Celestial holography on non-trivial backgrounds

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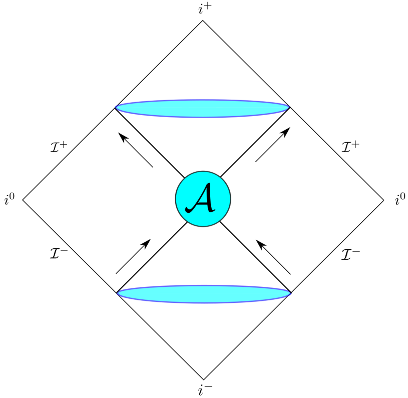
Content

Motivation and introduction (I)

- Scattering amplitudes are at the heart of most of the developments in celestial holography in flat space ...



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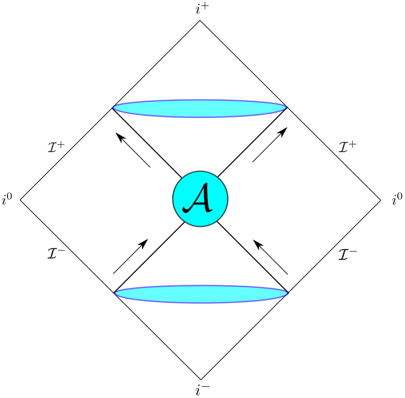
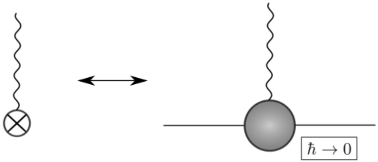


- what can they teach us about asymptotically flat backgrounds?

Motivation and introduction (II)

- Question 1: Universal (point-like and plane-wave) backgrounds do have a classical amplitude-like interpretation, is there a simple dual description?



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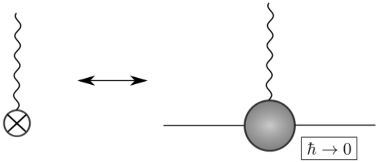

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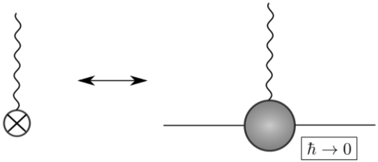

- Question 2: Can we interpret the scattering on these backgrounds as conformal correlators?

- Question 3: Can we define infrared-finite amplitudes on backgrounds?

Perturbiner method and two-point amplitudes

- Framework: Perturbiner method in QFT. Tree-level amplitudes can be computed perturbatively using the classical eoms

$$Z[J] = \int \mathcal{D}\Phi e^{i(S[\Phi]+J\Phi)} \to \Phi_{cl}[J] = \frac{\delta W[J]}{\delta J}.$$

The two-point amplitude is defined as

$$\boxed{A_2(p_1,p_2) = -\prod_{k=1}^{2}(\lim_{p_k^2\to 0} p_k^2)\ \frac{\delta}{\delta J(p_1)}\bar{\Phi}_{cl}(-p_2)\Big|_{J=0}\,,}$$

which we can formally transform into the celestial basis

$$\begin{aligned}\widetilde{A}_2(\Delta_1,\Delta_2) &= \prod_{i=1}^{2}\left[\int d\omega_i\,\omega_i^{\Delta_i-1}\right] A_2(p_1,p_2)\\ &= \langle \mathcal{O}^{\eta_1}_{\Delta_1}(z_1,\bar{z}_1)\mathcal{O}^{\eta_2}_{\Delta_2}(z_2,\bar{z}_2)\rangle_{\mathrm{CCFT}}\,.\end{aligned}$$

The boundary on-shell action in ASF spacetimes (I)

- As in AdS/CFT, we expect that the generating functional of the dual tree-level correlators

$$\mathcal{Z}_{\text{boundary}} \overset{\text{saddle point}}{\sim} e^{i\mathcal{S}_{\text{on-shell}}}$$

is entirely captured by the on-shell action. But how exactly?

