CSIC Institute of Space Sciences

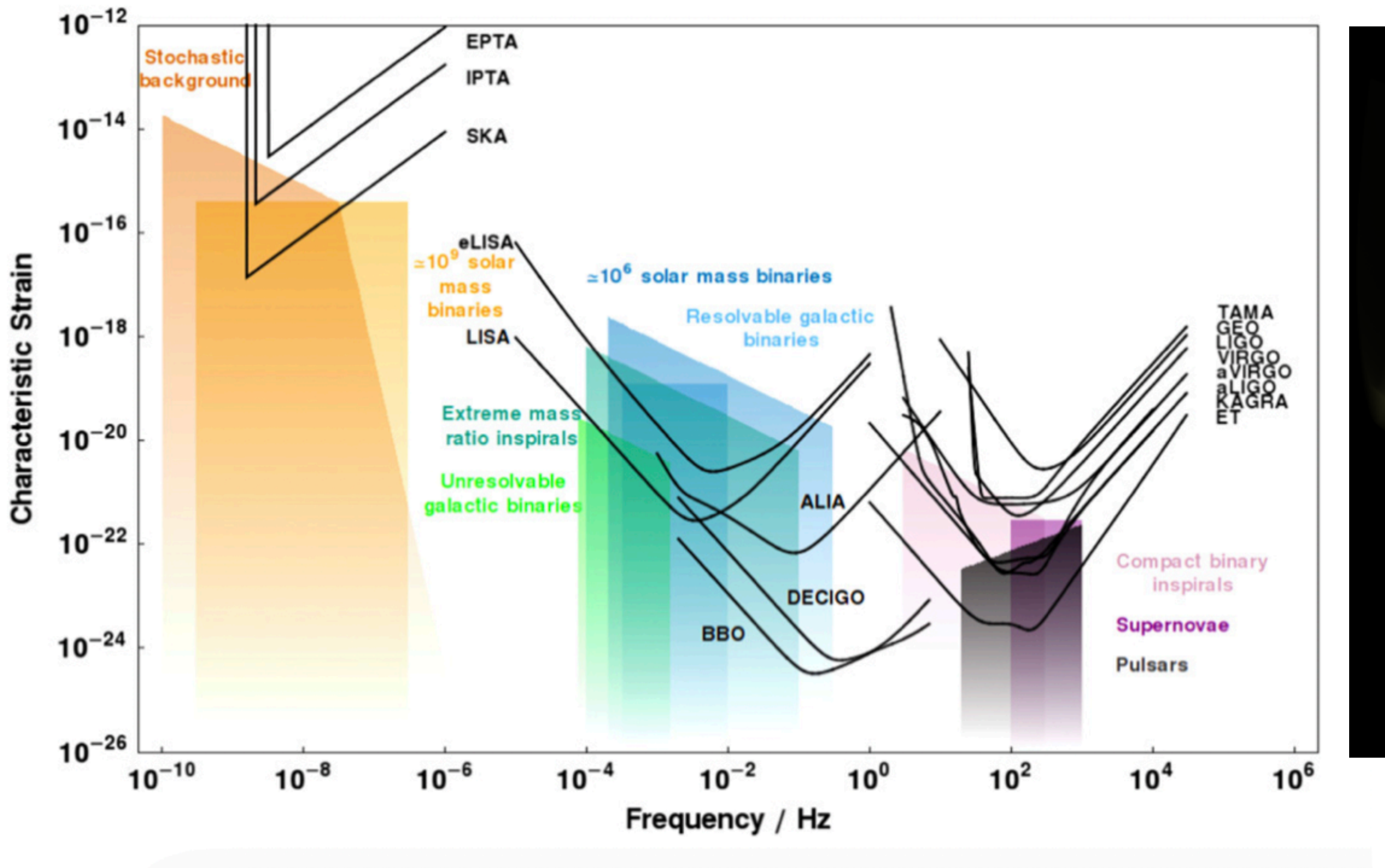
EXCELENCIA MARÍA DE MAEZTU

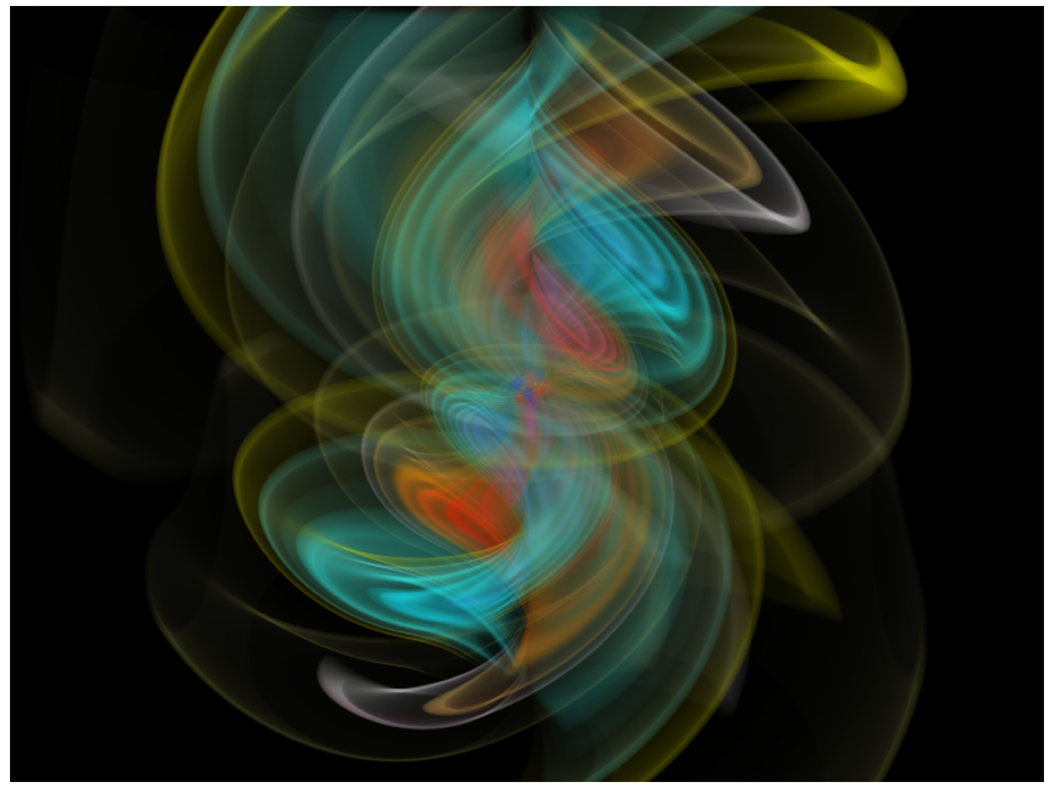
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
A WAY TO MAKE EUROPE

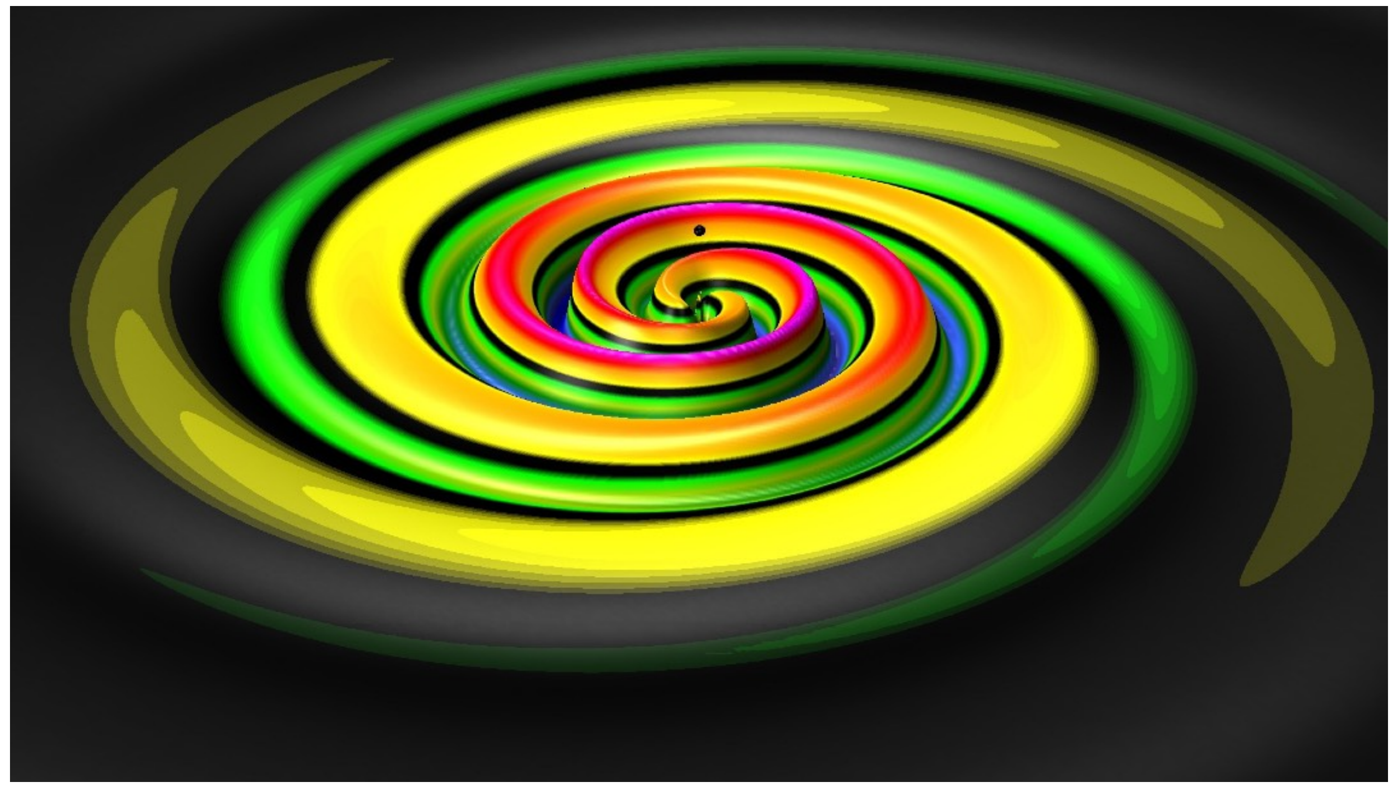
IEEC
Institut d'Estudis Espacials de Catalunya

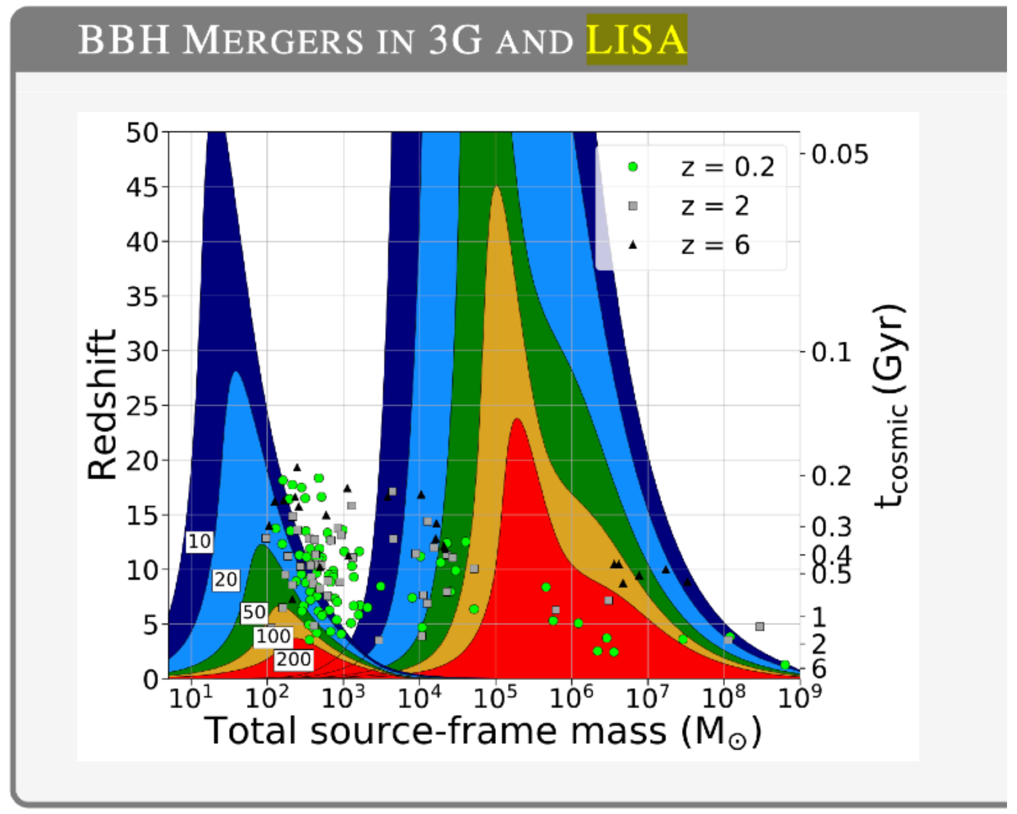
The LISA Distributed Data Processing Center and waveform modelling

