

Celestial Holography

Strings 2020 Capetown, South Africa

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Harvard

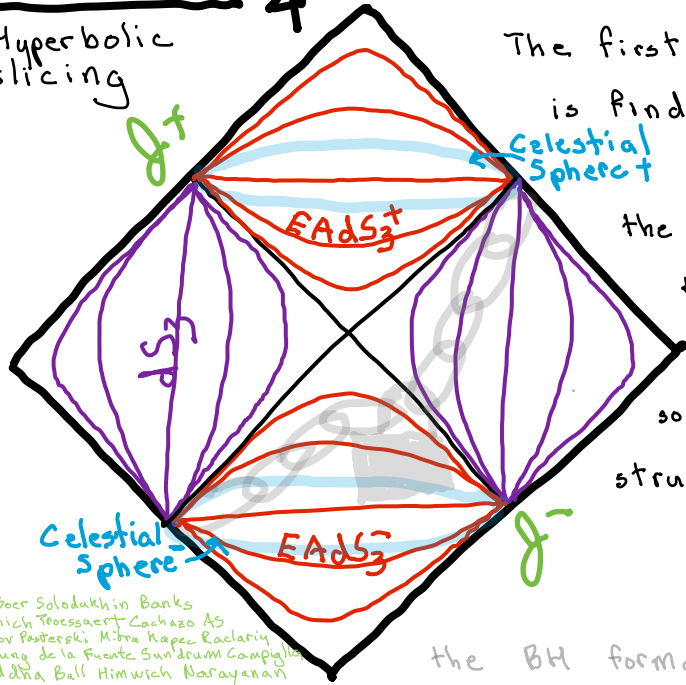
The black hole area-entropy law

$$S_{\text{BH}} = \frac{\text{Area (horizon)}}{4 G_N \hbar}$$

is the primeval holographic relationship: $N_{\text{dof}} \propto \partial V$
Understanding it for BHs with near-horizon AdS regions went hand-in-hand with understanding AdS/CFT holography. One might guess that understanding black holes in flat space - where the information paradox takes its most striking form - will go hand-in-hand with understanding holography for quantum gravity in asymptotically flat spacetimes.

Minkowski 4

Hyperbolic
slicing



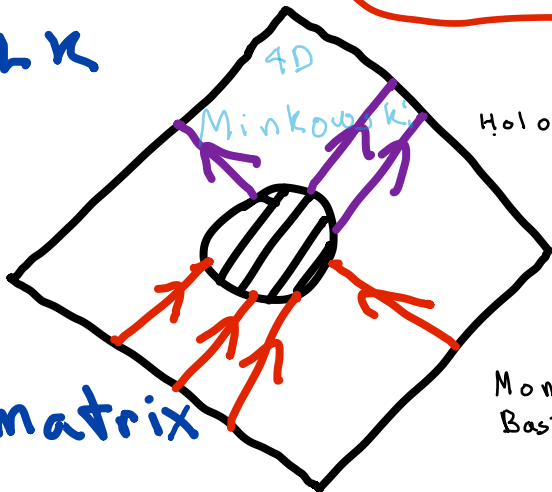
The first step in finding a holographically dual pair is finding the symmetries both sides obey. Thanks to the subleading soft graviton thm, we now know the ∞ -dimensional 2D conformal symmetry is uplifted to the celestial sphere. But there are ∞ -ly many more from supertranslations, subsubleading soft gravitons, subleading soft gluons... a rich & beautiful structure to explore.

These symmetries greatly constrain the BH formation/evaporation S-matrix as partially analyzed in Hawking Perry AS Zhiboedov Papanagan Nichols Bousso Porrati Senzoff Neuenfeld.....
c/f Raju

de Boer Solodukhin Banks
Barnich Troessaert Cachazo AS
Lysov Pasterski Mitra Neftci Raclariu
Cheung de la Fuente Sundrum Campiglia
Badhwa Bell Himwich Narayanan
.....

