Fundamental Physics Meets Waveforms with LISA Workshop

2 September 2024

# Effect of systematics on parametrized inspiral-merger-ringdown tests

Elisa Maggio

Marie Skłodowska-Curie Postdoctoral Fellow

Max Planck Institute for Gravitational Physics, AEI Potsdam

Niels Bohr Institute

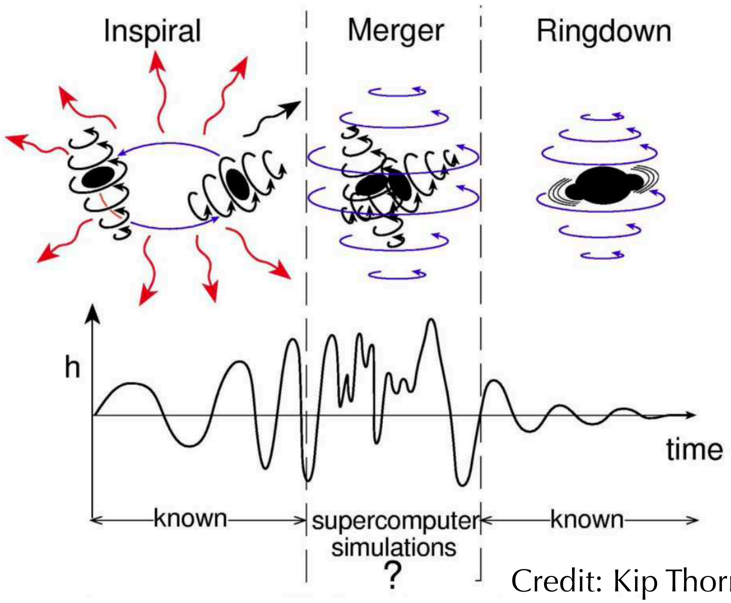
strong. niels bohr institute

Funded by the European Union

# Motivation

**Waveform models** are intrinsically imperfect, due to:

- Missing physics: spin-precession, eccentricity, higher modes, …
- Truncation errors in perturbative schemes
- Calibration inaccuracy with NR waveforms
- Numerical errors in NR simulations




Credit: Kip Thorne

# Motivation

The **signal-to-noise ratio** of compact binary coalescences is increasing with the improvements in the sensitivity of current detectors and next generation detectors.

Abbott et al., Living Rev. Rel. 23, 3 (2020)

**Massive black hole binaries with LISA:**

| Parameter | Notation | Astrophysically relevant range |
|---|---|---|
| Total mass in the detector frame | $M$ | $10^5 - 10^7 M_\odot$ |
| Mass ratio ($> 1$) | $q$ | $1 - 10$ |
| Dimensionless spin | $\max\lvert\chi_i\rvert$ | $0 - 0.998$ |
| Eccentricity entering LISA band | $e_{\rm init}$ | $0 - 0.99$ |
| Eccentricity at last stable orbit | $e_{\rm merge}$ | $< 0.1$ |
| Signal to noise ratio | SNR | $10 - 10^4$ |

LISA Consortium Waveform Working Group, arXiv:2311.01300

# Motivation

Tests of general relativity could show **false deviations of GR** if the systematics is not negligible with respect to a putative GR deviation. Gupta et al., arXiv:2405.02197

