Observing the Orbital Hang-up Effect in a Binary Black Hole Merger Through a Gravitational Wave Burst Search

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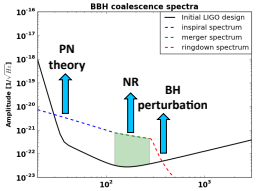
Orbital hang-up

higher aligned binary black hole spins ⟶ longer time to merge

When both the black hole spins are aligned with the orbital angular momentum; it increases the binary's total angular momentum. If this total angular momentum exceeds the maximal angular momentum of a Kerr black hole then the binary cannot merge until a sufficient amount of angular momentum has been radiated away [1].

Phenomenological waveform

waveform constructed by patching Post Newtonian (PN), Numerical Relativity (NR) and perturbation theory

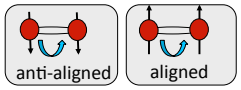


non-precessing spinning waveform family parameterized by 3 parameters [2]:

① total mass: $M = m_1 + m_2$

② symmetric mass ratio: $\eta = \frac{m_1 m_2}{M^2}$

③ mass weighted spin: $\chi = (1+\delta)\frac{\chi_1}{2} + (1-\delta)\frac{\chi_2}{2}$, $\delta = \frac{(m_1 - m_2)}{2}$, $\chi_i = \frac{S_i}{m_i^2}$

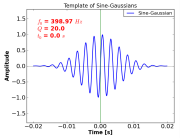


Burst search

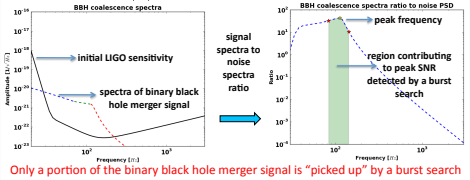
excess signal energy in the data to look for gravitational wave bursts

•The Omega burst search [3]: a multi-resolution time-frequency search for statistically significant excess signal energy ➔ templated matched filter search for sine-Gaussians in whitened data.

•Sine-Gaussians are characterized by peak time (t_0), peak frequency (f_0) and Q (ratio of peak frequency to bandwidth).



Sine-Gaussian: $\Psi(t) = Ae^{-(2\pi f_0)^2 (t-t_0)^2 / Q^2} e^{i 2\pi f_0 (t-t_0)}$

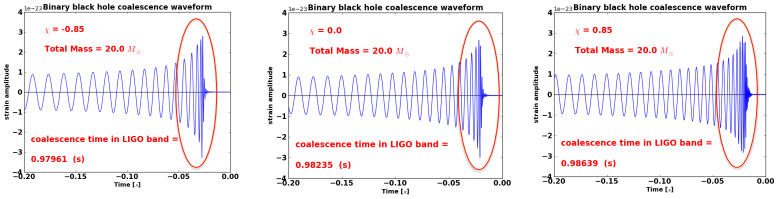


Only a portion of the binary black hole merger signal is "picked up" by a burst search without the clustering of triggers.

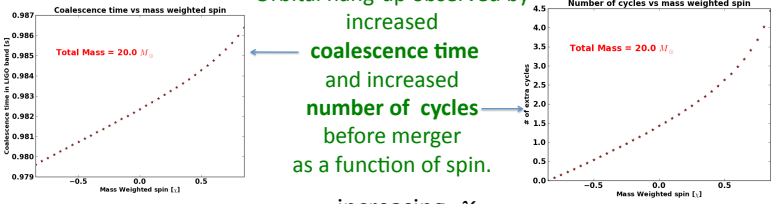
Coalescence time in initial LIGO band

orbital hang-up seen with increasing spin parameter

increasing χ ⟶

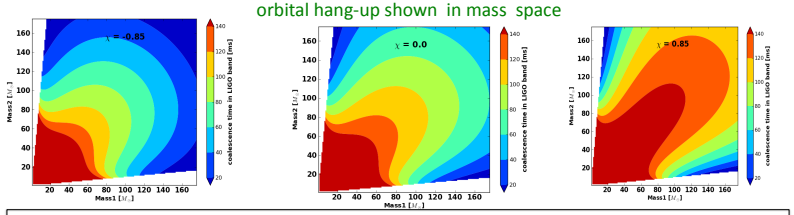


Orbital hang-up observed by increased **coalescence time** and increased **number of cycles** before merger as a function of spin.



