Title: From Gluon Scattering to Black Hole Orbits

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Abstract: The study of scattering amplitudes has uncovered extraordinary dualities linking real-world particles such as gravitons, gluons, and pions. We discuss how these developments have been amalgamated with classic tools from effective field theory to derive new results relevant to the search for gravitational waves at LIGO. This approach has produced now state-of-the-art results on conservative orbital dynamics of binary black holes in the post-Minkowskian expansion. We also comment on recent work extending this framework to include tidal effects and spin.

From Gluon Scattering to Black Hole Orbits

Cliff Cheung
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CC, Rothstein, Solon (1808.02489)
Bern, CC, Roiban, Shen, Solon, Zeng (1901.04424, 1901.01493)
CC, Solon (2003.08351, 2006.06665)

“ the theory ”

action

↓

amplitudes

“ the observables ”

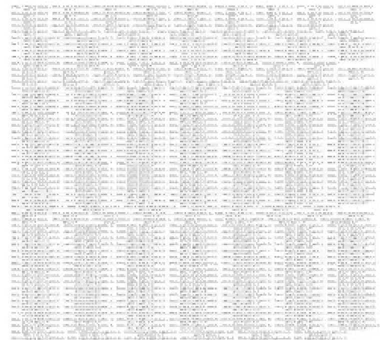
action

↑ *“ S-matrix program ”*

amplitudes

Gauge symmetry manifests Poincare invariance and locality at the cost of redundancy.

$$A(1^{h_1}2^{h_2}3^{h_3}4^{h_4}5^{h_5}) \quad = $$



Feynman diagrams
(*factorization manifest*)

$$A(1^+2^+3^+4^+5^+) \quad = \quad A(1^-2^+3^+4^+5^+) \quad = 0$$

$$A(1^-2^+3^-4^+5^+) \quad = \quad \frac{\langle 13\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle}$$

$$A(1^-2^-3^+4^+5^+) \quad = \quad \frac{\langle 12\rangle^3}{\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle}$$

modern tools
(*factorization obscure*)

Gravity suffers also, due to diffeomorphisms.

$$\frac{\delta^3 S}{\delta\varphi_{\mu\nu}\delta\varphi_{\sigma'\tau'}\delta\varphi_{\rho''\lambda''}} \longrightarrow$$

$$\mathrm{Sym}\Big[-\tfrac{1}{4}P_3(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda})-\tfrac{1}{4}P_6(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda})+\tfrac{1}{4}P_3(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda})+\tfrac{1}{2}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda})+P_3(p^\sigma p^\lambda\eta^{\mu\nu}\eta^{\tau\rho})$$
$$-\tfrac{1}{2}P_3(p^\tau p'^\mu\eta^{\nu\sigma}\eta^{\rho\lambda})+\tfrac{1}{2}P_3(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau})+\tfrac{1}{2}P_6(p^\rho p^\lambda\eta^{\mu\sigma}\eta^{\nu\tau})+P_6(p^\sigma p'^\lambda\eta^{\tau\mu}\eta^{\nu\rho})+P_3(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu})$$
$$-P_3(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu})\Big], \quad (2.6)$$

3pt graviton *vertex*

$$\frac{\delta^4 S}{\delta\varphi_{\mu\nu}\delta\varphi_{\sigma'\tau'}\delta\varphi_{\rho''\lambda''}\delta\varphi_{\iota'''\kappa'''}} \longrightarrow$$

$$\mathrm{Sym}\Big[-\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{8}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{4}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})+\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})$$
$$+\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{4}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{2}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})-\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})$$
$$+\tfrac{1}{4}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{24}(p^\sigma p^\tau\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{12}(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\iota\kappa})+\tfrac{1}{2}P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\lambda}\eta^{\iota\kappa})$$
$$-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu}\eta^{\iota\kappa})+\tfrac{1}{2}P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\nu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\sigma})$$
$$-P_{12}(p^\sigma p^\tau\eta^{\nu\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})-P_{12}(p^\rho p'^\lambda\eta^{\nu\iota}\eta^{\kappa\sigma}\eta^{\tau\mu})-P_{24}(p_\sigma p'^\rho\eta^{\tau\iota}\eta^{\kappa\mu}\eta^{\nu\lambda})-P_{12}(p^\rho p'^\iota\eta^{\lambda\sigma}\eta^{\tau\mu}\eta^{\nu\kappa})$$
$$+P_6(p\cdot p'\eta^{\nu\rho}\eta^{\lambda\sigma}\eta^{\tau\iota}\eta^{\kappa\mu})-P_{12}(p^\sigma p^\rho\eta^{\mu\nu}\eta^{\tau\iota}\eta^{\kappa\lambda})-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\lambda}\eta^{\rho\iota}\eta^{\tau\kappa})-P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\iota}\eta^{\nu\kappa})$$
$$-P_6(p^\rho p'^\iota\eta^{\lambda\kappa}\eta^{\mu\sigma}\eta^{\nu\tau})-P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\iota}\eta^{\kappa\lambda})-P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\nu})+2P_6(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})\Big]. \quad (2.7)$$

4pt graviton *vertex*

$$M(1^-2^-3^+) \quad = \quad \frac{\langle 12\rangle^6}{\langle 13\rangle^2\langle 32\rangle^2}$$

3pt graviton *amplitude*

$$M(1^-2^-3^+4^+) \quad = \quad \frac{\langle 12\rangle^4[34]^4}{stu}$$

4pt graviton *amplitude*

Redundancy is not an affliction of spin. Not even scalars are safe. Consider on-shell amplitudes in

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 g(\phi) \quad \longleftrightarrow \quad \mathscr{L} = \frac{1}{2}(\partial\phi)^2$$

At 3pt, 4pt, 5pt, ... you will find they are all zero!

$$f(\phi) \longleftrightarrow \phi \quad \text{where} \quad f'(\phi)^2 = g(\phi)$$

Field redefinitions: a non-symmetry of the action that leaves the S-matrix invariant.

lessons from scattering

Amplitudes can reveal genuinely new structures, e.g. the duality between color and kinematics.

