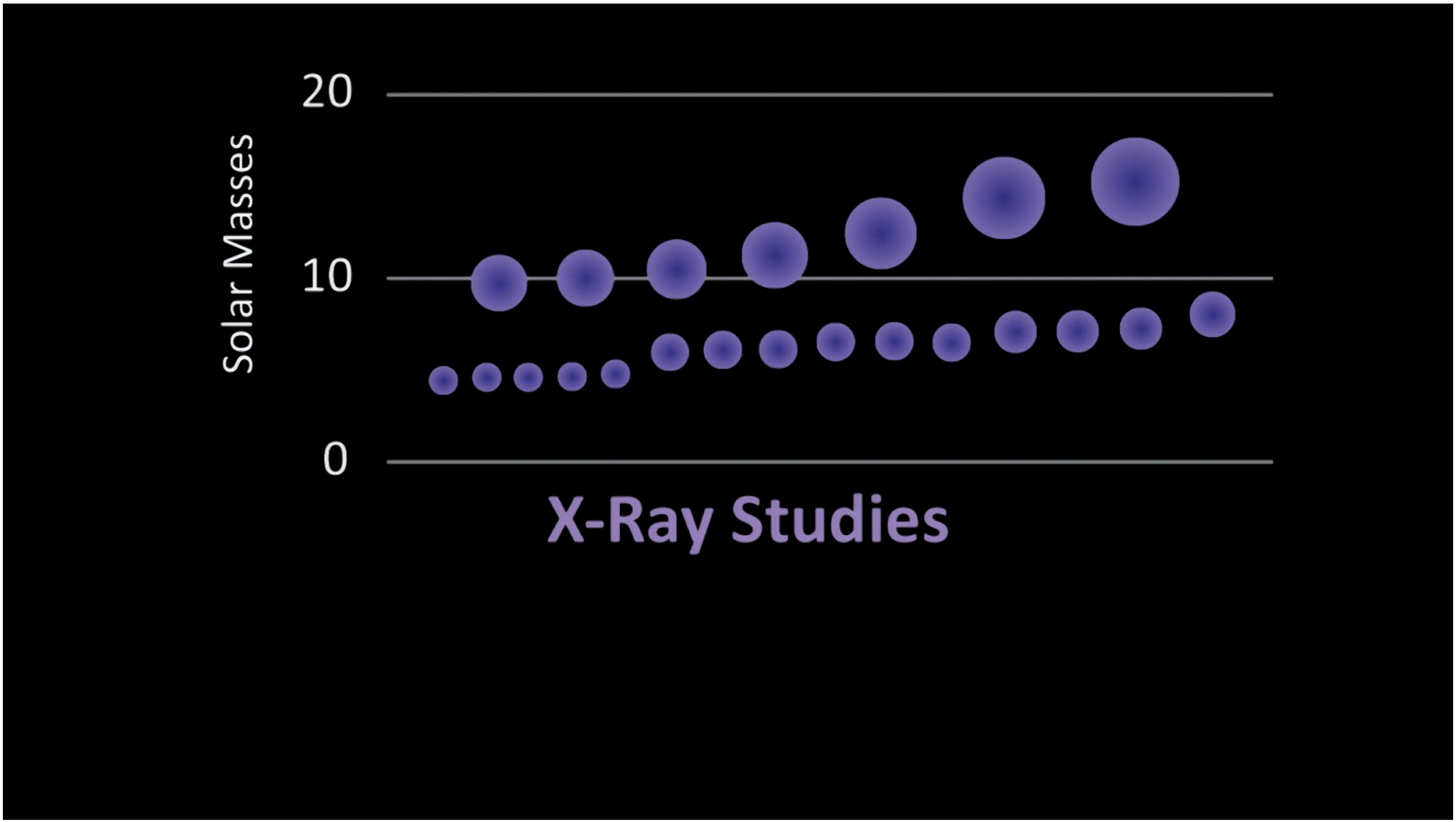
Title: Gravitational Waves from Dynamically-formed Binary Mergers

Date: Nov 15, 2018 01:00 PM

URL: http://pirsa.org/18110035

Abstract: Since the first detection two years ago, gravitational waves have promised to revolutionize the physics and astrophysics of compact objects. But to understand what these gravitational waves are telling us, we need to understand how these relativistic binary systems form in the first place. In this talk, I will describe the various astrophysical pathways for forming the binary mergers detected by LIGO/Virgo, and how specific features of the gravitational waves (such as the eccentricities and spins) can illuminate the formation histories of these exotic objects. In particular, I will discuss how black holes can undergo multiple mergers in dense star clusters, creating a second generation of black holes more massive (and with potentially greater spins) than those formed through the collapse of isolated stars.


20
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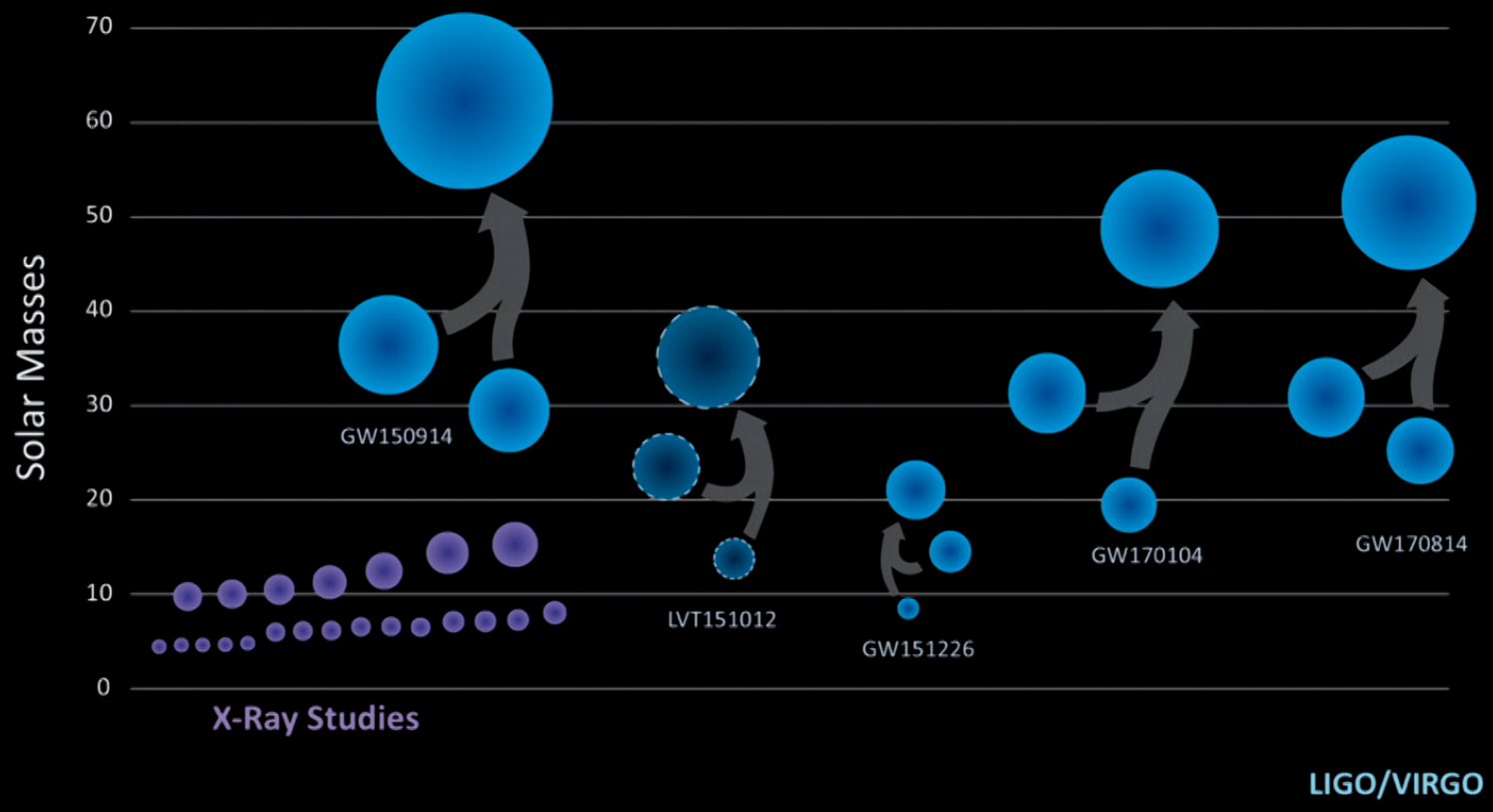
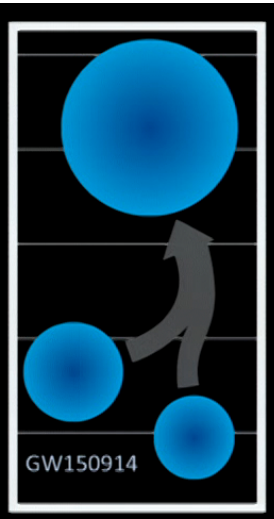
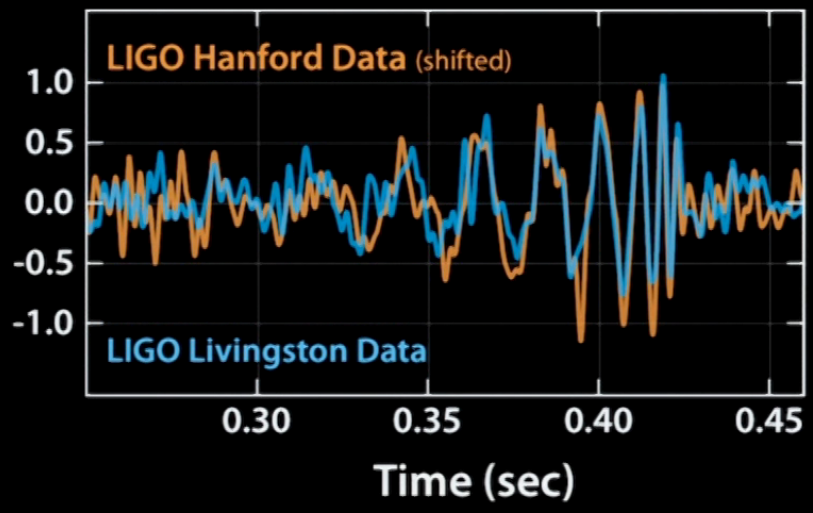
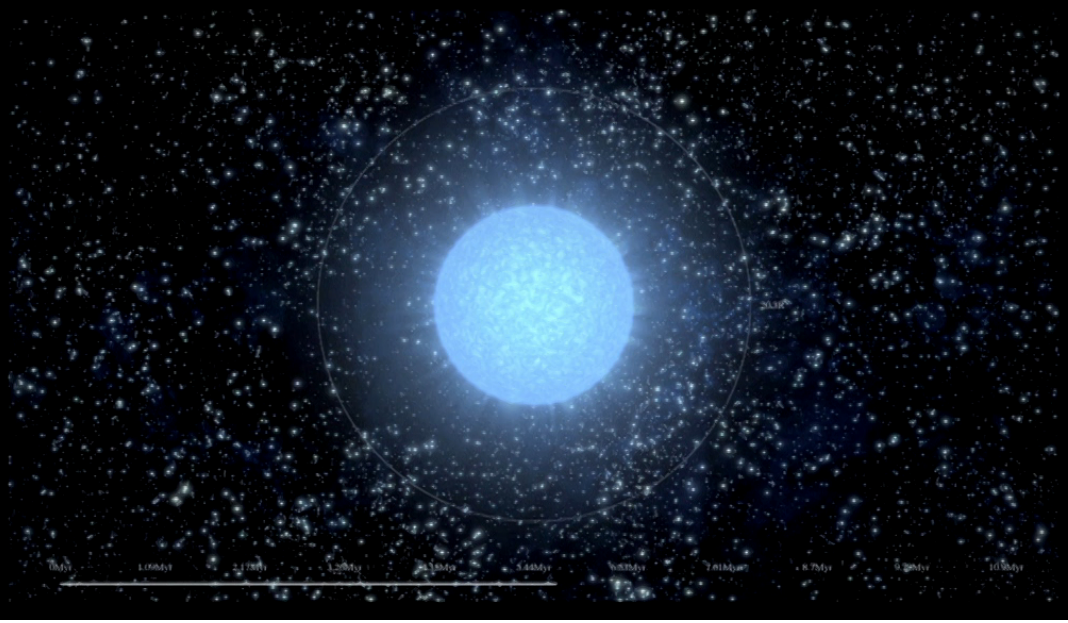
Solar Masses
X-Ray Studies

Black Holes of Known Mass

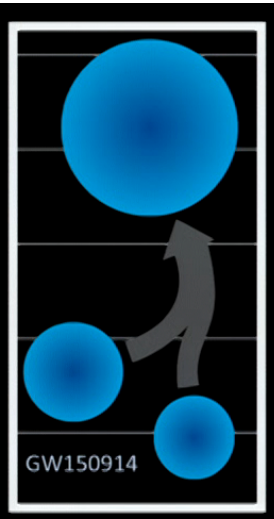


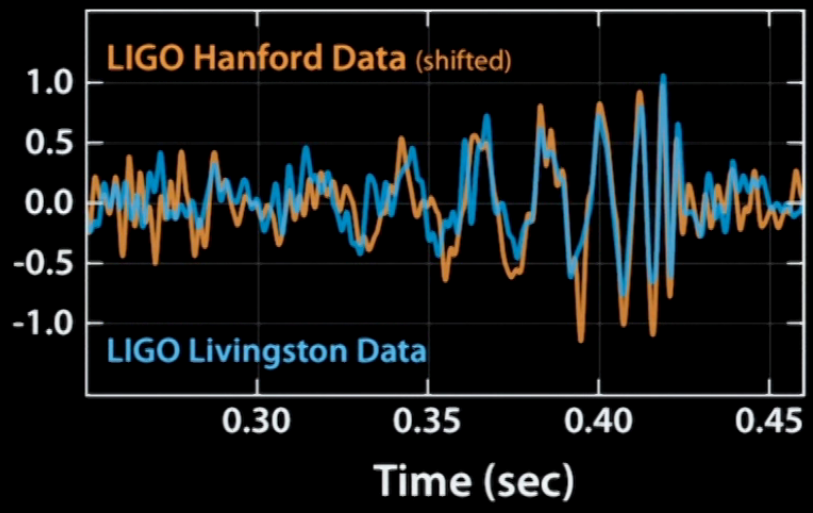


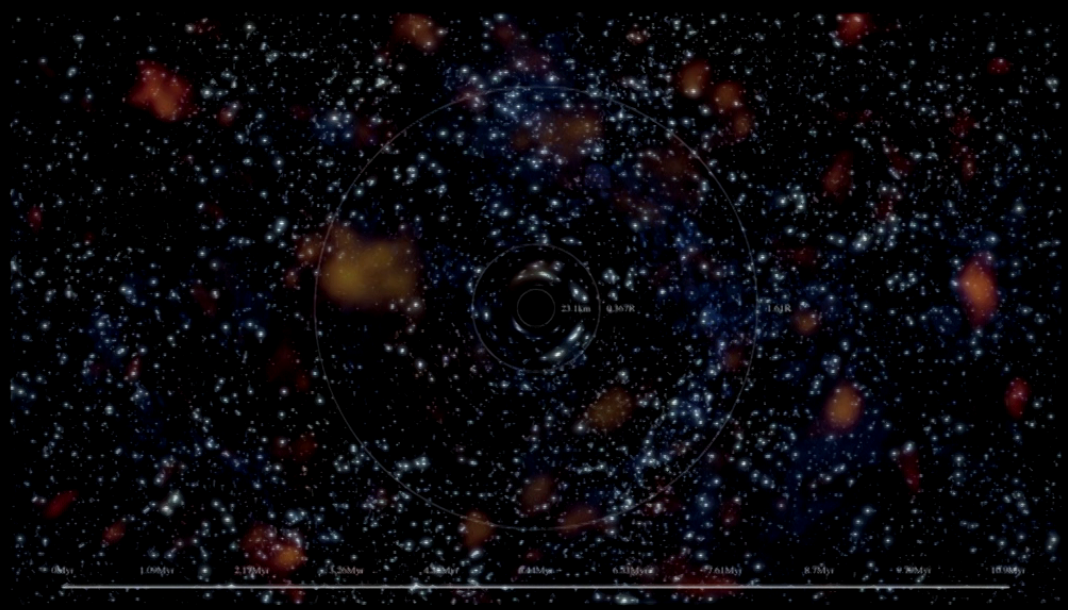




Kalogera,
Wilems,
Valsecchi,
NU Viz







Kalogera,
Wilems,
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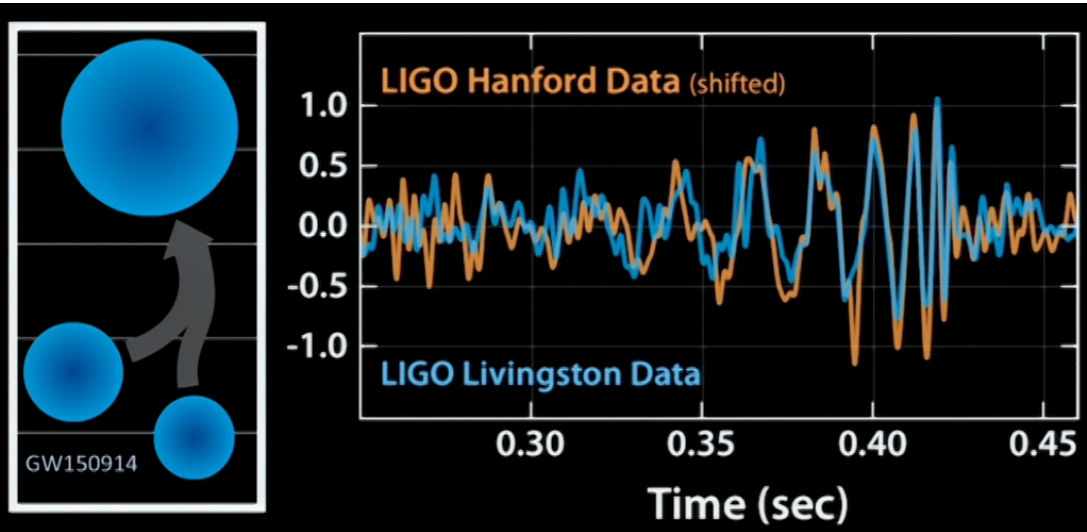
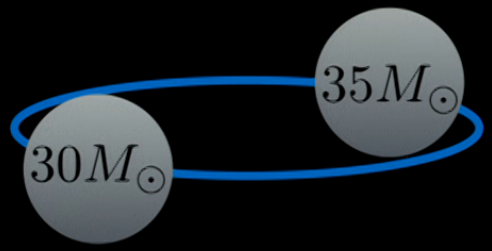
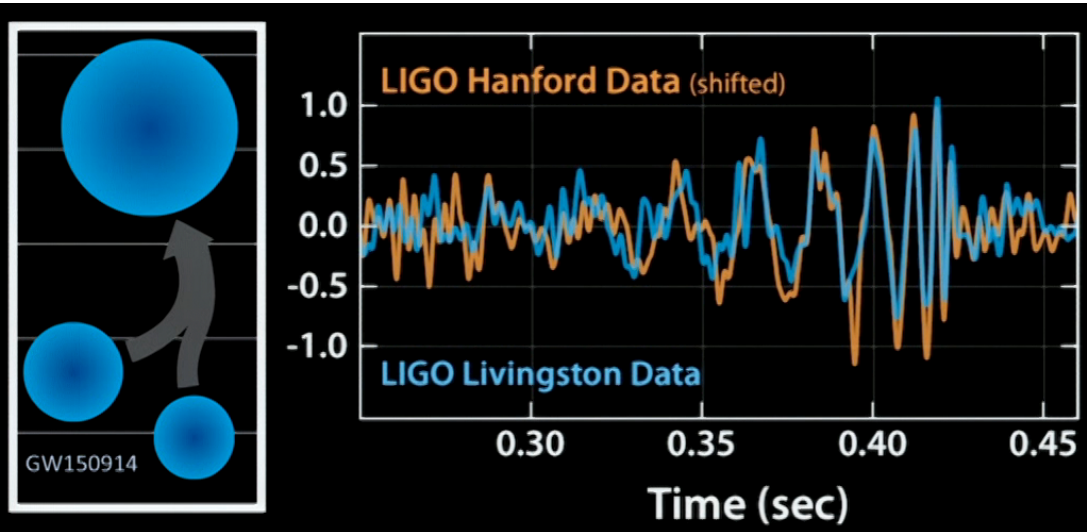

GW150914
LIGO Hanford Data (shifted)
LIGO Livingston Data
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


