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An Effective-one-body model calibrated to 143 NR simulations for the O2 observing run by advanced LIGO

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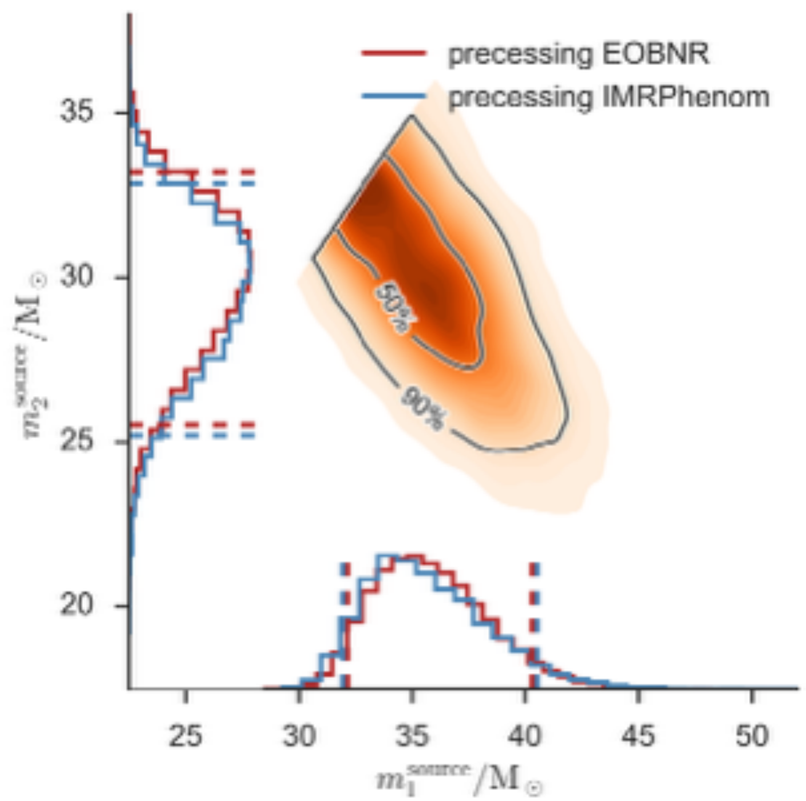
Effective-One-Body (EOB) and the first GW detections

- Effective-one-body models calibrated to numerical-relativity simulations (EOBNR) have been used by initial and advanced LIGO and Virgo.

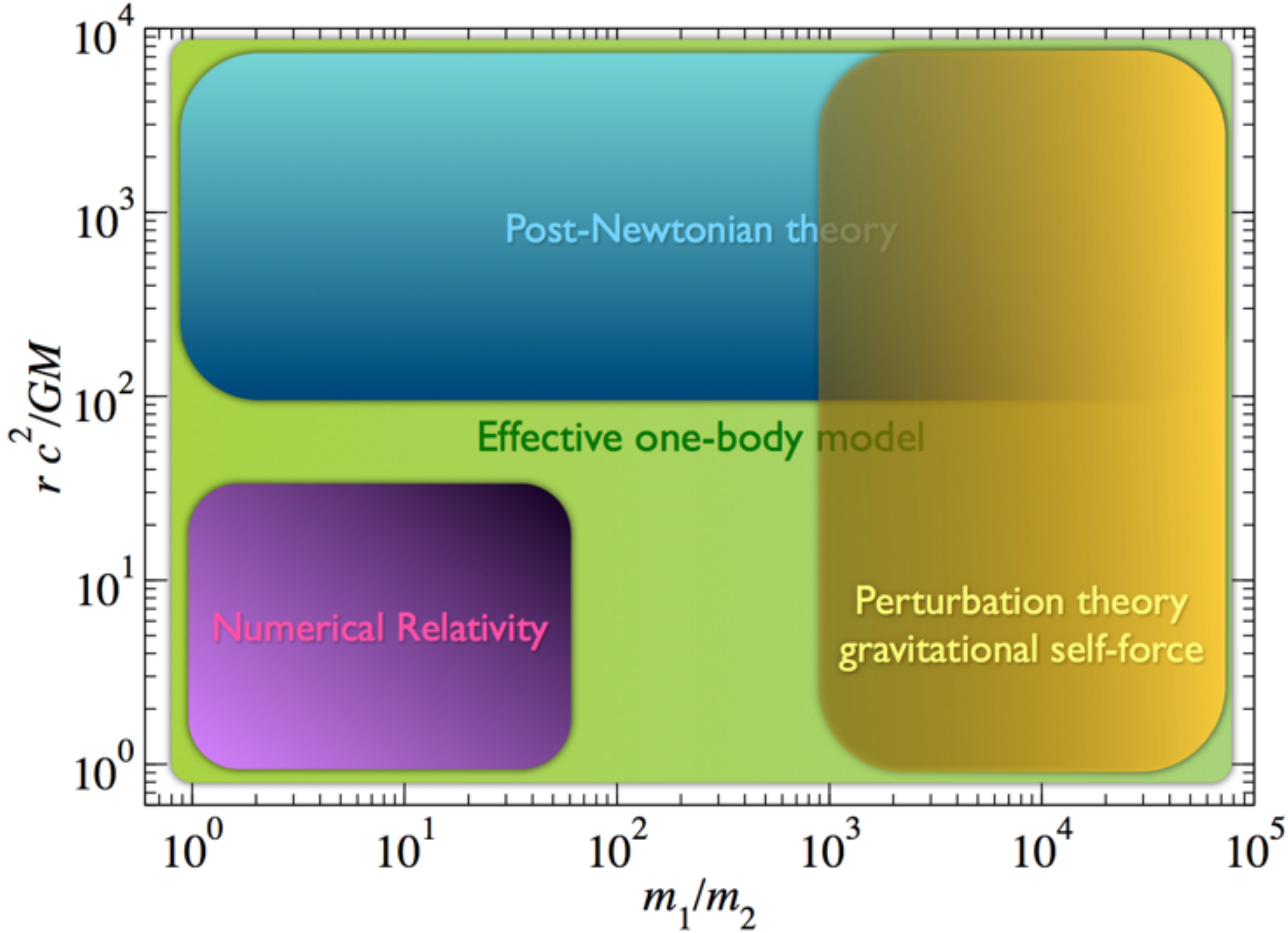
- An aligned-spin EOB model *(Taracchini et al. 2013)* was used in the first observing run :
  - to detect GW from binary systems with total mass above 4 Msun.
  - to estimate the astrophysical parameters of the detected signals.
  - to perform tests of General Relativity



