Searching for Binary Black Holes using Full Hybrid Waveforms

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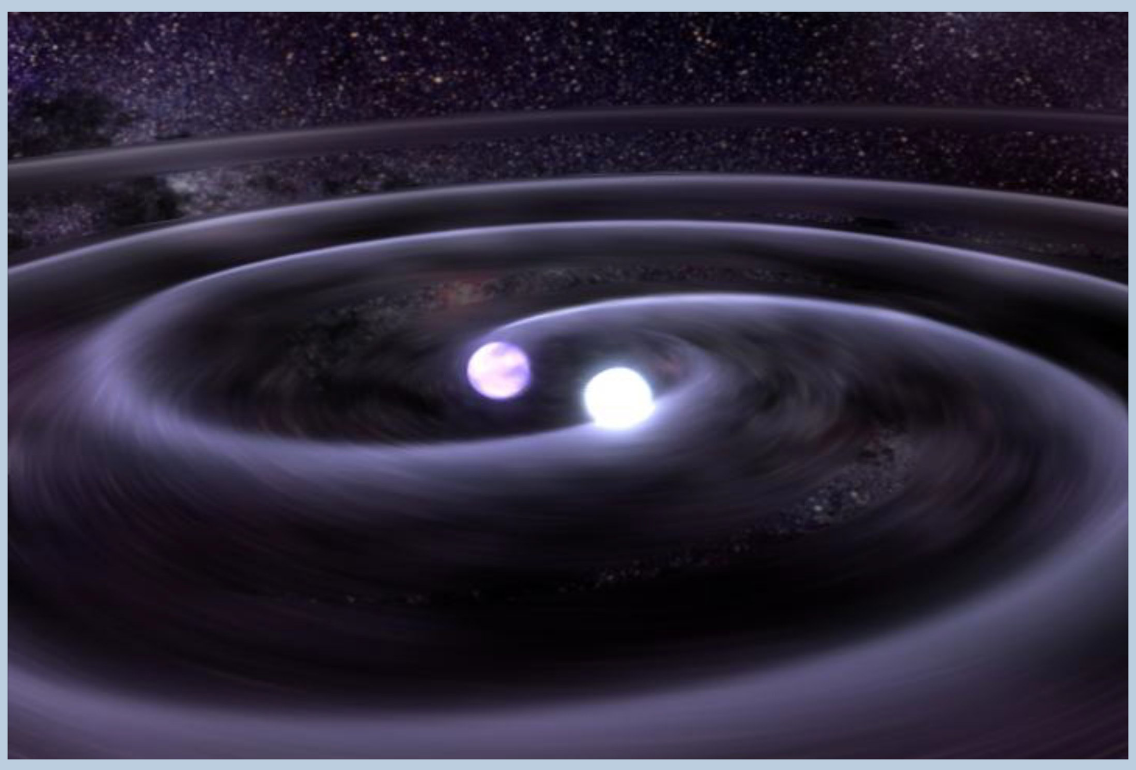
Introduction

Compact Binary Coalescences are among the most promising candidates for a first gravitational wave detection. Current searches consider only the dominant part of the emission neglecting higher modes. Here we present a method to obtain hybrid waveforms containing higher modes and make a first study of their effect in terms of achievable volume for non-spinning systems.