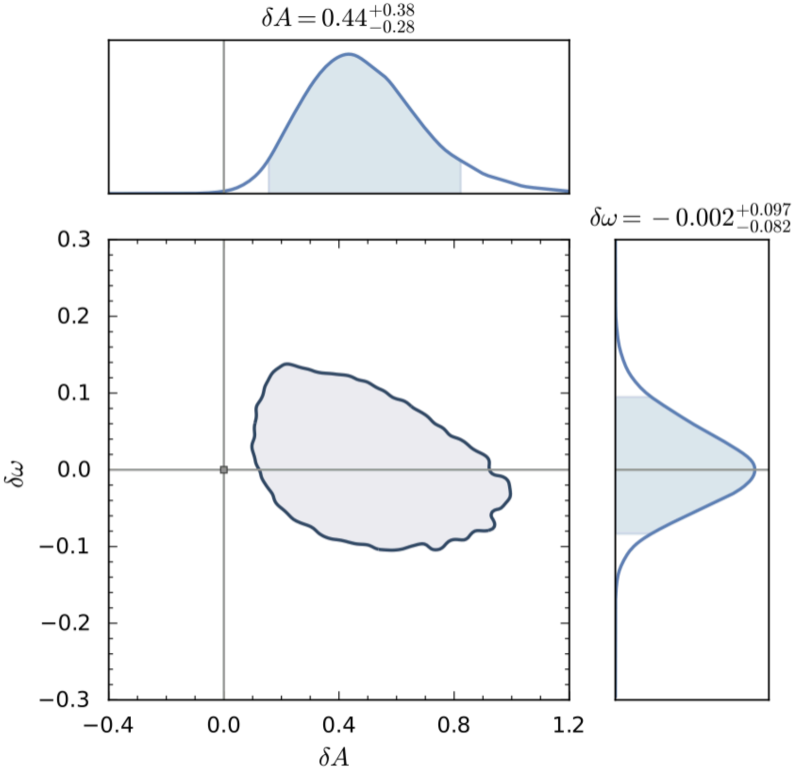
## Example: GW200129

The analysis with a parametrized plunge-merger-ringdown test shows a violation of GR in the merger amplitude.

Possible causes:

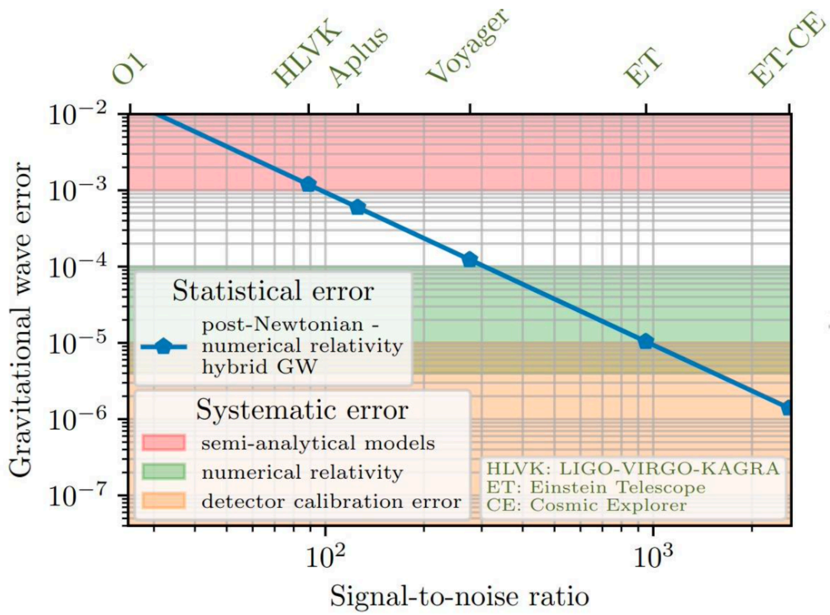
- Spin precession Hannam et al., Nature 610 (2022)
- Glitch mitigation Payne et al., PRD 106, 104017 (2022) Macas et al., PRD 109, 062006 (2024)
- Eccentricity Gupte et al., arXiv:2404.14286

EM et al., PRD 108, 024043 (2023)



# Motivation

- **Waveform systematics** could dominate over statistical errors as we approach next-generation detectors.
- Stringent accuracy requirements on waveform models: need to improve accuracy by two orders of magnitude for Einstein Telescope/Cosmic Explorer, possibly even more for LISA.




