Comparing gravitational waveform models for binary black hole mergers through a hypermodels approach

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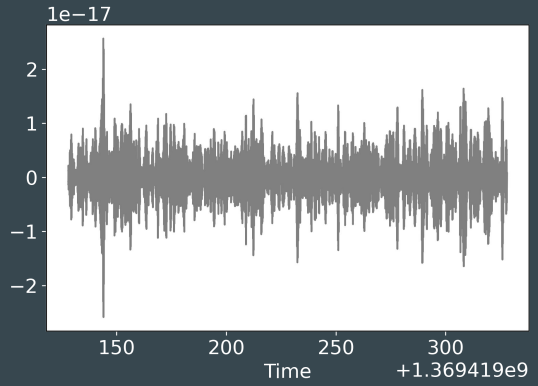
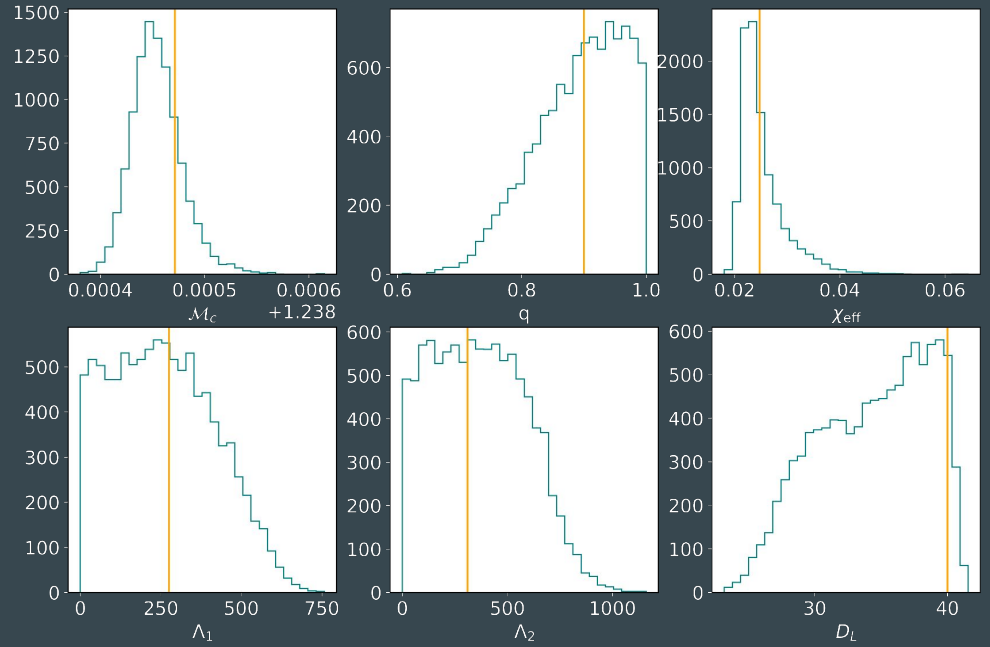
Introduction



Parameter estimation



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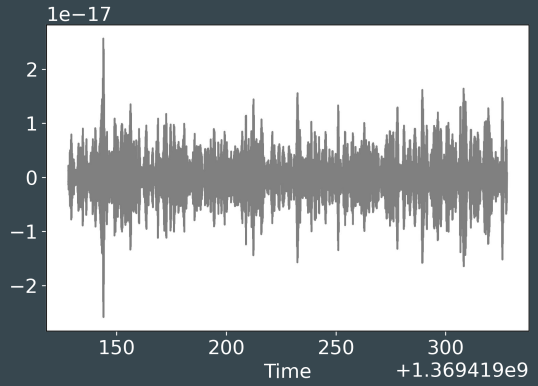

