Title: Vision Talk

Speakers:

Collection: Celestial Holography Summer School 2024

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Celestial Holography

Past, Present and Future

Andy Strominger
Perimeter/Simons Celestial Summer School
July 2024

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Talk Outline

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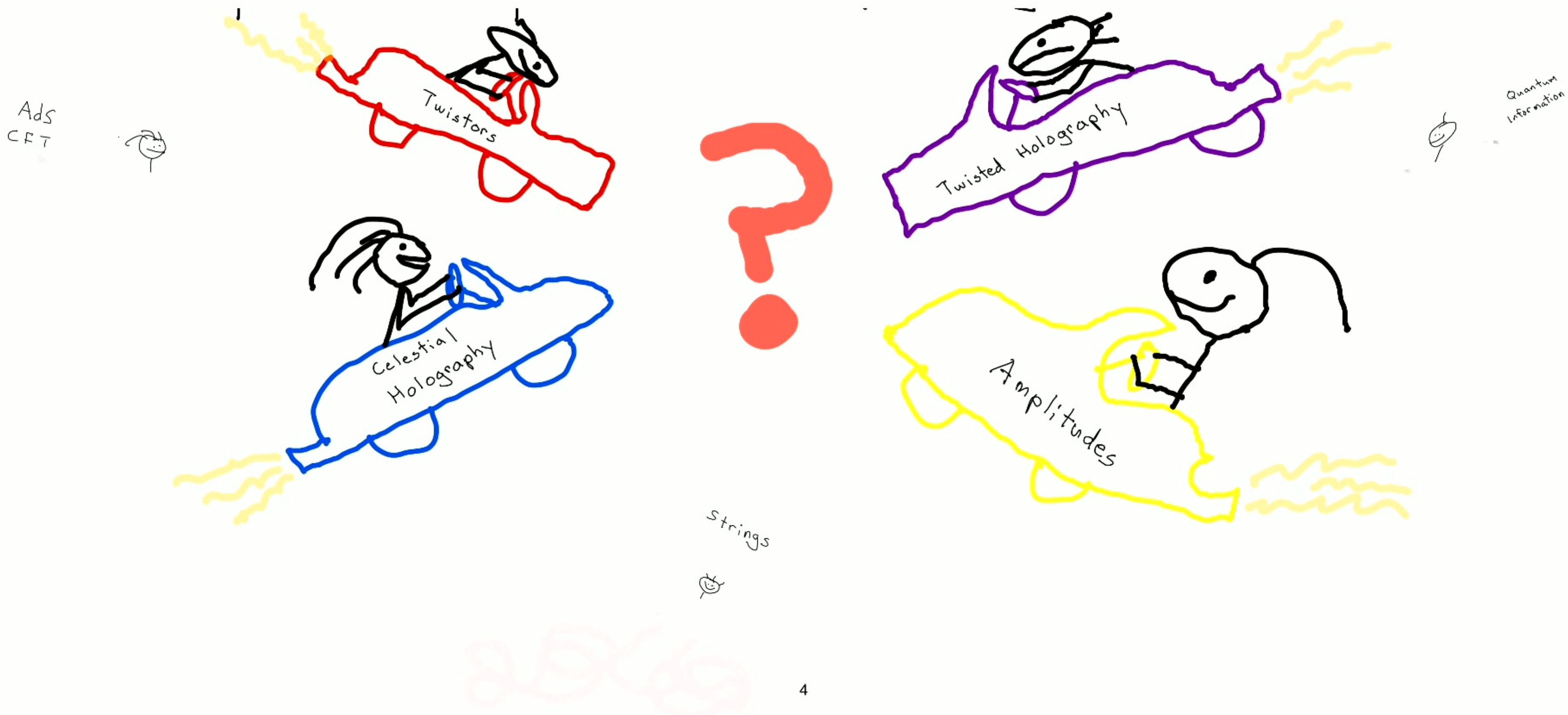
- Motivations, assumptions and philosophy
- Highlights of some basic past results
- Present conundrums

My motivation, assumptions and philosophy

- We have learned a fantastic amount, much of it driven by string theory over the last 40 years, about quantum mechanics, gravity and QFT. The time is ripe to apply these insights to learn something about quantum gravity in the real world.
- Assume the holographic principle holds in flat space as well as BHs and AdS <=> QG S-matrix = QFT on ‘spacetime boundary’.
- Take lessons from, but do not assume, string theory or AdS/CFT.
- Not seeking TOE, or even fundamental new laws of physics. (Although would be happy to find them!) Largely bottom-up.
- Guided by (i) self-consistency (ii) symmetries (iii) top-down toy models = very powerful guides.