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- Consider the on-shell massless scalar action for an ASF background $g^{\mu\nu}$

$$\mathcal{S}_{\text{bdy}} \equiv - \int \mathrm{d}^4 x \sqrt{-g} \nabla_\mu [\phi^*(x) g^{\mu\nu} \nabla_\nu \phi(x)] \,,$$

and expand around $\mathcal{I}^\pm$ [Fabbrichesi, Pettorini, Veneziano, Vilkovisky]

$$\mathcal{S}_{\mathcal{I}^- \cup \mathcal{I}^+} = - \lim_{r\to\infty} r^2 \int d\Omega \left[\int_{-\infty}^{+\infty} du \left(\phi^* n^+_\mu \partial^\mu \phi \right) + \int_{-\infty}^{+\infty} dv \left(\phi^* n^-_\mu \partial^\mu \phi \right) \right]$$

where $n^+_\mu = \partial_\mu \left(\frac{v}{2} \right)$ and $n^-_\mu = \partial_\mu \left(-\frac{u}{2} \right)$.

The boundary on-shell action in ASF spacetimes (II)

- We can recast the perturbative wave equation in terms of an effective source

$$\eta^{\mu\nu}\partial_\mu\partial_\nu\phi(x) = J_{\text{eff}}(x)$$

and we expand the field as

$$\phi = \phi_{\text{in}} + \phi_{\text{out}}\,, \quad \phi_{\text{in}} = e^{ip\cdot x}\,, \phi_{\text{out}}\Big|_{\mathcal{I}^\pm} \sim \frac{c_\pm}{r}\int_{\mathbb{R}} d\omega_k\, e^{\mp i\omega_k(t\mp r)}\,\tilde{J}_{\text{eff}}(\pm\omega_k, \omega_k\hat{x})\,,$$

where $c_\pm$ are related to the choice of retarded/advanced boundary conditions.

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where $c_\pm$ are related to the choice of retarded/advanced boundary conditions.

- We find that the boundary term localizes at large radial distances

$$\mathcal{S}^{\text{in/out}}_{\mathcal{I}^-\cup\mathcal{I}^+}(p) = \left(\frac{c_+ + c_-}{2}\right)\bar{J}_{\text{eff}}(\omega, \omega\hat{p})\,,$$

which means that

$$\boxed{A_2(p_1,p_2) = \lim_{p_1^2\to 0}\lim_{p_2^2\to 0} p_2^2\,\frac{\delta\left[\left(\frac{2}{c_+ + c_-}\right)\mathcal{S}^{\text{in/out}}_{\mathcal{I}^-\cup\mathcal{I}^+}(-p_1)\right]}{\delta\bar{J}(p_2)}\,.}$$

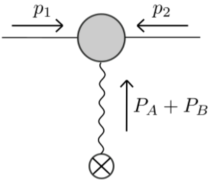
Tree-level scattering on point-like backgrounds (I)

- The leading order 2-pt amplitude is proportional to the Fourier transform of the potential: for minimally coupled massless scalar fields, in EM we get

$$\mathcal{A}_2^{(1)}(p_1, p_2) = e(p_1 - p_2)_\mu \bar{A}^\mu(p_1 + p_2)$$

while in GR

$$\mathcal{M}_2^{(1)}(p_1, p_2) = -\left[(p_1)_\mu (p_2)_\nu - \tfrac{1}{2}\eta_{\mu\nu}(p_1 \cdot p_2)\right] \bar{h}^{\mu\nu}(p_1 + p_2)\,.$$



Tree-level scattering on point-like backgrounds (II)

- The 2-pt amplitude on a point-like EM background is given by

$$\mathcal{A}_2^{(1)}(p_1, p_2) = 2\pi e Q \frac{(p_1 - p_2) \cdot u}{(p_1 + p_2)^2} \delta((p_1 + p_2) \cdot u) \ ,$$

where $u^\mu = (1, 0, 0, 0)$ for Coulomb, $u^\mu = (1, 0, 0, 1)$ for the EM shockwave.

