String community questions

Dear Fellow Speakers/Organizers for recent string theory meetings,

At Strings 2024, we (Andy Strominger and Hirosi Ooguri) are scheduled to lead discussion at the last session of the conference. At the session, we would like to present a list of interesting questions from our community that might plausibly be answered in the next ten years. We are asking each of you to contribute one question to this list. We are not trying to make a list of the ten "best" or anything like that: the goal is just to provide food for thought. Any question will do: it doesn't have to be the "best" one, and please don't spend too much time writing it. The questions should be one sentence, and an optional additional one sentence hint would be good. We'd like to know if you'd like to have your name attached to your proposed question, with the default being yes. The questions will also be posted on the Strings 2024 website.

Please respond by May 21 so that we have time to review your questions and prepare for the session.

We are sending this to all the speakers and organizers for Strings 2022, 2023, and 2024 and for the KITP Workshop "What is String Theory? Weaving Perspectives Together."

Thanks a lot!

Regards,
Andy and Hirosi

The Future of String Theory: Open Questions

We are scheduled to convene the last session of the conference on a future vision for string theory. To stimulate the discussion, we asked speakers and organizers of recent Strings conferences and of this year's KITP program to submit questions that might plausibly be answered in the next ten years. We have received the following questions, some with hints and all of them very interesting.

We encourage you to think of comments and questions on these questions that you can share at our session. You are also welcome to suggest new scientific questions that might plausibly be answered in the next ten years. We hope that these will serve to stimulate discussion at the session as well as future research.

Our plan for the session is for each of us to speak for 15 minutes and then open the floor to your comments and questions on any topic.

You may also consider submitting your comments and questions to us in advance. While we cannot guarantee that we will have enough time for everyone, we will try to start with those who have contacted us in advance.

We look forward to an interesting session!

Sincerely,
Hirosi Ooguri and Andy Strominger

1. What are useful observables to sharply describe a chaotic-integrable phase transition in quantum systems? Are there examples where we could have a holographic description of the intermediate phase? (*Sergio Aguilar*)

Hint: Very interesting progress in SYK systems, spin chains, and billard-like systems (see e.g. 2207.07701, 2401.04764, 2403.01950, 2405.11254). The tools of quantum information theory and Von Neumann algebras seem promising, and, in principle, applicable to more general examples.

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2. What is the classical string theory dual to the large N limit of (3+1 dimensional) QCD? (*Ofer Aharony*)

Hint: For asymptotically free gauge theories, a good starting point could be understanding the string dual of the free gauge theory.

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3. Within a given string theory, what topological data of the background specifies distinct branches of the moduli space of 4-dimensional, *N = 1* compactifications? In other words, is there a generalization of the distinguishing minimal "Wall's data" of Calabi-Yau threefolds (which fully determines 4-dimensional, *N = 2* Type II backgrounds) to 4-dimensional, *N = 1* string theory compactifications? (*Lara Anderson and James Gray*)

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4. Is dark energy explained by quintessence? (*David Andriot*)

Hint: Can string theory provide a controlled and viable quintessence model?

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5. What is the theoretical underpinning, or even axiomatic structure, governing cosmological spacetimes? (*Dionysios Anninos*)

Hint: Some hints (cautiously interpreted) might stem from the appearance of horizons of the cosmological type, and the structure of semiclassical Wheeler-DeWitt wave equation.

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6. How should we interpret the breakdown of bulk EFT at late times in evaporating black holes/in closed universes? (*Stefano Antonini*)

Hint: A holographic dual theory should be able to describe the experience of a bulk observer. In highly non-isometrically encoded spacetimes this seems to not be the case, even at low curvature, unless the observer experiences a drastic breakdown of EFT. Is there a consistent way to describe this bulk EFT from a holographic theory? Or should we completely give up the bulk EFT?

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7. There has been a great deal of work on counting black hole microstates, and on using Euclidean saddle points to achieve this. But what does the actual Lorentzian microstate structure look like? (*Iosif Bena*)

Hint: Some coherent states may have a semiclassical description as horizonless microstate geometries.

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8. What are we averaging over in gravity? How much does it wash over relative to the various dual theories (if at all)? In, it seems that various proposal work in some regime, but none works in all regimes. (*Micha Berkooz*)

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9. Why is the same scattering equation used by Gross-Mende near the tensionless limit of the string also useful for computing $\alpha' = 0$ super-YM/sugra scattering amplitudes as shown by Cachazo *et al.*? (*Nathan Berkovits*)

Hint: Try to find a method for computing α' superstring corrections to super-YM/sugra scattering amplitudes by perturbing near solutions of the scattering equation

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10. Is there a version of the OSV conjecture for (supersymmetric) black holes in AdS? (*Nikolay Bobev*)

Hint: Perhaps use AdS/CFT and the many explicit results for partition functions of supersymmetric CFTs on compact Euclidean manifolds as guidance to formulating such a conjecture.

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11. Is quantum gravity in the expanding universe described by a dual quantum mechanical system? (*Shira Chapman*)

Hint: Can quantum information measures point us in the right direction to look for such a system?

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12. What can be learned about quantum gravity from a non-perturbative computation of correlators in holographic CFTs for finite *N* and coupling? (*Shai M. Chester*)

Hint: Black hole states should be dual to high dimension operators in the CFT, and quantum gravity should give a prediction of how the statistics of these states change as a function of *N* and coupling.