3pt gluon

$$A(1_a^-2_b^-3_c^+) = \frac{\langle 12\rangle^3}{\langle 13\rangle\langle 32\rangle} f_{abc}$$

$$A(1_a^+2_b^+3_c^-) = \frac{[12]^3}{[13][32]} f_{abc}$$

3pt graviton

$$M(1^-2^-3^+) = \frac{\langle 12\rangle^6}{\langle 13\rangle^2\langle 32\rangle^2}$$

$$M(1^+2^+3^-) = \frac{[12]^6}{[13]^2[32]^2}$$

Simply replace f_{abc} with the kinematic structure.

The double copy generalizes to any number of external gluons and gravitons.

$$A_4 = \frac{c_s n_s}{s} + \frac{c_t n_t}{t} + \frac{c_u n_u}{u}$$

4pt gluon
($polarization = e_\mu$)

$\downarrow\downarrow\downarrow$ "*double copy*"

$$M_4 = \frac{n_s \tilde{n}_s}{s} + \frac{n_t \tilde{n}_t}{t} + \frac{n_u \tilde{n}_u}{u}$$

4pt graviton + two-form + dilaton
($polarization = e_\mu \tilde{e}_{\tilde{\mu}}$)

Double copy is proven at tree and recycled to loop via unitarity methods for collider physics, SUGRA, and LIGO.

Bern, Carrasco, Johansson (0805.3993)

Double copy is weirdly ubiquitous among "nice" theories with very few coupling constants.

$\mathcal{N} > 4$ supergravity	• $\mathcal{N} = 4$ SYM theory • SYM theory ($\mathcal{N} = 1, 2, 4$)	[1, 2, 31, 291, 292]	
$\mathcal{N} = 4$ supergravity with vector multiplets	• $\mathcal{N} = 4$ SYM theory • YM-scalar theory from dim. reduction	[1, 2, 31, 293]	• $\mathcal{N} = 2 \times \mathcal{N} = 2$ construction is also possible
pure $\mathcal{N} < 4$ supergravity	• (S)YM theory with matter • (S)YM theory with ghosts	[188]	• ghost fields in fundamental rep
Einstein gravity	• YM theory with matter • YM theory with ghosts	[188]	• ghost/matter fields in fundamental rep
$\mathcal{N} = 2$ Maxwell-Einstein supergravities (generic family)	• $\mathcal{N} = 2$ SYM theory • YM-scalar theory from dim. reduction	[120]	• truncations to $\mathcal{N} = 1, 0$ • only adjoint fields
$\mathcal{N} = 2$ Maxwell-Einstein supergravities (homogeneous theories)	• $\mathcal{N} = 2$ SYM theory with half hypermultiplet • YM-scalar theory from dim. reduction with matter fermions	[121, 294]	• fields in pseudo-real reps • include Magical Supergravities
$\mathcal{N} = 2$ supergravities with hypermultiplets	• $\mathcal{N} = 2$ SYM theory with half hypermultiplet • YM-scalar theory from dim. red. with extra matter scalars	[121, 240]	• fields in matter representations • construction known in particular cases
$\mathcal{N} = 2$ supergravities with vector/hypermultiplets	• $\mathcal{N} = 1$ SYM theory with chiral multiplets • $\mathcal{N} = 1$ SYM theory with chiral multiplets	[239, 241, 295]	• construction known in particular cases
$\mathcal{N} = 1$ supergravities with vector multiplets	• $\mathcal{N} = 1$ SYM theory with chiral multiplets • YM-scalar theory with fermions	[188, 239, 241, 295]	• fields in matter reps • construction known in particular cases
$\mathcal{N} = 1$ supergravities with chiral multiplets	• $\mathcal{N} = 1$ SYM theory with chiral multiplets • YM-scalar with extra matter scalars	[188, 239, 241, 295]	• fields in matter reps • construction known in particular cases
Einstein gravity with matter	• YM theory with matter • YM theory with matter	[1, 188]	• construction known in particular cases

$R + \phi R^2 + R^3$ gravity	• YM theory + $F^3 + F^4 + \ldots$ • YM theory + $F^3 + F^4 + \ldots$	[296]	• extension to $\mathcal{N} \leq 4$ replacing one of the factors by undeformed SYM theory
Conformal (super)gravity	• DF^2 theory • (S)YM theory	[152, 153]	• $\mathcal{N} \leq 4$ • involves specific gauge theory with dimension-six operators
$3D$ maximal supergravity	• BLG theory • BLG theory	[119, 243, 297]	• $3D$ only
YME supergravities	• SYM theory • YM + ϕ^3 theory	[120, 125, 133, 134, 140, 214, 216, 257, 283, 285, 289]	• trilinear scalar couplings • $\mathcal{N} = 0, 1, 2, 4$ possible
Higgsed supergravities	• SYM theory (Coulomb branch) • YM + ϕ^3 theory with extra massive scalars	[122]	• $\mathcal{N} = 0, 1, 2, 4$ possible • massive fields in supergravity
$U(1)_R$ gauged supergravities	• SYM theory (Coulomb branch) • YM theory with SUSY broken by fermion masses	[123]	• $0 \leq \mathcal{N} \leq 8$ possible • SUSY is spontaneously broken • only theories with Minkowski vacua
gauged supergravities (nonabelian)	• SYM theory (Coulomb branch) • YM + ϕ^3 theory with massive fermions	[284]	• SUSY is spontaneously broken • only theories with Minkowski vacua
DBI theory	• NLSM • (S)YM theory	[125, 126, 285, 298–301]	• $\mathcal{N} \leq 4$ possible • also obtained as $\alpha' \to 0$ limit of abelian Z-theory
Volkov-Akulov theory	• NLSM • SYM theory (external fermions)	[125, 302–308]	• restriction to external fermions from supersymmetric DBI
Special Galileon theory	• NLSM • NLSM	[125, 285, 301, 306, 309]	• theory is also characterized by its soft limits
DBI + (S)YM theory	• NLSM + ϕ^3 • (S)YM theory	[125, 126, 156, 285, 298–300, 306, 310]	• $\mathcal{N} \leq 4$ possible • also obtained as $\alpha' \to 0$ limit of semi-abelianized Z-theory
DBI + NLSM theory	• NLSM • YM + ϕ^3 theory	[125, 126, 156, 285, 298–300]	

Bern, Carrasco, Chiodaroli, Johansson, Roiban (1909.01358)

Double copy is closely connected to open/closed string duality but goes beyond it.