Sascha Husa, Institute of Space Sciences









LISA Spain Meeting - 15/10/2024

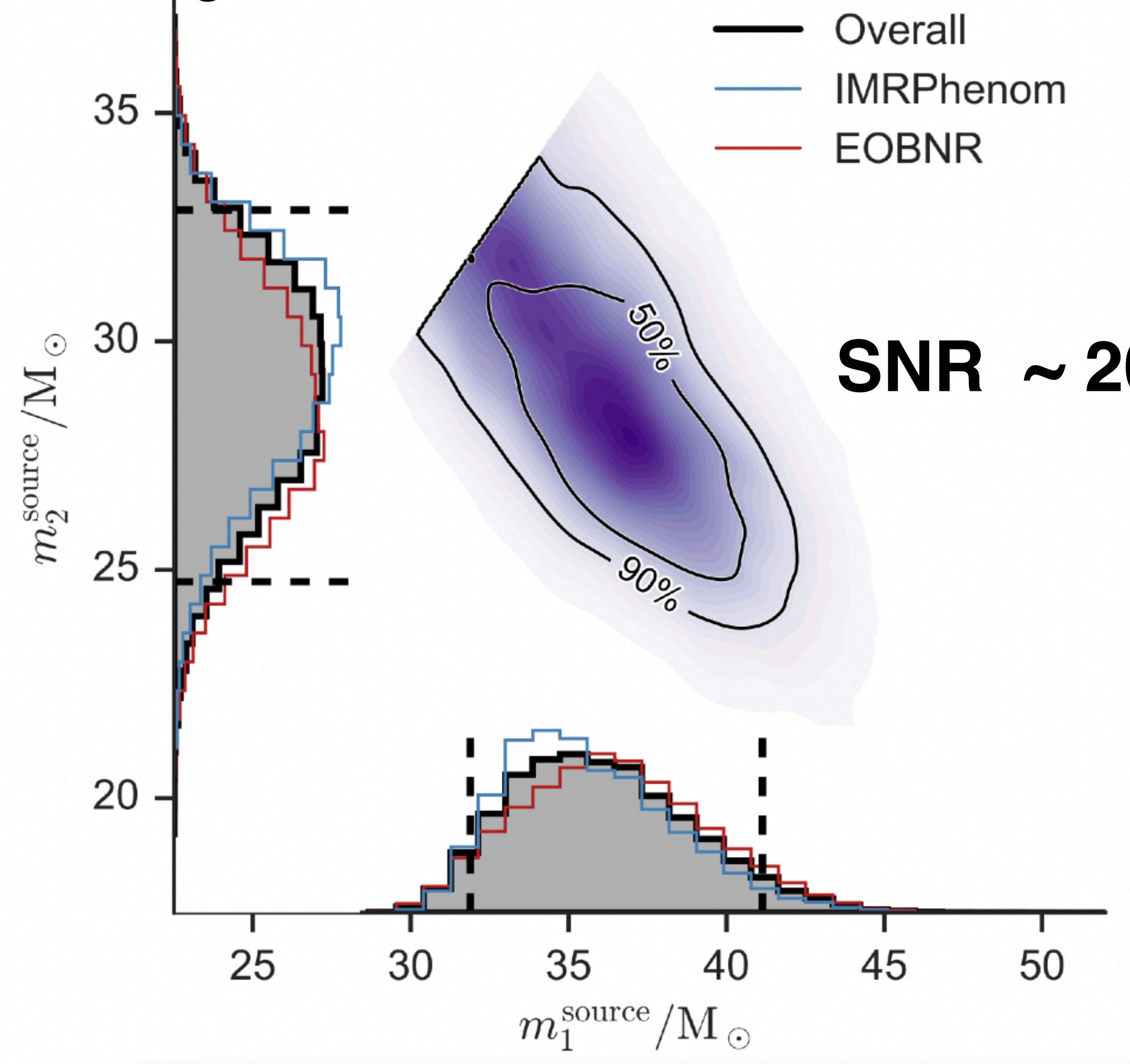
Universitat de les Illes Balears

IAC3 Institute of Applied Computing & Community Code.

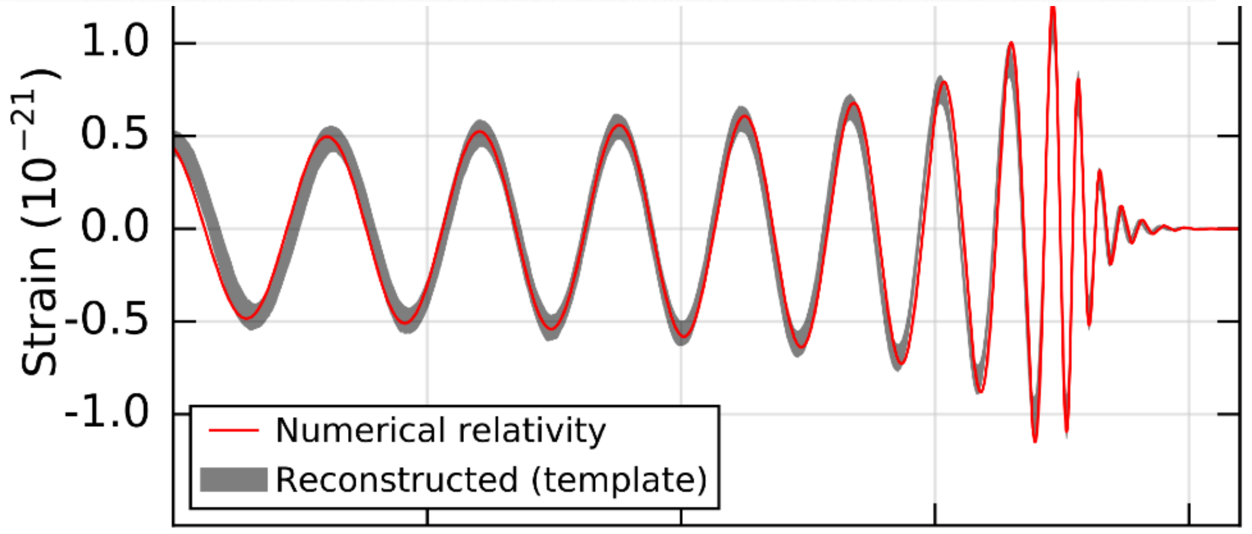
Why waveform modelling?

- To **identify the sources of GW signals:**
  compare data with waveform models.
- LVK: split into searches + Bayesian Parameter Estimation (PE) for CBC
  -> see Yumeng's talk for waveform agnostic time-frequency methods
- LISA: rapid alerts ("searches + basic PE") + Global fit
- Also:
  - Train simulation based inference models.
  - Evaluate data analysis pipeline performance with injections.
  - Explore what can be measured => shape science cases.
  - Source modelling beyond waveforms: EM counterparts …
- **Models need to be fast and accurate, need to understand systematic errors.**
- **Status and requirements: white paper - arXiv:2311.01300, 239 pages.**

