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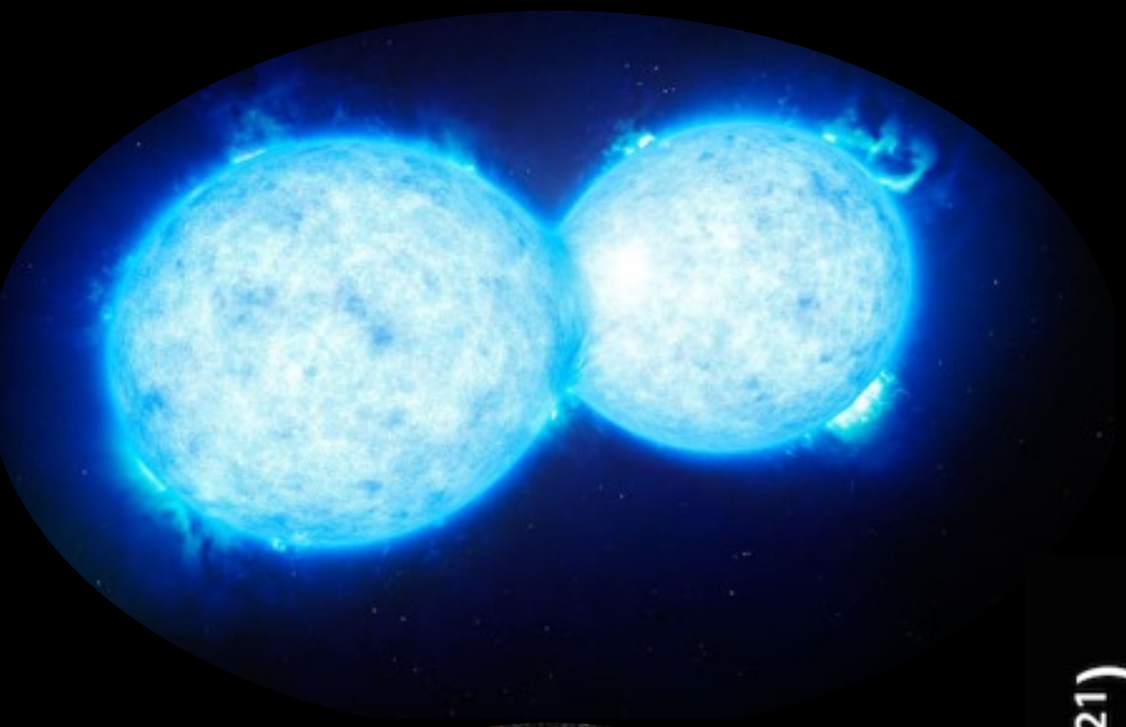
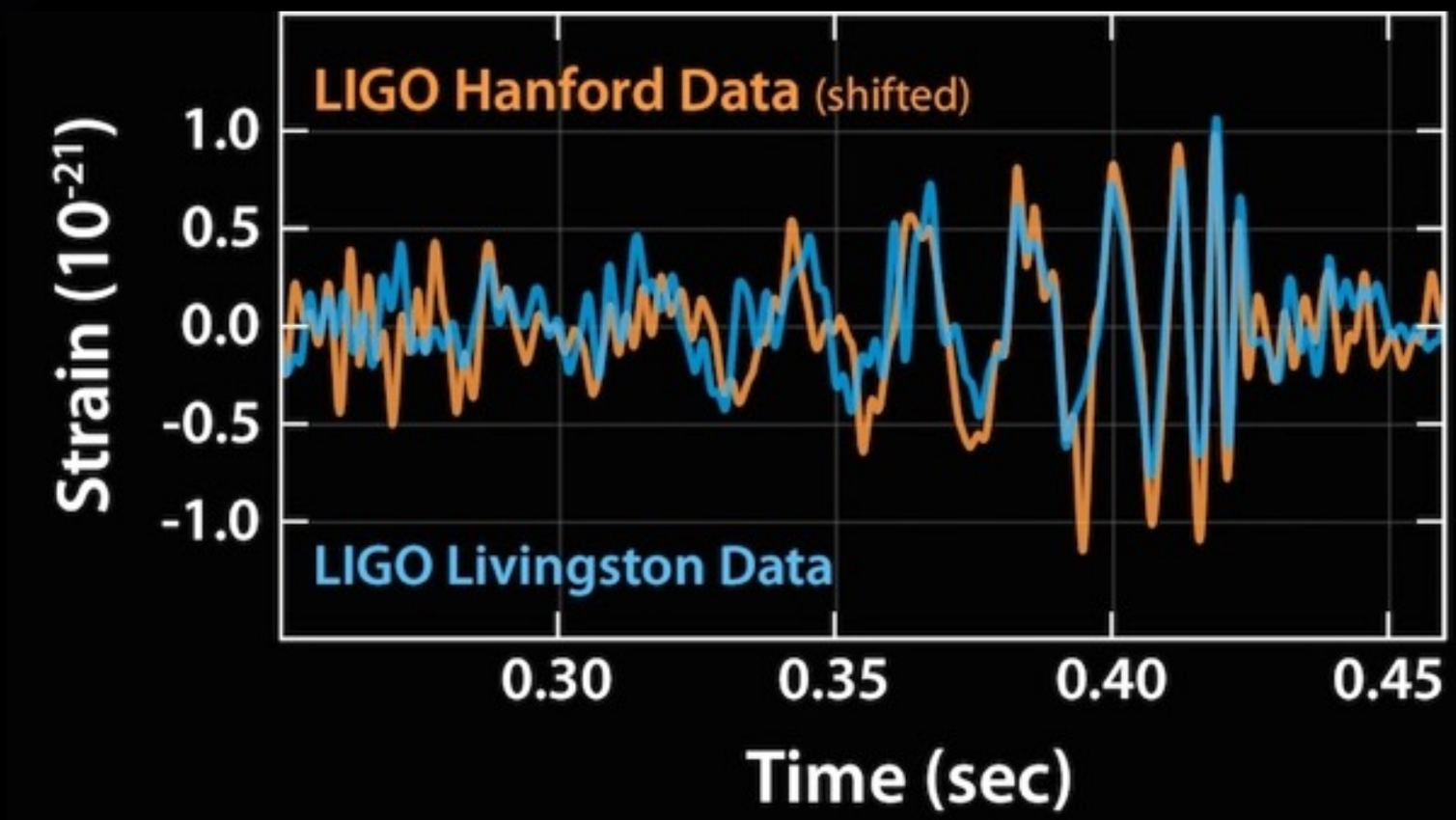
Dense Star Clusters as Binary Black Hole Factories

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

Siggurdson & Hernquist 1993, Kulkarni 1993, 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, Downing et al. 2010, 2011, Bae et al. 2014, Ziosi et al. 2014, 2016, Morscher et al. 2013, 2015, Rodriguez et al. 2015,2016a,b,c, Mapelli 2016, Abbas et al. 2016, Banerjee 2017




LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

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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a

b

Black Holes in GCs

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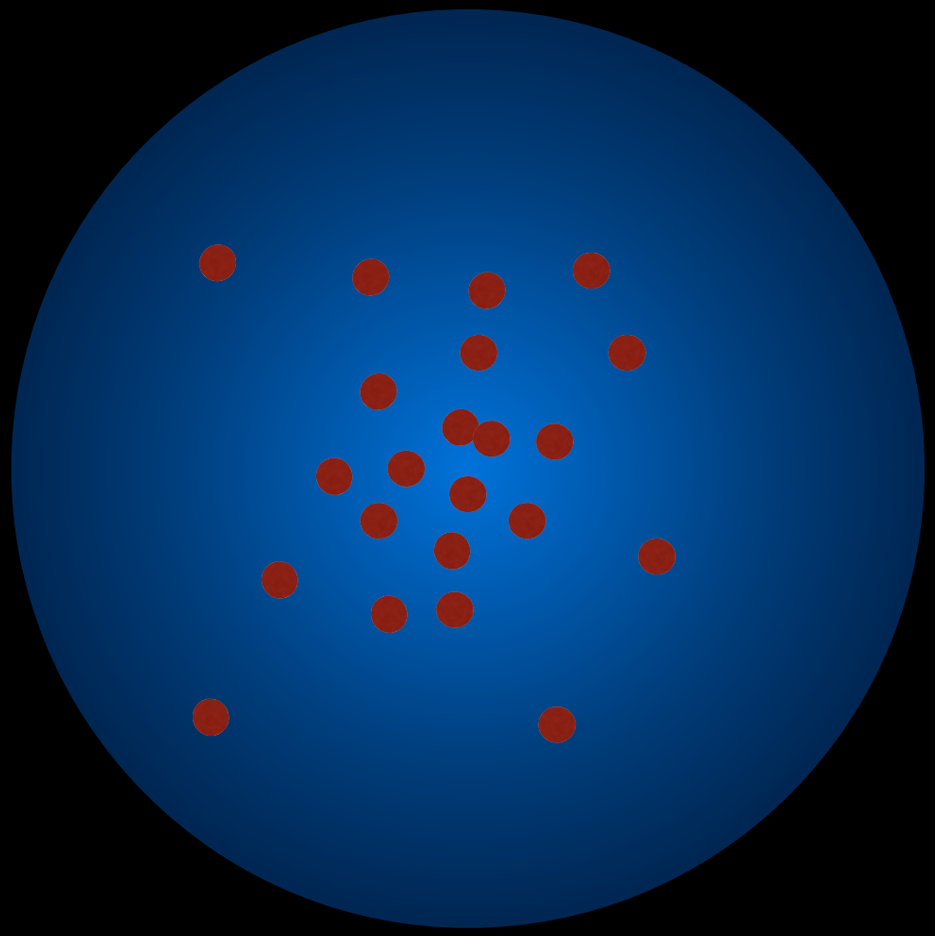
a



Dynamical Friction

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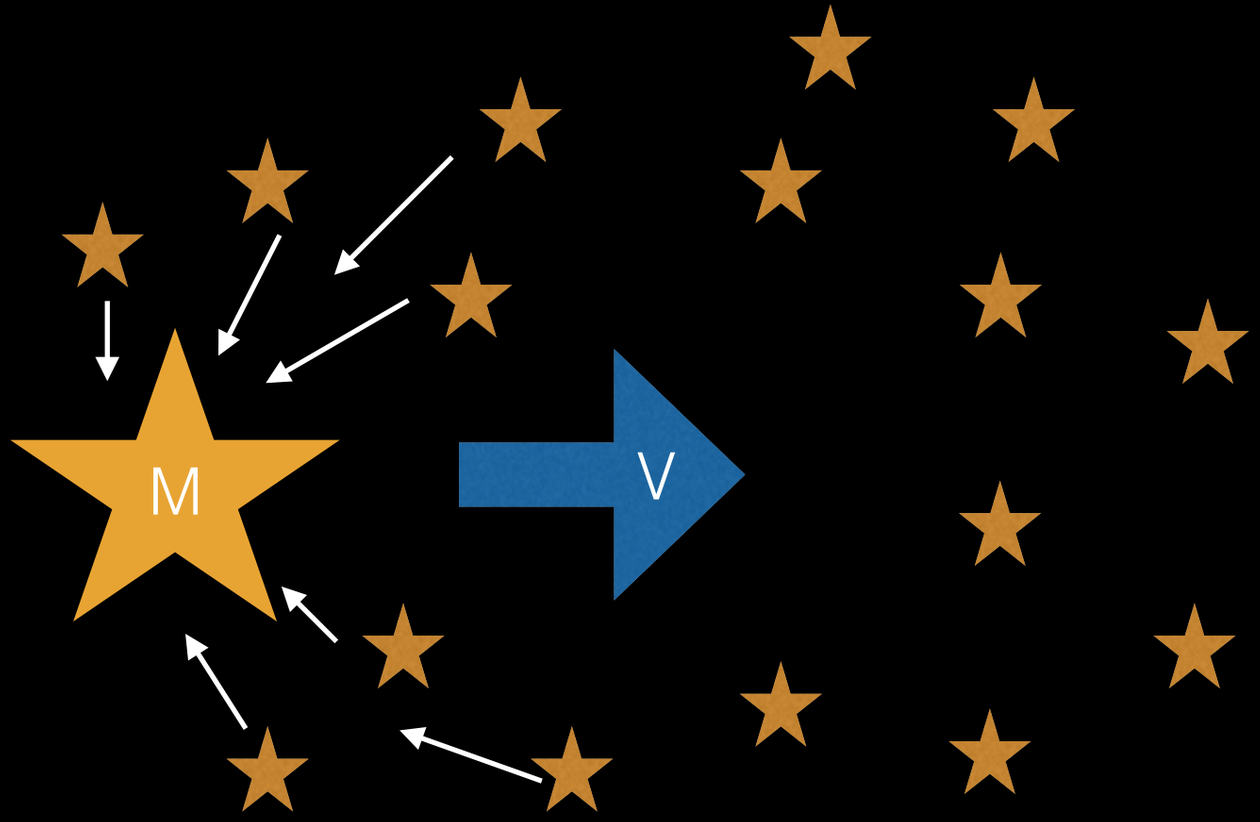

Dynamical Friction

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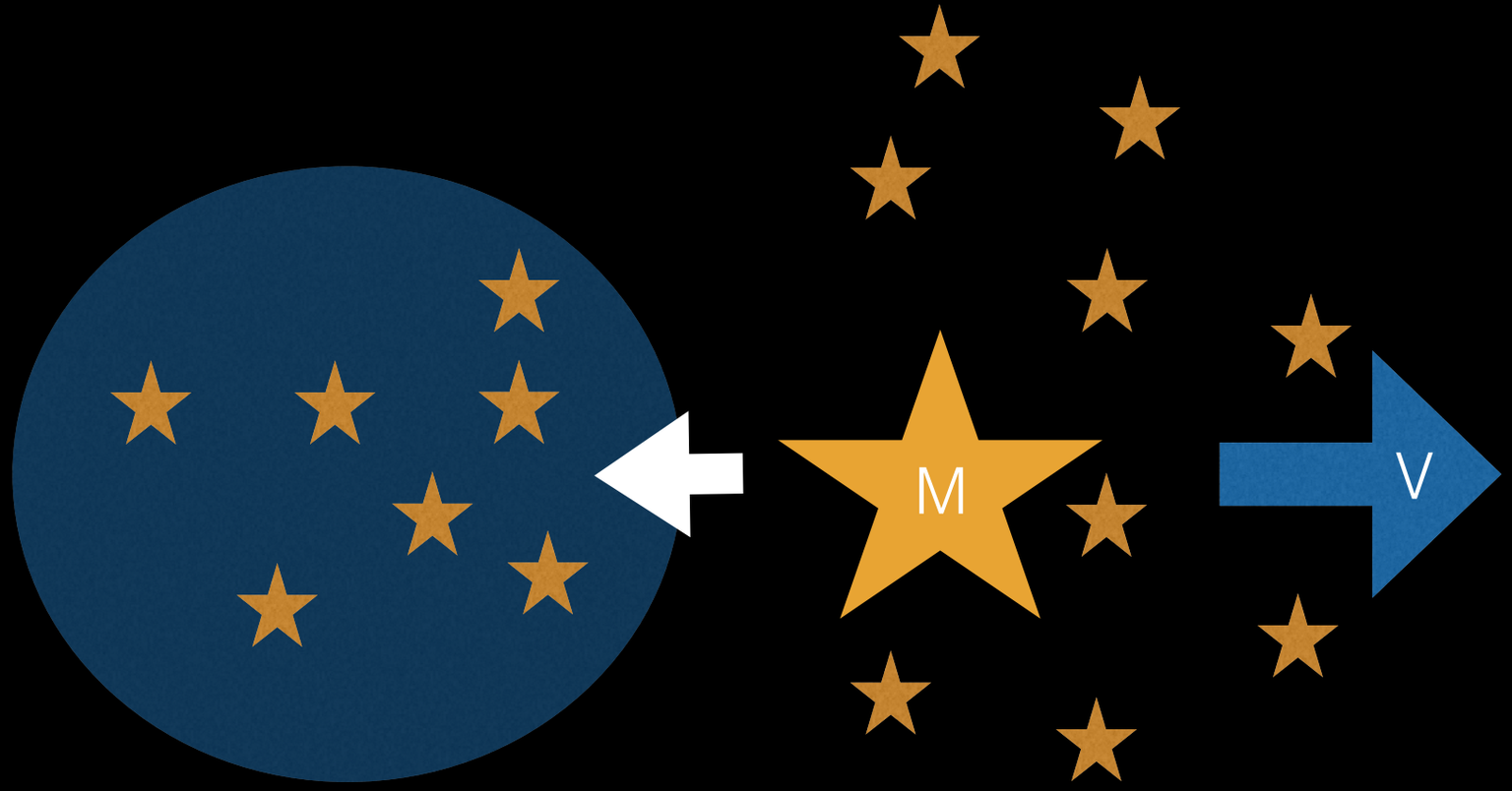

Massive particles will “segregate” into center of the cluster

Black Holes in GCs

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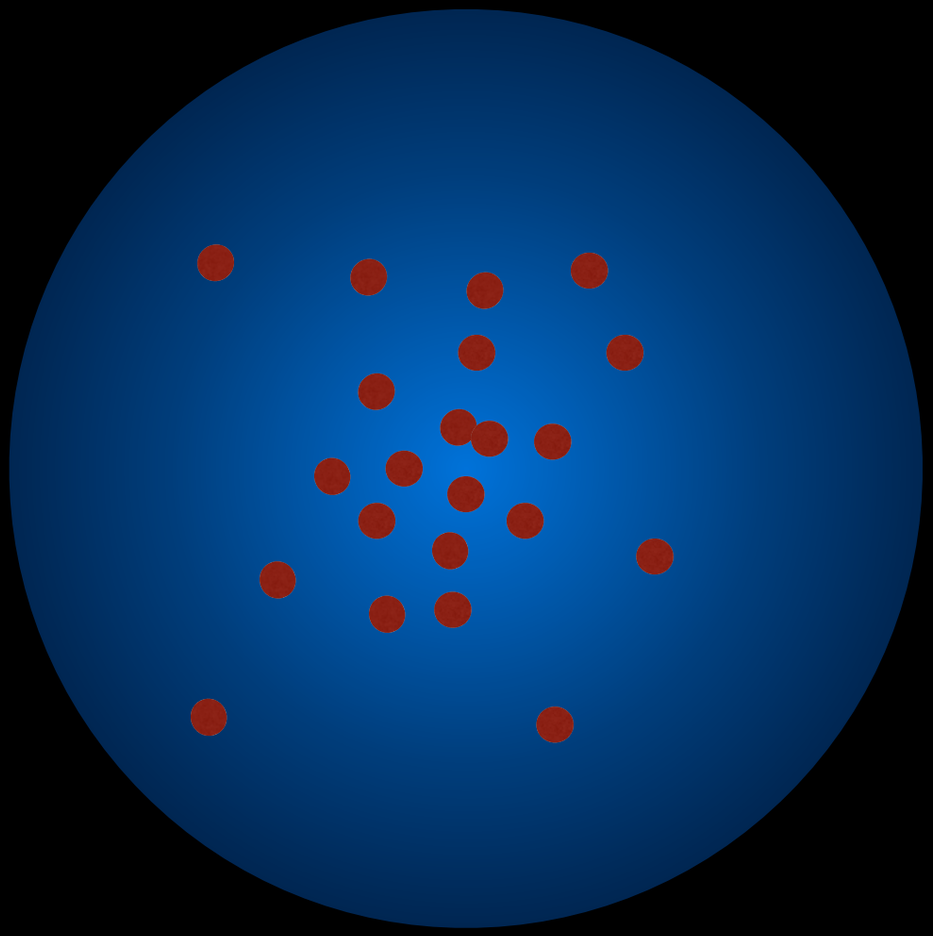
a



Black Holes in GCs

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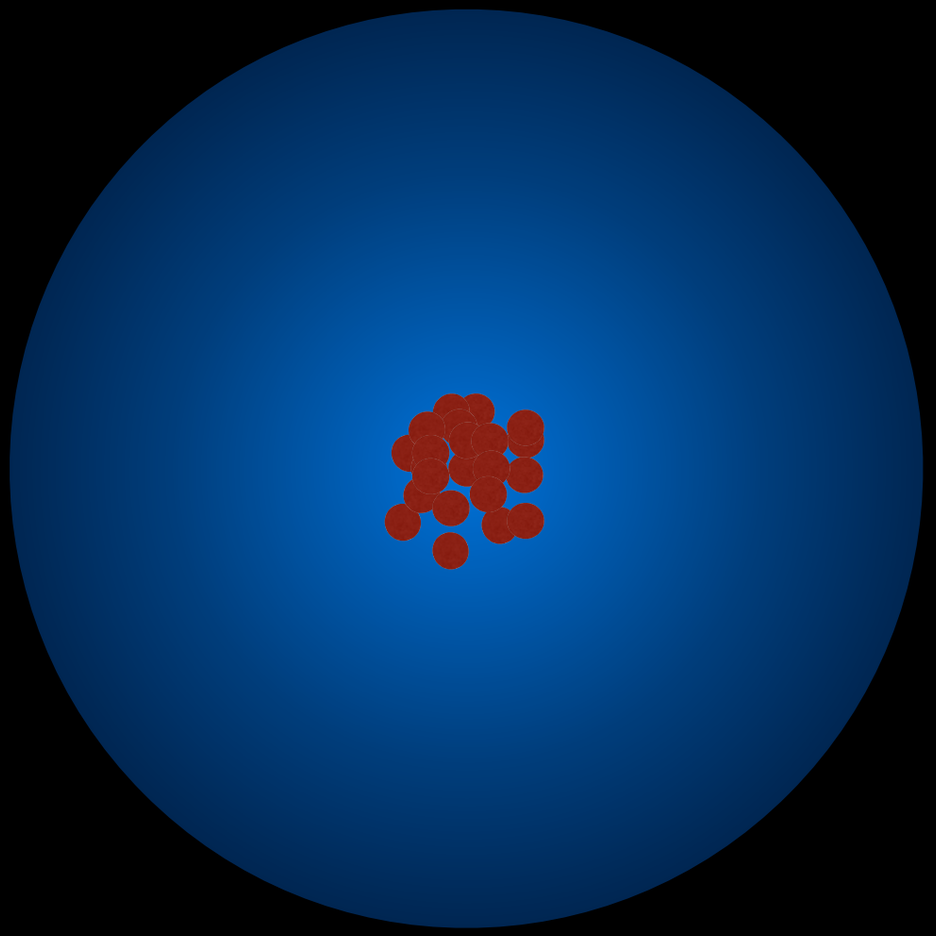
a



Black Holes in GCs

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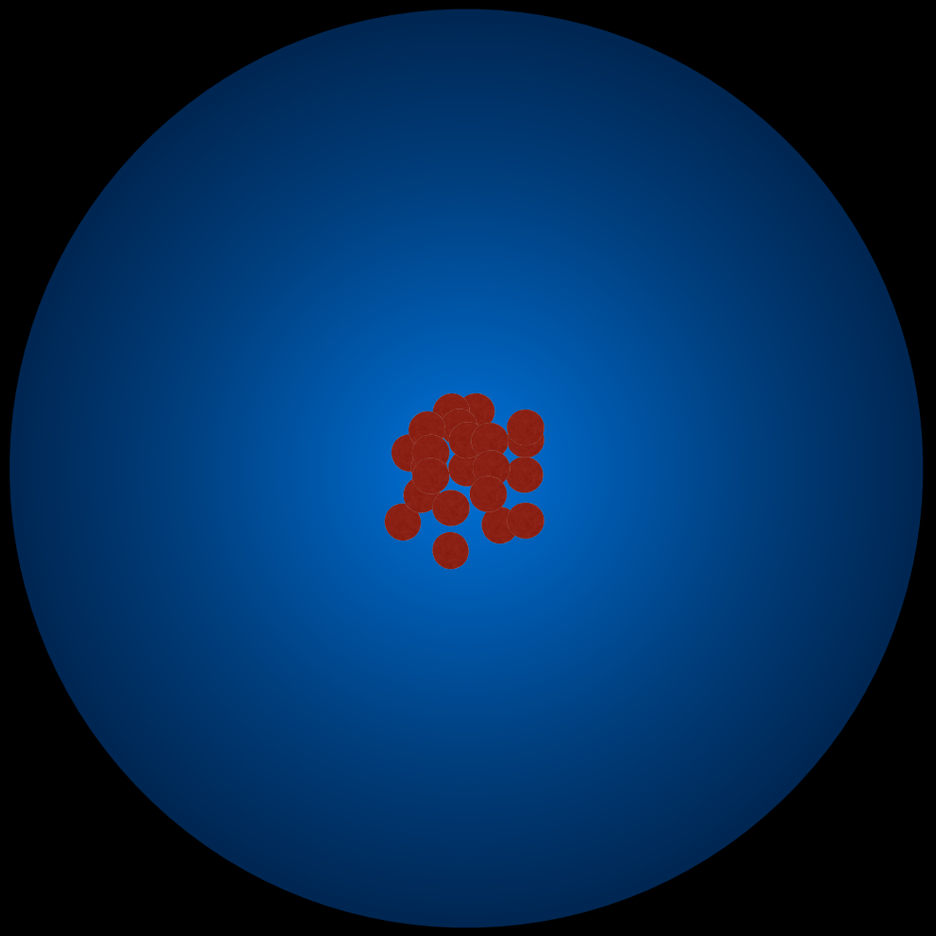
a



