Black Hole Binaries
from
Dense Star Clusters

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Recent papers:

- *Binary Black Holes in Dense Star Clusters: Exploring the Theoretical Uncertainties.* Chatterjee, S., *Rodriguez*, C.L., & Rasio, F.A. 2016, *Astrophys. J.*, in press, arXiv:1603.00884 [astro-ph.GA]
- *Merging Black Hole Binaries in Galactic Nuclei: Implications for Advanced-LIGO Detections.* *Antonini*, F., & Rasio, F.A. 2016, *Astrophys. J.*, in press, arXiv:1606.04889v2 [astro-ph.HE].
- *Illuminating Black Hole Binary Formation Channels with Spins in Advanced LIGO*. *Rodriguez*, C.L., *Zevin*, M., *Pankow*, C., Kalogera, V., & Rasio, F.A. 2016. *Astrophys. J. Letters*, in press, arXiv:1609.05916v2 [astro-ph.HE].
- *Million-Body Star Cluster Simulations: Comparisons between Monte Carlo and Direct N-body*. *Rodriguez*, C.L., *Morscher*, M., Wang, L., Chatterjee, S., Rasio, F.A., & Spurzem, R. 2016, *Monthly Notices of the RAS*, **463**, 2109–2118.
- *Distinguishing Between Formation Channels for Binary Black Holes with LISA*. Breivik, K., *Rodriguez*, C.L., Larson, S.L., Kalogera, V., & Rasio, F.A. 2016, *Astrophys. J. Letters*, **830**, id. L18, 5 pp.
- *Dynamical Formation of the GW150914 Binary Black Hole.* *Rodriguez*, C.L., Haster, C.-J., Chatterjee, S., Kalogera, V., & Rasio, F.A. 2016, *Astrophys. J. Letters*, **824**, id. L8, 9 pp.
- *Formation of Black Hole Low-mass X-Ray Binaries in Hierarchical Triple Systems.* Naoz, S., Fragos, T., *Geller*, A., & Rasio, F.A. 2016, *Astrophys. J. Letters*, **822**, id. L24, 6 pp.
- *Binary Black Hole Mergers from Globular Clusters: Masses, Merger Rates, and the Impact of Stellar Evolution.* *Rodriguez*, C.L., Chatterjee, S., & Rasio, F.A. 2016, *Phys. Rev. D*, **93**, id. 084029, 22 pp.
- *Black Hole Mergers and Blue Stragglers from Hierarchical Triples Formed in Globular Clusters.* *Antonini*, F., Chatterjee, S., *Rodriguez*, C.L., *Morscher*, M., *Pattabiraman*, B., Kalogera, V., & Rasio, F.A. 2016, *Astrophys. J.*, **816**, id. 65, 16 pp.

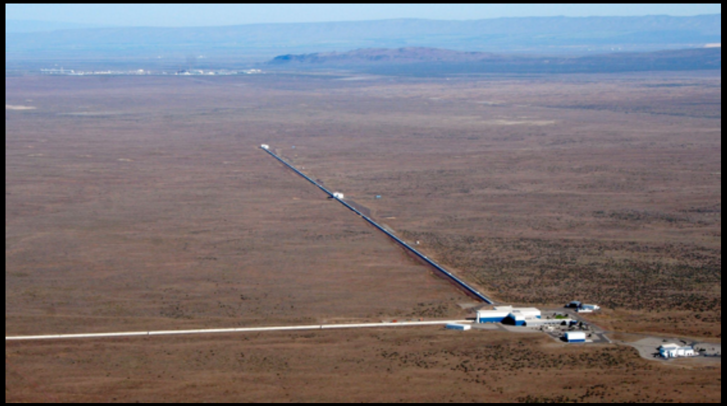
First LIGO detection! →

- *Binary Black Hole Mergers from Globular Clusters: Implications for Advanced LIGO*. *Rodriguez*, C.L., *Morscher*, M., *Pattabiraman*, B., *Chatterjee*, S., Haster, C.-J., & Rasio, F.A. 2015, *Phys. Rev. Letters*, **115**, id. 051101, 9 pp; erratum 2016, **116**, id. 029901.
- *The Dynamical Evolution of Stellar Black Holes in Globular Clusters.* *Morscher*, M., *Pattabiraman*, B., *Rodriguez*, C.L., Rasio, F.A., & *Umbreit*, S. 2015, *Astrophys. J.*, **800**, id. 9, 21 pp.
- *Black Holes in Young Stellar Clusters.* *Goswami*, S., *Kiel*, P., & Rasio, F.A. 2014, *Astrophys. J.*, **781**, id. 81, 14 pp.

