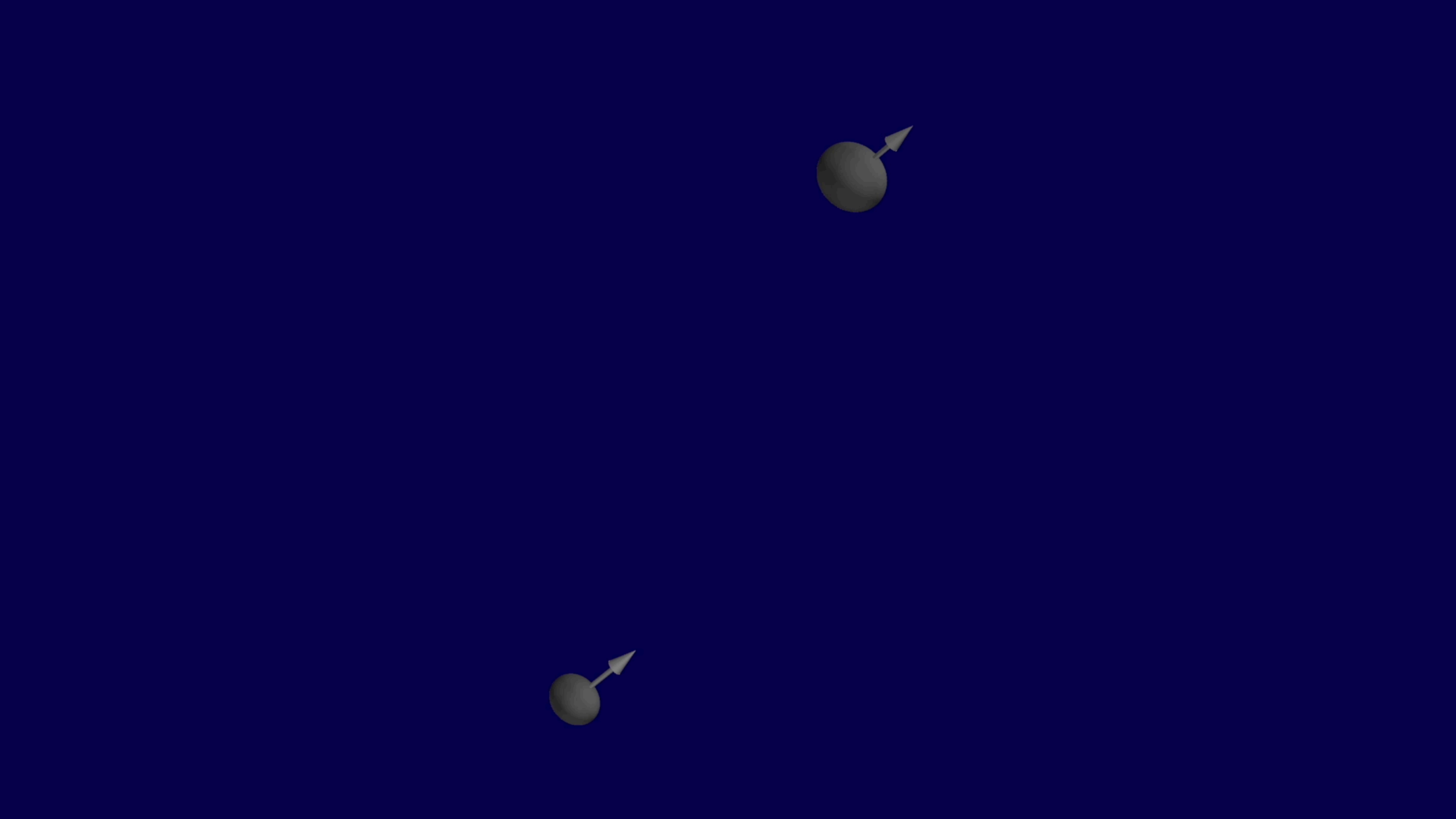
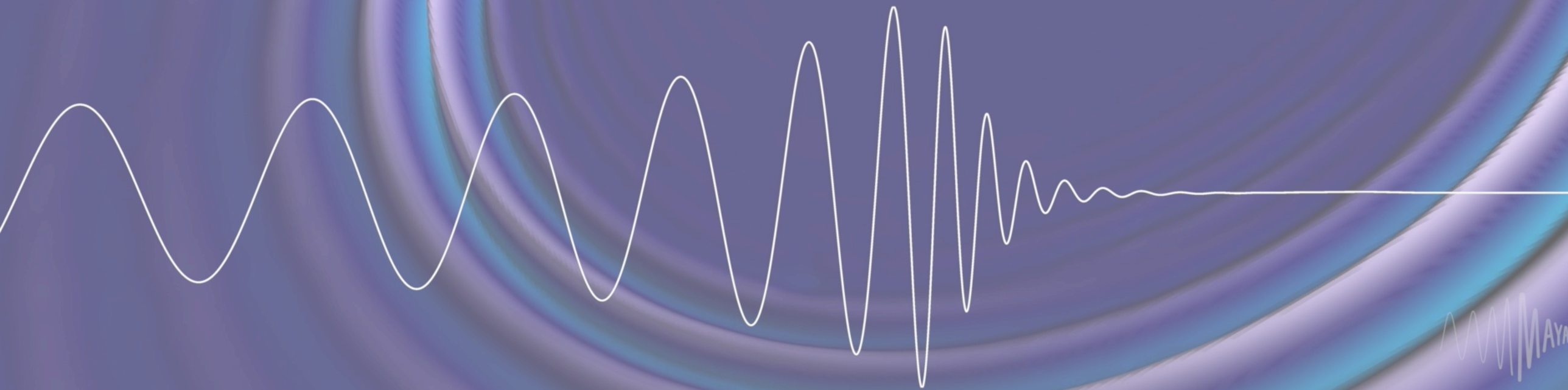


