Studying the properties of higher order modes in gravitational wave emission from binary black hole merger events

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Outline

- What are higher order modes in gravitational waves from binary black hole mergers, and why are they important?

- Modeling gravitational wave events with different binary black hole waveform models.

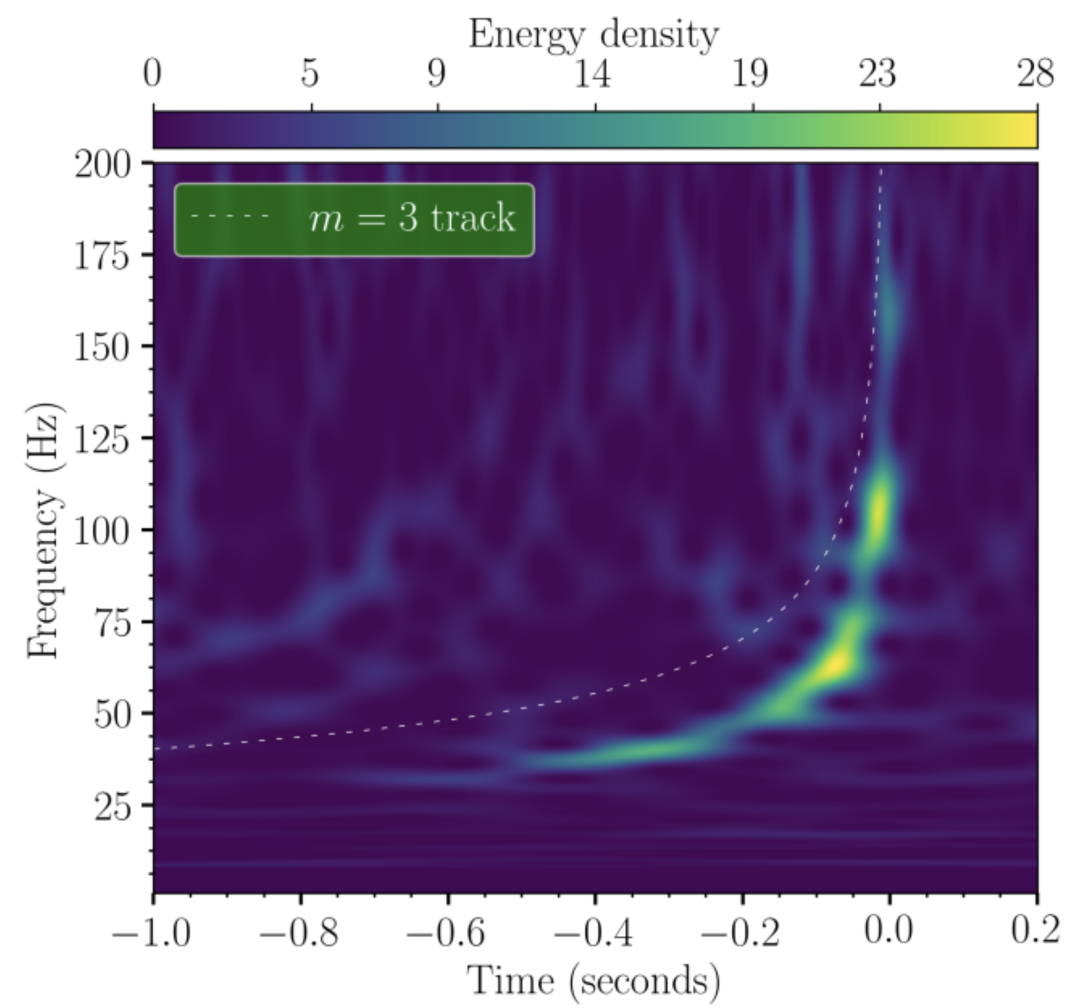
-Effects of higher order modes in gravitational wave signals from binary black holes.

- Reanalyzing GW190412 with IMRPhenomXPHM (in progress).

Higher order modes

- Gravitational wave emission can be described as a sum of spin-weighted spherical harmonics.
- Spin weighted spherical harmonics, $_{-2}Y_{\ell,m}(\theta,\phi)$, give the strength of the emission in the (θ,ϕ) direction toward the observer.
- Higher order multipoles are terms in the expansion beyond the dominant quadrupole term, $_{-2}Y_{2,2}(\theta,\phi)$, and are especially important in the late inspiral where the binary system deviates from circularity.
- Studying higher order multipoles provides us with a new and powerful way to test General relativity.

$$h_+ - ih_\times = \sum_{\ell\geq 2} \sum_{-\ell\leq m\leq\ell} \frac{h_{\ell m}(t,\boldsymbol{\lambda})}{D_\mathrm{L}} \, {}_{-2}Y_{\ell m}(\theta,\phi)$$



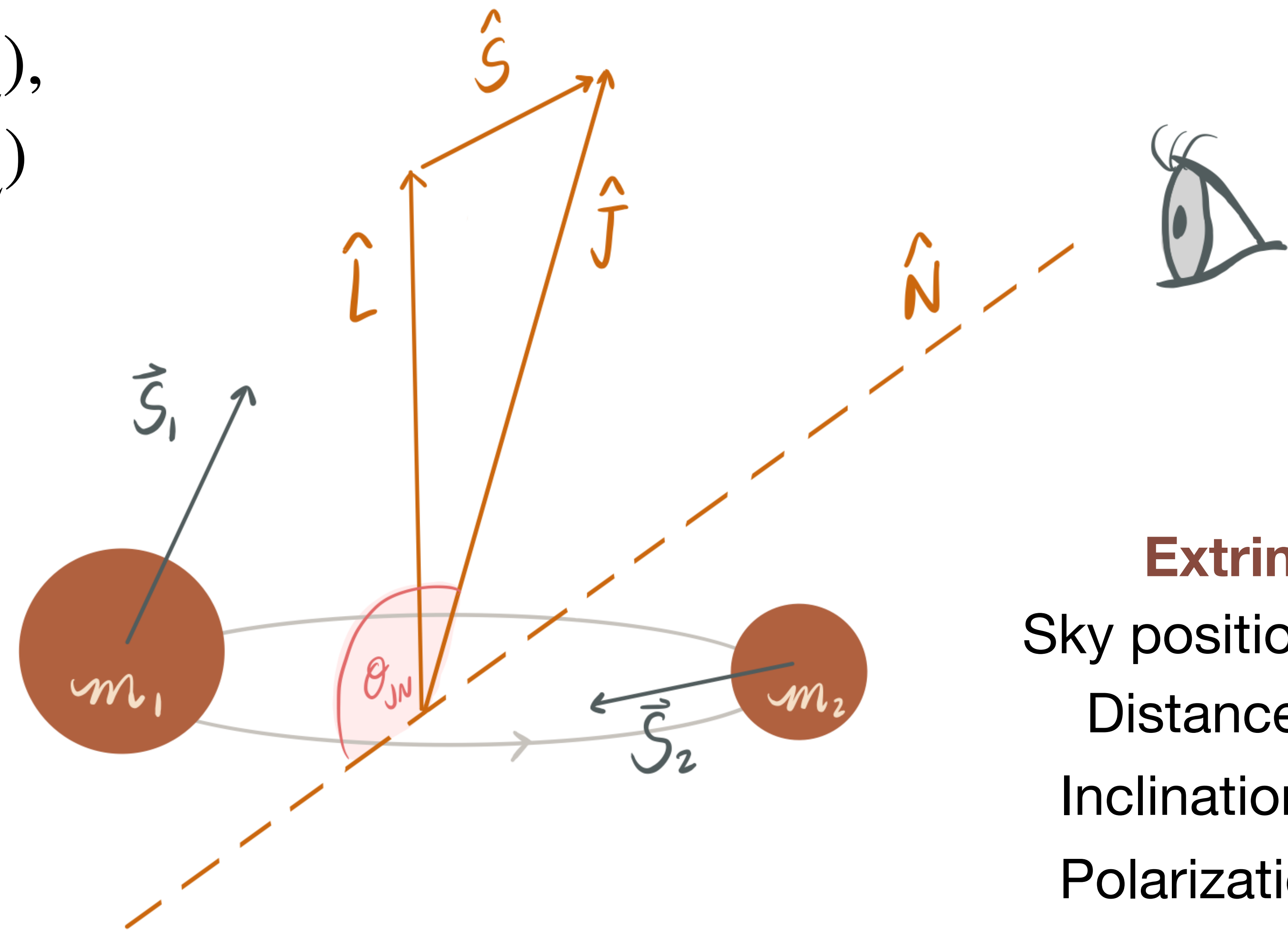
arXiv:2004.08342 [astro-ph.HE]

