Black-hole - neutron-star mergers: new numerical-relativity simulations and multipolar effective-one-body model with spin precession and eccentricity

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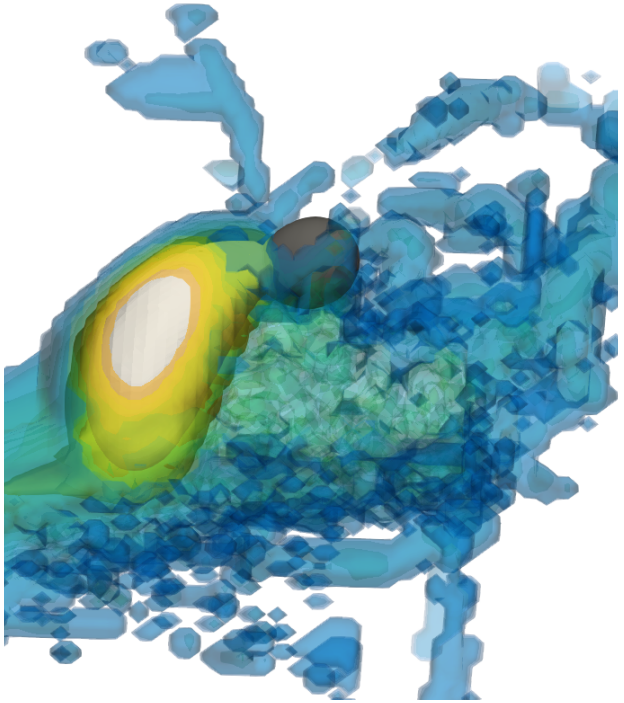
Why black-hole - neutron star mergers?

- More BHNS to be observed!
- They are promising sources of GRBs and kilonovae, and their GWs can provide information on their neutron star.
- GW data analysis requires waveform models.



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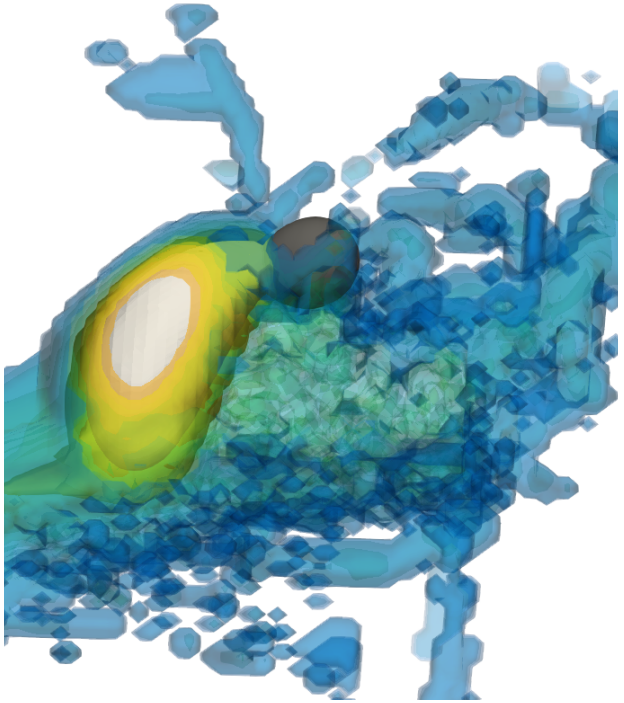

BHNS waveform models

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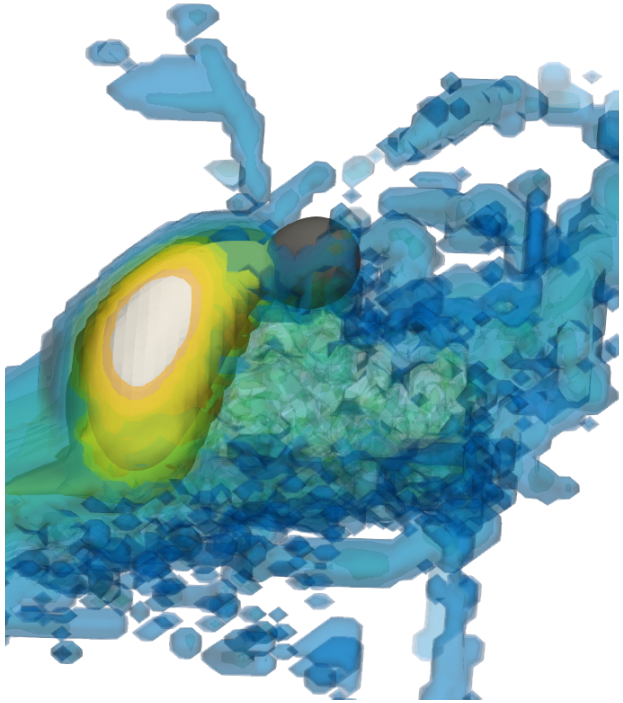