(Abbott et al. arXiv:1606.01210)

- A precessing-spin EOBNR model *(Pan et al. 2013, Babak et al. (in prep))* was recently used to improve the parameter estimates.

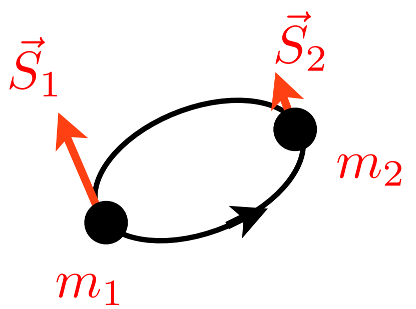
Effective One Body : combining approaches



Buonanno and Sathyaprakash (2014)

Effective One Body approach

"Real" 2-body problem in GR

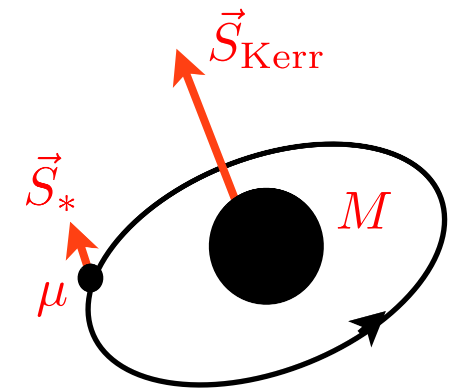


$H_{\rm real}$

mapping

$$H_{\rm real} = Mc^2 \left[\sqrt{1 + 2\nu \left(\frac{H_{\rm eff}}{\mu c^2} - 1 \right)} - 1 \right]$$

Effective problem : test particle in a deformed Kerr spacetime



$$M = m_1 + m_2$$

$$\vec{S}_{\rm Kerr} = \vec{S}_1 + \vec{S}_2$$

$$\mu = \frac{m_1 m_2}{m_1 + m_2} \qquad \vec{S}_*[\vec{S}_1, \vec{S}_2]$$

The EOB model [Buonanno & Damour 99] describes the 2-body problem via

- an effective one body Hamiltonian
- radiation reaction force
- analytic inspiral-merger-ringdown waveforms

- Each ingredient is a resummation of PN results
- Test particle limit included by construction
- Capture non-linear information from NR by adjusting a reduced set of calibration parameters

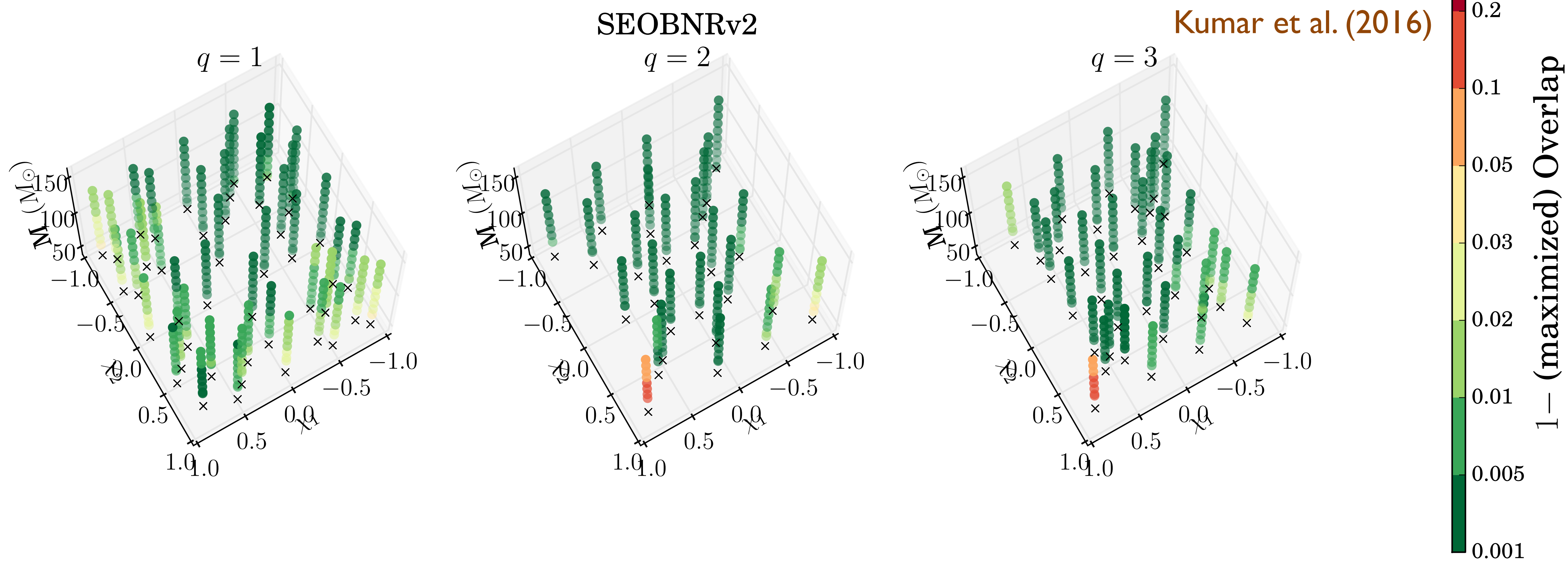
The EOB model improved during the last 15 years. Many people contributing:

Buonanno, Pan, Taracchini, Barausse, Hinderer; Damour, Nagar, Bernuzzi, Bini, Balmelli; Iyer; Jaranowski, Schaefer, ...