$35M_\odot$
$30M_\odot$


GW150914
LIGO Hanford Data (shifted)
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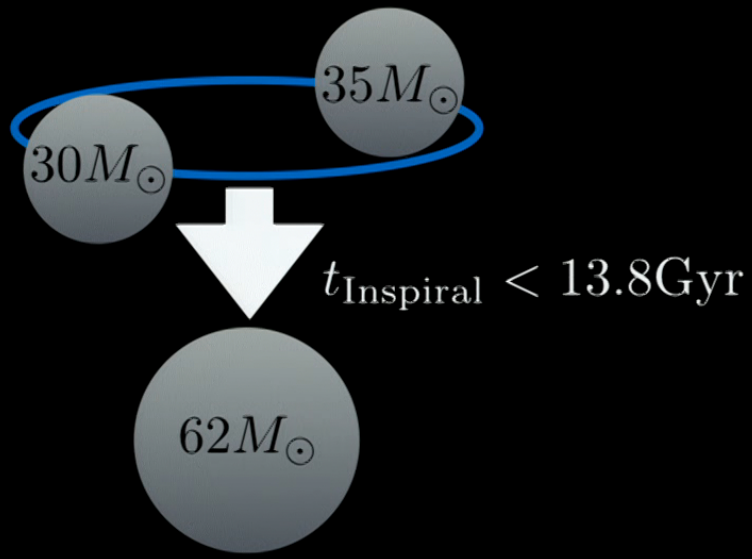
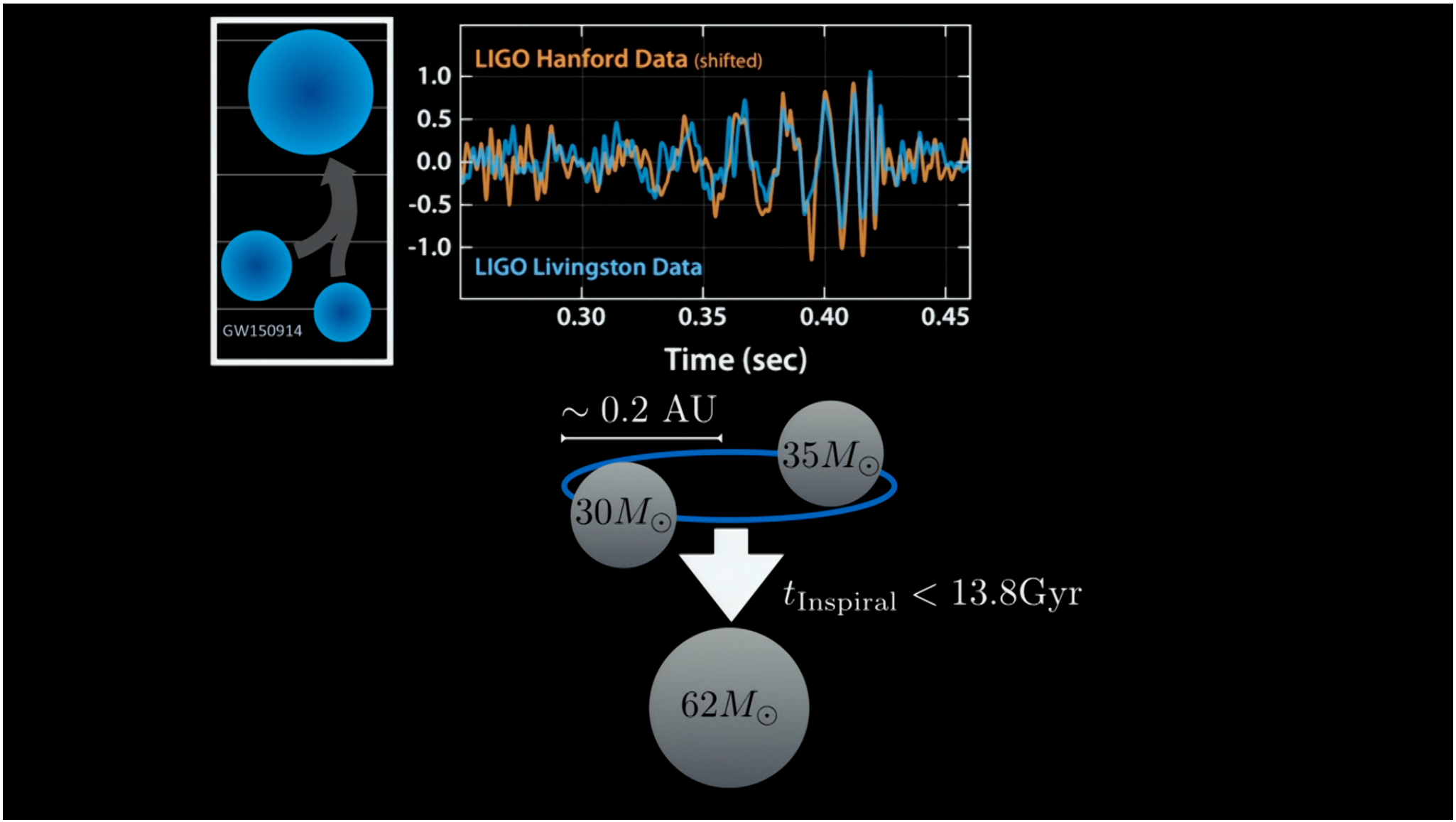
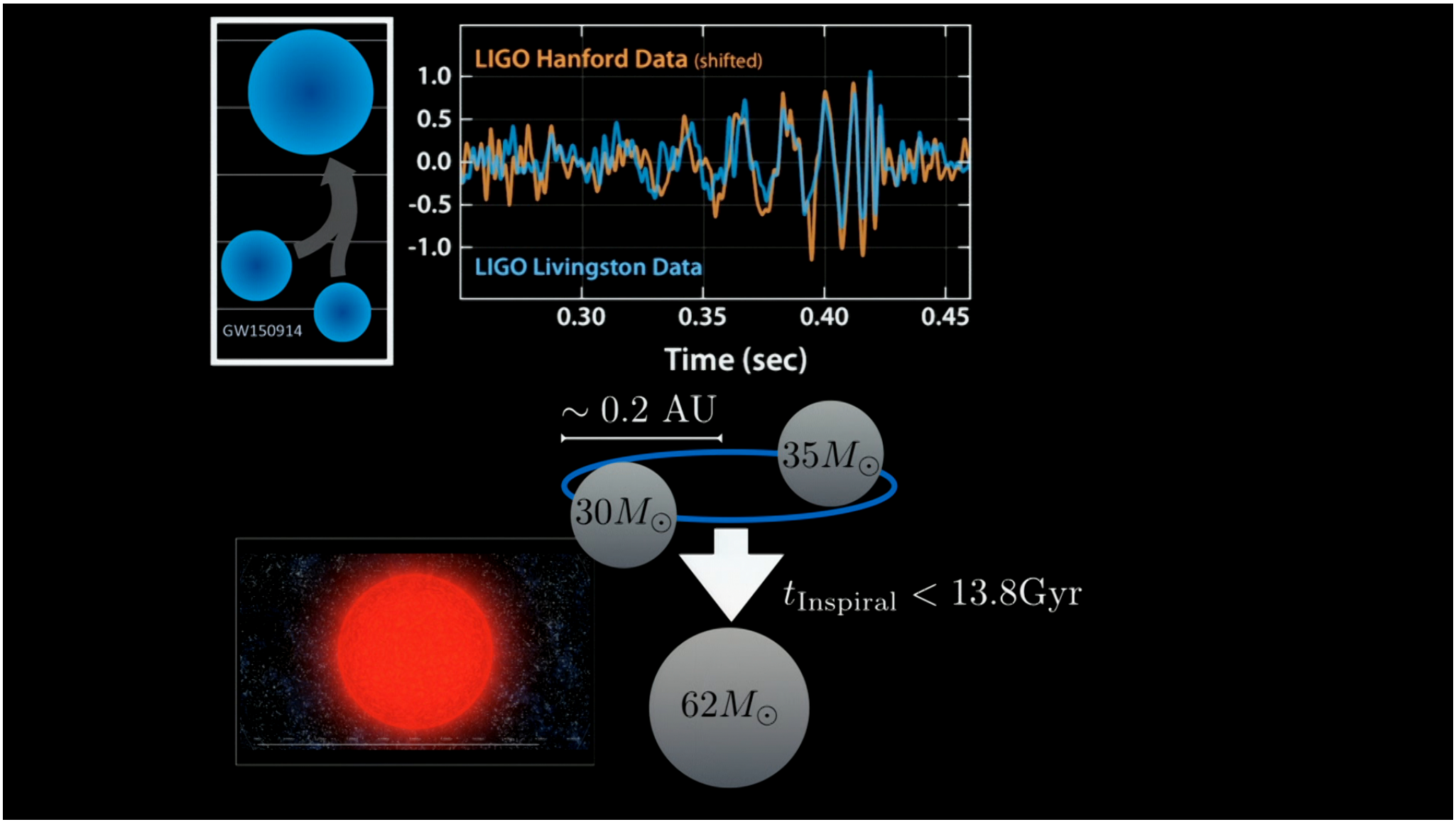
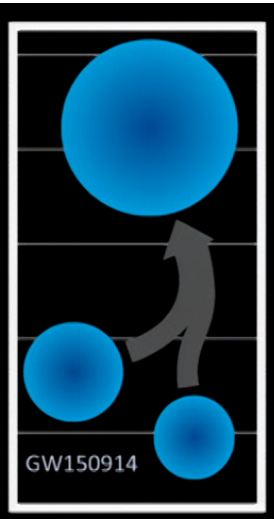
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


$35M_\odot$
$30M_\odot$
$t_{\rm Inspiral} < 13.8{\rm Gyr}$
$62M_\odot$


GW150914
LIGO Hanford Data (shifted)
LIGO Livingston Data
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
~ 0.2 AU
$35M_\odot$
$30M_\odot$
$t_{\rm Inspiral} < 13.8{\rm Gyr}$
$62M_\odot$


GW150914
LIGO Hanford Data (shifted)
LIGO Livingston Data
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
~ 0.2 AU
$35M_\odot$
$30M_\odot$
$t_{\rm Inspiral} < 13.8{\rm Gyr}$
$62M_\odot$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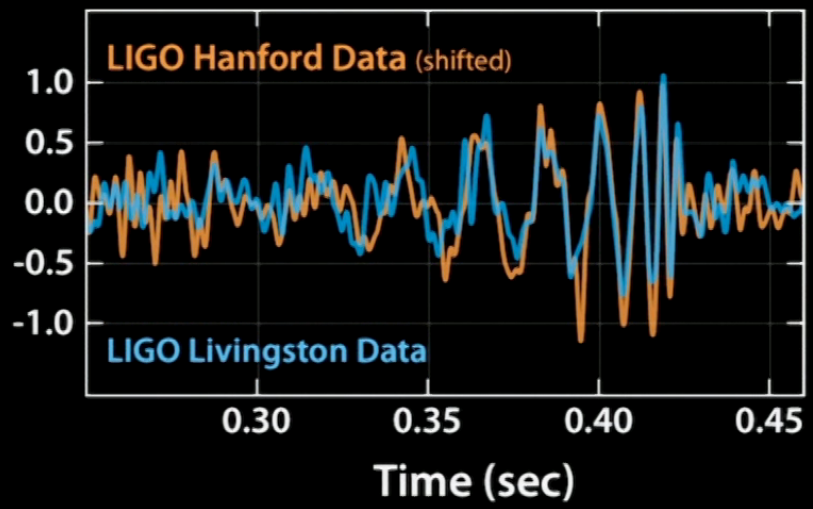
LIGO Hanford Data (shifted)
LIGO Livingston Data
1.0
0.5
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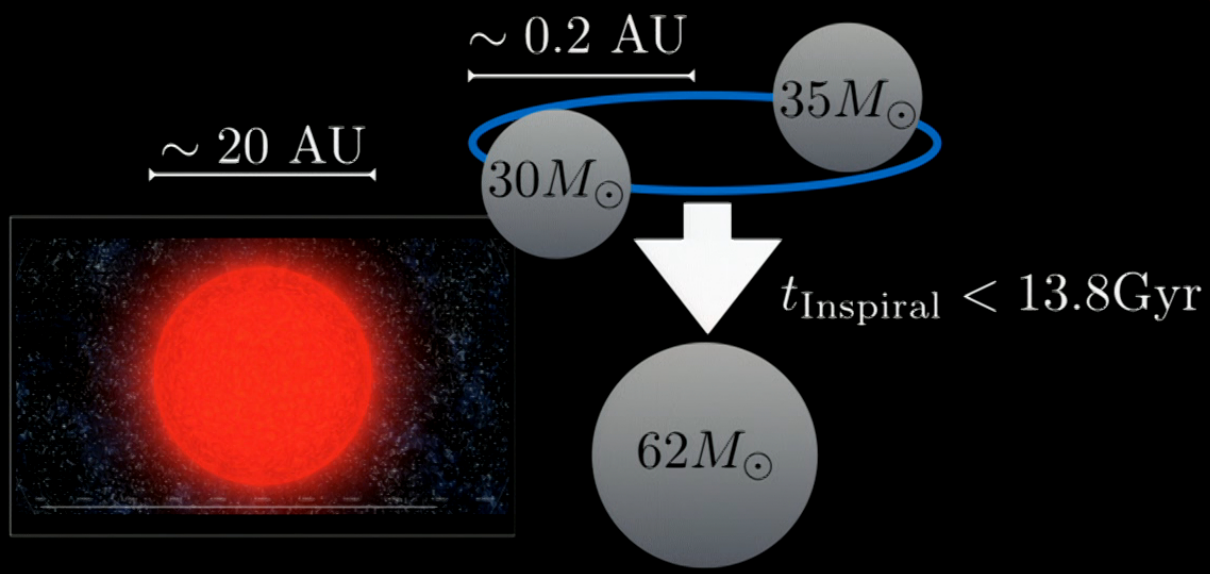
Time (sec)


~ 0.2 AU
~ 20 AU
$35M_\odot$
$30M_\odot$
$t_{\rm Inspiral} < 13.8{\rm Gyr}$
$62M_\odot$

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Dynamical Formation of Merging Compact Binaries

Carl Rodriguez, Scott Hughes, Fabio Antonini, Caitlin Fischer

Sourav Chatterjee, Meagan Morscher, Bharath Pattabirimin, Carl-Johan Haster, Mike Zevin, Chris Pankow, Katie Breivik, Kyle Kremer, Shane Larson, Vicky Kalogera, Fred Rasio

Portegies Zwart & McMillan 2000, Gültekin et al. 2004, 2006, Kocsis et al. 2006, O'Leary et al. 2006, 2007, Sadowski et al. 2008, Banerjee et al. 2010, 2017, Downing et al. 2010, 2011, Benacquista et al. 2013, Clausen et al. 2014, Bae et al. 2014, Ziosi et al. 2014, 2016, Morscher et al. 2013, 2015, Rodriguez et al. 2015, 2016a,b,c, Mapelli 2016,2017, Abbas et al. 2016, 2017, Giesler et al. 2017

Forming BH Binaries

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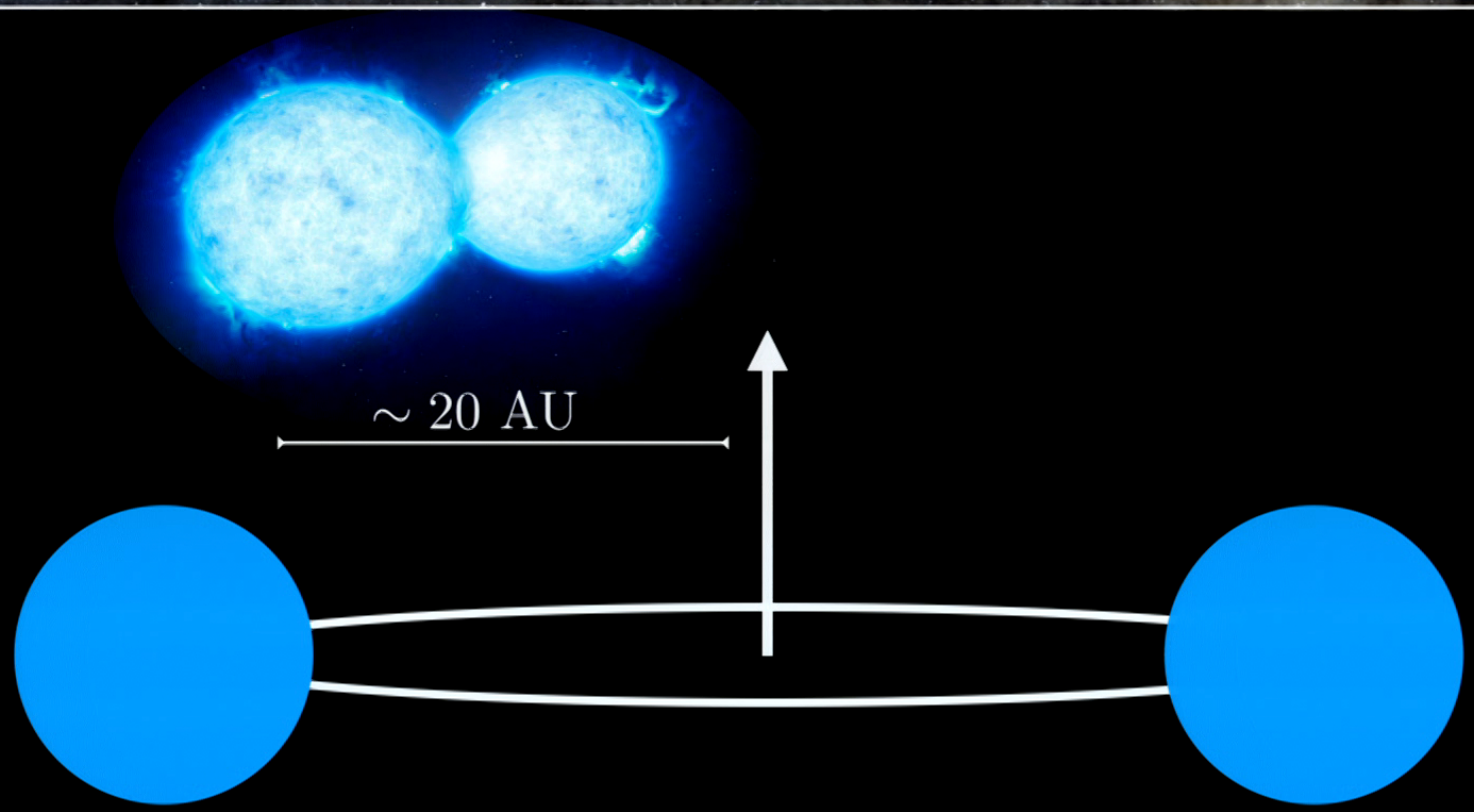

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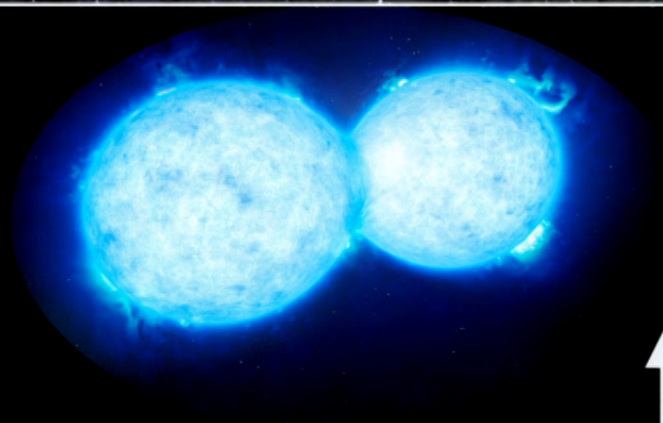

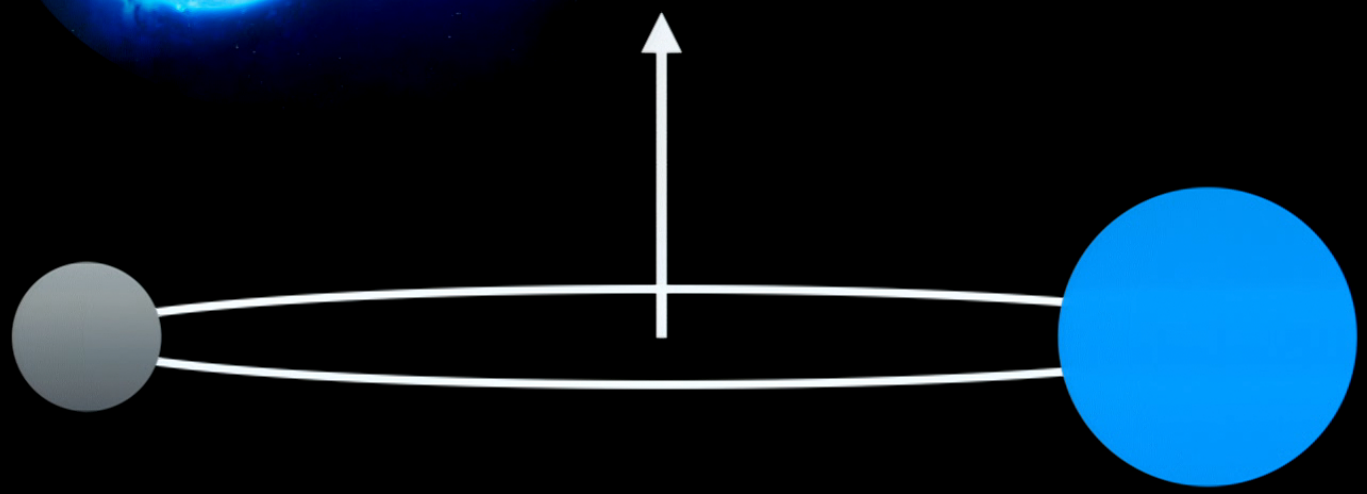

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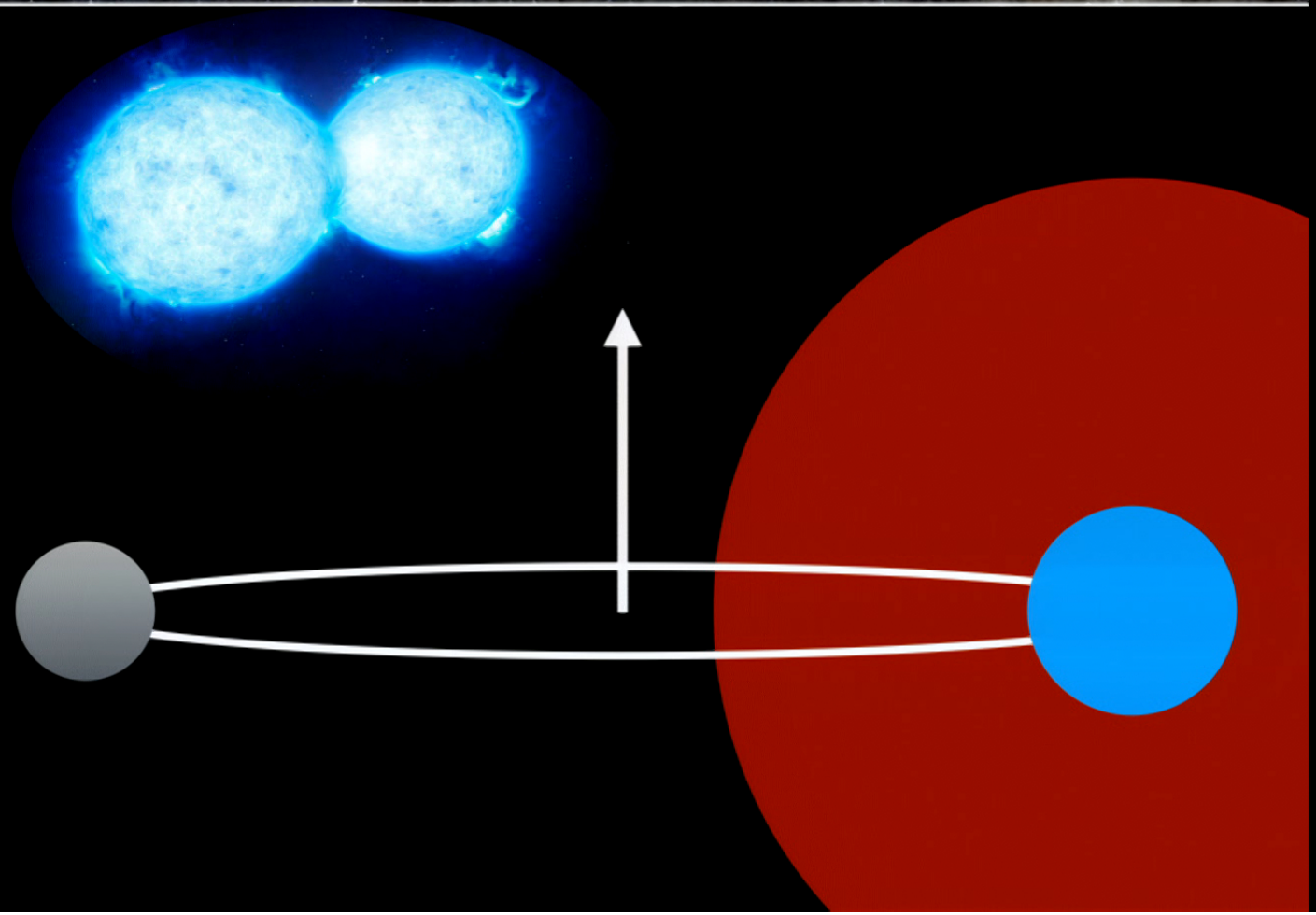

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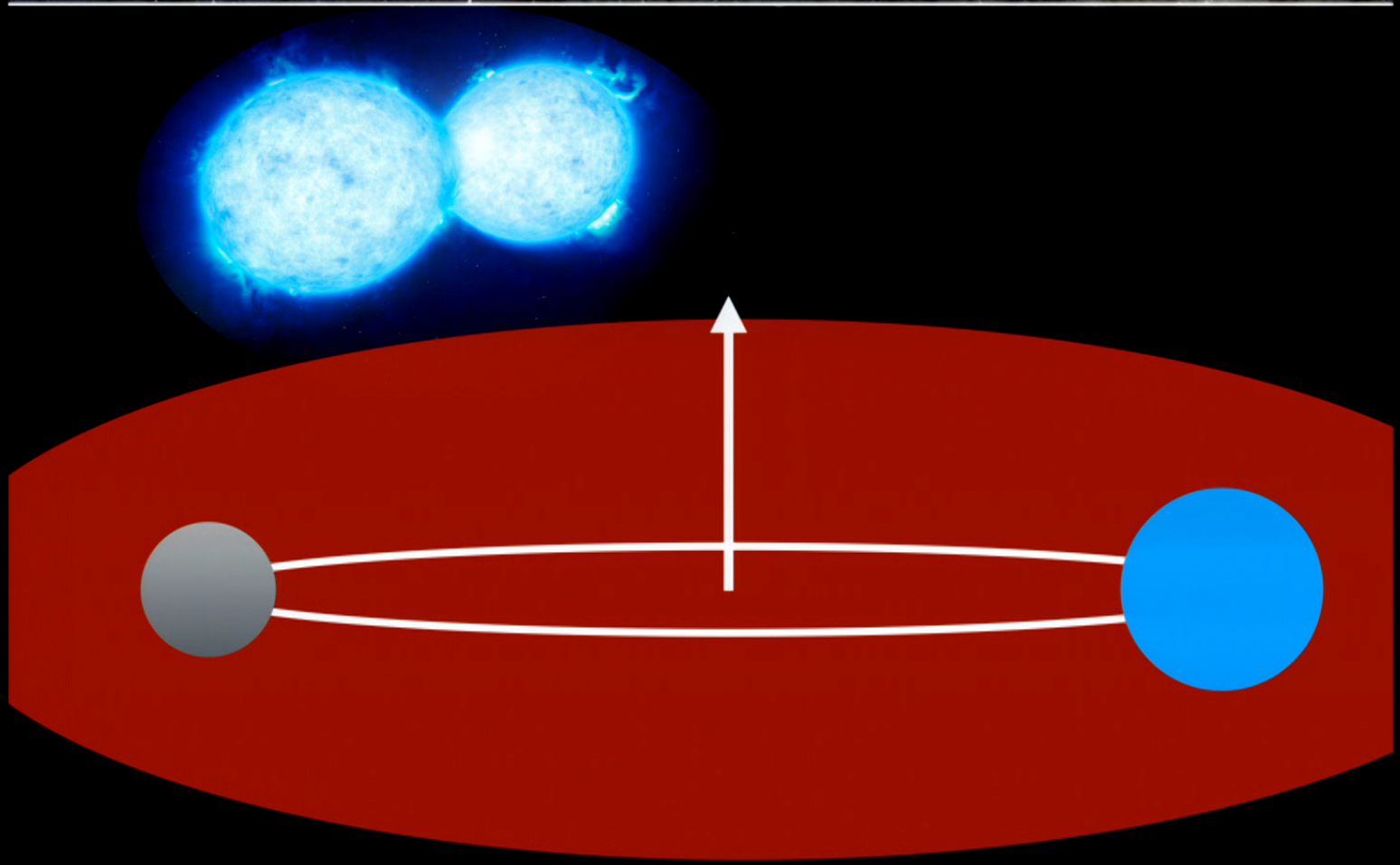