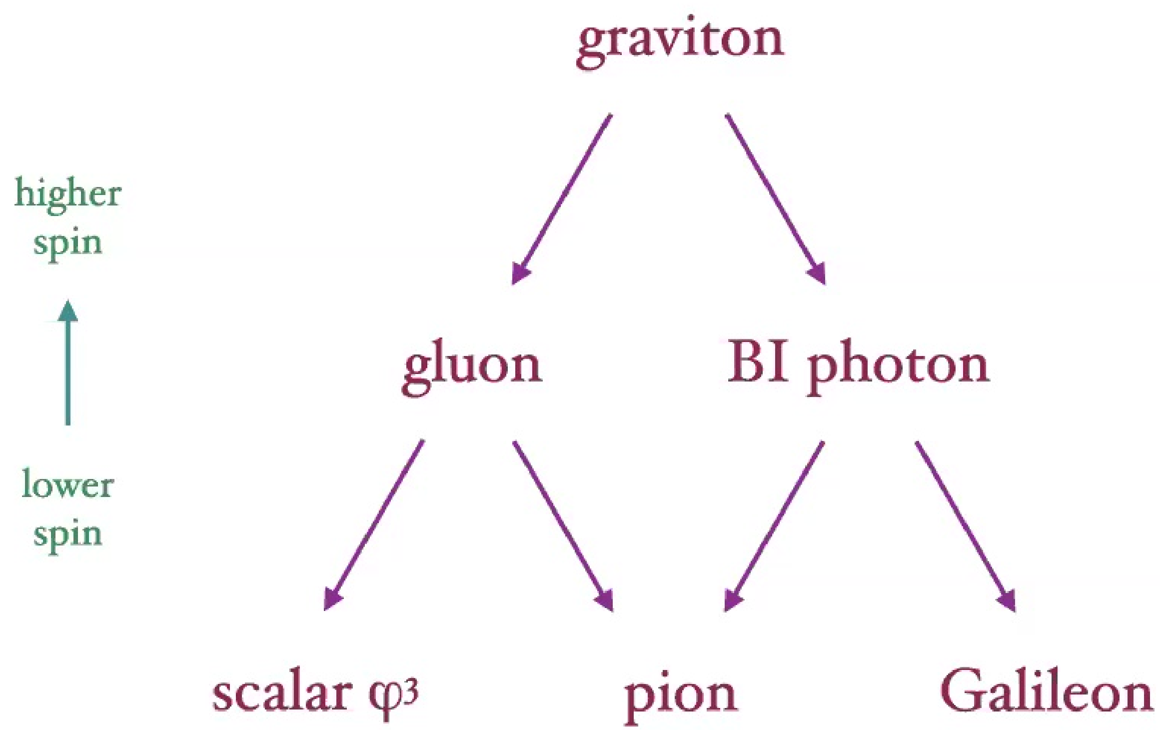
- gluon $\otimes$ gluon = graviton

- pion $\otimes$ pion = special Galileon

- gluon $\otimes$ pion = Born-Infeld photon

These theories keep appearing in amplitudes discoveries, e.g. BCJ, CHY, amplitudedra.

Another lesson from the study of scattering amplitudes: gravity is the mother of all theories!



CC, Shen, Wen (1705.03025)

Simple "transmutation operators" generate lower spin amplitudes from higher spin amplitudes.

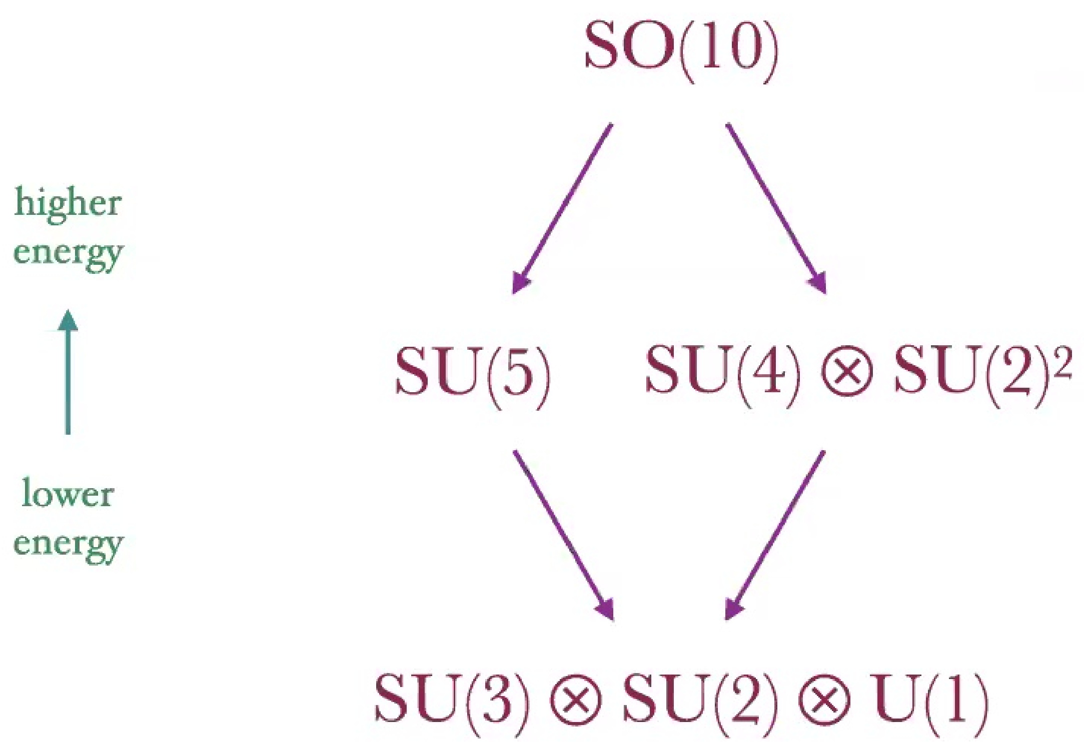
$$T_{ij} = \frac{\partial}{\partial (e_i e_j)}$$ 2 gluon → 2 scalar