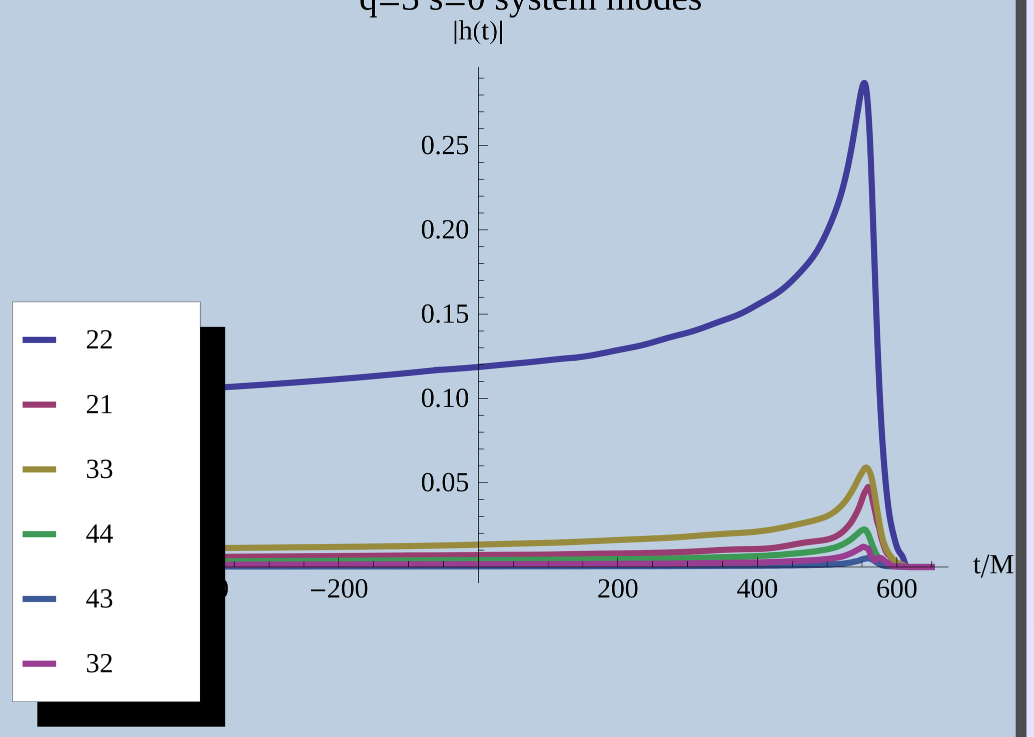
Key Concepts

1. **Higher Modes** The GW strain can be mode-decomposed as:

$$h_f(t,\theta,\phi) = \sum_{l,m} Y^{-2}_{l,m}(\theta,\phi) h_{l,m}(t)$$

In current searches, templates only include $l=2, m=\pm 2$ modes. We call them h_d.

2. **Hybrid Waveforms** A Hybrid Waveform is the result of gluing PN and NR data.
We use BAM code data[a] [b] as NR input and Taylor T1 and T4 as PN. Hybrids are glued at quite late times to avoid noisy NR data when using higher modes.



[a] Hannam et al. Phys. Rev. D 82, 124008 (2010)
[b] Husa et al. 2008 Class. Quantum Grav. 25 105006

Matching Full Waveforms

Optimization over phase gets involved when including higher modes.

$$\left|\max_{t_0} \frac{\langle h_f(\theta,\varphi)|h_f(\theta',\varphi')\rangle}{\sqrt{\langle h_f(\theta,\varphi)|h_f(\theta,\varphi)\rangle\langle h_f(\theta',\varphi')|h_f(\theta',\varphi')\rangle}}\right| \neq 1$$

Given this, we compute matches and SNR's for signals and templates with same physical parameters and located at same sky location. (Here, we only optimize over time) These are denoted by $\mu(h,h',\theta,\phi)$ and $\rho(s,h,\theta,\phi)$ respectively. Relevant facts are:

1. **SNR** is not axisymmetric.
2. $\rho(s_f,h_d,\theta,\phi) = \rho(s_f,h_f,\theta,\phi) \times \mu(h_f,h_d,\theta,\phi)$ works because optimization in phase and polar angle is not needed.

