

# Testing GR with GWs



Vítor Cardoso  
(Niels Bohr & Técnico)

# LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less  
Agog Over Results of Eclipse  
Observations.

## EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed  
or Were Calculated to be,  
but Nobody Need Worry.

## A BOOK FOR 12 WISE MEN

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# DON'T WORRY OVER NEW LIGHT THEORY

Physicists Agree That It Can Be  
Disregarded for Practical  
Purposes.

## NEWTON'S LAW IS SAFE

At Most It Suffers Only Slight  
Correction, Says Prof. Bum-  
stead of Yale University.

## OTHER PROFESSORS' VIEWS

# EINSTEIN EXPOUNDS HIS NEW THEORY

It Discards Absolutè Time and  
Space, Recognizing Them Only  
as Related to Moving Systems.

## IMPROVES ON NEWTON

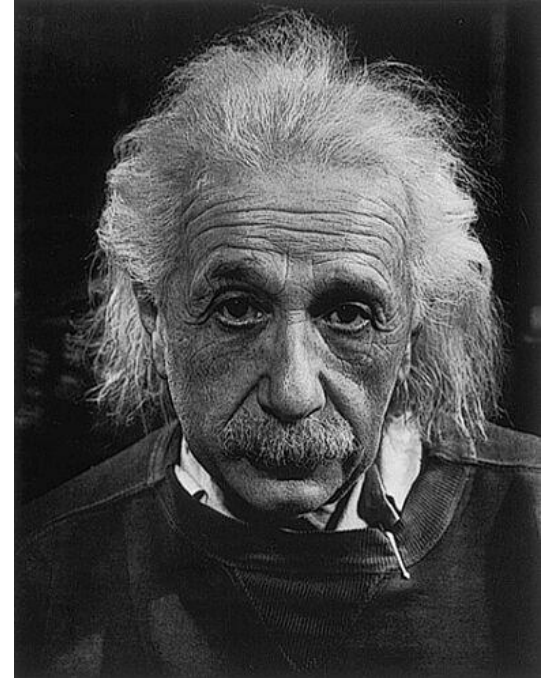
Whose Approximations Hold for  
Most Motions, but Not Those  
of the Highest Velocity.

INSPIRED AS NEWTON WAS

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Articles in The Times  
from Nov. 10, 1919,  
left; Nov. 16, 1919,  
center; and Dec. 3,  
1919.

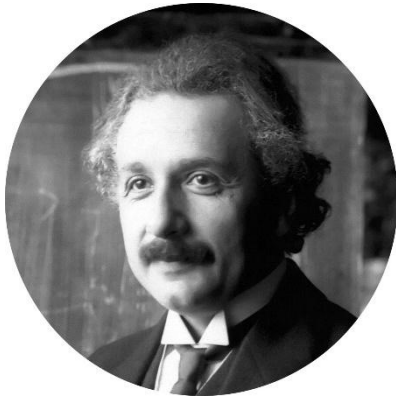
In 1916, Einstein shows that GWs are a consequence of the linear theory.





*“I made at once by good luck a search for a full solution. A not too difficult calculation gave the following result: ...”*

K. Schwarzschild to A. Einstein  
(Letter dated 22 December 1915)



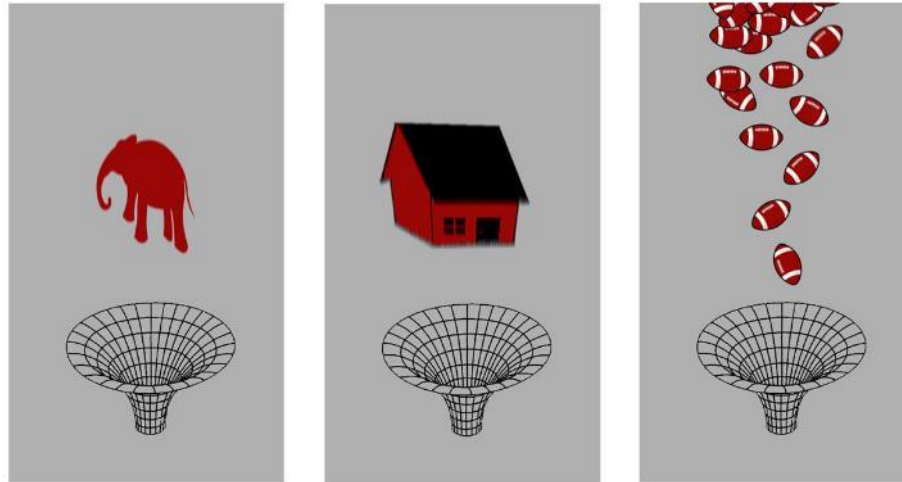
Solution re-discovered by many others:

J. Droste, May 1916 (part of PhD thesis under Lorentz):  
Same coordinates, more elegant

P. Painlevé, 1921, A. Gullstrand, 1922: P-G coordinates (not  
realize solution was the same)

...and others

# Black holes have no hair



Incidentally, the first mention of the theorem was refused by PRD Editor, on the grounds of being obscene (in Kip Thorne's *Black Holes and Time Warps*)

# Black holes have no head!

Theorem (Penrose 1965; 1969):

For “reasonable” matter, black hole formation results in “singularity,” where at least one of the following holds:

- a. Negative local energy occurs.
- b. Einstein's equations are violated.
- c. The space-time manifold is incomplete.
- d. The concept of space-time loses its meaning at very high curvatures – possibly because of quantum phenomena.