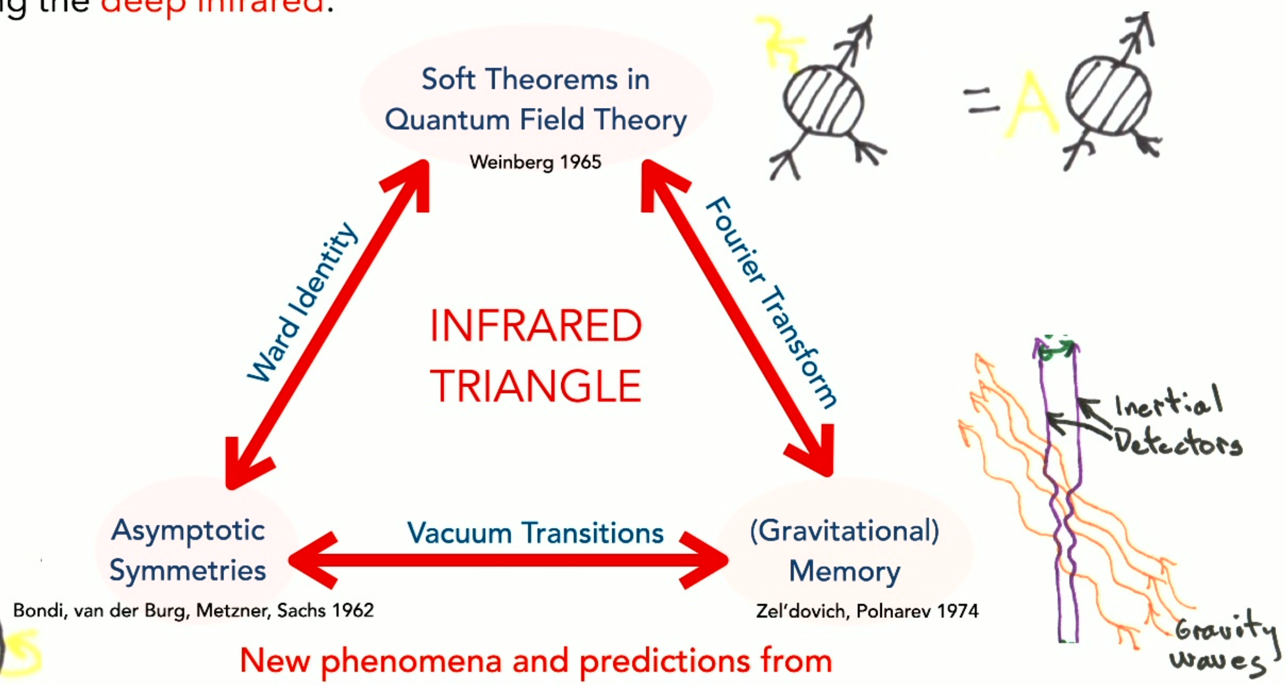
This is my perspective: as you have heard the field is a fertile amalgamation of colliding approaches, armed with other sets of motivations, assumptions and philosophies:

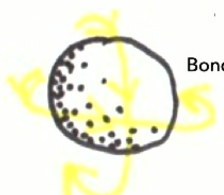


Highlights of past results

New insights on the Infrared

Progress on ? has been enabled by the recent discovery of an exact mathematical equivalence between three seemingly disparate half-century-old discoveries concerning the deep infrared:

