

Putting a universe inside a black hole

Daniel L Jafferis
LITP at Harvard University

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Introduction

- The fundamental formulation of de Sitter quantum gravity remains mysterious. There are questions of both framework and what are the specific theories.
- We propose a construction of AdS/CFT states whose duals contain cosmological regions. Their physics is, in principle, encoded in complicated properties of the dual states.
- What to do with dS/CFT if you had one. Use it to make a state in someone else's Hilbert space. Consistent with triviality of closed universe Hilbert space.

AdS quantum gravity

- In AdS quantum gravity, there is a time-like boundary frozen at large scale factor with fixed coordinates. Leads to an ordinary quantum system that is local in time, with H_{ADM} unitarily acting on Hilbert space.
- Extra symmetries of AdS lead to a local CFT with particularly clear bootstrap rules. Could classify all UV complete theories in AdS that way.
- However, we don't actually fully understand the rules for bulk observables – seem not to be just complicated CFT operators, due to the overcompleteness of bulk configurations.

Closed Universes

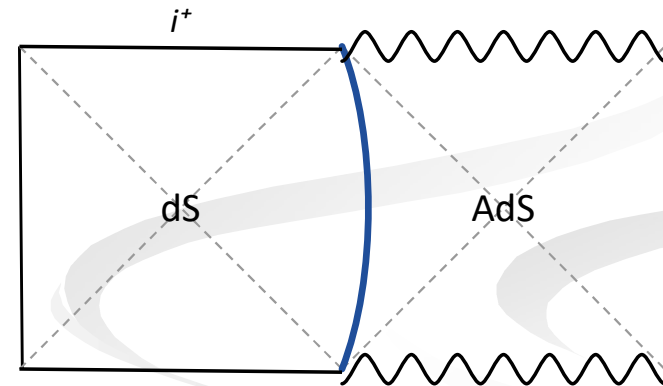
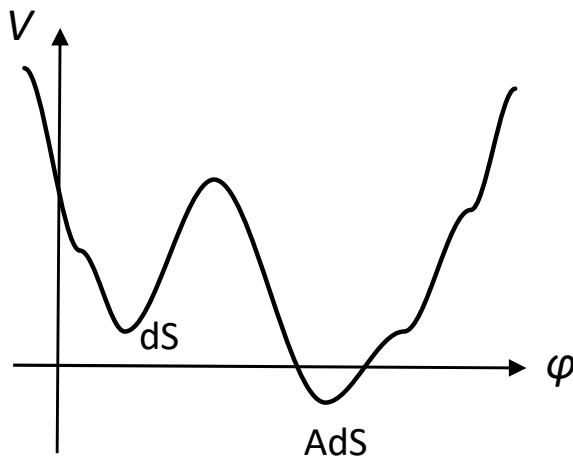
- These puzzles are multiplied in closed universes with no timelike boundaries. $H=0$ is a constraint equation. Large semi-classical Hilbert space. But all observables are like AdS bulk observables.
- Many arguments that the non-perturbative Hilbert space is one dimensional. Only have the no boundary state.

[Marolf Maxfield; Usatyuk Wang Zhao; Harlow Usatyuk Zhao; Balasubramanian Nomoura Ugajin; Sahu van Raamsdonk; Dong Xi Shangnan Yang; Penington Witten; Anninos Hartnoll Hofman]

- Can define boundary anchored path integrals with Euclidean boundaries at large scale factor with frozen coordinates. Generally complex path integrals that compute tiny amplitudes (given expected dS instability). Local, non reflection positive CFTs. [Strominger; Maldacena]

AdS-dS bridges

- In gravitational effective theories with a scalar potential admitting both AdS and dS minima, there exist, as classical solutions, two sided black holes with interpolating domain walls in the ER bridge.