Pürrer, Haster, Phys. Rev. Research 2, 023151 (2020)

# LISA collaborative projects

**Goals:**

- Implement current tests of GR in the LISA tools
- Study how waveform systematics can affect tests of GR with LISA

**Tests of general relativity:**

- Plunge-merger-ringdown test pSEOBNR

  Brito et al., PRD 98, 084038 (2018); Ghosh et al., PRD 103, 124041 (2021); EM et al., PRD 108, 024043 (2023)

- Flexible-Theory-Independent Method

  Mehta et al., PRD 107, 044020 (2023)

- TIGER

  Li et al., PRD 85, 082003 (2012); Agathos et al., PRD 89, 082001 (2014)

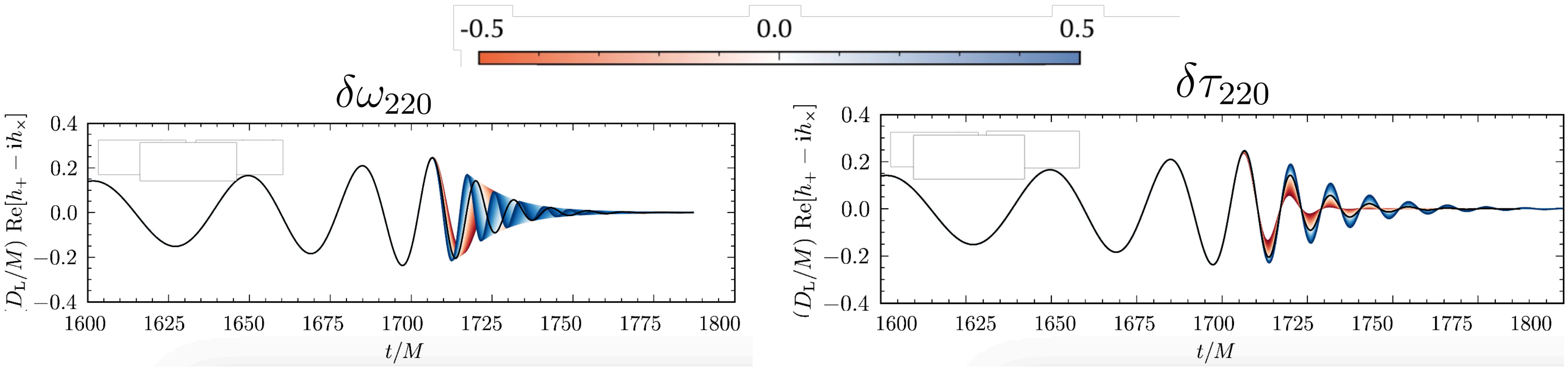
# Plunge-merger-ringdown test pSEOBNR

The pSEOBNR analysis introduces fraction deviations to the frequency and the decay time of the fundamental quasi-normal modes in the **ringdown**:

$$\omega_{\ell m 0} = \omega_{\ell m 0}^{\mathrm{GR}}(1 + \delta\omega_{\ell m 0})$$

$$\tau_{\ell m 0} = \tau_{\ell m 0}^{\mathrm{GR}}(1 + \delta\tau_{\ell m 0})$$

where the GR values are predicted from estimates of the mass and spin of the remnant and fits with NR simulations.




Ghosh et al., PRD **103**, 124041 (2021); Brito et al., PRD **98**, 084038 (2018)

# Plunge-merger-ringdown test pSEOBNR

We introduced fractional deviations to the **plunge-merger**:

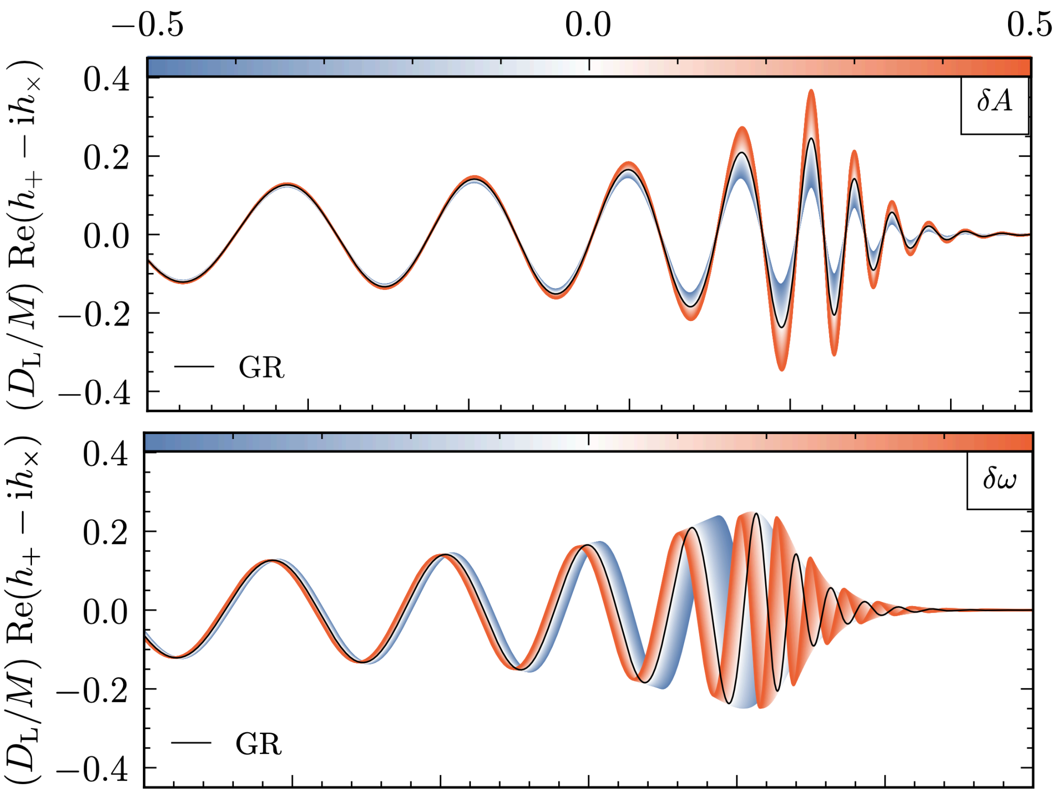
Amplitude

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

Frequency

$$\omega_{\ell m} \rightarrow \omega_{\ell m}(1+\delta\omega_{\ell m})$$

at the peak time of the (2,2) mode.




EM, Silva, Buonanno, Ghosh, PRD 108, 024043 (2023)

# Plunge-merger-ringdown test pSEOBNR

We introduced parametrized inspiral deviations to the **NR calibration parameters**:

$$a_6 \to a_6 + \delta a_6$$ → Non-spinning 5PN Hamiltonian coefficient

$$\Delta t_{22} \to \Delta t_{22} + \delta \Delta t_{22}$$ → Peak-time of the (2,2) mode waveform

$$d_{\rm SO} \to d_{\rm SO} + \delta d_{\rm SO}$$ → Spin-orbit 4.5PN Hamiltonian coefficient

They can be interpreted as nuisance parameters to absorb systematics by marginalizing over them with suitable priors.

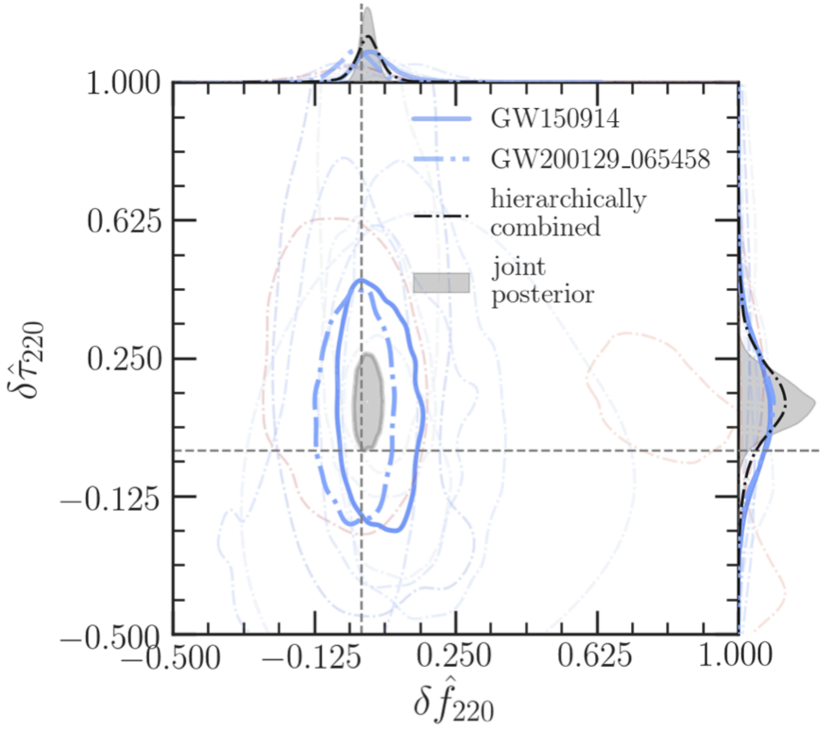
The baseline model is the SEOBNRv5 waveform.

