

# Simulation of GW150914 binary black hole merger: black holes properties

This notebook shows how to analyse the data from a simulation of the GW150914 binary black hole merger event, which was the source of the first ever detection of gravitational waves by the LIGO experiment. It shows how to analyse the physical properties of the black holes, and is accompanied by other tutorials that show how to extract waveforms from the simulated spacetime, study the numerical properties of the simulation, and visualise the 3D data generated by the simulation.

The simulation data and other tutorials can be downloaded separately from <http://einstein toolkit.org/about/gallery/gw150914>, or can be independently reproduced using the Einstein Toolkit.

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## Load SimulationTools

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## Retrieve First Data Set

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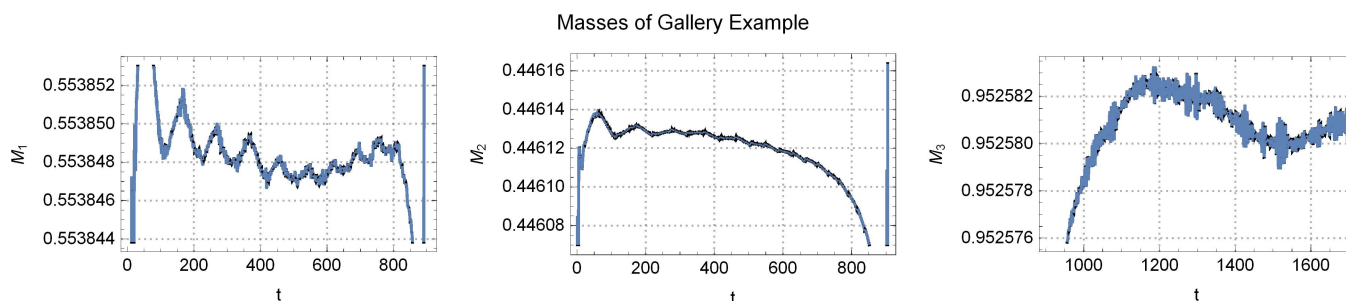
## Retrieve Second Data Set

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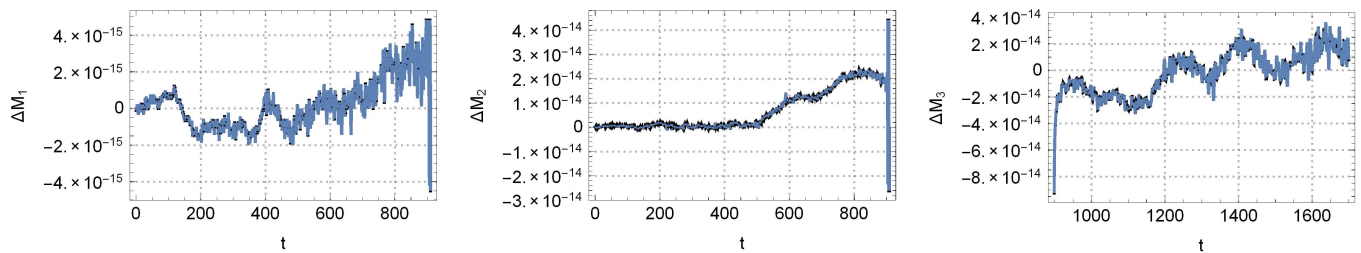
## Black hole properties

The simulation tracks the properties of three black holes: the two inspiralling black holes, and the final remnant. When simulating binary systems, the inspiralling black holes are conventionally taken to be 1 and 2, and the final merged black hole is 3. Properties such as irreducible mass,  $m_{\text{irr}}$ , and spin vector,  $S^i$ , are measured on the apparent horizon of each black hole using the AHFinderDirect and IsolatedHorizon thorns.