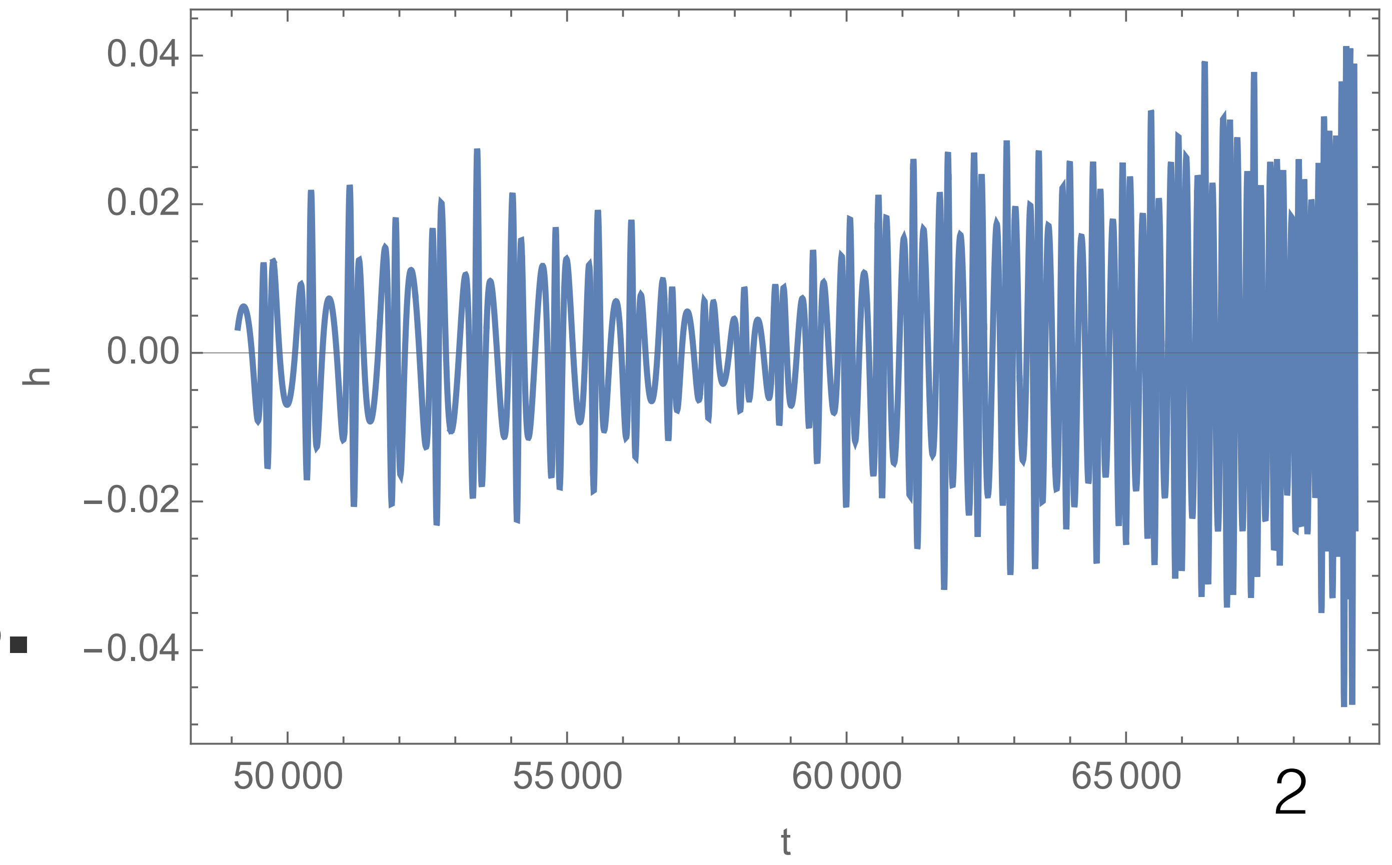
LIGO+Virgo, PRL2016: GW150914



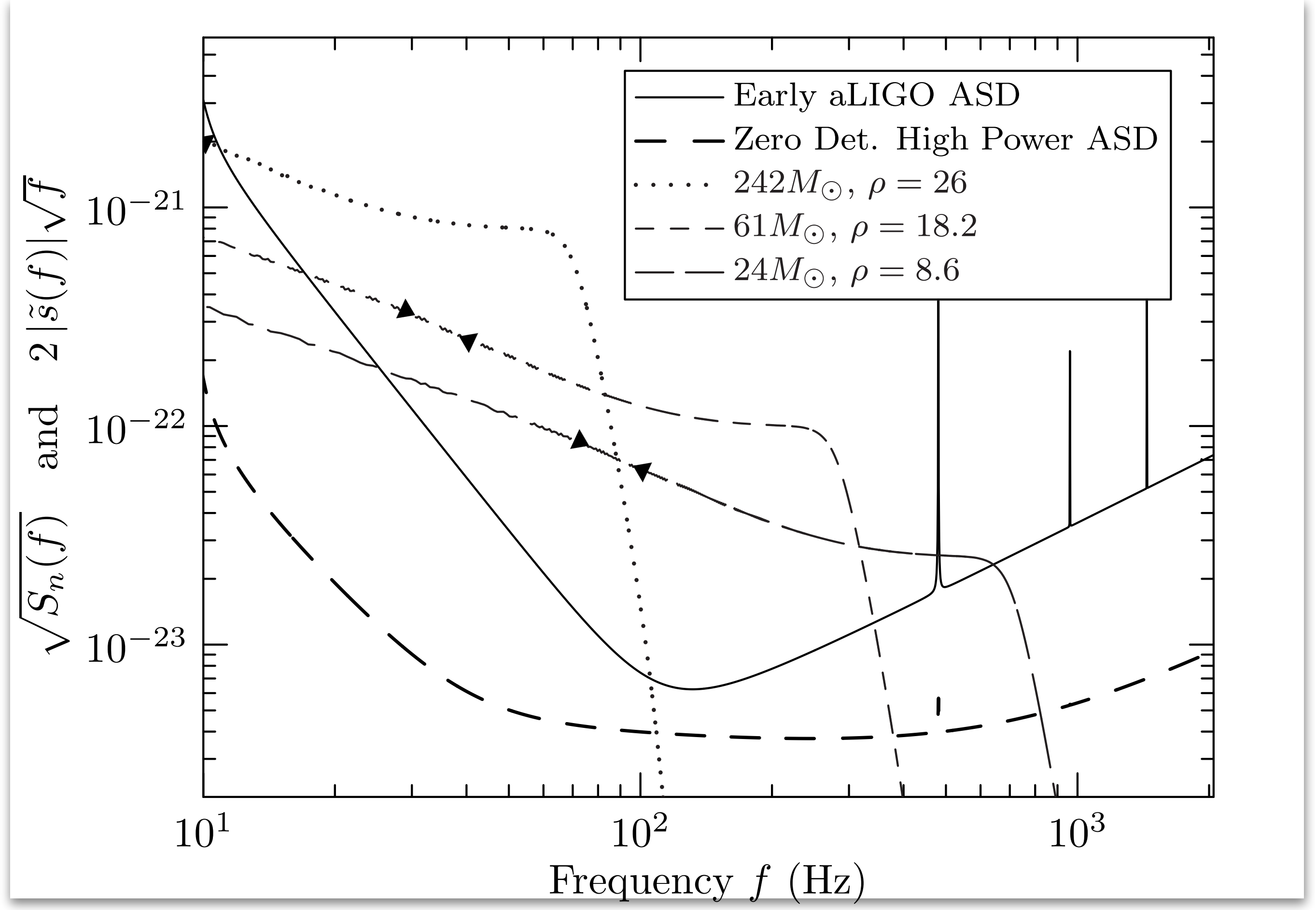
SNR ~ 20.



Not all CBC waveforms are simple.



What waveforms do we need?

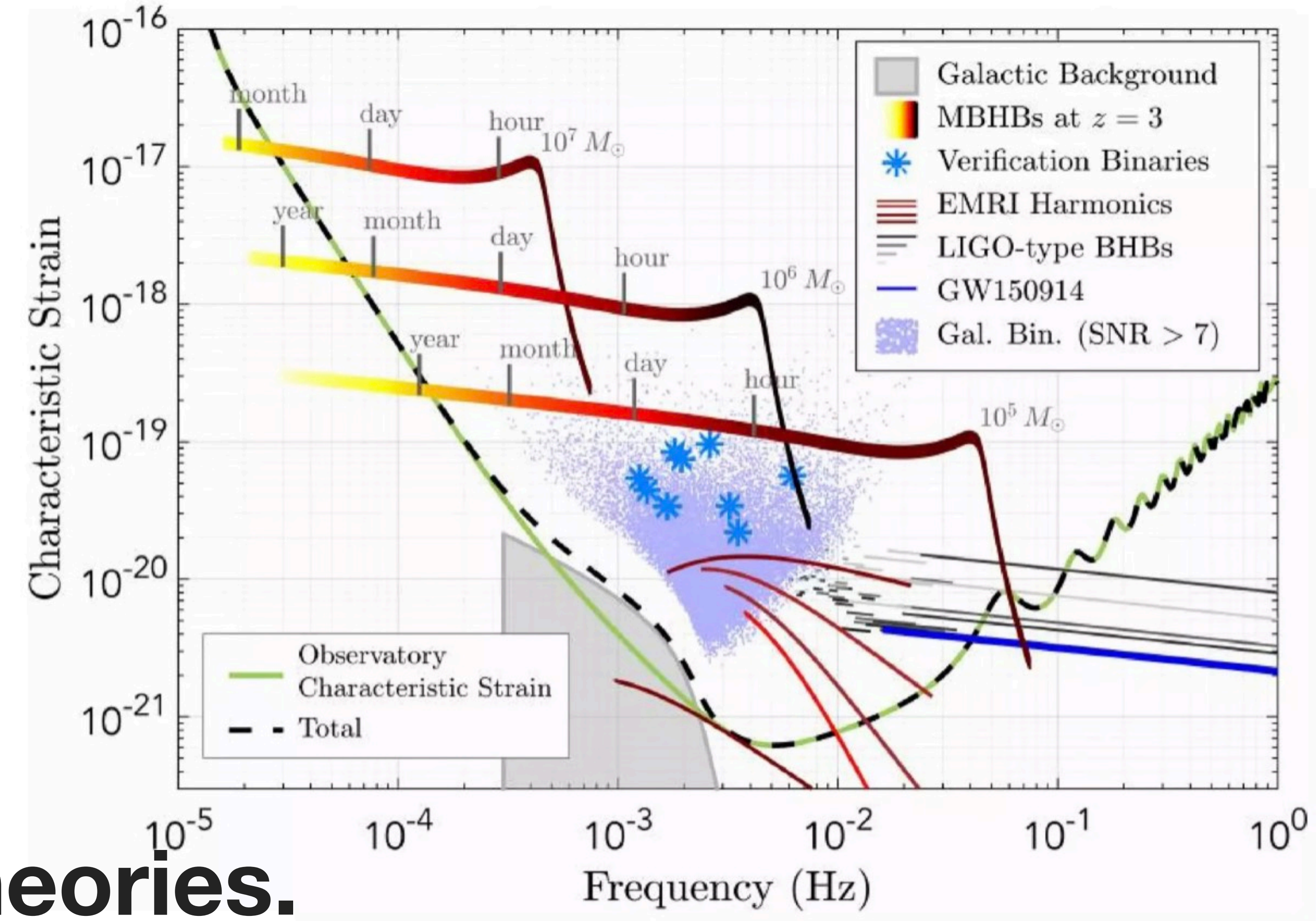


- **Coalescence of massive black hole binaries (MBHB):**
  - scale LVK waveforms for higher mass (for free).
  - much higher accuracy: **max SNR ~ 10 000**
    => small statistical errors.
  - higher complexity: Eccentricity + spin precession more important.
  - larger bandwidth => longer waveforms
    => more expensive evaluation

$$T_{coalescence} \approx \eta^{-1} f_{initial}^{-8/3} M \qquad \eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$$

CBC waveforms ~1000 times longer for LISA/3G

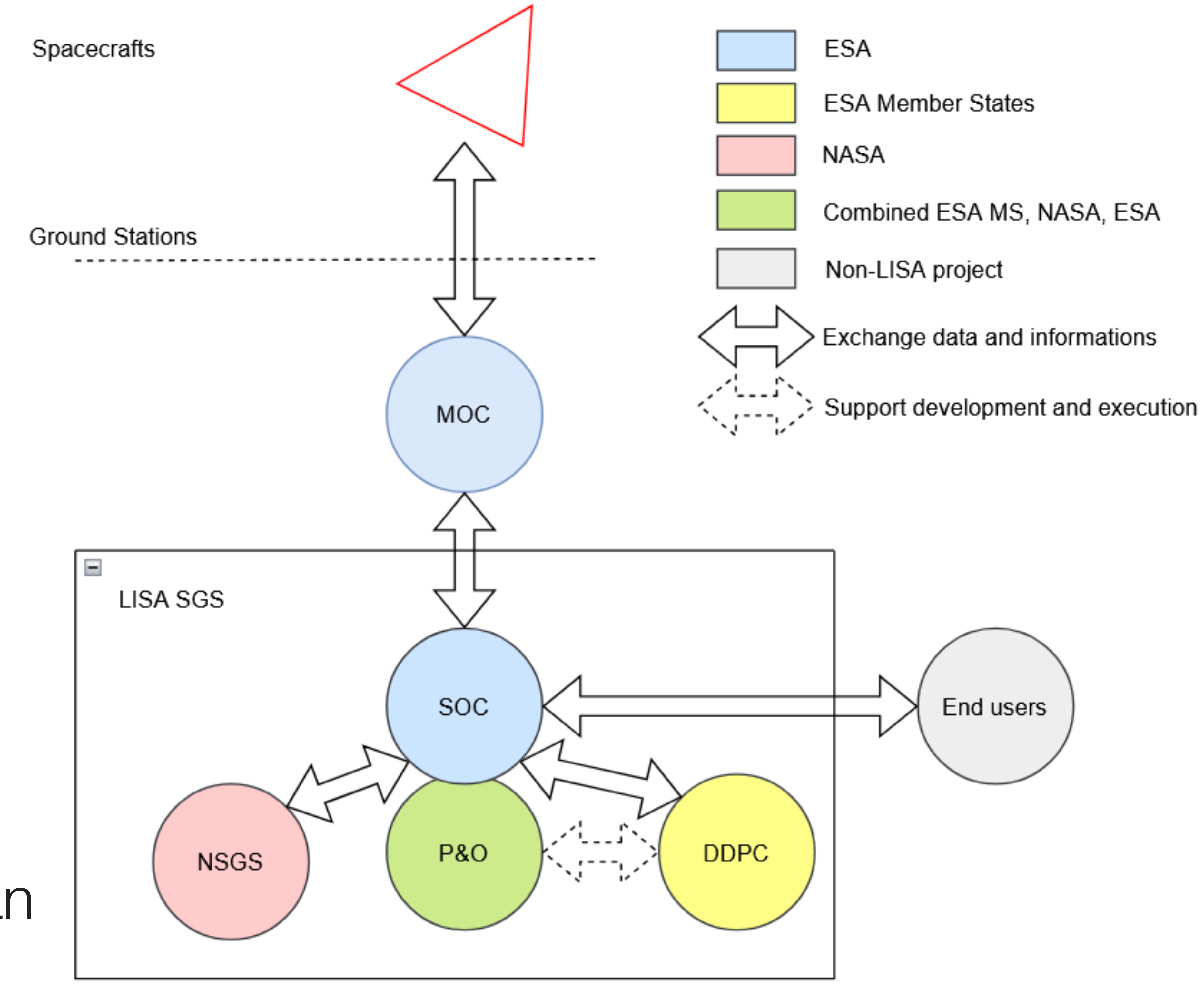
- **EMRIs / IMRIs: use self-force perturbative approach.**
  - WFs are extremely long and extremely complex.
- **Stellar Object Black Hole Binaries:**
  post-Newtonian WFs sufficient, but extremely long. Multi-band!
- **Galactic Binaries (GB): continuous waves, many sources.**
- **Also consider: Environmental effects, beyond GR, exotic physics.**
- **Cosmic Strings, other transients?**
- **Cosmology (Cosmo): spectra of stochastic signals from different theories.**