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13. How do we describe strings in time-dependent backgrounds? (*Minjae Cho*)

Hint: Find a time-dependent solution to the string field equations (if no exact worldsheet CFT description is available). What are the physical observables we should compute in such a background?

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14. Can we define a notion of entanglement entropy in a quantum theory of gravity? (*Atish Dabholkar*)

Hint: Can we use a generalization of the replica trick in string theory?

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15. How do we formulate quantum gravity non-perturbatively in cosmological spacetimes with accelerated expansion? (*Xi Dong*)

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16. Is there a simple description of the complete set (or moduli space) of all string/M compactifications with *8* supercharges? And, of all such quantum gravity theories. Are they the same? (*Michael R. Douglas*)

Reference: Washington Taylor, http://arxiv.org/abs/1009.1246

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17. Which singularities can string theory resolve, and which it likely cannot? (*Roberto Emparan*)

Hint: String theory (with finite alpha' effects, but no loops) seems to be able to deal with naked singularities, despite the weak cosmic censorship, but appears powerless to resolve the ones in black hole interiors.

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18. Can we use recent developments in string theory for a new look at understanding non-Abelian gauge theories? (*Johanna Erdmenger*)

Hint: Combine insights from bootstrap, amplitudes, dual resonance, AdS/QCD, EFTs, you name it...

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19. Can concepts from quantum information theory be used to find the space of QFTs with gravity duals, possibly beyond string theory, and/or to prove the AdS/CFT conjecture?

Hint: Translate insights from computational complexity theory and information geometry into string theory.

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20. Is the Higgs particle fundamental or composite? Does the Higgs sector consist of a single Higgs state as in the Standard Model, or of a multi-state sector, as in the two Higgs doublet models and the supersymmetric models? Can one construct composite Higgs string models that can be competitive with existing models that utilise a fundamental scalar Higgs state (*e.g.* hep-ph/9306235 or 2404.16933) in producing qualitatively detailed flavour structure? To what extent can the cubic and quartic SM Higgs couplings be probed at the HL-LHC? (*Yvon Faraggi*)

Hint: All phenomenological string models constructed to date utilise a fundamental scalar representation in the spectrum of the string model.

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21. Can we prove the AdS_5/CFT_4 duality at least at one point in moduli space? (*Matthias Gaberdiel*)

Hint: Can we construct the worldsheet theory that is dual to free SYM in *4D*?

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22. How does string theory address the question of scattering at energies far beyond the Planck energy, and particularly that of its unitarity? (*Steven Giddings*)

Hint: Many may believe that the resolution lies in dualities like AdS/CFT; for those that do: What is the precise nature of the "holographic map," and in particular how do we use it to sharply construct quantities relevant for describing physics seen by bulk observers? (And is it described as an isometry between Hilbert spaces, or something else?)

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23. Do conformal bootstrap constraints on holographic CFTs place nontrivial constraints on the worldsheet CFTs of the dual AdS string theories? (*Rajesh Gopakumar*)

Hint: Short distance (UV) on the boundary CFT translates into short distance on the worldsheet of the dual string theory. Should therefore be able to translate OPEs in the former to that of the latter.

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24. What is the worldsheet theory of the confining string in pure large-N Yang-Mills? (*Victor Gorbenko*)

Hint: It may be easier to understand very long static or rotating strings first.

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25. What is the axiomatic structure of non-gravitational theories dual to non-AdS spacetimes? (*Monica Guica*)

Hint: Understand the axiomatic structure of a simple theory such as a TTbar-deformed CFT, and investigate whether it plays any role in non-AdS holography, namely for linear dilaton backgrounds. Of course, it would be ideal if one directly understood the axiomatic structure of little string theory.

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26. What is the world-sheet theory for type IIb strings on $AdS_5 \times S^5$? (*Tobias Hansen*)

Hint: Recent progress on fixing the AdS Virasoro-Shapiro amplitude from conformal bootstrap provides new input for this question.

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27. What is the space of quantum field theories which arise from decoupling limits of quantum gravity? (*Jonathan Heckman*)

Hint: Use string theory.

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28. What replaces the semiclassical description of spacetime near a black hole singularity, and how is it described holographically? (*Gary Horowitz*)

Hint: First decide if black holes have a conventional interior.

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29. If entanglement underlies the essence of physical systems and in particular the emergence of classical dynamical spacetime, how does it work in (or chime with) the generally covariant context of a Lorentzian spacetime? (*Veronika Hubeny*)

Hint: Figure out what type of subsystems can be meaningfully associated to bulk regions, understand how bulk locality can arise from these, and subject the proposal to scrutiny in extreme regimes (such as for gravitational shock waves and more ambitiously black hole interior and cosmology).

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30. What is the framework that describes observations in the interior of dynamical spacetimes? (*Daniel Jafferis*)

Hint: What lessons should be taken from state specific reconstructions and the role of the observer?

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31. Can we get the holographic dual of type IIB on *10d* Minkowski space from the Carroll limit of *N* = 4 SYM? (*Andreas Karch*)

No hint. But if the answer is yes, I assume we'll know within the next 10 years :)

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32. Can we develop a mathematically precise measure as to when effective field theory will break down in the context of quantum gravity? (*Cindy Keeler*)

Hint: We have evidence that EFT provides inaccurate answers (*e.g.* for quantum information questions about black holes), and some notion that the complexity of the question asked may hinder EFT's accuracy. However we have not codified which theories, or which questions within those theories, fail to be accurately addressed by EFT means.

