Analytic structure of the high-energy gravitational amplitude

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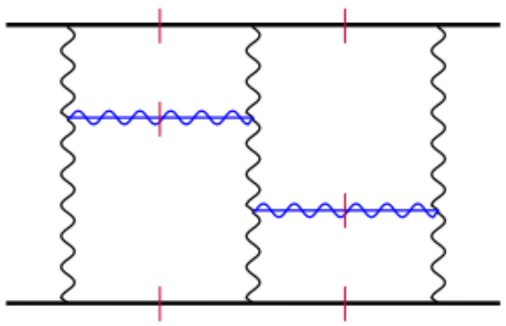
INFN LNF



in collaboration with Francesco Alessio & Emanuele Rosi (INFN LNF)

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Ira Rothstein (Carnegie Mellon U.)

Michael Saavedra (UCLA)

Rothstein Saavedra 2412.04428

Alessio VDD Gonzo Rosi Rothstein Saavedra 2511.11457

Alessio VDD Gonzo Rosi 26xx.yyyyy

QCD meets Gravity   Sao Paulo 19 December 2025

Regge limit

- we want to examine how (massive or massless) 4-pt amplitudes behave in the Regge limit

- Regge limit for massless amplitudes: $s \gg |t|$

- Regge limit for massive amplitudes: $s \gg |t|, m_1^2, m_2^2$

  in the leading log approximation, relative size of |t| and m^2 is immaterial

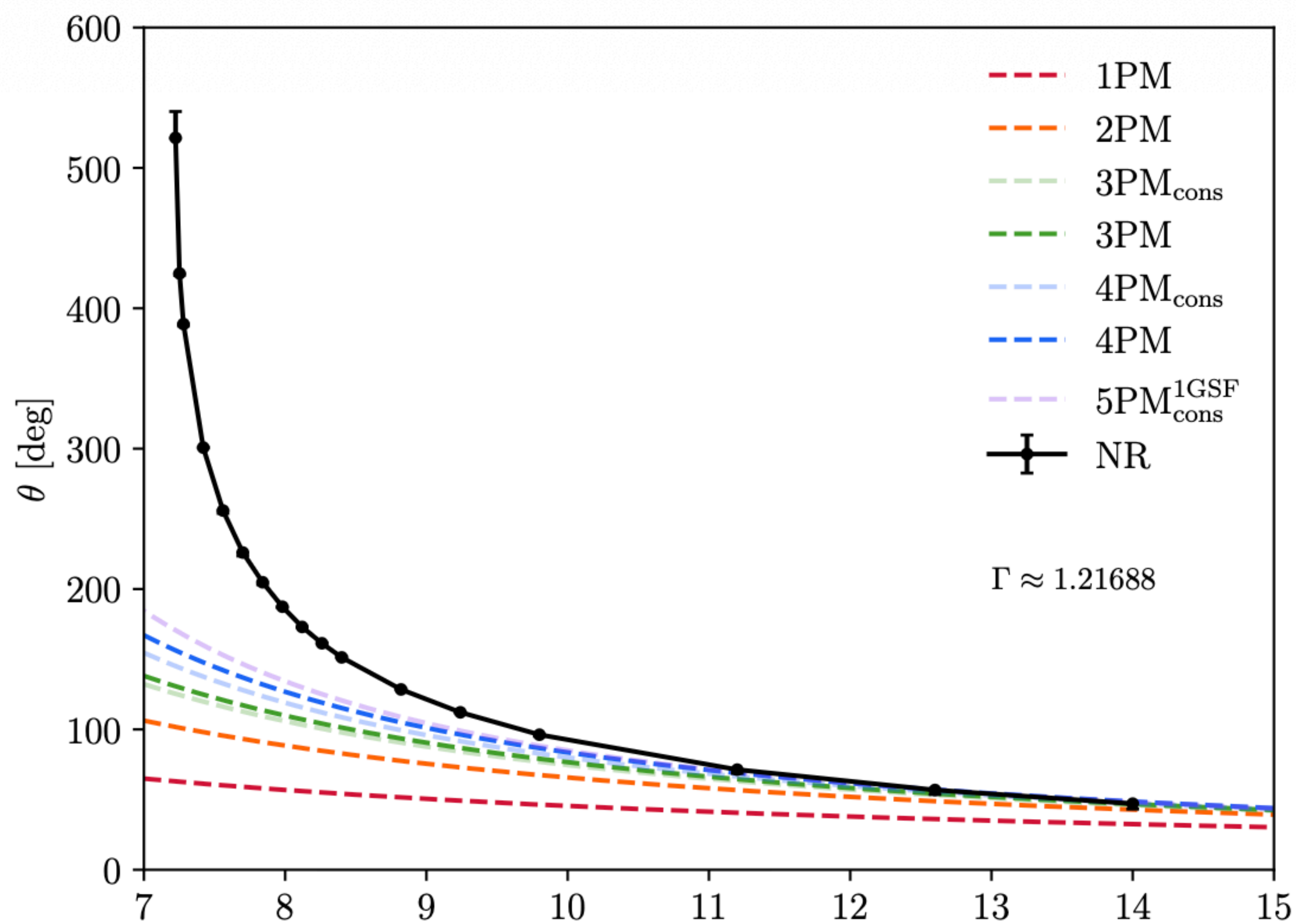
- Caveat: $s \gg m_1^2, m_2^2 \gg |t|$ is a different forward limit

- Post Minkowskian (PM) expansion: G/r

Comparison of PM to Numerical Relativity

scattering angle from NR data vs. PM

see also Radu Roiban's talk



angular momentum

Pratten Schmidt Swain 2411.09652

Γ: energy in the NR simulation

"It has been shown that the non-resummed PM-expanded scattering angles demonstrate poor convergence towards NR. This motivates the exploration of *resummation* strategies… … in particular we focus on the approach to the high-energy limit for equal-mass non-spinning binaries, which proves to be challenging for all resummation schemes considered …"

- comparison worsens as we approach strong-field regime

Power scaling of PM expansion

4-pt amplitude for the scattering of two massive scalars minimally coupled to gravity

$$c_{n\mathrm{SF}}^{(\ell)} \equiv c_{n\mathrm{SF}}^{(\ell)}(s,t,m_1,m_2)$$

1PM: $A^{(0)}(s,t) \simeq G\, c_{0\mathrm{SF}}^{(0)}\, m_1^2 m_2^2$

2PM: $A^{(1)}(s,t) \simeq G^2\, c_{0\mathrm{SF}}^{(1)}\, m_1^2 m_2^2\,(m_1+m_2)$

3PM: $A^{(2)}(s,t) \simeq G^3 \left[c_{0\mathrm{SF}}^{(2)}\, m_1^2 m_2^2 (m_1^2+m_2^2) + c_{1\mathrm{SF}}^{(2)}\, m_1^3 m_2^3\right]$