BHNS waveform models

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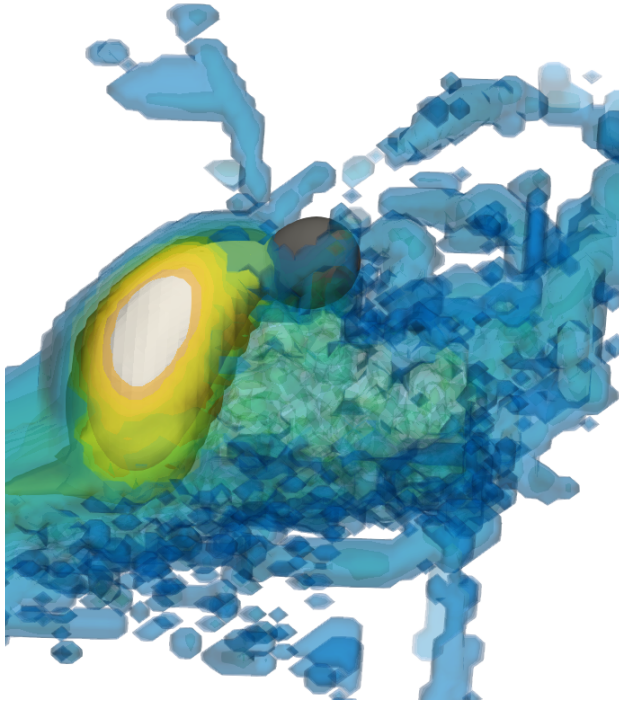


BHNS waveform models

- They don’t reach the level of sophistication as the models for BBH
- Not enough numerical data to inform the models

