

Ringdown Tests of the No-Hair Theorem with LISA

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on behalf of the FPWG Ringdown Group



Group Projects

Currently, our group consists of pushing forward four different projects:

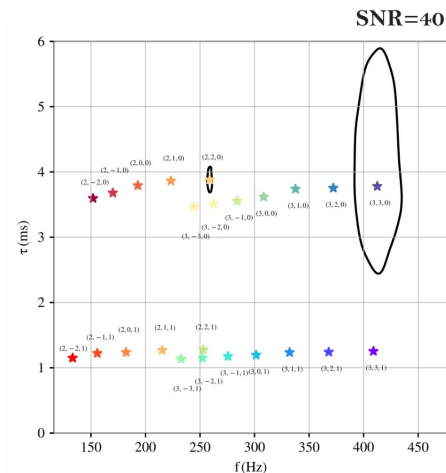
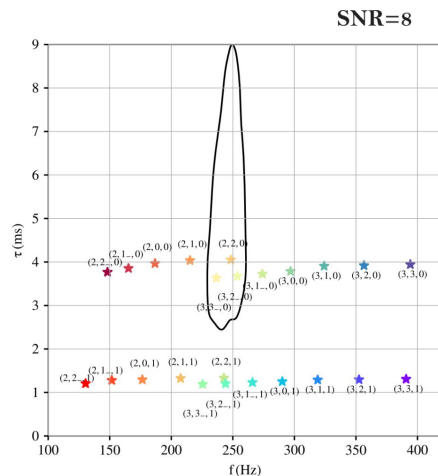
- pyRing for LISA
- Memory detectability
- Beyond GR QNMs
- pSEOBNR for testing deviations from GR

pyRing for LISA

pyRing for LISA

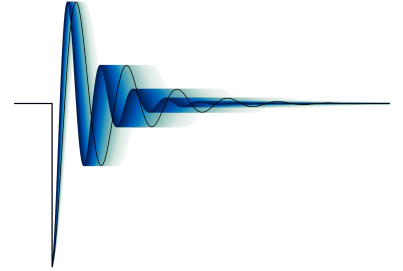
- Aim to do a bayesian ringdown analysis in the time domain for LISA with pyRing.
- Implementation requires translating the strain to a response in TDI variables and model LISA noise in the time domain.

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[LISA FPWG Wiki](#), [Presentation](#)



Credit: Gregorio Carullo

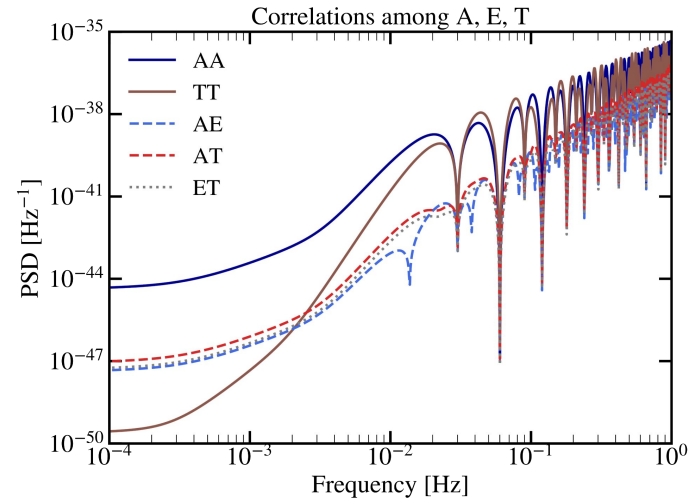
pyRing



- Python code for ringdown analysis, model comparison and parameter estimation
 - Can handle interferometric, simulated or numerical relativity data
 - Natively incorporates several analytical ringdown templates
 - Supports parameterised test of GR and a variety of QNM spectra predicted for alternatives or modifications to the Kerr QNM spectrum
- Internally reviewed for scientific usage within the LVK collaboration
- LVK git repo: git.ligo.org/lscsoft/pyring and docs: lscsoft.docs.ligo.org/pyring

LISA specific tasks

1. LISA response (adiabatic approximation) from LISA GW Response ✓
2. Calculate TDI variables quickly from strain (linear interpolation) ✓
3. Set ACF (and CCF) from LISA PSD (and CSD) for TDI variables (in progress 🙄)
4. Implement multi-channel likelihood calculation for a single detector
5. Validate parameter estimation, especially for high SNR signals