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- Similarly in GR the 2-pt amplitude on a point-like background is

$$\mathcal{M}_2^{(1)}(p_1, p_2) = -32\pi^2 G r_0 \frac{(p_1 \cdot u)(p_2 \cdot u)\delta((p_1 + p_2) \cdot u)}{(p_1 + p_2)^2}.$$

where $u^\mu = (1, 0, 0, 0)$, $r_0 = M$ for Schwarzschild, $u^\mu = (1, 0, 0, 1)$,$r_0 = P^+$ for the Aichelburg-Sexl solution.

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- Remark: alternative derivation by a suitable matching with the 4-pt eikonal amplitude in flat space [t'Hooft;Adamo,Cristofoli,Tourkine]

Tree-level scattering on point-like backgrounds (III)

- The corresponding celestial 2-pt amplitude can be written as

$$\widetilde{\mathcal{A}}^{(1)}_{2,shockwave}(\Delta_1,\Delta_2) = \frac{\pi e Q}{|z_{12}|^2}\left(\frac{|z_1|^2}{|z_2|^2}\right)^{\Delta_2-1}\mathcal{I}(\Delta_1+\Delta_2-2),$$

$$\widetilde{\mathcal{A}}^{(1)}_{2,Coulomb}(\Delta_1,\Delta_2) = \frac{\pi e Q}{|z_{12}|^2}\left(\frac{1+|z_1|^2}{1+|z_2|^2}\right)^{\Delta_2-1}\mathcal{I}(\Delta_1+\Delta_2-2),$$

$$\widetilde{\mathcal{M}}^{(1)}_{2,shockwave}(\Delta_1,\Delta_2) = \frac{16\pi^2 G P^+}{|z_{12}|^2}|z_2|^2\left(\frac{|z_1|^2}{|z_2|^2}\right)^{\Delta_2}\mathcal{I}(\Delta_1+\Delta_2-1),$$

$$\widetilde{\mathcal{M}}^{(1)}_{2,Schwarzschild}(\Delta_1,\Delta_2) = \frac{8\pi^2 G M}{|z_{12}|^2}(1+|z_2|^2)\left(\frac{1+|z_1|^2}{1+|z_2|^2}\right)^{\Delta_2}\mathcal{I}(\Delta_1+\Delta_2-1)\,,$$

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$$\mathcal{I}(s) \equiv \int_0^\infty d\omega\,\omega^{s-1}\,.$$

- Note: striking power-law behaviour in z_{12} and no kinematic delta function!

Shock-wave correlators on the CCFT (I)

- The EM (resp.GR) shockwave corresponds to a generalised conformal vector (resp. metric) primary in the CCFT [Pasterski,Puhm]

$$A^{\mu}_{\Delta=0,J=0}(x;z_{\mathrm{sw}}) = q^{\mu}_{\mathrm{sw}}\phi_{\Delta=1}(x;z_{\mathrm{sw}})\,,\;\; h^{\mu\nu}_{\Delta=-1,J=0}(x;z_{\mathrm{sw}}) = q^{\mu}_{\mathrm{sw}}q^{\nu}_{\mathrm{sw}}\phi_{\Delta=1}(x;z_{\mathrm{sw}})\,,$$
$$\phi_{\Delta=1}(x;z_{\mathrm{sw}}) = \log x^2\delta(q_{\mathrm{sw}}\cdot x)\,,$$

with a reference null vector q_{sw}

$$q^{\mu}_{\mathrm{sw}} = (1+|z_{\mathrm{sw}}|^2, z_{\mathrm{sw}}+\bar{z}_{\mathrm{sw}}, i(\bar{z}_{\mathrm{sw}}-z_{\mathrm{sw}}), 1-|z_{\mathrm{sw}}|^2)\;.$$

What does this imply?