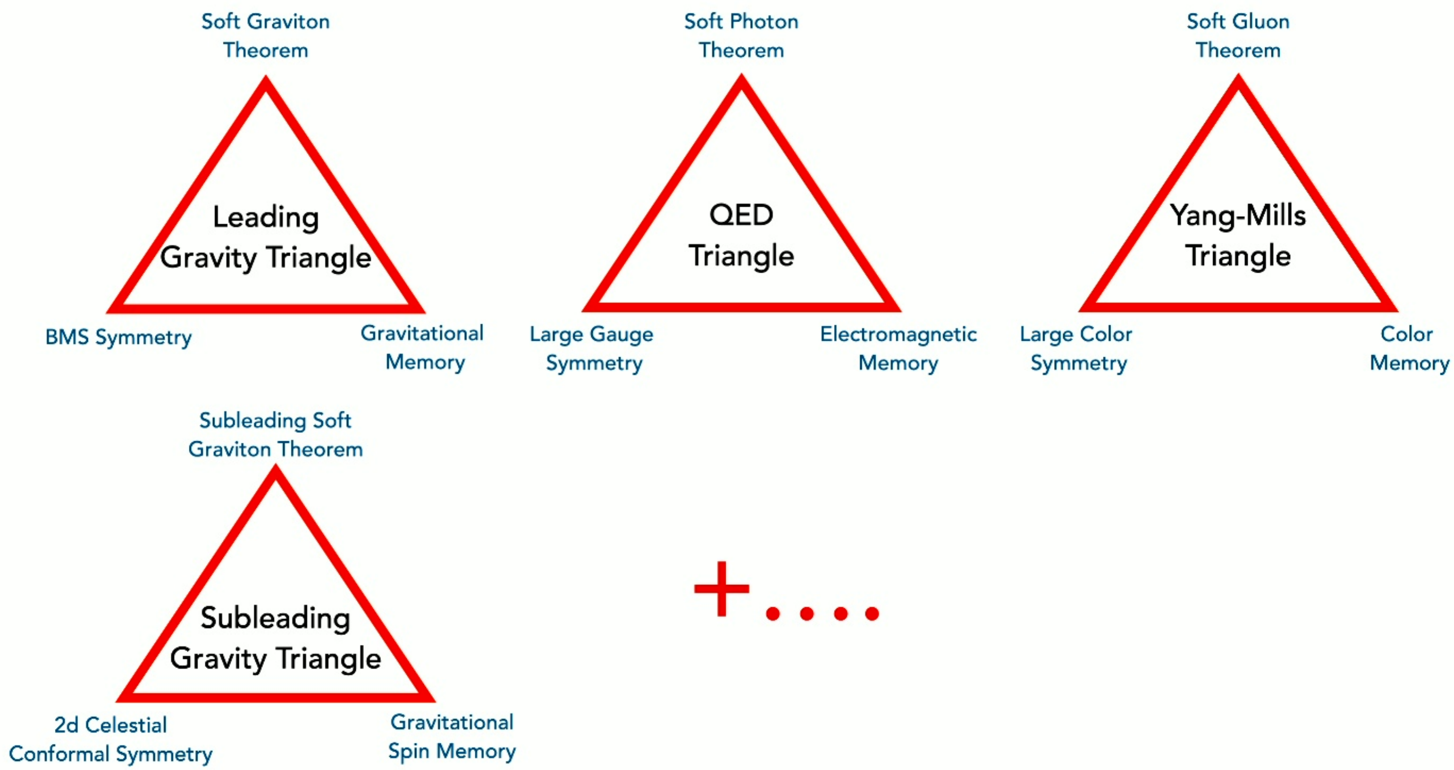




New phenomena and predictions from established physical laws c.f Bose-Einstein condensation

More infrared relations

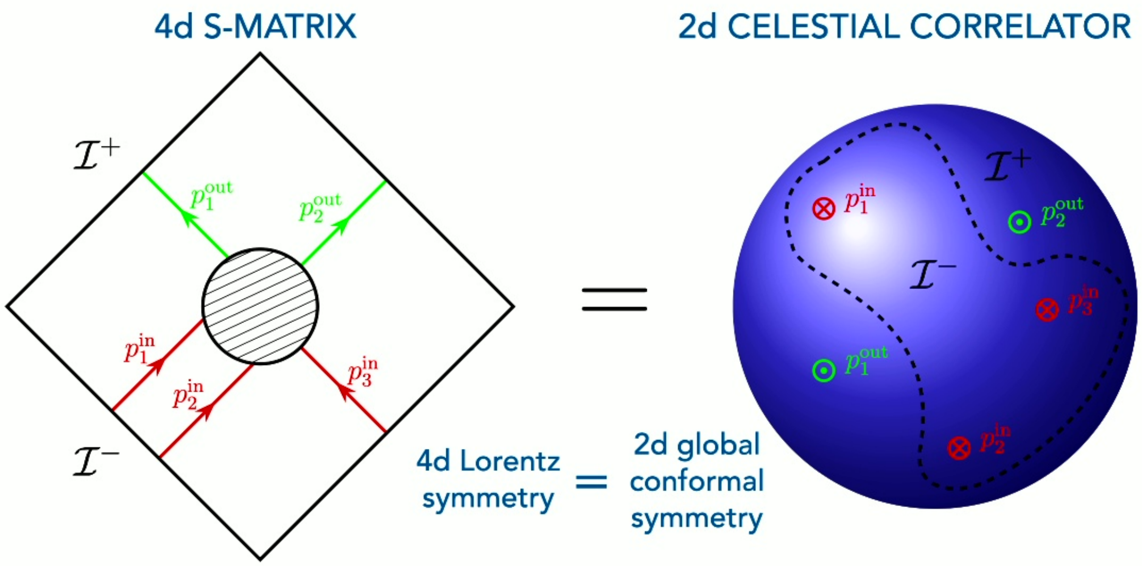
reverberate throughout gravity, QED and Yang-Mills Theory:



Akhoury, Ball, Banerjee, Cachazo, Campiglia, Casali, Cheung, Choi, He, Himwich, Kapec, Laddha, Lysov, Mittman,Mitra, Nande, Nichols, Pasterski, Pate, Porfyriadis, Raclariu, AS, Teukolsky, Venugopalan, Zhiboedov,…

Celestial holography

This improved understanding of symmetries in flat space is just what the doctor ordered for applying the holographic principle to flat space: the first step in the construction of a dual pair is identifying the symmetries that both sides must obey. The subleading soft graviton theorem → local 2d conformal symmetry of the celestial sphere (+spin memory). We may therefore rewrite:



So far the LHS largely defines the RHS. The goal is to give an intrinsic definition to the RHS.