Methods and parameter space

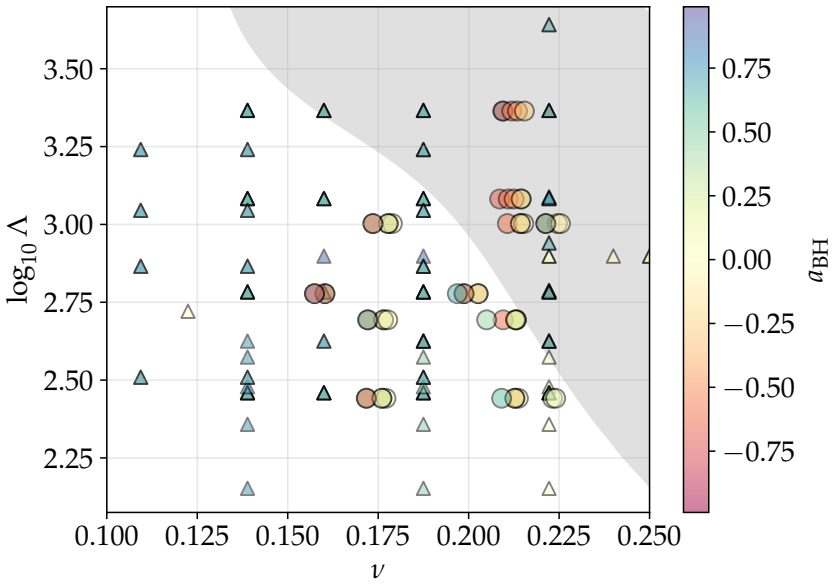
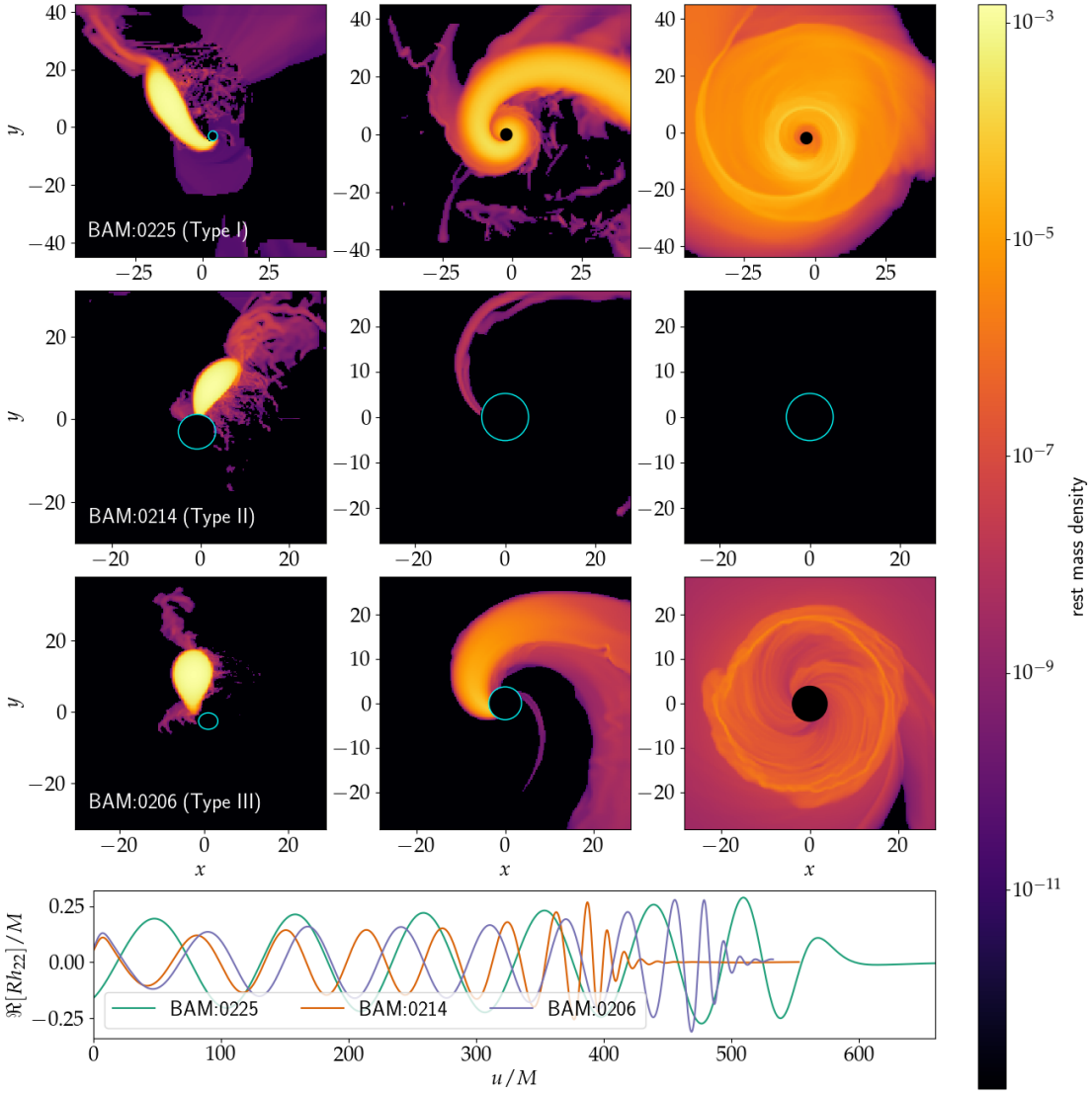


Figure: SXS+SACRA data (triangles) and this work (circles)

- Initial data: `Elliptica` [a]
- Evolution code: `BAM` [b]
- 51 non precessing + 1 precessing configurations
- Released as part of the CoReDB [c]

[a] Rashti+, Phys. Rev. D 105, 104027 (2022)
[b] Bruegmann+, Phys.Rev. D77, 024027 (2008)
[c] Gonzalez+, CQG 40 085011 (2023)