# Compact objects exist and we see them



GW150914



GW151012



GW151226



GW170104



GW170608



GW170729



GW170809



GW170814



GW170817



GW170818



GW170823



GW190408\_181802



GW190412



GW190413\_052954



GW190413\_134308



GW190421\_213856



GW190424\_180648



GW190425



GW190426\_152155



GW190503\_185404



GW190512\_180714



GW190513\_205428



GW190514\_065416



GW190517\_055101



GW190519\_153544



GW190521



GW190521\_074359



GW190527\_092055



GW190602\_175927



GW190620\_030421



GW190630\_185205



GW190701\_203306



GW190706\_222641



GW190707\_093326



GW190708\_232457



GW190719\_215514



GW190720\_000836



GW190727\_060333



GW190728\_064510



GW190731\_140936



GW190803\_022701



GW190814



GW190828\_063405



GW190828\_065509



GW190909\_114149



GW190910\_112807



GW190915\_235702



GW190924\_021846

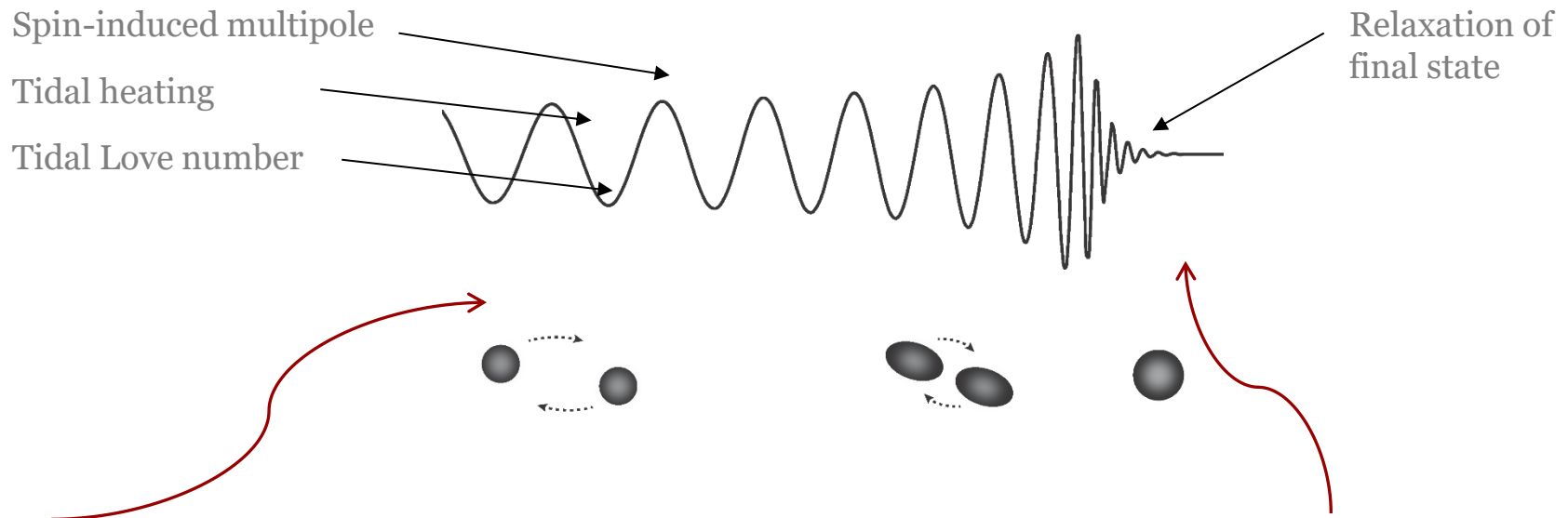


GW190929\_012149



GW190930\_133541

# Black holes exist and they emit gravitational waves



## Inspirational stage, quasi-Newtonian:

Determine individual masses and spins

Determine multipole moments, tidally induced multipoles

Is there dipolar radiation, other polarizations?

Dark matter imprints?

## Breathing of final object:

Determine final mass and spin

Are there postmerger features?

Is Cosmic Censorship preserved?

Are there horizons?

Cardoso & Pani, *Nature Astronomy* 1: 586 (2017); *Living Reviews in Relativity* 22: 1 (2019)

Berti, Cardoso, Carullo + arXiv:2505.23895

# An informal query

(12, 4 LIGO members)

## **2-10 most important discoveries or outcomes of the gravitational-wave astronomy revolution**

Binary black holes exist, merge within a Hubble time

They exist across mass gap

Gravitational waves travel at speed of light

Gold and heavy elements produced during neutron-star mergers

Evidence for light-rings

We are probing horizons

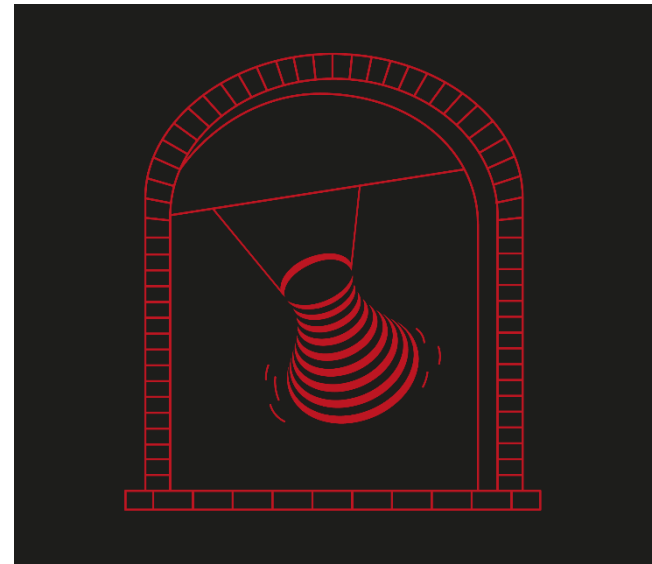
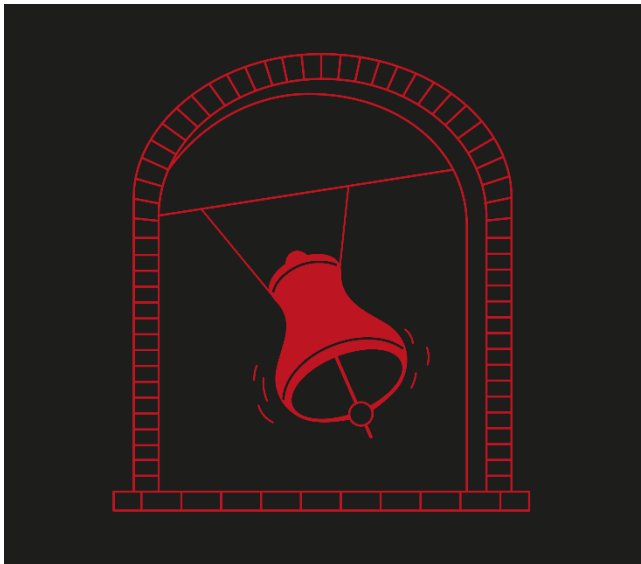
“However, I think that the most important discoveries from GW astronomy are still to come”

# Fundamental questions

Are we really looking at black holes?

