Progress in dS/CFT

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deSitter space appears at the forefront of both theoretical & experimental physics. A sharp theory question is

WHAT IS THE MICROSCOPIC ORIGIN OF

$$S_{dS} = \frac{A_{horizon}}{4\hbar G_{Newton}}$$

OR

$$\text{STAT MECH} = \frac{\text{GRAVITY}}{\text{QUANTUM MECH}}$$

Where are the microstates? The existence of such a basic, deep & unanswered question is very promising for our field. No worries, I won't answer it today!

Other questions I won't answer:

1. What are the physical observables in dS?
2. Does eternal dS exist?
3. Does dS have a finite # of states?
4. In near-dS, is there a beginning of time?
5. Is there unitarity in dS or quantum gravity in general?

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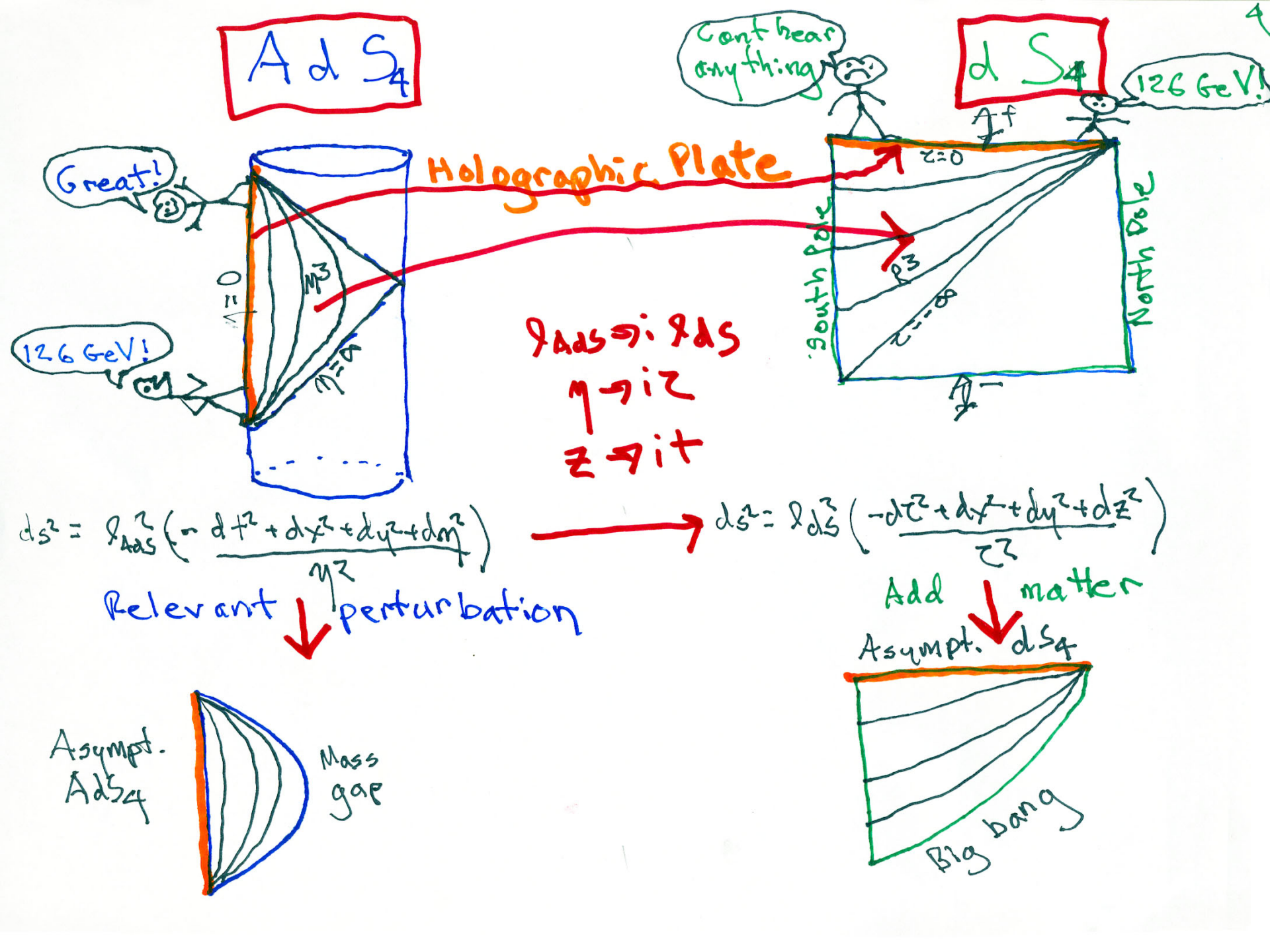
Proposed tool/approach to address these questions

dS/CFT Correspondence

2001

suggested by the mathematical similarity of dS and AdS, attempts to adapt success of AdS to dS.


