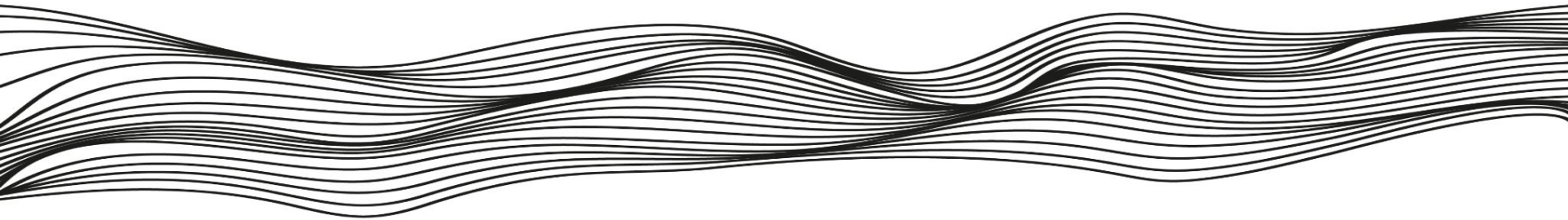
The Sound of Black Holes

Marina De Amicis, Lorena Magaña Zertuche & Jaime Redondo-Yuste



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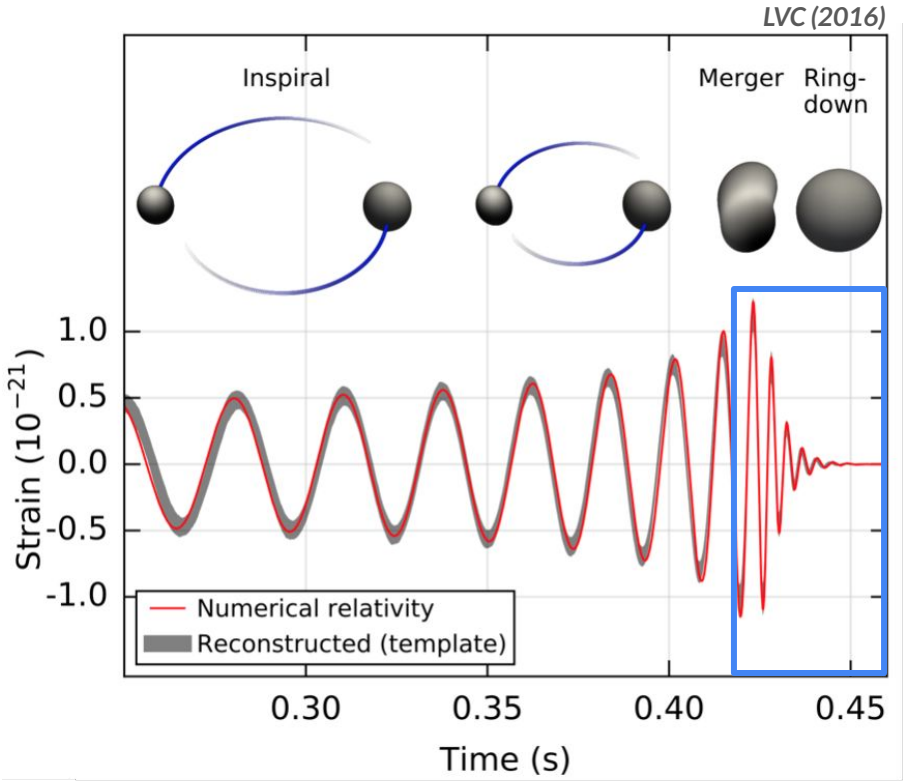
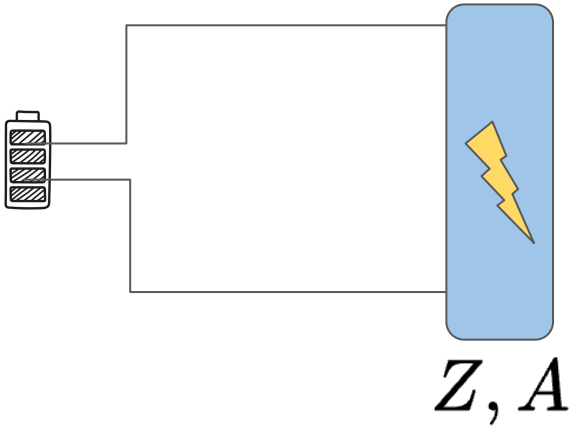
Outline