Waveform model parameters

Intrinsic:

Masses (m_1, m_2),

Spins $(\vec{S}_1, \vec{S}_2)$



Extrinsic:

Sky position (α, δ),

Distance (d_L),

Inclination (θ_{Jn}),

Polarization (ψ),

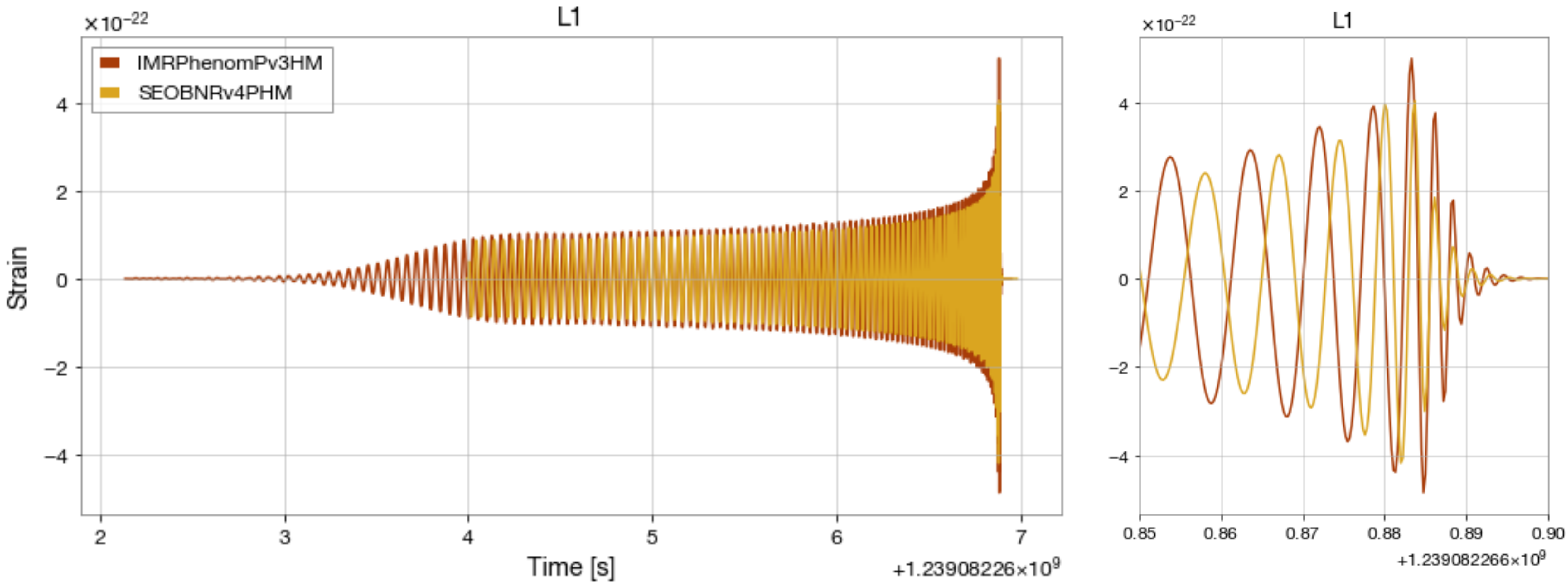
Time at coalescence (t_c),

Reference phase (φ_c)

Modeling gravitational wave signals with different waveform models

Source properties

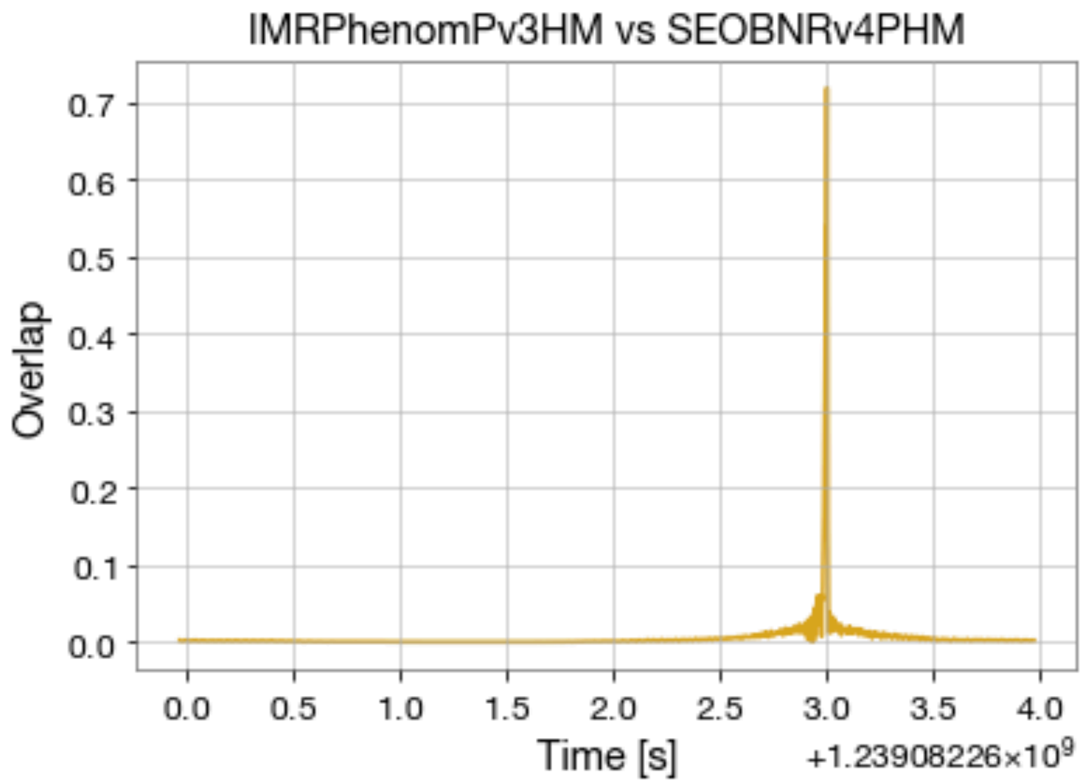
Detector response: $h^{\mathrm{L1}}(t) = F_+^{\mathrm{L1}}(\theta, \phi, \psi)h_+(t) + F_\times^{\mathrm{L1}}(\theta, \phi, \psi)h_\times(t)$