AdS4
Great!
126 GeV!
Holographic Plate
z=0
η=∞
R3
dS4
Can't hear anything
126 GeV!
South Pole
North Pole
z=0
z=∞
lAdS → i lds
η → iz
z → it
ds² = lAdS² (−dt² + dx² + dy² + dη²) / η²
ds² = lds² (−dt² + dx² + dy² + dz²) / z²
Relevant perturbation
Add matter
Asympt. AdS4
Mass gap
Asympt. dS4
Big bang

dS/CFT is an adaptation of minimal AdS/CFT

$$\langle \mathcal{O}(\vec{x}_1)\mathcal{O}(\vec{x}_2)\dots\rangle_{\text{boundary CFT}} \approx \lim_{\eta\to 0} a^{-h_1-h_2\dots}\langle \Phi(x_1)\Phi(x_2)\dots\rangle_{\text{bulk AdS gravity}}$$

(with some b.c. specification)

$$(\Box - m^2)\Phi = 0 \Rightarrow h = \frac{3}{2} \pm \sqrt{\frac{9}{4} + m^2 \ell_{AdS}^2}$$

AdS/CFT is more

dS/CFT conjecture

$$\langle \mathcal{O}(\vec{x}_1)\mathcal{O}(x_2)\dots\rangle_{\text{boundary CFT}} \tilde{=} \lim_{\tau\to 0} \tau^{-h_1-h_2\dots}\langle \Phi(x_1)\Phi(x_2)\dots\rangle_{\text{bulk dS gravity}}$$

(with some b.c. specification)

$$(\Box - m^2)\Phi = 0 \Rightarrow h = \frac{3}{2} \pm \sqrt{\frac{9}{4} - m^2 \ell_{dS}^2}$$

To get a physical theory, we need in addition a physical interpretation of these correlators. For now, we concentrate on assembling the building blocks.

Comments

1. $h_\pm$ in general complex - unusual
2. CFT ~~unitary~~ - but must have some good property. Classical version — positive energy theorem, cosmic baldness?
3. Time evolution = RG flow ~ dissipative ~~unitary~~ radical!
4. Relevant perturbation → mass gap = big bang?
5. Relation to area law not understood

Problem

No concrete examples!

Many structural properties of ds/CFT have been deduced from symmetry/consistency over the last 10 years under the assumption it exists. However, also many inconclusive discussions & unanswered questions.

STRING THEORY — loves AdS / hates dS

no stable solution known (?)

Recent progress

Dio Anninos, Tom Hartman & AS

begins with

$\Lambda \to -\Lambda$ $\quad h_\pm \to h_\pm$

$dS \to AdS$

Also recent & relevant
Harlow & Stanford
Anninos, Ng & AS
Ouyang
Das Das Jevicki Ye
Ng & AS

Lightning ~~review~~ overview of Xi Yin's ~~talk~~ overview

$$N = \frac{1}{\hbar G_N \Lambda}$$

Two boundary flavors

Critical O(N)
Free O(N)

match two bulk flavors

Dirichlet scalar b.c.
Neuman scalar b.c.

Vasiliev
Sezgin Sundell
Klebanov Polyakov
Giombi Yin

Under $\Lambda \to -\Lambda$

Vasiliev AdS_4 gravity $\to$ Vasiliev dS_4 gravity

Neuman Dirichlet

Neuman Dirichlet

holographic duality

$N = \frac{1}{\hbar G_N \Lambda} \to -N$

$O(N)$ free critical $\to$ $O(-N)$ free critical $=$ $Sp(N)$ free critical (next slide)

$$AdS_4/CFT_3 \to dS_4/CFT_3$$

There is some tedious work in showing reality conditions & correlators, properly continue. Anninos, Hartman & AS

also $h_\pm \to h_\pm$, no complex conformal weights

doesn't work for string theory so far...

Hull

$O(N) = S_p(N)$

$$S = \int d^3x \left(M_{ab} \nabla \phi^a \nabla \phi^b + \lambda \alpha M_{ab} \phi^a \phi^b + \alpha^2 \right)$$

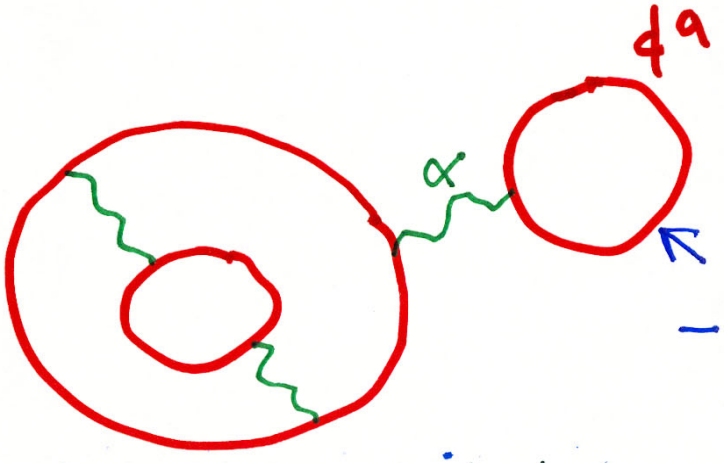
$\lambda = 0$ or $\lambda = \lambda_{crit}$

$a, b = 1, \ldots N$

$O(N)$: $M_{ab} = \delta_{ab}$, ϕ^a commuting

$S_p(N)$: $M_{ab} = \Omega_{ab}$, ϕ^a anticommuting

LeClair & Neubert



$-N$ for $S_p(N)$

Perturbative $S_p(N)$ correlators (singlets)

$= O(N)$ correlators w/ $N \to -N$

Summary

There is good evidence that Vasiliev gravity in dS_4 with Neumann (Dirichlet) boundary conditions at $\mathcal{I}^+$ is holographically dual to the free (critical) $Sp(N)$ CFT_3 living at $\mathcal{I}^+$, at the level of correlators.