Is it the black hole predicted by General Relativity?

Is it evolving in vacuum?



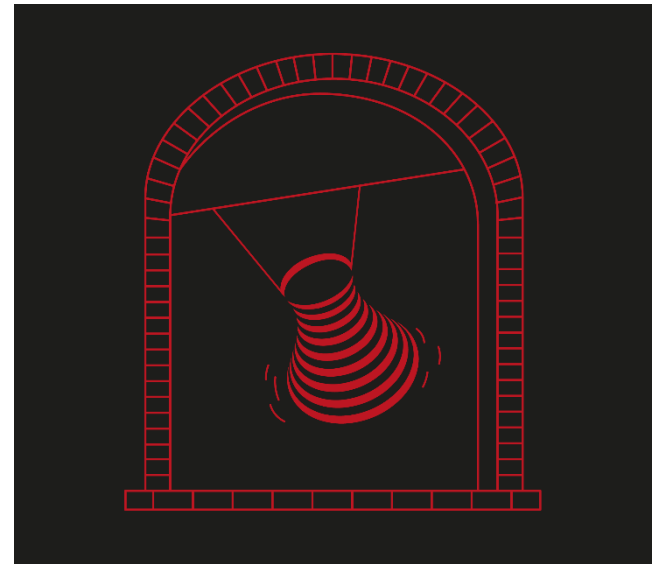
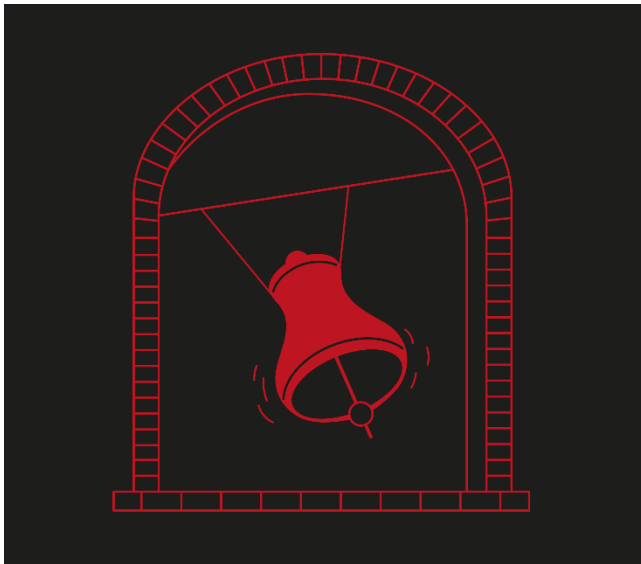
Answer requires understanding of theoretical framework, PDE analysis, precise modelling, observations, challenging simulations & data analysis techniques

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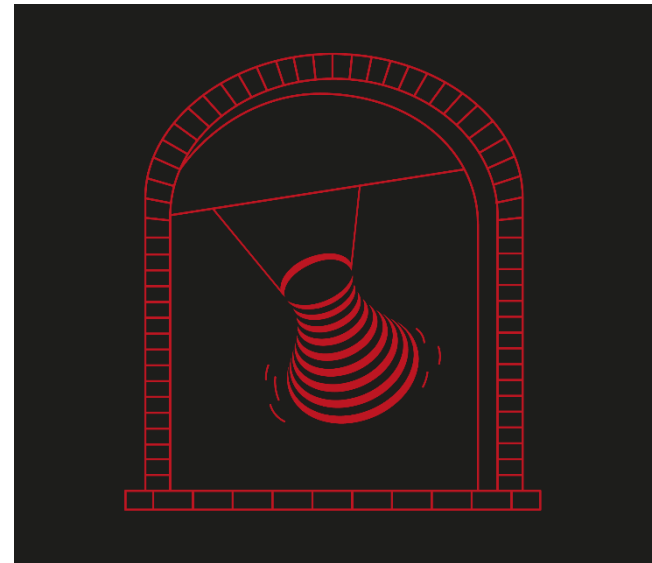
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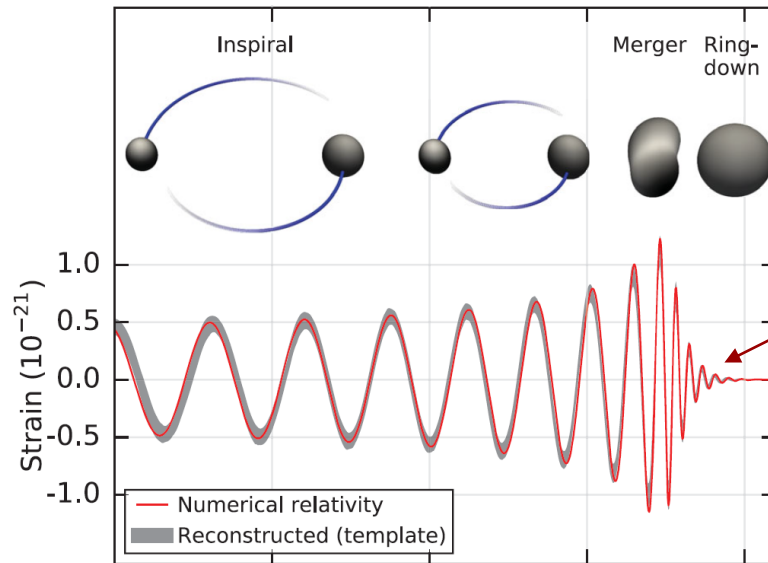
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# BH spectroscopy: testing the Kerr nature



