LIGO SURF

First Interim Report

Name: **Alicia Lima** (alima@bowdoin.edu.edu)
Mentor: **Davide Gerosa** (dgerosa@caltech.edu)

Visualizing 2PN Binary Black Hole Spin Precession

Objective

Given the variables identified in [1] that respect the timescale separation of the dynamics of precessing binary black holes (ξ, J, S), we will build a 3D visualization routine in Python to explore the phenomenology of spin precession.

From Black Hole Spins to Stellar Physics

Besides seeing them through electromagnetic waves (EM), nature has allowed us to "hear" distant astrophysical objects through gravitational waves (GW) [4]. Given their strong gravitational field, binary compact objects, made of Black Holes (BHs) and neutron stars, are most promising source of GW for detection at LIGO. Studying binary system not only allows us to enrich our astrophysical understanding of nature, but it also allows to test General relativity (GR). Hence, understanding the properties of binary systems from a theoretical and observational point of view is crucial step to fulfill the promise of gravitational-wave astronomy.

The No-Hair Theorems tell us that black holes can be completely characterized by three parameters: mass, spin, and charge. To describe Kerr black holes, we need to specify their masses and spins. Masses enter the waveform at lower Post-Newtonian (PN) order and are thus easier to infer than spins from GW data [5]. It is,therefore, very important to study the spin dynamics of BBHs system and generate more accurate templates, which in turn would improve GW parameter estimation [3]. In fact, it has been shown that templates which do not include spin effects might be poor at matching GW coming from spinning BBH [6]. In addition, from astrophysical point of view, spin dynamics can be used to infer the astrophysical mechanisms that led to the formation of BBHs system. There are two ways in which BBHs system could be formed: from the evolution of massive binary stars and capture binaries. Due to conservation of total momentum, one could infer that capture binaries systems should have no a priori preference for any particular spin orientation, while the spins of binaries formed from the collapse of binary stars should have some correlation [3].

BBHs have complicated dynamics, principally when both black-holes are spinning. One could reduce the complexity of the dynamics of spinning BBHs system by performing a multi-timescale analysis [1, 7]. Spinning BBHs have three angular momenta: the two spins, $\mathbf{S_1}$ and $\mathbf{S_2}$, and the orbital angular momentum, $\mathbf{L}$. On top of the binary's orbital motion, spin-spin and spin-orbit couplings cause the three angular momenta to precess [8], complexifying the dynamics. But in the post-Newtonian regime, the time it takes the two black-holes to orbit each other $t_{\rm orb}$ is much shorter than the time it takes the spins and the orbital angular momentum to precess about the direction of the total angular momentum $t_{\rm pre}$, which, in turns, is much shorter than the time it takes the binary's orbit to shrink due to GW emission $t_{\rm RR}$. In short, the dynamics of precessing BHs has the following timescale hierarchy: $t_{\rm orb} \ll t_{\rm pre} \ll t_{\rm RR}$. The second inequality $t_{\rm pre} \ll t_{\rm RR}$ allows us to study spin precession on $t_{\rm pre}$ and ignore all other effects which vary on $t_{\rm RR}$.

In an inertial frame, the parameter space associated with the evolution of $\mathbf{S_1}$, $\mathbf{S_2}$ and $\mathbf{L}$ is characterized by nine variables. Using geometry and constants of motion, one can decrease the number of variables in this parameter space to three. These three degrees of freedom are:

1. The magnitude of the total angular momentum
$$J = |\mathbf{S_1} + \mathbf{S_2} + \mathbf{L}|. \tag{1}$$
2. The projected effective spin
$$\xi = M^{-2}[(1+q)\mathbf{S_1} + (1+q^{-1})\mathbf{S_2}] \cdot \mathbf{L} \tag{2}$$
where $M = m_1 + m_2$, $q = m_1/m_2$,

   and m_1 and m_2 are the masses of the two black-holes.
3. The magnitude of the total spin
$$S = |\mathbf{S_1} + \mathbf{S_2}|. \tag{3}$$

On the precession timescale both J and ξ are conserved, while S is not. The mutual orientation of S_1,S_2 and L on the timescale $t_{\rm pre}$ is therefore fully characterized by the evolution of S [1, 7].

Yet, one of the most difficult aspects of studying the spinning binary system is visualization and analyze of the orientation of the three angular momenta, in such a way that is both intuitive and informative. In [1], the authors provided plots in the (J, ξ) and (S, ξ) parameter space for BBHs, which provides a first partial classification of the precessional dynamics.

