Scattering Amplitudes in Effective Gravitational Theories

Stavros Mougiakakos

Based on:

- M. Levi, S. Mougiakakos and M. Vieira; arXiv : 1912.06276

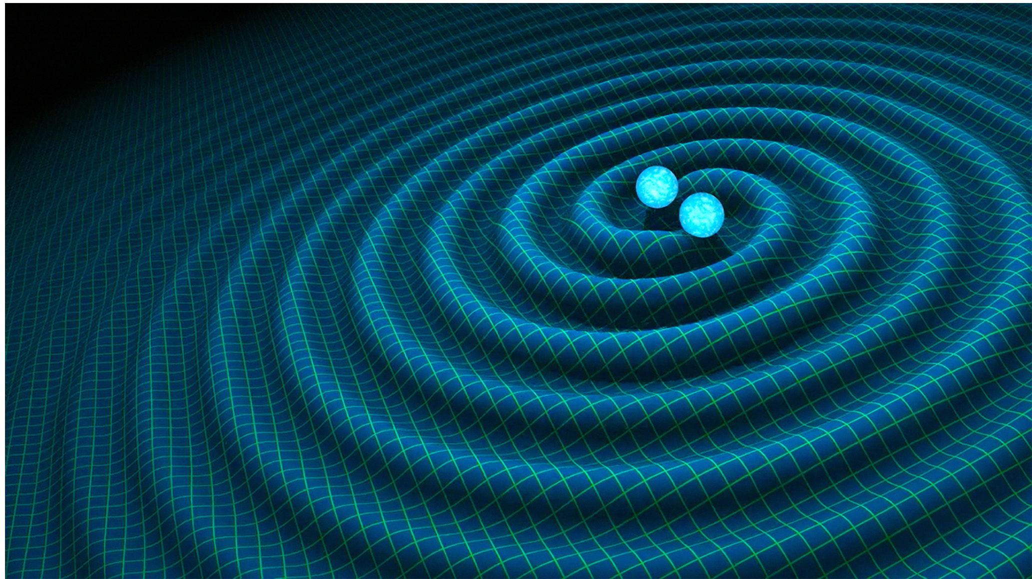
Waveforms and Tests of general relativity and alternative theories, 4 February 2020, Paris

Observational Window on gravity

The detection of gravitational waves (GW150914) has opened a new window on the physics of our universe:

- For the first time detection and test of GR in the “strong” gravity coupling regime
- For the first time dynamics of BH/NS

(not just static object curving space-time)



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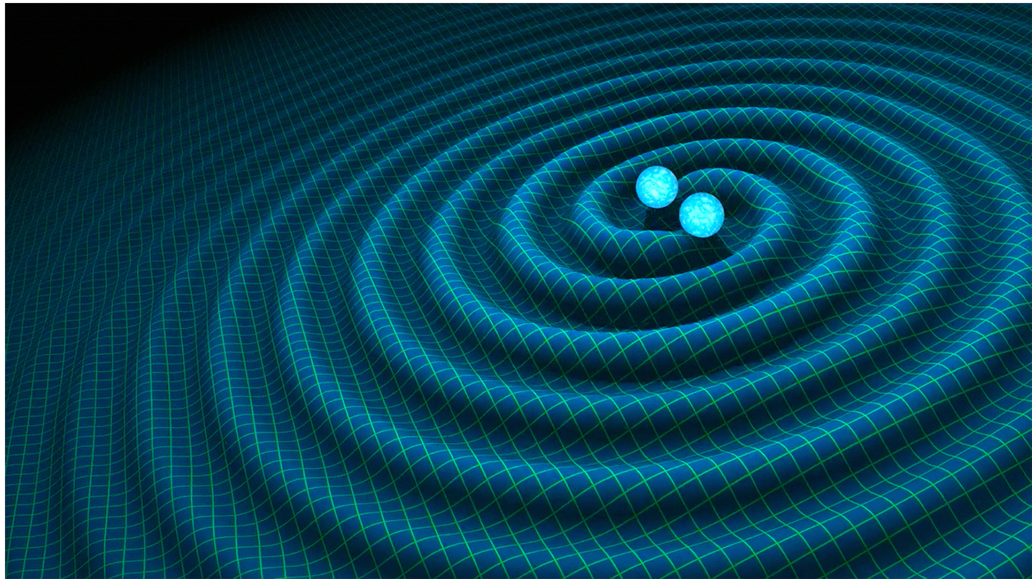
Gravitational Wave Era has began!