Previous aligned-spin EOB model vs new NR simulations

Comparison of the Taracchini et al. (2013) "SEOBNRv2" model, (calibrated to 38 NR waveforms) against a set of 138 new NR simulation from the SXS collaboration.

Kumar et al. (2016)



- The (maximized) Overlap is the match maximizing only on time and phase, keeping the same parameters.
- SEOBNRv2 performs very well against most of the new simulations, but for mass ratios 2 and 3 and (dimensionless) spins 0.85 it has an Overlap of only about 90%.
- 1- (maximized) Overlap of about 10% will not impact detection (effectualness above 99%), but it may affect parameter estimation, depending on SNR.

Improving the EOBNR model

Routes to improve the accuracy of the EOBNR model :

- modify/simplify the structure of the different ingredients (Hamiltonian, radiation reaction, GW modes)
- incorporate newly available information from PN theory and or gravitational self-force
- recalibrate to a larger set of NR simulations

Work is in progress at the AEI on all of these aspects. Given the time frame of O2 (starting in the fall), we focused on the following improvements :

- Addition of spin-orbit corrections (up to 3.5PN) to the (2,2) mode amplitude
- Analytical ringdown model (in the spirit of Baker et al. 2008; Nagar et al. 2015)
- Incorporation of the most recent final spin formula (Barausse et al., 2016) and NR peak values for amplitude and frequency.
- Recalibration to a set of recent NR waveforms produced by the SXS collaboration. (Kumar et al. 2016; Hinder, Ossokine et al. (in prep))

Calibration to NR waveforms

Main improvements with respect to the calibration of the previous EOBNR model

- Set of new NR waveforms that extends the domain of calibration, notably for spins > 0.5 and mass ratios 2 and 3.

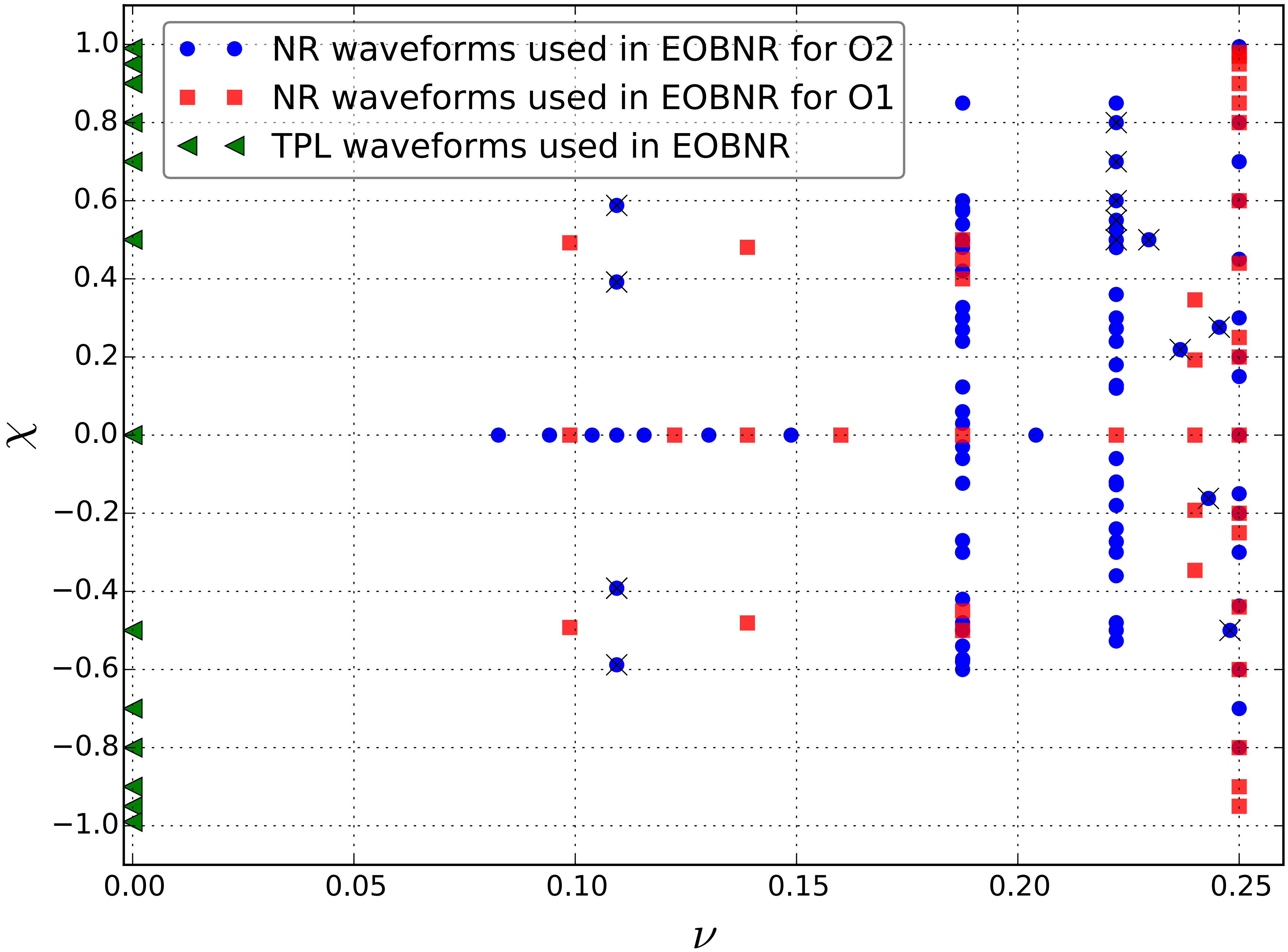
- Removed one calibration parameter (in the phase) and added a spin dependence on the others. $\{K, d_{\rm SO}, d_{\rm SS}, \Delta_{\rm NQC}\}(\nu, \chi)$

- We developed an MCMC code to perform the calibration against each NR waveform.

