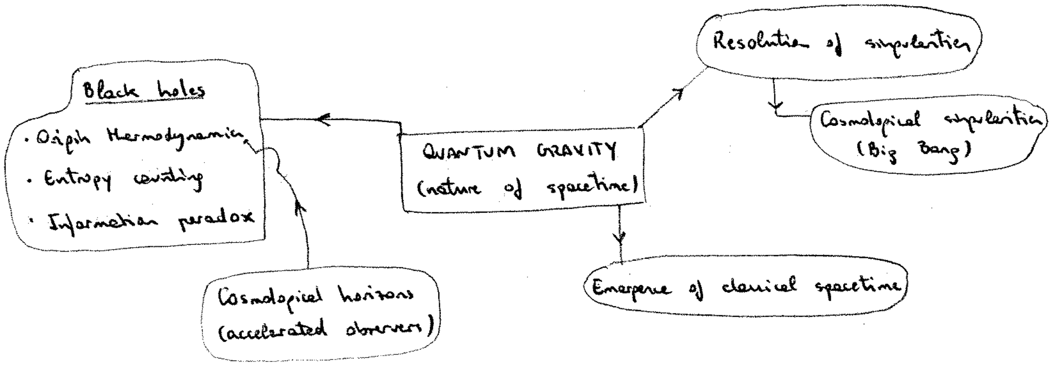
COARSE-GRAINING GRAVITY : BLACK HOLES AND SINGULARITIES

INTRODUCTION / MOTIVATION / PROPOSAL



All notions listed above exist or have been derived (extrapolated) by using scales $\boxed{L \gg \ell_p}$

Equivalently, we use an effective theory (GR or generalizations of it) in which there is a natural scale $\{\ell_p\}$.

Strictly speaking we infer some of the issues listed above in regimes in which effective theory breaks down

[This is NOT generically true for black holes, since horizon physics can be classical if charges are large enough]

Black holes.

- Questions: Where are states of a black hole?. What properties should they satisfy?.

↳ NO HORIZON ! (single microstate $\Rightarrow S = 0$) + global charges of the hole

Can it be realized geometrically?. ⟶ depends on curvature! (charge)

Small curvatures ⇒ foamish picture (quantum mechanically)

Macroscopic horizons ⇒ details matter at horizon scale (Mathur proposal)

- ∃ scale (Planck scale or larger): if you coarse-grain above it ⇒ no distinction over microstates

PROPOSAL (V. Balasubramanian, V. Jejjala, J. de Boer, J.S.)

i) Origin of gravitational thermodynamics ⟷ difficulty/inability to tell apart different microstates (analogy with a gas)

↳ gauge theory intuition (loop operators/polynomials of gauge invariant operators ⟶ identification of state?)

* Large charges are assumed (~ large degeneracies) ⇒ statistical mechanics / information theory to describe "typical states"
(TOOL; generic at this point)

ii) Each microstate ⟶ "foamish" description at a given scale (ℓ_p or another ~ dependence of charges)

↳ by coarse-graining system ($L \gg \ell_p$), we lose the ability to identify uniquely the state ⟶ emergence of semiclassical spacetime

↳ we have access to "typical" properties (charges, multipole moments) ⟶ "typical" state ⟶ Singular spacetime

• Singular classical spacetimes emerge as "geometrical averages" after coarse-graining details over ℓ_p scale.

What shall we do?

- Embed our ideas into string theory: AdS/CFT (*)
- Find a subsector of the theory with enough symmetry so that BOTH, field theory and gravity are under control
- Put such system into test
- Check our philosophy.

