Data analysis efforts at UIB from the ground up

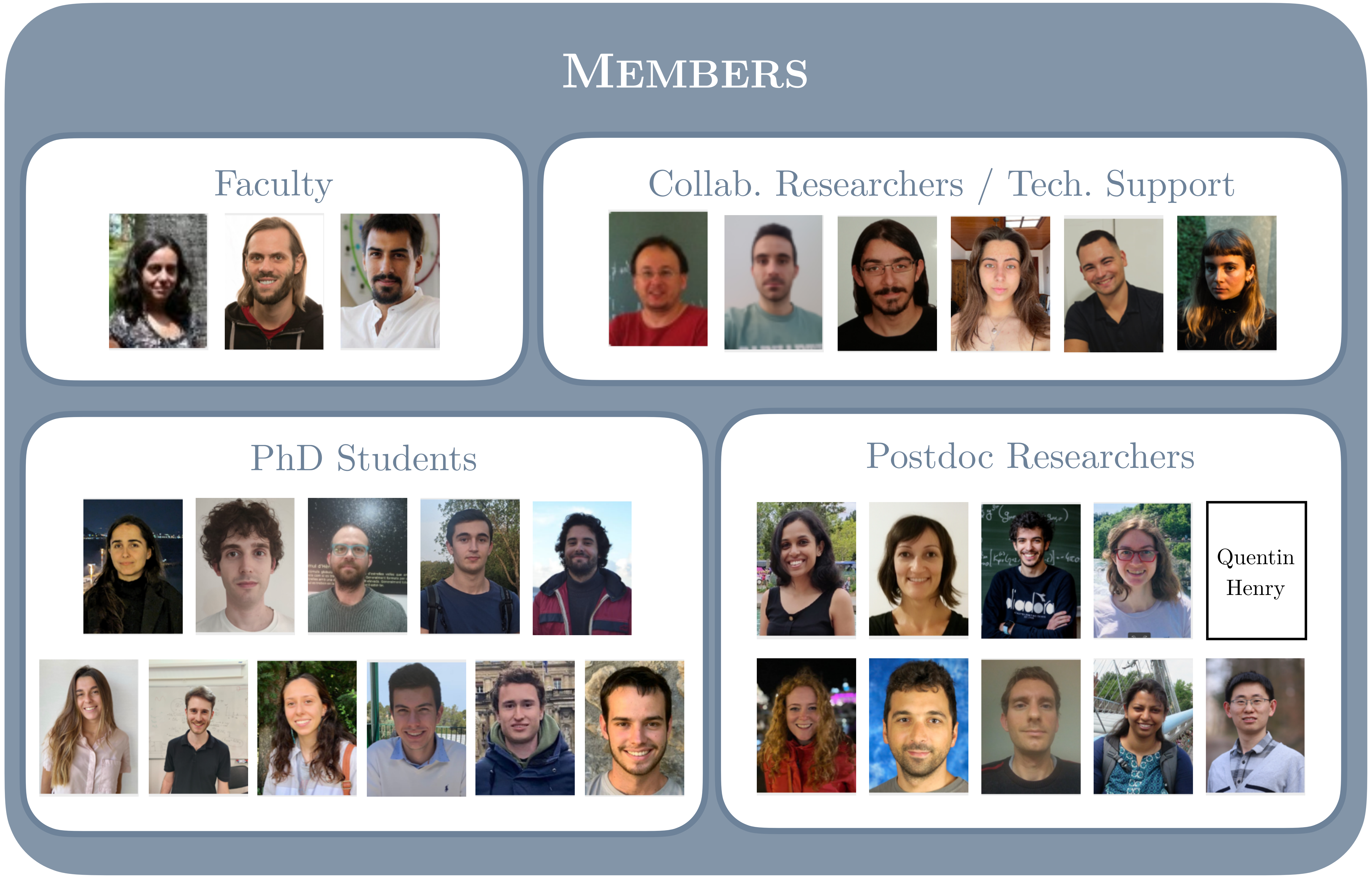
Jorge Valencia
on behalf of the UIB Gravitational Wave Group

LISA Spain Meeting
Barcelona, 15 October 2024

Universitat de les Illes Balears
IAC3 Institute of Applied Computing & Community Code.

UIB Gravitational Physics Group

- **+25** people, PI Alicia Sintes
- Members of LVK, ET, LISA Consortium, DDPC, Anna Heffernan of LST
- IMRPhenom waveform models:
  - used routinely by LVK for all events detected,
  - LISA data challenges
- Data analysis:
  - continuous waves and long transient searches
  - lensing searches
  - CB parameter estimation



UIB Gravitational Physics Group

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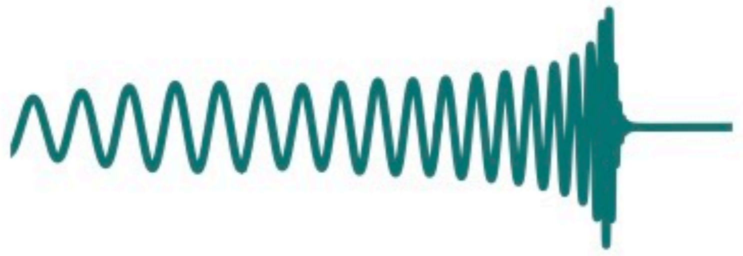

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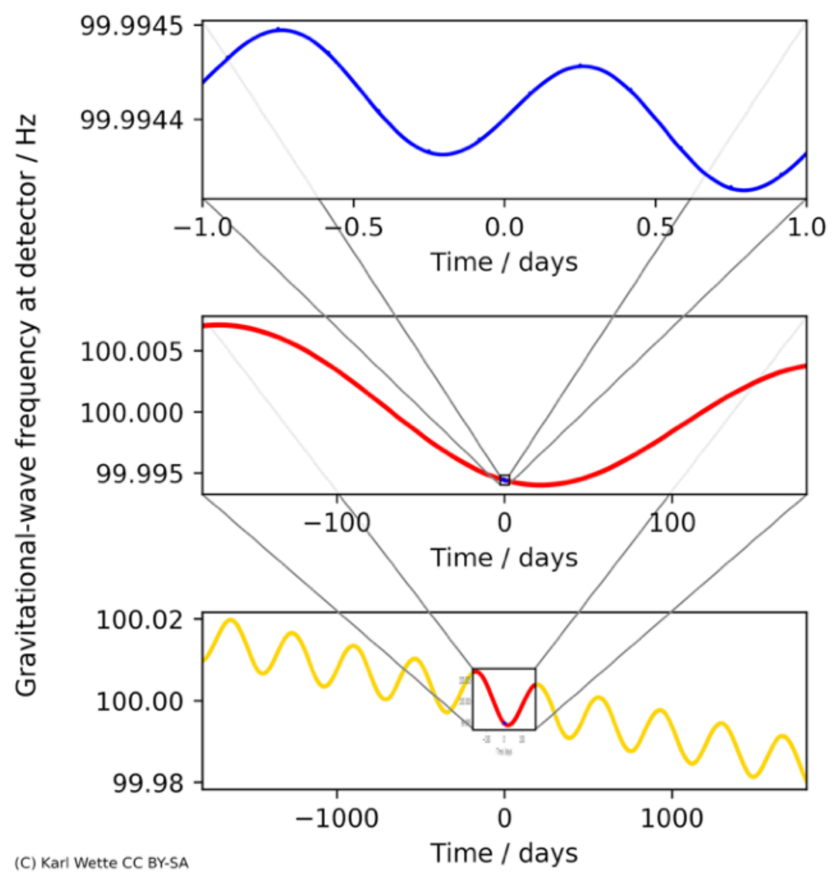

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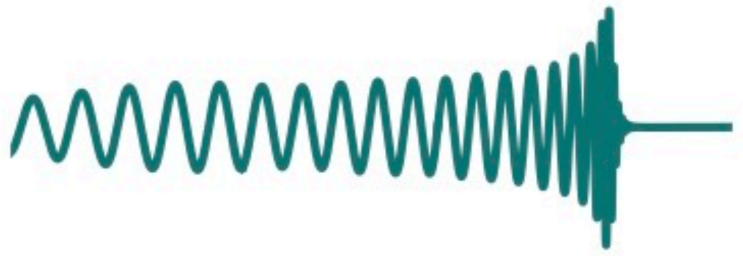
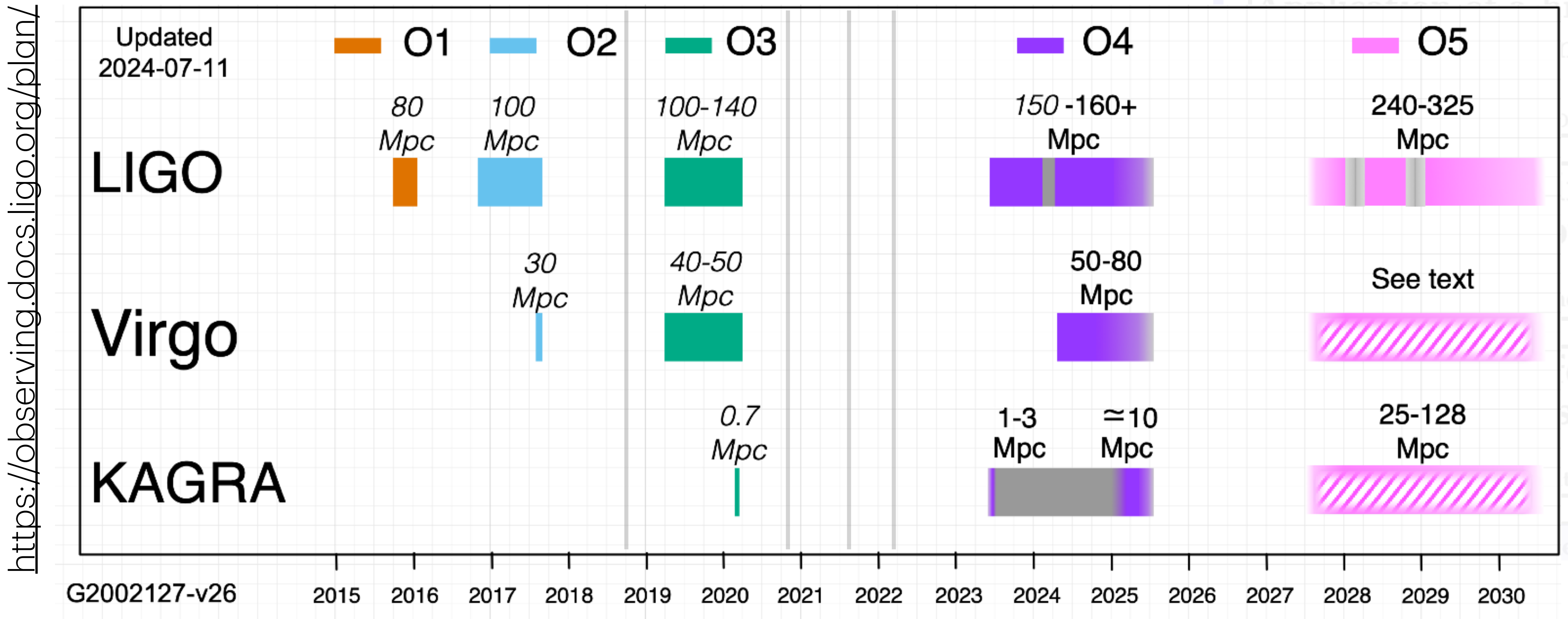


- Periodic data releases after observing periods → same for LISA



GWTC-1, [Phys. Rev. X 9, 031040](#)

GWTC-2, [Phys. Rev. X 11, 021053](#)

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UIB Gravitational Physics Group

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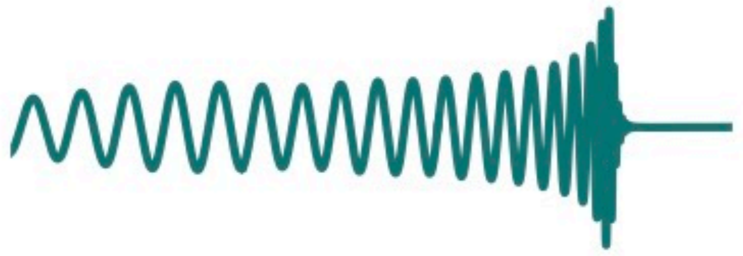

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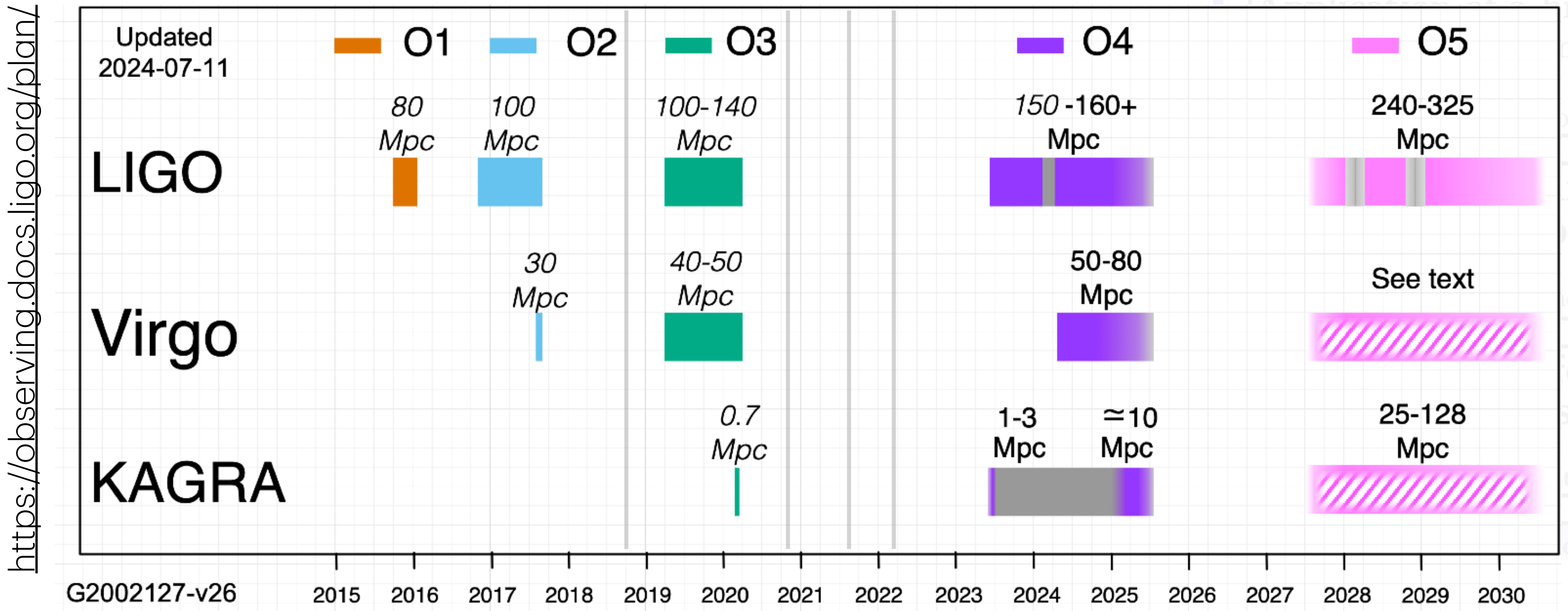

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- During observing periods:
  - ROTA: PE exploratory runs of detected events
  - Public alerts in https://gracedb.ligo.org/
  - PE investigations of specific events
  - Searches: CWs, lensing.
  - Waveform code maintenance
  - Review of results/catalogs