$$T_{ijk} = \frac{\partial}{\partial (p_i e_j)} - \frac{\partial}{\partial (p_k e_j)}$$ 1 gluon → 1 scalar

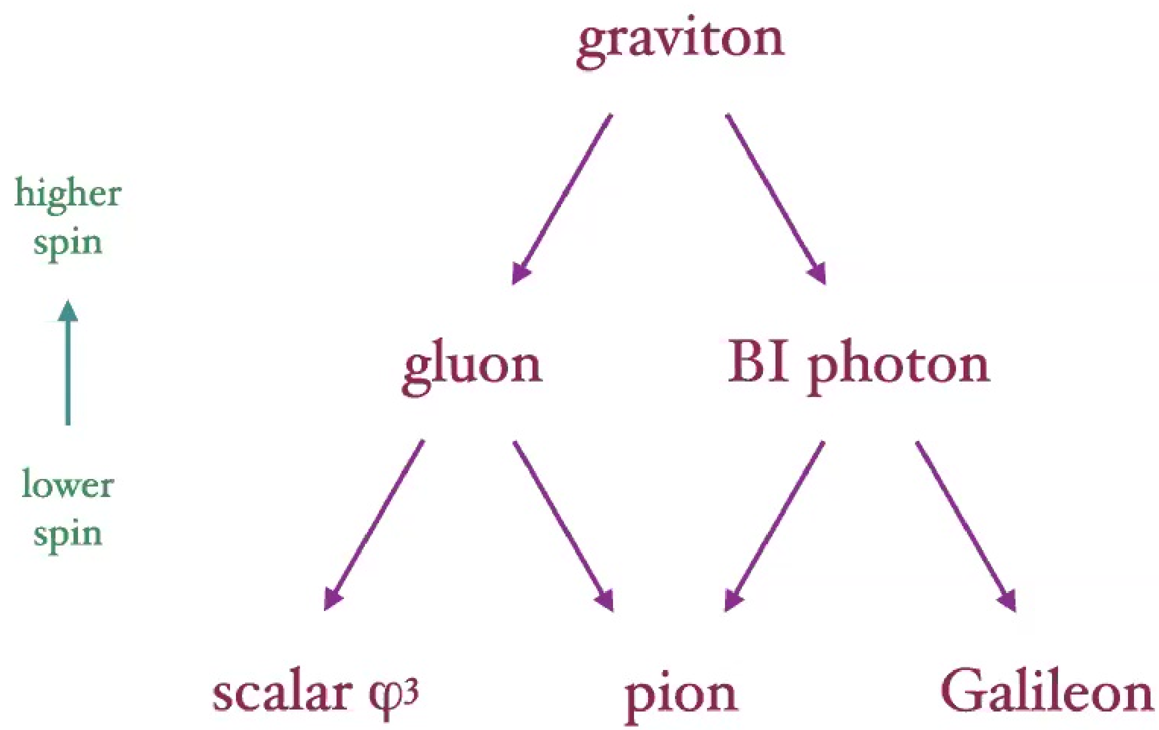
$$T_i = \sum_j p_i p_j \frac{\partial}{\partial (p_j e_i)}$$ 1 gluon → 1 pion

We proved transmutation for all graviton, gluon, pion tree amplitudes + explicit checks up to 8pt.

This is distinct from textbook grand unification.



Another lesson from the study of scattering amplitudes: gravity is the mother of all theories!



CC, Shen, Wen (1705.03025)

Remarkably, hints of a double copy have appeared in classical solutions. The Schwarzschild metric in Kerr-Schild gauge is

(monopole)^2

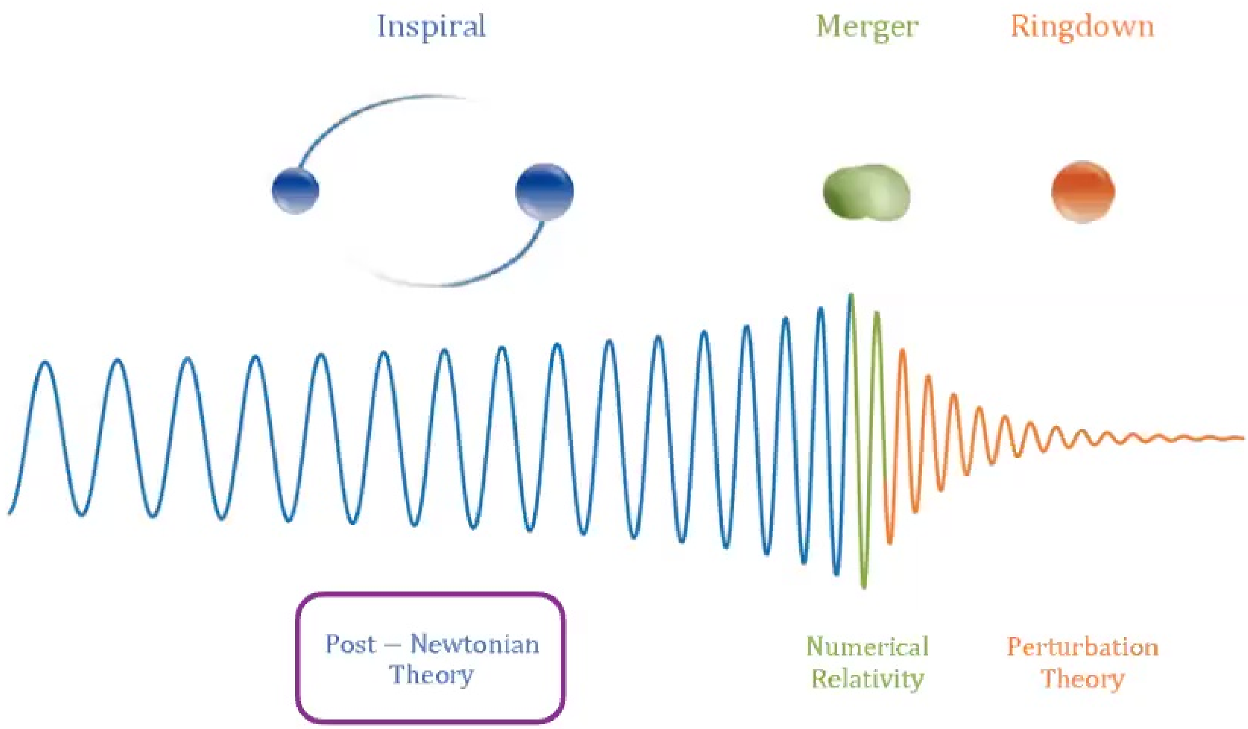
black hole → $$g_{\mu\nu} = \eta_{\mu\nu} + \frac{2GM}{r} A_\mu A_\nu$$

