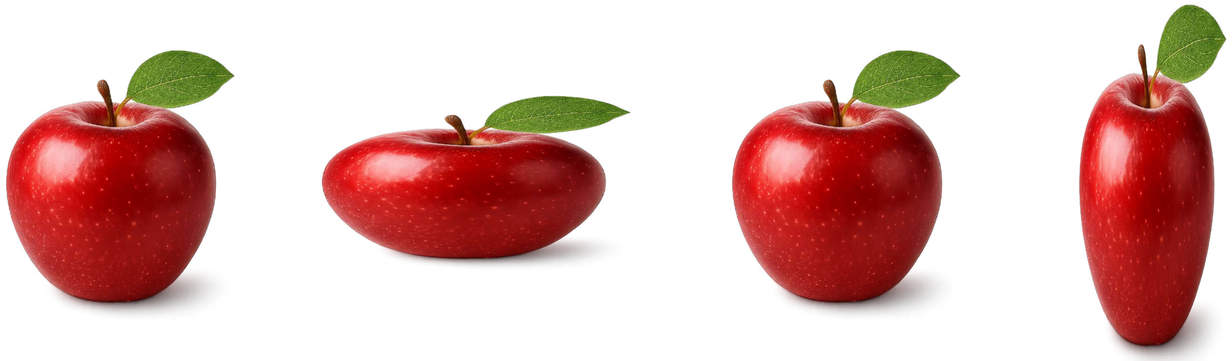
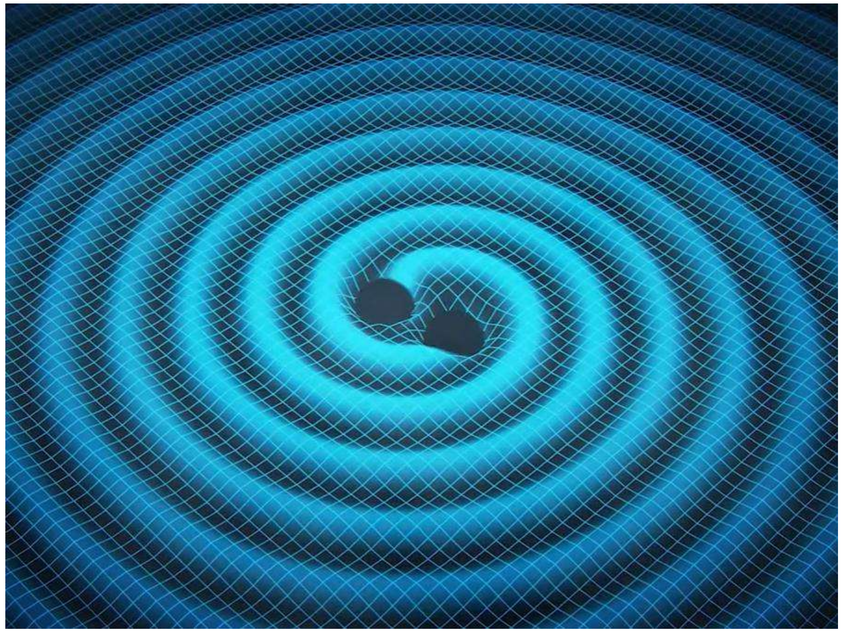
The Discovery Potential of Gravitational Waves