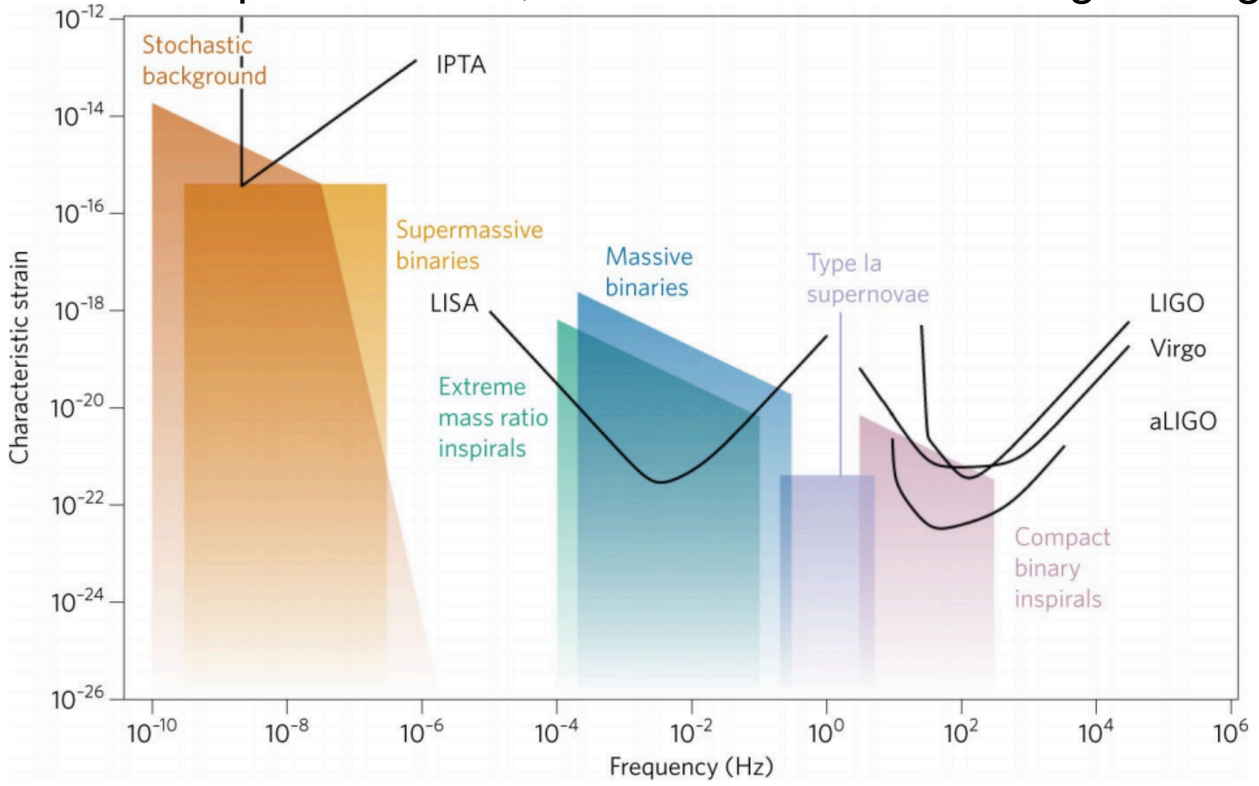
Waveforms

Deirdre Shoemaker
Center for Gravitational Physics
University of Texas at Austin

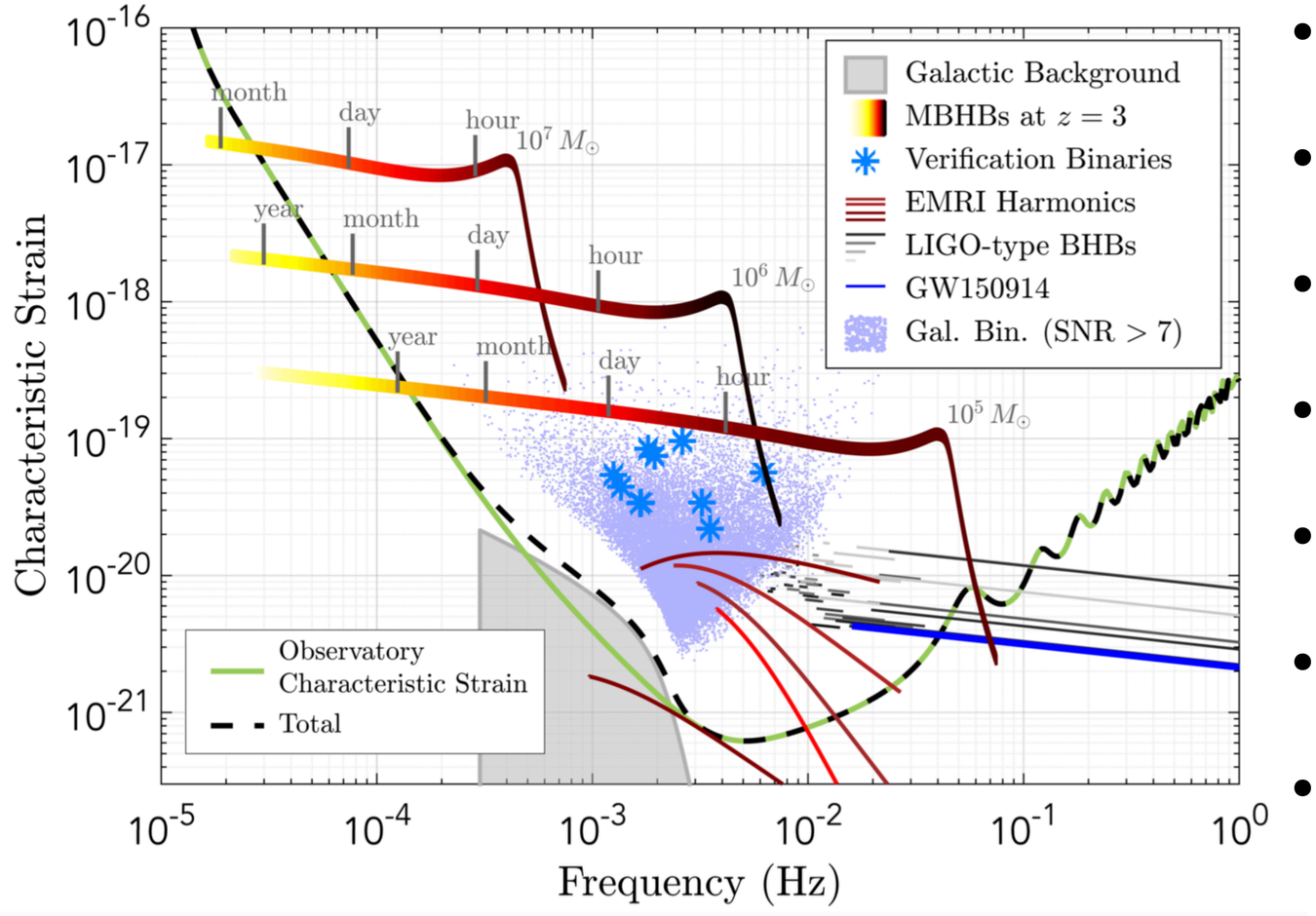


Gravitational Wave Detectors

- Advanced LIGO Plus (A+): An incremental upgrade to aLIGO, x5 greater event rate than advLIGO
- Einstein Telescope: European, underground 10 km arm length in triangle - European Strategy Forum on Research Infrastructures just added it to roadmap
- Cosmic Explorer: US, LIGO Voyager technology expanded to 40 km arms
- LISA: ESA lead space mission, 2.5 million km arms triangle design