Pompili+, PRD **108**, 124035 (2023); Khalil+, PRD **108**, 124036 (2023); Ramos-Buades+, PRD **108**, 124037 (2023); Van de Meent+, PRD **108**, 124038 (2023); Mihaylov+, arXiv: 2303.18203 (2023)

See Lorenzo Pompili's talk on Thursday afternoon

# GWTC-3 analyses

The fundamental quasinormal mode has been observed in the ringdown of $\mathcal{O}(10)$ GW events.




Abbott+, arXiv: 2112.06861 (2021)

The ringdown observations are compatible with **Kerr black hole remnants** with:

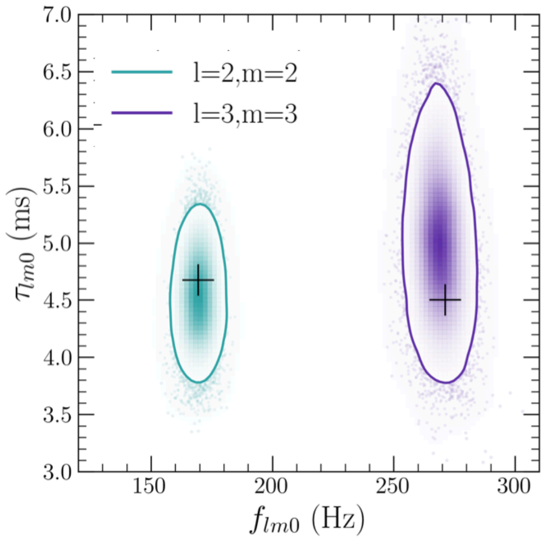
$$\delta\hat{f}_{220} = 0.02^{+0.07}_{-0.07}$$

$$\delta\hat{\tau}_{220} = 0.13^{+0.21}_{-0.22}$$

# Tests of the no-hair theorem

- The (2,2,0) and (3,3,0) modes can be inferred from NR injections with a total SNR of 70 in the detector network of LIGO Hanford, Livingston and Virgo.

  Ghosh et al., PRD **103**, 124041 (2021)




- LISA will measure $\mathcal{O}(100)$ events with at least 3 independent QNMs at 1% error.

  Bhagwat et al., PRD 105, 124063 (2022)

- In some systems, the high SNR leads to erroneous deviations from GR due to waveform systematics.

  Toubiana et al., PRD 109, 104019 (2024)

See Alexandre Toubiana's talk later

# Implementation of pSEOBNR in the LISA tools

**Coordinators**: Lorenzo Pompili, Sascha Husa

**Tasks**: Identification of the required LISA tool
Implementation of pSEOBNR in the identified LISA tool
Validation of the code with injections
Measurement of GR deviations with LISA

**2-day meeting** in May to learn about currently available LISA tools.

- LISA Data Challenge tools
- new LVK waveform interface (gwsignal)
- Fast EMRI Waveforms
- lisabeta
- bilby for LISA Hoy, Nuttall, arXiv:2312.13039
- pyCBC for LISA Weaving et al., arXiv:2306.16429

# Flexible-Theory-Independent (FTI) Method

During the inspiral, each GW mode can be written as $\tilde{h}_{\ell m}(f) = A_{\ell m}(f) e^{i\psi_{\ell m}(f)}$ where the phase can be obtained from the **post-Newtonian theory** using the stationary-phase approximation:

$$\psi_{\ell m}^{(\mathrm{GR})}(f, \boldsymbol{\lambda}) = \frac{3}{128 \nu v^5} \frac{m}{2} \left[ \sum_{n=0}^{7} \psi_n^{(\mathrm{PN})}(\boldsymbol{\lambda}) v^n + \sum_{n=5}^{6} \psi_{n(l)}^{(\mathrm{PN})}(\boldsymbol{\lambda}) v^n \log v \right]$$

