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Bulk Physics, Algebras and All That
Part Three: Strings 2024 Edition -I

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Abstract: In Part Three, we will discuss some interesting topics based on the themes discussed in talks and gong shows in Strings 2024. The point of this edition is to provide very short questions and hints at some interesting problems that have been brought (or bought I don't know) to light in the Strings conference. I mostly won't expand too much and will instead include lengthier discussions in later editions. This is basically my version of "Future Prospects in String Theory" by Andy Strominger and Hirosi Ooguri.

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1 Introduction

Strings 2024 was an amazing conference with many fascinating talks. I had an awesome time with listening to the talks and having subsequent discussion with some of my colleagues. I skipped some talks I did not get time for, like most of the bootstrap sessions and the human AI and ML for Calabi-Yau geometries talks. I had tweeted on the talks and subsequently wrote a blog post based on the tweet here. However, I am not the kind to harvest links and engagement clicks, so I have written the thread below.

Strings 2024 ended. It was an amazing conference and a lot of good progress was made. Amazing work to everyone involved, and great works in several good directions like chaos theory, QIT, de Sitter, etc. (as usual celestial holography gets cut out.) Some of the talks:

The first talk was by Miguel Monterro on string compactifications, which was a review talk on supersymmetric vacua, swampland constraints, non-SUSY string vacua among others. The next one was by Wiesner on bottom-top proof of the emergent string and dependence of species on higher-derivative corrections to the Einstein-Hilbert action. I then listened to Chang's talk (skipping Figuiredo's talk) on supercharge "Q" cohomologies and fortuitous states and near-BPS black holes. Next was Collier's talk on 2D dS as a matrix model was fascinating. It was based on his work with Beatrix, Victor and Lorenz on Virasoro minimal string in 2023, and has directions I am interested in reading more on. Blommaert then had a talk on the gravity dual of DSSYK and fake DSSYK temperature relations to real temperature.

This was followed by Stanford, Maxfield, Turiaci, Malda, Lorenz and Lin's discussion on JT gravity, which was a dope review.

Next day was kicked off by Juan's talk on BFSS conjecture, followed by a soft theorems talk that I didn't attend. Then, Cho had a talk on nonworldsheet string backgrounds, followed by a review by Yin and Erler on SFT. I skipped Budzik's twisted holography talk and listen to Mahajan's talk on non-perturbative minimal super string duality with matrix integrals. There was then a gong show with Tourkine, Zhong, Tamargo, Biggs, Delgado (on bordisms group which was fascinating), Gesteau, Guo, Ji, Kundu, Levine, Lin, Parihar and Priyadarshi. Next day, Palti talked about emergent kinetic terms in string theory, and an ML talk on CY geometry that I skipped. Norris had a great talk on dS vacua, which I have to review again. I skipped most of the next observational talks except for van Riet's talk, and skipped the Townhall (on postdoc applications) and the AI talk by Kaplan. The next day (Thu) I skipped the talk by Duffin and attended Casini's talk on the ABJ anomaly and U(1) symmetry.

I skipped all the bootstrap talks unfortunately, but was pleasantly greeted with Wong's talk on 3D gravity and random ensemble of approx CFTs. Next, Vardhan had a talk I did not quite understand, but was followed up by Faulkner's gravitational algebras talk, which was great and is timely for me, since I'm working on algebras. The last session yesterday was by Chris Akers and Dan Jafferis, which was great but I had internet issues. Today started with Nameki's talk on generalized symmetries which I did not get either, and had to skip Dumitrescu's QCD talk. Hansen had an interesting talk on bootstrapping Virasoro-Shapiro amplitudes in AdS which I have to review again.

I also skipped Bobev's talk on M2 branes. Yonekura had an interesting talk on non-SUSY branes in heterotic string theory, followed by Minwalla's talk on large J+E holographic CFTs. I couldn't attend Dabholkar's talk on stringy quantum entanglement entropy, nor Beiras' talk on topological strings. Zhiboedov had a talk on the future of strings, and and the outro was Hirosi and Andy's discussion on 100 string problems, which was very good and had de Sitter comments. I asked about analytic continuation, but unfortunately my internet connection dropped out as he was answering. On an all, it was a great conference, and a particularly better improvement over Strings 2023 in light of non-stringy talks. Already feeling nostalgic and missing the talks, and this is how amazing these talks are. David Gross + Ahmed Almheiri's comments were really touching to hear, especially Ahmed's joke on the UV index being in Planck units. Can't wait for Strings 2025@NYUAD in Jan 2025, and since Ahmed +Suvrat+Eva et al are hosting, won't be surprised if it is as good and even better than this one. Thank you everyone @CERN for this wonderful event.

