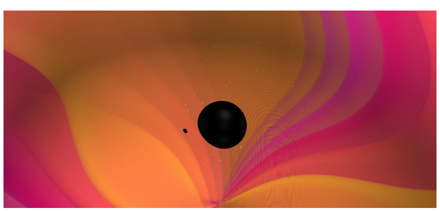
2024 Gravitational Waves

Synopsis

In early 2016, one hundred years after Einstein predicted the existence of gravitational waves on the basis of his theory of General Relativity, the LIGO Scientific Collaboration and the Virgo Collaboration announced the first observation of gravitational waves passing through the Earth emitted by the merger of two black holes one billion four-hundred million light years away. Since then, about one hundred gravitational-wave signals have been observed by LIGO and Virgo detectors, including the coalescence of binary neutron stars, and mixed binaries composed of a neutron star and a black hole.

In this course we will review what gravitational waves are, how they are produced, what are the main astrophysical and cosmological sources and how we model them, using analytical and numerical relativity. We will also review the quest for gravitational waves, which culminated with the discovery by LIGO and Virgo, and discuss how those new astronomical messengers are detected and how they can probe strong gravity and unveil the properties of the most extreme astrophysical objects in the universe.



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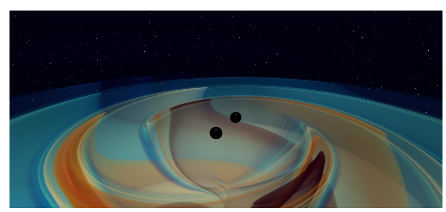

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(Click on the images to learn more on the events)

Classes schedule:

Classroom: **Online** (for the students at the location where the lecturer is not present)

Lecture days: **Mondays: 4:00pm – 5:30pm / Tuesdays: 3:30pm – 5:00pm (CEST) [90 min]** (after Oct 27, CEST changes to CET, but the times remain the same numerically)

Training days: **Fridays: 3:30pm – 5:00pm (CEST) [90 min]** (after Oct 27, CEST changes to CET, but the times remain the same numerically)

First day of classes: **October 14th**

Last day of classes: **December 9th for UMD students, December 20th for IMPRS/HU students**

Instructor contact info:

Name: Alessandra Buonanno

Office rooms: office # 1.24 @ AEI; office # 3149 @ UMD
E-mail: alessandra.buonanno@aei.mpg.de; buonanno@umd.edu
Phone: +49 331 567 7220; +1 301 405 1440
Office hours: by appointment

Teaching Assistants contact info:

Names: Aldo Gamboa and Marcus Haberland
Office rooms: office # 1.65, 0.15 @ AEI
E-mail: aldo.gamboa@aei.mpg.de, marcus.haberland@aei.mpg.de
Phone: +49 331 567-7248, +49 331 567-7113
Office hours: by appointment

Textbooks:

Required textbook: “Gravitational Waves Volume 1: Theory and Experiments”, by Michele Maggiore.

Other useful textbooks:
“Gravitational Waves Volume 2: Astrophysics and Cosmology”, by Michele Maggiore.

“Gravitational Waves in Physics and Astrophysics: An artisan’s guide”, by M. Coleman Miller and Nicolas Yunes.
“Gravitational Wave Physics and Astronomy” by Jolien Creighton & Warren Anderson.
“Gravity” by Eric Poisson & Cliff Will.
“Introduction to General Relativity, Black Holes & Cosmology” by Yvonne Choquet-Bruhat.

Prerequisites:

To follow the classes, students should be already familiar with the material covered in an introductory General Relativity course. It is not necessary to have followed a course in astrophysics and/or cosmology.

Exam:

Master students at Humboldt University are required to collect at least half of the whole points available in the homeworks in order to access to the final exam, which will consist in an online oral examination. **Graduate students at UMD and IMPRS students at the Max Planck Institute for Gravitational Physics** do not have to take an exam.

Homeworks policy:

- Late homeworks are accepted only under serious circumstances (to be discussed before due day).
- You are encouraged to discuss homeworks with other students, however the work you turn in should be your own formulation and reflection.
- Use of previous solutions is not allowed (violation of this rule is cause for failure of the course).
- Homework sets must show reasoning leading to the final answers in a clear and readable fashion to obtain credit.
- Please, include your name and, if you submit handwritten homeworks, write very clearly.
- Please, hand in homeworks, digitally typeset or as a clear scan, to both TAs by email on the due day before class starts.