Acknowledgements

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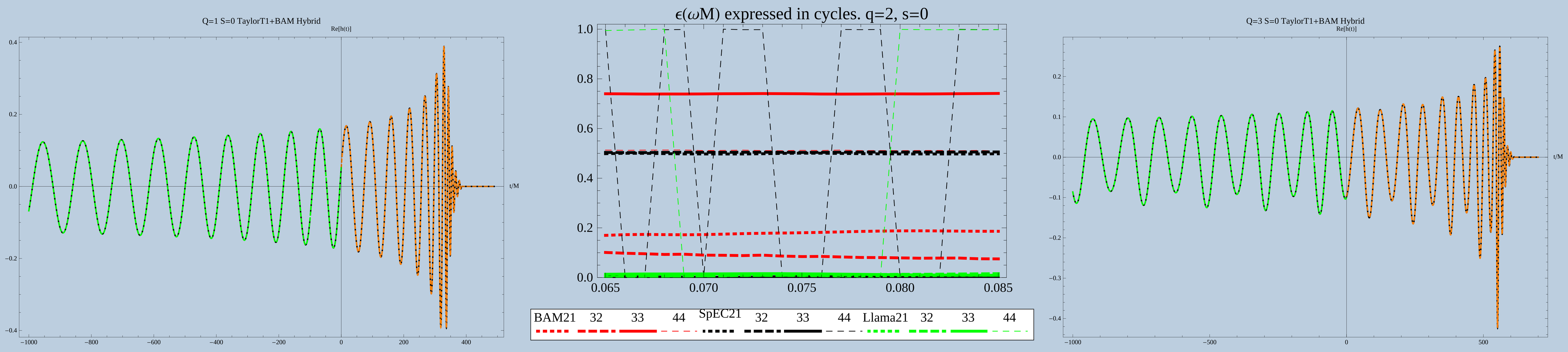
Full Hybrid Waveforms Construction

PN and NR modes can be expressed as $h^j_{l,m}(t) = a^j_{l,m}(t)e^{-i\phi^j_{l,m}(t)}$ with $a_{l,m}(t) \in R$, j =PN,NR .

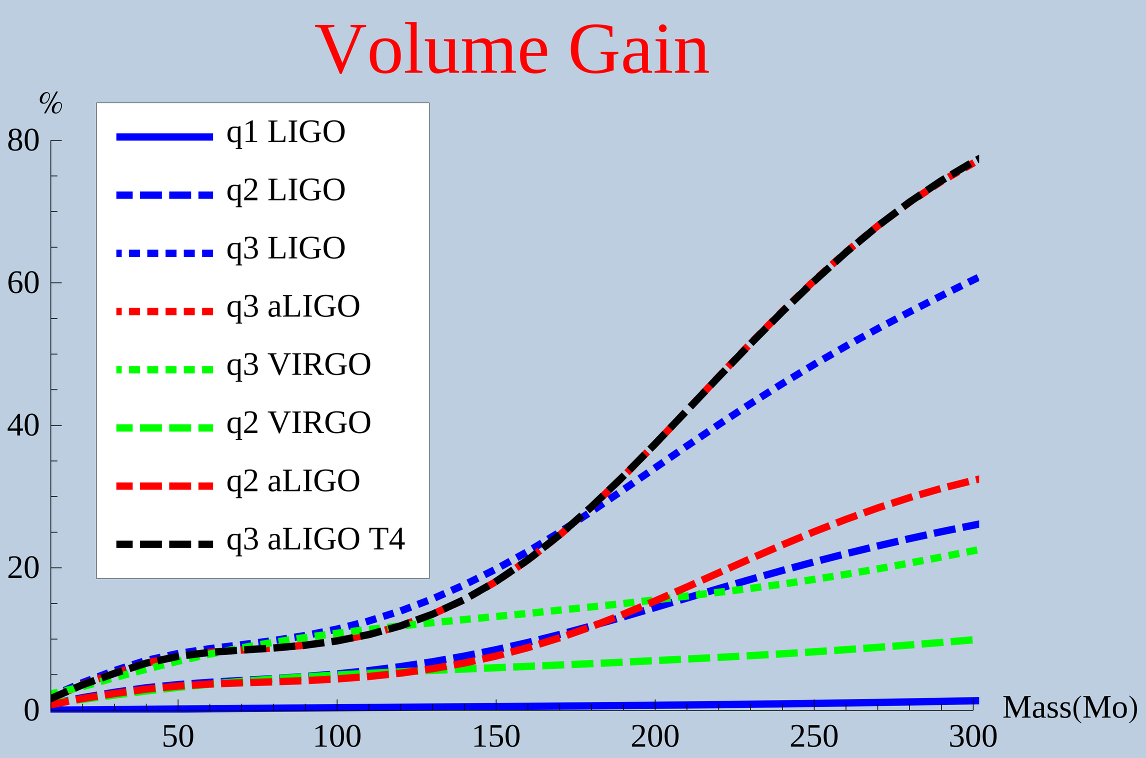
In order to build the higher modes hybrids, the following method is applied.