Basic Idea

BULK

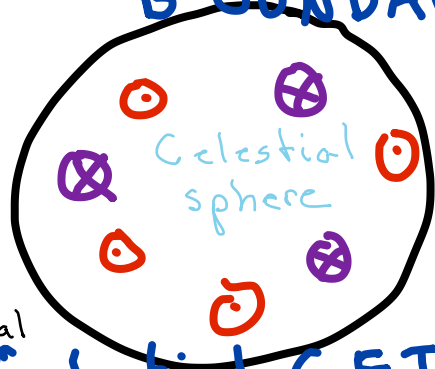


S-matrix

Holographic Duality

=

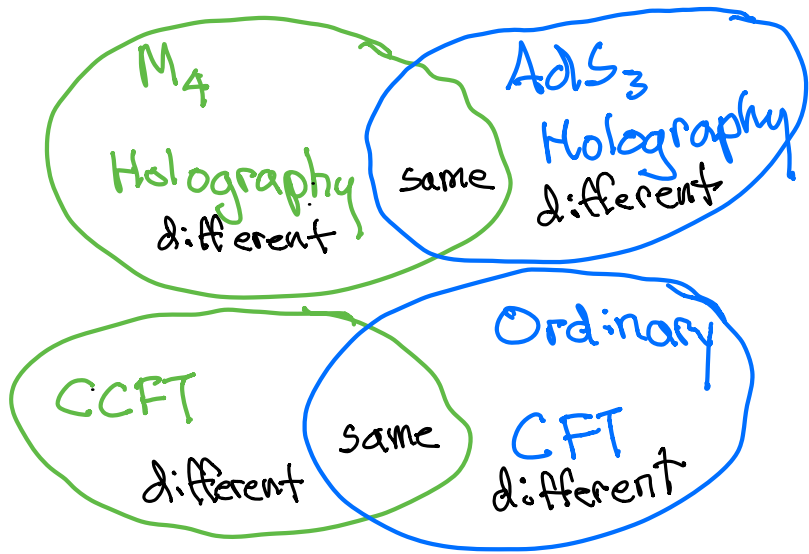
BOUNDARY



Celestial CFT correlator

Momentum Basis \Leftrightarrow Conformal Basis

$SL(2, \mathbb{C})$ Lorentz = global 2D conformal
 Superrotations = local 2D conformal
 Supertranslations $\mathcal{O}_{\Delta}(z, \bar{z}) \rightarrow \mathcal{O}_{\Delta+1}(z, \bar{z})$!
 ... more ...



SO WHAT ARE THE PROPERTIES OF A CCFT?



So far, mostly BOTTOM \rightarrow UP. LHS defines RHS.
c.f. Brown-Henneaux.

TOP \rightarrow DOWN approach from string theory
not ruled out.

String WS CFT $\xrightarrow{\Delta \rightarrow \infty}$ CCFT

CHY WS CFT $\xrightarrow{?}$ CCFT

stieberger
Taylor
c.f. Gopakumar talk

Intrinsic construction of a CCFT = Major Breakthrough!

Many string-like structures encountered.
Strings without strings?

CCFT

Two Virasoros
Current Algebras
Collinear Singularities

Continuous Complex
Highest Weight Reps
Single valued

$$S^+ S = 1$$

Spacetime crossing
 ∞ -dim supertranslation
& subleading soft
symmetry

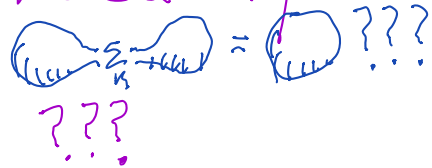
New!

USUAL CFT

Two Virasoros
Current Algebras
OPE Singularities

Discrete Highest
Weight Reps

Locality



No analog

Old!

A lot to understand

Interesting developments in the last years indicate a rich & fascinating structure. But a coherent overarching picture has not yet emerged - so I can't give you one! Instead I will share some tantalizing tidbits.....



For massless particles, the map between momentum-space and conformal basis amplitudes is a Mellin transform

$$A(\lambda_1, z_1, \dots, \lambda_n, z_n) \equiv \int dw_1 \dots dw_n w_1^{h_1 + \bar{h}_1 - 1} \dots w_n^{h_n + \bar{h}_n - 1} A(p_1, \dots, p_n) \\ = \langle \mathcal{O}_1(z_1) \dots \mathcal{O}_n(z_n) \rangle_{\text{CCFT}}$$

$$h = \frac{1}{2}(1 + s + i\lambda)$$

$$\bar{h} = \frac{1}{2}(1 - s + i\lambda)$$

$$z_k = \frac{p_k^1 + i p_k^2}{p_k^3 + p_k^0}$$

$\lambda \in \mathbb{R}$ (subtleties range, $\lambda=0$)
 Donnay, Buhm AS
 Pasterski & Shao

complete basis of states

Full CCFT operator content is known! \Leftrightarrow
 Spectrum of stable particles.