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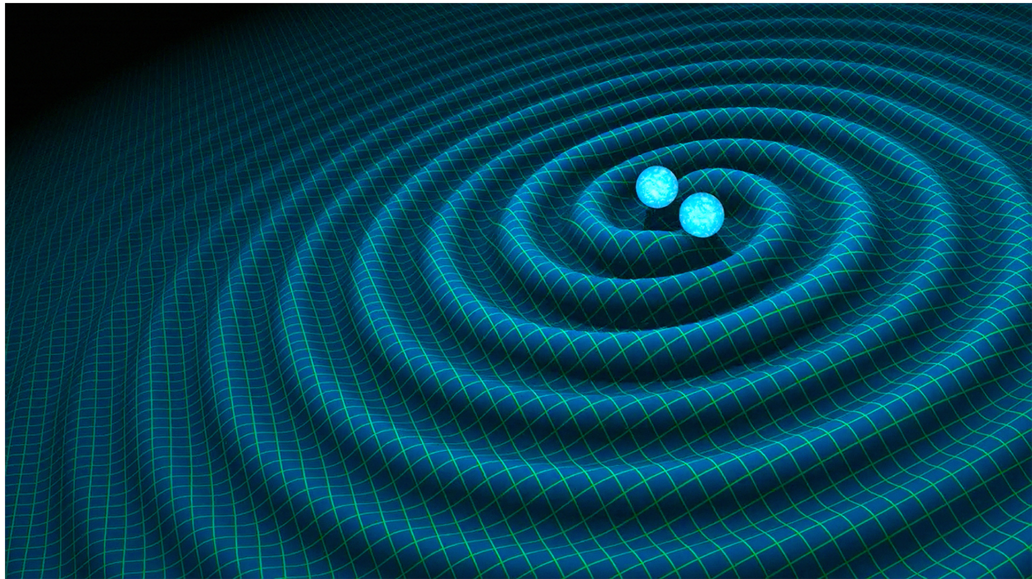
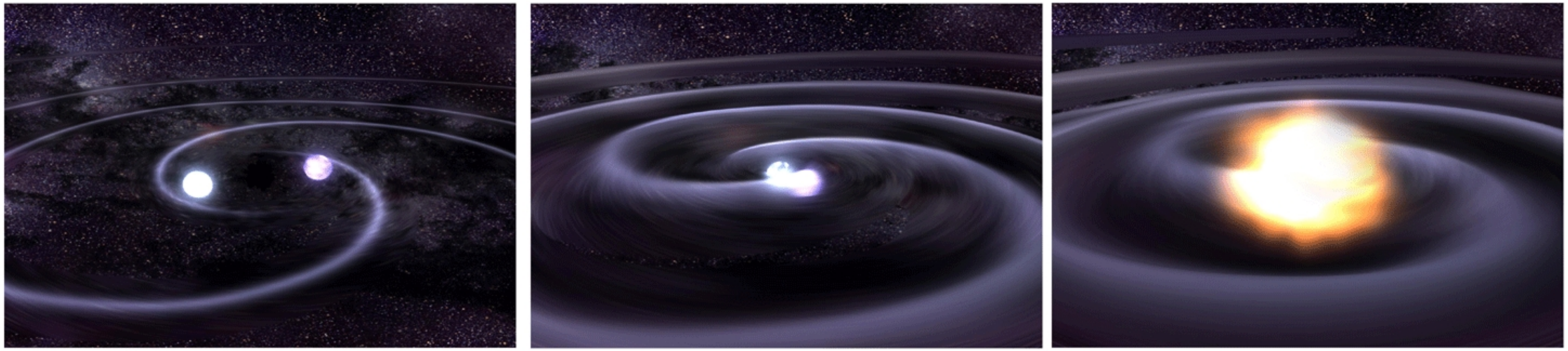
What can we learn from the gravitational wave signals?



2-body problem



Inspiral Merger Ringdown

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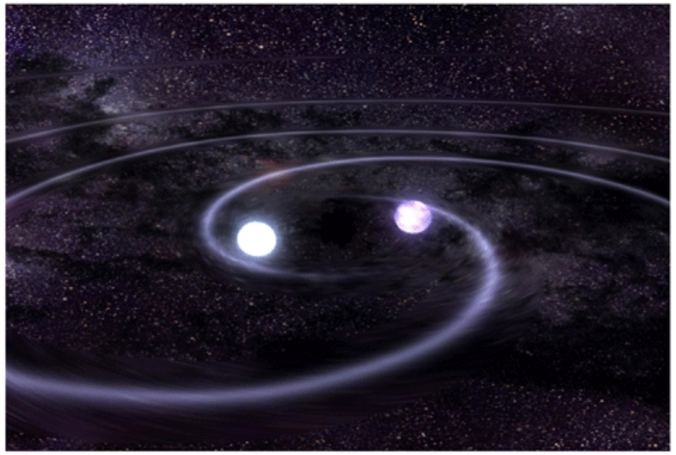
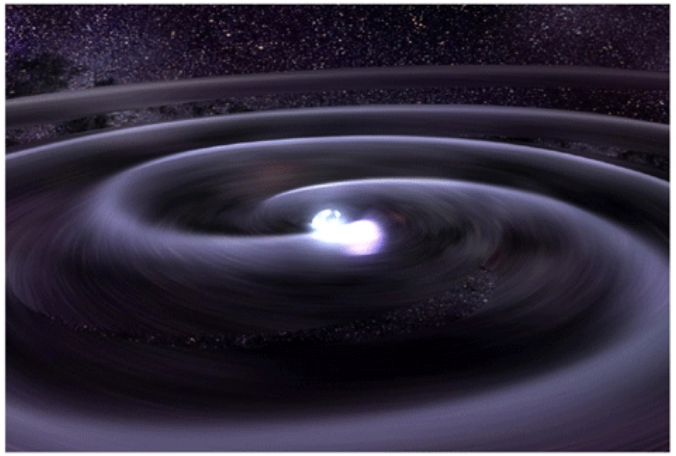
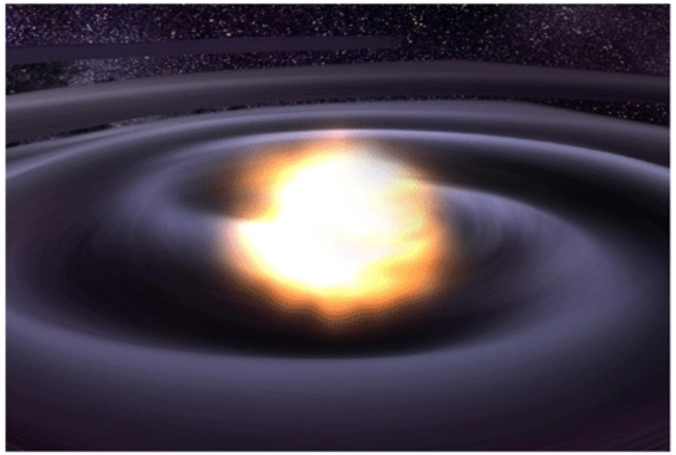


Inspiral



Merger



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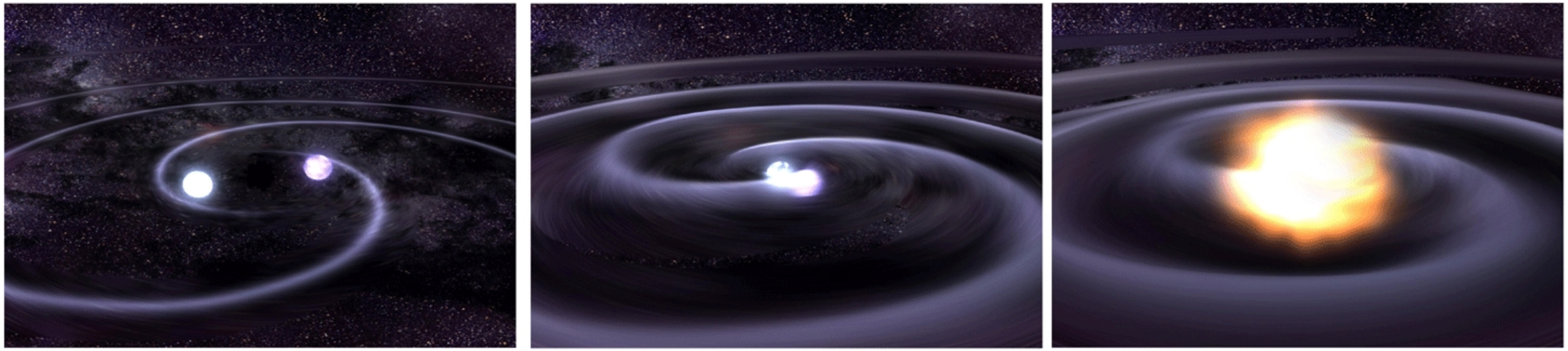

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A lot of work has already been done in the analytical solution in perturbative GR.

