Title: What is chaos, and what does it have to do with black holes and gravitational waves?

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Abstract: <p>The era of gravitational wave detection is upon us. Advanced LIGO (aLIGO) is now in full operation. It has successfully detected the gravitational waves emitted from distant pairs of black holes (BHs) as they spiral together and merge. And we have many more detections to look forward to. But where are these BH-BH mergers happening, in the vast wilderness of the cosmos? </p>

<p>One of the preferred candidates are globular clusters, massive systems of very old stars densely packed together and bound together by gravity. Globular clusters are factories for black hole binary mergers. But we are only able to observe these factories in operation now. In order to understand how they were built and the treasures they should be expected to produce at present, we must somehow rewind their evolution over billions of years to say something about the initial conditions. Only then will we be able to understand how these beasts birth BH binaries, and are contributing to the gravitational waves currently being observed by aLIGO. After a brief overview of the concept of chaos, I will discuss recent progress in advancing our understanding of the origins of BH-BH mergers.</p>

AMERICAN MUSEUM OF NATURAL HISTORY

What is Chaos, and What Does it Have to do with Black Holes and Gravitational Waves?

Nathan W. C. Leigh

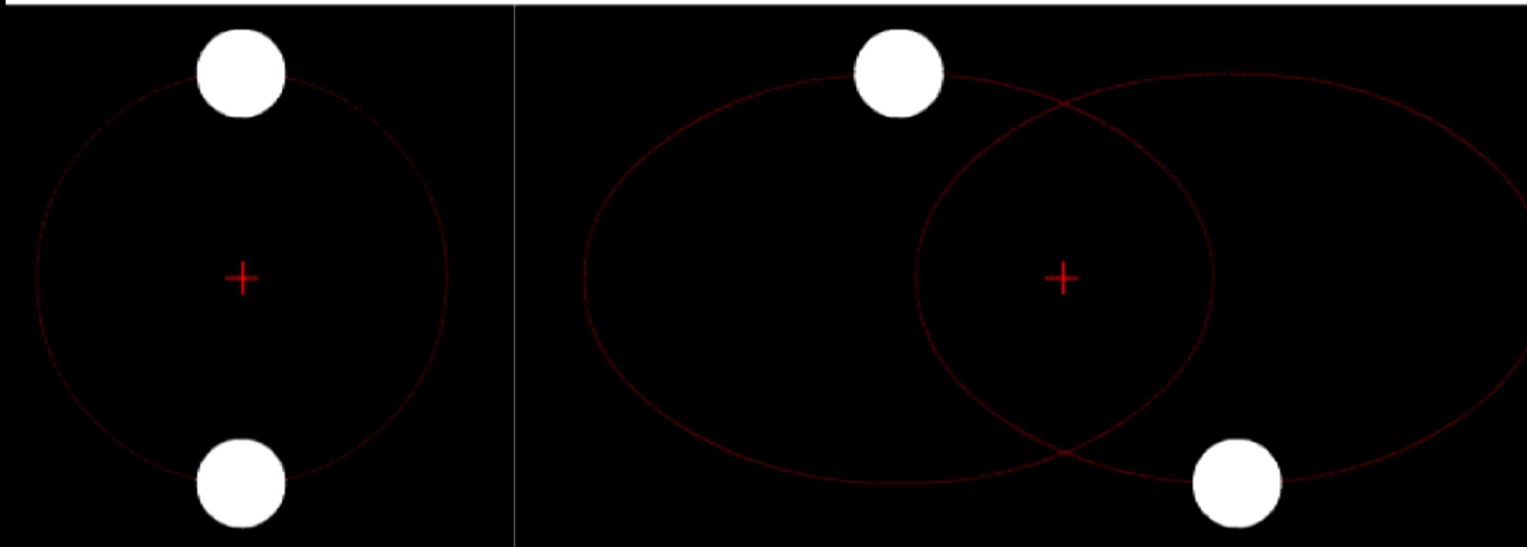
Kalbfleisch Research Fellow

American Museum of Natural History

Department of Physical Sciences

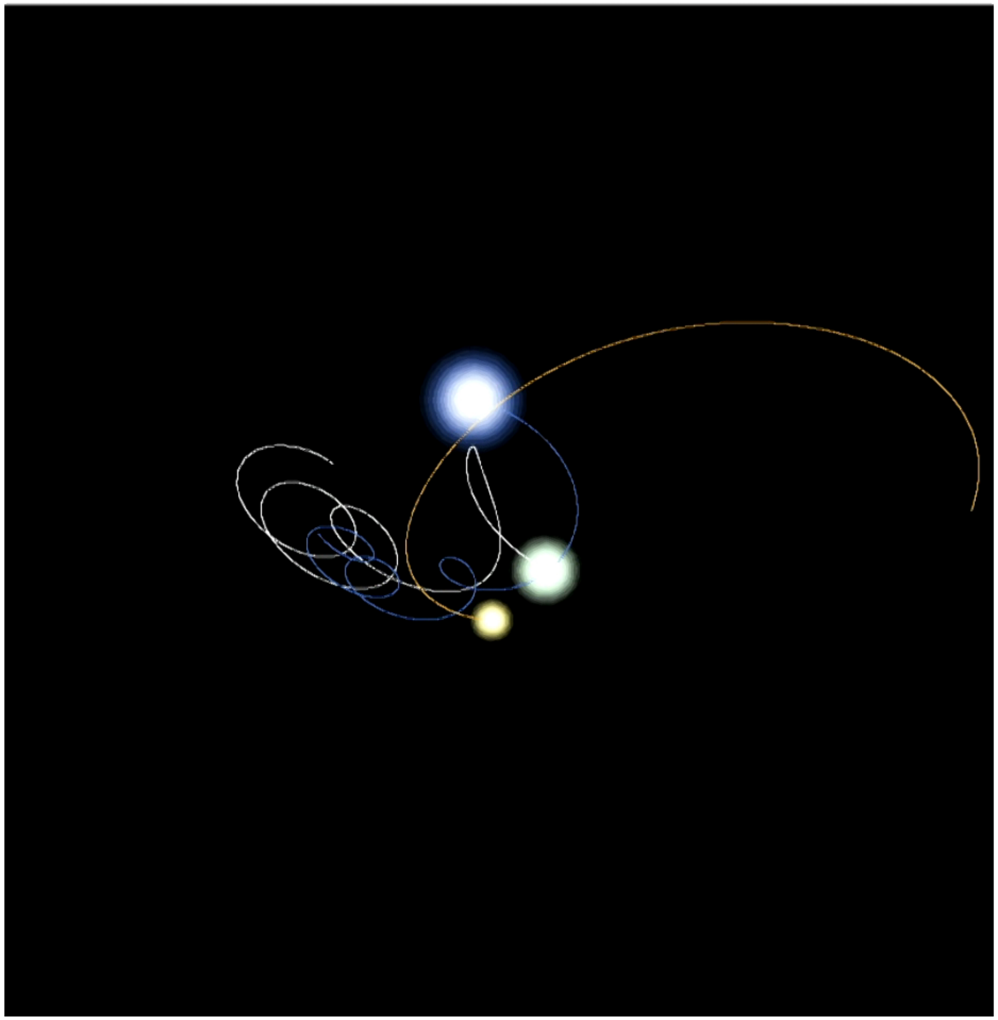
Collaborators: Nicholas C. Stone, Aaron M. Geller, Michael M. Shara, Jeremy J. Webb, Timur Ibragimov, Johan Samsing

Two bodies make a binary.



An equal-mass binary pair with both circular (left) and eccentric (right) orbits.