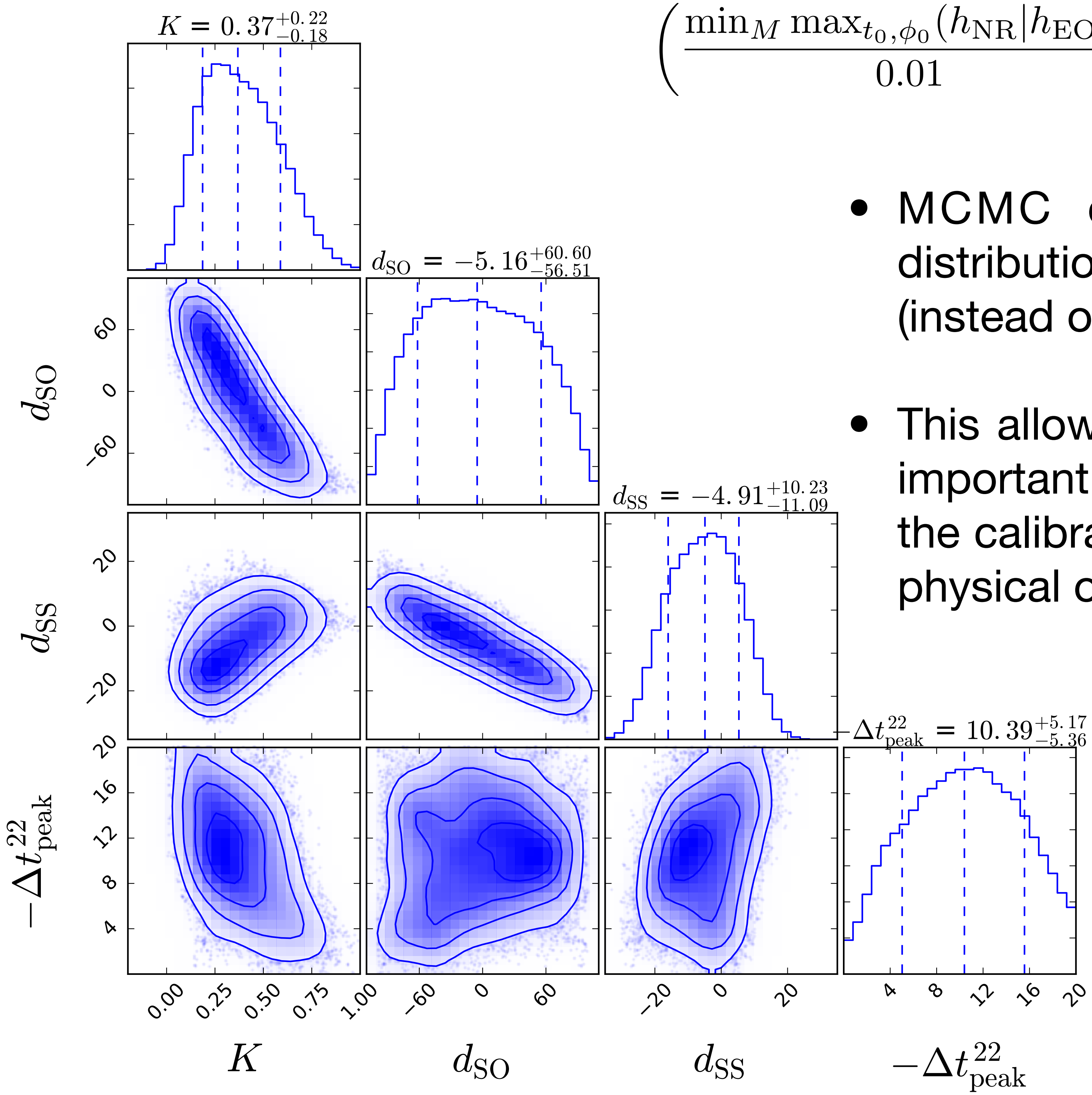
- Statistics used to measure the agreement between the NR and the model combines the noise weighted overlap and the time to merger.

- Extrapolation to high spins : monitoring the number of cycles to merger.

NR waveforms used for calibration/tests



Example of calibration : q=3, s=(0.73, -0.85)



$$\left(\frac{\min_M \max_{t_0,\phi_0}(h_{\rm NR}|h_{\rm EOB})}{0.01}\right)^2 + \left(\frac{\delta t\,\text{peak after low freq. align.}}{5}\right)^2$$

- MCMC code gives us access to full distributions for the calibration parameters (instead of just the best fit values)
- This allows to visualize correlations and most importantly provides error bars for the fit of the calibration parameters as a function of the physical ones.

