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PhenomGSF: A new phenomenological model of GSF tides for inspiralling binary neutron stars with unequal masses

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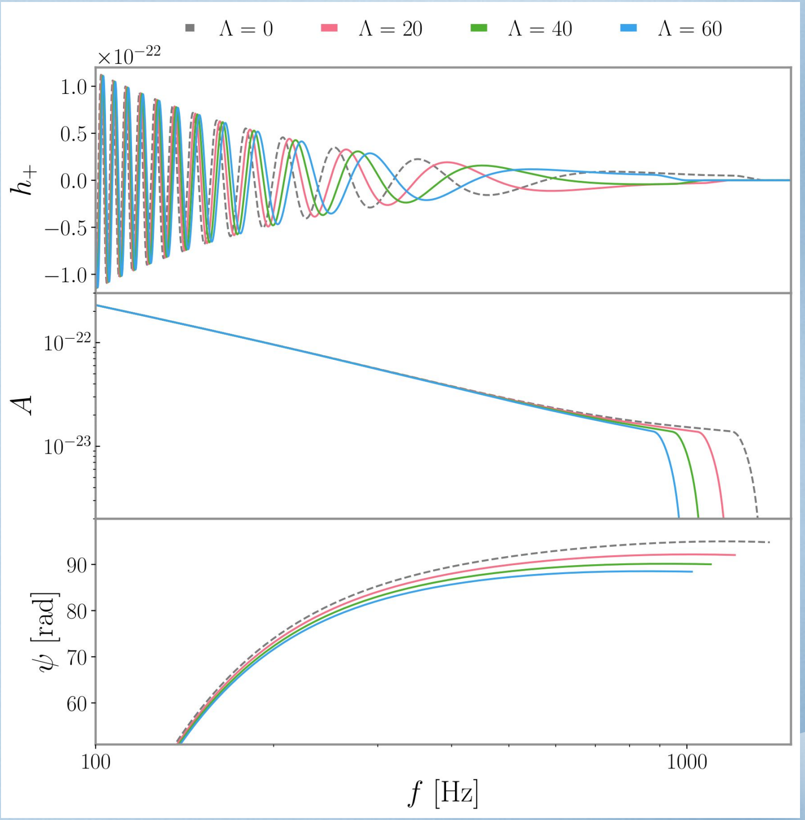
Motivation

BNS detections have the potential to **probe the neutron star equation of state** through measuring the effect of matter within the gravitational wave phase.

This relies on fast, accurate waveform models, however due to their masses **BNS waveform models can be computationally expensive**.



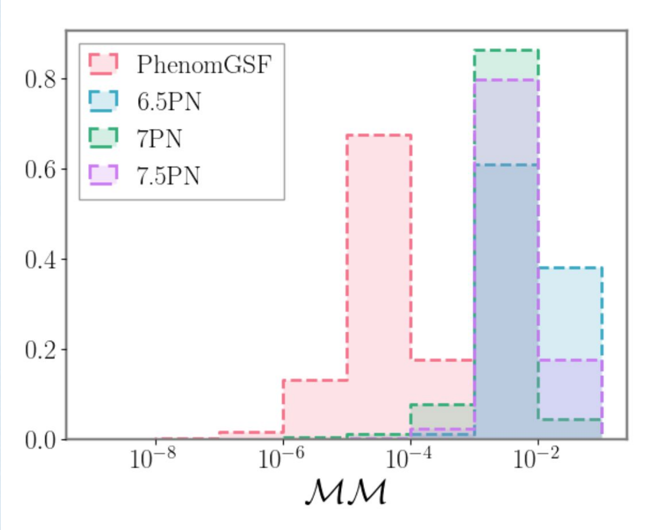
Example waveform of varying tidal deformability, showing the real part of the strain (top), the amplitude (middle) and the phase (bottom).

Motivation

Phenomenological models tackle this bottleneck with analytical fits to these models.

We present **PhenomGSF: A new phenomenological inspiral phase model fitted to TEOBResumS which includes gravitational self-force (GSF) information** within its calculation.

PhenomGSF allows fast replication of TEOBResumS tides which can be modularly added to any binary black hole waveform models.