~ 100 Myr

Black Holes in GCs

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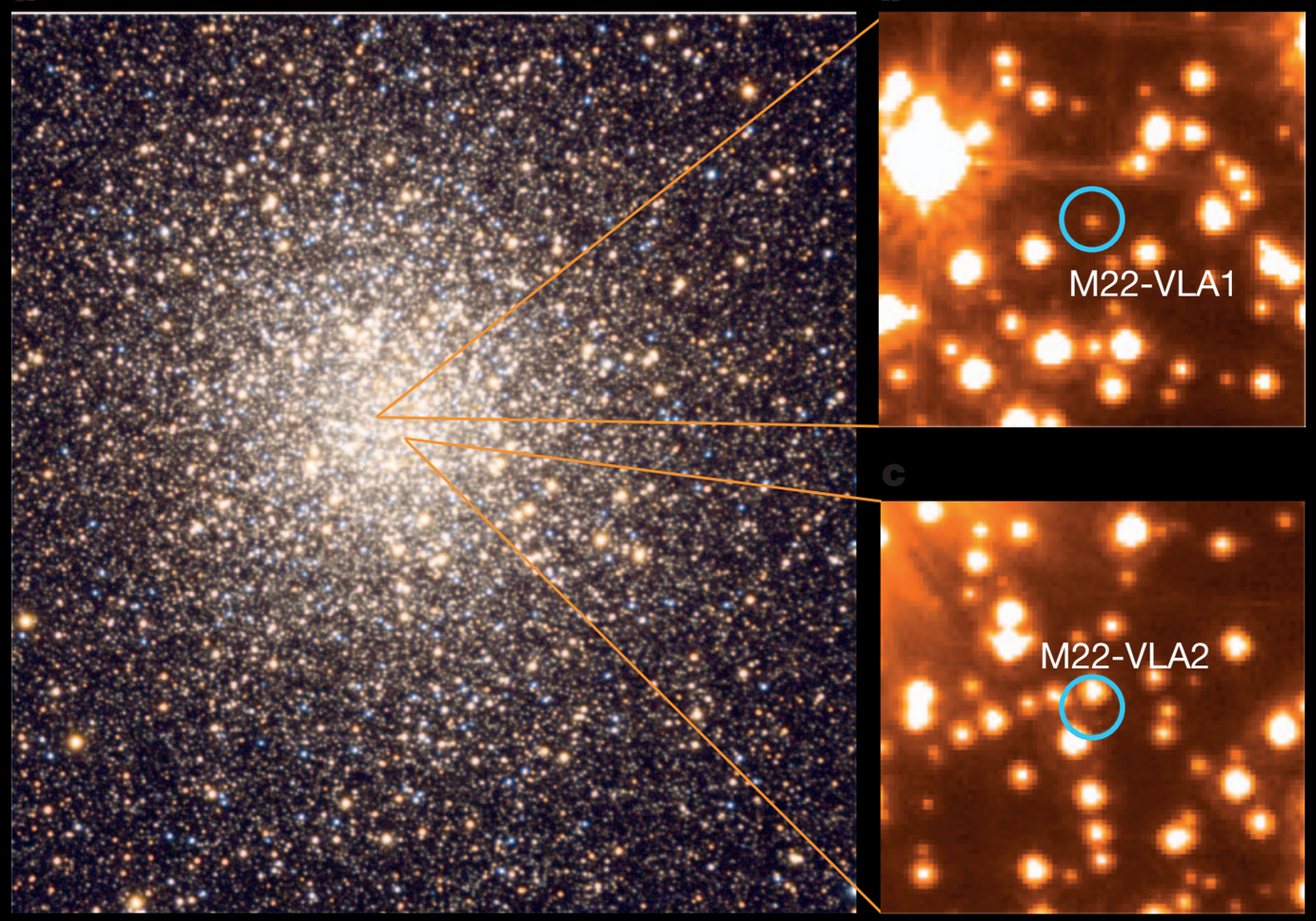
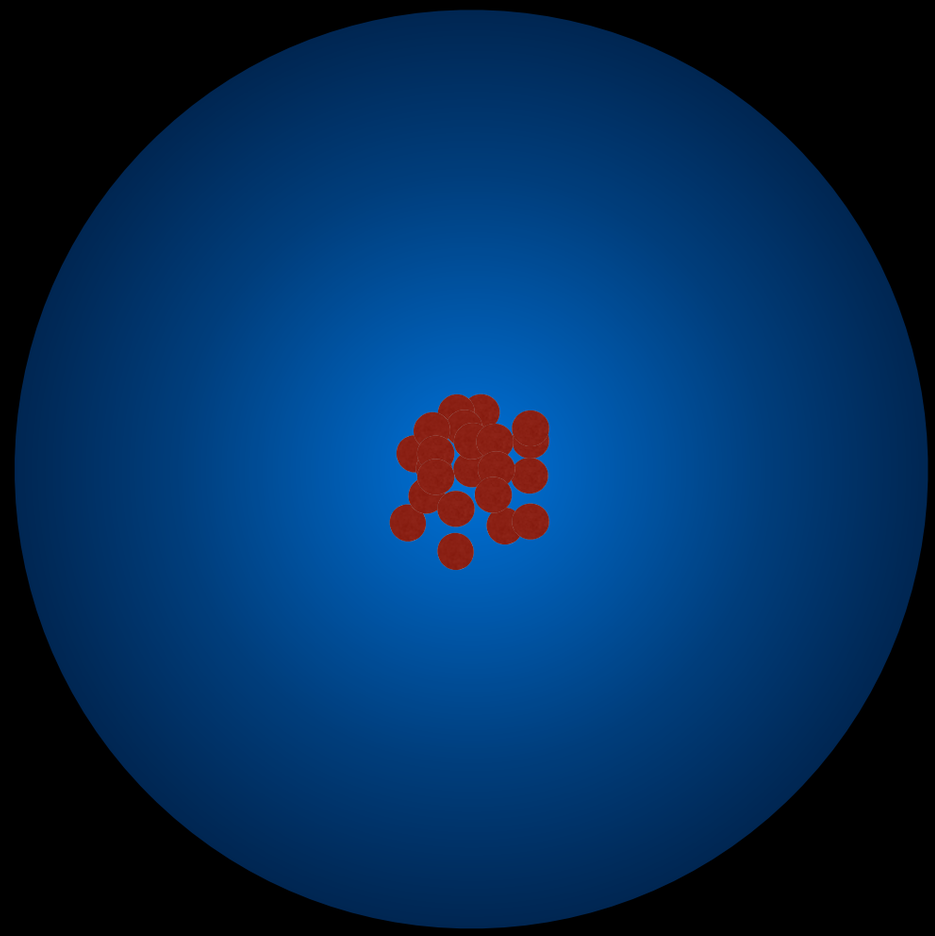


Strader et al., 2012



~ 100 Myr

Chaotic Interactions

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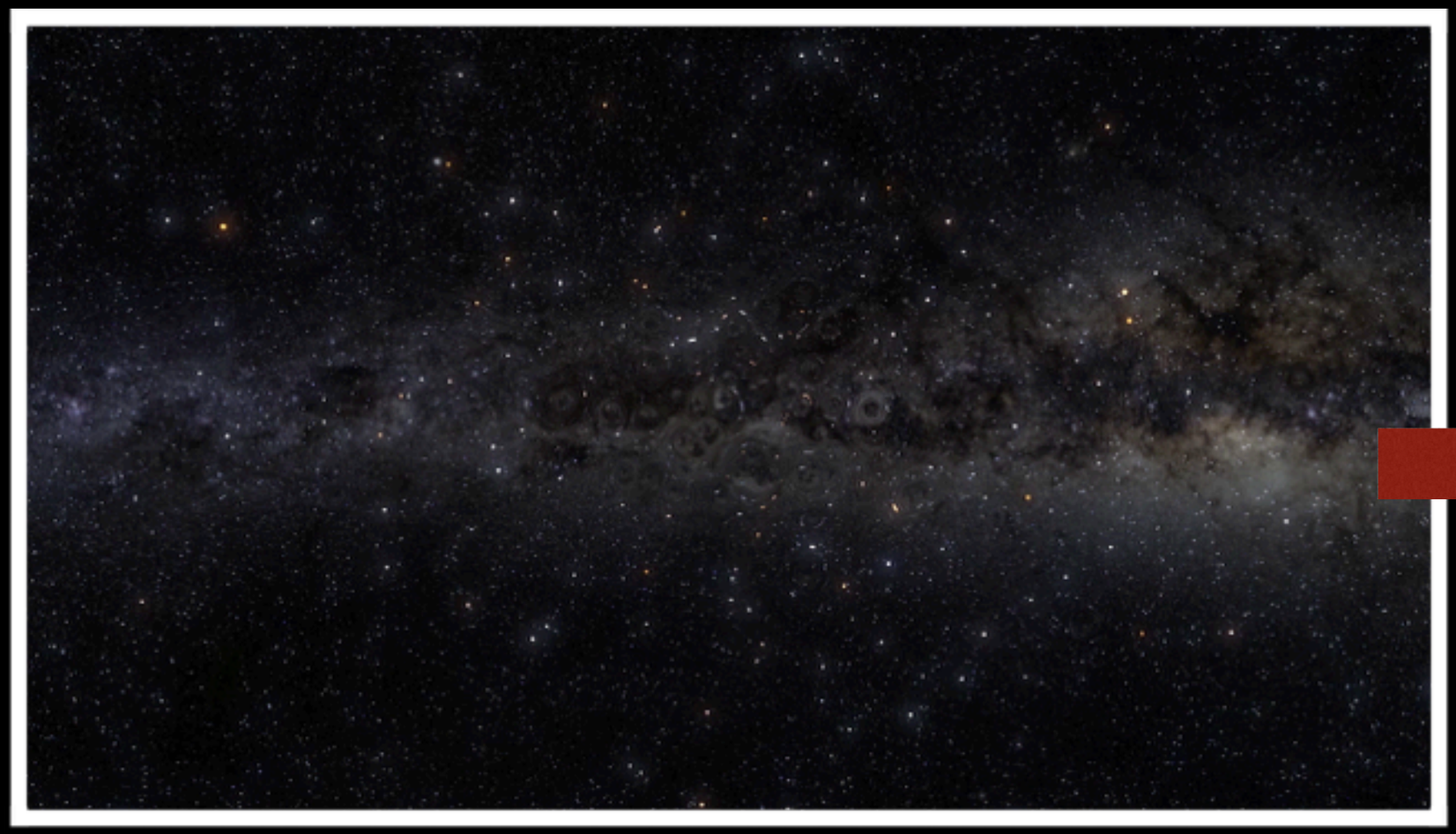

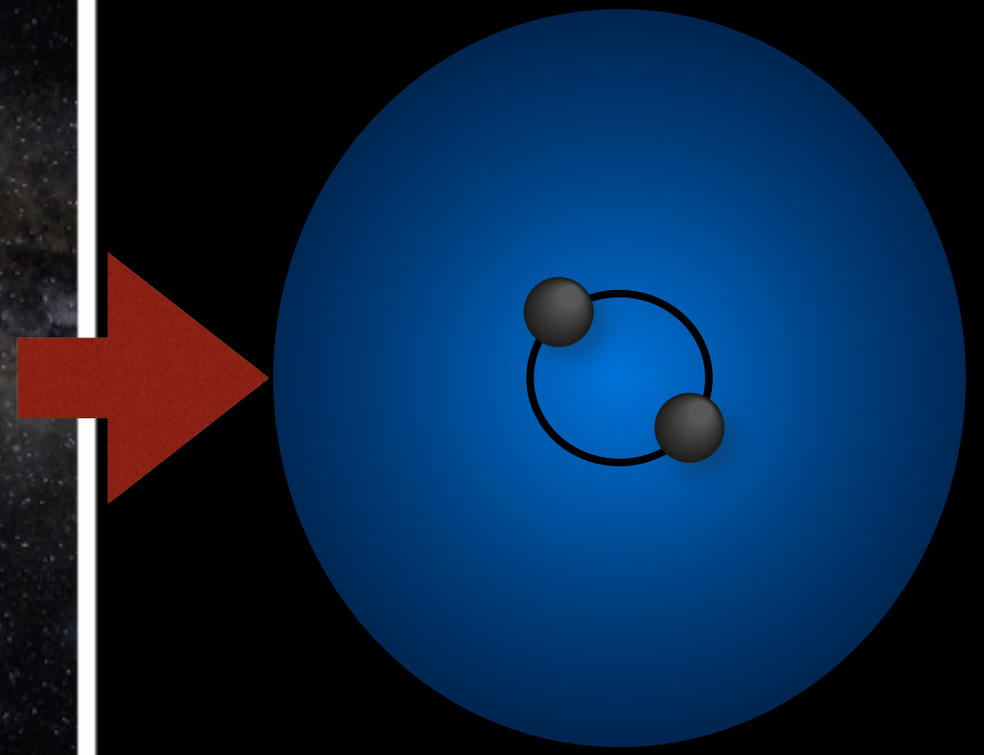

Chaotic Interactions

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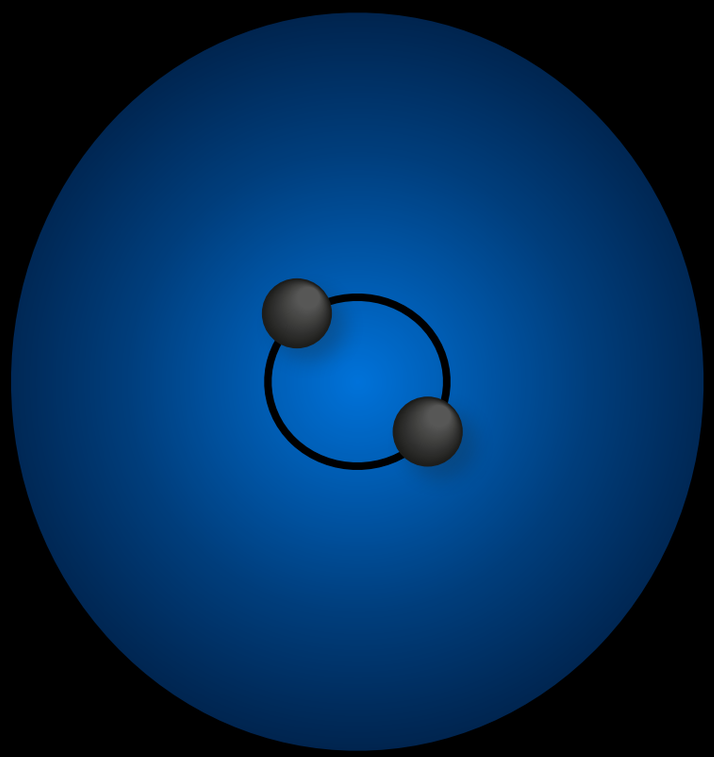

Chaotic Interactions

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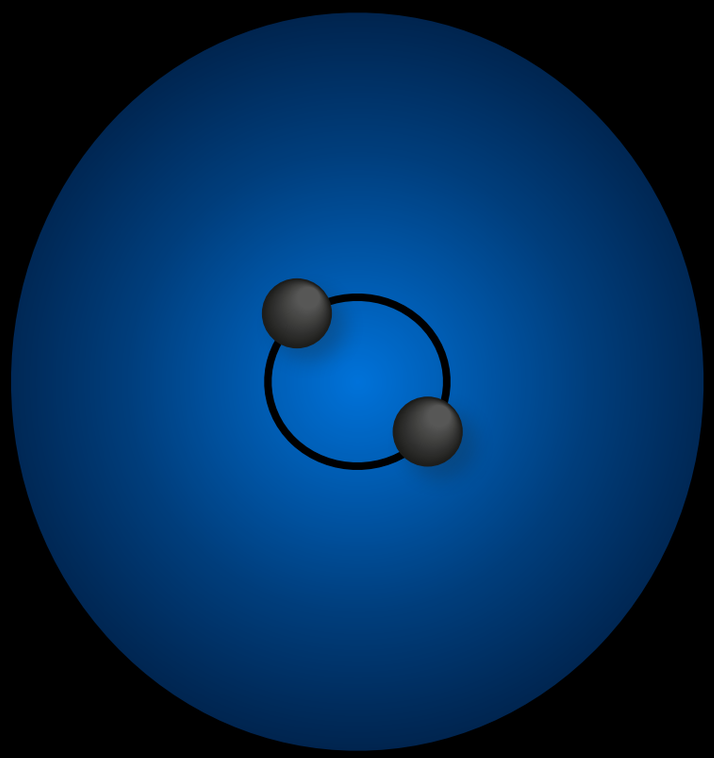

Chaotic Interactions

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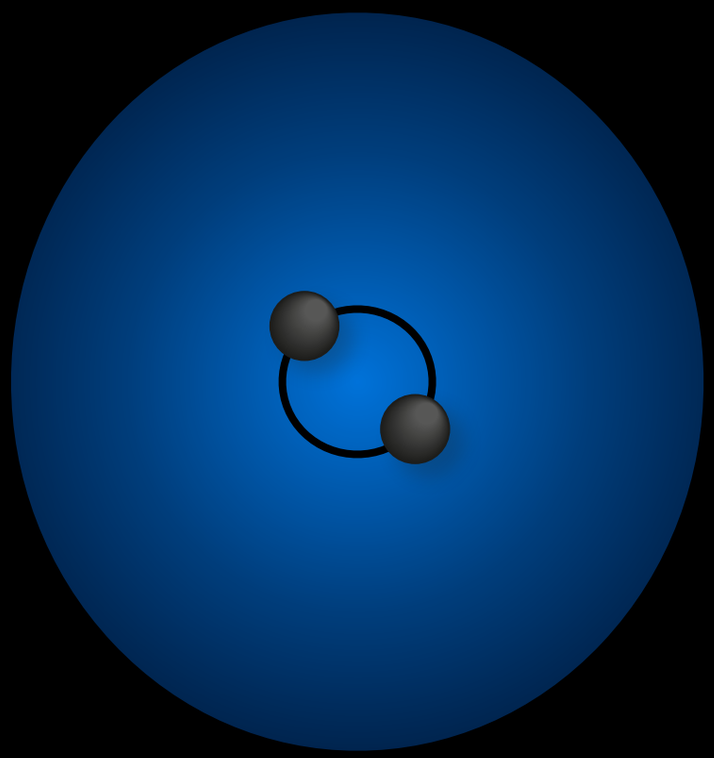

Chaotic Interactions

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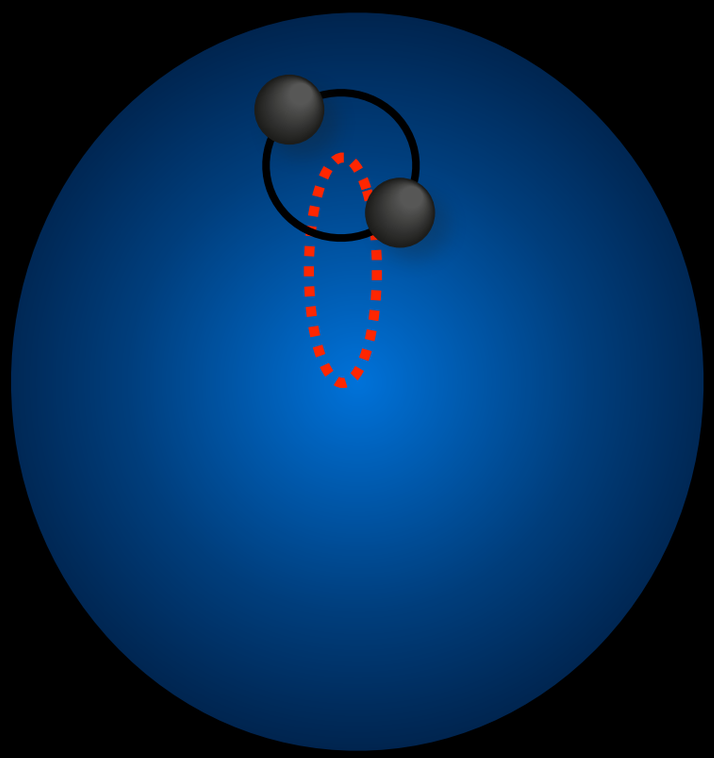

Chaotic Interactions

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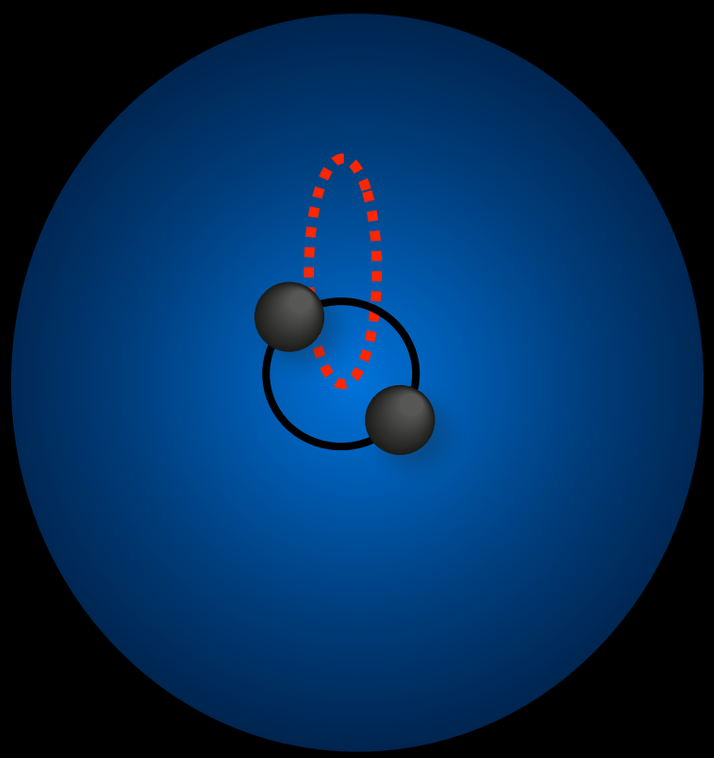

Chaotic Interactions

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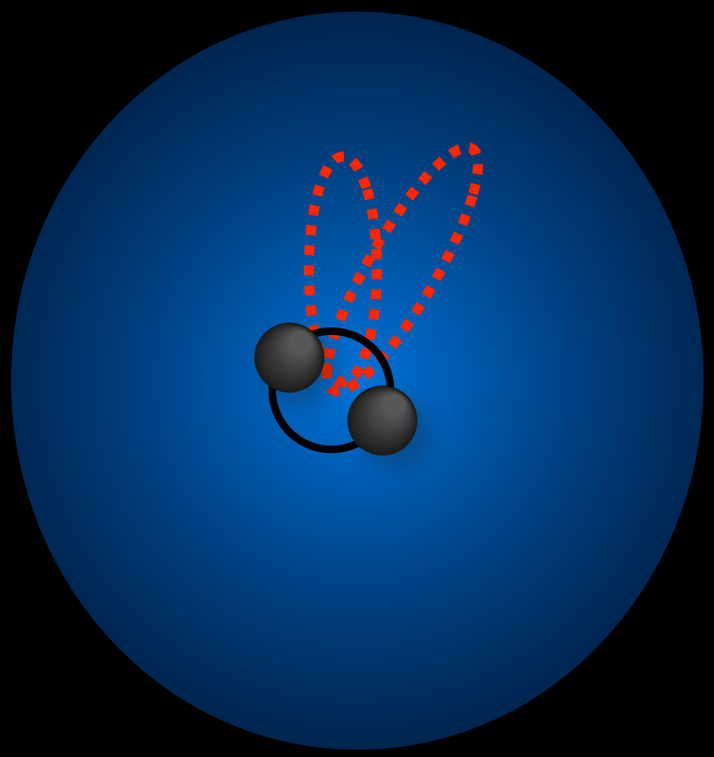

Chaotic Interactions

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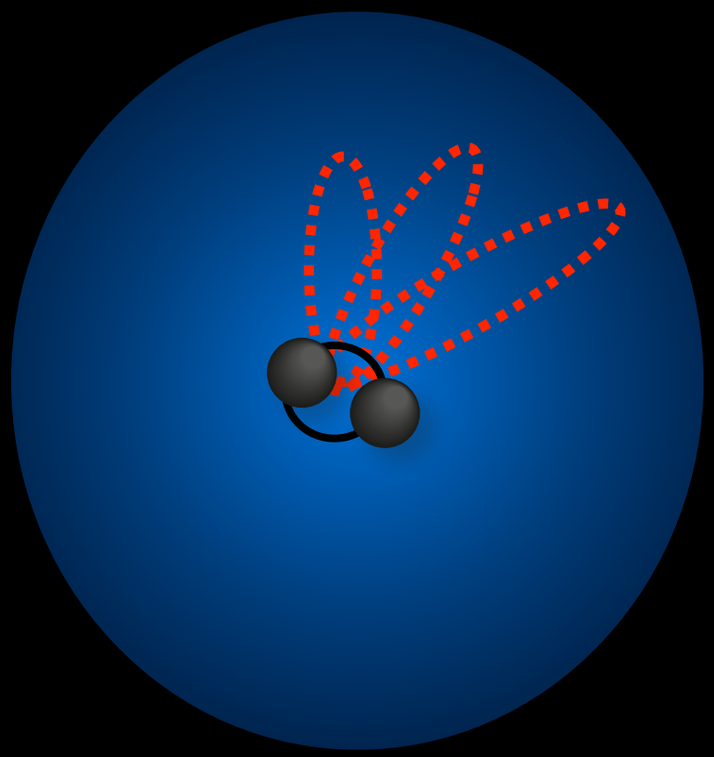

Chaotic Interactions

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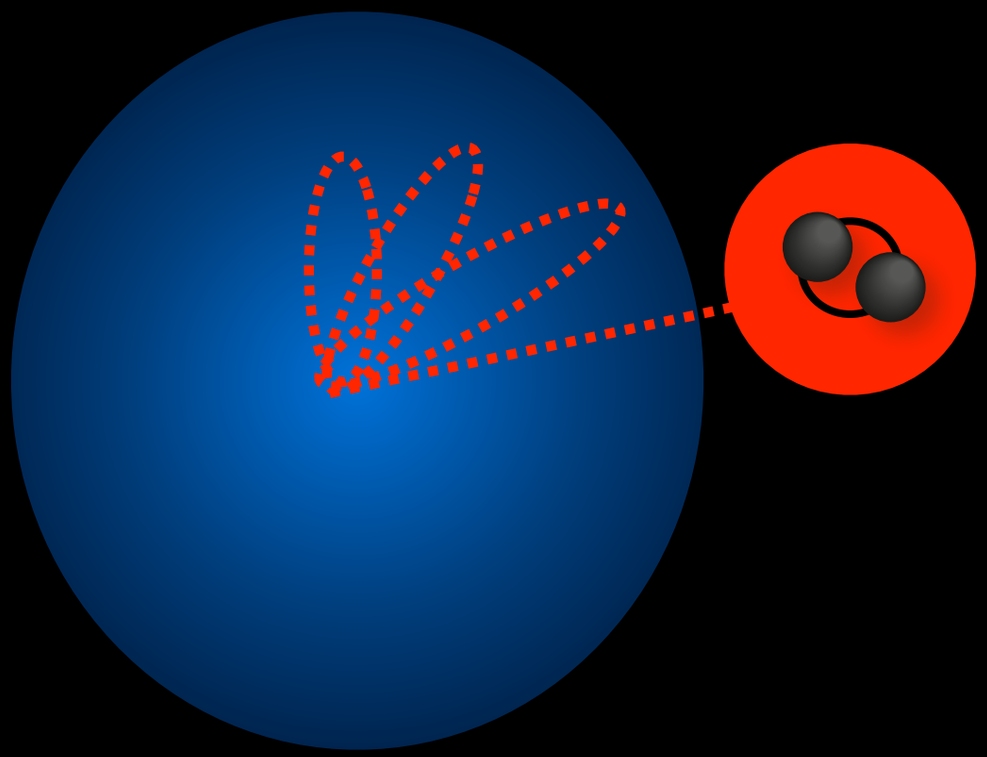