PSD/CSD of 2nd gen. TDI A, E & T [arXiv:2302.12573]

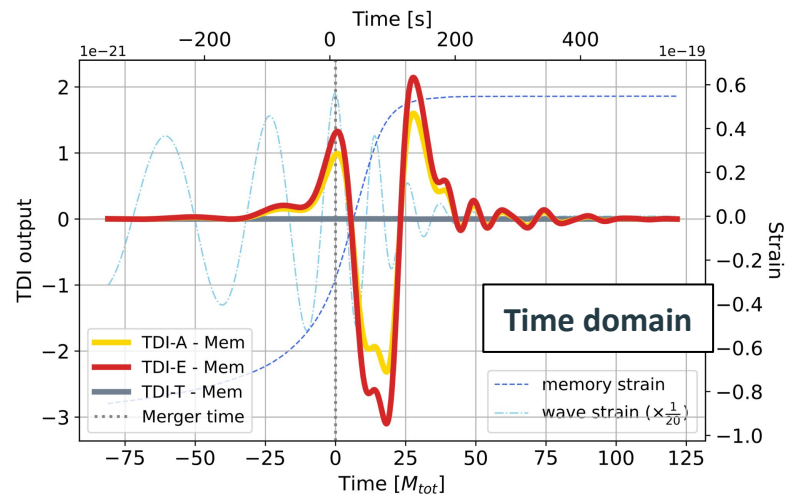
Memory Detectability

Measuring GW memory with LISA

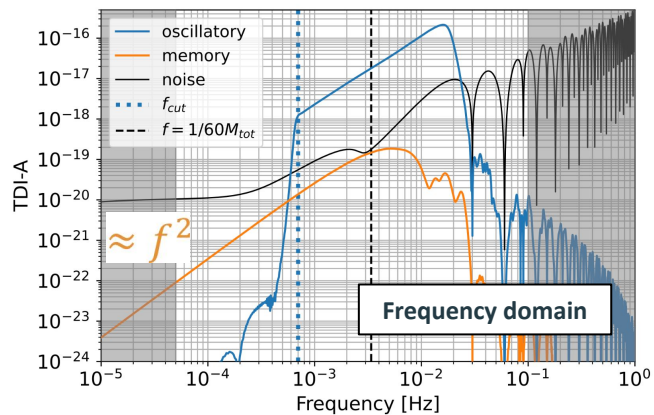
- Implement the full time-domain TDI response to the GW memory. Extending on [\[Gasparotto et al, 2023\]](#) using **LISA simulation suite** AND the new **surrogate model** for the (2,0) mode and the GW memory.
- Study the GW memory signature and phenomenology on LISA TDI data (time, frequency, time-freq domains).
- Comprehensive, Quantitative SNR study (as function of M , z , q , spin, sky pos, inclination)
- Confrontation with up-to-date population model forecasts [\[Barausse et al, 2020\]](#)

<http://arxiv.org/abs/2406.09228>



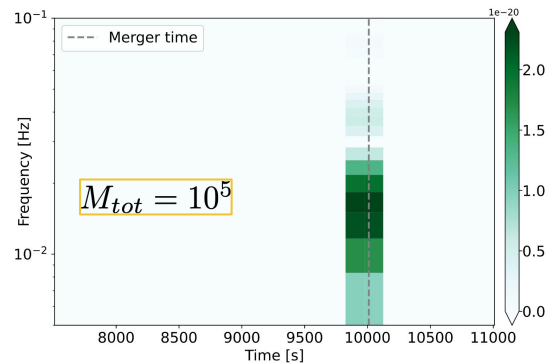
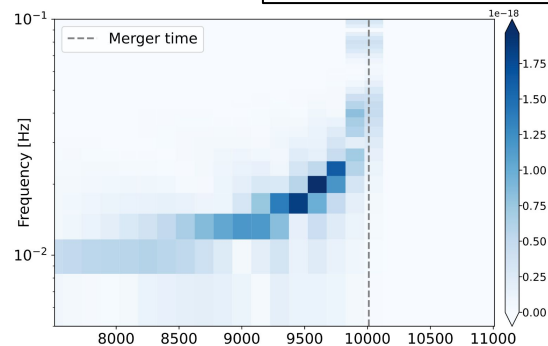


$$M_{tot} = 10^6 M_{\odot}, z = 1.0, q = 1.0, \iota = 1.047 \text{ rad}, S = 0.0$$