4d QUANTUM GRAVITY = 2d CELESTIAL CFT

Conformal Primary Basis

2D conformal covariance of 4D scattering amplitudes are manifest in a conformal basis of modes:

Pasterski, Shao, AS

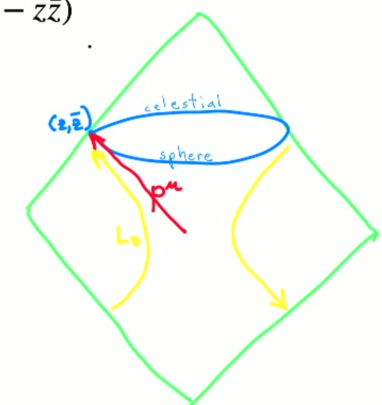
conformal primary wavefunction; Mellin transform; plane wave; boost weight; point on celestial sphere

$$\Phi_\Delta(z,\bar{z}) = \int_0^\infty d\omega\, \omega^{\Delta-1} e^{i\omega(\hat{p}\cdot X + i\epsilon)} = \frac{\Gamma(\Delta)}{(i\hat{p}\cdot X - \epsilon)^\Delta}$$

$$\hat{p}^\mu(z,\bar{z}) = (1+z\bar{z}, z+\bar{z}, i(z-\bar{z}), 1-z\bar{z})$$

$$L_1 \Phi_\Delta = 0$$

$$L_0 \Phi_\Delta = \frac{\Delta}{2}\Phi_\Delta$$



$$A^{\text{celestial}}(\Delta_1, z_1, \bar{z}_1, \ldots \Delta_n, z_n, \bar{z}_n) = \int d\omega_1 \omega_1^{\Delta_1 - 1} \ldots d\omega_n \omega^{\Delta_n - 1} A^{\text{momentum}}(p_1, \ldots p_n)$$

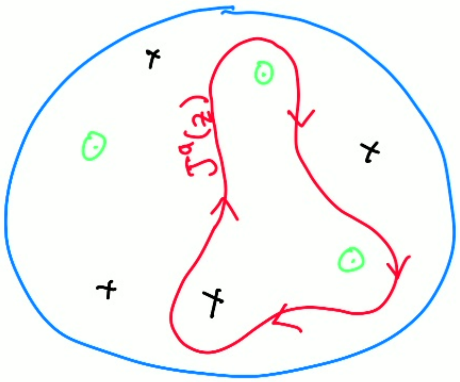
There have been extensive studies of these ` celestial amplitudes' and their properties.

(Conformally) soft theorems imply 2D current algebras

The $\Delta = 1$ conformal primary in nonabelian gauge theory

$$J^a(z) = \int_{\mathcal{I}} du F^a_{uz}$$

is holomorphic on the celestial sphere. It generates a Kac-Moody algebra:



Ditto for gravity.

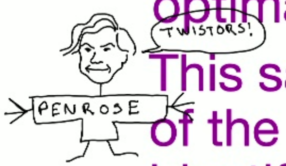
Sure looks like string theory!

He, Mitra, AS, Pate, Raclariu, Donnay, Puhm, Pasterski, Trevisani, Banerjee, Paul…

$\mathscr{L}w^{\wedge}_{1+\infty}$ soft symmetries

Primary operators at $\Delta = 1, 0, -1, \ldots$ are all governed by a tower of soft theorems. For minimally-coupled tree-level gravity they generate the well-known loop algebra of 2D area-preserving diffeomorphisms $\mathscr{L}w^{\wedge}_{1+\infty}$. The conformal basis organizes the tower of soft theorems in gauge theory and gravity into a chiral soft algebra. This result is relevant for flat space holography whether or not a celestial CFT is the optimal formulation.

Guevara, Himwich, Pate, AS, Donnay, Freidel, Herfray, Raclariu, Pranzetti



This same symmetry was used 50 years ago in Penrose's construction of the non-linear graviton and plays a central role in twistor theory. The identification is established by explicit comparison of the graviton wave functions. This forges a powerful connection and brings the analytic methods of twistor theory along with those of 2D CFT to bear on the problem of 4D gravity!

Adamo, Mason, Sharma, Casali, AS, Costello, Paquette, Skinner, Bu, Bittleston, Hueveline,…

These symmetries exist in the `holomorphic expansion' around $z \to 0$, $\bar{z}$ fixed. This is tantamount to analytic continuation to $(2,2)$ signature Klein space, which has many interesting subtleties.

Exciting recent generalization of chiral soft algebra to AdS/dS, Hueveline poster, Skinner lecture(?)

Taylor, Zhu,Bittleston,Bogna,Hueveline,Kmec,Mason,Skinner

More!