Chaotic Interactions

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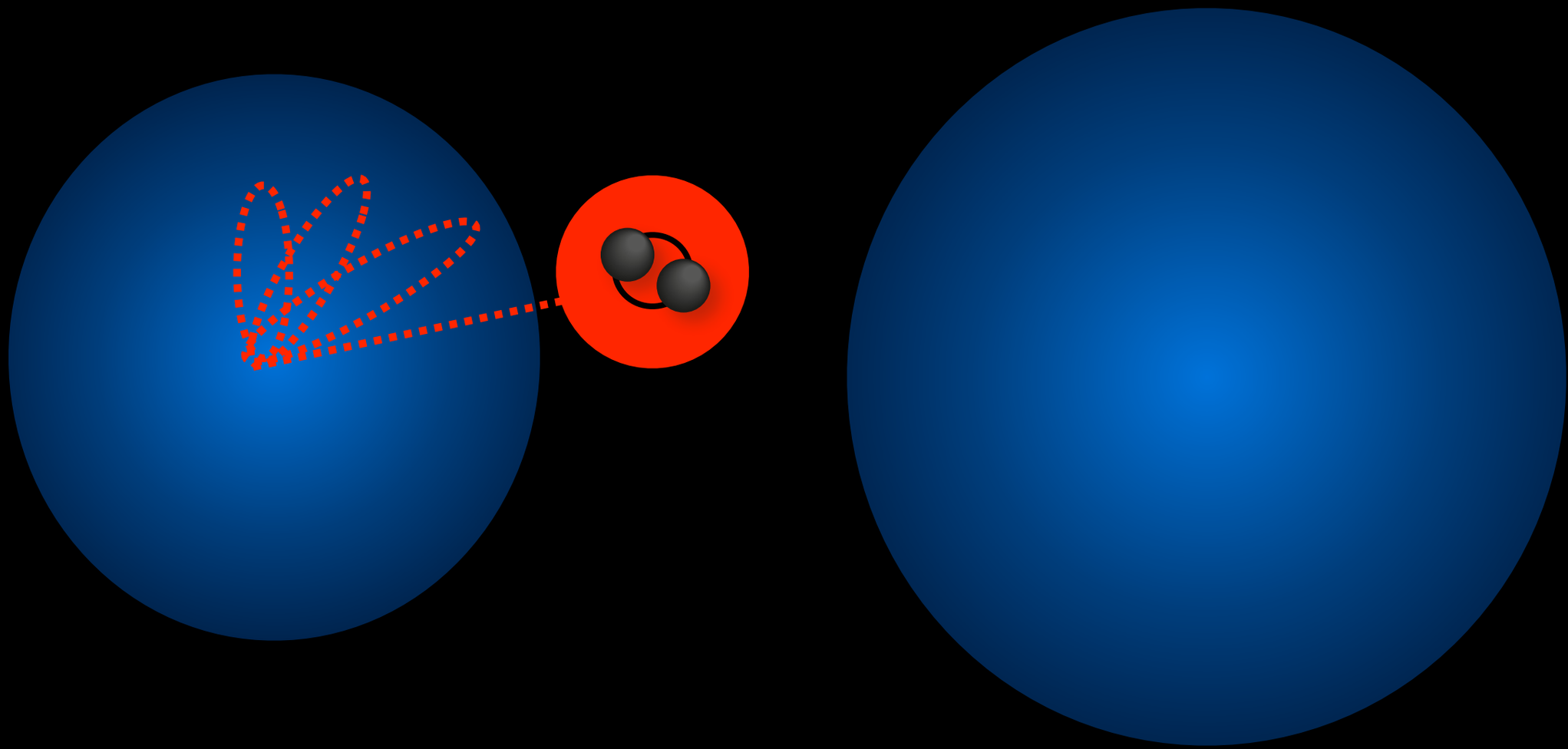

Chaotic Interactions

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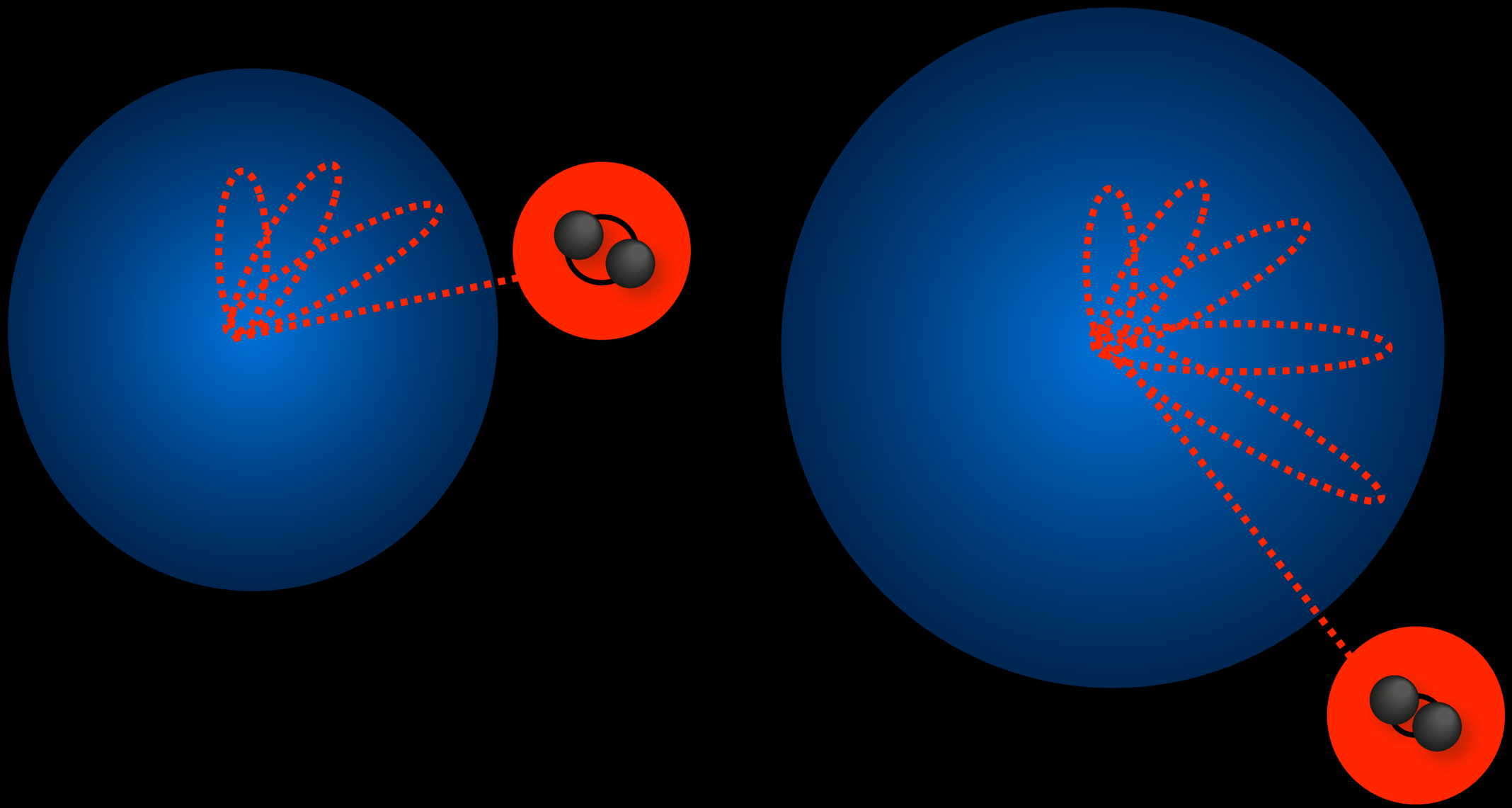

Chaotic Interactions

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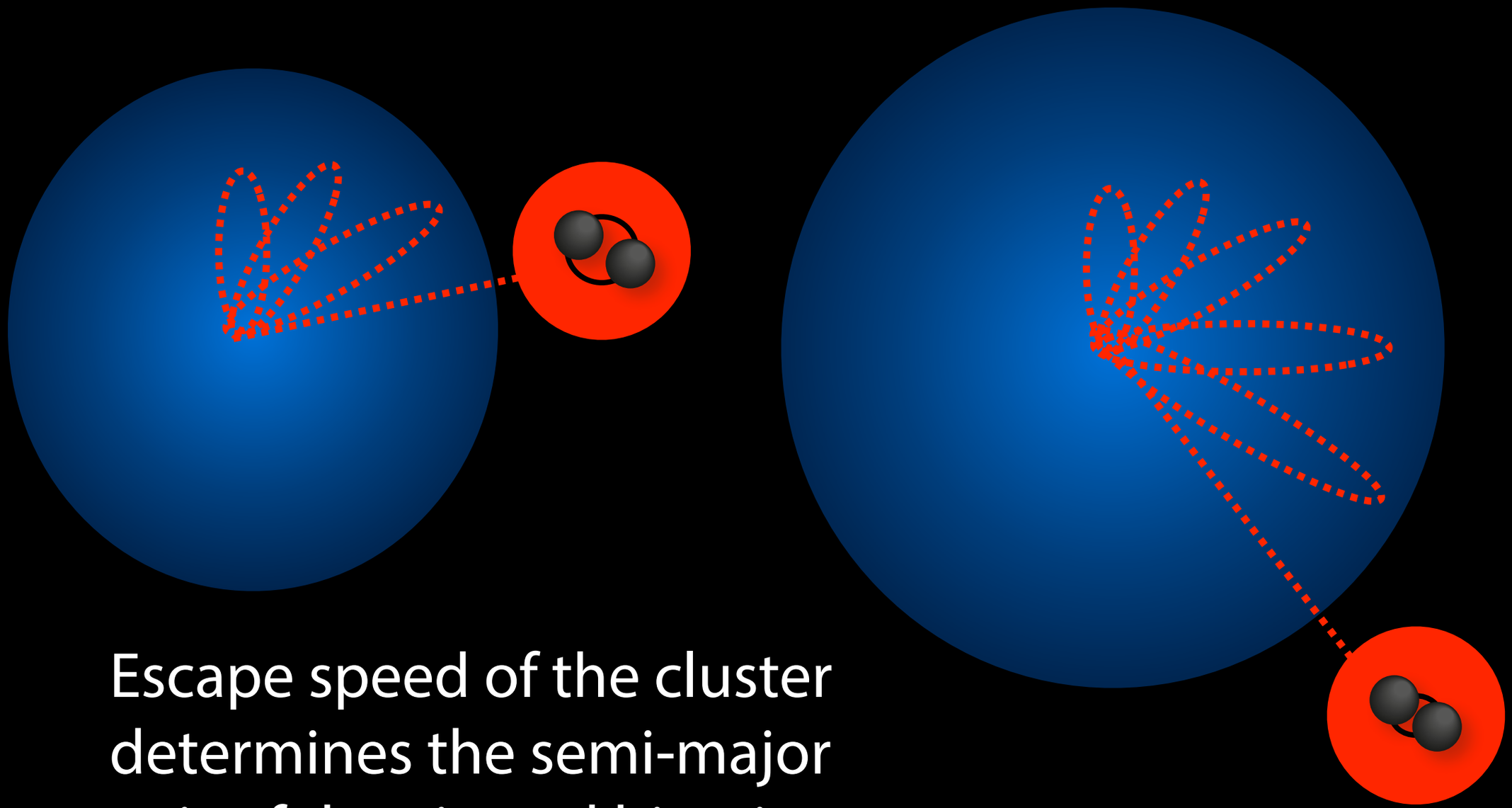

Escape speed of the cluster determines the semi-major axis of the ejected binaries

Chaotic Interactions

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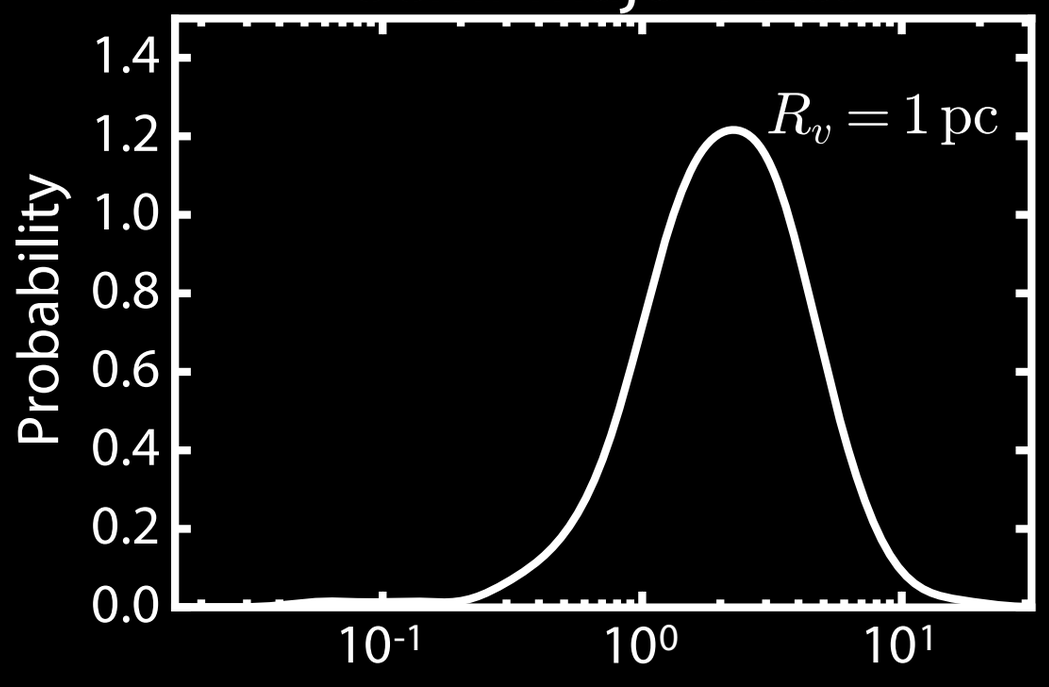

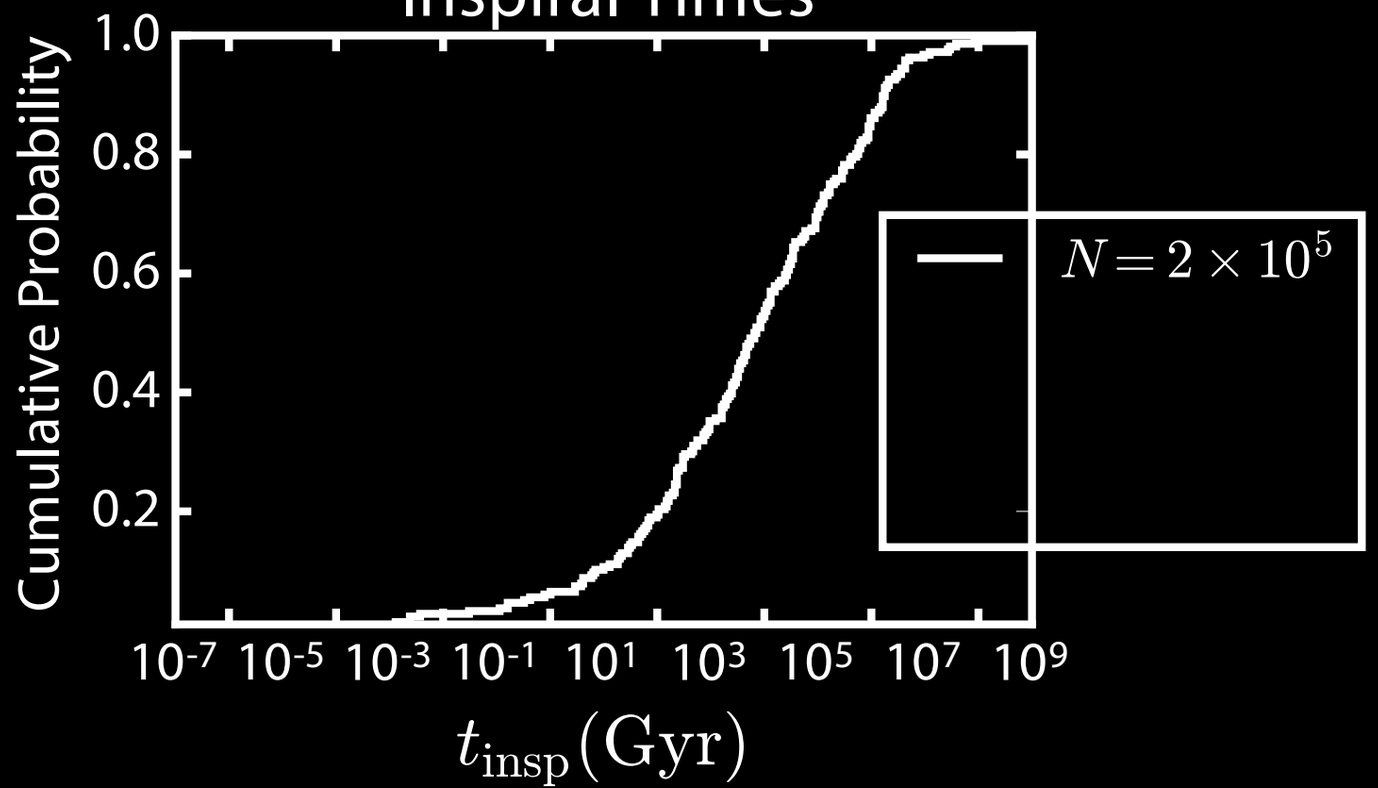

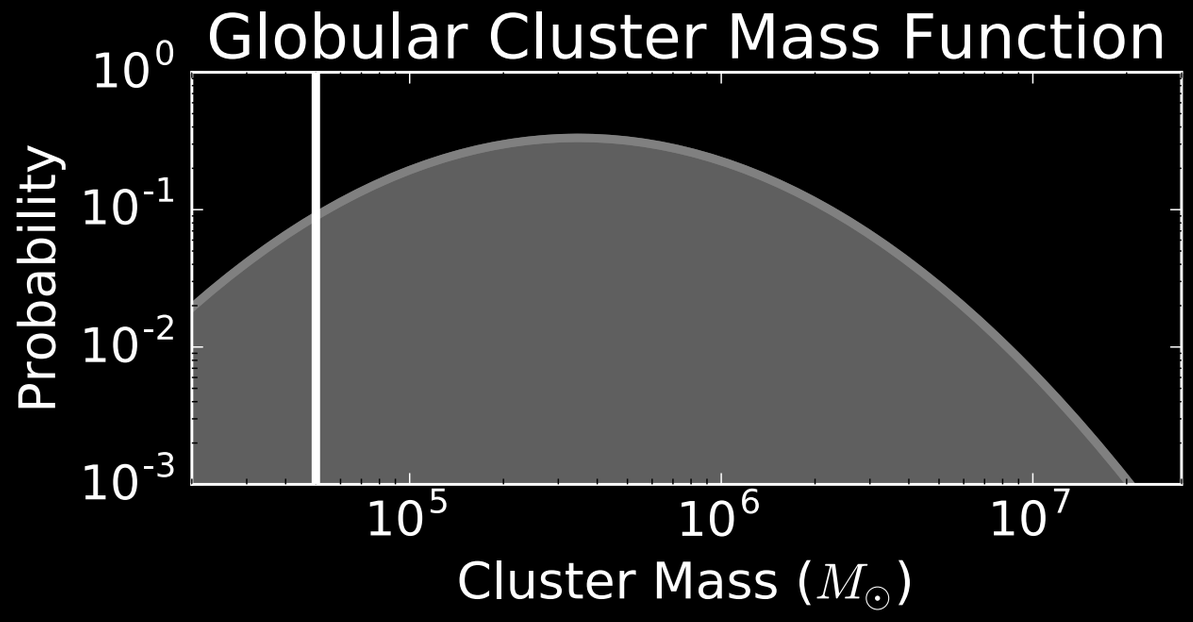

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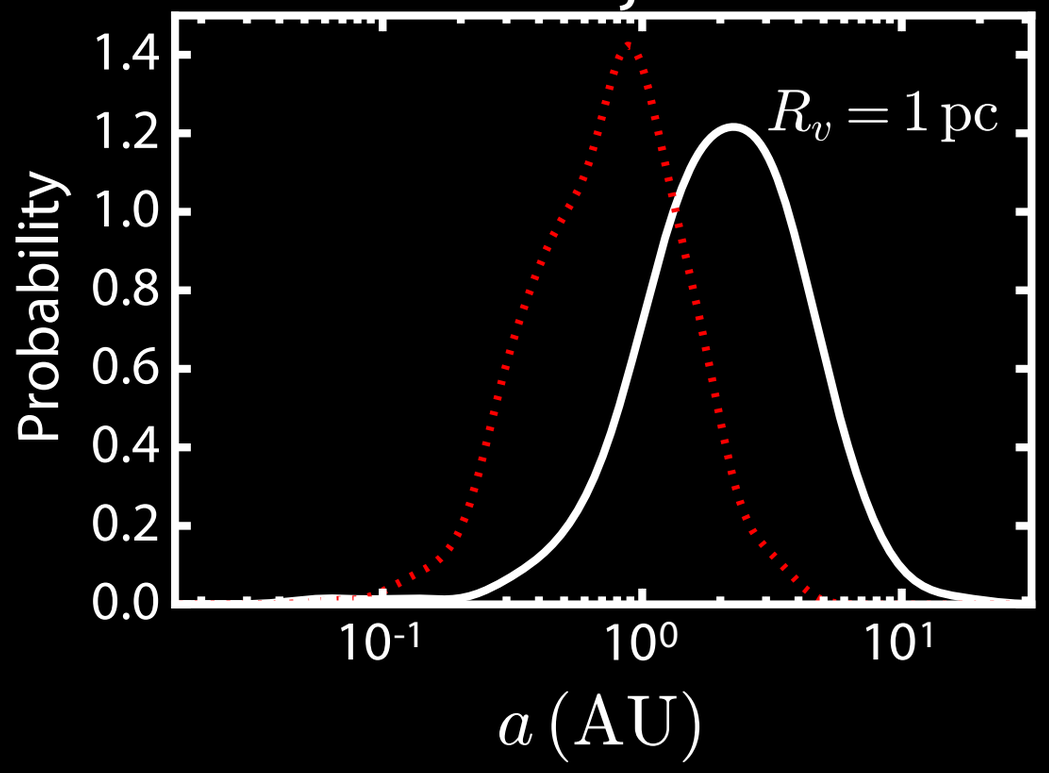
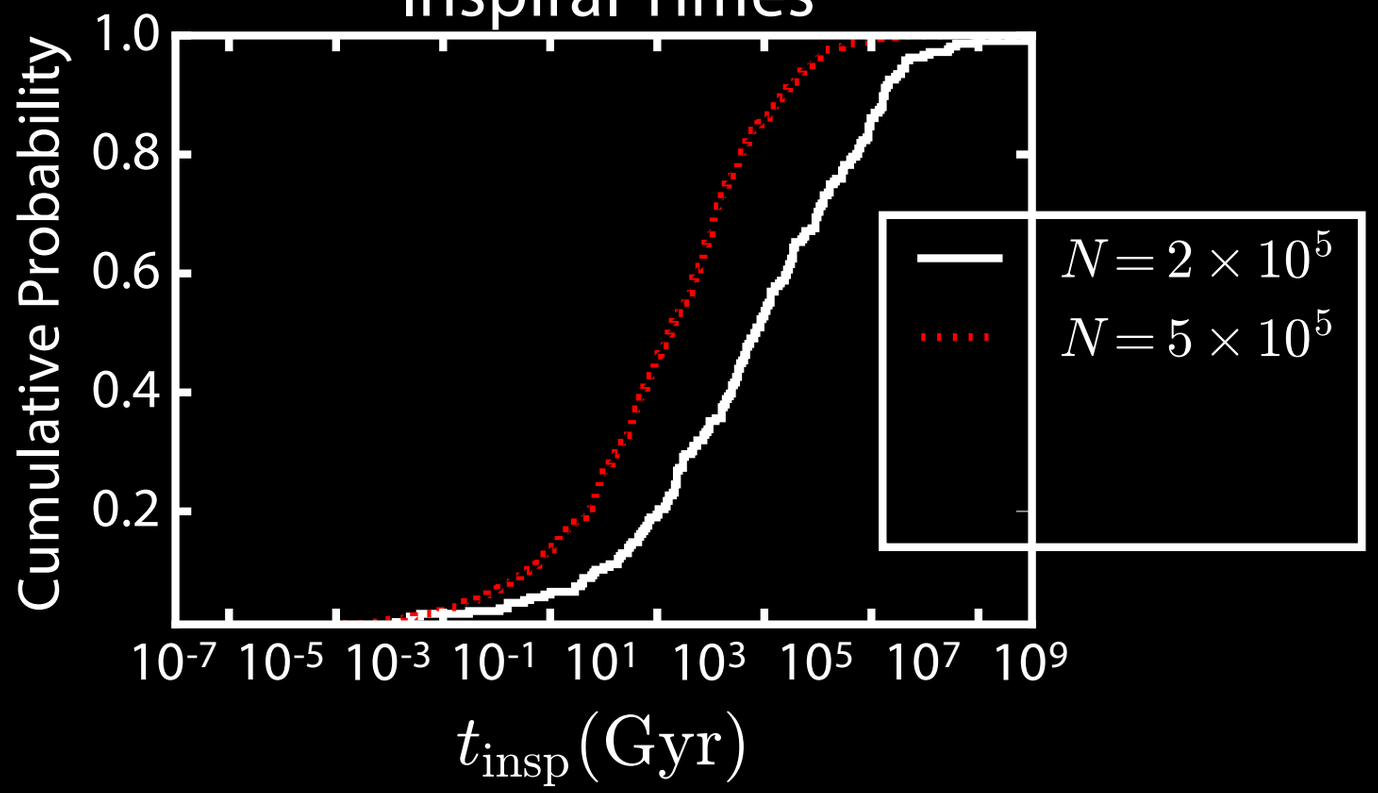
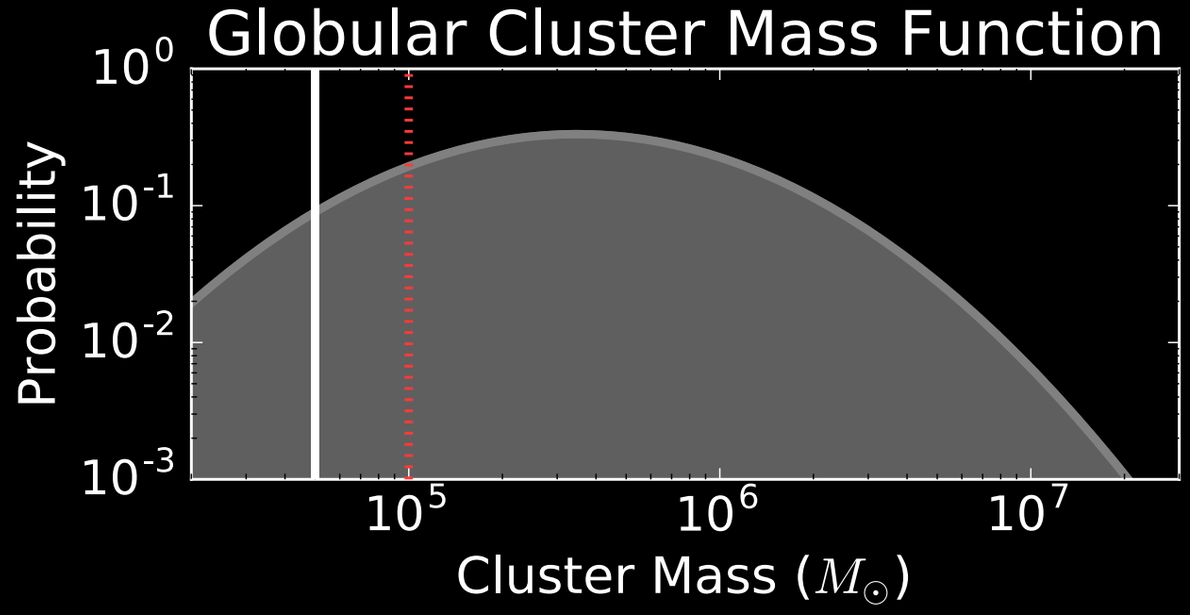
Semi-major Axes