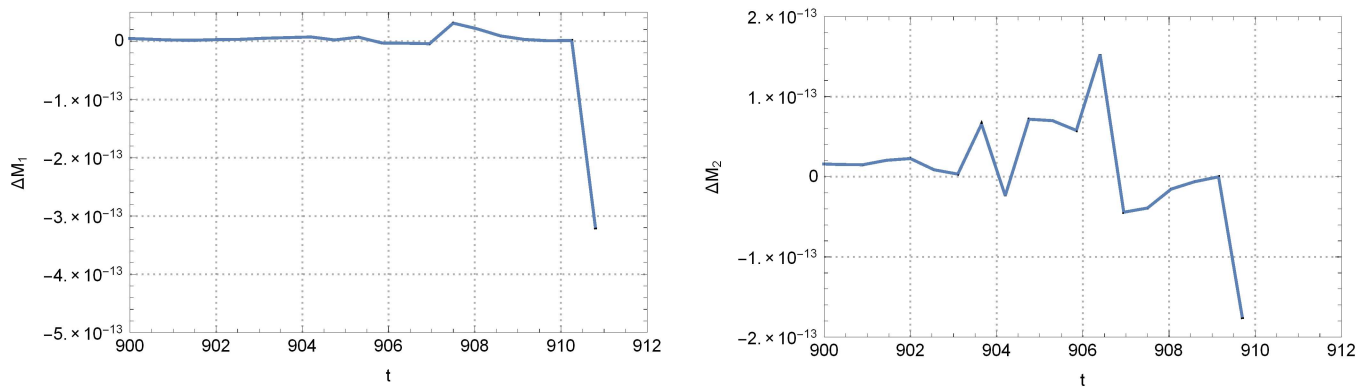
### Black hole masses



Absolute Difference between Gallery and New Data



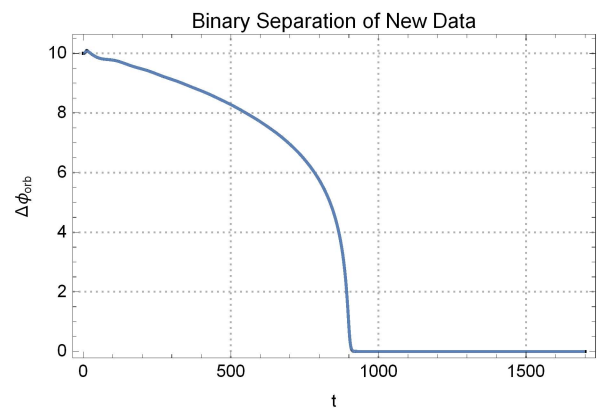
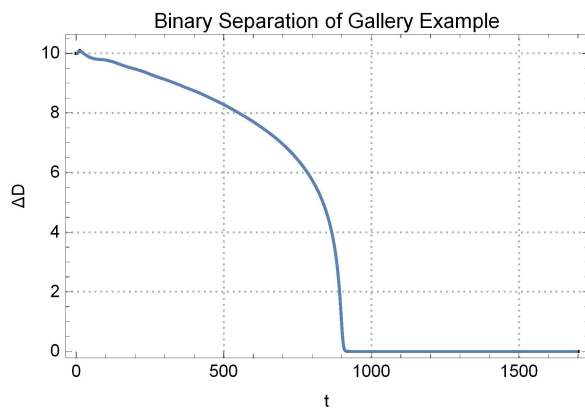
Plot of High-Error Regions