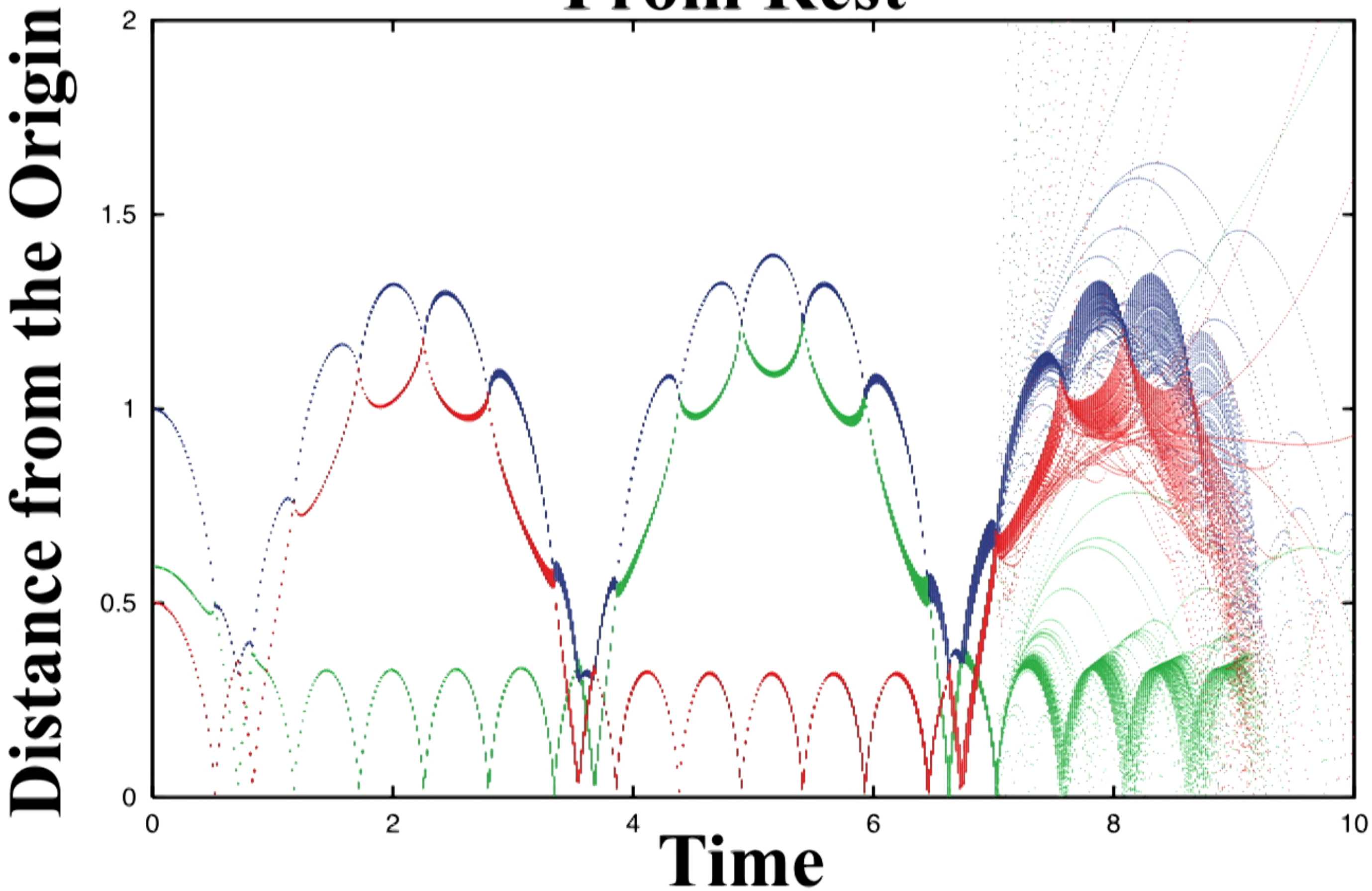
Three bodies make a mess.



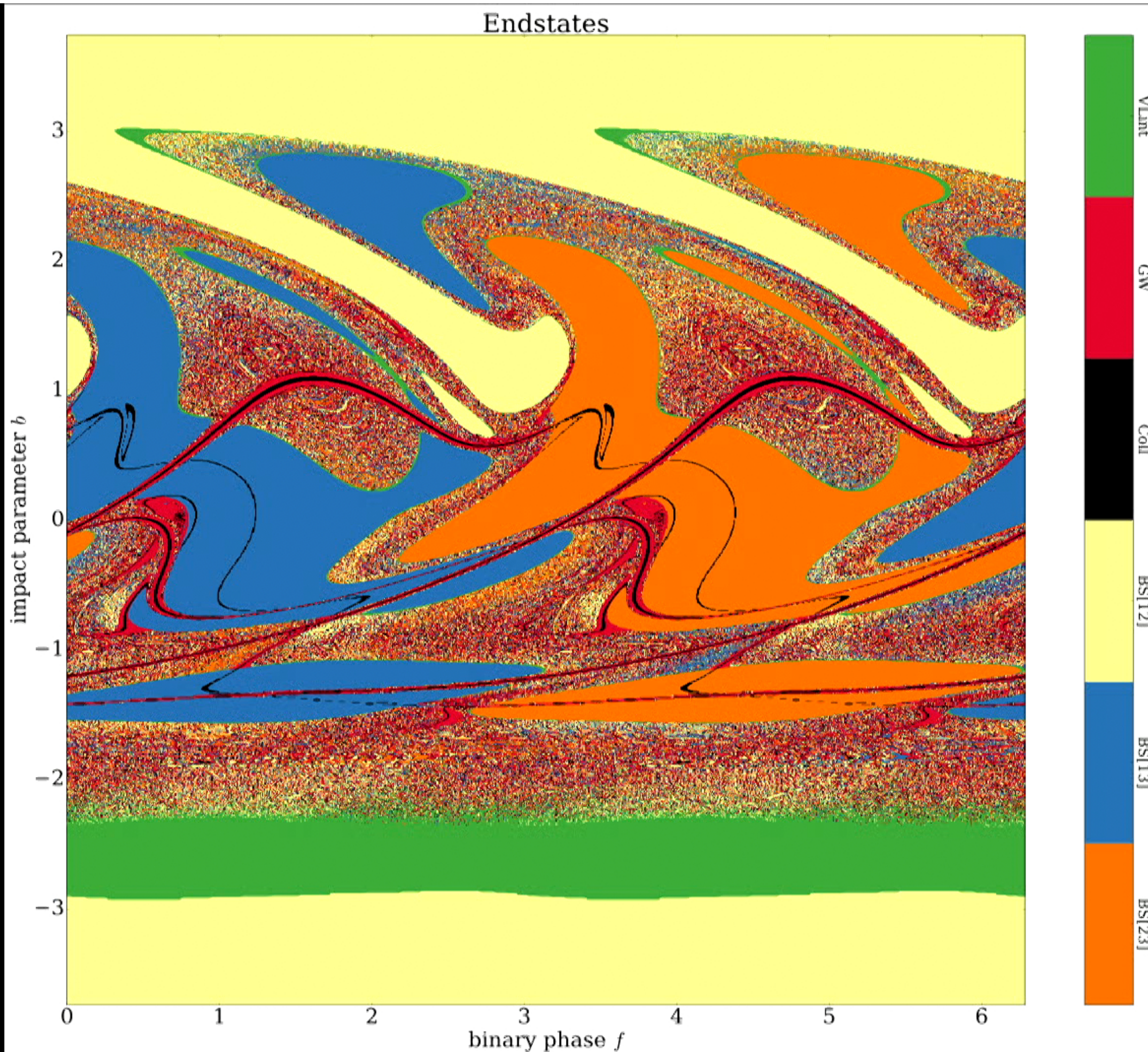
Consider a typical chaotic three-body interaction in the point-particle limit.

Movie credit:
Aaron Geller
(Northwestern University and Adler Planetarium)