Grading:

For **master students at Humboldt University**, the course grade will be based on the final exam (50%) and the homeworks (50%). However, they are required to collect at least half of the whole points available In the assignments in order to access the final exam. For **graduate students at UMD** and **IMPRS students at the Max Planck Institute for Gravitational Physics**, the course grade will be based on the homeworks.

Notes:

The lectures will be given entirely remotely for master students at Humboldt University. Most of the lectures will be given in person at the Max Planck Institute for Gravitational Physics, and some of them will be given in person at UMD. The Zoom link will be emailed to all students enrolled to the course.

Students and researchers of the AEI (Hannover and Potsdam) and of partner institutions in the Potsdam area who are not part of the Gravitational-Wave IMPRS at the AEI-Potsdam and who would like to audit the course will need to register by sending an email to Brit Holland: brit.holland@aei.mpg.de

Syllabus:

Note: what is below is a tentative course plan. It will be adjusted during the course.

The section numbers in the table below refer to the books by M. Maggiore

Date (week)	Monday & Tuesday (lectures)	Friday (lectures or tutorials)	Reading material
Oct 14, 15 & 18 (week 1)	A glimpse of GW astrophysics Linearization of Einstein equations, Lorenz gauge, TT gauge [1.1, 1.2] Interaction of GWs with freely falling test particles, key ideas underlying GW detectors [1.3] Effective EMT of GWs, GW energy, and linear momentum fluxes [1.4]	Tutorial	Einstein (1916) Einstein (1918) Eddington (1922) Einstein-Rosen (1937) 100 years of GWs First GW detection by LIGO Basic physics of GW150914 Flanagan & Hughes (2005)
Oct 21, 22 & 25 (week 2)	Leading-order generation of GWs in the slow-motion approximation, quadrupole formula [3.1–3.3] Characteristics of GWs and power radiated from binary systems [4.1] GWs from binary systems on inspiraling, circular orbits [4.1]	Tutorial	1957 Chapel Hill Conference: Pirani & Feynman Ni-Zimmermann (1972) Estabrook-Wahlquist (1975) Rakhmanov (2004) Kennefick (1997) Isaacson (1968)
Oct 28, 29 & Nov 1 (week 3)	GWs from pulsars [4.2] GWs from early Universe	PN templates and their range of validity [7.2]	
Nov 4, 5 & 8 (week 4)	Effective-one-body theory: conservative dynamics	Effective-one-body theory: dissipative dynamics and waveforms	Buonanno-Damour (1999) Buonanno-Damour (2000) Buonanno & Sathyaprakash (2014) (see Sec. 6.2.3) Damour (2012)

			Finn & Chernoff (1993) Buonanno (2007) (see Sec. 6.4) Vishveshwara (1970) Press (1971)
Nov 11, 12 & 15 (week 5)	**Numerical relativity**	**Tutorial**	
Nov 18, 19 & 22 (week 6)	**Analytical/numerical relativity templates for searches and inference studies of GWs from compact-object binaries**	**Matched filtering [7.1, 7.3]**	
Nov 25 & 26 (week 7)	**Probing non-GR theories with GW observations** [guest lecturer: Félix Julié]	**Tutorial**	
Dec 2, 3 & 6 (week 8)	**Black-hole perturbation theory and quasi-normal modes**	**Detection and parameter estimation of GWs from compact-object binaries [7.4]**	Regge-Wheeler (1957) Detweiler-Chandrasekhar (1975) Ferrari-Mashhoon (1984) Mashhoon (1985) Schutz-Will (1985)
Dec 9, 10 & 13 (week 9)	**Inferring astrophysical, cosmological and fundamental- physics information from GW signals [15]**	**Gravitational self- force theory**	GW150914-properties GW150914-tests-of-GR
Dec 16, 17 & 20 (week 10)	**Post-Newtonian and effective-field theory**	**Tutorial**	

Homeworks:

Homework sheets assigned