1. Black Hole Spectroscopy
2. How Does a Black Hole Relax?
3. State-of-the-Art
4. Recent Developments
5. Outlook

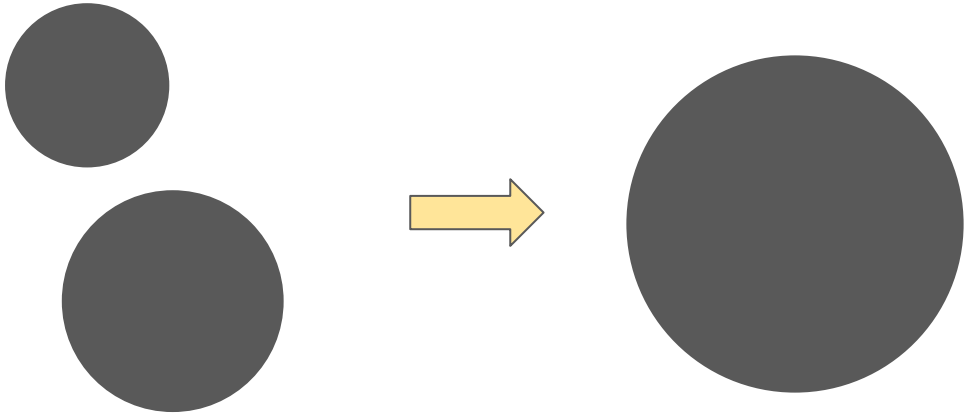


Black Hole Spectroscopy

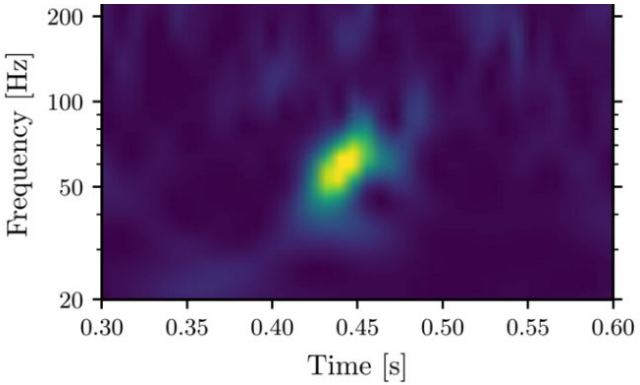


Frequencies of the emission lines → Fundamental properties of the gas

Black Hole Spectroscopy

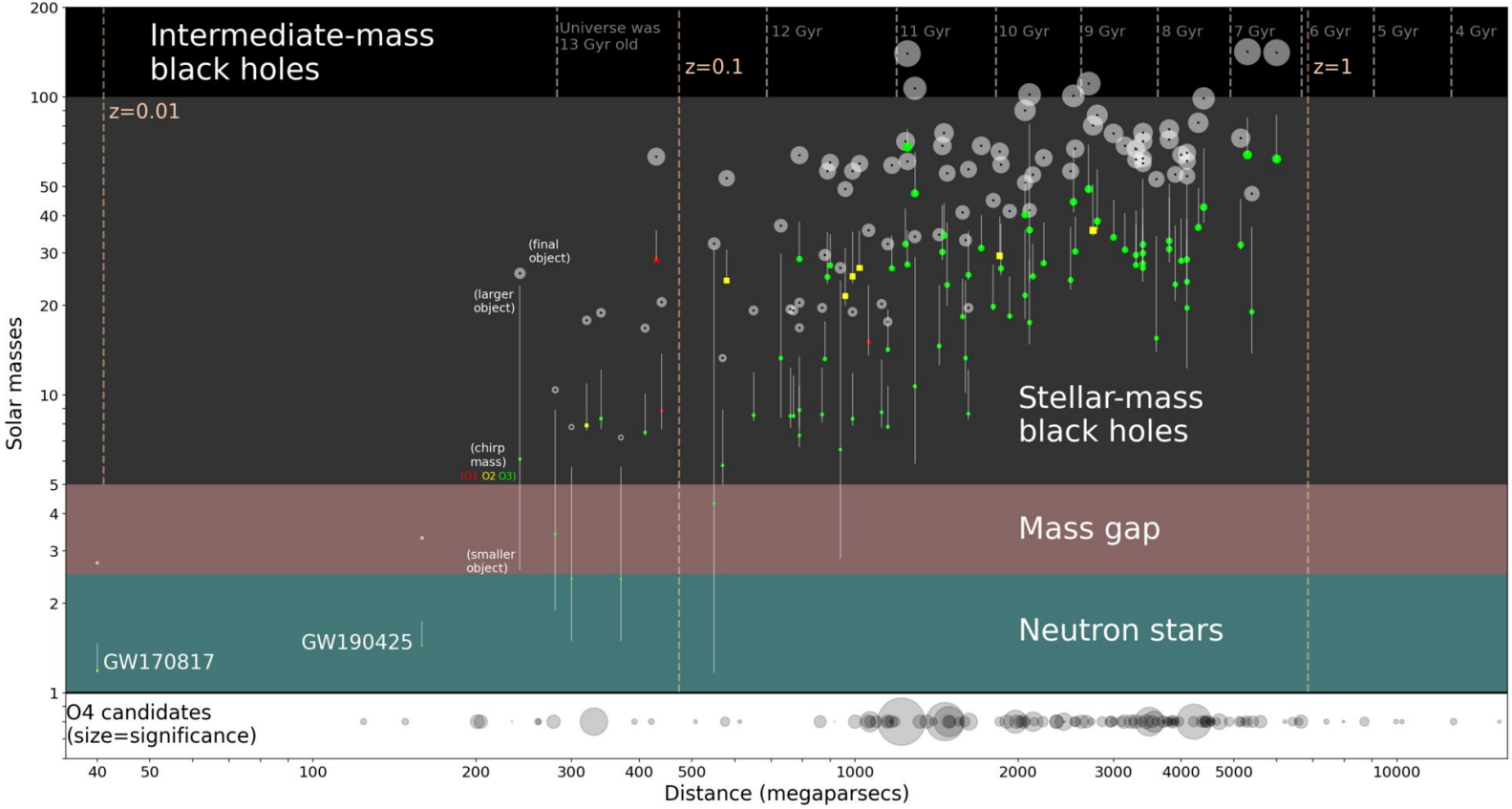


$M, J, (Q)$



Relaxation frequencies (and half-lives) → Fundamental properties of the compact object