Three Equal-Mass Bodies Released From Rest

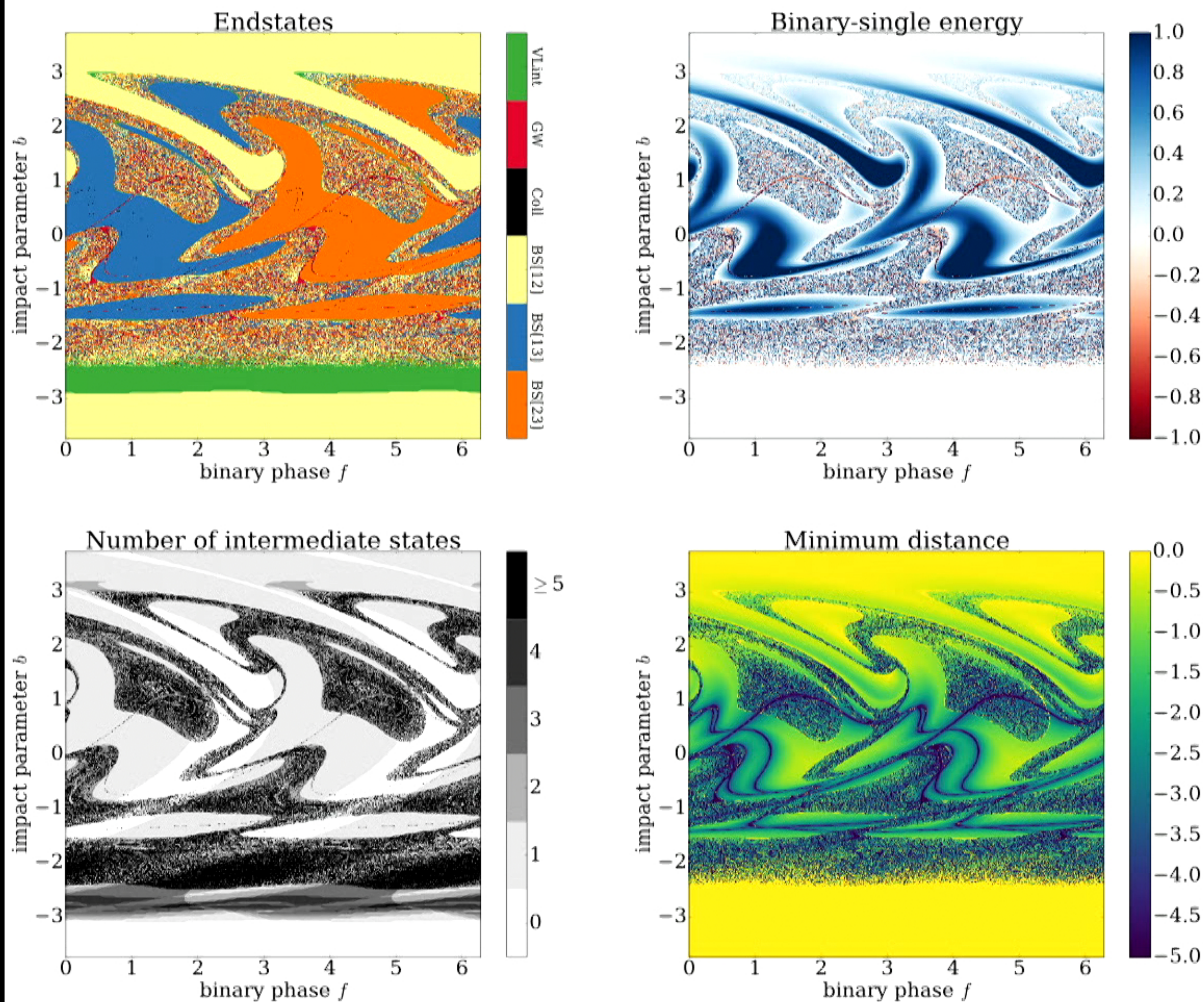


Time is in units of the system crossing time (Heinamaki et al. 1999).



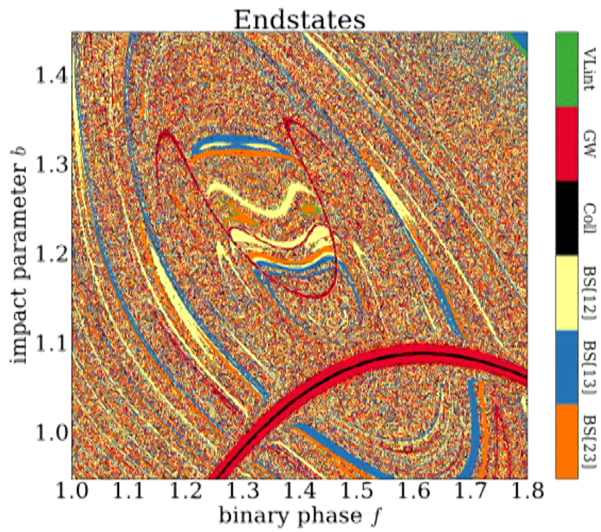
Topological map of binary-single endstates, for BH mass $m = 10M_{\odot}$, initial SMA $a_0 = 10^{-2}$ AU, relative velocity $v = 0.01$, and orbital plane angle $\gamma = 0.0$.

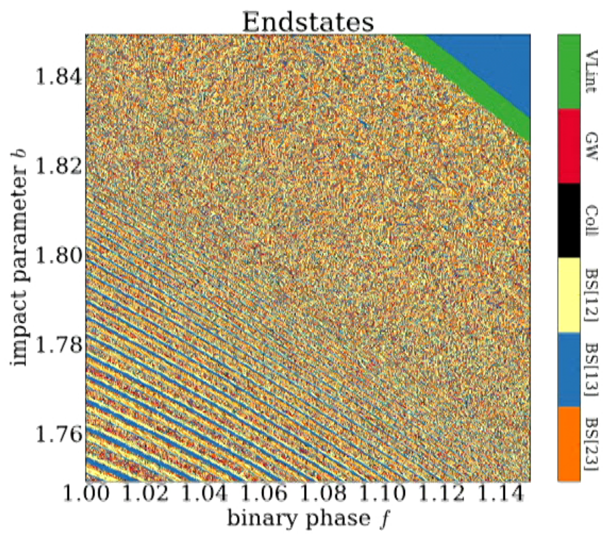
Samsing & Ilan (2017)



Topological map of binary-single endstates, for BH mass $m = 10M_\odot$, initial SMA $a_0 = 1$ AU, relative velocity $v = 0.01$, and orbital plane angle $\gamma = 0.0$.

Samsing & Ilan (2017)



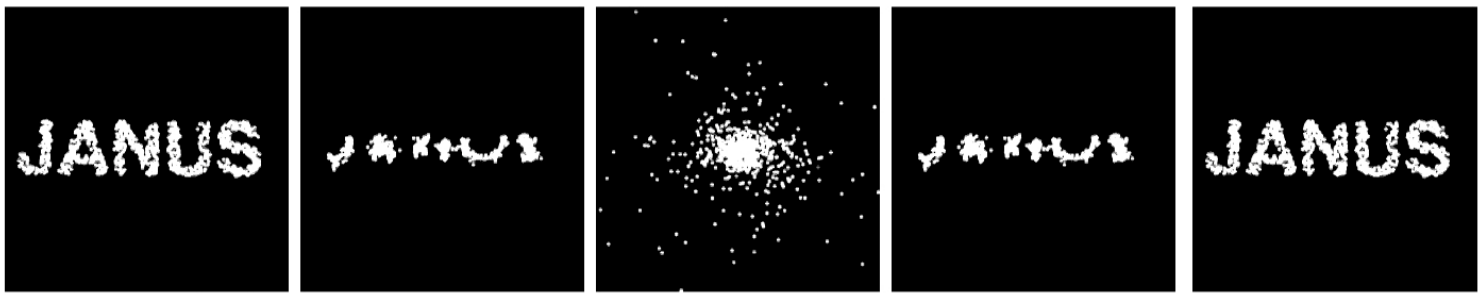


Topological endstate maps derived in a similar way to the ones shown in the previous figure with a_0 =1AU and γ=0. ***Top plot*:** Zoom in on the center of one of the larger resonant interaction (RI) regions. ***Bottom plot*:** Zoom in on the boundary between one of the larger RI regions and its neighboring direct interaction (DI) region.

Samsing & Ilan (2017)

Chaos: For a given set of initial conditions, there is a distribution of outcomes.