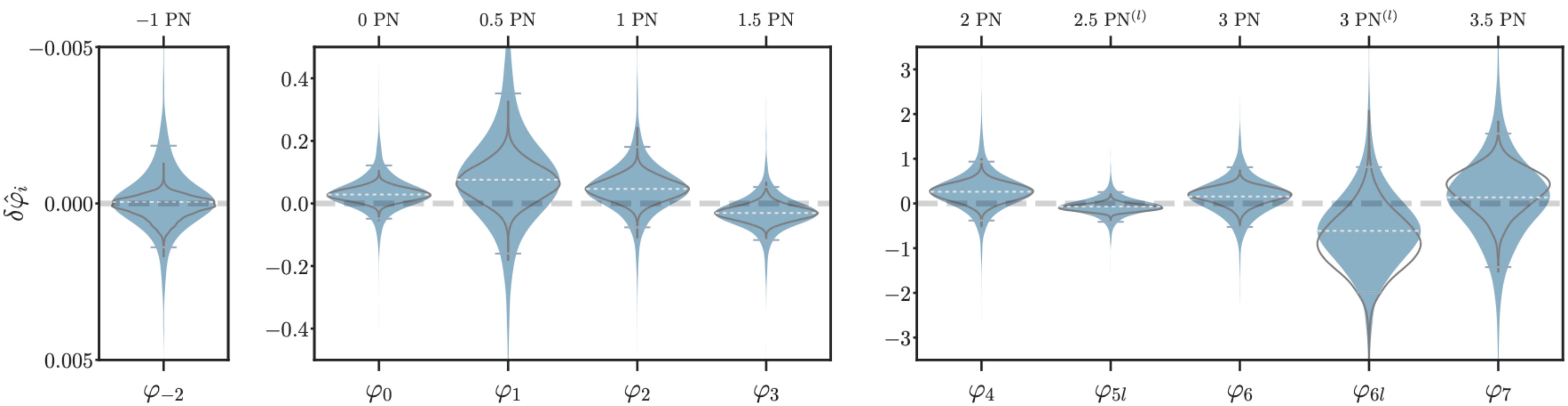
In the FTI method, each deviation parameter is a fractional deviation to the corresponding PN coefficient in GR:

$$\delta\psi_n(\boldsymbol{\lambda}, \delta\hat{\varphi}_n) \equiv \delta\hat{\varphi}_n \psi_n^{(\mathrm{PN})}(\boldsymbol{\lambda}),$$
$$\delta\psi_{n(l)}(\boldsymbol{\lambda}, \delta\hat{\varphi}_{n(l)}) \equiv \delta\hat{\varphi}_{n(l)} \psi_{n(l)}^{(\mathrm{PN})}(\boldsymbol{\lambda}).$$

Mehta et al., PRD 107, 044020 (2023)

# GWTC-3 analyses

In the combined GWTC-3 results, all the post-Newtonian deformation coefficients are consistent with the predictions from general relativity.




Abbott et al., arXiv: 2112.06861 (2021)