- Top-down twisted holography (Gaiotto lectures(?))
- Carollian holography (Ruzziconi lectures)
- Twistorial developments (Mason, Skinner lectures?)
- Gravitational memory experiments
- IR divergences (Honnesdottir lectures)
- Asymptotic structure (Mitra lectures)

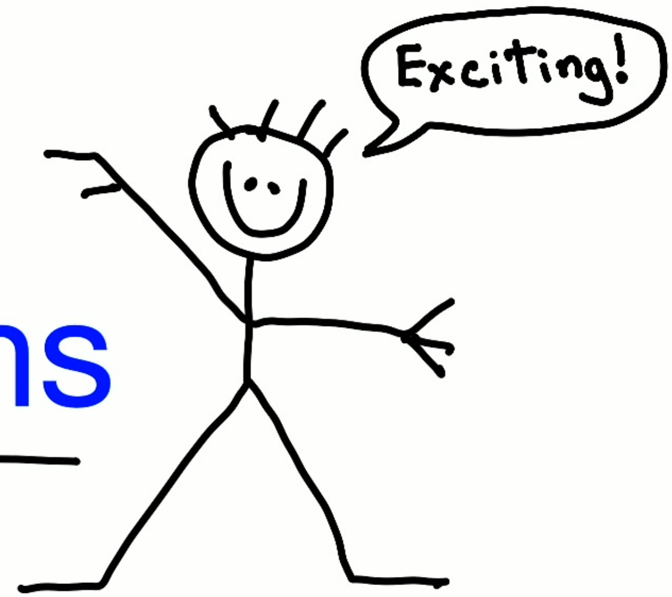
Present conundrums

some basic things we don't understand now under active investigation

- What is the physical spectrum of operator dimensions Δ? $1 + i\lambda$? Integers?
- How do we understand/resolve the distributional nature of some low point celestial amplitudes implied by 4D translation invariance? (Puhm lecture)
- What kind of corrections can the chiral soft algebras have?

The Future

Open Questions



The general subjects of quantum gravity in flat space or dS along with the associated mathematics and experiments are wide open and developing in multiple directions. In advance of the annual meeting last April I collected 70+ very interesting questions (with hints in some cases) and posted them on the Simons Collaboration website.This is a good place to get ideas for reseaarch projects! I am now going to discuss a few of the collected questions.

OPEN QUESTIONS

1: Can one compute loop corrections to soft theorems in non-abelian gauge theories using celestial holography?

HINT: The non-abelian soft current is fully known (from conventional calculations) at two loops, and partially at three loops.

– Lorenzo Magnea

2: What replaces the semiclassical description of spacetime near a black hole singularity, and how is it described holographically?

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

– Gary Horowitz

3: What is the relationship, if any, between asymptotic symmetries and generalized symmetries, e.g. higher form/higher group/noninvertible symmetries, of gauge theories and gravity?

HINT: Higher form symmetries are abelian and probably can't capture the full structure of asymptotic symmetries, but it would be interesting to see if there are connections to higher group symmetries.

– Temple He

4: Does the holographic behavior of gravity arise from the constraints, and if so, does constructing the holographic map rely on their solution, i.e. on first having a description of bulk evolution?

HINT: Try to give a systematic construction of the holographic map, e.g. in AdS.

– Steve Giddings

5: What is the global form of infinite-dimensional conservation laws for a black hole in asymptotically flat spacetime?

HINT: They should be derived from a matching between the black hole's horizon charges and asymptotic symmetry charges at the different boundaries.

– Laura Donnay

6: Do the large pure gauge/diffeomorphism profiles have their own dynamics and in what sense are they holographic?

HINT: The large pure gauge/diffeomorphism profiles allow for additional bulk field configurations to be summed over, which amounts to promoting the profiles themselves to quantum fields living on the boundary.

– Anonymous

7: Find observable memory effects corresponding to $w_{1+\infty}$ symmetries of celestial holography.

8: Find memory observables corresponding to black hole horizon symmetries (of course one can think about displacement of test masses, but no experimenter would buy that!).

HINT: Contact author for hints and possible collaboration!

– Ali Seraj

9: In string theory, is there a direct relation between celestial OPEs and the OPEs of the associated worldsheet OP-vertex operators?

– Anonymous

10: Find and prove the best possible upper bound on the asymptotic complexity of computing a tree-level n-gluon (or n-graviton) amplitude.

HINT: Answering this question may require or enable the discovery of a completely new formulation of the problem.

– Marcus Spradlin

11: What is the celestial analog of a Ryu-Takayanagi surface?

– Anonymous

36: One thing I'm curious about is the interplay between the celestial developments and the 2-body problem in GR. Could any of the infinite dimensional celestial symmetry algebras help in this problem? Is there a celestial counterpart of the analytic continuation from open to bounded orbits?

– Miguel Campiglia

37: Can gravitational waveforms be computed from correlations functions in a two-dimensional conformal field theory? To what precision, in what expansion (post-Newtonian, post-Minkowski, self-force, post-background,...) and how easily?