(*) Emphasize: dual field theory provides the tools/variables to identify "the atoms of spacetime" in this particular construction. In general, we do lack such description [in particular, for Big Bang physics]

- Focus on extremal R-charge black holes in $AdS_5 \times S^5$ (single R-charge):

$$\Delta = M \cdot L = \frac{1}{2} N^2 w \qquad w = q_1 / L^2$$

$$N_c = N \cdot w \quad (\#\ \text{giant gravitons})$$

SET-UP

- We shall consider $\frac{1}{2}$ BPS vector $(\Delta = \mathcal{R})$ of $\mathcal{N}=4$ SYM

Field theory considerations ($\mathbb{R}\times S^3$)

Absence of angular momentum $(j=\bar{j}=0) \Rightarrow$ zero modes on S^3
Simple R-charge $\Rightarrow$ $X, \bar{X}$ (no Y, Z excitations)

$\Pi(\mathrm{Tr}\, X^k)^j \longleftrightarrow B_{[0,k,0]}{}^{(0,0)}$ representation
↳ microscopic counting: partition problem of Δ boxes

$\Downarrow$ reduction of $\mathcal{N}=4$ SYM on S^3

matrix quantum mechanics: one single complex matrix + $\Delta = R$ constraint $\Rightarrow$ real matrix quantum mechanics

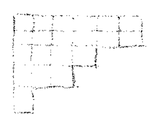
Degrees of freedom: eigenvalues of the matrix $\{\lambda_i\}$ $i=1,..,N$
↳ van der Monde determinant: N fermions in an harmonic potential $\Rightarrow$ spectrum, wavefunctions, ... fully known

Characterisation of states: $E_i = e_i\hbar + \frac{\hbar}{2}$ $(w=1)$ (single particle spectrum)

$E_i^0 = (i-1)\hbar + \hbar/2$ (ground state energies; Pauli exclusion principle; $i=1,..,N$)

$\Downarrow$

$\boxed{r_i = \frac{1}{\hbar}(E_i - E_i^0) = e_i - i + 1}$ (excitation of particle i over ground state)

$\{r_i\}$ non-decreasing set of integers $\Longleftrightarrow$ Young diagram  $\longleftrightarrow \{r_i\}$

Useful variables.

$c_N = r_1$; $c_{N-i} = r_{i+1} - r_i$ $i=1,..,(N-1)$ $c_j \equiv$ # colums of length j (maximum length is N!!)

$r_{i+1} = e_{i+1} - i = c_{N-i} + \dots + c_N$

Physical interpretation

i) Colums $\Longleftrightarrow$ giant gravitons (gravitons with large momentum, due to Myers effect, blow up into spherical D3-branes spinning on $S^5 \Leftrightarrow$ R-charge)
↳ They carry a maximum angular momentum of N, which matches the maximum length (# boxes) of a given column

(*) # columns = # giant gravitons (important later)

ii) Rows $\Longleftrightarrow$ dual giant gravitons

Gravity considerations

- We are looking for asymptotically $AdS_5 \times S^5$ with $\underset{\underset{\underset{AdS_5}{\cap}}{S^3}}{SO(4)} \times \underset{\underset{\underset{S^5}{\cap}}{S^3}}{SO(4)} \times \underset{t}{\mathbb{R}}$ global symmetry and 16 supercharges

$\Rightarrow \{y, x^1, x^2\}$ dimensions

  - Assume $\Phi = \Phi_0$ (constant dilaton), no 2-form fluxes and "standard" RR 5-form flux (to stabilize $AdS_5 \times S^5$ itself)
    ↳ this matches results (previous) from non-extremal R-charge black holes

- This problem was fully solved by LLM:

$$\boxed{g = -h^{-2}(dt + V_i dx^i)^2 + h^2(dy^2 + dx^i dx^i) + y e^{G} g_{S^3} + y e^{-G} g_{\tilde{S}^3}}$$; y^2 = product of radii of two spheres

$z = \frac{1}{2}\tanh G$

Solution (full) is characterized by a single scalar function $z = z(y, x^1, x^2)$ satisfying a linear diff. equation

$$\boxed{\partial_i \partial_i z + y\,\partial_y\left(\frac{\partial_y z}{y}\right) = 0} \qquad i = 1,2$$

(*) $\Phi(y; x^1, x^2) = z \cdot y^{-2}$ satisfies a Laplace eq. for an electrostatic potential in 6 dimensions being spherically symmetric in 4 directions: $\mathbb{R}^6 = \underset{(y, S^3)}{\mathbb{R}^4} \times \underset{(x^1, x^2)}{\mathbb{R}^2} \mapsto \Phi(y; x^1, x^2)$ and is characterized by a boundary condition at $y = 0$

$$\boxed{z(y; x^1, x^2) = \frac{y^2}{\pi}\int dx_1' dx_2' \frac{z(0; x_1', x_2')}{[(x - x')^2 + y^2]^2}}$$