Dynamics


BAM:0225 (Type I)
BAM:0214 (Type II)
BAM:0206 (Type III)
y
x
rest mass density
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
$\Re[Rh_{22}]/M$
BAM:0225
BAM:0214
BAM:0206
u/M

Main results from the NR data

Remnant BH

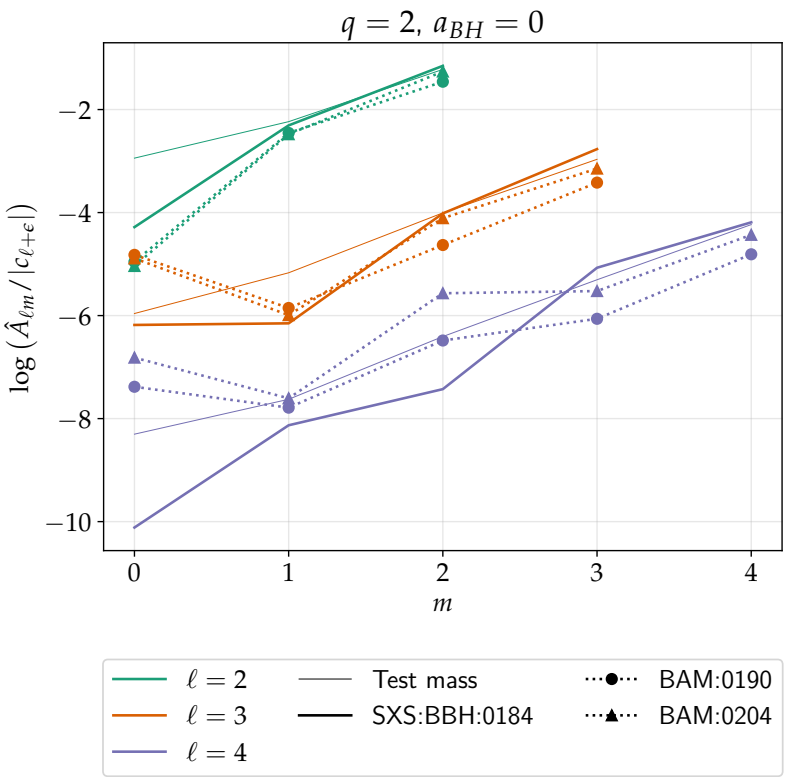
- Updated remnant mass and spin model

GW kick velocity

- Tides have a supressing effect on the GW recoil
- New fit model for BHNS GW kick velocity

Multipolar amplitude hierachy

- Highest contribution from (2,1), (3,2), (3,3), (4,4)
- (2,0) and (3,0) have a more significant contribution than for BBH



GW230529

- BAM:0223 has compatible paramaters with the GW event
- Mismatches indicate than an analysis with tides may bring new results

BHNS Waveform Model: Overview

- TEOBResumS-GIOTTO BHNS model for quasi-circular binaries with spin precession [1]

[1] Gonzalez+, Phys. Rev. D 107, 084026 (2023)
[2] Albanesi+, arXiv:2503.14580 (2025)

BHNS Waveform Model: Overview

- TEOBResumS-GIOTTO BHNS model for quasi-circular binaries with spin precession [1]

TEOBResumS-Dalí [2] BHNS model for binaries with arbitrary orbits and spins

- NR-informed remnant BH model
- Next-to-quasicircular-corrections (NQC) to the waveform
- Ringdown model

[1] Gonzalez+, Phys. Rev. D 107, 084026 (2023)
[2] Albanesi+, arXiv:2503.14580 (2025)