Shock-wave correlators on the CCFT (II)

- Idea: write the shockwave wavefunction in the plane-wave basis

$$A^{\mu}_{\rm sw}(x;q_{\rm sw}) = 8\pi^2 Q q^{\mu}_{\rm sw} \int \frac{d^4p}{(2\pi)^4} \frac{\delta(p\cdot q_{\rm sw})}{p^2} e^{ip\cdot x} \,.$$

and contract it with the 3-pt form factor

$$\mathcal{A}_{3;\mu}(p_1,p_2,p) = \left\langle p_1 \left| \tilde{j}_{\mu}(p) \right| p_2 \right\rangle = e(2\pi)^4 \delta^{(4)}(p_1+p_2+p)(p_{1\mu}-p_{2\mu}) \,.$$

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- In the celestial basis we get

$$\begin{aligned}\widetilde{\mathcal{A}}_3(\Delta_1, \Delta_2, \Delta_{\rm sw} = 0) &\equiv 2\prod_{i=1}^{2}\left[\int d\omega_i \omega_i^{\Delta_i - 1}\right] \int \frac{d^4 p}{(2\pi)^2} \frac{\delta(p\cdot q_{\rm sw})}{p^2} q_{\rm sw}\cdot \mathcal{A}_3(p_1, p_2, p) \\ &= \frac{eQ(2\pi)^3 \boldsymbol{\delta}(i(\Delta_1 + \Delta_2 - 2))}{|z_{12}|^{\Delta_1+\Delta_2} |z_{1\rm sw}|^{\Delta_1 - \Delta_2} |z_{2\rm sw}|^{\Delta_2 - \Delta_1}} \\ &= \widetilde{\mathcal{A}}^{(1)}_{2,shockwave}(\Delta_1, \Delta_2)\end{aligned}$$

The 2-pt amplitude on a shock-wave background can be interpreted as a standard 3-pt CFT correlator with a shock-wave operator insertion!

Scattering on spinning backgrounds and finite-size effects

- Spinning backgrounds have an additional length scale set by the spin parameter a. How does that affect the description in the celestial basis?

Scattering on spinning backgrounds and finite-size effects

- Spinning backgrounds have an additional length scale set by the spin parameter a. How does that affect the description in the celestial basis?
- The 2-pt amplitude for the spinning GR shock-wave solution

$$h_{\mathrm{ssw}}^{\mu\nu} = -q_{\mathrm{sw}}^{\mu} q_{\mathrm{sw}}^{\nu} P^{+} \delta(q_{\mathrm{sw}} \cdot x) \log\left(x^2 - a^2\right)$$

is given by

$$\widetilde{\mathcal{M}}_{2,ssw}^{(1)}(\Delta_1, \Delta_2) = 16\pi^2 G P^{+} \frac{a^{1-\Delta_1-\Delta_2}}{|z_{12}|^{\Delta_1+\Delta_2+1}} |z_2|^2 \left(\frac{|z_1|^2}{|z_2|^2}\right)^{\frac{\Delta_2-\Delta_1+1}{2}} \mathcal{I}'(\Delta_1+\Delta_2-1)$$

$$\mathcal{I}'(s) = -\frac{i\pi}{2} \frac{\Gamma(1+s/2)}{\Gamma(1-s/2)} \left(1 + i\cot(\pi s/2)\right), \quad 0 < \mathrm{Re}(s) < \tfrac{1}{2}.$$

The celestial amplitude is well-defined (away from the principal series) because spin provides a natural regulator for UV physics!

IR-finite S-matrix on asymptotically flat backgrounds (I)

- It is instructive to revisit the problem of infrared divergences with the perturbiner method: the iteration of eoms gives, in GR,

$$\bar{\phi}(p) = \frac{-1}{p^2} \sum_{n=0}^{\infty} \int \prod_{\ell=1}^{n} \frac{d^4 k^{(\ell)}}{(2\pi)^4} \frac{\mathcal{M}_2'(p, -k^{(1)})}{k^{(1)2}} \dots \frac{\mathcal{M}_2'(k^{(n-1)}, -k^{(n)})}{k^{(n)2}} \bar{J}(k^{(n)})$$

and in the infrared soft region we find the famous Wilson line exponentiation

$$\mathcal{M}_2^{con,IR}(p_1, p_2) = \exp\Big[- \int \frac{d^4 k}{(2\pi)^4} \frac{\bar{h}^{\mu\nu}(-k) p_{2\mu} p_{2\nu}}{2k \cdot p_2} \Big] \mathcal{M}_2^{(1)}(p_1, p_2) \; .$$