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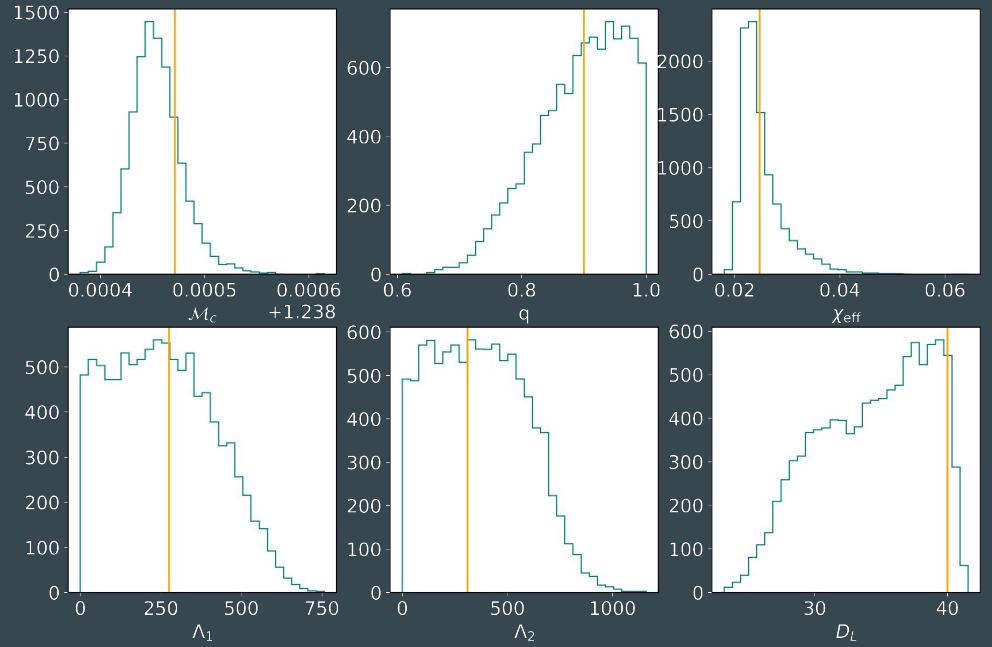

Waveform models:
different approximations to build waveform models for parameter estimation analyses can lead to differences and biases in the results

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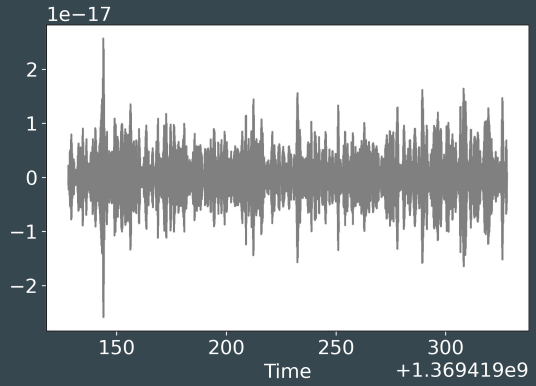
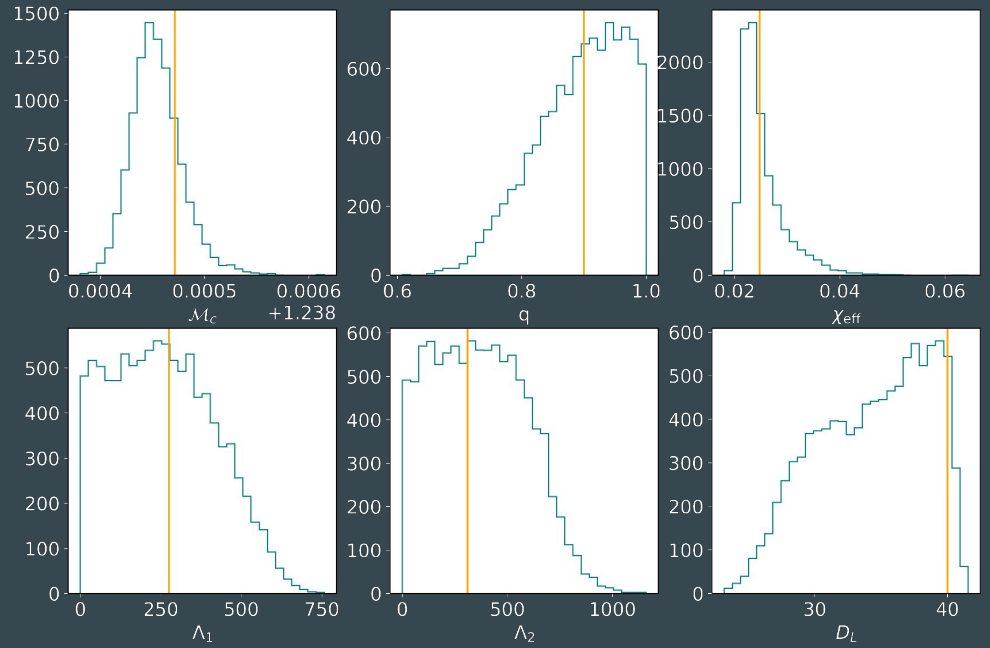