BHNS Ringdown Model

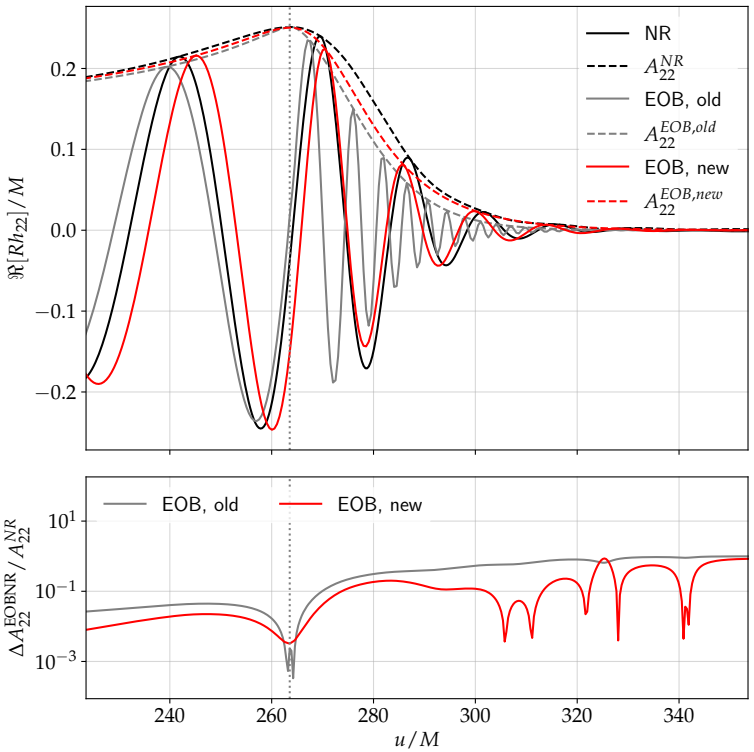
Main idea: Fit relevant quantities by quantifying how much they deviate from the BBH case.

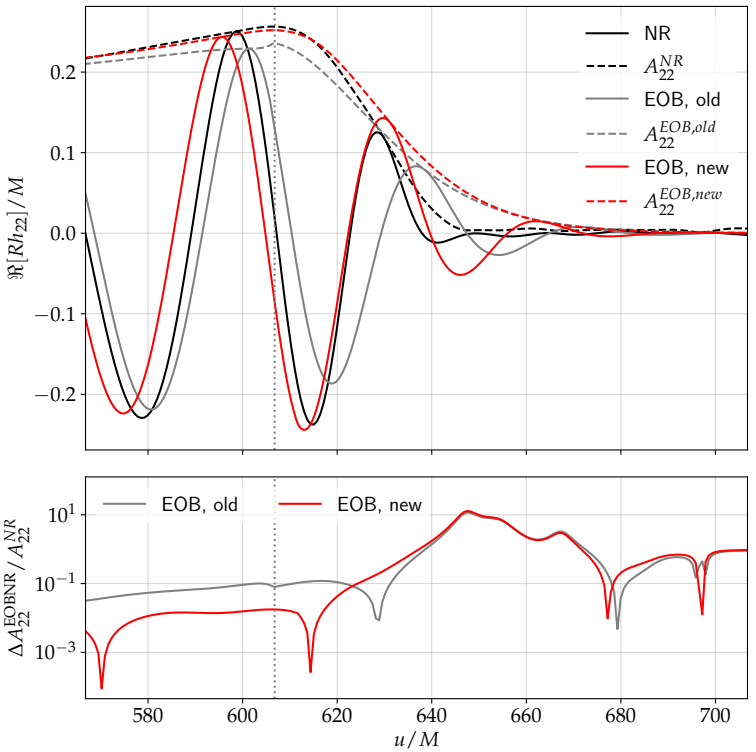
$$(a_{\rm BH}, \Lambda, \nu) \to \mathcal{F}^{\rm BHNS}/\mathcal{F}^{\rm BBH}$$

