Graviton scattering in a self-dual gravitational wave

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QCD Meets Gravity

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work in progress with L. Mason & A. Sharma
see also work with A. Ilderton

Reminder:

Graviton scattering in Minkowski space:

At tree-level, we know everything

$$M_n^{(0)} = \delta^d\left(\sum_{i=1}^{n} k_i\right) \int \mathrm{d}\mu_n \prod_{j=1}^{n} \delta(\mathcal{S}_j)\, \mathrm{Pf}'(M)\, \mathrm{Pf}'(\tilde{M})$$

[Cachazo-He-Yuan]

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[Cachazo-He-Yuan]

In 4d, refined by N^{d-1}MHV degree:

$$M_{n,d}^{(0)} = \int \frac{\mathrm{d}^{4|8(d+1)}\mathcal{Z}}{\mathrm{vol}\,\mathrm{GL}(2,\mathbb{C})} \det{}'(\mathbb{H}) \det{}'(\mathbb{H}^\vee) \prod_{i=1}^n h_i$$

[Cachazo-Skinner]

Curved space-times?

We know **very** little, even in simple space-times

- Plane waves: 3-points [TA-Casali-Mason-Nekovar, TA-Ilderton]
- pp-waves: 3-points [Constable-et al., Spradlin-Volovich]
- AdS: 5-points [Gonclaves-Pereira-Zhou]

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Big knowledge gap vs. flat space!

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Seems hard...

- Background field Einstein-Hilbert Lagrangian a nightmare
- *Functional* degrees of freedom in the background
- No 4-momentum conservation
- No Huygens' principle $\Rightarrow$ tails [Friedlander, Harte, TA-Casali-Mason-Nekovar]
- Memory effect [Christodoulou, Bieri-Garfinkle-Yau,...]

However...

Some reasons to be optimistic:

- Explicit solutions in momentum basis [Ward, Mason, TA-Casali-Mason-Nekovar]
- Explicit Feynman rules [Gibbons, TA-Casali-Mason-Nekovar, Nekovar]
- Some on-shell methods still work: spinor-helicity [TA-Ilderton]

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and...

further simplification possible!

Self-dual plane waves

Positive helicity GW; one functional degree of freedom:

$$
\begin{aligned}
\mathrm{d}s^2 &= 2\left(\mathrm{d}x^+\,\mathrm{d}x^- - \mathrm{d}z\,\mathrm{d}\tilde{z} + f(x^-)\,\mathrm{d}\tilde{z}^2\right) \\
&= \epsilon_{\alpha\dot{\alpha}}\,\epsilon_{\beta\dot{\beta}}\left(\mathrm{d}x^{\alpha\dot{\alpha}} + f(x^-)\,o^{\alpha}\tilde{\iota}^{\dot{\alpha}}\mathrm{d}\tilde{z}\right)\left(\mathrm{d}x^{\beta\dot{\beta}} + f(x^-)\,o^{\beta}\tilde{\iota}^{\dot{\beta}}\mathrm{d}\tilde{z}\right)
\end{aligned}
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$$= \epsilon_{\alpha\dot{\alpha}}\,\epsilon_{\beta\dot{\beta}}\left(\mathrm{d}x^{\alpha\dot{\alpha}} + f(x^-)\,o^\alpha\tilde{\iota}^{\dot{\alpha}}\mathrm{d}\tilde{z}\right)\left(\mathrm{d}x^{\beta\dot{\beta}} + f(x^-)\,o^\beta\tilde{\iota}^{\dot{\beta}}\mathrm{d}\tilde{z}\right)$$

- Covariantly constant null Killing vector:
  $n = \iota^\alpha\,\tilde{\iota}^{\dot{\alpha}}\partial_{\alpha\dot{\alpha}} = \partial_+$
- Vacuum-flat, self-dual Weyl curvature:
  $\widetilde{\Psi}_{\dot{\alpha}\dot{\beta}\dot{\gamma}\dot{\delta}} = -\ddot{f}(x^-)\,\tilde{\iota}_{\dot{\alpha}}\tilde{\iota}_{\dot{\beta}}\tilde{\iota}_{\dot{\gamma}}\tilde{\iota}_{\dot{\delta}}$
- Holomorphic frame for SD spin bundle:
  $H^{\dot{\alpha}}{}_{\dot{\beta}}(x,\lambda) = \delta^{\dot{\alpha}}_{\dot{\beta}} - \frac{\langle o\,\lambda\rangle}{\langle \iota\,\lambda\rangle} f\,\tilde{\iota}^{\dot{\alpha}}\tilde{\iota}_{\dot{\beta}}$
- $\ddot{f}(x^-)$ compactly supported $\leftrightarrow$ well-defined S-matrix