Parameter estimation



Waveform models:
different approximations to build waveform models for parameter estimation analyses can lead to differences and biases in the results

This work

Analyze 13 BBH events in GWTC-3 with different models, to quantify preferences between models

Hypermodels

Introduced in Ashton&Dietrich,*Nature Astronomy*(2022)

Sample over the waveform model too, with a categorical parameter ω:

$$\text{parameters space} = \{\vec{\theta}, \omega\} \qquad \omega \in [0, m-1]$$

source parameters — waveform model

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Sample over the waveform model too, with a categorical parameter ω:

$$\text{parameters space} = \{\vec{\theta}, \omega\} \qquad \omega \in [0, m-1]$$

$\vec{\theta}$: source parameters; ω: waveform model

Probability for each waveform ℓ :

$$p_\ell = \frac{n_\ell}{N}$$

$n_\ell \rightarrow$ number of samples for model ℓ

$N \rightarrow$ total final posterior samples

Odds ratio between two models A and B:

$$\mathcal{O}^A_B = \frac{p_A}{p_B} = \frac{n_A}{n_B}$$

Analysis

- Four different models, all with precession and higher-order modes:

  NRSur7dq4, IMRPhenomXPHM, SEOBNRv4PHM, IMRPhenomTPHM

- $(\ell, m) = (2, 2), (2, 1), (3, 3), (4, 4), (2, -2), (2, -1), (3, -3), (4, -4)$
- Heaviest events in GWTC-3 ($M_{\rm tot} \geq 59.4 M_{\odot}$, NRSur7dq4 validity)

  with significant SNR ($\rho_{\rm net} \geq \sqrt{N_{\rm d} * 8^2}$) -> 13 events

- bilby MCMC
- recover source parameters (chirp mass $\mathcal{M}_c$, mass ratio q, effective inspiral spin $\chi_{\rm eff}$, effective precessing spin $\chi_{\rm p}$) and probabilities for the different models

Results - Single events

- For most events, no clearly favored model
- Only for 3 events we find a strong preference for some of the models

  but
  -> not the same models are preferred
  -> short duration and data quality issues