Mismatches against TEOBResumS for PhenomGSF and various TaylorF2 PN orders

Outline of Model

PhenomGSF describes the adiabatic tidal phase of the (2,2) gravitational wave mode in the frequency domain as a correction of Taylor F2

We isolate the tidal phase so that it can be **modularly added to any binary black hole baseline**.

$$\psi_{\mathrm{BNS}}(f) = \psi_{\mathrm{BBH}}(f) + \psi_{\mathrm{PhenomGSF}}(f)$$

We treat Λ_1, Λ_2 as fully free parameters across the calibration space

$$q \in \{1, 3\}, \Lambda_1, \Lambda_2 \in \{0, 5000\}$$

This allows PhenomGSF to be equation of state independent and make no assumptions of universal relations or hadronic matter.

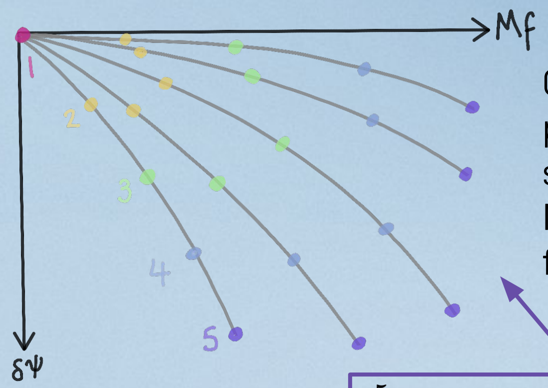
PhenomGSF: The fitting

PhenomGSF is **fitted to the tidal phase** of 8446 TEOBResumS waveforms

Fits are **computed at discrete points** in frequency to avoid overfitting with rational functions for sensible extrapolation

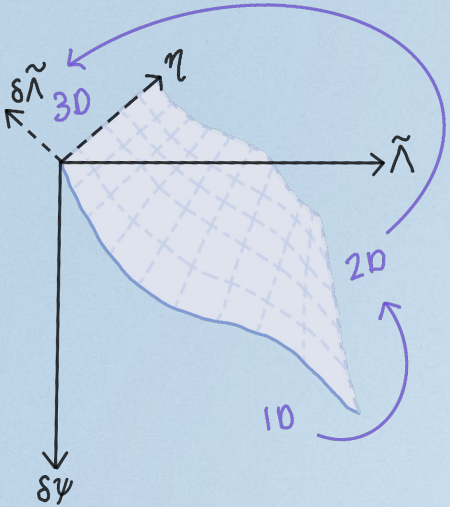
A **hierarchical fitting process** expands from a 1D fit to a 3D fit

The **resulting equations give the tidal phase at any point** in the calibration space



Colocation point selection to MECO frequency

$$\psi_{\mathrm{PhenomGSF}}(f) = \psi_{7.5\mathrm{PN}}(f) + \boxed{\sum_{i=1}^{5} a^i(q, \Lambda_1, \Lambda_2) f^{\frac{10+i}{3}}}$$



Schematic of hericarcical fitting

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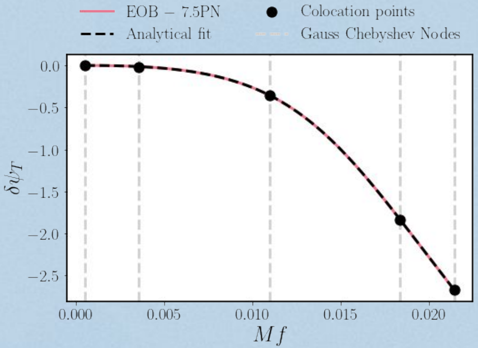
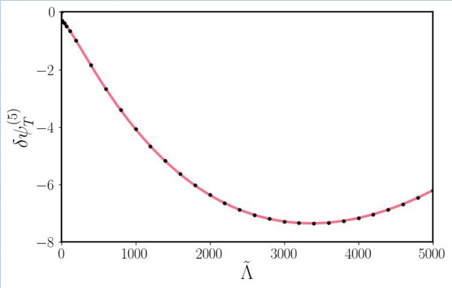
Hierarchical fitting