Conformal basis for massive particles involves bulk-to-boundary propagator on H_3 .

$A(\lambda_1, z_1, \dots, \lambda_n, z_n)$ has been computed in a number of examples, sometimes via AdS-Witten diagrams:

① Scalars: massive, massless, 1-loop

Pasterski Shao AS Huang Cardona Lavin

② All tree-level n -point YM

Pasterski Shao AS Cheung de la Fuente Sundrum Schreiber Volovich Zlotnik

Kinematic singularities @ 3 & 4 pt, 5+ are smooth.

MARGINALLY CONVERGENT

③ All n -point Einstein gravity
 ∞ !!!

DEFINES

Good UV behavior
"Baked-in".

④ String theory up to 4pt gauge + gravity

CONVERGENT

Stieberger Taylor

CONFORMALLY SOFT THEOREM

cf. Andrea

A conformally soft operator is one for which

Dormay Puhm AS

$$(h, \bar{h}) = (n, 0) \quad (\text{or } (0, n))$$

It is not energetically soft! Nevertheless it has been recently shown in gauge theory

$$\lim_{\lambda_n \rightarrow 0} A(\lambda_1 z_1, \dots, \lambda_n z_n) = -\frac{i}{\lambda_n} \sum_k \frac{1}{z_n - z_k} A(\lambda_1 z_1, \dots, \lambda_k z_k, \dots, \lambda_{n-1} z_{n-1})$$

Fan Fotopoulos Taylor, Puhm
Pete Raclariu AS

using UV convergence & usual soft thm.

Expected in conformal picture, surprising in momentum space picture. Subleading soft graviton \Rightarrow

$(2, 0)$ celestial stress tensor T_{ww} is a further example

SUPERTRANSLATIONS are more subtle. For gravity:

$$(h, \bar{h}) = \left(\frac{3}{2} + \frac{i\lambda}{2}, -\frac{1}{2} + \frac{i\lambda}{2} \right)$$

for $\lambda \rightarrow 0$

$$(h, \bar{h}) = \left(\frac{3}{2}, -\frac{1}{2} \right)$$

The associated operator P_z obeys

$$P_z(z) \mathcal{O}_{h, \bar{h}}(w) \sim \frac{1}{z-w} \mathcal{O}_{h+\frac{1}{2}, \bar{h}+\frac{1}{2}} !$$

∞ constraints on amplitudes/OPEs correlators. Even global translations nontrivial. Illustration...

YM + + + OPE from asymptotic symmetries

M. Pate
A. Raclariu
A.S.
E. Yuan
Fan Fotopoulos
Stieberger Taylor

collinear singularity

$$\mathcal{O}_{h_1}^{+a}(z_1) \mathcal{O}_{h_2}^{+b}(z_2) \sim \frac{B(h_1, h_2)}{z_1 - z_2} f^{+abc} \mathcal{O}_{h_1+h_2-1}^{+c}(z_2)$$

Global translation invariance requires

$$B(h_1, h_2) = B(h_1 + \frac{1}{2}, h_2) + B(h_1, h_2 + \frac{1}{2})$$

Subleading soft symmetry requires ($h_1 = 0$ pole)

$$(2h_1 - 3) B(h_1 - \frac{1}{2}, h_2) = (2h_2 - 3) B(h_1, h_2 - \frac{1}{2})$$

These two recursion relations, together with $h \rightarrow \infty$ falloff, imply the OPE coefficient

$$B(h_1, h_2) = B(2h_1 - 2, 2h_2 - 2) \quad B(x, y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$$

in agreement w/ direct Mellin transform of collinear singularities. Fan Fotopoulos Taylor