Richard Brito
CENTRA, Técnico



110 years ago: General Relativity

Albert Einstein: Gravity is curvature



Credit: Swinburne Astronomy Productions

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

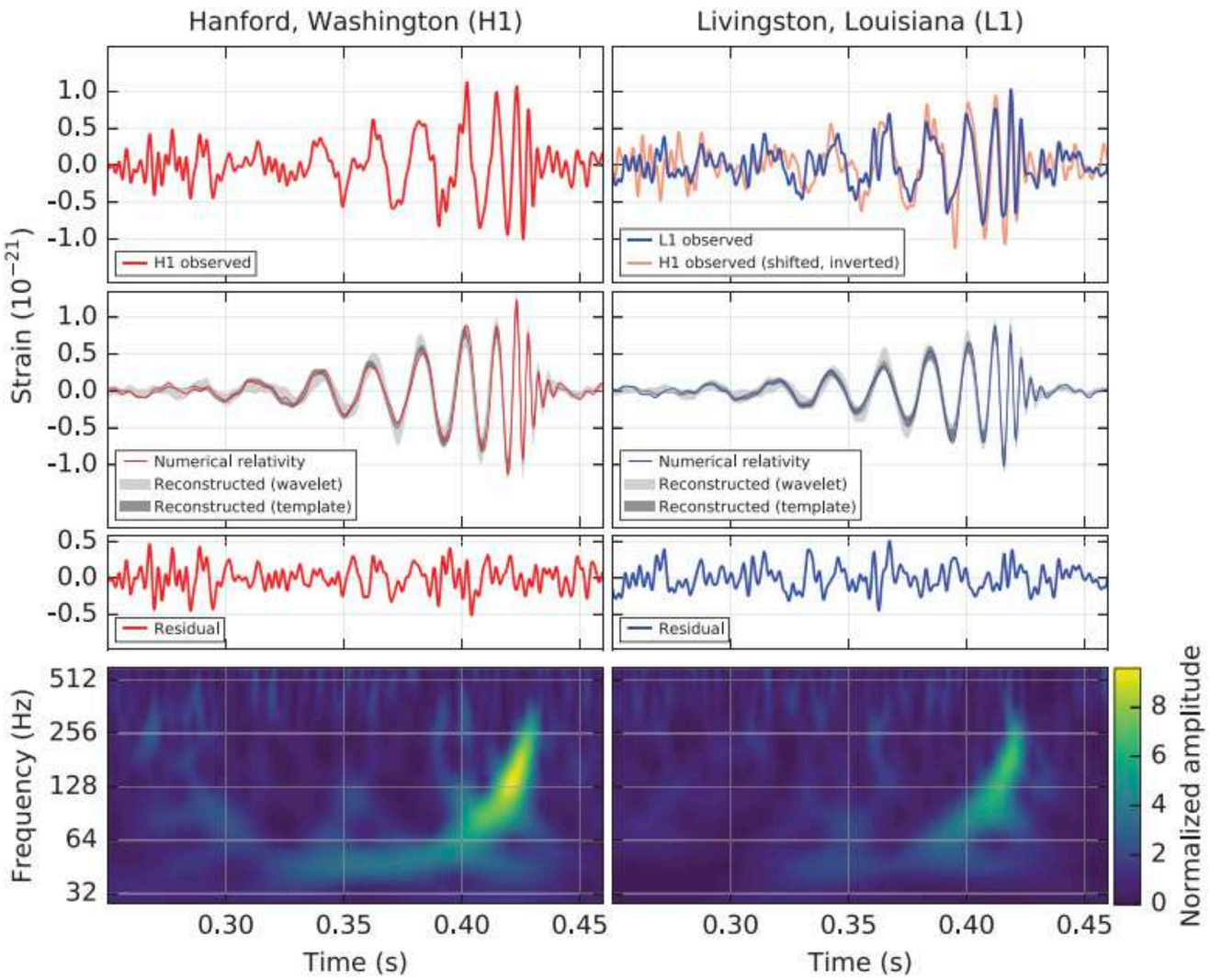
*"**Spacetime** tells **matter** how to move; **matter** tells **spacetime** how to curve."*

- John Wheeler in Geons, Black Holes and Quantum Foam: A life in Physics

Einstein equations represent a system of *10 coupled, nonlinear partial differential equations*!

A **loooot** of work (combining analytical, perturbative and numerical methods) goes into solving those equations in different scenarios...