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- For point-like backgrounds (like Schwarzschild and Aichelburg-Sexl) we get an IR-divergent phase [Weinberg]

$$- \int \frac{d^4 k}{(2\pi)^4} \frac{\bar{h}^{\mu\nu}(-k) p_{2\mu} p_{2\nu}}{2k \cdot p_2} = - \frac{i(p_2 \cdot u) G r_0}{\epsilon}$$

  which can be removed by a suitable dressing as in the flat space S-matrix!

IR-finite S-matrix on asymptotically flat backgrounds (II)

- Focus on the 2-pt amplitude in the shock-wave background. We can define the Goldstone bosons $C^{\pm}(z,\bar{z})$, for incoming $(-)$ or outgoing $(+)$ particles, which have the 2-pt function [Himwich, Narayanan, Pate, Paul, Strominger]

$$\langle C^{\eta_i}(z_i,\bar{z}_i)C^{\eta_j}(z_j,\bar{z}_j)\rangle = -\frac{\eta_i\eta_j}{4\pi^2\epsilon}|z_{ij}|^2(\ln|z_{ij}|^2 - i\pi\delta_{\eta_i,\eta_j}) \, .$$

The IR divergences are then captured by the correlation function

$$\langle e^{iR^{\mathrm{GR}}_{\mathrm{sw}}} e^{iR_1^{-,\mathrm{GR}}} e^{iR_2^{+,\mathrm{GR}}}\rangle \, ,$$

$$R^{\mathrm{GR}}_{\mathrm{sw}} = \frac{\kappa P^+}{4}(C^+(z_{\mathrm{sw}},\bar{z}_{\mathrm{sw}}) + C^-(z_{\mathrm{sw}},\bar{z}_{\mathrm{sw}})) \, , \qquad R_k^{\pm,\mathrm{GR}} = \frac{\kappa}{2}\omega_k C^{\pm}(z_k,\bar{z}_k) \, .$$

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- We can then define dressed operators

$$\hat{\mathcal{O}}^{\pm}_{\Delta_k}(z_k,\bar{z}_k) = e^{-iR_k^{\pm,\text{GR}}}\mathcal{O}^{\pm}_{\Delta_k}(z_k,\bar{z}_k)\,, \quad \hat{\mathcal{O}}_{\Delta_{\text{sw}}}(z_{\text{sw}},\bar{z}_{\text{sw}}) = e^{-iR_{\text{sw}}^{\text{GR}}}\mathcal{O}_{\Delta_{\text{sw}}}(z_{\text{sw}},\bar{z}_{\text{sw}})\,,$$

so that we get an IR finite two-point amplitude defined as

$$\boxed{\widetilde{\mathcal{M}}_{2,sw}^{\text{dressed}} = \langle\hat{\mathcal{O}}_{\text{sw}}(z_{\text{sw}},\bar{z}_{\text{sw}})\hat{\mathcal{O}}^-_{\Delta_1}(z_1,\bar{z}_1)\hat{\mathcal{O}}^+_{\Delta_2}(z_2,\bar{z}_2)\rangle \ .}$$

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- New insights on the definition of an infrared finite S-matrix on backgrounds: there exists a universal dressing which removes the infrared divergent phase
- We have just began to explore the structure of amplitude on backgrounds from the celestial perspective, lots more to be understood! (spinning external fields, massive backgrounds, dilaton backgrounds [Fan, Fotopoulos, Stieberger, Taylor, Zhu], connection with AdS/CFT [Pipolo de Gioia, Raclariu; Casali, Melton, Strominger],...)