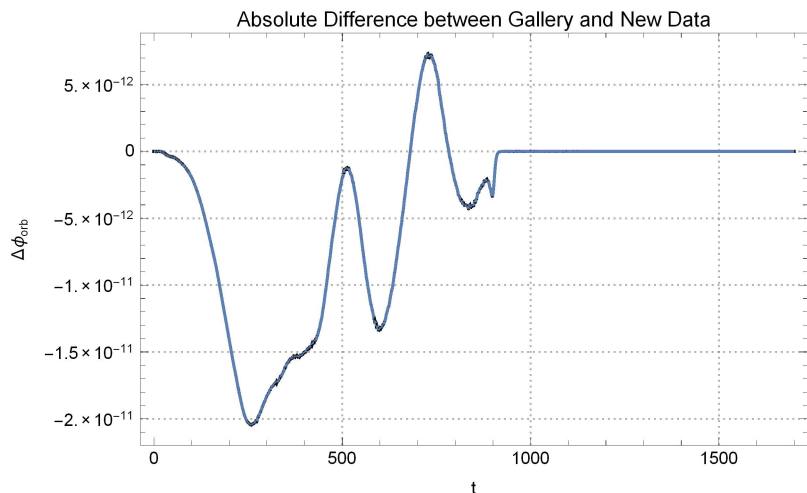


## Black hole trajectories

### Orbital separation

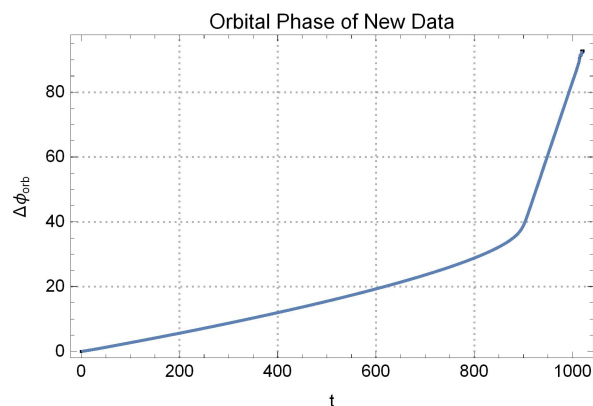
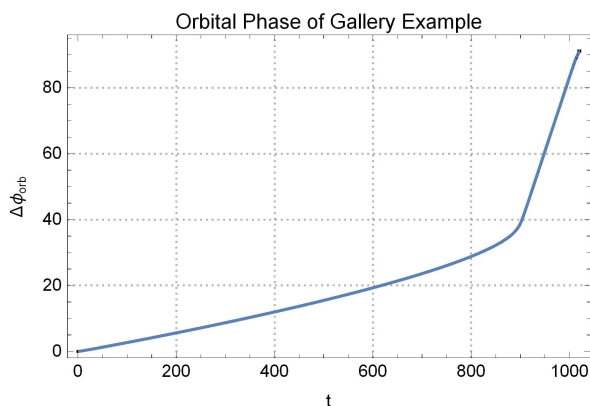
`ReadBinarySeparation` gives the coordinate distance between the two black holes as a function of time. In the case of the current configuration, we see that the binary starts out at an initial separation of  $D = 10 M$  and merges shortly before  $t = 1000 M$



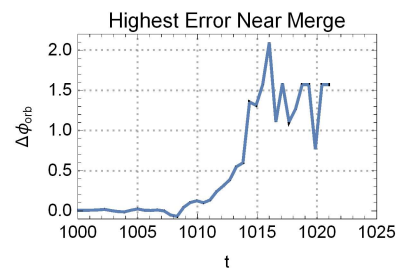
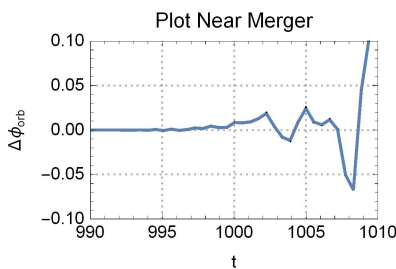
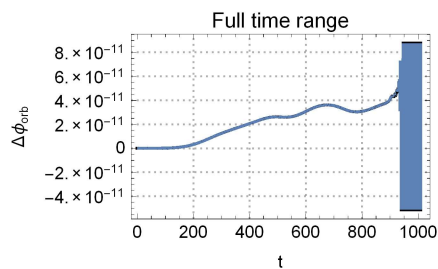


