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Precision Gravity: Gravitational waves using Feynman diagrams

The observations of gravitational waves (GW) have proved to be a probe for the physics of celestial objects like black holes (BH) and neutron stars (NS). Such detections have the potential to unravel the mysteries of cosmic origins, equations of state of compact objects and will prove to be a test of the theory of general relativity. To successfully achieve these scientific goals, it is crucial to have waveform templates of high precision and accuracy. As the upgrades and the next generation of ground-based and space-based gravitational wave observatories become ever more sensitive, we need even more accurate waveform models to avoid systematics. My talk will focus on computing state-of-the-art effective two-body Hamiltonians for BHs and NSs using the techniques of quantum field theories and scattering amplitudes. These Hamiltonians are building blocks for waveform templates and they dictate the precision of the waveform model.

In the inspiral phase, the effective field theory techniques are used to obtain the post-Newtonian (PN) expansion i.e. expanding in orders of the small orbital velocity of binary constituents. Here nPN order is usually referred to as (v/c)^(2n) order correction to the Newtonian interaction. The determination of the effective Hamiltonian at a given PN order is equivalent to the computation of corresponding scattering amplitudes. These amplitudes are then calculated using Feynman diagrams, where tree diagrams represent leading contributions and higher-order corrections come from multiple-loop diagrams. Here tree diagrams are rational functions of the kinematic variables and are easy to compute, whereas loop diagrams represent very challenging integrals that necessitate advanced techniques like integration-by-parts identities and differential equations.

In particular, I will focus on analyzing the effects of spin and tidal interaction on the dynamics of compact binary systems. Astrophysical compact objects usually have a non-zero angular momentum and the effects of this "spin" are studied in order of spin interactions. I will describe the computation of linear-in-spin Hamiltonian that describes the interaction between the orbital angular momentum of the binary and the spin of one of its constituents at 4.5PN order [1] and quadratic-in-spin Hamiltonian that describes the coupling between spins of the constituents of the binary at 5PN order [2]. Furthermore, I will also describe oscillation modes of NS that arise due to tidal interactions, in particular, the fundamental-mode (f-mode) dynamical tides, which have been argued to be important in inferring the NS equation-of-state in upcoming observing runs of present GW detectors. I will talk about the computation of the effective Hamiltonians up to 3PN order [3,4] for dynamic f-mode tidal interactions. This is particularly interesting since it requires the introduction of counterterms to eliminate divergences, leading to a renormalization group flow of the post-adiabatic Love number.

In summary, my talk describes the computation of a two-body effective Hamiltonian that includes effects of spin and f-mode dynamic tides using effective field theories.

[1] "Gravitational spin-orbit Hamiltonian at NNNLO in the post-Newtonian framework," JHEP 03, 130 (2023) [arXiv:2209.00611]
[2] "Gravitational quadratic-in-spin Hamiltonian at NNNLO in the post-Newtonian framework," JHEP 07, 128 (2023) [arXiv:2210.09176]
[3] "Gravitoelectric dynamical tides at second post-Newtonian order," [arXiv:2304.02030]
[4] "Renormalizing Love: tidal effects at the third post-Newtonian order," [arXiv:2308.01865]

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