– Anonymous

38: What is the most general form of the four graviton scattering amplitude consistent with all known symmetries and constraints?

HINT: Constraints include those arising from unitarity, crossing, towers of soft theorems and black hole production at high energies.

– Andy Strominger

39: What makes unitarity of the S-matrix obvious in celestial holography?

– Nima Arkani-Hamed

40: Can the study of infrared physics in QCD and the array of soft theorems give us new insight on the mechanism for confinement?

HINT: Confinement is an infrared phenomena, classical and quantum IR divergences suggest that one should look at Infrared QCD and its goldstone physics in a new light.

– Laurent Freidel

41: What are the celestial CFT axioms?

– Andrea Puhm

42: How can Celestial Holography help bridge results from Amplitudes, the Conformal Bootstrap and It from Qubit?

– Sabrina Pasterski

43: Is the $W_{1+\infty}$ symmetry partially preserved, spontaneously broken, or explicitly broken at the quantum level?

HINT: The answer to this question might depend on what space of state we apply it to. Scattering states versus well behaved wave packets for instance

– Laurent Freidel

44: Aside from the uplift of N=8 self-dual supergravity, does there exist an anomaly-free variant of Poisson-Chern-Simons theory on twistor space?

– Roland Bittleston

45: Is the tree-level Einstein S matrix the only consistent asymptotically flat n graviton S matrix (i.e. only poles and no cuts) that does not include pole exchange contributions from particles of arbitrarily high spin? 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?

HINT:

– "Consistent" means respecting all relevant general physical principles.

– A 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. 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 compactifications that have the dilaton as a modulus.

– Shiraz Minwalla

12: How can we relate the various definitions of charges in extended BMS existing in GR literature to the behavior of asymptotic probes? In particular, how do we distinguish the various definitions of angular momentum and angular momentum flux found in the literature using asymptotic inertial detectors?

– Massimo Porrati

13: Gravity is non-renormalizable as a QFT. How does the study of asymptotic symmetries and celestial OPE depend on its UV completion? Does this study give us any clue about the nature of UV completion? Or is it independent of it?

– Laurent Freidel

14: Can one predict an observable which is a direct consequence of the subleading structure of soft theorems/memories/symmetries and design a protocol to observe it in the coming years?

HINT: The leading order displacement memory effect is on the way to be observed.

– Geoffrey Compère

15: How are gravitational bulk subregions encoded in (celestial) CFT and what is an associated physical observable?

HINT: In AdS/CFT the entanglement structure of the CFT knows about bulk geometry.

– Ana-Maria Raclariu

16: How does BFSS fit into the framework of celestial holography?

HINT: There have been several recent works exploring soft theorems in BFSS, which clarify the manifestation of certain symmetries.

– Jordan Cotler

17: Do gravitons exist? If yes, are they elementary or composite?

HINT: Gravitational waves, Weinberg-Witten's theorem.

– Tomasz Taylor

18: What are the symmetry algebras of gauge theories and gravity at the quantum level?

– Andrea Puhm

19: Does one expect a holographic dual to flat space that is fully decoupled from gravity? In how many dimensions does it live and what are its locality properties?

HINT: String- theoretical realization of/insights into flat holography?

– Monica Guica

20: Do the "high energy" (higher spin) symmetries of flat space string scattering amplitudes (Gross) have a nice realisation in terms of the conformal symmetries of the celestial sphere?

HINT: The Stieberger-Taylor approach to string scattering amplitudes suggests a close relation between the worldsheet and the celestial sphere and perhaps there is a relation to the W_{∞} higher spin symmetry of the free worldsheet theory (leading one to further ask what, if any, is the relation to the soft W_{∞} or to the tensionless limit of AdS_3/CFT_2 ?)

– Rajesh Gopakumar

21: Certain theories in asymptotically flat space–such as gravity coupled to a CFT–do not have the S matrix as a well-defined observable. Boundary observables still exist, such as energy correlators. How should we think about the celestial hologram for such theories?

– Nima Arkani-Hamed

22: How can we see celestial amplitudes in low energy (e.g. LHC) data? Does decoupling of UV physics from low-energy amplitudes manifest here?

– Massimo Porrati

23: Generalize Hawking's Lorentzian computation of black hole radiance in gravitational collapse spacetimes to include the effect of soft modes, in three stages:

1. For free fields
2. For interacting fields (tree level), including the nonlinear interactions that excite memory
3. Somehow include the effect of secularly growing fluctuations in black hole charges

Then, fix a cut of future null infinity at some retarded time u after the Page time, and trace over soft modes including the edge modes associated with that cut.

See if this tracing is enough to remove entanglement between internal Hawking quanta and external Hawking quanta (as it would for a GHZ like state), following suggestion of arXiv:1706.07143.

– Eanna Flanagan

46: Do non-supersymmetric holographic dualities exist?

HINT: Celestial holography has become a ripe arena for answering this through work on integrable theories, self-dual sectors, topological and N = 2 strings, etc.