## Orbital phase

ReadBinaryPhase gives the orbital phase, or azimuthal angle (in radians) projected into the x-y plane, of the relative orbit vector (i.e. the vector joining the two black holes). We see that the binary accumulates  $\sim 12 \pi$  radians of orbital phase prior to the plunge, in agreement with our previous measurement of 12 gravitational wave cycles prior to merger (the number of gravitational wave cycles in the  $l=2, m=2$  mode should be twice the number of orbits of the binary)

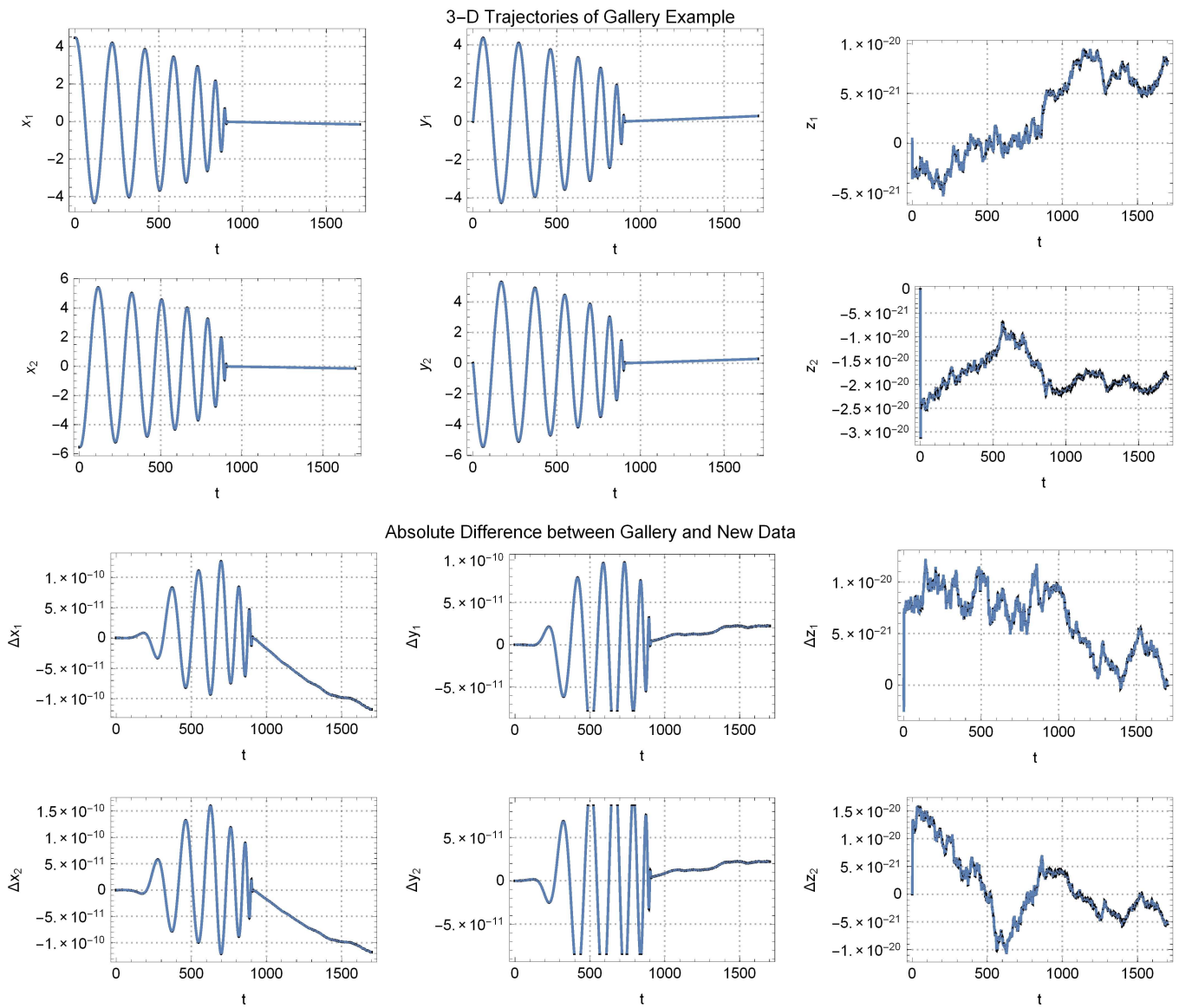


Absolute Difference between Gallery and New Data



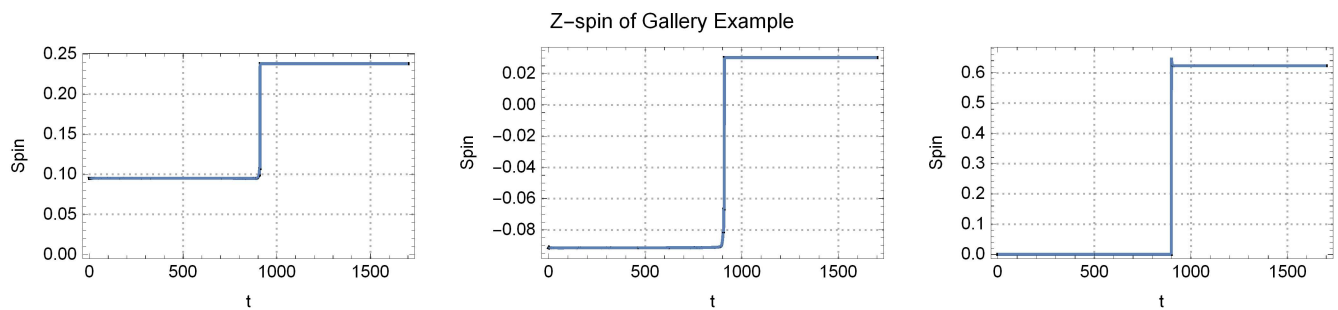
## Trajectories

We can also read the full 3-D trajectories of each black hole. ReadBinaryCoordinates gives a list of coordinates  $x$ ,  $y$  and  $z$ , each of which gives a coordinate position as a function of time. We then plot the coordinates as a function of time