4PM: $A^{(3)}(s,t) \simeq G^4 \left[c_{0\mathrm{SF}}^{(3)}\, m_1^2 m_2^2 (m_1^3+m_2^3) + c_{1\mathrm{SF}}^{(3)}\, m_1^3 m_2^3 (m_1+m_2)\right]$

5PM: $A^{(4)}(s,t) \simeq G^5 \left[c_{0\mathrm{SF}}^{(4)}\, m_1^2 m_2^2 (m_1^4+m_2^4) + c_{1\mathrm{SF}}^{(4)}\, m_1^3 m_2^3 (m_1^2+m_2^2) + c_{1\mathrm{SF}}^{(4)}\, m_1^4 m_2^4\right]$

0SF | 1SF | 2SF

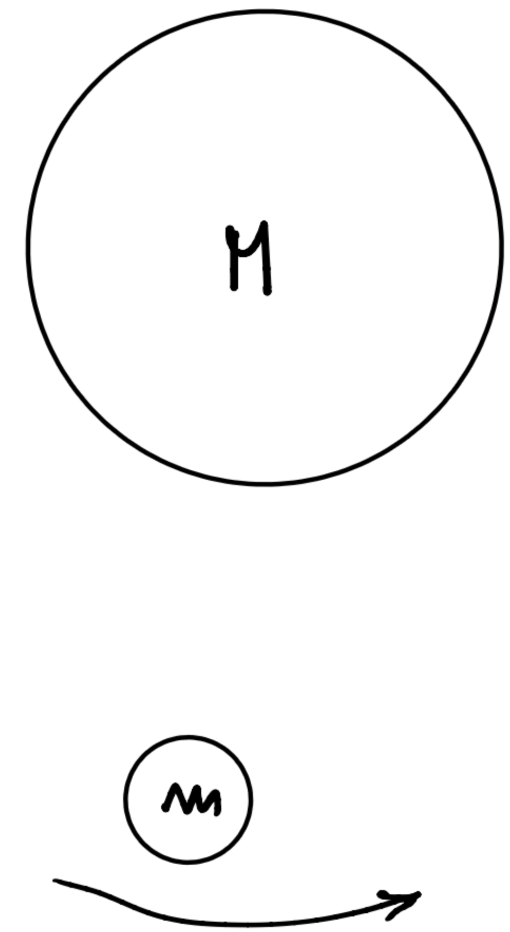
see also Radu Roiban's talk

Self force

- Probe limit corresponds to Schwarzschild geometry: static (infinitely heavy) black hole

- in Self Force (SF) expansion, one expands Einstein's equation in powers of m/M

  0 SF = Probe limit = Schwarzschild
  1 SF: m/M
  2 SF: $(m/M)^2$

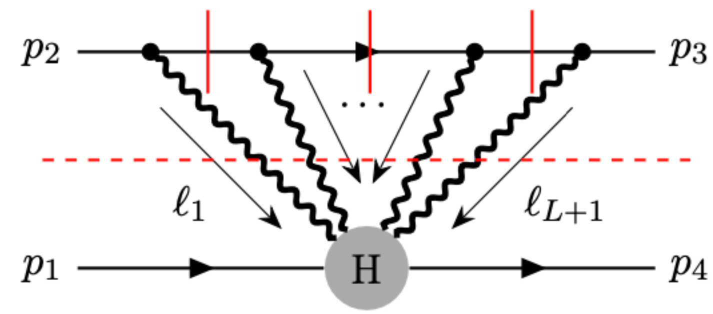


see Alexandre Le Tiec's talk

Probe limit

(*L*+1)-PM, 0 SF: $A^{(L)}_{0\mathrm{SF}}(s,t) \simeq G^{L+1} m_1^2 m_2^{L+2}\, y^2 (1 + O(1/y^2))$

$$y = \frac{s - m_1 - m_2}{2 m_1 m_2}$$



Brandhuber Chen Travaglini Wen 2108.04216 conjectured polynomial form, with unknown coefficients

Sasank Chava (2023, MSc thesis unpublished)

obtained polynomial coefficients leveraging geometric info from geodesic eq. for test particle in a Schwarzschild background

Cheung Shah Solon 2010.08568
Damour 1710.10599

$$\mathcal{M}^0_{\text{probe}} = \frac{16\pi G_N m_1^2 m_2^2 (2y^2 - 1)}{(-q^2)},$$

$$\mathcal{M}^1_{\text{probe}} = 6\pi^2 G_N^2 m_1^2 m_2^3 \left(5y^2 - 1\right) (-q^2)^{-\frac{1}{2} - 2\epsilon},$$

$$\mathcal{M}^2_{\text{probe}} = \frac{2\pi G_N^3 m_1^2 m_2^4 (-q^2)^{-2\epsilon} \left(64y^6 - 120y^4 + 60y^2 - 5\right)}{3\epsilon \left(y^2 - 1\right)^2},$$

$$\mathcal{M}^3_{\text{probe}} = -\frac{35\pi^2 G_N^4 m_1^2 m_2^5 (-q^2)^{\frac{1}{2} - 3\epsilon} \left(33y^4 - 18y^2 + 1\right)}{8\left(y^2 - 1\right)},$$

$$\mathcal{M}^4_{\text{probe}} = -\frac{\pi G_N^5 m_1^2 m_2^6 (-q^2)^{1 - 4\epsilon} \left(1792y^{10} - 5760y^8 + 6720y^6 - 3360y^4 + 630y^2 - 21\right)}{40\epsilon \left(y^2 - 1\right)^4}$$

$$\mathcal{M}^5_{\text{probe}} = \frac{77\pi^2 G_N^6 m_1^2 m_2^7 (-q^2)^{3/2 - 5\epsilon} \left(221y^6 - 195y^4 + 39y^2 - 1\right)}{96\left(y^2 - 1\right)^2},$$

Bern Parra-Martinez Roiban Ruf Shen Solon Zeng 2021
Bjerrum-Bohr Planté Vanhove 2021

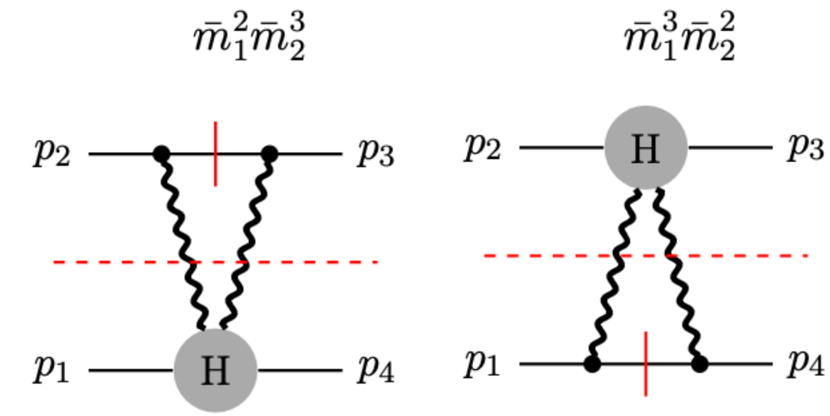
- an analytic resummation of next-to-probe (1 SF) terms is not yet known

