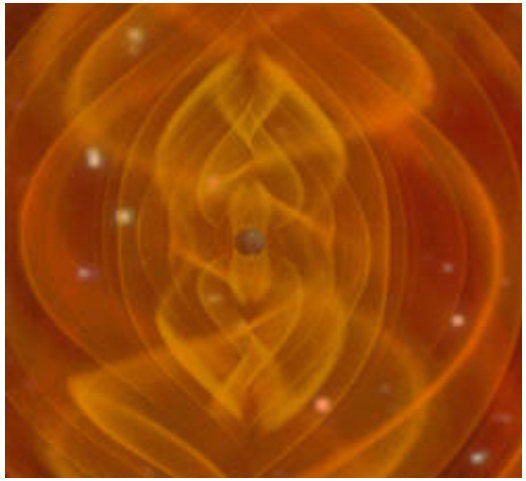

Gravitational waves as a probe of black hole mimickers

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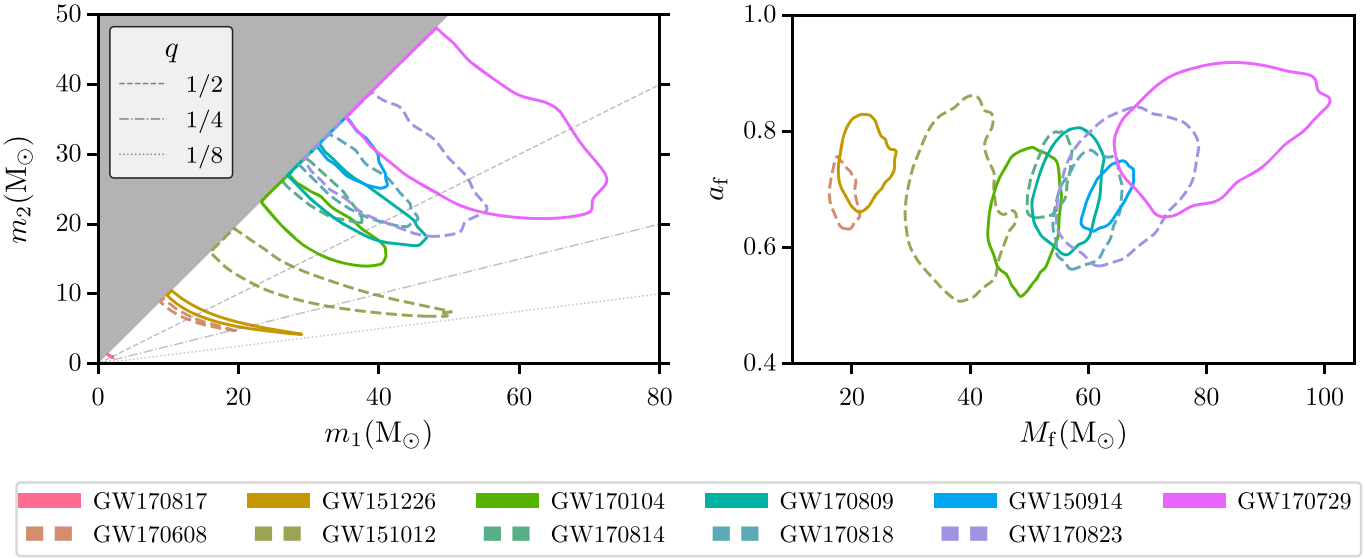
Nikhef

Nikhef Jamboree, 16-17 December 2019

What is the nature of compact objects?

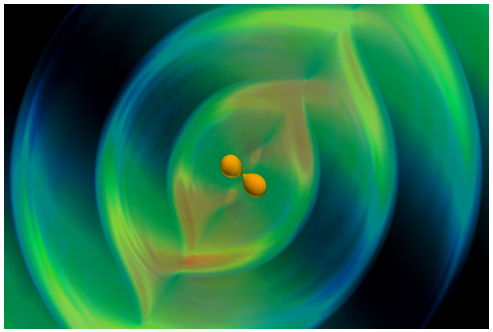


- We regularly see mergers of binaries involving masses above 3 solar masses: *presumed black holes*

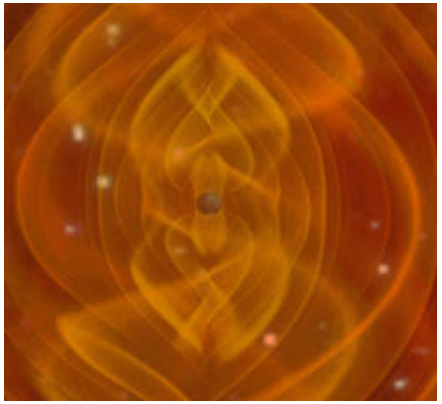
How certain are we that these are the standard (Kerr) black holes of classical general relativity?