Many entries in dS/CFT dictionary needing writing.

What can we learn from this?

dS Exclusion Principle

Ng Kitaboys Shenker AS 13

Near $\mathcal{I}^+$ $\quad \Phi(\vec{x},t) \sim \Phi_+(\vec{x})\, t^{h_+} + \Phi_-(\vec{x})\, t^{h_-}$

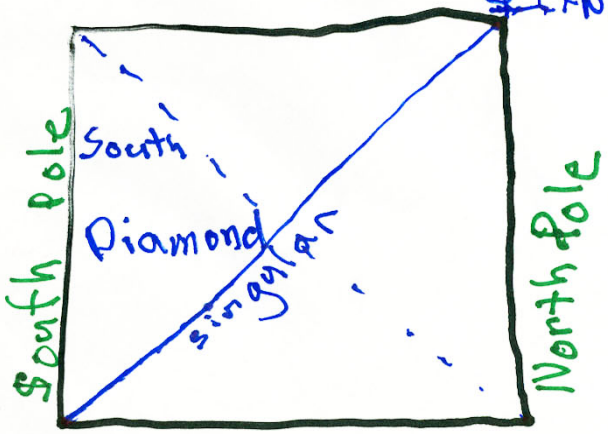
$h_- = 1, \; h_+ = 2$

$\exists$ "plane-wave" states $\quad \Phi_+^+ |0^+\rangle = 0$ Neuman, free CFT$_3$

$\Phi_-^- |0^-\rangle = 0$ Dirichlet, critical

Ng, AS

$\Phi^-(\vec{x}_{N.Pole})\,|0^+\rangle$ creates a **quasinormal mode** for the southern causal diamond. But



$$(\Phi^-)^{\frac{N}{2}+1} = (\Omega_{ab} q^a q^b)^{\frac{N}{2}+1} = 0$$

Only $\frac{N}{2}$ bosonic quanta allowed in each mode! Related to finite # of dS states.

c.f. Maldacena & dS, Shenker & Yin

A Proposal for Physical Observables in dS

AS unpublished

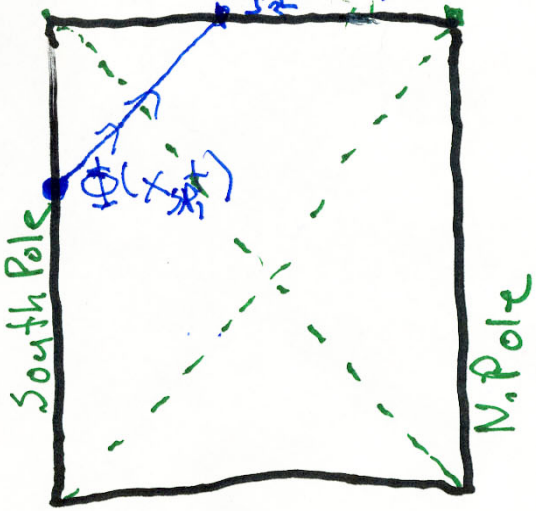
dS = space of oriented geodesic spheres in $\mathcal{J}^+(dS)$

Southern causal diamond

★ = space of g. spheres dividing N & S poles of $\mathcal{J}^+$

$$\int_{S^2}\left[\Phi^+(\vec{x}) + \partial_n \Phi^-(\vec{x})\right] = \int_{S^2}\left[\mathcal{O}^+(x) + \partial_n \mathcal{O}^-(x)\right]$$

= Wilson surface operator



c.f. Kabat, Lifschytz
Ray & Sarkar
for AdS

Proposal

The set of conformally invariant Wilson surface operators on S^2's dividing the N & S pole of $\mathcal{J}^+$ geodesic comprise the physical observables in dS/CFT

Good points

1. Mathematically well-defined & coordinate invariant.
2. Reduces to causal diamond correlators at weak coupling.

To do (conclusion)

1. Complete dS/CFT dictionary: correlators, deformations, states on $\mathcal{I}^+$, finite deformations. ...
2. Add relevant operator $\mathcal{L}_{ab}\phi^a\phi^b \to$ big bang?
3. CFT_3 duals for other (non-parity invariant) Vasiliev gravity?
4. dS_3/CFT_2 Ouyang
5. Compute/understand dS entropy.
6. Embed in string theory.. Giombi, Minwella, Prakash, Trivedi, Wadtagyin

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