Overlap between two waveform models

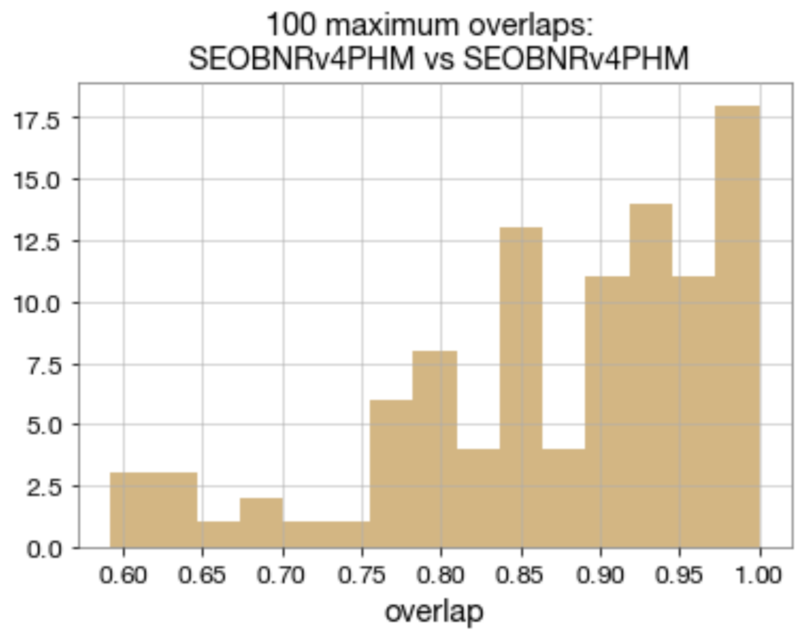
$$\mathcal{O}(h_1 | h_2) = \left[\frac{(h_1 | h_2)}{(h_1 | h_1)^{1/2}(h_2 | h_2)^{1/2}}\right]_{max\ t_c, \varphi_c}$$

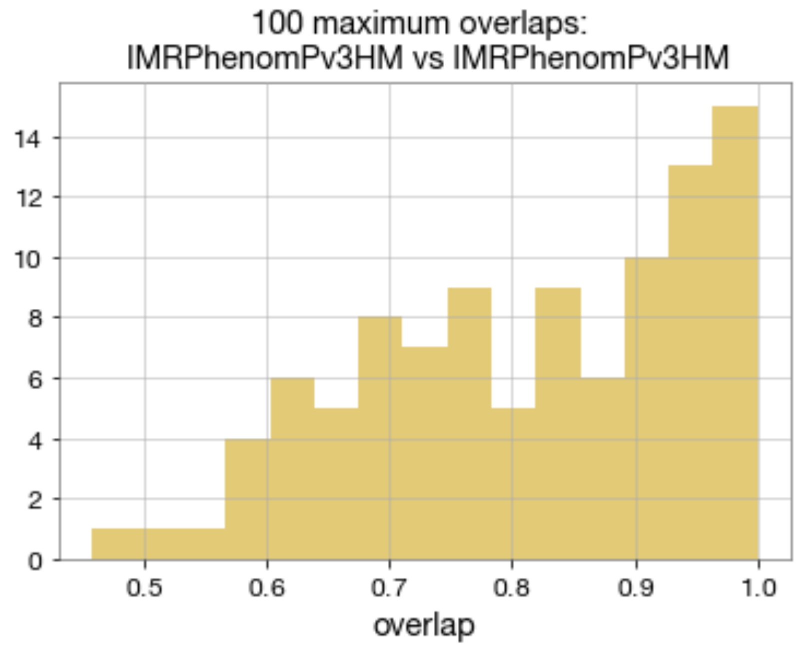
$$(h_1 | h_2) = \int_{f_{min}}^{f_{max}} df \frac{\tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)} e^{2\pi i f t_c}$$

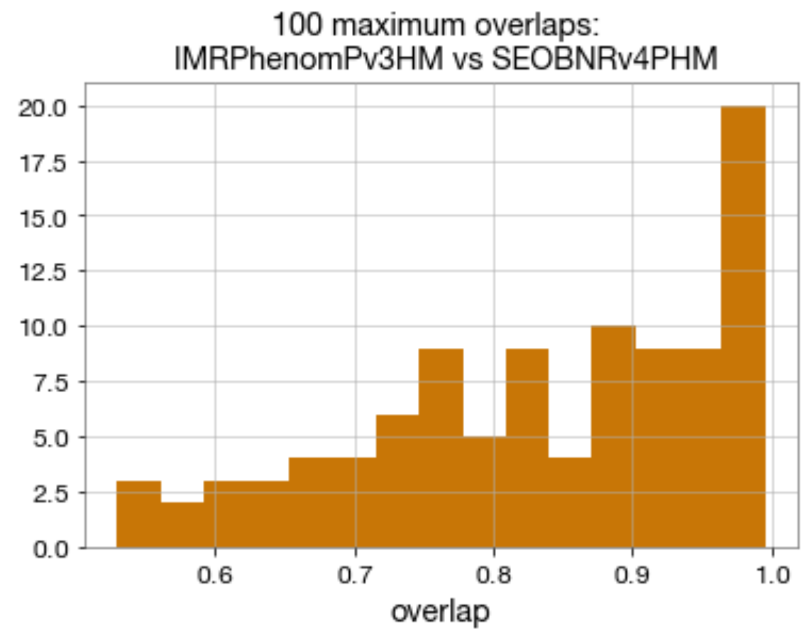


$\tilde{h}_1(f)$ = Fourier transform of the strain a(t)
$\tilde{h}_2^*(f)$ = complex conjugate of the Fourier transform of the strain b(t)
$S_n(f)$ = power spectral density of a gravitational wave detector