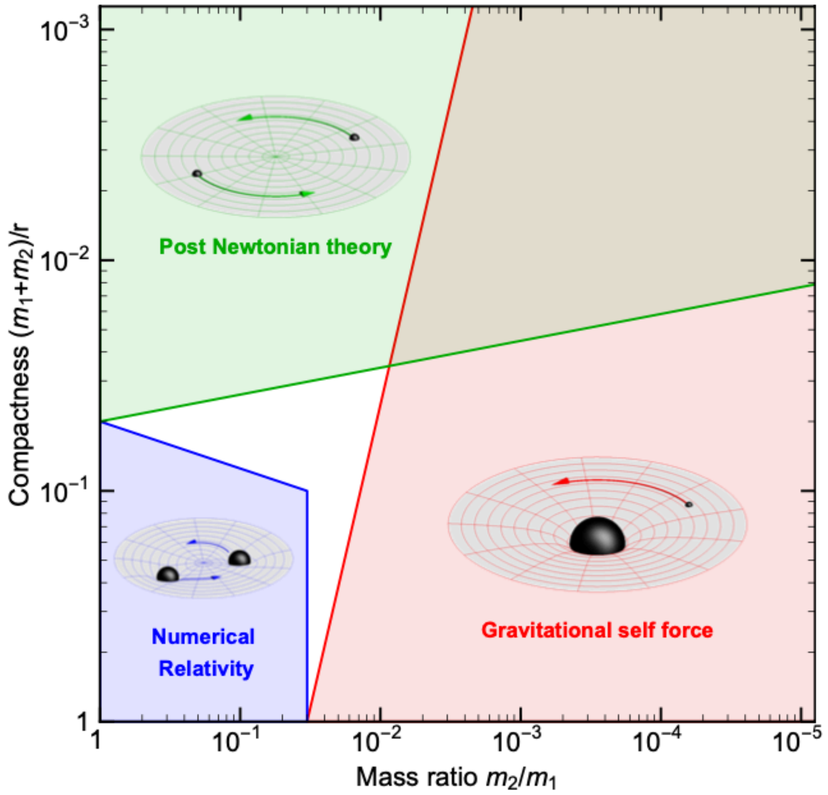


LISA SOURCES



- Massive black hole binaries (MBHBs)
- Extreme mass-ration inspirals (EMRIs)
- Intermediate mass ratio inspirals (IMRIs)
- Galactic Binaries (GBs)
- Stellar origin black hole binaries (SOBHs)
- Transient and others
- Beyond GR and standard model