T. Damour, L. Blanchet, A. Buonanno et al.

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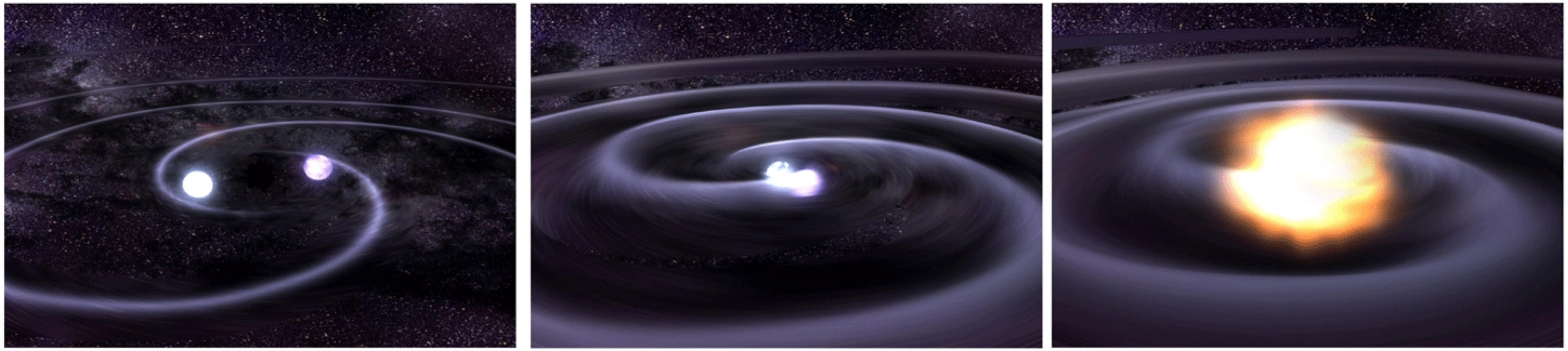

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Can the particle physics community contribute to this problem?

Quantum Gravity

↙

UV Completion of Gravity

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- Main candidate: **Superstring Theory**
- Exciting field of research with many questions left to be answered

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I will not talk about it...

(“useful” for our problem) Quantum Gravity

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Quantum Gravity as an EFT

John F. Donoghue; arXiv : gr-qc/9512024

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PNEFT

W. D. Goldberger, I. Z. Rothstein; arXiv : hep-th/0409156

Very efficient for classical contributions due to good control of power counting

Particle Physicist’s Point of View on the gravitational 2-body problem

↙ ↘

EFT of Post-Newtonian Gravity

W.D Goldberger, I. Rothstein, R. Porto , M. Levi et al

- Classical computation
- Takes advantage of QFT toolbox
- Non relativistic computation
- Can deal effectively with spin effects
- State of the art (conservative):
  4-PN without spins
  4,5-PN(S^3)

Scattering Amplitudes and Post-Minkowskian

Z. Bern, N. Arkani-Hamed, P. Vanhove, N.E.J. Bjerrum-Bohr, J. Donoghue, D. Kosower et al.

- Quantum computation
- Takes advantage of modern methods for on-shell scattering amplitudes (BCJ relations/double copy)
- Fully relativistic computation
- Active work for inclusion of spin effects
  arXiv:1709.04891, arXiv:1812.08752
- State of the art (conservative): 3-PM without spins

Scattering Amplitudes and Post-Minkowskian expansion

John F. Donoghue; arXiv : gr-qc/9512024v1

- Non-renormalizability can be handled order by order
- Long-range contributions can be calculated in this framework since they depend only on the structure of the low-energy fields and the classical background

$$\mathcal{L}_g = \sqrt{g}\left\{\frac{2}{\kappa^2}R + c_1 R^2 + c_2 R_{\mu\nu}R^{\mu\nu} + \mathcal{O}(R^3)\right\}$$

Scattering Amplitudes and Post-Minkowskian expansion

Loops give classical contributions!

$$\mathcal{M}_{n-loop} = \frac{M^3}{\hbar\sqrt{-s}^3}(r_S\sqrt{-s})^{n+1}\sum_{k=0}^{n}\alpha_k(\lambda\sqrt{-s})^k$$

where $\lambda = \frac{\hbar}{M}$

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WHY?!

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BECAUSE

Restoring units in Klein-Gordon eq:

$$(\Box + \frac{m^2}{\hbar^2})\phi(x) = 0$$

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$\downarrow$

When we have massless+massive particles, the powercounting gives us above.

Scattering Amplitudes and Post-Minkowskian expansion

The problem of getting a Post-Minkowskian expansion of the potential comes down to computing loop diagrams.

$$V(\boldsymbol{p}, \boldsymbol{r}) = \sum_{n=1}^{\infty} \left(\frac{G}{|\boldsymbol{r}|} \right)^n c_n(\boldsymbol{p}^2)$$

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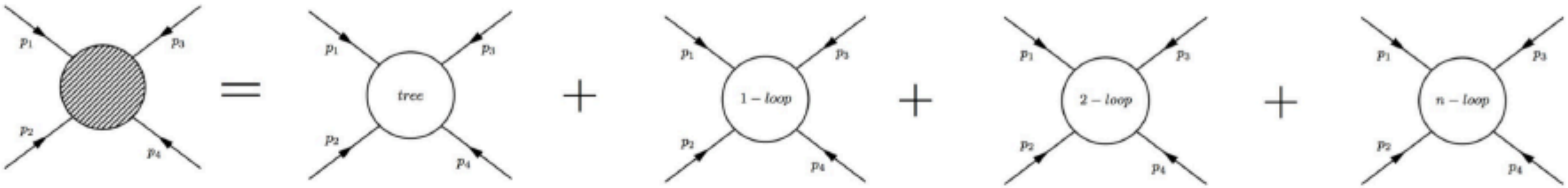
<u>WHICH TOPOLOGIES ARE WE LOOKING FOR?</u>