*Ringdown*

$$f = \omega_R / 2\pi = 1.207 \left( \frac{10 M_\odot}{M} \right) \text{ kHz}$$

$$\tau = 1/|\omega_I| = 0.5537 \left( \frac{M}{10 M_\odot} \right) \text{ ms}$$

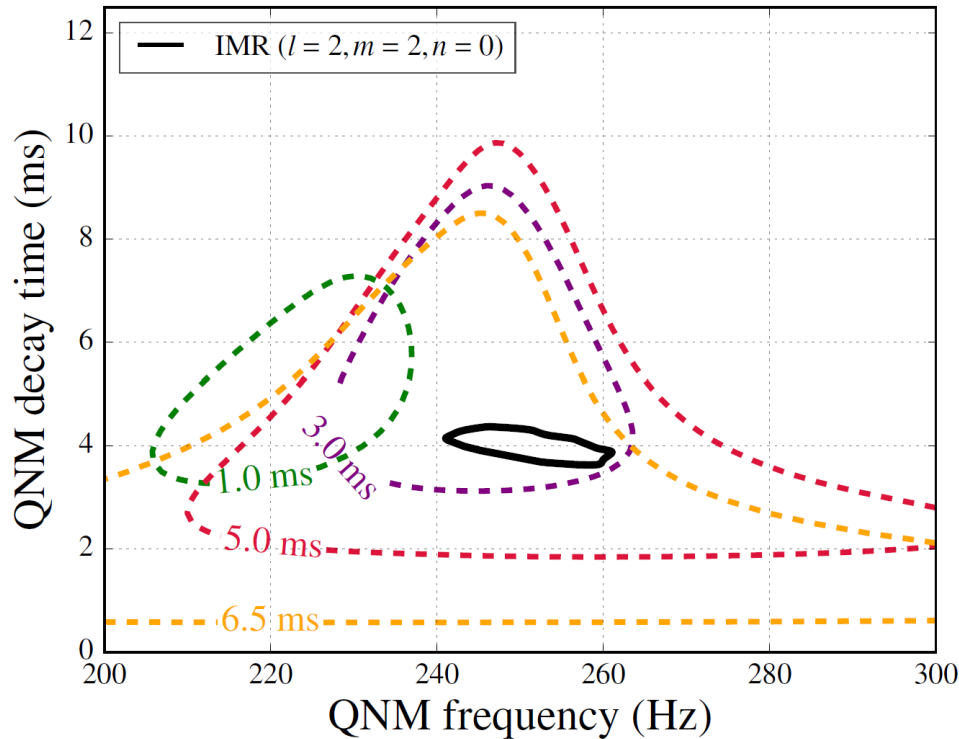
$$\omega = 0.7473433688360837 - i 0.1779246313778714$$

Quality factors of  $\sim 3$ . Black holes don't ring, they relax with a thud.

Berti, Cardoso, Starinets, Classical and Quantum Gravity 26: 163001 (2009)

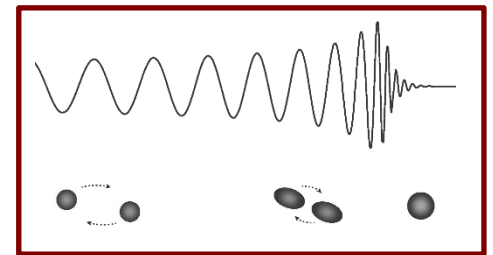
Berti, Cardoso, Carullo + arXiv:2505.23895

# The start of spectroscopy



90% posterior distributions.

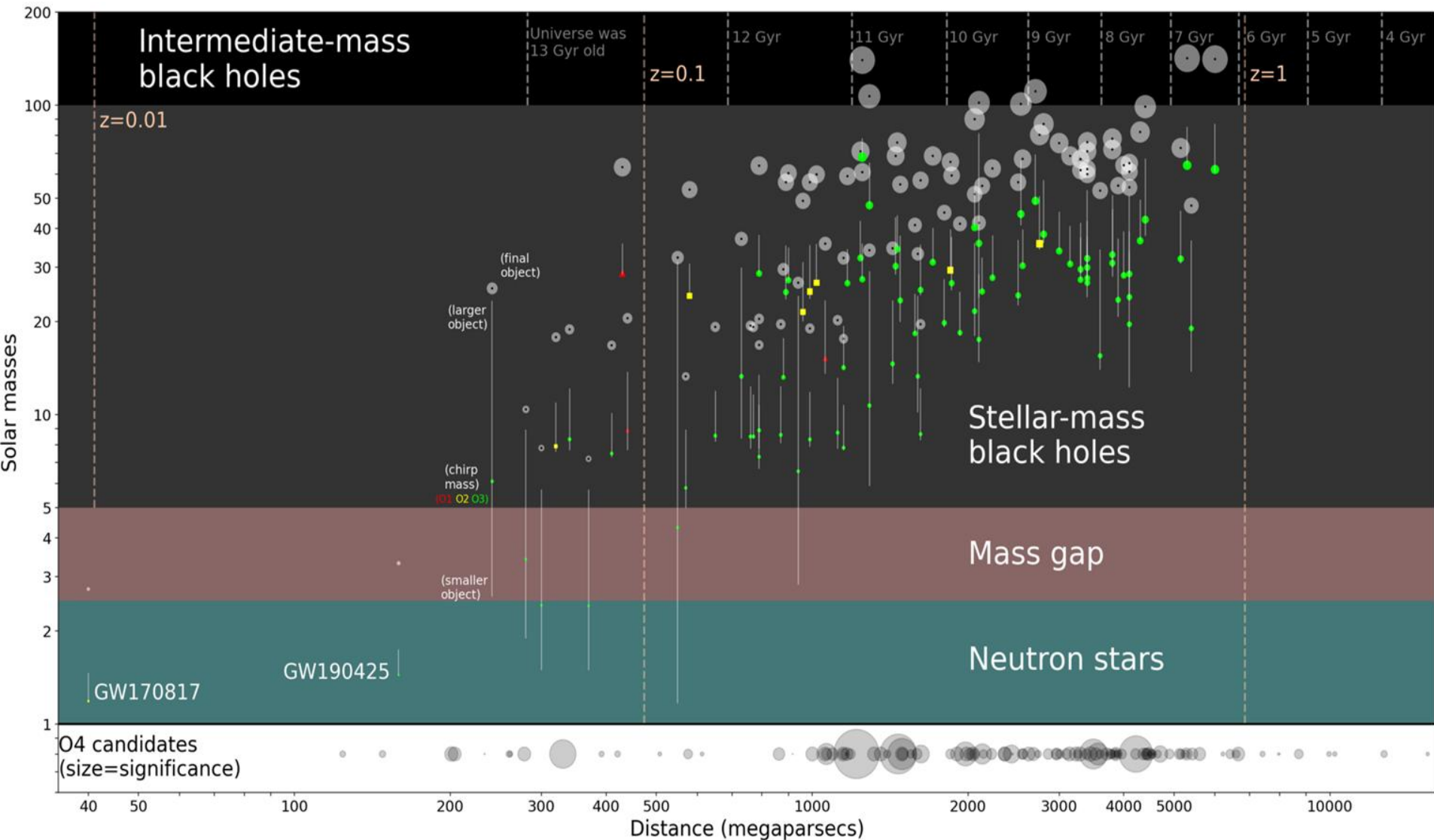
Black solid is 90% posterior of QNM as derived from the posterior mass and spin of remnant