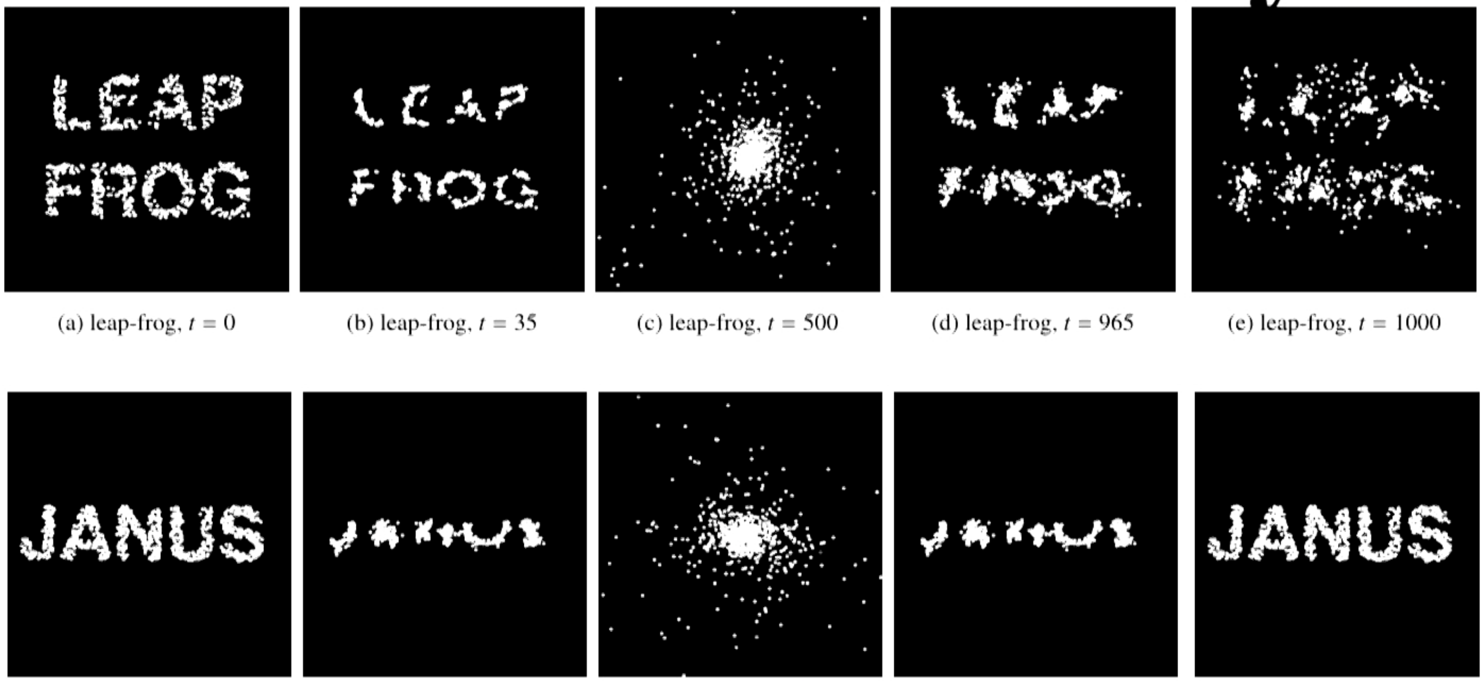
Time-Reversibility



(f) JANUS, $t = 0$ (g) JANUS, $t = 35$ (h) JANUS, $t = 500$ (i) JANUS, $t = 965$ (j) JANUS, $t = 1000$

Initially at rest, the particles collapse in the first 500 timesteps due to self-gravity. The sign of the velocities is flipped after 500 timesteps, and integrated for another 500 steps **(Rein & Tamayo 2017)**.

Time-Reversibility



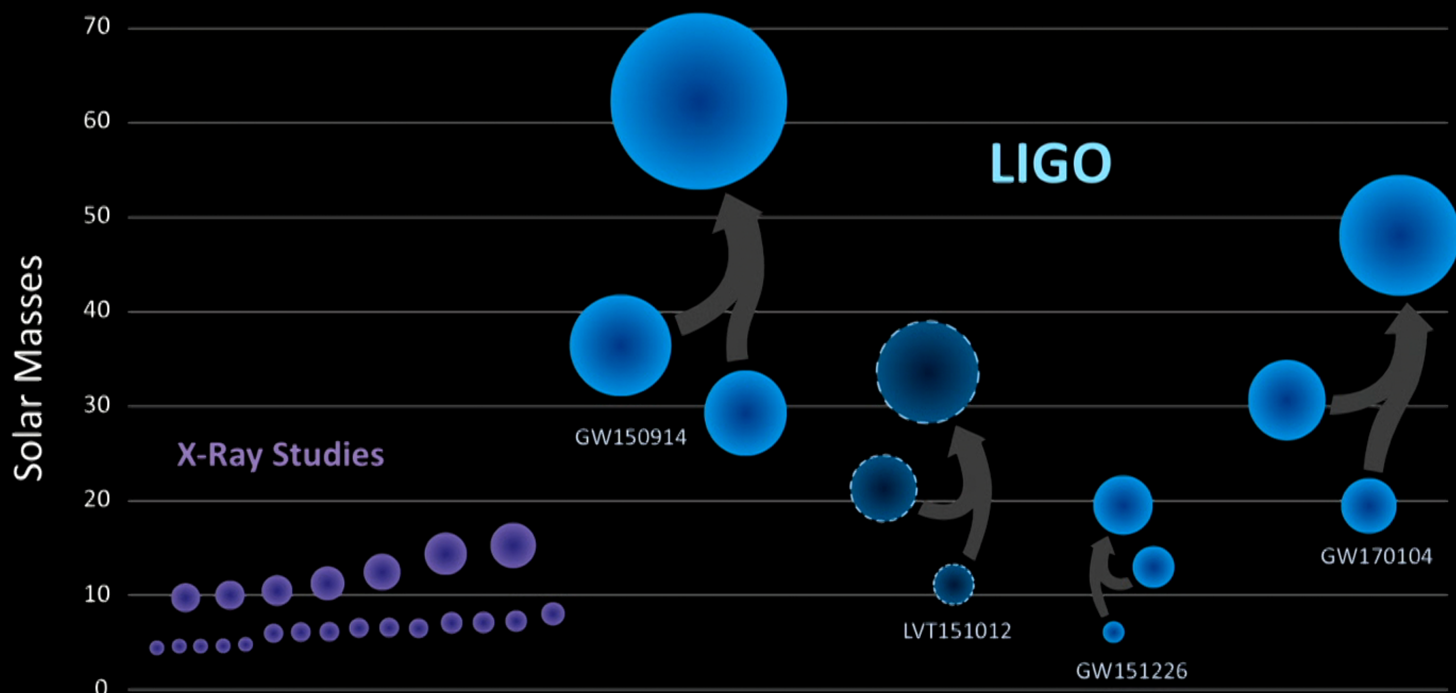
(a) leap-frog, $t = 0$ (b) leap-frog, $t = 35$ (c) leap-frog, $t = 500$ (d) leap-frog, $t = 965$ (e) leap-frog, $t = 1000$

(f) JANUS, $t = 0$ (g) JANUS, $t = 35$ (h) JANUS, $t = 500$ (i) JANUS, $t = 965$ (j) JANUS, $t = 1000$

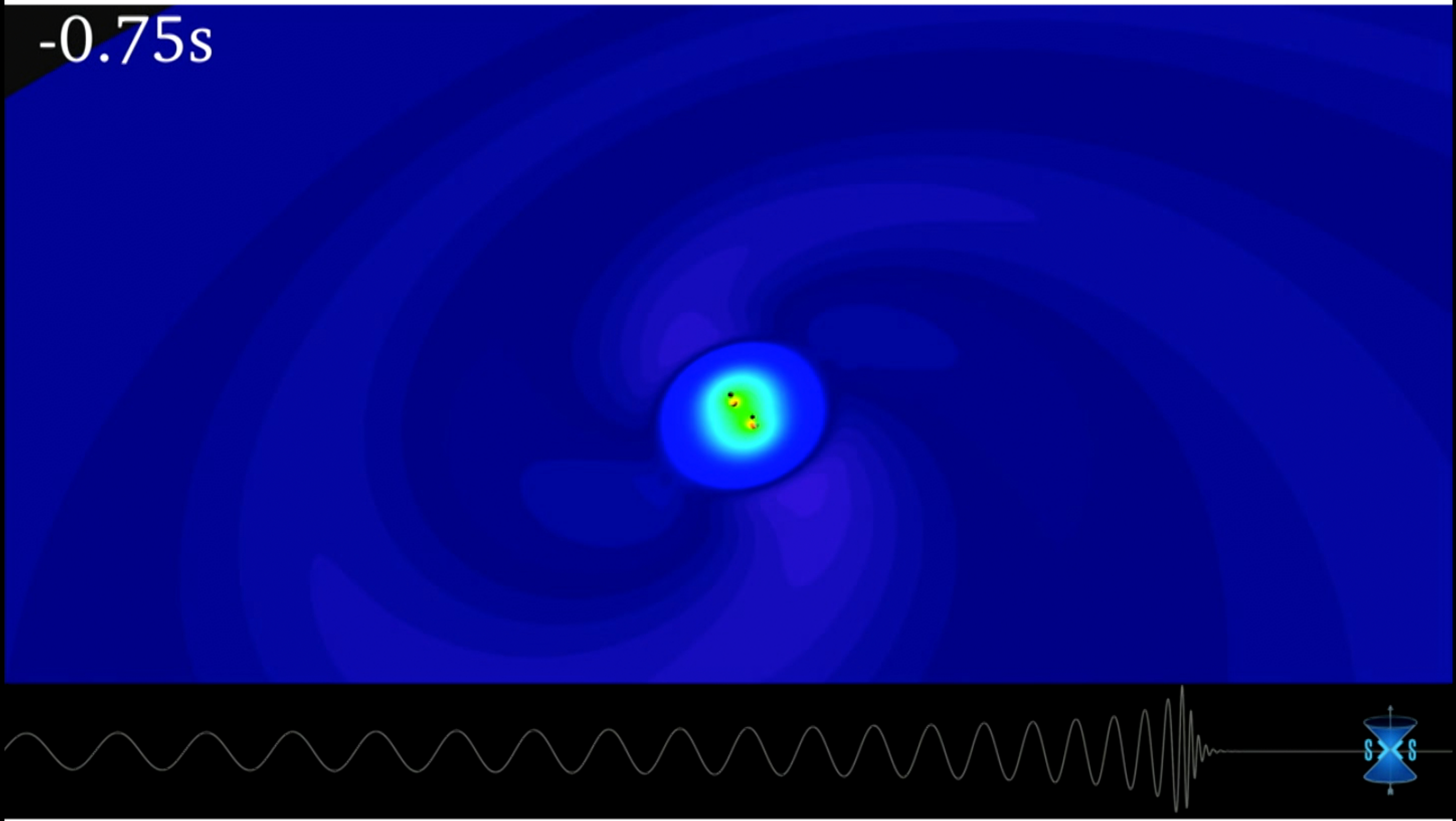
Comparison between the leap-frog integrator (top) and JANUS (bottom) with 1000 gravitationally interacting particles each. Initially at rest, the particles collapse in the first 500 timesteps due to self-gravity. The sign of the velocities is flipped after 500 timesteps, and integrated for another 500 steps **(Rein & Tamayo 2017)**.