Progress

During this LIGO SURF, Davide Gerosa and I are working on the construction of 3D plots that combines graphs in the (J, ξ) and (S, ξ) parameter space for BBHs. We plan to build a python infrastructure using the public code PRECESSION [4], and develop an interactive web interface to facilitate the exploration of spin precession in merging BHs. Over the past three weeks, I have made substantial progress. I used the first week for background study on LIGO, black holes, and spin precession. I have a much better understanding of the methodology used in [1] and the findings. I,then, used the second week to familiarize with the public code PRECESSION and enrich my python coding skill, using my mentor support and help. While learning, I also put those new skills in use by reproducing FIG 4 and FIG 5 of [1], which are plots in the (S, ξ) and in the (J, ξ) parameter space for BBHs,respectively. In additon, I created a new graph in the (S, J) parameter space. The code we wrote to create plots in the $(S,\ \xi)$, $(J,\ \xi)$ and $(S,\ J)$ will be used in the the construction of 3D plots (S,J,ξ), since each of therm are different sections of the 3D plots. Below are some of the plots I am now able to create.

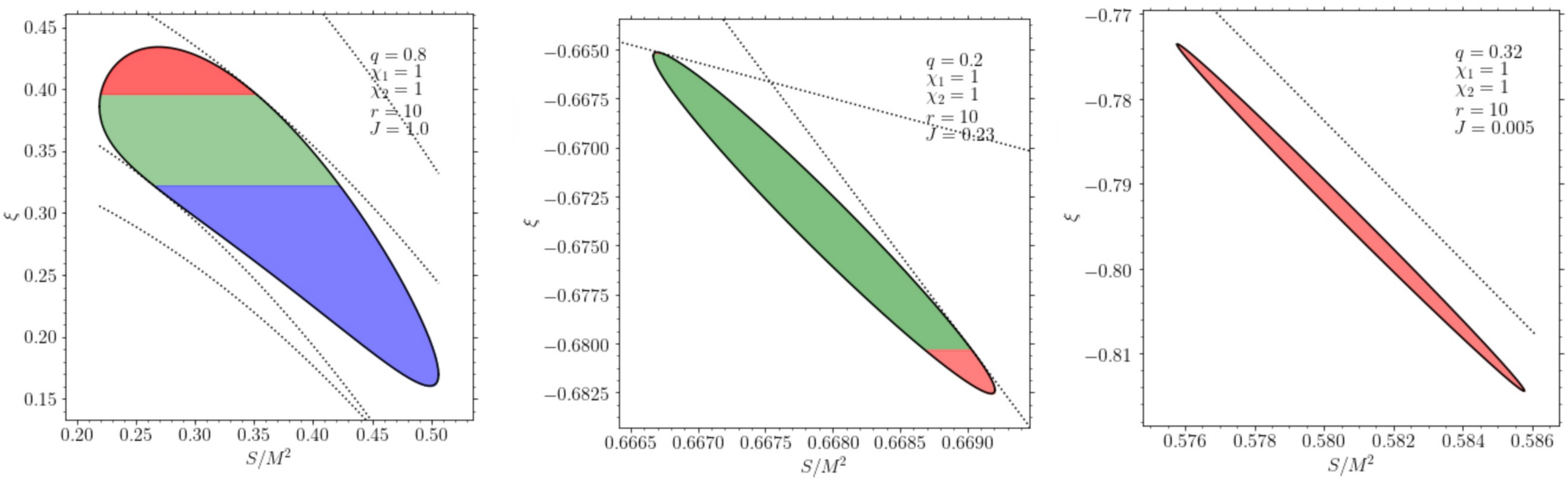

Figure 1: The (S,ξ) parameter space for BBHs for different values of L, J, S_1 and S_2.BBHs spin morphology is shown with different colors, which are determined by the behavior of $\Delta\Phi$ during a precession cycle: oscillation about 0 (blue region),circulation from $-\pi$ and π (green region), or oscillation about π (red region). Due to conservation of ξ, BBHs spins are restricted precess along horizontal lines between the turning points $S_{\pm}$.