10 years ago: GW150914

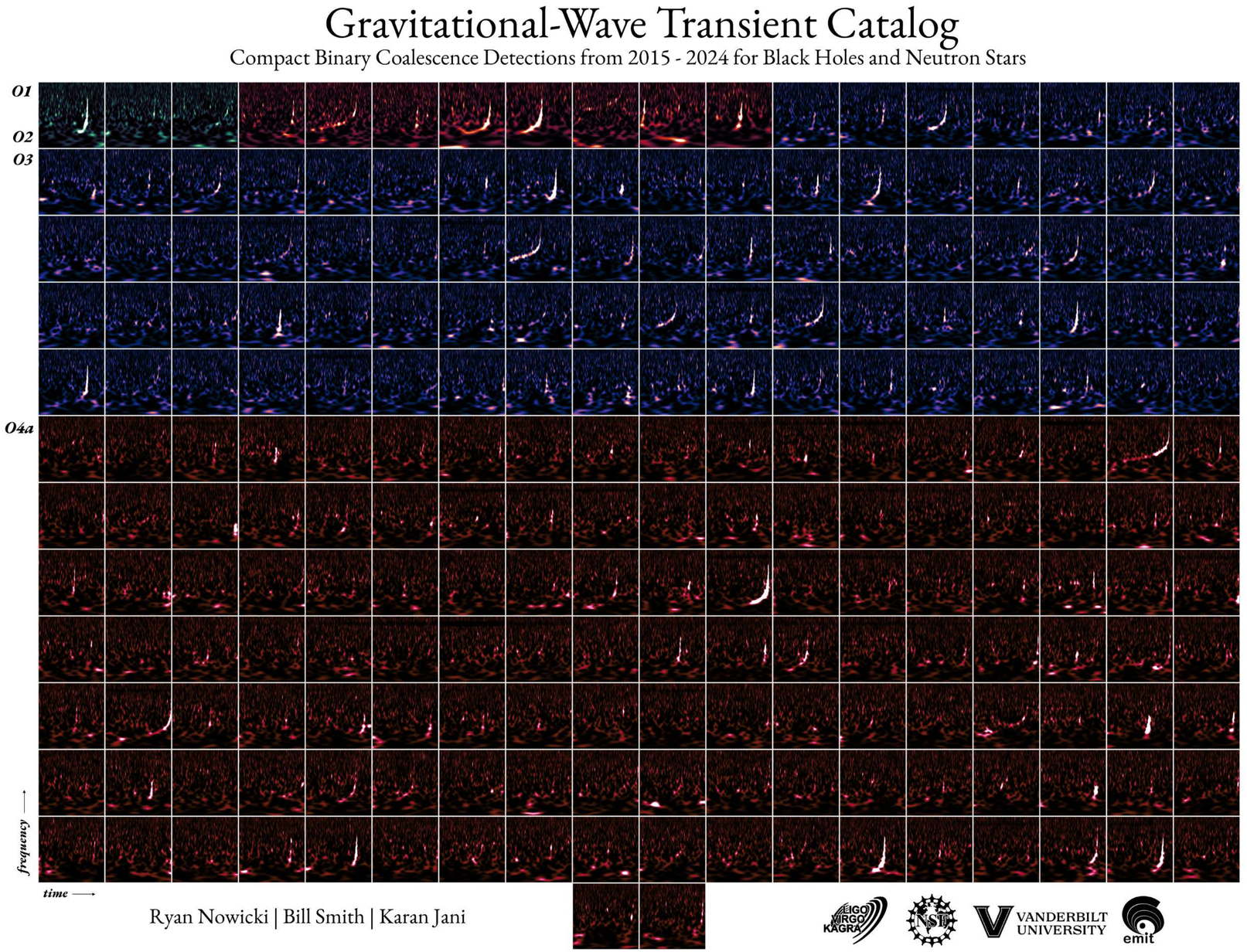


Credit: LIGO and Virgo Scientific Collaborations
PRL116, 061102 (2016)

First direct gravitational-wave (GW) detection:
GW150914

(**14th September 2015**)