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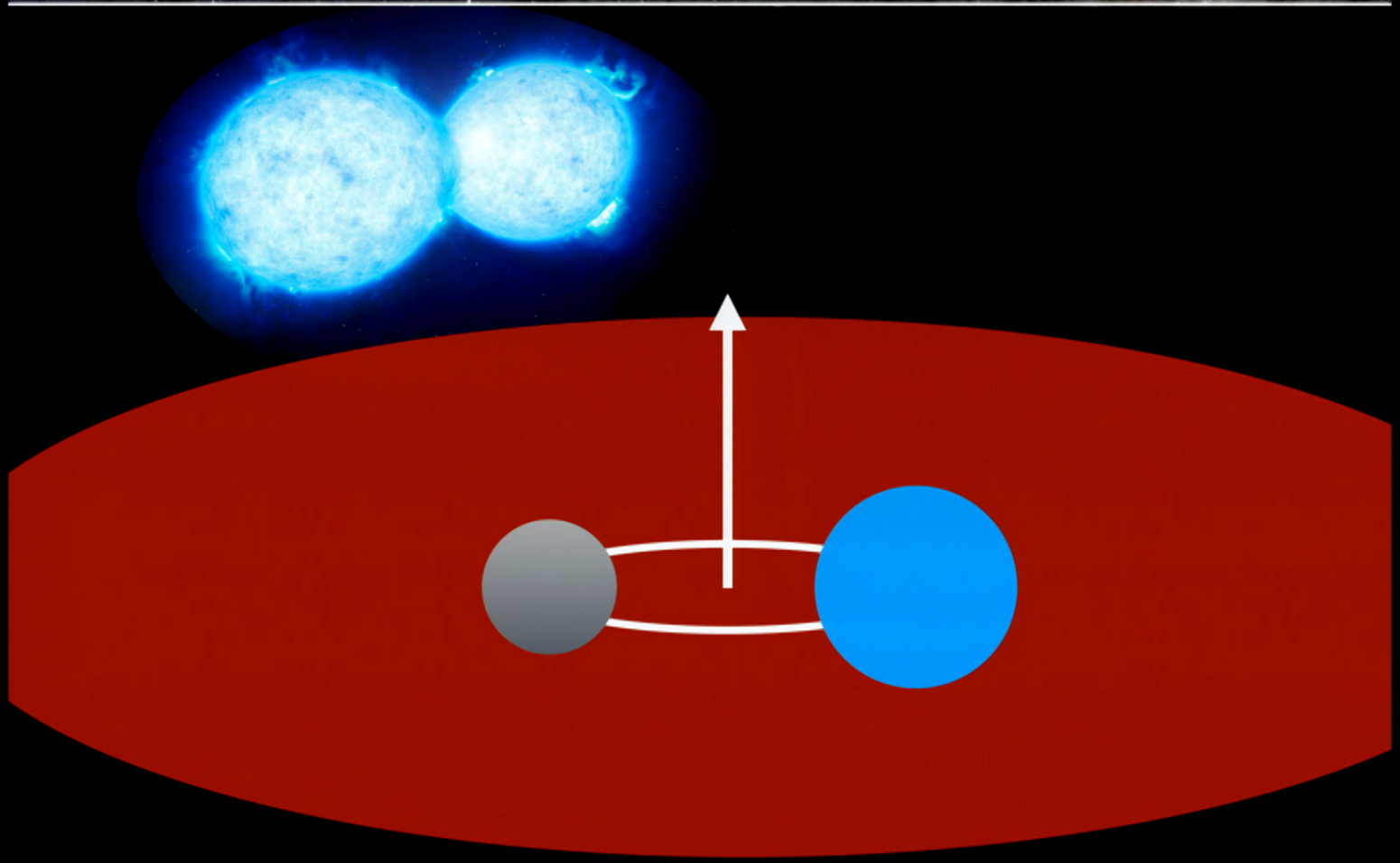

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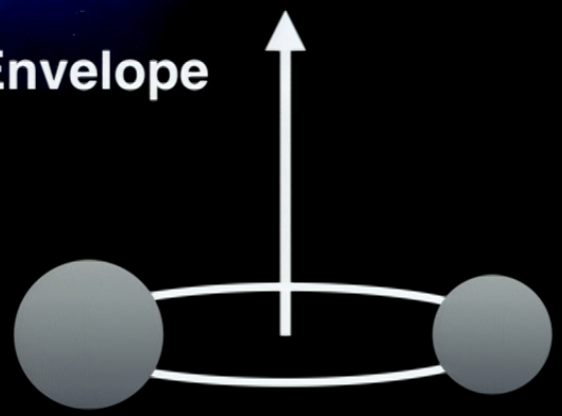
Common Envelope



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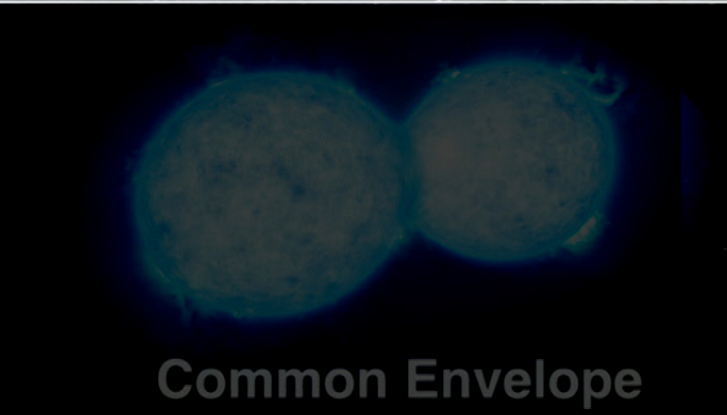

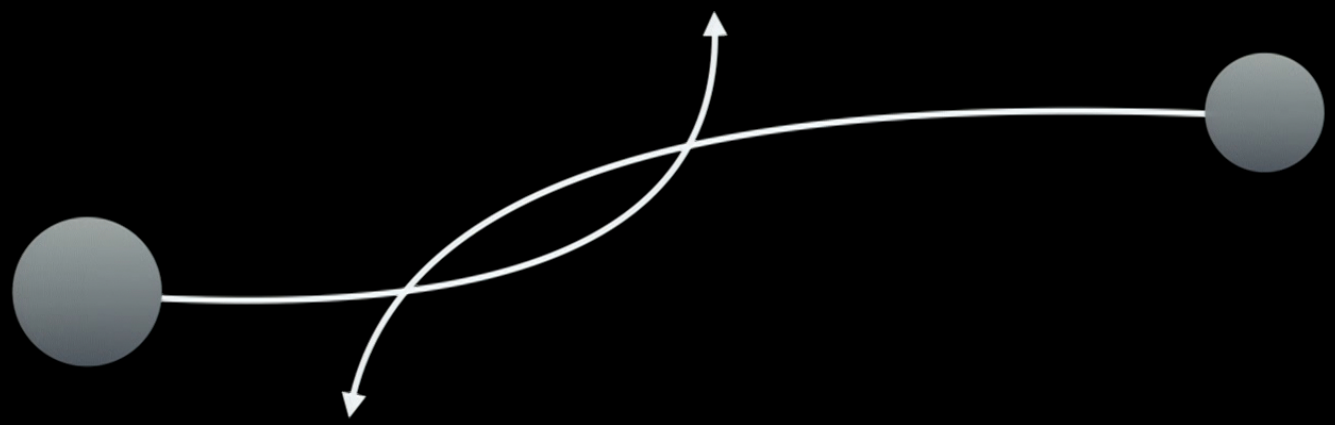

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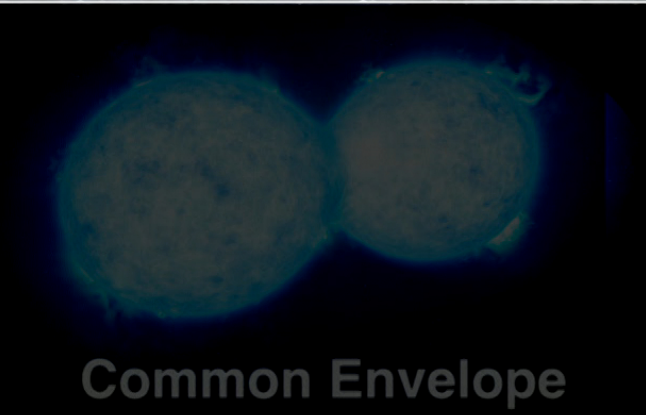

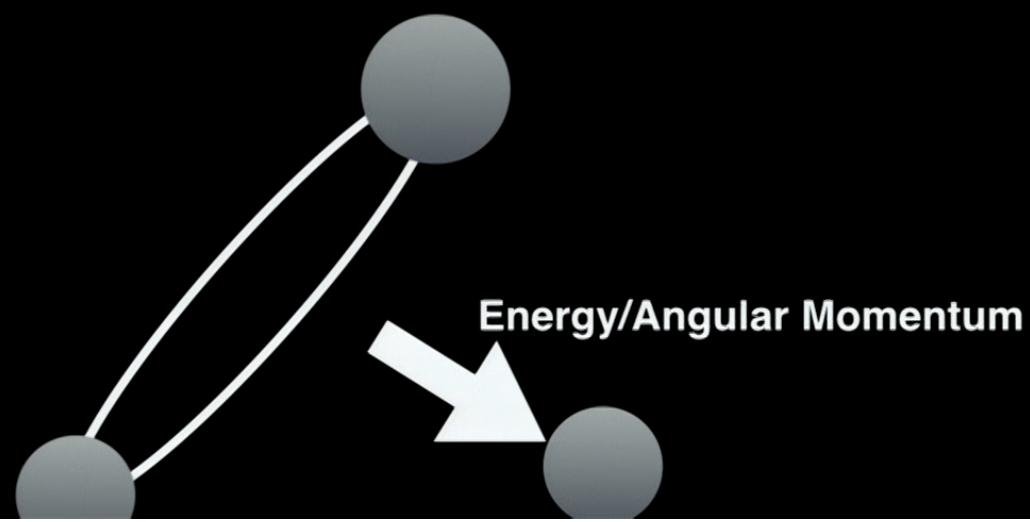

Forming BH Binaries

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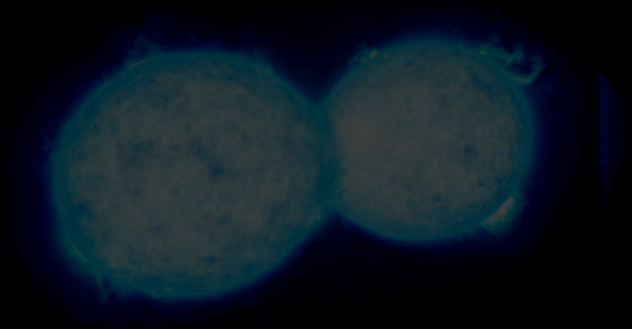
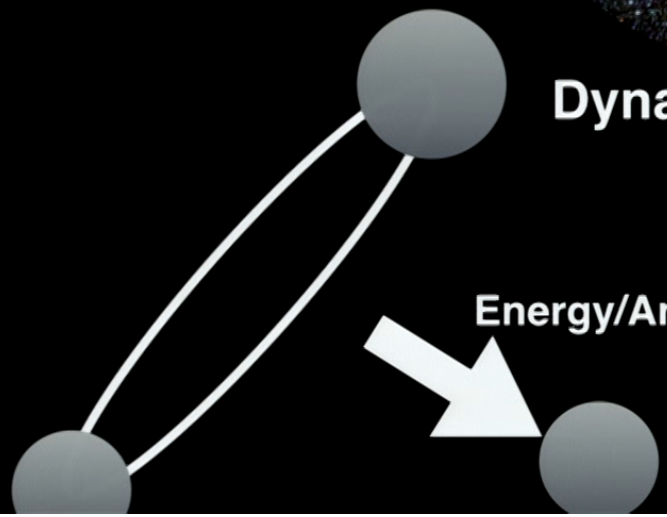


Common Envelope

Dynamical Formation



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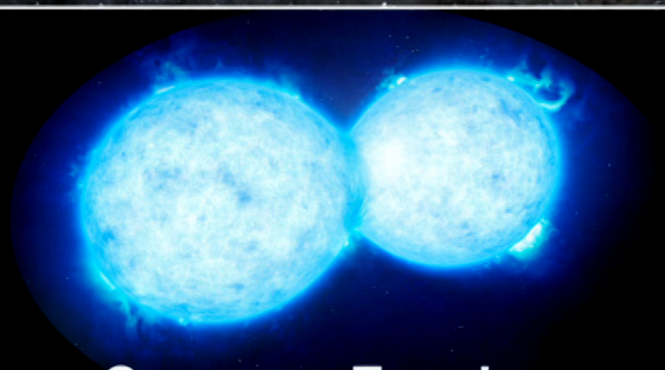

Common Envelope

Dynamical Formation

- Chemically Homogeneous Evolution
- Triples (Lidov-Kozai)
  - Stellar triples (field or dynamical)
  - Stellar BBH/SMBH
- Primordial black holes
- Highly-eccentric captures in scattering encounters
- Formation in AGN disks
- And many more…

Forming BH Binaries

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Common Envelope

Dynamical Formation

Can we tell the difference?

- Chemically Homogeneous Evolution
- Triples (Lidov-Kozai)
  - Stellar triples (field or dynamical)
  - Stellar BBH/SMBH
- Primordial black holes
- Highly-eccentric captures in scattering encounters
- Formation in AGN disks
- And many more…

Globular Clusters (GCs)

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- Old (~12 billion years) / low metallicity
- Massive (~100,000 to ~1 million stars)
- Compact

M30
(NASA/ACS Survey)

47 Tuc
(NASA/HST)

Globular Clusters (GCs)

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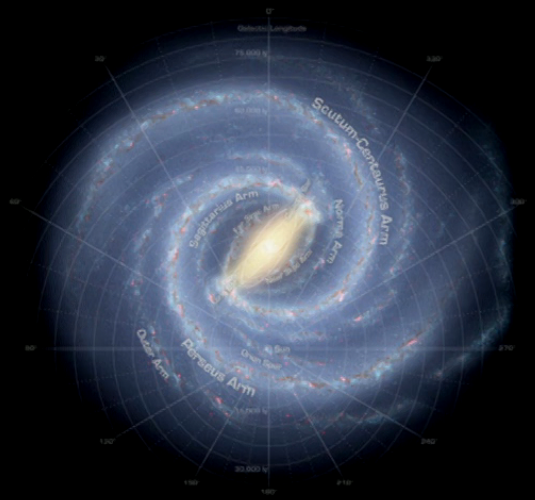
- Found in almost all galaxies



Milky Way

NASA/Adler/U. Chicago/Wesleyan/JPL-Caltech

M87

Adam Block/Mt. Lemmon SkyCenter/U. Arizona

Black Holes in GCs

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Black Holes in GCs

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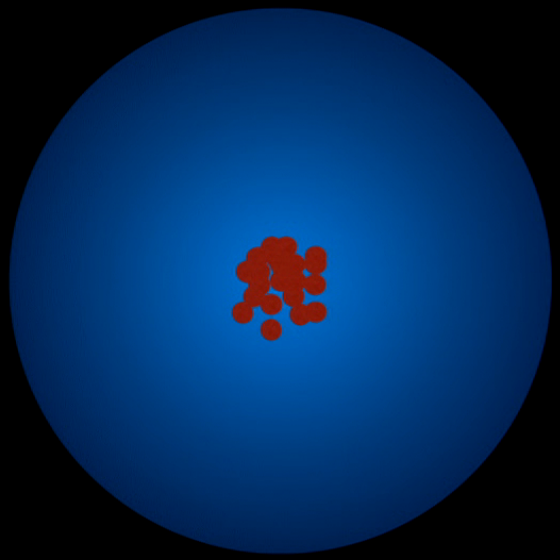

~ 100 Myr

Black Holes in GCs

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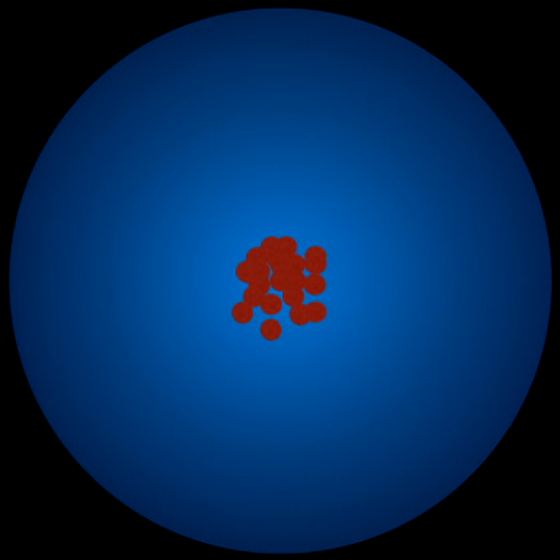
Strader et al., 2012



~ 100 Myr

Black Holes in GCs

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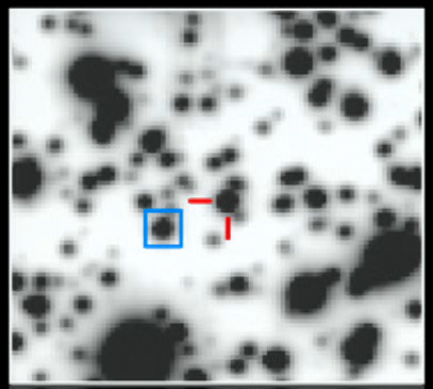
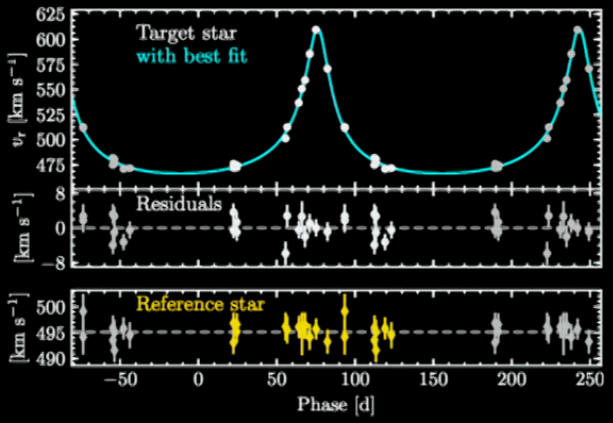
Strader et al., 2012



Giesers et al., 2018



Chaotic Interactions

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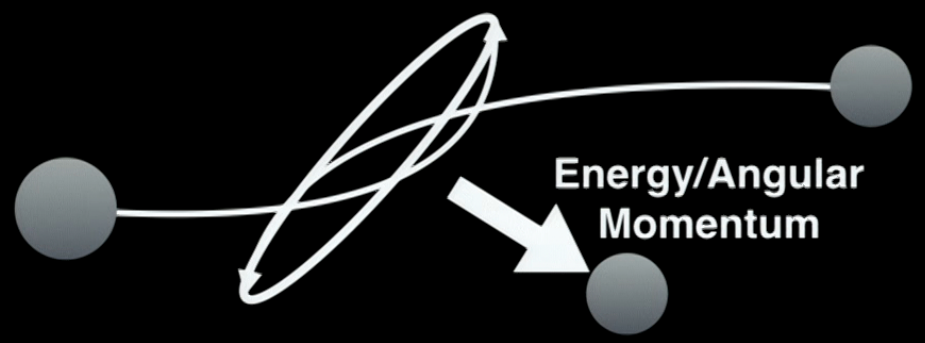

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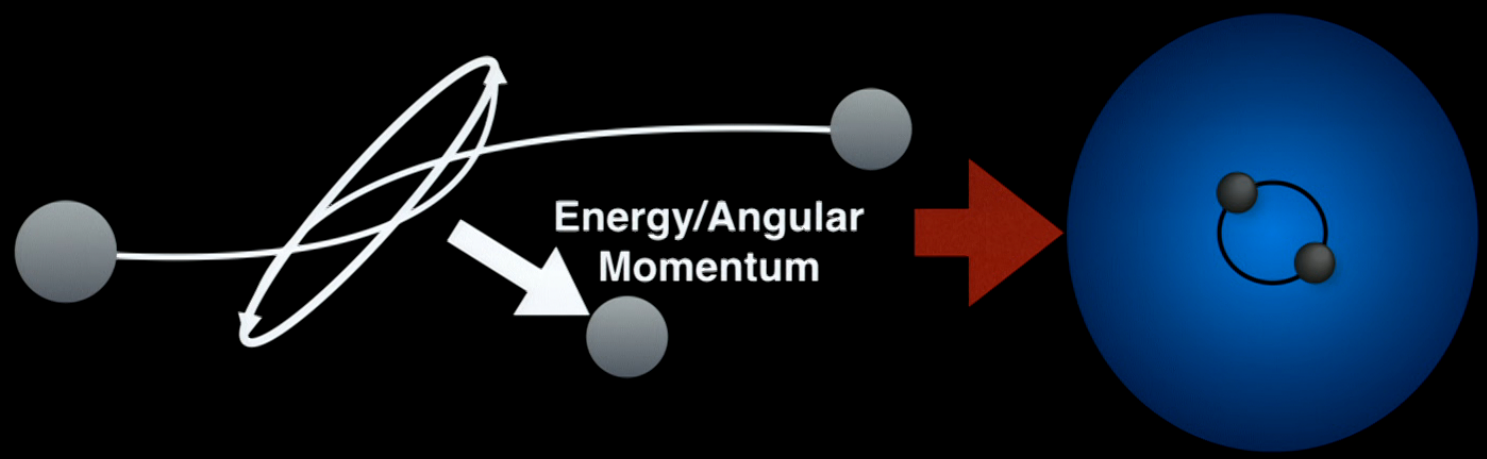

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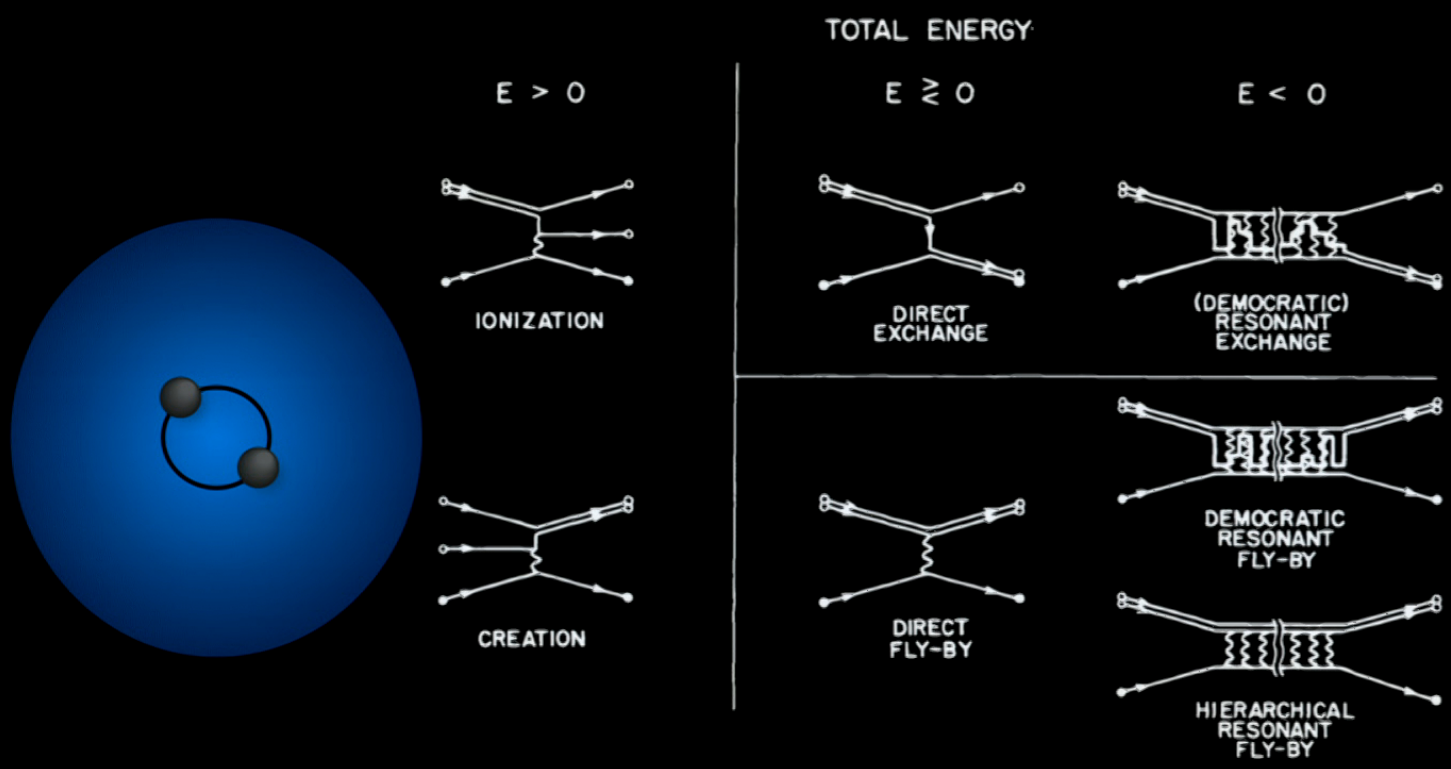