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33. Can we formulate string theory in cosmological backgrounds, *e.g.*, de Sitter and quintessence? (*Manki Kim*)

Hint: String field theory in Ramond-Ramond and time dependent backgrounds?

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34. Can we provide a UV complete prescription for gravitational path integral? Does this lead to a better understanding of black hole information problem?

Hint: Can we find a manifestly non-perturbatively background independent formulation of string (field) theory, and can we integrate out heavy fields in BV master action of string field theory?

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35. Quantum Chromodynamics is expected to have a dual description in terms of string theory. Can this idea be used in the coming years to make a new prediction, which is testable experimentally or at least numerically? (*Igor Klebanov*)

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36. Is there a non-perturbative formulation of topological string on compact Calabi-Yau? (Shota Komatsu)

Hint: Based on the analogy with quantization of non-compact and compact phase spaces, one possibility may be to replace matrix integral dual to non-compact Calabi-Yau with finite discrete sums.

Background: String theory has its origin as a theory of hadrons. Since then, we've discovered there's an enormously rich structure of string theory as a fundamental theory. But the utility of having a "string-like" theory of hadrons, to bridge the gap between perturbative QCD and low-energy expansions such as chiral Lagrangians, would still be great. It would allow a systematization of nonperturbative contributions to jet physics and improve the precision of theory predictions for collider physics. The required theory would be an "effective" string theory, by analogy with effective Lagrangians it would have a cut-off above which it would lose validity; it would have many parameters which would be determined by matching to the cut-off (in the case of strong interactions, to perturbative QCD). The evolution of these parameters would be determined by string RG equations, and so on.

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37. What are the prospects for developing these ideas in the next ten years? (David Kosower)

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38. It would be desirable to have a classical action for closed string field theory which is not an infinite series of n-point amplitudes. What is the correct underlying mathematical structure that is needed to write down such an action? Or is it simply not possible? (*Raghu Mahajan*)

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39. Could we understand better any holographic example relating matrix integrals to Euclidean gravity solutions that are described by Einstein gravity? (*Juan Maldacena*)

Hint: Understand better the connection between the D(-1) brane matrix integral and its gravity dual, the near horizon region of D(-1) branes. Are there interesting quantities we can compute on both sides and make a comparison?

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40. In gauge/gravity duality, horizon formation in the bulk geometry is dual to the deconfinement transition in the gauge theory, how are these deconfined degrees of freedom described on the bulk side of the duality? (*Emil J. Martinec*)

Hint: Can we use giant gravitons, supertubes and/or other stringy probes to keep track of the underlying branes in the bulk?

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41. When does perturbative quantum GR provide a reliable approximation for cosmological spacetimes? (Henry Maxfield)

Hint: For old black holes, for calculating some quantities, we've recently learned of large non-perturbative gravitational effects. Do similar considerations apply to late time de Sitter space, for example?

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42. Can string theory unravel the physics of the strange metal phase of high temperature superconductors? (*René Meyer*)

Hint: We have successful bottom-up AdS/CFT models which reproduce the main properties of the strange metallic phase of high temperature superconductors. In order to make further progress in understanding these phases, the construction and analysis of top-down AdS/CFT dual pairs inspired by our bottom-up models might be useful.

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43. Can we make progress in M theory beyond the supergravity limit? (*Joseph Minahan*)

Hint: Can we use AdS/CFT and future progress in understanding $(2,0)$ SCFTs beyond the BPS level (perhaps involving bootstrapping) to address the M theory question?

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44. Is the tree-level Einstein S matrix the only consistent asymptotically flat classical n graviton S matrix (classical= only poles and no cuts) that does not include pole exchange contributions from particles of arbitrarily high spin? (*Shiraz Minwalla*)

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45. Do the tree-level n graviton Einstein, Type II and Heterotic S matrices constitute an exhaustive listing of such S matrices once we drop the constraint on the spins of exchange poles?

Notes:

- `Consistent' means respecting all relevant general physical principles.
- #44 has been established for *4*-graviton scattering assuming a constraint on growth of tree level S matrices with energy (CRG conjecture). Exercise: Prove CRG and extend to n-point scattering.
- Either a proof or counterexample would be interesting. In searching for counterexamples note that

[a] Tree-level Type II/ Heterotic graviton S matrices on $R^4 \times CY$ are universal (independent of the CY).

[b] May be useful to systematically study warped string compactifications for which the dilaton is a modulus.

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46. Can recent insights into the S-matrix bootstrap lead to a better understanding of confining strings in non-Abelian gauge theories? (*Sebastian Mizera*)

Hint: Reexamine the analytic properties of multi-body scattering amplitudes and develop a comprehensive theory of dispersion relations.

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47. Can we precisely quantify or prove a bound on the amount of breaking of global symmetries in quantum gravity? (*e.g.*, scale/coefficient of symmetry breaking operators) (*Miguel Montero*)

Hint: Try to make sense of black hole loops or wormhole effects generating EFT operators. Perhaps first try AdS quantum gravity, where CFT crossing can relate light to heavy stuff.

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48. Can methods of supersymmetric field theory and/or string theory be used to define new invariants of smooth four-dimensional manifolds? (``New" in the sense that they can distinguish non-diffeomorphic manifolds which cannot be distinguished by the Seiberg-Witten invariants (and hence by the Donaldson invariants). (*Gregory W. Moore*)

Hint: Evidence is mixed whether (K-theoretic or elliptic) Donaldson invariants for non-Lagrangian field theories will produce such invariants.