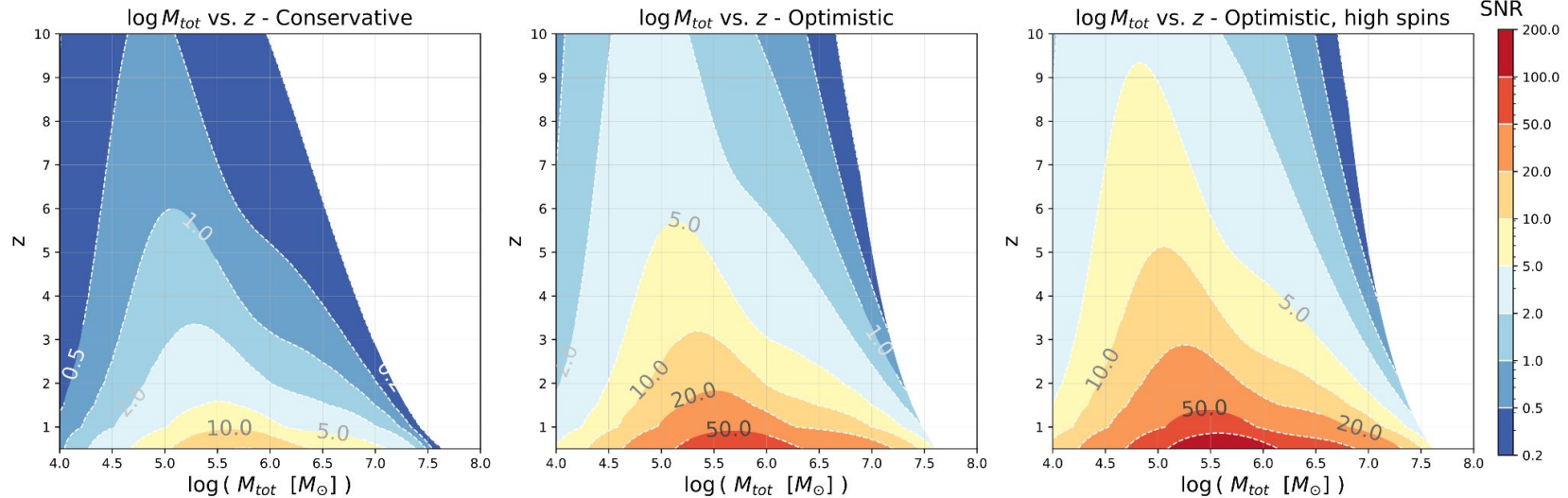
GW memory imprint on LISA data

Freq-Time representation

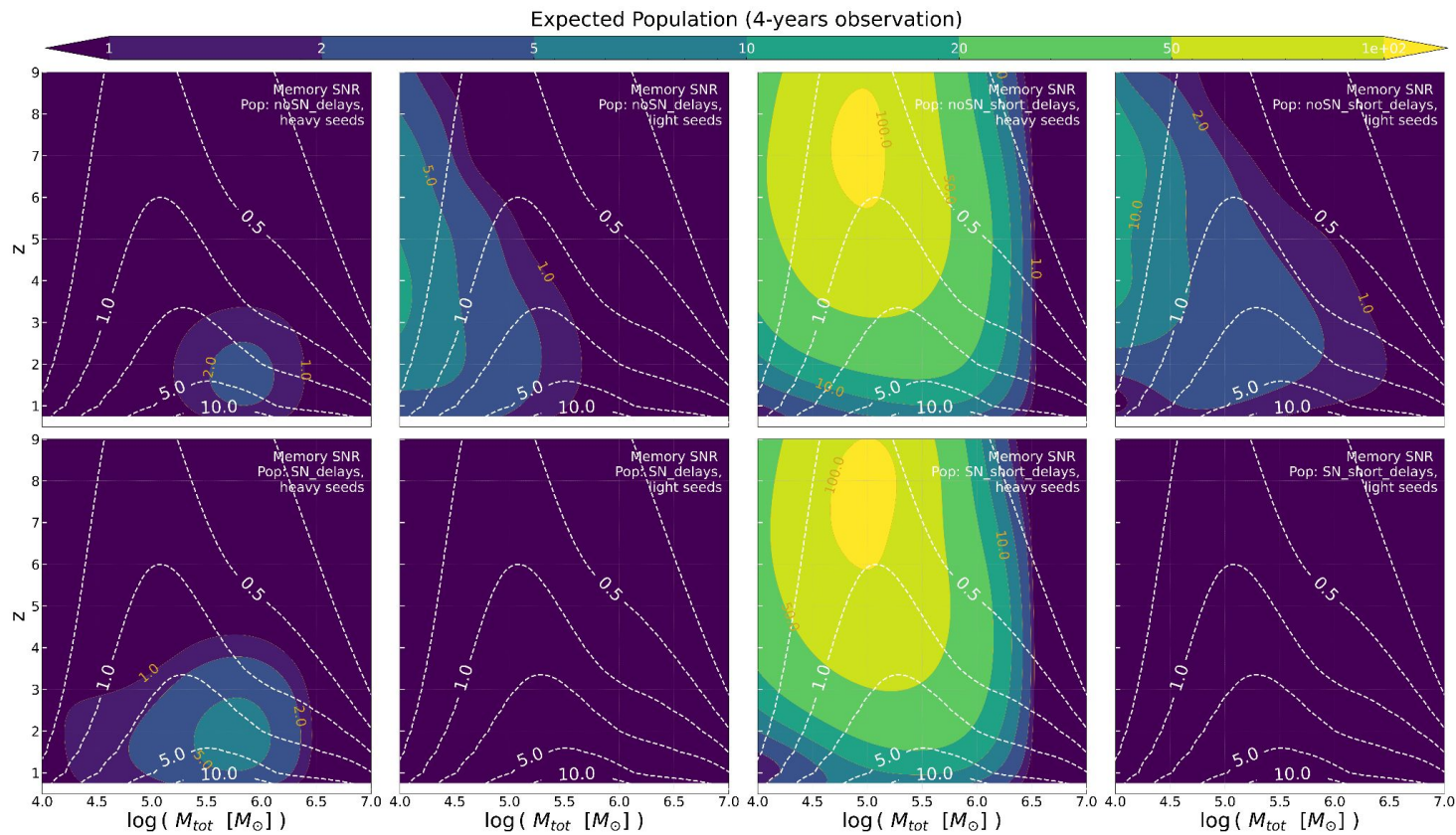


SNR waterfalls, three reference baselines

Baseline	q	χ	inclination ι [rad]	lat. β [rad]	long. λ [rad]	pixel p
1. Conservative	2.5	0.0	1.047	0.62	0.20	145
2. Optimistic	1.0	0.0	1.571	0.52	3.24	192
3. Opt. & Spin.	1.0	0.8	1.571	0.52	3.24	192



Comparison with MBHBs population forecasts (conservative baseline)



Future Extensions

Currently, our group consists of pushing forward four different projects:

- **PE and Bayesian analysis to evaluate evidence of memory detection with full memory data** (extending [\[Gasparotto et al, 2023\]](#))
- **Agnostic search of the memory / Consistency Test of GR combining parametrised waveform model with template-free representation** (following [\[Heisenberg et al., 2023\]](#))
- Effect of the memory in the ringdown analysis
- Additional memory effects: **spin**, velocity...

Beyond GR Effects

Beyond GR vs additional physics

- Beyond GR effects are supposed to be a small correction to the dominant signal.
- Are these corrections small enough to be detected?
- Can they be stronger compared to or mistake with other subtle effects?
 - Modes with higher ℓ
 - Higher overtones
 - Nonlinearities

Compare different effects

- Model independent treatment – ParSpec type of parametrization of beyond GR
- Use a simplified or surrogate QNM model in GR, adjusted to NR simulations
- Perform Fisher analysis to estimate degeneracies and check detectability of beyond GR corrections vs nonlinearities/higher overtones.
- Beyond model-independent?
 - Use a specific beyond GR QNM model where frequency corrections depend on a single parameter: possible in very limited beyond GR theories.

pSEOBNR Tests of GR

Implementation of pSEOBNR in the LISA tools

Sub-project joint with “Systematics on parameterized IMR tests”.

To quantify the accuracy to which LISA will be able to constrain deviations from GR in the inspiral-merger-ringdown stages for astrophysically motivated MBHBs and to assess for which binary configurations one could measure false deviations from GR due to waveform systematics, expanding on [Toubiana+ \(2023\)](#).