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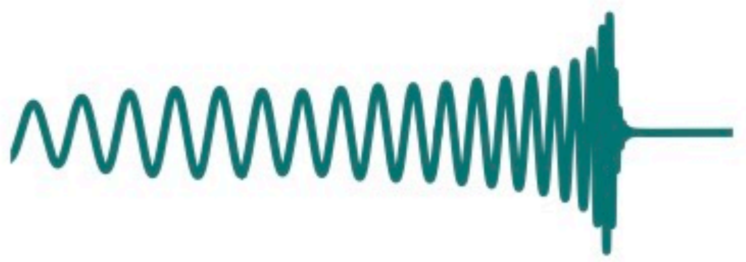
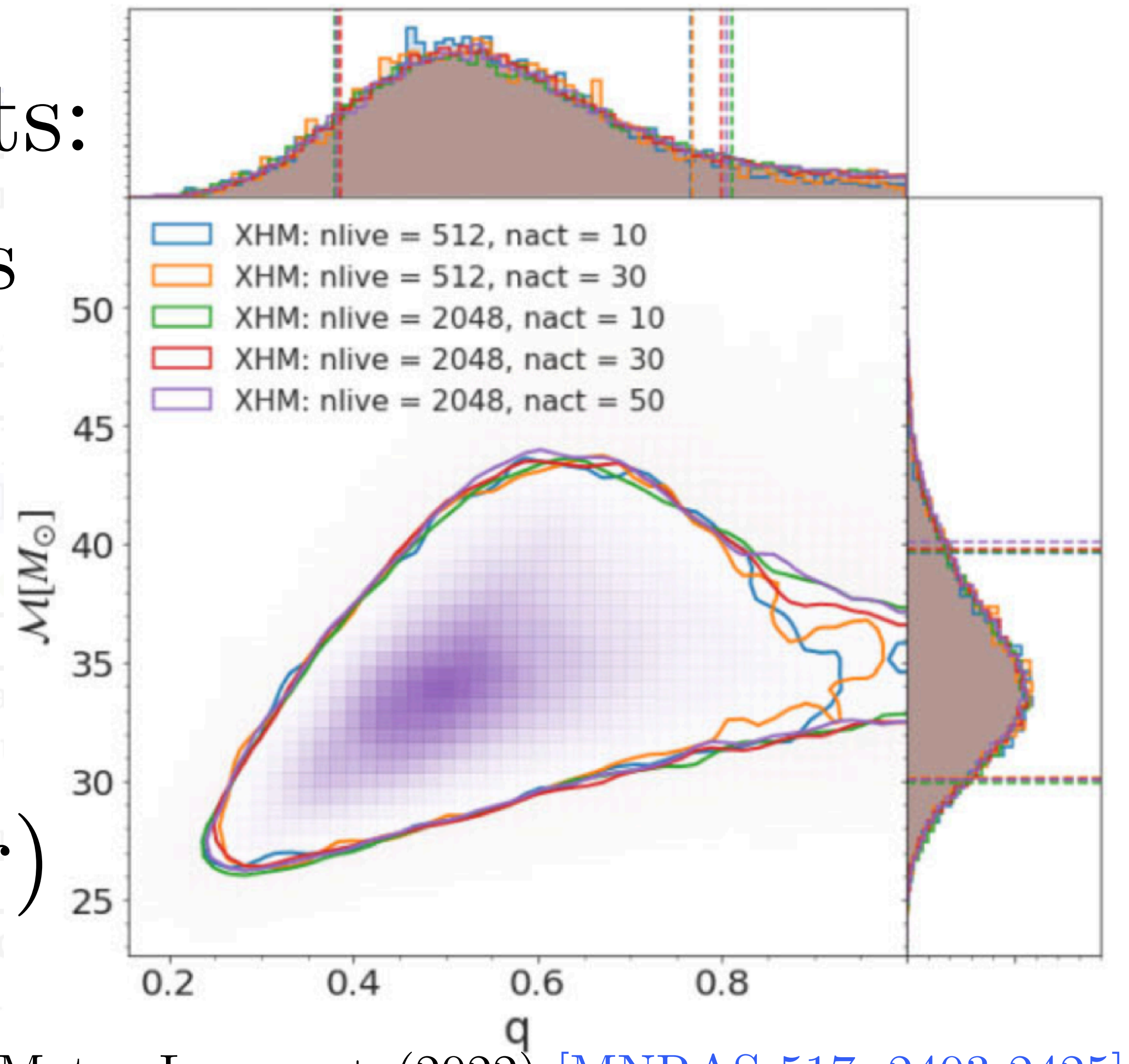
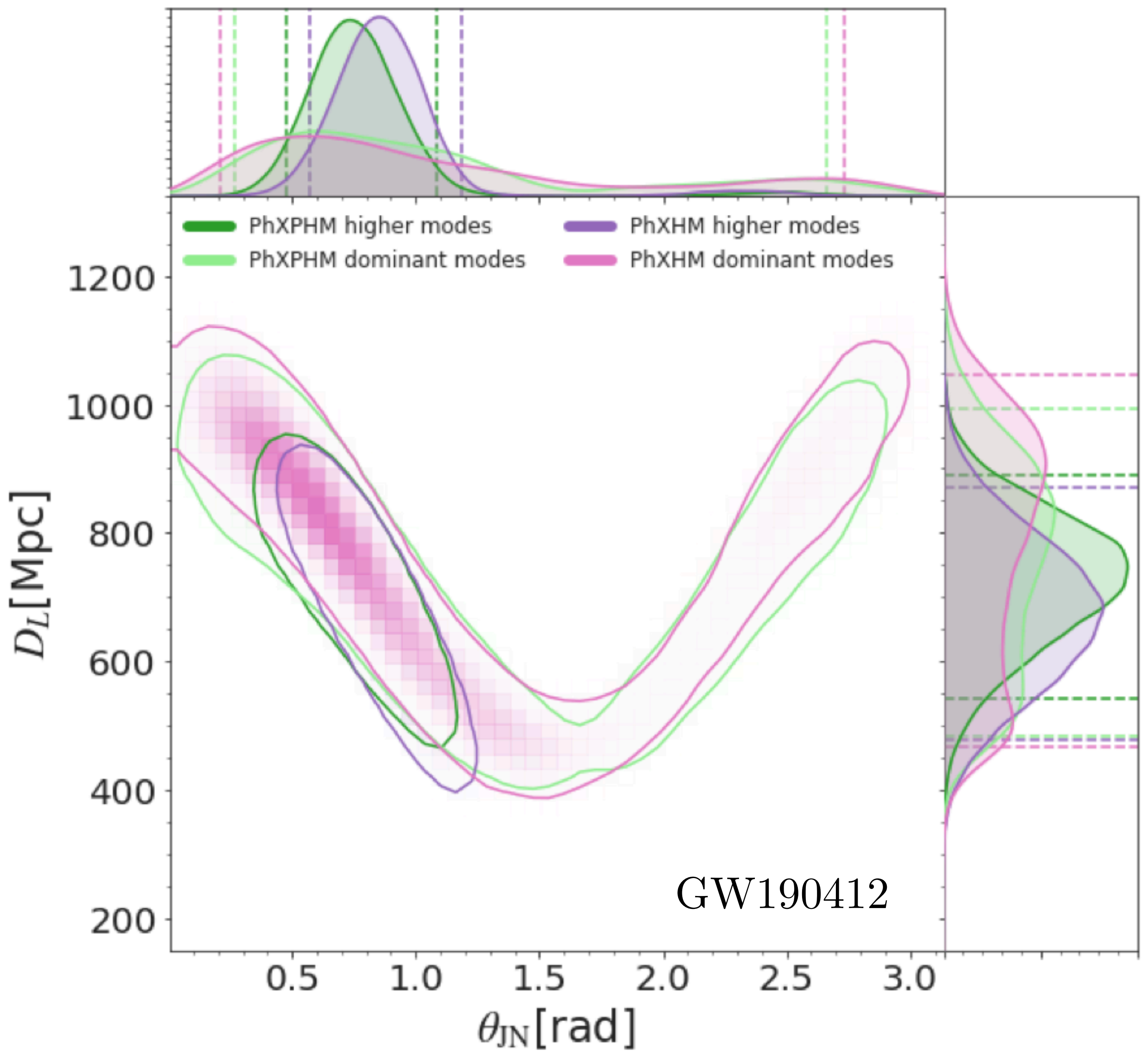


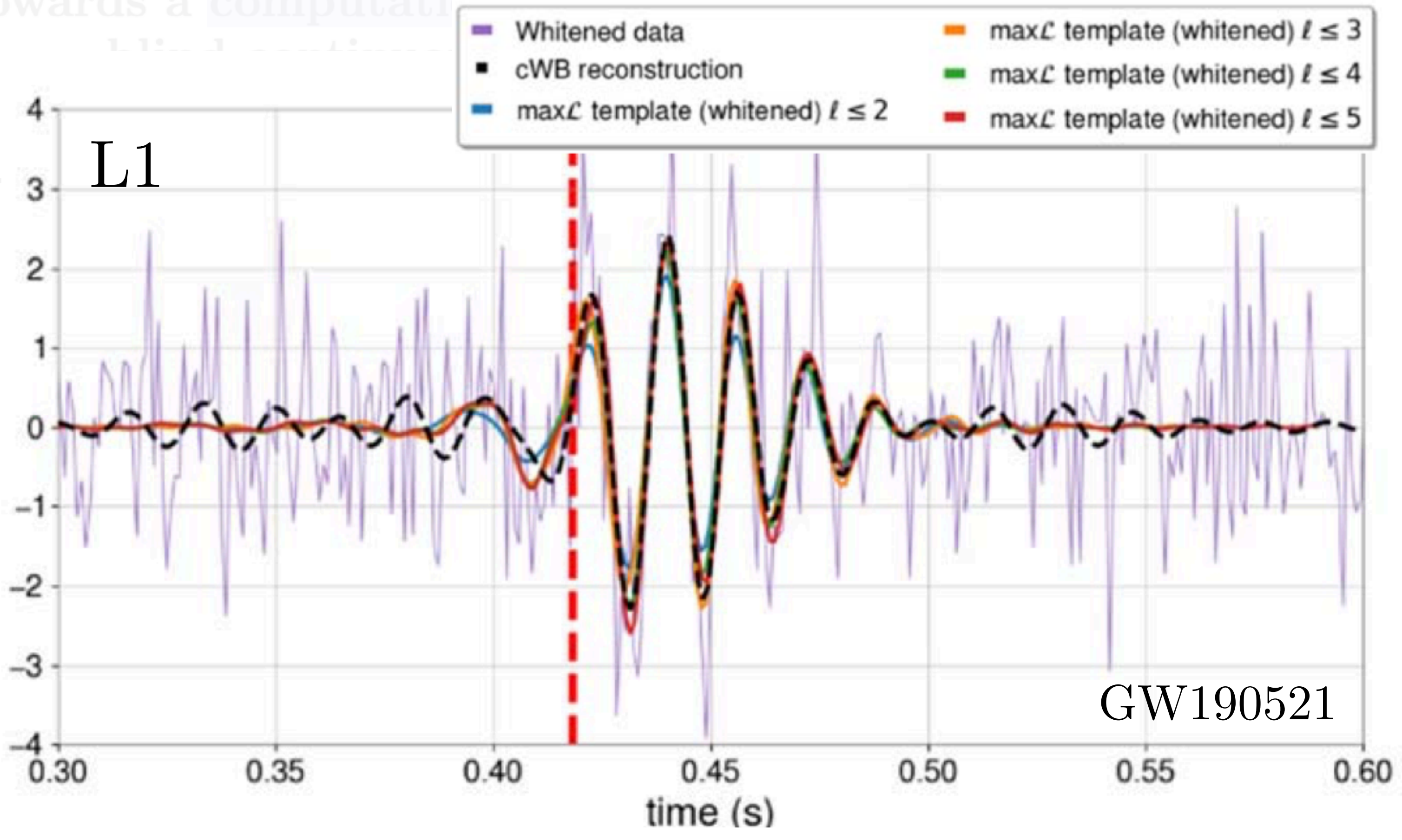
- Very **detailed studies** of specific LVK events:
  - Sampler convergence for different configurations
  - Higher harmonic content in the recovery of source parameters
  - Reconstructing whitened GW signal
- **LISA:** much more complex studies (see later)



Maite Mateu-Lucena + (2022) [MNRAS 517, 2403-2425]



Marta Colleoni + (2021) [Phys. Rev. D 103, 024029]



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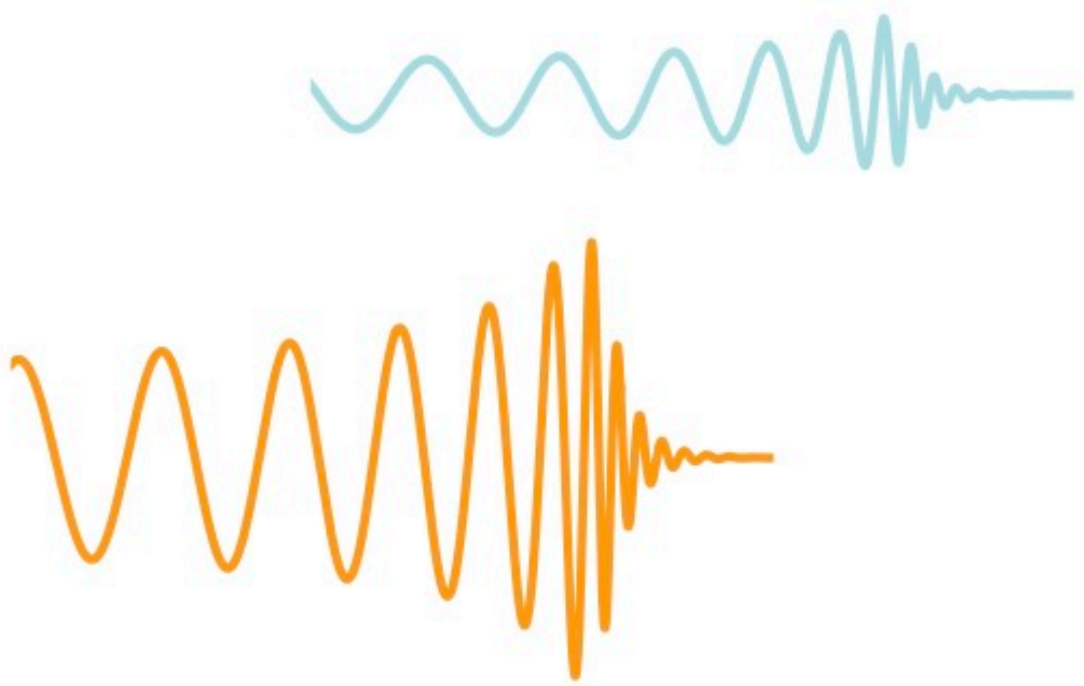

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GW Lensing

- Lensing studies for LISA

Continuous Waves:

- Machine Learning searches
- Galactic binaries
- Almost monochromatic signals

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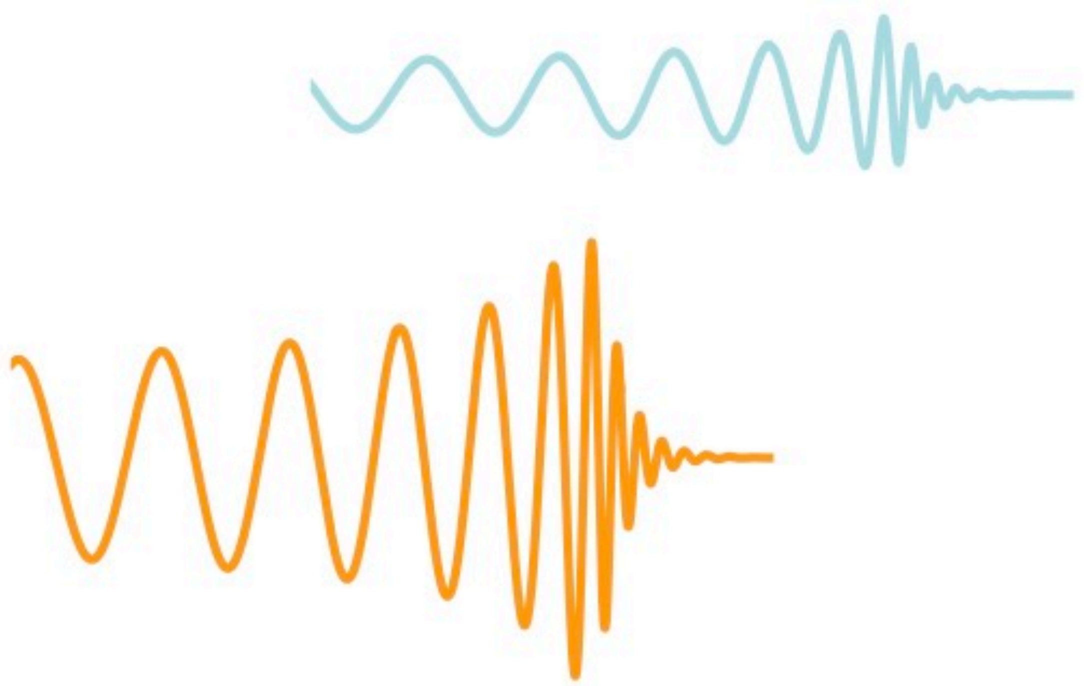

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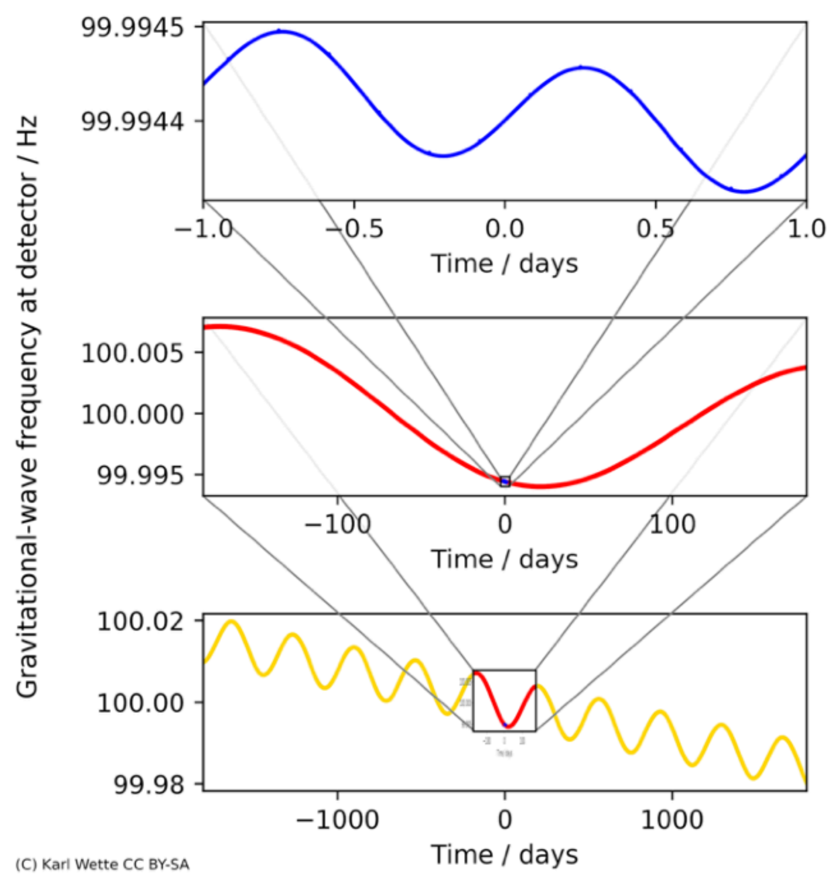

Previous experience with LISA

LISA parameter estimation of supermassive black holes
Miquel Trias[1] and Alicia M Sintes[1,2]

LISA observations of supermassive black holes: parameter estimation using full post-Newtonian inspiral waveforms
Miquel Trias[1] and Alicia M. Sintes[1,2]

Weak lensing effects in the measurement of the dark energy equation of state with LISA
Chris Van Den Broeck,[1,2,*] M. Trias,[3,†] B. S. Sathyaprakash,[2,‡] and A. M. Sintes[3,§]

Universitat de les Illes Balears
MASTER'S THESIS
TESTING WAVEFORM MODELS FOR THE LISA AND EINSTEIN TELESCOPE GRAVITATIONAL WAVE DETECTORS
Friso Snel
Master's Degree in Advanced Physics and Applied Mathematics
Centre for Postgraduate Studies
Academic Year 2019-20