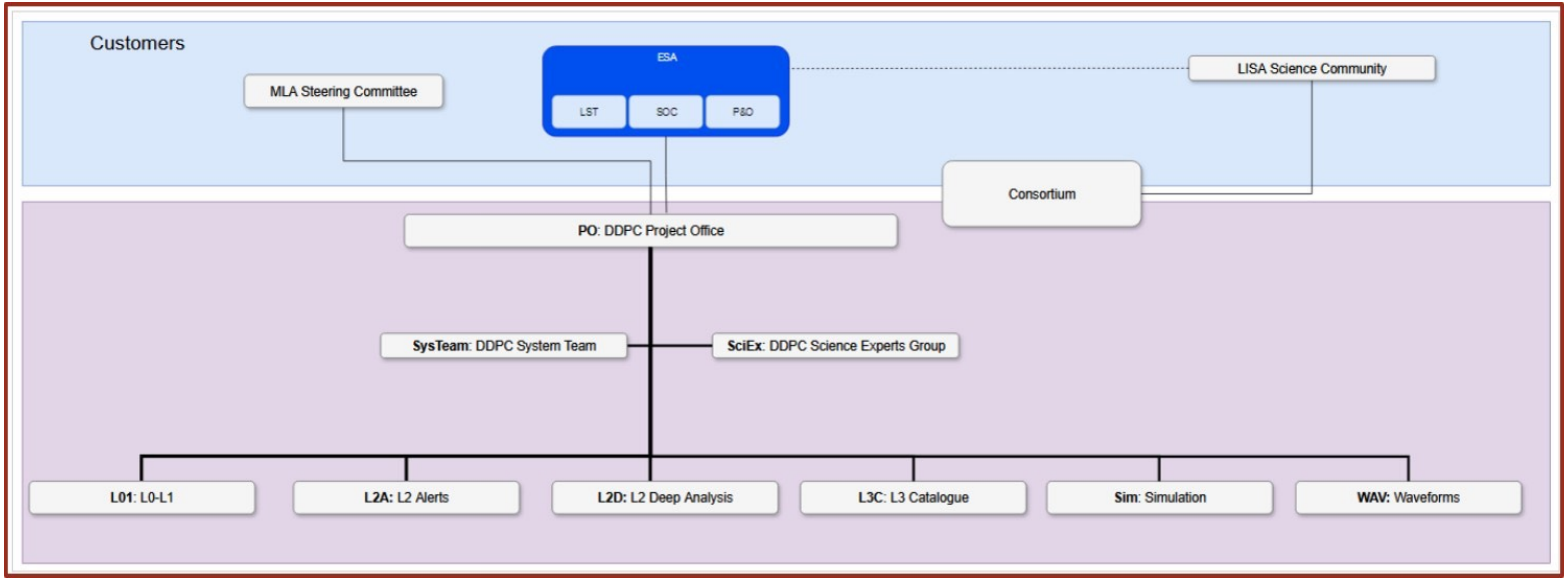
- Mission adopted - time for concrete plans to develop LISA waveform codes.

LISA DDPC - Distributed Data Processing Center - Mission

- Part of the Science ground Segment (SGS), **distributed entity - ESA member states.**
- Member state commitments: **Multi-lateral agreement (MLA)**
- **Functions:**
  - design + validate the pipelines reconstructing virtual interferometers (noise suppression, time synchronisation, …), model noise.
  - design + validate the alerts pipelines (executed by SOC @ ESA).
  - **perform the extraction of GW sources from the data**
    develop + execute global fit pipelines ~ 200 x 10^6 CPU hrs/yr.
    - = compare data with accurate and computationally efficient models of the signals = “waveform models”, with the techniques of Bayesian statistics, matched filtering, machine learning, …
    - integrate waveform models developed by the LISA consortium in the global fit pipelines
      waveform models = computationally expensive kernel
    - produce source catalog.
- Paralleled by the NASA ground segment - will perform an "independent" analysis - cross-check + consolidate final products.

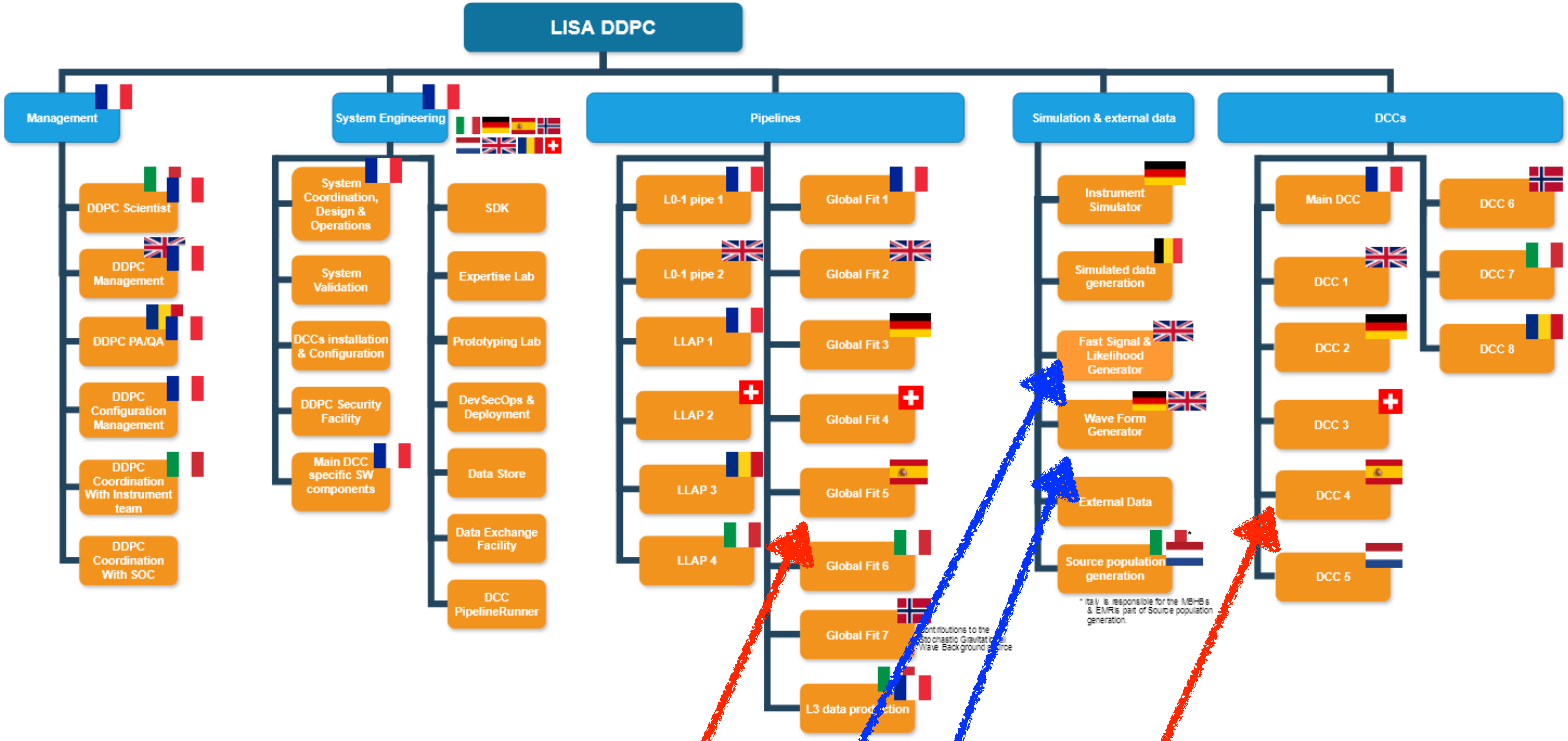


DDPC organisation



- Overall management is organised by the project office (PO).
- Computing: DCC - data computing centers. Spain: Ongoing talks with BSC and PIC.
- Work is organised in 8 coordination units (CUs):
  - 4x Data processing pipeline: L01 (TDI data), L2a (alerts) + L2D (global fit), L3C (catalogue)
  - 2x Scientific Support: SIM (instrument + data simulation), WAV (waveform generators)
  - 2x Software engineering support: SysTeam, Scientific Experts group (CU leads)

DDPC commitments in the MLA



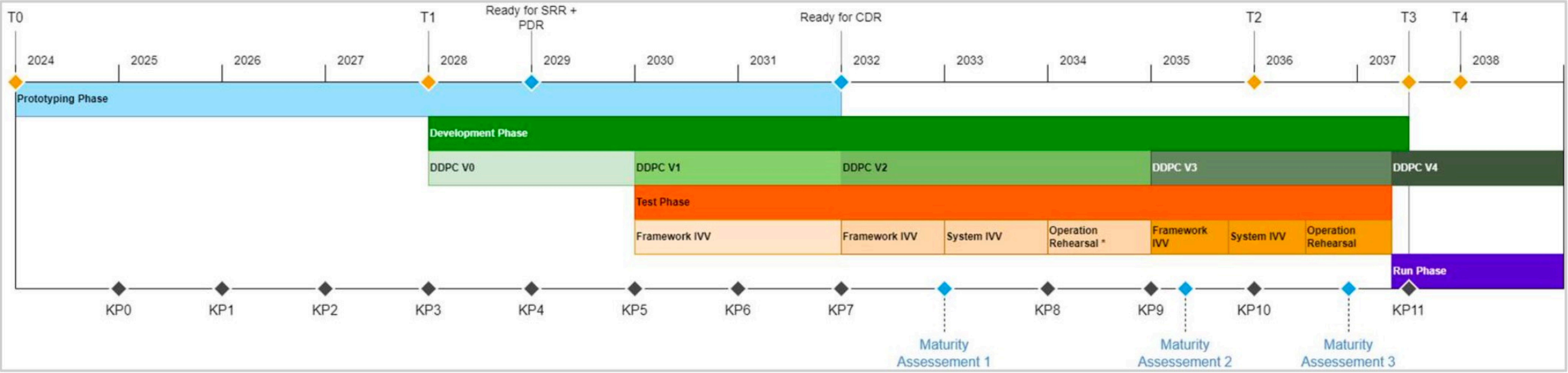
- MLA countries:
  - France
  - Belgium
  - Germany
  - Italy
  - Netherlands
  - Norway
  - Romania
  - Spain
  - Switzerland
  - UK

- Spain MLA: Global fit pipeline, Distributed computing center
- Spain currently in kind: waveforms

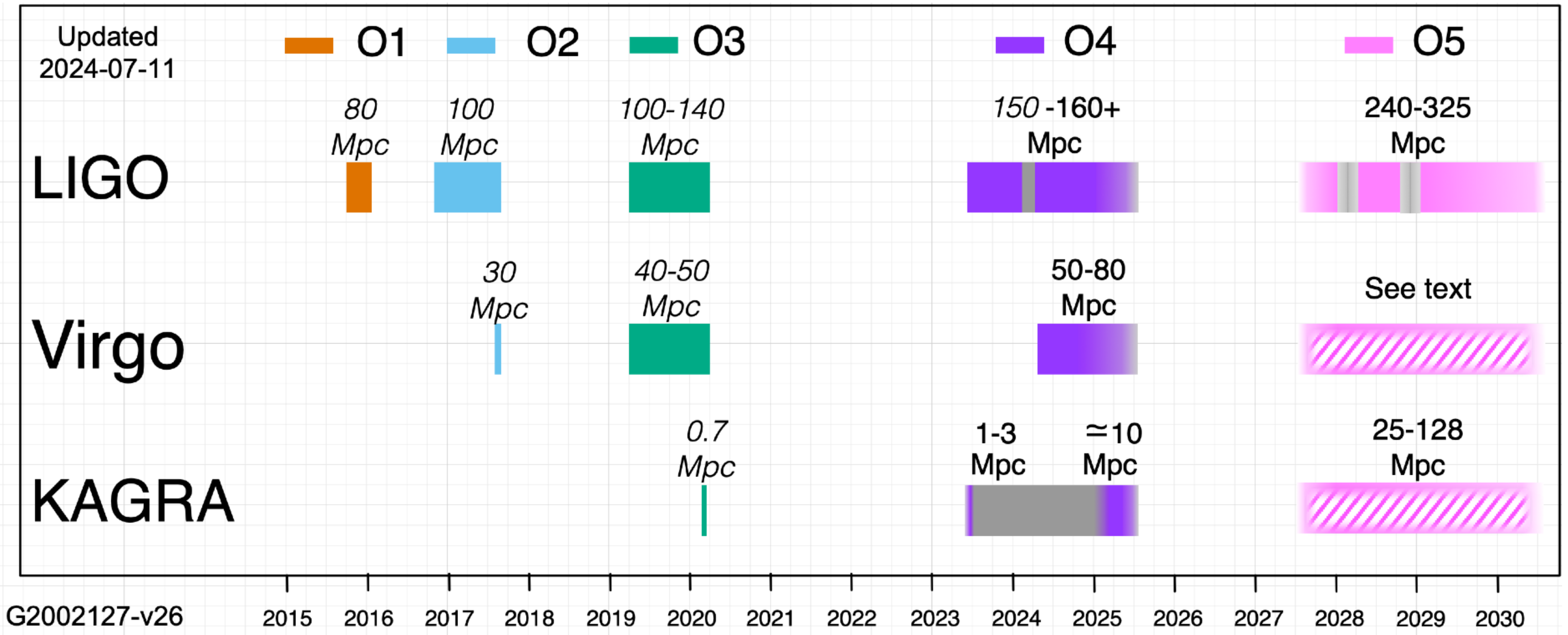
DDPC membership

- **Membership procedure is currently being drafted.**
- Basic ideas:
    - Country should be part of the MLA. Exceptions?
    - Institution should be recognised by the MLA country.
    - Researcher should be part of the “LISA consortium”/LISA mission directory.
    - Accepted by coordination unit lead(s).
- Members can be funded by national space agencies to be part of DDPC, or contributions “in kind”.
    - Contributors “in kind” should accept commitment.
    - Benefits of being part of the DDPC still need to be regulated. Authorship - of what? Access to data?