Scattering Amplitudes and Post-Minkowskian expansion



$$\frac{Gm_1m_2}{r} \qquad \frac{G^2m_1^2m_2}{r^2},\ \frac{G^2m_1m_2^2}{r^2} \qquad \frac{G^3m_1^3m_2}{r^3},\ \frac{G^3m_1^2m_2^2}{r^3},\ \frac{G^3m_1m_2^3}{r^3} \qquad \frac{G^{n+1}m_1m_2}{r^{n+1}}\sum_{k=0}^{n} m_1^k m_2^{n-k}$$

In general:

$$\frac{\hbar G^2m_1m_2}{r^3} \qquad \frac{\hbar G^3m_1^2m_2}{r^4}\ \ \frac{\hbar G^3m_1m_2^2}{r^4} \qquad \frac{\hbar G^{n+1}m_1m_2}{r^{n+2}}\sum_{k=0}^{n-1} m_1^k m_2^{n-1-k}$$

$$\frac{\hbar^2 G^3m_1m_2}{r^5} \qquad \frac{\hbar^2 G^{n+1}m_1m_2}{r^{n+3}}\sum_{k=0}^{n-2} m_1^k m_2^{n-2-k}$$

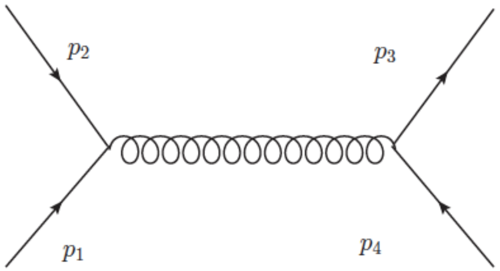
$$\dots$$

$$\frac{\hbar^n G^{n+1}m_1m_2}{r^{2n+1}}$$

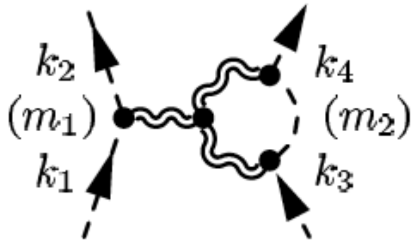
Scattering Amplitudes and Post-Minkowskian expansion

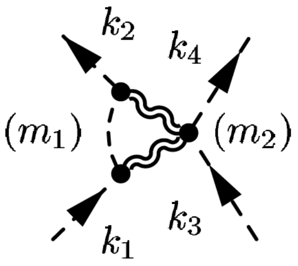
Classical terms

- Tree-level:



- 1-loop:

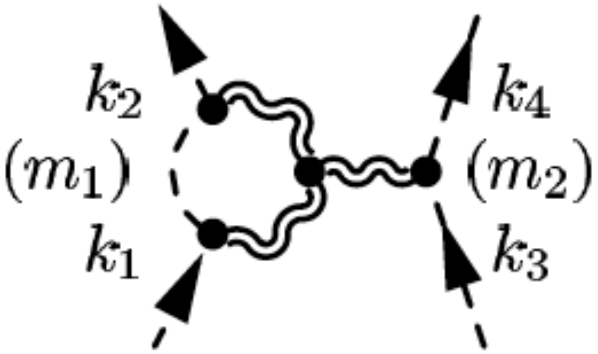


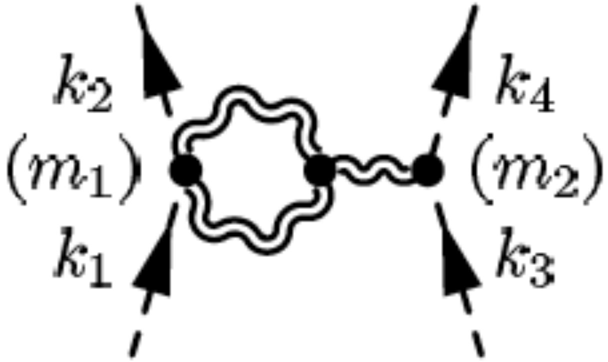


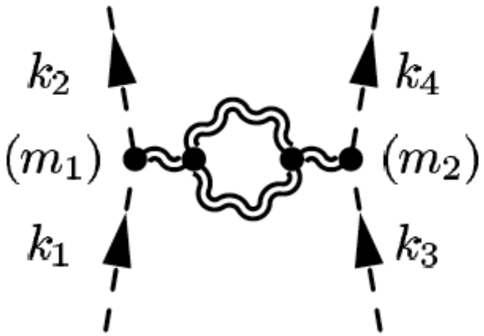
Scattering Amplitudes and Post-Minkowskian expansion

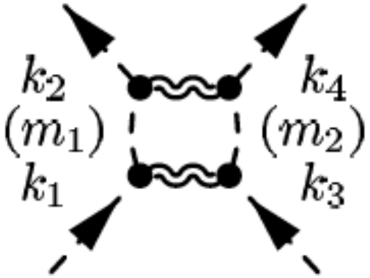
Quantum contributions

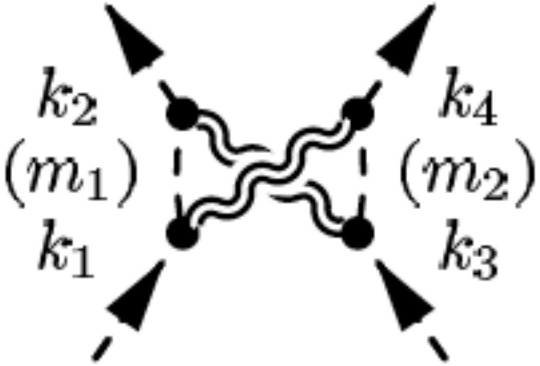
- 1-loop:

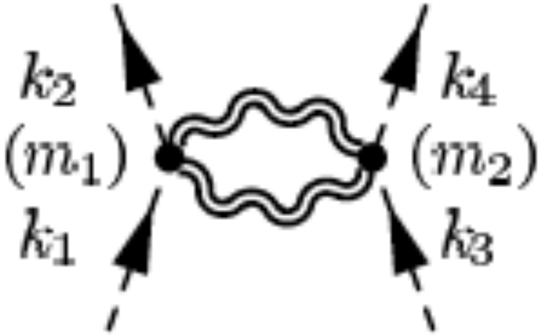






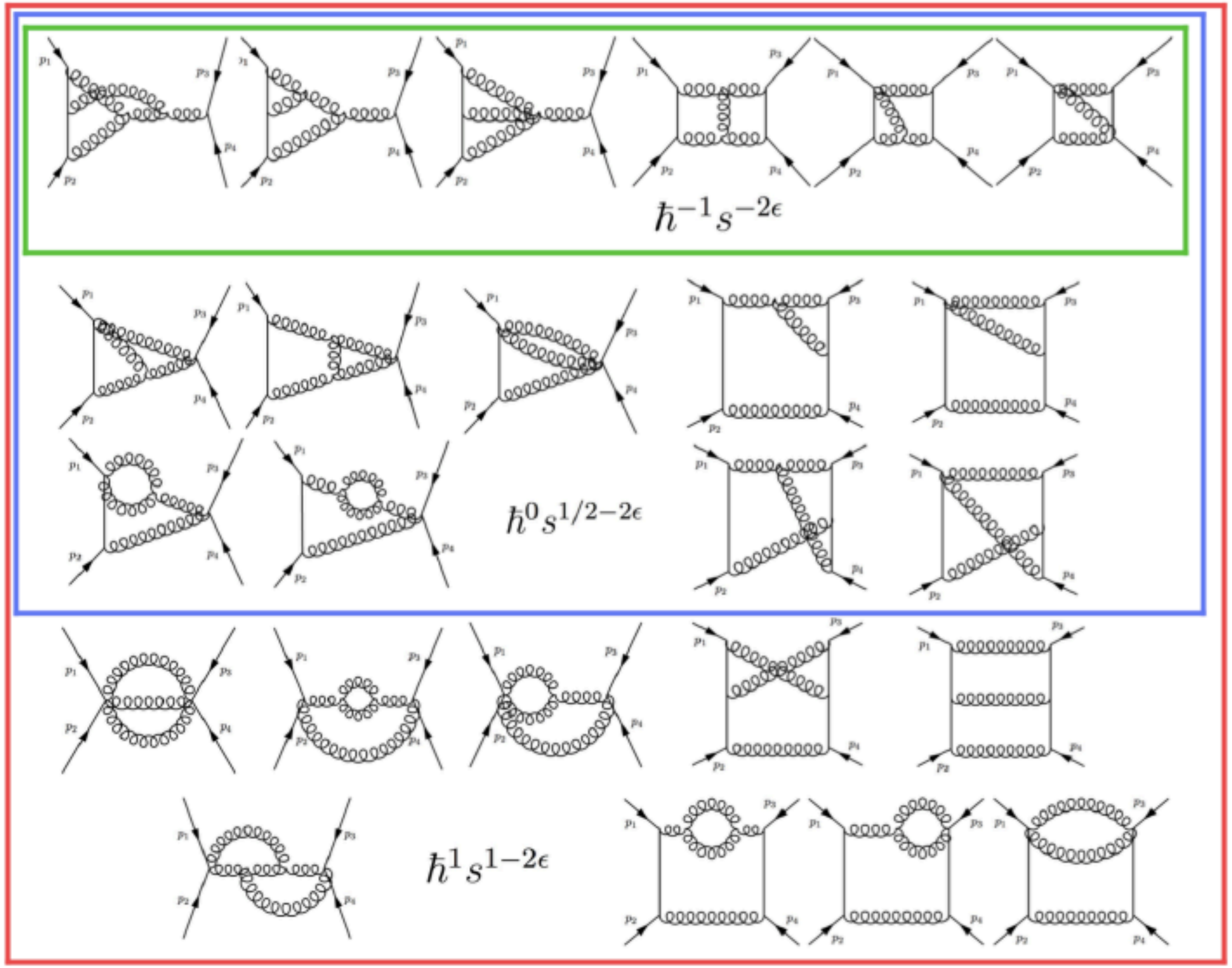






Scattering Amplitudes and Post-Minkowskian expansion

- 2-loops:
(both classical and quantum contributions)



Scattering Amplitudes and Post-Minkowskian expansion

We know which diagrams we are looking for and what contributions they give.

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BUT graviton amplitudes are really hard!!

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DOUBLE COPY!!

$$\text{gravity} \sim (\text{gauge theory}) \times (\text{gauge theory}).$$

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$$\text{gravity} \sim (\text{gauge theory}) \times (\text{gauge theory}).$$

KLT relation of string amplitudes → BCJ relations/ double copy

spinor helicity formalism

Generalized Unitarity

Scattering Amplitudes and Post-Minkowskian expansion

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

$\vdots$

Scattering Amplitudes and Post-Minkowskian expansion

State of the art computation (Conservative Sector)

- Spin-less: 3 PM (2 loops) arXiv:1908.01493v1.
- Spin effects: 2 PM (1 loop) arXiv:1812.08752v3

EFT of Post-Newtonian Gravity

EFT of Post-Newtonian Gravity

EFT of Post-Newtonian Gravity

Hierarchy of scales:

scale of internal structure: $r_s \sim Gm$

scale of orbital separation: $r \sim r_s/v^2$

scale of radiation wavelength: $\lambda_{\rm rad} \sim r/v$

EFT of Post-Newtonian Gravity

$$S\left[g_{\mu\nu}\right] = -\frac{1}{16\pi G}\int d^4x\sqrt{g}R.$$

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$$S_{\text{eff}}\left[y^\mu, e^\mu_A, \bar{g}_{\mu\nu}\right] = -\frac{1}{16\pi G}\int d^4x\sqrt{\bar{g}}R\left[\bar{g}_{\mu\nu}\right] + \underbrace{\sum_i C_i \int d\sigma O_i(\sigma)}_{S_{pp}\equiv\text{point particle action}}$$

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In the following we consider the **conservative sector**, so the radiation modes are absent.