Universitat de les Illes Balears
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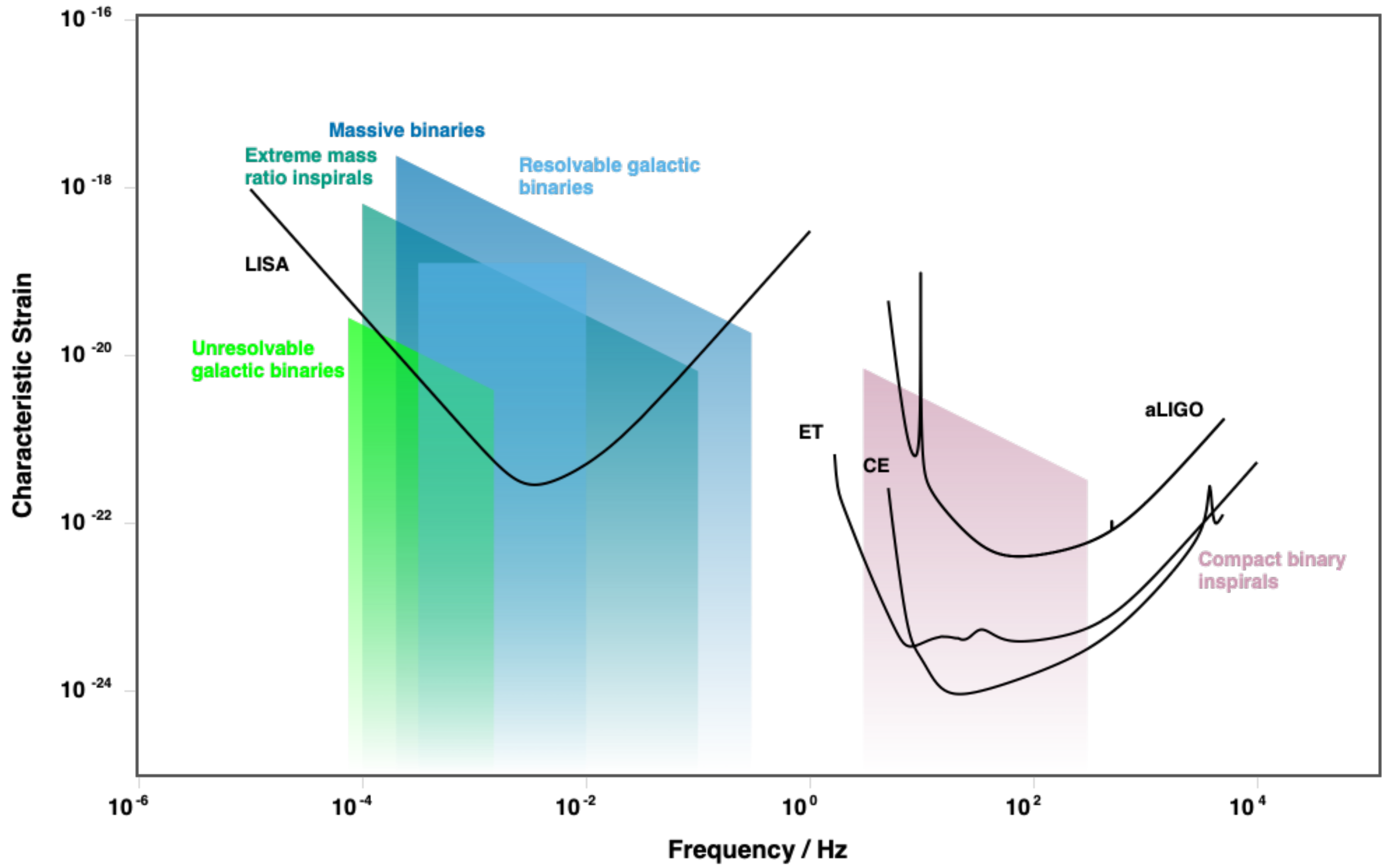
A STUDY OF WAVEFORM REQUIREMENTS FOR THE LISA SPACE MISSION WITH CURRENT INSPIRAL-MERGER-RINGDOWN MODELS
Jorge Valencia Gómez
Master's degree in Advanced Physics and Applied Mathematics
Centre for Postgraduate Studies
Academic Year 2022-23

LISA

- Detector response
- Variety of new sources
- Overlapping signals
- Really high SNRs



Christopher J. Moore + 2014, http://gwplotter.com/

IMRPhenom Models

	Aligned spin	Precessing
Quasi-circular	IMRPhenomTHM [Estellés+(2020)] IMRPhenomXHM [García-Quirós+(2020)]	IMRPhenomTPHM [Estellés+(2021)] IMRPhenomXPHM [Pratten+(2021)] IMRPhenomXO4A [Thompson,Hamilton+(2024)] IMRPhenomXPNR [Colleoni,Hamilton+(in prep.)]
Eccentric		

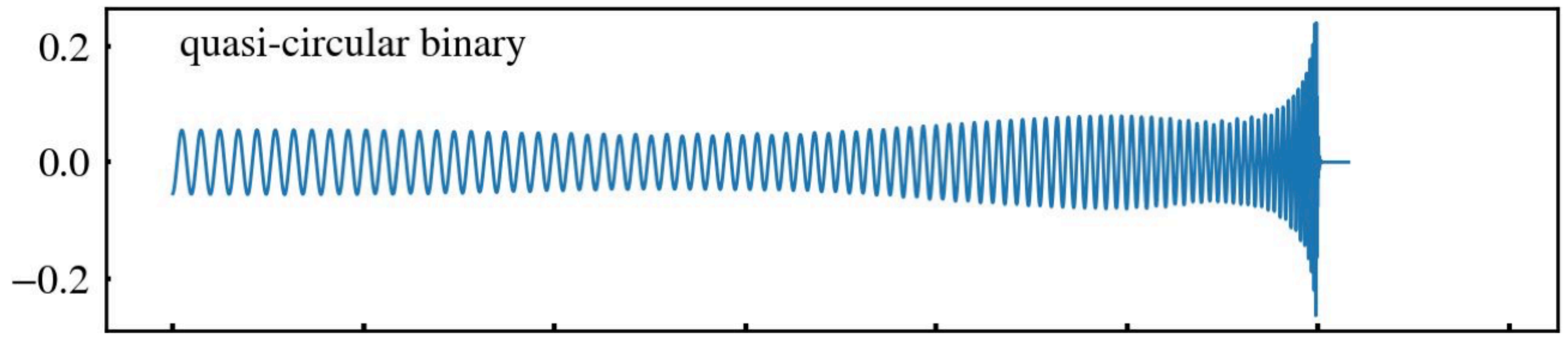


Image taken from Antoni Ramos-Buades talk
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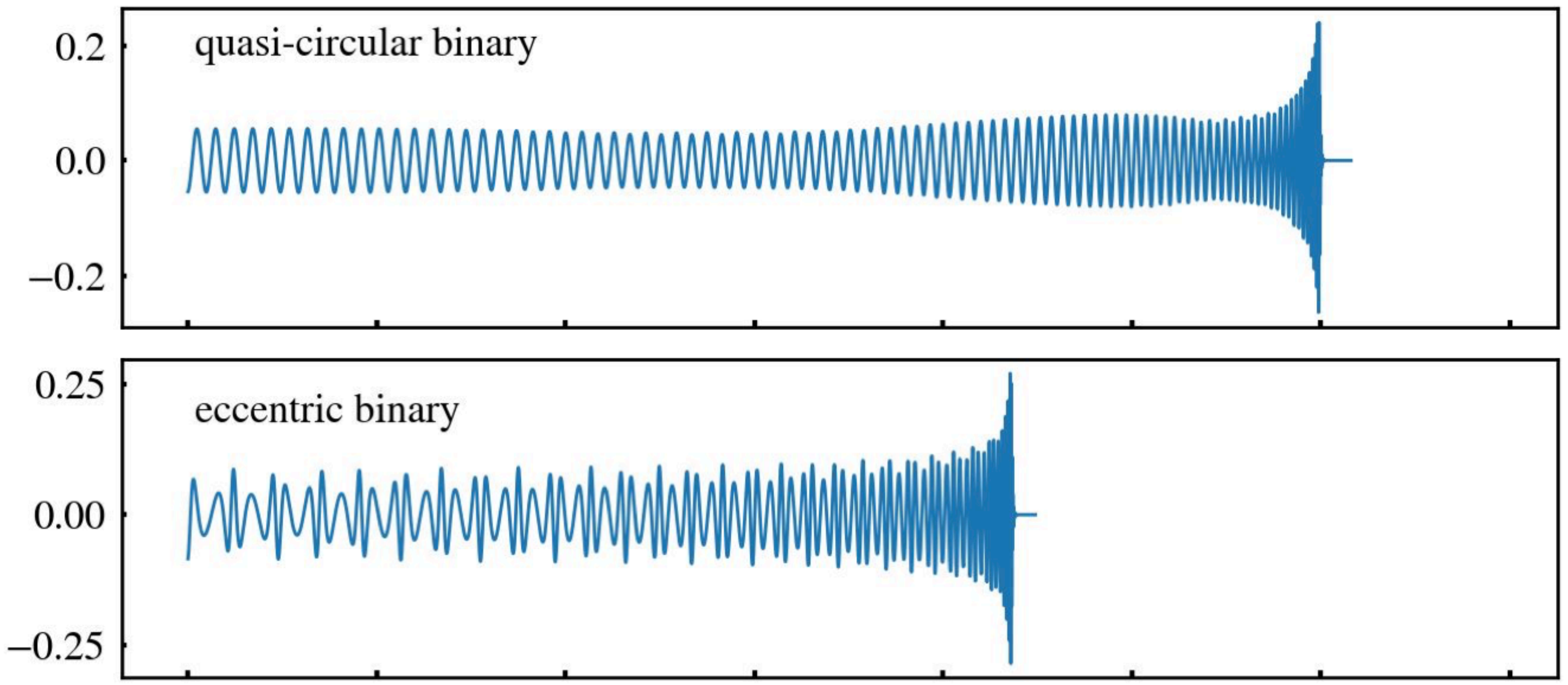
Eccentric	IMRPhenomTEHM [Planas+(in prep.)] IMRPhenomXE [Ramos-Buades+(in prep.)]	



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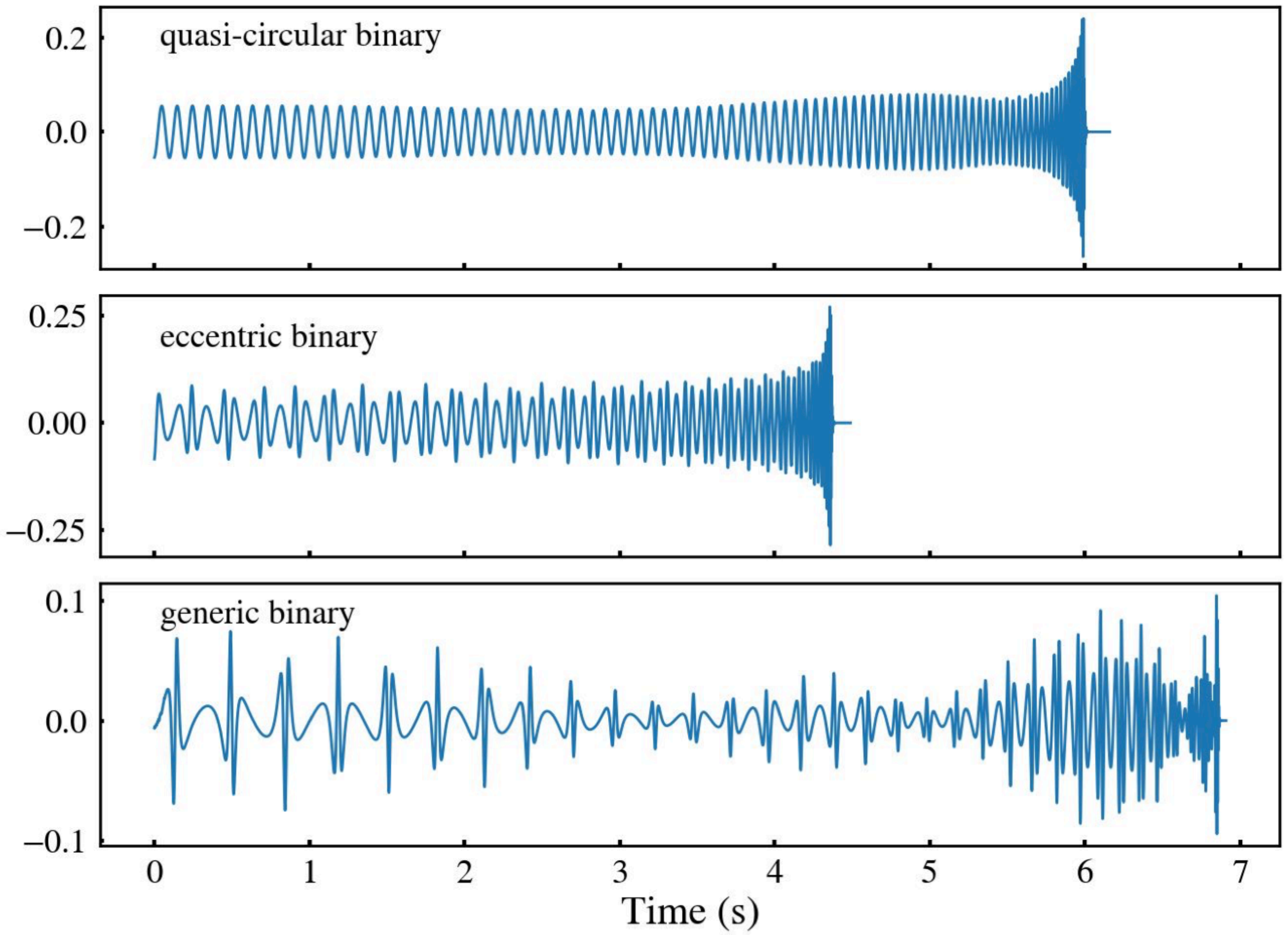

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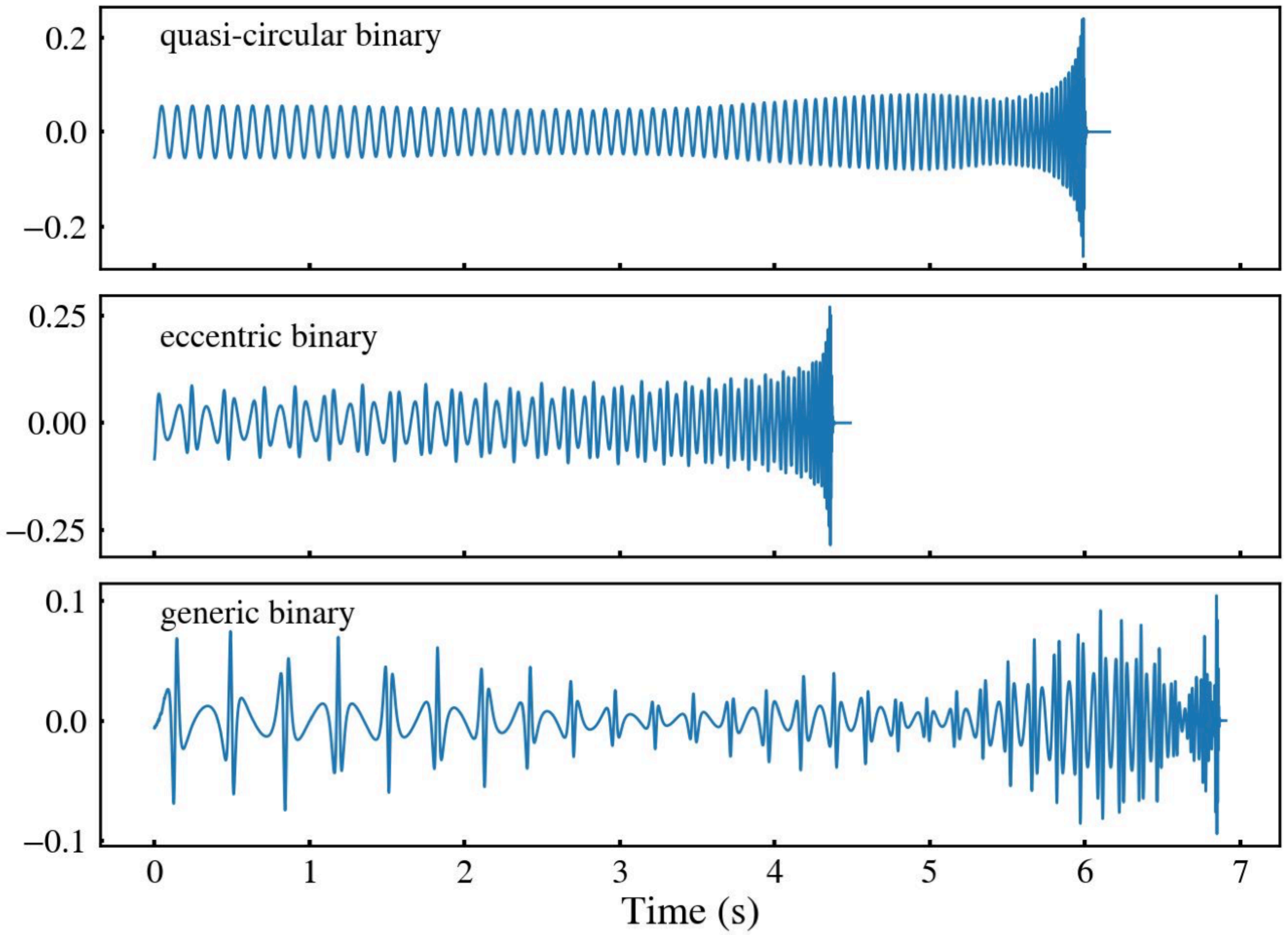

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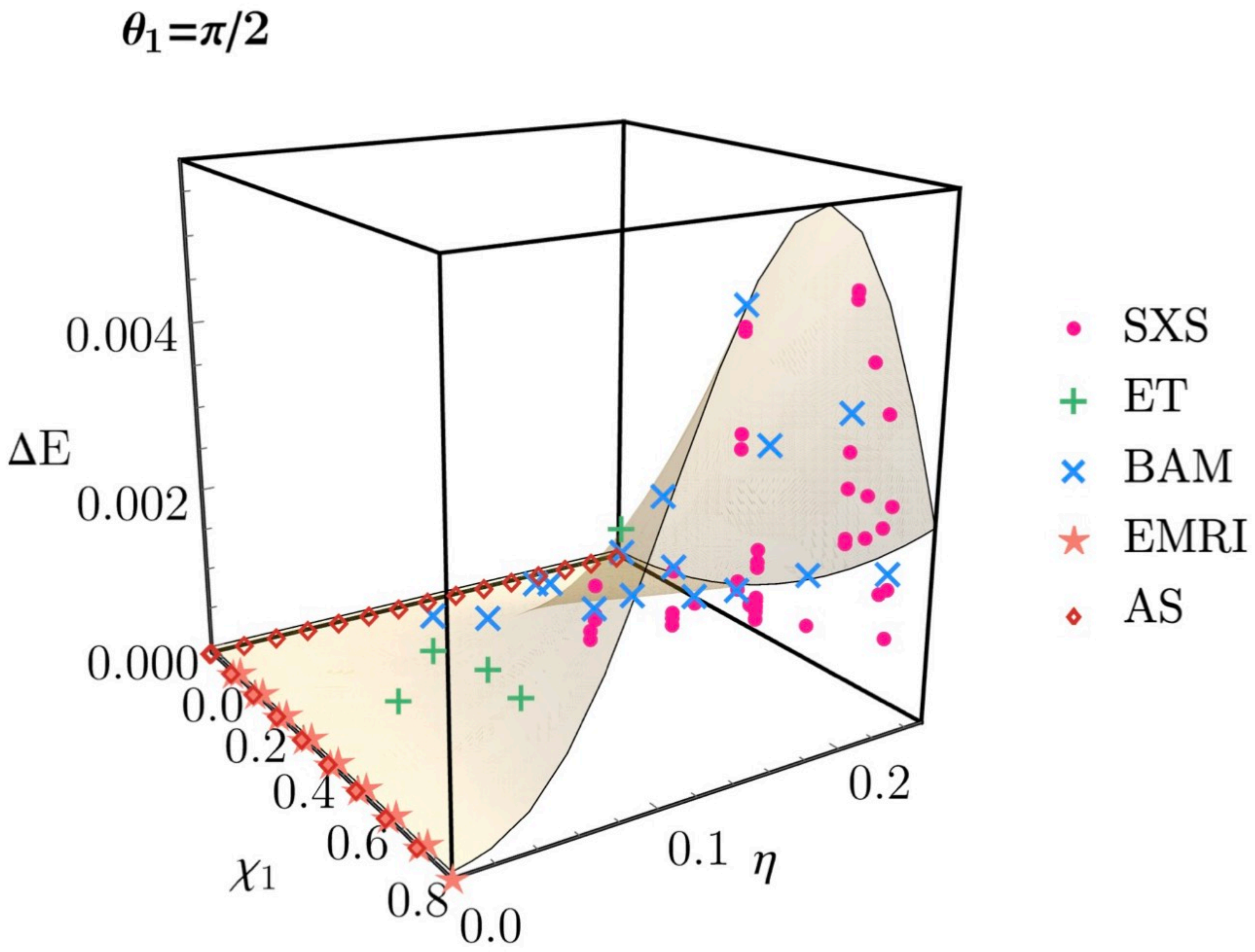
New Python infrastructure for Phenom models:
phenomxpy (GPUs)
[see talk by Cecilio García-Quirós]

Recent and some Ongoing modelling work @ UIB: I

Data sets for the entire parameter space

- Build IMRPhenom models with data from all available NR catalogues.
  - Consistent precessing data: different NR catalogs, NRSurrogate, EMRI waveforms. L. Planas, J. Llobera, S. Husa [Phys. Rev. D 109, 124028]
  - First application: single spin final state model across all mass ratios.
  - Ongoing: systematic approach to build precessing "complete" hybrids from inspiral waveforms + NR: J. Llobera, S. Husa (in prep.)



