Computing remnant mass of binary black hole mergers using EMRI surrogate model

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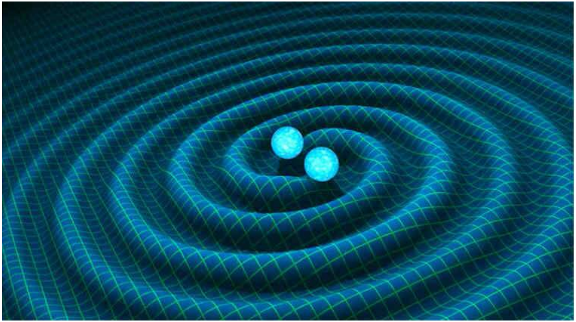
Binary black hole mergers



GW150914 was the first direct observation of gravitational waves emanating from the coalescence of binary black hole system made by LIGO observatories on 14^{th} September,2015.

Phases of a binary black hole system

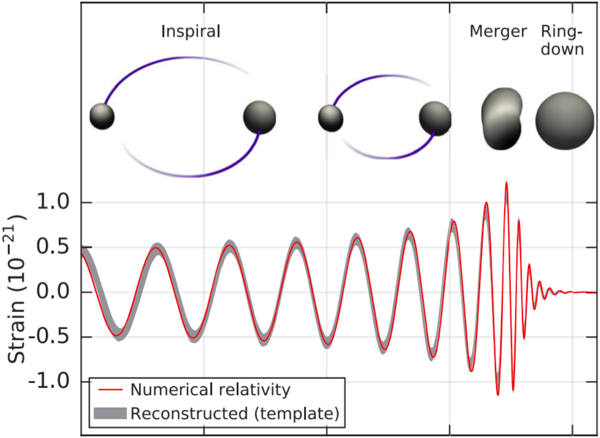


Figure: Inspiral-Merger-Ringdown[1]

[1] B. P. Abbott et al. "Observation of Gravitational Waves from a Binary Black Hole Merger". In: *Phys. Rev. Lett.* 116 (6 2016), p. 061102.

GW150914[2]

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

[2]Abbott et al., "Observation of Gravitational Waves from a Binary Black Hole Merger".

Extreme mass ratio inspirals (EMRIs)

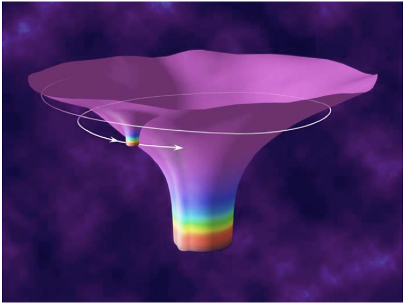
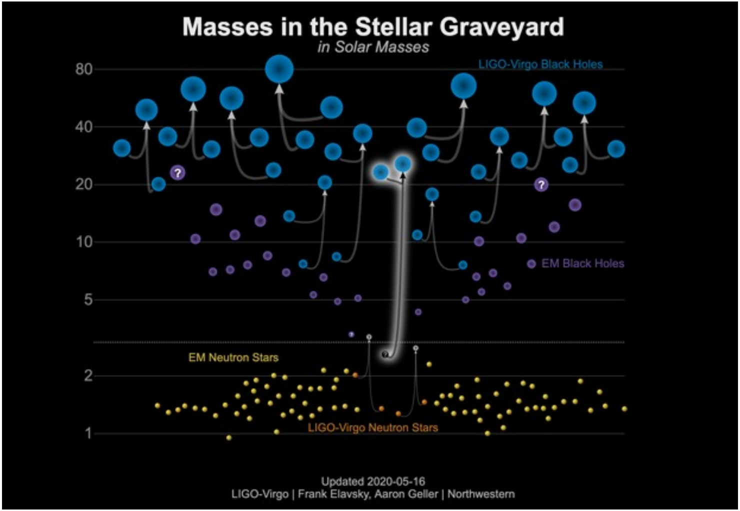


Figure: EMRI (Credits- NASA)

- Orbit of a relatively light object (neutron star, stellar black hole) around a much heavier object(supermassive black hole).
- It gradually decays due to emission of gravitational waves.
- The waves are computed using black hole perturbation theory.

Final mass of the remnant



Credits- LIGO Caltech

Surrogate modeling

Motivation

- LIGO doesn't directly measure the remnant mass after the merger and thus we require a waveform model along with mathematical framework to compute it.
- Numerical relativity simulations are unable to simulate mass ratios much beyond 15.
- They become computationally very expensive.
- LISA would need a vast range of mass ratios.