LSC PRL116:221101 (2016); arXiv:2010.14529;

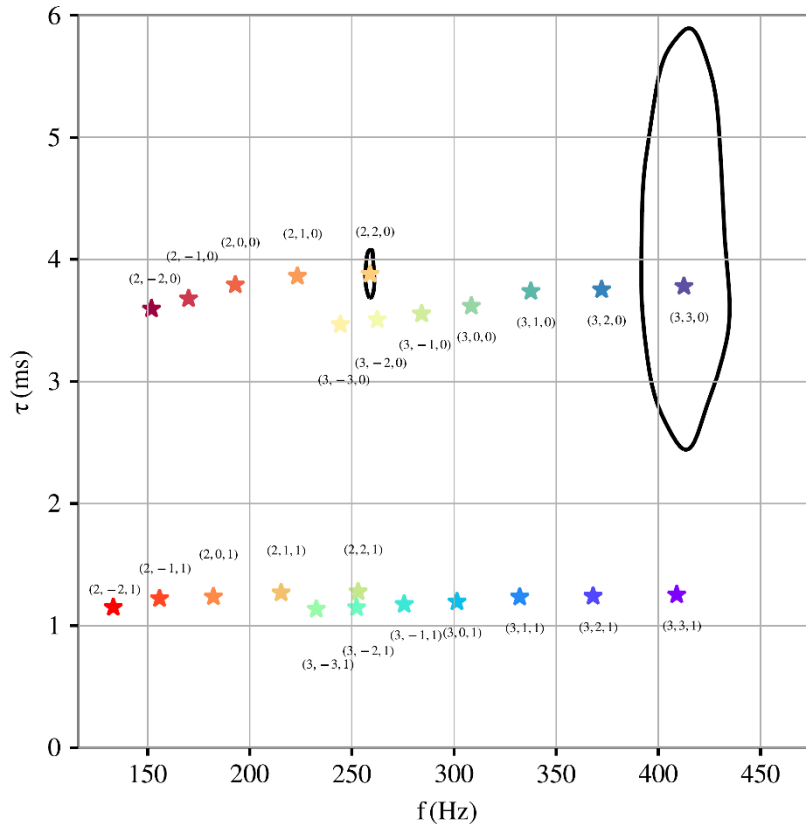
For future detectors: Berti+ PRL117:10102 (2016); Berti, Cardoso, Carullo + arXiv:2505.23895

# The start of spectroscopy





# The future of spectroscopy



90% posterior distributions.

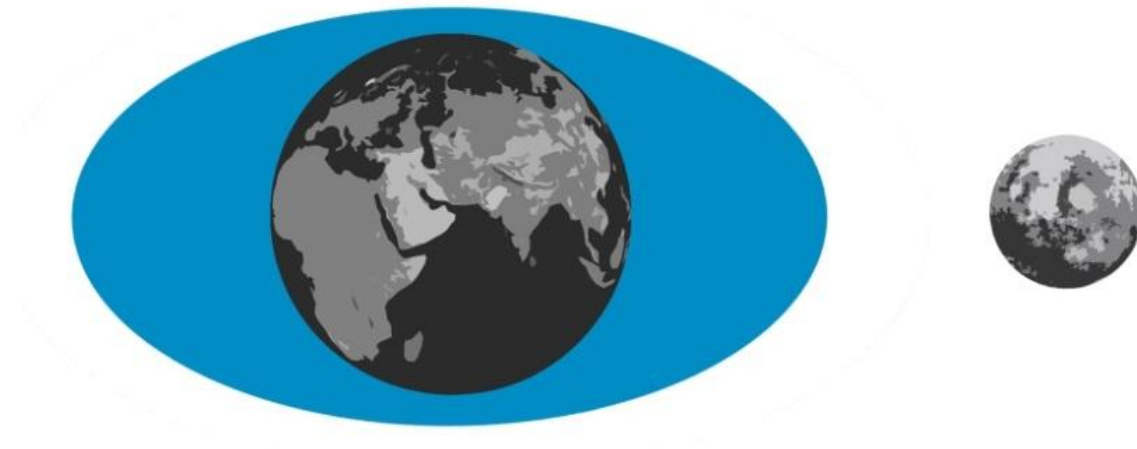
Black solid is 90% posterior of QNM from a future event with SNR=40 in ringdown.