Theoretical Landscape



Courtesy M. van de Meent

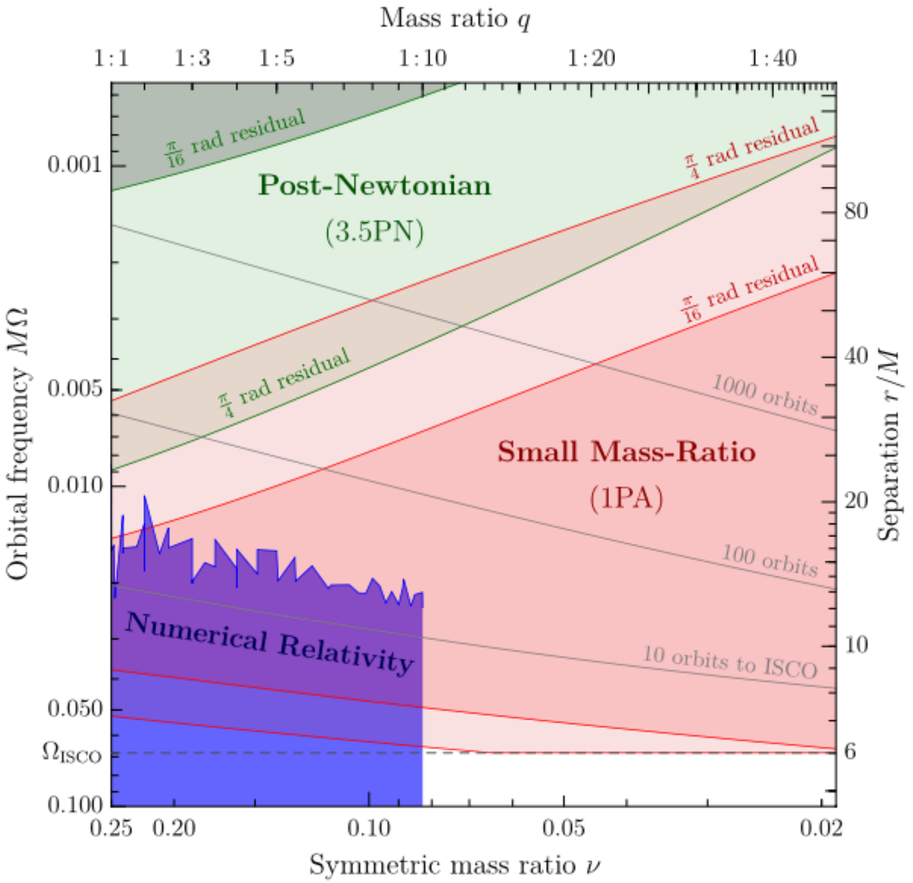
Post-Newtonian

Perturbation

Numerical relativity

Modelling Waveforms

- Numerical relativity
- Weak-field approximations (post-Newtonian/ post-Minkowskian)
- Small mass-ratio approximation (gravitational self-force)
- Effective-one-body waveform models
- Phenomenological waveform models
- Modelling beyond GR and cosmic strings



Van de Meent and Pfeiffer PRL 2020
Applicability of approximations for non-spinning MBH inspiral

LISA Waveforms working group




email: wav-wg-chairs@lisamission.org

Current chairs: Deirdre Shoemaker, Maarten van de Meent, Niels Warburton, Helvi Witek

Goal: Ensure that quality of LISA science is not limited by capacity to solve Einstein's equations

Role: Liaison between waveform community and LISA Consortium

LISA Working Groups: Astrophysics, Cosmology, Fundamental Physics, LISA Data Challenges and Waveforms

Targets of the WavWG

- Determine status of current waveforms and parameter coverage
- Determine accuracy requirements for waveforms (source dependent)
- Encourage waveforms for new science cases (as compared to ground-based)
  - massive binaries: high spin, eccentricity, precession
  - intermediate mass ratios (modelling gap between 1/10 and $1/10^6$)
  - extreme mass ratio inspirals
  - environmental effects and strong-field tests of gravity

WavWG Activities

- Working Group Meetings
  - In person annually
  - Virtual monthly (last Wednesday of month)
- List possible projects for PhD/PD as entry into LISA Consortium (https://wiki-lisa.in2p3.fr/WorkingGroups/WFWG)

- LISA WavWG Whitepaper (near completion)
- Get involved! Join the LISA Waveform Working Group (wav-wg-chairs@lisamission.org)

WavWG White Paper

Writing strategy and community building:

- inclusive: invited entire WavWG to participate
- 1-2 coordinators per section & WavWG co-chairs
- team-up junior/senior scientists → training and networking opportunities

Status:

- draft completed (160 pages);
- 2nd iteration in progress; will shortly be circulated to WavWG & LSG
- coordination with other LISA working groups
- To be submitted in Living Reviews Relativity

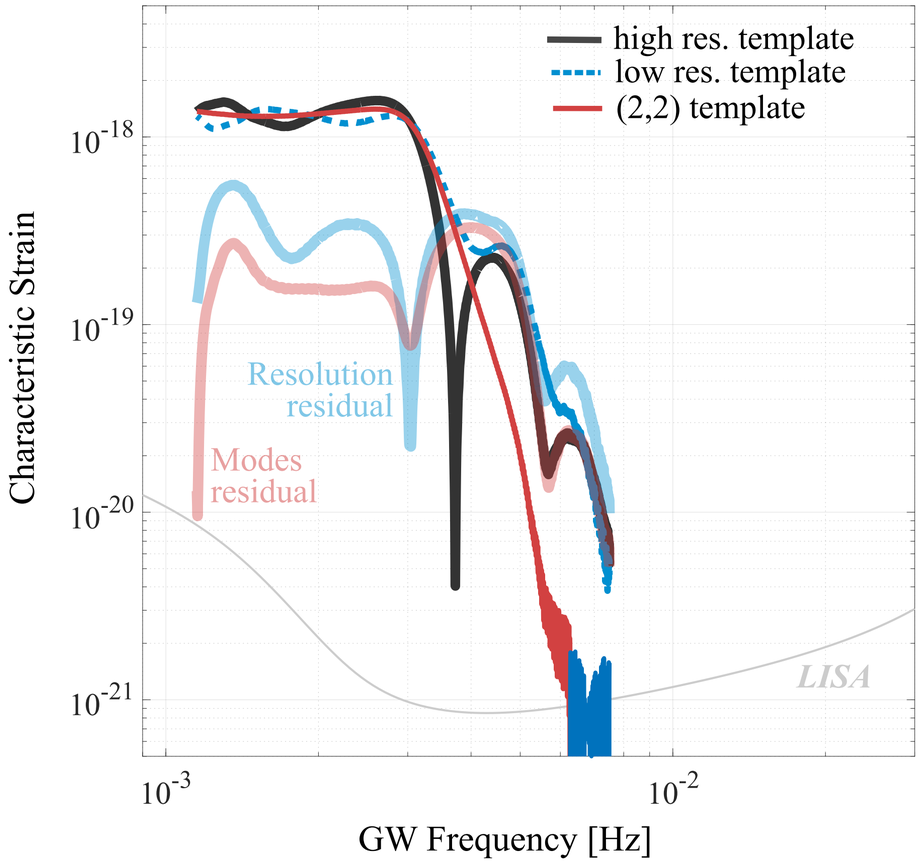
Example from white paper
Preliminary & Incomplete Table of NR Codes
(current and in progress)

