Visualizing 2PN Binary Black Hole Spin Precession

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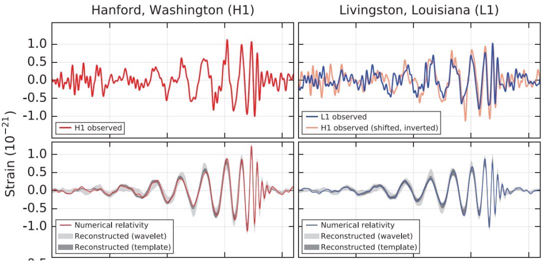
Outline

- Motivation: Binary Black Hole (BBH) Spin Precession and LIGO
- Post-Newtonian Approximation: Timescale Hierarchy
  - $t_{\rm orb} \ll t_{\rm pre} \ll t_{\rm RR}$
- Reference Frames Used to Study BBH Spin Precession
  - $(\theta_1, \theta_2, \Delta\Phi)$
  - (ξ, J, S)
  - 2D Parameter spaces:(S, ξ), (J, ξ), and (S, J)
- 3D Visualization in the (ξ, J, S) Parameter space
  - Peculiar Configuration: "Wide Precession"
- Conclusion

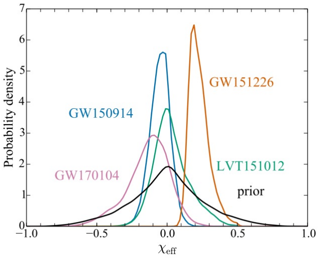
Motivation: LIGO and Spinning BBHs



First GW Detection!!
GW150914

$$\mathcal{M}/M_\odot = 28.1^{+1.8}_{-1.5}$$
$$m_1/M_\odot = 36.2^{+5.2}_{-3.8}$$
$$m_2/M_\odot = 29.1^{+3.7}_{-4.4}$$
$$\xi = -0.06^{+1.4}_{-1.4}$$
$$\chi_1 = ?,\ \chi_2 = ?$$

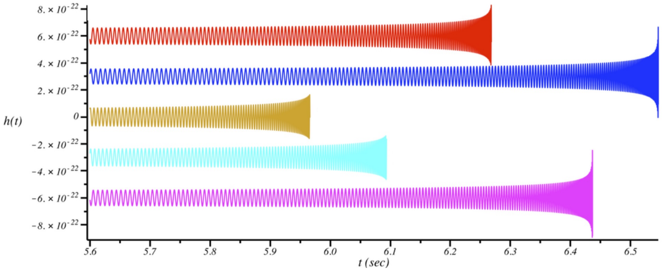
$$\xi = \frac{\chi_1 \cos(\theta_1) + q\chi_2 \cos(\theta_2)}{1+q}$$

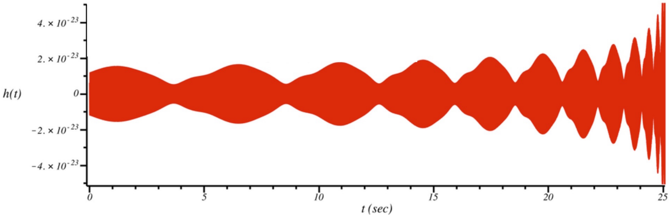


LIGO and Vitale et al.

Motivation: LIGO and Spinning BBHs

- Astrophysics: Spin orientation is the most promising source!





soundsofspacetime.org

Post-Newtonian Approximation: Timescale Hierarchy

- Newtonian description in the lowest order and GR effects as higher order perturbations;
  - Background spacetime is Minkowski spacetime
  - Expansion in $\epsilon = v^2/c^2$

- In the Post-Newtonian Regime, the precession equations:

$$\dot{\mathbf{S}}_1 = \frac{1}{2r^3}\left[(4+3q)\mathbf{L} - \frac{3qM^2\xi}{1+q}\hat{\mathbf{L}} + \mathbf{S}_2\right] \times \mathbf{S}_1$$

$$\dot{\mathbf{S}}_2 = \frac{1}{2r^3}\left[(4+\frac{3}{q})\mathbf{L} - \frac{3M^2\xi}{1+q}\hat{\mathbf{L}} + \mathbf{S}_1\right] \times \mathbf{S}_2$$

Racine 2018

Post-Newtonian Approximation: Timescale Hierarchy

In the PN regime, the dynamics of precessing BBHS has a strong timescale hierarchy:

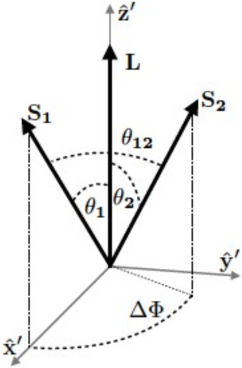
- Orbital time: $t_{\rm orb} \sim r^{3/2}/(GM)^{1/2}$
- Precession time: $t_{\rm pre} \sim c^2 r^{5/2}/(GM)^{3/2}$
- Radiation-reaction time: $t_{\rm RR} \sim c^5 r^4/(GM)^3$

$$t_{\rm orb} \ll t_{\rm pre} \ll t_{\rm RR}$$

Gerosa el at.,arXiv:1506.03492 [gr-qc]