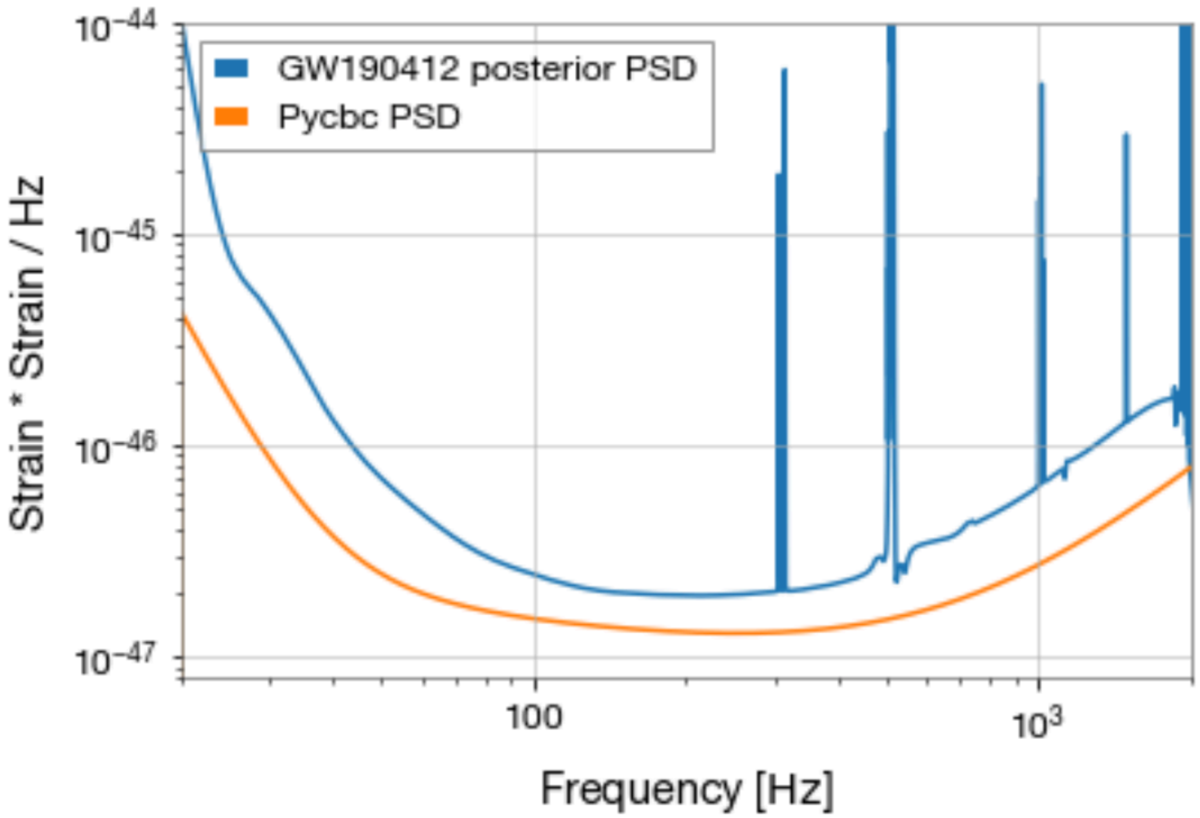
Overlap between two waveform models

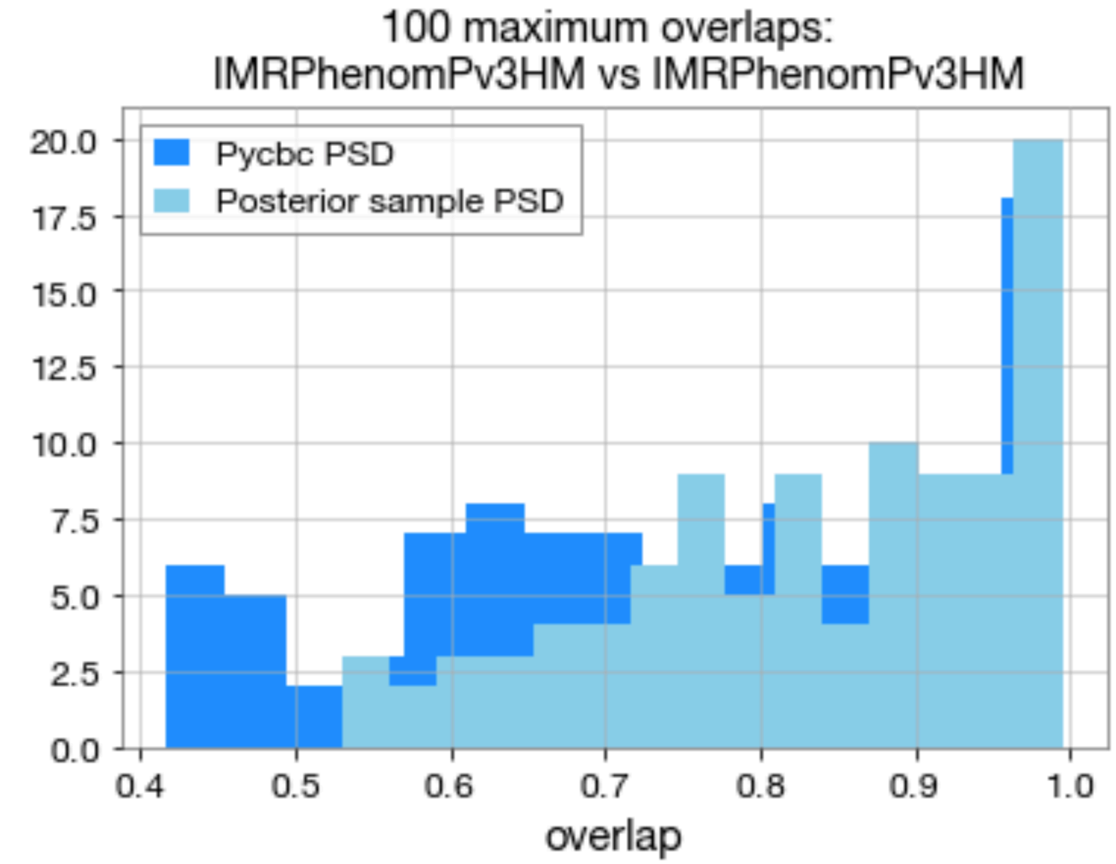






Overlap between two waveform models



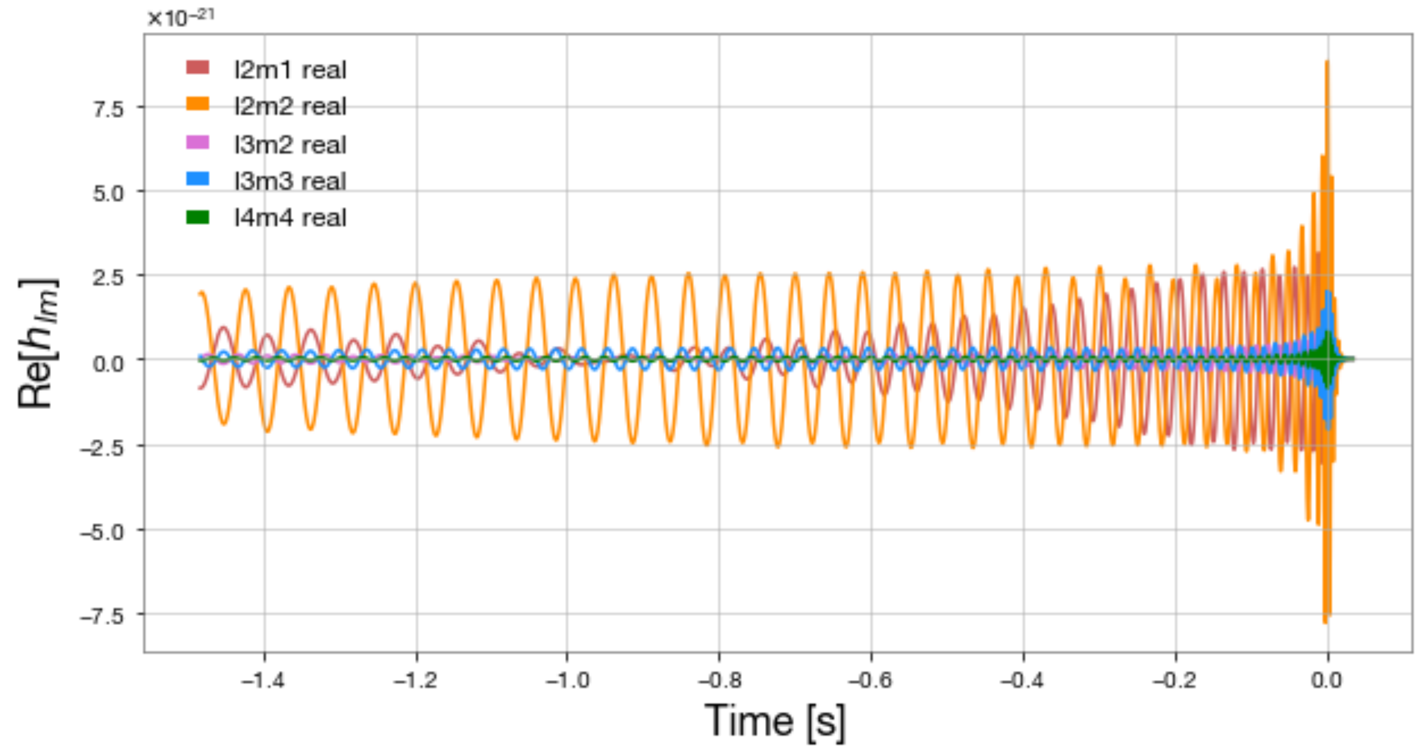