At present it is not known how this observation is directly linked to the amplitudes double copy.

Nevertheless, in recent years, the amplitudes field has mobilized to make real bonafide progress relevant to gravitational wave physics at LIGO.

Montiero, O'Connell (1105.2565)

The binary black hole merger has three phases.



perturbation theory
is applicable here

figure from 1610.03567

Conventional perturbative computations in gravitational wave physics center on the "post-Newtonian" expansion, based on

$$v^2 \sim \frac{GM}{r} \ll 1$$

which is tiny and perturbatively calculable during the inspired phase of the merger.

The so-called "post-Minkowskian" expansion parameter is G, and we call it perturbation theory.

map of perturbation theory

	0PN	1PN	2PN	3PN	4PN	5PN	6PN	7PN	
1PM	$(1$	$+v^2$	$+v^4$	$+v^6$	$+v^8$	$+v^{10}$	$+v^{12}$	$+v^{14}$	$+\cdots)\,G$
2PM		$(1$	$+v^2$	$+v^4$	$+v^6$	$+v^8$	$+v^{10}$	$+v^{12}$	$+\cdots)\,G^2$
3PM			$(1$	$+v^2$	$+v^4$	$+v^6$	$+v^8$	$+v^{10}$	$+\cdots)\,G^3$
4PM				$(1$	$+v^2$	$+v^4$	$+v^6$	$+v^8$	$+\cdots)\,G^4$
5PM					$(1$	$+v^2$	$+v^4$	$+v^6$	$+\cdots)\,G^5$

map of perturbation theory

0PN 1PN 2PN 3PN 4PN 5PN 6PN 7PN

1PM $\left(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + v^{14} + \cdots \right) G$

2PM $\left(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + v^{12} + \cdots \right) G^2$

3PM $\left(1 + v^2 + v^4 + v^6 + v^8 + v^{10} + \cdots \right) G^3$

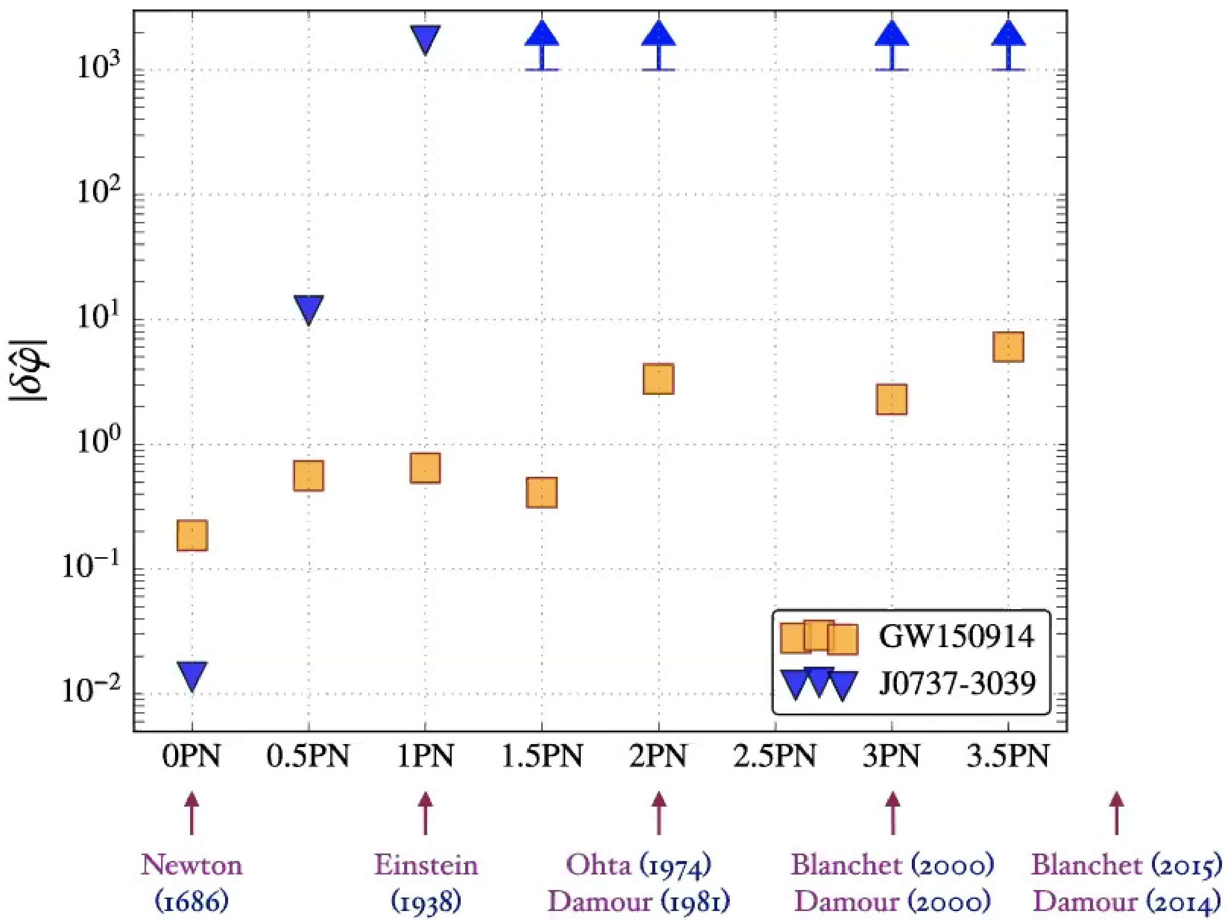
4PM $\left(1 + v^2 + v^4 + v^6 + v^8 + \cdots \right) G^4$