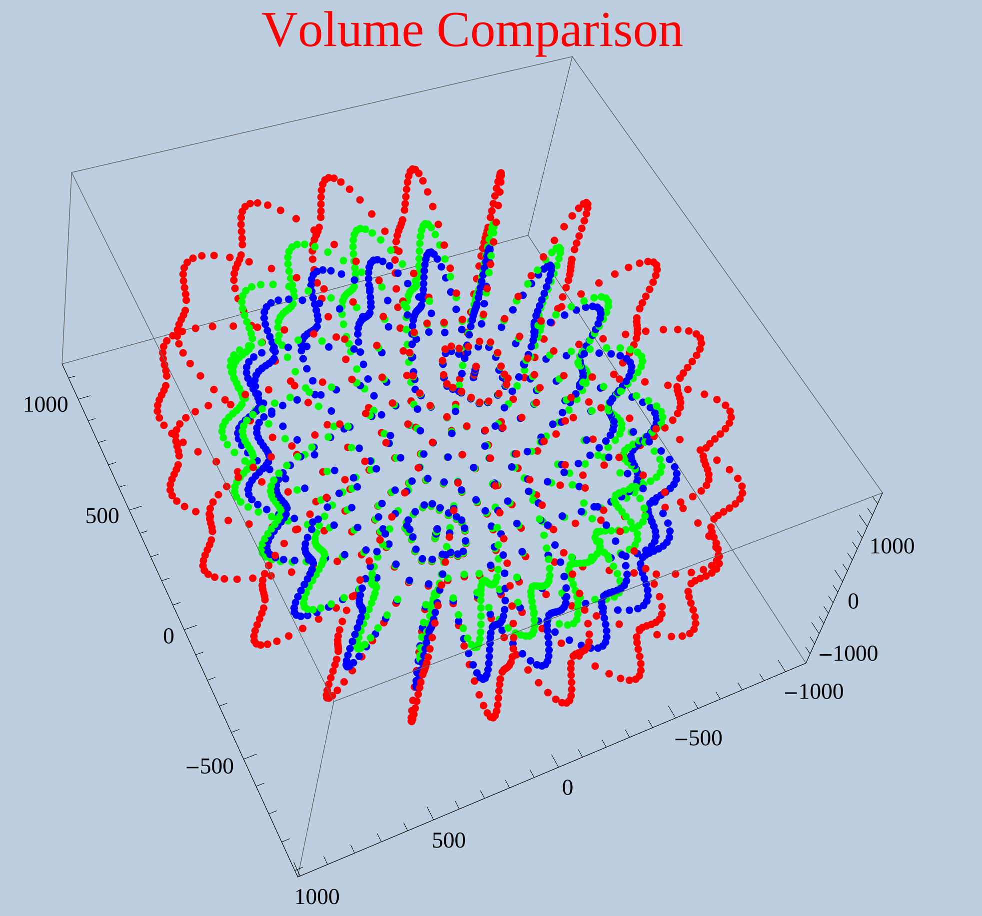
1. Time domain 22 mode hybrid is glued at certain frequency $\omega_0(t_0)$ and applying a shift to the NR phase $\Delta^p\phi_{22} = \phi^{PN}_{22}(t_0) - \phi^{NR}_{22}(t_0)$.
2. Same is done for the second most dominant $\{l^*, m^*\}$ mode at time t_0 using a phase shift $\Delta^p\phi_{l^*m^*}$
3. Extra $\{lm\}$ higher modes are built gluing at t_0 and applying a shift $\Delta^t\phi_{lm} = \frac{m}{2}\Delta^p\phi_{22}$ where.
4. Quality of data is estimated computing $\epsilon_{l,m} = \Delta^p\phi_{lm} - \Delta^t\phi_{lm}$ which should be equal to $2n\pi$ in a perfect case. If not, it is smoothed over a time window.