[Gibbons, TA-Casali-Mason-Nekovar]

SDPW Kinematics

Graviton pert.s in SDPWs have *chiral* kinematics

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Graviton with incoming momentum $k_{\alpha\dot{\alpha}} = \kappa_\alpha \tilde{\kappa}_{\dot{\alpha}}$: $\mathcal{E}^{(\pm)}_{\mu\nu}\, \mathrm{e}^{\mathrm{i}\phi_k}$,

$$\phi_k = k \cdot x + \frac{k_z^2}{k_+} \int^{x^-} \mathrm{d}t\, f(t) := \langle \kappa | x | \tilde{\kappa}] + \frac{\langle o\, \kappa \rangle^2\, [\tilde{\iota}\, \tilde{\kappa}]}{\langle \iota\, \kappa \rangle}\, \mathcal{F}(x^-)$$

Dressed momentum & polarizations:

$$\kappa_\alpha\, \tilde{K}_{\dot{\alpha}}(x^-)\,, \qquad \tilde{K}_{\dot{\alpha}} := H^{\dot{\beta}}{}_{\dot{\alpha}}(x,\kappa)\tilde{\kappa}_{\dot{\beta}} = \tilde{\kappa}_{\dot{\alpha}} - \frac{\langle o\, \kappa \rangle\, [\tilde{\iota}\, \tilde{\kappa}]}{\langle \iota\, \kappa \rangle}\, \tilde{\iota}_{\dot{\alpha}}\, f$$

$$\mathcal{E}^{(-)}_{\alpha\dot{\alpha}\beta\dot{\beta}} = \frac{\kappa_\alpha \kappa_\beta\, \tilde{\iota}_{\dot{\alpha}} \tilde{\iota}_{\dot{\beta}}}{[\tilde{\iota}\, \tilde{\kappa}]^2}\,,$$

$$\mathcal{E}^{(+)}_{\alpha\dot{\alpha}\beta\dot{\beta}} = \frac{\iota_\alpha \iota_\beta}{\langle \iota\, \kappa \rangle^2} \left(\tilde{K}_{\dot{\alpha}} \tilde{K}_{\dot{\beta}} - \mathrm{i}\, \dot{f}\, \tilde{\iota}_{\dot{\alpha}} \tilde{\iota}_{\dot{\beta}} \right)$$

Basic idea

Use *twistor theory* to trivialize SDPW background & encode graviton fluctuations

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- Encode integrability of SD sector
- Use twistor string to compute amplitudes

Twistor theory

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A 3d complex manifold, which:

- is a $\mathbb{C}$-deformation of (open regions of) $\mathbb{CP}^3$
- contains a 4-parameter family of rational curves $X \cong \mathbb{CP}^1$, with $N_X \cong \mathcal{O}(1) \oplus \mathcal{O}(1)$

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Theorem (Penrose)

There is a 1:1 correspondence between Ricci-flat SD 4-manifolds $\mathscr{M}$ and $\mathbb{P}\mathscr{T}$ which admit a fibration $\mathbb{P}\mathscr{T} \to \mathbb{CP}^1$

In real money:

SDPW described by $\mathbb{P}\mathscr{T}$ with complex structure $\bar{\nabla} = \bar{\partial} + V$ obeying $\bar{\nabla}^2 = 0$

Let $(\mu^{\dot{\alpha}}, \lambda_\alpha)$ be homog. coords on $\mathbb{P}\mathscr{T}$ [Sparling, Newman]

$$V = \frac{\partial \mathsf{h}}{\partial \mu_{\dot{\alpha}}} \frac{\partial}{\partial \mu^{\dot{\alpha}}}\,, \qquad \mathsf{h} = \int \frac{\mathrm{d}s}{s^3}\,\bar{\delta}^2(\iota - s\,\lambda) \int^{s[\mu\,\tilde{\iota}]} \mathrm{d}t\,\mathcal{F}(t)$$

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Fibration $\mathbb{P}\mathscr{T} \to \mathbb{CP}^1$: identify $[\lambda_\alpha] \in \mathbb{CP}^1$,

$$\mu^{\dot{\alpha}}|_X = F^{\dot{\alpha}}(x, \lambda) = x^{\alpha\dot{\alpha}} \, \lambda_\alpha + \frac{\langle o\,\lambda\rangle^2}{\langle \iota\,\lambda\rangle} \, \tilde{\iota}^{\dot{\alpha}} \, \mathcal{F}(x^-)$$

Twistor toolkit

Simple form of complex structure $\bar{\nabla}$:

- Easy to find explicit reps in $\bar{\nabla}$-cohomology
- $+$ helicity gravitons: $H^{0,1}_{\bar{\nabla}}(\mathbb{PT}, \mathcal{O}(2))$
- - helicity gravitons: $H^{0,1}_{\bar{\nabla}}(\mathbb{PT}, \mathcal{O}(-6))$

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OK, but...

how to actually compute amplitudes with this machinery?