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49. Is there a conceptual explanation of Mathieu (and Umbral) Moonshine, including the genus zero phenomena?

Hint: Good people have tried hard for the past 14 years, and we are still waiting for the "Ah Ha!" moment. So if the answer is yes, probably a new idea is required.

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50. Is there a universally applicable (and acceptable) definition of fully local (aka fully extended) Quantum Field Theory?

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51. Will AI answer all the questions in this document, and render the profession of theoretical physicist obsolete?

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52. Can we use microscopic construction of de Sitter cosmologies in string theory, such as KKLT, in order to find a notion of microstates that can account for the de Sitter entropy? Or, given any Anti de Sitter vacuum in string theory, can we give a general prescription for finding microscopic degrees of freedom that produce the dual CFT in the IR? (Jakob Moritz)

Hint: should we enumerate degrees of freedom on suitable end-of-the-world-branes?

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53. Do non-unitary *2d* CFTs and RG flows around them represent Lefschetz thimbles for non-perturbative definition of string theory? *(Nikita Nekrasov)*

Hint: Liouville theory at complex values of the b parameter, WZW model for complex k, to some extent, can be defined through unitary $(d = 4, N = 2$ theory.

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54. What is the world-sheet formulation of string theory in non-stationary backgrounds?

Hint: In the complexification of the moduli space of complex structures on a Riemann surface, is there a middle dimensional cycle representing worldsheet geometries, which are mostly Lorentzian along the handles, mostly Euclidean near the vertices, and smoothly interpolate in between.

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55. String Universality seems to be almost established in theories with a lot of Susy and spacetime dimensions but is there anything we can really say from the bottom up when there is no supersymmetry? (*Paul-Konstantin Oehlmann*)

Hint: Non-Susy string theories provide one top-down direction for UV complete non-susy theories but is there a bottom-up principle as to why those may be the only one.

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56. Can we define a distance between any pair of conformal field theories that are not necessarily related by marginal perturbations? More generally, what is the structure of the space of all quantum field theories? (*Hirosi Ooguri*)

Hint: Can we use a domain wall between such a pair?

Reference:

- Michael R. Douglas, http://arxiv.org/abs/1005.2779.
- Constantin P. Bachas, Ilka Brunner, Michael R. Douglas, Leonardo Rastelli, http://arxiv.org/abs/1311.2202.

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57. What is the space of chaotic and/or holographic CFTs? (*Sridip Pal*)

Hint: Tools like modular/crossing bootstrap, Tauberian-like theorems, and harmonic analysis can help us list the necessary and sufficient conditions for a CFT to be chaotic and/or holographic. We would like to probe the CFT spectra beyond the usual coarse-grained approximation, at a mesoscopic as well as microscopic level, injecting the information of discreteness.

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58. How can category theory and representation theory be extended to fully understand the embedding of the Standard Model in string theory? (*Veronica Pasquarella*)

Hint: This is my current ongoing work.

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59. What is more fundamental to fully understand a QFT: amplitudes or operators? Which of the two will lead to the most important advancements in understanding how QFT arises from string theory?

Hint: As far as I know there are several attempts towards understanding the role they play in different setups. My opinion is that they are complementary parts of a more complete perspective.

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60. Given a low-energy EFT with a large spectral gap and a global symmetry which appears to forbid a scattering process: is there a lower bound on the corresponding cross section implied by "no global symmetries in quantum gravity"? *e.g.*, is there a a minimum value of the cross section for proton decay implied by QG? (*Julio Parra Martinez*)

Hint: The lore is that the symmetry must be either broken or gauged at high energies. If it's broken, is the minimum value of the cross section simply related to the scale of breaking? If it's gauged, is it related to the scale of magnetically charged objects? For proton decay, an oft-used bound is given by the lowest dimension baryon-number-violating operator in the SMEFT with a coefficient suppressed by the Planck scale. Is this naive expectation actually correct?

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61. How can we better utilize the annual Strings meeting to foster collaboration among the various subfields of high-energy theoretical physics? (*Sabrina Pasterski*)

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62. Can we identify the essential property of some quantum mechanical systems that leads to an emergent gravitational description? (*João Penedones*)

Hint: Study an example with a finite number of degrees of freedom. How are the Lin-Maldacena geometries encoded in the wavefunctions of the degenerate ground states of the Berenstein-Maldacena-Nastase matrix quantum mechanics?

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63. Can we find a set of axioms that help rule out inconsistent ensemble average theories? (Cheng Peng)

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64. Can we quantitatively describe large scale structures in the space of unitary, generic CFTs? (*Eric Perlmutter*)

Hint: Inject chaos and discreteness of high-dimension operators into bootstrap approaches (*e.g.* for $2d$ CFT at large central charge).

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65. What is the holographic dual of a black hole in asymptotically flat space and are infrared effects important in the discussion of unitary evolution? (*Andrea Puhm*)

Hint: What tools from AdS can we carry over or adapt to flat space?

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66. Can we prove that string theory is the only consistent perturbative ultraviolet completion of gravity? (*Grant Remmen*)

Hint: Can we cast the question in terms of the S-matrix at weak coupling and identify a set of constraints that uniquely bootstrap the amplitudes of string theory, including crossing, dual resonance, n-point factorization, and possibly other criteria?

We have 100 questions across a disparate array of disciplines. It's so exciting!

Ivo Sachs

70. Formulate RNS String Field Theory in non-trivial backgrounds.

Hint: Explore finite exactly marginal backgrounds with mixed RR and NS fluxes.