MODEST-14 here! →

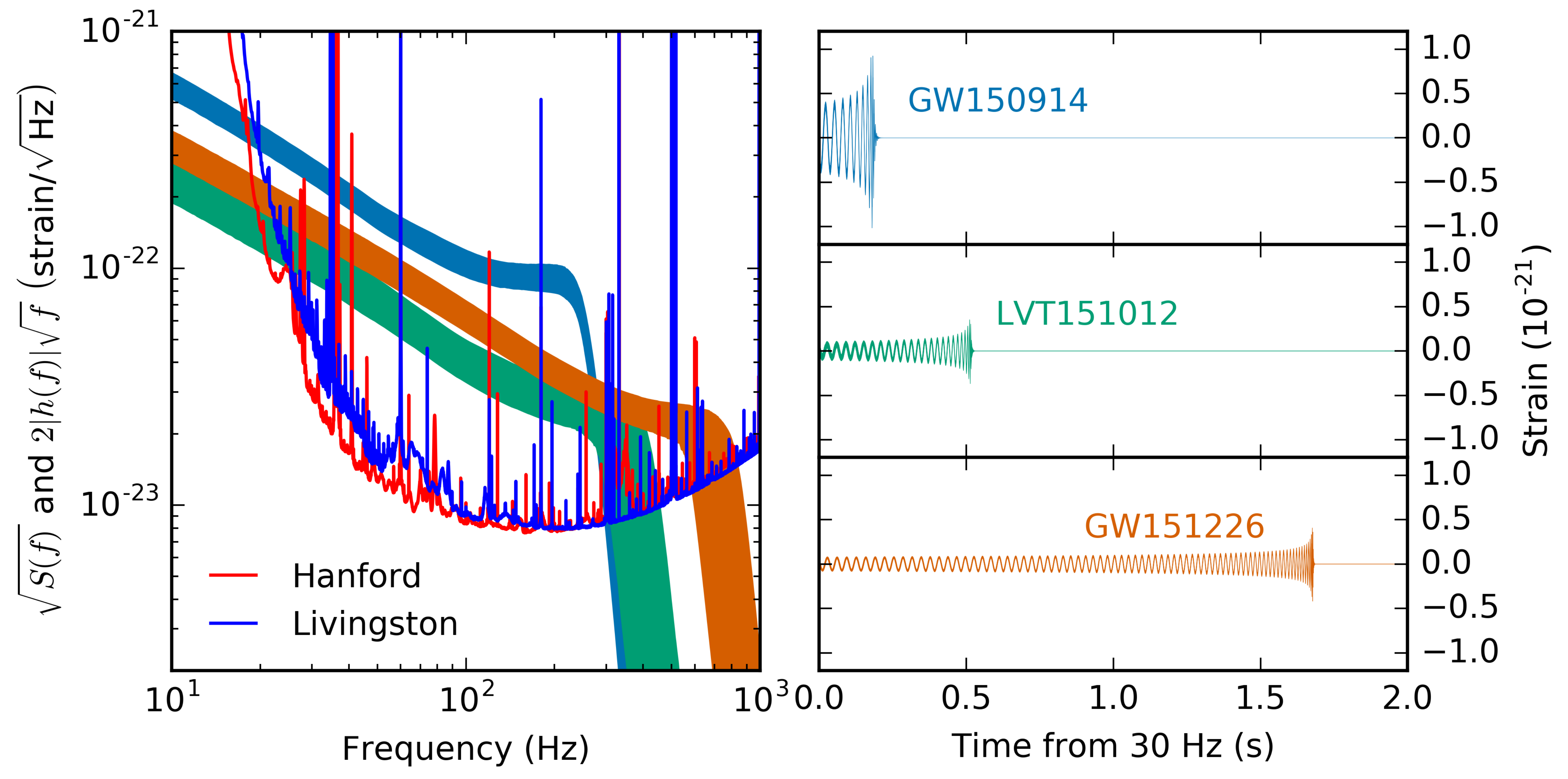
- *A Parallel Monte Carlo Code for Simulating Collisional N-body Systems.* *Pattabiraman*, B., *Umbreit*, S., Liao, W.-k., Choudhary, A., Kalogera, V., Memik, G., & Rasio, F.A. 2014, *Astrophys. J. Supp.*, **204**, id. 15, 16 pp.