– Atul Sharma

47: What is the complete spectrum, including single-particle operators, multi-particle operators, and descendants, that one can extract from (tree-level) correlation functions?

HINT: One way could be implementing the partial wave expansion for a generic n-point diagram and directly starting from momentum space (instead of doing Mellin transforms first) might be easier.

– Anonymous

48: What timelike boundaries are allowed in four-dimensional cosmology – motivated by genericity of such topology and by holography – and what are observational bounds on their presence within our horizon?

HINT: From the bottom up, for some cases Dirichlet (fixed intrinsic boundary geometry) evidently make sense, while in the general case conformal boundary conditions (fixing the trace of the extrinsic curvature and the conformal class of the metric) appears better behaved; from the top down this is UV sensitive (being a short scale feature) and requires further investigation in string theory.

– Eva Silverstein

49: Some initial data will lead to Black-Hole creation at the classical level. How does this process affects the amplitudes, soft theorems and symmetry action and celestial OPEs?

HINT: Dig deeper in connection between OPE and asymptotic symmetry in the presence of black holes.

– Laurent Freidel

50: Can we add Black Holes to CCFT dynamically?

HINT: Compute Black Hole microstates.

– Luca Ciambelli

51: (How) Do the symmetry algebras extend beyond the single helicity sector?

– Andrea Puhm

52: What are all the non-trivially acting symmetries of nature?

HINT: At tree level, they include the loop group of $W_{1+\infty}$.

– Anonymous

53: Is it possible to derive celestial holography in terms of quantum information theory?

HINT: Progress can be borrowed from AdS3/CFT2, e.g. tensor networks for estimating entanglement entropy. Klein signature could help.

– Alfredo Guevara Gonzalez

54: What is the most promising method for detecting a memory effect?

HINT: Consider all fundamental forces: gravitational, electromagnetic, strong, and perhaps even weak.

– David Nichols

55: Is there a clean fingerprint of unstable massive particles, important in the UV (such as massive string modes at weak string coupling, super-planckian black hole microstates), on celestial amplitudes?

– Nima Arkani-Hamed

56: What is the simplest top-down model of celestial holography that isn't self-dual?

HINT: Is the asymptotically flat part of the bulk four or higher dimensional? If the bulk theory is a string theory, does the celestial dual admit a perturbative expansion as well as a 1/N expansion? Can it be obtained as a limit of AdS/CFT, perhaps in Mellin space?

– David Skinner

57: How does the SO(4,2) conformal group act on celestial amplitudes and soft symmetries?

HINT: See Chen, Myers and Raclariu for relevant observations.

– Anonymous

24: What is the celestial CFT state dual to black holes?

– Andrea Puhm

25: How should we define (the analogue of) the entanglement wedge for arbitrary spacetimes?

– Anonymous

26: Is there a "self-dual sector" of AdS/CFT?

– Akshay Yelleshpur Srikant

27: What microscopic physical principle(s) that aren't visible in semiclassical gravity (analogous to boundary unitarity and locality in AdS/CFT) should constrain the celestial CFT?

HINT: This seems to me to be the key ingredient if celestial holography is supposed to be a flat space version of AdS/CFT rather than just a flat space version of Brown-Henneaux. Obviously, the S matrix should be unitary but I don't see anything beyond that.

– Geoffrey Penington

28: Are large gauge charge conserving amplitudes in non-abelian gauge theory always free of IR divergences? Can they usefully define unitary IR finite s-matrix.

HINT: Analogous statements held in QED and gravity.

– Anonymous

29: There is a strong suspicion that without supersymmetry, we should not be able to find exactly flat space solutions in quantum gravity–the cosmological constant problem. The string landscape is argued to let us to get a "discretum" with arbitrarily small CC without SUSY, but not exactly zero. What does celestial holography say about this? What if anything is special about supersymmetric theories given that the celestial boundary of flat space is automatic in this program?

– Nima Arkani-Hamed

30: How does the Planck length emerge out of a celestial CFT with finite central charge?

HINT: Planck's length is the only scale at asymptotic infinity. It's unclear how/if it can be related to a nonzero, finite dimensionless central charge.

– Roberto Emparan

31: What are the unitarity/causality constraints on amplitudes in various formalisms?

– Massimo Porrati

32: What celestial CFT reproduces the one-loop exact all-plus amplitudes of self-dual gravity?

HINT: Bulk self-duality is related to boundary chirality.

– Anonymous

33: How much further progress can be achieved in the asymptotic approach to classical and quantum gravity by (i) using a double null foliation and (ii) by deriving the bracket structure from first/action principles?

– Glenn Barnich

34: Can black hole entropy be computed directly from the string theory (or other UV complete theory) path integral, S-matrix, or other on-shell quantity, without recourse to low energy effective field theory?

HINT: The action for the Schwarzschild solution comes entirely from a boundary term at infinity.