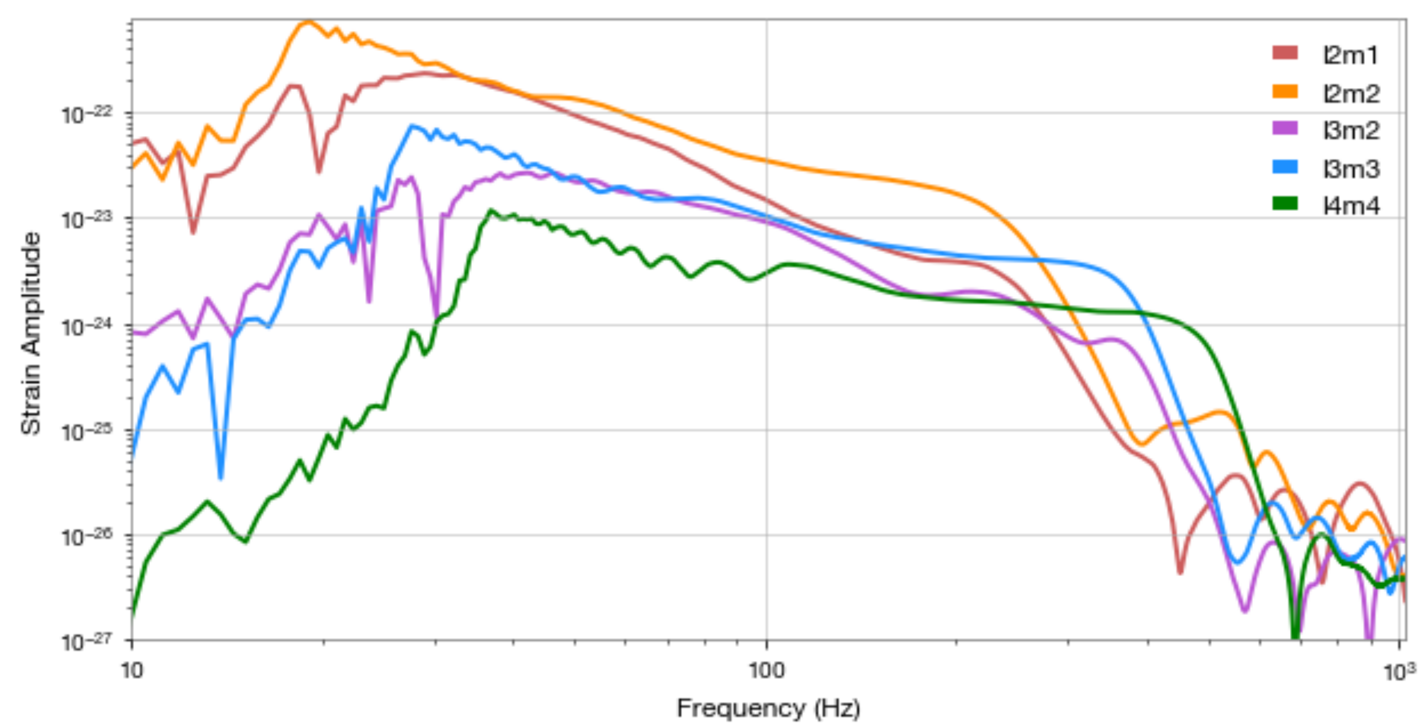
Effects of higher order modes in gravitational wave signals

NRSur7dq4

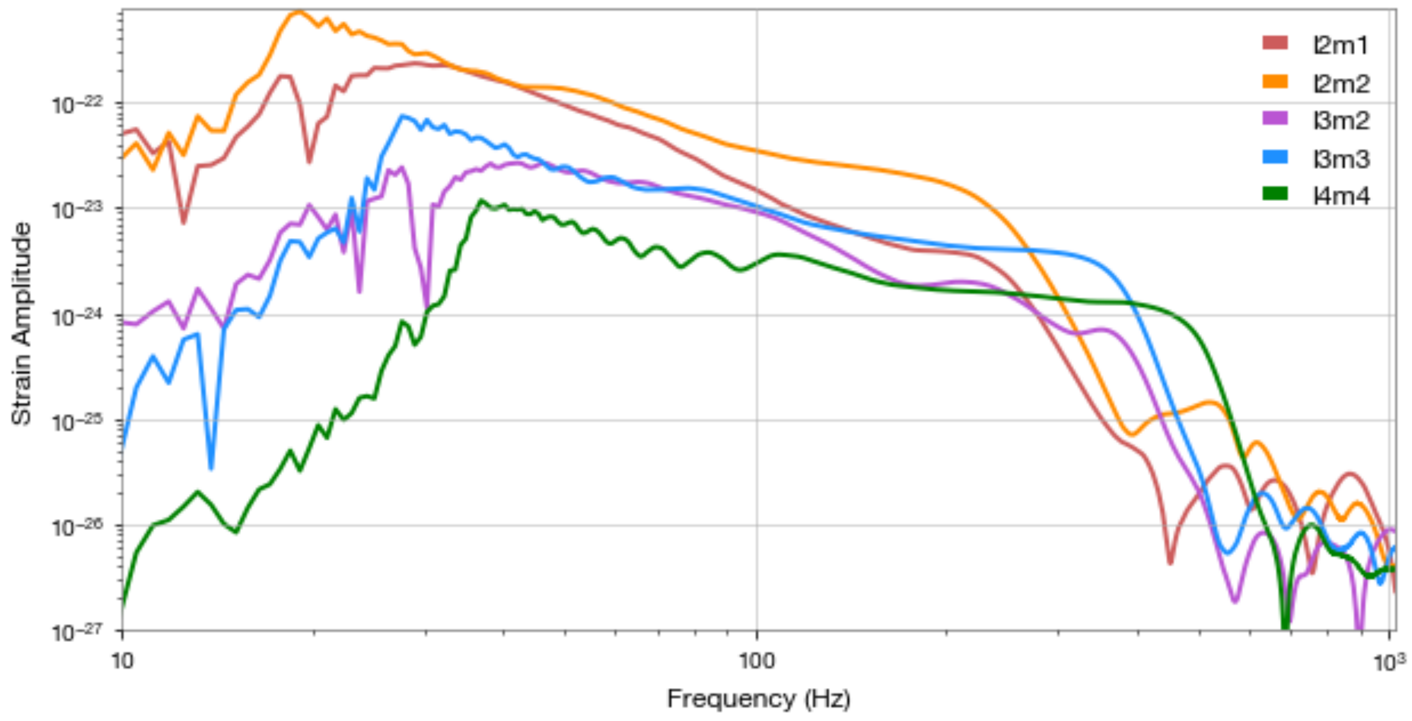
Parameters:

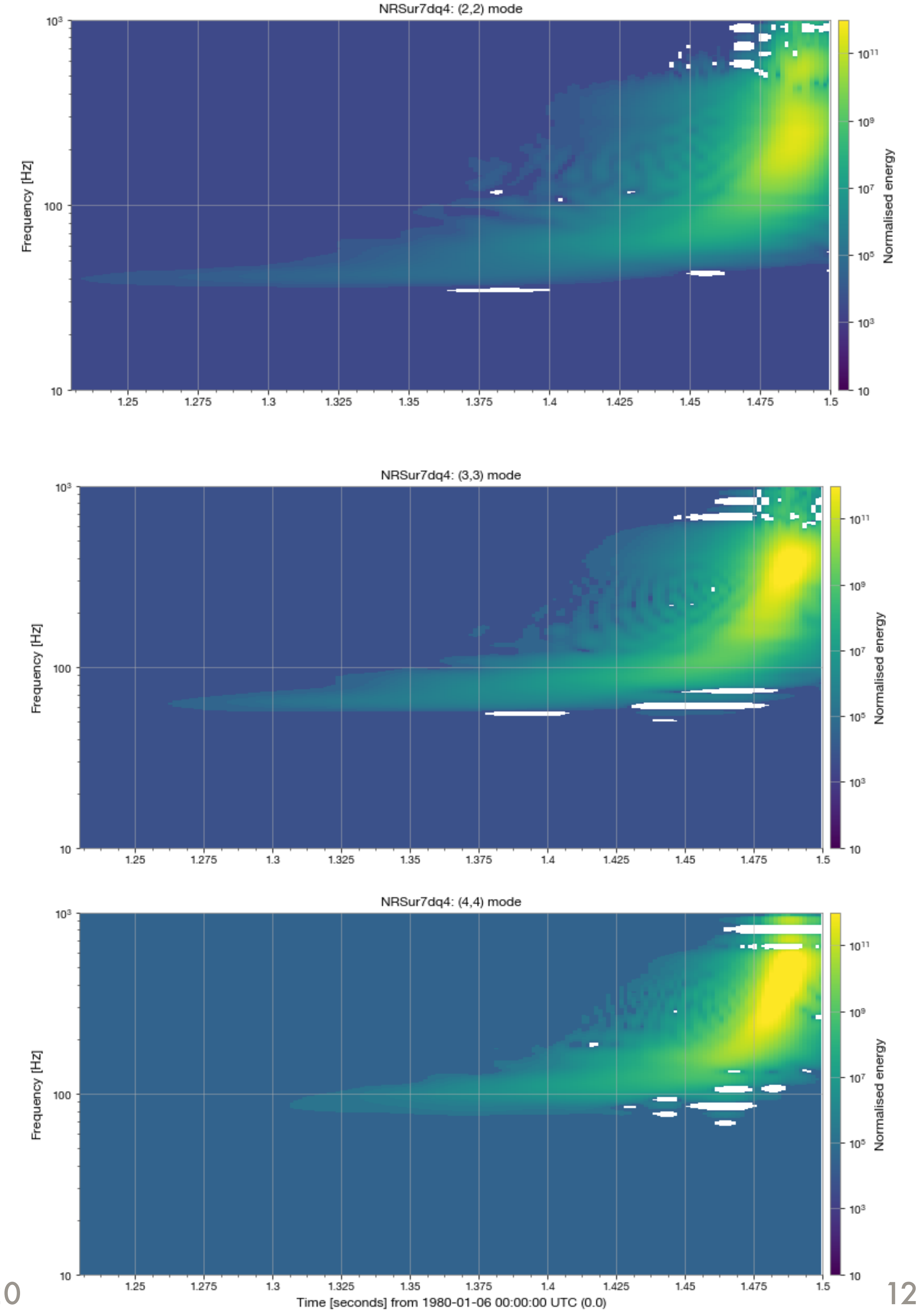
$q = 4$
χ_1 = [-0.2, 0.4, 0.1]
χ_2 = [-0.5, 0.2, -0.4]
$M = 70_\odot$
d = 100 Mpc
$\ell_{max} = 4$
f_{low} = 20 Hz
dt = 1/4096