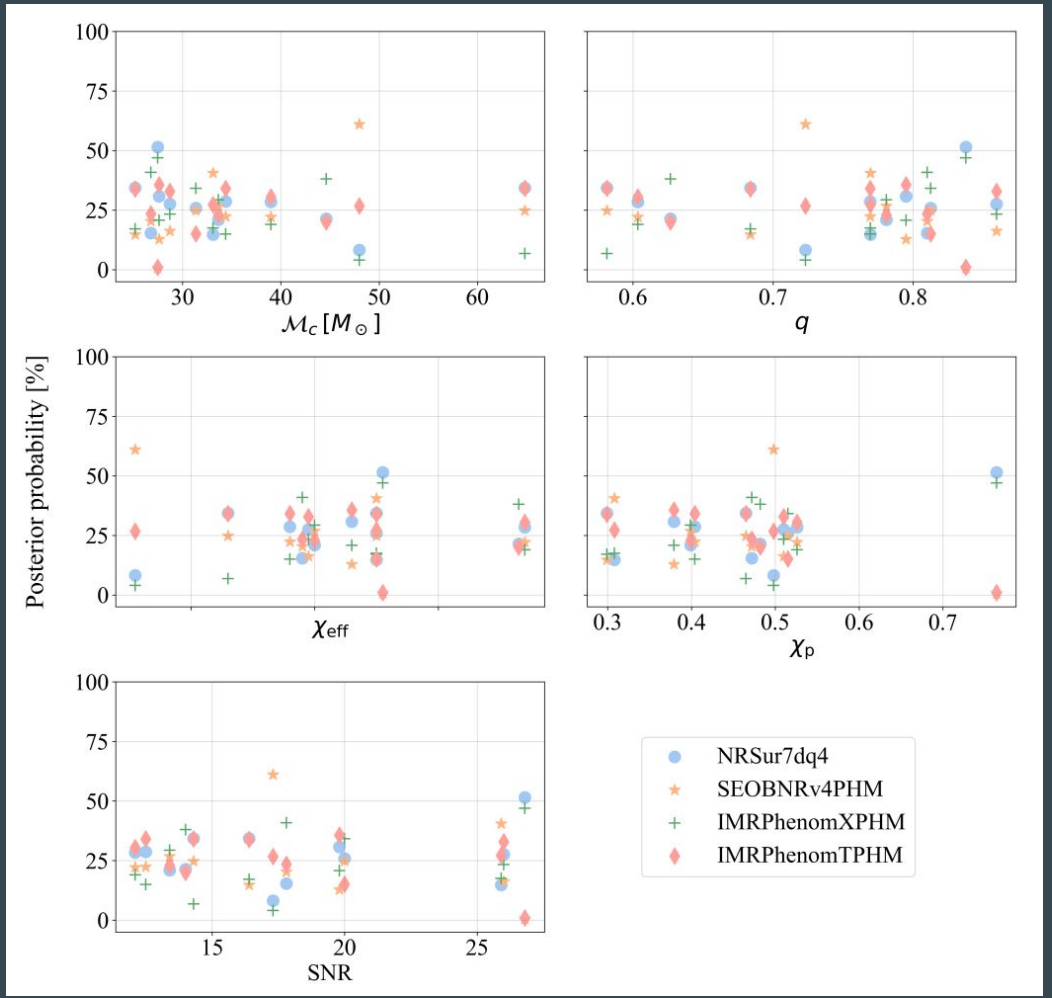
Models' probability $p_\ell = \frac{n_\ell}{N}$

Event	NRSur	SEOB	IMRX	IMRT
GW150914	27.55 ± 0.7	16.22 ± 0.8	23.34 ± 0.7	32.88 ± 0.7
GW190519_153544	20.82 ± 0.6	20.95 ± 0.6	40.87 ± 0.5	17.35 ± 0.6
GW190521_074359	14.76 ± 1.2	40.50 ± 1.0	17.53 ± 1.2	27.22 ± 1.1
GW190620_030421	32.98 ± 0.6	19.48 ± 0.6	20.22 ± 0.6	27.32 ± 0.6
GW190630_185205	33.79 ± 0.6	15.36 ± 0.6	18.90 ± 0.6	31.95 ± 0.6
GW190910_112807	22.86 ± 0.6	25.92 ± 0.6	27.85 ± 0.6	23.37 ± 0.6
GW191222_033537	28.11 ± 0.5	20.58 ± 0.6	18.78 ± 0.6	32.53 ± 0.5
GW200112_155838	30.56 ± 0.6	15.61 ± 0.6	19.82 ± 0.6	34.01 ± 0.5
GW200224_222234	21.82 ± 0.6	23.39 ± 0.6	40.43 ± 0.5	14.36 ± 0.7
GW200311_115853	15.68 ± 0.6	27.70 ± 0.6	35.69 ± 0.6	20.93 ± 0.6
GW190521	31.78 ± 0.6	26.39 ± 0.6	4.60 ± 0.7	37.23 ± 0.5
GW191109_010717	7.54 ± 1.6	62.29 ± 1.0	5.06 ± 1.7	25.11 ± 1.5
GW200129_065458	46.94 ± 1.4	$0.66^{+1.9}_{-0.66}$	51.14 ± 1.3	$1.25^{+1.9}_{-1.25}$