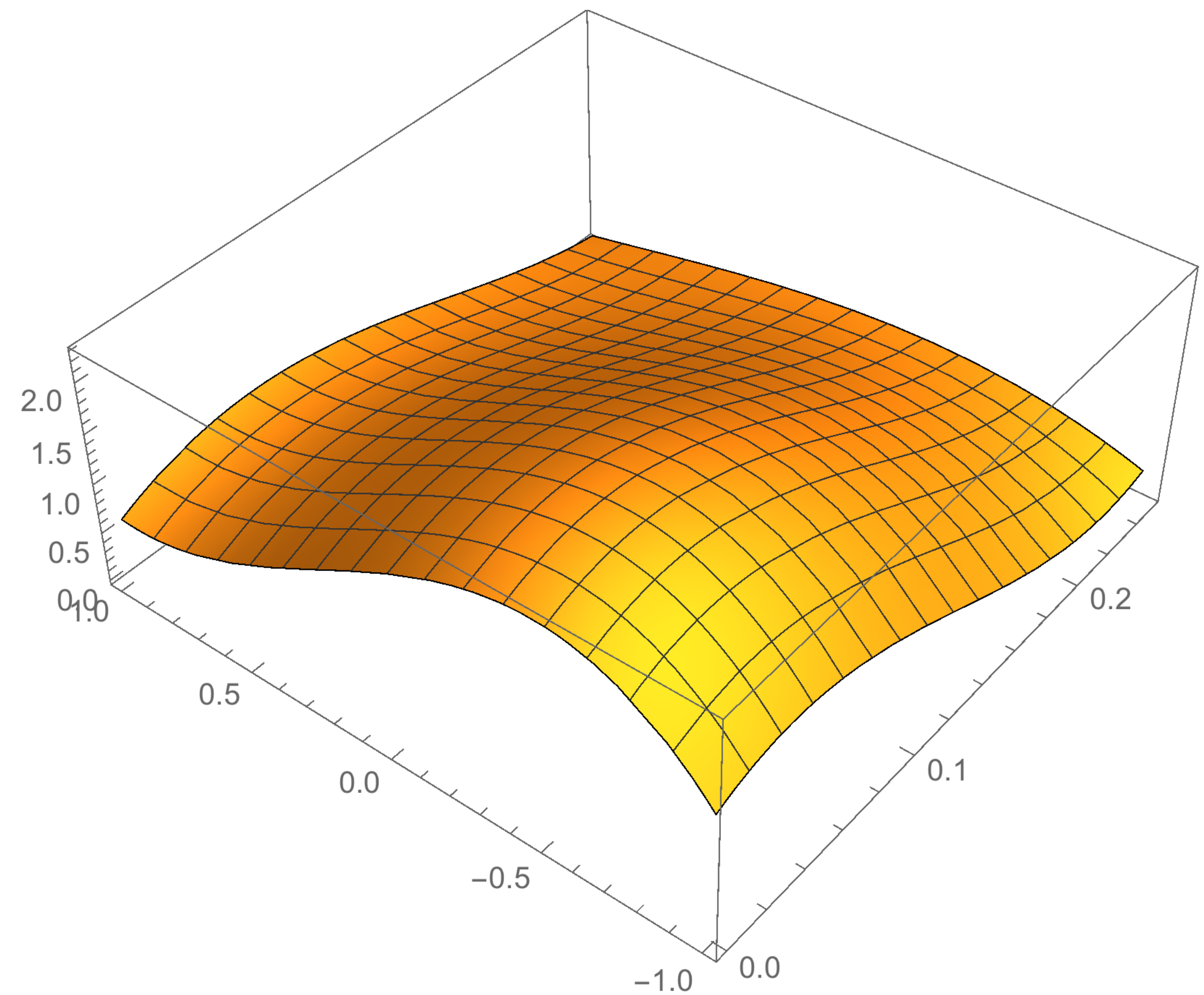
Fit as a function of physical parameters

We finally need to predict the calibration parameters as functions of the physical ones.

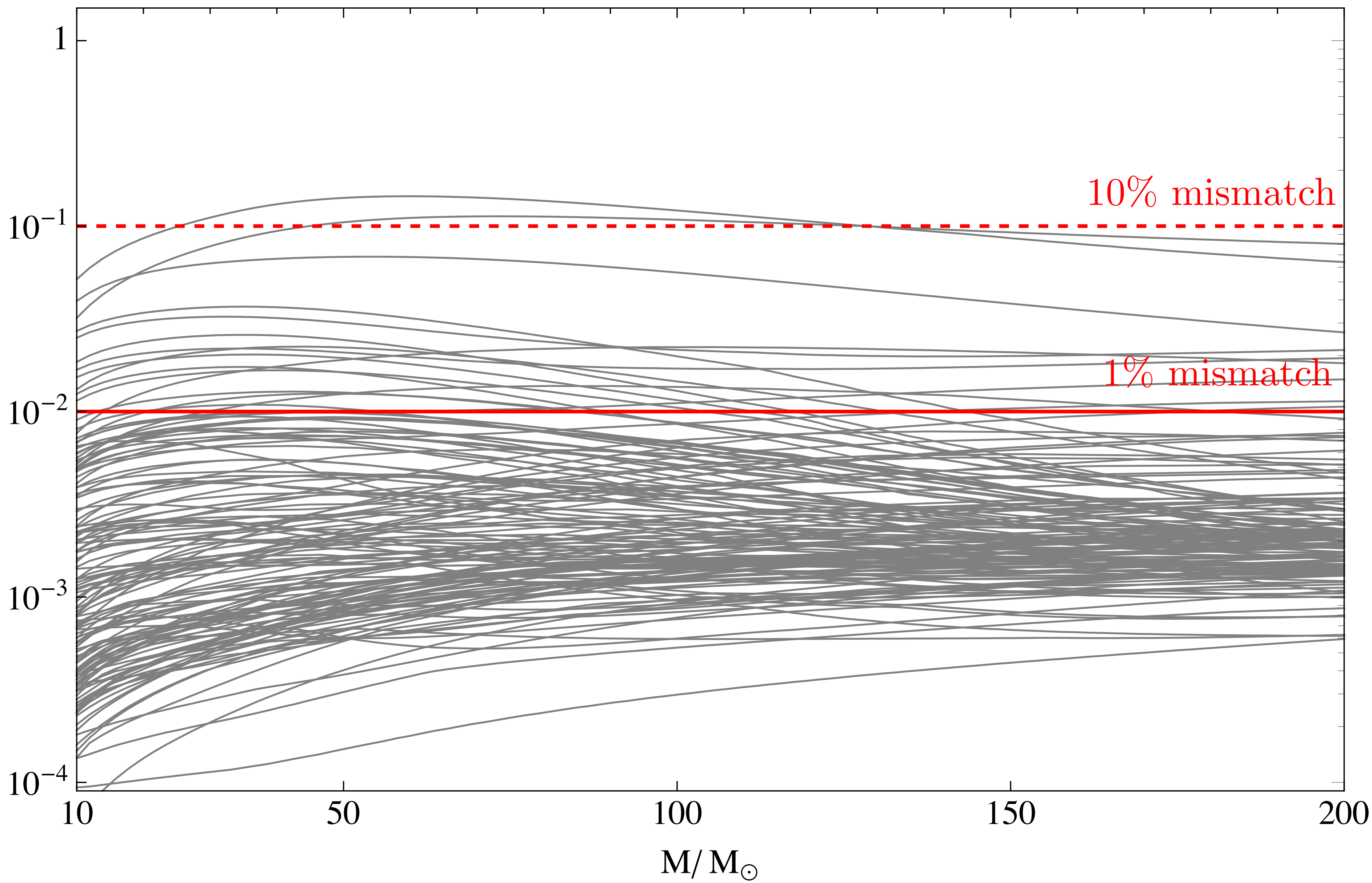
For instance, $K(\nu, \chi_1, \chi_2) = K(\nu, \chi)$