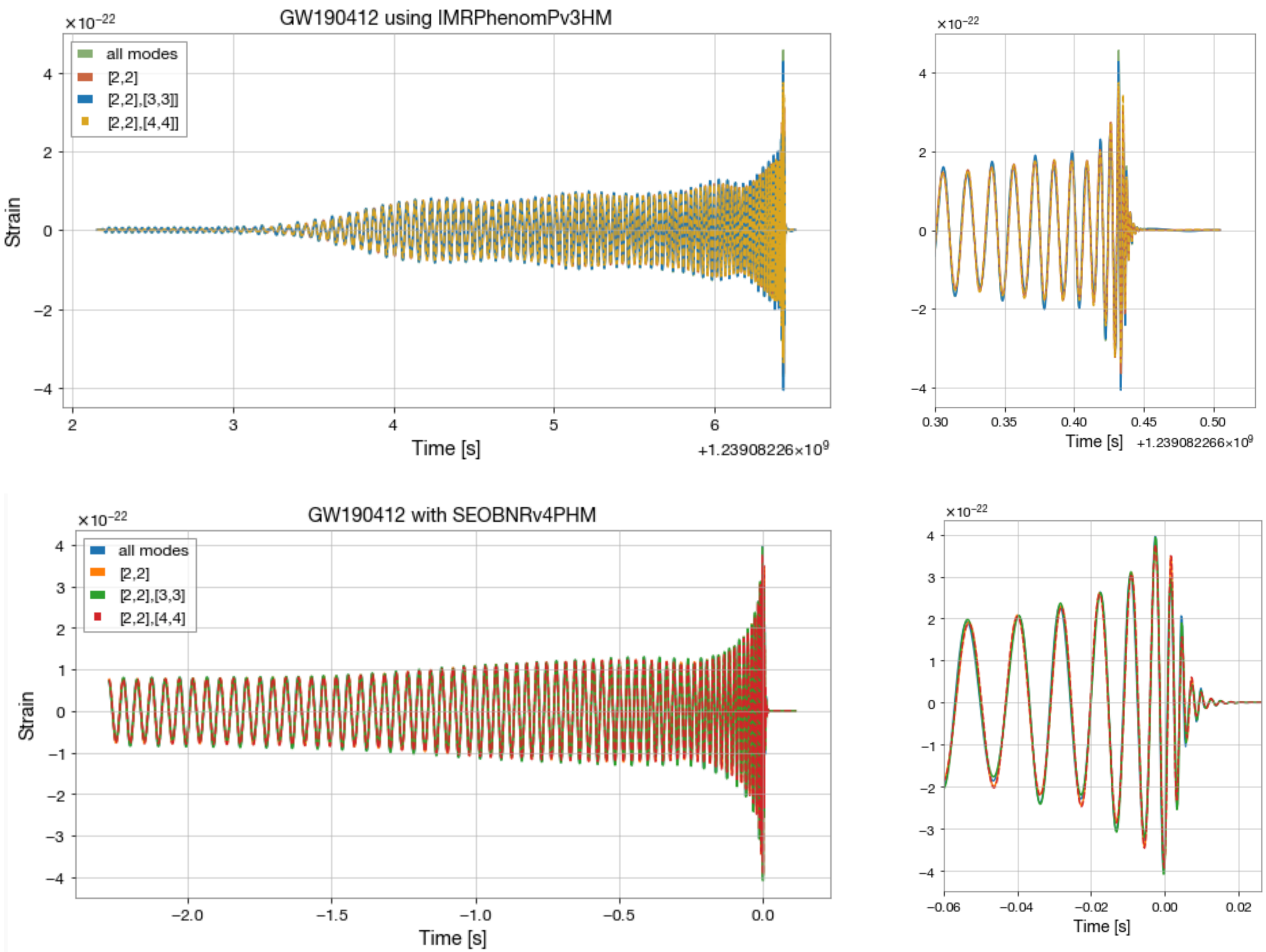


NRSur7dq4

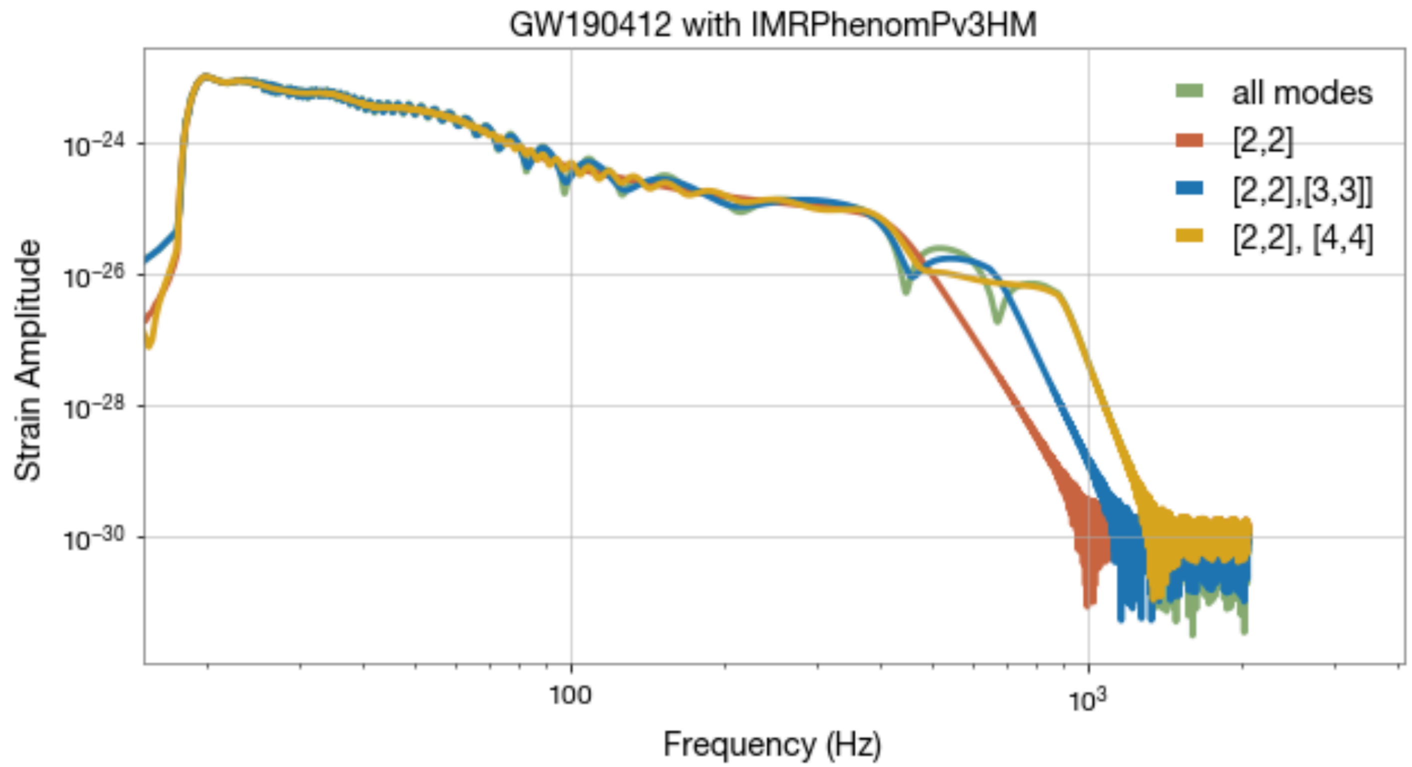

Strain Amplitude
Frequency (Hz)
l2m1
l2m2
l3m2
l3m3
l4m4

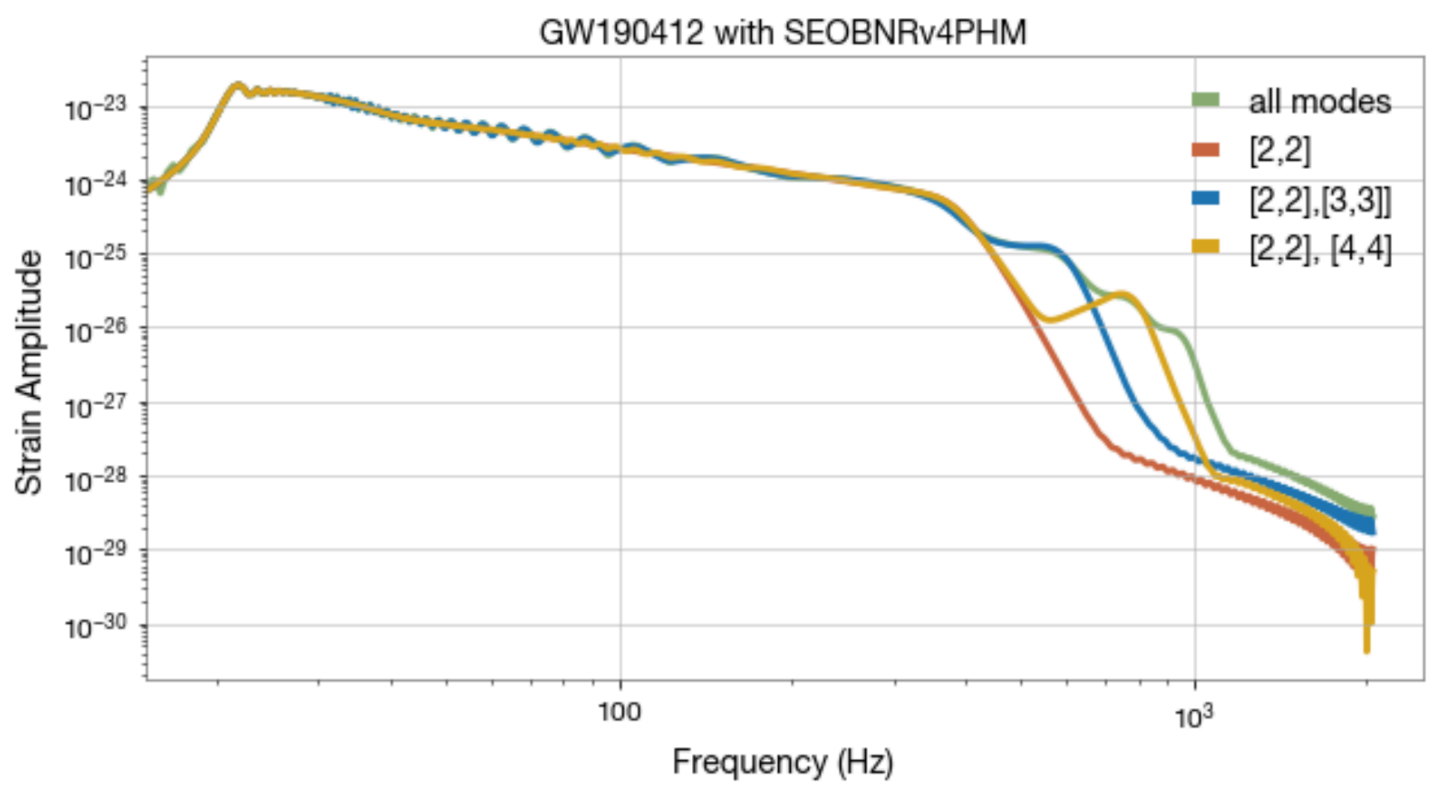

NRSur7dq4: (2,2) mode
Frequency [Hz]
Normalised energy
NRSur7dq4: (3,3) mode
Frequency [Hz]
Normalised energy
NRSur7dq4: (4,4) mode
Frequency [Hz]
Normalised energy
Time [seconds] from 1980-01-06 00:00:00 UTC (0.0)