DDPC time line

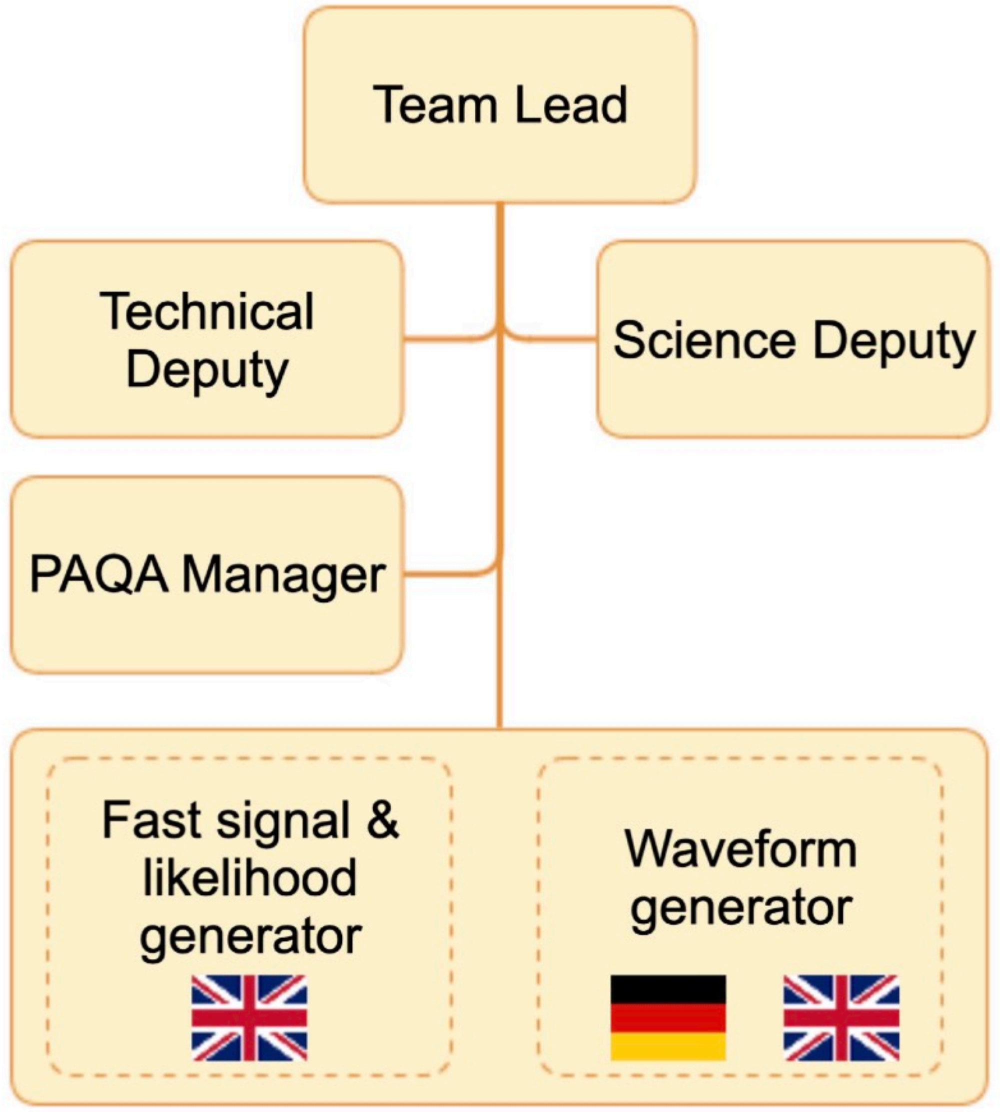


- First prototyping phase until the end of 2027.
- Second prototyping phase until end of 2031 in parallel
- Waveform development by LISA consortium
  + driven by LVK and 3G needs.
- MBHB: build upon LVK waveforms + WF generator.

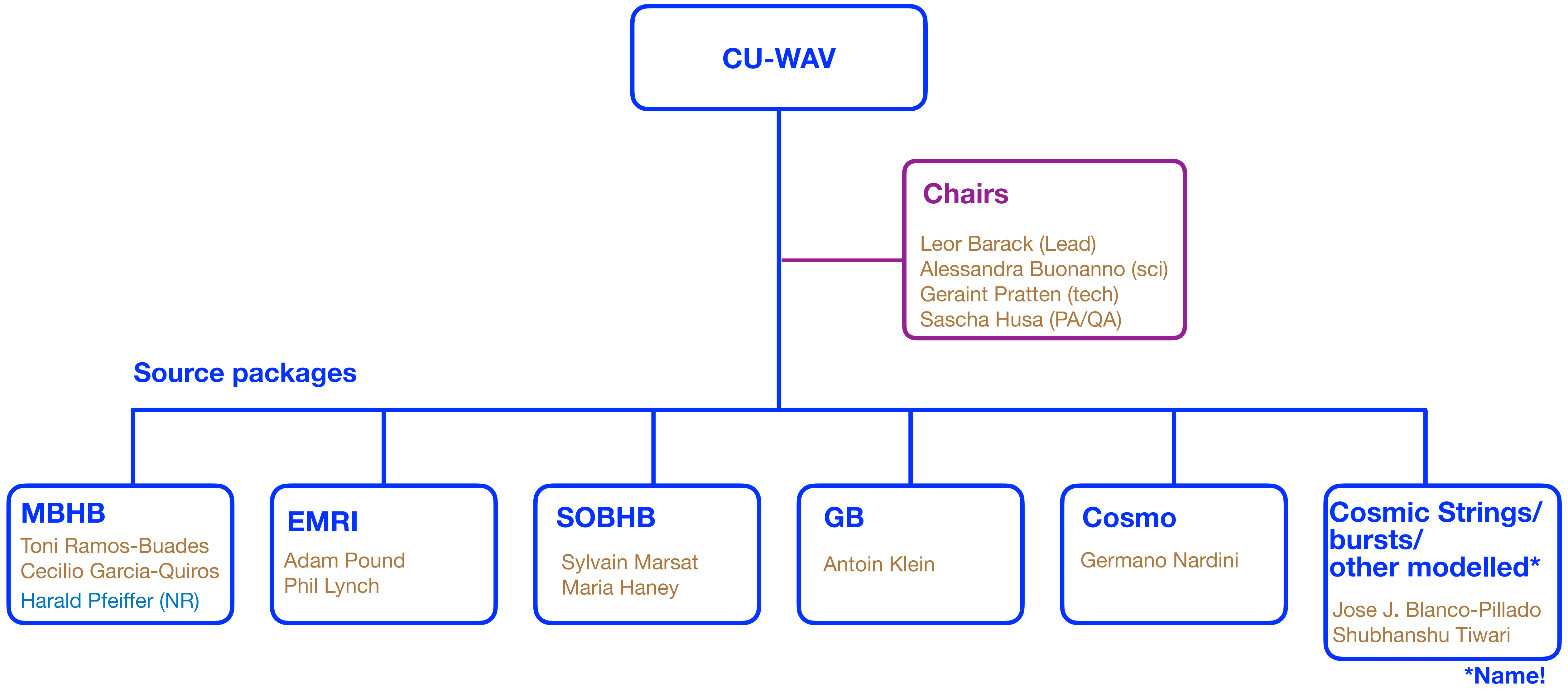


DDPC Waveform Coordination unit: CU-WAV

- **Mission: develop waveform generator, including (very) fast signal and likelihood evaluation.**
- Waveform models for LISA are envisioned to be developed by the LISA Consortium.
- CU-WAV responsible for fast implementations of these models, callable from a general interface that serves the needs of data analysis pipelines, data simulation, ….
- Also: evaluate whether waveforms are good/fast enough,.
- Organised in terms of source packages - sub-projects.



CU-WAV management structure

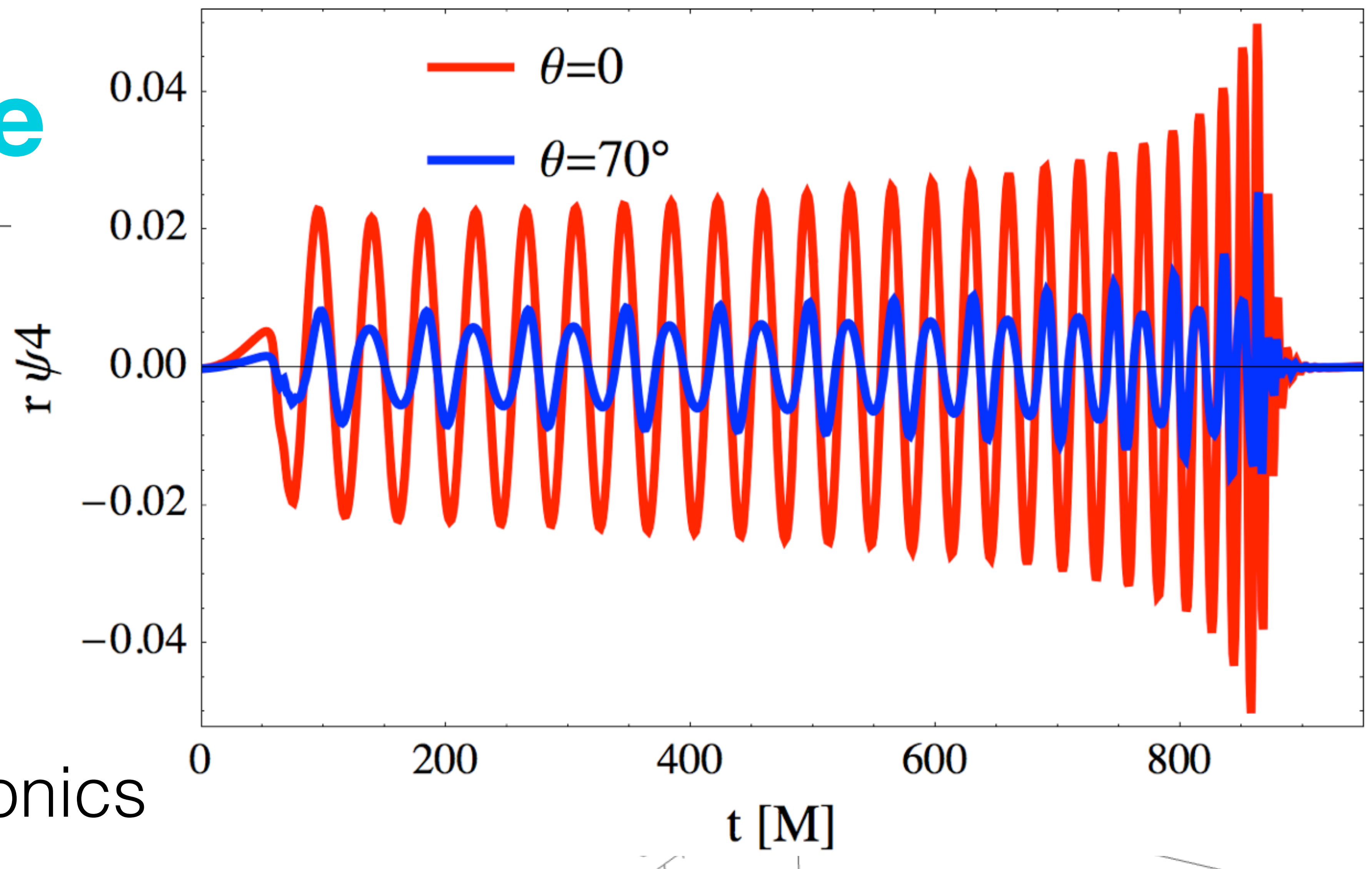


- Currently 10 (of 47) “Spanish” members:
- SH (ICE): PAQA
- Toni Ramos (Nikhef->UIB) + Cecilio García (U Zurich) : MBHB leads
- Jose Juan Blanco-Pillado (EHU): Cosmic string lead.
- Marta Colleoni, Eleanor Hamilton, Jorge Valencia (UIB), Héctor Estellés (AEI): MBHB members.
- Sachiko Kuroyanagi (IFT-CSIC): cosmic strings/burst member.
- Josu Aurrekoetxea (Oxford): cosmology