Black Hole Spectroscopy



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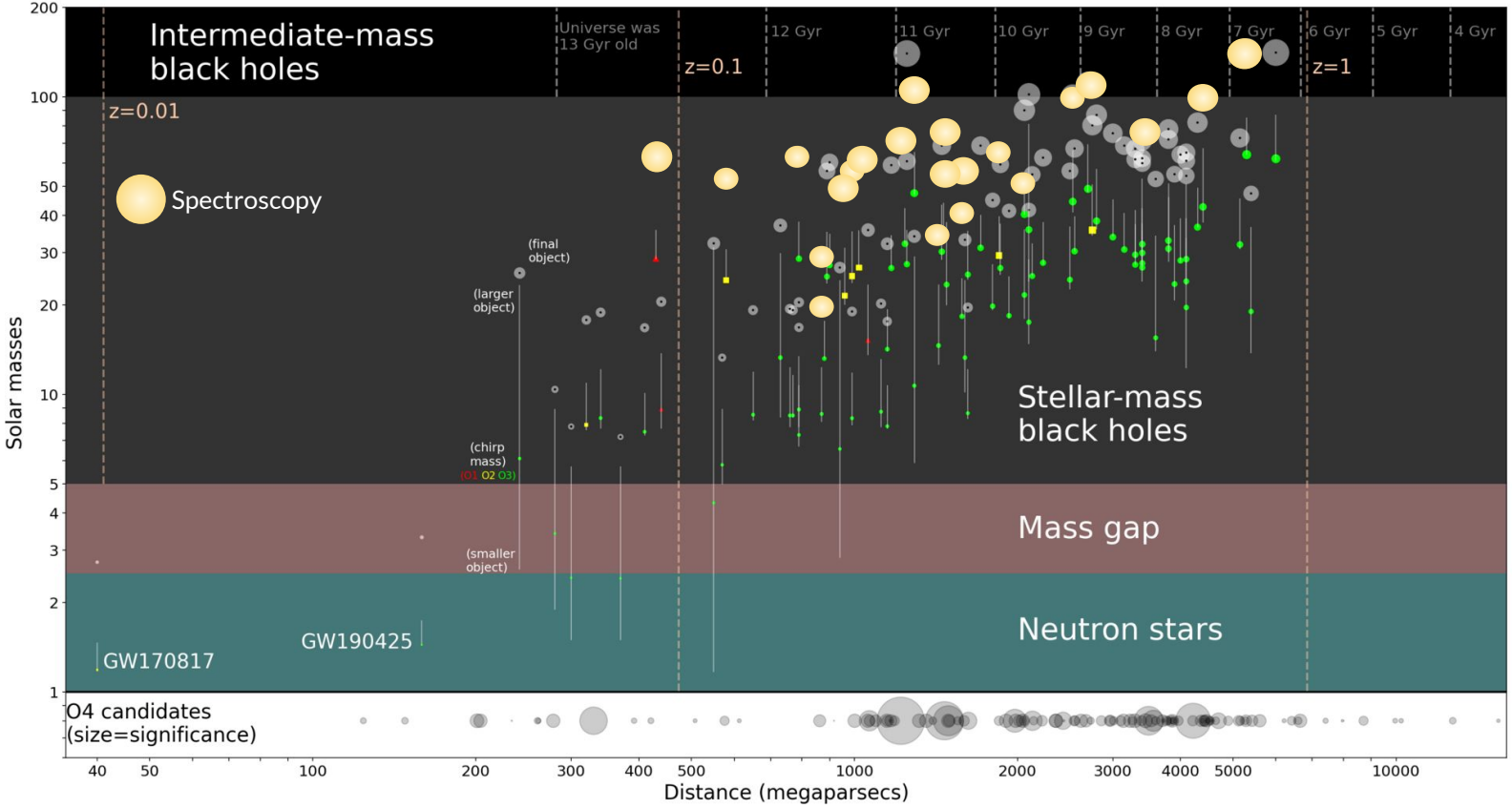
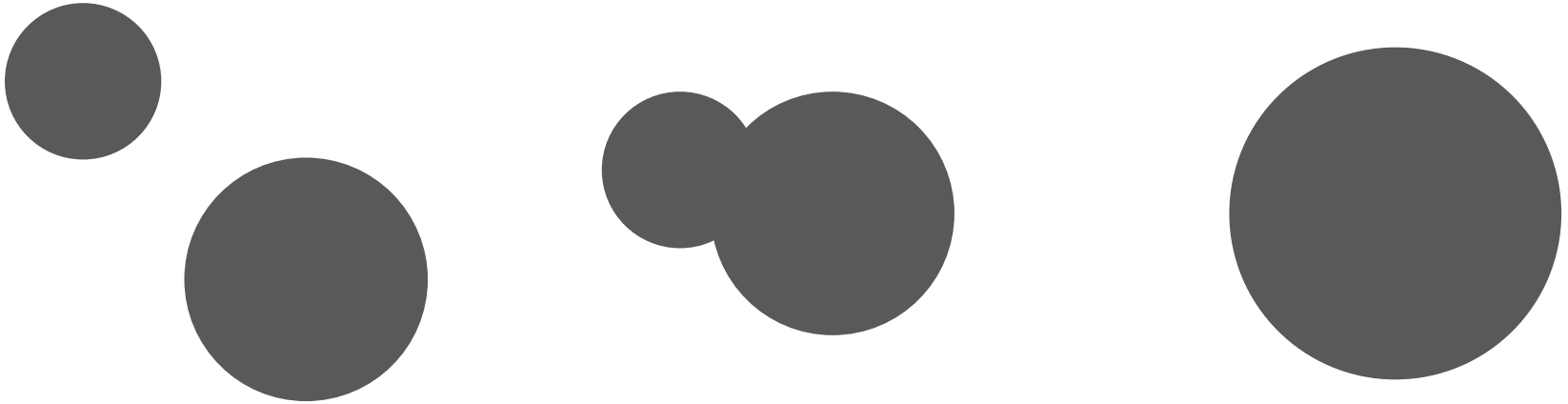
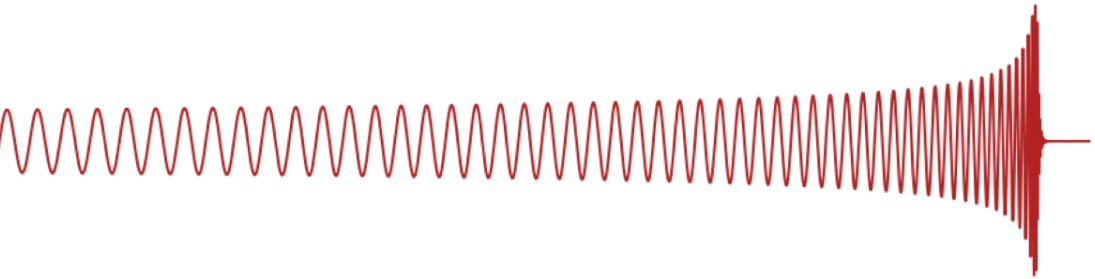


