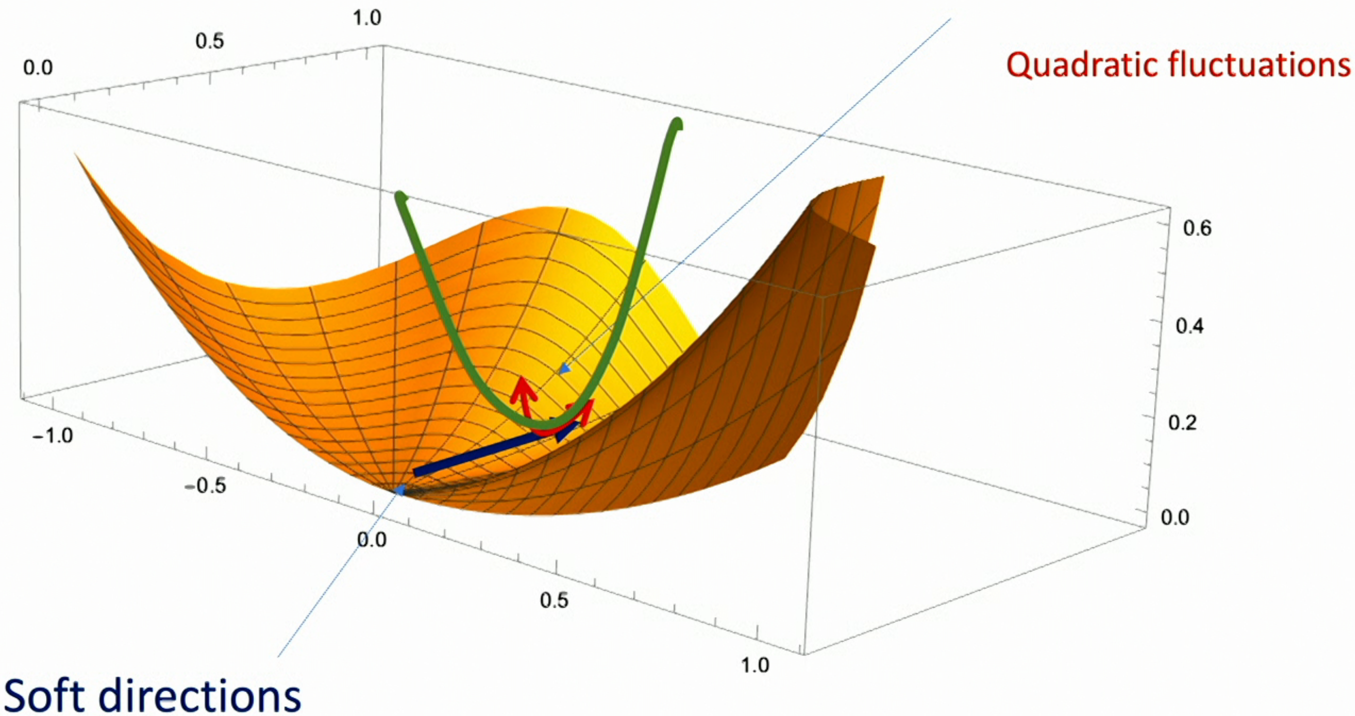
Eigenvalues

$$W \sim C_{ijk}\bar{\phi}_i\delta\phi_j\delta\phi_k = M_{jk}\delta\phi_j\delta\phi_k$$

Random matrix whose scale is set by $\bar{G}_\phi \sim \bar{\phi}^2$. Gives the previous quadratic result.



Quadratic fluctuations + their interactions →
lead to a saddle along the soft directions.



Quadratic fluctuations + their interactions → lead to a saddle along the soft directions.

Since there are these many almost flat directions, do we get a spin glass behavior?

As conjectured by Anninos, Anous, Denef

This question was analyzed in a purely bosonic model, the p-spin model.

$$V \sim C_{ijk}\phi_i\phi_j\phi_k \ , \qquad \phi_i^2 = \text{fixed}$$

It indeed had a spin glass phase at low temperatures.

Cugliandolo, Grempel, da Silva Santos

...