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where $$S_{\text{pp}} = \int d\sigma\left[-m\sqrt{u^2} - \frac{1}{2}S_{\mu\nu}\Omega^{\mu\nu} + L_{\text{SI}}\left[u^\mu, S_{\mu\nu}, g_{\mu\nu}\left(y^\mu\right)\right]\right]$$

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and $$L_{\text{SI}} = \sum_{n=1}^{\infty}\frac{(-1)^n}{(2n)!}\frac{C_{ES^{2n}}}{m^{2n-1}}D_{\mu_{2n}}\cdots D_{\mu_3}\frac{E_{\mu_1\mu_2}}{\sqrt{u^2}}S^{\mu_1}S^{\mu_2}\ldots S^{\mu_{2n-1}}S^{\mu_{2n}}$$
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Proven useful to make a Kaluza-Klein reduction over the time dimension to decompose the metric, since we are working in the NR limit and the orbital modes are instantaneous at leading order:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu \equiv e^{2\phi}(dt - A_i dx^i)^2 - e^{-2\phi}\gamma_{ij}dx^i dx^j$$

EFT of Post-Newtonian Gravity Spinning Particle

M. Levi, S. Mougiakakos and M. Vieira; arXiv : 1912.06276

MOTIVATION 1

l \ n	$(N^0)LO$	$N^{(1)}LO$	N^2LO	N^3LO	N^4LO
S^0	1	0	3	0	25
S^1	2	7	32		
S^2	2	2	18		
S^3	4	24			
S^4	3				

$n + l + \text{Parity}(l)/2$

PN correction

The number of n-loop graphs that enter at each order=measure for loop computational scale

EFT of Post-Newtonian Gravity Spinning Particle

M. Levi, S. Mougiakakos and M. Vieira; arXiv : 1912.06276

MOTIVATION 2

The Tulczyjew gauge for the rotational degrees of freedom, which involves the linear momentum, can no longer be approximated by the 4-velocity:

$$p^{\mu} = m\frac{u^{\mu}}{\sqrt{u^2}} + \mathcal{O}(S^2)$$

MOTIVATION 3

We can compare with results coming from scattering amplitudes for s>1, specifically s=3/2

arXiv:1709.04891, arXiv:1812.08752

EFT of Post-Newtonian Gravity Spinning Particle

Degrees of Freedom

- Gravitational field: metric+tetrad fields

$$\eta^{ab}\tilde{e}_a{}^{\mu}(x)\tilde{e}_b{}^{\nu}(x) = g^{\mu\nu}(x)$$

- Particle Coordinate
- Particle Worldline Rotating DOFs:

worldline tetrad: $\eta^{AB}e_A{}^{\mu}(\sigma)e_B{}^{\nu}(\sigma) = g^{\mu\nu}$

$\swarrow$

$$\Omega^{\mu\nu} \equiv e^{\mu}_{A}\frac{De^{A\nu}}{D\sigma} \quad \rightarrow \quad S_{\mu\nu} \equiv -2\frac{\partial L}{\partial\Omega^{\mu\nu}}$$

We then disentangle the worldline tetrad from the tetrad field such that we are left with the local worldline DOFs:

$$\eta^{AB}\Lambda_A{}^{a}(\sigma)\Lambda_B{}^{b}(\sigma) = \eta^{ab}$$

$$S_{ab}(\sigma)$$

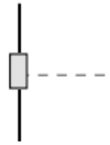
EFT of Post-Newtonian Gravity Spinning Particle

$$S_{\text{eff}}\left[y_1^\mu, y_2^\mu, e_{(1)}{}_A^\mu, e_{(2)}{}_A^\mu, \bar{g}_{\mu\nu}\right] = -\frac{1}{16\pi G}\int d^4x\sqrt{\bar{g}}R\left[\bar{g}_{\mu\nu}\right] + S_{(1)\text{pp}} + S_{(2)\text{pp}}$$

where $$S_{\text{pp}} = \int d\sigma\left[-m\sqrt{u^2} - \frac{1}{2}S_{\mu\nu}\Omega^{\mu\nu} + L_{\text{SI}}\left[u^\mu, S_{\mu\nu}, g_{\mu\nu}\left(y^\mu\right)\right]\right]$$

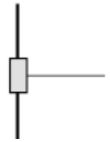
and $$L_{\text{SI}} = \sum_{n=1}^{\infty}\frac{(-1)^n}{(2n)!}\frac{C_{ES^{2n}}}{m^{2n-1}}D_{\mu_{2n}}\cdots D_{\mu_3}\frac{E_{\mu_1\mu_2}}{\sqrt{u^2}}S^{\mu_1}S^{\mu_2}\ldots S^{\mu_{2n-1}}S^{\mu_{2n}}$$
$$+\sum_{n=1}^{\infty}\frac{(-1)^n}{(2n+1)!}\frac{C_{BS^{2n+1}}}{m^{2n}}D_{\mu_{2n+1}}\cdots D_{\mu_3}\frac{B_{\mu_1\mu_2}}{\sqrt{u^2}}S^{\mu_1}S^{\mu_2}\ldots S^{\mu_{2n-1}}S^{\mu_{2n}}S^{\mu_{2n+1}}$$

EFT of Post-Newtonian Gravity
Spinning Particle

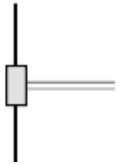


$$= \int dt \left[\frac{C_{\mathrm{BS}^3}}{12m^2} S^i S^j \epsilon_{klm} \Big[S^m \Big(\partial_i \partial_j \partial_l A_k (1 + \frac{v^2}{2}) + v^l (\partial_t A_{i,jk} + \partial_t A_{k,ij}) + \right.$$

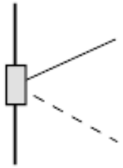
$$\left. + v^l v^n (A_{i,jkn} - A_{n,ijk}) \Big) - \frac{v^i}{2} A_{k,jln} (S^m v^n + S^n v^m) \Big] \right],$$



$$= \int dt \left[\frac{C_{\mathrm{BS}^3}}{3m^2} S^i S^j \epsilon_{klm} S^m v^l \Big(\partial_i \partial_j \partial_k \phi \, (1 + \frac{v^2}{2}) - \frac{1}{2} v^i v^n \partial_j \partial_k \partial_n \phi \Big) \right],$$