Status of the project:

- Identification of the required LISA tools: [bilby lisa](#) [[Hoy+ \(2023\)](#)] ✓
- Implementation on pSEOBNR in the required LISA tool: implemented interface to SEOBNR and LALSuite waveforms with TD LISA response ✓
- Validation of the code with injections: GR and TGR parameters well recovered for a few configurations ✓
- Measurement of GR deviations with LISA: in progress.

Sascha Husa, Lorenzo Pompili, Alessandra Buonanno, Elisa Maggio.

The pSEOBNR analysis

The pSEOBNR analysis adds fractional deviations to the **frequency** and the **decay time** of the **fundamental QNMs** in the ringdown, to an effective-one-body (EOB) waveform model in GR [[Brito+ \(2018\)](#); [Ghosh+ \(2021\)](#)].

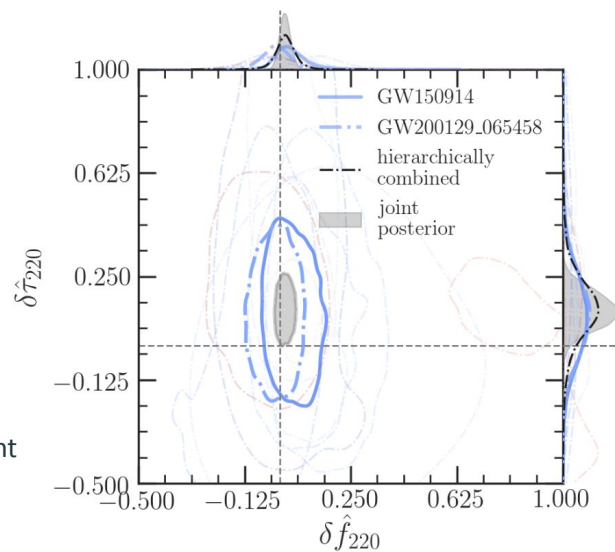
$$f_{\ell m 0} \rightarrow f_{\ell m 0} (1 + \delta f_{\ell m}), \quad \tau_{\ell m 0} \rightarrow \tau_{\ell m 0} (1 + \delta \tau_{\ell m})$$

We introduce fractional deviations at **merger**, in the **amplitude** and **frequency** at the peak-time of the (2,2) mode [[Maggio+ \(2022\)](#)].

$$|h_{\ell m}| \rightarrow |h_{\ell m}| (1 + \delta A_{\ell m}), \quad \omega_{\ell m} \rightarrow \omega_{\ell m} (1 + \delta \omega_{\ell m})$$

We also introduce parameterized **inspiral-plunge** deviations in the **NR-calibration** parameters:

$$\left. \begin{aligned} a_6 &\rightarrow a_6 + \delta a_6 \\ \Delta t_{22} &\rightarrow \Delta t_{22} + \delta \Delta t_{22} \\ d_{\text{SO}} &\rightarrow d_{\text{SO}} + \delta d_{\text{SO}} \end{aligned} \right\} \begin{aligned} &\text{Non-spinning 5PN Hamiltonian coefficient} \\ &\text{Peak-time of the (2,2) mode waveform} \\ &\text{Spin-orbit 4.5PN Hamiltonian coefficient} \end{aligned}$$