Anous, Haehl

We expected the answer to be yes…

We expected the answer to be yes…

Introduce replicas

Replica indices: a,b = 1,..,n

$$G_\phi \longrightarrow G_\phi^{ab}$$

Now we have similar equations but with n x n matrices

$$\overline{\log Z} = \lim_{n\to 0} \frac{\overline{Z^n} - 1}{n} = \lim_{n\to 0} \frac{1}{n}(e^{-NI_n} - 1) = -N \lim_{n\to 0} \frac{I_n}{n}$$

In cases with a spin glass phase, the first signature is usually a solution of the following form

Consider matrices with off diagonal components

$$G_\phi^{ab} = \begin{pmatrix} G_\phi & g & g \\ g & G_\phi & g \\ g & g & G_\phi \end{pmatrix}$$

Edwards, Anderson

Independent of τ

We found no solutions of this kind, with $0 < g \leq \bar{G}_\phi$, as n → 0

One step replica symmetry breaking

$$G_\phi^{ab} = \begin{pmatrix} G_\phi & \hat{g} & g & g & g & g \\ \hat{g} & G_\phi & g & g & g & g \\ g & g & G_\phi & \hat{g} & g & g \\ g & g & \hat{g} & G_\phi & g & g \\ g & g & g & g & G_\phi & \hat{g} \\ g & g & g & g & \hat{g} & G_\phi \end{pmatrix}$$

We found no solutions of this kind, with $0 < g, \hat{g} \leq \bar{G}_\phi$ as n→0

For small temperatures, we also considered the full Parisi ansatz. We did not find a solution either.

Interpretation:

It looks like the field does not get ``stuck'' in one valley.

It manages to spread across all valleys.

Chaos in the model?

Since, the leading expression is due to a quadratic approximation

→

we expect that the Lyapunov exponent is NOT maximal, and it is probably small at low temperatures.

Conclusions

- We discussed an SYK-like model which has a peculiar low energy behavior.
- We discussed the physical origin of this behavior.
- The model has important differences with BFSS
  - The zero temperature entropy
  - Not maximally chaotic
  - Growing vacuum expectation value at low temperatures.

- No spin glass behavior.

Maybe it is useful for something else...