We will now discuss some related topics very briefly, and I will also write a blog post in a more condensed and clear-er form soon. I hope that some of these topics find your interest and that some problems I mention at the end find a resolution soon.

The Future of String Theory (FOST) questions are available at the indico.cern.ch Strings 2024 webpage. While I do find some of the contributions very vague or without enough subtext, most of the questions are very good and have inspired the problems in this edition strongly.

2 Problems...

I have added 18 problems with bold headings (**A**, **B**, to **Q**). Some handwritten discussions will be added next week with some discussions on some of the problems discussed here.

2.1 JT Gravity

Well, JT gravity needs no introduction. Who doesn't love JT gravity?[1] JT gravity links to many aspects of AdS/CFT. To list a few, there are links to (1) von Neumann algebras[2], on which there is a great paper by Pennington and Witten, (2) the SYK model, (3) aspects of matrix integrals, (4) cosmologies and (5) near-extremal black hole solutions, of which I know very little about. In this order, we will talk about JT gravity aspects in this section.

A. von Neumann algebras: The formalism that is considered for JT gravity is somewhat similar to that of AdS/CFT with the two-sided setup, so we have some notion of a left and right boundary, but instead of corresponding *exactly* to some one-sided setup that is usually done in AdS/CFT, we only work with the two boundaries. In a sense it does not make sense to talk about individual field theories on either boundary. One further considers this JT gravity coupled to a bulk QFT, and the algebra for this is a type II_∞ algebra. As with the large N microcanonical ensemble crossed product construction by Chandrasekaran, Penington and Witten [1], one can define entropies and density matrices.

This is all nice. Particularly because JT gravity is a great model to work with, in terms of canonical purification [2] and in making use of things like algebraic ER=EPR, which are of interest. It would further be nice to see if there are generalizations from the Virasoro minimal string theory [3] and if there is a general argument for the type of algebras for the minimal string, but I do not know any particular argument to that effect. This would be very fascinating, since the large central charge c limit for the minimal string model is JT gravity, which is something we *do* know the type of operator algebra for.

So, the open directions are: **How can we use the general nature of the minimal string model and can we work with operator algebras for certain families of models?**

[1] If you don't like JT gravity you are a sad person and must like David Lynch's Dune more than Denis Villeneuve's Dune 2021 and 2024. Hint: Denis' is the only correct answer.

[2] At this point everyone knows I am a von Neumann algebras fukboi.

B. SYK model: This is the model with interacting fermions with usually (for non-zero temperature) Schwarzian actions. There are many relations to the SYK model CITE, but as such I will not discuss this here, and will instead focus in the upcoming edition of *Bulk Physics, Algebras and All That.* This also becomes interesting in the de Sitter aspect where we try to find some QM description for de Sitter dual theories.

The general directions are: **What do links between JT gravity and SYK models imply?**

C. Matrix Integrals: The paper by Saad, Shenker and Stanford [4] showing JT gravity as a random matrix integral laid the motivation for most of the modern works with JT gravity and matrix integrals. The result was that the gravitational path integral has a "dual" description from an integral with the Weil-Petersson volume, bulk graviton and moduli integral [see Stanford's talk]. This becomes an indication that the dual to the gravitational path integral is a random matrix integral. In particular, the talk by Collier discusses how a 2D de Sitter matrix model could be conceived from the above mentioned Virasoro minimal string model. This matrix model description is rather intriguing and again, how relations to de Sitter JT gravity arise and how they become more "effective" in a sense is also of interest.

The overall nice thing and interesting directions are: **How can we use these aspects of JT gravity and matrix models more generally in anti-de Sitter and de Sitter spaces?**

D. Cosmologies: As said above, de Sitter and JT gravity are a very interesting combination of models. Sandip et al's work [5] on using the dilaton Φ as a physical clock is a good example of where things could go. Things like perturbations of black holes in JT gravity are also of interest, but I am not particularly well-versed or interested in such aspects.