Compute the tidal phase residual across all input waveforms → Polynomial fit across 5 collocation points for each waveform → 1D rational fit in $(\tilde{\Lambda})$ for each collocation point $\eta = 0.25, \delta\tilde{\Lambda} = 0$ → Expand into 2D $(\eta, \tilde{\Lambda})$ fit, then again to 3D $(\eta, \tilde{\Lambda}, \delta\tilde{\Lambda})$ fit

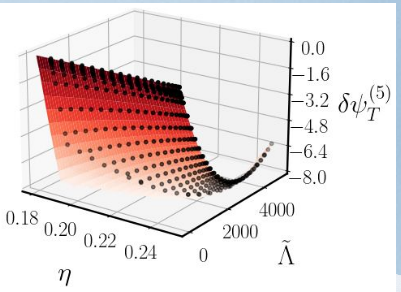
$$\delta\psi = \psi_{\mathrm{T}}^{\mathrm{TEOB}} - \psi_{\mathrm{T}}^{7.5\mathrm{PN}}$$



Example of tidal residual fitted to at discrete points



Example of 1D fit at 5th discrete point across parameter space



Example of 2D fit at 5th discrete point across parameter space

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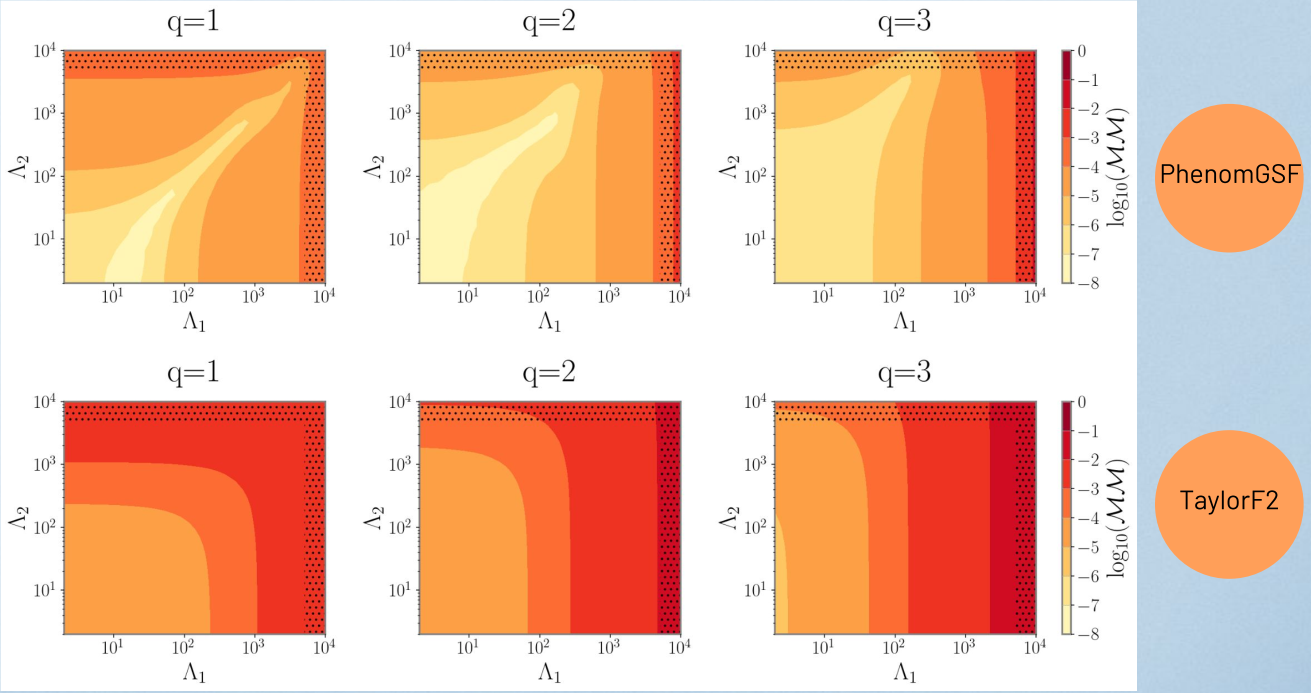
Mismatches to TEOBResumS

Mismatches ~O(3) orders of magnitudes better than that of TaylorF2.