Data sets for the entire parameter space

- Build IMRPhenom models with data from all available NR catalogues.
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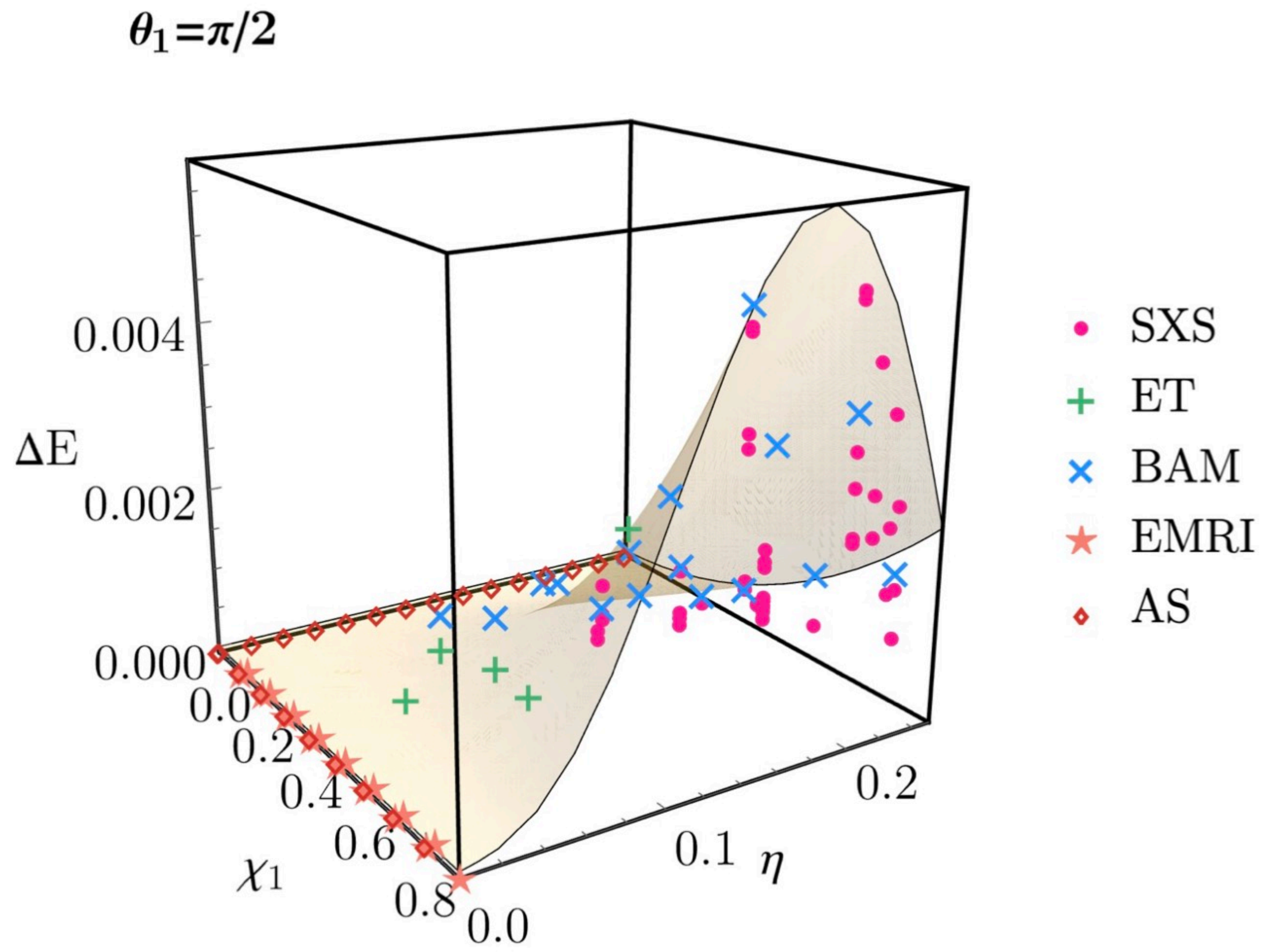
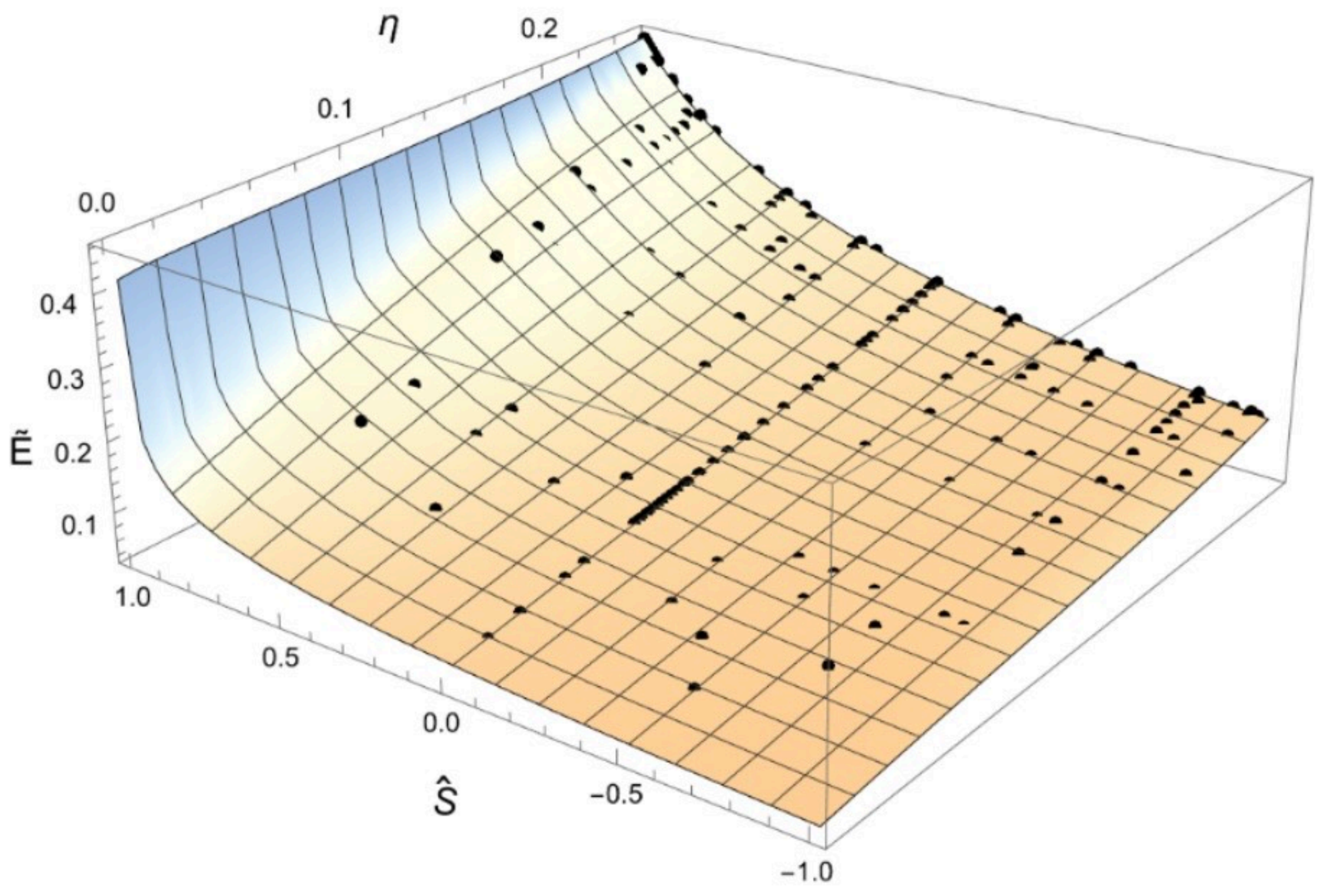


Regular Aligned spin final state model

- Singular behaviour for EMRIs + extreme spins has previously not been incorporated into models.
- Solve by appropriate rescaling: R. Santos, P. Mourier, S. Husa, (in prep.)



RECENT AND SOME ONGOING MODELLING WORK @ UIB: I

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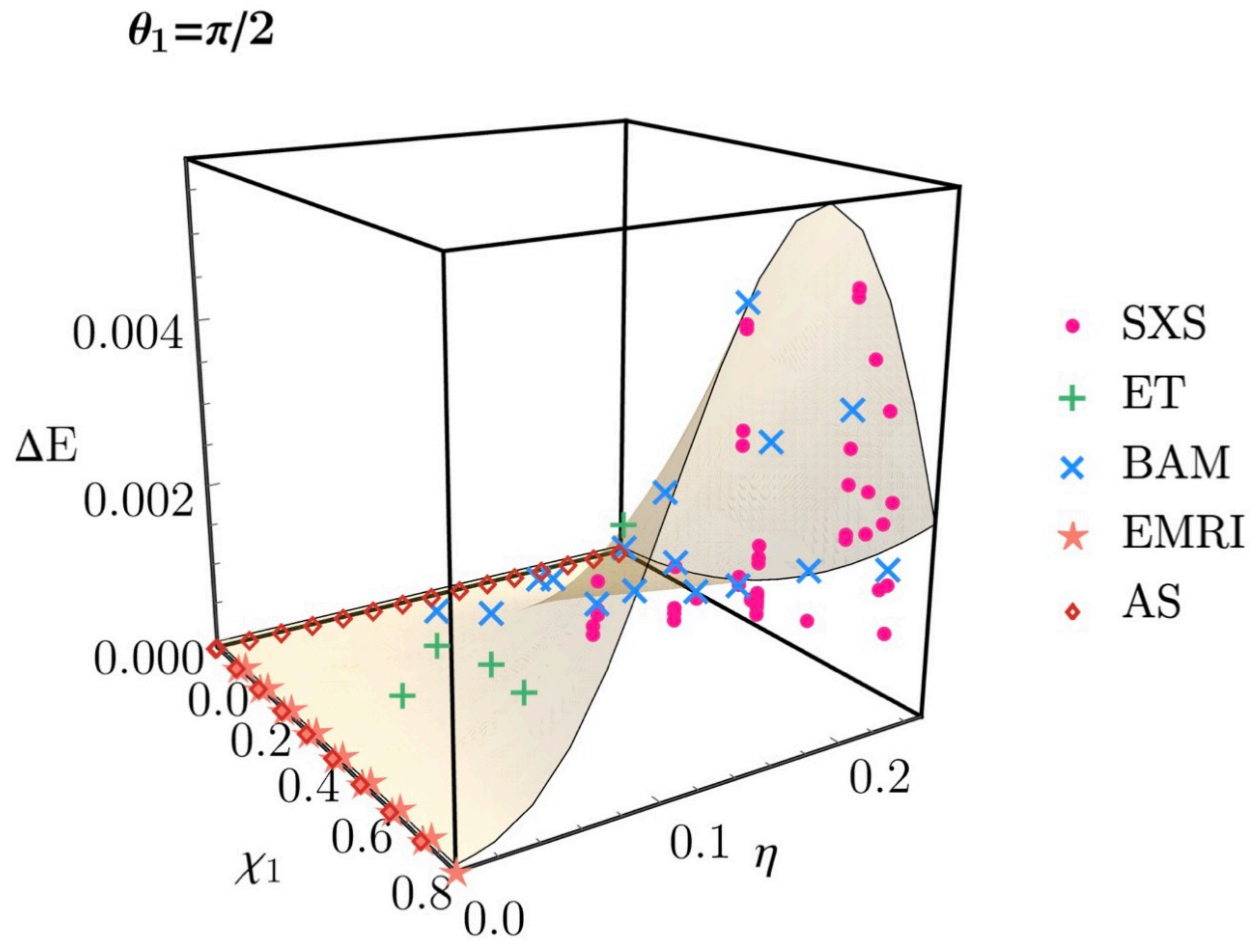

REGULAR ALIGNED SPIN FINAL STATE MODEL

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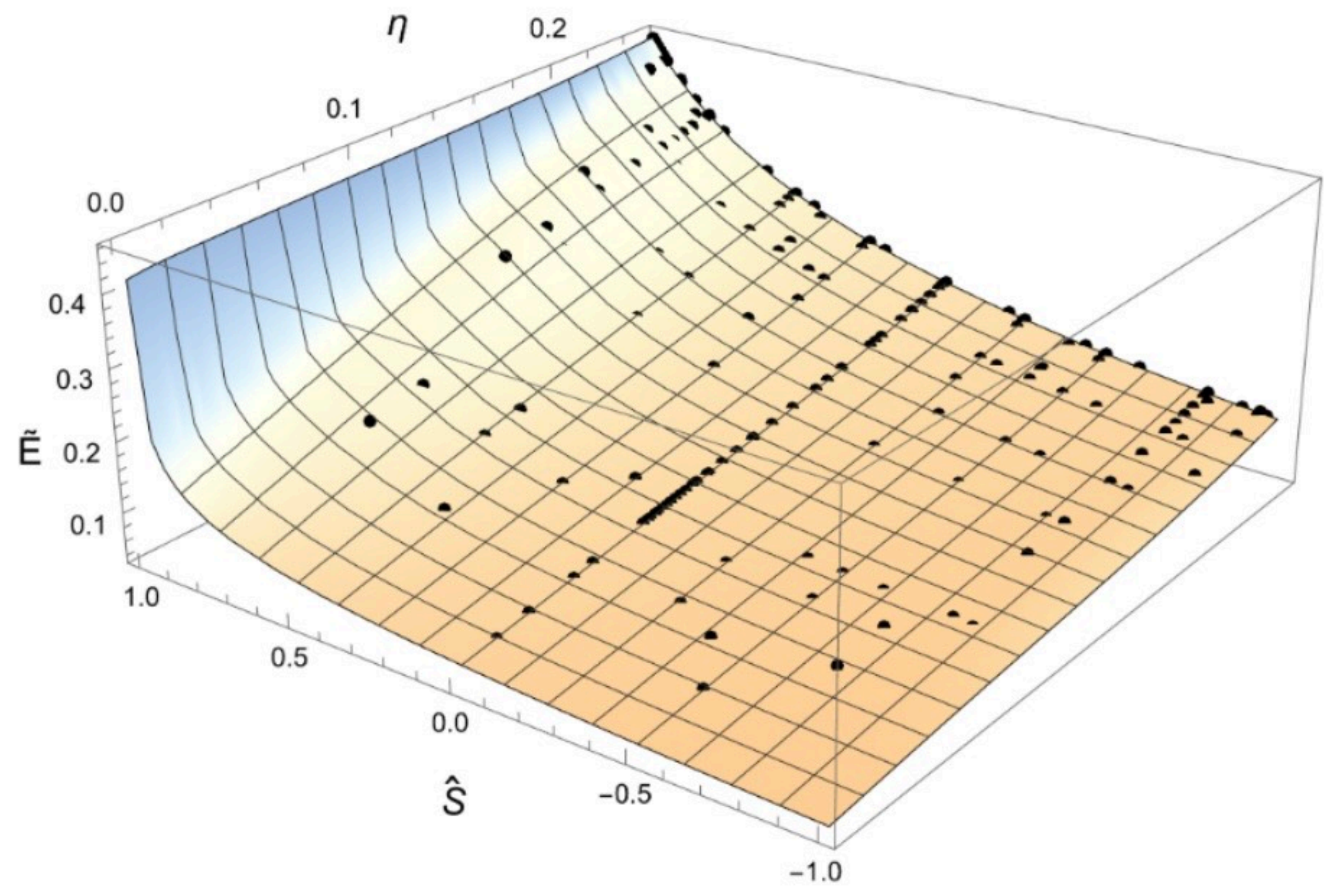


NR SIMULATIONS FOR ECCENTRIC WAVEFORMS AND LARGE MASS RATIOS

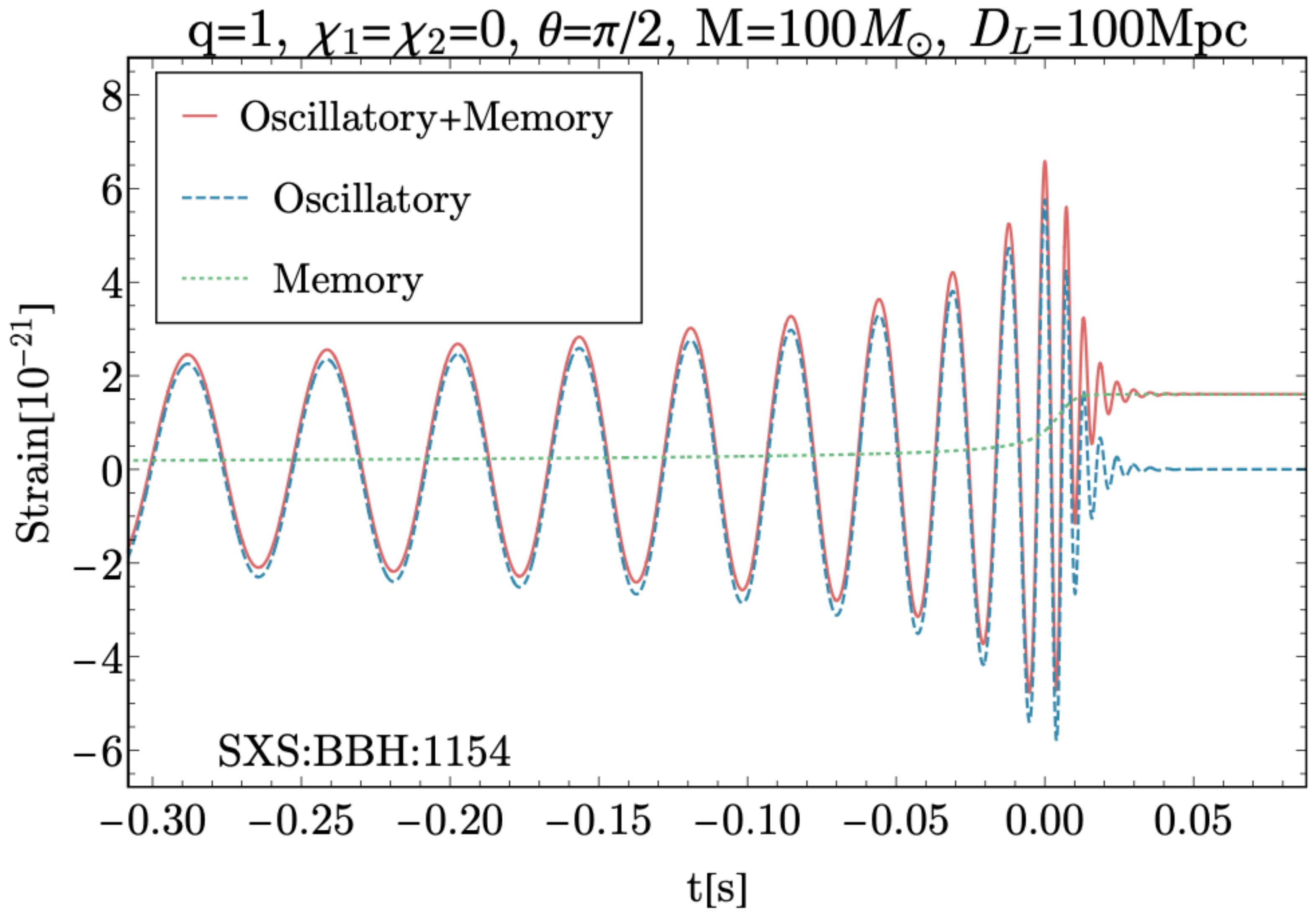
- Einstein Toolkit code, simulations on MN5.