What does this have to do with black holes and gravitational waves?

Black Holes of Known Mass



How did each of these BH pairs end up in a binary?



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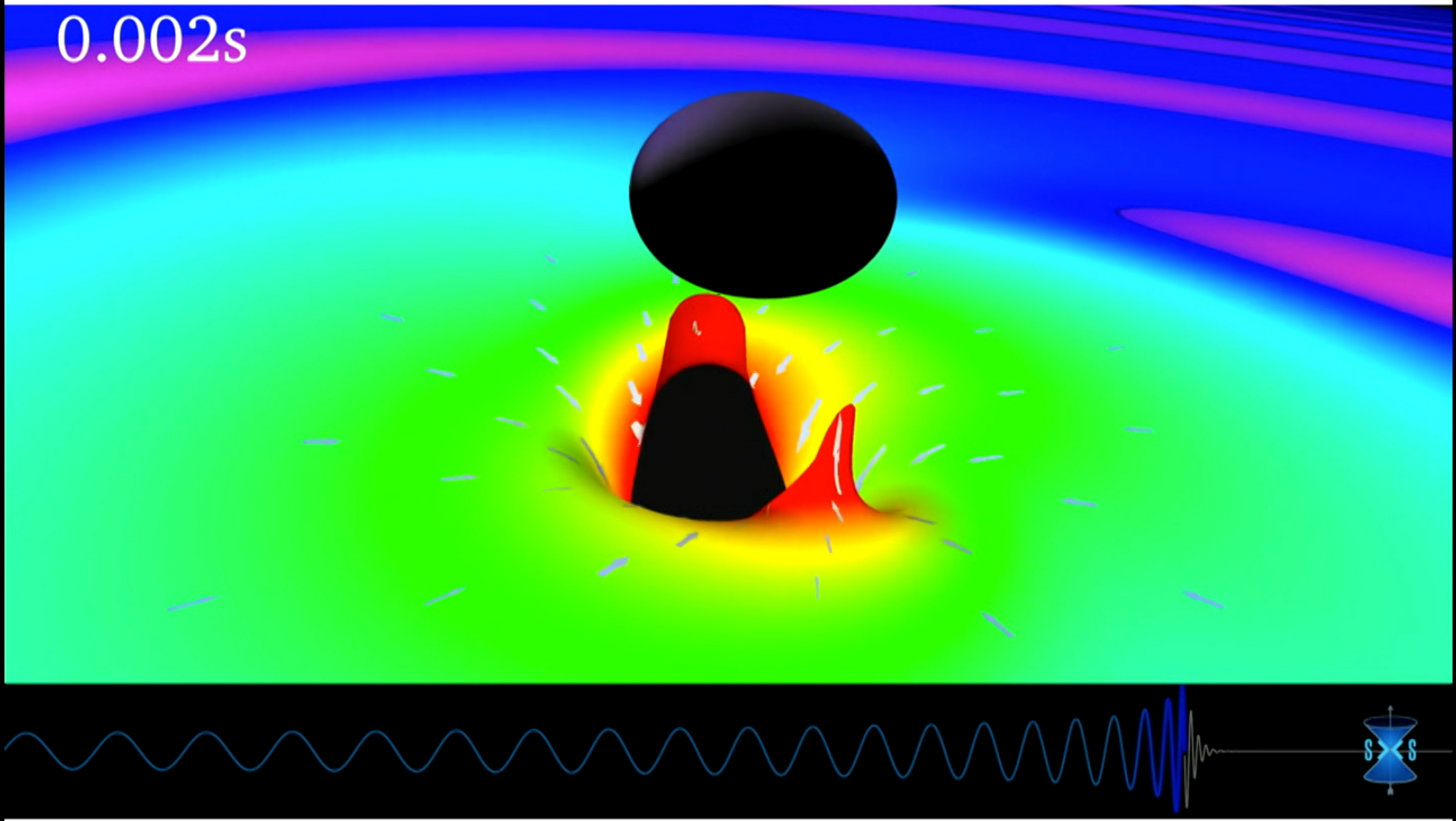
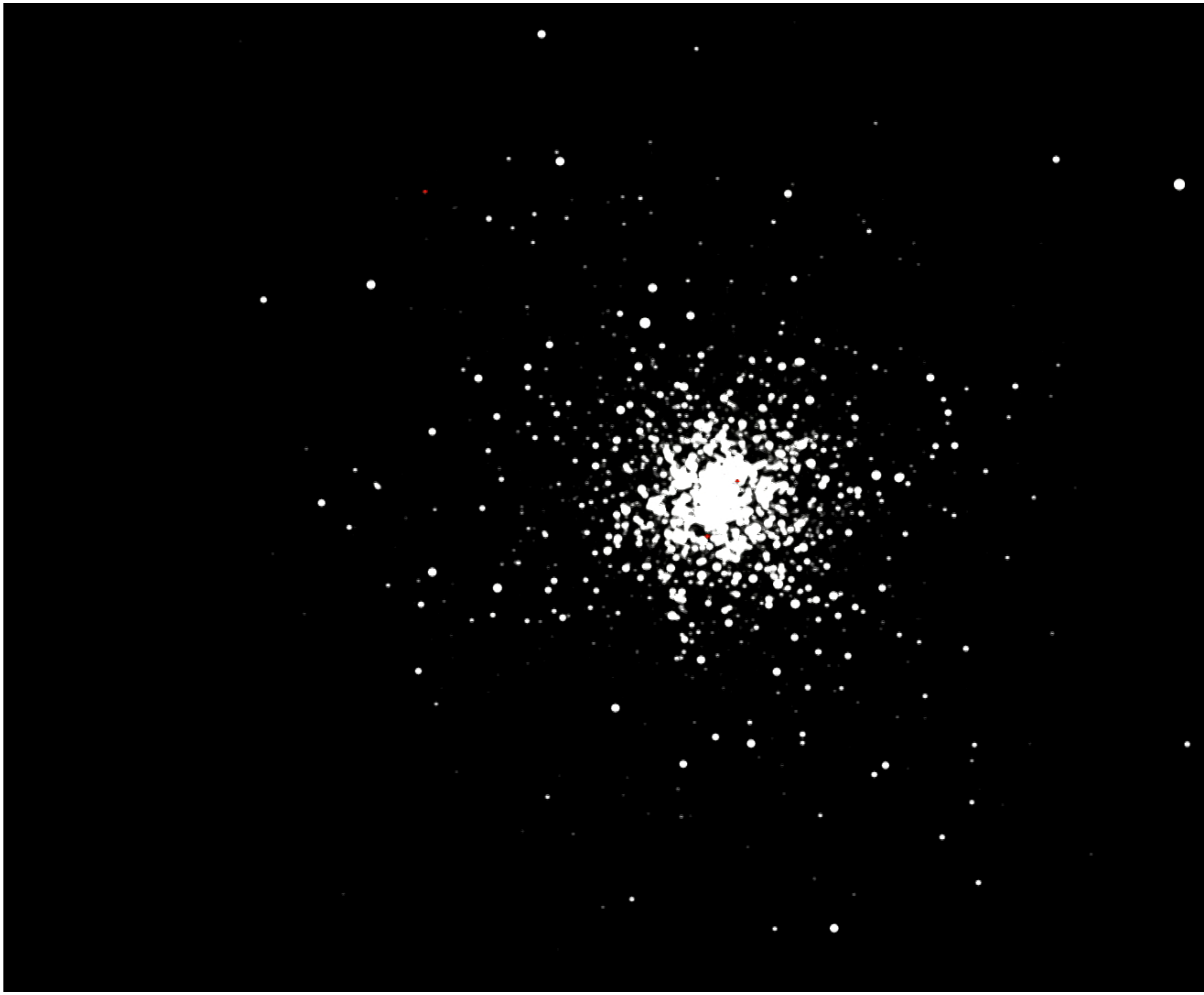


What astrophysical environments birth black hole binary mergers?