PhenomGSF log(mismatch) < -3 for all calibration space and extrapolates beyond for near equal masses



Mismatches for PhenomGSF (top row) and 7.5PN TaylorF2 (bottom row) against TEOBResumS at q = 1 (left column), 2 (middle column), 3 (right column). Dotted regions show parts of the parameter space beyond the calibration region

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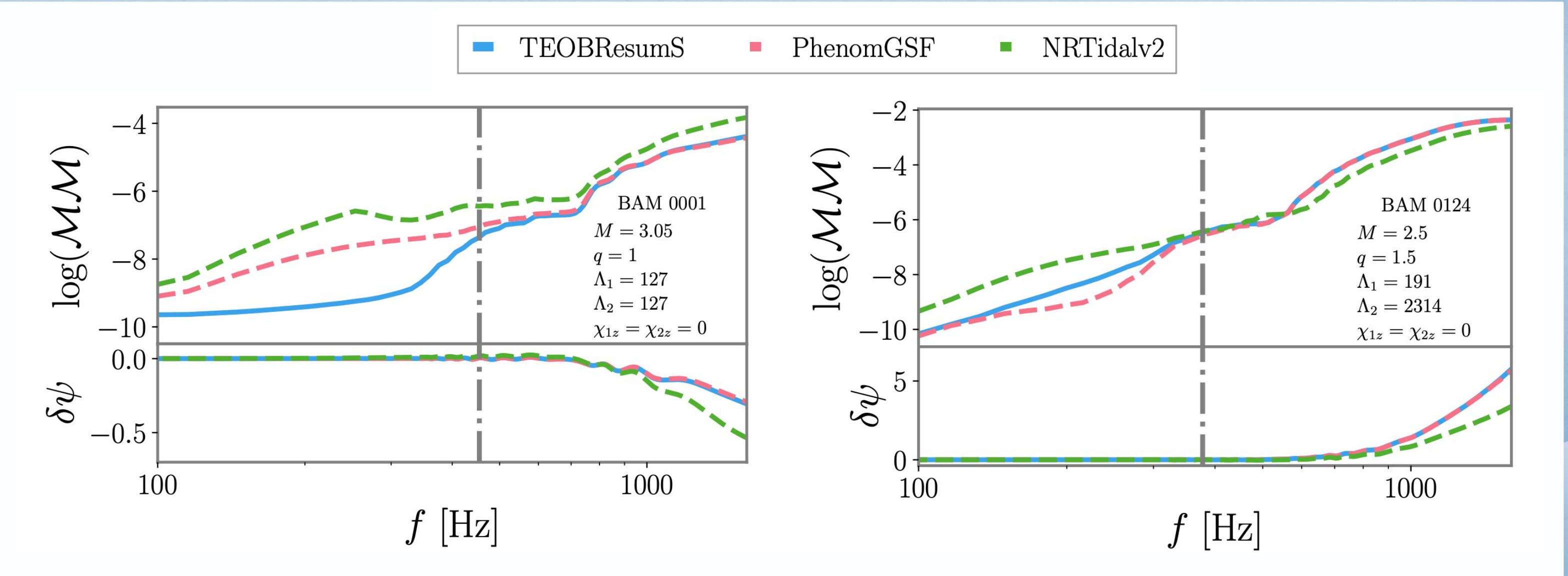
NR Mismatches

PhenomGSF retains the same accuracy as TEOBResumS against TEOBResumS-NR hybrids



Mismatches against a TEOBResumS-NR hybrid from 40Hz to maximum frequency f for TEOBResumS, PhenomGSF and NRTidalv2. An equal mass case (left) and a unequal mass case (right) are shown, with log mismatch (top) and phase residual (bottom).