Ricardo Schiappa

71. Can we use resurgence to compute transseries —including all nonperturbative transmonomial contributions— for (large classes of) observables/ correlation functions in generic string theoretic backgrounds?

Hint: This is likely reachable within matrix models, minimal, and topological string theories. Will those results serve as a clue towards generic string theoretic backgrounds or will something else be required?

Ashoke Sen

72. Can non-perturbative string theory be defined as the sum of the contributions from its saddle points?

Hint: For generic complex values of the coupling constant, the Borel resummation of the perturbation expansion around a saddle point is expected to generate the result of the path integral over the Lefschetz thimble associated to that saddle point. So, if we knew how to generate perturbation expansion around all the saddle points and also how the desired integration contour is expressed as a sum of the Lefschetz thimbles, we have in principle a non-perturbative definition of the theory. In string theory, we have a systematic procedure for generating perturbation expansion around the perturbative saddle and the Euclidean D-brane saddles. Can we develop such expansions around other saddle points (*e.g.* the NS 5-brane saddles, wormholes *etc*) and in parallel explore how the desired integration contour might be expressed as a union of the Lefschetz thimbles of different saddles?

Atul Sharma

73. What are celestial symmetries good for?

Hint: Find a use for the w-infinity symmetry of celestial holography to bootstrap graviton loop amplitudes in Einstein gravity, similar to Costello's two-loop all plus gluon amplitude computation in certain QCD-like theories using celestial holographic and twistorial techniques.

Gary Shiu

74. Does the Gibbons-Hawking entropy for (quasi) de Sitter space actually count microstates?

Hint: Perhaps progress in understanding the wavefunction of the universe can shed light on this problem.

Aninda Sinha

75. Can Quantum information ideas help us narrow the space of theories in the S-matrix bootstrap and along these lines is string theory special?

Hint: Since generating entanglement is resource intensive, is there an entanglement minimization principle at work in scattering, i.e., couplings are chosen in the appropriate manner.

Kostas Skenderis

76. Would holography help us understand, or shed new light on, some of the mysteries of the Standard Model (why this specific field content, neutrino masses, *etc.*), or more generally to questions like "what is dark matter and dark energy"?

Hint: Holography maps gauge symmetries in the bulk to global symmetries of the boundary theory, so if there is a dual three-dimensional QFT which is dual to our four-dimensional universe it should have as its global symmetry the gauge group of the standard model. Can we classify, say using bootstrap ideas, (or find examples of) such theories with low-lying spectrum of operators that matches the field content of the Standard Model? Such QFTs would provide a non-perturbative definition of quantum gravity coupled to the standard model and may provide new insight about long-standing questions.

Julian Sonner

77. Can quantum gravity be realized and explored as an [illegible] in real-world experiments? If so, what can be learned [illegible]?

Hint: various quantum platforms (digital, analog, solid-state,...) may actually be engineered to host strongly coupled many-body systems dual to (low-D) gravity in AdS. Can these quantum simulations beat state-of the art classical approaches, such as Euclidean lattice simulations? Real-time simulations? What are the prospects for higher dimensions? non-AdS gravity?

Douglas Stanford

78. Do correlation functions decay to zero for large time/space separation in de Sitter quantum gravity?

Hint: Perhaps there is a non-decaying wormhole contribution?

Andrew Strominger

79. What is one example of a top-down construction of a 2D celestial dual for a string compactification to four dimensions?

Hint: Work of Stieberger and Taylor and Castiblanco, Giribet, Marin and Rojas suggest a relation to the 2D string worldsheet CFT. Both compute the 4D S-matrix.

80. Does conformally self-dual gravity with $G_{\mu\nu} = \Lambda g_{\mu\nu}$ have a consistent quantum definition on AdS_4? If so, what is its holographic dual?

Hint: See Ward, Richard S. "Self-dual space-times with cosmological constant." *Comm. Math. Phys.* 78 (1980).

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81. What is a clean method to measure the electromagnetic memory effect?

Hint: The effect is roughly proportional to the change in the first time derivative of the dipole moment, which is large at a beam dump. The experimental challenges, which include minimizing field transients, resemble those for the electric Aharonov-Bohm effect as discussed for example in van Oudenaarden et.al., *Nature* 391 (1998) or R. Weder *J. Math. Phys.* 52 (2011).

Haoyu Sun

82. Is it possible to systematically extend the power of integrability beyond the planar limit?

Hint: A rather comprehensive review was given in arXiv:1012.3997, consistent with the common lore that integrability is not too useful beyond the planar limit. The latest results, which are from arXiv:1711.05326, suggest that one should consider the worldsheet in general topology, and treat handles using twisted operators to always maintain locality. Is there a non-perturbative way to implement this? This perspective begs a further question: can one use integrability to compute correlators or anomalous dimensions of extended operators, say in the planar limit for simplicity?

Yuji Tachikawa

83. The founding members of modern string theory, who have been so influential thus far, will gradually retire and/or go to their next stage of existence. Will the string theory community as a whole survive this transition? We will definitely see how well we would cope with this in the next ten years.

Hint: Train an LLM with the very best papers written by the founding members, so that it can continue to set the trend of the community.

Piotr Tourkine

87. Can we build numerically consistent two-to-two S-matrices in four dimensions that satisfy crossing, unitarity, analyticity, and display Froissart growth?