5PM $\left(1 + v^2 + v^4 + v^6 + \cdots \right) G^5$

1808.02489

1901.04424
2003.08351
2006.06665

LIGO will continue to probe PN corrections.



Can amplitudes give an efficient and scaleable path to higher PN? Naively, there are issues.

- black holes $\neq$ SYM gluons

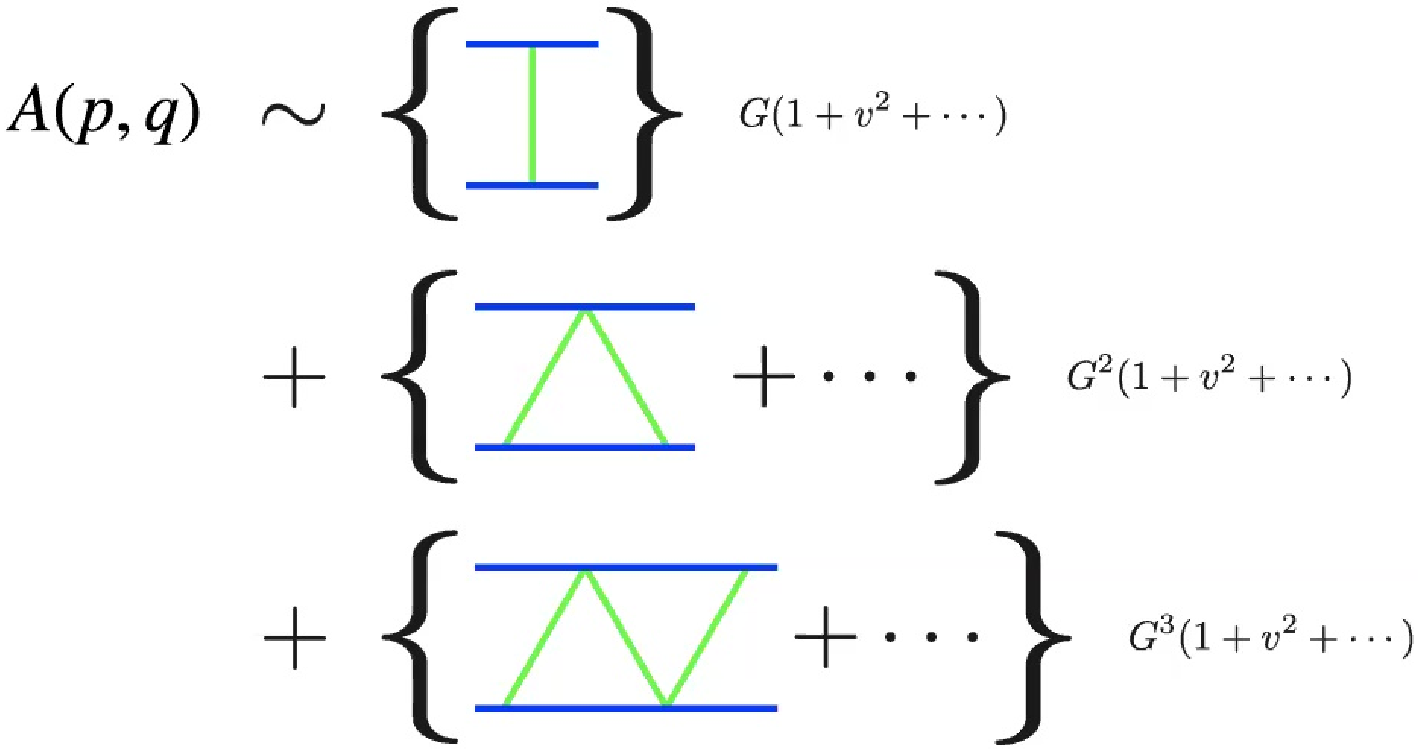
  (double copy, recursion, etc. all apply to masses)

- LIGO does not observe scattering

  (NRQCD solved the amplitudes / potentials map)

All these puzzles have been surmounted. New results on conservative dynamics, radiation, spin, finite size effects are appearing swiftly.

The n loop amplitude encodes all corrections up to $(n+1)$ PM order and at n PN order.