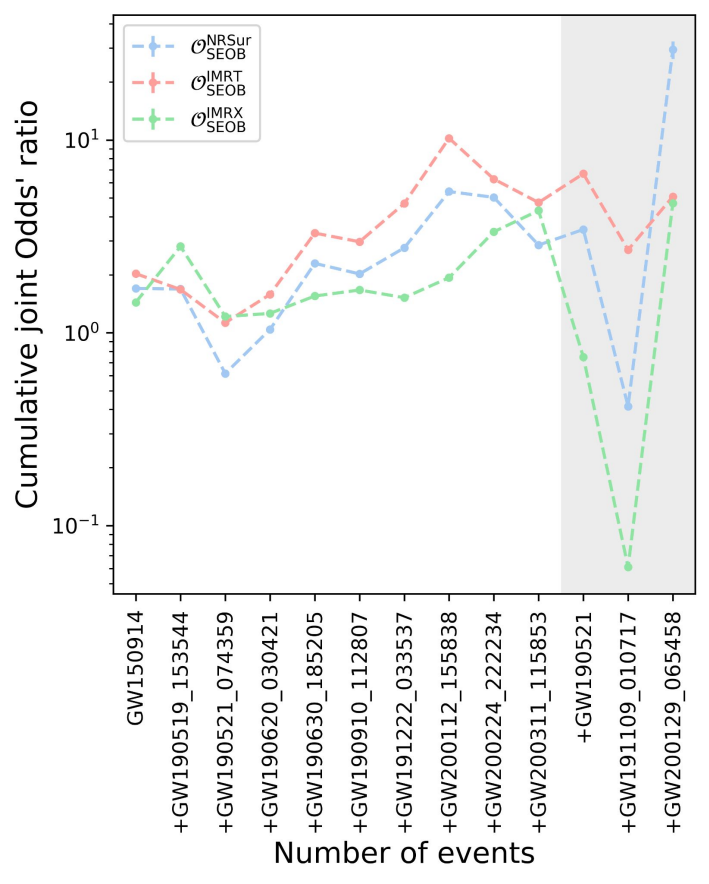
Results - Trends

No trends with respect to source parameters or SNR

? NRSur7dq4 for large masses



Results - Combined events



	$\mathcal{O}^{\rm NRSur}_{\rm SEOB}$	$\mathcal{O}^{\rm IMRX}_{\rm SEOB}$	$\mathcal{O}^{\rm IMRT}_{\rm SEOB}$	$\mathcal{O}^{\rm NRSur}_{\rm IMRX}$	$\mathcal{O}^{\rm NRSur}_{\rm IMRT}$	$\mathcal{O}^{\rm IMRX}_{\rm IMRT}$
All events	29.43 ± 1.11	4.70 ± 0.07	5.09 ± 0.08	6.26 ± 0.11	5.78 ± 0.10	0.92 ± 0.01
No GW200129_065458	0.42 ± 0.00	0.06 ± 0.00	2.69 ± 0.03	6.82 ± 0.12	0.15 ± 0.00	0.02 ± 0.00
No GW190521	24.44 ± 0.84	26.99 ± 0.97	3.61 ± 0.05	0.91 ± 0.01	6.77 ± 0.12	7.48 ± 0.14
No GW191109_010717	243.31 ± 26.35	57.84 ± 3.05	12.62 ± 0.31	4.21 ± 0.06	19.27 ± 0.59	4.58 ± 0.07
Without all three	2.85 ± 0.03	4.30 ± 0.06	4.74 ± 0.07	0.66 ± 0.00	0.60 ± 0.00	0.91 ± 0.01

NRSur favored over SEOB, but result mainly determined only by one event (GW200129_065458)

Without the three events that significantly favor or disfavor one of the models, we find no preference for any of the approximants.

Results - Precession

Probability

Event	NRSur	SEOB	IMRX	IMRT
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χ_p JS divergence with prior

Event	NRSur	SEOB	IMRX	IMRT	Combined
GW150914	0.008	0.010	0.050	0.017	0.015
GW190519_153544	0.010	0.017	0.010	0.011	0.011
GW190521_074359	0.037	0.029	0.027	0.029	0.029
GW190620_030421	0.010	0.006	0.016	0.012	0.006
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GW200112_155838	0.012	0.015	0.011	0.014	0.012
GW200224_222234	0.008	0.011	0.024	0.010	0.010
GW200311_115853	0.026	0.018	0.041	0.038	0.031
GW190521	*0.243*	*0.158*	*0.007*	*0.264*	*0.202*
GW191109_010717	*0.095*	*0.227*	*0.070*	*0.422*	*0.243*
GW200129_065458	*0.459*	*0.005*	*0.330*	*0.051*	*0.378*