Hint: A better understanding of Regge theory and a way to implement it within the S-matrix bootstrap would allow to improve the control on the various limits of the S-matrix, high energy, large spin, *etc.* Conversely, the numerical S-matrix program should tell us precious information on possible non-perturbative Regge behaviours.

Gustavo J. Turiaci

88. Can we derive the rules for computing the gravitational path integral from string theory? How constraining is the expectation that black holes behave as ordinary quantum systems on such rules?

Mithat Unsal

89. In all semi-classically calculable regimes adiabatically connected to the $SU(N)$ Yang-Mills theory on R^3, $4d$ instantons always split up into N fractional instantons. In all cases, these fractional configurations are responsible for confinement, fractional theta dependence, and mass gap. Yet, none of these effects are attributed to instantons in $4d$ Yang-Mills theory! Is it possible that our current understanding of instantons in $4d$ is rather primitive? If so, should we try to find formulations of instantons that may reveal its true nature?

Irene Valenzuela

90. Can we find a bottom-up rationale for the Swampland Distance Conjecture (i.e. the existence of towers of states becoming exponentially light at the infinite distance boundaries of the moduli space)?

Hint: Can we find an inconsistency using black hole physics or S-matrix bootstrap if the tower is not there?

Thomas Van Riet

91. Do we think holography without supersymmetry in the UV & full stability of the vacuum (dS holography, non-SUSY AdS & celestial holography) is achievable?

Hint: Should one look at non-unitary field theories as a proxy for describing meta-stable vacua inside theories with stable SUSY vacua?

Mark Van Raamsdonk

92. For cosmological solutions of $\Lambda < 0$ gravitational effective field theories associated with holographic CFTs, can we relate the cosmological physics to the physics of the associated CFT? Can we give a microscopic calculation of the density perturbations after the big bang in some example?

Hint: There are often asymptotically AdS regions in the Euclidean continuation of the cosmological spacetime.

Tadashi Takayanagi

84. Can we regard the AdS/CFT correspondence as a version of quantum computers?

Hint: Understand how the AdS/CFT calculates various quantities (*e.g.* energy spectra, correlation functions, entanglement entropy and complexity) in the language of quantum circuits or their generalization.

Washington Taylor

85. Can recent progress on holography and the black hole information problem provide useful insights into the formulation of a nonperturbative background-independent theory of quantum gravity and/or the structure of the string landscape?

Ethan Torres

86. How do we classify all of the possible branes in supersymmetric string theories?

Hint: In the past couple of years, some works motivated by the Swampland Cobordism Conjecture have provided evidence for new non-BPS branes in Type II and heterotic string theories.

Extra credit: One of these branes (a non-BPS 4-brane in $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic string theory) has an integer charge lattice. Does taking a large-N limit of these lead to a sensible non-SUSY $\mathrm{AdS}_6/\mathrm{CFT}_5$ correspondence?

Shreya Vardhan

93. What is the bulk dual of a single high energy eigenstate of the boundary theory?

Hint: If we could show that such states have exponentially high circuit complexity, what would that tell us about the region behind the horizon?

Vatsal

94. What is a completely non-perturbative, manifestly gauge-invariant, background-independent formulation of string theory?

Hint: (momentum space) string field theory?

Spenta Wadia

95. What is the signature of the black hole singularity in the dual field theory on the boundary of $\mathbf{AdS}_d$ $(d > 2)$?

Xi Yin

96. Can string field theory be formulated at a fully non-perturbative and quantum level?

Masahito Yamazaki

97. Can we rediscover/extend current formulation of string theory, by some version of reinforcement learning?

Hint: Formulate string theory as a "game" with a well-defined "reward", and let the machines take care of the "trial and error" part.

Alexander Zhiboedov

98. What is the space of holographic CFTs?

Hint: Current bootstrap bounds allow essentially any QFT at low energies. This is in sharp contrast with explicit constructions in string theory which come with a lot of extra structure. To narrow this theoretical gap we perhaps need to learn how to impose quantum consistency of black holes.

Yoav Zigdon

99. Can we construct a ground-state wavefunction of the Universe from string theory that corresponds to our Universe?

Hint: Such a wavefunction might describe a phase of the early Universe with extended objects wrapping Euclidean time.

Anonymous

100. Can we describe cosmological spacetimes using quantum mechanics? How should we think about cosmological spacetimes in a full quantum gravity theory?

FUTURE

The fertility of our field is measured not by distant (and likely naive) visions of an ultimate "theory of everything," but by the wealth of deep & interesting questions that we (and variety) can concretely address and plausibly hope to answer in the next 5-10 years. I asked the speakers and organizers to contribute such questions and have compiled an inspiring list.

AS, Princeton Strings 2014 https://www.youtube.com/watch?v=TfRpyu0HWEI

This old statement is still pertinent! It is interesting to compare the 2014 list with the current list. While much progress has been made on the problems posed then, many of the discoveries over the last decade have stemmed from unanticipated developments. We may continue to expect the unexpected! The new 2024 list is broader, incorporating an expansion of goals and more nearby areas of science. A few notable additions are

Quantum Information Theory

Swampland constraints

Asymptotic symmetries

Chaos theory

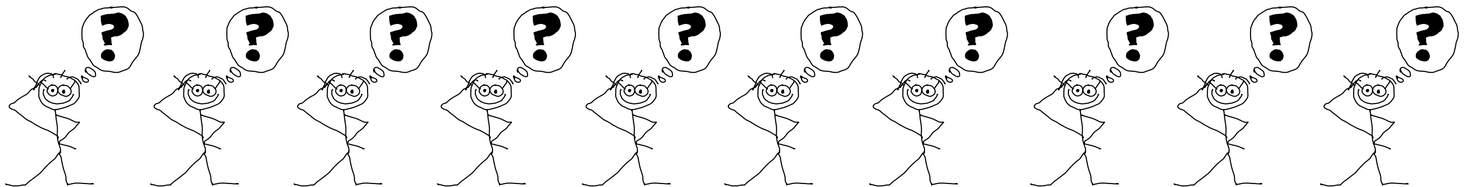
Flat Holography

Bootstrap

QCD

Bottom-up flavor

Yet not losing sight of the central puzzles. Personally, I found myself wishing for ten more of me to work on all the interesting and fertile problems!