Comments on It from Qubit themes

Juan Maldacena

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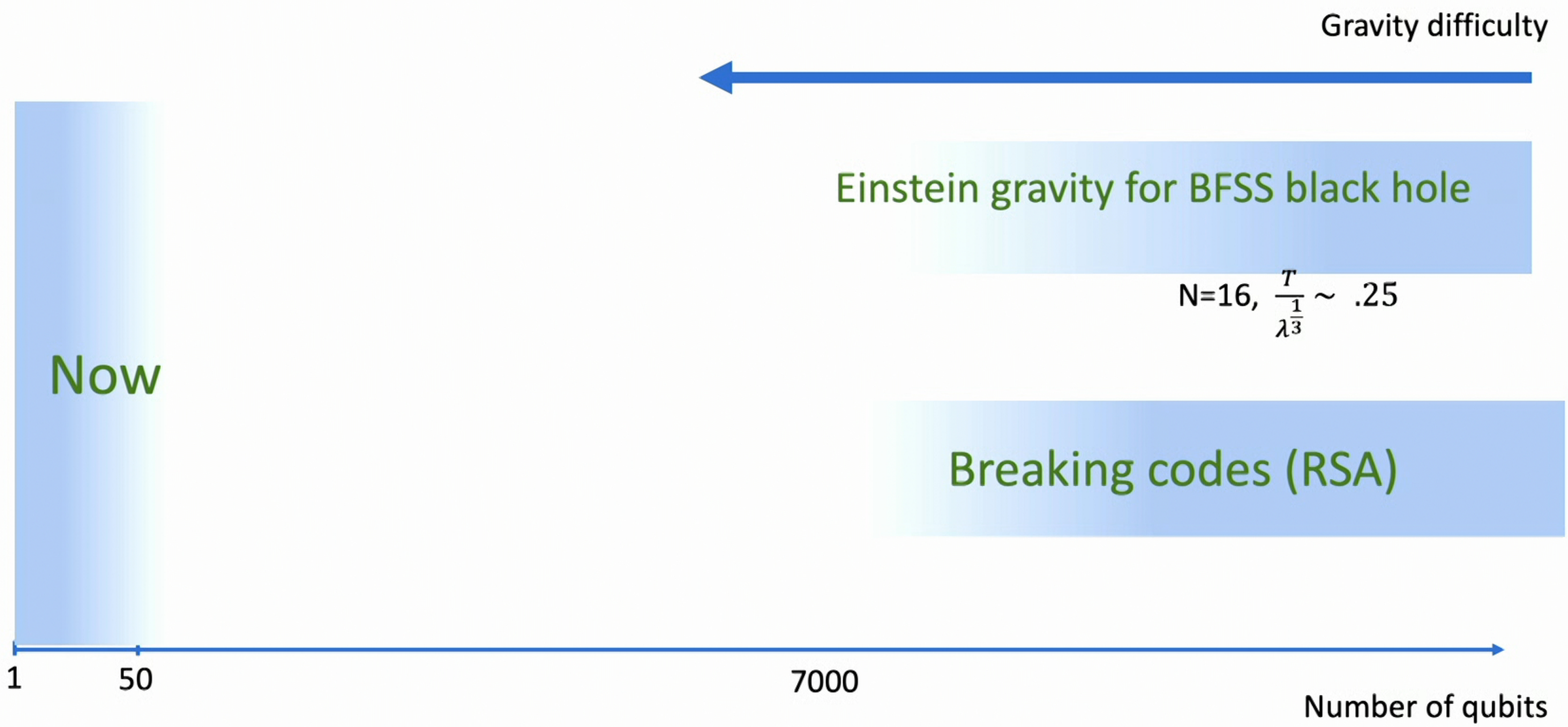
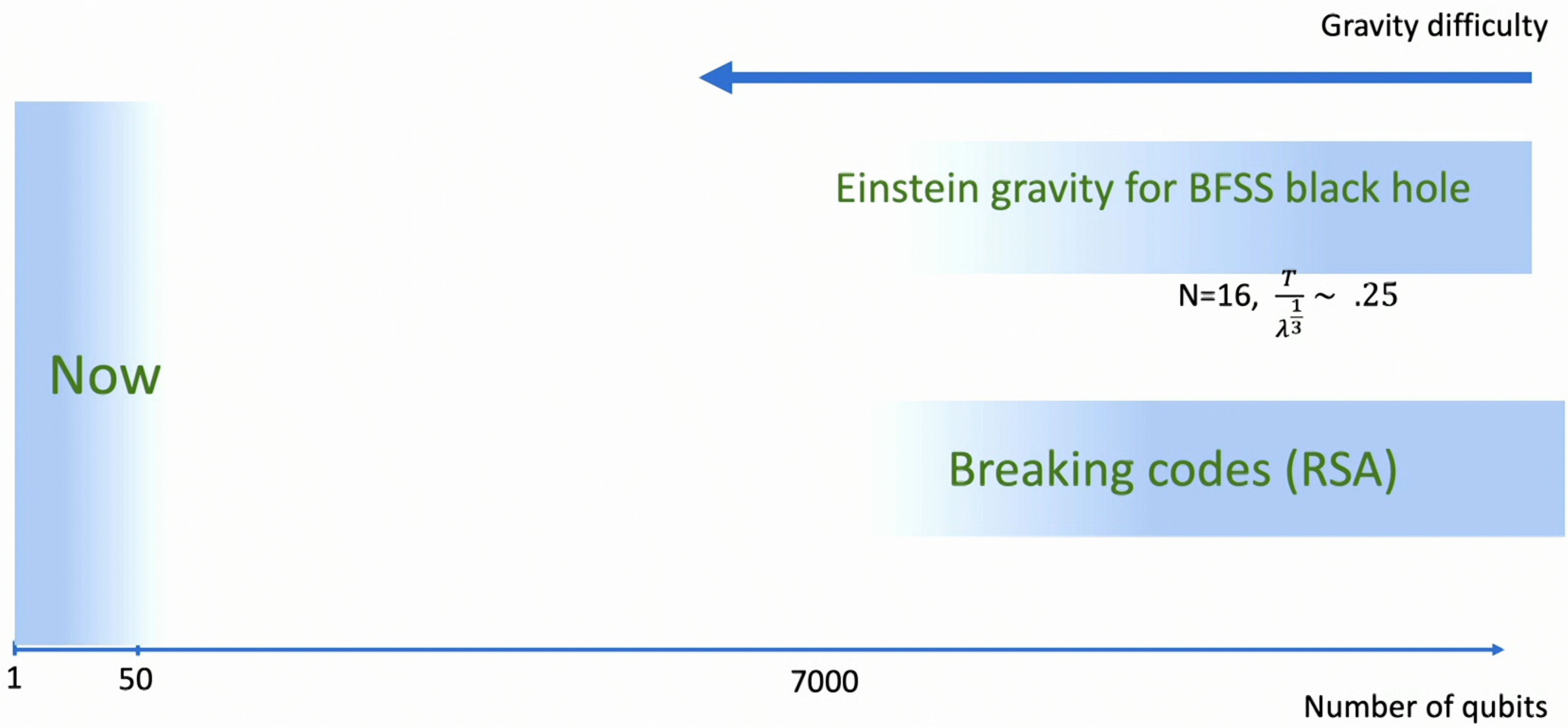
Perimeter Institute, July 2023