Today: GWs all over the place

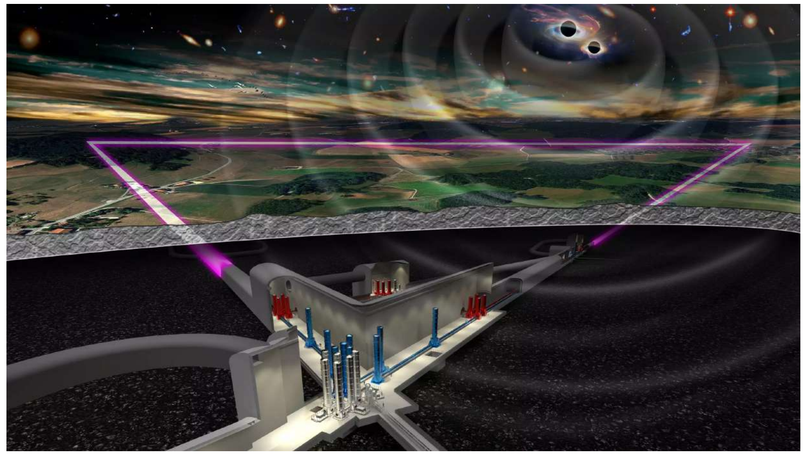


≈ 220 confirmed GW detections to date (and more to come)!

LIGO-Virgo-KAGRA Collaboration, arXiv:2508.18082

Tomorrow: precision GW physics

Next generation ground-based detectors currently under study.



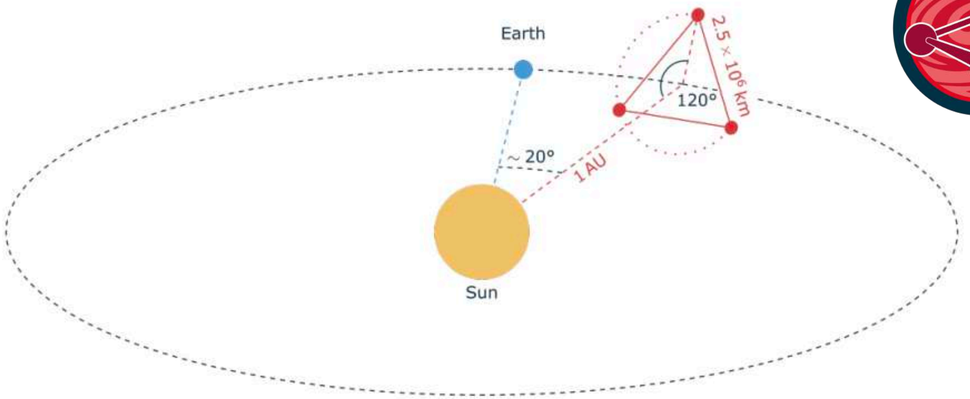
© NIKHEF

EINSTEIN TELESCOPE

COSMIC EXPLORER

LISA: a GW detector in space
(Laser Interferometer Space Antenna)

Launch in 2035!



LISA Red Book, arXiv: 2402.07571

Era of ***precision*** and ***data-driven*** GW physics is coming!

Plenty of ***opportunities*** but also (big) ***challenges*** in the road ahead.

An endless list of questions

How do **black holes** form? Where do they live? How do they grow?

How does matter behave inside **neutron stars**?

Is **General Relativity** still valid in the highly dynamical strong-field regime?

Do black holes really form/exist? Any signs of **new physics** at horizon scales?

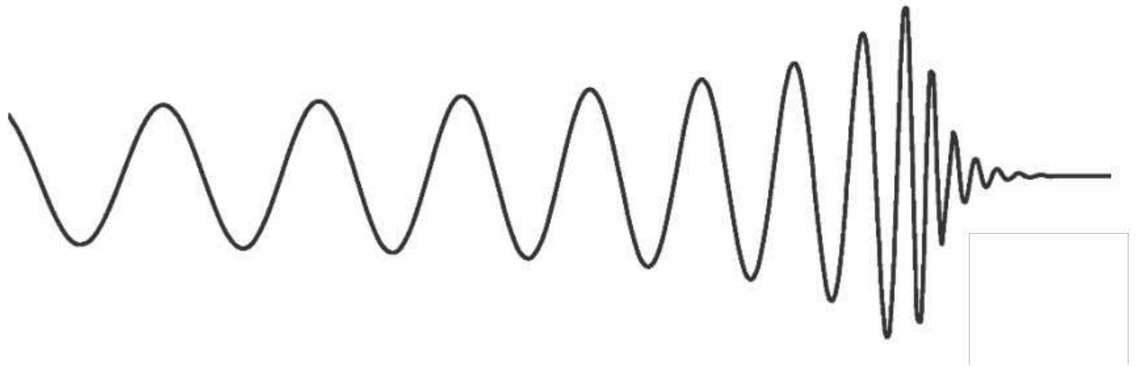
What is **dark matter**? Can GWs help decipher its nature?