– Per Kraus

35: How can translationally-invariant spacetime emerge from a celestial CFT with only unbroken Lorentz invariance?

– Anonymous

58: Is there a local two dimensional Euclidean quantum field theory that calculates soft exchange and soft emission (at each order in perturbation theory) in four dimensional non-abelian gauge theory?

HINT: The answer is yes for abelian gauge theory and gravity, and the form of the lower dimensional models is fixed by (asymptotic) symmetries

– Daniel Kapec

59: What is the exact role of timelike infinity (i^+ and i^-) in flat space holography?

– Marc Henneaux

60: Is the universality of the tower of logarithmic soft theorems a consequence of asymptotic symmetries of the S-matrix?

– Sangmin Choi

61: How do $W_{1+\infty}$ soft symmetries act on the Love numbers of a Kerr black hole?

HINT: Understand how black holes can source the $W_{1+\infty}$ charges.

– Anonymous

62: Standard AdS/CFT relates certain AdS_4 supergravity/string theories to ABJM theories. what truncations/adjustments need to be made to reduce this to the self-dual sector? (and to Carollian and celestial limits?)

– Lionel Mason

63: Is there a celestial dual of the Schwarzschild black hole, and how do we describe it?

– Bin Zhu

64: How does the non-commutativity of the consecutive soft limits in the mixed helicity sector get reflected in the (soft) symmetry algebra of GR?

– Shamik Banerjee

65: Which types of boundary conditions (finite or asymptotic) on a UV-complete gravitational/string theory do we expect to give rise to a holographic dual description? Under which conditions do we expect this holographic dual to (i) obey the usual rules of quantum mechanics (ii) be unitary and (iii) have a suitable notion of locality?

– Jan de Boer

66: To what extent can the rules of quantum field theory be written in a manifestly gauge invariant way? (e.g. in terms of field strengths rather than potentials) If this cannot be done, is there a simple way to say what the obstruction to doing so is?

– David Garfinkle

67: It has been suggested by Vafa and collaborators that there is a dark fifth dimension whose size is several microns. How could this be incorporated in celestial holography?

– John H. Schwarz

68: What is the relation between what happens at scriplus and at the final dynamical horizon in binary mergers?

– Abhay Ashtekar

69: Are BMS_4 symmetries composite?

HINT: Infinite-dimensional symmetries sometimes can be (Sugawara-)decomposed into more fundamental building blocks (like Kac-Moody currents for Virasoro, BMS_3 or W_N symmetries). Something analogous could be possible for BMS_4 and might help us to constrain scattering amplitudes, count Kerr black hole microstates, sharpen statements regarding asymptotic symmetries, etc

– Daniel Grumiller

54: What is the most promising method for detecting a memory effect?

HINT: Consider all fundamental forces: gravitational, electromagnetic, strong, and perhaps even weak.

– David Nichols

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HINT: Contact author for hints and possible collaboration!

– Ali Seraj

Experiment

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- In principle observable memory effects exist for gravity, QED and QCD.
- They measure the transition between degenerate vacua induced by outgoing radiation, or equivalently edge modes at the boundary of spacetime. There is an infinite tower of such effects.
- The leading gravitational memory is predicted to be measured with 5 years of running at advanced LIGO.
- Newly predicted subleading `spin memory' might be measured at LIGO or LISA, and QCD color memory at the electron-ion colliders.
- Finding the clean and practical methods for observing memory is a theoretically and experimentally interesting problem.

Constraining the 4-graviton tree amplitude

45: Is the tree-level Einstein S matrix the only consistent asymptotically flat n graviton S matrix (i.e. only poles and no cuts) that does not include pole exchange contributions from particles of arbitrarily high spin? 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?

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- 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 compactifications that have the dilaton as a modulus.

– Shiraz Minwalla

- Few constraints in the Wilsonian paradigm.
- UV/IR connections give new perspectives.
- UV softness required by high energy black hole production `baked in' to celestial amplitudes.
- `Relevant physical principles' include soft symmetries.
- 2D crossing of 4D amplitude => $\sum_s poles = \sum_t poles$ as in string theory!

$\mathscr{L}w^{\wedge}_{1+\infty}$ soft symmetries

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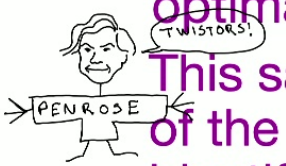

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Adamo, Mason, Sharma, Casali, AS, Costello, Paquette, Skinner, Bu, Bittleston, Hueveline,…

These symmetries exist in the `holomorphic expansion' around $z \to 0$, $\bar{z}$ *fixed. This is tantamount to analytic continuation to* $(2,2)$ *signature Klein space, which has many interesting subtleties.*

Exciting recent generalization of chiral soft algebra to AdS/dS, Hueveline poster, Skinner lecture(?)

Taylor, Zhu,Bittleston,Bogna,Hueveline,Kmec,Mason,Skinner