Making It from Qubit



Making It from Qubit



The 1970's was the era of gravitational thermodynamics

Wheeler, Bekenstein, Hawking, Gibbons, …

Thermodynamics from geometry, areas*

*Really generalized entropies: $A + S_{outside}$

The ideas of the 70's stayed outside the horizon.

We can now go behind the horizon.

Wormhole calculus

The surprising effectiveness of the semiclassical gravitational path integral

- The Page curve

  Penington, Alhmeiri, Engelhardt, Marolf, Maxfield, …

- Long time behavior of partition functions and correlators.

  Saad, Shenker, Stanford, …

The current ones lead us to think that gravity is related to entanglement, with complexity constraints.

We now seem to be heading into algebraic geometry…

Leutheusser, Liu, Witten, Chandrasekaran, Longo, Penington, Jensen, Sorce, Speranza, Kolchmeyer, Engelhardt,….

The developments of the 70's lead to the search for microstates.

In the 90's, this succeeded via D-branes, AdS/CFT, etc.

Strominger, Vafa, ...

What are the ``hidden parameters'' or the interpretation of the ``ensemble''?

Are they not there?

Is it just an illusion of our defective understanding?

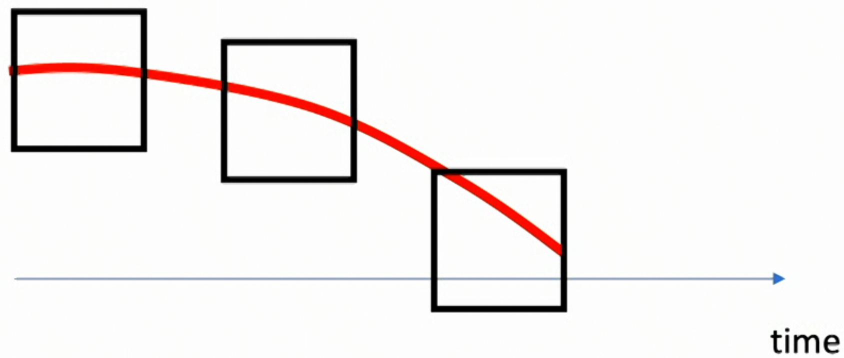
Approximate solutions of the constraints?

Sums over all solutions of the constraints?

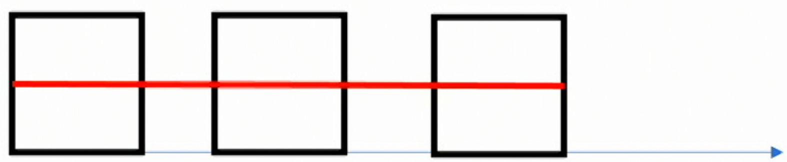
Coleman, Giddings, Strominger, Polchinski, Saad, Shenker, Stanford, Marolf, Maxfield, Chandra, Hartman, Maloney, Collier, Belin, DeBoer, Nayak, Sonner, Anous, Jefferis, Kolchmeyer, Mukhametzhanov, ...