Heggie & Hut 1993

Chaotic Interactions

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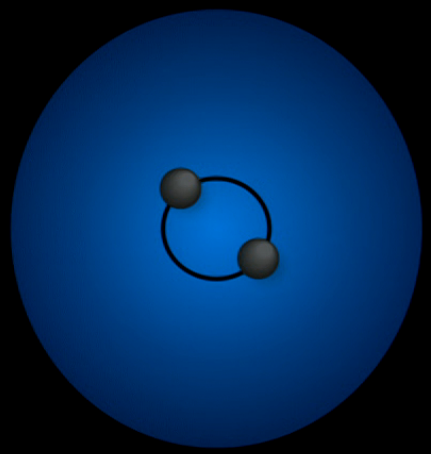

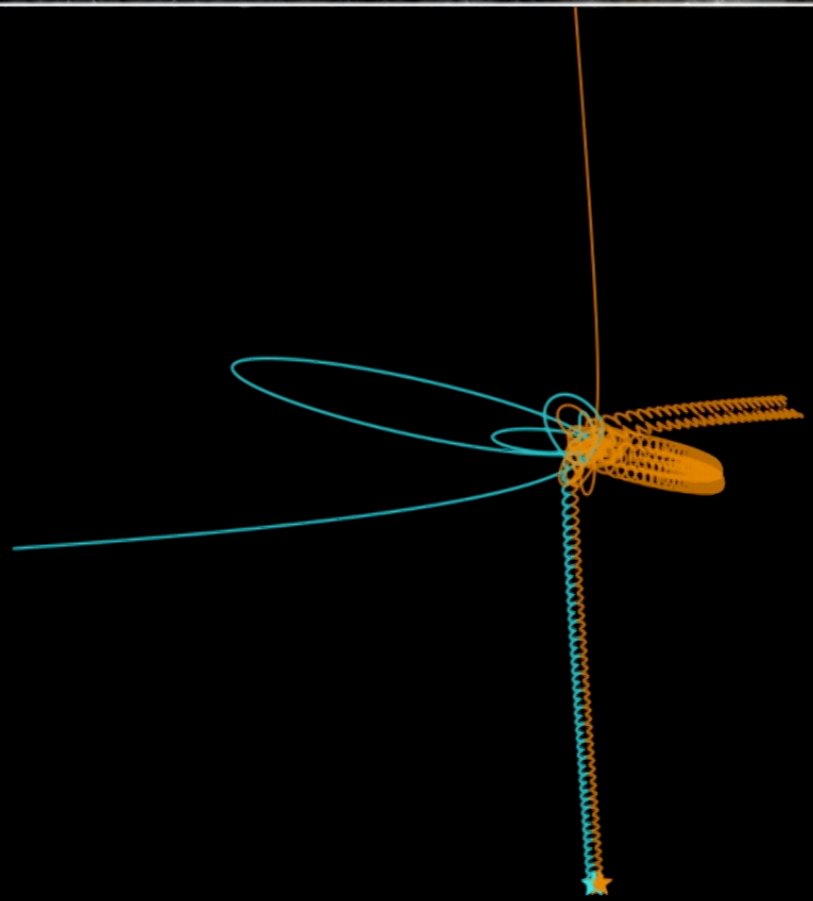

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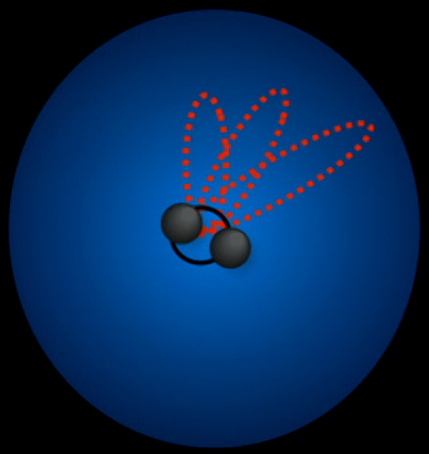
$$T_{\rm bs} \sim (n\Sigma v)^{-1} \propto \left[n a^2 \sigma \left(1 + \frac{GM}{2a\sigma^2} \right) \right]^{-1}$$



$a = 0.4$ AU
$e = 0$
$n = 10^6$ pc^{-3}
$\sigma = 10$ km/s
$m = 30 M_\odot$

$$T_{\rm bs} \approx 40 \text{ Myr}$$

$$T_{\rm GW} \propto \frac{a^4 (1-e^2)^{7/2}}{m_1 m_2 M} \approx 150000 \text{ Myr}$$

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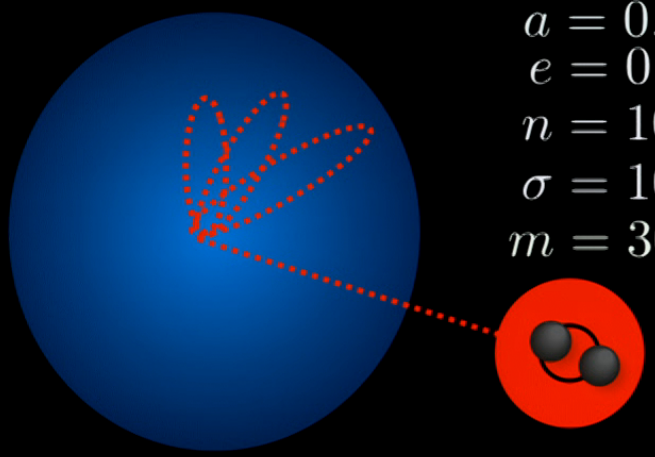
$$T_{\rm bs} \sim (n\Sigma v)^{-1} \propto \left[n a^2 \sigma \left(1 + \frac{GM}{2a\sigma^2} \right) \right]^{-1}$$



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$n = 10^6$ pc^{-3}
$\sigma = 10$ km/s
$m = 30 M_\odot$

$$T_{\rm bs} \approx 40 \text{ Myr}$$

$$\frac{T_{\rm GW}}{T_{\rm bs}} \sim 4000$$

$$T_{\rm GW} \propto \frac{a^4 (1-e^2)^{7/2}}{m_1 m_2 M} \approx 150000 \text{ Myr}$$

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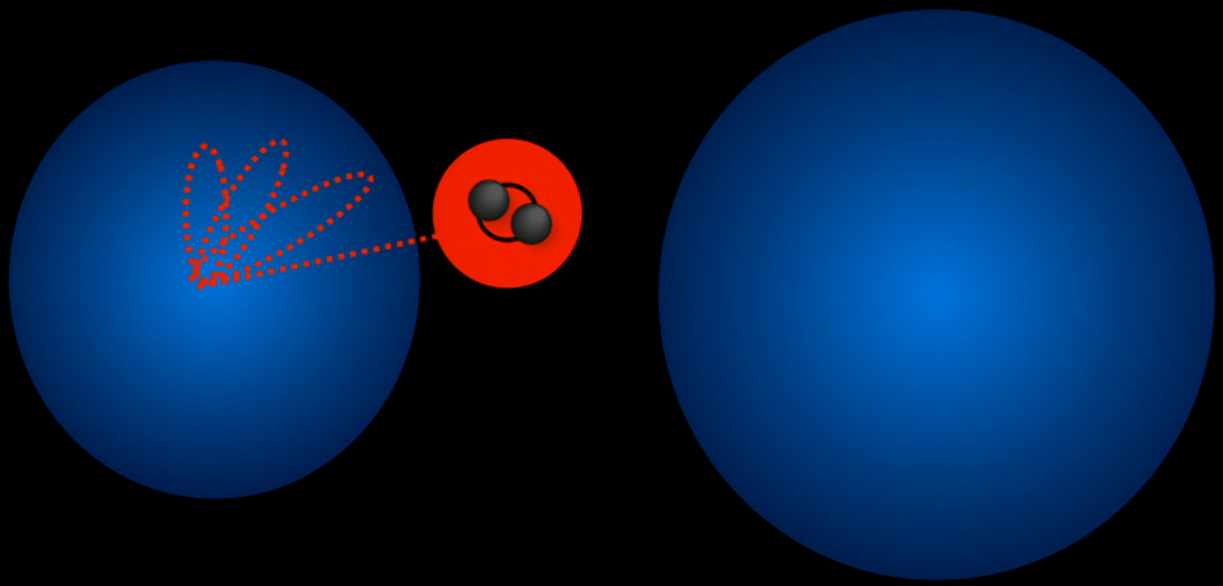

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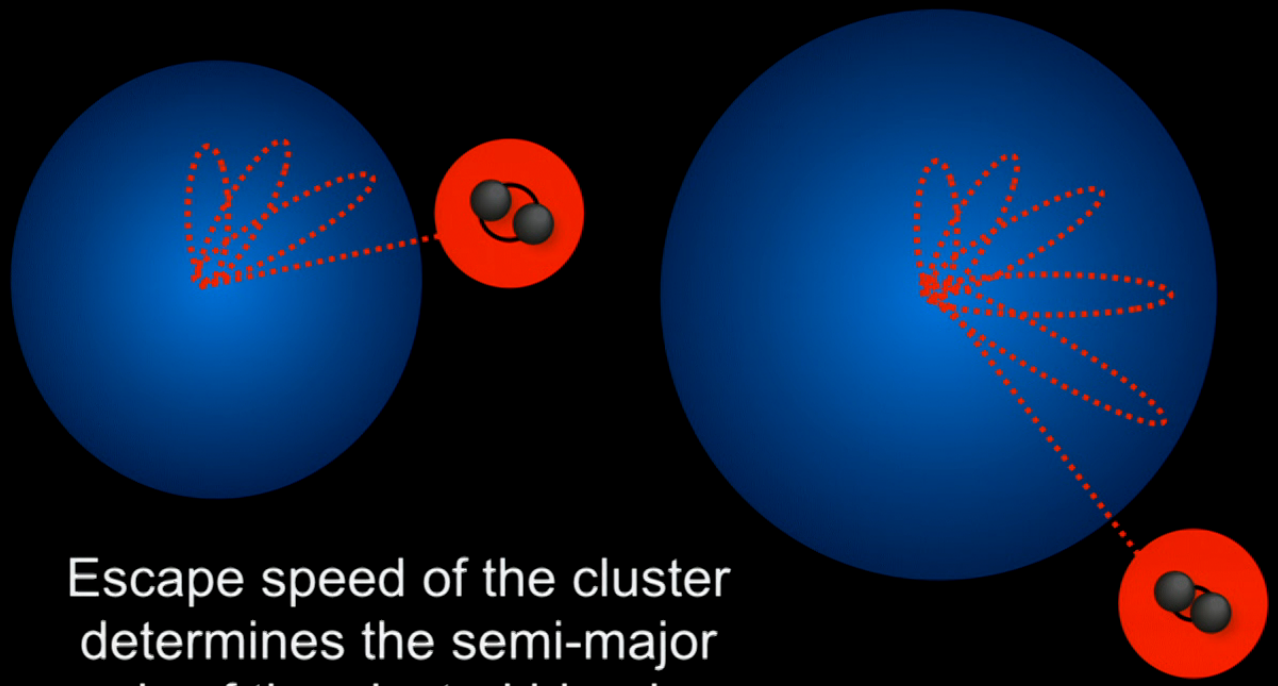

Escape speed of the cluster determines the semi-major axis of the ejected binaries

Chaotic Interactions

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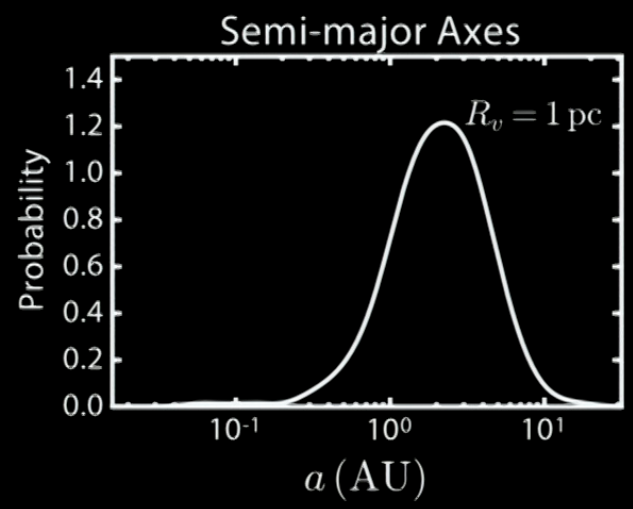

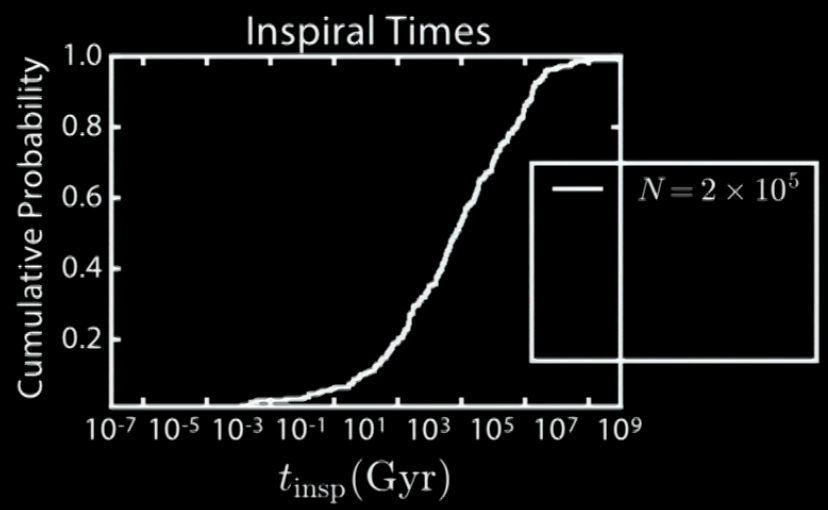

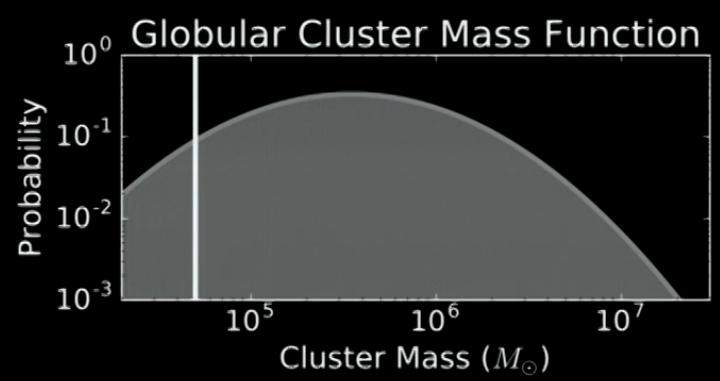

Rodriguez et al. 2016a
1602.02444

Chaotic Interactions

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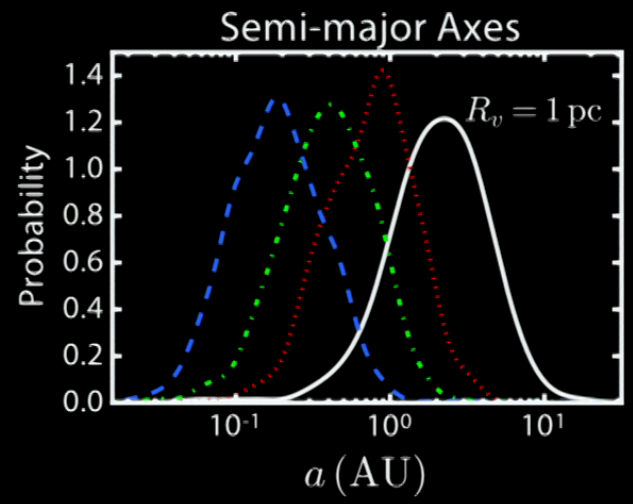

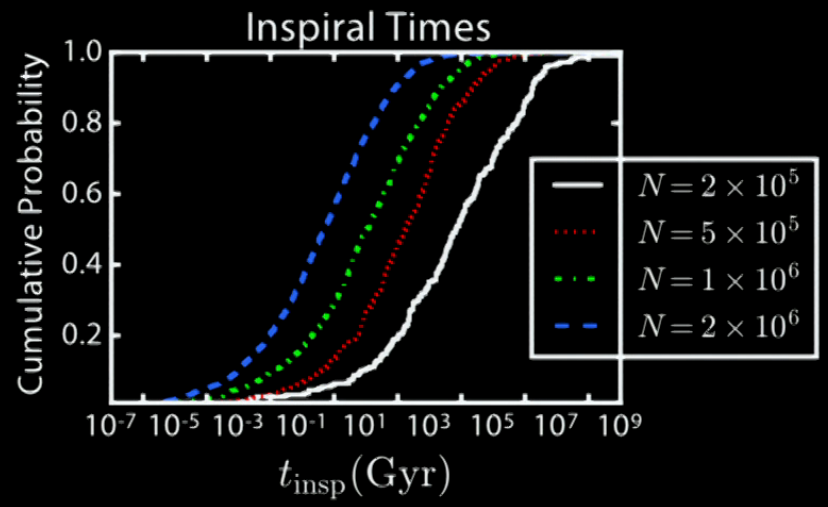

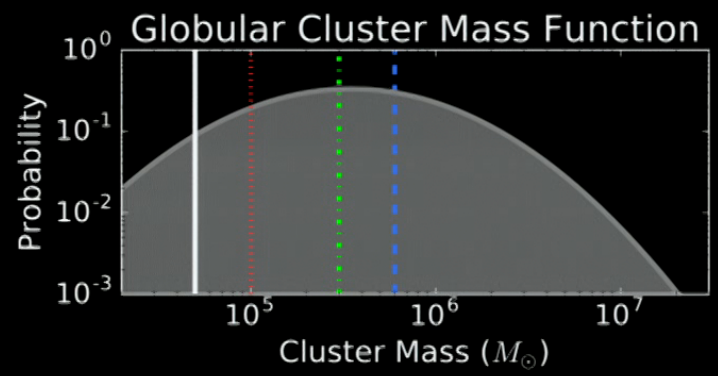

Rodriguez et al. 2016a
1602.02444

Monte Carlo Stellar Dyn.

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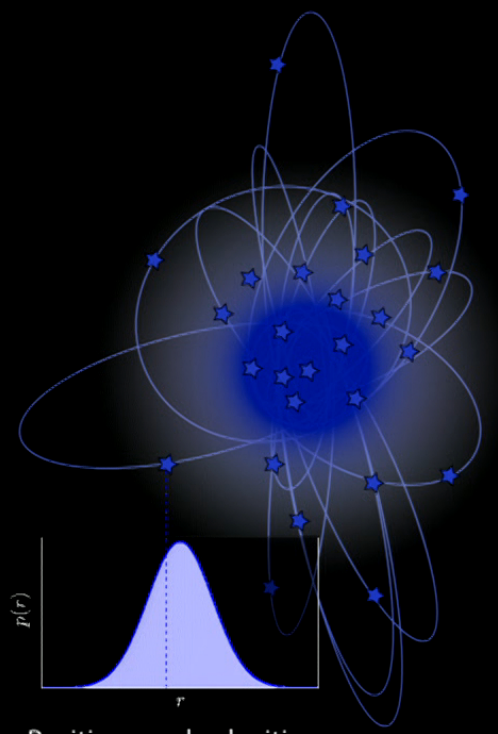
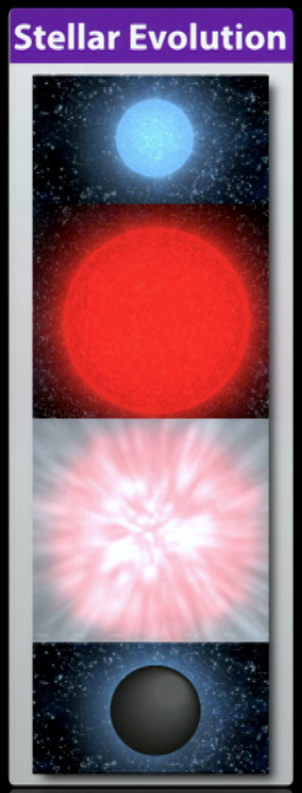
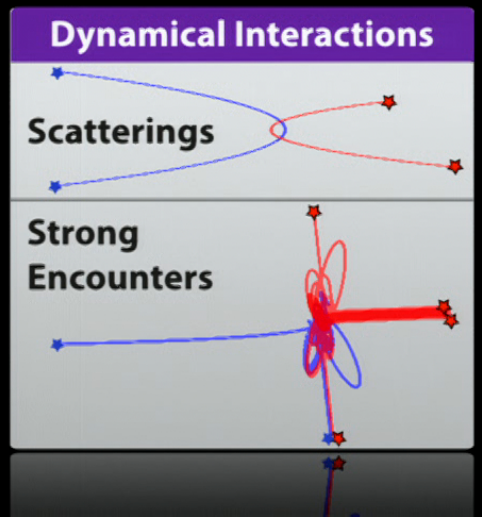


Positions and velocities determined by sampling orbits in a spherical potential



Cluster Monte Carlo code (CMC) allows us to simulate massive, dense star clusters (~10^6 particles) with all the relevant physics



Monte Carlo Stellar Dyn.

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PRL **115,** 051101 (2015) PHYSICAL REVIEW LETTERS week ending 31 JULY 2015

Binary Black Hole Mergers from Globular Clusters: Implications for Advanced LIGO

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Carl-Johan Haster,[1,3] and Frederic A. Rasio[1]

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[3]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*

(Received 2 May 2015; published 30 July 2015)

The predicted rate of binary black hole mergers from galactic fields can vary over several orders of magnitude and is extremely sensitive to the assumptions of stellar evolution. But in dense stellar environments such as globular clusters, binary black holes form by well-understood gravitational interactions. In this Letter, we study the formation of black hole binaries in an extensive collection of realistic globular cluster models. By comparing these models to observed Milky Way and extragalactic globular clusters, we find that the mergers of dynamically formed binaries could be detected at a rate of ~100 per year, potentially dominating the binary black hole merger rate. We also find that a majority of cluster-formed binaries are more massive than their field-formed counterparts, suggesting that Advanced LIGO could identify certain binaries as originating from dense stellar environments.