Phenomenology of compact binary coalescence

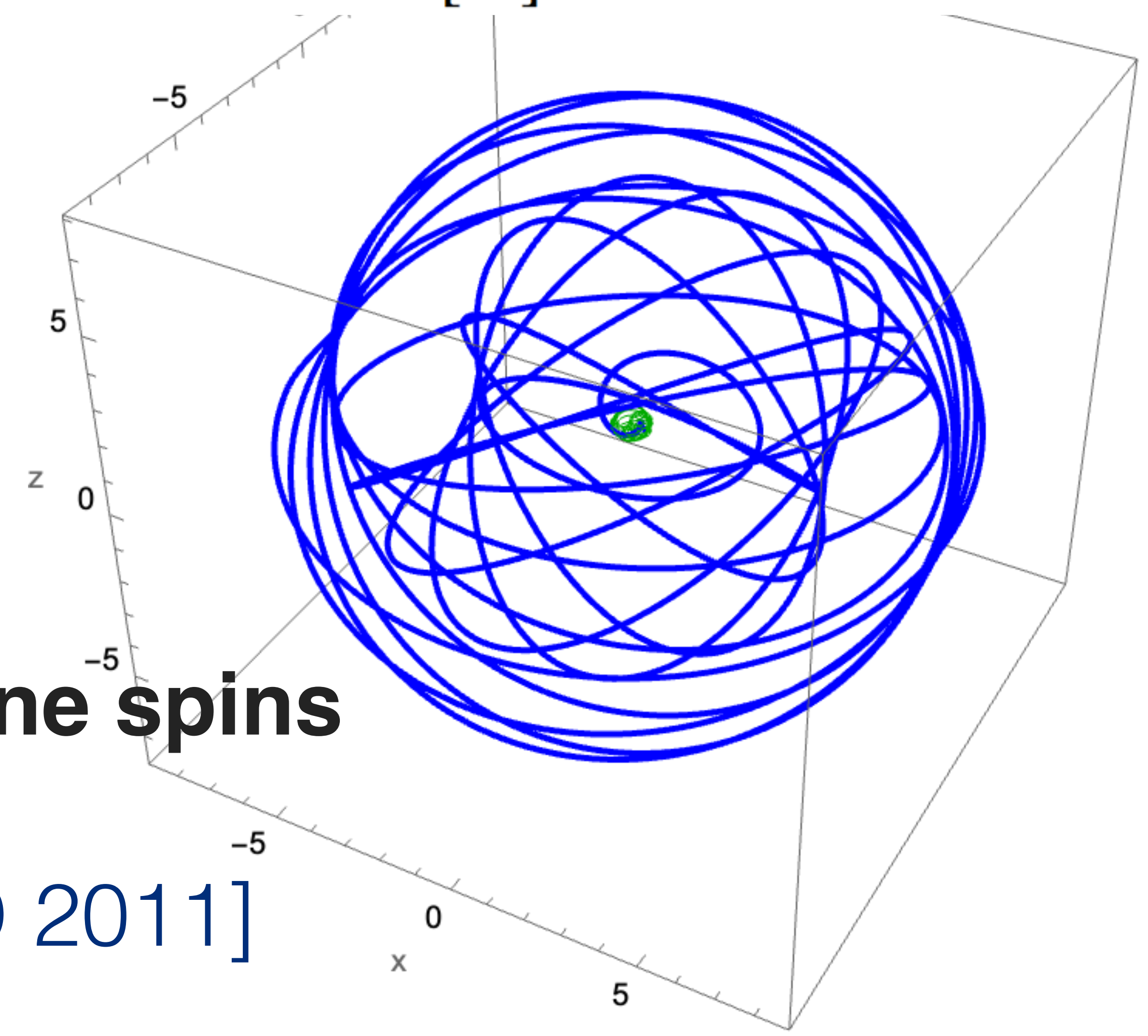
Unless environmental effects: no hair theorem => BHs are simple (masses, spin vectors): => 9 intrinsic parameters describe binary m_1/m_2 (1), spin vectors (6), eccentricity (2)

But: beyond GR, boson stars, …



$$h(t,r,\theta,\phi) = \frac{1}{r} \sum_{\ell=2,m=-\ell}^{\ell_{max},\ell} h_{\ell m}(t)\, Y_{\ell m}(\theta,\phi)$$

How many spherical harmonics do we have to include?



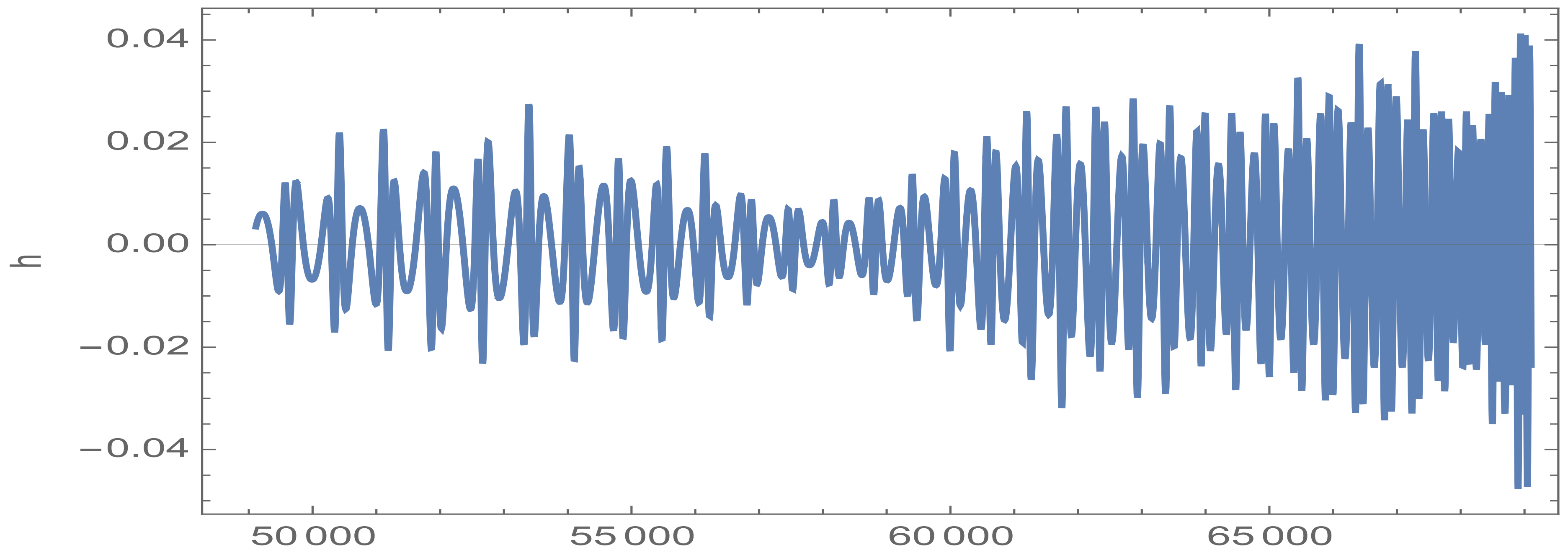
Spins orthogonal to orbital plane: plane and spins are preserved (drop 4 dimensions).

- **Leading order PN spin effect: spin-orbit => amplitude modulations driven by in-plane spins**

  orbital time scale << precession time scale => **"twisting up paradigm"** [Schmidt+ PRD 2011]

- Eccentricity: radiated away rapidly, but complex phenomenology and large parameter space.

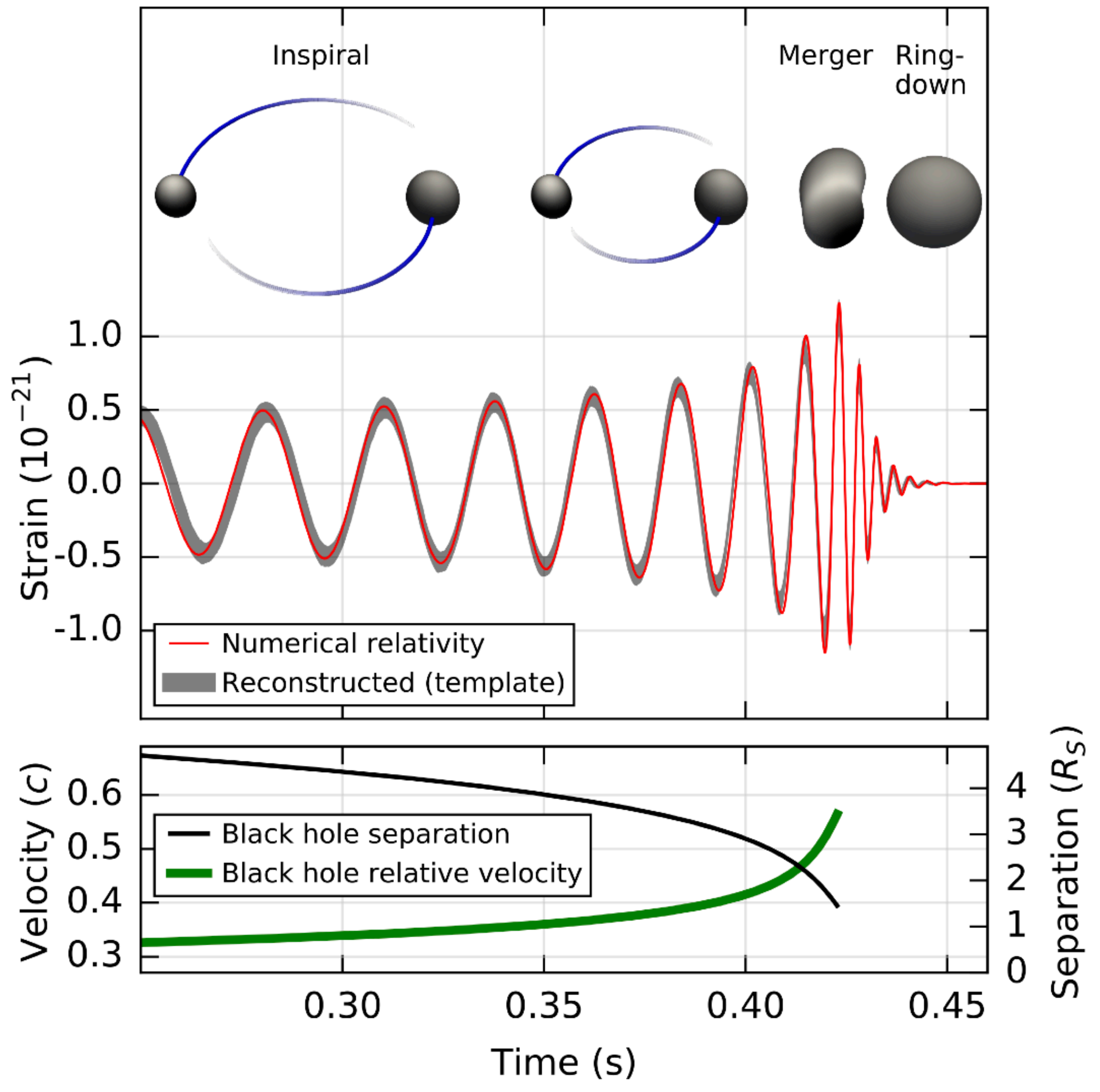
PN waveform: eccentric and precessing, ~20 seconds to generate.