Inspiral Times



Globular Cluster Mass Function



Chaotic Interactions

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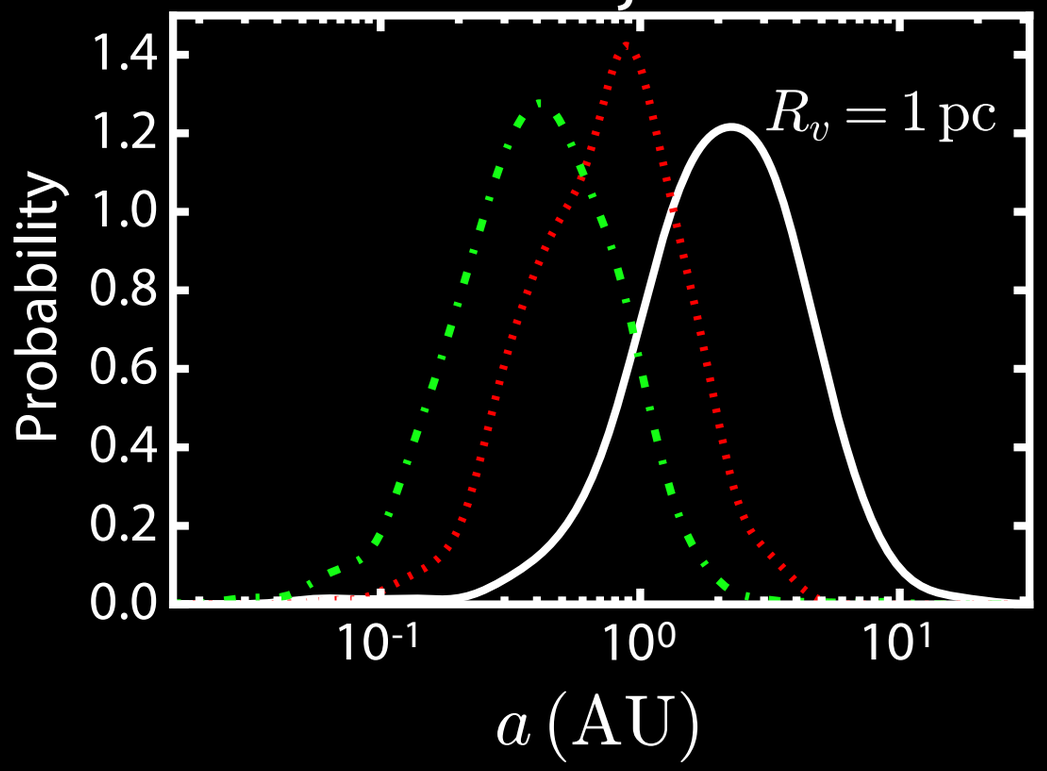
Semi-major Axes



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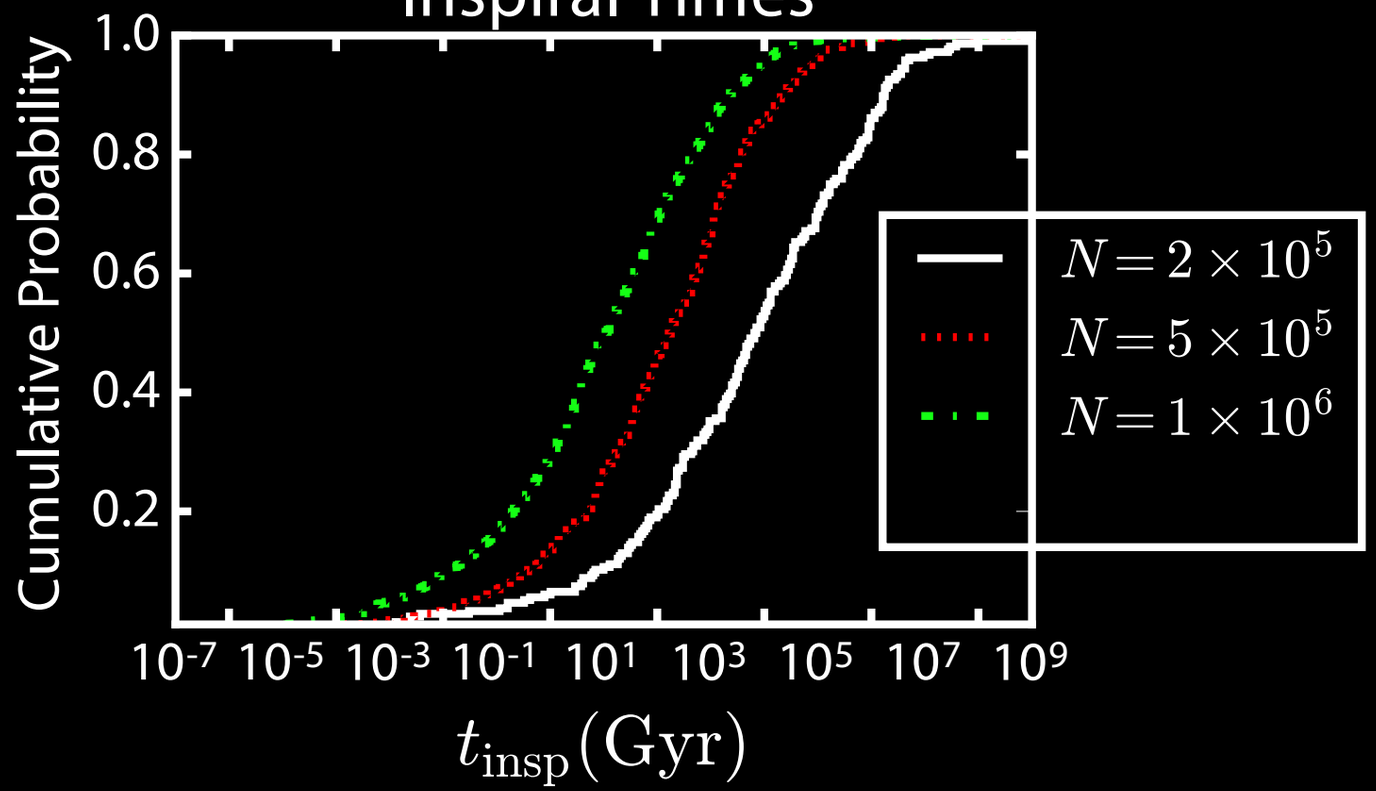
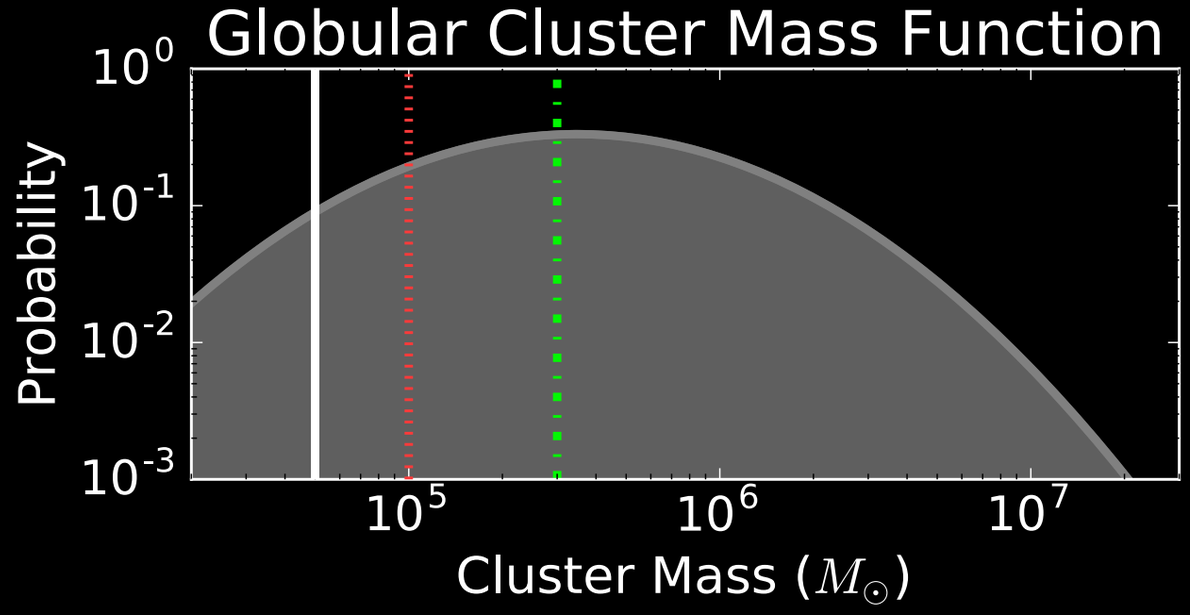


Globular Cluster Mass Function



Chaotic Interactions

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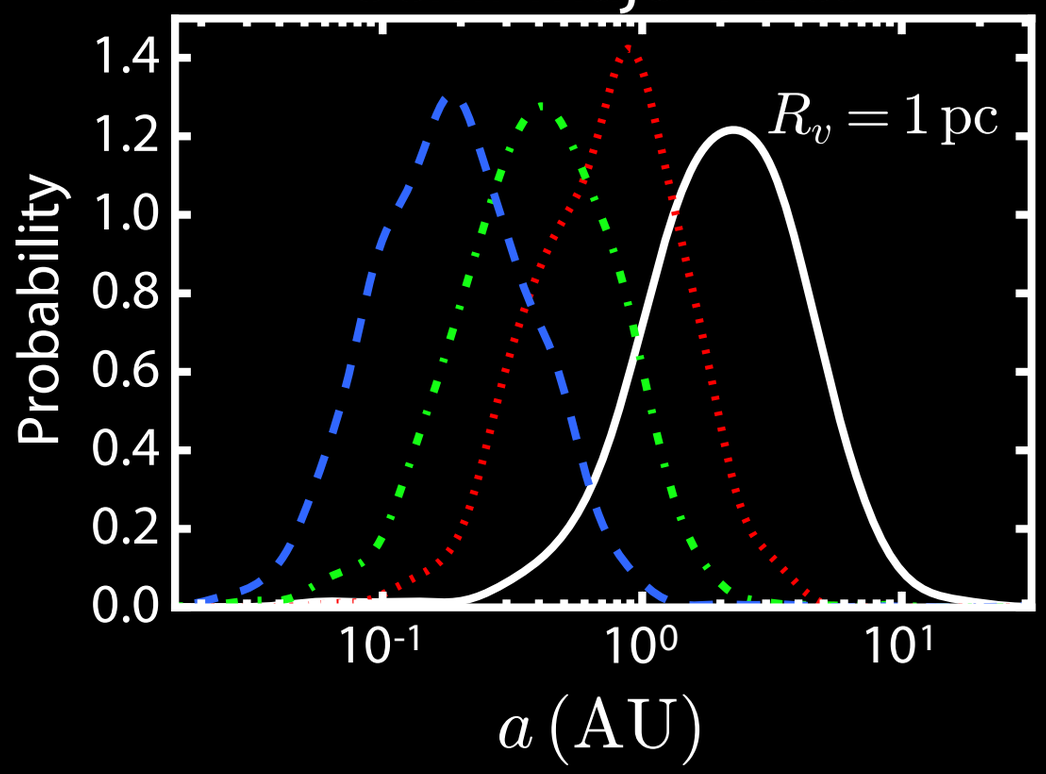

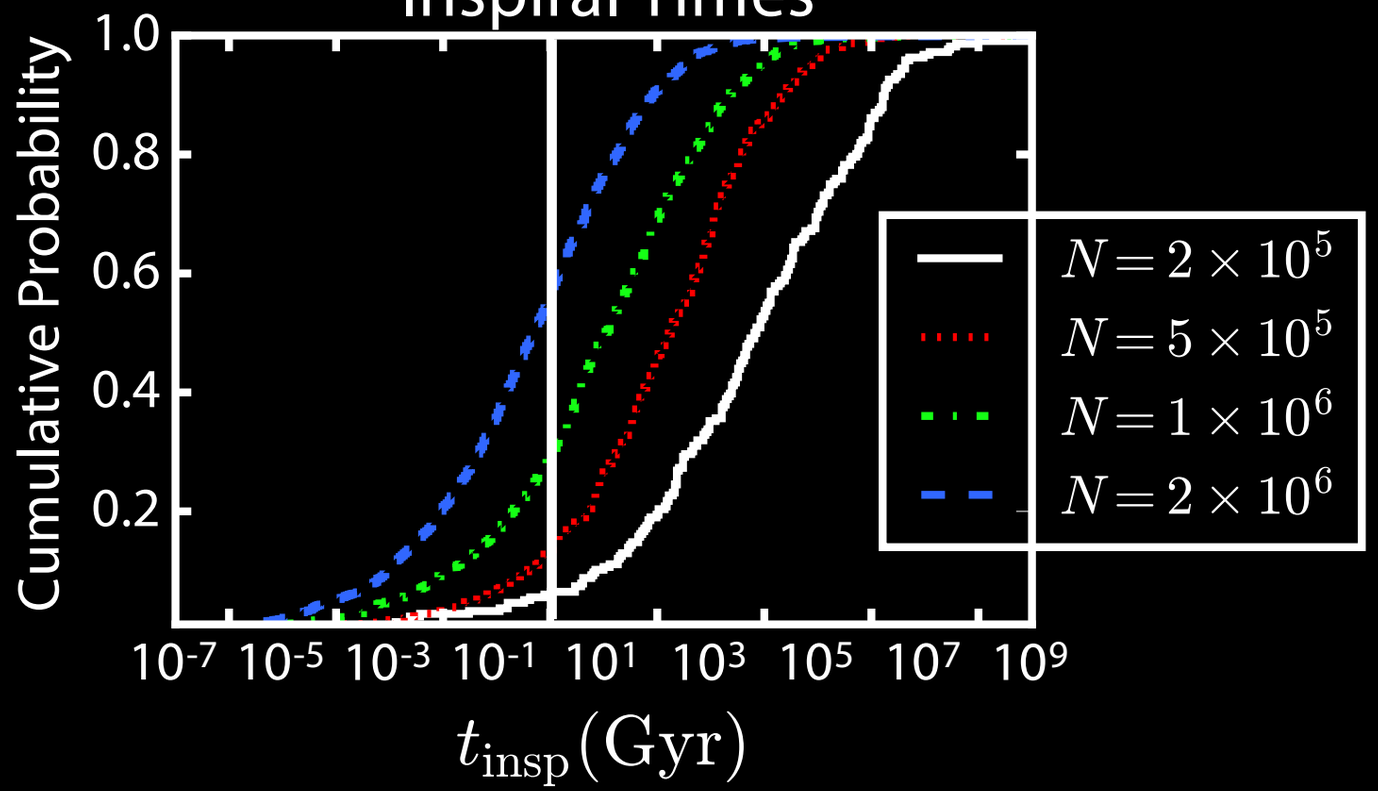

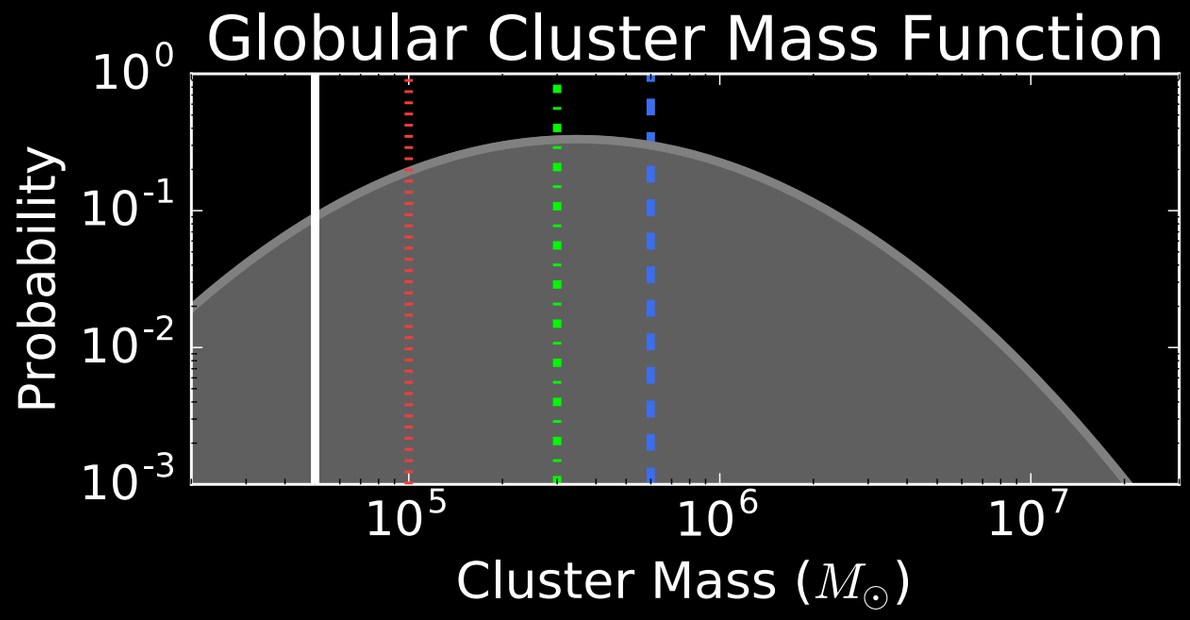

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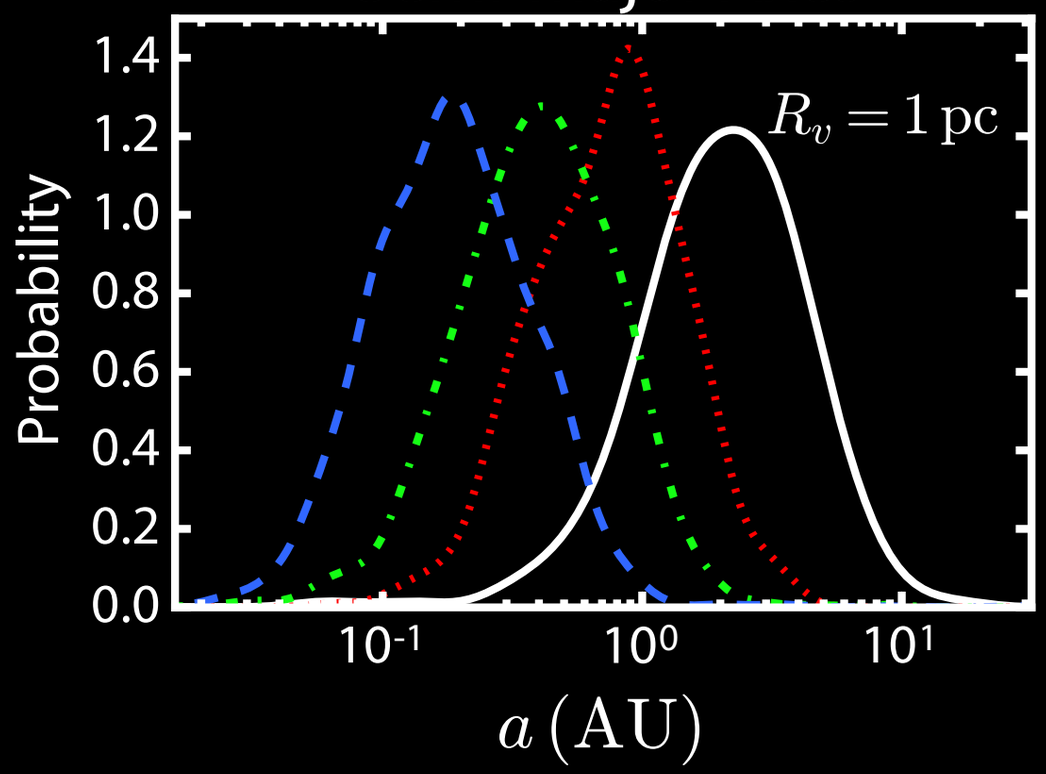
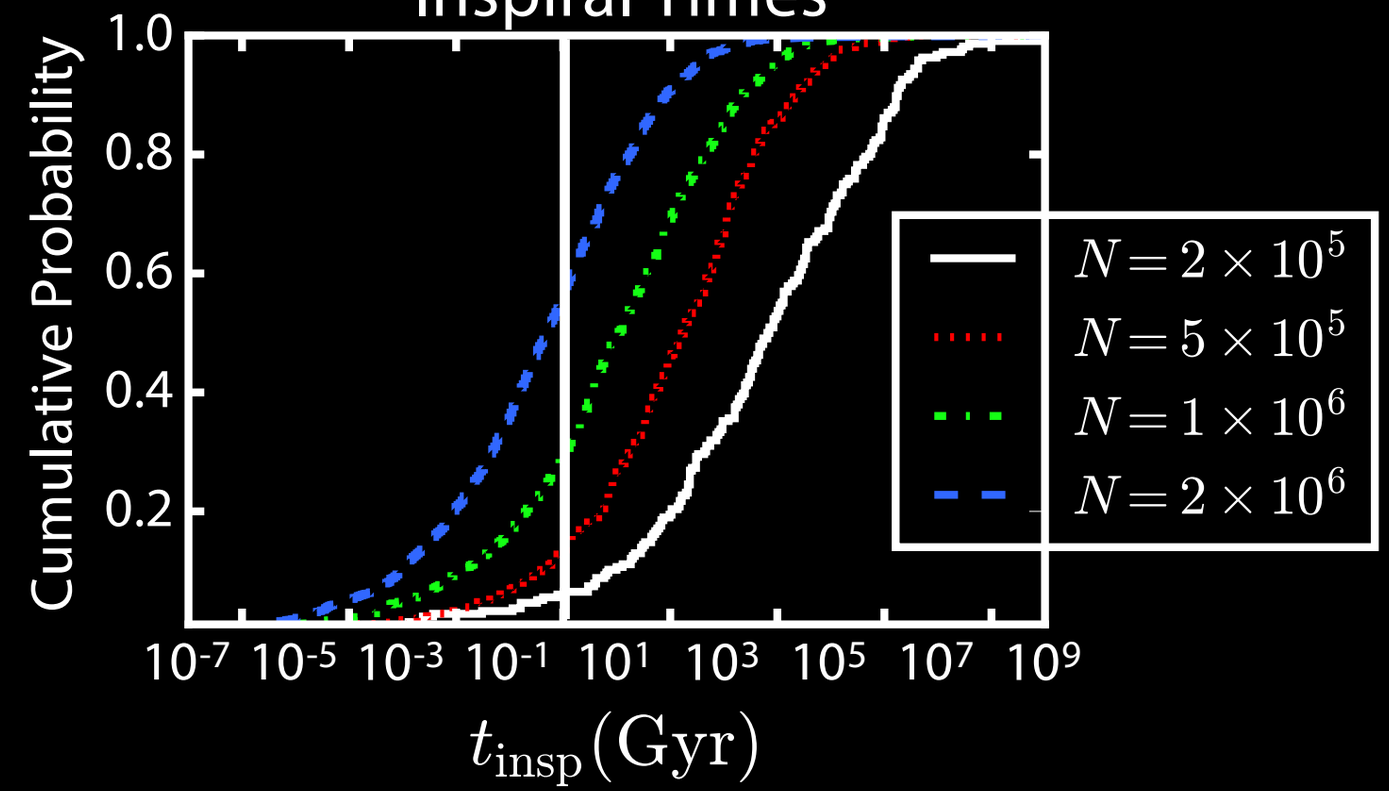
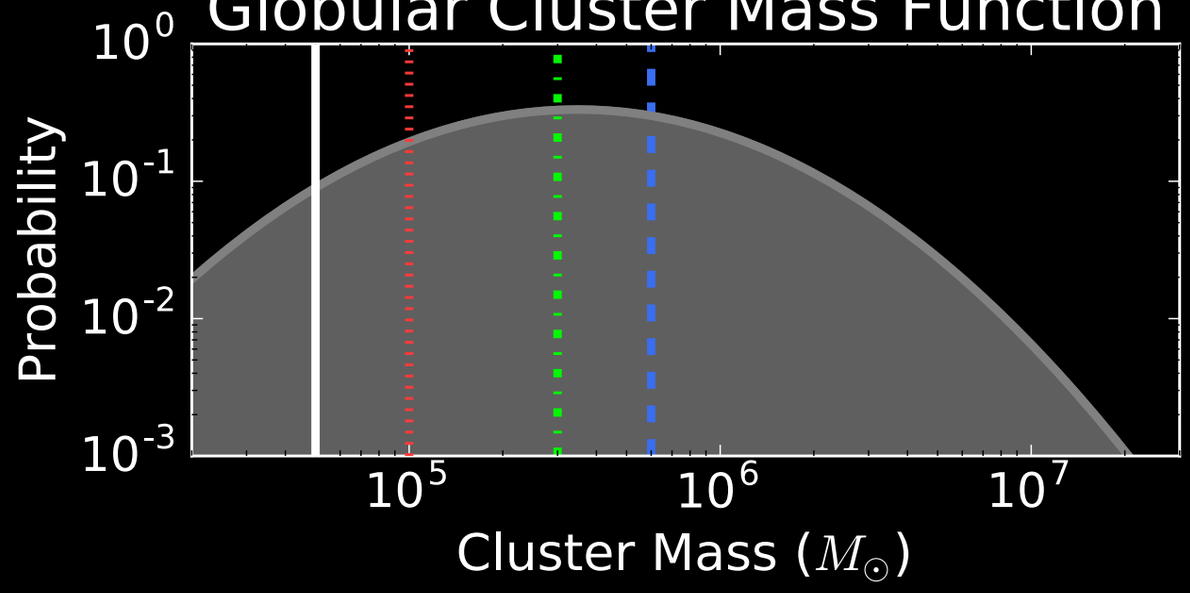




$$P(e)\,de = 2e\,de$$

$$P(a|M_{GC}, R_h, \mu_{\mathrm{bin}})\,da = \frac{1}{a\sigma\sqrt{2\pi}} \times \exp\left[-\frac{\left(\log\frac{\mu_{\mathrm{bin}} R_h}{a M_{GC}} - a^*\right)^2}{2\sigma^2}\right] da$$



Monte Carlo Stellar Dyn.