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Masses from GCs

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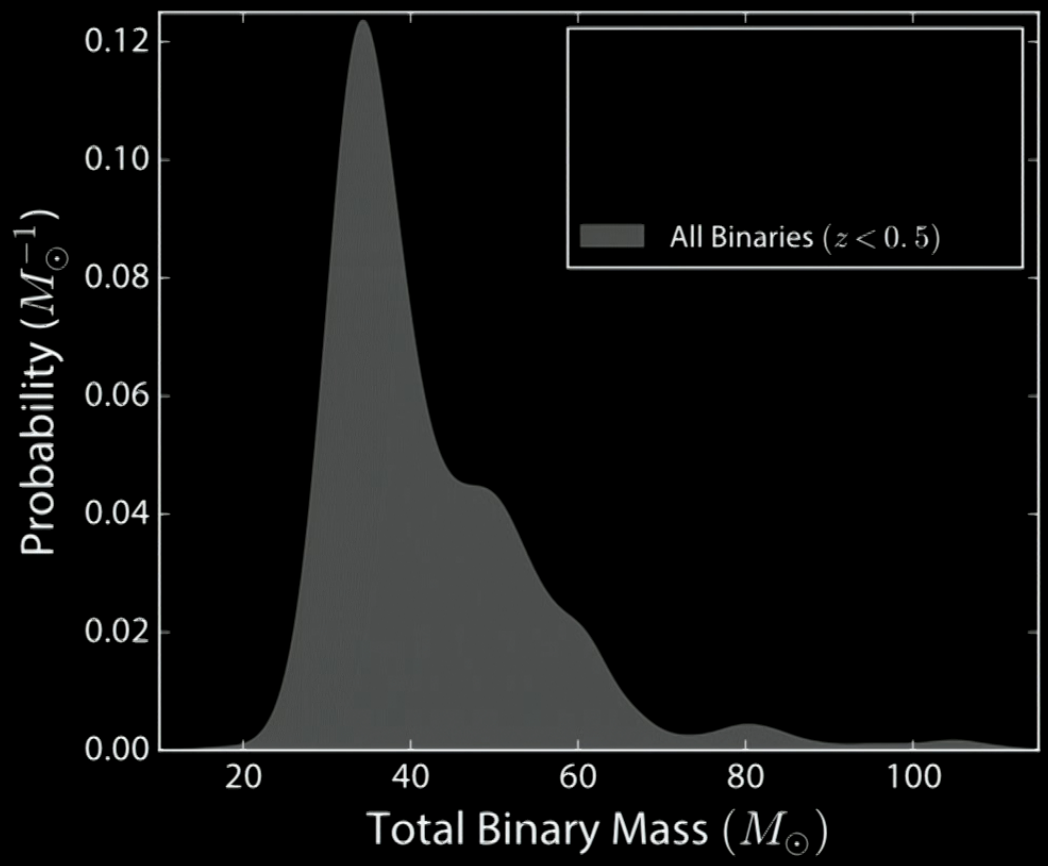
Rodriguez et al. 2016b, 1604.04254



Masses from GCs

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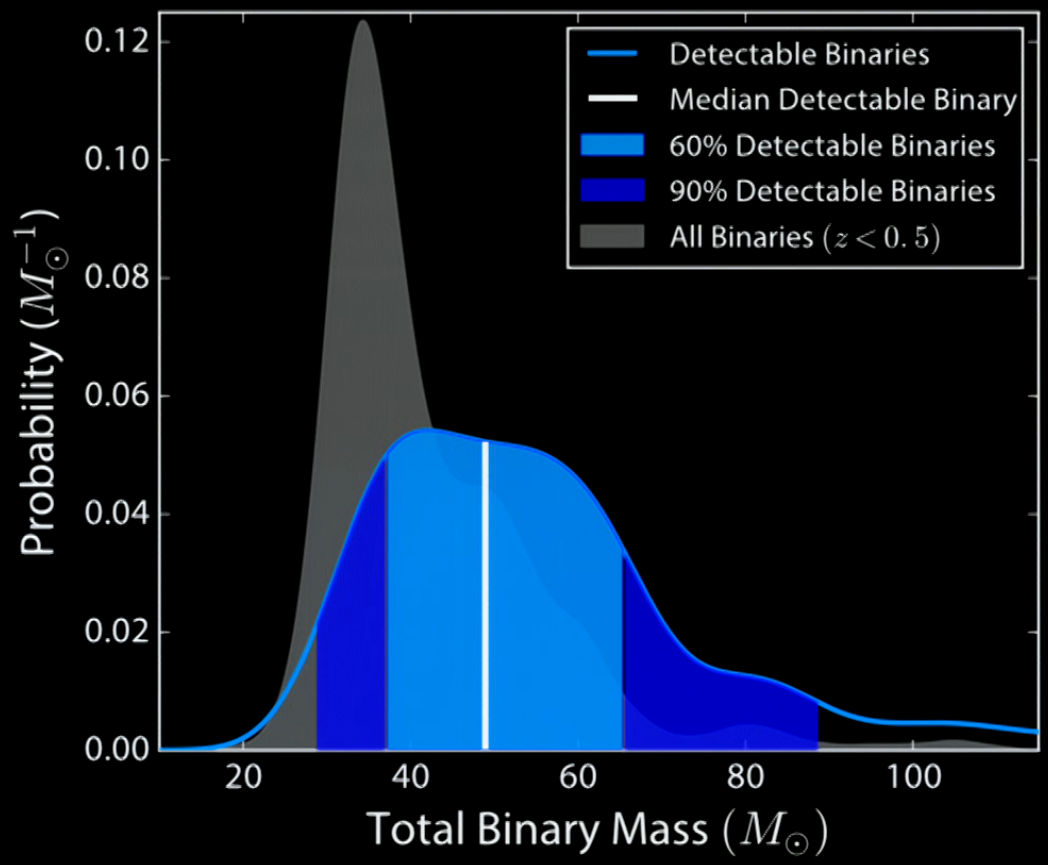
Rodriguez et al. 2016b, 1604.04254



Masses from GCs

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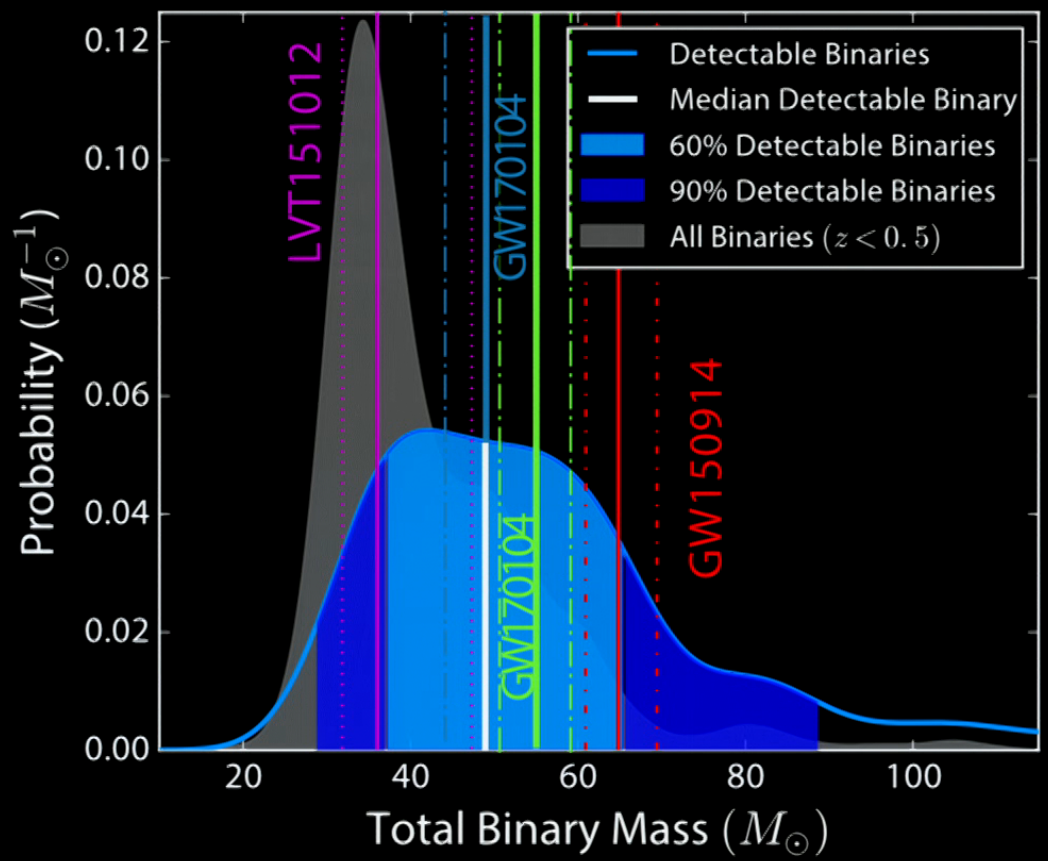
Rodriguez et al. 2016b, 1604.04254

(updated)



Merger Rates

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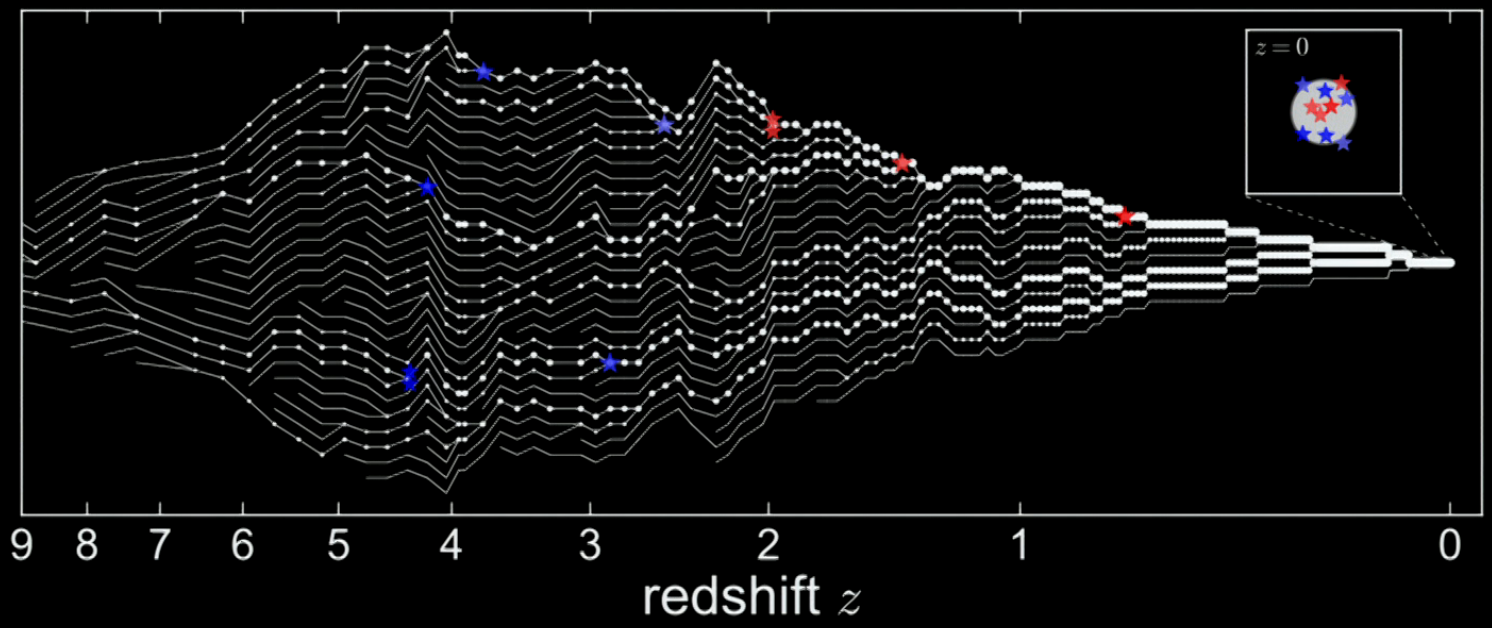
El-Badry et al. 2018



Merger Rates

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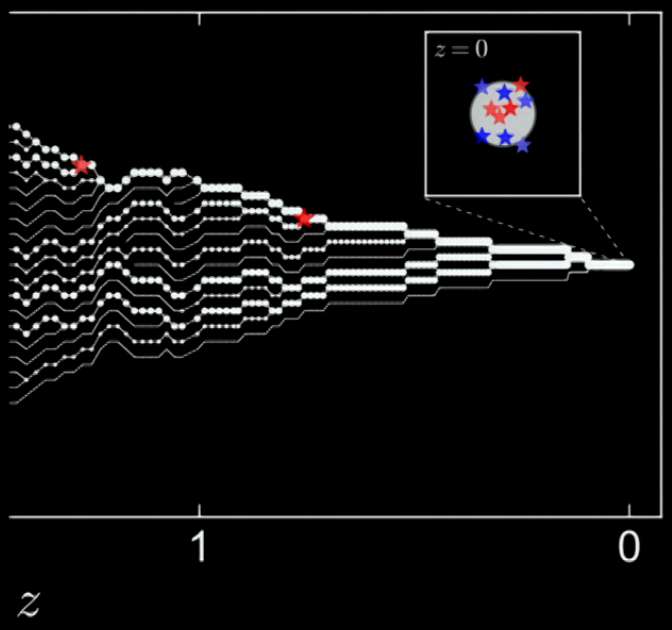

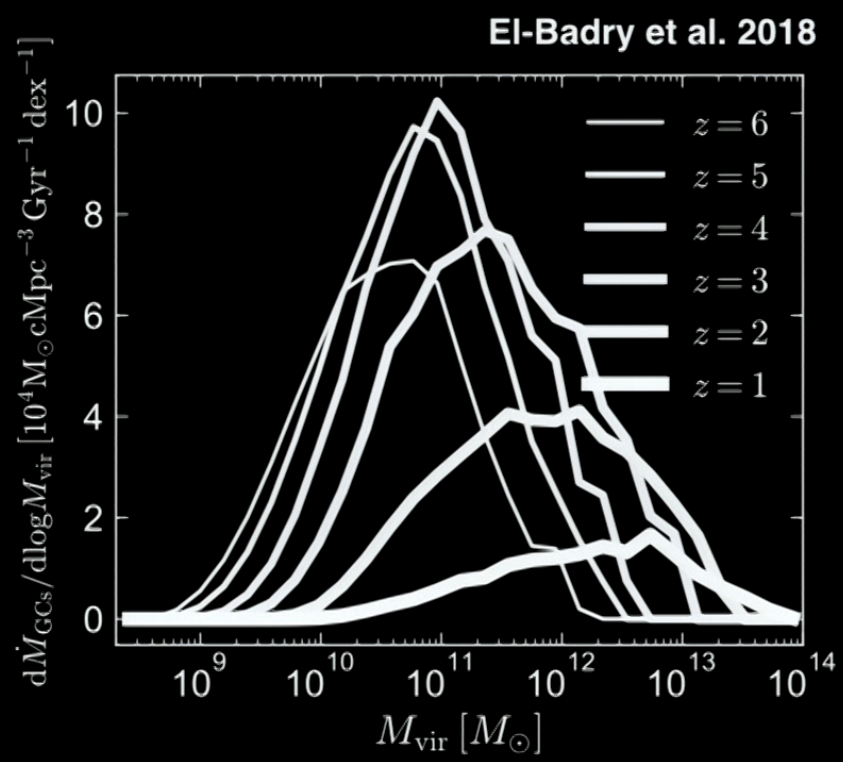

Merger Rates

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LIGO Rates

Uniform-in-Log

$32^{+33}_{-22}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Power-Law, -2.3 Index

$103^{+110}_{-63}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Merger Rates

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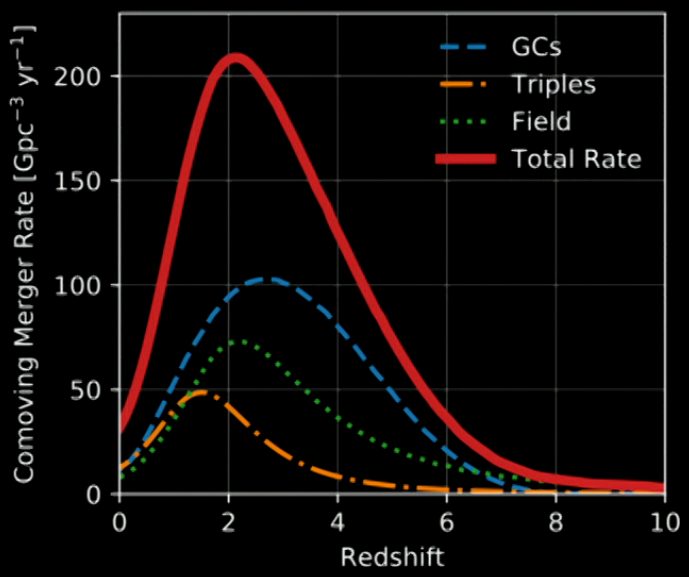
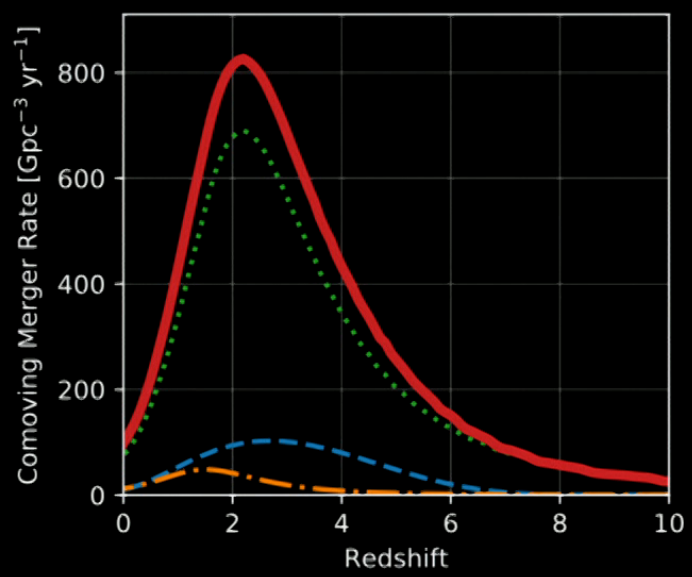
$32^{+33}_{-22}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$



Power-Law, -2.3 Index

$103^{+110}_{-63}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$



Rodriguez and Loeb, 1809.01152

$$14\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}\Big|_{z=0}$$

Forming BH Binaries

Carl Rodriguez
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Common Envelope

Dynamical Formation

Can we tell the difference?

- Chemically Homogeneous Evolution
- Triples (Lidov-Kozai)
  - Stellar triples (field or dynamical)
  - Stellar BBH/SMBH
- Primordial black holes
- Highly-eccentric captures in scattering encounters
- Formation in AGN disks
- And many more…

Forming BH Binaries

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~~Masses~~
~~Merger Rates~~
~~Mass Ratios~~

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Can we tell the difference?

Dynamical Formation

Spins
Eccentricities
Masses

Spins

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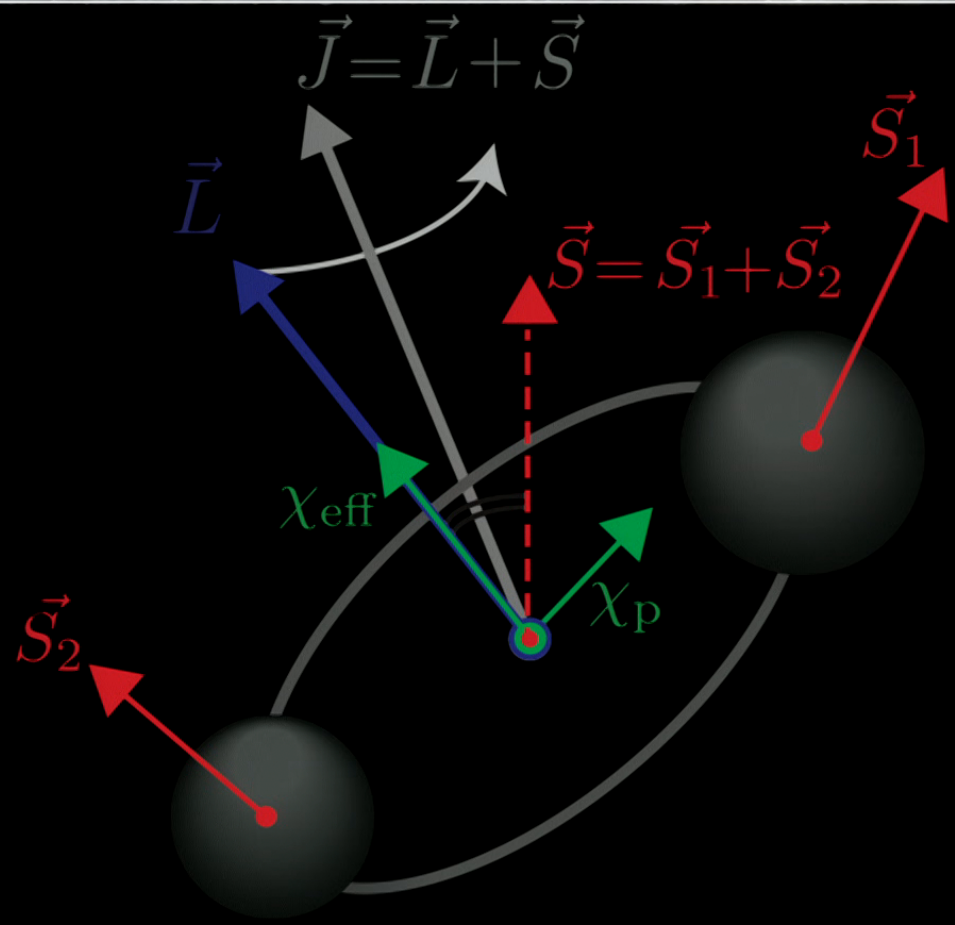
Spins
Eccentricities
Masses



Spins

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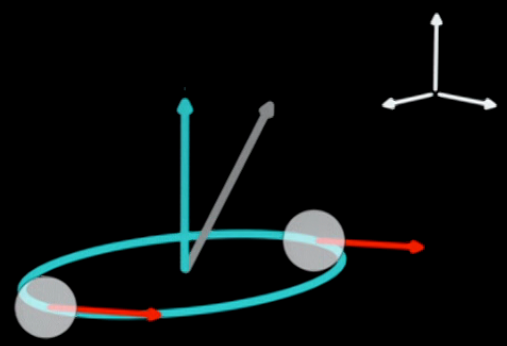

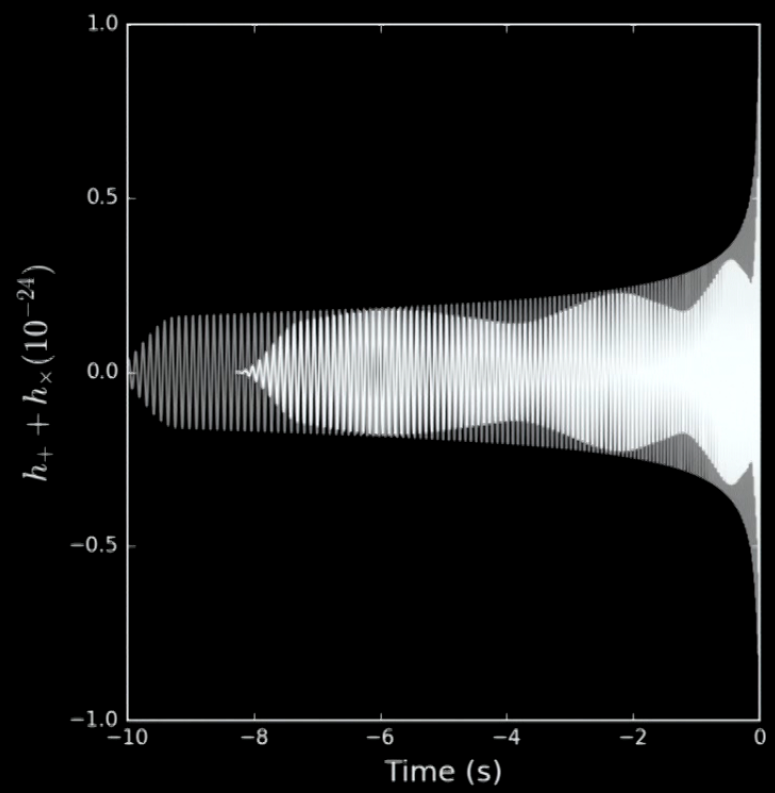

Spins

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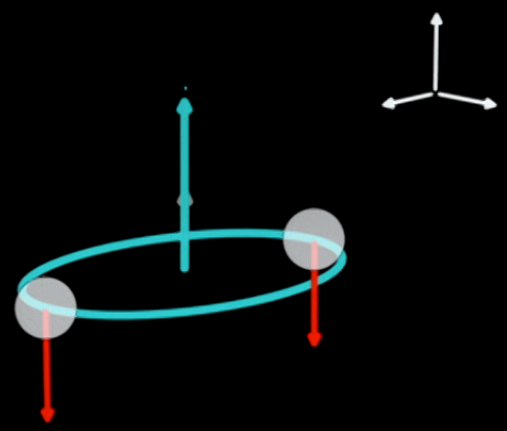