The open problems generally concern: **What applications to general cosmologies does JT gravity provide?**

E. Near-extremal black holes: As Stanford mentioned in his talk, the near-horizon geometry of near-extremal black holes are interesting; for instance, for a Kerr-Newmann black hole in ordinary Minkowskian 4D spacetime, the near-horizon geometry becomes that of 2D AdS$\times S$. Other interesting aspects include near-BPS states, but these aspects will not be discussed here and will be deferred to a later edition.

The open problem is: **What other interesting aspects of near-extremal or near-BPS black holes link to JT gravity?**

2.2 de Sitter

In the de Sitter directions, there are many open problems, Here, I will take a detour and include aspects that aren't purely stringy. To outline the problems, basically we have (1) the problem of the dual field theory, (2) de Sitter vacua, (3) a stronger touch of string theory? and (4) the issue with the present de Sitter progress.

F. Dual field theory: I have posted on this way too much on my blog and worked on two reviews with Aayush, enough to drive any sane man crazy[3]. So instead of reiterating the same thing, I will point out some things that people should do, and I will point it out rather bluntly. **NO**, dS/CFT does not work enough as it stands right now because we don't quite know what the dual field theory is. Sure, do what floats your boat and calculate entanglement entropy from analytic continuation from AdS to dS as much as you want, but that doesn't solve the problem of giving a field theory dual. The whole point of doing AdS/CFT was that you knew that there were these kinds of operators in $\mathcal{N} = 4$ SYM and that those operators did that stuff. When we say "this is the entanglement wedge" we know *exactly* what that is supposed to mean, but in de Sitter we have peeps saying "well from analytic continuations ..." – nope.

Even from a non-stringy background I would say calling it "holography" is an overshot unless we understand it. To this end even canonical quantum gravity gives us holography by pushing Wheeler-DeWitt states to the asymptotic boundary and turning them into CFT partition-like functions. Yeah, they obey Diff×Weyl properties, but it doesn't mean they are *actually* CFT functions.

So, the open problem is: **What is the dual field theory for de Sitter?**

G. de Sitter vacua: This is not something I can comment much on considering how naive I am with much of the string theoretic construction involved in finding de Sitter vacua, but I would say that following the KKLT paper [6], there are some interesting aspects that Moritz talked about.

So, the open problem is: **What are de Sitter vacua?**

H. Stronger touch of string theory? On the more stringy side of things, trying to find de Sitter vacua in general is a part of a larger family of problems involving de Sitter string theory. This has to do with a no-go theorem from Maldacena-Nunez, which states that there are no non-singular wrapped compactifications to de Sitter space (or Minkowski space). As far as I remember, the case for massive type IIA supergravity had some additional arguments but in general there were some natural assumptions on the gravitational action and contributions to the potential and massless scalar field strengths. The paper by Hull back in 1998 (if I remember correctly[4]) on T-duality had some interesting arguments as well, but I am not formally fluent enough to actually fully provide an exposition on it.

So, the open problem is: **How do we do string (field!) theory in de Sitter space?**

I. The issue with current de Sitter progress: The thing about current

[3] Although, worth it, because people doing Wick rotations like mad are just sad.

[4] No, I didn't read the paper in 1998.

de Sitter progress is that not enough stringy aspects are being communicated on a larger time scale basis. To illustrate an example, I myself do not fully understand de Sitter string theory. So if someone can write a book about it I would gladly read it. For a large set of problems that concern de Sitter, string theory is usually not the background and instead for the most part the background formalism concerns something like canonical quantum gravity for perturbative bulk computations, which are not bad. But if we condense this problem more broadly, we end up with a question similar to the previous points concerning too much of reliance on crappy analytic continuations and whether de Sitter string theory is formal enough; although from papers like KKLT, it is clear that formal de Sitter string theory is a thing. So this point condenses into the previous open problem for point **H**.