$$ds^2 = -f_s(r) dt^2 + dr^2/f_s(r) + r^2 d\Omega^2$$

$$ds^2 = -f_a(r) dt^2 + dr^2/f_a(r) + r^2 d\Omega^2$$

$$f_s = 1 - r^2/\ell_{dS}^2$$

$$f_a = (r^2 - r_h^2)/\ell_{AdS}^2$$

$$\Delta K = 4\pi G_n T r$$

$$ds_{DW}^2 = -d\tau^2 + r(\tau)^2 d\Omega^2$$

$$\dot{r}^2 + V_{eff}(r) = 0$$

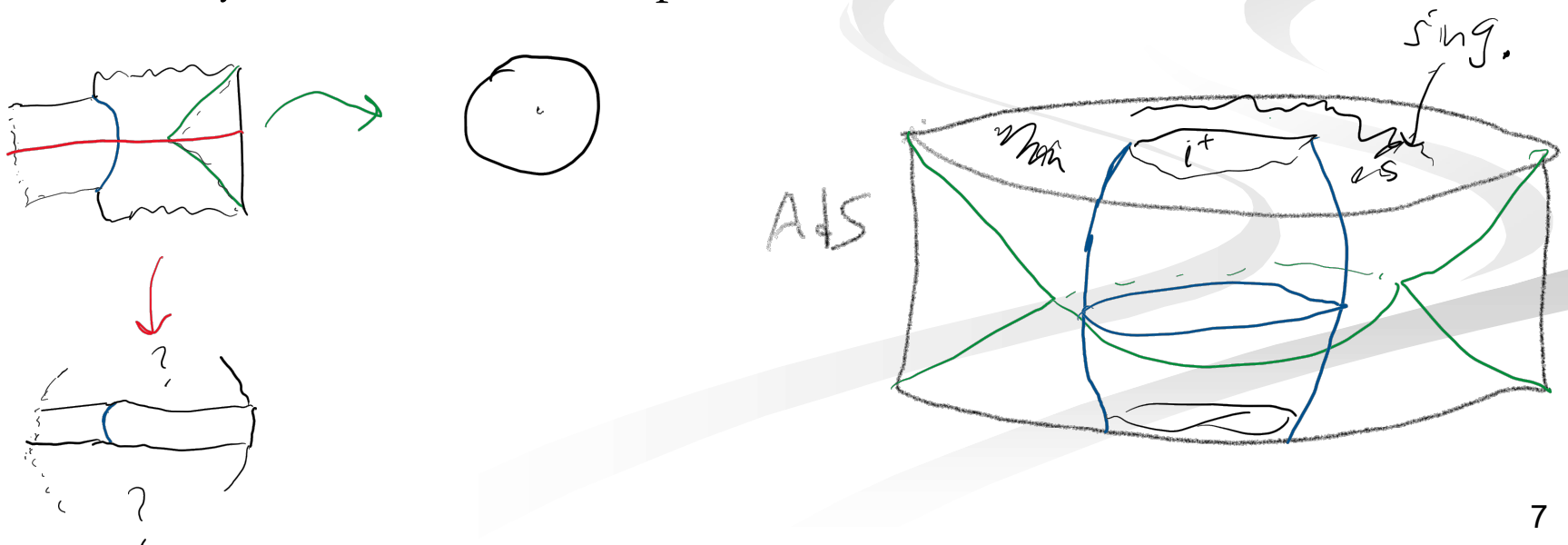
$$V_{eff} = f_a - \frac{(f_s - f_a - T^2 r^2)^2}{4T^2 r^2}$$

Pure state of the CFT_{AdS}

- From the perspective of the AdS boundary, these are black holes with a large region behind the horizon that happens to have an inflating patch. Continuously connected to configurations where the dS region collapses, or where the scalar never goes over the potential barrier. The latter seem obviously dual to pure states of the AdS boundary CFT. Gives another argument that isolated dS would have a trivial Hilbert space.
- Can view this as a closed dS universe with some degrees of freedom (a black hole) that in the semi-classical description are entangled with a reference (the AdS black hole). Here that entanglement is geometrized to the ER bridge. In the exact theory, we expect a pure state of the reference, ie. the CFT_{AdS} .

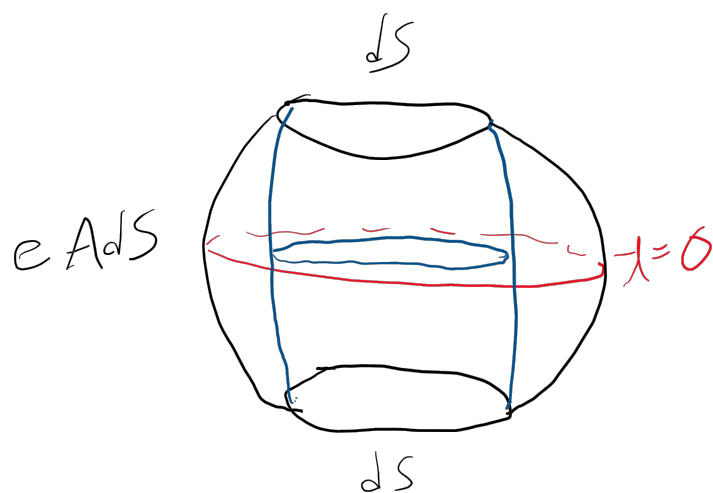
AdS-dS Euclidean continuation?