Recall light in a falling elevator

Einstein

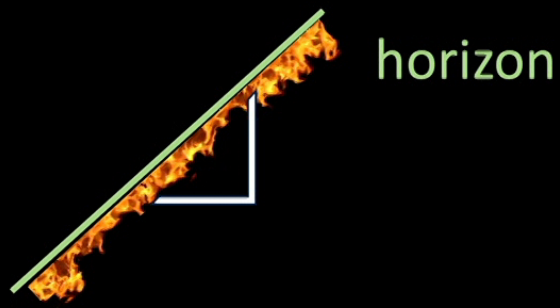


Outside view



Inside view

We now have a similar experiment



Outside view: burns due to Hawking radiation

Inside view: nothing happens

We have not yet made them fully compatible

Stanford, Yang

…Akers, Engelhardt, Harlow, Penington, Vardhan

We have not yet made them fully compatible

- When is it smooth?
- When is it not?
- Firewalls can sometimes form.

Stanford, Yang

...Akers, Engelhardt, Harlow, Penington, Vardhan

We have not yet made them fully compatible

- When is it smooth?
- When is it not?
- Firewalls can sometimes form.
- They do not have to form after the Page time.

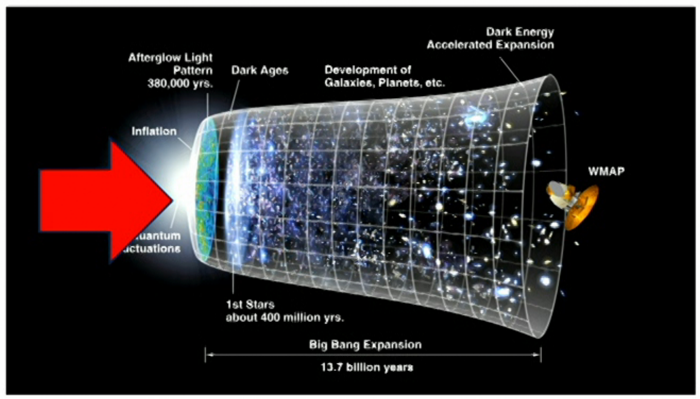
Stanford, Yang

...Akers, Engelhardt, Harlow, Penington, Vardhan

There is probably a great lesson about gravity <u>still</u> to be discovered.

The most important problem in quantum gravity

The beginning of our universe



Understanding the black hole singularity should help.

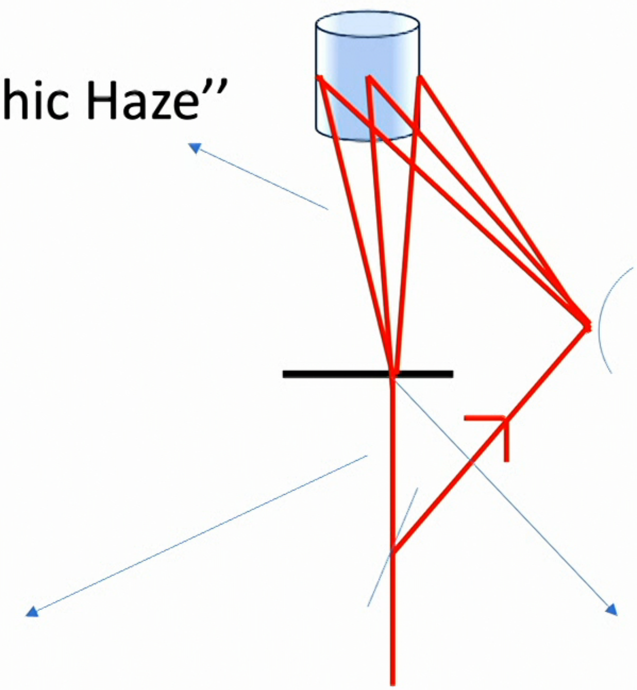
I thought that we would need to understand locality at sub-AdS scales, since the proper time to the singularity is of order the radius of curvature of the black hole geometry.

Maybe not..