- Comments:

  1. A given supergravity configuration $\Longleftrightarrow$ $z(0; x^1, x^2) \equiv$ charge distribution in (x^1, x^2) plane
  2. As $y \to 0$, S^3 or $\tilde{S}^3$ (or both) shrink to zero size: singularities?
     ↳ LLM concluded that only regular boundary conditions correspond to $\boxed{z = \pm \frac{1}{2}}$ $\begin{cases} 1/2 & S^3 \subset S^5 \text{ zero size} \\ -1/2 & S^3 \subset AdS^5 \text{ zero size} \end{cases}$

  3. Charges:

$$\boxed{\Delta = R = \int_{\mathcal{D}} \frac{d^2x}{2\pi\hbar}\, \frac{1}{2}\frac{x_1^2 + x_2^2}{\hbar} - \frac{1}{2}\left(\int_{\mathcal{D}} \frac{d^2x}{2\pi\hbar}\right)^2}$$

$\mathcal{D} \equiv$ droplet (region) in x^1-x^2-plane where $z = -1/2$.

$\hbar = 2\pi \ell_p^4$ [it has L^4 units because both x^1, x^2 have L^2 units]

Quantization of flux: $N = \int_{\mathcal{D}} \frac{d^2x}{2\pi\hbar}$

Introduce: $\boxed{u(0; x^1, x^2) = \frac{1}{2} - z(0; x^1, x^2)}$ $\Rightarrow$ $\boxed{\Delta = \int_{\mathbb{R}^2} \frac{dx^1 dx^2}{2\pi\hbar} \frac{(x^1)^2 + (x^2)^2}{2\hbar} u(0; x^1, x^2) - \frac{1}{2}N^2}$

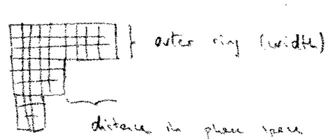
i) Integral over (x^1, x^2) of hamiltonian ($\frac{1}{2}q^2 + \frac{1}{2}p^2 \sim$ harmonic oscillator) minus vacuum energy $\frac{1}{2}N^2$.

ii) Suggests to interpret $u(0; x^1, x^2)$ as a "density" (later phase space distrib. function)

  4. Examples:

Vacuum: disk $\longleftrightarrow$ absence of diagram

U(1) invariant states: bunch of rings $\longleftrightarrow$



Non-U(1) invariant states

Comment for talk:

i) Keep metric LLM, Δ formulas in the blackboard [leave space to write superstar and compare]

Typical States

General Philosophy.

Large N ~ large degeneracy $\Longrightarrow$ canonical ensemble [fix β so that $\langle E\rangle = \Delta$] (statistical mechanics in general)

$\langle r_i\rangle$, $\langle c_j\rangle$ $\longrightarrow$ averaged tableaux/diagram (state) $\longrightarrow$ average state/typical state (overwhelming many of them will lie close to that state)

fluctuations $\longrightarrow$ deviations from typical state

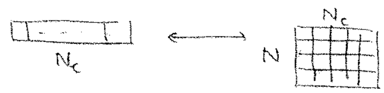
Comment: large degeneracy (scaling with N) does NOT guarantee a MACROSCOPIC gravitational horizon.

Different ensembles: consider system with fixed # fermions (rows)

i) Unfixed energies: # columns is not constrained

Averaged energy grows without bound as the temperature grows [$S>0$, $E>0$, $T>0$]

ii) Fixing # columns = fixing # giant gravitons [relevant to discuss the physics of extremal R-charge black holes]

$\Delta \in [N_c,\ N\cdot N_c]$ 

$S(\Delta = N_c) = S(\Delta = N\cdot N_c) = 0$ (1 microstate!)

iia) As Δ increases from N_c, entropy increases, heating up system ; $T>0$ branch

But as $\Delta \to N_c\cdot(N+1)/2$ [half filled diagram], entropy should reach a maximum ($T\to\infty$)

iib) As Δ continues to grow, S decreases : $T<0$ branch, and decreases in absolute value.