I can’t possibly review or summarize all of these. Here are for example some questions concerning deSitter space and cosmology. I will briefly comment on them and add hints.

Dionysios Anninos

5. **What is the theoretical underpinning, or even axiomatic structure, governing cosmological spacetimes?**

Hint: Some hints (cautiously interpreted) might stem from the appearance of horizons of the cosmological type, and the structure of semiclassical Wheeler-DeWitt wave equation.

Douglas Stanford

76. **Do correlation functions decay to zero for large time/space separation in de Sitter quantum gravity?**

Hint: Perhaps there is a non-decaying wormhole contribution?

Shira Chapman

11. **Is quantum gravity in the expanding universe described by a dual quantum mechanical system?**

Hint: Can quantum information measures point us in the right direction to look for such a system?

Henry Maxfield

41. **When does perturbative quantum GR provide a reliable approximation for cosmological spacetimes?**

Hint: For old black holes, for calculating some quantities, we’ve recently learned of large non-perturbative gravitational effects. Do similar considerations apply to late time de Sitter space, for example?

Xi Dong

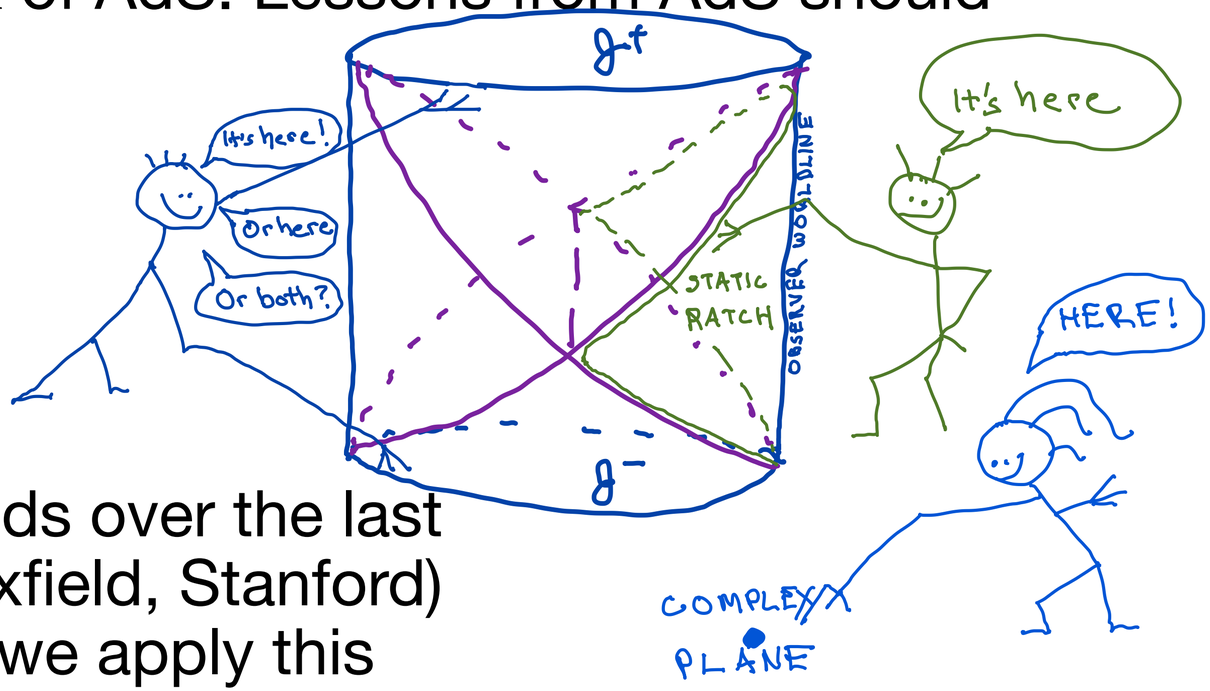
15. **How do we formulate quantum gravity non-perturbatively in cosmological spacetimes with accelerated expansion?**

Anonymous

100. **Can we describe cosmological spacetimes using quantum mechanics? How should we think about cosmological spacetimes in a full quantum gravity theory?**

COMMENTS

- dS is the analytic continuation $\Lambda \to -\Lambda$ of AdS. Lessons from AdS should somehow be useful!
- Is there a hologram (Chapman)?
- It should be some kind of analytic continuation!
- We have learned a lot about different kinds over the last decade: complex Euclidean saddles (Maxfield, Stanford) and Minkowski to (2,2) Klein space. Can we apply this knowledge to dS→AdS?