LIGO Detections

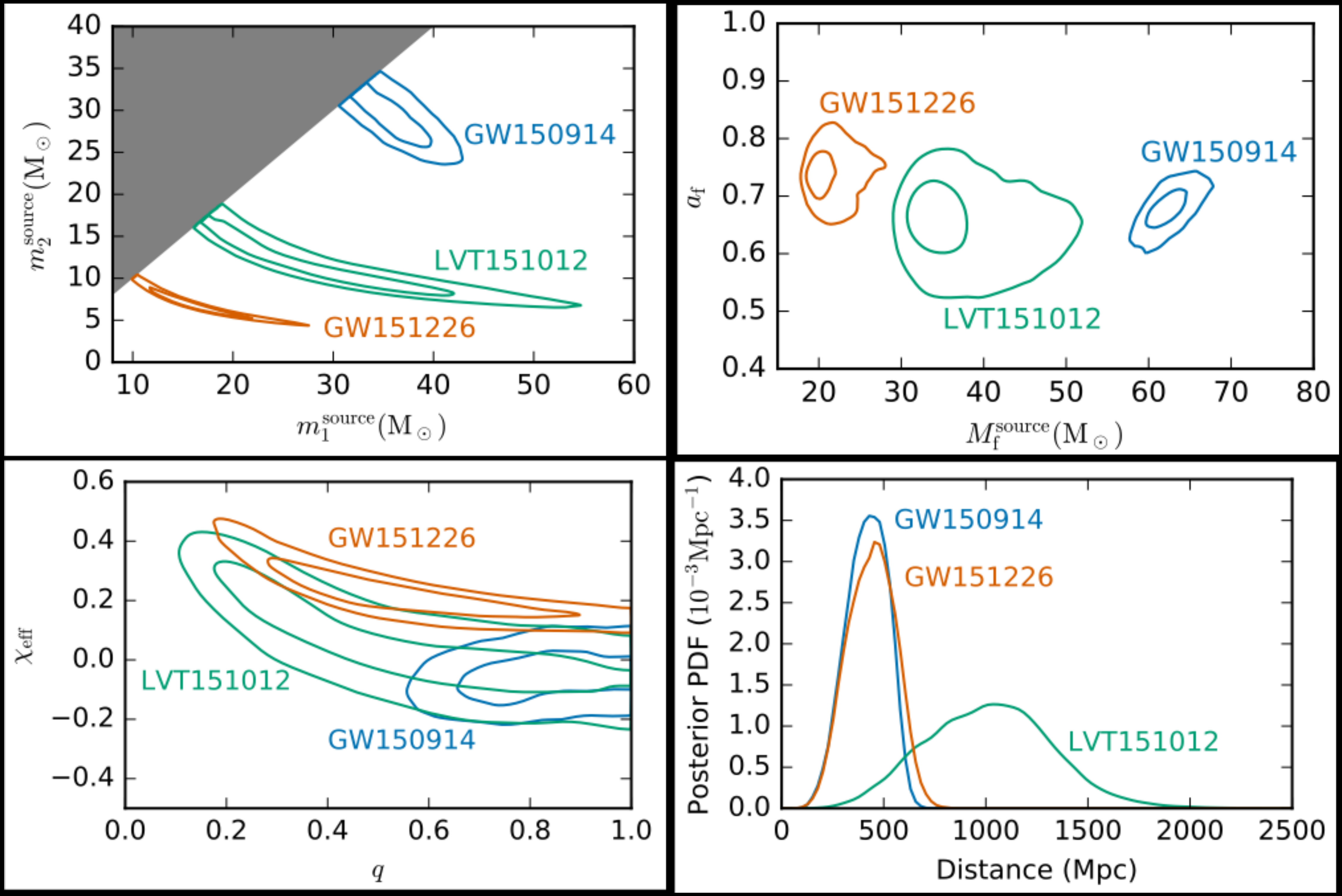


- Merging Binary Black Holes!
- Three Detections in O1 Run (50 days):
  - GW150914: $M_{1,2} \sim 30\ M_{sun}$, $z \sim 0.1$
  - LVT151012: $M_{1,2} \sim 20\ M_{sun}$, $z \sim 0.2$
  - GW151226: $M_{1,2} \sim 10\ M_{sun}$, $z \sim 0.1$

LIGO Detections



LIGO Detections



How do Merging Black Hole Binaries Form?