This physical picture is confirmed by the $\exists$ one-to-one map between Young diagrams with Δ and $N_c(N+1)-\Delta$

$$S(\Delta) = S(N_c(N+1)-\Delta)$$

Details

$$Z = \sum_{c_1,\dots c_N=1}^{\infty} e^{-\beta\sum j c_j - \lambda(\sum_k c_k - N_c)}$$

where λ Lagrange multiplier : $\boxed{\sum_j c_j = N_c}$

$$Z = \zeta^{-N_c}\prod_j \frac{1}{1-\zeta q^j} \qquad q = e^{-\beta};\ \ \zeta = e^{-\lambda}$$

$$\langle E\rangle = \Delta = q\partial_q \log Z = \sum_{j=1}^{N} \frac{j\zeta q^j}{1-\zeta q^j}$$

$$N_c = \sum_{j=1}^{N}\langle c_j\rangle = \sum_{j=1}^{N}\frac{\zeta q^j}{1-\zeta q^j}$$

These are the equations fixing β,λ as a function of Δ, N_c (data from physics) !!

Checks

Low temperature : large-β

1. $T>0 \Rightarrow q = e^{-\beta} \ll 1 \Longrightarrow \Delta \sim \frac{\zeta q}{1-\zeta q}$; $N_c \sim \frac{\zeta q}{1-\zeta q} \Rightarrow$ single row ($\Delta = N_c$)

2. $T<0 \Rightarrow q = e^{-\beta} \gg 1 \Longrightarrow N_c \sim \langle c_N\rangle = \frac{\zeta q^N}{1-\zeta q^N}$ (rectangular diagram)

$$\Delta = \sum_{s=1}^{\infty}\zeta^s\sum_{j=1}^{N} j\, q^{sj} = \sum_{s=1}^{\infty}\zeta^s\left\{ q^s\,\frac{1-q^{sN}}{1-q^s} + q^{2s}\,\frac{1-Nq^{(N-1)s}+(N-1)q^{Ns}}{(1-q^s)^2}\right\} \sim N\sum_{s=1}^{\infty}(\zeta q^N)^s = N\cdot N_c$$

High temperature.

$$S = \beta \langle E \rangle + \log Z$$

Solving N_c constraint: $\quad z(N, N_c) = \frac{w}{1+w}\left(1 + \beta \frac{A_1}{N} + \beta^2 \frac{N+1}{12}\left[(N+2) - w(N-1)\right]\right) + O(\beta^3) \quad ; \quad w = \frac{N_c}{N} \; ; \; A_1 = \sum_{j=1}^{N} j = \frac{N(N+1)}{2}$

Solving $\langle E \rangle$ constraint:

$$\Delta = w A_1 - \beta \frac{A_1}{6} w(1+w)(N-1) + O(\beta^2)$$

Comment: $\quad \Delta = \frac{1}{2} N \cdot N_c + O(\beta) + O(N_c) \Longrightarrow$ dominant contribution at large N and large temperature $\Longleftrightarrow$ superstar energy

$$\boxed{S = -\log\left(\frac{w^{N_c}}{(1+w)^{N+N_c}}\right) - \beta^2 \frac{w(1+w)}{24} N(N^2-1) + O(\beta^4)}$$

Thus, $\beta = 0$ $(T \to \infty)$ is indeed a maximum for the entropy.

Conjecture: $\beta \to 0$, large N limit describes typical states for the superstar (extremal $\frac{1}{2}$ BPS R-charge black hole)

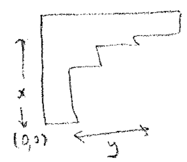
Check.

$$S \sim (\text{log cont.}) \cdot \sqrt{\Delta} \underset{N_c = wN}{\approx} N \sim \frac{L^5 r_h^3}{G_{10}} \sim \frac{L^8}{\ell_p^8}\left(\frac{r_h}{L}\right)^3 \sim N^2 \left(\frac{r_h}{L}\right)^3 \Rightarrow r_h \sim \frac{L}{N^{1/3}} \Longleftrightarrow \frac{r_h}{\ell_p} \sim N^{1/4 - 1/3} = \frac{1}{N^{1/12}} \to 0$$

Even though entropy is maximum, degeneracy $(\sim N)$ is NOT enough to generate a macroscopic horizon $\sim$ superstar etc.