Let’s make an amusing comment on the connection between quantum gravity and holography

Reminder on optical holography

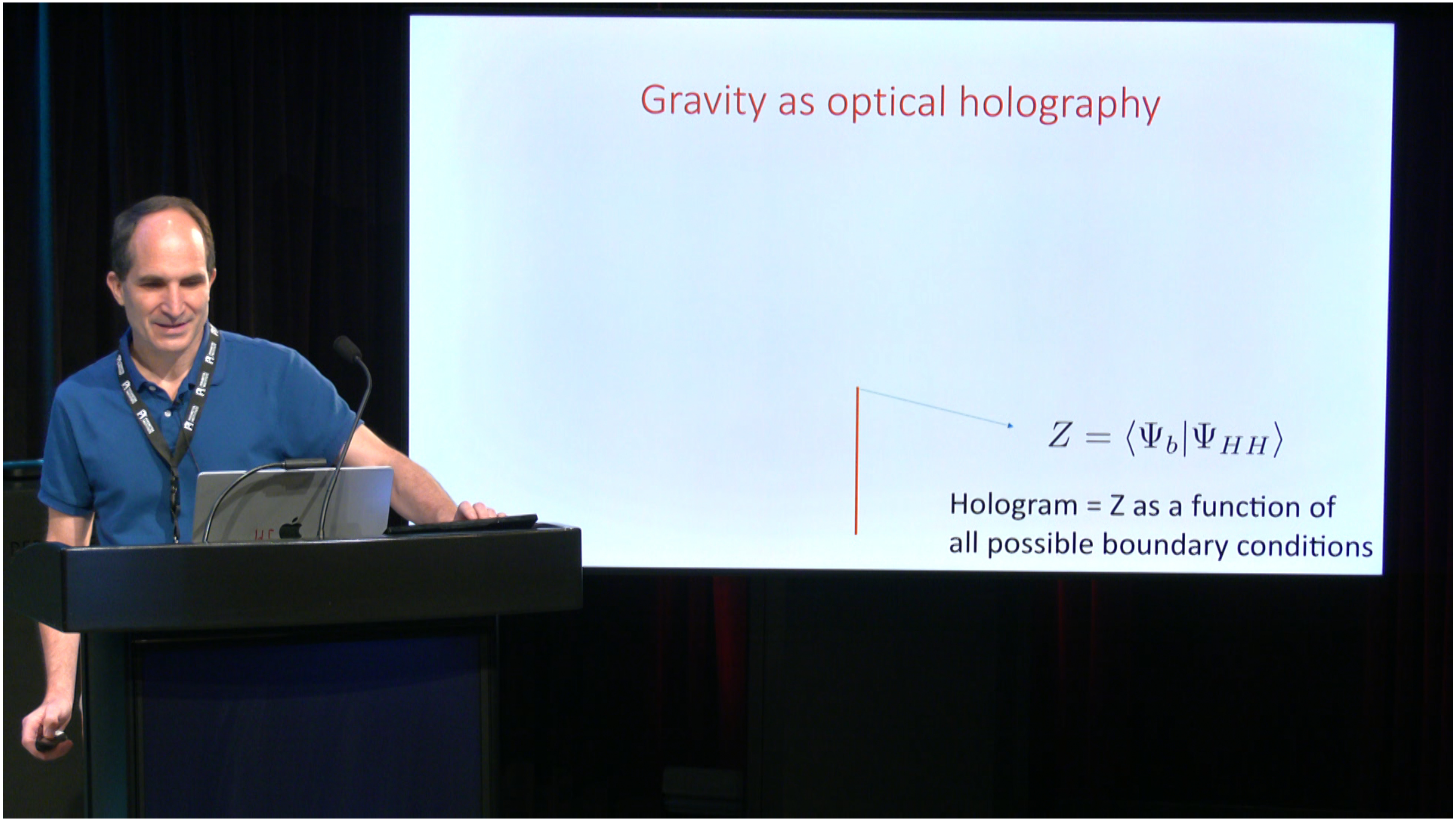
Reflected rays,
call them ``Holographic Haze''



Interference pattern involves

$$I \sim \Psi_b^* \Psi_{HH} + c.c.$$

Reference ray,
Call it "basic" ray


Gravity as optical holography
$Z = \langle \Psi_b | \Psi_{HH} \rangle$
Hologram = Z as a function of
all possible boundary conditions