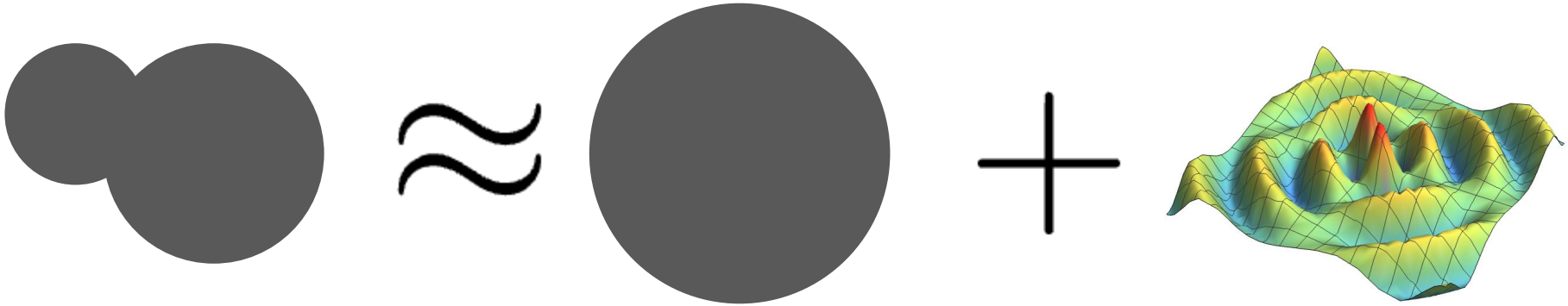
How does a black hole relax?





Timescale: $\tau \sim 3\mathrm{ms}\left(\frac{M}{50M_{\odot}}\right)$

How does a black hole relax?

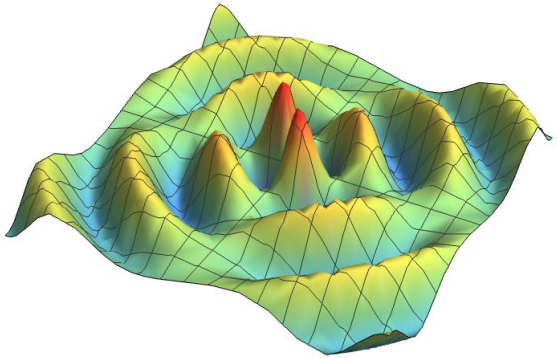


Kerr Black Hole

$M, J, (Q)$

small fluctuation

How does a black hole relax?



Perturbations governed by a wave-like equation in curved space

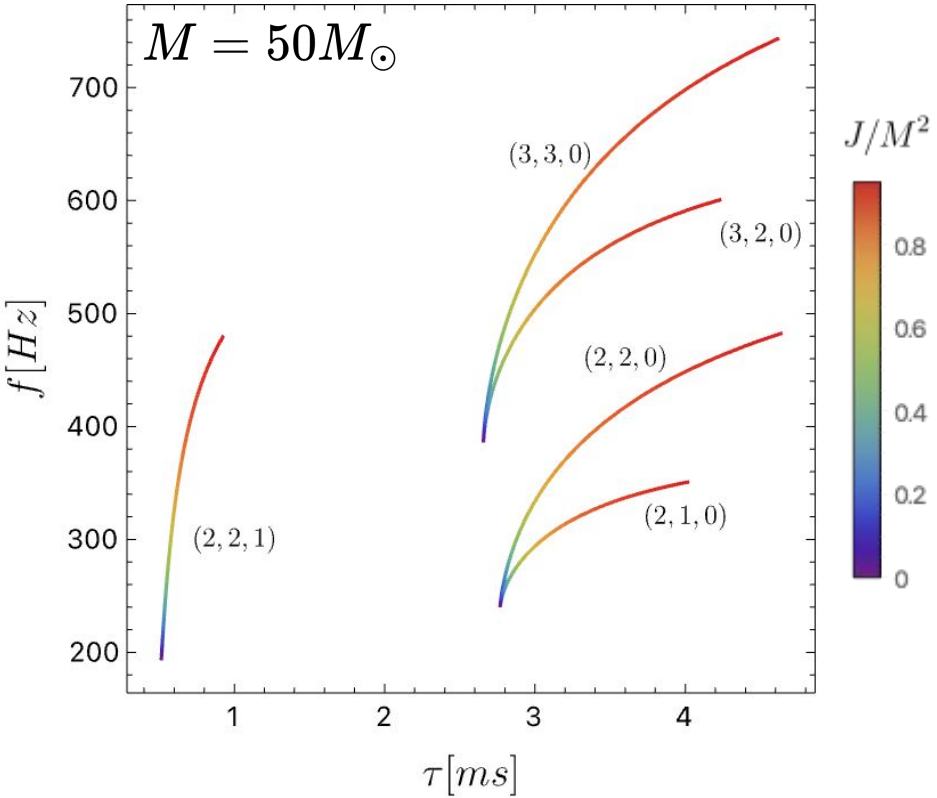
Black hole horizon + Radiation at infinity fix boundary conditions