Heavy effective field theory

Brandhuber Chen Travaglini Wen 2108.04216

2PM: $A^{(1)}(s,t) \simeq G^2 m_1^2 m_2^2 \,(m_1+m_2)\, y^2 (1+O(1/y^2))$

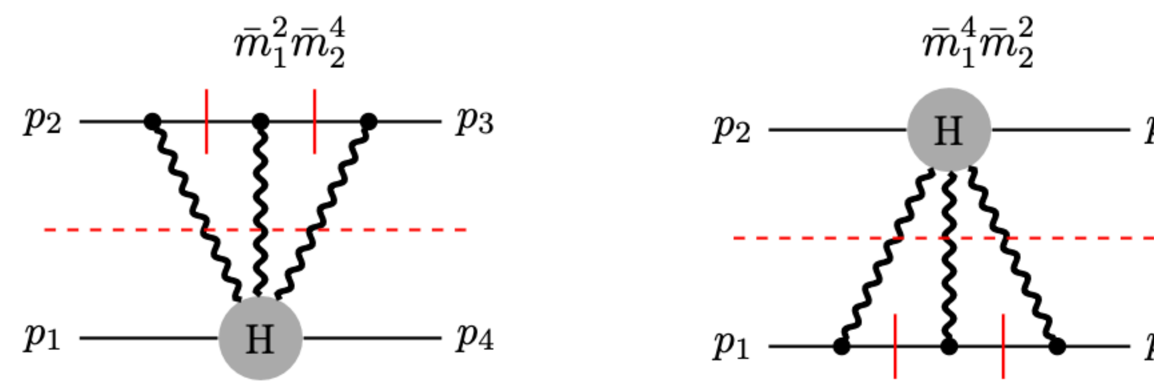
$$y = \frac{s - m_1 - m_2}{2 m_1 m_2}$$



(probe limit)

3PM, 0SF:

$$A^{(2)}_{0\mathrm{SF}}(s,t) \simeq G^3 m_1^2 m_2^2 \,(m_1^2+m_2^2)\, y^2 (1+O(1/y^2))$$

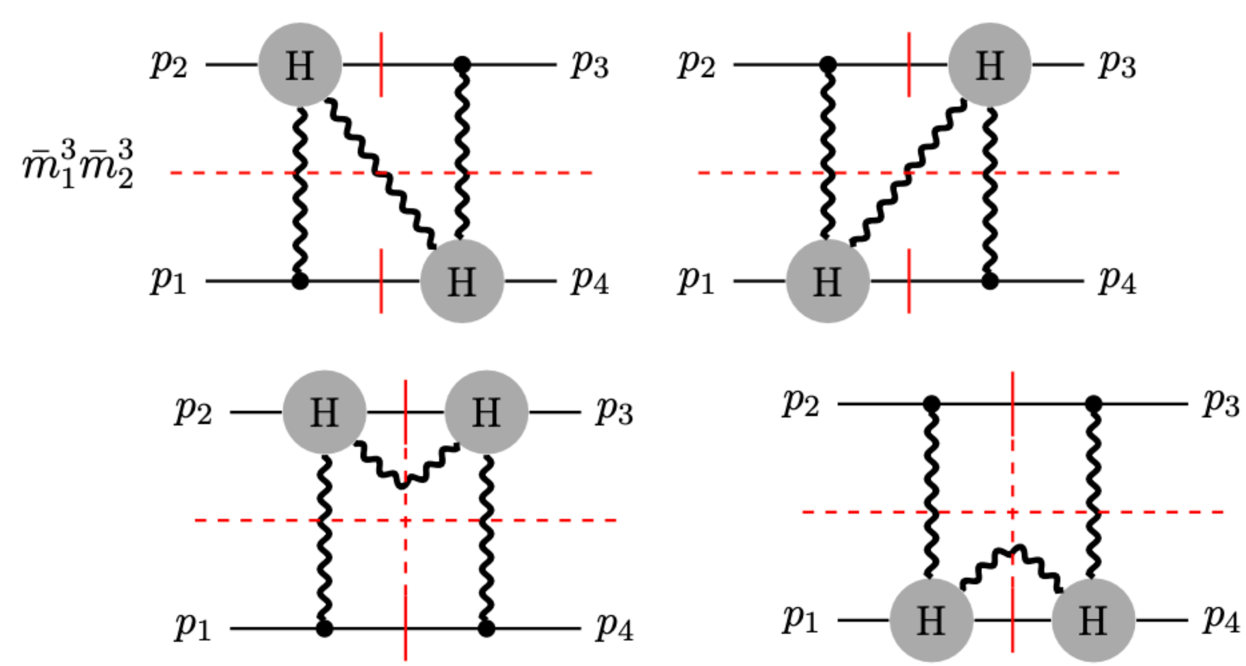


3PM, 1SF: (beyond the probe)

$$\mathrm{Re}A^{(2)}_{1\mathrm{SF}}(s,t) \simeq G^3 m_1^3 m_2^3\, y^3 (1+O(1/y))$$

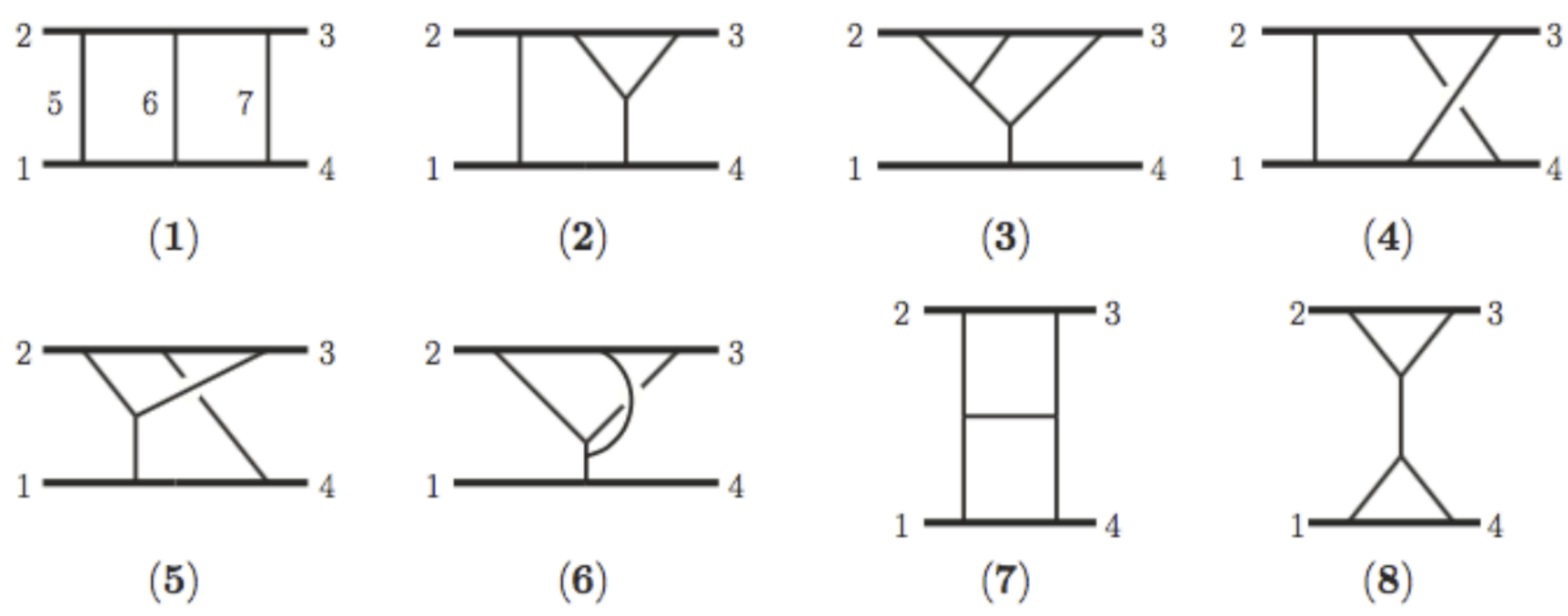
$$\mathrm{Im}A^{(2)}_{1\mathrm{SF}}(s,t) \simeq G^3 m_1^3 m_2^3\, y^3 (\log(2y)+O(1/y))$$