How do GWs propagate through Universe? Are there signs of new physics at **cosmological scales**?

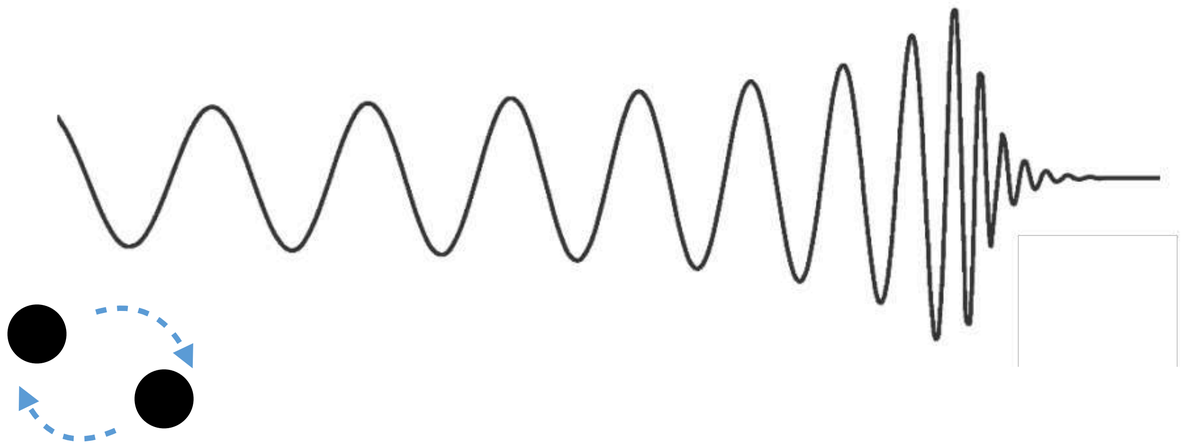
GW signatures from the **early Universe**?

....

Dissecting a GW: a detective's work

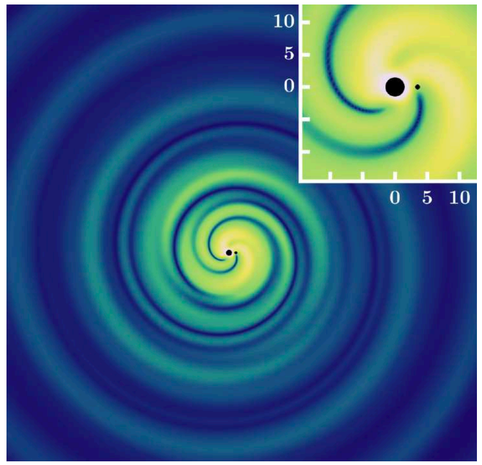


Dissecting a GW: a detective's work



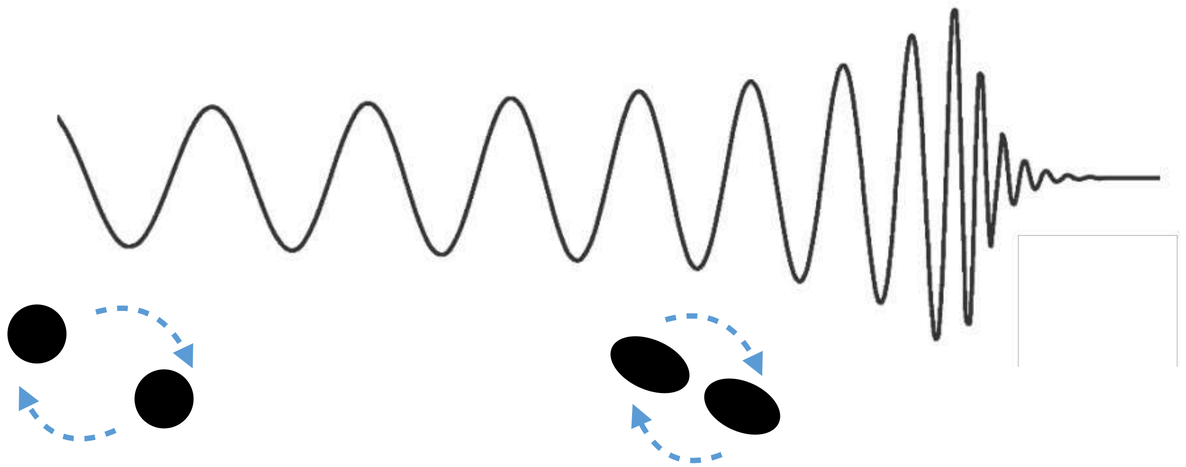
Is the orbital decay **consistent with GR**?