Puzzle #1: how is this process perturbative?

$$GM^2 \gg 1$$

classical
black hole

Puzzle #2: what happened to "classical = tree"?

$$\frac{\hbar}{J} \ll 1$$

classical orbital
angular momentum

Since $J/\hbar \sim p/q \gg 1$, this requires a controlled eikonal expansion in $s/t \gg 1$.

full theory | effective theory

full theory		effective theory	
amplitudes methods ↓		↓ build ansatz	
double copy or Feynman diagrams	A_{tree}	$V(p,q)$	effective BH Lagrangian
generalized unitarity ↓		↓ Feynman diagrams	
integration	$A = \sum_i d^{(i)} I^{(i)}$	$A_{\text{EFT}} = \sum_i d^{(i)}_{\text{EFT}} I^{(i)}$	integration
multi-loop integration ↓		↓ multi-loop integration	
full loop amplitude	$A(p,q)$	$A_{\text{EFT}}(p,q)$	EFT loop amplitude

identical physics

$$A(p,q) = A_{\text{EFT}}(p,q)$$

gluons

(double copy) ↓ $A_{\text{grav}} = A_{\text{YM}} \otimes A_{\text{YM}}$

gravitons

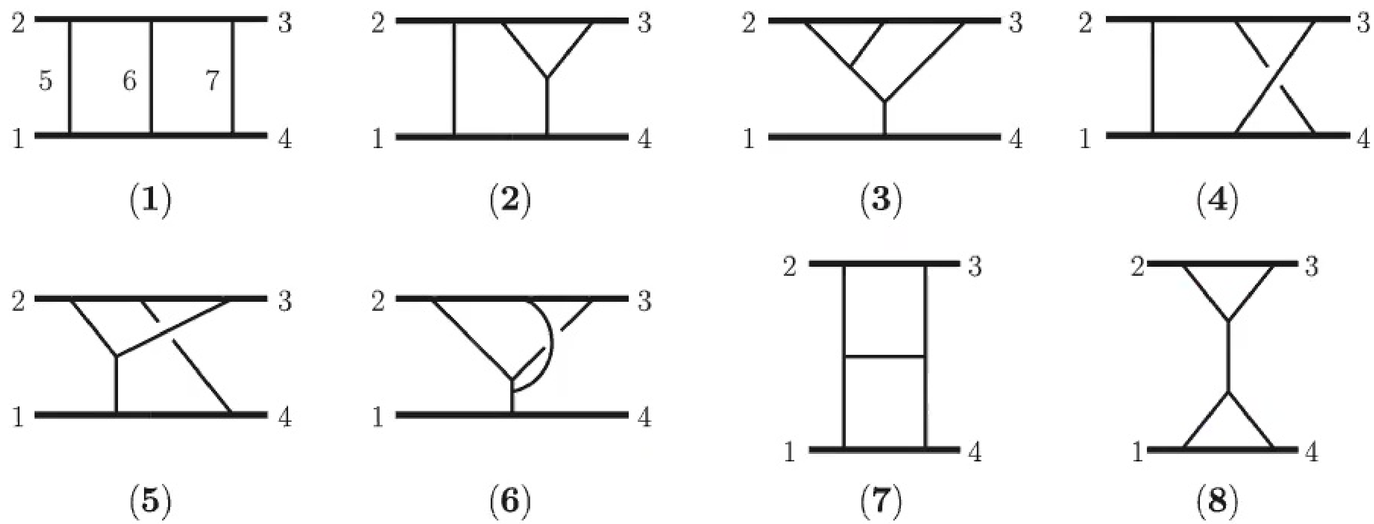
(transmute) ↓ $A_{\phi_1\phi_2+\text{grav}} = \dfrac{\partial A_{\text{grav}}}{\partial(e_1 e_2)}$

massless scalars + gravitons

(add mass) ↓ $A_{\phi_1'\phi_2'+\text{grav}} = A_{\phi_1\phi_2+\text{grav}}\Big|_{p_1p_2 \to p_1p_2 - m_1m_2}$

massive scalars + gravitons

Use generalized unitarity to build integrands from trees. Feynman diagrams also doable at low loop.



Since we want classical dynamics we can drop numerous self energy and contact diagrams.

Define a general Lagrangian for the EFT in which the interaction is the conservative potential.

$$\mathscr{L}_{\text{EFT}} = \sum_{A=1,2} \int_p \phi_A^\dagger(-p)\left(i\partial_t - \sqrt{p^2 + m_A^2}\right)\phi_A(p)$$

$$- \int_{p,p'} V(p,p')\,\phi_1^\dagger(p')\,\phi_1(p)\,\phi_2^\dagger(-p')\,\phi_2(-p)$$

This effective theory is obtained by integrating out potential mode gravitons in the full theory. It straightforward and mechanical to incorporate spin, tidal effects, and radiation.

Our result is now the state-of-the-art in PM, and matches all known results at overlapping orders.

$$V(\boldsymbol{p},\boldsymbol{r}) = \sum_{i=n}^{\infty} \frac{G^n c_n(\boldsymbol{p}^2)}{|\boldsymbol{r}|^n}$$

$$c_1 = \frac{\nu^2 m^2}{\gamma^2\xi}\left(1-2\sigma^2\right),$$

$$c_2 = \frac{\nu^2 m^3}{\gamma^2\xi}\left[\frac{3}{4}\left(1-5\sigma^2\right) - \frac{4\nu\sigma\left(1-2\sigma^2\right)}{\gamma\xi} - \frac{\nu^2(1-\xi)\left(1-2\sigma^2\right)^2}{2\gamma^3\xi^2}\right],$$

$$c_3 = \frac{\nu^2 m^4}{\gamma^2\xi}\left[\frac{1}{12}\left(3-6\nu+206\nu\sigma-54\sigma^2+108\nu\sigma^2+4\nu\sigma^3\right) - \frac{4\nu\left(3+12\sigma^2-4\sigma^4\right)\operatorname{arcsinh}\sqrt{\frac{\sigma-1}{2}}}{\sqrt{\sigma^2-1}} - \frac{3\nu\gamma\left(1-2\sigma^2\right)\left(1-5\sigma^2\right)}{2(1+\gamma)(1+\sigma)} - \frac{3\nu\sigma\left(7-20\sigma^2\right)}{2\gamma\xi} + \frac{2\nu^3(3-4\xi)\sigma\left(1-2\sigma^2\right)^2}{\gamma^4\xi^3} - \frac{\nu^2\left(3+8\gamma-3\xi-15\sigma^2-80\gamma\sigma^2+15\xi\sigma^2\right)\left(1-2\sigma^2\right)}{4\gamma^3\xi^2} + \frac{\nu^4(1-2\xi)\left(1-2\sigma^2\right)^3}{2\gamma^6\xi^4}\right].$$

Bern, CC, Roiban, Shen, Solon, Zeng (1901.04424, 1908.01493, 2003.08351)

LIGO/Virgo folks have continued to ask for more perturbative orders. We are happy to oblige.