with the spin combination $\chi = \frac{(\chi_1 + \chi_2)}{2} + \frac{(\chi_1 - \chi_2)}{2} \frac{\sqrt{1-4\nu}}{(1-2\nu)}$

We fit the data using polynomials in ν and χ

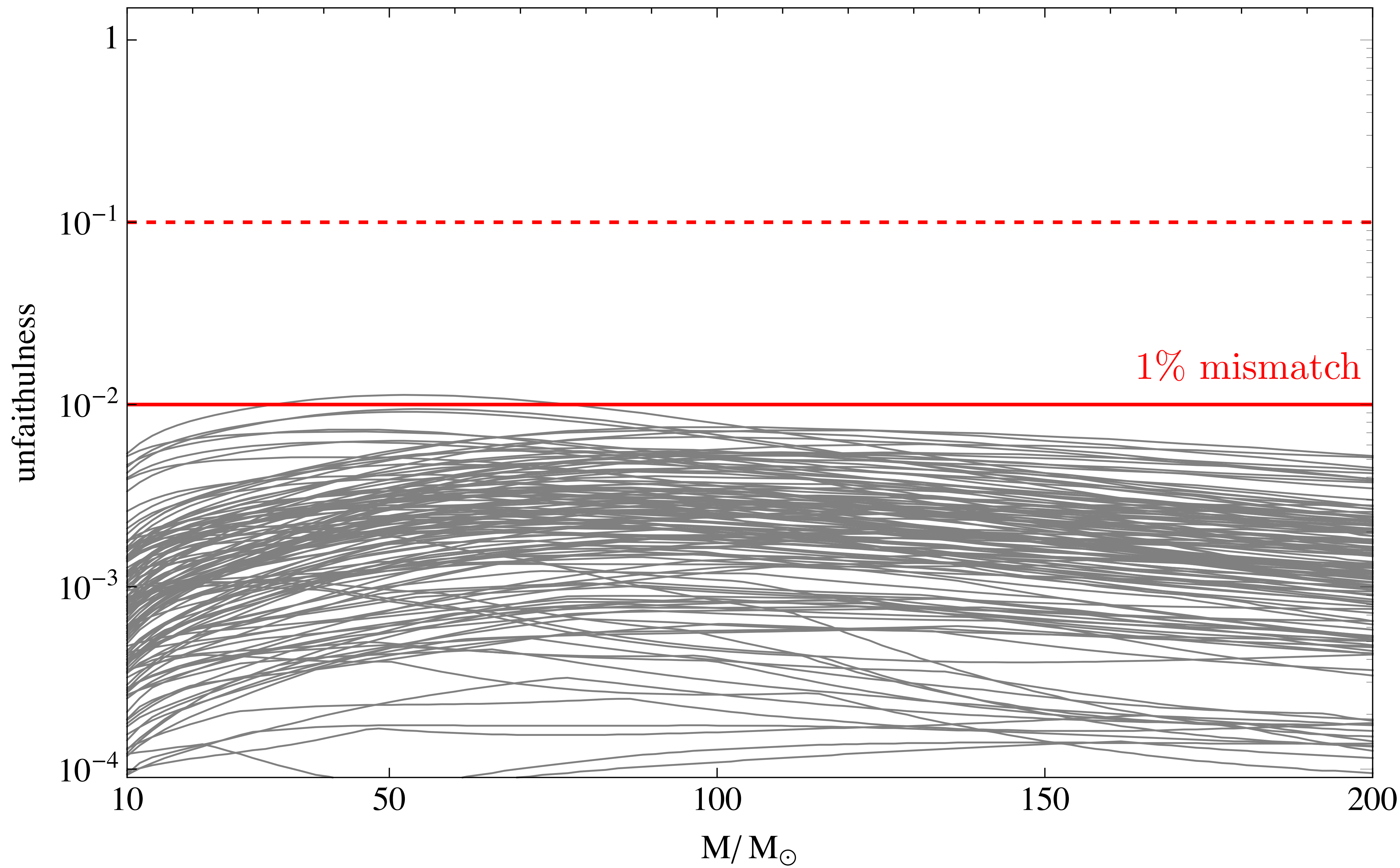


SEOBNRv2 faithfulness against the NR catalog



model of Taracchini et al. (2013)