- Alternatives:
  - Boson stars
  - Dark matter stars
  - Gravastars
  - Wormholes
  - Firewalls
  - *The unknown*

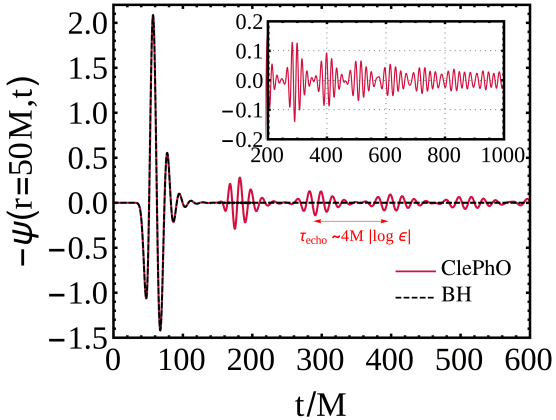
Gravitational wave signatures of alternative objects



1. Anomalous effects during inspiral

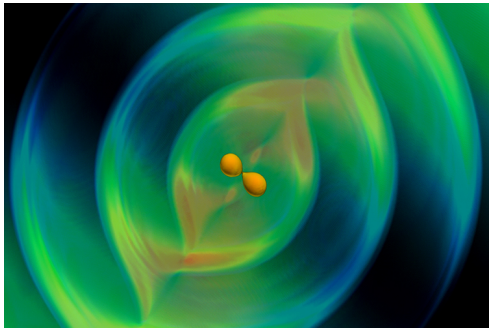


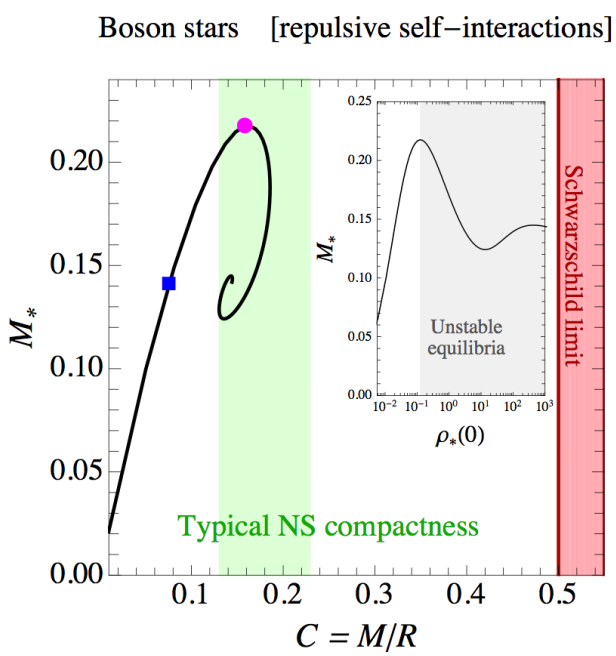
2. Ringdown of newly formed object



3. Gravitational wave echoes

Gravitational wave signatures of alternative objects





1. Anomalous effects during inspiral

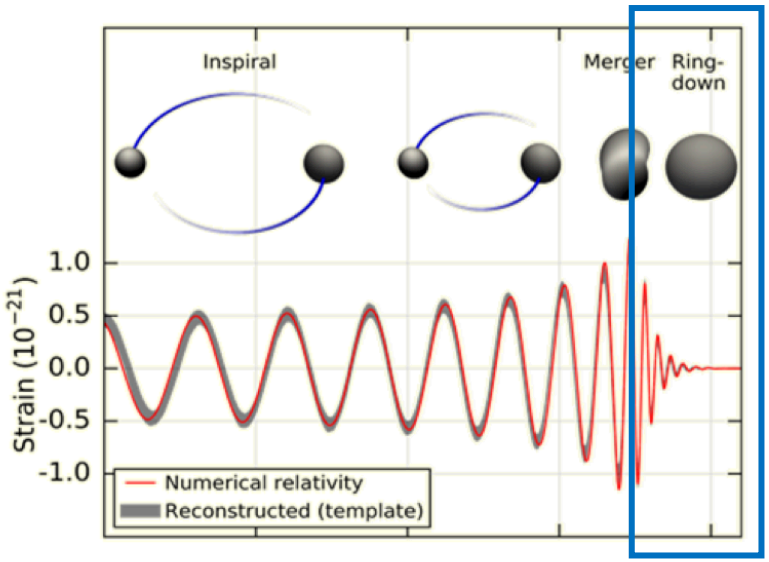
- Tidal effects cause quadrupole moments in each object, which modify GW signal
- Effect enters the waveform through *compactness C* = mass/radius
  - In particular, through $1/C^5 = (R/M)^5$
- Boson stars can exist in wide mass range and have more noticeable effect than neutron stars

$$M_* = \left(\frac{M}{1.64 \times 10^6\, M_\odot}\right)\left(\frac{m_B}{\mathrm{MeV}}\right)^2\left(\frac{4\pi}{\lambda}\right)^{1/2}$$