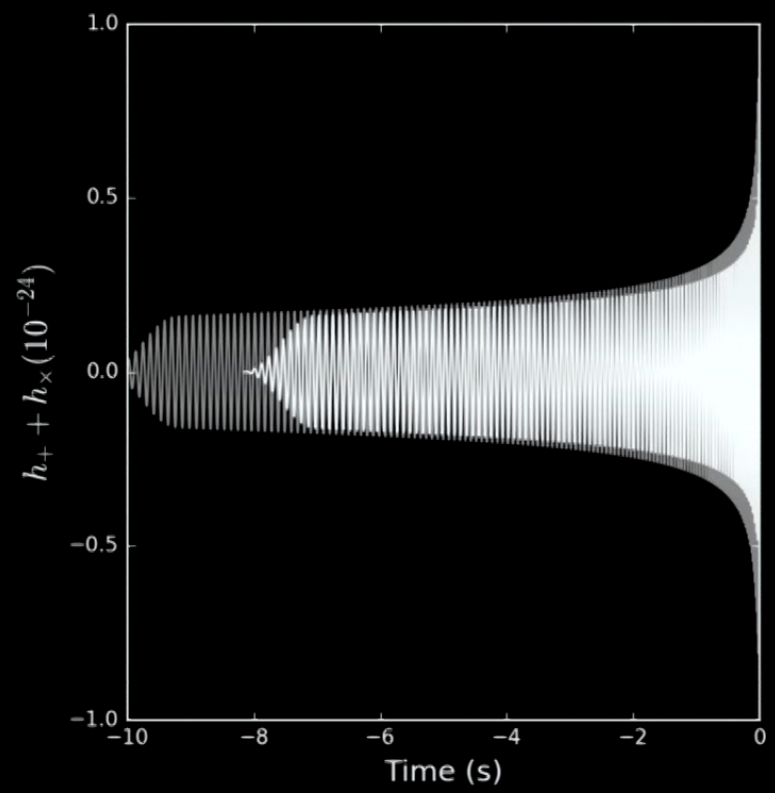

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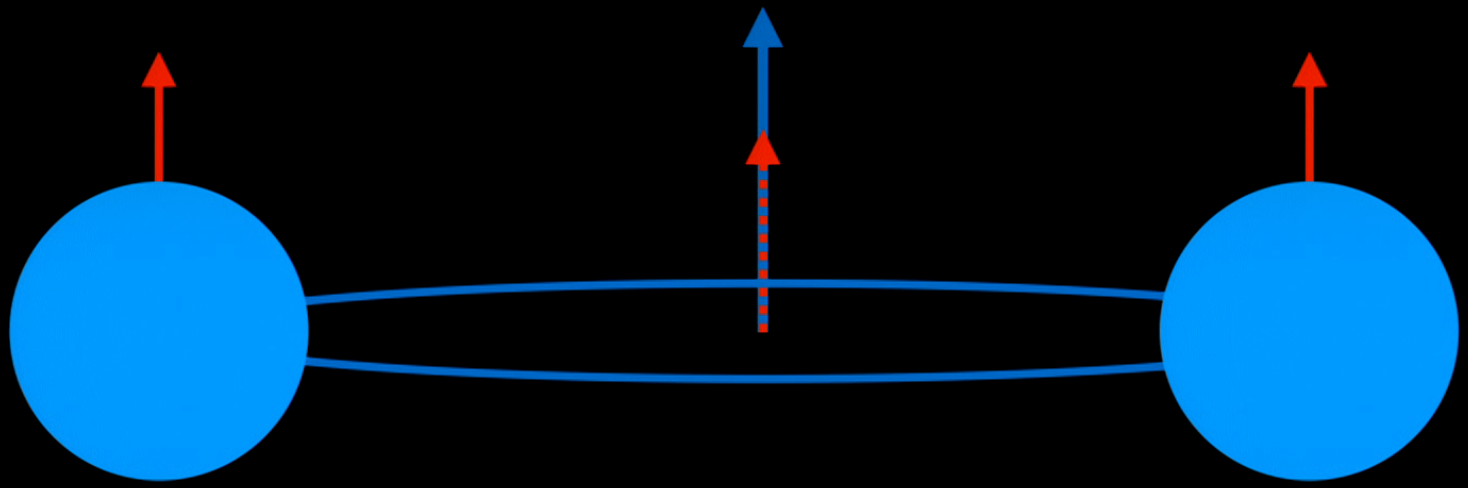

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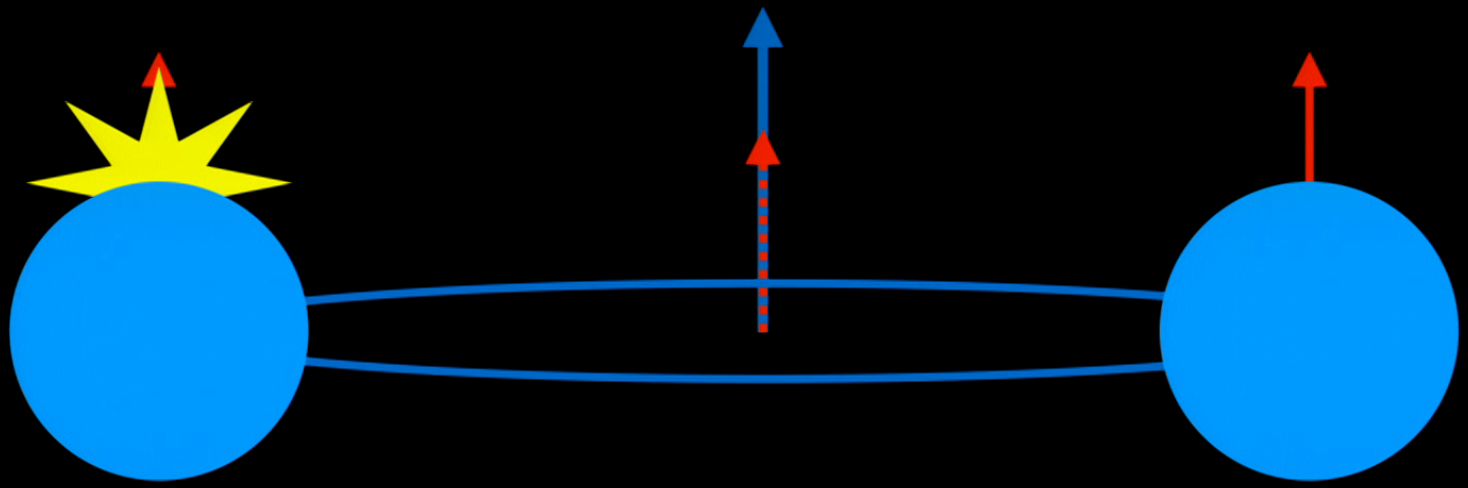

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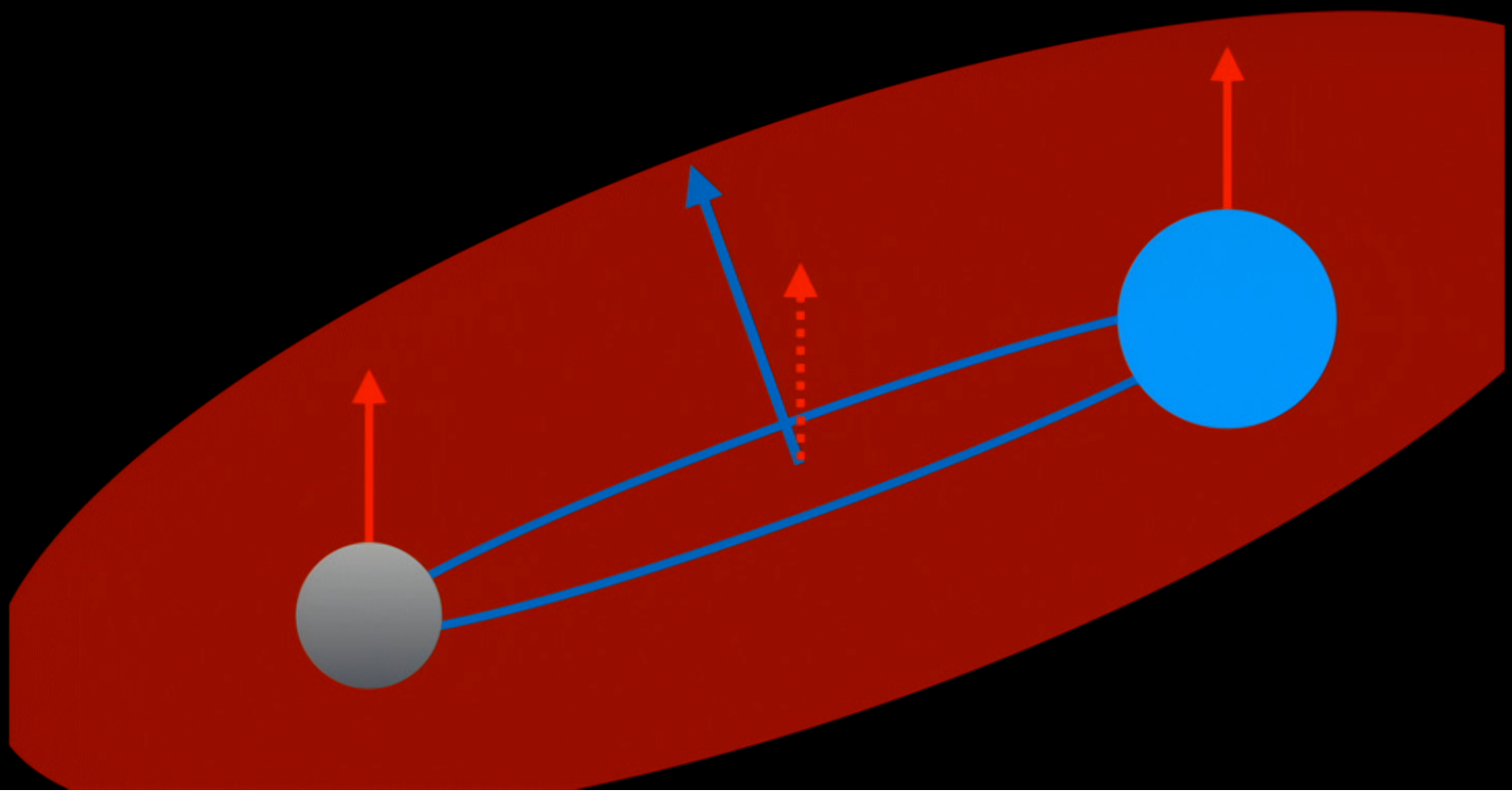

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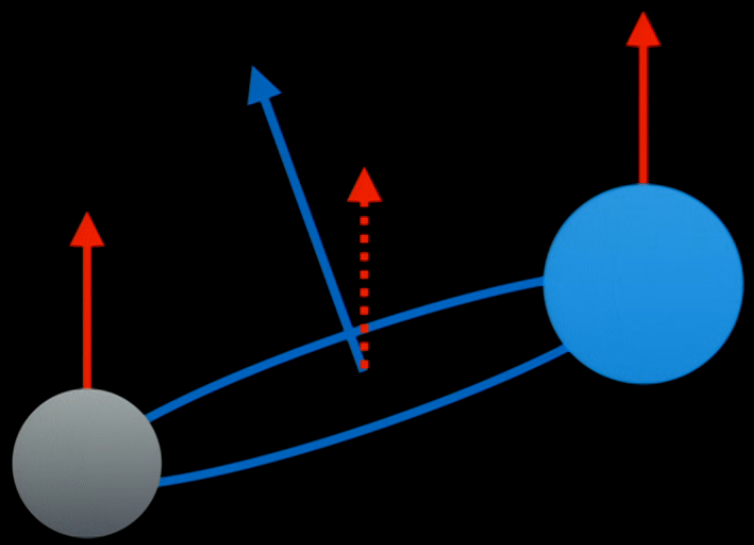

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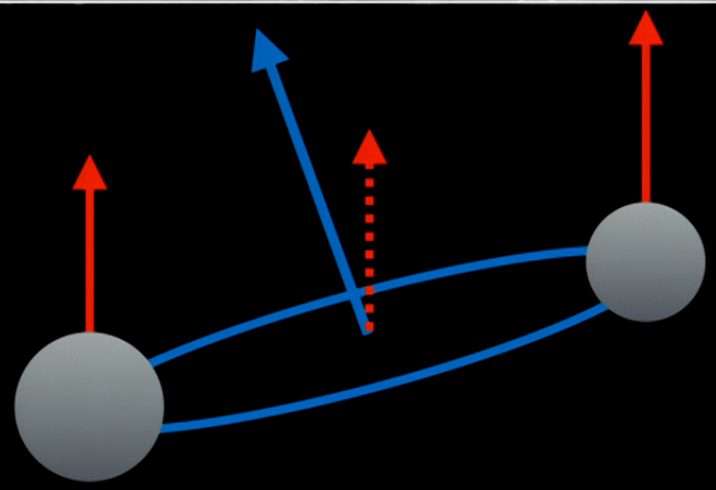

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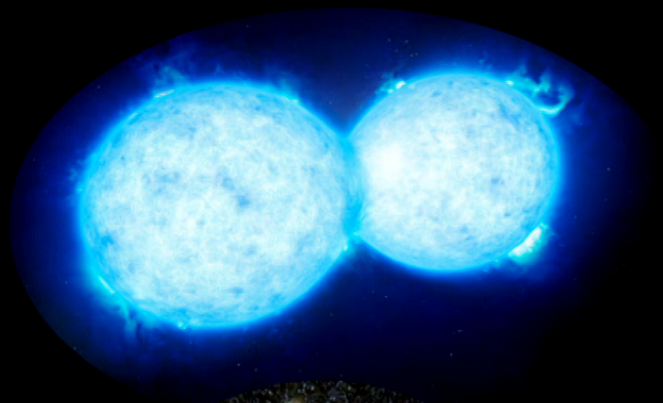

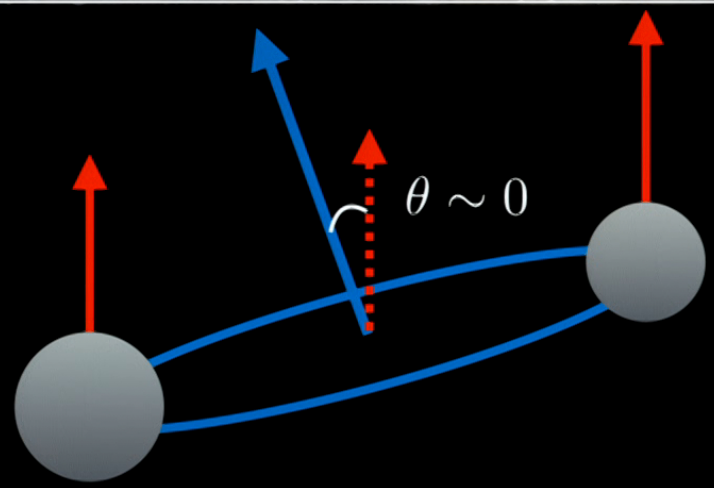

Spins

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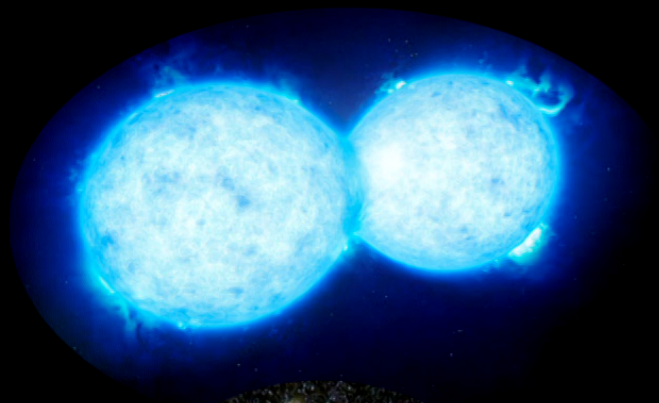

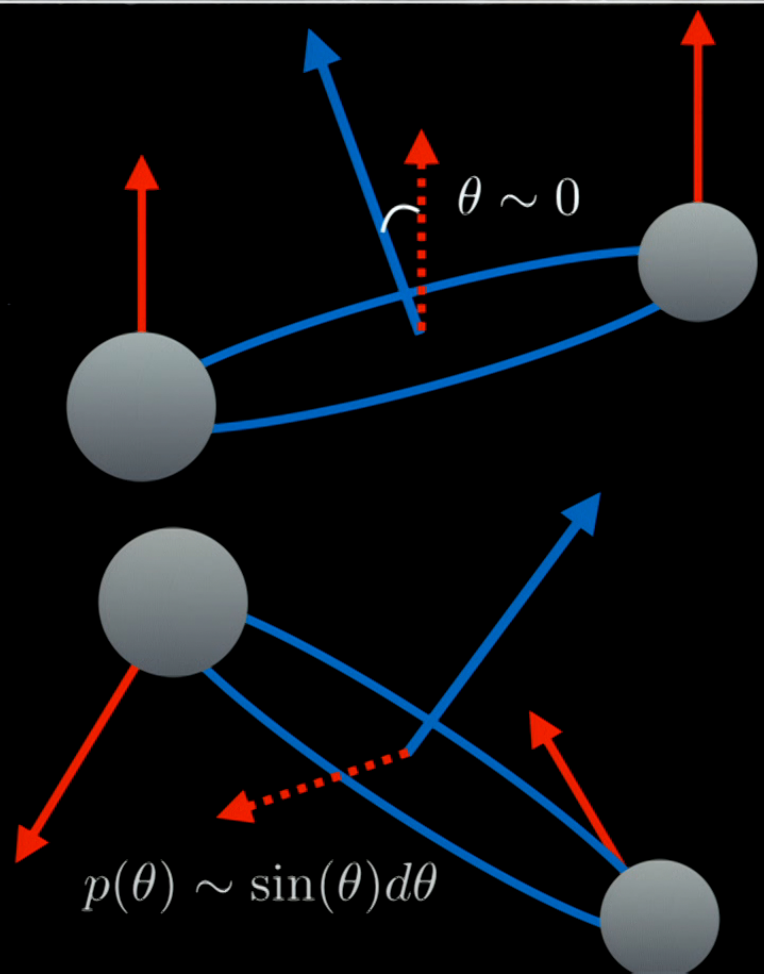

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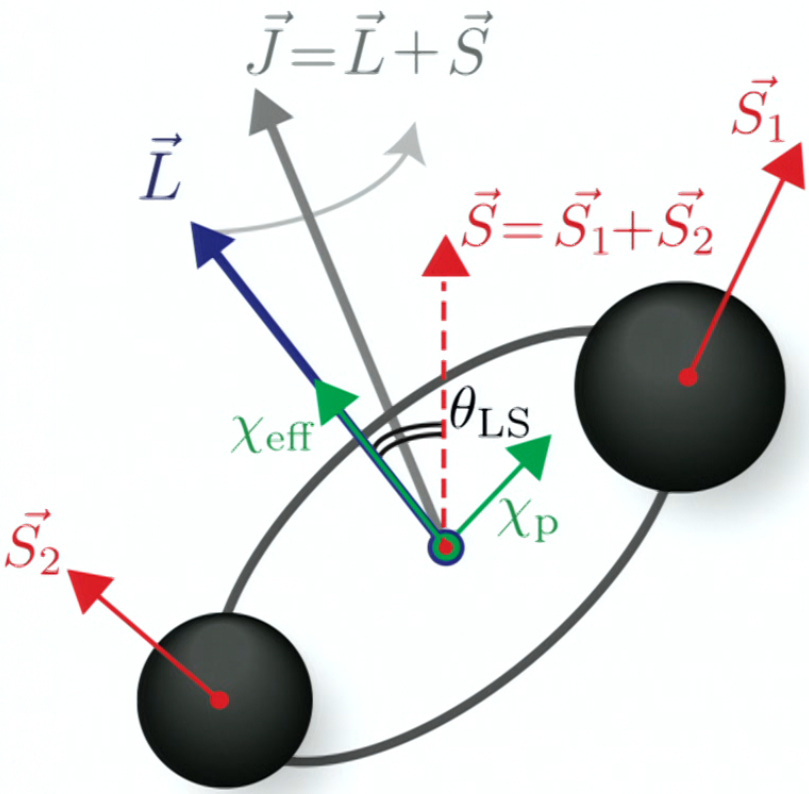

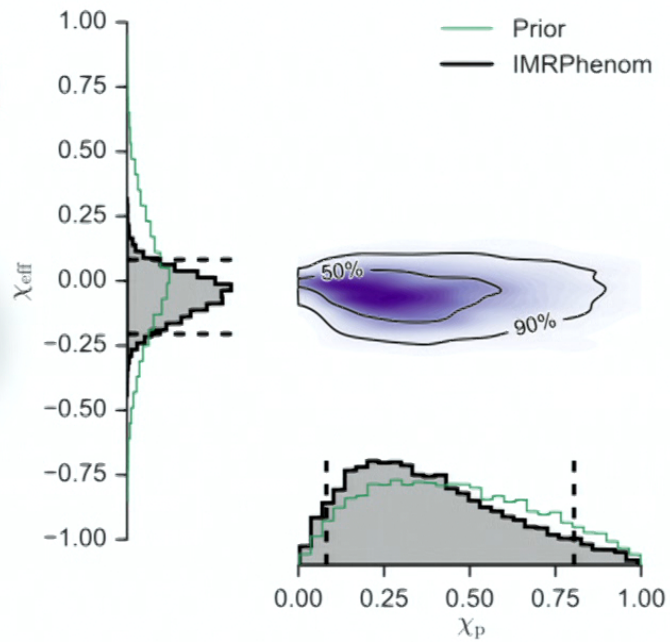

Abbott et al., 2016

Spins

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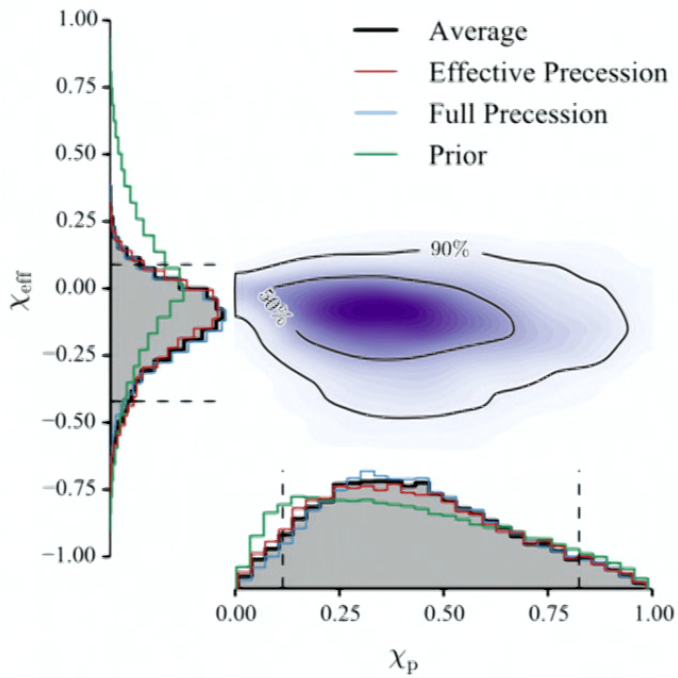
GW170104



Abbott et al., 2017

Spins

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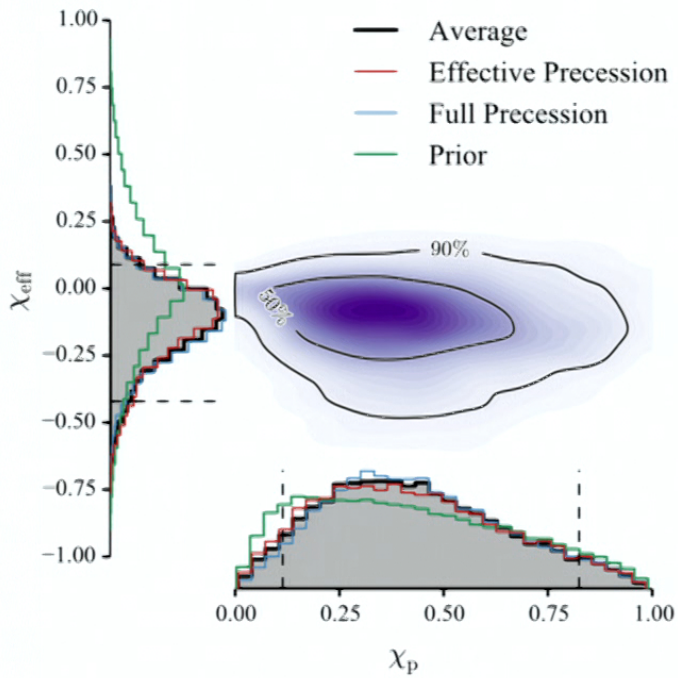
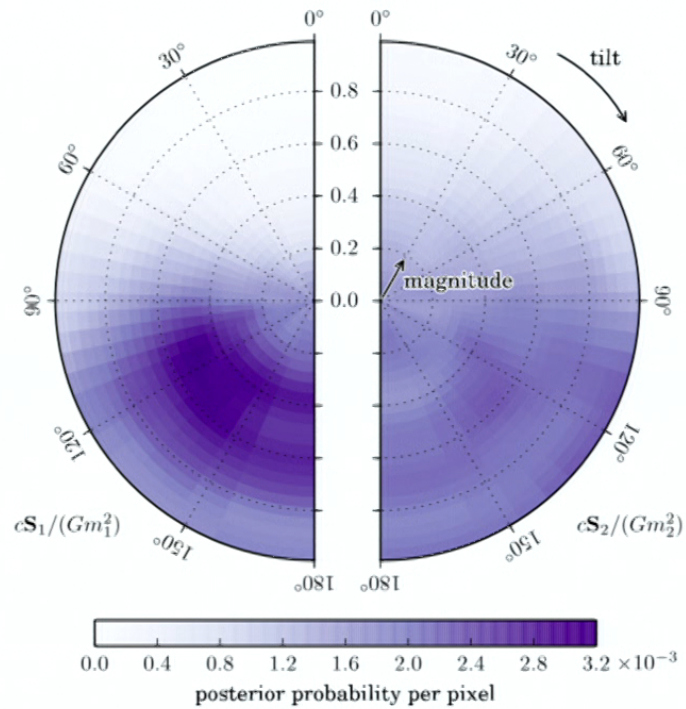
GW170104