2.3 Algebraic String Theory?

One common theme with some discussions I had throughout Strings was that of how algebras appear in string theory. Seemingly in AdS/CFT, which we understand well enough, the stringy description in and of itself implies the presence of algebraic functionalities. For instance, the dual theory to AdS is the $\mathcal{N} = 4$ SYM theory, for which we can exploit operator algebras based on certain operators we find of interest, particularly the (ren.) boundary Hamiltonian for either boundary in the two-sided setup. However, this also tells us how the overall factorization of the theory looks like; so we know that for the usual Liu-Leutheusser type III_1 algebra, the boundary CFT copies in the thermofield double state are not factorized, whereas as we go down the von Neumann algebra type we would expect "more factorization". So if we go from type III to type II, there is some level of factorization with some extra contributions to the path integral, whereas if we somehow (at least I don't know how) obtain a type I algebra, the copies will be "fully factorized". Some arguments to this effect were presented by Hong Liu and Netta Engelhardt in their paper last year [7] on algebraic ER=EPR, where they basically say – well if you have a type II algebra like in the crossed product construction (say in the large N algebra setting) then basically the Cauchy slice is quantum-connected via a quantum wormhole in the sense of quantum volatility, if it is type III it is classical connected (which is naturally expected), and otherwise if it is type I it is disconnected because the Cauchy slice would be disconnected. I had myself made an argument around the same time on a "strong No Transmission principle". But how do we view this more clearly in the stringy context?

J. Algebras and string theory: One possibility from this is that if we exploit operator algebras in the stringy background for anti-de Sitter space, it could be possible to do the same with de Sitter string theory, in which case a more clear operator algebraic framework could be established. This at present is a slightly naive question, but I believe once stated more formally, this could have some nicer implications to the de Sitter dogma.

So, the open problem is: **Can we work with operator algebras in the stringy context of holography to better have a mathematical idea of what holography is?**

2.4 Canonical Quantum Gravity

While I am not yet aware of a very string theoretic framework to Cauchy slice holography [8] (also considering it is very young at this moment, I do not expect there to be such a framework in the first place), the overall framework of semiclassical solutions to the Wheeler-DeWitt equation seems to have some intermittent links to string theory. As Anninos asked in his contribution to the Future of String Theory paper, finding such links would be great since cosmological horizons appear in many models. One more nice thing about this landscape is that CSH provides a way of working with microscopic physics in an interesting way; see for instance the case with $T\overline{T}+\Lambda_2$-deformations in static patch de Sitter setting by Vasu Shyam [9]. Therefore, it is natural to ask if these descriptions of cosmological horizons and in particular reflecting on de Sitter horizons have a stringy description.

K. Canonical QG links? Putting the above things together, it is obvious to ask if there are links between stringy and canonical QG descriptions of certain kinds of spacetimes, particularly anti-de Sitter and de Sitter spaces.

So, an open direction is: **Are there correlations between predictions from canonical QG and string theory?**

L. Cauchy Slice Holography: Subsequently, we also arrive at the question of whether CSH has stringy descriptions.

So, an open direction is: **Does Cauchy slice holography have a stringy explanation?**

It must be noted that $T\overline{T}$-deformations also could have relations to JT gravity, which is also an interesting direction. As such, these deformations are naturally of interest in string theory as well in the sense of finite-cutoff holography (which is the motivation behind CSH), and it would be interesting to see how the original Maldacena argument for AdS/CFT with the bulk a type IIB supergravity theory is deformed under these deformations.

2.5 Entanglement Entropy in String Theory

Dabholkar's question to the FOST[5] was if there is a general notion of entanglement entropy from the Replica trick in quantum gravity. This is an interesting question, and partly I am tempted to say that answering the algebraic aspects of string theory problem **J** could answer this, but considering that most of our understanding with algebras is still very informal, it would be nice to actually substantiate a definition for calculating entanglement entropy in quantum gravity. Also, I don't think the stringy

[5]Future of string theory. It is harder than you imagine to type this every time.

context of calculating entanglement entropy needs to be *this* formal, and there are papers and calculations with stringy entanglement entropy that are meaningful without always finding out subtleties with the type of von Neumann algebra, etc.

M. Stringy entanglement entropy: As Dabholkar's paper with Moitra [10] calculates, entanglement entropy in string theory at the end of the day does not need you to find out the type of algebra, issues with defining density matrices, etc. and can be done without appealing to all of this (although to be fair addressing von Neumann side of things is also important). Their paper does a calculation for $D = 10$ type II string theory, and shows that tachyonic contributions can be finitely summed over to get a finite entanglement entropy. In this setting, it would be nice to invoke the type of algebra and other intrinsic aspects of operator algebras.