- The main question today – what kind of states are these? Usually look at the Euclidean continuation to see how to prepare AdS states.
- There is no global smooth Euclidean continuation. The AdS portion continues to the complete Euclidean AdS-Schwarzschild solution, and there is no room behind $r = 0$ for the rest. Analogous to dS-Schwarzschild. There is a continuation of a finite band around the $t = 0$ slice, as guaranteed mathematically, but it can't be completed to a solution.



Complex saddle

- Type equation here. However, we can join the spacelike i^+ boundary of dS to a Euclidean AdS boundary by a domain wall if we allow the bulk coordinate to be complex. Note that the asymptotic limit even of a thick wall is strict interface. In the bulk solution, to maintain the thin wall approximation, one must pick the contour so that the wall lies in it.



$$ds^2 = \frac{-dw^2 + dr^2 + r^2 d\Omega^2}{w^2} L_{dS}^2 \quad dS_3$$

$$ds^2 = \frac{dz^2 + d\rho^2 + \rho^2 d\Omega^2}{z^2} L_{AdS}^2 \quad AdS_3$$

near boundary, $\dot{R} = \gamma R$, $R = \frac{r}{w} L_{dS} = \frac{\rho}{z} L_{AdS}$.

$$z = \epsilon + iu \Rightarrow ds_{DW}^2 = \frac{(1 - \alpha^2) du^2 - \rho^2 d\Omega^2}{(u - i\epsilon)^2},$$

$$\rho|_{DW} = \rho_0 + \alpha u$$

More properly, need to solve a differential equation for $z(u)$ to match $r(u)$.

Lorentzian physics

- Recall that the boundary state cut is being made only in the AdS region. Have a perfectly valid state of that unitary theory. States are allowed to have complex numbers. The full complex saddle is for $\langle \Psi | \Psi \rangle$, which is reflection conjugate.
- The dS Dirichlet boundary is not in the Lorentzian section. The physical i^+ that appears is produced dynamically – it will approach the dS vacuum (not Dirichlet state) and exhibit any instabilities in the theory like bubble nucleation.
- Will be interesting to see how that region can be probed by boundary observables, like left-right correlators in a two sided version.

Consistency of the duals

- One way to address the question of whether a local, non-reflection positive CFT is defined by the gravitational path integral with dS Euclidean boundary conditions is to note that there seems to be nothing wrong in principle with having a non-reflection-positive CFT that admits a local interface with a unitary holographic CFT. What would the dual then be?
- Perturbatively, the gravity path integral would be defined by a complex contour that picks out the desired saddle (to avoid any instabilities). A related question is if there can be non-unitary CFT duals to AdS maxima of the effective potential.

dS brane example

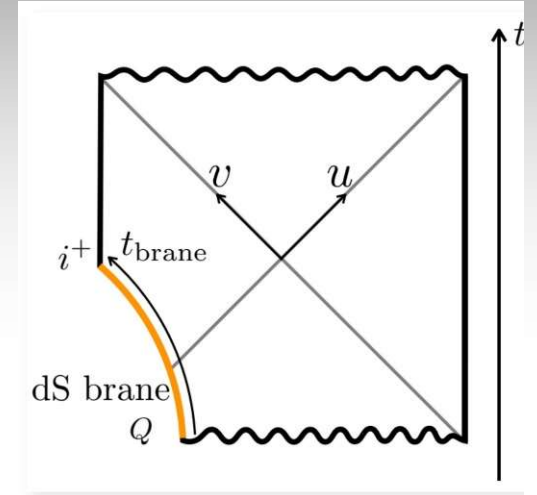
- A version that be can made especially concrete is to have a (d-1)-dimensional dS brane in a d-dimensional AdS universe. The case of AdS_3 pure gravity with a thin wall end of the world brane is particularly simple.

$$S = \frac{1}{16\pi G_N} \int_M \sqrt{g} (R + 2) + \frac{1}{8\pi G_N} \int_Q \sqrt{h} (K - T) + \frac{1}{8\pi G_N} \int_\Sigma \sqrt{\gamma} K$$

- Tension between -1 and +1 leads to AdS branes, less than -1 nucleates instability of AdS. But $T > 1$ allows positively curved inflating EoWs, which are always behind a horizon, by singularity theorems.