Can look for mode solutions–much like modes of a guitar string

$$h = \sum_{\ell,m,n,\pm} A_{(\ell,m,n,\pm)} e^{i\omega_{(\ell,m,n,\pm)}(t-t_{\rm Peak})}$$

$$\omega_{(\ell,m,n,\pm)} = f - i/\tau$$

How does a black hole relax?



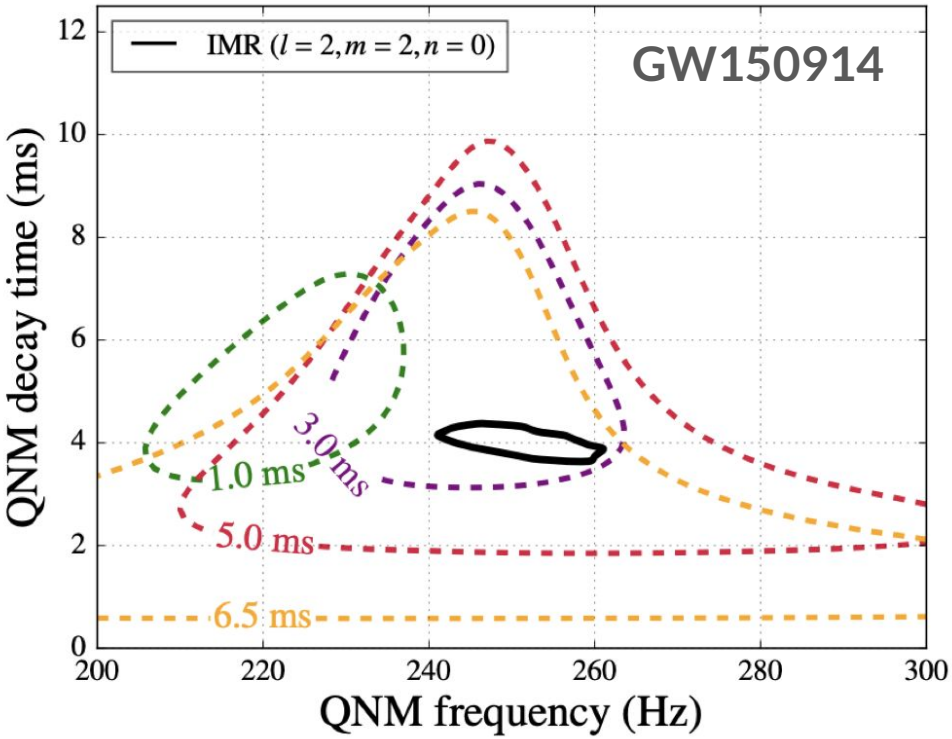
Amplitudes depend on binary configuration

(Eccentricity, Precession, Mass Ratio…)

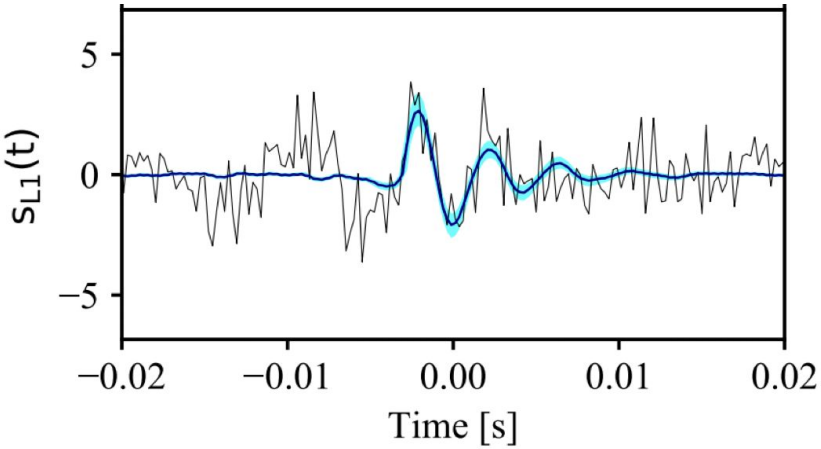
Frequencies depend only on (M,J)!