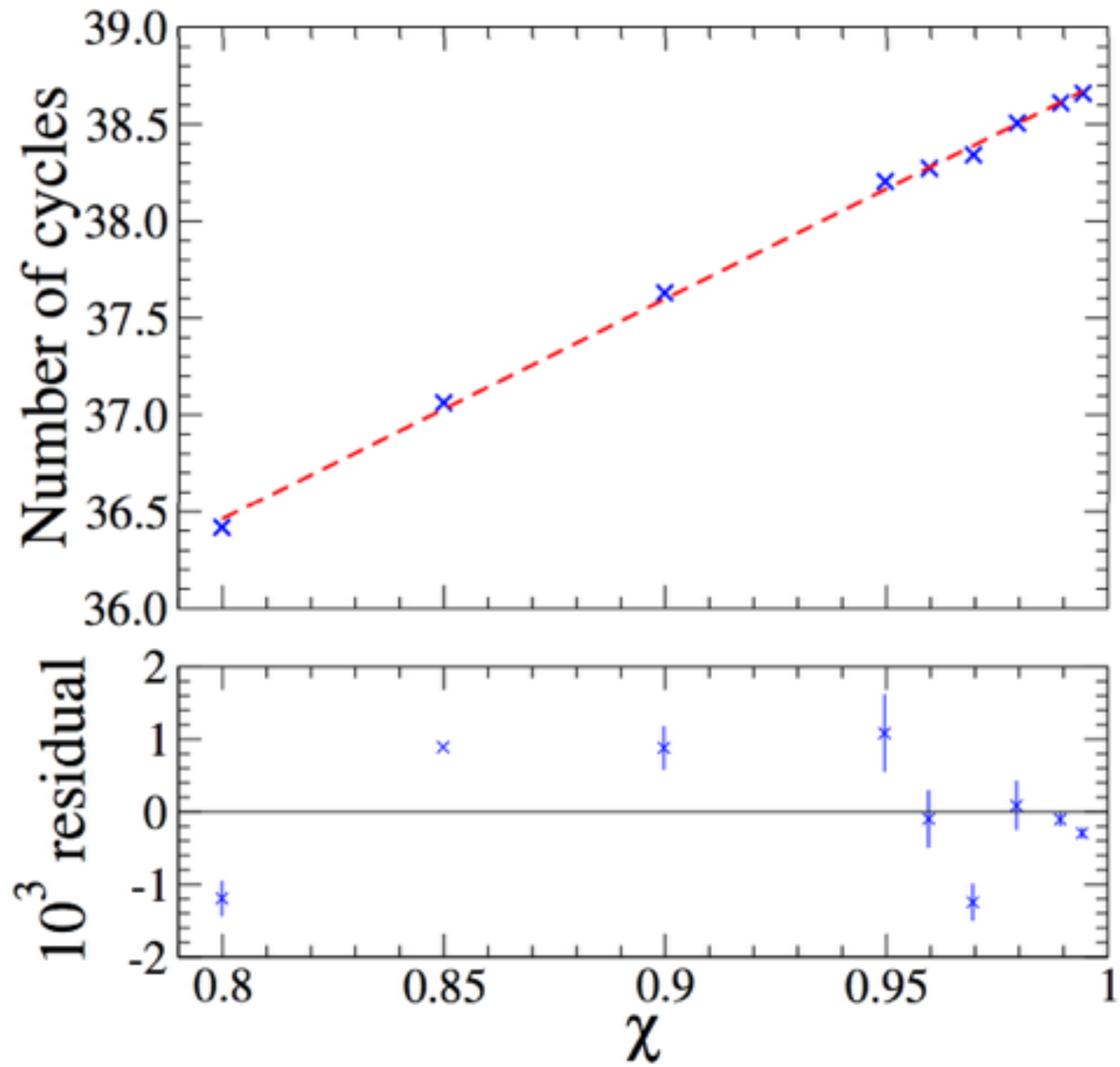
SEOBNRv4 faithfulness against the NR catalog



this work

Extrapolating to high spins : number of cycles to GW peak

For equal mass equal spin binaries, it was noted in Scheel et al. (2015) that the number of cycles from a fixed geometric frequency to the GW peak has a simple (linear) dependence on spin, even as one approaches extremality.