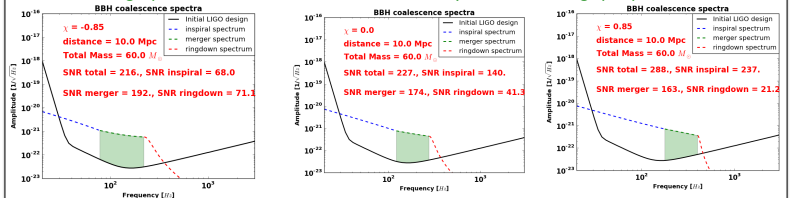
increasing χ ⟶

orbital hang-up shown in mass space



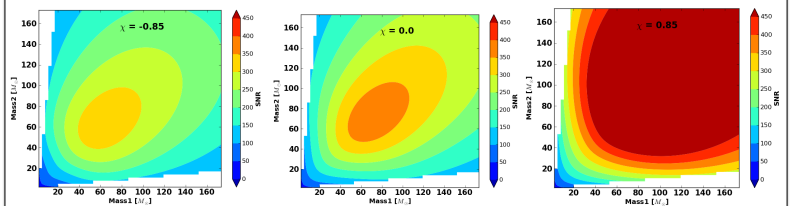
Signal-to-noise ratio (SNR)

orbital hang-up ➔ increased SNR and detectability with increasing spin parameter



increasing χ ⟶

orbital hang-up ➔ increased SNR shown in mass space

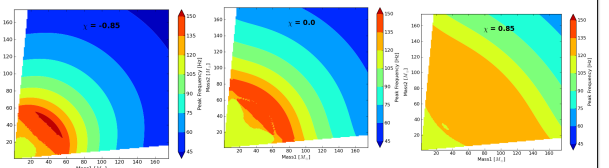


Peak frequency

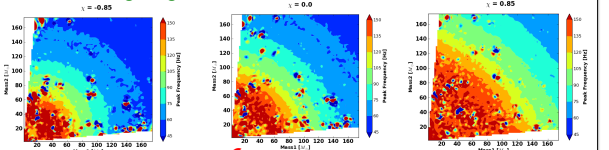
orbital hang-up ➔ peak frequency of merger signal changes with spin

increasing χ ⟶

expected peak frequency from phenomenological model



peak frequency observed by Omega burst search: black hole merger signal added to simulated initial LIGO noise

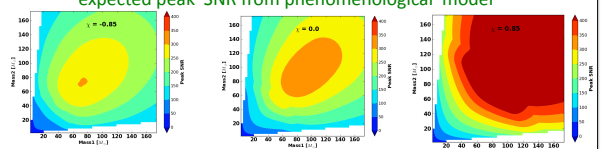


Peak SNR

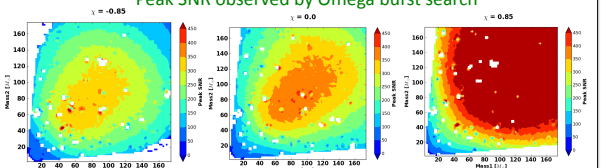
orbital hang-up ➔ increased peak SNR observed in a burst search

increasing χ ⟶

expected peak SNR from phenomenological model



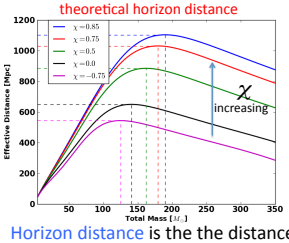
Peak SNR observed by Omega burst search



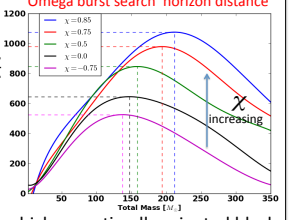
Horizon Distance

increased detectability due to orbital hang-up

theoretical horizon distance



Omega burst search horizon distance



Horizon distance is the distance at which an optimally oriented black hole binary can be observed with an SNR = 8.

Reference:
[1] Campanelli et al. Spinning-black-hole binaries: The orbital hang up, PRD 74, 041501.
[2] Ajith et al. *"Complete" gravitational waveforms for black-hole binaries with non-precessing spins*, 2009. arXiv:0909.2867.
[3] https://trac.ligo.caltech.edu/omega/