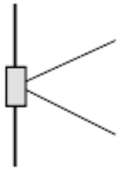


$$= \int dt \left[\frac{C_{\mathrm{BS}^3}}{12m^2} S^i S^j \epsilon_{klm} S^m \partial_i \partial_l \big(\partial_j \sigma_{kn} v^n - \partial_n \sigma_{jk} v^n - \partial_t \sigma_{jk} \big) \right]$$



$$= \int dt \left[\frac{C_{\mathrm{BS}^3}}{12m^2} S^i S^j \epsilon_{klm} S^m \big(2\phi_{,ijl} A_k - \phi \ A_{k,ijl} + 6\phi_{,il} A_{k,j} + 6\phi_{,j} \ A_{k,il} + \right.$$

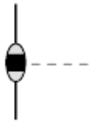
$$\left. + 4\phi_{,l} \ A_{k,ij} + 4\phi_{,ij} A_{k,l} + 2\phi_{,ik} A_{j,l} + 2\phi_{,k} \ A_{j,il} - \delta_{ij} \phi_{,n} A_{k,ln} \big) \right],$$



$$= \int dt \left[\frac{C_{\mathrm{BS}^3}}{3m^2} S^i S^j \epsilon_{klm} S^m v^l \big(3\phi_{,j} \ \phi_{,ik} + 3\phi_{,k} \ \phi_{,ij} - 3\phi \ \phi_{,ijk} - \delta_{ij} \phi_{,kn} \phi_{,n} \big) \right]$$

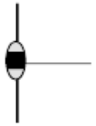
$$p^\mu = m \frac{u^\mu}{\sqrt{u^2}} + \mathcal{O}(S^2)$$

↓



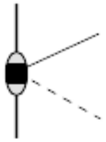
$$= \int dt \left[\frac{C_{\mathrm{ES}^2}}{4m^2} S^i S^j \epsilon_{klm} \Big[2S^m a^k \Big(A_{l,ij} - A_{j,il} + \delta_{ij} \left(A_{n,ln} - A_{l,nn} \right) \Big) \right.$$

$$\left. + \dot{S}^m v^k \Big(A_{l,ij} - A_{j,il} + \delta_{ij} \left(A_{n,ln} - A_{l,nn} \right) \Big) \Big] \right],$$

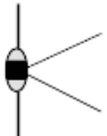


$$= \int dt \left[\frac{C_{\mathrm{ES}^2}}{2m^2} S^i S^j \epsilon_{klm} \Big[2S^m a^k \Big(\phi_{,il} v^j - \phi_{,ij} v^l + \delta_{ij} \left(\partial_t \phi_{,l} + \phi_{,nn} v^l \right) \Big) \right.$$

$$\left. + \dot{S}_m v^k \Big(\phi_{,il} v^j + \delta_{ij} \partial_t \phi_{,l} + \delta_{jl} \left(\partial_t \phi_{,i} + \phi_{,in} v^n \right) \Big) \Big] \right]$$

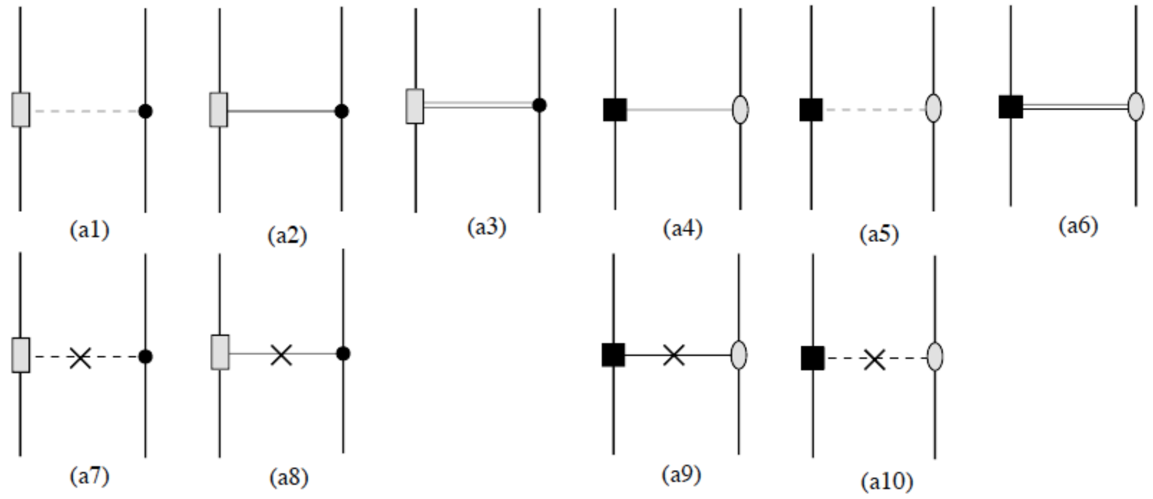


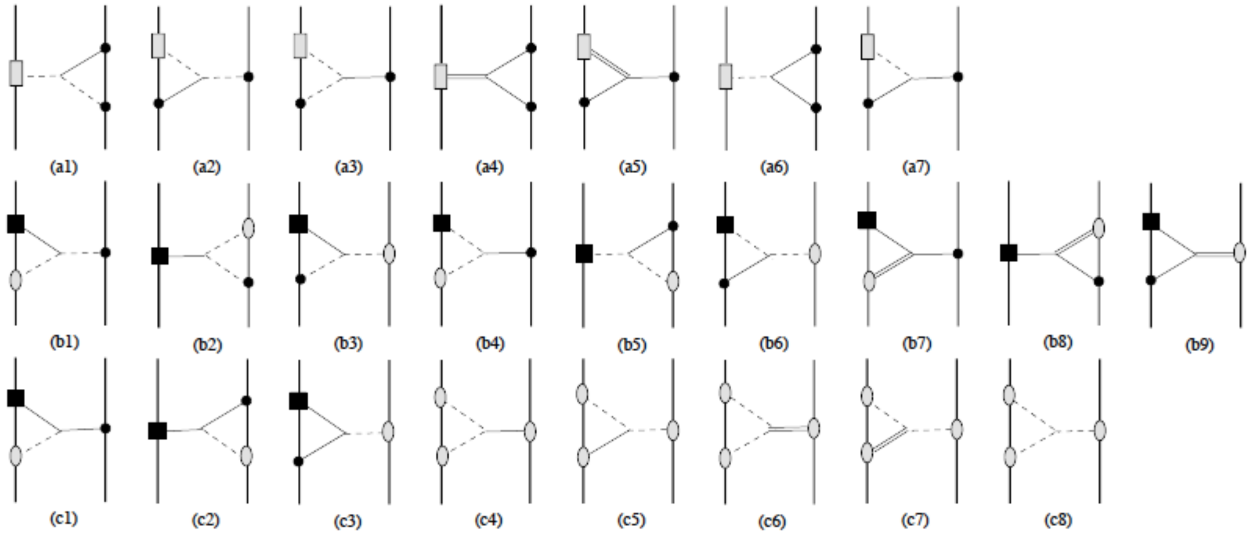
$$= \int dt \left[\frac{C_{\mathrm{ES}^2}}{2m^2} S^i S^j \epsilon_{klm} S^m \phi_{,k} \left(A_{j,il} - A_{l,ij} - \delta_{ij} \left(A_{n,ln} - A_{l,nn} \right) \right) \right]$$