[Randall Sundrum; Karch Randall; Akal Kusuki Takayanagi Wei]

Lorentzian solution



- In the BTZ metric in Kruskal coordinates,

$$ds^2 = -\frac{4}{(1+uv)^2} du dv + r_h^2 \frac{(1-uv)^2}{(1+uv)^2} d\phi^2, \text{ the brane lies at}$$

$$u(v) = -\frac{1+\alpha v}{\alpha+v}, u < v, \text{ where } \alpha = \frac{\sqrt{T^2-1}}{T}.$$

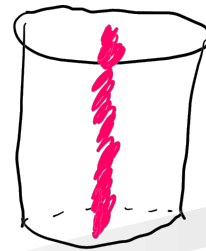
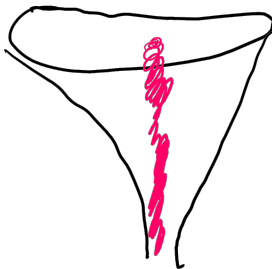
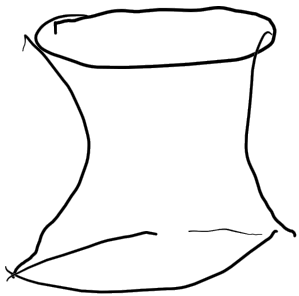
- The intrinsic brane metric is an $R_{dS_2} = \sqrt{1-\alpha^2}/\alpha$ de Sitter

$$\text{cosmology } ds^2|_Q = -\frac{4(1-\alpha^2)}{\alpha^2(1-v^2)^2} dv^2 + r_h^2 \left[\frac{\alpha(1+v^2)+2v}{\alpha(1-v^2)} \right]^2 d\phi^2$$

- This is a time dependent solution with only rotational symmetry.

Another picture

- In double holography, we can consider 2d dS gravity coupled to a large c matter CFT. The 3d dual is a cosmological spacetime.
- Now take that matter CFT in an entangled state (in the “semi-classical” picture) with another copy that’s not coupled to gravity. In the exact theory, the entire thing is a pure state of the rigid CFT.



[Hawking Maldacena Strominger, Maldacena]

Finding the CFT dual

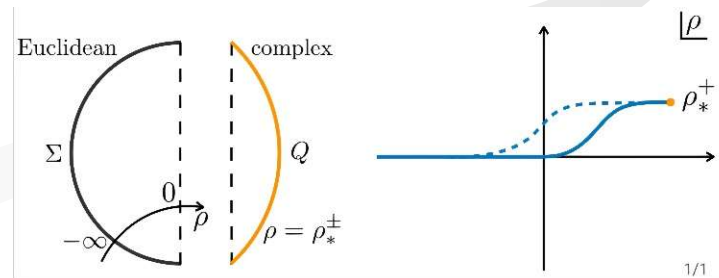
- The EoW brane cannot reach a real Euclidean AdS boundary (since it can reach the Lorentzian AdS boundary), and there are no global Euclidean continuations. However, to find the dual we just follow the usual rules and have complex saddles.
- A theory admitting such $T > 1$ branes has a conformal bc, and we can compute the disk partition function to find the g function.



$$g = \exp \left(\frac{1}{4G_N} \coth^{-1} T + \frac{i\pi}{8G_N} \right)$$

$$d\rho^2 + \cosh^2 \rho (d\eta^2 + \sinh^2 \eta d\phi^2)$$

$$\rho_* = \coth^{-1} T + i\pi/2$$



Non-unitary boundary conditions

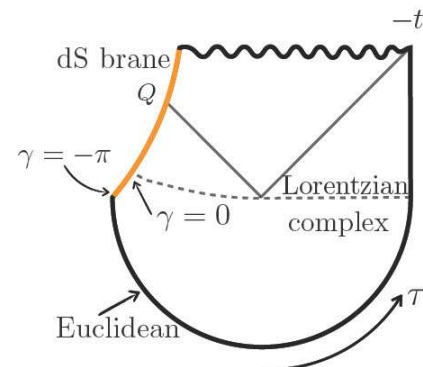
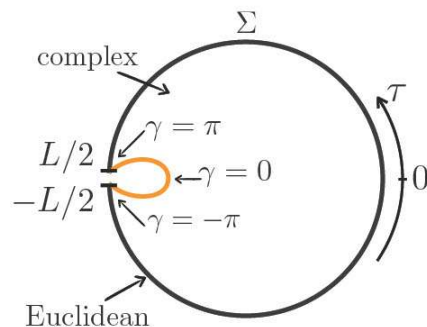
- Therefore it is a non-reflection positive boundary condition. But again, we are only using it to create a state in the unitary CFT dual to AdS.

$$|\psi\rangle = e^{-\frac{\beta H}{2}} |B\rangle$$

- However, boundary condition must be local, and have a well-defined spectrum of operators (positive spectral density, although complex weights).
- One can find complex gravitational saddles for cylinder with BB boundaries, one of which matches the identity boundary operator.