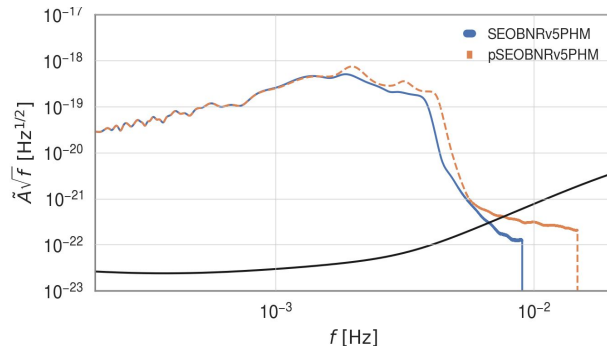
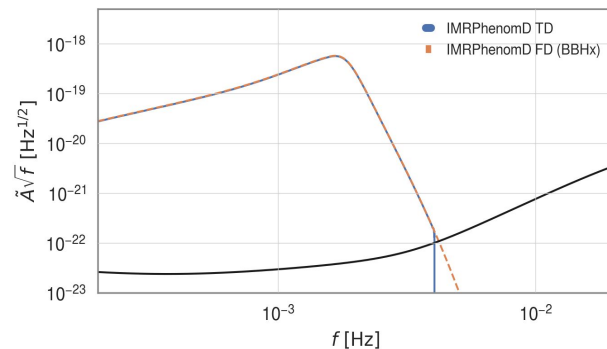
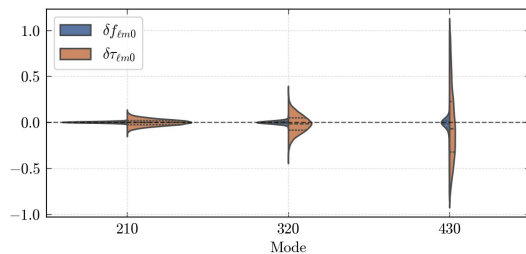
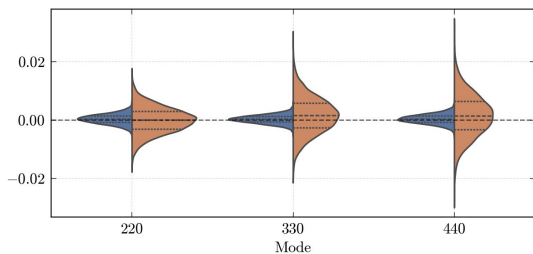


[[LVK \(2021\)](#)]

Identification of the required LISA tools

Organized 2-day meeting in May to learn more about currently available LISA tools. Slides & recordings [here](#).

- Focusing on [bilby_lisa](#) [[Hoy+ \(2023\)](#)] given experience from LVK analyses.
- Interfacing LALSuite and SEOBNR waveforms via [gwsignal](#) (new LVK waveform interface), including inspiral-merger-ringdown parameterized deviations.
- Interfacing TD LISA response via [LDC tools](#), since the pSEOBNR model is natively in TD. Excellent agreement with FD response in BBHx.
- Preliminary code validation with model injections.



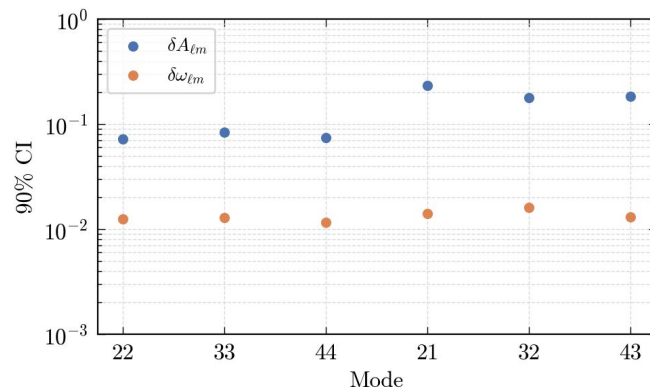
Measurement of GR deviations with LISA

Model injections:

- Quantify the accuracy to which LISA will constrain deviations from GR in the inspiral-merger-ringdown stages, when using information from the whole signal, including spin-precession effects.

NR injections:

- Explore under which conditions one would measure false deviations from GR due to waveform systematics in the inspiral-merger-ringdown stages.
- Inspiral-merger parameters correspond to NR calibration parameters in the SEOBNR model: inspiral-merger deviations can be interpreted as TGR parameters, or as NR calibration uncertainty.
- Understand if false GR deviations in the ringdown due to waveform systematics at high SNR can be mitigated by incorporating and marginalizing over inspiral-merger deviation parameters.



Contact Information

Currently, our group consists of pushing forward four different projects:

- pyRing for LISA: Simon Maenaut (simon.maenaut@kuleuven.be)
- Memory detectability: Henri Inchauspé (inchauspe@tphys.uni-heidelberg.de) or Silvia [Gasparotto](mailto:sgasparotto@ifae.es) (sgasparotto@ifae.es)
- Beyond GR QNMs: Daniela Doneva (daniela.doneva@uni-tuebingen.de) or Nicola Franchini (franchini@apc.in2p3.fr)
- pSEOBNR for testing deviations from GR: Sascha Husa (sascha.husa@csic.es) or Lorenzo Pompili (lorenzo.pompili@aei.mpg.de)

For questions about our group: Lorena (lorena.zertuche@nbi.ku.dk) Marc (marc.besancon@cea.fr)