All stars are born in star clusters. By extension, all black holes (BHs) originate in clusters.

The old globular cluster M80.

Image Credit: Hubble Space Telescope (STScI/ NASA/ESA).



N-body simulation of an intermediate mass cluster.

Movie credit: Anna Sippel (Swinburne University) and Jeremy Webb (University of Toronto).

What astrophysical environments birth black hole binary mergers?

This connection ensures that learning about BH-BH mergers from aLIGO indirectly tells us about:

- star formation
- stellar evolution
- stellar death
- binary evolution
- cluster dynamics

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Simulating the Simulator. Beyond the Machine.

There are two problems:

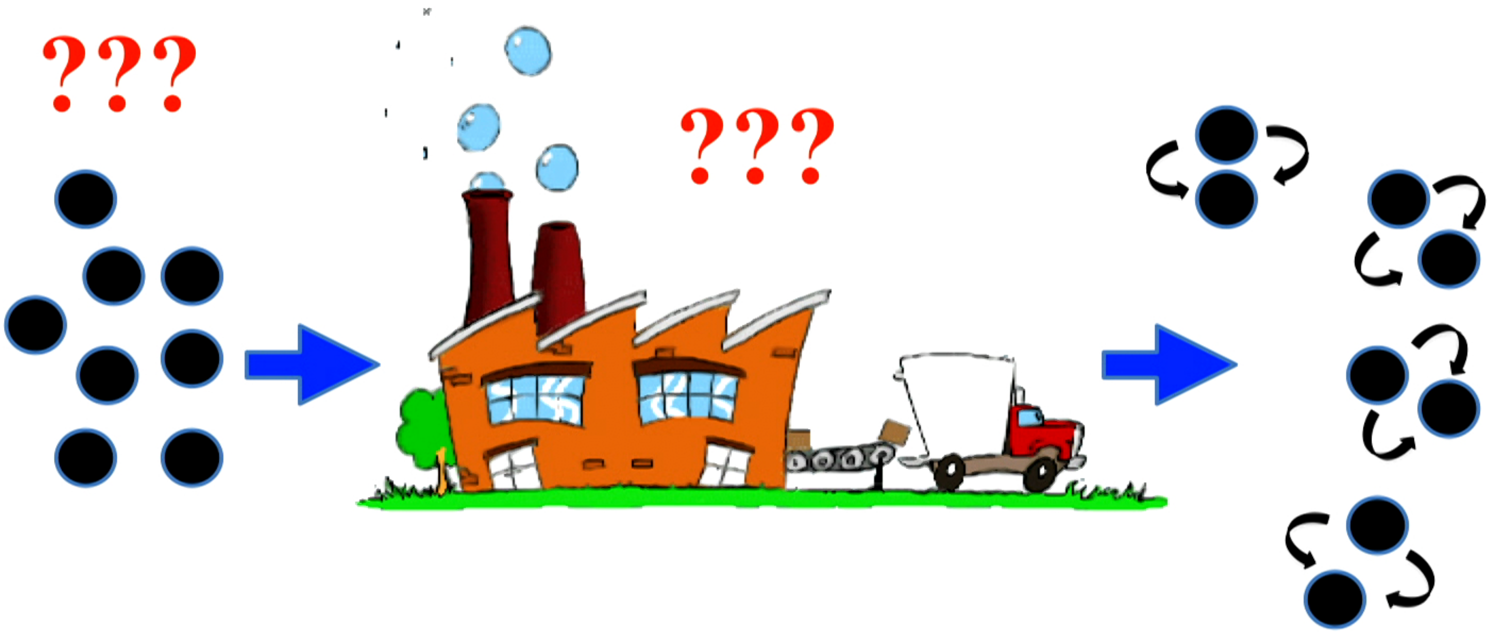
Chaos

Initial Conditions

How do we solve these problems?

Computers cannot simultaneously solve both problems. One approach is to create analytic models that accurately describe the simulations. This removes the computational expense.

Globular Clusters: Factories for BH Binary Mergers



The Three- and Four-Body Problems

- Every BH-BH binary is formed during one or more isolated three- or four-body interactions
- Consider the products of a ***binary-binary interaction:***

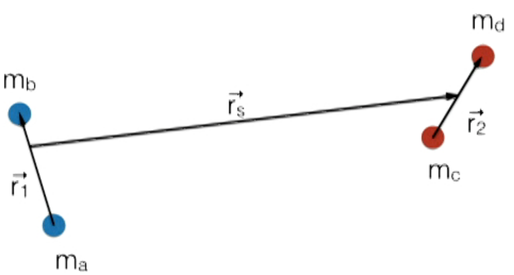


Figure 1. The configuration of the 2+2 outcome.

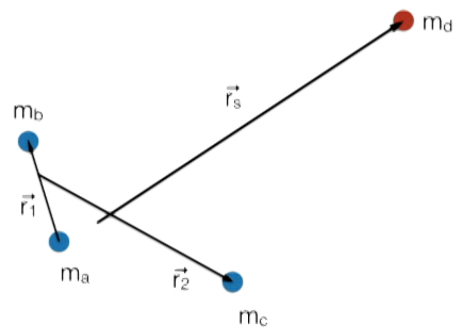


Figure 2. The configuration of the 3+1 outcome.

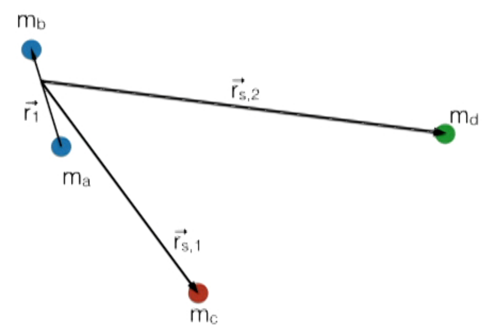
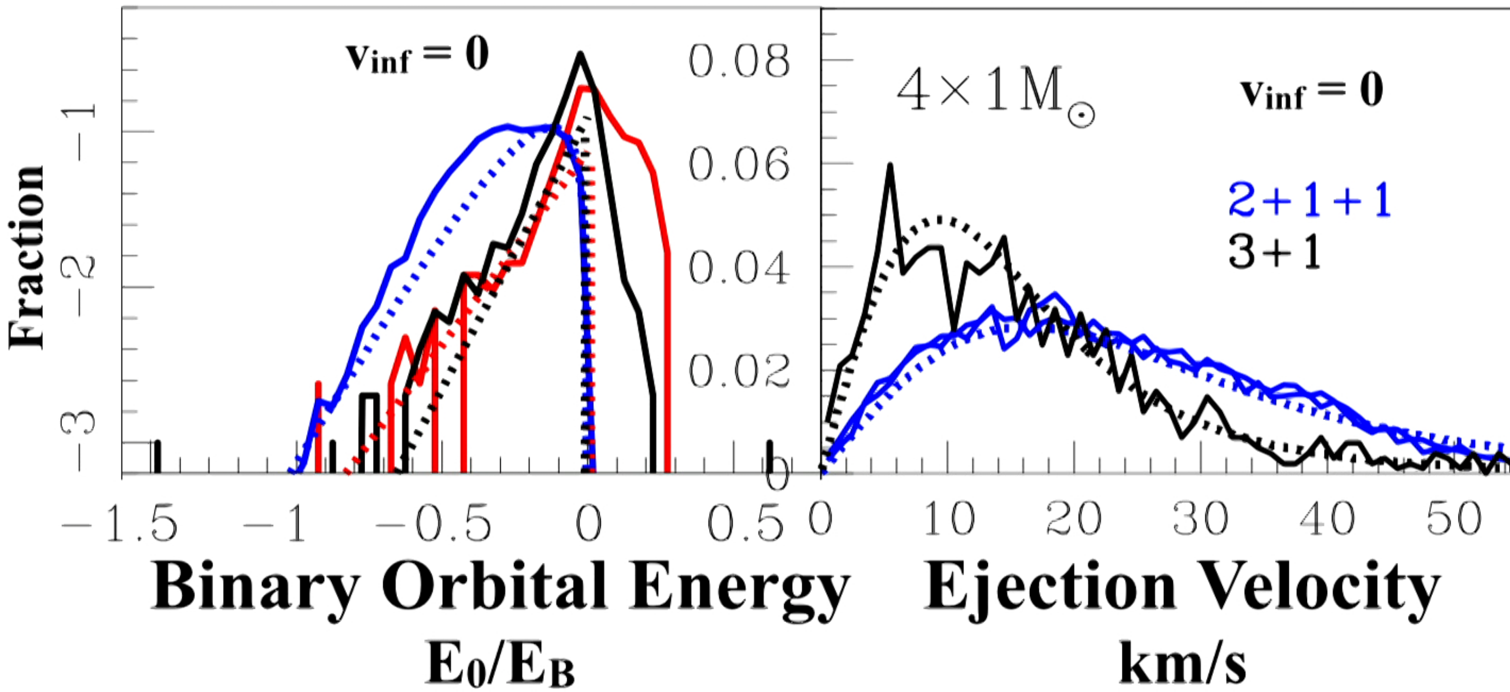