Einstein Equations: Need perturbative approaches + numerical relativity

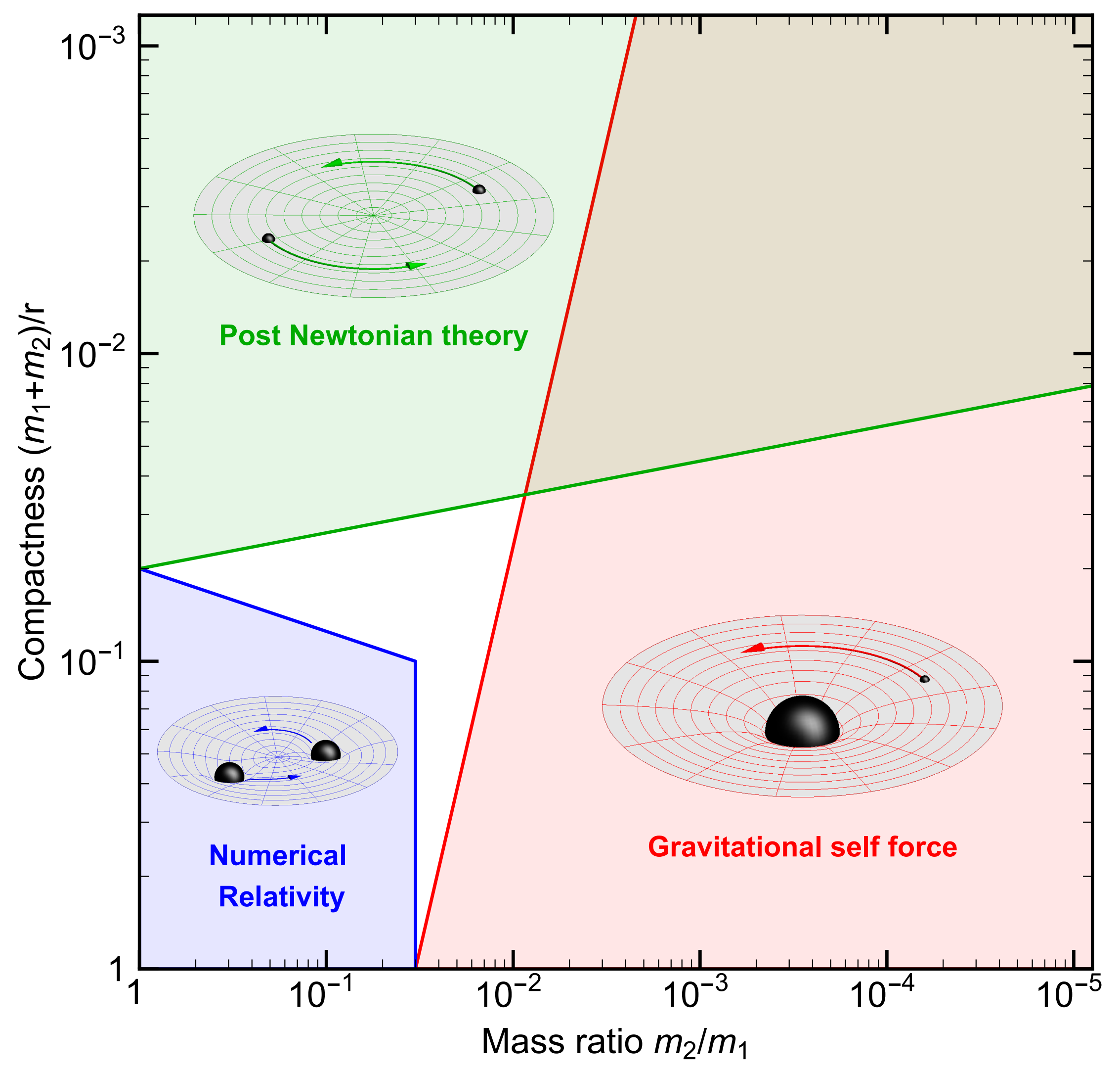
Basic ideas:

- Use numerical relativity to solve for the last orbits and merger
  - Currently very limited for high mass ratio/extreme spins.
- Use post-Newtonian or self-force for the long inspiral
- EOB (re-summed PN) can go all the way, ongoing efforts to also make self-force go all the way to merger/ringdown.
- Obtain ringdown information from linear and > linear BH perturbation theory.



Problems:

- perturbation theory does not provide intrinsic error estimates.
- Numerical relativity is expensive - restrictions in waveform length and parameter space coverage, especially for misaligned spins and eccentricity.
- In parts of parameter space phenomenology becomes particularly complicated:
  - EMRI resonances
  - instability for close to anti-aligned spins
  - unconventional phenomenology for higher harmonics

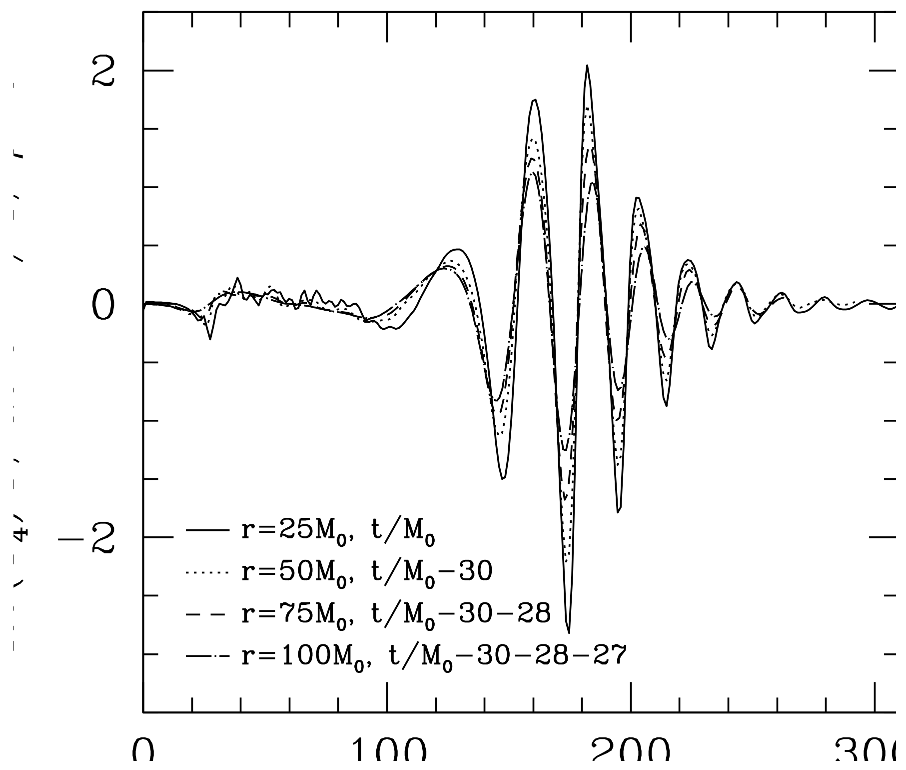


Solution: compensate for shortcomings by combining information from different approaches.

Status: numerical relativity

First (short) NR simulation: 1963, Hahn & Lindquist, IBM 7090

- **First orbit + GWs: Frans Pretorius 2005**



Pretorius, PRL, 2005.

Detection of first GW with inspiral-merger-ringdown waveform models 10 years later.

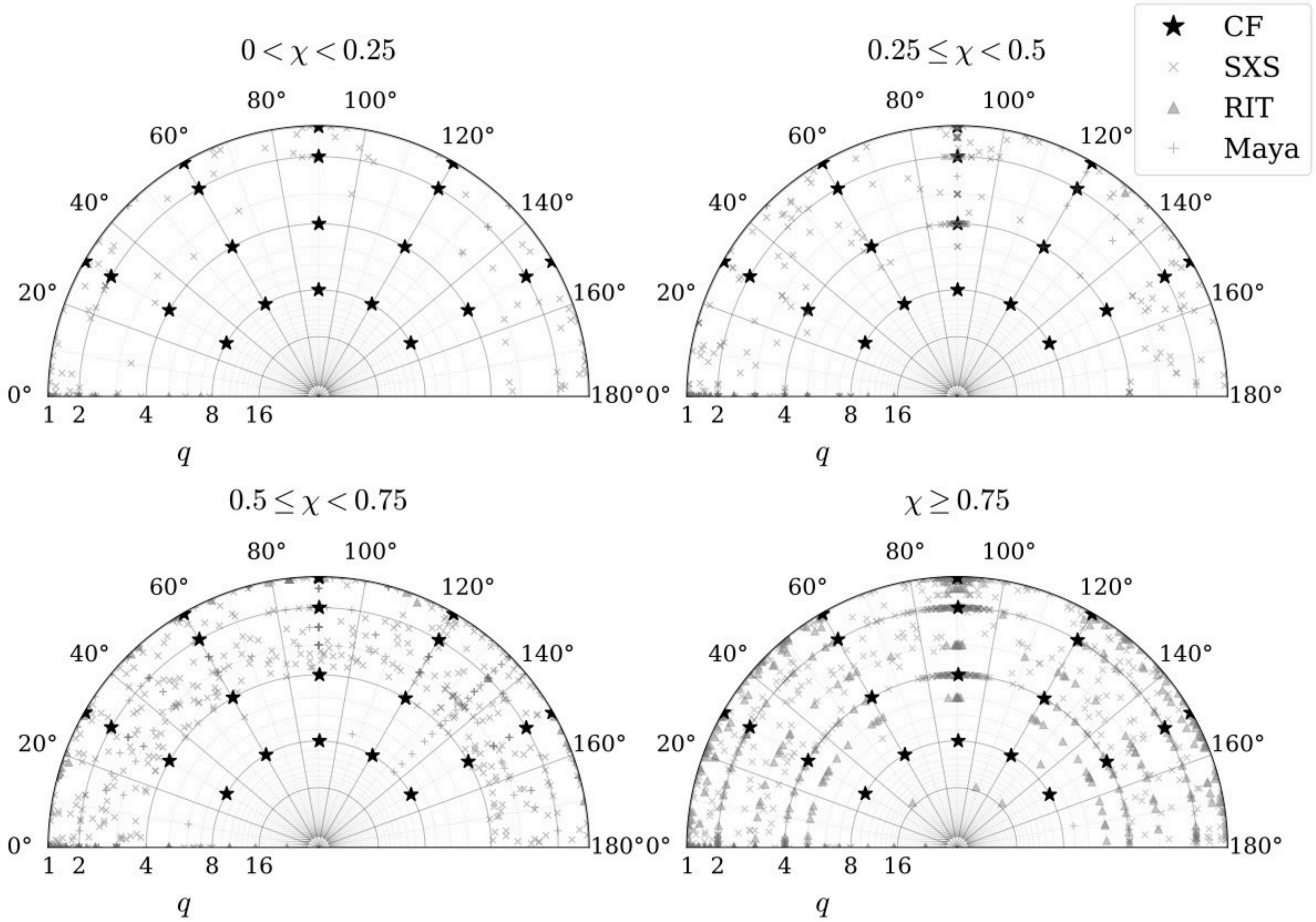


FIG. 16. Comparison between the parameters of the new BBH simulations presented here (CF) and the existing BBH simulations in the the SXS, RIT and Maya catalogues. The *Top left* spin disk shows simulations with spin on the larger black hole $0 < \chi < 0.25$, *Top right* $0.25 \leq \chi < 0.5$, *Bottom left* $0.5 \leq \chi < 0.75$ and *Bottom right* $\chi \geq 0.75$. The radius of each disk shows the mass ratio of the binary and the orientation shows the spin tilt angle of the larger black hole. Spin tilt angles of 90° means that the spin vector lies in the binary's orbital plane.