Surrogate modeling

Modeling

- The model uses point particle perturbation theory.
- At large mass ratios, the smaller BH is modeled as point-particle in with no internal structure.
- It generates a metric perturbation about the background spacetime.
- Einstein equation becomes a linear differential equation for the perturbation (the Teukolsky equation).

EMRI surrogate model[3]

- Teukolsky equation is solved at 30 different values for mass ratio from 3 to 10^4.
- Then the training data is used to build model.
- The full surrogate model looks like:

$$h_S(t, \theta, \phi; q) = \sum_{l,m} h_s^{l,m}(t; q)\,_{-2}Y_{l,m}(\theta, \phi)$$

$$h_s^{l,m}(t; q) = A_s^{l,m}(t; q) e^{-i\phi_s^{l,m}(t;q)}$$

- Newest inspiral-merger-ringdown model to cover mass ratios in the intermediate mass-ratio regime (10 to 10^4).

[3] Nur E. M. Rifat et al. "Surrogate model for gravitational wave signals from comparable and large-mass-ratio black hole binaries". In: *Phys. Rev. D* 101 (8 2020), p. 081502.

Energy flux and Bondi mass[4]

Energy Flux emitted in GWs-

$$\frac{dE}{dt} = \lim_{r\to\infty} \frac{r^2}{16\pi} \sum_{l,m} \mid \dot{h}^{l,m} \mid^2 \tag{1}$$

Integration constant-

$$\frac{E_0}{M} = \left(\frac{5}{1024} \frac{q^3}{(1+q)^6} \dot{E}_0 \right)^{1/5} \tag{2}$$

Time-dependent(Bondi) mass of the binary-

$$M(t) = M - E(t) + E_0 \tag{3}$$

[4] Davide Gerosa, Fran çois Hébert, and Leo C. Stein. "Black-hole kicks from numerical-relativity surrogate models". In: *Phys. Rev. D* 97 (10 2018), p. 104049.

Main features of the code

- Written in python 2.7.
- trapz (uses trapezoidal rule) function from scipy.integrate module for integration
- PN formula used for calculating the constant of integration.
- Written in modular style so that it can be integrated into other modules easily.

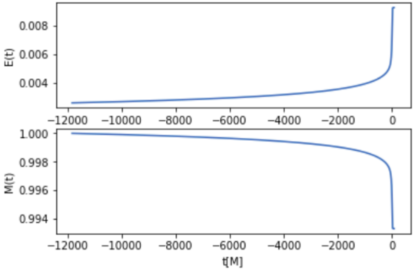


Figure: q=10

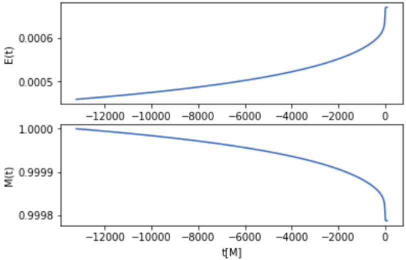


Figure: q=100

Results

Mass ratio (q)	Remnant Bondi mass
10	0.9933059810395991
100	0.9997870047973797
1000	0.999994445043402
10,000	0.9999999056356944

Table: Remnant mass obtained by implementing the code

Sanity check

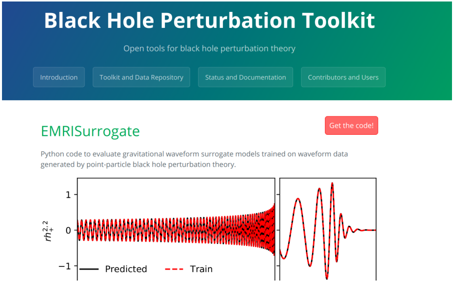
- To verify results we require information about remnant mass values for mass ratios between 10<q<10,000.
- Most models provide values for q<=8. Thus hard to corroborate results.
- For q=8, EMRISur using my code gave 0.9907173749485071.
- Other models used- NRSur3dq8Remnant[5](0.9893060467437979 with error- 0.0001327823469476848) and NRHybSur3dq8[6] (0.992376698721572)

[5] Vijay Varma et al. "High-Accuracy Mass, Spin, and Recoil Predictions of Generic Black-Hole Merger Remnants". In: *Phys. Rev. Lett.* 122 (1 2019), p. 011101.

[6] Vijay Varma et al. "Surrogate model of hybridized numerical relativity binary black hole waveforms". In: *Phys. Rev. D* 99 (6 2019), p. 064045.

Future work

- Develop codes for emitted linear momentum and post-merger kick.
- Testing the code for upcoming surrogate model which accounts for spin of the black holes.
- Making the code open source as part of the BHP toolkit (https://bhptoolkit.org/EMRISurrogate/).



Thank You!