So, an open direction is: **How do string theoretic computations of entanglement entropy look like when formalized in terms of operator algebras, and is there a general notion of stringy entanglement entropy?**

2.6 Singularities and Resolutions

Whether string theory (or indeed any theory of quantum gravity) can resolve singularities and/or address violations of the weak cosmic censorship conjecture is a still-standing problem. It might seem that resolving singularities (at least in holographic models) has some subtleties; a natural notion of independence of CFT copies and bulk duals arises in holography, and implies that resolving singularities could imply strange violations of the No Transmission principle. Some aspects of α' effects seem to work in resolving singularities, but in a sense I would expect that these resolutions to singularities are only possible or limited to certain cases. Again, this links to some interesting mathematical links from problems **J** and **O** (below), but how general this resolution of singularities could be is yet to be addressed.

N. Singularities in string theory: Given that singularities could have α' corrections and resolutions, one has to clarify whether this resolution is general for *any* kind of singularity in GR.

The direction for this would be: **Which singularities does string theory allow to be resolved?**

O. Constraints and Penrose inequality: Folkestad CITE showed that the Penrose inequality in AdS by Engelhardt and Horowitz can be considered a swampland condition for low energy limit of quantum gravity. In such cases, it would be important to understand the relation between the strength of this inequality and the stringy implications of this, which are apparent from Folkestad's paper.

So, a direction for this would be: **How does the Penrose inequality serve as a string theoretic check? Bonus – general swampland conditions.**

2.7 Black Holes!

P. Semiclassical Exterior Description: Straight off the bat, the first problem is: **What is the semiclassical description of the black hole exterior?**

Which seems to be answered primarily from the perspective of complementarity, but usually we have to relax some of the arguments for complementarity in order to be able to work with firewalls, fuzzballs, etc. See Bulk Physics, Algebras and All That: Part Two - Black Hole Information Problem notes. Of course, black holes made physicists cry in every Strings conference, and nothing different happened this year, although there weren't many explicit mentions of it. The question of what happens around a black hole and whether black hole interiors are what we conventionally consider them to be is still open (cf. Gary Horowitz's question in FOST). We then get some interesting directions that are more or less open[6], which mostly revolve around the black hole information problem. Well, to summarise, here are some things to consider: (1) we do holography partly because it gives us a way to understand black holes, (2) we also know from bulk unitarity that there is a version of the black hole information problem we can directly work with in AdS/CFT, (3) our understanding of entanglement wedges (see Geoff's paper from 2019) gives us a way to understand radiation entanglement wedge and CFT-side reconstruction, and (4) usually we do not require a particular fuzzy or firewall setup.

Q. Horizon Structures: The question is then whether the assumption of horizon structures becomes important to solve the BHIP, which does not seem to necessarily be the case. However, one could make use of bulk operators in the two-sided setup similar to Raju-Papadodimas' construction and try to interpret such structures. However, a more direct approach is to try and relax assumptions of locality/complementarity in general, and identify dual states in the CFT for the bulk firewall, which is a doable thing and to identify stringy descriptions for this.

So, the open direction for this is: **To or Not to Firewalls?**

R. Black Hole Interiors: A continuation on this aspect is that string theory also posits the possibility of fuzzballs replacing the black hole interior in the conventional sense. Which is significantly different from the usual notion of black hole interiors, but would greatly change also how we view the semiclassical description around black holes for that matter.

The open direction for this is: **What is the "right" description for black hole interiors?**

[6] However it must be noted that "open" here does not signify necessarily questions that haven't been solved, but rather to understand stringy subtleties in such directions.

3 Remarks

These are a few questions that I think are quite elementary in comparison to other problems, which are usually much *much* more technical. In the next edition, we will highlight some of the more technical details of some of these and some other problems in string theory. In an upcoming revision to this edition next week, I will provide some handwritten discussions on some of the problems discussed in this edition.

Note: To give a version-check on this edition, I have provided a "Commit date" followed by version number (i.e. *v1* for this version). For every version change, I will provide a short comment signifying what has been added. Go watch Dune Part 2.

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