Are the objects moving in ***vacuum***?



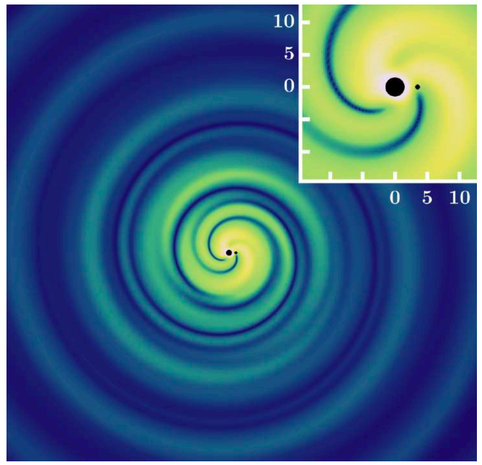
From: Dyson, Spieksma, RB+ '25

Dissecting a GW: a detective's work



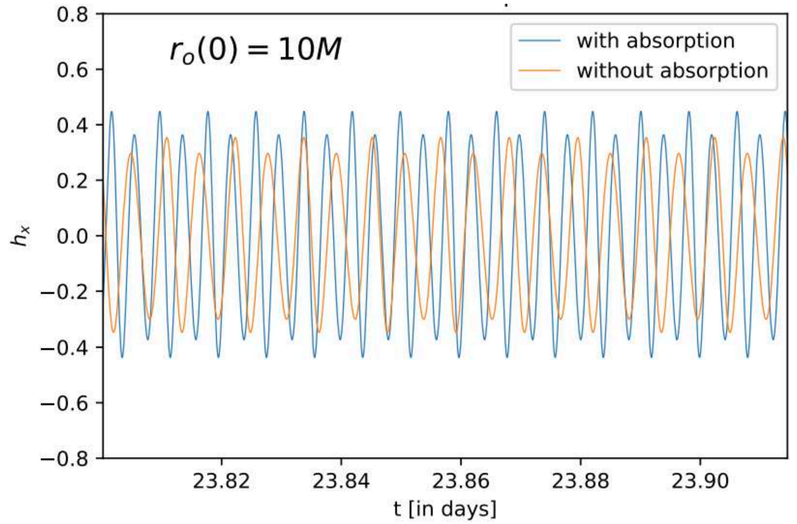
Is the orbital decay **consistent with GR**?

Are the objects moving in ***vacuum***?