Energetics of two-body Hamiltonians in post-Minkowskian gravity

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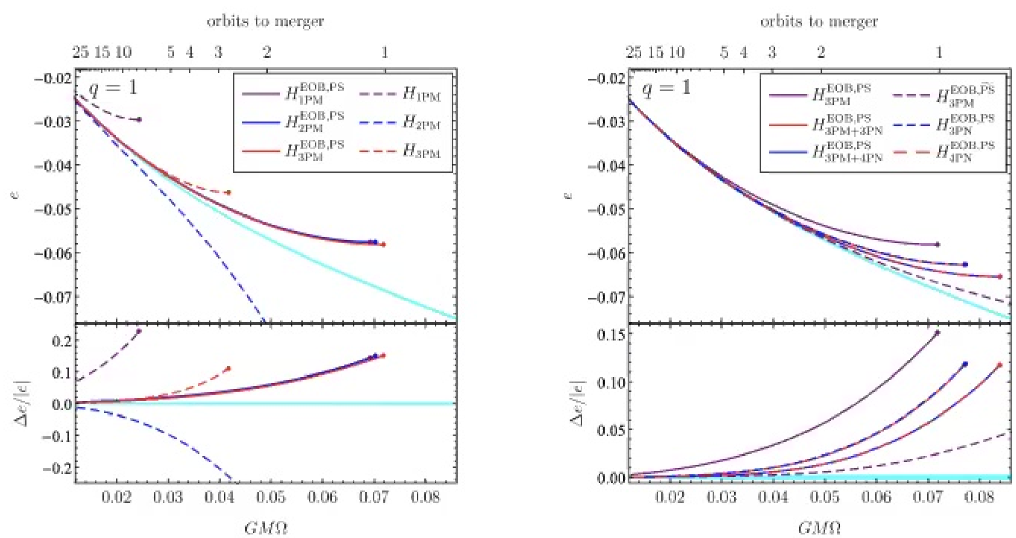
(Dated: January 23, 2019)



Finite size corrections are crucial for neutron star mergers. We can also include tidal effects from the mass and current quadrupole moments.

$$\Delta S = \sum_{A=1,2} \int d\tau_A \left(\frac{\mu_A^{(2)}}{4} E^2 + \frac{2\sigma_A^{(2)}}{3} B^2 \right)$$

↕ (worldline vs QFT)

$$\Delta S = \int \sqrt{-g}\, C_{\mu\alpha\nu\beta} C^{\rho\alpha\sigma\beta} \sum_{A=1,2} \left(\lambda_A \phi_A^2 \delta_\rho^\mu \delta_\sigma^\nu + \frac{\eta_A}{m_A^4} \nabla^\mu \nabla^\nu \phi_A \nabla_\rho \nabla_\sigma \phi_A \right)$$

Then compute the tidal corrections to scattering.

Applying the same tools as before yields state-of-the-art results for leading tidal effects in PM.

$$\Delta V(\boldsymbol{p},\boldsymbol{r}) = \sum_{n=2}^{\infty} \frac{G^n \Delta c_n(\boldsymbol{p}^2)}{|\boldsymbol{r}|^{n+4}}$$

$$\Delta c_2 = -\frac{3m_2^3}{E^2\xi}\left[4\lambda_1 + \frac{\eta_1}{32}(11 - 30\sigma^2 + 35\sigma^4)\right],$$

$$\begin{aligned}\Delta c_3 = \frac{15m_2^3}{2E^2\xi}\Bigg[&4\lambda_1\left(\frac{8m_2}{5} - \frac{m_1\sigma(5-2\sigma^2)}{(\sigma^2-1)^2} + \frac{6m_1 \sinh^{-1}\sqrt{\frac{\sigma-1}{2}}}{(\sigma^2-1)^{5/2}}\right) + \eta_1\Bigg(\frac{m_2(305 - 363\sigma^2 - 110\sigma^4)}{560} \\ &- \frac{m_1\sigma(5401 - 195\sigma^2 - 94\sigma^4)}{80} - \frac{m_1\sigma(673 + 2168\sigma^2)}{2(\sigma^2-1)^2} + \frac{3m_1\left(33 + 474\sigma^2 + 440\sigma^4\right)\sinh^{-1}\sqrt{\frac{\sigma-1}{2}}}{(\sigma^2-1)^{5/2}}\Bigg) \\ &+ 2(1-2\sigma^2)\left[4\lambda_1 + \frac{\eta_1}{32}(11 - 30\sigma^2 + 35\sigma^4)\right]\frac{E(E_2 - m_2)}{m_2(\sigma^2-1)}\Bigg] \\ &+ \frac{3\nu m_2^3}{m\gamma^5\xi^3}\left[\nu(1-\xi)(1-2\sigma^2)\left[4\lambda_1 + \frac{\eta_1}{32}(11 - 30\sigma^2 + 35\sigma^4)\right] + 4\gamma^2\xi\sigma\left[4\lambda_1 + \frac{\eta_1}{32}(26 - 95\sigma^2 + 105\sigma^4)\right]\right]\end{aligned}$$

CC, Solon (2006.06665)

conclusions

- Scattering amplitudes have uncovered hidden structures lurking inside real-world theories like gravitons, gluons, and pions.

- We have fused cutting edge tools like double copy and generalized unitarity with classic methods from EFT matching to formulate a new approach to the binary inspiral problem.

- We have derived the now leading PM results for spinless black holes, also including tidal effects from finite size corrections.

thank you!