Abbott et al., 2017

Spins

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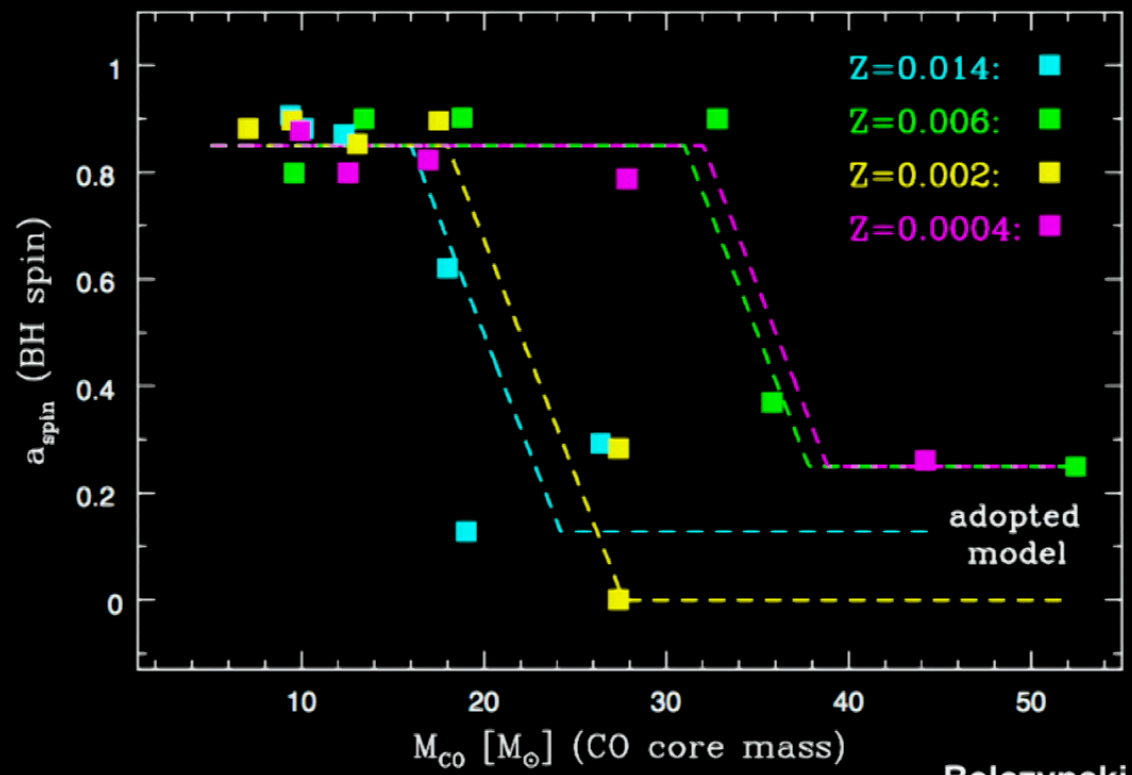
What if heavy black holes are born with low spins?



Belczynski et al., 2017

Forming BH Binaries

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~~Masses~~
~~Merger Rates~~
~~Mass Ratios~~

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Can we tell the difference?

Dynamical Formation

Spins
Eccentricities
Masses

Post-Newtonian Dynamics

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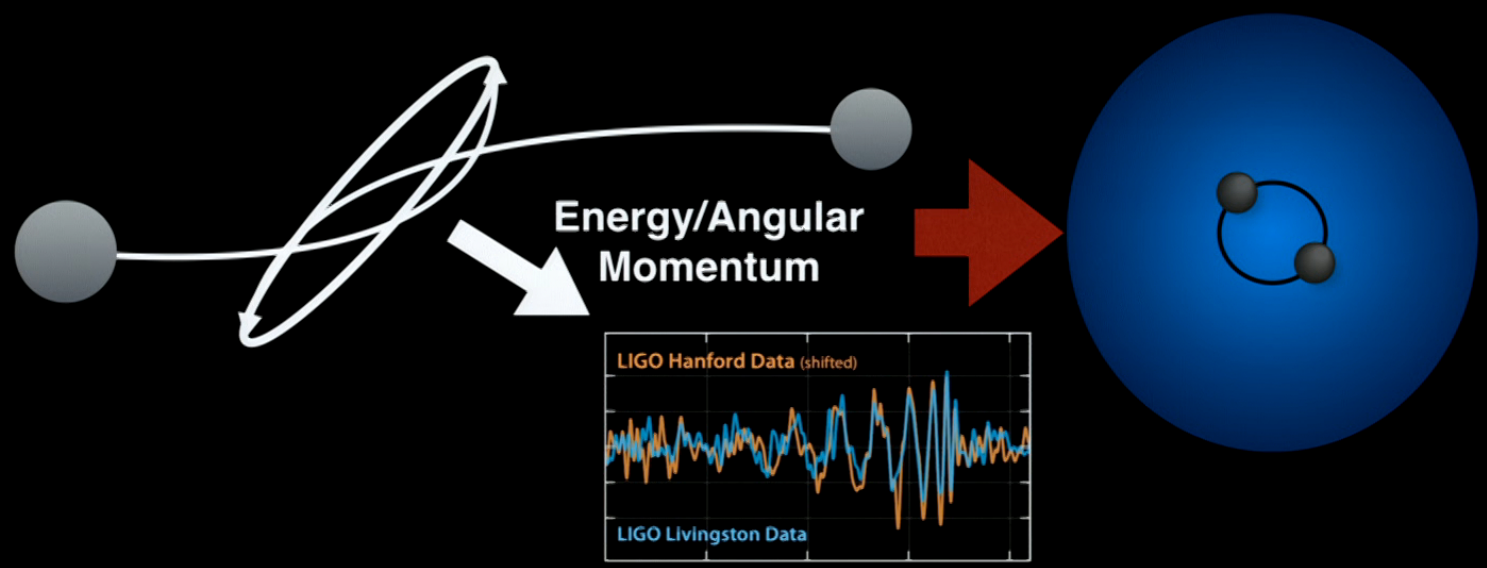

Post-Newtonian Dynamics

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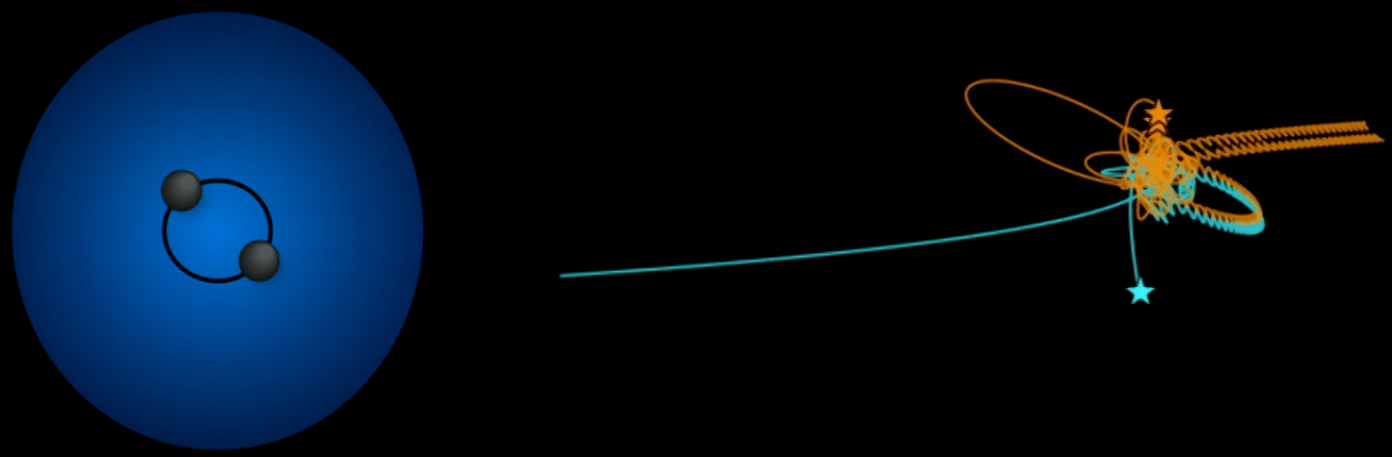

Post-Newtonian Dynamics

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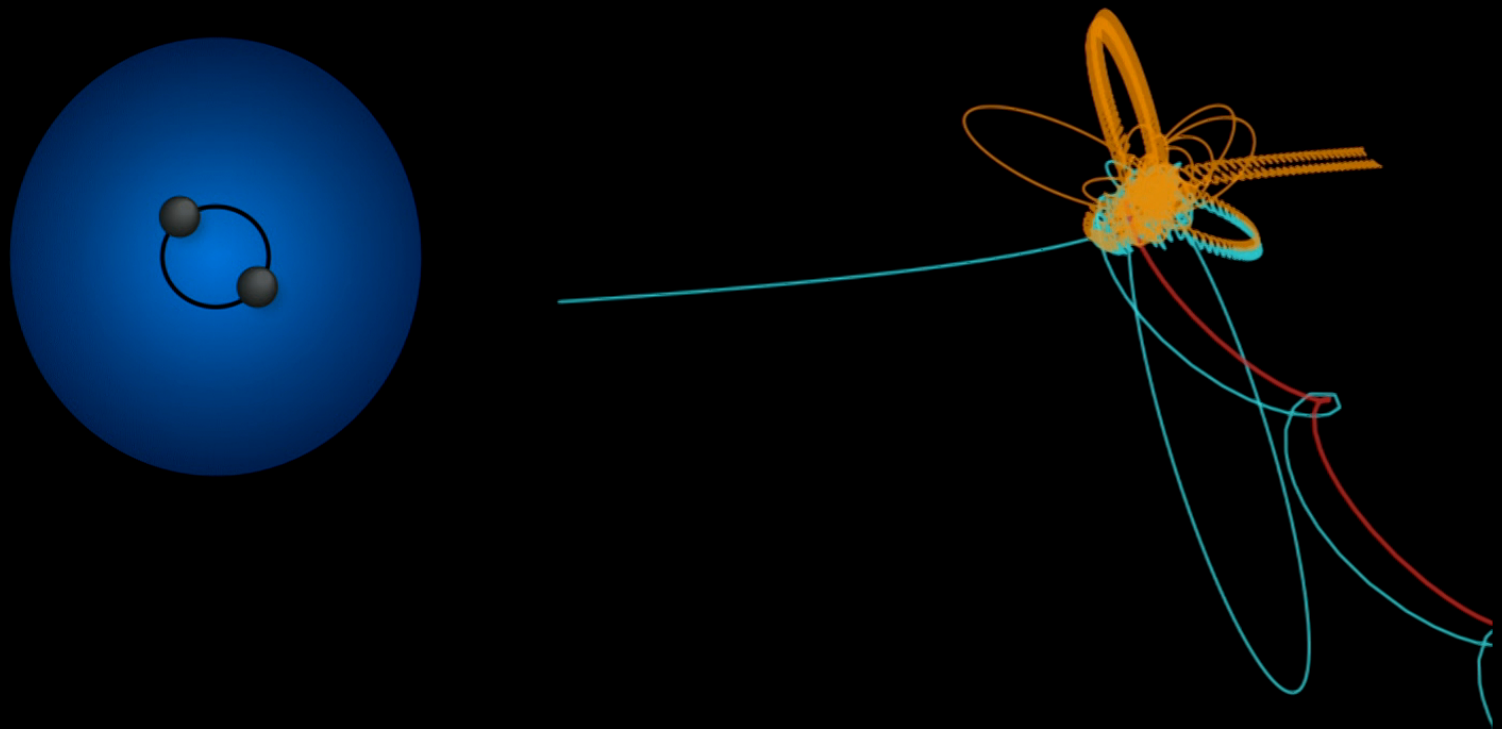

Post-Newtonian Dynamics

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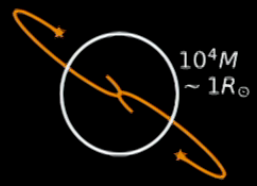

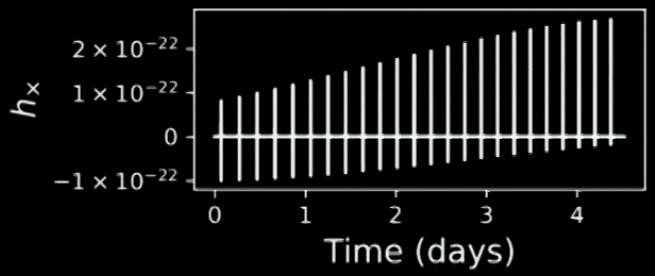

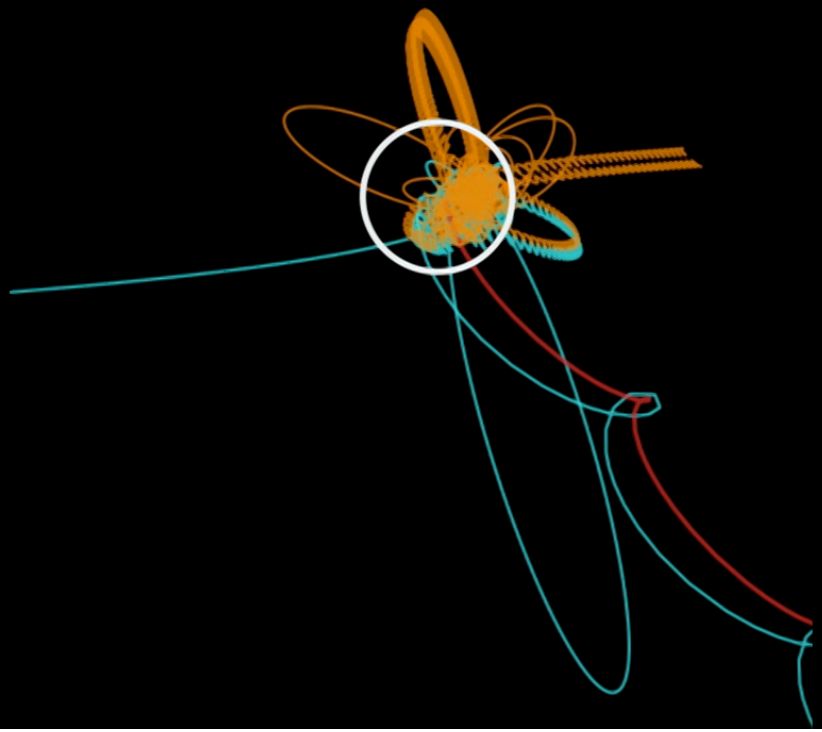

Post-Newtonian Dynamics

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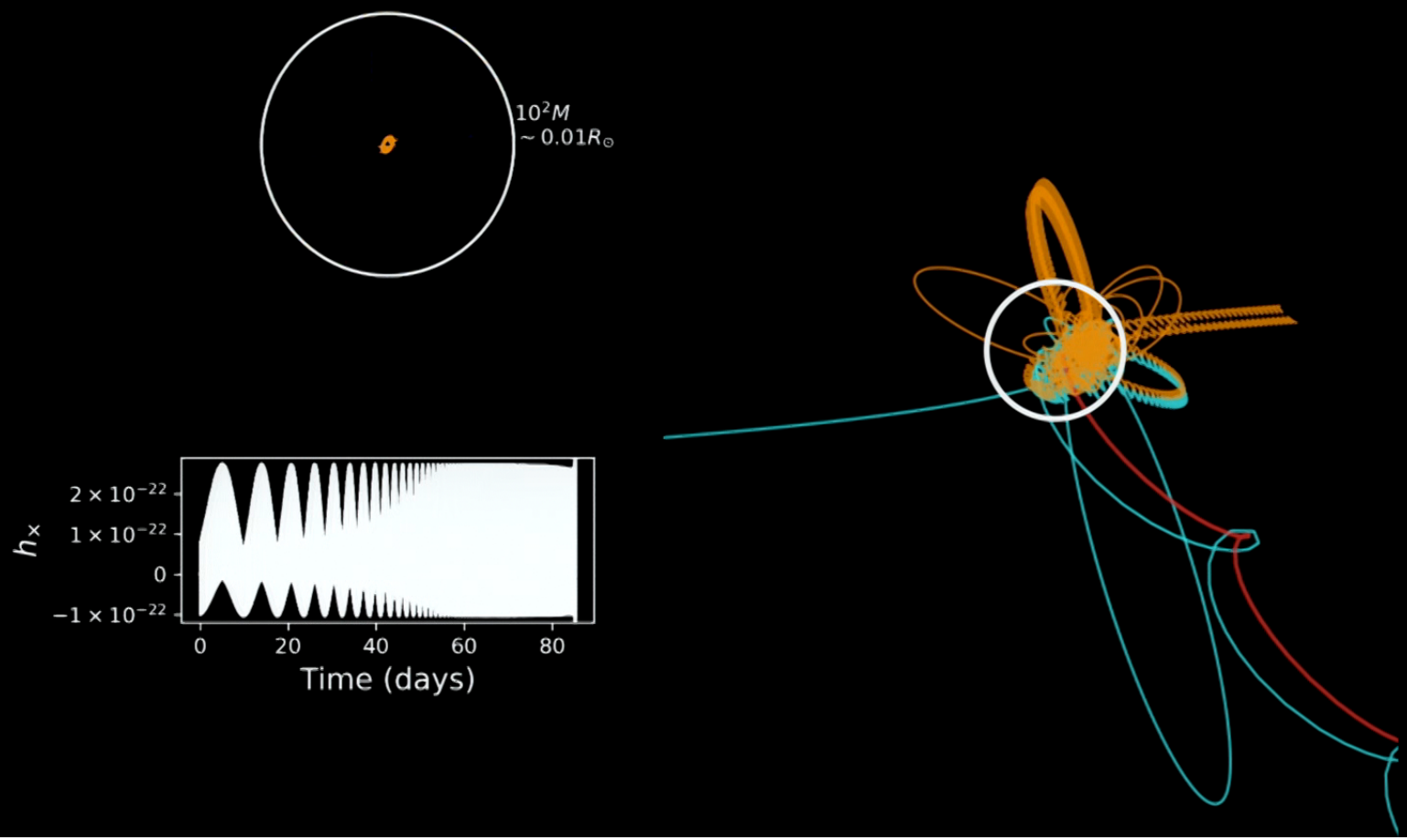

Post-Newtonian Dynamics

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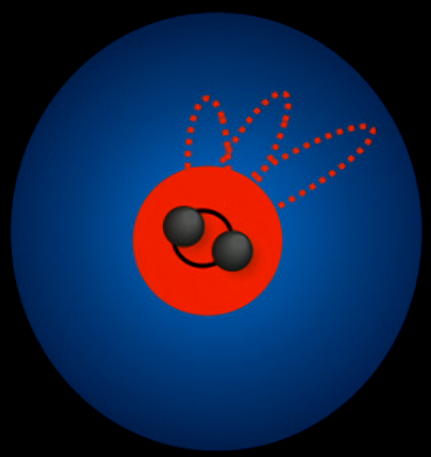
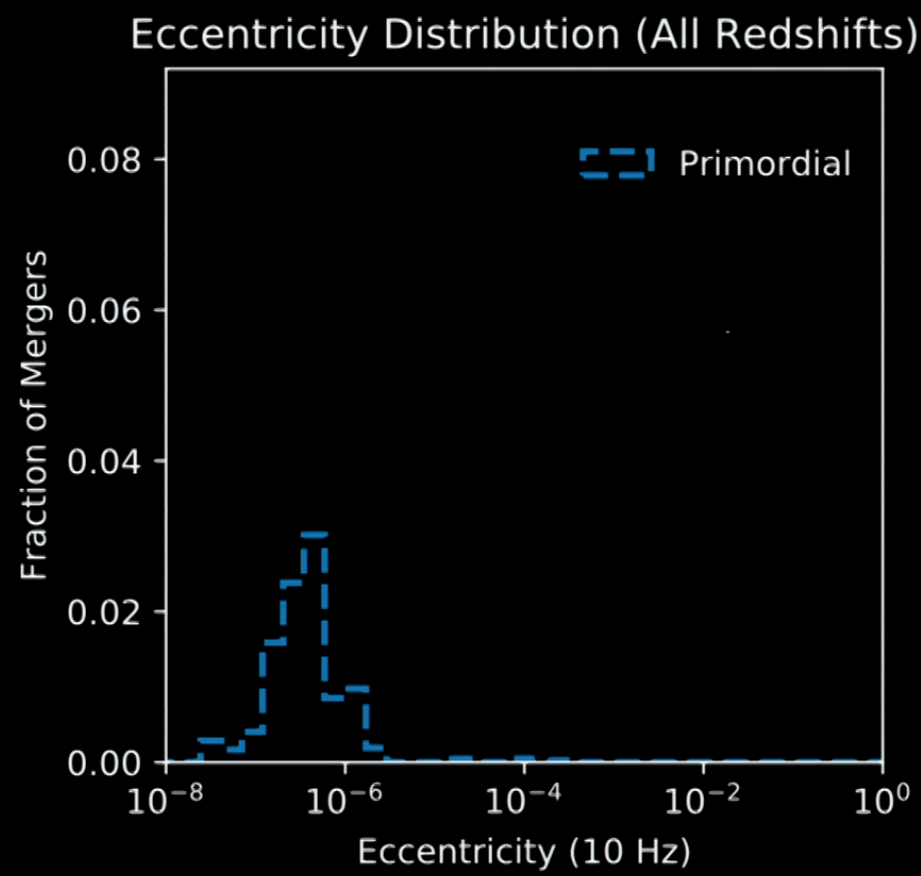
Rodriguez et al., in prep





Post-Newtonian Dynamics

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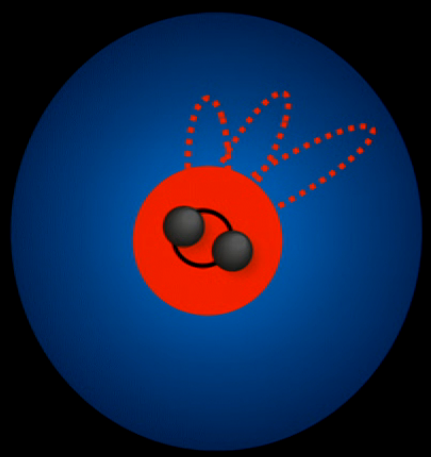
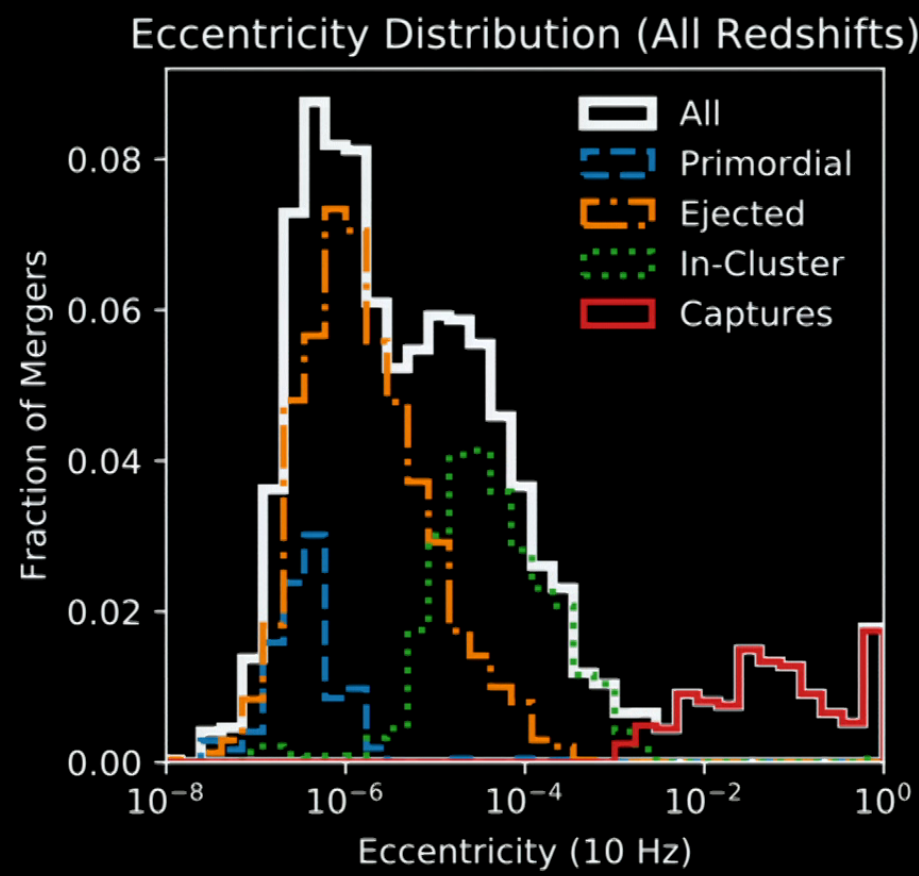
Rodriguez et al., in prep