LISA will see SNRs of thousands...

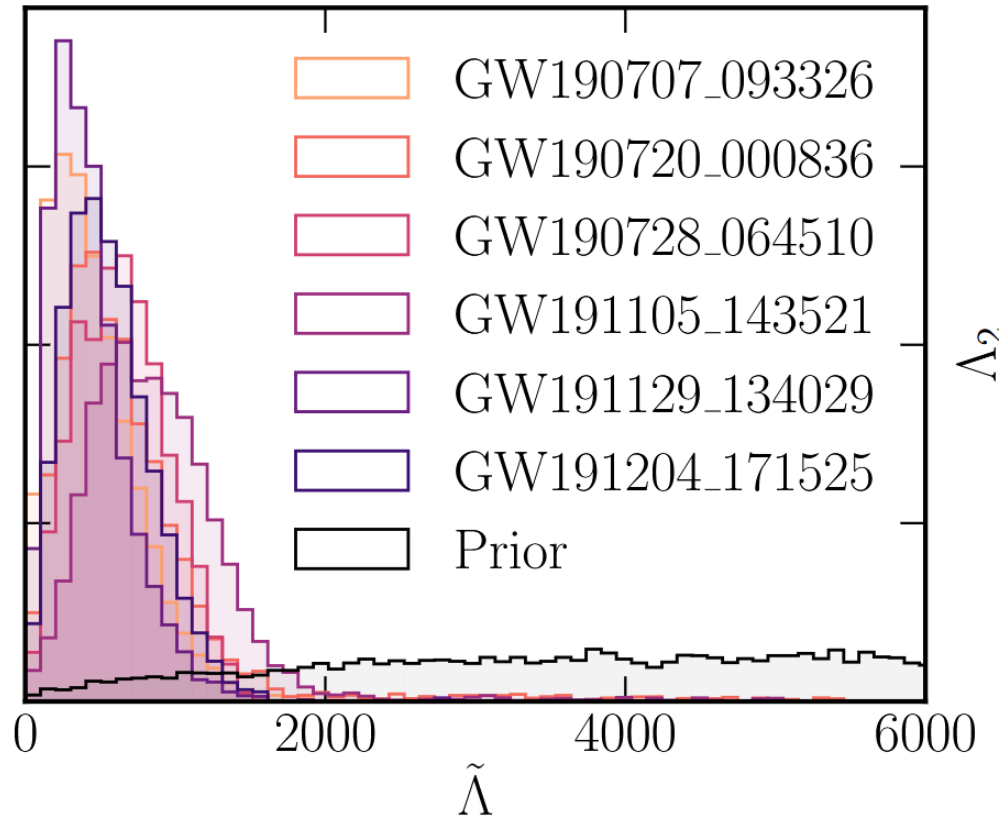
Courtesy of Gregorio Carullo

See also Berti+ PRL117:10102 (2016); Bhagwat+ arXiv:2304.02283

# Black holes have no hair and raise no tides

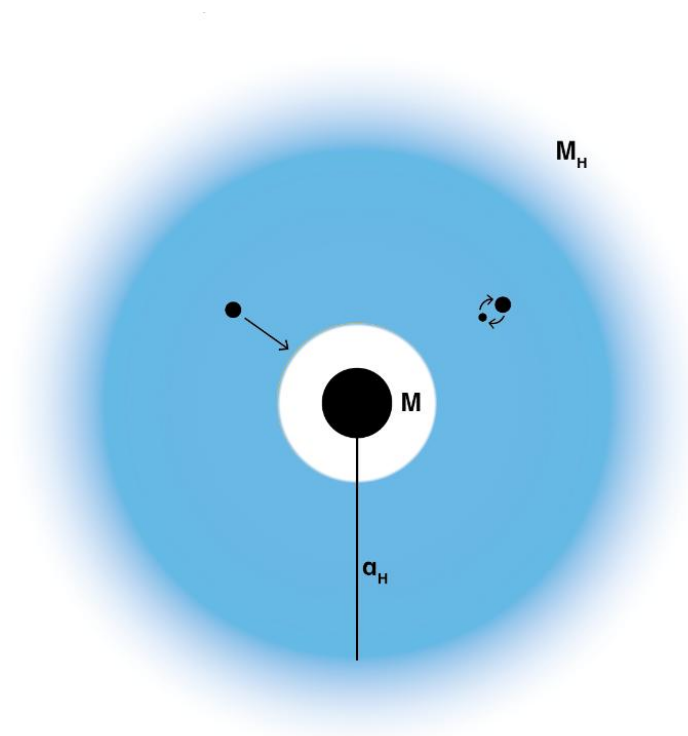


Binnington and Poisson PRD80:084018 (2009);  
Damour and Nagar PRD80:084025 (2009);  
Cardoso+ PRD95:084014 (2017)