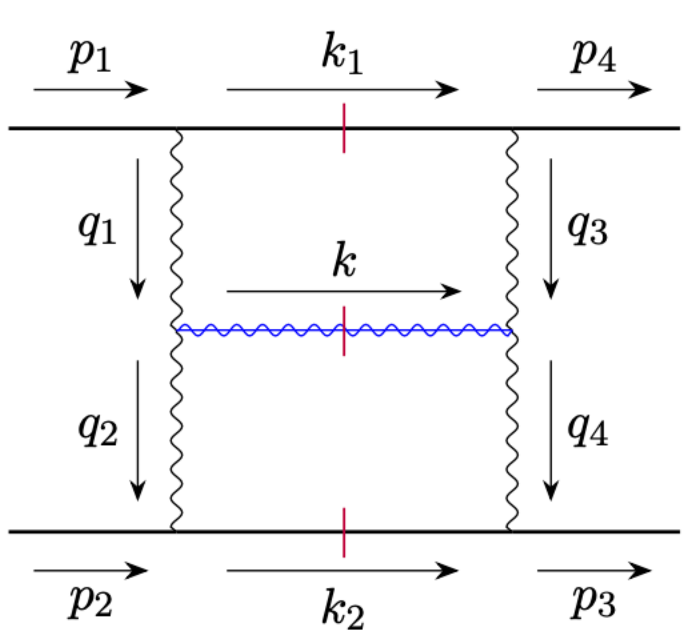
radiation reaction needed
to cancel additional power of log(s/|t|)



(radiation reaction)

3 PM: Bern Cheung Roiban Shen Solon Zeng 1901.04424 & 1908.01493





H diagram

Amati Ciafaloni Veneziano 1990

Regge limit $s >> |t|$ massless

$$\mathrm{Im}A^{(2)}(s,t) \simeq G^3 s^3 \log(s/t) \cdot (\text{poles in } \varepsilon)$$

$$\mathrm{Re}A^{(2)}(s,t) \simeq \frac{1}{\log(s/t)} \mathrm{Im}A^{(2)}(s,t)$$

Di Vecchia Heissenberg Russo Veneziano 2008.12743

massive

4 PM, 0 SF: $A^{(3)}_{0\mathrm{SF}}(s,t) \simeq G^4 m_1^2 m_2^2\,(m_1^3+m_2^3)\,y^2(1+O(1/y^2))$

4 PM, 1 SF: $A^{(3)}_{1\mathrm{SF}}(s,t) \simeq G^4 m_1^3 m_2^3\,(m_1+m_2)\,y^3 f^{(3)}_{1\mathrm{SF}}(m_1,m_2,y)$

Bern Parra-Martinez Roiban Ruf Shen Solon Zeng 2101.07254 & 2112.10750
Dlapa Kälin Liu Neef Porto 2106.08276, 2112.11296 & 2210.05541

5 PM, 0 SF: $A^{(4)}_{0\mathrm{SF}}(s,t) \simeq G^5 m_1^2 m_2^2\,(m_1^4+m_2^4)\,y^2(1+O(1/y^2))$

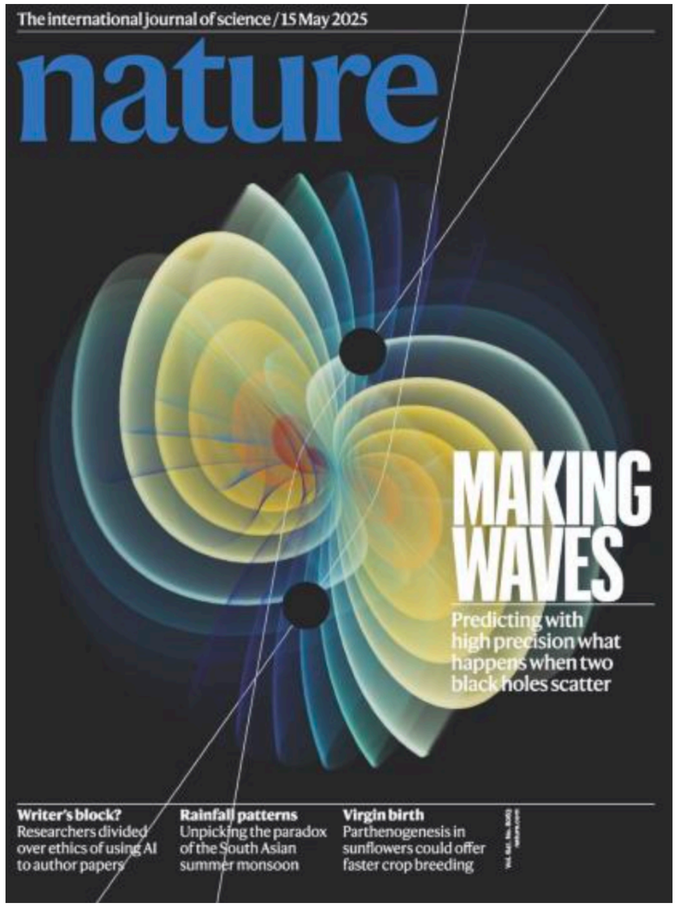
5 PM, 1 SF: $A^{(4)}_{1\mathrm{SF}}(s,t) \simeq G^5 m_1^3 m_2^3\,(m_1^2+m_2^2)\,y^3 f^{(4)}_{1\mathrm{SF}}(m_1,m_2,y)$