Limit curve.

- Introduce two coordinates (x, y) to describe the diagram: x along the rows and y along the columns.



Consider: $N \to \infty$, N_c fixed, rescaling diagram $\Longrightarrow$ continuum limit

- Notice that: $\quad r_{i+1} = e_{i+1} - i = c_{N-i} + \dots + c_N \Longleftrightarrow \quad y(x) = \sum_{i=N-x}^{N} c_i \quad$ (excitation of particle "x")

$$\langle y(x) \rangle = y(x) = \sum_{i=N-x}^{N} \langle c_i \rangle \sim \int_{N-x}^{N} di \, \langle c_i \rangle$$

$$\boxed{\alpha\, q^{N-x} + \hat{\beta}\, q^{y} = 1} \qquad \alpha = \frac{1-q^{N_c}}{1-q^{N+N_c}} \; ; \; \hat{\beta} = \frac{1-q^{N}}{1-q^{N+N_c}}$$

- In particular: as $\beta \to 0$ (to check our conjecture) [Comment on triangular diagram]

$$\boxed{y = \frac{N_c}{N} x = w x}$$

MATCHING GRAVITY : SEMICLASSICAL CONSIDERATIONS

- LLM suggested $(x^1, x^2) \Longleftrightarrow (q, p)$ phase space of a single particle in the eigenvalue picture
- We shall give one step further:

$$\boxed{u(0; x^1, x^2) = u_{\text{wigner}}}$$ (equality meaning up to normalization and taking semiclassical limit appropriately)

WIGNER

$$W(\vec{q}; \vec{p}) = \frac{1}{(2\pi\hbar)^n} \int_{-\infty}^{\infty} d\vec{y} \, \langle \vec{q} - \vec{y} | \hat{\rho}_n | \vec{q} + \vec{y} \rangle \, e^{2i \, \vec{p} \cdot \vec{y} / \hbar}$$ (definition, given a density matrix $\hat{\rho}_n$)

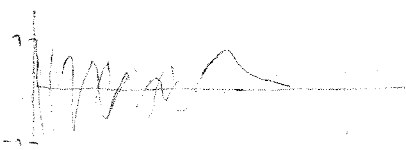
$$\langle \hat{A}_W \rangle = \text{tr}(\hat{\rho}_n \, \hat{A}_W(\hat{q}, \hat{p})) = \int d\vec{q} \, d\vec{p} \; A(\vec{q}, \vec{p}) \, W(\vec{q}; \vec{p})$$ [it computes expectation values of Weyl ordered operators]

Properties:

- Though bounded, it oscillates rapidly in the classically allowed phase space, and decays exponentially outside.

In our set-up: (after integrating out $N-1$ particles !!)

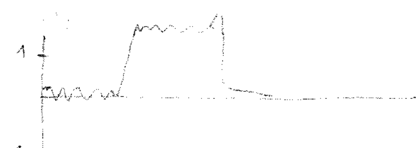
$$W(q, p) = \frac{1}{\pi\hbar} e^{-(p^2+q^2)/\hbar} \sum_{j \in F} (-1)^j L_j\left(\frac{2}{\hbar}(p^2+q^2)\right)$$ F set of excitation levels



Main observation: oscillations have a natural $\hbar$ scale $\Rightarrow$ very quantum mechanical sensitive quantity

$\exists$ maximum at classical energy

- Even if we add the effect of many fermions, $\exists$ quantum mechanical oscillations

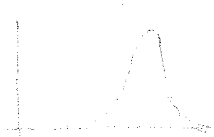


Suggestion: coarse-grain Wigner at $\hbar$ scale $\Rightarrow$ Husimi distribution.