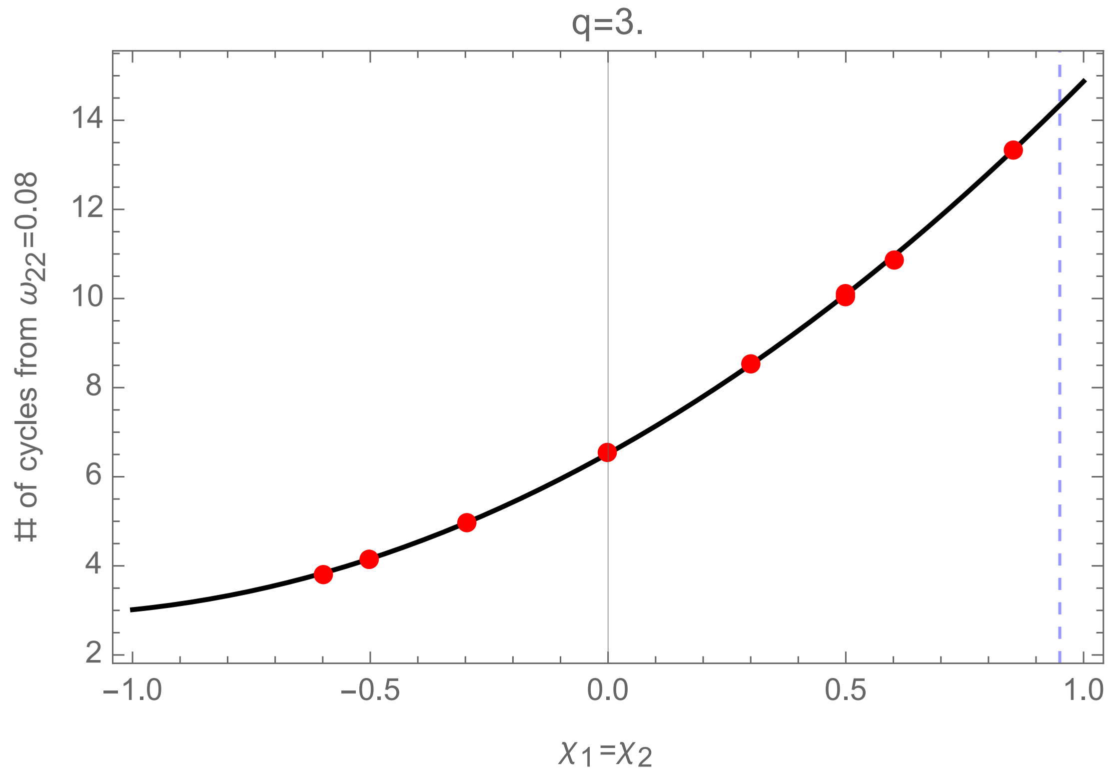
from $\omega_{22} = 0.036$

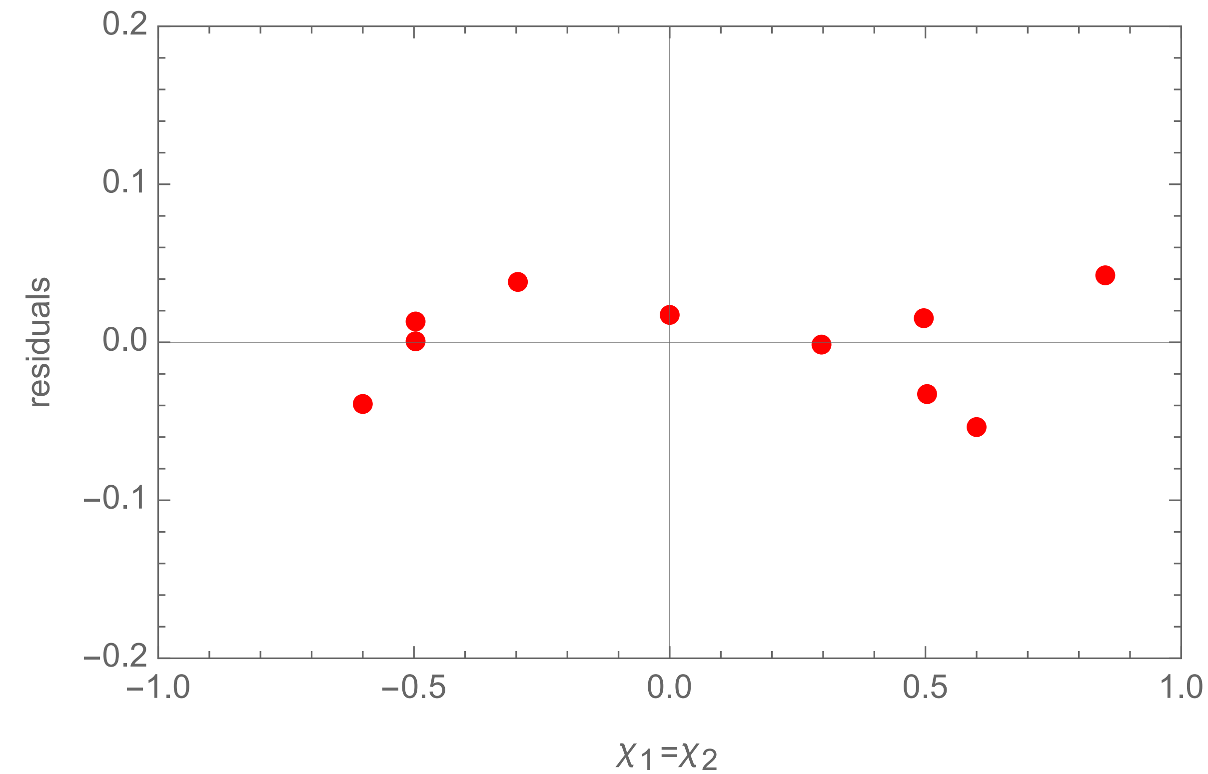
to GW peak

Fig. 15 of Scheel et al. (2015)

Extrapolating to high spins : unequal mass case

For q= 2 and 3, we find that a quadratic fit to the NR data produces very small residuals for equal spin binaries.





The *Taracchini et al. (2013)* model at q=2,3 and spins 0.85 (which had ~10% unfaithfulness to NR) had ~1 cycle deviation from that prediction.

We monitor the agreement between our recalibrated model and this fit to NR up to extremal spins and find significantly smaller deviations up to ~.3 cycles.

In the future, extending such fits to larger mass ratios could allow to tame the extrapolation in different regions of parameter space by adding a constraint to the calibration process.

Conclusions

- We have produced an improved EOBNR model for aligned spin binaries which faithfully reproduces NR simulations in a larger region of parameter space.
- The extrapolation of the model at large spins for unequal but comparable masses (i.e., up to 3) is checked by monitoring the number of cycles to merger.
- This model will be available for data-analysis in the second observing run.
- The recalibrated dynamics obtained in this model can be ported to the precessing-spin EOBNR model.
- Future studies will address the stability of the calibration at low frequency (Pan et al. 2013).