Driesse Jakobsen Klemm Mogull Nega Plefka Sauer Usovitsch 2403.07781 & 2411.11846
Dlapa Kälin Liu Porto 2506.20665

see Johann Usovitsch's talk

through world-line formalism

$$S = -\sum_{i=1}^{2} \frac{m_i}{2} \int d\tau_i g_{\mu\nu}(x_i(\tau_i))\, v_i^{\mu}(\tau_i) v_i^{\nu}(\tau_i)$$



5 PM, 2 SF: unknown yet

we have grounds to expect

$A^{(4)}_{2\mathrm{SF}}(s,t) \simeq G^5 m_1^4 m_2^4\, y^4(\log^2(2y) + O(1/y))$

- Regge limit: large-*y* limit $y \to \frac{s}{2m_1 m_2}$

- (*n*+1)PM 0SF (probe limit) amplitudes go like $G^{n+1}\, s^2\, (m_1^n + m_2^n)$

- 3PM 1SF amplitudes go like $G^3\, s^3\, \log(s)$ Amati Ciafaloni Veneziano 1990
  Di Vecchia Heissenberg Russo Veneziano 2008.12743

- 4PM 1SF amplitudes go like ?

- 5PM 1SF amplitudes go like ?

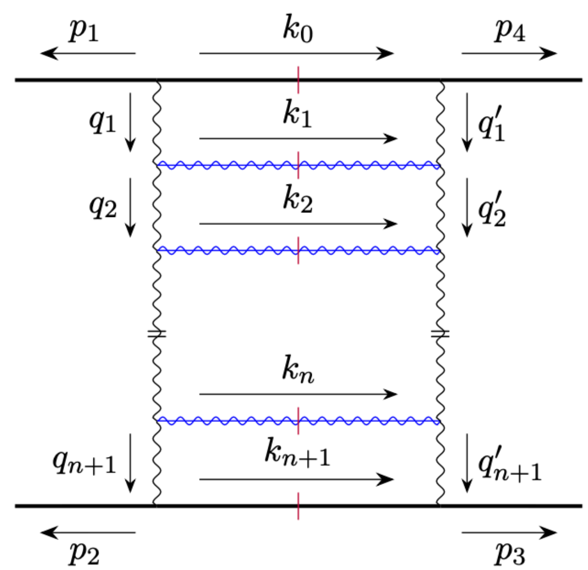
- 5PM 2SF amplitudes go like $G^5\, s^4\, \log^2(s)$

Alessio VDD Gonzo Rosi Rothstein Saavedra 2511.11457 massless
Alessio VDD Gonzo Rosi 26xx.yyyyy massive

Regge theory of QCD and Gravity

- In the Regge limit, radiative corrections to 2→2 massless amplitudes display iterative patterns of the evolution in rapidity $y \simeq \log(s/|t|)$, either if the evolution occurs in the t channel or in the s channel

- In the Regge limit of QCD, the leading radiative corrections are associated to a gluon ladder exchanged in the t channel, the Reggeised or Glauber gluon. BFKL 1976-77
  t channel two-gluon ladder and s channel terms are logarithmically suppressed



$$\mathcal{A} \simeq \exp\left(i\pi \mathbf{T}_s^2 + \mathbf{T}_t^2 \log\left(\frac{s}{-t}\right)\right)$$

- In the Regge limit of gravity, the leading radiative corrections are due to the eikonal phase terms (Weinberg's soft gravitons).
  t channel one-graviton ladder is power suppressed in t/s

Bartels Lipatov Sabio-Vera 1208.3423
Melville Naculich Schnitzer White 1306.6019

colour-kinematics duality

$$\mathbf{T}_s^2 \to s \qquad \mathbf{T}_t^2 \to t$$

- s channel ladders win over t channel ladders

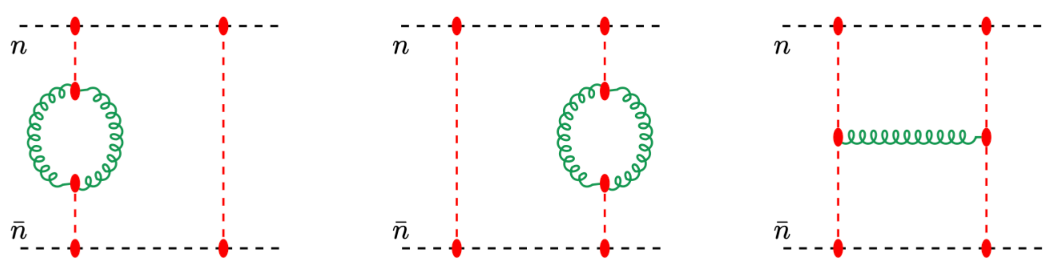
Gravity massless scattering: Glauber EFT

- Mimicking Glauber EFT of QCD Rothstein Stewart 1601.04695

$$\mathcal{M}_{2\to 2} = i \sum_M J_{(M)} \otimes S_{(M)} \otimes \bar{J}_{(M)}$$

Rothstein Saavedra 2412.04428 showed that the exchange of a *t*-channel two-graviton ladder is ruled by a rapidity RGE, whose anomalous dimension is Lipatov gravity (BFKL-like) kernel with graviton trajectory and graviton central-emission vertex (CEV) Lipatov 1982

$$\nu \frac{d}{d\nu} S_{(N)} = -\gamma^{\nu}_{(N)} \otimes S_{(N)} - S_{(N)} \otimes \gamma^{\nu}_{(N)}$$



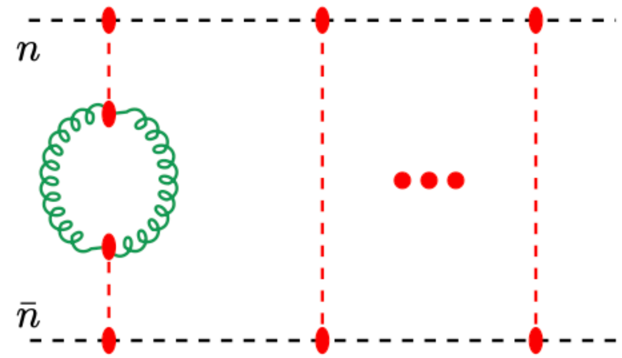
$$\gamma^{\nu}_{(M)} \sim \sum_j \omega_G(q_i) I_{\perp(M-1)} + \sum_{\text{Pairs } i,j} \mathcal{K}^{\text{GR}}(q_i, q_j; q)\, I_{\perp(M-2)}$$