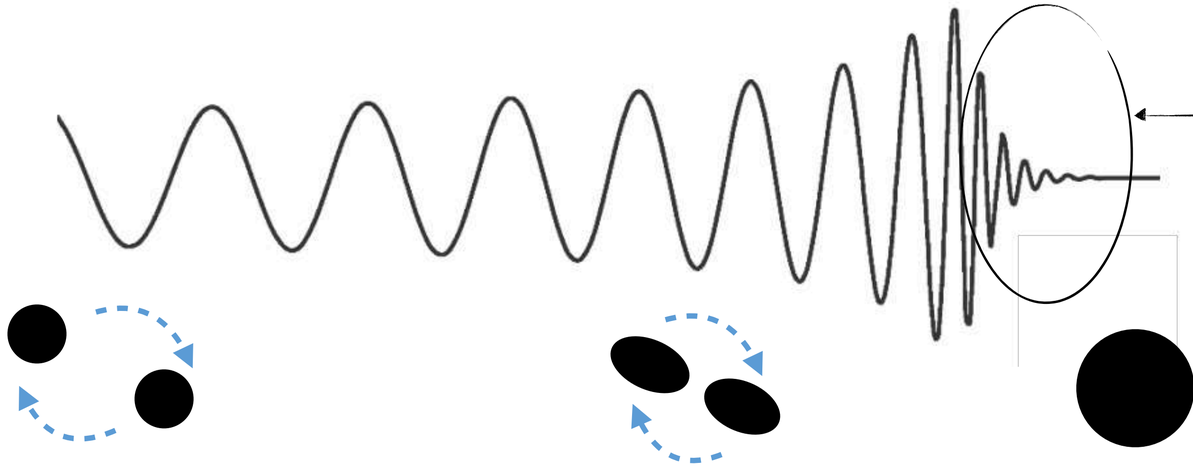
From: Dyson, Spieksma, RB+ '25

Are the objects **black holes** or **something else**?



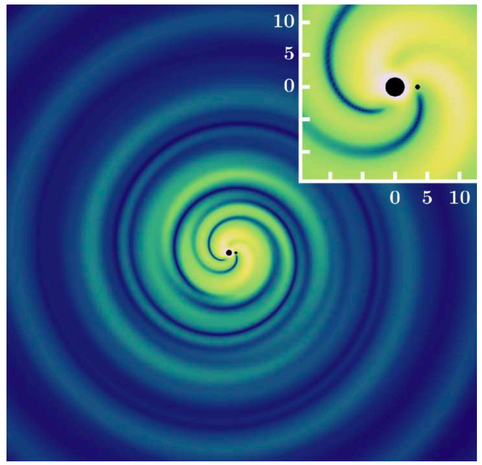
From: Datta, RB+ '20

Dissecting a GW: a detective's work



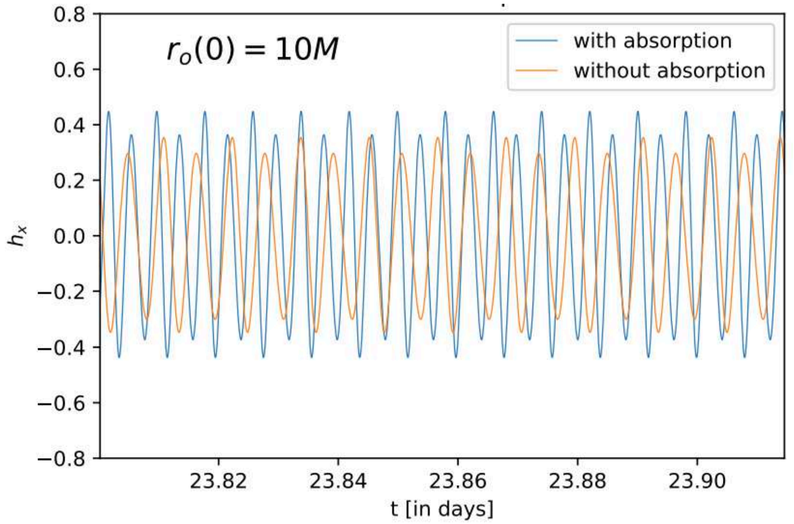
$$h(t) \sim \sum_k A_k e^{-t\omega_I^{(k)}} \sin(\omega_R^{(k)} t)$$

Is the orbital decay **consistent with GR**?
Are the objects moving in ***vacuum***?