Flat space reminder

Lesson from Minkowski space: [Cachazo-Skinner, Skinner]

- Tree-level GR amplitudes live on rational holomorphic curves in $\mathbb{CP}^3$
- N^kMHV degree related to degree of curve $d = k + 1$

$$Z^A(\sigma) = (\mu^{\dot{\alpha}}, \lambda_\alpha)(\sigma) = \mathcal{Z}^A_{\mathbf{a}_1 \cdots \mathbf{a}_d} \, \sigma^{\mathbf{a}_1} \cdots \sigma^{\mathbf{a}_d}$$

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N^{d-1}MHV amplitude of $\mathcal{N} = 8$ SUGRA:

$$M^{(0)}_{n,d} = \int \frac{\mathrm{d}^{4|8(d+1)}\mathcal{Z}}{\mathrm{vol}\,\mathrm{GL}(2,\mathbb{C})}\, \mathrm{det}'(\mathbb{H})\, \mathrm{det}'(\mathbb{H}^\vee) \prod_{i=1}^{n} h_i(Z(\sigma_i))$$

For h_i momentum eigenstates, no residual integrals!

Twistor string theory

Where did that formula come from?

Worldsheet action for holo. maps $Z : \Sigma \hookrightarrow \mathbb{CP}^{3|8}$

$$\frac{1}{2\pi}\int_\Sigma Y_I\,\bar{\partial}Z^I + \tilde{\rho}_I\,\bar{\partial}\rho^I + \text{ghosts}$$

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Vertex operators:

$$V = \int_\Sigma \delta^2(\gamma)\,h(Z)\,, \qquad \mathcal{V} = \int_\Sigma \left[Y\,\frac{\partial h}{\partial \mu}\right] + \left[\tilde\rho\,\frac{\partial}{\partial\mu}\left(\rho^I\,\frac{\partial h}{\partial Z^I}\right)\right]$$

Picture changing operators:

$$\Upsilon = \delta^2(\mu)\,\left(\langle\rho\,\lambda\rangle\,\tilde\rho_I\,Z^I + \cdots\right)$$

Tree-amps $\leftrightarrow$ correlators on $\Sigma \cong \mathbb{CP}^1$:

$$M^{(0)}_{n,d} = \left\langle \prod_{i=1}^{d+2} V_i \prod_{j=d+3}^{n} \mathcal{V}_j \prod_{k=1}^{d} \Upsilon_k \right\rangle$$

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Background-coupled twistor string: On Σ, $\bar{\partial} \to \bar{\nabla}$

Two important changes:

- Worldsheet OPEs: $Y_{\dot\alpha}(\sigma)\,\mu^{\dot\beta}(\sigma') \sim \frac{H_{\dot\alpha}{}^{\dot\gamma}(\sigma)\,H^{\dot\beta}{}_{\dot\gamma}(\sigma')}{(\sigma\,\sigma')}$
- Background vertex operators, U

Result

Need to sum over background VO insertions

$\rightarrow$ truncated by non-zero-mode saturation

$$M_{n,d}^{(0)} = \sum_{t=0}^{\infty} \left\langle \prod_{i=1}^{d+2} V_i \prod_{j=d+3}^{n} \mathcal{V}_j \prod_{k=1}^{d} \Upsilon_k \prod_{\mathrm{m}=1}^{t} U_{\mathrm{m}} \right\rangle =$$

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$$\delta\left(\sum_{i=1}^{n} k_{z\,i}\right) \int \frac{\mathrm{d}^{d+1} b\, \mathrm{d}^{d+1}\nu\, \mathrm{d}^d x}{\mathrm{vol}\, \mathrm{GL}(2,\mathbb{C})}\, J\, \delta^{1|8(d+1)}\left(\sum_{i=1}^{n} s_i\, [\tilde{\imath}\, i]\, \sigma_j^{\mathbf{a}(d)}\right)$$

$$\det{}'(\mathbb{H}^{\vee}) \sum_{t=0}^{\lfloor \frac{n-d-2}{2} \rfloor} \sum_{\mathbf{a}_1,\ldots,\mathbf{a}_t} \det{}'(\mathcal{H}[\mathbf{a}])$$

$$\times \prod_{i=1}^{n} \frac{\mathrm{d} s_i}{s_i^3} \bar{\delta}^2(\kappa_i - s_i\, \lambda(\sigma_i))\, \mathrm{e}^{\mathrm{i}\,\phi_i} \prod_{\mathrm{m}=1}^{t} \mathcal{T}_m$$