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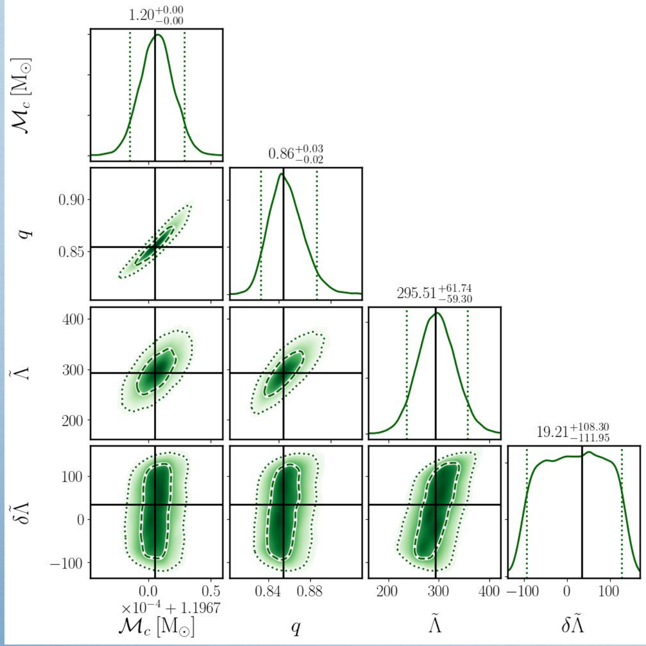
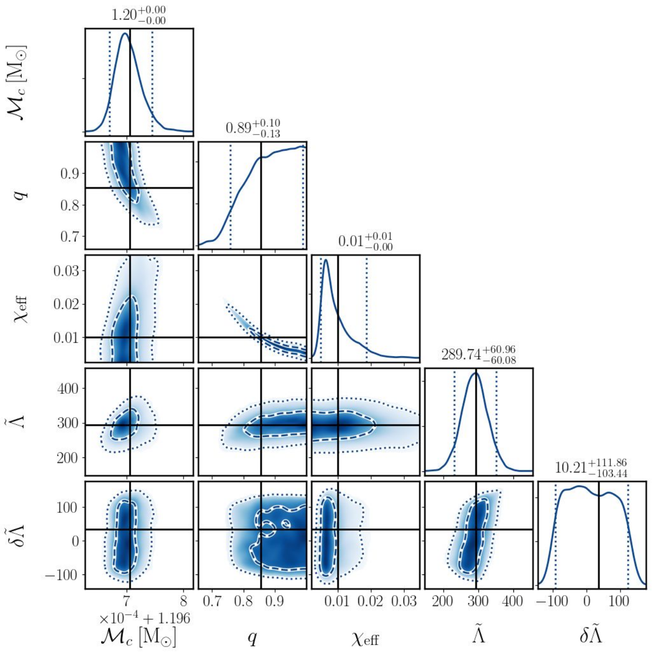
Parameter Estimation: Injection - Recovery

Zero spin injection recovery



Accurate recovery of all parameters

Low aligned spin injection recovery



Accurate recovery of all parameters with observed q-$\chi_{\rm eff}$ correlation

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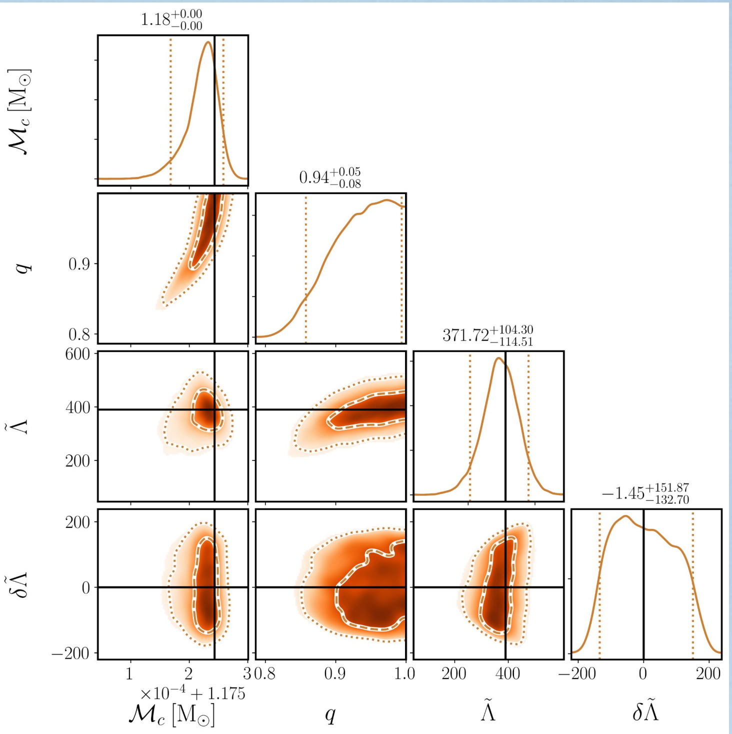
Parameter Estimation: EOB-NR Hybrid Injection