Results - Precession

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GW190521_074359	0.037	0.029	0.027	0.029	0.029
GW1					6
GW1					0
GW1					4
GW191222_033537	0.012	0.011	0.014	0.012	0.011
GW200112_155838	0.012	0.015	0.011	0.014	0.012
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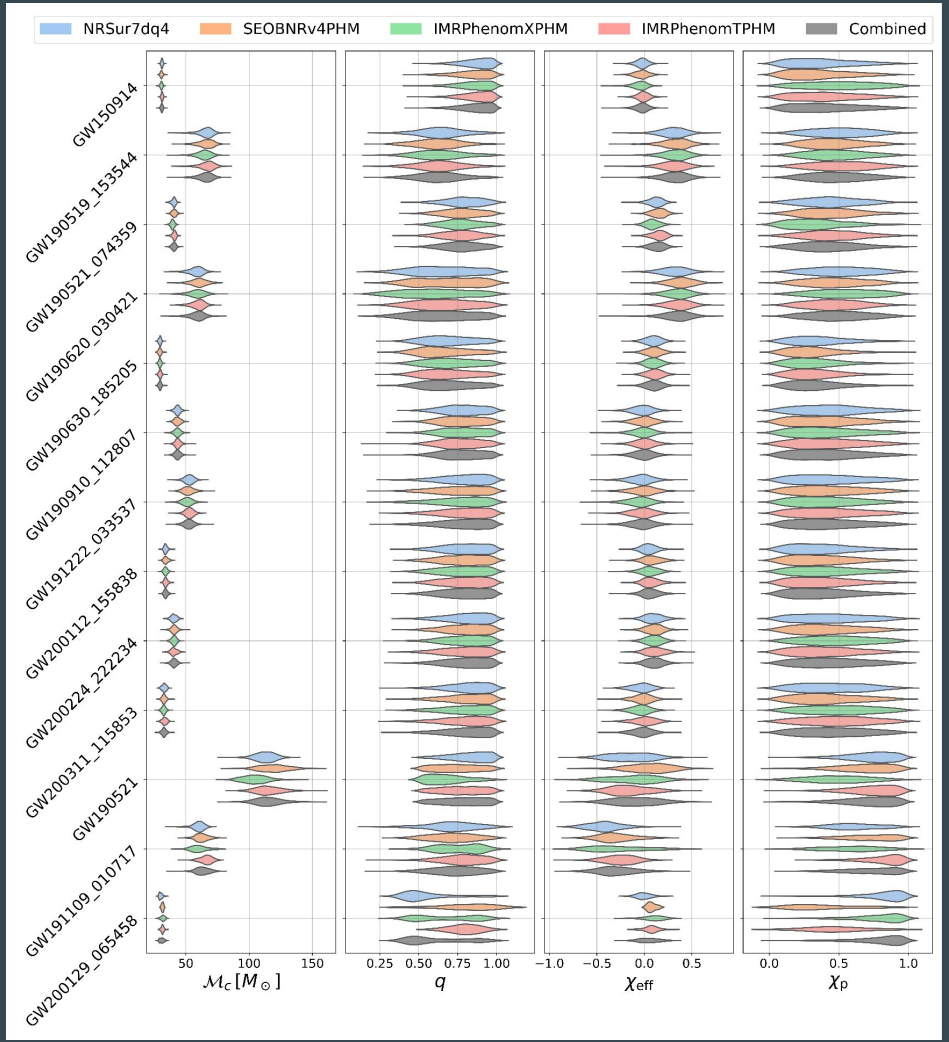
Models that recover precession have a higher probability

Conclusions

- We analyzed the 13 heaviest events with significant SNR in GWTC-3 with a hypermodels approach to quantify model preferences
- Overall, no model is consistently preferred or disfavored
- No trends of model preference based on source parameters or signal SNR
- For three events (GW190521, GW191109, GW200129) we find strong preference for some of the models, ***but***
    - different models
    - these events have short duration or potential data quality issues
- Combining results from all the events: $\mathcal{O}^{\mathrm{NRSur}}_{\mathrm{SEOB}} = 29.43$, but this result is determined only by GW200129. Without the three events above, no significant preference for any model
- However, for all the events with a strong preference, we find that the preferred models are the ones which recover precession

Backup - Parameters Posteriors



Backup - Injections