Recent and some Ongoing modelling work @ UIB: II

GW Memory

- Developed IMRPhenom model for the **complete (2,0) mode**: memory + oscillatory part.
  M. Rosselló-Sastre, S. Husa, S. Bera (2024) [arXiv:2405.17302]

- Fast: implemented in IMRPhenomTHM (LALSuite + phenomxpy)



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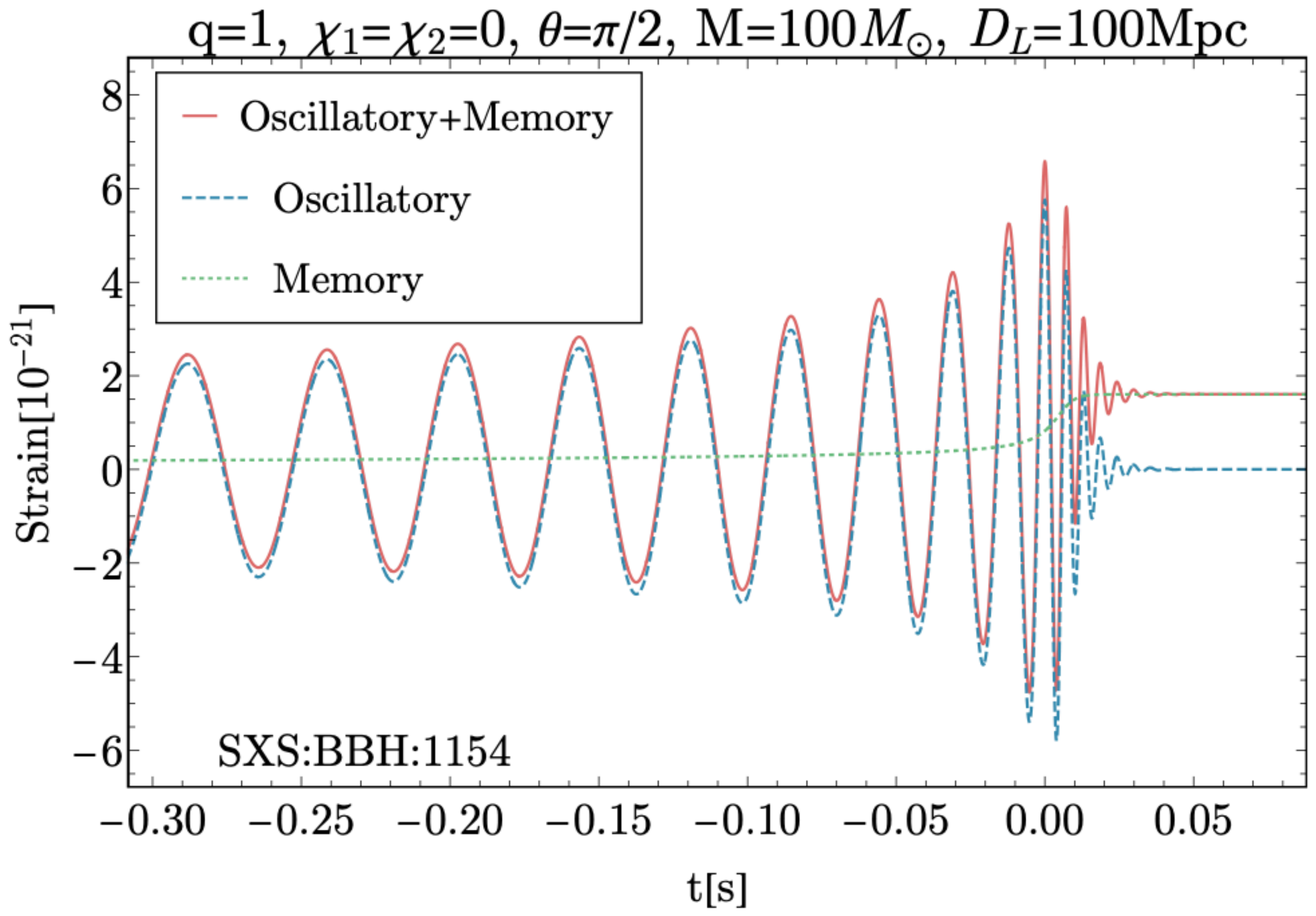
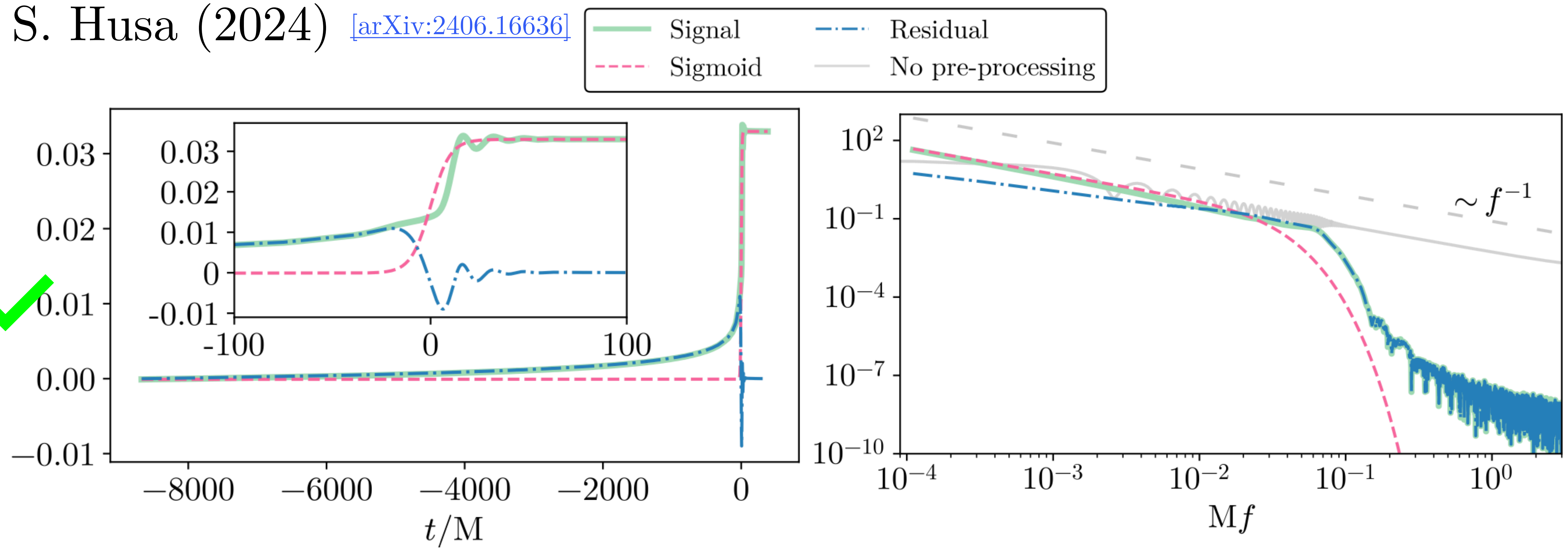


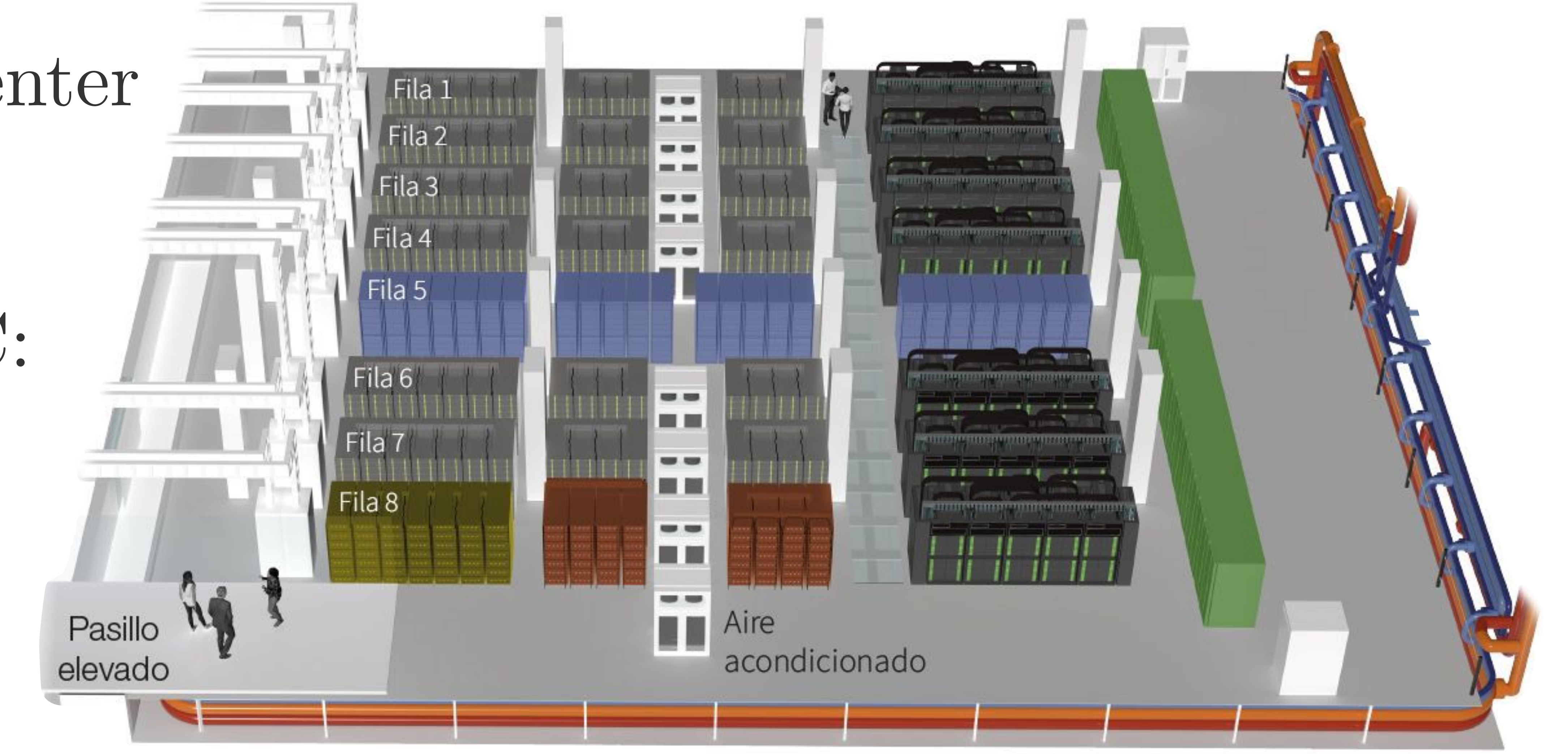
Data Analysis with Step-like Functions

- Method to compute FT of data with **step-like behaviour**
  J. Valencia, R. Tenorio, M. Rosselló-Sastre, S. Husa (2024) [arXiv:2406.16636]
  - DFTs assume periodic data
  - Padding + windowing ✗
  - Remove the step and treat it analytically ✓
  - Add it back artifact-free



Computing resources

MareNostrum 5 installed at Barcelona Supercomputing Center

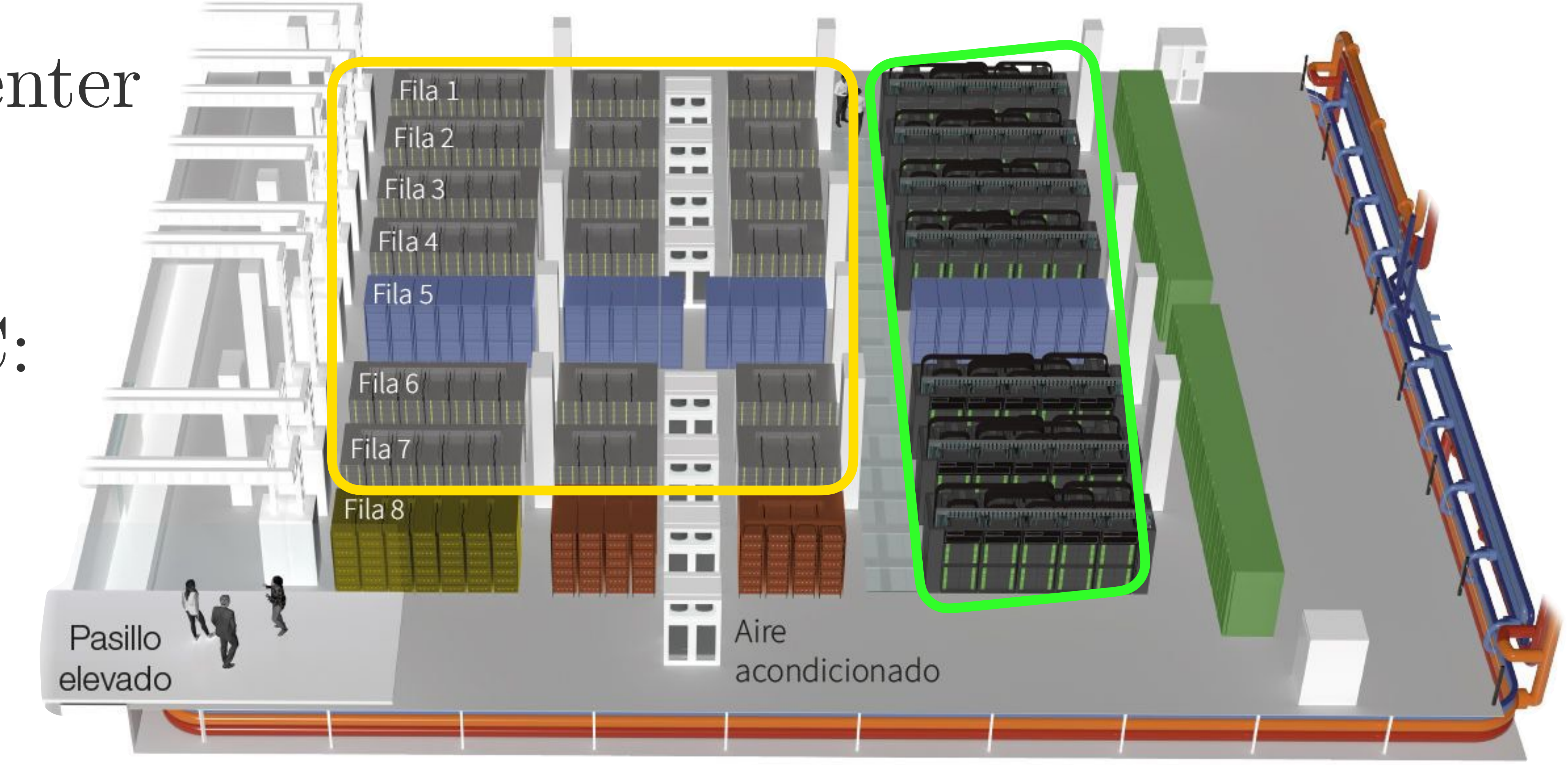


- Excellent resource for LISA Spain community
- First allocation toward role of BSC/MareNostrum for DCC:

"Preparations for the Spanish Contribution to the LISA Distributed Data Processing Centre"

7 active users

Images taken from: https://www.bsc.es/es/noticias/noticias-del-bsc/arranca-marenostrum-5-el-nuevo-supercomputador-europeo-instalado-en-el-bsc



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General Purpose Partition

• 6192 nodes	112 CPUs	256 GB
• 216 nodes	112 CPUs	1024 GB
• 72 nodes	112 CPUs	128 GB

Allocation time: 985 kh

Currently running:

- CBC PE
- High-mass ratio NR simulations toward comparison with GSF

Accelerated Partition

- 1120 nodes
- Total of ~700,000 compute units

Allocation time: 85 kh

Currently running:

- Code benchmarks
- LISA PE exploratory runs

Hardware info taken from: https://www.bsc.es/supportkc/docs/intro

Images taken from: https://www.bsc.es/es/noticias/noticias-del-bsc/arranca-marenostrum-5-el-nuevo-supercomputador-europeo-instalado-en-el-bsc

LISA Current Results...