In fact, all the

The mixed helicity gluon OPEs are

$$\begin{aligned}
 O_{\Delta_1}^{+a,\epsilon}(z_1, \bar{z}_1) O_{\Delta_2}^{-b,\epsilon}(z_2, \bar{z}_2) &\sim \frac{-if_c^{ab}}{z_{12}} \epsilon B(\Delta_1 - 1, \Delta_2 + 1) O_{\Delta_1 + \Delta_2 - 1}^{-c,\epsilon}(z_2, \bar{z}_2) \\
 &\quad + \frac{\kappa \bar{z}_{12}}{2 z_{12}} \delta^{ab} B(\Delta_1, \Delta_2 + 2) G_{\Delta_1 + \Delta_2}^{-,\epsilon}(z_2, \bar{z}_2), \\
 O_{\Delta_1}^{+a,\epsilon}(z_1, \bar{z}_1) O_{\Delta_2}^{-b,-\epsilon}(z_2, \bar{z}_2) &\sim \frac{-if_c^{ab}}{z_{12}} \epsilon [-B(\Delta_2 + 1, 1 - \Delta_1 - \Delta_2) O_{\Delta_1 + \Delta_2 - 1}^{-c,\epsilon}(z_2, \bar{z}_2) \\
 &\quad + B(\Delta_1 - 1, 1 - \Delta_1 - \Delta_2) O_{\Delta_1 + \Delta_2 - 1}^{-c,-\epsilon}(z_2, \bar{z}_2)] \\
 &\quad + \frac{\kappa \bar{z}_{12}}{2 z_{12}} \delta^{ab} [B(\Delta_2 + 2, -1 - \Delta_1 - \Delta_2) G_{\Delta_1 + \Delta_2}^{-,\epsilon}(z_2, \bar{z}_2) \\
 &\quad + B(\Delta_1, -1 - \Delta_1 - \Delta_2) G_{\Delta_1 + \Delta_2}^{-,-\epsilon}(z_2, \bar{z}_2)].
 \end{aligned} \tag{106}$$

The graviton OPEs are

$$\begin{aligned}
 G_{\Delta_1}^{+,\epsilon}(z_1, \bar{z}_1) G_{\Delta_2}^{\pm,\epsilon}(z_2, \bar{z}_2) &\sim -\frac{\kappa \bar{z}_{12}}{2 z_{12}} B(\Delta_1 - 1, \Delta_2 + 1 \mp 1) G_{\Delta_1 + \Delta_2}^{\pm,\epsilon}(z_2, \bar{z}_2), \\
 G_{\Delta_1}^{+,\epsilon}(z_1, \bar{z}_1) G_{\Delta_2}^{\pm,-\epsilon}(z_2, \bar{z}_2) &\sim \frac{\kappa \bar{z}_{12}}{2 z_{12}} [B(\Delta_2 + 1 \mp 2, 1 \pm 2 - \Delta_1 - \Delta_2) G_{\Delta_1 + \Delta_2}^{\pm,\epsilon}(z_2, \bar{z}_2) \\
 &\quad + B(\Delta_1 - 1, 1 \pm 2 - \Delta_1 - \Delta_2) G_{\Delta_1 + \Delta_2}^{\pm,-\epsilon}(z_2, \bar{z}_2)].
 \end{aligned} \tag{107}$$

The gluon-graviton OPEs are

$$\begin{aligned}
 G_{\Delta_1}^{+,\epsilon}(z_1, \bar{z}_1) O_{\Delta_2}^{\pm a,\epsilon}(z_2, \bar{z}_2) &\sim -\frac{\kappa \bar{z}_{12}}{2 z_{12}} B(\Delta_1 - 1, \Delta_2 + 1 \mp 1) O_{\Delta_1 + \Delta_2}^{\pm a,\epsilon}(z_2, \bar{z}_2), \\
 G_{\Delta_1}^{+,\epsilon}(z_1, \bar{z}_1) O_{\Delta_2}^{\pm a,-\epsilon}(z_2, \bar{z}_2) &\sim -\frac{\kappa \bar{z}_{12}}{2 z_{12}} [B(\Delta_2 + 1 \mp 1, 1 \pm 1 - \Delta_1 - \Delta_2) O_{\Delta_1 + \Delta_2}^{\pm a,\epsilon}(z_2, \bar{z}_2) \\
 &\quad - B(\Delta_1 - 1, 1 \pm 1 - \Delta_1 - \Delta_2) O_{\Delta_1 + \Delta_2}^{\pm a,-\epsilon}(z_2, \bar{z}_2)].
 \end{aligned} \tag{108}$$

From (8), we recall a factor of g_{YM} is absorbed in f_c^{ab} . The $\bar{z}_{12} \rightarrow 0$ celestial OPEs are obtained in a similar way by imposing the δ symmetry instead.

The presence of higher-dimension operators due to quantum, stringy or other corrections is expected to augment this list with the finite number of additions allowed by the general formula (13). A list of all possible corrections in theories with only gluons and gravitons is given in appendix B.