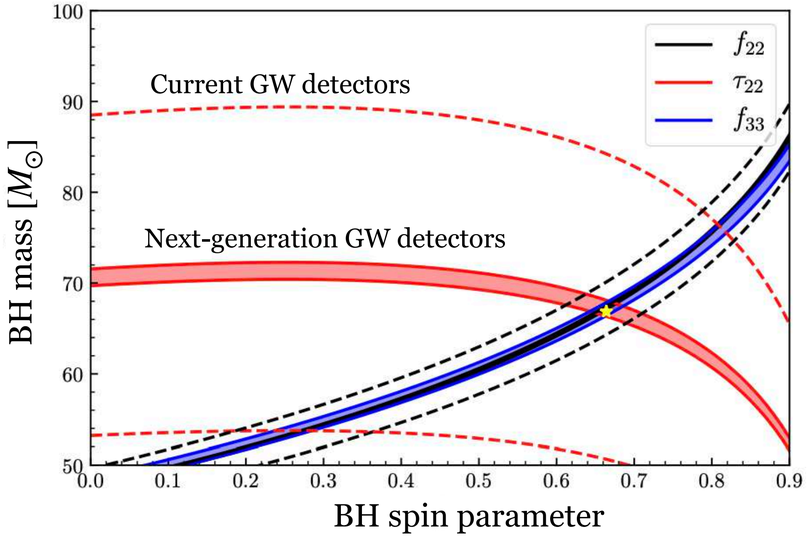
From: Dyson, Spieksma, RB+ '25

Are the objects **black holes** or **something else**?



From: Datta, RB+ '20

Does it **ring** like a black hole, as predicted by GR?



From: RB, Buonanno & Raymond+ '18

“When we contemplate the enormous revolution in our understanding of the universe that has come from electromagnetic astronomy over the four centuries since Galileo, **we are led to wonder what revolution will come from gravitational astronomy over the coming four centuries**, and from its multi-messenger partnerships, over the coming four centuries.” -

Kip S. Thorne, Nobel Lecture, December 8, 2017

“When we contemplate the enormous revolution in our understanding of the universe that has come from electromagnetic astronomy over the four centuries since Galileo, **we are led to wonder what revolution will come from gravitational astronomy over the coming four centuries**, and from its multi-messenger partnerships, over the coming four centuries.” -

Kip S. Thorne, Nobel Lecture, December 8, 2017

10 Anos
Ondas Gravitacionais

Sunday, 14th September 2025
Venue: Pavilhão do Conhecimento, Lisbon
10:00 - 18:00: Exhibition about GWs
16:30 - 18:00: Public lecture by Prof. Vitor Cardoso
(**Note:** lecture will be in Portuguese)

“When we contemplate the enormous revolution in our understanding of the universe that has come from electromagnetic astronomy over the four centuries since Galileo, **we are led to wonder what revolution will come from gravitational astronomy over the coming four centuries**, and from its multi-messenger partnerships, over the coming four centuries.” -

Kip S. Thorne, Nobel Lecture, December 8, 2017

10 Anos
Ondas Gravitacionais

Sunday, 14th September 2025
Venue: Pavilhão do Conhecimento, Lisbon
10:00 - 18:00: Exhibition about GWs
16:30 - 18:00: Public lecture by Prof. Vitor Cardoso
(**Note:** lecture will be in Portuguese)

Thank you!

Backup slides

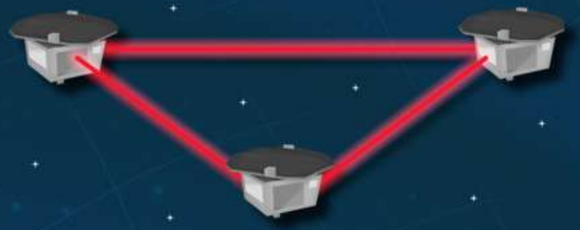
THE SPECTRUM OF GRAVITATIONAL WAVES

esa

Observatories & experiments

Ground-based experiment

Space-based observatory



Pulsar timing array

Cosmic microwave background polarisation

Timescales

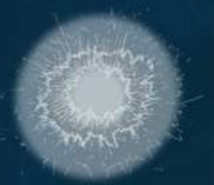
milliseconds — seconds — hours — years — billions of years

Frequency (Hz)

100 — 1 — 10^{-2} — 10^{-4} — 10^{-6} — 10^{-8} — 10^{-16}

Cosmic fluctuations in the early Universe

Cosmic sources



Supernova

Pulsar

Compact object falling onto a supermassive black hole

Merging supermassive black holes

Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

#lisa

ESA | NASA lisa