# Implementation of FTI in the LISA tools

**Coordinator**: Manuel Piarulli

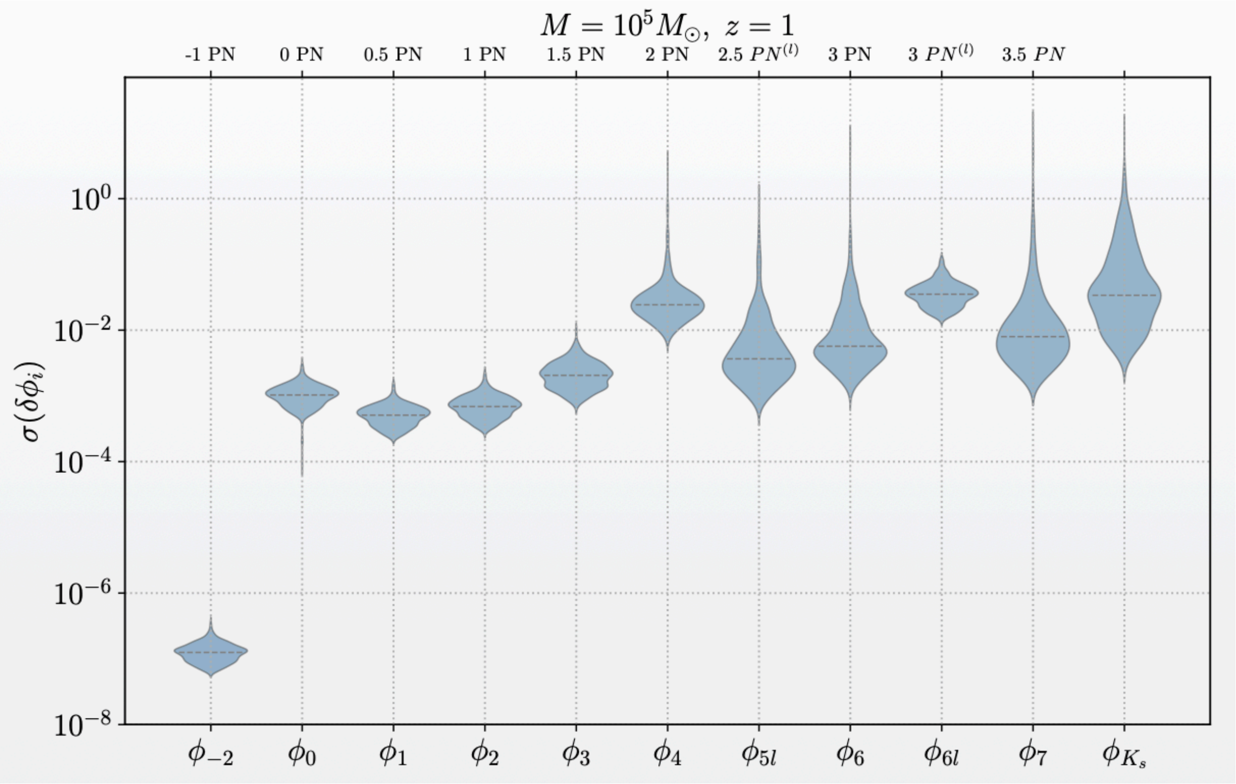
**Tasks**:

- Identification of the required LISA tool: lisabeta
- Identification of the implementations needed in the waveform interface and the TGR pipeline for compatibility with the LISA tool
- Validation of the code with injections
- Measurement of GR deviations with LISA

See Sylvain Marsat's talk and Manuel Piarulli's discussion later

# Implementation of FTI in the LISA tools

With a Fisher information matrix, it is assessed that the parameter uncertainties the post-Newtonian deformation coefficients decrease by ~2 orders of magnitude compared to the LVK analysis on GWTC-3.




Piarulli et al., in preparation

# Collaborative projects: next steps

- Implementation of other parametrized tests of GR (e.g. TIGER)

  Li et al., PRD 85, 082003 (2012); Agathos et al., PRD 89, 082001 (2014)

- Effect of **waveform modeling**, **eccentricity** and **spin-precession** in tests of GR

  Injection studies as a function of the binary parameters. Assessment of biases and false violations of general relativity in the recovery of the parameters.

- Injection studies with **beyond-GR** and **beyond-Standard-Model** waveforms

  Short presentations of waveform models for future mock data challenge

# Conclusions

- There is an ongoing effort in the LISA Consortium to study the effect of systematics in parametrized tests of general relativity.

- If you are interested in contributing to the projects, you can write to:

  **fpwg-chairs@lisamission.org**

  You will be added to the mailing list of the projects

  fpwg-systematics@lisamission.org
  fpwg-ringdown@lisamission.org

Webpage:
**https://wiki-lisa.in2p3.fr/LSGFPWG/EffectOfSystematicsOnParametrizedIMRTests**