GW Memory

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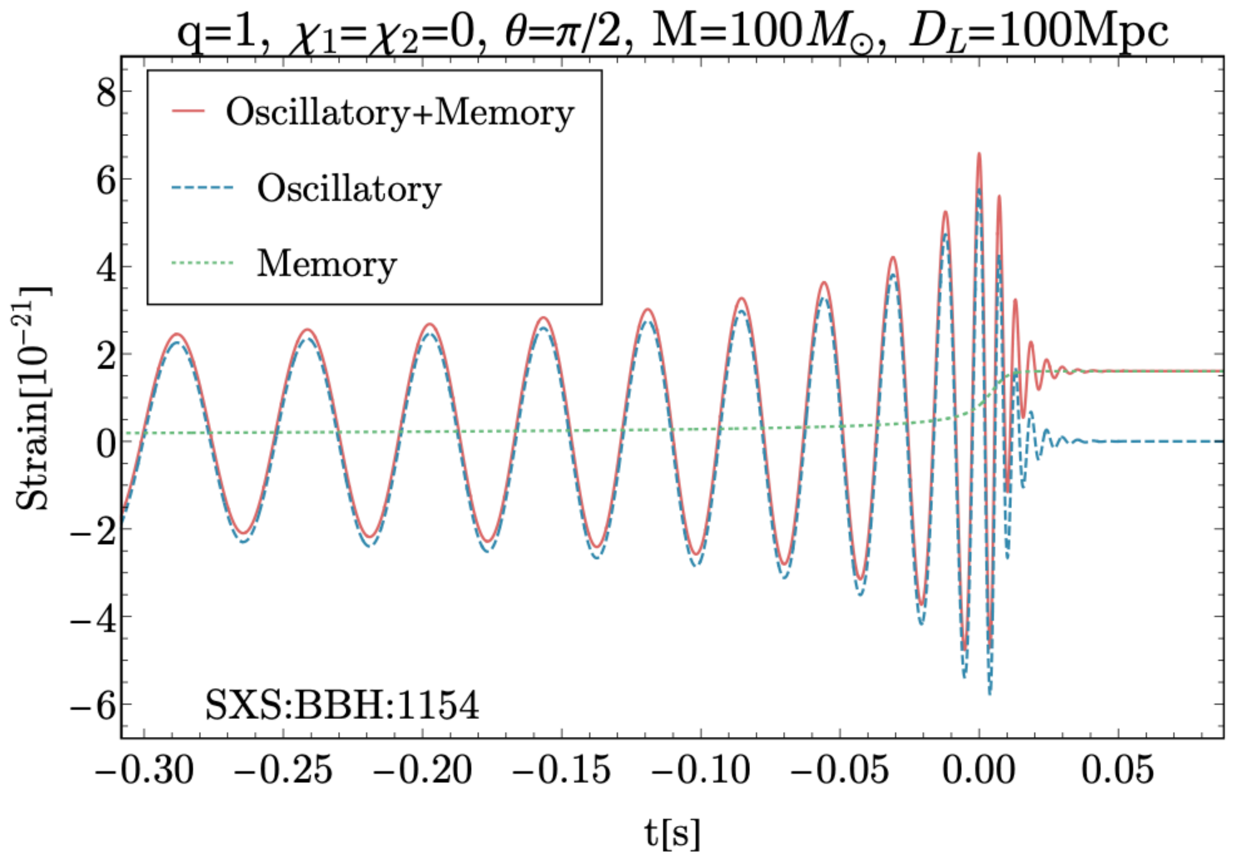

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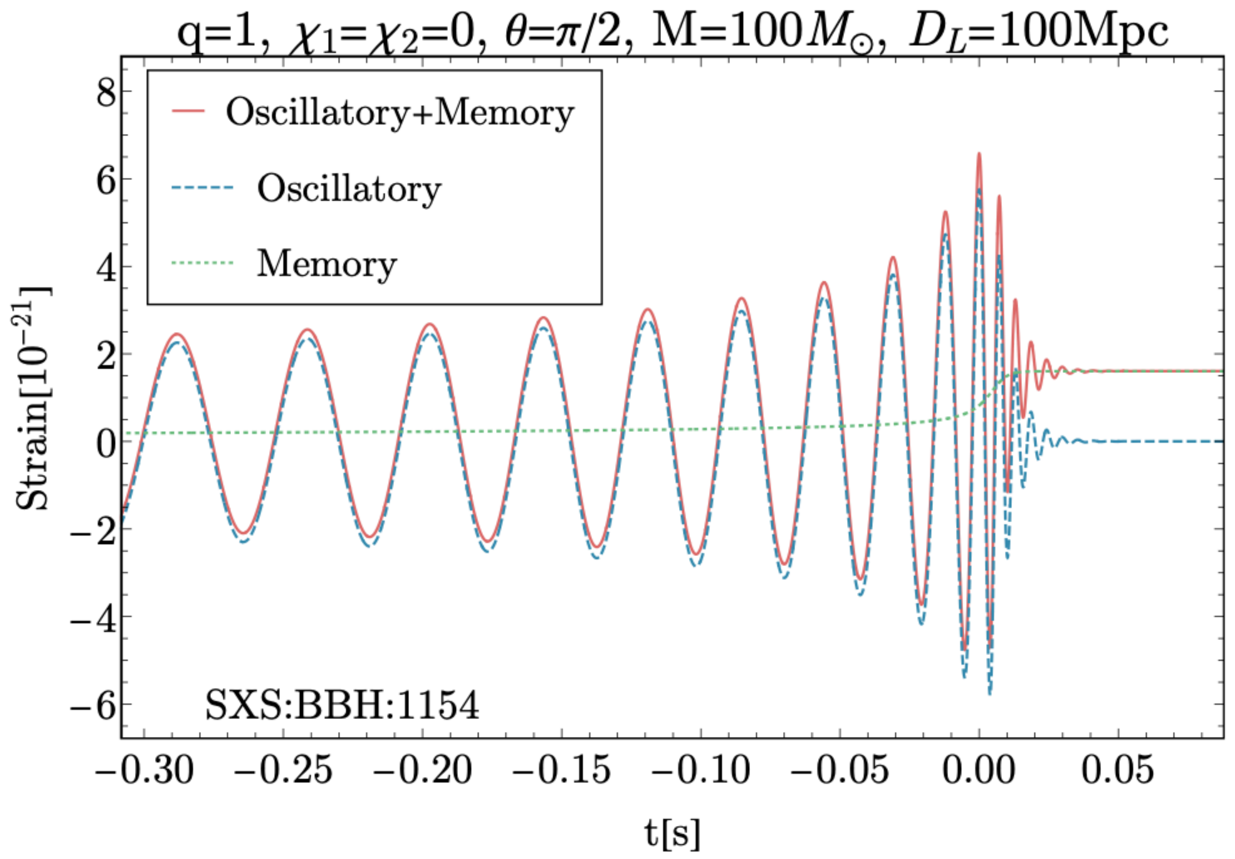

LISA Parameter Estimation

LDC + phenomxpy (GPU)

- Zero noise injection with HMs + (2,0)
- Duration ~70 days, $M = 1.8 \times 10^6 M_\odot$, $q = 1.25$
- SNR ~2500
- $f_{\rm low} = 10^{-4}$ Hz
- Sampler ptemcee with Fisher initialization

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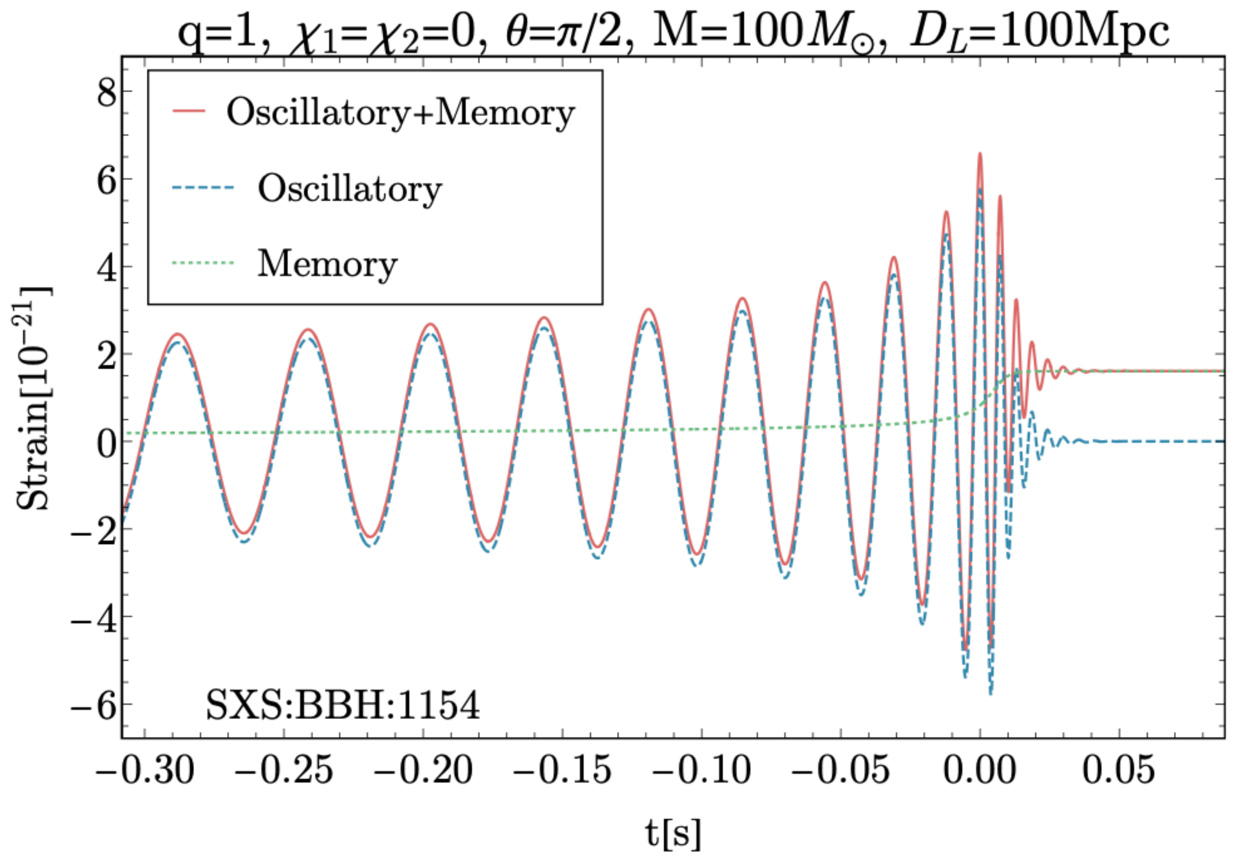

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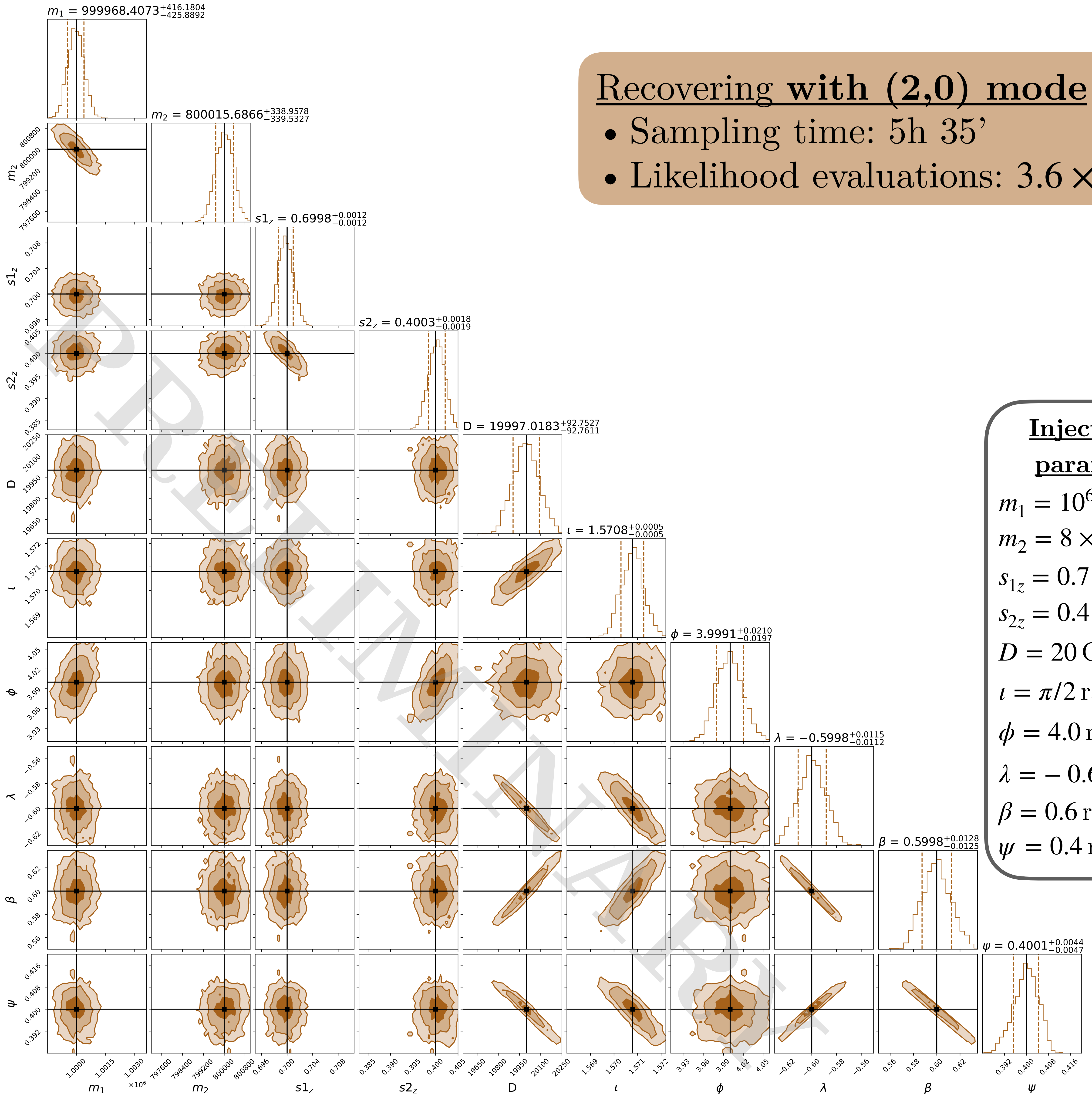

Recovering with (2,0) mode

- Sampling time: 5h 35'
- Likelihood evaluations: 3.6×10^5

Injection params.

$m_1 = 10^6 M_\odot$
$m_2 = 8 \times 10^5 M_\odot$
$s_{1z} = 0.7$
$s_{2z} = 0.4$
$D = 20$ Gpc
$\iota = \pi/2$ rad
$\phi = 4.0$ rad
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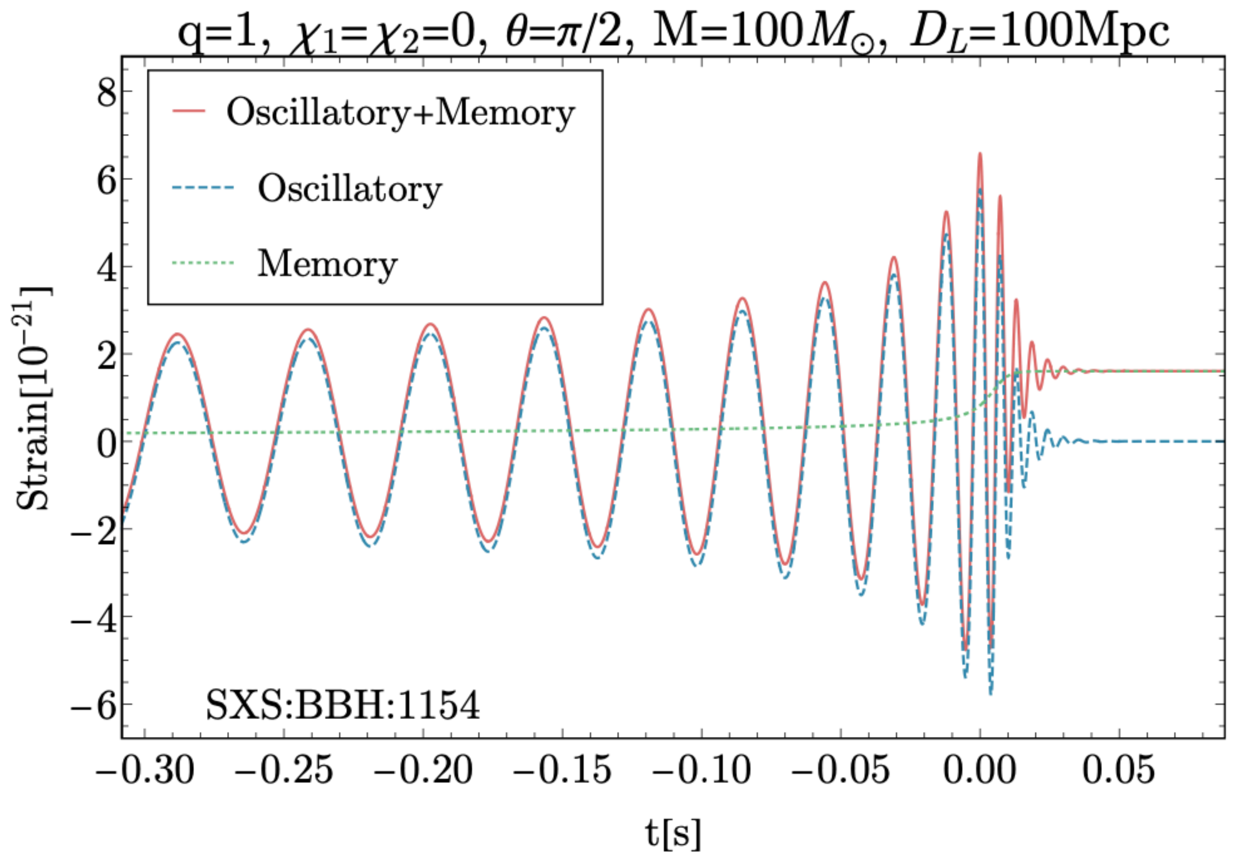

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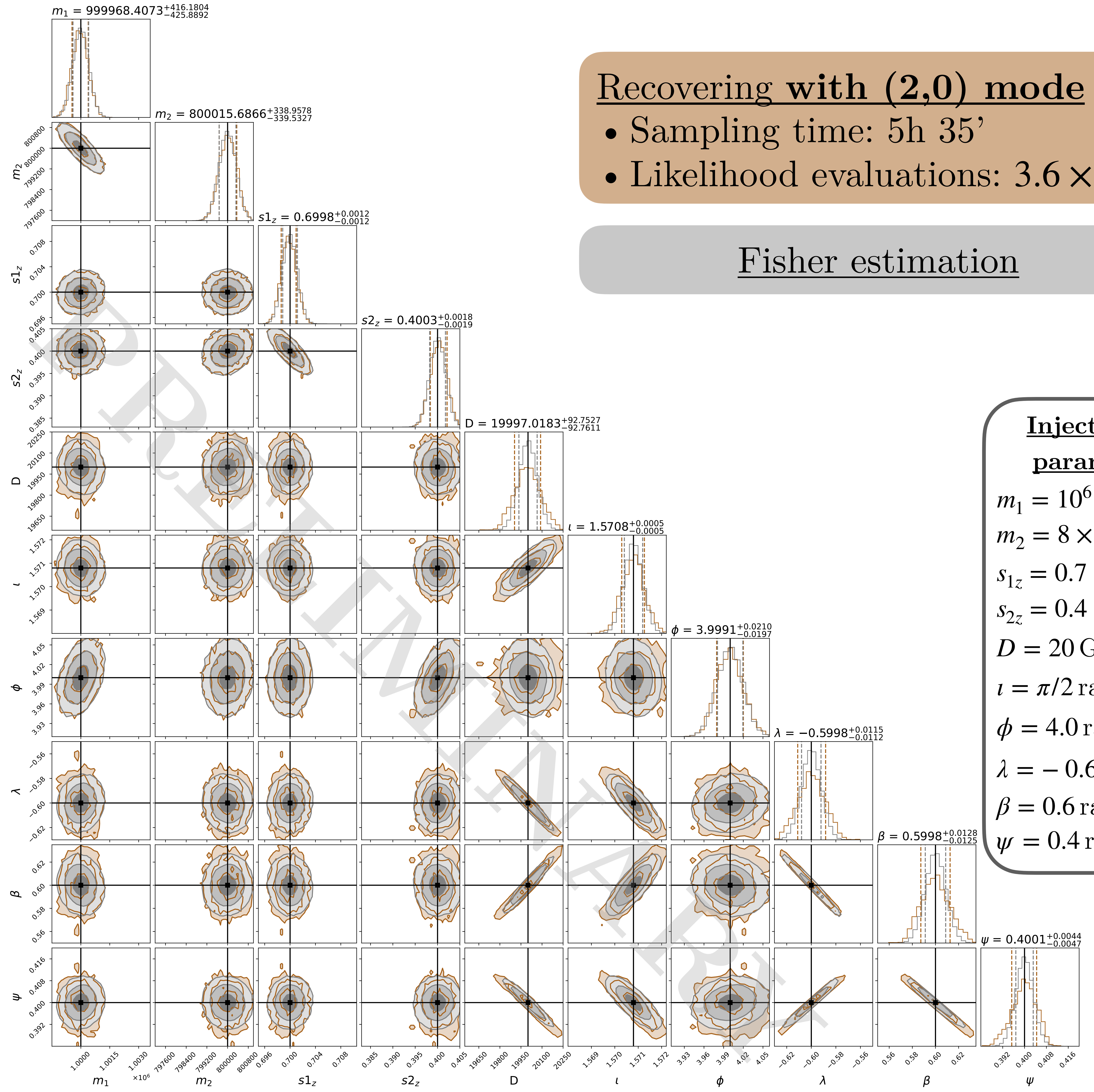