Ingredients

$\mathbf{a}_1, \ldots, \mathbf{a}_t$ a partition of $\{d+3, \ldots, n\}$, $|\mathbf{a}_\mathrm{m}| > 2$,

sum over $t \leftrightarrow$ *tail* contributions

$$\mathcal{T}_m := \frac{\mathrm{d}t_\mathrm{m}}{t_\mathrm{m}^3}\, \mathrm{D}\sigma_\mathrm{m}\, \bar{\delta}^2(\iota - t_\mathrm{m}\, \lambda(\sigma_\mathrm{m}))\, f^{(|\mathbf{a}_\mathrm{m}|-2)}(x, \sigma_\mathrm{m})$$

$\mathcal{H}[\mathbf{a}]$ a $(n+t) \times (n+t)$ matrix; example entries

$$i \neq j: \quad \mathbb{H}_{ij} = s_i s_j \frac{[\![i\, j]\!]}{(i\, j)}, \qquad \mathbb{H}_{\mathrm{mm}} = -t_\mathrm{m} \sum_{i \in \mathbf{a}_\mathrm{m}} s_i \frac{[\tilde{\iota}\, i]}{(\mathrm{m}\, i)} \prod_{k=1}^{d+1} \frac{(i\, k)}{(\mathrm{m}\, k)},$$

Reduced determinant:

$$\det{}'(\mathcal{H}[\mathbf{a}]) := \frac{\left|\mathcal{H}[\mathbf{a}]^{1\cdots d+2}_{1\cdots d+2}\right|}{|\sigma_1 \cdots \sigma_{d+2}|^2} \prod_{\mathrm{m}=1}^{t} \prod_{k=1}^{d+1} (\mathrm{m}\, k)^{|\mathbf{a}_\mathrm{m}|}$$

$J = J(b, \nu)$ Jacobian for reparam. of $\lambda_\alpha(\sigma)$ moduli

Gravitational Volkov exponent:

$$\phi_i := s_i \sum_{r=1}^{d} x_r \, \nu_r \, [\tilde{o}\, i] \, \mathfrak{s}_r(\sigma_i) + [\tilde{\iota}\, i] \, \mathcal{F}(x, \sigma_i)$$

where $\{s_r(\sigma)\}$ a basis of $H^0(\mathbb{CP}^1, \mathcal{O}(d))$.

So what?

Looks a bit of a mess, but...

- Surprising to find anything this explicit
- Better than expectations from background-coupled EH action:

$$2d - 1 \text{ vs. } n - 2 \text{ residual integrals}$$

- Impulsive limit $\rightarrow$ further simplification
- Can be generalised from SDPW to SD radiative space-times

Consistency checks

Background obstructs usual unitarity-based checks...

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...however:

- Background diffeo. invariant.
- Explicit checks at $n = 3, 4$
- Can prove formula in MHV ($d = 1$) sector
- Flat-background limit $\rightarrow$ Cachazo-Skinner formula
- Perturbative limit: $\mathcal{M}_{n,d}[\bar{\nabla}] \rightarrow \mathcal{M}_{n+1,d}[\bar{\partial}]$

Double copy?

Analogous formula for gluons in SDPW gauge field:

[TA-Mason-Sharma]

$$\delta\left(\sum_{i=1}^{n} k_{z\,i}\right)\int \frac{\mathrm{d}^{d+1}b\,\mathrm{d}^{d+1}\nu\,\mathrm{d}^{d}x}{\mathrm{vol}\,\mathrm{GL}(2,\mathbb{C})}\,J\,\delta^{1|4(d+1)}\left(\sum_{i=1}^{n} s_i\,[\tilde{\iota}\,i]\,\sigma_j^{\mathbf{a}(d)}\right)$$

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Explicit, all-multiplicity DC on a non-trivial background?

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...not sure we have optimal answer for RSVW and Cachazo-Skinner even in flat background

[Litsey-Stankowicz, Zhang, Geyer]

Questions

Many things to think about:

- Prove formula for arbitrary d
- Generalise to other SD backgrounds (dyons, instantons...)
- Non-chiral PWs
- Non-asymptotically flat backgrounds [TA-Mason, TA, Röhrig-Skinner, Eberhardt-Komatsu-Mizera]
- Background field effects for GW detectors