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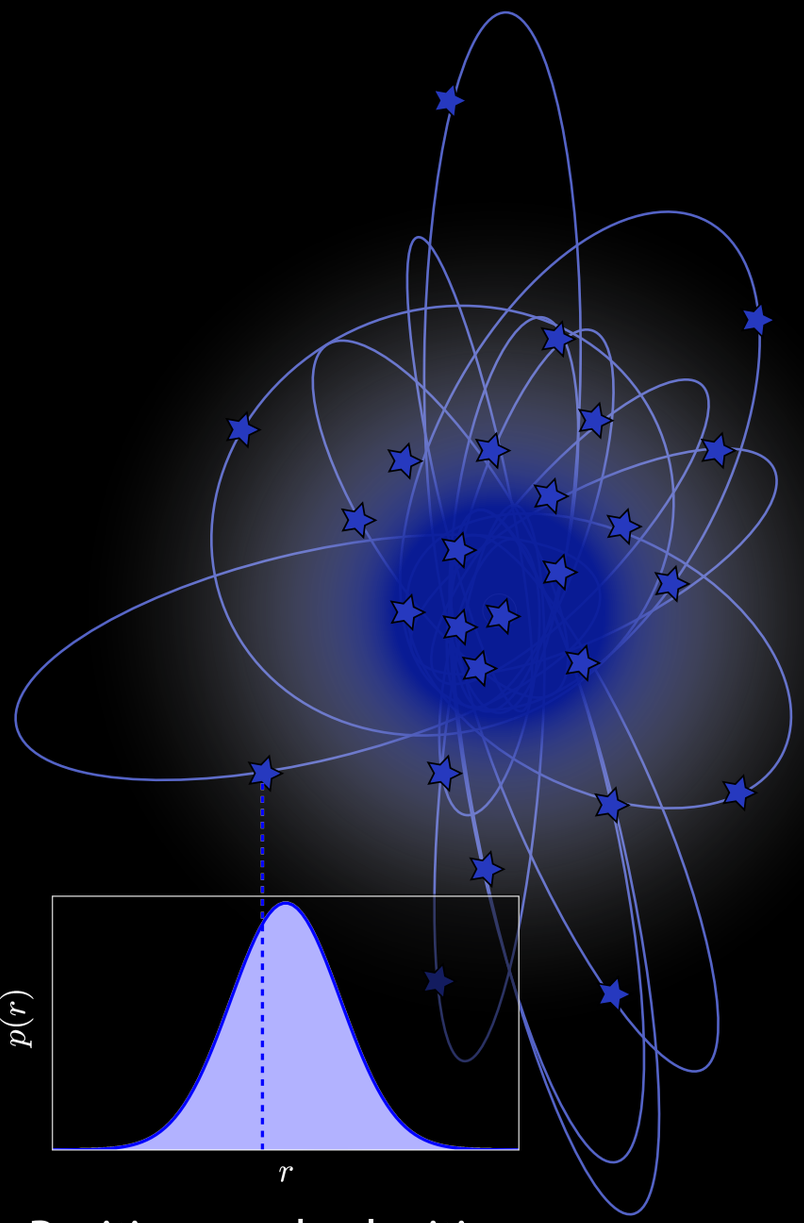
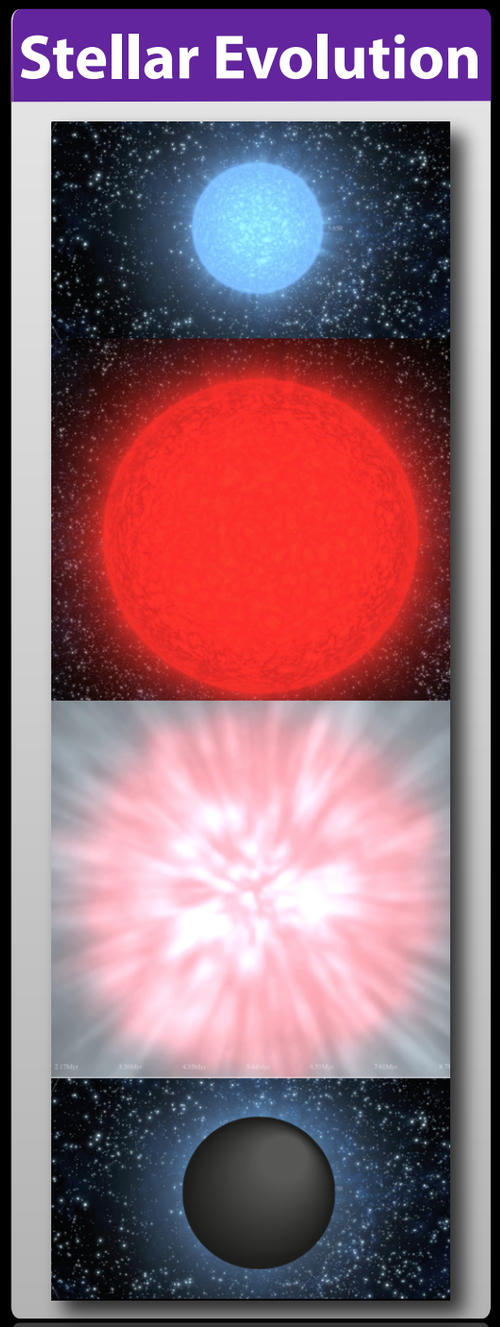


Positions and velocities determined by sampling orbits in a spherical potential



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

Masses from GCs

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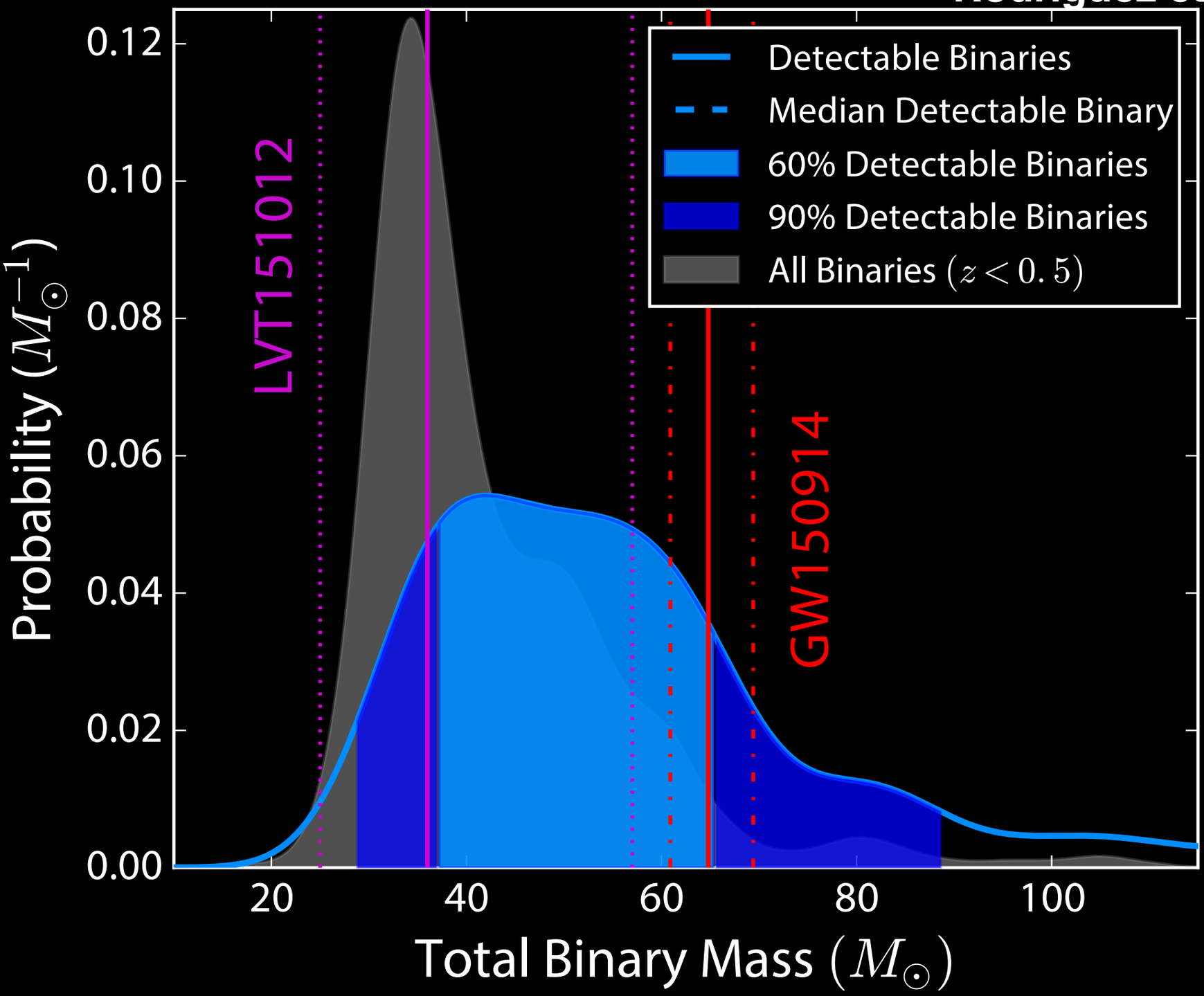
Rodriguez et al. 2016



Merger Rates

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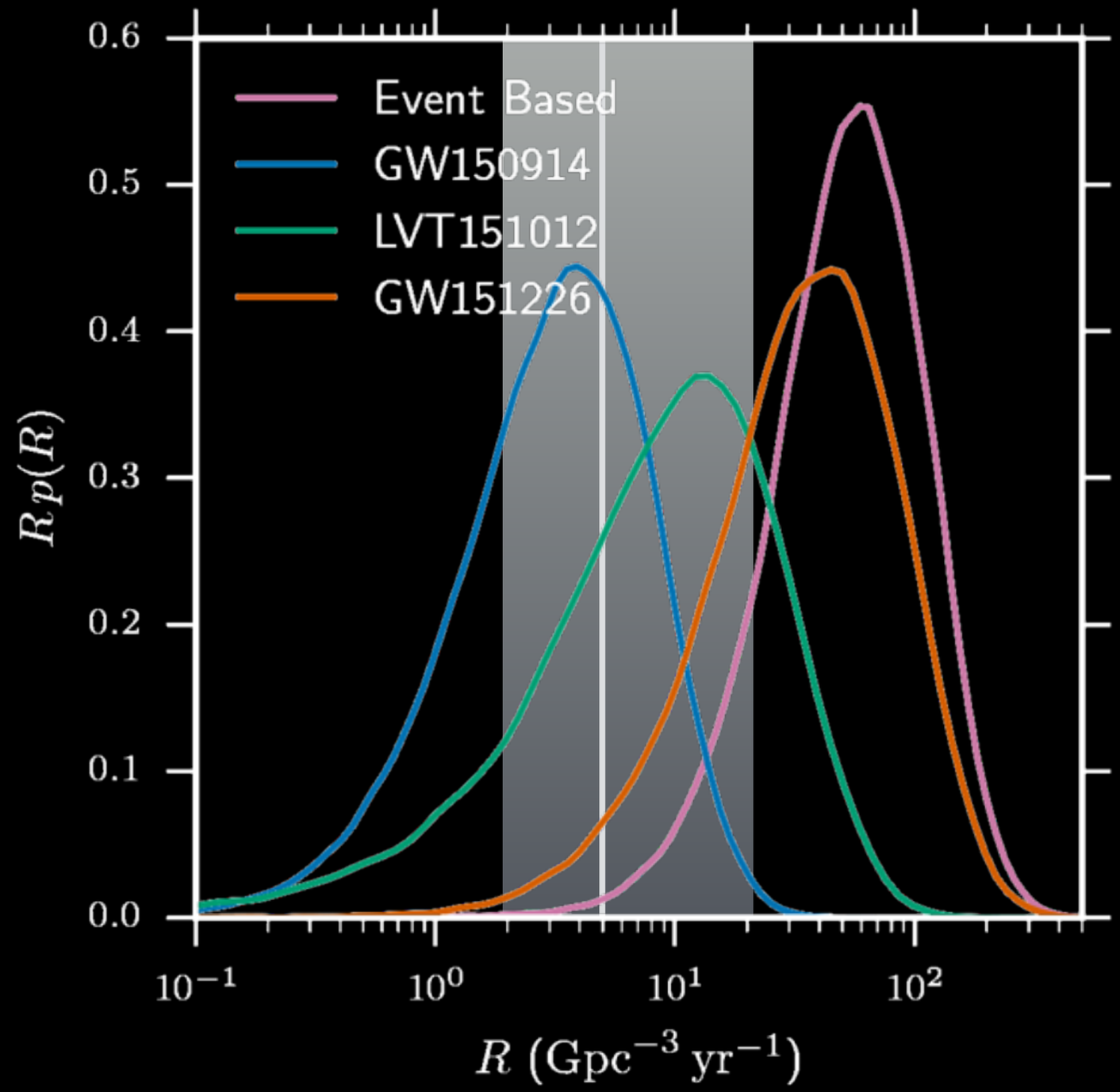
Abbott et al. 2016



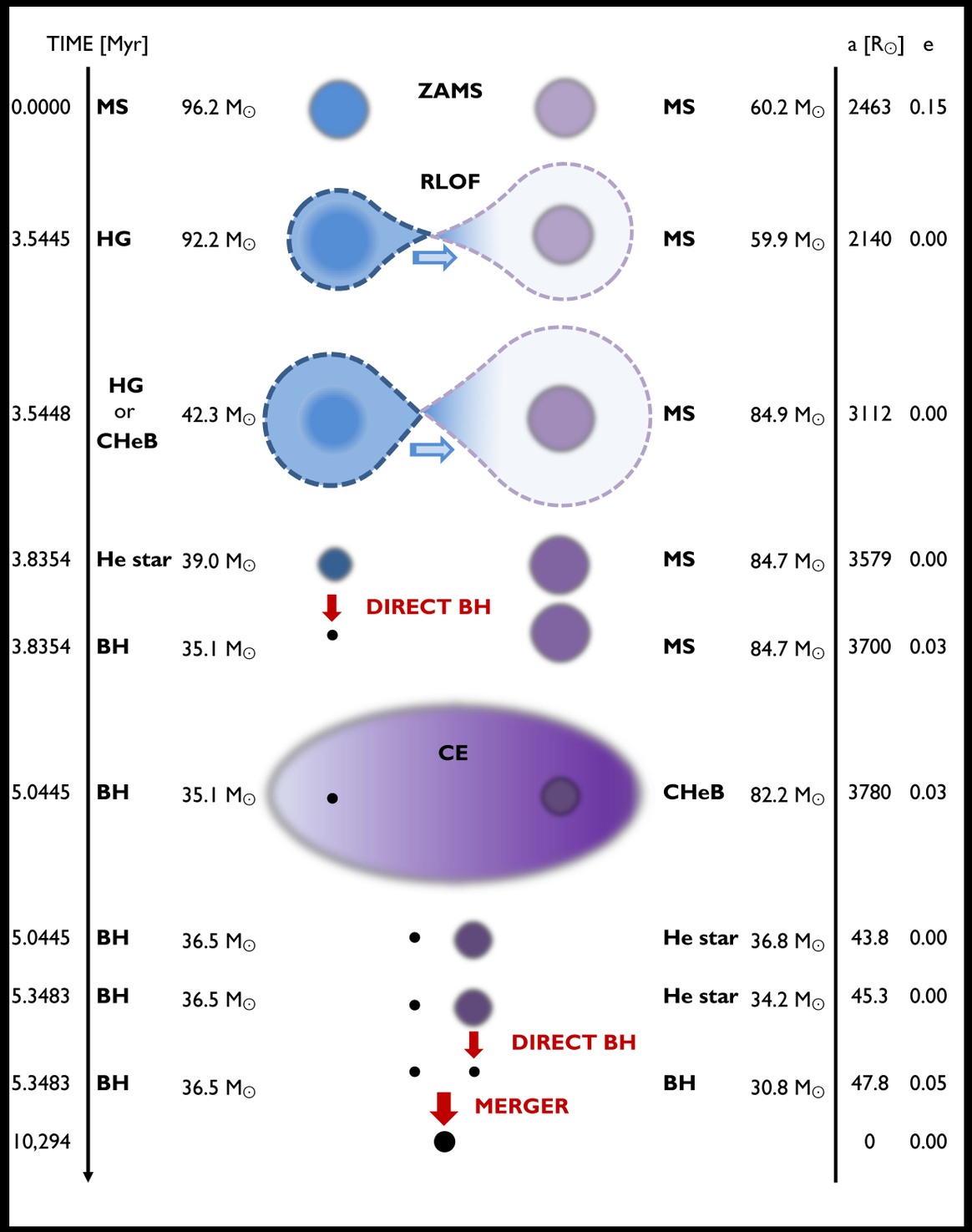
5^{+15}_{-3} $\mathrm{Gpc}^{-3}\mathrm{yr}{-}1$

Rodriguez et al. 2016

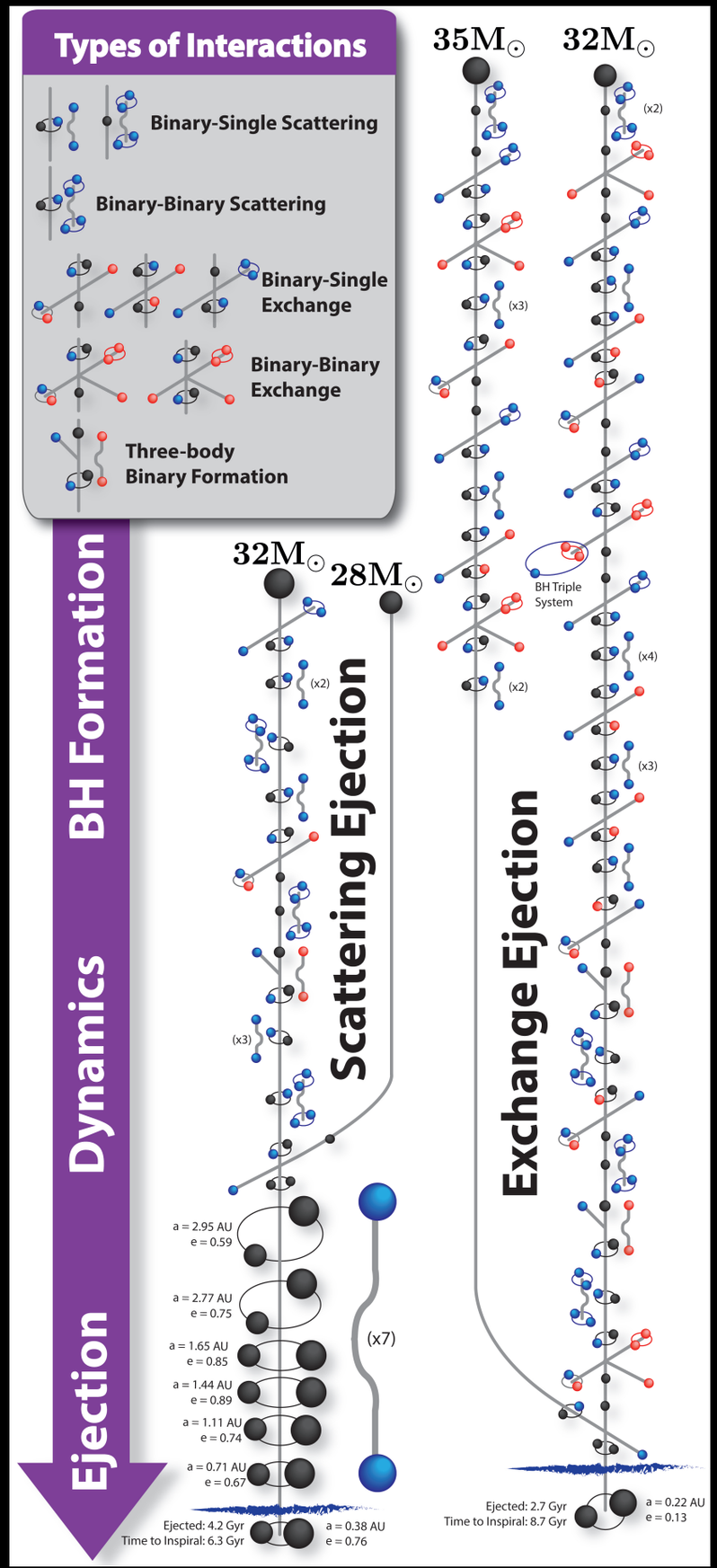
5.4 $\mathrm{Gpc}^{-3}\mathrm{yr}{-}1$

Abbas et al. 2016

Isolated Binary - Belczynski et al., 2016



Cluster - Rodriguez et al., 2016



Field vs Clusters

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- Masses
- Merger Rates
- Eccentricity
- Spins

Eccentricities

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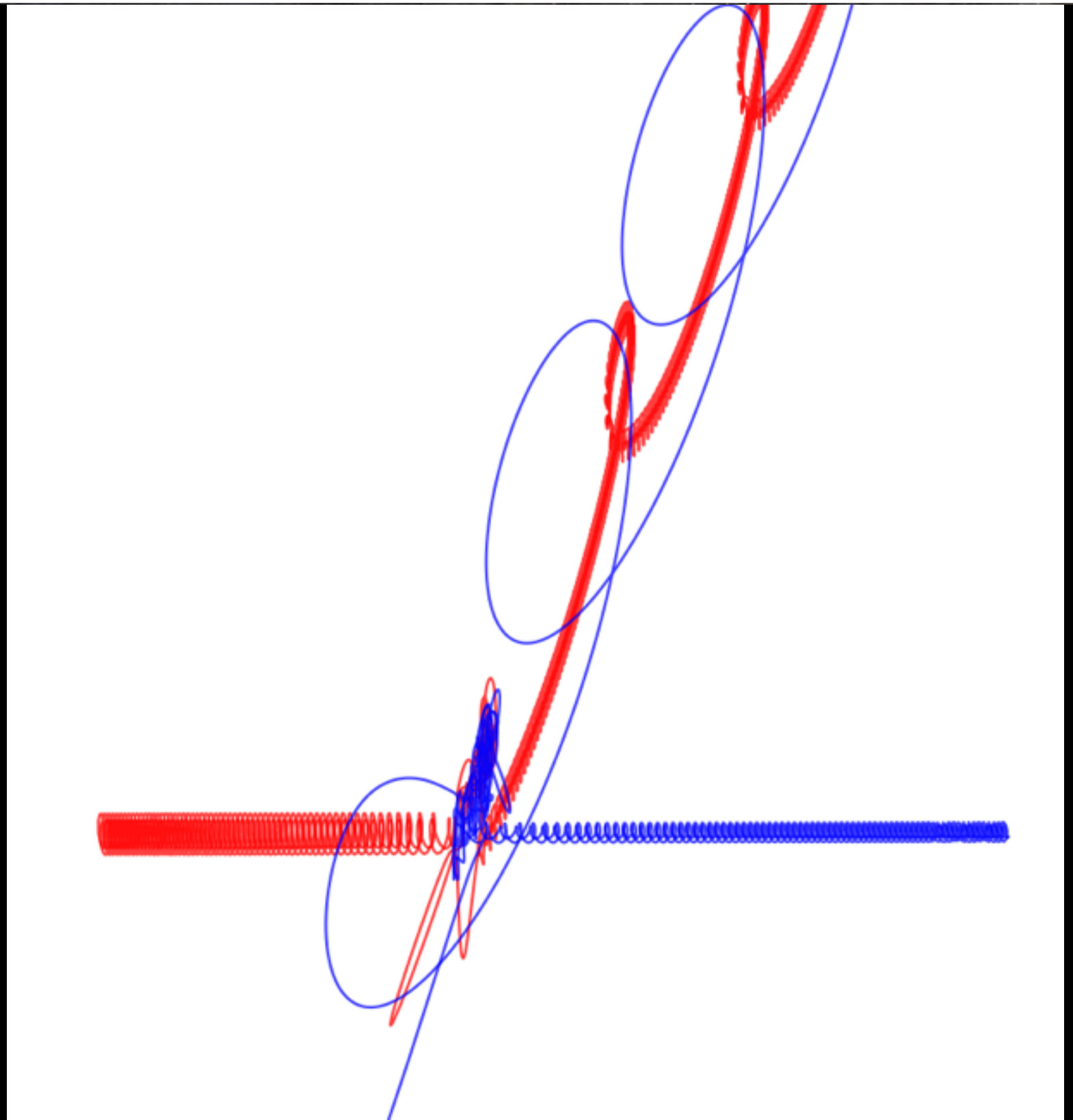