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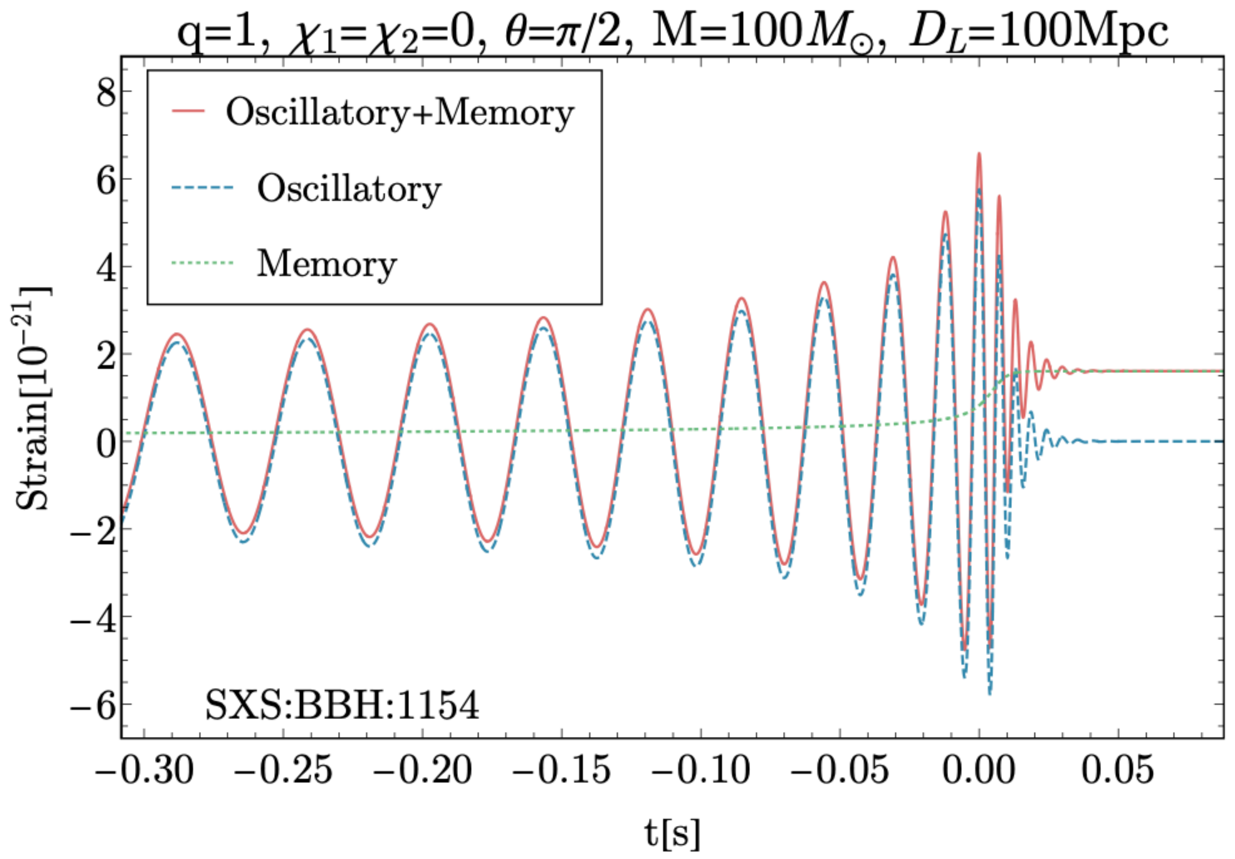

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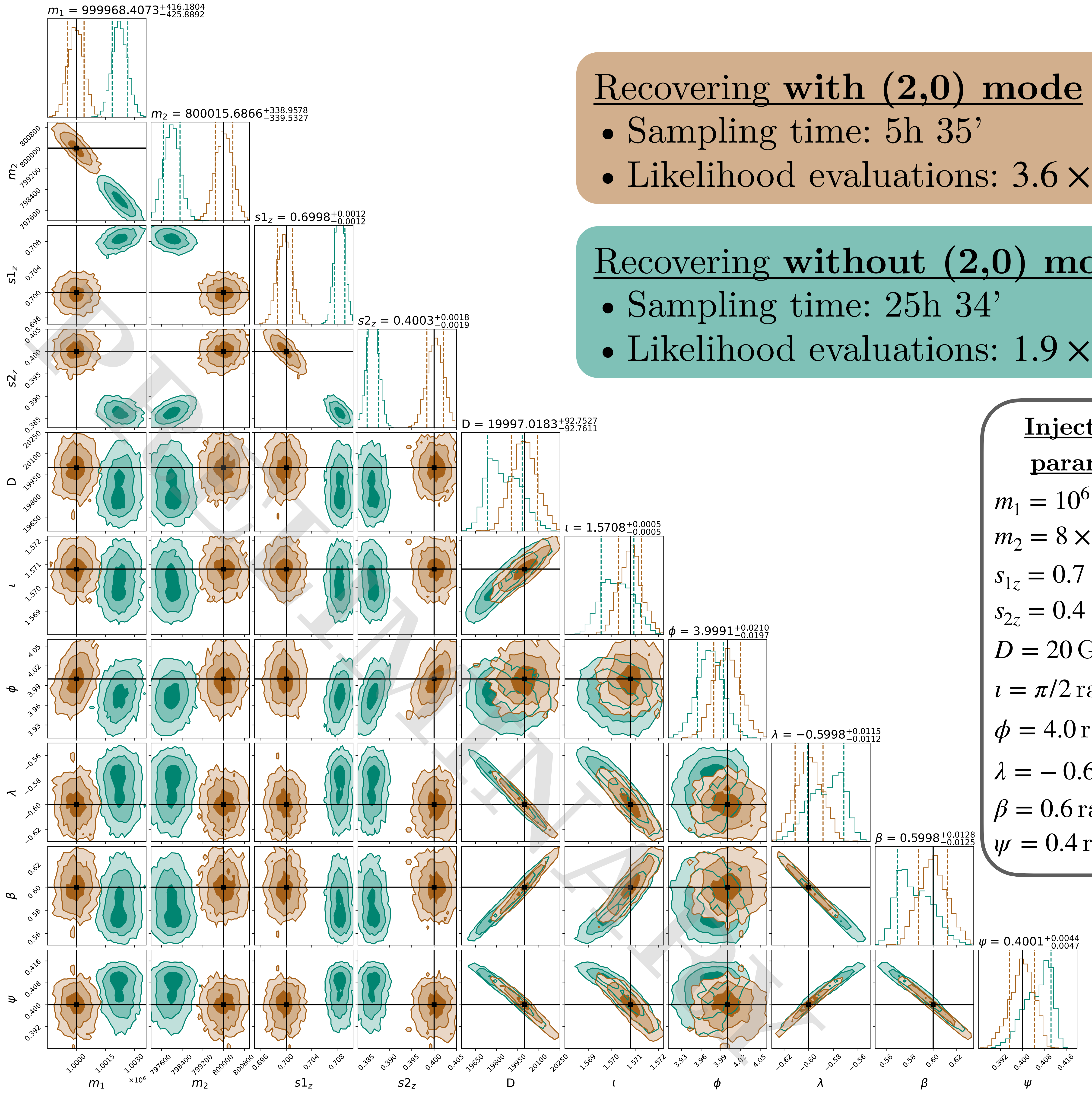

Recovering with (2,0) mode
- Sampling time: 5h 35'
- Likelihood evaluations: 3.6×10^5

Recovering without (2,0) mode
- Sampling time: 25h 34'
- Likelihood evaluations: 1.9×10^6

Injection params.

$m_1 = 10^6\, M_\odot$
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Conclusions

- Bring experience with different types of data analysis in the context of ongoing observation campaigns, interpretation of challenging events - interpretation of events in the real world can be challenging!
- Bring experience with workflows in a large collaboration: code development, reviews, bylaws, dealing with open data releases, ...
- Group is committed to further develop IMRPhenom models, including precession + eccentricity. Cover larger parameter space, increase speed and accuracy.
  - Current development is based on LALSuite and Cecilio's `phenomxpy`.
  - How can we make future waveform models run fast, e.g. on GPUs, integrate with fast LISA response.
- **Ongoing:** LISA analyses with the (2,0) mode

Acknowledgments

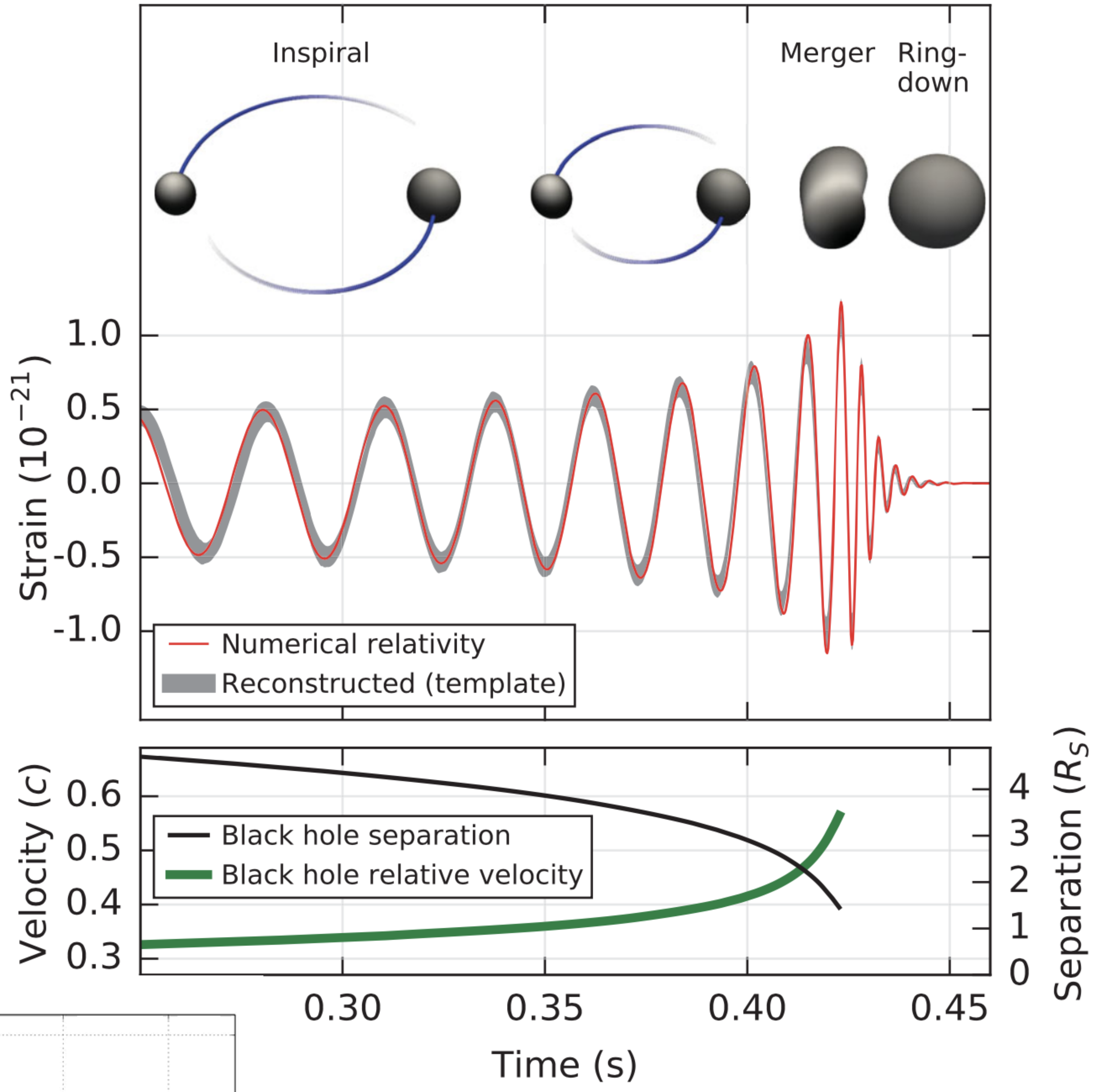
Jorge Valencia Gómez is supported by the Spanish Ministry of Universities (FPU22/02211).

This work was supported by the Universitat de les Illes Balears (UIB); the Spanish Agencia Estatal de Investigación grants PID2022-138626NB-I00, RED2022-134204-E, RED2022-134411-T, funded by MICIU/AEI/10.13039/501100011033, by the ESF+ and ERDF/EU; the MICIU with funding from the European Union NextGenerationEU/PRTR (PRTR-C17.I1); the Comunitat Autònoma de les Illes Balears through the Direcció General de Recerca, Innovació I Transformació Digital with funds from the Tourist Stay Tax Law (PDR2020/11 - ITS2017-006), the Conselleria d'Economia, Hisenda i Innovació grant numbers SINCO2022/18146 and SINCO2022/6719, co-financed by the European Union and FEDER Operational Program 2021-2027 of the Balearic Islands.

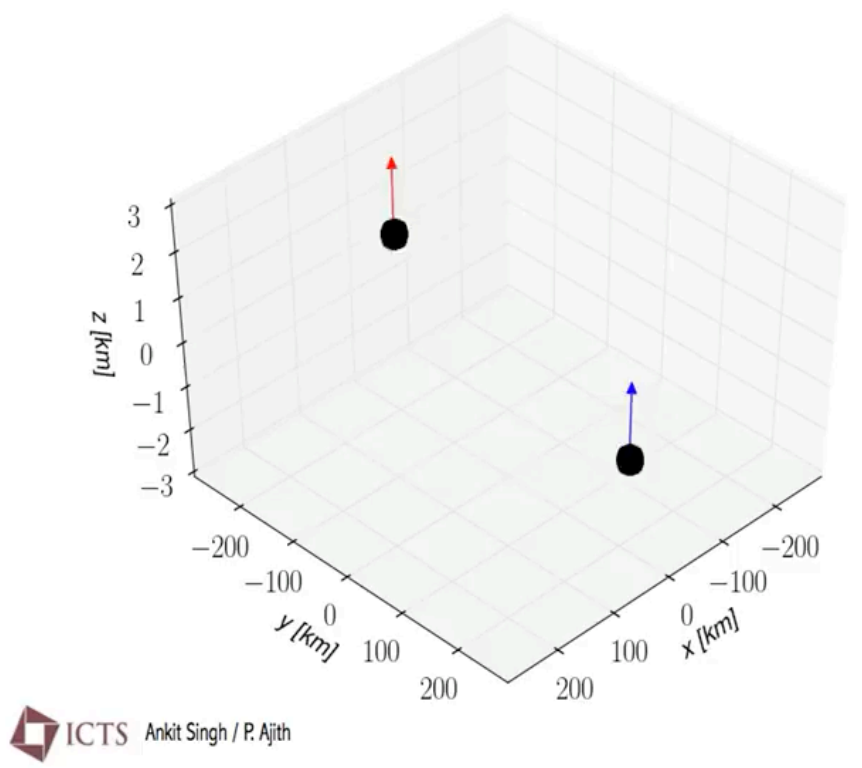
Backup slides

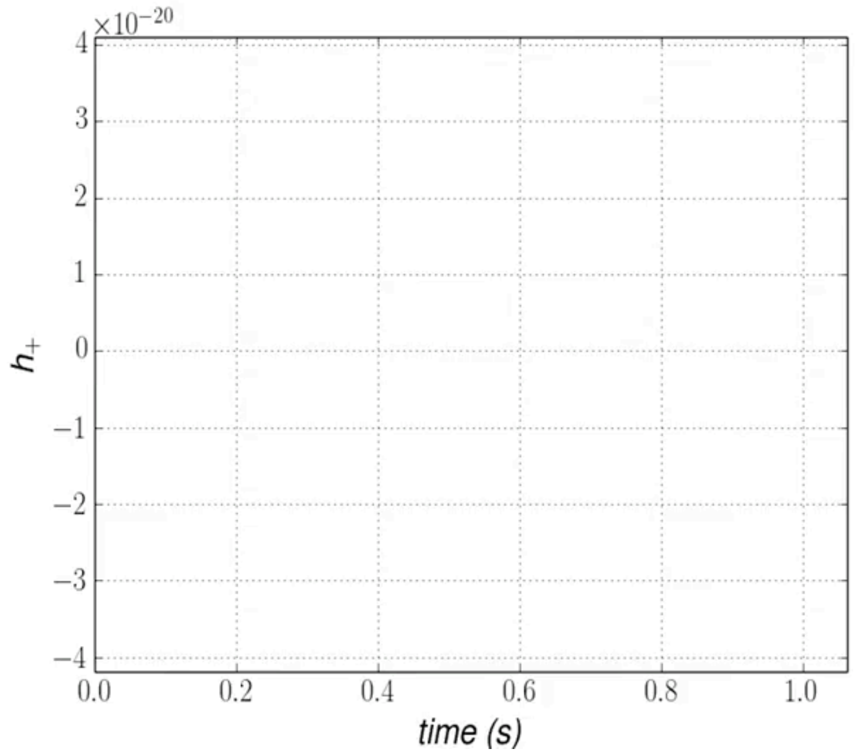
Waveform Modelling

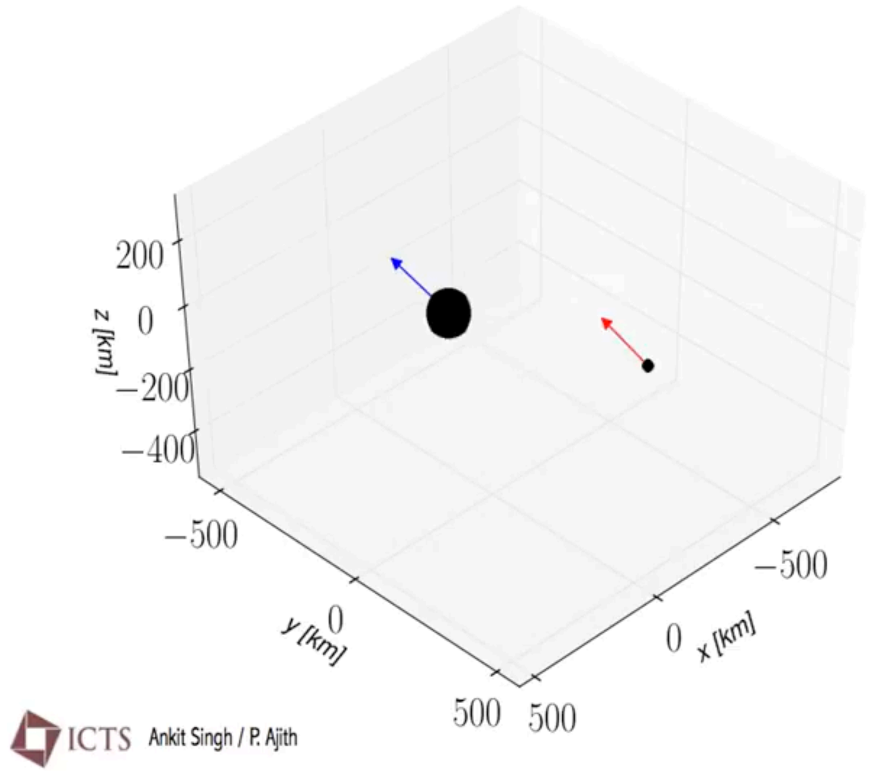
- **Binary Black Holes** (BBHs) are so far the **most detected** source of gravitational waves (GWs).
  - The evolution of the binary is divided into 3 stages:
  - Circular orbits: **8 intrinsic parameters**: $\{m_1, m_2, \vec{\chi}_1, \vec{\chi}_2\}$, (+2 if eccentric)
  - $0 \leq \chi_{1,2} \leq 1, \quad M = m_1 + m_2, \quad q = \dfrac{m_1}{m_2} \geq 1, \quad \eta = \dfrac{q}{(1+q)^2}.$
  - **7 extrinsic parameters**: $\{d_L, \lambda, \beta, \psi, \iota, t_c, \phi\}$.