- From (isolated) massive binary star evolution
- Through stellar dynamics in dense star clusters
- As part of “primordial” black holes

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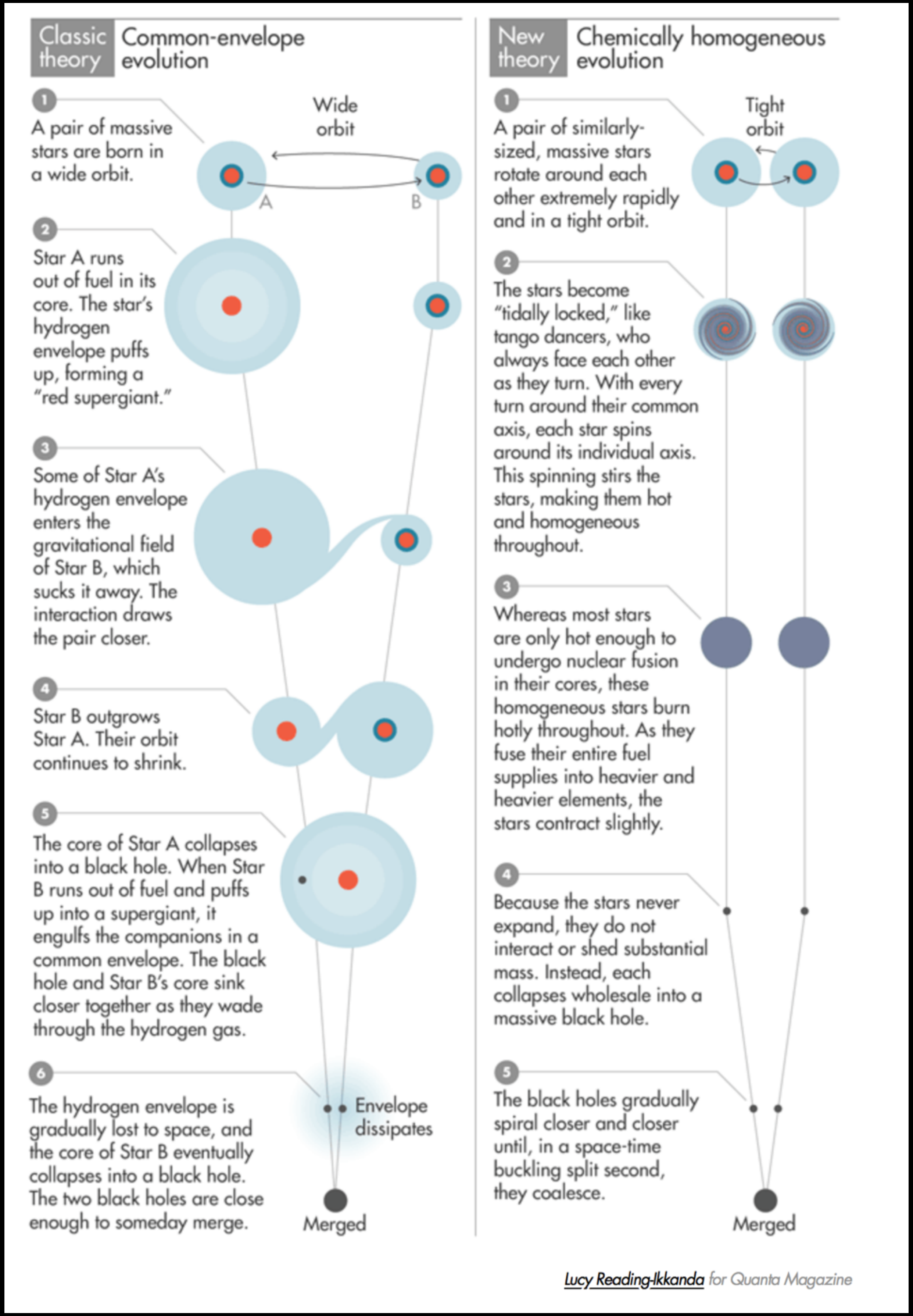
Binary evolution vs Dynamics