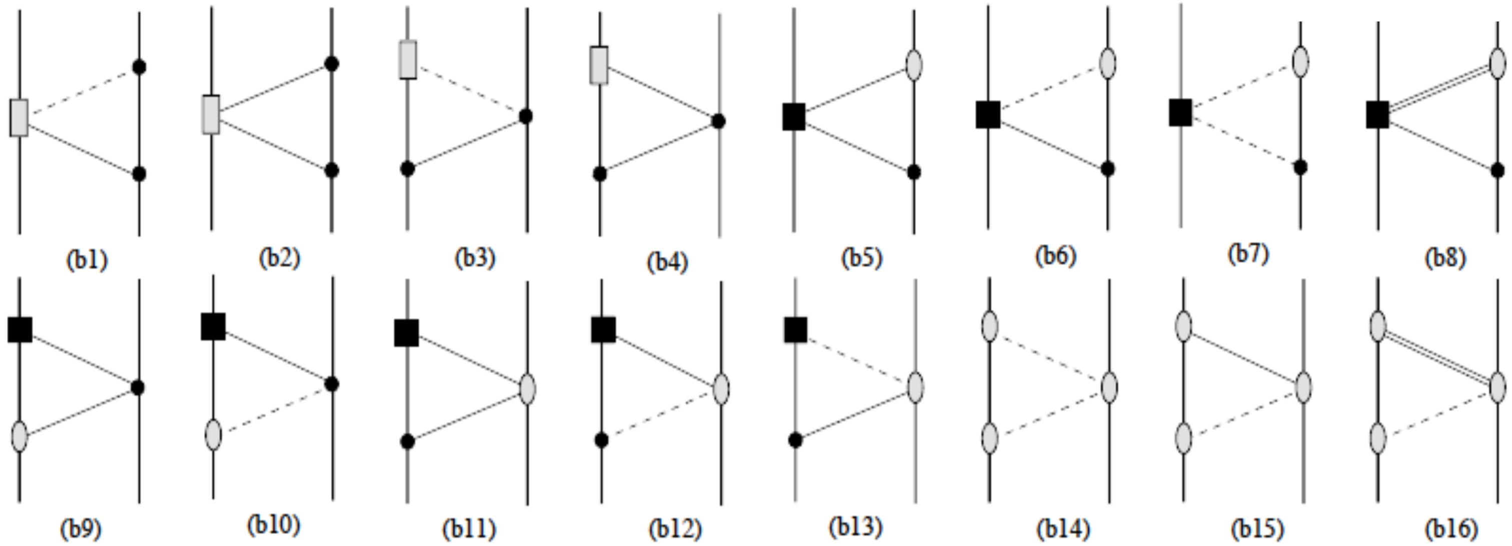


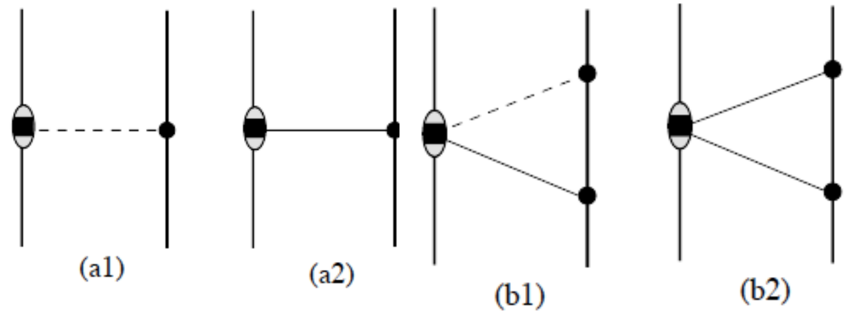
$$= \int dt \left[-\frac{C_{\mathrm{ES}^2}}{m^2} S^i S^j \epsilon_{klm} S^m \phi_{,k} \left(\phi_{,il} v^j - \delta_{ij} \partial_t \phi_{,l} \right) \right].$$

EFT of Post-Newtonian Gravity
Spinning Particle









EFT of Post-Newtonian Gravity

State of the art computation (Conservative Sector)

- Spin-less:4 PN arXiv:1607.04252.
- Spin-less:5 PN- static piece arXiv:1902.11180
- Spin-Orbit at NNLO (3.5 PN) arXiv:1506.05794
- Spin-Orbit at NNLO (4 PN) arXiv:1506.05794
- Cubic in Spin interactions at NLO (4.5 PN)-M. Levi, S.M. et all arXiv : 1912.06276

Outline

Scattering Amplitudes and Post-Minkowskian expansion

By utilizing the powerfull **on-shell techniques** (spinor-helicity formalism, generalized unitarity, BCJ relations etc), we can calculate both classical and quantum corrections:

- Higher order calculation of Post-Minkowskian expansion (needed for GW detectors)
- Inclusion of spin effects
- Inclusion of finite size effects
- Long-range quantum effects
- Modified gravity
- Supplementary computation to the Post-Newtonian expansion

Thank you for your attention

Outline

EFT of Post-Newtonian Gravity

By extending the computation to higher PN orders and spins:

- Tidal effects entering at 5 PN. Information about microphysics of internal structure
- Extension to radiation modes and non conservative sector
- Quantum corrections
- Modified gravity
- Supplementary computation to the Post-Minkowskian expansion