Code	Open Source	Waveform catalog	Formulation	Hydro	Beyond GR
SpEC	No	Yes	GHG	Yes	Yes
SpECTRE	Yes	No	GHG	Yes	No
LazEv	No	Yes	BSSN+CCZ4	No	No
Einstein Toolkit	Yes	Yes	BSSN	Yes	?
MAYA-ETK	Yes	Yes	BSSN	No	Yes
GR-Athena++	Yes	No	Z4c	Yes	No
SACRA-MPI	No	Yes	BSSN+Z4c	Yes	No
BAM	No	Yes	BSSN/Z4c	Yes	No
BAMPS	No	No	GHG	Yes	No
GRChombo	Yes	No	BSSN+CCZ4	No	Yes
ExaHyPE	Yes	No	CCZ4	Yes	No
Simflowny	Yes	No	CCZ4	Newtonian	No
SPHINCS_BSSN	?	No	BSSN	SPH	No
Dendro-GR	Yes	No	BSSN	No	No
NRPy+/SENR	Yes	No	BSSN	Yes	No

This PRELIMINARY Table will be published in the LISA Waveform Working Group WhitePaper

Preparing for the future

- Future ground and space GW detectors will be more sensitive
- Potential for SNR in the 1000s (LISA)
- Want waveform errors to be less than the noise
- In 3G, mismatch of the models needs to be reduced by three orders of magnitude (Pürrer and Haster 2019)
- In aLIGO, 3G and LISA, NR errors are significant as SNR increases (specifically for resolution in Ferguson et al 2020)



Ferguson et al 2020

GW Frequency [Hz]

Challenges for BBH Numerical Relativity in future Gravitational Waves

"Solved"

- Non-spinning, mass ratios q<15 (Jani et al, Healy et al, Mroue et al, Boyle et al, Gonzalez et al) and some up to 128 (Lousto et al)
- Moderate random spins for q<8 (Jani et al, Healy et al, Mroue et al) aligned spins up to 0.85, q<18 (Husa et al, Khan et al), q=1, aligned up to 0.99 (Zlochower et al, Scheel et al)
- Eccentric for q<10 (Hinder et al, Huerta et al, Gayathri et al)
- Order tens of orbits
- Harmonics unto ~l=6

Challenging

- Faster, more efficient codes to achieve 100s of cycles and high mass ratios
- Accuracy for high SNR and lots of harmonics
- Means to set accuracy requirements
- Beyond GR to the point where we have waveforms
- Better gauge and extraction

Getting Involved

- NR Community Calls Organized by Nils Fischer and Maria (Masha) Okounkova (1st Monday of month)
- Capra meetings on radiation reaction in GR (next June 11 2021 Perimeter Institute)
- LISA Waveform Working Group (last Wednesday of month)
- LISA Early Career Scientists Group (lecs-chairs@lisamission.org)
- LISA Consortium (https://signup.lisamission.org)

Gravitational Physics Now Driven By Observations

- Gravitational waves and multi-messenger astronomy are here
- Future prospects of ground and space gravitational wave detectors provides incredible opportunities to test our understanding of black holes as astrophysical objects and the limits of general relativity
- Waveforms are necessary for the success of LISA science
- Lots of work ahead

This is the time to reveal gravity's role in the universe and what governs its interaction.