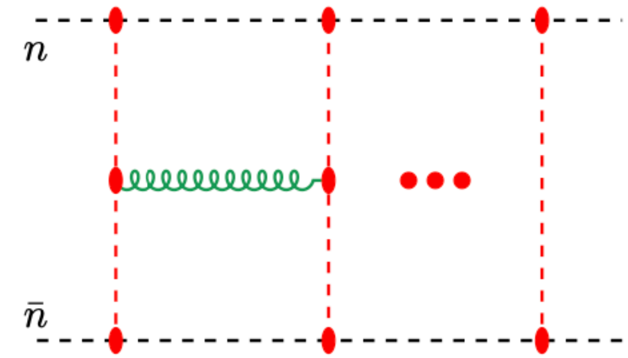
- through $\hbar$ counting, easy to see that trajectory is quantum, in fact the whole two-graviton ladder is quantum, except for one graviton CEV emission: the *H* diagram

$$\text{Im}\, \mathcal{M}^{(n+1)}_{2\to 2}(s, q^2) \sim s^3 \log\left(\frac{s}{-t}\right)^n \frac{G}{q_\perp^2}\, G\, q_\perp^n\, (G\, q_\perp)^n$$

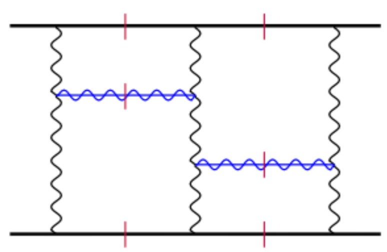
Gravity massless scattering: Glauber EFT

- Rothstein Saavedra 2412.04428 showed that the exchange of a *t*-channel multi-graviton ladder is ruled by a rapidity RGE, whose anomalous dimension is a convolution of gravity BFKL-like kernels





- through $\hbar$ counting, easy to see that the whole three-graviton ladder is quantum, except for the convolution of two gravity BFKL-like kernels



In fact, a *t*-channel ladder with *(n+2)* gravitons in the *s* channel features a classical term of (2n+3)-PM order, and provides a correction of $O((G^2\, s \log(s/|t|))^n)$ to the *H* diagram

Gravity massless scattering: shock waves

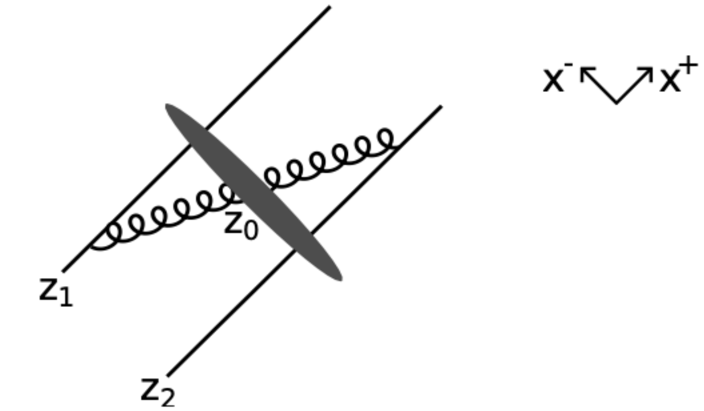
- early work by Dray 't Hooft 1985, Lodone Rychkov 0909.3519

Alessio VDD Gonzo Rosi 26xx.yyyyy

- colliding particles, projectile (target) moving in the + (-) light-cone directions. with a transverse position z offset, $|\tilde{\Psi}_i\rangle \sim \tilde{\Phi}_i(z)\,|0\rangle$

  are modelled by infinite light-like Wilson lines

$$\tilde{\Phi}_i(z) = \exp\left(i\frac{\kappa}{\hbar}\int_{-\infty}^{\infty} ds\, p_i^\mu p_i^\nu h_{\mu\nu}\,(sp_i + z)\right)$$



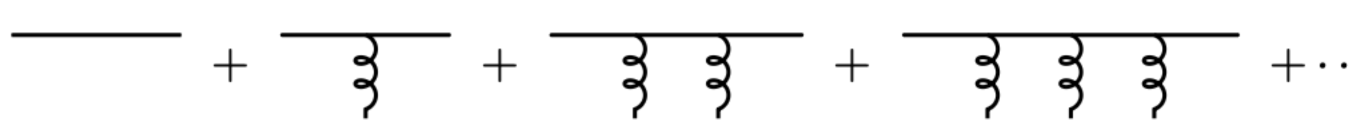
- because of motion in +/- directions, infinite Wilson lines yield rapidity divergences, regulated by rapidity cutoff η.
  Then states Φ renormalised by evolution equation, driven by boost Hamiltonian

$$-\frac{d}{d\eta}\tilde{\Phi}_i^\eta = \hat{H}\,\tilde{\Phi}_i^\eta$$

gravity analog of Balitsky-JIMWLK

- parametrise Wilson line through Reggeised graviton expansion

$$\tilde{\Phi}_i(z) = \exp\left[i\frac{\kappa}{\hbar}\sqrt{\frac{s}{2}}\,\tilde{W}(z)\right] \qquad \tilde{W}(z) = \int_{-\infty}^{\infty} dx^+\, h_{++}(x^+,0,z)\,.$$

$\Phi_i(q)|0\rangle =$ 

Caron-Huot 1309.6521
Caron-Huot Gardi Vernazza 1309.6521

Gravity massless scattering: shock waves

- amplitude driven by rapidity evolution between projectile & target

$$i\mathcal{M}^{\rm MRK}_{2\to 2}(s,q^2)\,\hat\delta^{(d)}\left(q-q'\right) = 2s\,\langle\Psi_j(q')|\,e^{-\hat H L}|\Psi_i(q)\rangle$$

with boost Hamiltonian

$$\hat H \begin{pmatrix} W \\ WW \\ WWW \\ \vdots \end{pmatrix} = \begin{pmatrix} \hat H_{1\to1} & 0 & 0 & \cdots \\ 0 & \hat H_{2\to2} & 0 & \cdots \\ 0 & 0 & \hat H_{3\to3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} W \\ WW \\ WWW \\ \vdots \end{pmatrix} + \mathcal{O}(\kappa^4)$$

- amplitude is $s \leftrightarrow u$ crossing symmetric, thus off-diagonal *H* terms mixing even and odd number of Reggeised gravitons are forbidden $\hat H_{k,k\pm 2n+1} = 0$
- off-diagonal terms $\hat H_{k,k\pm 2n} = 0$ are also forbidden because either quantum or sub-leading
- $\hat H_{k,k} = \hat{\mathcal{R}}_1 + \hat{\mathcal{R}}_2$

$$\hat{\mathcal{R}}_1 = \int d^d q_\perp\, \alpha^{(1)}(q_\perp)\, W(q)\, \frac{\delta}{\delta W(q)}$$

dresses Reggeised graviton with Regge trajectory: quantum

$$\hat{\mathcal{R}}_2 = \frac{\hbar\kappa^2}{8\pi} \int \hat d^d \ell_\perp\, d^d q_{1\perp}\, d^d q_{2\perp} H_{22}(\ell; q_1, q_2) W(q_1+\ell) W(q_2-\ell) \frac{\delta}{\delta W(q_1)}\, \frac{\delta}{\delta W(q_2)}$$