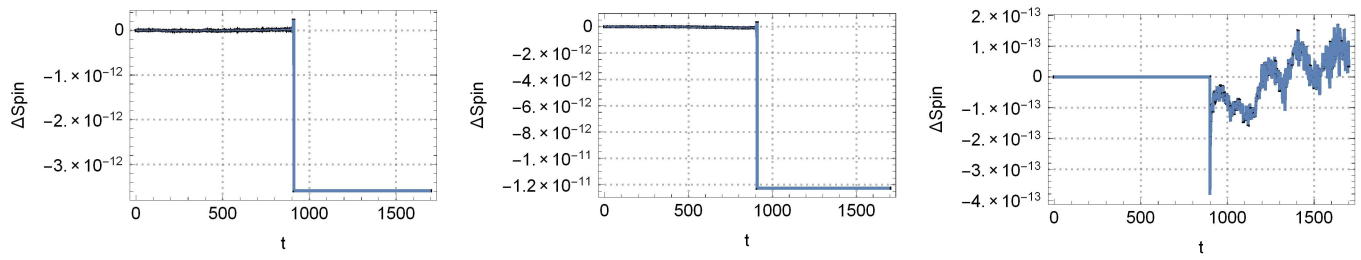


## Spin evolution

The spin 3-vector of each black hole can be defined and measured using the method of Campanelli et al., Phys.Rev. D75 (2007) 064030. The function ReadBlackHoleSpin reads the spin vector of a black hole as a function of time. This is the dimensionful angular momentum; i.e. it has units of  $[\text{mass}]^2$ . Let's read in the spins of our three black holes and plot the z-components (these are the only non-zero components in this configuration)



Absolute Difference between Gallery and New Data



## Waveforms

The plots below are generated using the methods from the Waveforms.nb in the Gallery Example.

Calculated Waveforms For Data Sets