Each frequency– 2 parameters

State of the Art

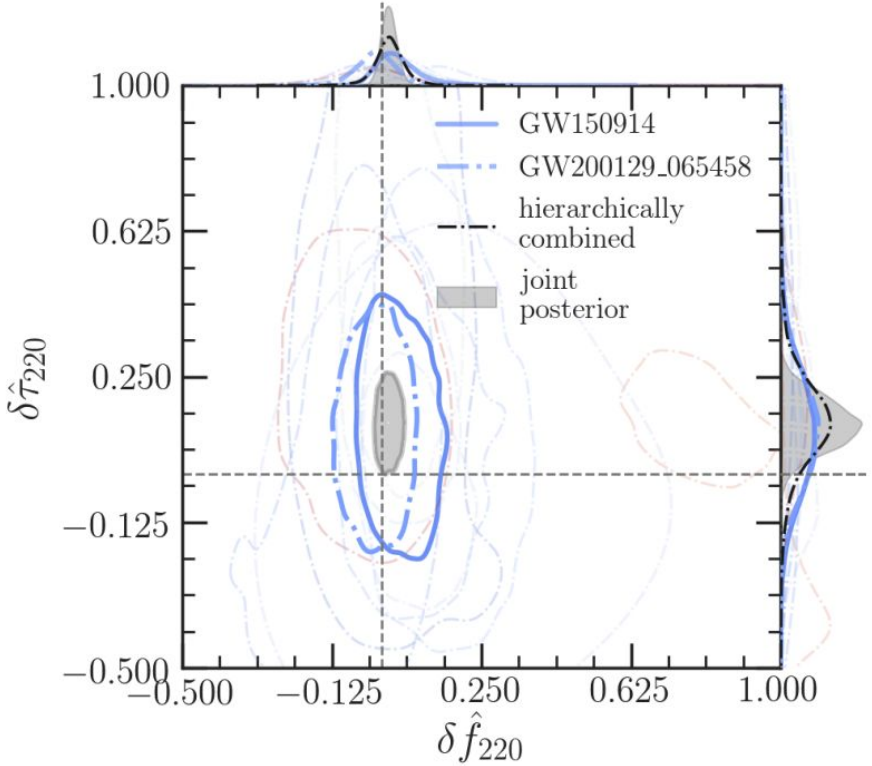


LVC (2016)



Measured 1 mode consistently–independent measurement of the mass and spin

State of the Art

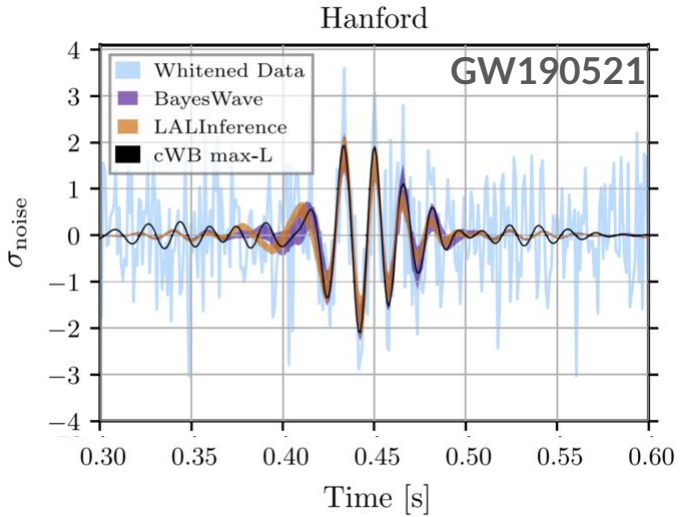


LVK (2021)

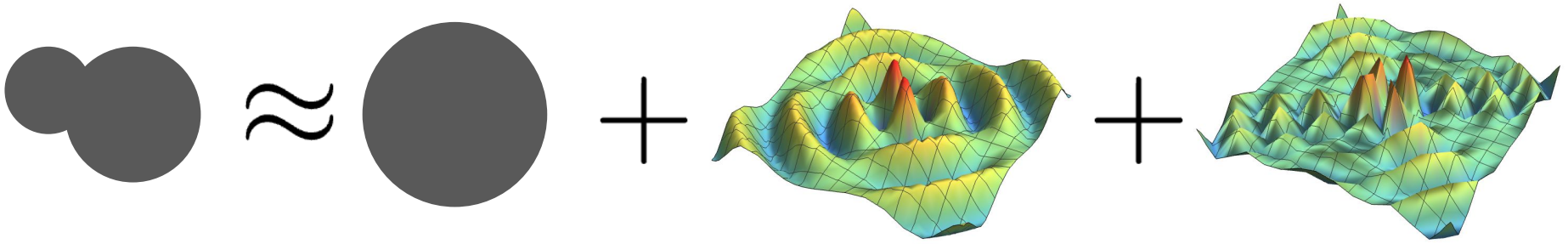
No surprises after the 1st event (so far!)

Some puzzles remain open:

ringdown dominated events?