exchanges soft graviton between 2 Reggeised gravitons

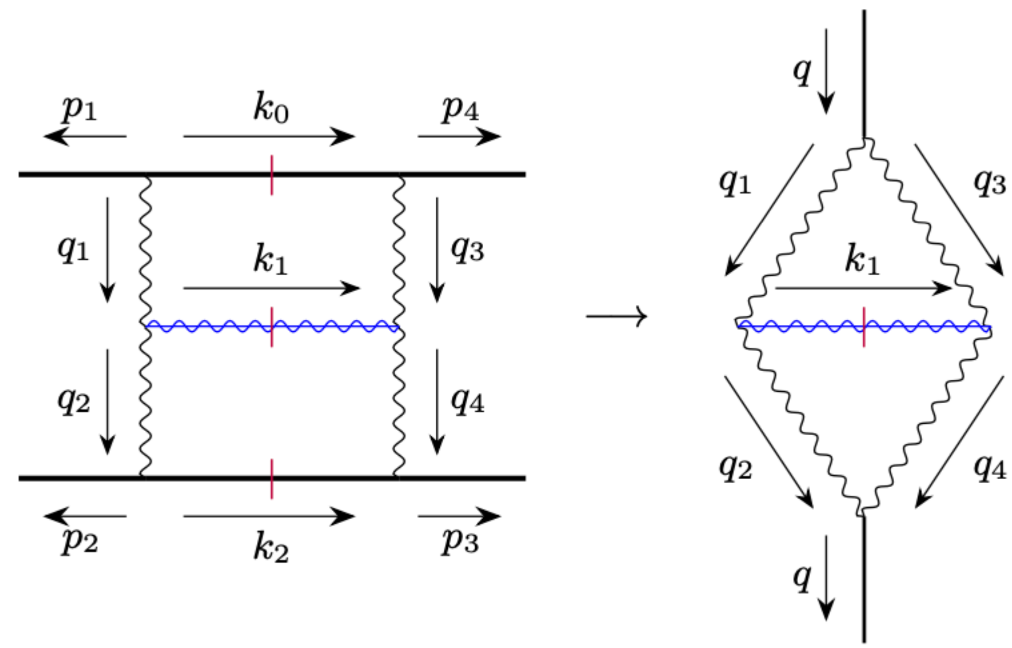
$$H_{22}(\ell;\, q_1, q_2) = \frac{\mathcal{H}_{\rm GR}(q_1, q_1+l; q_1+q_2)}{q_1^2\, q_2^2}$$

H_{GR}: Gravity (BFKL-like) kernel

Gravity scattering: *s*-channel unitarity cuts

- Revisiting the *H* diagram   Amati Ciafaloni Veneziano 1990

in MRK, the light-cone dof's decouple from the transverse dof's



$$2\mathrm{Im}\,\mathcal{M}^{(2)}_{2\to2}(s,q^2) \simeq \frac{(8\pi G_N)^3 s^3}{8\pi}\log(s) H_1(q_\perp^2),$$

$$H_1(q_\perp^2) \equiv \varsigma^{2\epsilon}\int_{q_{1\perp},\,q_{2\perp}} \frac{\mathcal{K}^{\mathrm{GR}}(q_1,q_2;q)}{q_{1\perp}^2 q_{2\perp}^2 (q-q_1)_\perp^2 (q-q_2)_\perp^2}$$

$\varsigma = \mu^2 \exp(\gamma_E)$. Gravity (BFKL-like) kernel

$$\mathcal{K}^{\mathrm{GR}}(q_1,q_2;q_3,q_4) = \left[(q_{1_\perp}+q_{3_\perp})\cdot(q_{2_\perp}+q_{4_\perp}) - \frac{q_{2_\perp}^2 q_{3_\perp}^2 + q_{1_\perp}^2 q_{4_\perp}^2}{k_\perp^2}\right]^2 + \frac{4}{k_\perp^4}\left[q_{1_\perp}^2 q_{2_\perp}^2 q_{3_\perp}^2 q_{4_\perp}^2 - q_{3_\perp}^2 q_{4_\perp}^2 (q_{1_\perp}\cdot q_{2_\perp})^2 - q_{1_\perp}^2 q_{2_\perp}^2 (q_{3_\perp}\cdot q_{4_\perp})^2\right]$$

graviton CEV is double copy of gluon CEV   Lipatov 1982

in momentum space $2\mathrm{Im}\,\mathcal{M}^{(2)}_{2\to2}(s,q^2) = 8G_N^3 s^3 \log(s)\left(\frac{4\pi\mu^2}{q^2}\right)^{2\epsilon}\left(-\frac{1}{\epsilon^2}+\frac{2}{\epsilon}+\zeta_2+\mathcal{O}(\epsilon^0)\right)$

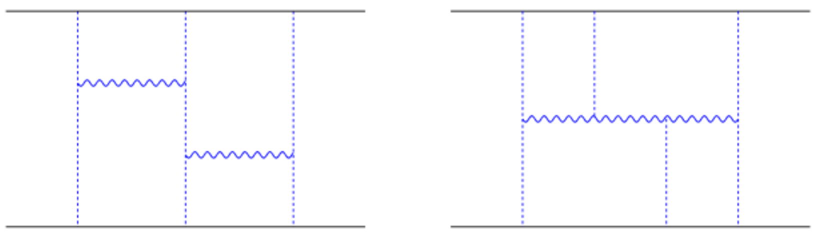
Fourier transforming to impact parameter space

$$\tilde{\mathcal{M}}_{2\to2}(s,b) \simeq \frac{1}{2s}\int \hat{d}^d q_\perp e^{ib\cdot q_\perp}\mathcal{M}_{2\to2}(s,-q_\perp^2) \equiv \mathrm{F.T.}[\mathcal{M}_{2\to2}](s,b)$$

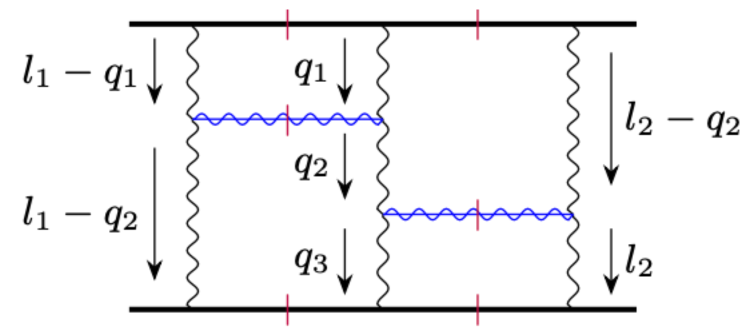
$$2\mathrm{Im}\,\tilde{\mathcal{M}}^{(2)}_{2\to2}(s,b^2) = \frac{8G_N^3 s^2}{\pi b^2}\log(s)\left(\pi b^2\varsigma e^{\gamma}\right)^{3\epsilon}\left(-\frac{1}{\epsilon}+2+\mathcal{O}(\epsilon^0)\right)$$

Gravity scattering: H^2 diagram

- early work by Amati Ciafaloni Veneziano 0712.1209
  Ciafaloni Colferai Coradeschi Veneziano 1512.00281