Cardiff group, arXiv:2303.05419

- Simulations ~ 10^4 - >10^6 core hours.
- 2 paradigms
  - Spatial excision of the BH interior + spectral methods, SpEC, BAMPS, SpECTRE (open source)
  - Temporal excision (singularity avoiding slicing) + high order finite differencing
    - Simpler, robust, benefits smaller groups.
    - Community code: Einstein Toolkit, several other codes.
- What can be done: few simulations ~ 100s of orbits, routine simulations of ~ 10 orbits, systematic exploration up to mass ratio 18, short simulations of higher mass ratios, high but not "extreme" spins.

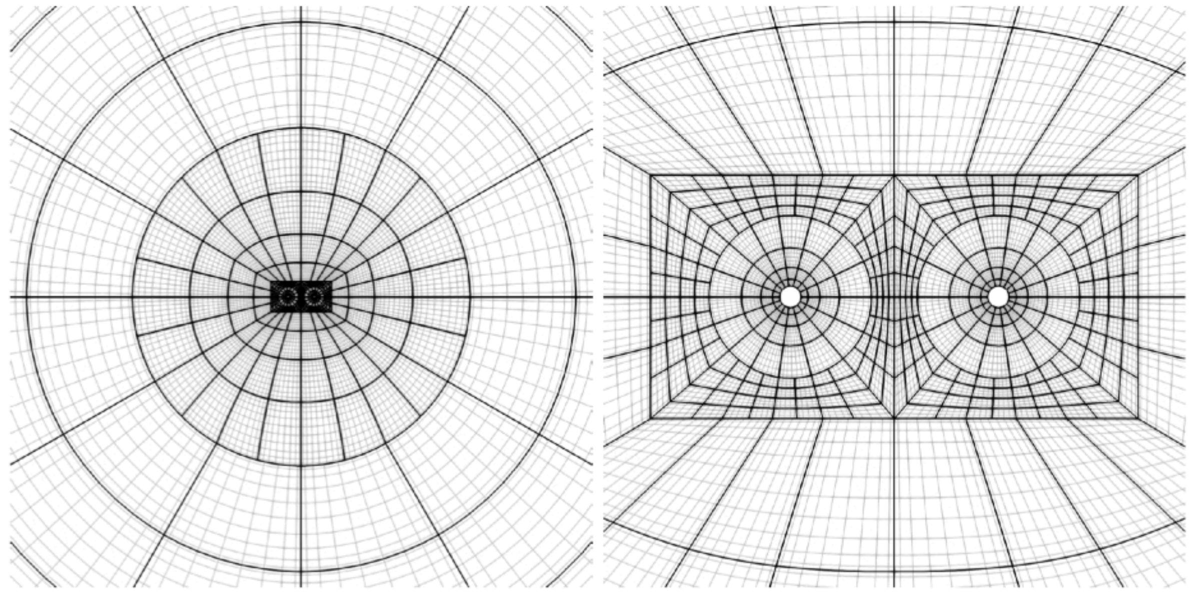


Figure 8. An illustration of the computational grid used during the inspiral. We make use of two excision regions, each region lying inside a black hole's apparent horizon. Each excision is surrounded by a spherical shell partitioned into six deformed cubes as in figure 2. Each spherical shell is then surrounded by another shell of six deformed cubes that transition to a cubical boundary. Then the two cubes themselves are surrounded by a transitionary envelope which becomes spherical. *Left:* The transitionary envelope. *Right:* A close-up of the domain structure around the excisions. The center of each excision is offset from the center of the cube.

SXS Collaboration, arXiv:2410.00265

Status: post-Newtonian

- Expansion in v/c for Hamiltonian + energy flux (or directly equations of motion).
- Simplification and faster evaluation: adiabatic approximation.
- Basis for EOB resummation and IMRPhenom inspiral ansatz.
- Lagging behind: eccentric and generic (eccentric+precessing) waveforms, but good enough for “proxy” inspiral models.
- Also actively pursued: beyond GR.

	Dynamics				Dissipative flux			
PN order	non-spinning	spinning			non-spinning	spinning		
		SO	SS	higher spins		SO	SS	higher spins
0	√	-	-	-	-	-	-	-
1	√	-	-	-	-	-	-	-
1.5	-	√	-	-	-	-	-	-
2	√	-	√	-	-	-	-	-
2.5	√	√	-	-	√	-	-	-
3	√	-	√	-	-	-	-	-
3.5	√	√	-	√ (S^3)	√	-	-	-
4	√	-	√	√ (S^4)	√	√	-	-
4.5	$*$	√	-	√ (S^3)	√	-	√	-
5	$*$	-	√	√ (S^4)	√	√	-	-
5.5	$*$			√ (S^5)	√	√	√	-
6				√ (S^6)	√	√	√	√ (S^3)
6.5				$\star$	√	√	√	
7				$\star$	√			

Table 9. State-of-the-art of known PN results for both the conservative and dissipative dynamics as well as for the gravitational flux. Contrary to the text, everything is stated as absolute order. For example, the 6PN absolute order for the non-spinning flux in the table corresponds to the 3.5PN relative order results as stated in the text. Hereditary effects are only known as non-local contributions. An instantaneous expression can be obtained by performing a low-eccentricity expansion. SO and SS refer to spin-orbit and spin-spin interactions respectively.

$*$ means that only a partial result is known at those orders. At 5 and 5.5PN order, the results were obtained by the combination of PN traditional techniques with scattering amplitudes and self-force.

$\star$ means that the dynamics is known at all leading order in the spin.

Source: waveforms white paper, arXiv:2311.01300

Status: self-force

Second order self force agrees with non-spinning NR inspiral for mass ratio 10.

Framework for fast EMRI waveforms: FEW (Fast EMRI Waveforms) code:

Offline + online strategy.

https://bhptoolkit.org

arxiv.org/2104.04582
arxiv.org/2008.06071

Background Spacetime	Orbital Configuration	Adiabatic	Post-1-adiabatic			
		1SF (Dissipative)	1SF (Conservative)	2SF (Dissipative)	Spin Effects (Conservative)	Spin Effects (Dissipative)
Schwarzschild	Circular	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
	Eccentric	✓✓✓	✓✓✓	✗	✓✓ , ✓✓✓*	✓, ✓✓*
Kerr	Circular	✓✓✓	✓✓	✗	✓,✓✓*	✓✓✓*
	Eccentric Equatorial	✓✓✓	✓✓	✗	✓,✓✓*	✓✓*
	Generic	✓✓✓	✓	✗	✓	✓*
	Resonances	✓✓✓	✓	✗	✗	✗

✓✓✓ Evolving Waveform ✓✓ Driven Inspiral ✓ Snapshot Calculation *(Anti-)Aligned Spin Only

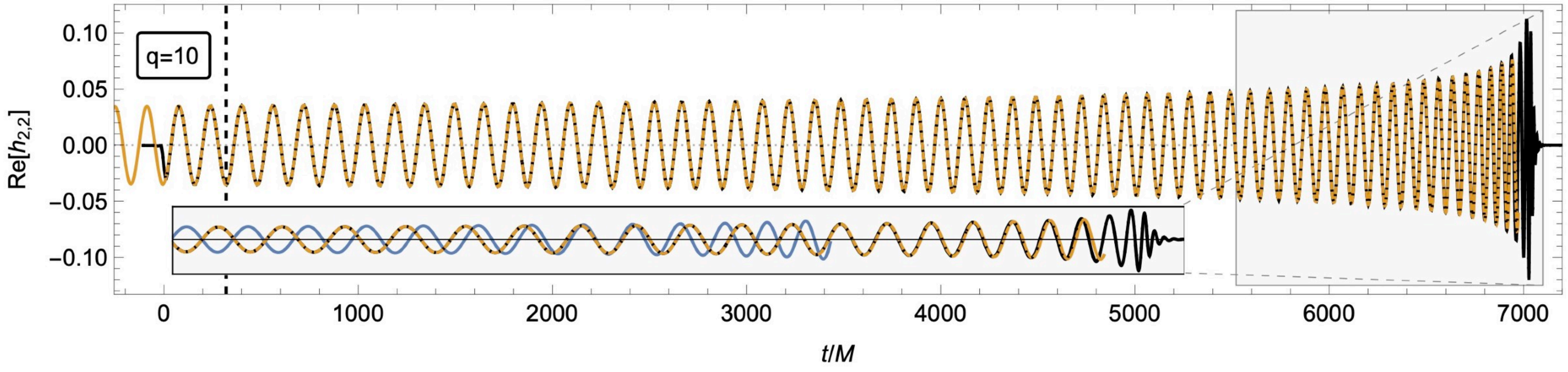


Figure 7. 1PA GSF waveform for a quasicircular, nonspinning binary with mass ratio $q = 10$ (orange). The inset shows a zoomed portion of the waveform near the merger. Also included for comparison are the 0PA GSF waveform (blue, inset only) and the waveform for the same binary produced using an NR simulation in the SXS catalog (SXS:BBH:1107, in black). The three waveforms are aligned in time and phase at $t = 320M$, when the orbital separation is $\approx 13.83M$. Image reproduced from Ref. [1119].

Source: waveforms white paper, arXiv:2311.01300

Status: waveform models for comparable masses

- Cross-pollination and competing ideas:
  - EOB (SEOBNR, TEOBResumS), IMRPhenom, ROM/surrogates!
  - Development of main “current” model families has become part of the LVK.
  - “Theoretical development”, (open source) code implementation, testing, review, maintenance & interpretation of parameter estimation results.
- Address trade-offs in different ways - 3 main strategies with different emphasis.
- **effective one body (EOB)** - analytical methods to compute waves from dynamics
  - model energy + flux/wave amplitude of a particle in effective metric => integrate ODEs numerically.
  - Slow - need a fast model of the phenomenological EOB model, or fast PE, e.g. with ML
- **“Surrogate models”** - algorithms to interpolate large parameter spaces
  - Fast evaluation of EOB or NR data directly.
- **phenomenological models** - model waveform directly
  - piecewise closed form expressions - **extreme compression of information**, fast, parallelizable. **used by LIGO-Virgo for all events to date.**

Status: waveform models for comparable masses - II

Parameter space coverage:

- Accurate (for LVK) aligned spin multi-mode waveforms: EOB, IMRPhenom, NRSurrogates
- Precession:
  - Full calibration to NR: NRSurrogate (NRSurd7q4)
  - Partial calibration to NR: IMRPhenom, EOB in progress —> moving toward good agreement for modern spin/moderate mass ratio QC sector
- Spinning eccentric: SEOBNR, IMRPhenom in progress (FD & TD, targeted toward speed).
- Processing eccentric: in progress.
- Full 20 mode aligned spins: NRSurrogate, IMRPhenom

Speed: IMRPhenom > NRSurrogates > EOB, many strategies of acceleration in development.

Fast IMRPhenom implementations for GPUs exist in the aligned spin sector, and with reduced accuracy (no ODE solving) for quasi-circular precessing waveforms.

Toward the future of waveform models …

- **We are far away from having generic (precession+eccentricity) waveform models calibrated to NR.**

- Parameter space fits become increasingly more difficult for larger regions due to more complicated functional behaviour (higher mass ratios, higher spins, larger eccentricity).
  - model smaller parameter space patches (e.g. SEOBNRv4PHM_ROM), machine learning (neural networks, …)?
  - Need multi-pronged strategy to cover parameter space with NR:
    - More efficient codes.
    - Systematic coverage - vary one parameter at a time vs optimal coverage for algorithms.
    - Small patches for highest accuracy, e.g. models tuned to "golden events".

- **Challenge: Meet requirements for computational efficiency+accuracy within ~ next decade (LISA+3G)!**
- Efficient and accurate models that satisfy data analysis requirements will require new paradigms mixing frequency domain, time domain, time-frequency domain models.
  - frequency and time-frequency domain models accurate but slower time domain models?

- **Can we repeat the success of the decade from 2005 - 2015?**

Acknowledgments

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 and ERDF/EU; the MICIU with funding from the European Union NextGenerationEU/PRTR (PRTR-C17.I1); the Comunitat Autonòma 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.

Universitat de les Illes Balears

IAC3 Institute of Applied Computing & Community Code.

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

Financiado por la Unión Europea NextGenerationEU

Plan de Recuperación, Transformación y Resiliencia

Govern de les Illes Balears
Conselleria d'Economia, Hisenda i Innovació

Illes Sostenibles
Impost de Turisme Sostenible

UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"

1