Figure 3. The configuration of the 2+1+1 outcome.

2+2 **3+1** **2+1+1**

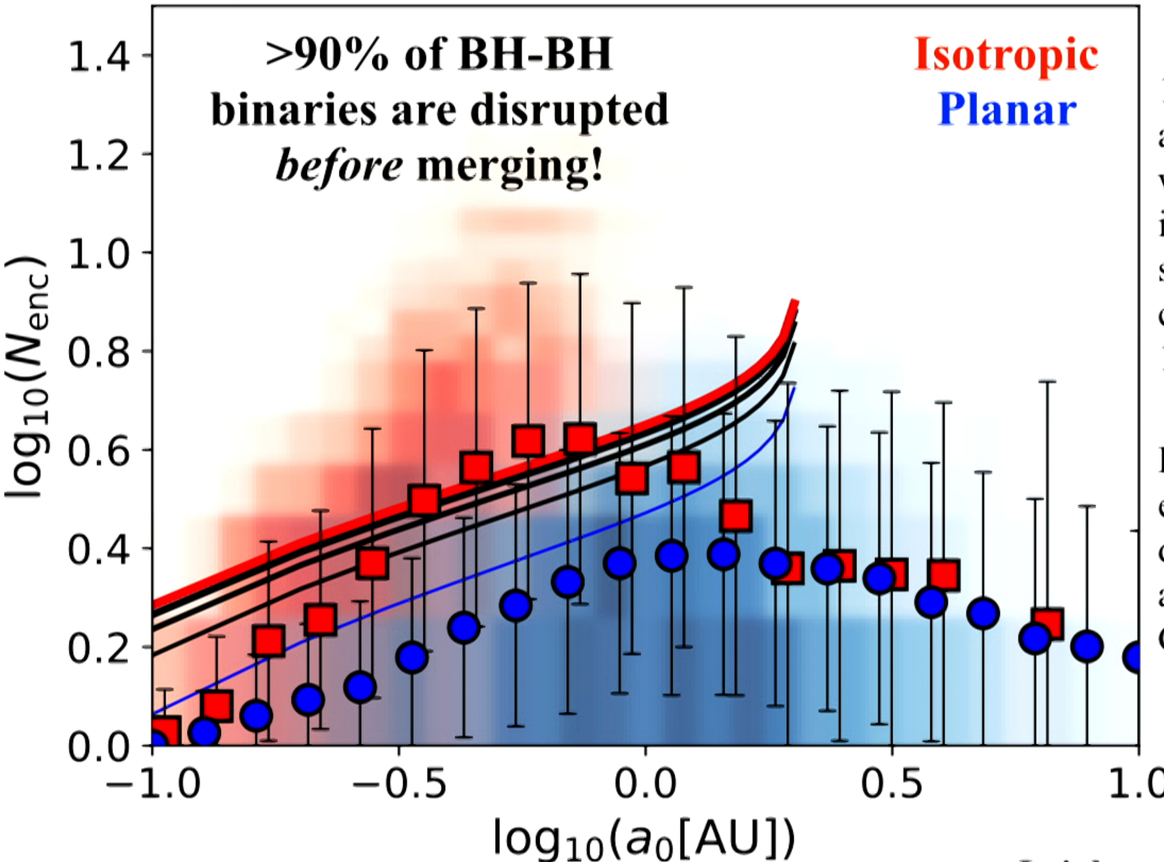
Statistical Mechanics



Dotted lines = Theory
Solid Lines = Simulations

Leigh et al. (2016)
Stone & **Leigh**
(2017, in prep)

BH-BH Binary Mergers in Galactic Nuclei?

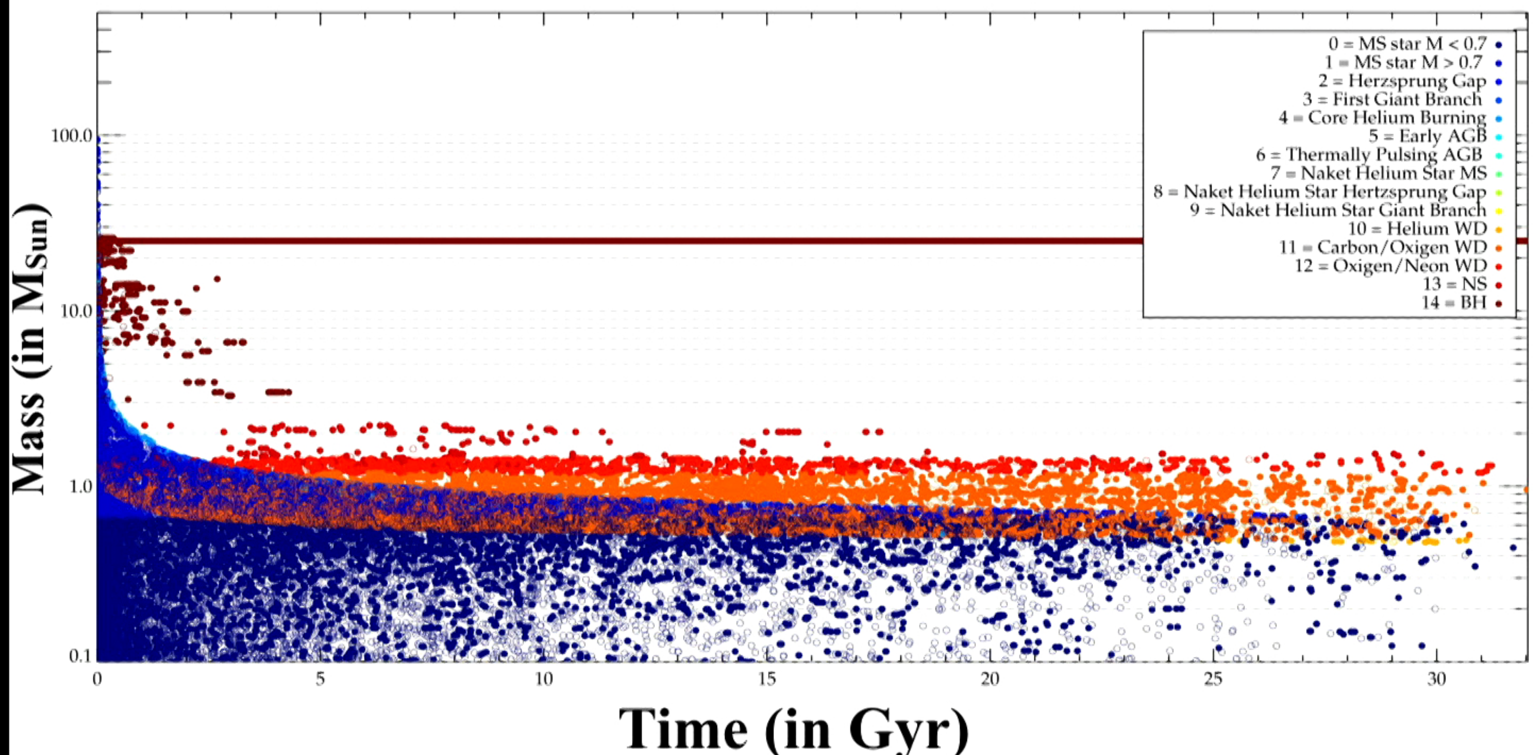


10^4 BH-BH binaries at the influence radius with the indicated initial binary orbital separation and component masses of 10 M_{Sun} and 15 M_{Sun}.