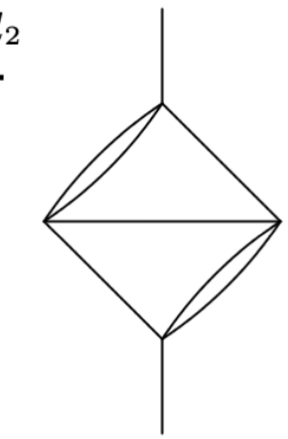
- through iterated *s*-channel 3-particle cuts



$$2\mathrm{Re}\,\mathcal{M}^{(4)}_{2\to 2}(s,q^2) \simeq -\frac{(8\pi G_N)^5 s^4}{64\pi^2}\log^2(s) H_2(q_\perp^2)$$

with H_2 the convolution of two gravity kernels

the result is reduced to bubbles and a kite integral



in momentum space

$$2\mathrm{Re}\mathcal{M}^{(4)}_{2\to 2}(s,q^2) \simeq -4\,G_N^5 s^4 \log^2(s)\frac{q^2}{\pi}\left(\frac{4\pi\mu^2}{q^2}\right)^{4\epsilon}\left[-\frac{1}{\epsilon^3}-\frac{1}{\epsilon^2}-\frac{9}{\epsilon}+\frac{2}{\epsilon}\zeta_2+\frac{2}{\epsilon}\zeta_3+O(1)\right]$$

i.e. an $O(G^5\, s^4 \log^2(s/|t|))$ term

in impact parameter space

$$2\mathrm{Re}\tilde{\mathcal{M}}^{(4)}_{2\to 2}(s,b^2) \simeq -256\,G_N^5\frac{s^3\log^2(s)}{(\pi b^2)^2}\left(\pi b^2 \varsigma e^{\gamma}\right)^{5\epsilon}\left[\frac{1}{8\epsilon^2}-\frac{1}{\epsilon}+\frac{5}{2}+\frac{5}{16}\zeta_2-\frac{1}{4}\zeta_3+O(\epsilon)\right]$$

Alessio VDD Gonzo Rosi Rothstein Saavedra 2511.11457

Discussion

- in Regge theory, 2→2 amplitudes are given by a t channel ladder convoluted with impact factors

$$\mathcal{M}_{2\to 2} = i\sum_{M} J_{(M)} \otimes S_{(M)} \otimes \bar{J}_{(M)}$$

- for a t channel ladder at leading logarithmic accuracy, we need impact factors at leading order (LO)

- the LO impact factors for a massless graviton and a for a massive scalar differ only by a phase

- since the t channel ladder is universal and the LO impact factors for a massless scalar/graviton and a for a massive scalar are the same up to a phase, due to the spin and not to the mass, this implies that the scattering of massive scalars and the scattering of gravitons or massless scalars share the same leading logarithms!

- … which then implies that in the scattering of massive scalars we have determined the leading logarithmic contribution to the 5PM-2SF amplitude

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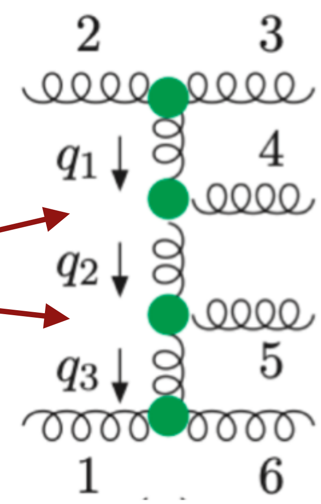
Going to next-to-leading log

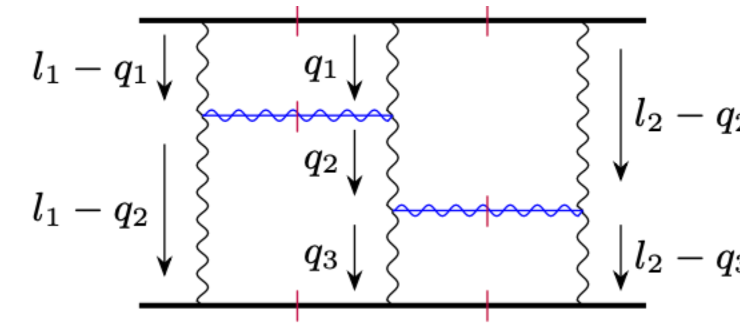
anatomy of gravity amplitudes in the Regge limit

- leading log

  one-graviton CEV

  Lipatov 1982

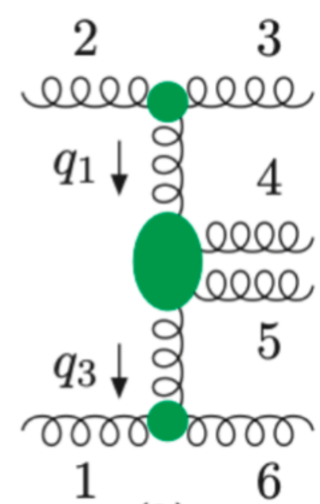




- next-to-leading log

  two-graviton CEV

  Barcaro VDD 2506.11822



?

requires NMHV graviton amplitudes

Cachazo Svrcek 2005
Hodges 1108.2227

we broke ground… but more work is required for a next-to-leading log ladder

Conclusions

- Using an EFT of gravity scattering of massless particles in the Regge limit, Rothstein & Saavedra showed that, at leading logarithmic accuracy, $2\to 2$ amplitudes exhibit an *s*-channel sequence of classical terms, which generalise the *H* diagram through corrections of $O((G^2\, s \log(s/|t|))^n)$

- Each of those terms, of (2n+3)-PM order, is the sole classical term of a tower of (quantum) terms associated to the exchange of (n+2) Glauber (Reggeised) gravitons

- In gravity scattering of massless particles, the same s-channel sequence may be obtained through a gravity version of the shock-wave formalism, which is equivalent to Rothstein-Saavedra's EFT, and through iterated *s*-channel unitarity cuts

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- The unitarity-cut formalism may be extended to the scattering of massive particles, and yields, at leading logarithmic accuracy, the same *s*-channel sequence of classical terms, which are of (2n+3)-PM and (n+1)-SF order, i.e. maximal SF within a given PM

- Using Rothstein-Saavedra's EFT, the shock-wave formalism, and iterated *s*-channel unitarity cuts, we computed the H^2 diagram, which is an $O(G^5 s^4 \log(s/|t|)^2)$ term, i.e. a 5 PM term, and represents the first correction to the *H* diagram

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- Through the unitarity-cut formalism, that computation is extended to the scattering of massive scalars, and yields the 5 PM, 2 SF term at leading logarithmic accuracy

so the take away is…

- For gravity scattering of massless particles in the Regge limit, we have 3 different but equivalent solutions:
  - Rothstein-Saavedra's EFT
  - shock-wave formalism
  - iterated *s*-channel unitarity cuts

- at leading logarithmic accuracy, unitarity-cut outcome can be ported to the scattering of massive particles for free