Eccentricities

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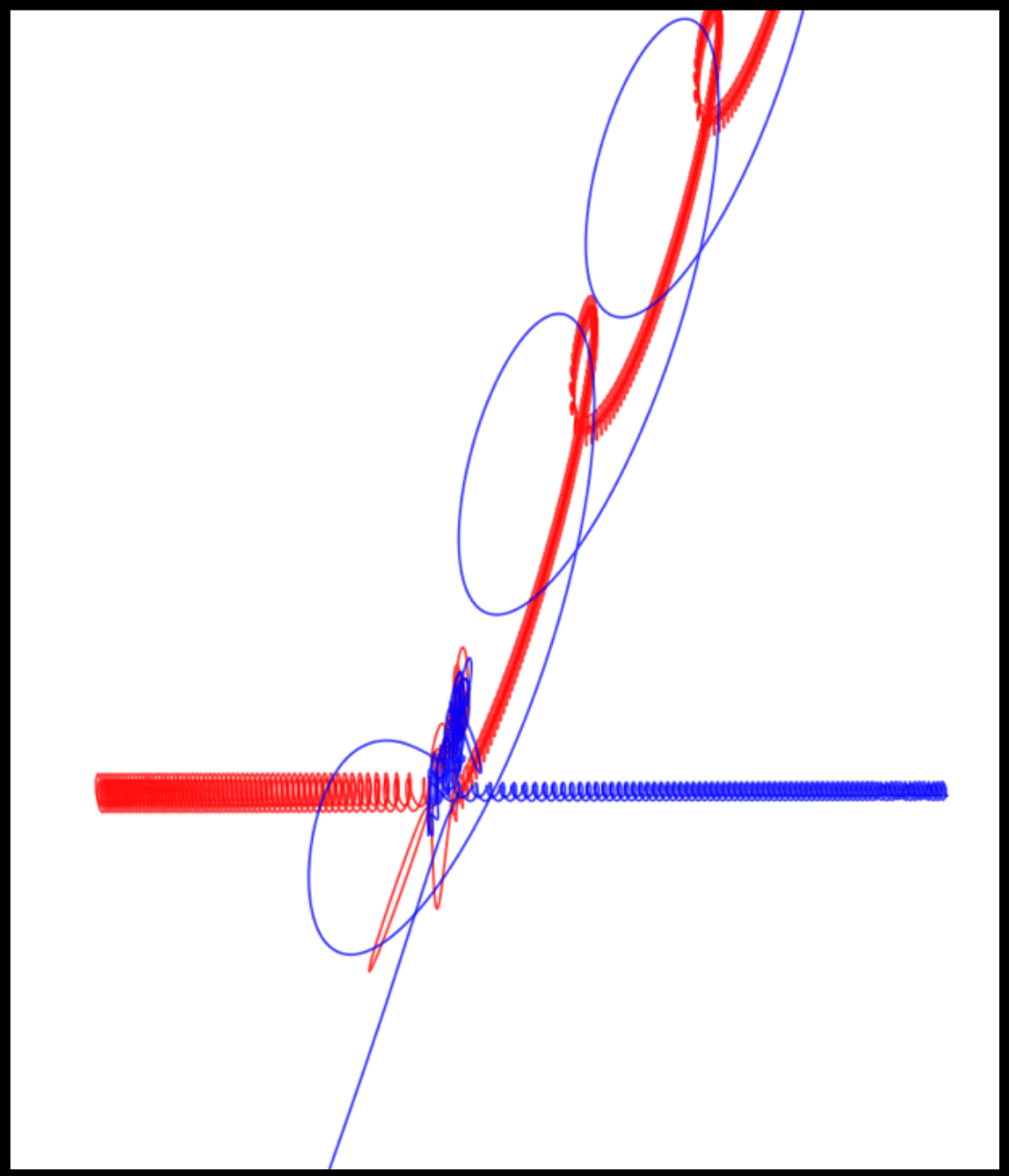

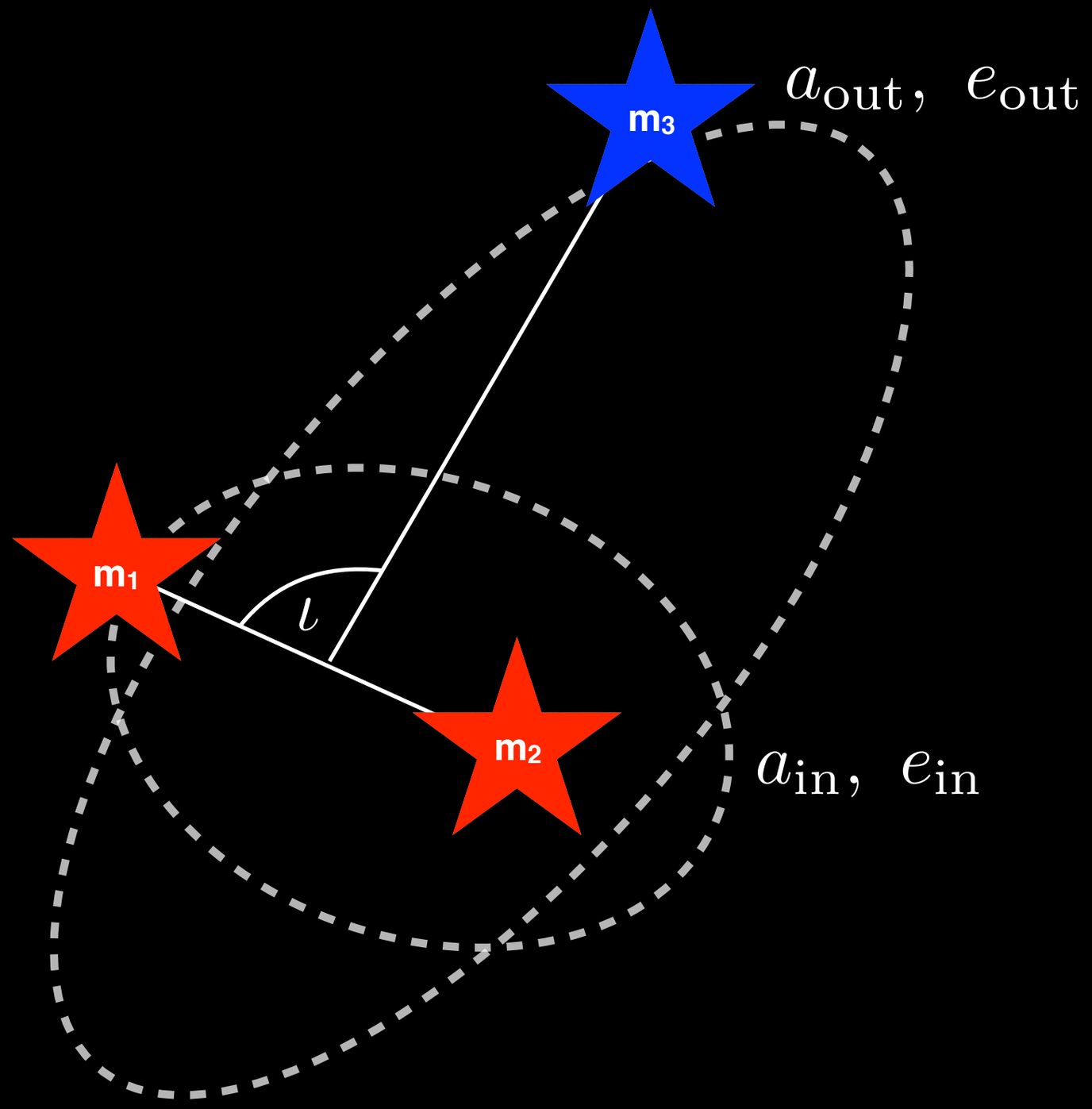

Eccentricities

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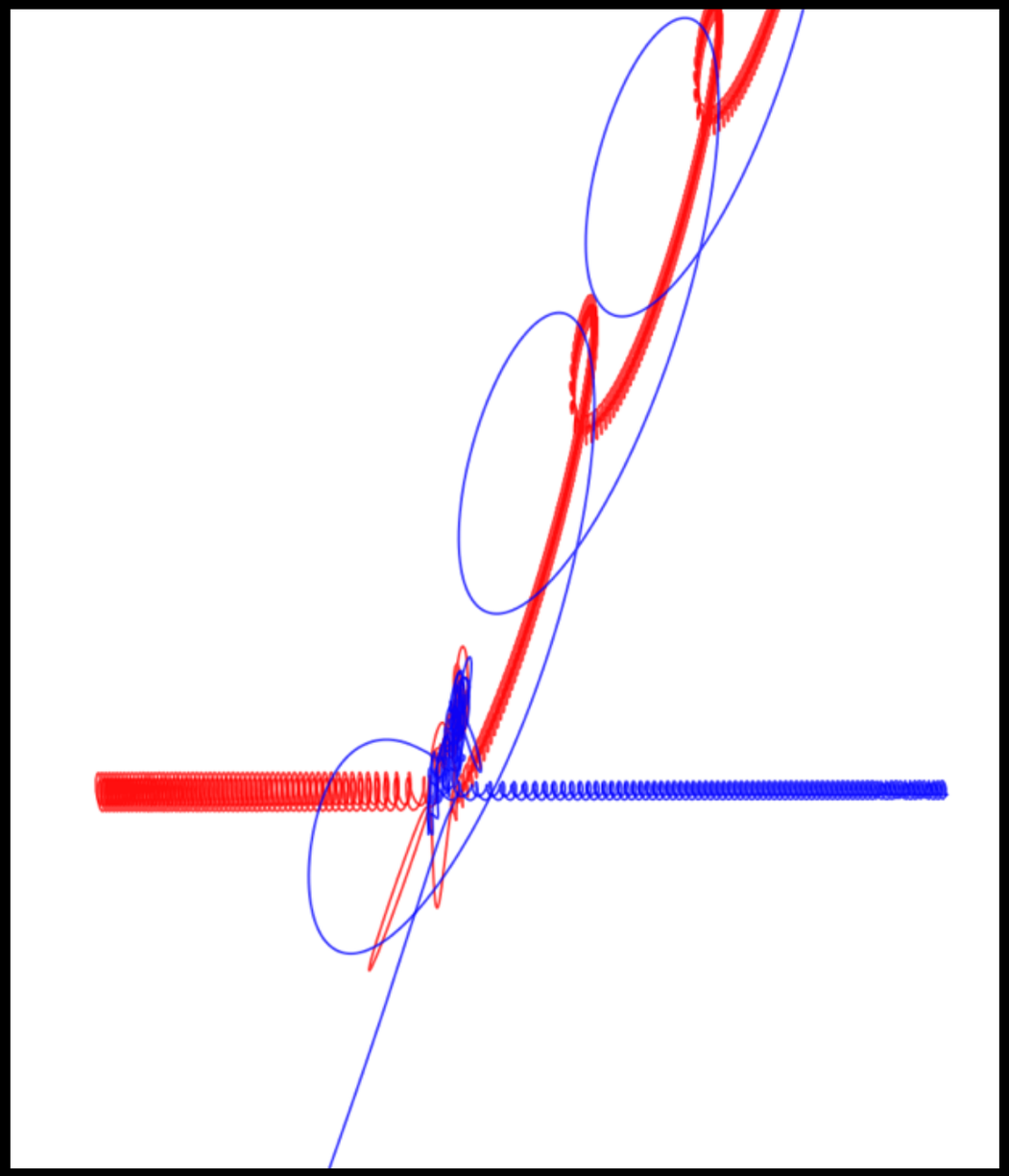

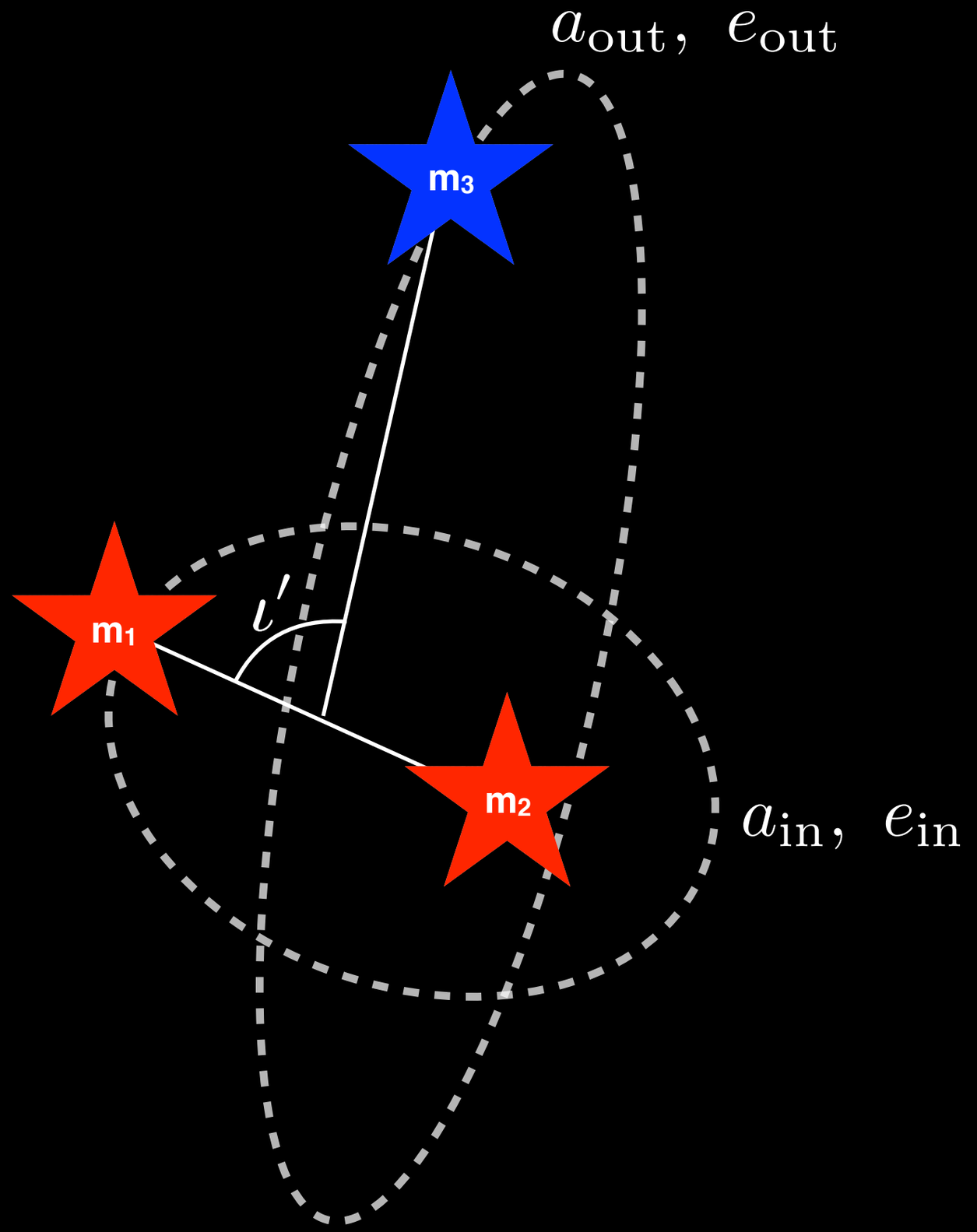

Eccentricities

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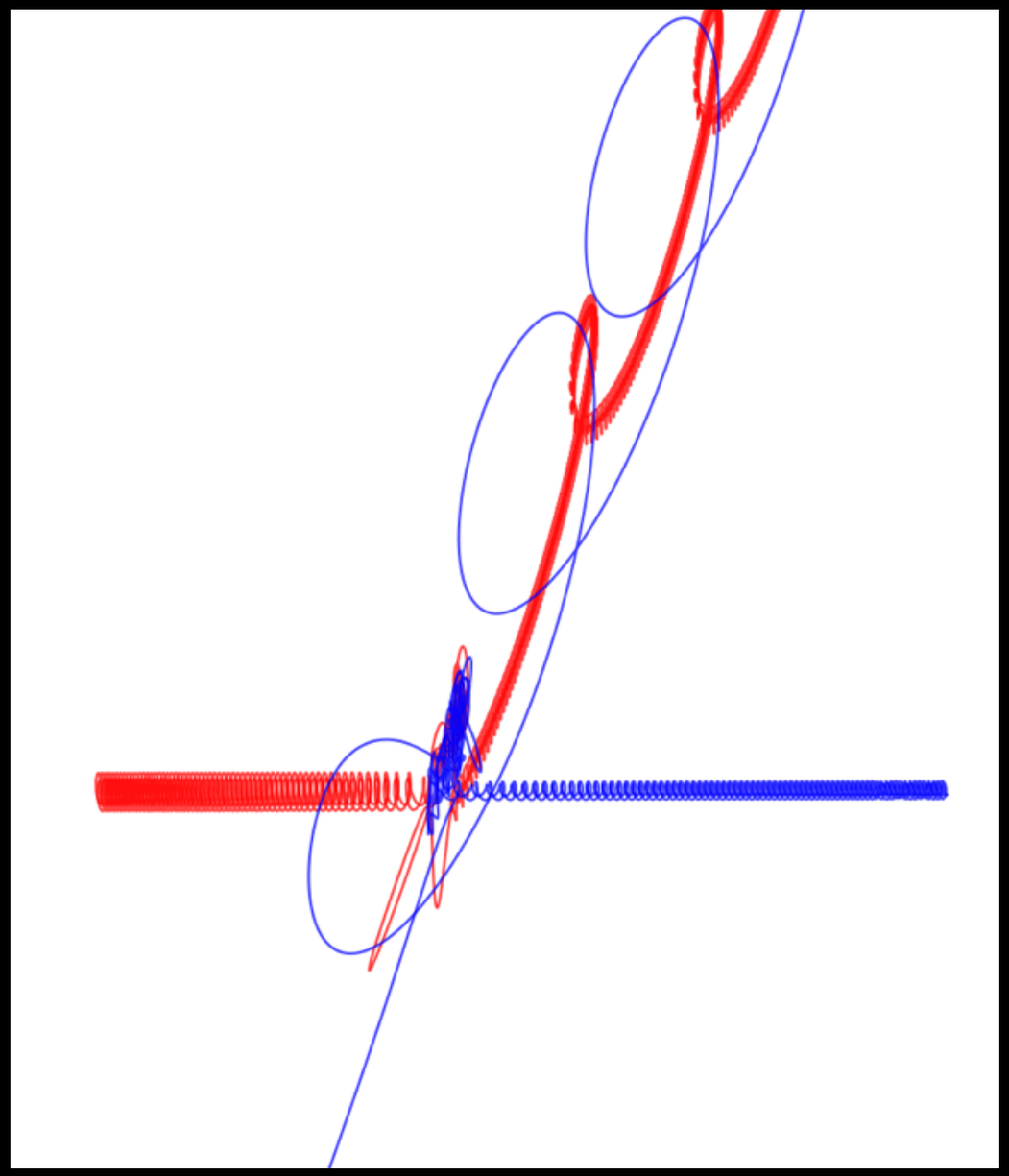

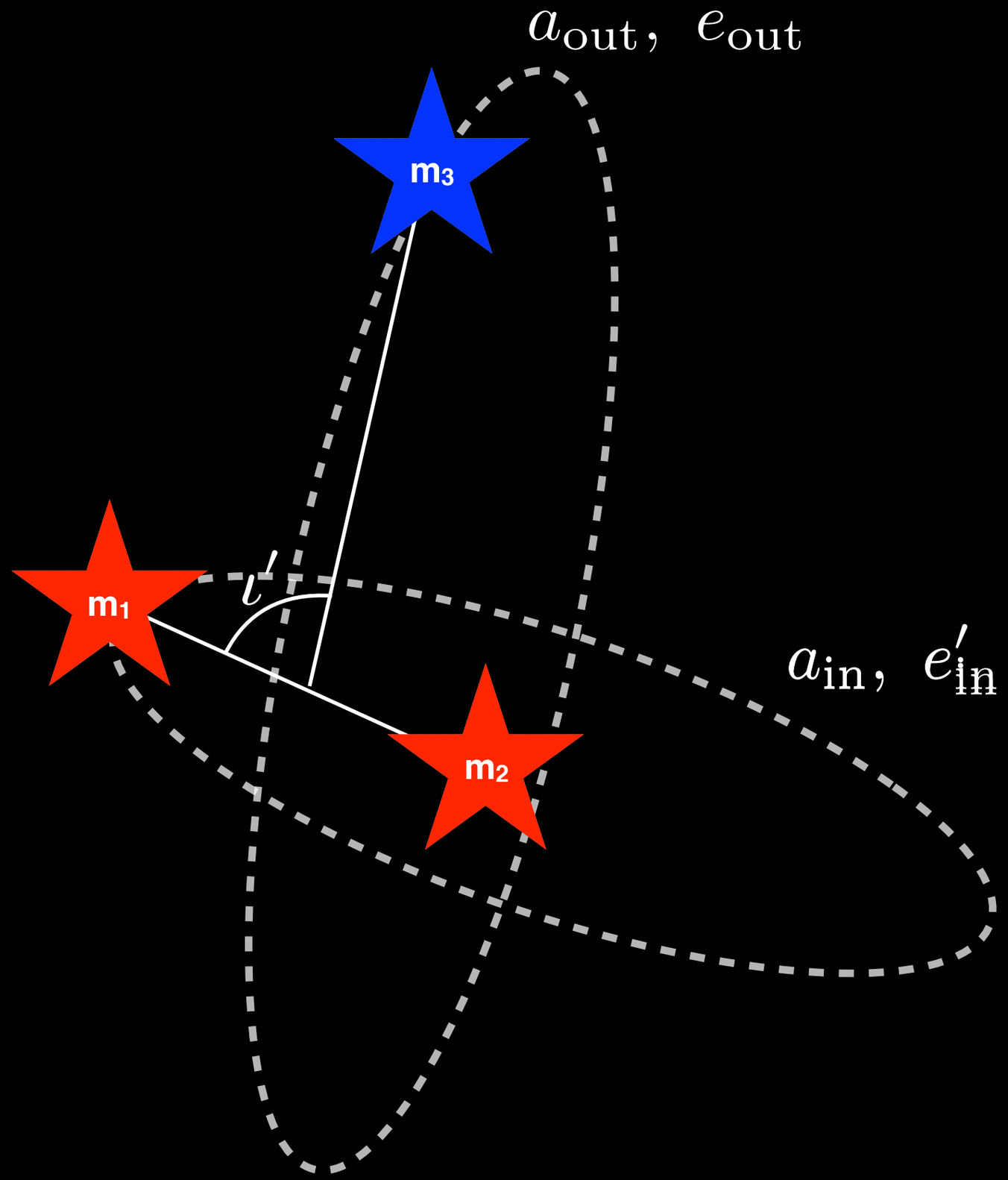

Eccentricities

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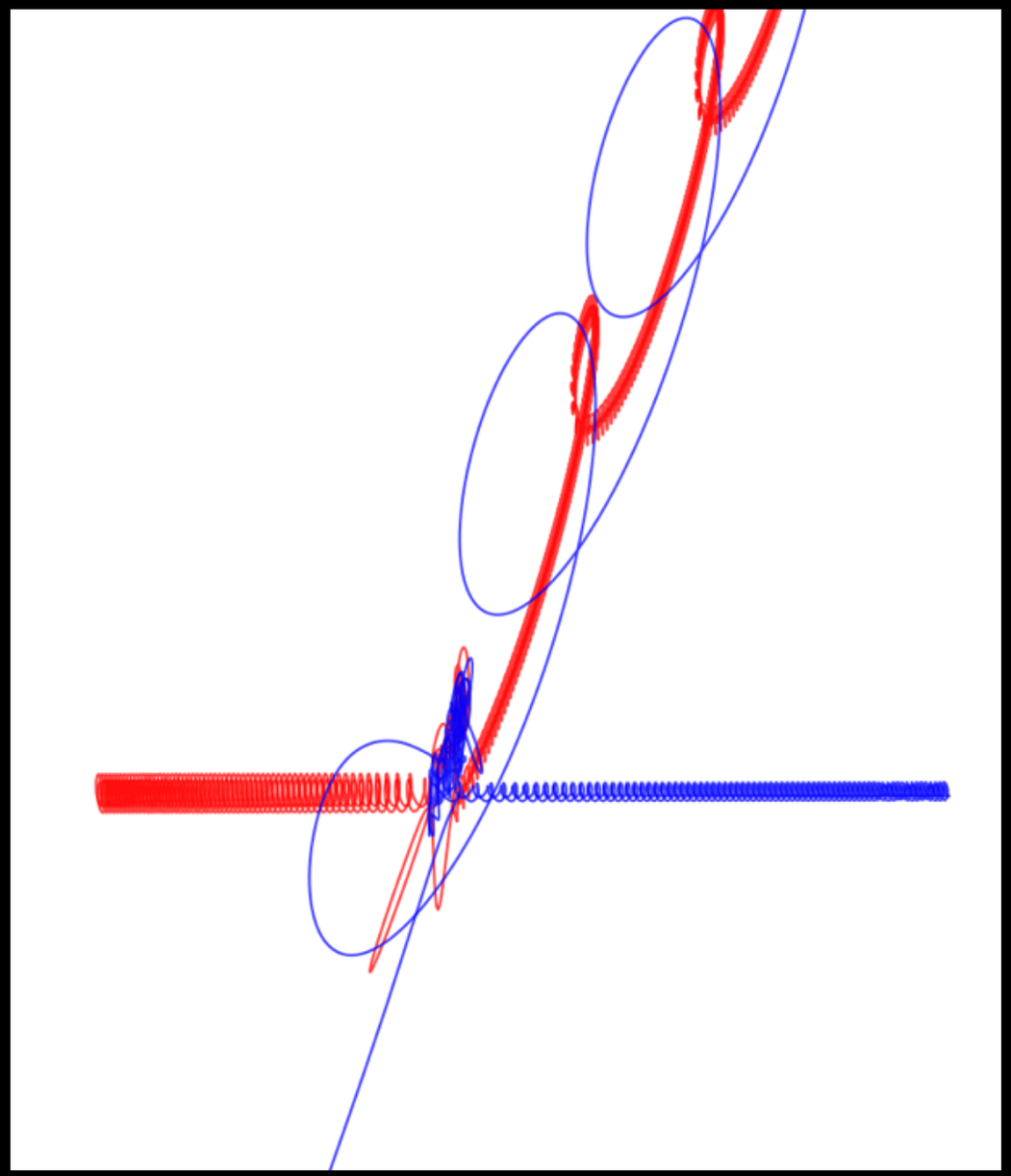