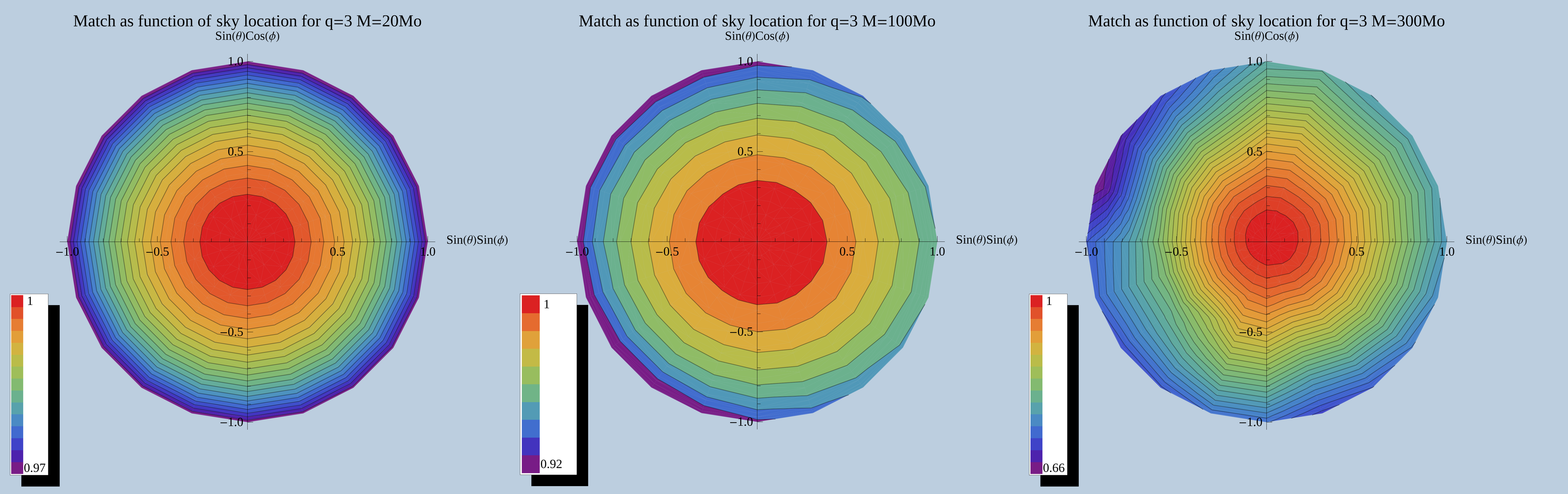
Sensitivity enhancement due to higher modes

For a system with mass ratio q and total mass M, consider a signal s and a template h which may contain only dominant modes (d) or also higher modes (f). For several (θ,ϕ) distributed on a grid on the sky of the source, we compute the horizon distances for the combinations $(s_f,h_f),(s_f,h_d),(s_d,h_d)$, (Red,Green,Blue). Only real parts of the waveforms are considered, only maximization in time is used and detector is considered to be optimally oriented. We then compare the volume of universe that we cover in each case.





We see there is a gain in volume which increases with q, M and θ when using full templates. For $q=3$, $M=100M_\odot$ an increment of 13% is achieved if considering LIGO as detector. It can also be seen that T1 and T4 results agree. In the upper right plot, volumes in which a $q=3$, $400M_\odot$ binary is detectable for Advanced LIGO are shown for the three described cases. We can see how the red volume is not axisymmetric unlike the case where only dominant modes are considered (blue). The green points show the shape of the volume that is covered in dominant mode searches (s_f,h_d). This is also non-axisymmetric due to the non-axisymmetry of the source.



Matches between full and dominant waveforms are also non-axisymmetric. One can see that at he pole the match is almost 1 (as expected) and how it decreases as we get close to the equator showing dependance on the azimuthal angle. Here we show results using LIGO as detector.

Conclusions

- A method for constructing full hybrid waveforms has been developed.
- Significant gain of volume can be achieved when employing full waveforms. This increases as we increase mass ratio, total mass and get closer to equatorial plane.
- Depending on sky location, current dominant mode models under or overestimate the SNR.
- Our checks for hybrid waveforms can be applied to the NINJA 2 hybrid waveforms catalogue.