Classic theory Common-envelope evolution

1 A pair of massive stars are born in a wide orbit.

2 Star A runs out of fuel in its core. The star's hydrogen envelope puffs up, forming a "red supergiant."

3 Some of Star A's hydrogen envelope enters the gravitational field of Star B, which sucks it away. The interaction draws the pair closer.

4 Star B outgrows Star A. Their orbit continues to shrink.

5 The core of Star A collapses into a black hole. When Star B runs out of fuel and puffs up into a supergiant, it engulfs the companions in a common envelope. The black hole and Star B's core sink closer together as they wade through the hydrogen gas.

6 The hydrogen envelope is gradually lost to space, and the core of Star B eventually collapses into a black hole. The two black holes are close enough to someday merge.

New theory Chemically homogeneous evolution

1 A pair of similarly-sized, massive stars rotate around each other extremely rapidly and in a tight orbit.

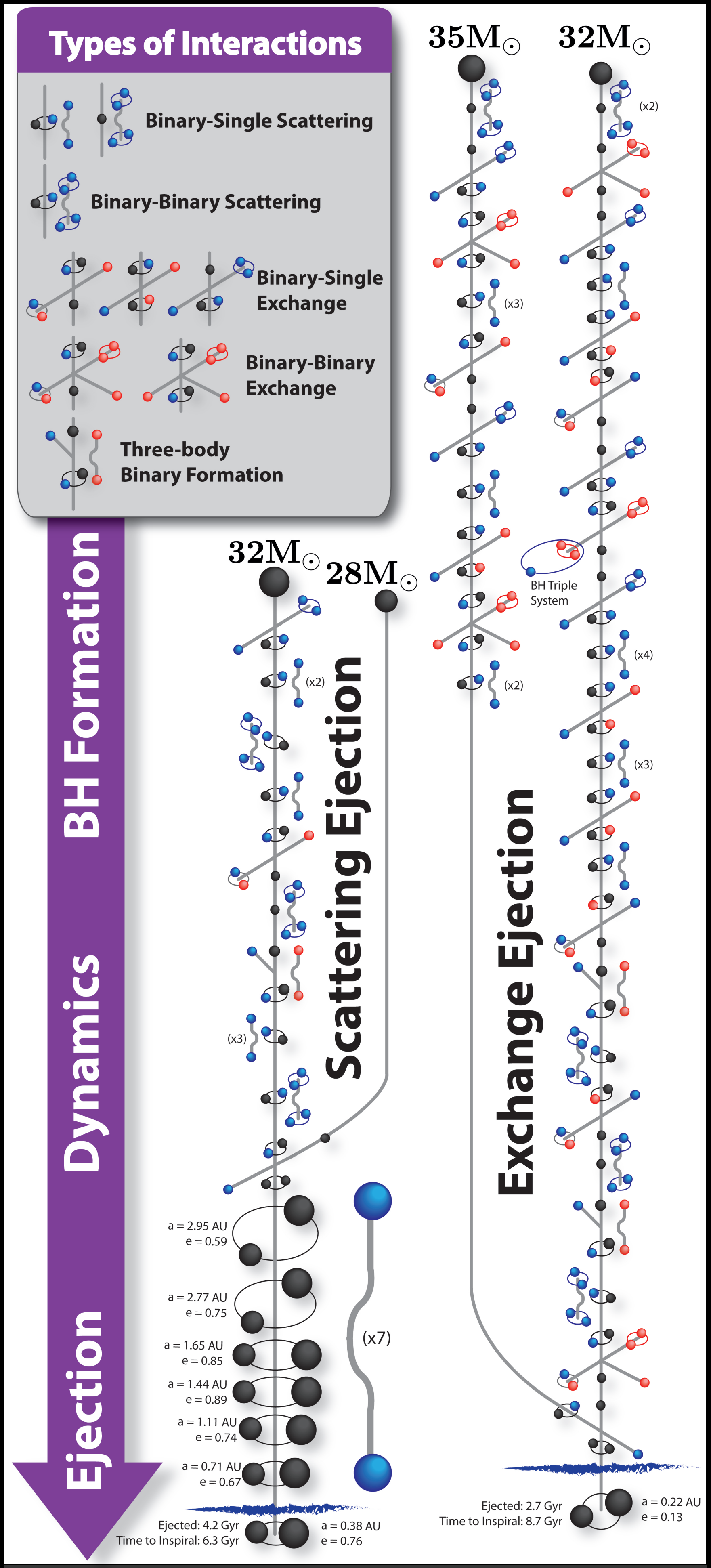
2 The stars become "tidally locked," like tango dancers, who always face each other as they turn. With every turn around their common axis, each star spins around its individual axis. This spinning stirs the stars, making them hot and homogeneous throughout.