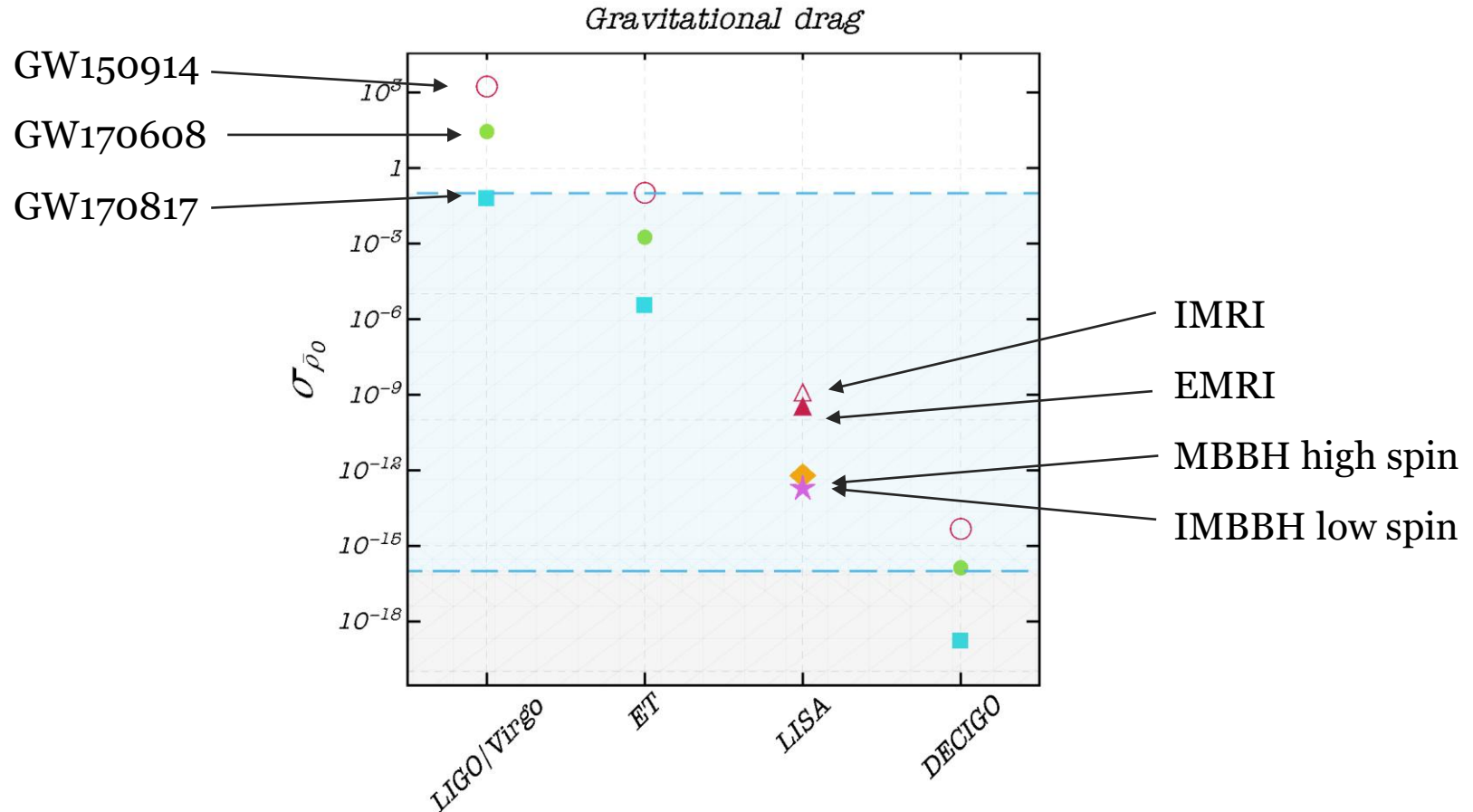
Marginalized  $\Lambda$  posteriors for the six best events. Posteriors are prior dominated at  $\Lambda \sim 0$ , therefore results do not suggest evidence for  $\Lambda > 0$  Chia + PRD 110:063007 (2024)

# Are results affected by environment?



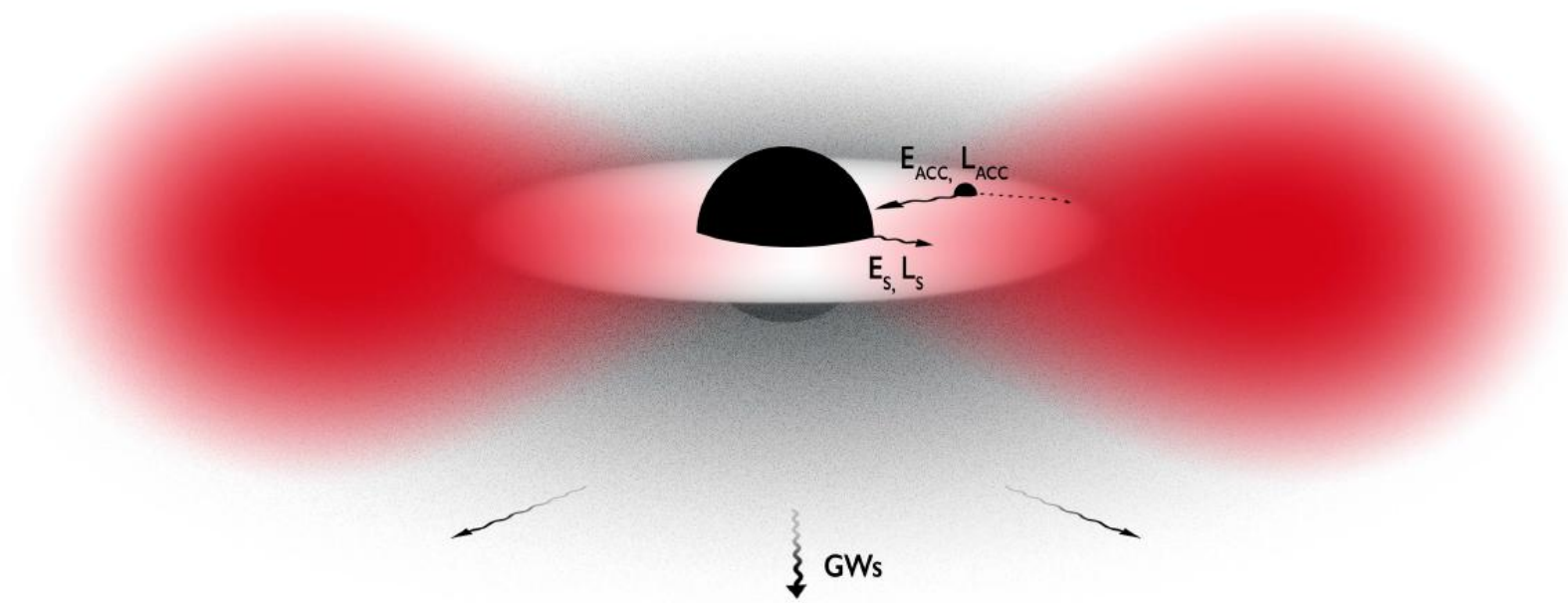
Yes

# Small Compton wavelength: heavy DM



Effect is -5.5 PN on GW phase

Cardoso & Maselli AA644: A147 (2020); Macedo+ApJ774 (2013) 48;  
Annunli+ PRD102;063022 (2020); see Santoro+ PRL132:251401 (2024) for updates