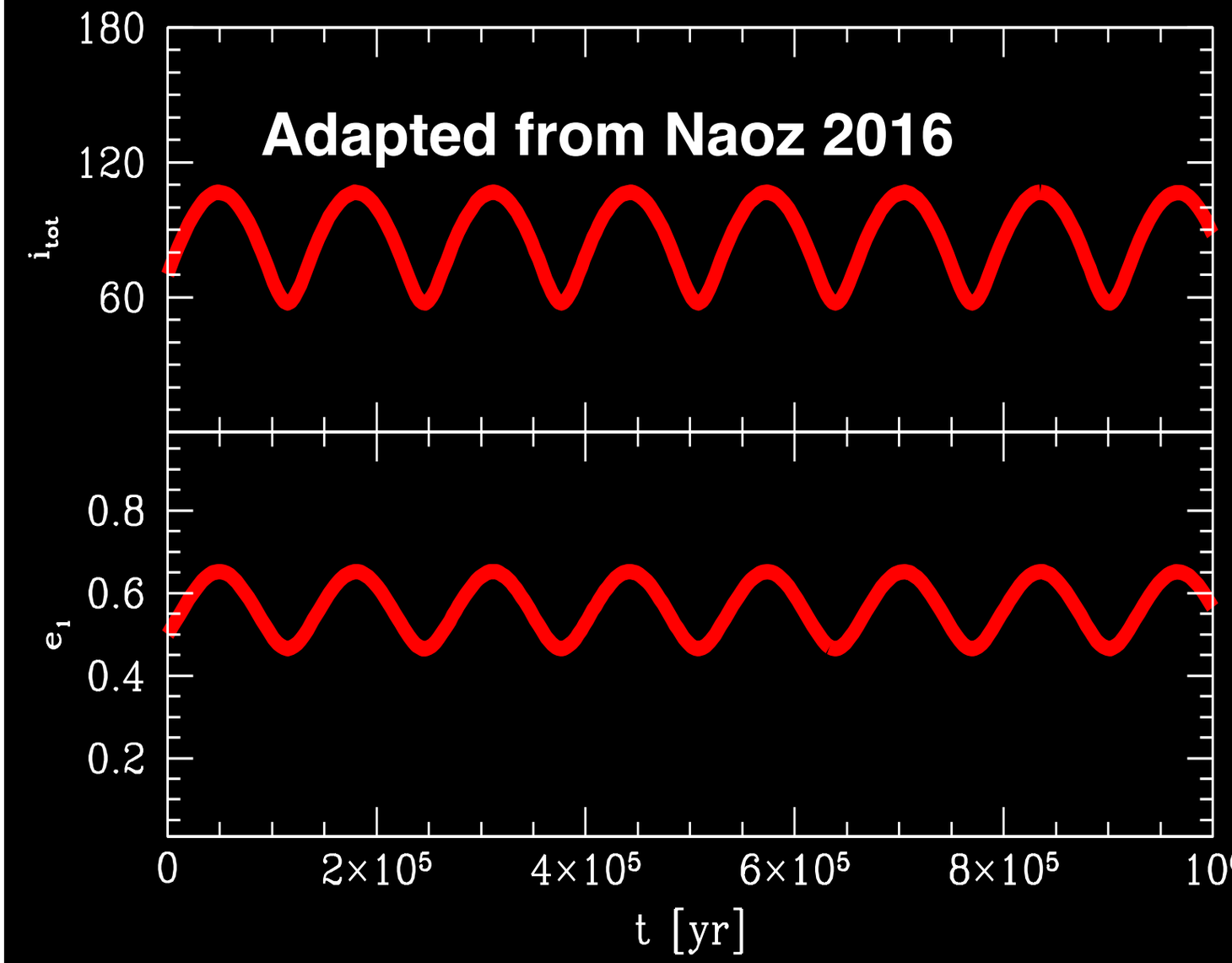

Field vs Clusters

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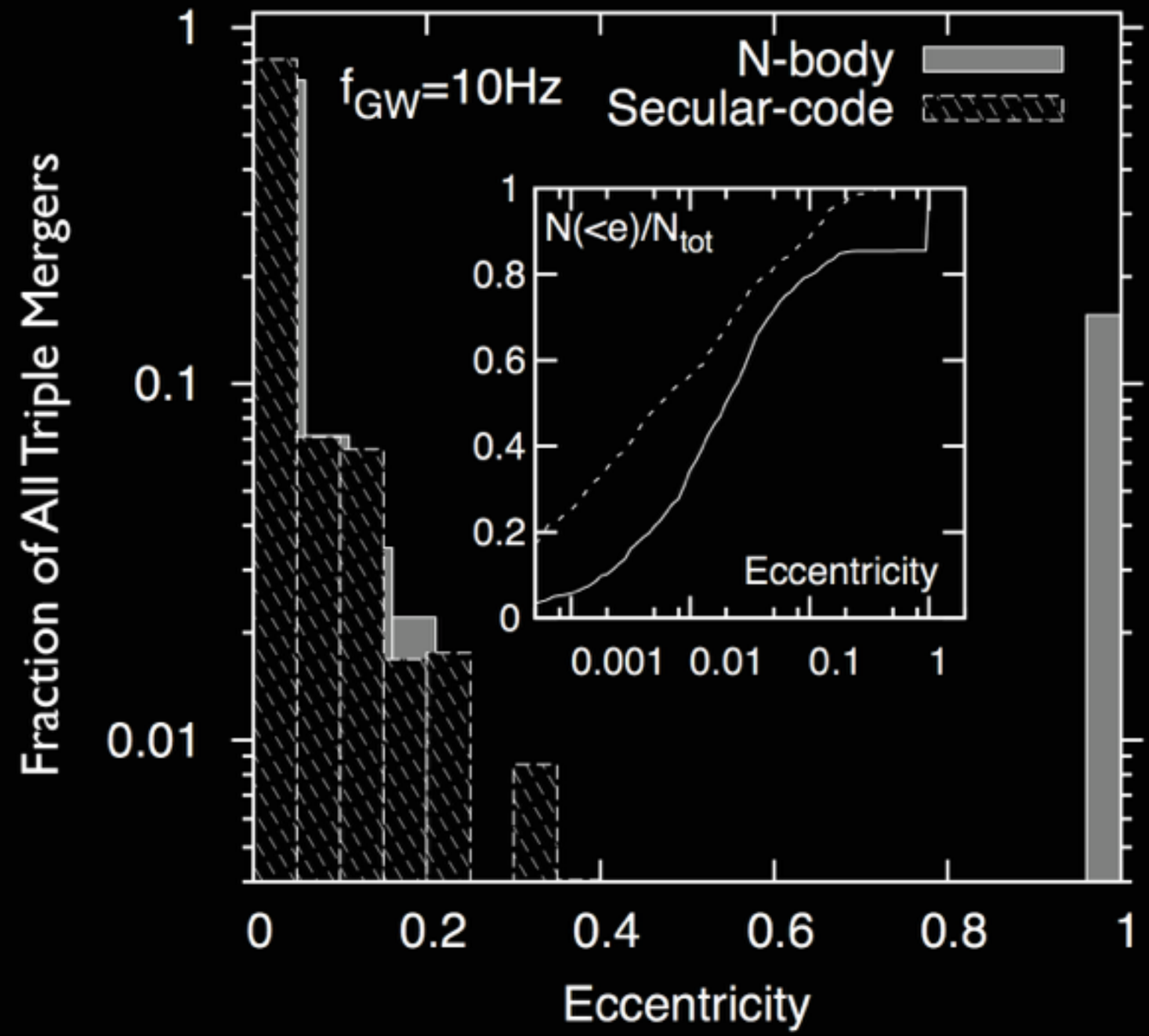
- Masses
- Merger Rates
- Eccentricity
- Spins

Antonini,Chatterjee,Rodriguez et al. 2016



Field vs Clusters

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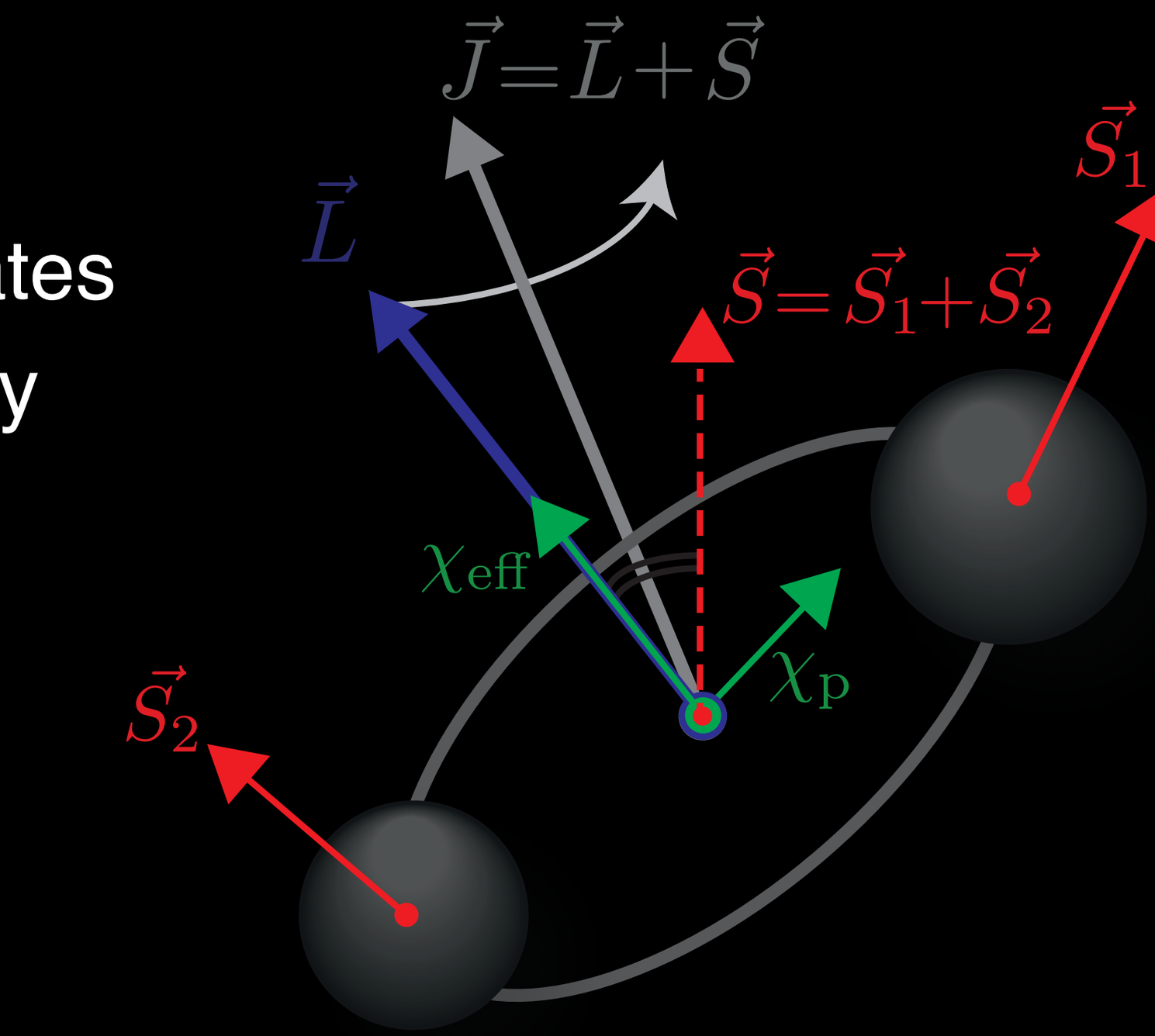
- Masses
- Merger Rates
- Eccentricity
- Spins



Spins

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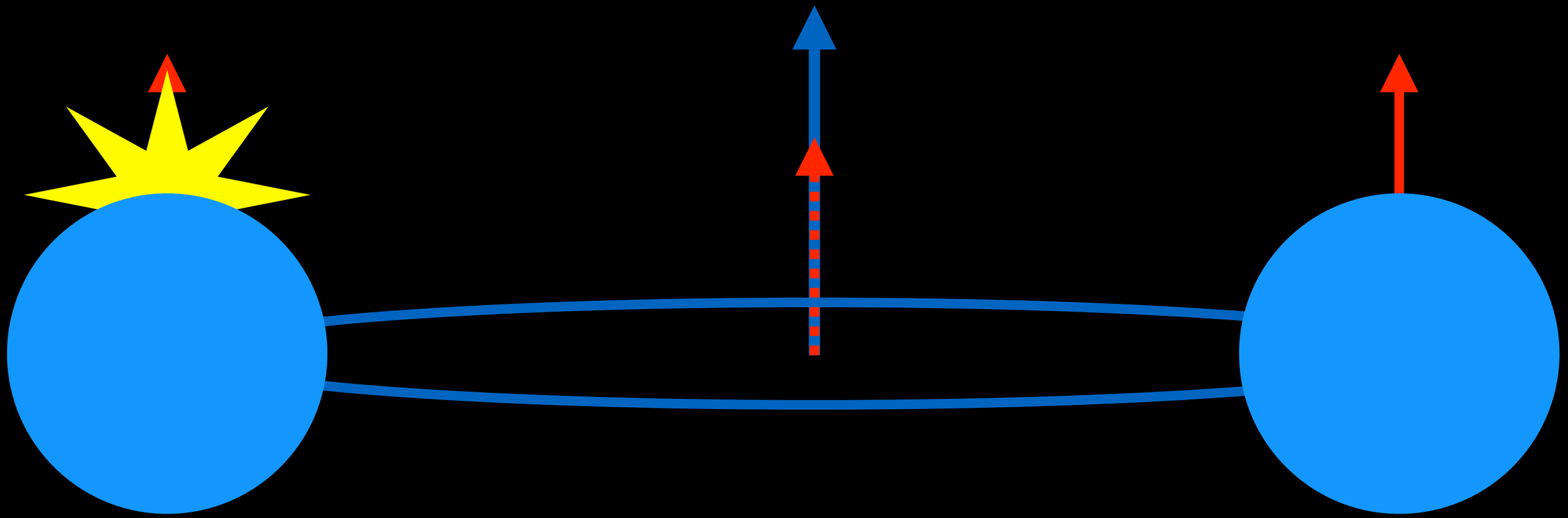

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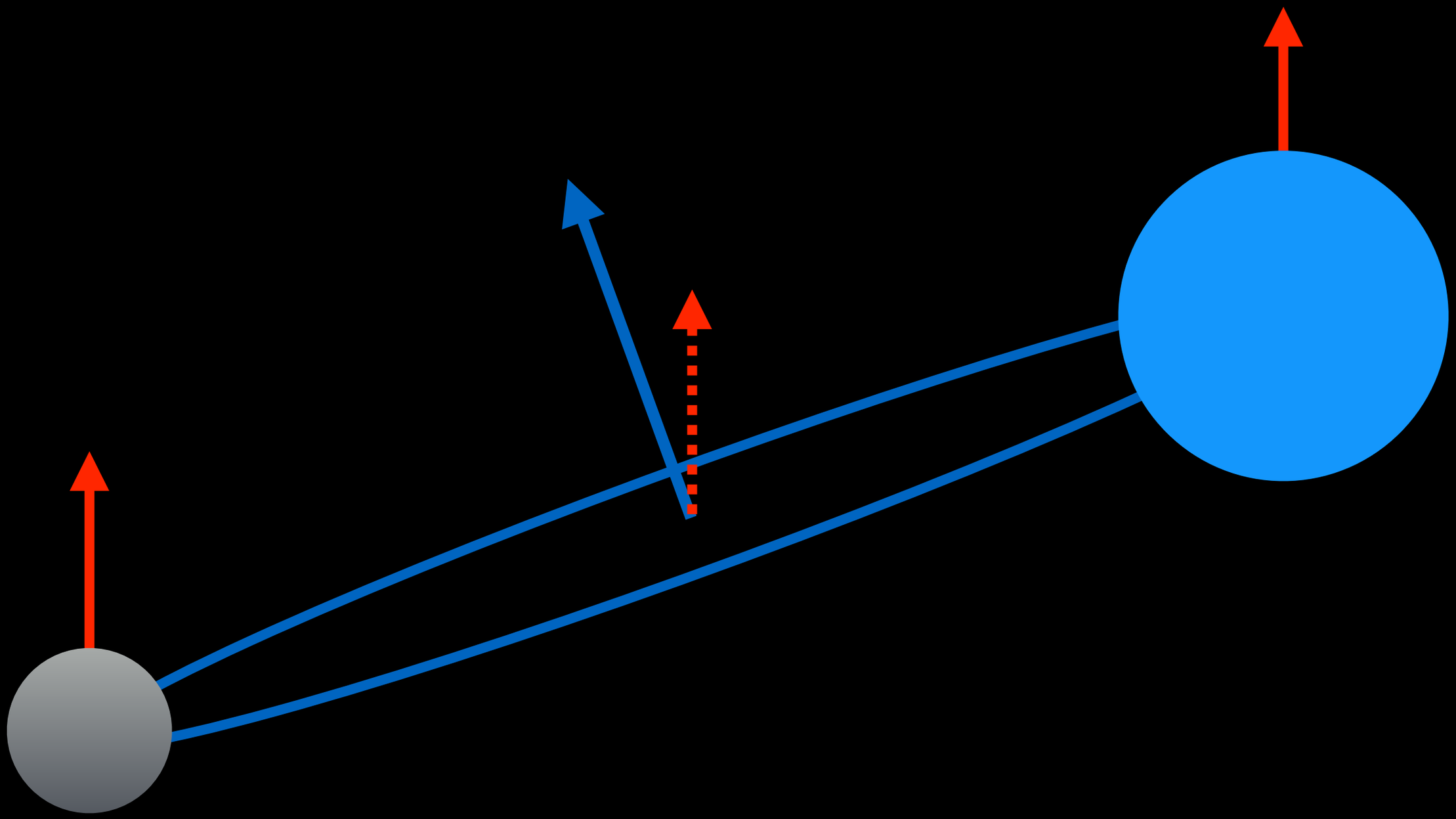

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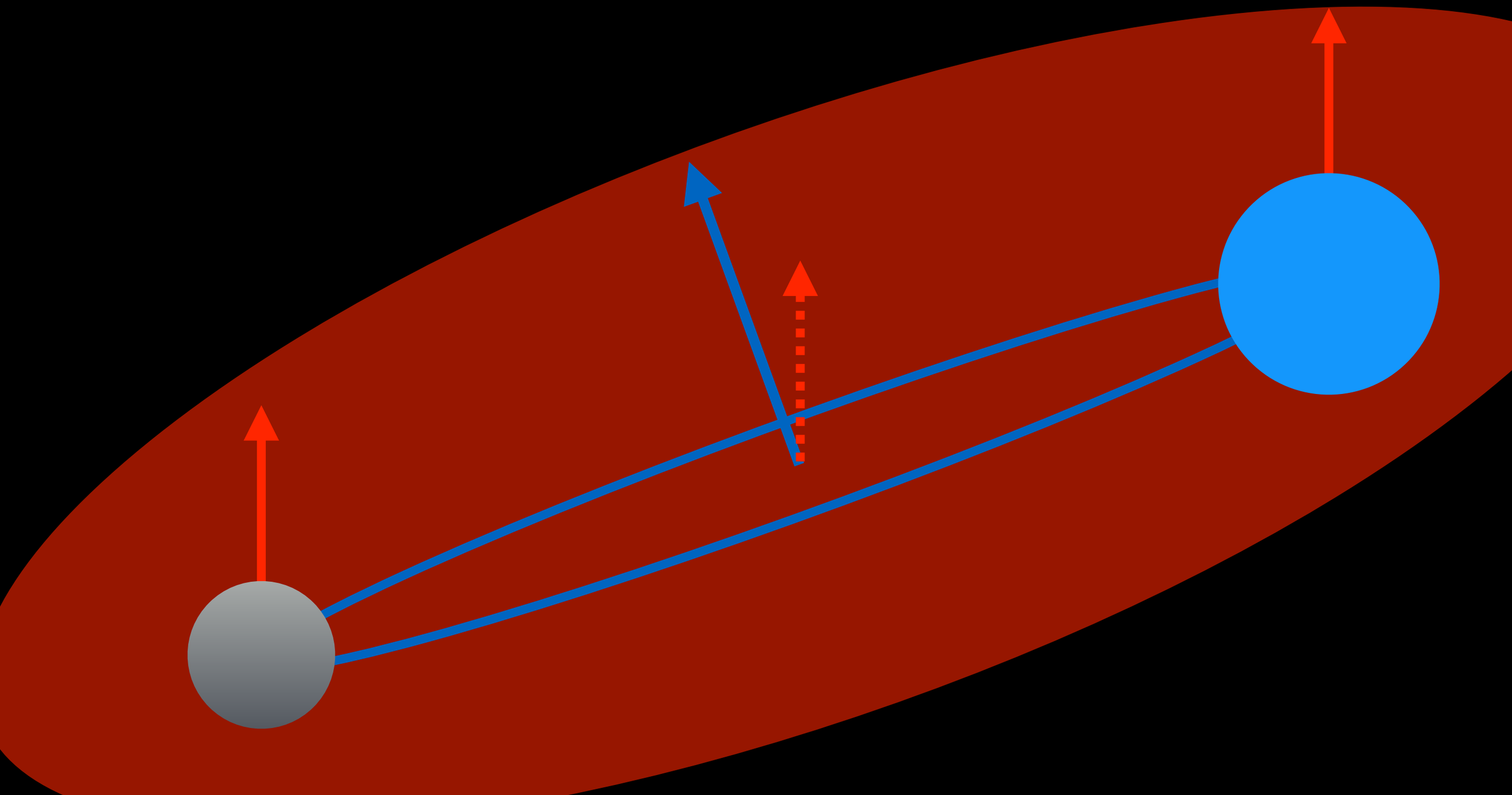

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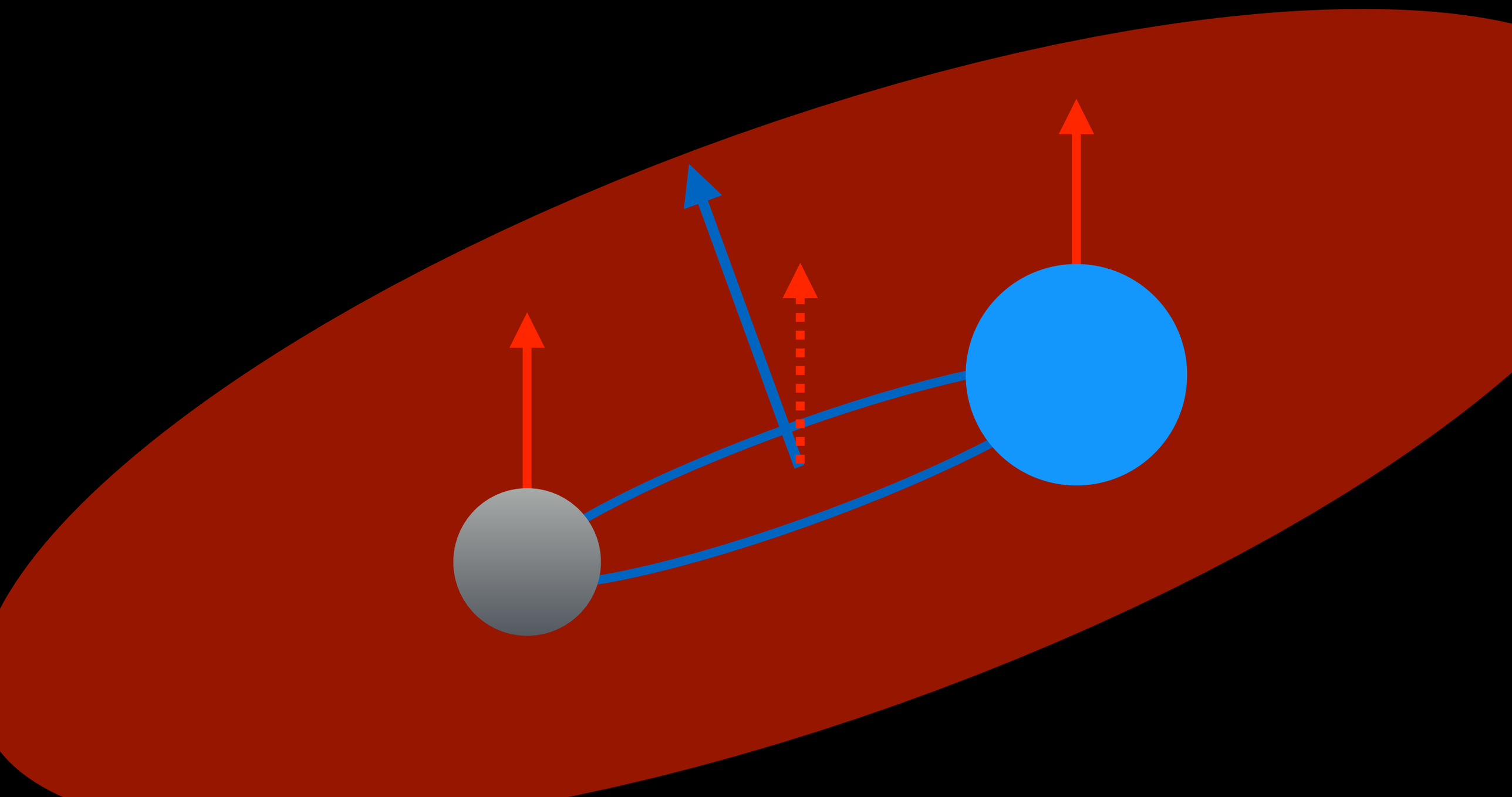