IMRPhenomPv3HM and SEOBNRv4PHM



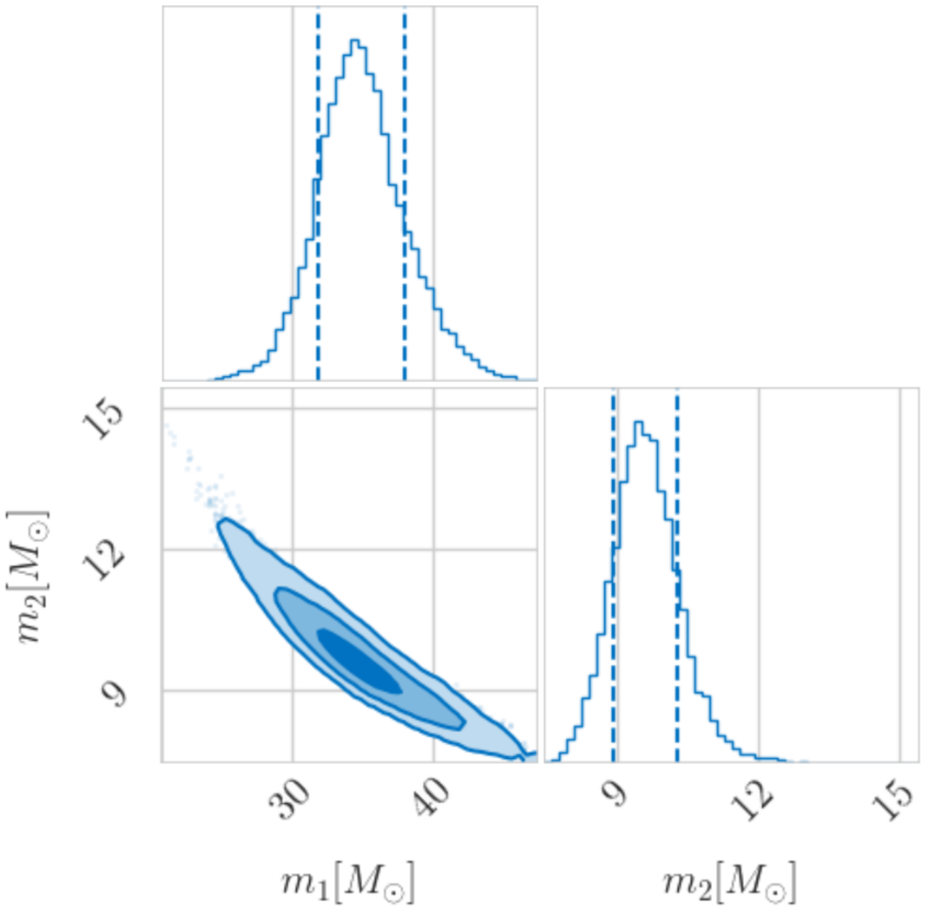
IMRPhenomPv3HM

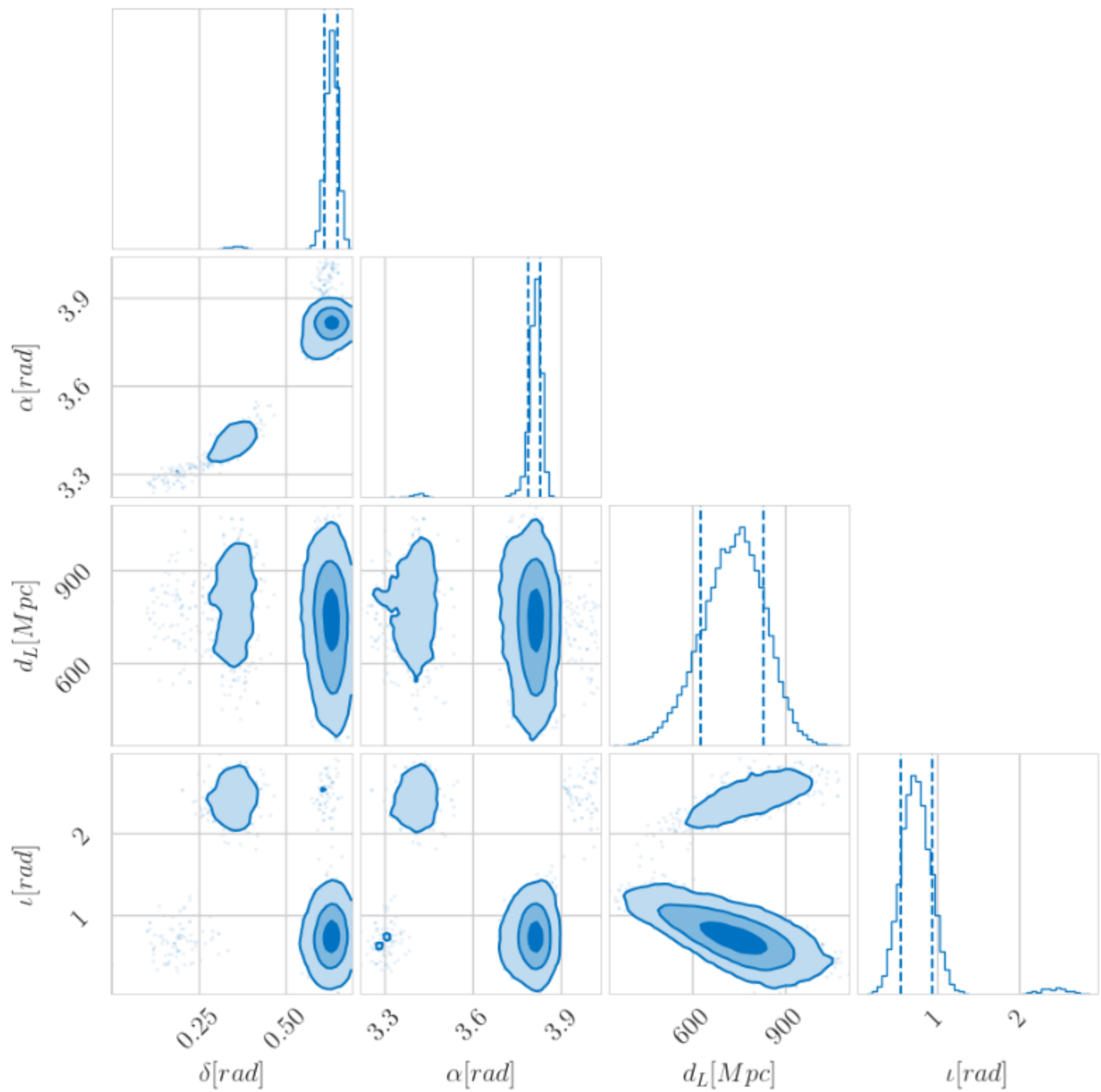




Reanalyzing GW190412 with IMRPhenomXPHM (in progress)

GW190412 with IMRPhenomXPHM





Conclusion

- **Take away:** Accurate waveform models which include higher order modes are needed to continue to describe the *full* black hole binary system through its inspiral, merger, and ringdown.
- For very high-mass ratio systems, higher order multipoles have a significant impact on gravitational wave signals and they are a power test in general relativity.
- When the spins of the system are misaligned with the orbital angular momentum, the orbital plane will precess.
- Despite the obvious differences in the waveform models used to generate the GW190412 signal, the overlap between them shows they agree well with the data.

- **Short term future:**
  1. Use different waveform models that include higher order modes to reanalyze GW190412, GW190814, and other O3 events.

References

- The LIGO Scientific Collaboration, the Virgo Collaboration, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, and et al., GW190412: Observation of a binary-black-hole coalescence with asymmetric masses (2020), arXiv:2004.08342 [astro-ph.HE].

- PyCBC: Free and open software to study gravitational waves, https://pycbc.org/

- G. Ashton, M. Hübner, P. D. Lasky, C. Talbot, K. Ackley, S. Biscoveanu, Q. Chu, A. Divakarla, P. J. Easter, B. Goncharov, and et al., Bilby: A user-friendly bayesian inference library for gravitational-wave astronomy, The Astrophysical Journal Supplement Series 241, 27 (2019).

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