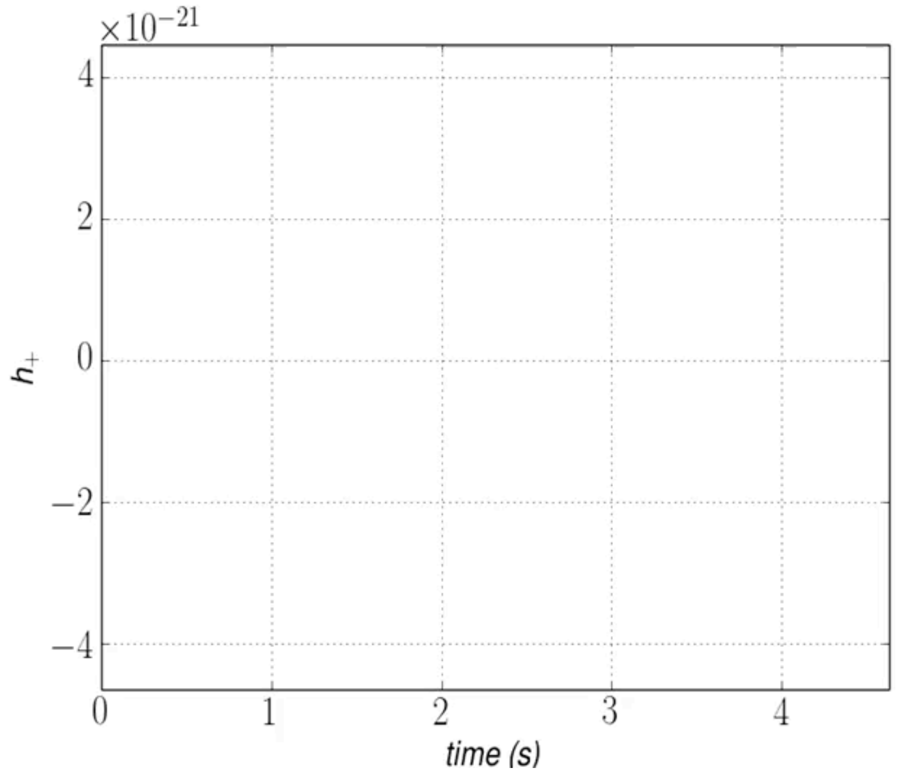


B. P. Abbott + (2016) [Phys. Rev. Lett. 116, 061102]



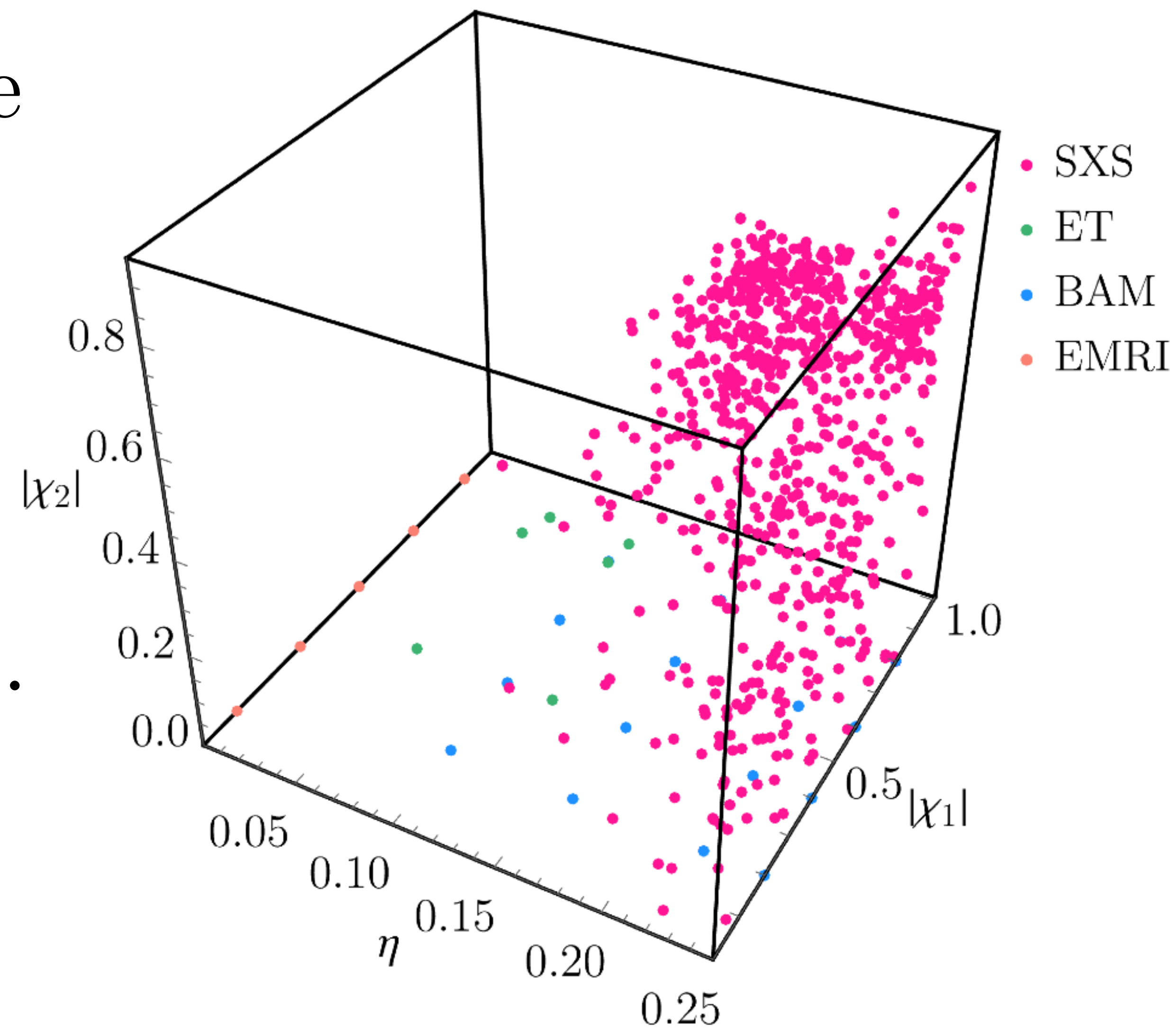






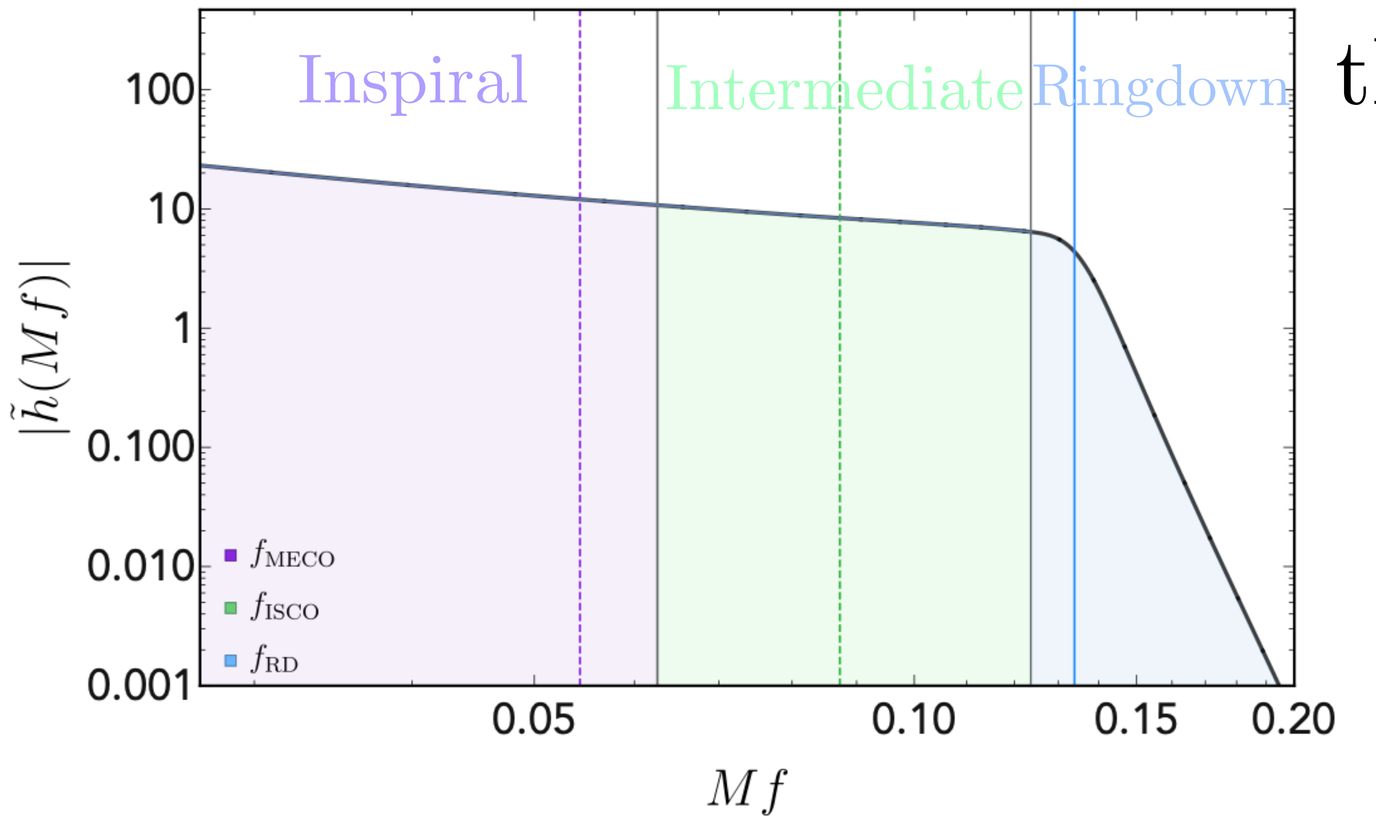
WAVEFORM MODELLING

Lluc Planas + (2024) [Phys. Rev. D 109, 124028]



Waveform models are essential to understand the GW signals emitted from the coalescence of compact binaries.

- **Post-Newtonian (PN) theory**: expands Newtonian equations in powers of (v^2/c^2). **Less accurate close to the merger**.
- **Numerical relativity (NR):** crucial to describe the **merger and ringdown**. Currently the most accurate descriptions of GWs. Catalogs: SXS, ET, BAM ...



G. Pratten + (2020) [Phys. Rev. D 102, 064001]

Efficient waveform models that cover the **full evolution** are needed to reconstruct the source parameters.

- **Effective one-body models (EOB)**: reformulate the two-body problem in GR into an effective one-body problem.
- **Surrogate models (NRSur)**: modern interpolation techniques for datasets of numerical waveforms.
- **Phenomenological models (IMRPhenom)**: use piecewise closed-form analytical expressions to model the three stages.

Final State Fits

$$\Delta E = E_{\rm rad}^{\rm prec}(\eta,\chi_1,\theta_1) - E_{\rm rad}^{\rm AS}(\eta,\chi_1\cos(\theta_1),\chi_2\cos(\theta_2)=0)$$

$$\overline{\Delta E} = \Delta E - \Delta E_{\rm EMR}$$

$$\begin{aligned}\overline{\Delta E}(\eta,\chi_1,\theta_1) = &\ \eta^3\chi_1\,[0.759123\sin(\theta_1) - 2.33392\sin(2\theta_1)] + \\ &\ \eta^3\chi_1^2\,[6.51059\sin(\theta_1) + 7.06906\sin(2\theta_1)] + \\ &\ \eta^4\chi_1\,[-11.7873\sin(\theta_1) + 22.364\sin(2\theta_1)] + \\ &\ \eta^4\chi_1^2\,[-37.0594\sin(\theta_1) - 63.3841\sin(2\theta_1)] + \\ &\ \eta^5\chi_1\,[35.0427\sin(\theta_1) - 51.36\sin(2\theta_1)] + \\ &\ \eta^4\chi_1^2\,[-37.0594\sin(\theta_1) - 63.3841\sin(2\theta_1)]\,.\end{aligned}$$

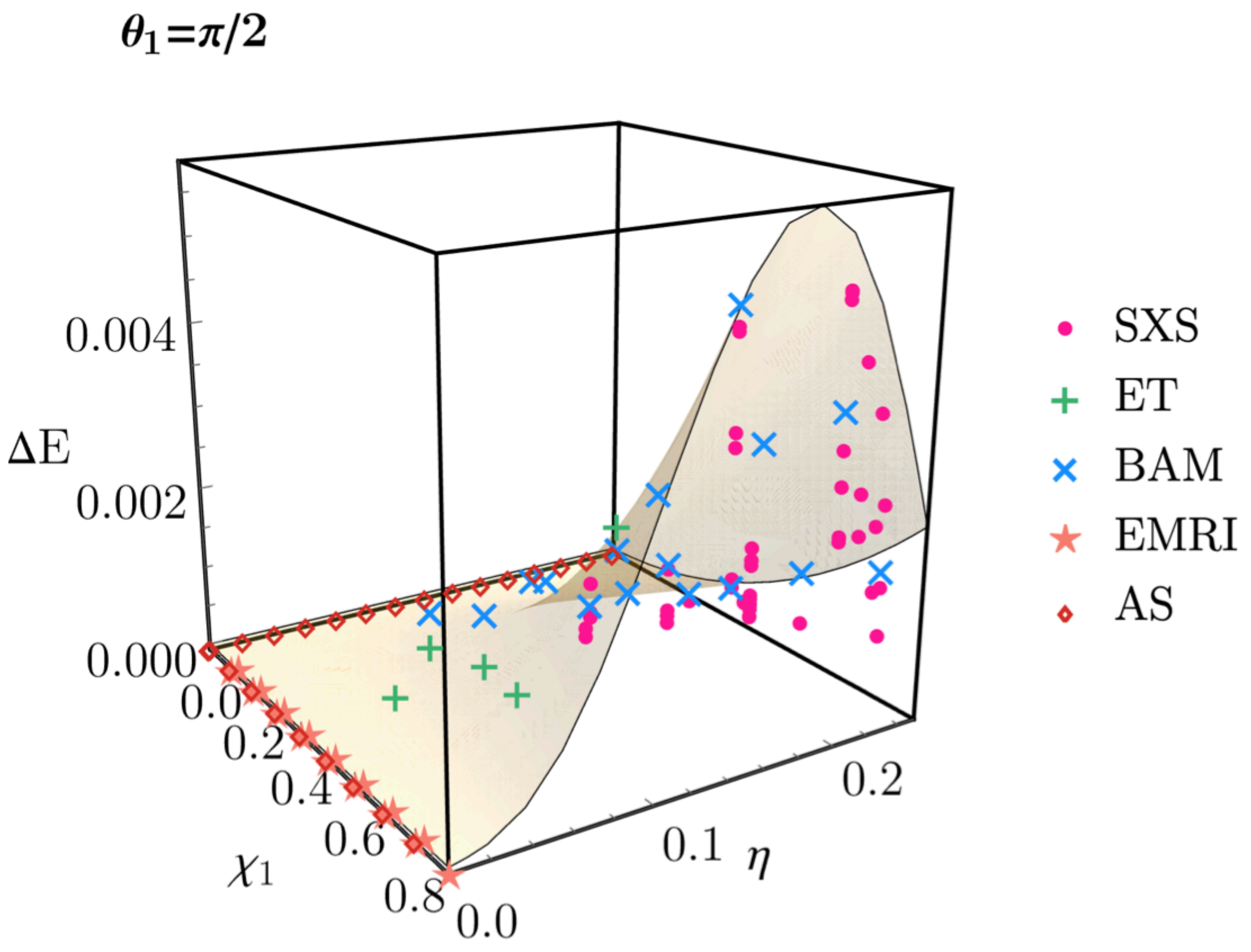


FIG. 10. Numerical evaluation of ΔE as defined in Eq. (3.1), obtained from the parameterized fit $\overline{\Delta E}$ (3.6) and $\Delta E_{\rm EMR}$, at a fixed spin orientation $\theta_1 = \pi/2$, while varying the mass ratio η and the spin magnitude χ_1. The figure includes the single spin precessing simulations shown in Fig. 2 that fall into this subspace.