HINTS: several possibly relevant old and new references for dS →AdS:

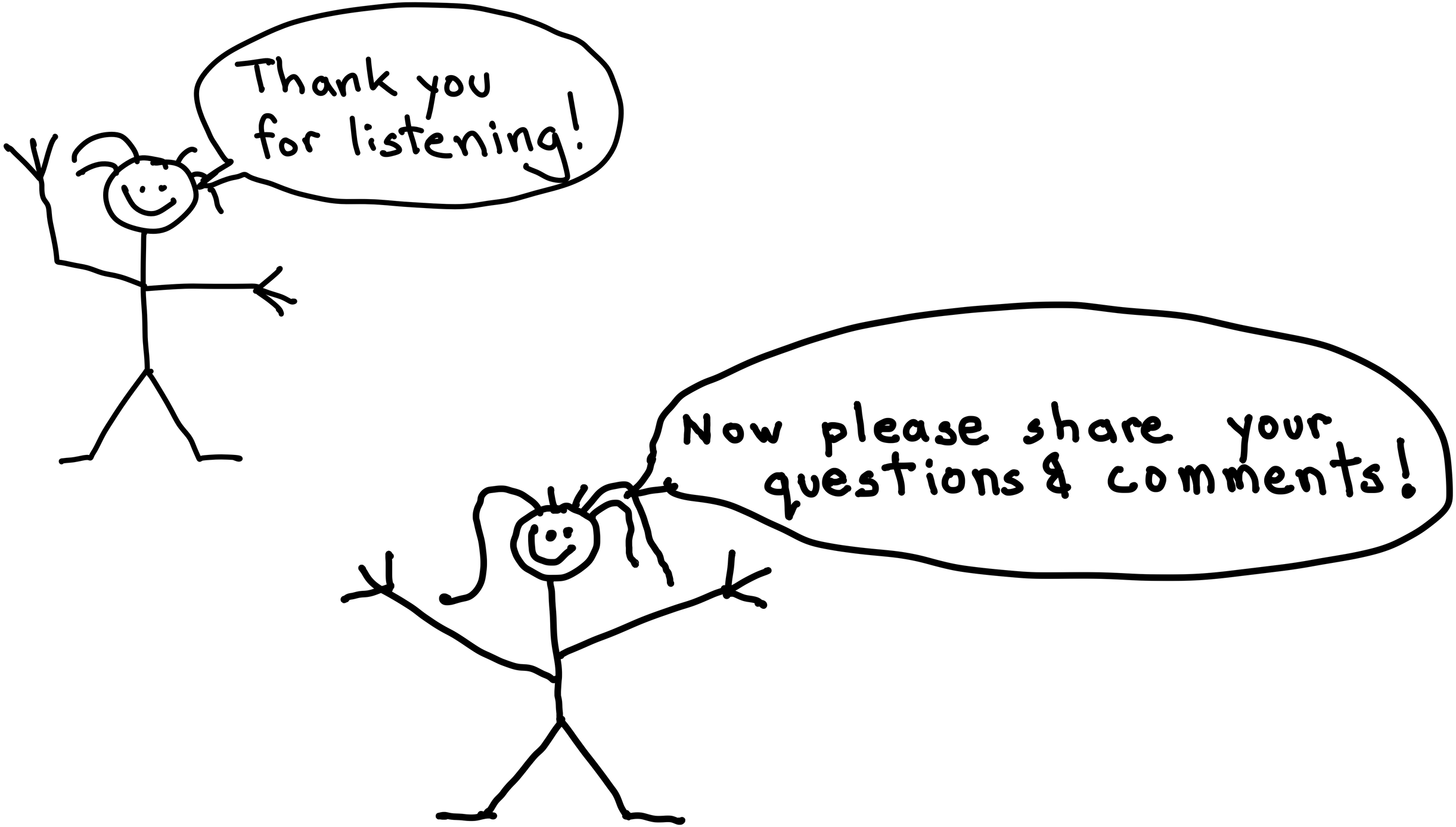
- Hull in *Timelike T duality, de Sitter space,…* (1998) constructs stringy brane duals for split signature dS. More recently Dijkgraaf, Heidenrech, Jefferson and Vafa in Negative Branes, Supergroups and the Signature of Spacetime in (2018) develop this in a variety of contexts this and define analytic continuations to `negative branes' in split signature. Also in mix Ooguri and Vafa, Selfduality and N=2 String MAGIC (1990).

- D-branes in analytically continued sections of time-dependent spacetimes have been considered for example in Maloney, AS and Yin S-Brane Thermodynamics (2003) and Gaiotto, Itzhaki and Rastelli Closed Strings as Imaginary D-branes (2003), and very recently in Z. Wei Holographic Dual in Crosscap Conformal Field Theory in (2024). The study of these objects is underdeveloped.

- Very recently, Taylor and Zhu in $w_{1+\infty}$ Algebra with a Cosmological Constant and the Celestial Sphere (2023) and Bittleston, Bogna, Heueveline, Kmec, Mason and Skinner in On AdS_4 deformations of celestial symmetries (2024) have shown that AdS_4, dS_4 and M_4 in split signature are all governed by a soft symmetry algebra

$$\{w^p_{m,a}, w^q_{n,b}\}_\Lambda = (m(q-1) - n(p-1))w^{p+q-2}_{m+n,a+b} - \Lambda(a(q-2) - b(p-2))w^{p+q-1}_{m+n,a+b}\,,$$

depending on the value of Λ. This may provide for a useful analytic continuation of the holographic principle $AdS_4 \to M_4 \to dS_4$.


Thank you for listening!
Now please share your questions & comments!