- M mass of the object
- m_B mass of the bosonic particle
- λ strength of self-coupling

Gravitational wave signatures of alternative objects

2. Ringdown of newly formed object



- Black hole ringdown: GW signal is superposition of damped sinusoids:

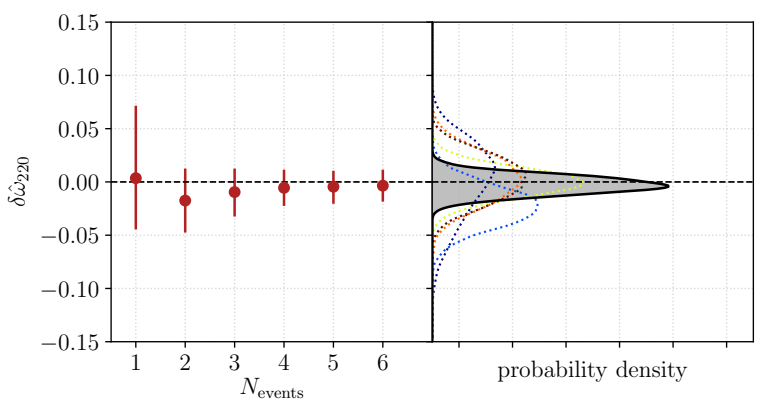
$$h(t) = \sum_{nlm} \mathcal{A}_{nlm} e^{-t/\tau_{nlm}} \cos(\omega_{nlm} t + \phi_{nlm})$$

Characteristic frequencies, damping times:

$$\omega_{nlm} = \omega_{nlm}(M_f, a_f)$$

$$\tau_{nlm} = \tau_{nlm}(M_f, a_f)$$

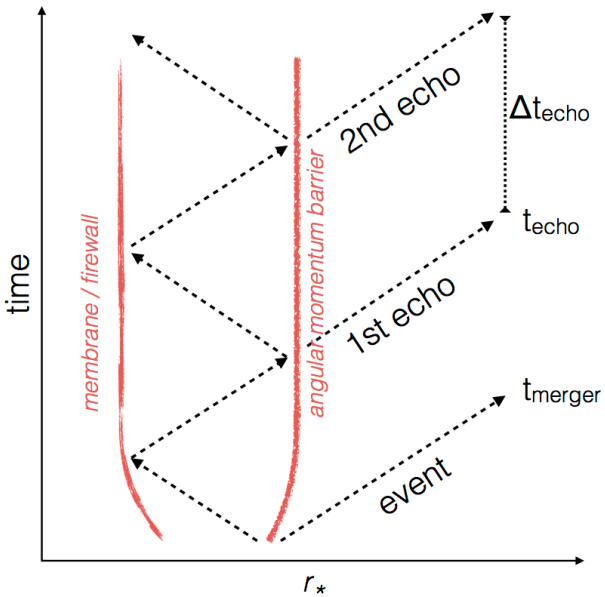
where M_f , a_f final mass and spin

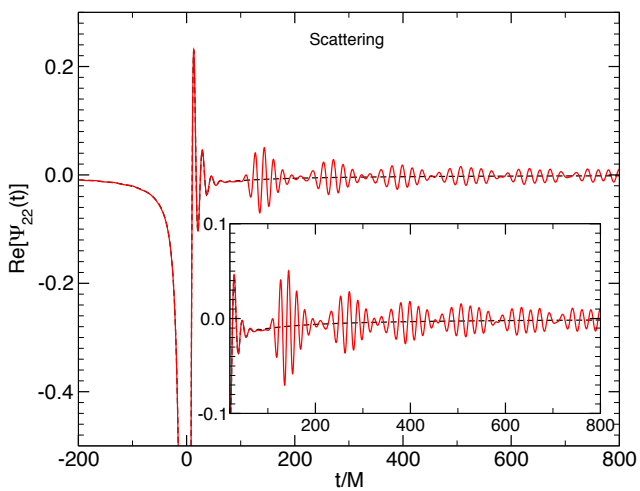


- Boson stars, dark matter stars: qualitatively different spectrum

- With upcoming LIGO/Virgo upgrades: *dominant mode frequency measurable to percent level*

Gravitational wave signatures of alternative objects





3. Gravitational wave echoes

- Sufficiently compact object without horizon: ingoing gravitational waves scatter many times at effective potential barriers

- If microscopic horizon modification scale $\ell \ll M$ then time between echoes is

$$\Delta t \sim -nM \log\left(\frac{\ell}{M}\right)$$

where *n* set by nature of object:
  - *n* = 8 for wormholes
  - *n* = 6 for thin-shell gravastars
  - *n* = 4 for empty shell

- For GW150914 (M = 65 M_{sun}), $\ell = \ell_{Planck}$, n = 4: Δt = 117 ms
  - Possibility of probing *quantum gravity* modifications of black holes (e.g. fuzzballs)