Parameter estimation using a **TEOBResumS-NR hybrid mock injection and recovery with IMRPhenomXAS_PhenomGSF** shows well recovered results in **agreement with the true values**



Posteriors for the TEOBResumS-NR parameter estimation with 50% (dashed lines) and 90% (dotted lines) credible intervals with true injected values (black solid lines)

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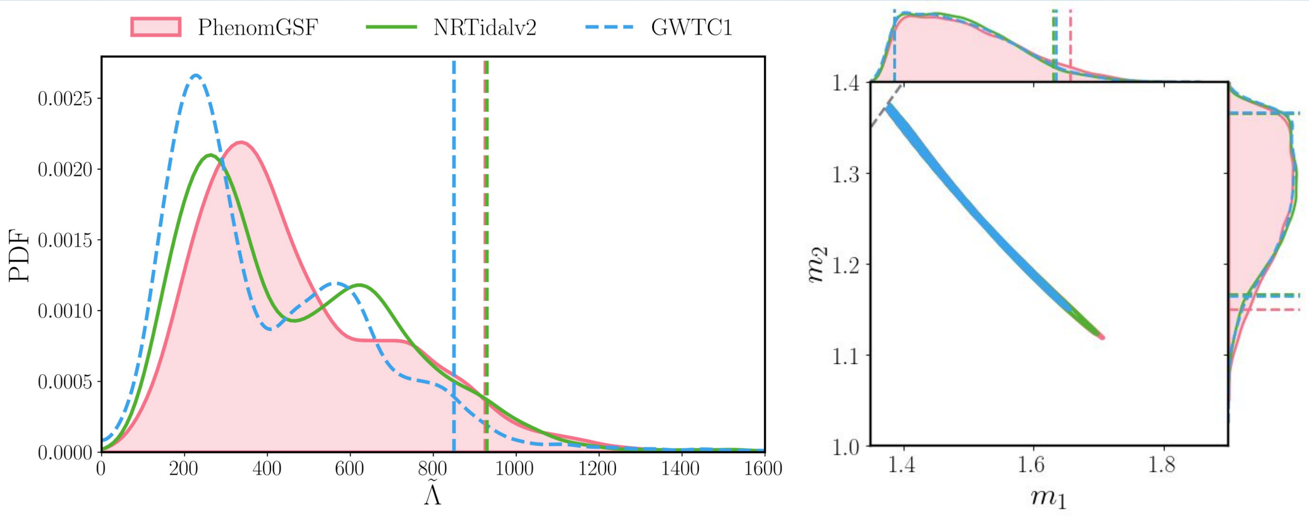
PhenomGSF: GW170817 analysis



GW170817 posteriors for joint dimensionless deformability (left) and component masses (right)

Results from GW170817 are broadly consistent with those from GWTC1, with tendency for slightly higher tides

Summary

PhenomGSF provides a fast to evaluate description of TEOBResumS GSF tides for systems of unequal masses which **can be added to any BBH baseline phase**.

Fitting directly to tidal deformabilities means **we make no assumptions about equation of state, universal relations or hadronic matter**.

PhenomGSF has shown to faithfully replicate TEOBResumS, parameter estimation of injections recover the true values, and **GW170817 analysis gives consistent results to those in GWTC-1**.

PhenomGSF can be used in parameter estimation, alongside other models to assess waveform systematics and to test exotic equations of state and breaking of universal relations.

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