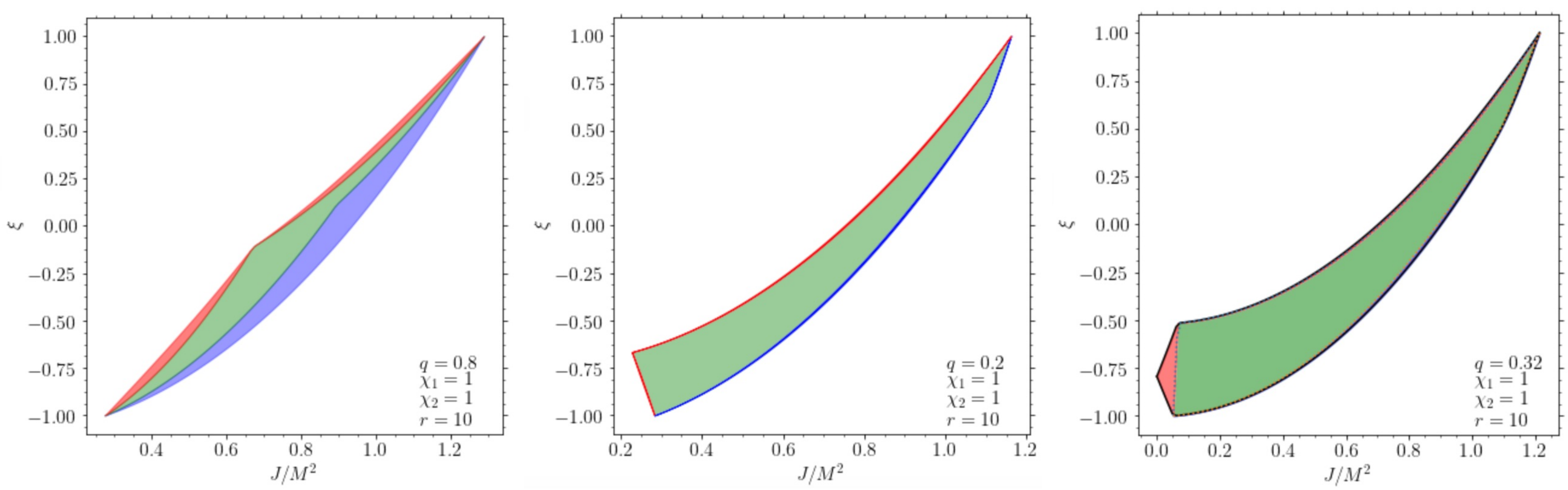

Figure 2: The (J,ξ) parameter space for BBHs with different $J_{\min}$, the minimum allowed total angular momentum. For the right panel $J_{\min} = L - S_1 - S_2$, the middle panel has $J_{\min} = |S_1 - S_2| - L$, and the level panel has $J_{\min} = 0$. The spin morphology is shown with different colors. Panels from Figure 1 can be thought of as vertical (constant J) "sections" of this figure.

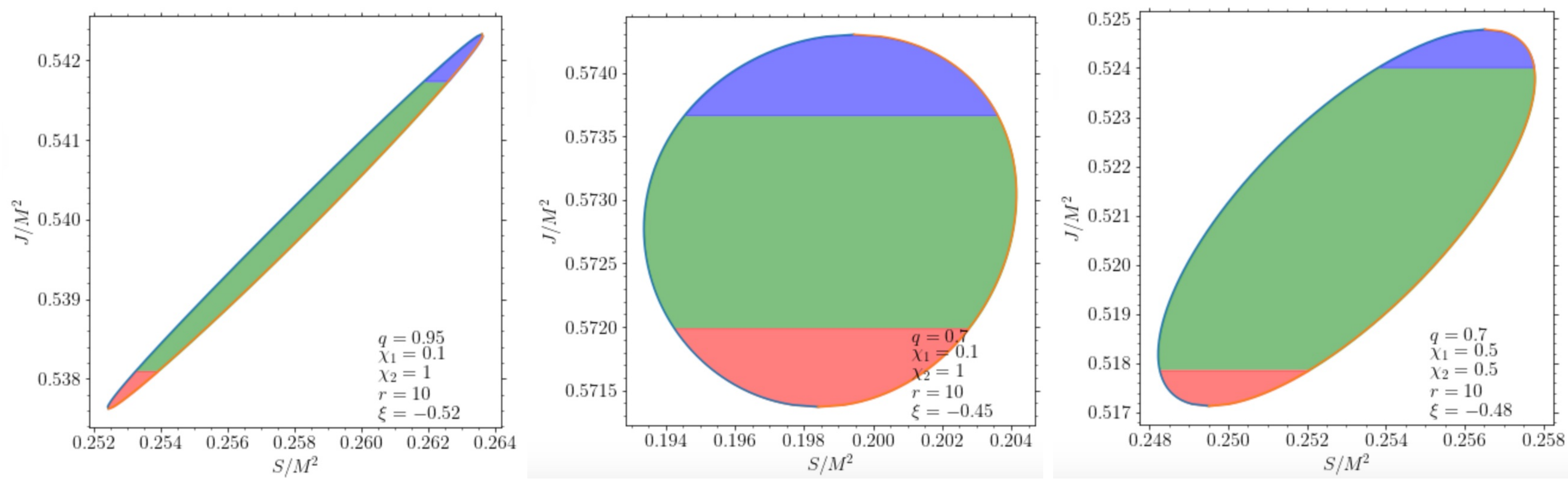

Figure 3: The (S,J) parameter space for BBHs with different values of q, χ_1, χ_2, and ξ, leading to different set of spin morphology. These panels can be thought of as horizontal (constant ξ) "sections" of Figure 2.

For the upcoming weeks, I will explore 3D plotting packages, and study how we can combine all three plots above, including time evolution to describe the inspiral of BBHs on the radiation-reaction timescale.

References

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