Repeated Mergers

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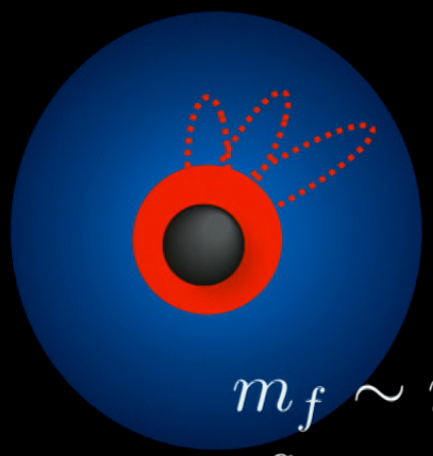
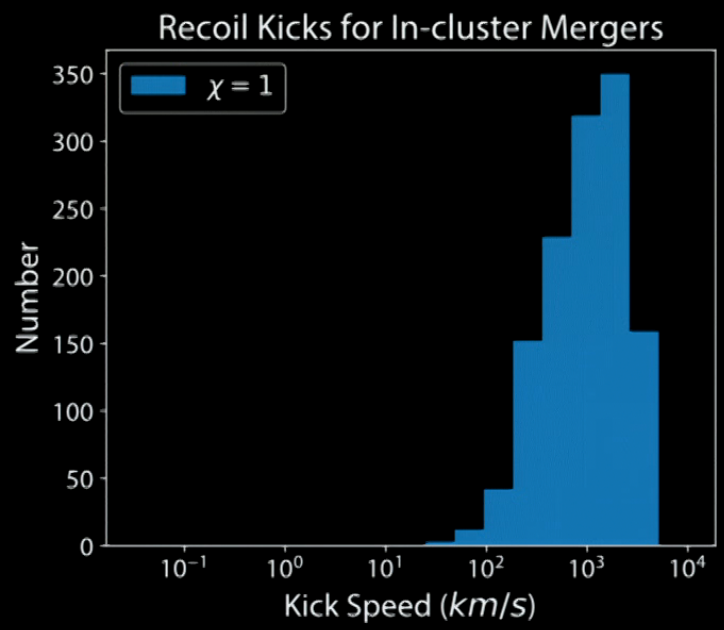


$$m_f \sim m_1 + m_2$$
$$a_f \sim 0.7$$



Repeated Mergers

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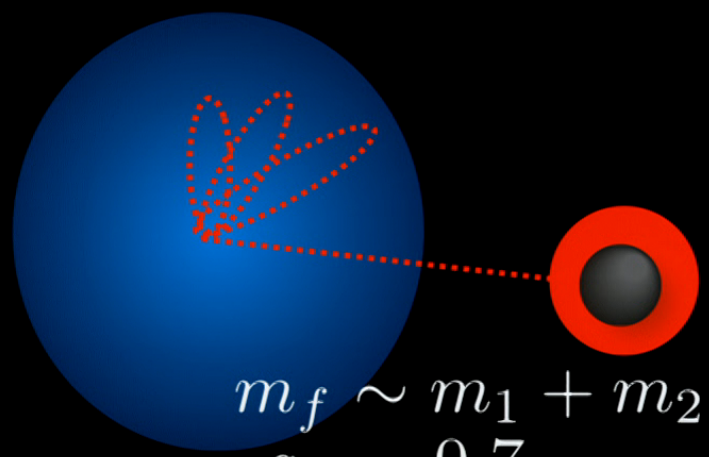
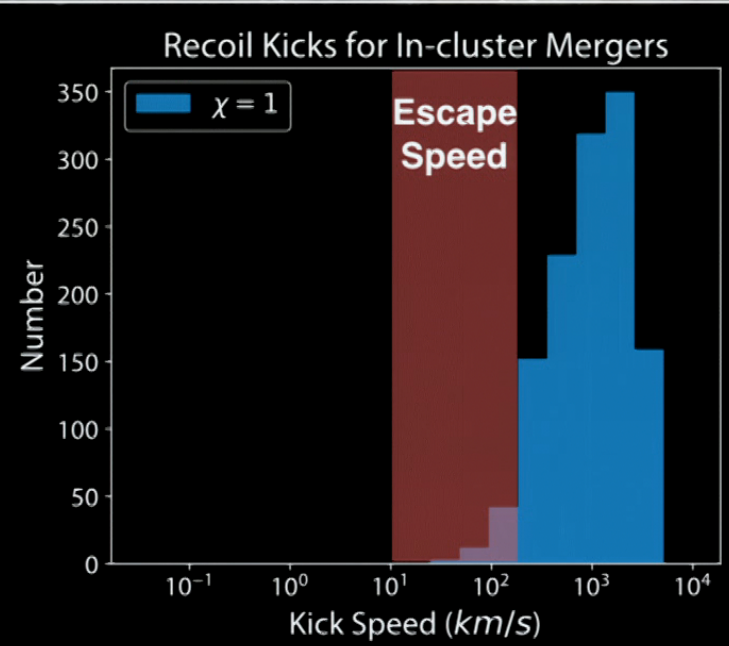


$$m_f \sim m_1 + m_2$$
$$a_f \sim 0.7$$



Repeated Mergers

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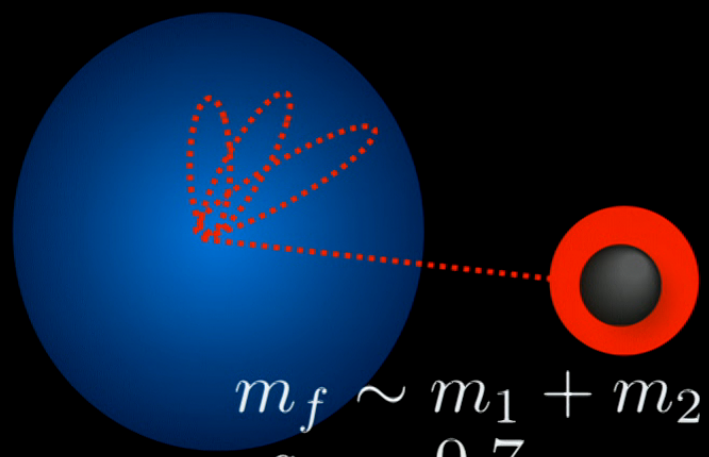

$$m_f \sim m_1 + m_2$$
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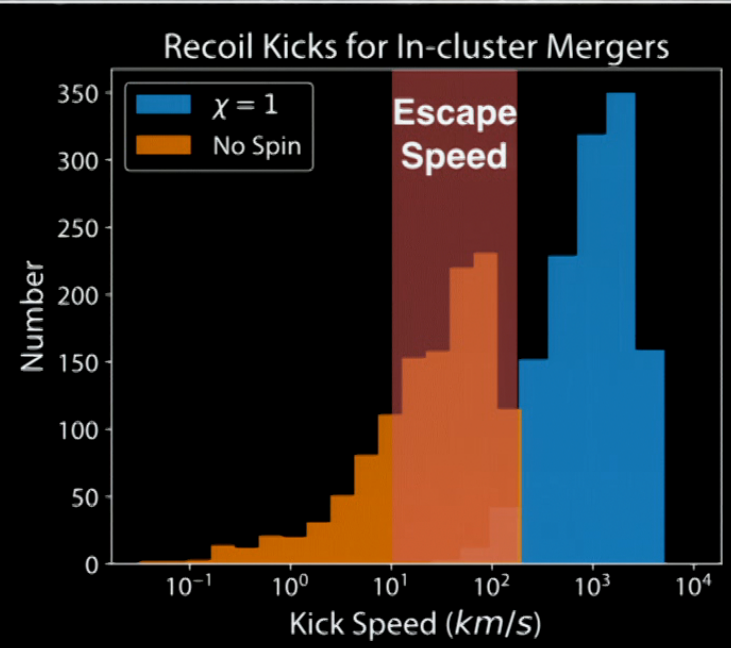

Repeated Mergers

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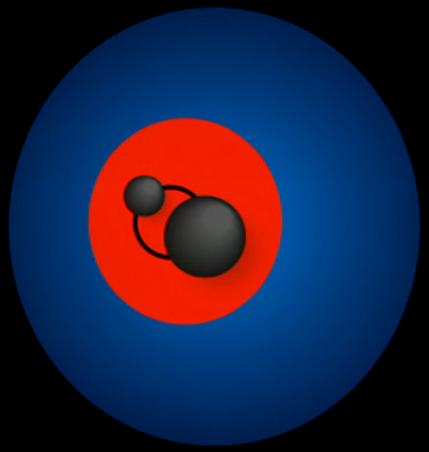

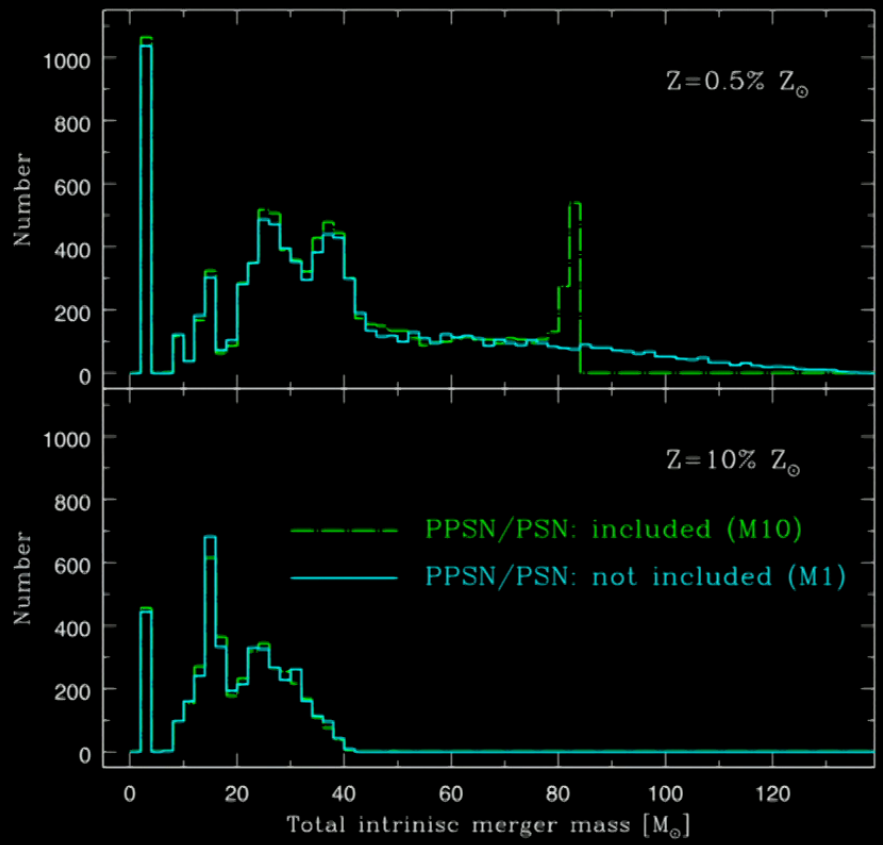

Belczynski et al., 2016

Masses

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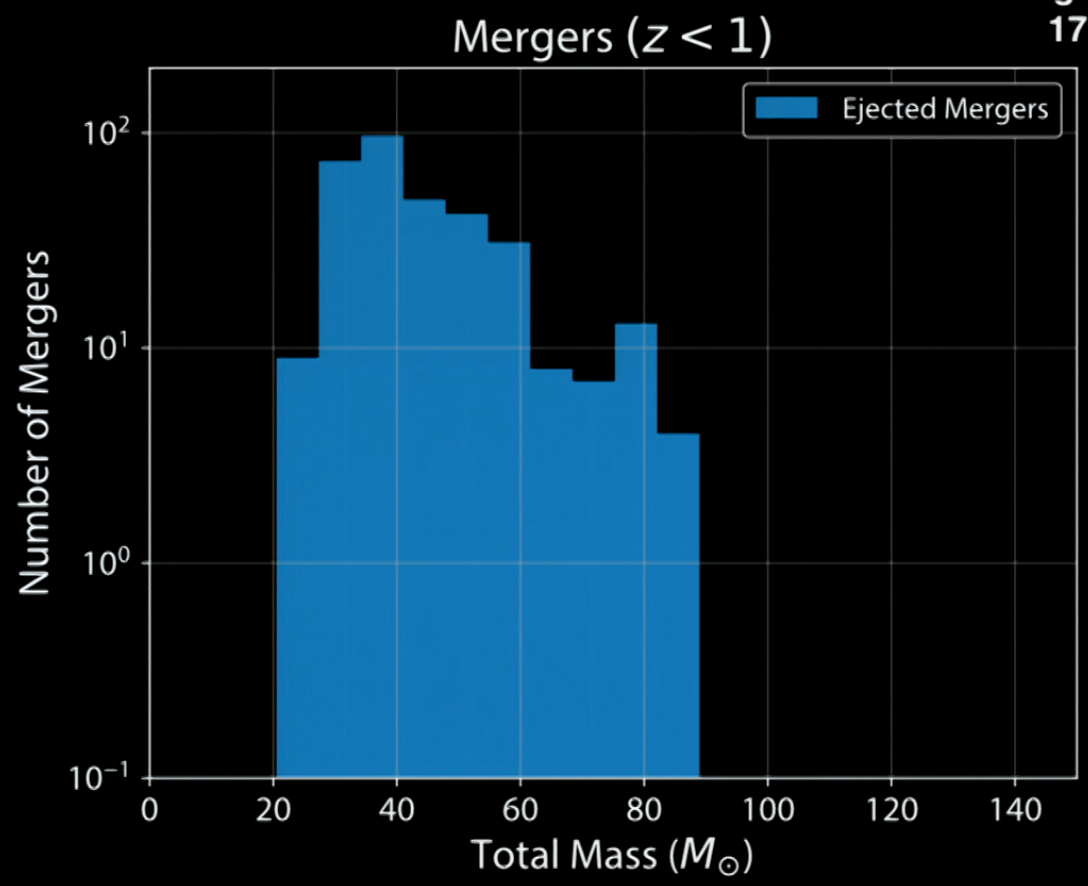
Rodriguez et al., 2017
1712.04937



Masses

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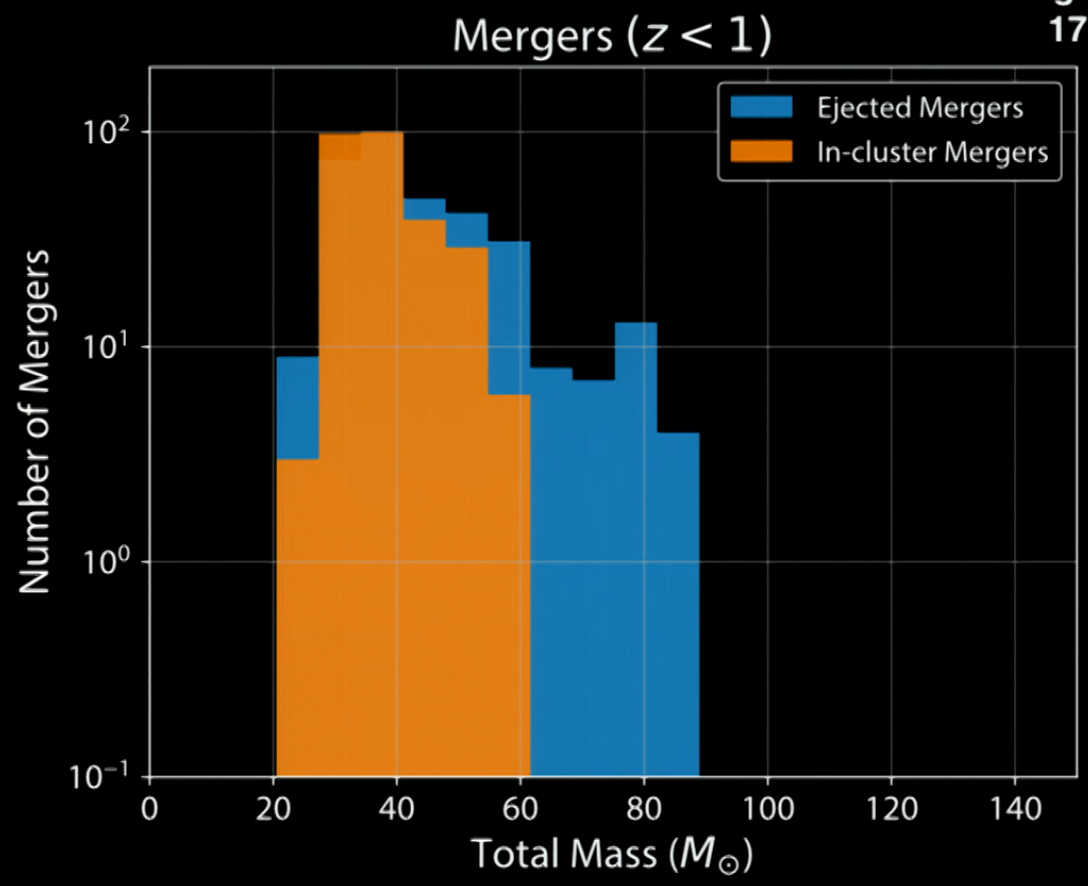
Rodriguez et al., 2017
1712.04937



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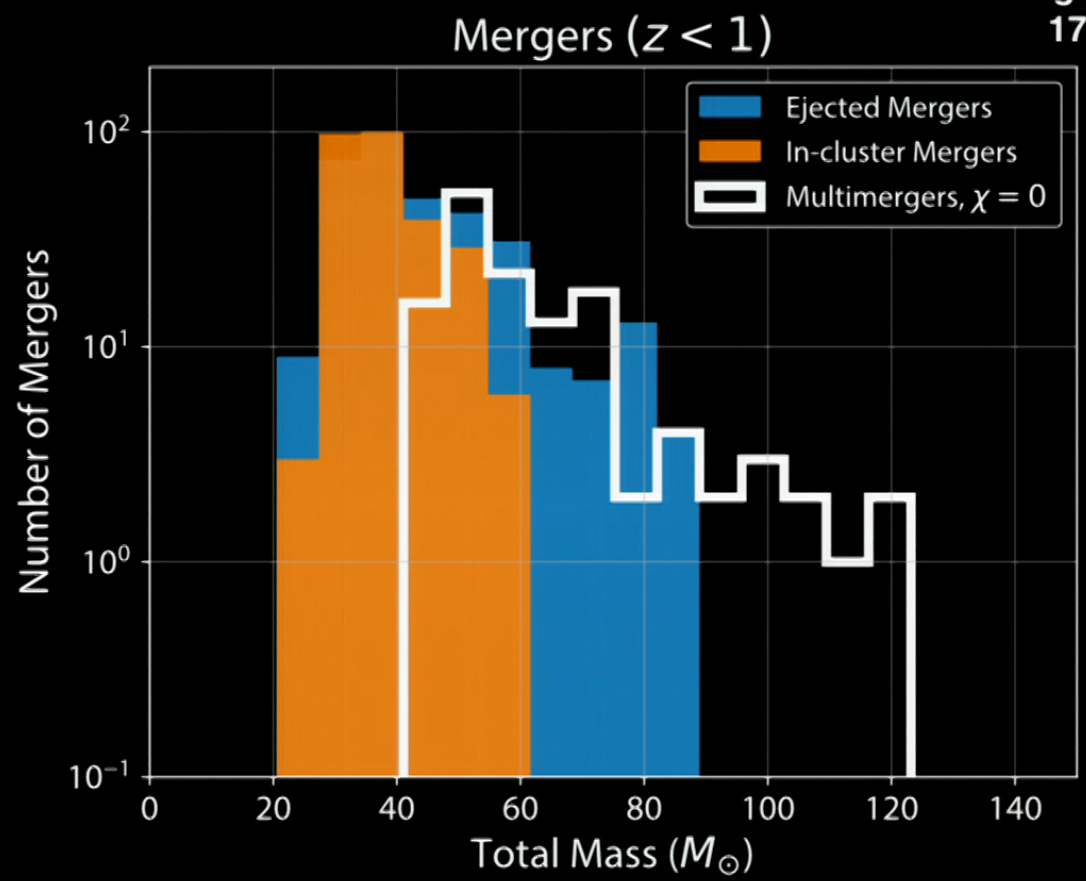
Rodriguez et al., 2017
1712.04937



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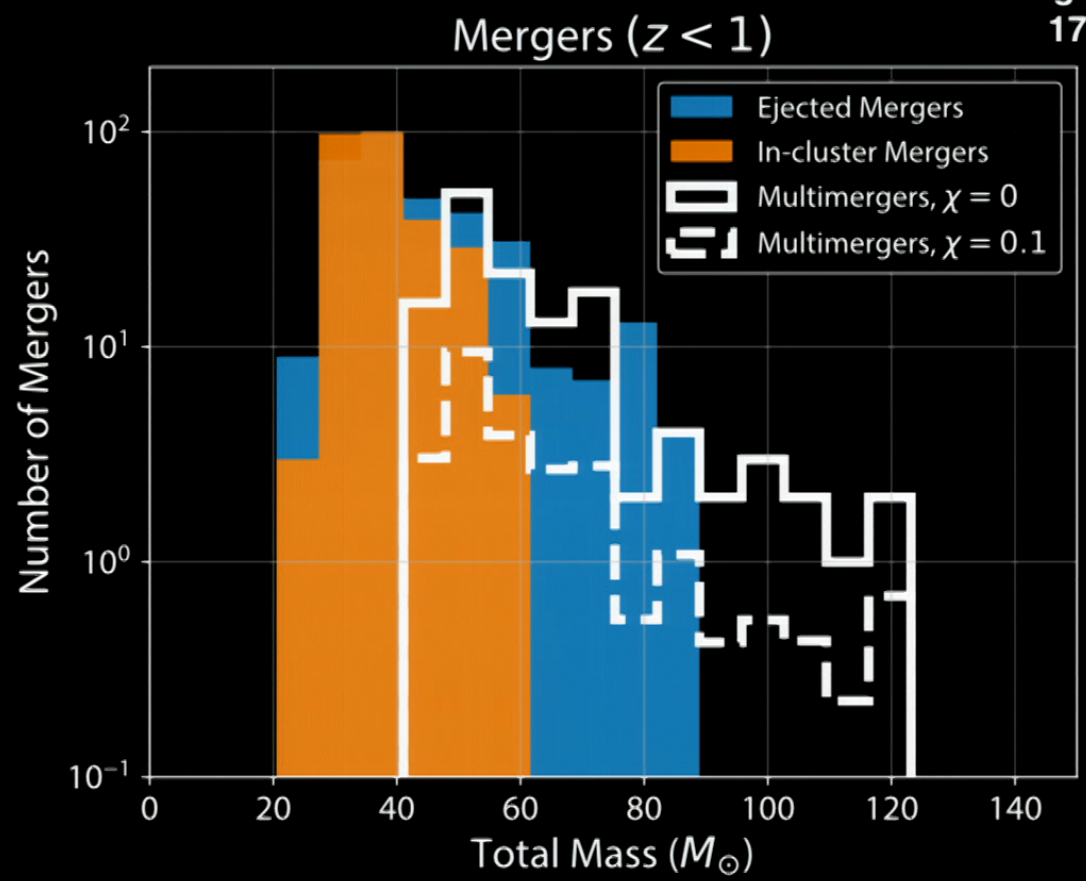
Rodriguez et al., 2017
1712.04937



Conclusions

Masses, eccentricities, and spins can all discriminate between different formation channels

If black hole birth spins are high, then we will eventually detect an anti-aligned binary black hole merger

If the black hole spins are low, then clusters can build up multiple generations of black holes with large masses and spins