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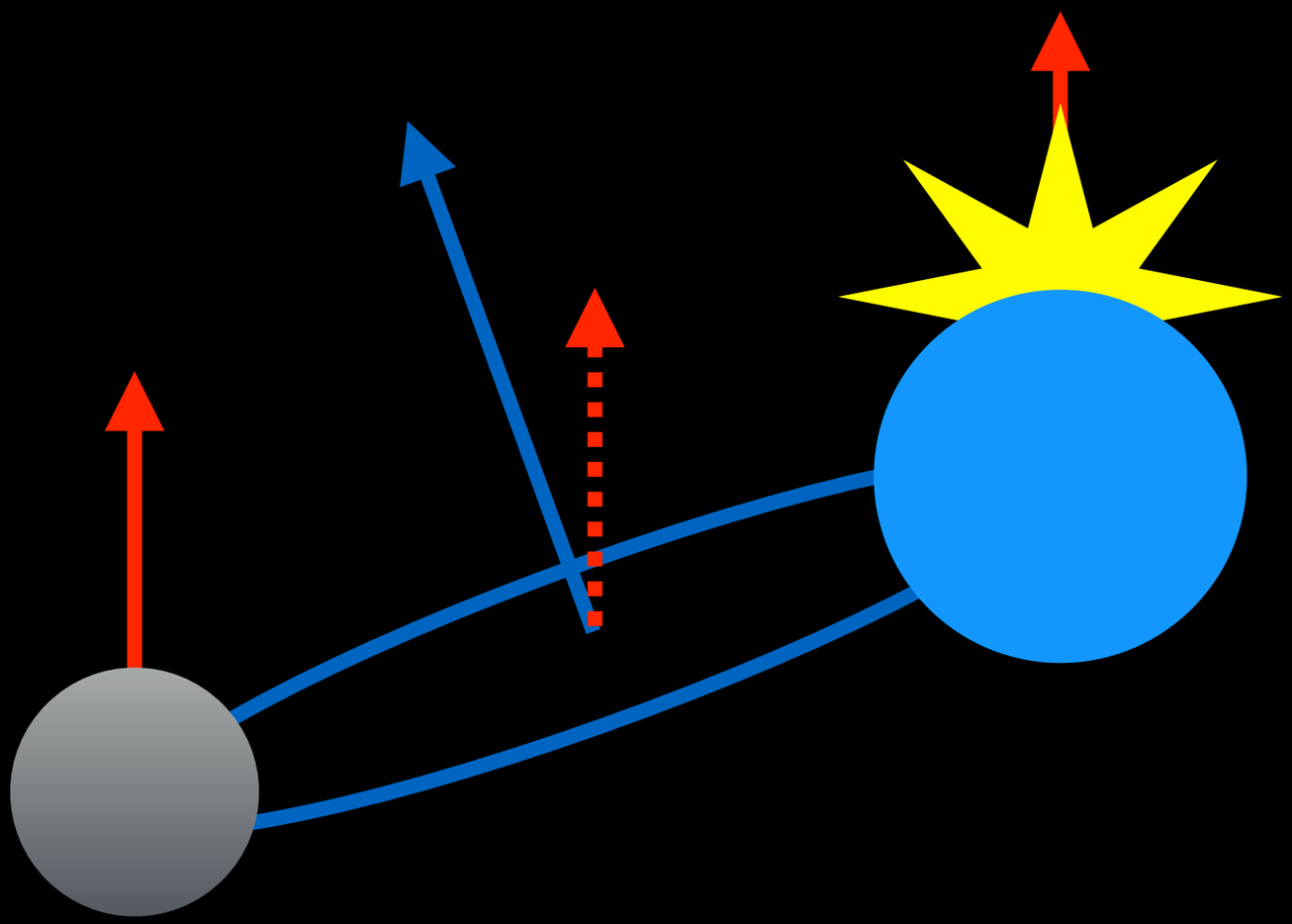

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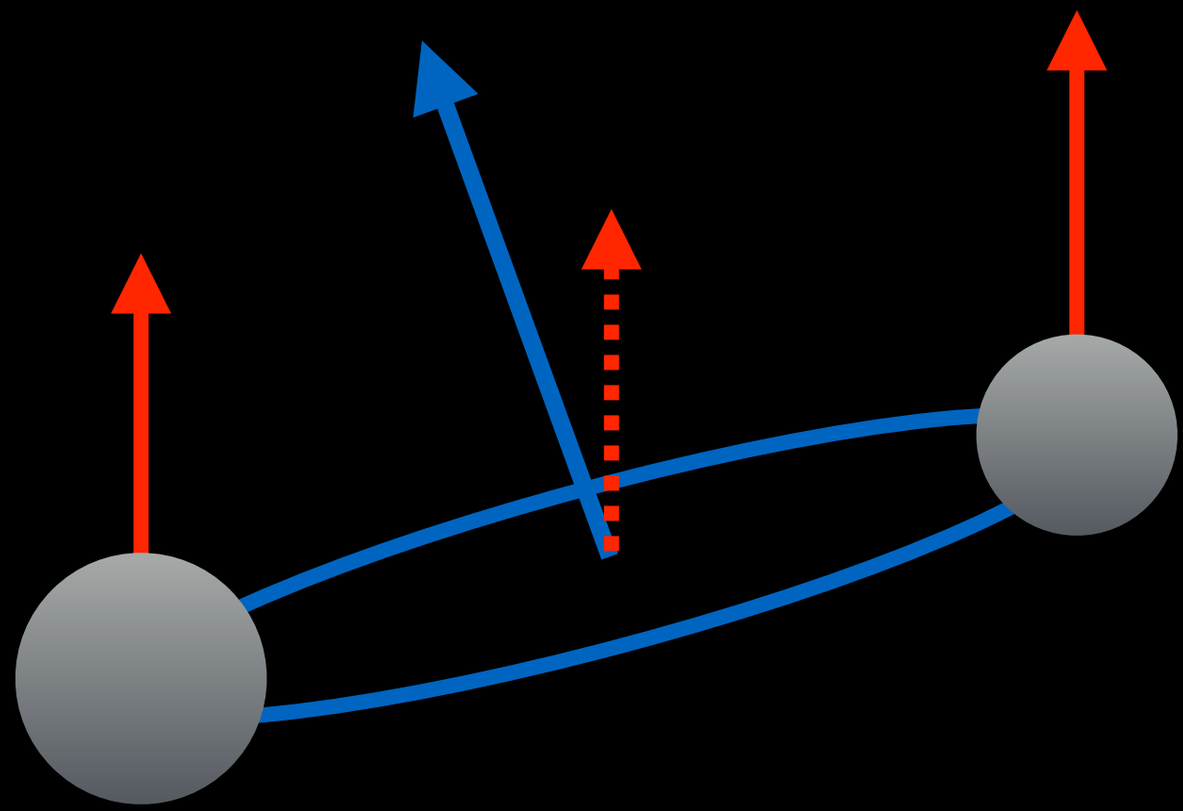

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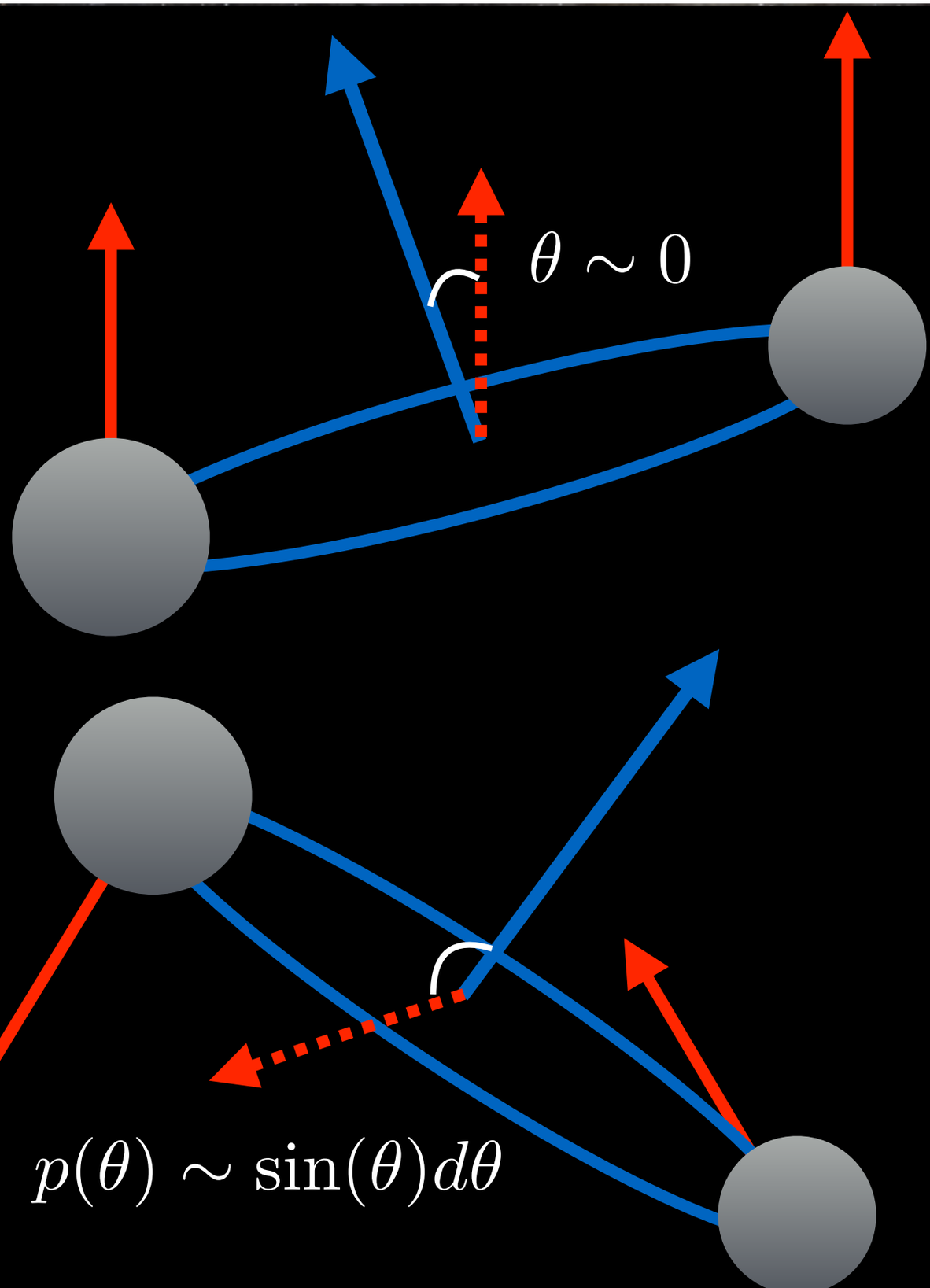

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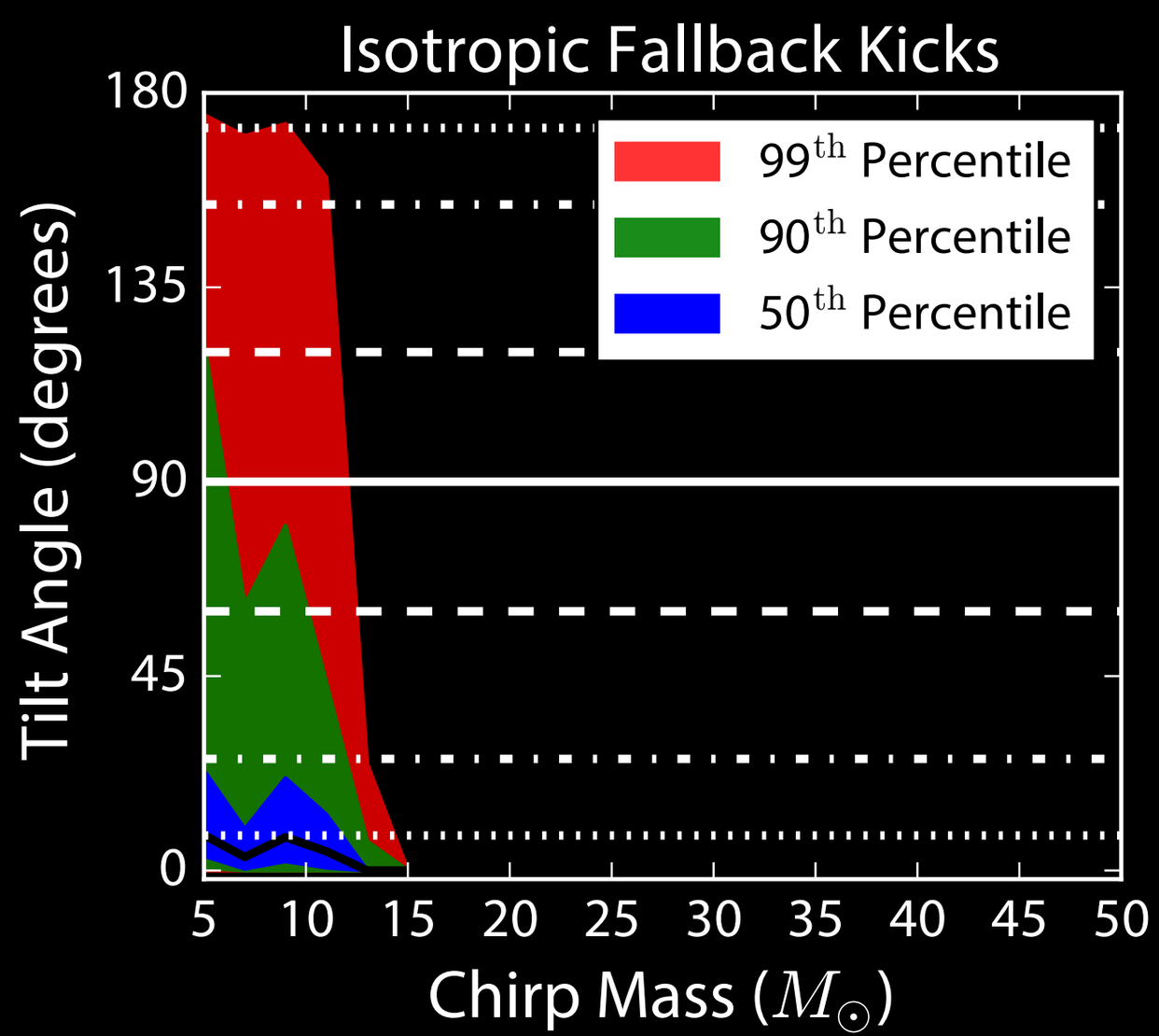
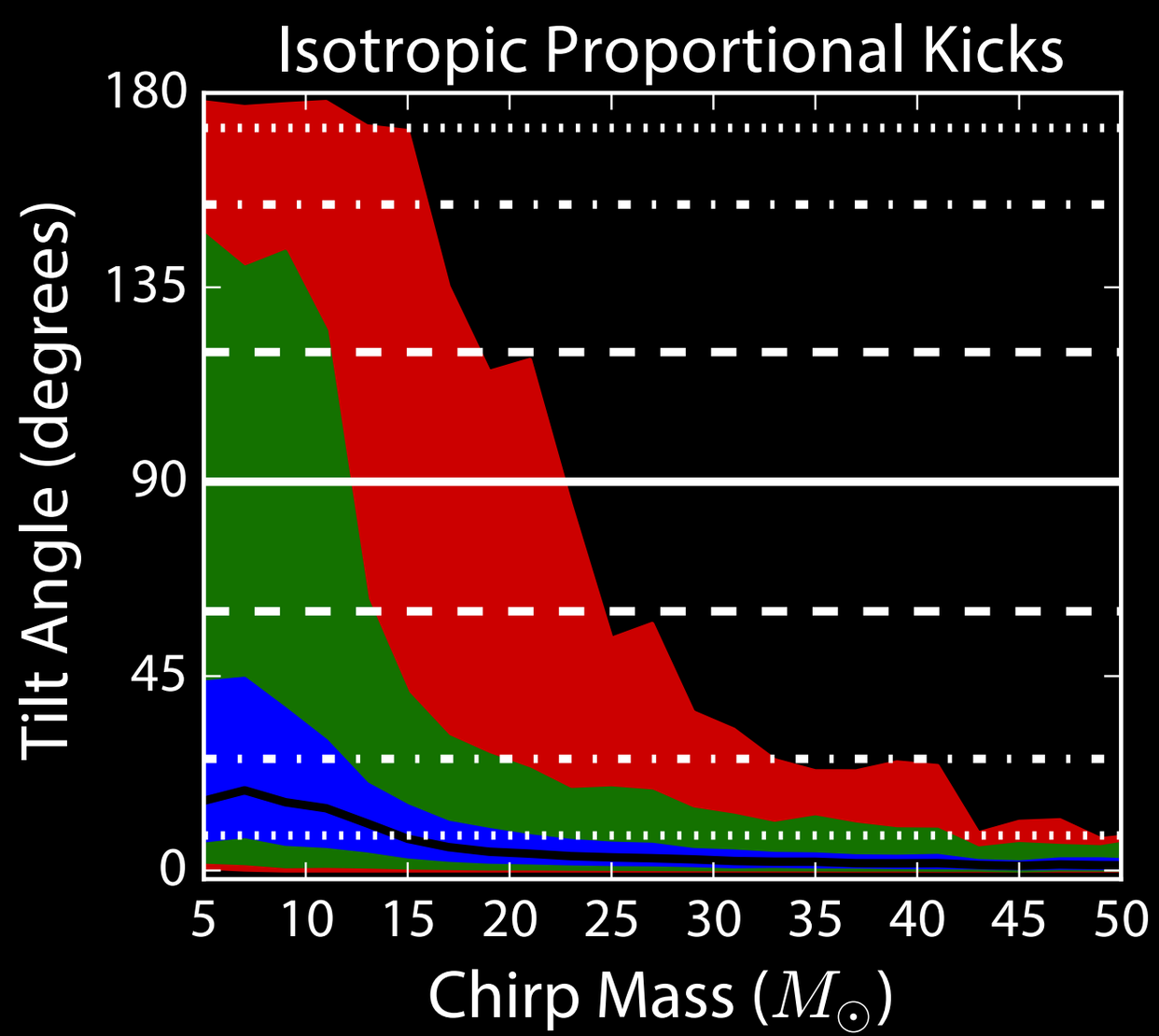
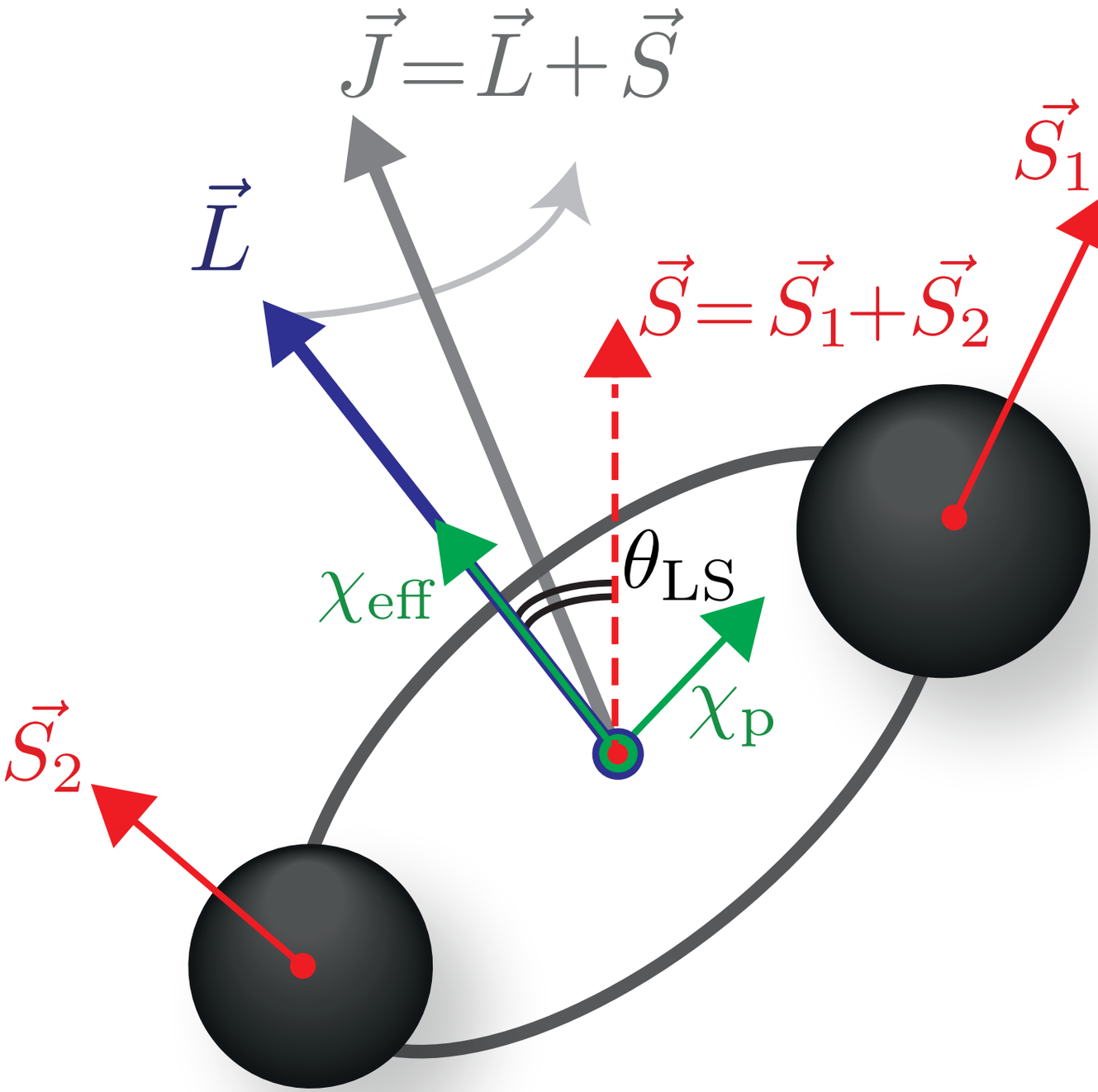
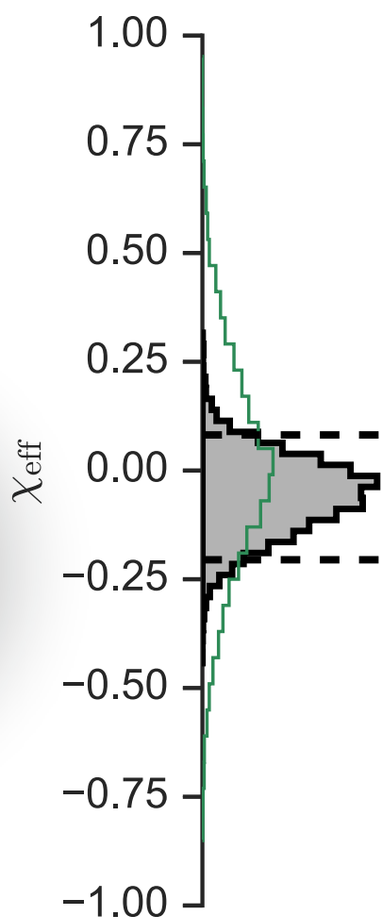


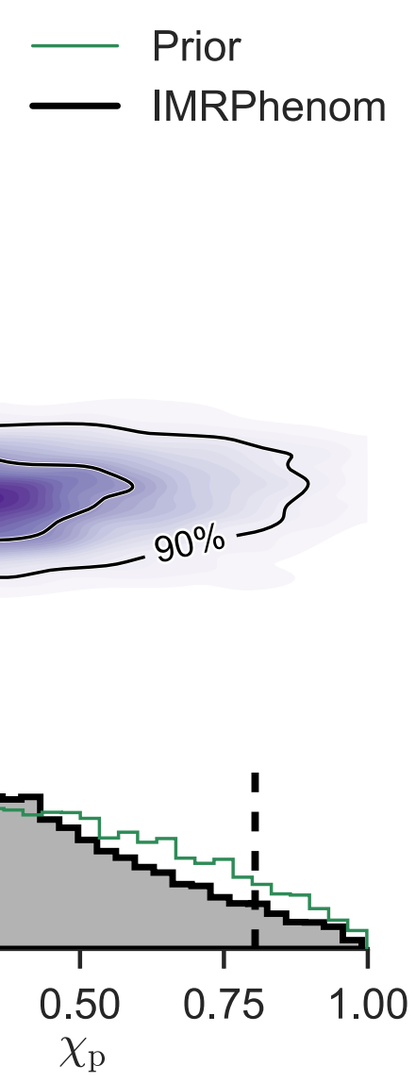


Rodriguez et al., 2016

Spins







Abbott et al., 2016

Spins

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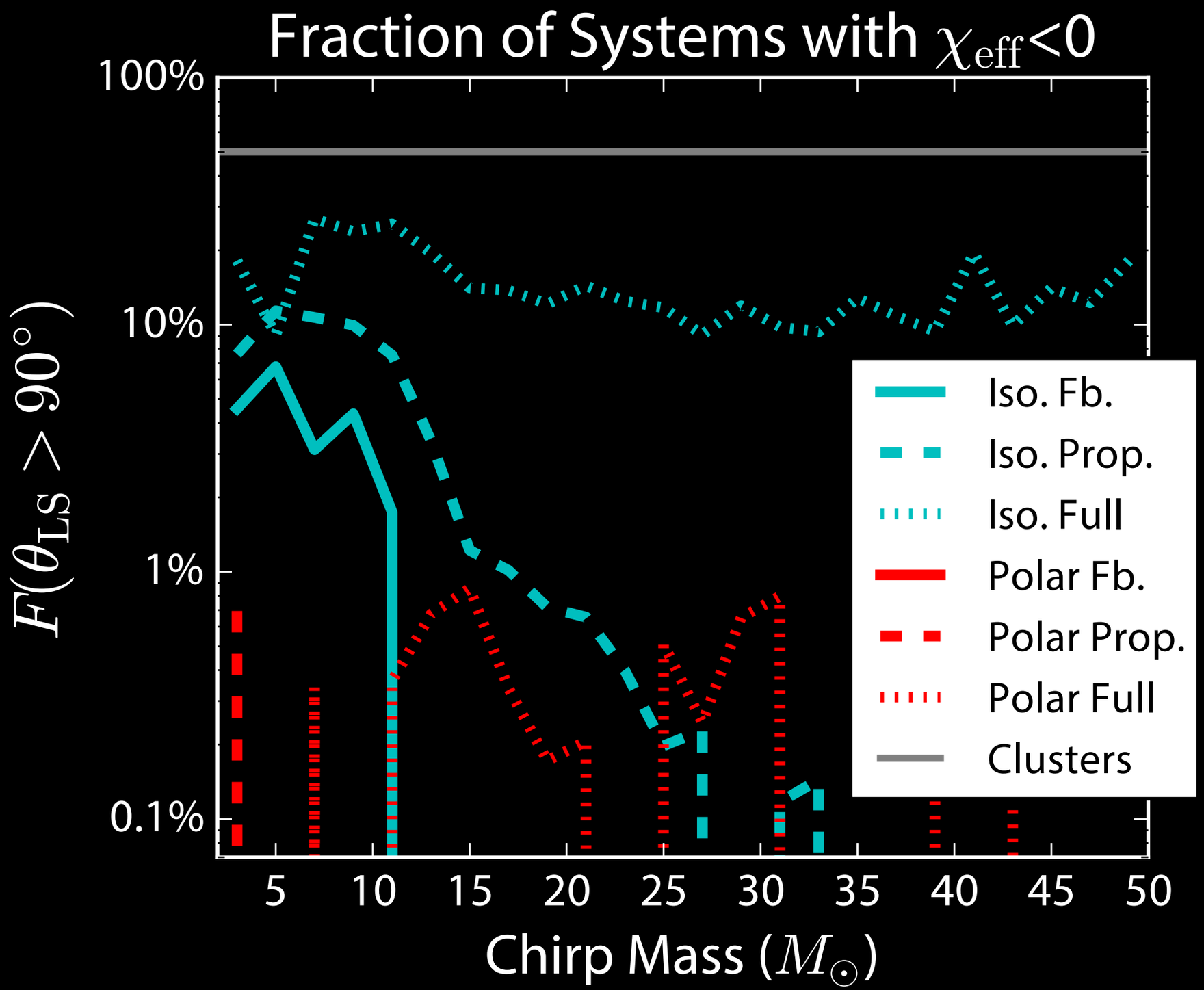

Rodriguez et al., 2016