Each binary is evolved by both dynamical hardening and inter-encounter GW emission.

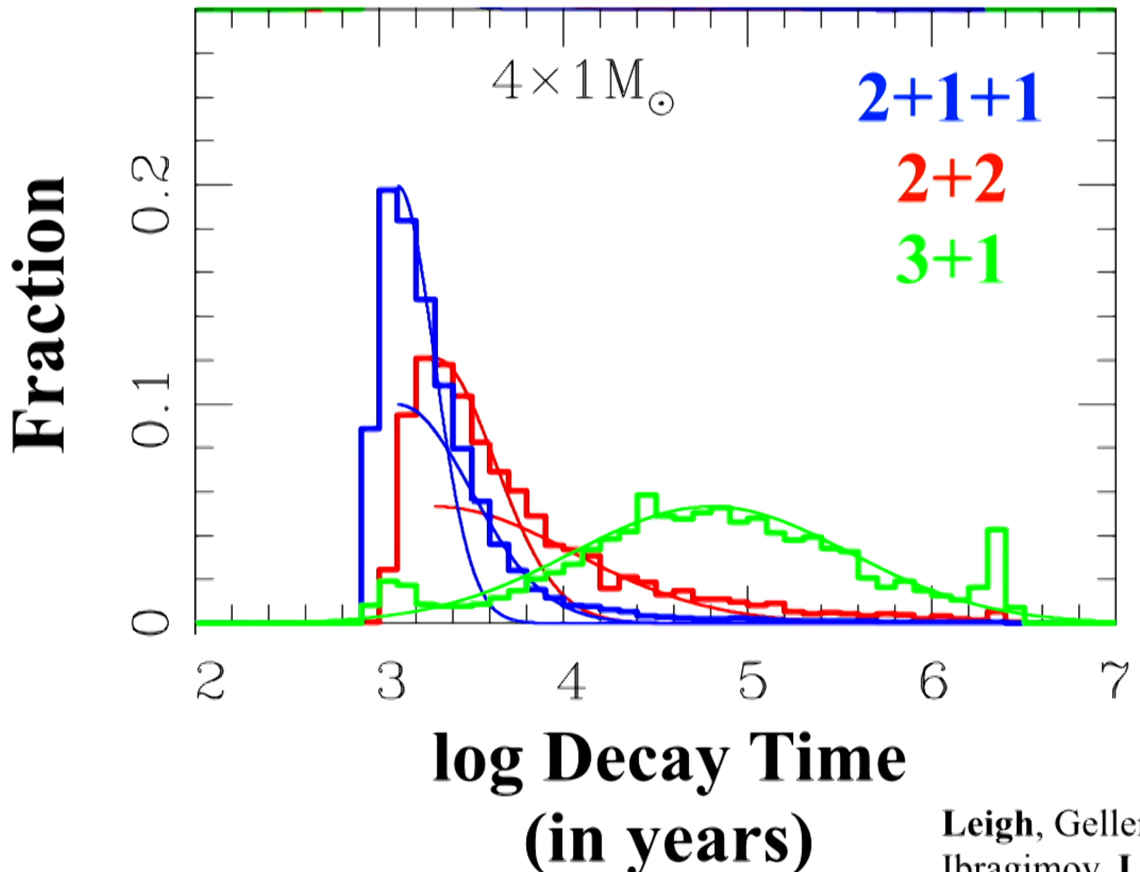
Leigh at al. (2017, submitted)

The Decay of Black Hole Sub-Clusters



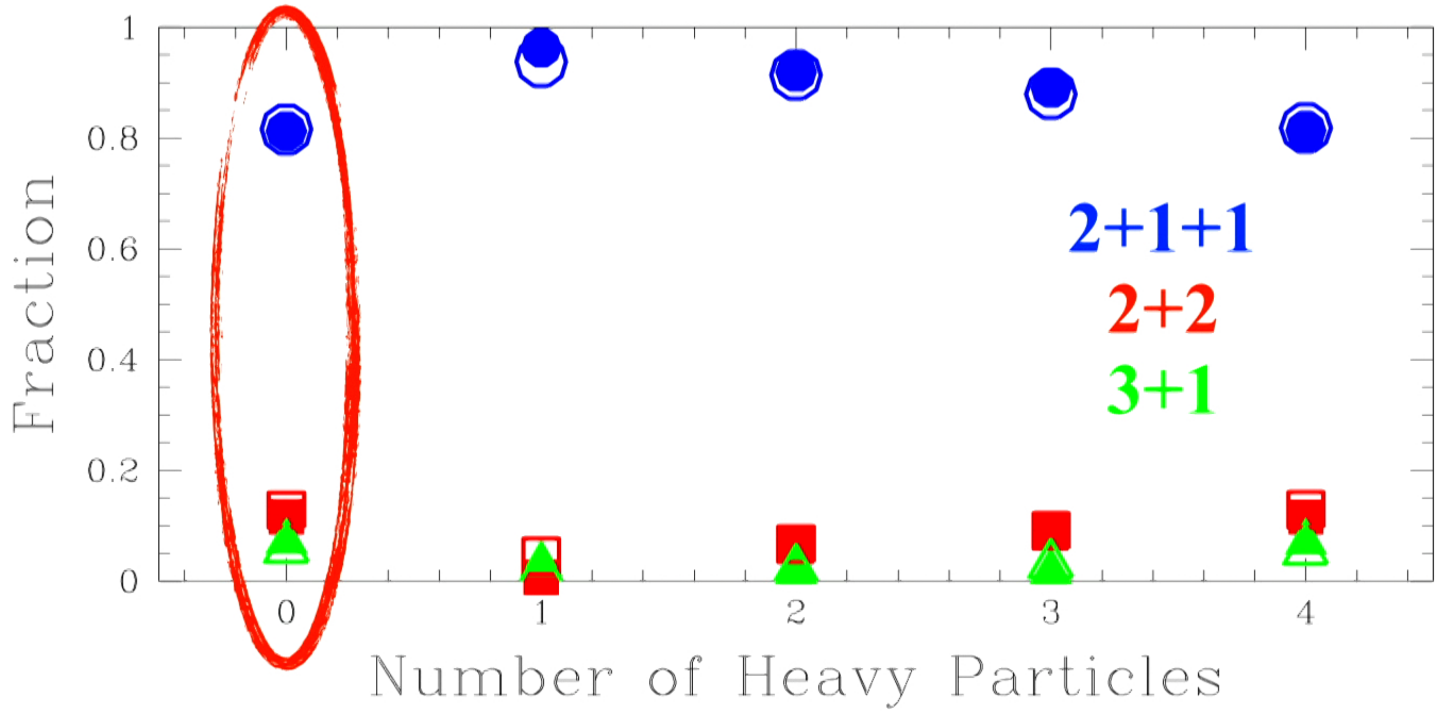
N-body simulation with an IMBH. Each time an object of a given mass experiences a strong encounter with the IMBH, a point is placed on the plot (taken from Figure 1 of Leigh et al. 2014, MNRAS, 444, 29).

Half-Lives and Radioactive Decay



Leigh, Geller & Shara (2016)
Ibragimov, **Leigh et al.** (2017, in prep)

Half-Lives and Radioactive Decay



Leigh, Geller & Shara (2016)
Ibragimov, **Leigh et al.** (2017, in prep)

Summary

- Chaos is at the heart of modern astrophysics, and permeates its many sub-disciplines
  - For a given set of initial conditions, you get a distribution of outcomes
- Together with the initial conditions problem, this spells doom for modern computers
- We need creative new methods and tools to bridge this gap
- By combining these tools with computers in clever ways, we stand to learn a great deal of astrophysics from future aLIGO detections of merging BH-BH binaries

Please visit www.nathanwcleigh.com for more information!