HUSIMI

$$Hu(q, p) = \frac{1}{2\pi\hbar} \int dQ \, dP \; Z(q, p; Q, P) \, W(Q, P)$$ where $Z = \exp\left[-\frac{1}{2\hbar}\left[(q-Q)^2 + (p-P)^2\right]\right]$ (Gaussian kernel of variance $\hbar$)

- It contains the same quantum mechanical information, but it computes normal ordered observables.



$$Hu_n(z) \sim \frac{1}{2\pi\hbar} \frac{1}{\sqrt{2\pi n}} e^{-(z-n)^2/2n}$$ where $z = (p^2+q^2)/2\hbar$

It is peaked at $z = n$ (classical energy), with variance $\sim n$ $\Rightarrow$ $\sigma(r) \sim \sqrt{\hbar}$ (variance in radial variable)

↳ it is a well-localized lump of energy as $\hbar \to 0$, BUT ...

$\sigma(E) \sim \sqrt{E\hbar} \gg \Delta E = \hbar \Rightarrow$ localized ring does not capture physics.
(classical limit)

GRAYSCALE DISTRIBUTION

- Assume $\exists$ semiclassical limit ($\hbar \to 0$, $\hbar N$ fixed)
- In phase space, we want to coarse-grain at scales $\Delta E/\hbar \to \infty$

A natural coarse-grained observable would depend on the coarse-grained Husimi distribution:

$$R(E,\Delta E) = 2\pi\hbar \int_E^{E+\Delta E} dq\,dp\; H_u(q,p) \quad \sim \quad \#\ \text{fermions between } E \text{ and } E+\Delta E$$

Effective density:

$$\boxed{\rho(E) = 2\pi\hbar\left(\frac{R(E,\Delta E)}{2\pi\Delta E}\right) = \hbar\,\frac{\Delta x}{\Delta E} = \frac{\hbar}{\partial E/\partial x}}$$

- If we assume $\exists$ semiclassical limit: $E = \hbar(x + y(x)) \Rightarrow \boxed{\rho(E) = \frac{1}{1+y'}}$

phase space distribution in the semiclassical limit (derived from limit curve) equals the notion of integrating out smaller scales (grayscale)

Equivalently:

$$\left.\begin{aligned} &\frac{u(0,r^2)}{2\hbar}\,dr^2 = dx \qquad (\#\ \text{particles in } dx,\ r,\ r+dr) \\ &r^2\,\frac{u(0,r^2)}{4\hbar^2}\,dr^2 = (y+x)\,dx \qquad (\text{energy in that band}) \end{aligned}\right\} \Rightarrow y(x)+x = \frac{r^2}{2\hbar}\ \checkmark, \quad \boxed{u(0,r^2) = \frac{1}{1+y'}}$$

MATCHING SUPERSTAR

- Gravity data:

$$g = -\frac{\sqrt{\gamma}}{H} f\,dt^2 + \frac{\sqrt{\gamma}}{f}dr^2 + \sqrt{\gamma}\,r^2 g_{S^3} + \sqrt{\gamma}L^2 d\theta_1^2 + \frac{L^2}{\sqrt{\gamma}}\sin^2\theta\, g_{\tilde{S}^3} + \frac{H}{\sqrt{\gamma}}\cos^2\theta\,[L\,d\phi + (H^{-1}-1)dt]^2$$

$$H = 1 + s/r^2\ ;\quad f = 1 + r^2 H/L^2\ ;\quad \gamma = 1 + q\sin^2\theta/r^2$$

Comparing sizes of S^3's:

$$y e^{G} = \sqrt{\gamma}\,r^2\ ;\quad y e^{-G} = \frac{L^2\sin^2\theta}{\sqrt{\gamma}} \iff y^2 = r^2L^2\sin^2\theta\ ;\quad e^{G} = \frac{r\sqrt{\gamma}}{L\sin\theta} \Rightarrow z = \frac{1}{2}\,\frac{r^2\gamma - L^2\sin^2\theta}{r^2\gamma + L^2\sin^2\theta}$$

We want to compute $z(0)$:

$$y = 0 \Rightarrow \begin{cases} \sin\theta = 0 \Rightarrow z = 1/2 \quad (\text{no D-branes excited!}) \\ r = 0 \quad (\text{density of giants does not vanish}) \Rightarrow \boxed{z(r=0) = \frac{1}{2}\,\frac{w-1}{w+1}} \end{cases} \quad \text{where } w = q/L^2 = N_c/N$$

MAGIC EXISTS ... !! — MATCH !