Acknowledgements

Pate, Ractaru, AS Yuan

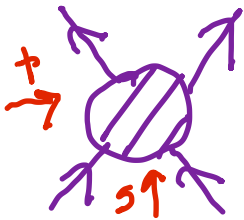
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Analyticity, Factorization & IR Safety on the Celestial Sphere

Arkani-Hamed, Pate, Raclariu & AS, to appear

Start w/ tree 4-pt:



$$A(s, t) \xrightarrow{s \rightarrow \infty} e^{-s \text{BH}} \sim e^{-s}$$

exponentially soft due to BHs

$$\underset{s \rightarrow 0}{=} \sum_P s^P a_P(z); z = \frac{t}{s}$$

conformal cross ratio

\mathcal{L}_{eff} , EFT hedron coefficients

Arkani-Hamed, Huang & Huang

$$\tilde{A}(\Delta, z) = \int ds s^{\Delta-3} A(s, z) \sim \sum_P \frac{a_P(z)}{\Delta - 4 + 2P} + \text{finite}$$

Celestial tree amplitudes are meromorphic in Δ with poles at even negative integers! Residues = coefficients of \mathcal{L}_{eff} /EFT hedron with rich positivity constraints.

Quantum Theory

i) UV behavior still soft, divergences in $\tilde{A}(\Delta, z)$ all from IR - still meromorphic

ii) IR divergences w/ logs in exclusive $A(s, t) \sim \frac{s^2}{t} \ln \frac{s}{\Lambda_{IR}} + \dots$
regulator required

iii) logs controlled by soft theorem. For QED/photons:

$$A(p_i, Q_i) = e^{-\Gamma \sum_{i,j} Q_i Q_j \ln(p_i \cdot p_j)} A_{\text{hard}}; \quad \Gamma = \frac{e^2}{4\pi} \ln \frac{\Lambda_{UV}}{\Lambda_{IR}} \quad \begin{array}{l} \text{cusp} \\ \text{anomalous} \\ \text{dimension} \end{array}$$

iv) Transforming to celestial sphere

$$\tilde{A}(z_i, \Delta_i) = \tilde{A}_{\text{soft}} + \tilde{A}_{\text{hard}}(z_i, \Delta_i - \Gamma Q_i^2); \quad \tilde{A}_{\text{soft}} = \prod_{i,j} |z_i - z_j|^{-\Gamma Q_i \cdot Q_j}$$

↙ shift in dimension

reveals exact current algebra factorization

v) \tilde{A}_{hard} are nothing but the IR safe scattering amplitudes w/ unique conformal primary Faddeev-Kulish dressings!!

SIM. FOR GRAVITY, WITH $Q_i \rightarrow P_i$, $\tilde{A}_{\text{soft}} \rightarrow \text{operator!}$

In order to ask if BH S-matrix is unitary, must have an S-matrix!

MORE
COOL STUFF!

To add to / echo Shiraz, Nima, ...

What is the most general form of the graviton 4pt amplitude consistent with

0. Shiraz's constraints

1. Conformal invariance

2. Supertranslation invariance

3. Causality

4. Crossing symmetry

5. Subsubleading soft symmetries

6.

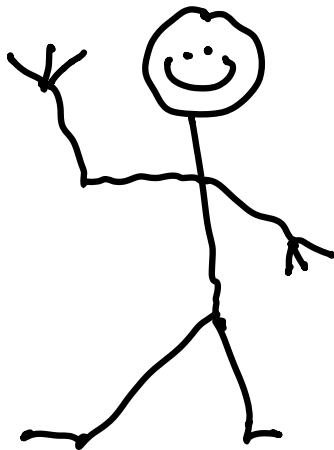


Does it look like string scattering?

CONCLUSION

The reformulation of Minkowski scattering as correlators on the celestial sphere is leading to novel insights. There is much to understand.

Thank you
for listening!



What does it mean to 'solve' the BH info. paradox?

info storage & retrieval paradoxes

My view!



- (i) No specific microphysical assumptions such as string theory. General ones OK: symmetries, Boltzmann's molecules, ... etc.
- (ii) Microscopic derivation of Schwarzschild entropy & universality of area law (+ log corrections) (c.f. Boltzmann)
- (iv) Microscopic derivation of inf. flux at \mathcal{I}^+ (Page curve?, logs...)

No guarantee this is possible, but not ruled out!