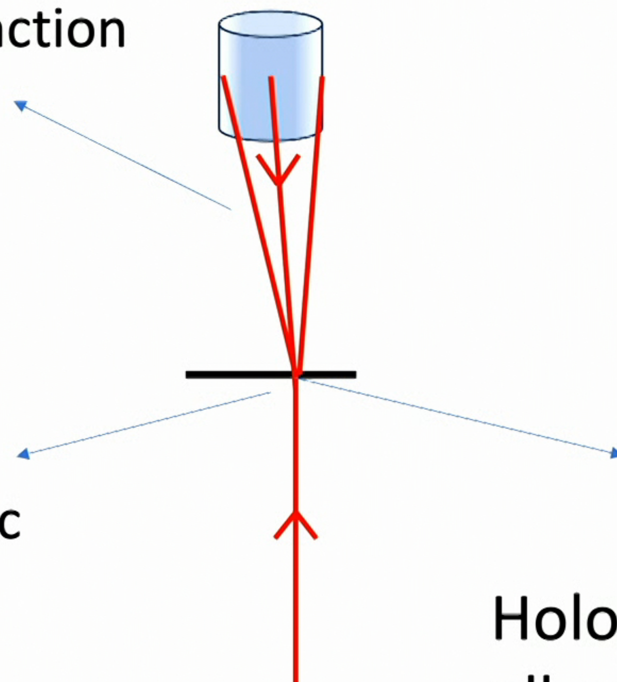
Gravity as optical holography

$$Z = \langle \Psi_b | \Psi_{HH} \rangle$$

Hologram = Z as a function of all possible boundary conditions

Gravity as optical holography

Hartle-Hawking wavefunction



Position on the screen =
Choice of boundary metric

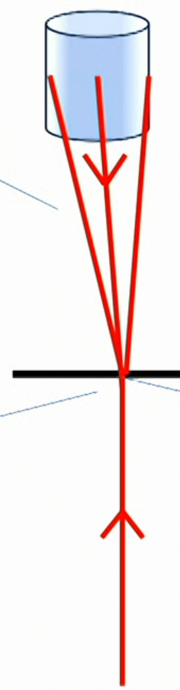
$$Z = \langle \Psi_b | \Psi_{HH} \rangle$$

Hologram = Z as a function of
all possible boundary conditions

Gravity as optical holography

Hartle-Hawking wavefunction

``Superspace'' = the metaverse

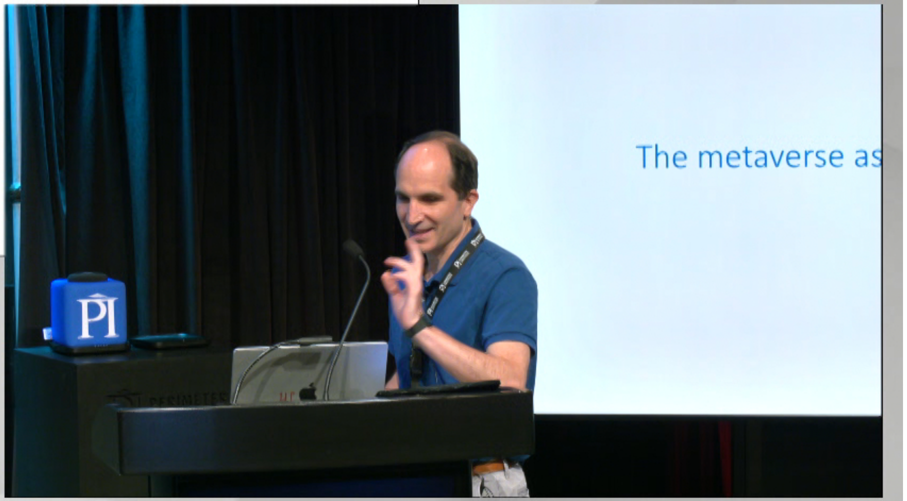


Position on the screen =
Choice of boundary metric

$$Z = \langle \Psi_b | \Psi_{HH} \rangle$$

Hologram = Z as a function of
all possible boundary conditions

The metaverse as a hologram



Thanks to Matt Headrick and Patrick Hayden for organizing the collaboration.

It from bit?

If gravity is emergent, and GR = QM, then why isn't QM emergent also?

Are these just old fashioned thoughts?

Thank you!