Complex saddle for the dS brane

- This is the dual of the CFT on a cylinder with B and $\bar{B}$ boundary conditions. Not the continuation of the BB AdS brane saddle.
- Non-trivial to check that the BTZ singularity in the complexified metric does not intersect the slice.
- The resulting smooth complex saddle has real on-shell action $S = -\frac{\pi^2 c}{3} \beta$. Identical to BTZ.



An observation

- The effective temperature of the dS brane states with a given β is twice that of AdS brane states. The latter are related by continuation to the BB cylinder, which is a different complex saddle.
- This implies that the lowest weight BB^* operator has dimension $-c/8$.
- The dS brane case matches with the temperature of random states $e^{-\beta H/2}|\chi\rangle$.

de Sitter entropy

- The analog of global de Sitter spacetime here is the 2d Lorentzian dS brane filled in with the AdS bulk. Its Euclidean continuation is the solid ball.

[Hawking Maldacena Strominger]

- The on-shell action leads to $-S_{dS} = \log(|g|^2)$. It remains to be seen what interpretation that has in the CFT, since here there is no AdS boundary at all.
- The dS brane black hole saddle dominates when $S_{dS} < A_{BH}/4G_N$.

Bootstrap problem

- The problem of finding local, conformal, but non-unitary boundary conditions of a unitary 2d CFT is a well-defined CFT bootstrap problem. In general, won't have a simple thin wall gravity dual, but one can search for them.
- Simple examples are analytic continuations of unitary bc's (real g), or continuation of Liouville bc (complex g , but noncompact).
- If CFT is a non-linear sigma model, a D-brane in the target space is a bc. One wants to look for a complexified minimal surface, which will generically have complex volume = g function.

Summary

- Found complex continuations of the AdS-dS black holes which tell us the dual states in bottom up holography. Detailed construction for dS branes in AdS.
- Clear set of rules that the dS dual Euclidean theory must obey (principally locality so that it can connect to the CFT_{AdS}). More complicated quantitative question of when the dS region is weakly curved, the wall thin, etc.
- The physics of de Sitter is encoded in the machinery that produces a state in someone else's Hilbert space.

JT gravity example

- Given bulk dilaton gravity actions $\int \sqrt{g}(\phi_0^i + \phi)R + \Lambda^i \phi$, the domain wall action is $\int_{DW} \sqrt{\gamma}(T + a\phi)$.



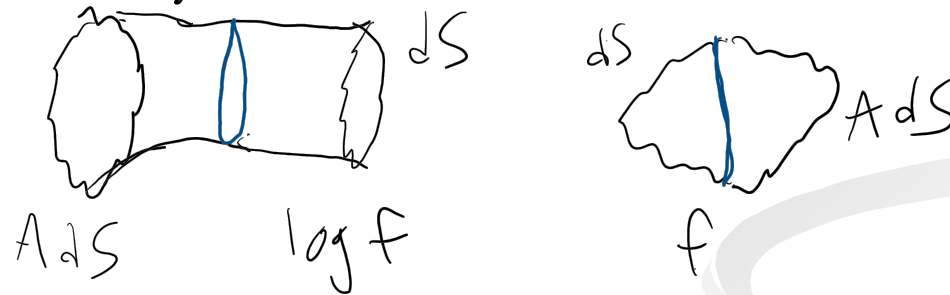
- For AdS, the dual quantum mechanics is a random matrix Hamiltonian with $\sinh(2\pi\sqrt{E})$ spectral density. For dS, it is a random anti-Hermitian matrix, K.

$$\int \exp[-\text{Tr}V_{SSS}(H) - \text{Tr}V_{SSS}(iK) - \sum_{i,a} |D_{ia}|^2 / f(E_i, K_a)^2]$$

[Saad Shenker Stanford; Cotler Jensen; Maldacena Turiaci Yang]

Ensemble dual

- The domain wall maps between AdS and dS vector space. Gaussian if the walls can't cross. The function f can be found by computing the disk diagram partition function starting with the Hamiltonian analysis.



[Jafferis Kolchmeyer Mukhametzhanov Sonner]

- Perform Hamiltonian analysis in the AdS-AdS case – two phase space variables for each region, lengths along geodesic slice and conjugates. From that one can determine the required partition functions, and analytically continue to AdS-dS.

Spectral imprint

- This gives a particular statistical ensemble of states that will match the gravity calculations.

$$|\Psi\rangle = e^{-\beta H/4} D^\dagger e^{\alpha K} D e^{-\beta H/4} \text{ as a state in } \mathbf{H}_{AdS} \otimes \mathbf{H}_{AdS}$$

- The existence of a dS minima is subtly encoded in the spectral statistics of the H matrix, by integrating out K and D from the ensemble.