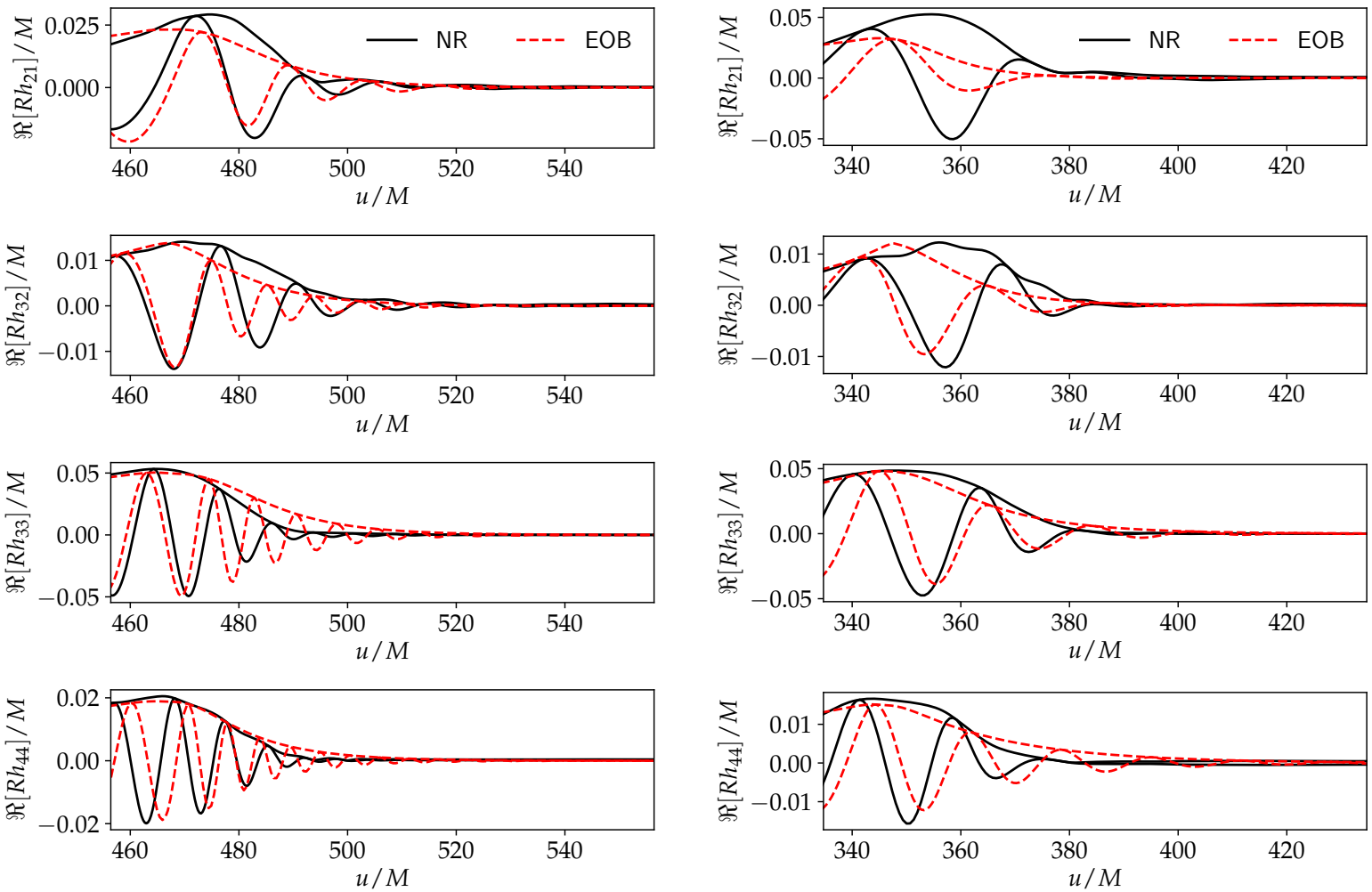
With information on spin, tides and masses:

- $a_{\rm BH}$: Initial BH spin
- Λ: Tidal polarizability of the NS $\Lambda = \frac{2}{3}\frac{k^2}{C^5}$
- ν: Symmetric mass ratio $\nu = m_1 m_2/(m_1+m_2)^2$