Our field theory analysis + typical state analysis + proposal to match:

$$z = \frac{1}{2} - u = \frac{1}{2} - \frac{1}{1+y'} = \frac{1}{2} - \frac{1}{1+w} = \boxed{\frac{1}{2}\,\frac{(w-1)}{w+1}}$$

LESSONS. (interpretation)

i) Simple microstates $\longrightarrow$ not classical geometry (foamish; topologically complex)

ii) Typical microstates can not be told apart (semiclassical observer) $\longrightarrow$ limit curve (differences integrated out) [origin of gravitational thermodynamics]

iii) Emergent spacetime is singular

(*) Quantum mechanical correlation functions: are they universal? (distinguishability of quantum microstates) [field theory side]

(**) Including quantum effects in gravity (knowing higher scale details) [gravity side]

SCHWARZSCHILD AdS BLACK HOLES

- One may wonder whether the previous lessons could shed some light on the microscopics of "real" black holes in AdS.

Gravity results.

$r_h \sim L \Rightarrow \frac{r_h}{\ell_p} \sim N^{1/4}$ (macroscopic horizon) ; $\Delta = M \cdot L \sim N^2$

$S \sim N^2$

Field theory expectations.

$\exists$ degeneracy of microstates : $|\Psi\rangle = O|0\rangle$; $\Delta(O) = N^2$ [at large N]

↳ LONG OPERATORS ~ built of words (traces) made of strings of letters (fields) that belong to an alphabet ($\mathcal{N}=4$ SYM)

Again, the crucial notion is : typical operator ~ typical word

Large $N \Longrightarrow$ use information theory theorem (statistical mechanics) to determine / characterise "typical word"

Information theory (Sanov's theorem)

typical word ~ statistical randomness of the sequence of fields in the long polynomial

$$P(x) = \frac{1}{k} \qquad k = \#\,\text{alphabet} \quad \text{and} \quad x = \text{field (letter)}$$

The probability that a given distribution differs from $P(x)$ is exponentially suppressed in the conformal dimension.

Caveats

i) Non-BPS operators ($X\bar{X}$ are allowed) : Δ renormalises
ii) Mixing of operators

} coupling (difference between a pair of particles and a black hole)

vs. ↕ (strong-weak AdS/CFT duality)

correspondence principle (classical results)

Our proposal.

$\boxed{\text{Correlation functions of probe operators } O_p \text{ computed in very heavy states } |\Psi\rangle \text{ depend only on } \Delta \text{ and global charges up to corrections of } O(e^{-\Delta}) \text{, for almost all states } |\Psi\rangle \text{ and probes } O_p.}$

- In free field theory, the contribution from planar diagrams is controlled by the number of times the probe operator appears within the state (pattern matching) $\Rightarrow$ this number is mostly determined by the statistics of long random polynomials.

Future Directions

1. Loss of information (N particle $\longrightarrow$ 1 particle phase space()); gravitational counterpart (α' effects ?))
   - universality of correlation functions (quantum version for origin of thermodynamics)
   - non-U(1) invariant states; non-pure states $\longrightarrow$ identification of quantum microstates $\sim$ lemons

2. Non-extremal superstars: perturbative expansion ($\mu \ll q$) $\longrightarrow$ Connection to Schw. black hole physics

   Toy model: throw 4pt perturbations ($\mathrm{tr}\, \bar{Z}\bar{Z}$), ($\mathrm{tr}\, X\bar{X}$) in large BPS operators (giants)

3. Cosmological singularities: is coarse-graining over Planck time scales responsible for the existence (classical) of the Big Bang singularity?.

   ↳ relevance of coupling effects, addition of degrees of freedom (*)

(*) In our talk, there was no need for adding those since we knew we had all of them included!