Reference Frames

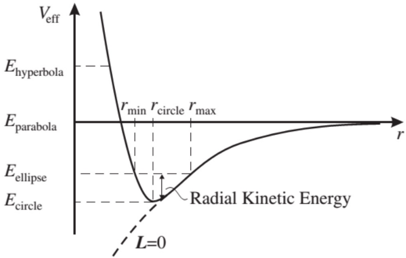
- $\mathbf{S_1}$, $\mathbf{S_2}$ and $\mathbf{L} \Rightarrow$ 9D parameter space
- Constant: χ_1, χ_2
- Reference frame: $L_x = L_y = S_{y_1} = 0$
- 4 parameter: $(r, \theta_1, \theta_2, \Delta\Phi)$
  - $\theta_1, \theta_2, \Delta\Phi = f(\xi, J, S)$
- 4 parameter:(r, ξ, J, S)
  - $\xi \Rightarrow$ constant on $t_{\rm pre}$ and $t_{\rm RR}$
  - $J \Rightarrow$ constant on $t_{\rm pre}$
  - $S_{\rm min} \le S \le S_{\rm max} \Rightarrow$ varies on $t_{\rm pre}$

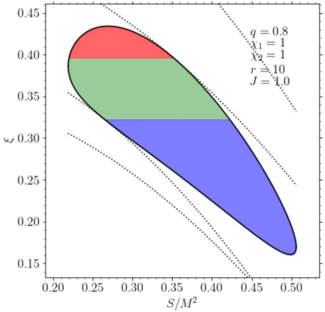


2D Parameter spaces: (S, ξ), (J, ξ)

- Analogy between Classical Mechanics two body problem and Spin precession

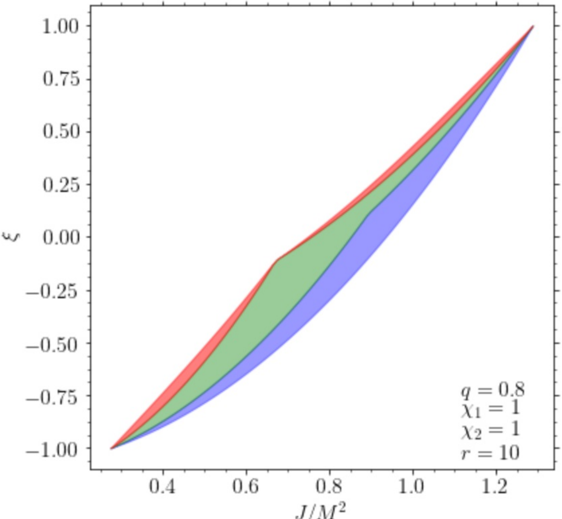
$$(t, E, L, r) = (r, \xi, J, S)$$





2D Parameter spaces: (J, ξ)

- S: Varies on t_{pre}
- J: Varies on t_{RR}
- ξ: Constant

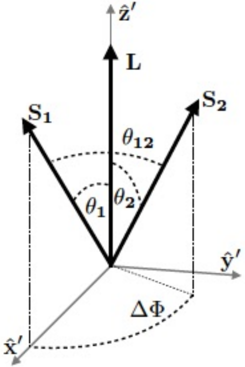


3D Visualization in the (ξ, J, S) Parameter space

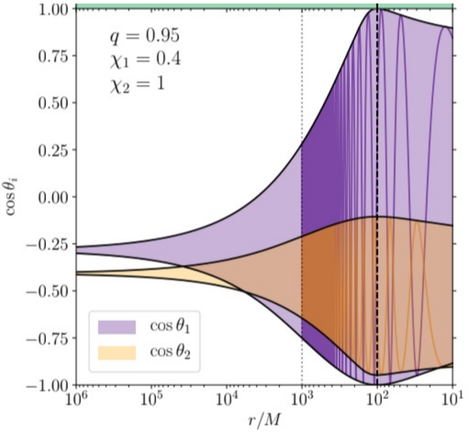
- Combine plots in the (ξ, J),(ξ, S) and (S, J) parameters space
- Includes all possible binaries for a fix r, q, χ_1, χ_2
  - 3D Plot (ξ, J, S)

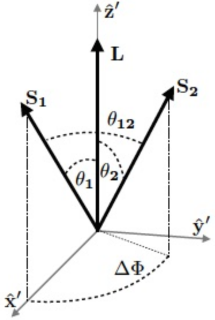
3D Visualization: Morphology

- The evolution of $\Delta\Phi$ allows us to categorize the precessional dynamics into three different classes:
  - $\Delta\Phi$ oscillates about 0 $\Rightarrow$ Blue
  - $\Delta\Phi$ circulates through the full range $[-\pi, \pi]$ $\Rightarrow$ Green
  - $\Delta\Phi$ oscillates about π $\Rightarrow$ Red
- 3D Plot (ξ, J, S): Morphology



Peculiar Configuration: "Wide Precession"





Conclusion

- Better understanding of the 3D Parameter space
- For future:
  - Make the surface itself dynamical
  - Have a binary evolve on the 3D plot
  - Add slider for r, q, χ_1, χ_2
  - Make a webpage!!!

Acknowledgement

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