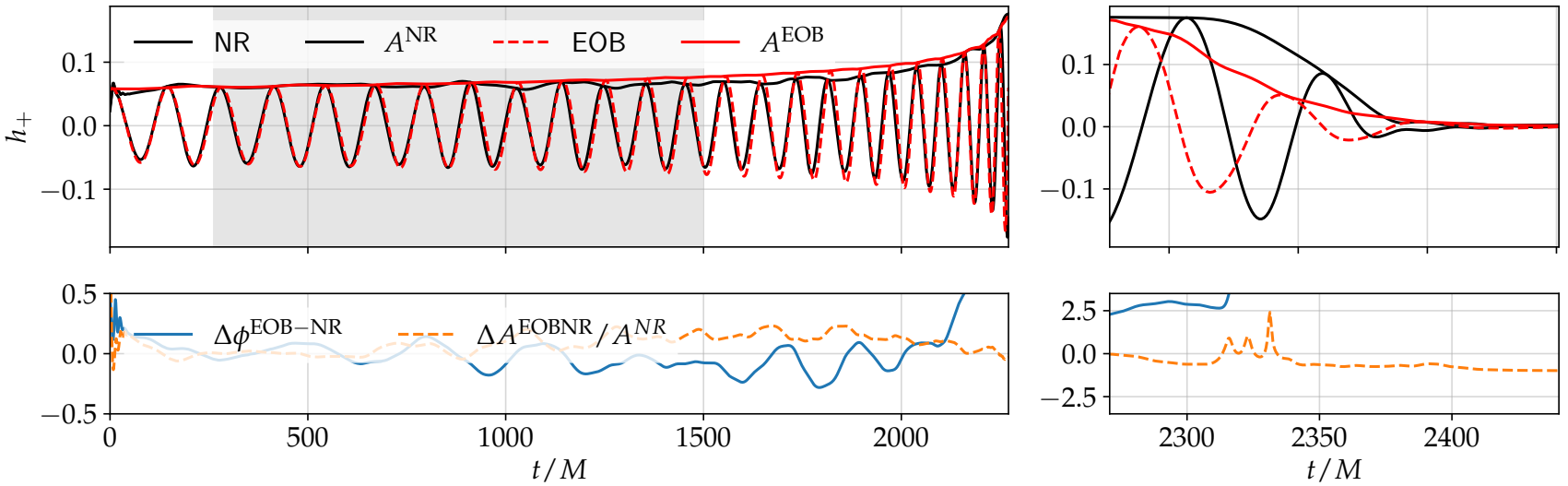
Ringdown: BHNS vs. BBH



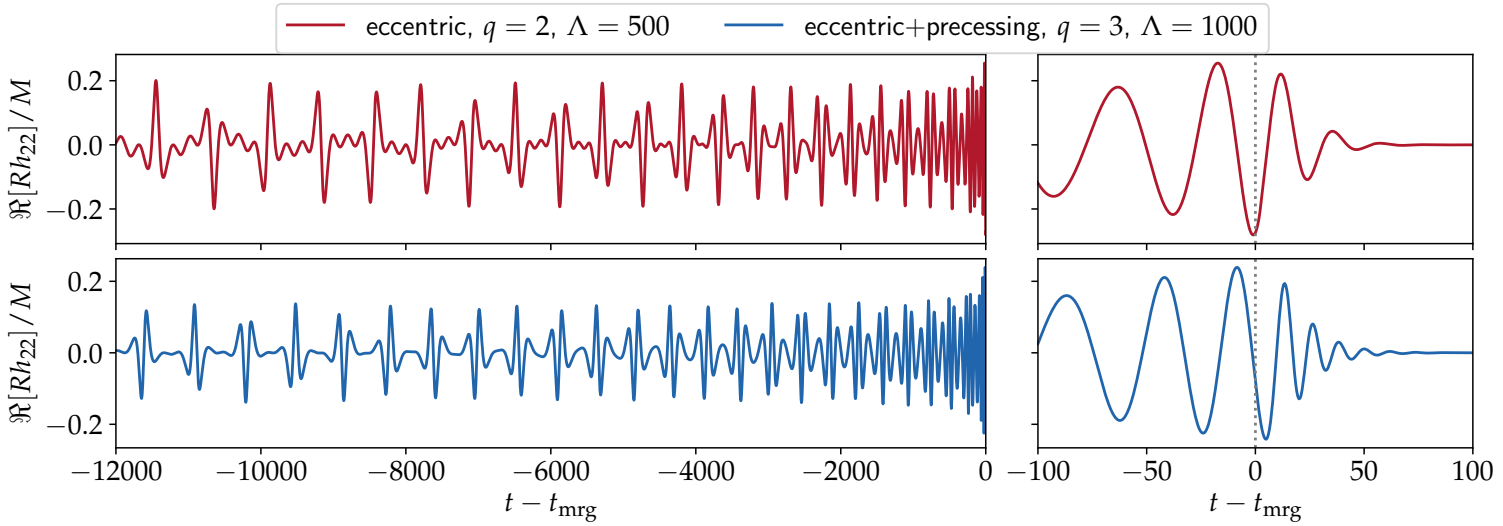



NR
EOB
$\Re[Rh_{21}]/M$
$\Re[Rh_{32}]/M$
$\Re[Rh_{33}]/M$
$\Re[Rh_{44}]/M$
u/M

Validation

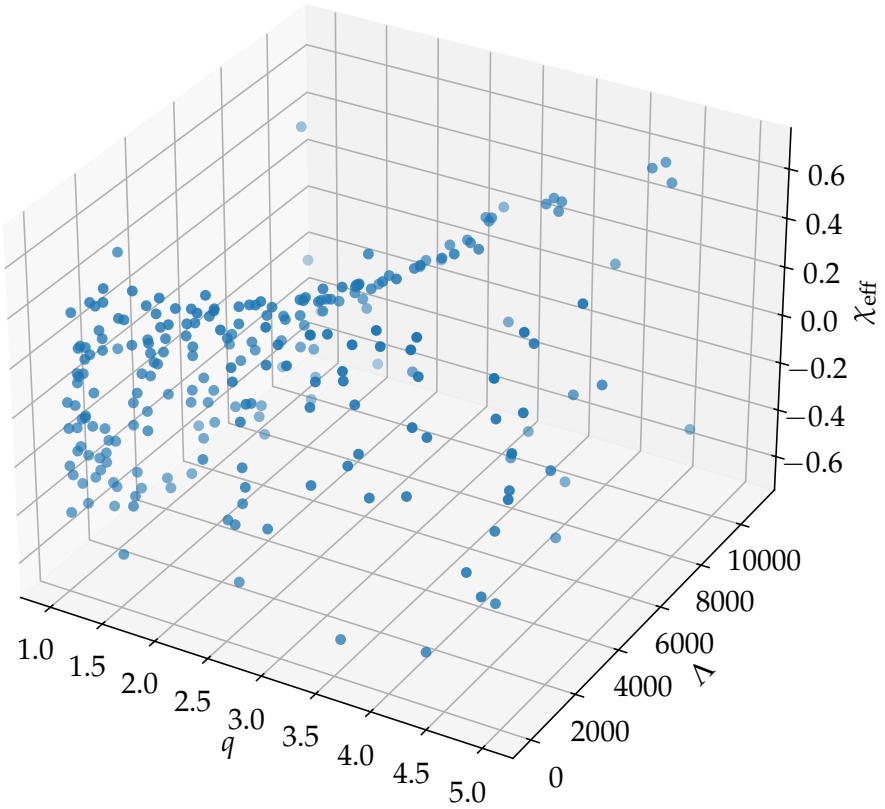


- BAM:0223 mismatches lie at 1% for LIGO and ET PSDs
- SACRA+CoRe+SXS mismatches: median values around $\sim 1\%$, highest: 18% (SACRA), lowest: 0.07% (SXS)



- Tidal oscillating features in the early inspiral $\rightarrow$ Need NR to verify!
- Generated 1000 smooth waveforms within the ranges:
  $q \in [1, 5]$,$a_{\rm BH} \in [-0.8, 0.8]$, $\Lambda \in [1, 5000]$ and $e_0 \in [0.01, 0.2]$

Where to further simulate?



Take away

- We presented 52 new BHNS simulations and employed them to inform an EOB waveform model.
- With the new data we develop an updated remnant BH model and a new GW kick velocity model.
- We explore the multipolar amplitude hierarchy and find a more significant contribution of the $m = 0$ modes.
- The newly informed TEOBResumS-Dalí model for BHNS improves on the earlier version in GIOTTO by:
  - Improving the amplitude at merger by an order of magnitude overall
  - Higher mode specific fits
  - Smooth eccentric(+precessing) waveforms in a selected parameter space

Useful links

Pre-print: arXiv:2503.14580 [gr-qc]

The model is publicly available at:
`https://bitbucket.org/teobresums/teobresums/src/Dali/`

For more information visit our websites:
`https://teobresums.bitbucket.io/`
`http://www.computational-relativity.org/`

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