Recent Developments



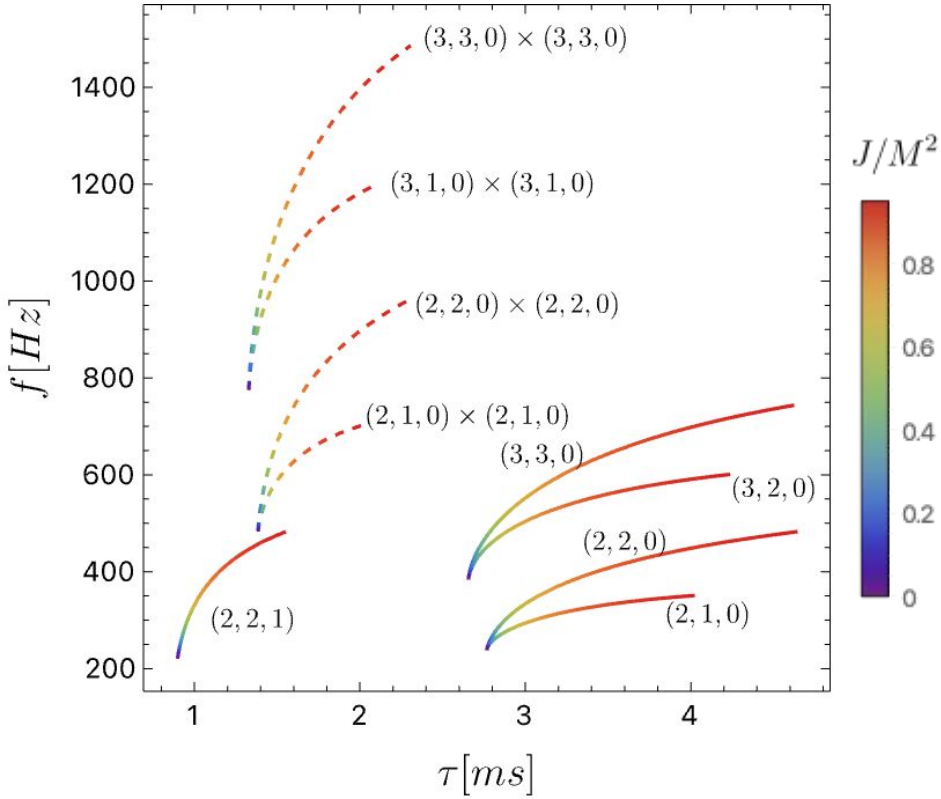
Kerr Black Hole

$M, J, (Q)$

small fluctuation

nonlinear effects!

Recent Developments



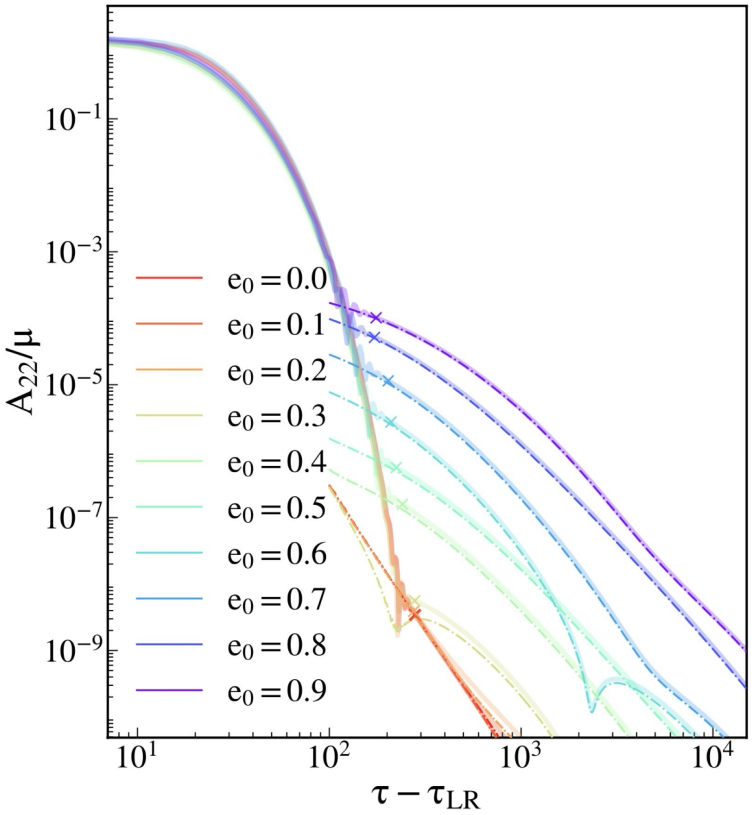
Quadratic modes (like higher harmonics)

Their amplitudes are fixed by (M,a) and the amplitude of the progenitors!

LISA / 3G will observe them (probably)!

Cheung+ (2022)
JRY+ (2023)
Yi+ (2024)