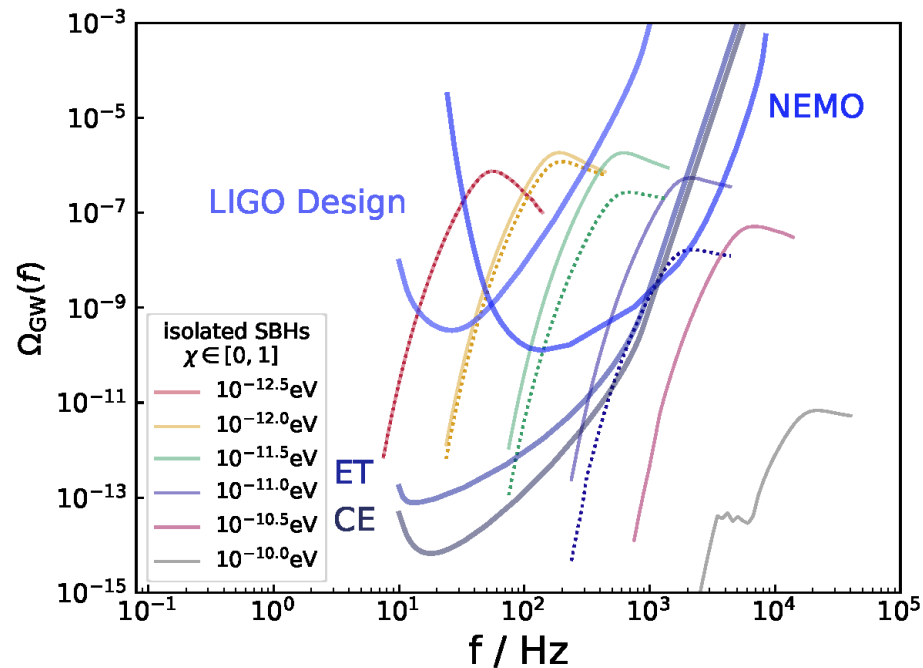
© a.s./grit

## Wonderful sources of GWs

*Brito, Cardoso, Pani, Lecture Notes Physics 971: 1-293 (2020)*

# Wonderful sources for different GW-detectors

Arvanitaki+ PRD91: 084011 (2015); Brito + PRL119: 131101 (2017); Yuan + PRD 104:044011 (2021)



Dotted lines only include  $m = 1$  mode, solid lines include all modes. Plot also shows power-law integrated sensitivity curves. Assume four-year-detection and two co-aligned and co-located identical detectors for NEMO/CE/ET.

Also LIGO Scientific Collaboration arXiv:2111.15507;  
For LISA see Brito + PRL119: 131101 (2017); PRD96:064050 (2017)

# Constraints on fundamental fields via superradiance

Review in Brito+ Lect. Notes Phys.971 (2020); Updated constraints to appear soon

	excluded region (in eV)	source
*	$5.2 \times 10^{-13} < m_S < 6.5 \times 10^{-12}$	Direct bounds from absence of spin down in Cyg X-1.
*	$1.1 \times 10^{-13} < m_V < 8.2 \times 10^{-12}$	
*	$2.9 \times 10^{-13} < m_T < 9.8 \times 10^{-12}$	
	$6 \times 10^{-13} < m_S < 2 \times 10^{-11}$	Indirect bounds from BH mass-spin measurements.
	$7 \times 10^{-20} < m_S < 1 \times 10^{-16}$	
*	$2 \times 10^{-14} < m_V < 1 \times 10^{-11}$	
*	$1 \times 10^{-20} < m_V < 9 \times 10^{-17}$	
*	$6 \times 10^{-14} < m_T < 1 \times 10^{-11}$	
*	$3 \times 10^{-20} < m_T < 9 \times 10^{-17}$	
	$1.2 \times 10^{-13} < m_S < 1.8 \times 10^{-13}$	Null results from blind all-sky searches for continuous GW signals.
	$2.0 \times 10^{-13} < m_S < 2.5 \times 10^{-12}$	
	$m_V$ : NA $m_T$ : NA	
	$5.8 \times 10^{-13} < m_S < 8.6 \times 10^{-13}$	Null results from searches for continuous GW signals from Cygnus X-1.
	$m_V$ : NA $m_T$ : NA	
	$2.0 \times 10^{-13} < m_S < 3.8 \times 10^{-13}$	
	$m_V$ : NA $m_T$ : NA	Negative searches for a GW background.
	$5 \times 10^{-13} < m_S < 3 \times 10^{-12}$	
	$m_V \sim 10^{-12}$ $m_T$ : NA	Bounds from pulsar timing.
	$2.9 \times 10^{-21} < m_S < 4.6 \times 10^{-21}$	
	$8.5 \times 10^{-22} < m_V < 4.6 \times 10^{-21}$	Bounds from mass and spin measurement of M87 with EHT.
*	$1.0 \times 10^{-21} < m_T < 8.2 \times 10^{-21}$	

# GW Fest

Strong field gravity is a fascinating topic.

From precise maps of our Universe to tests of Cosmic Censorship,  
and constraints on dark matter candidates, possibilities  
are endless and exciting.

**Thank you**