Recent Developments



Late-times tails

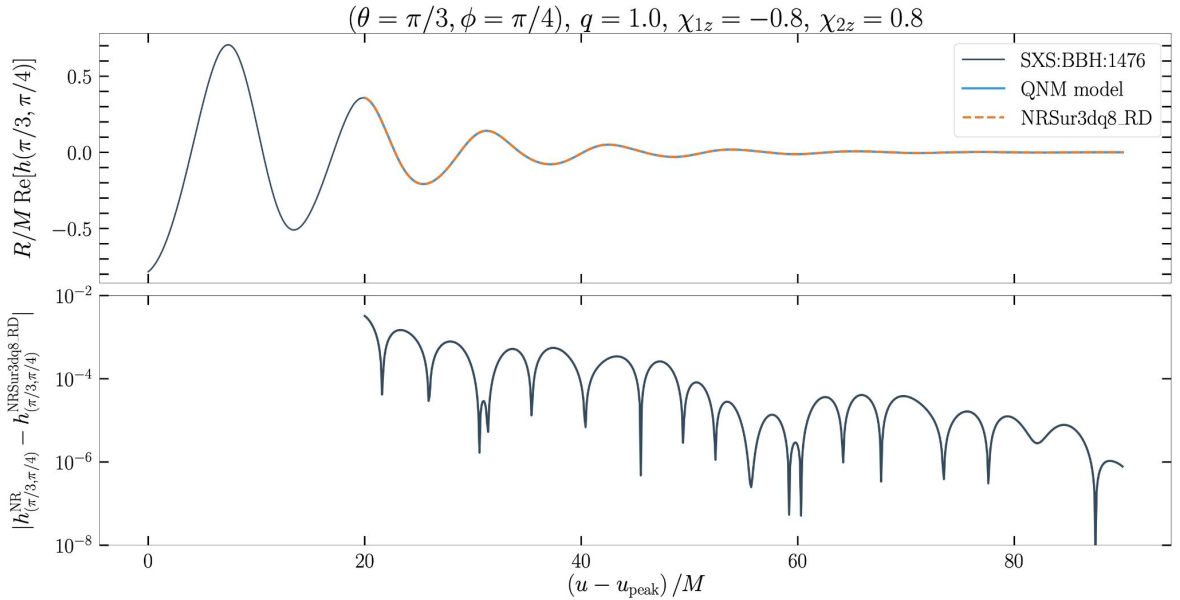
$$h_{\ell m} = \sum_{n,\pm} A_{\ell m n \pm} e^{-i\omega_{\ell m n \pm}(t - t_{\rm peak})} + \sum_{k} \frac{C_{\ell k}}{(t - r_*)^{\ell+2+k}}$$

Enhanced by inspiral eccentricity

Probes of large-scale effects

De Amicis + (2024)
Ma + (2024)

Recent Developments



Waveform Modelling

IMR models now include (2,0) memory modes and account for BMS frames.

Yoo+ (2023)
Albanesi (2024)
Rosselló-Sastre+ (2024)

High-precision ringdown-only surrogate built with multiple modes, overtones, and mirror modes + BMS frame fixing

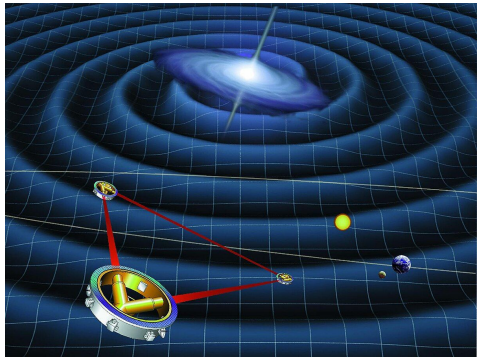
Magaña Zertuche+ (2024)

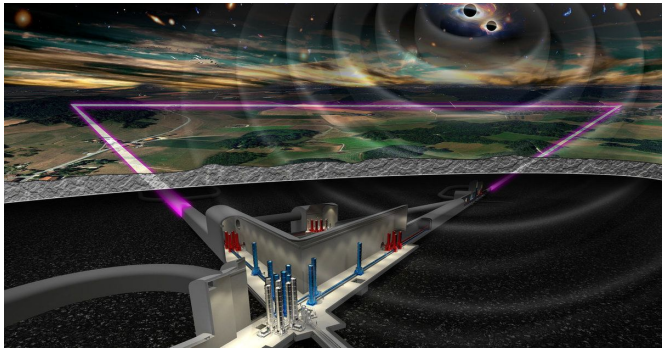
Outlook

Stay tuned for new LVK observing runs + LISA!

Fundamental physics: do we see Black Holes? Are observations consistent with GR?

Astrophysics: environmental effects? constraint better binary parameters?



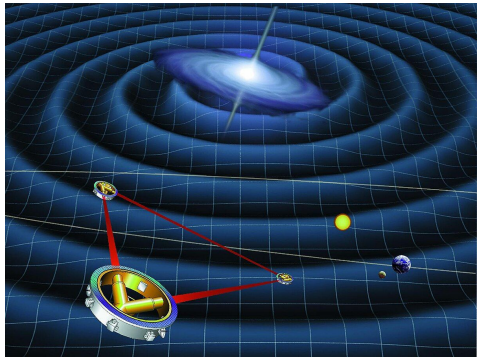


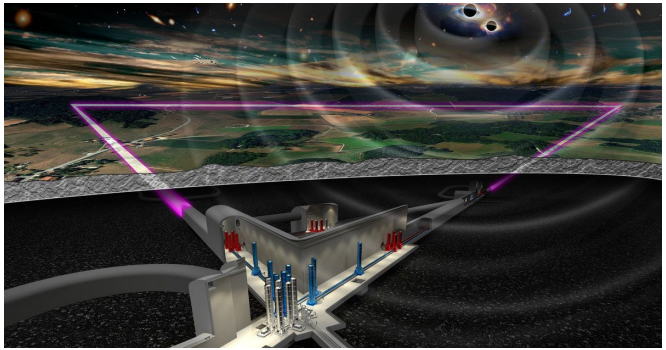
Outlook

LVK has already out-performed expectations–first multi-mode observation sooner than later

SMBHB in LISA + 3G detectors will reach enough precision to properly study ringdown

Prospects on fundamental physics (do we really see black holes?) but also astrophysics (are black holes alone?)





Outlook

LVK has already surpassed expectations–first multi-mode observation sooner than later.

Next generation detectors will reach enough precision to see a rich ringdown spectrum and test general relativity.

Prospects on fundamental physics (do we really see black holes?) but also astrophysics (are black holes alone?)