3 Whereas most stars are only hot enough to undergo nuclear fusion in their cores, these homogeneous stars burn hotly throughout. As they fuse their entire fuel supplies into heavier and heavier elements, the stars contract slightly.

4 Because the stars never expand, they do not interact or shed substantial mass. Instead, each collapses wholesale into a massive black hole.

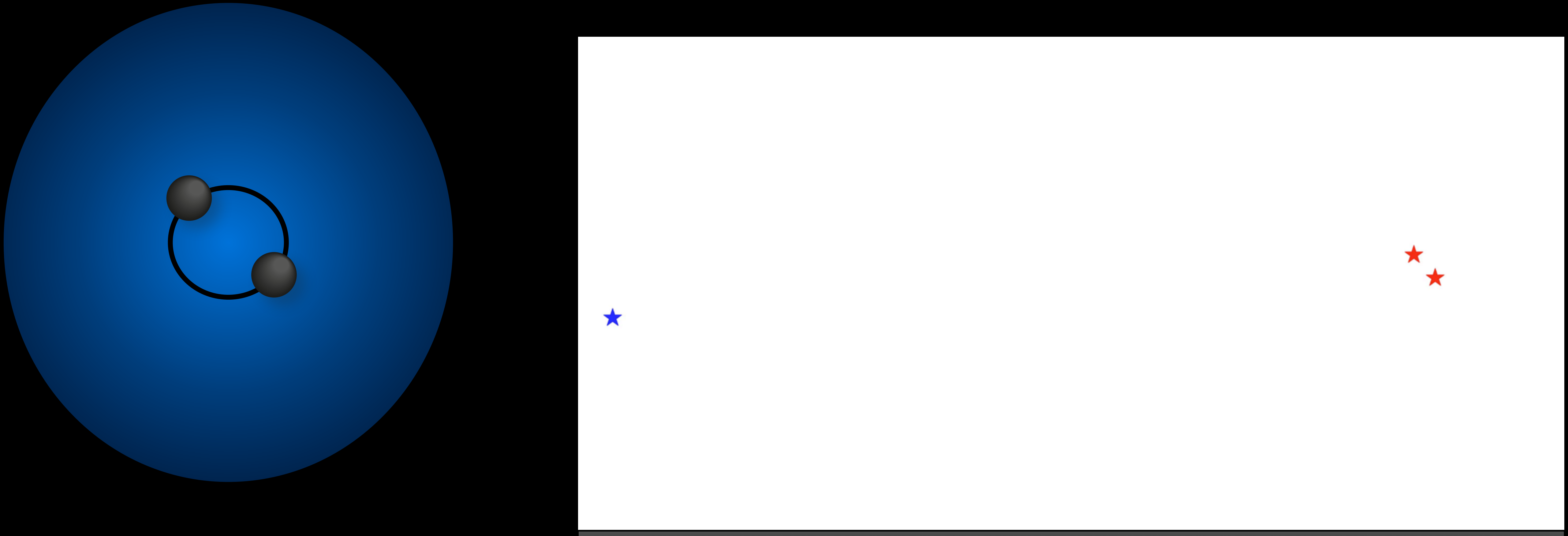
5 The black holes gradually spiral closer and closer until, in a space-time buckling split second, they coalesce.

Lucy Reading-Ikkanda for Quanta Magazine



Rodriguez et al. 2016, ApJL, 824. L8

Chaotic Interactions



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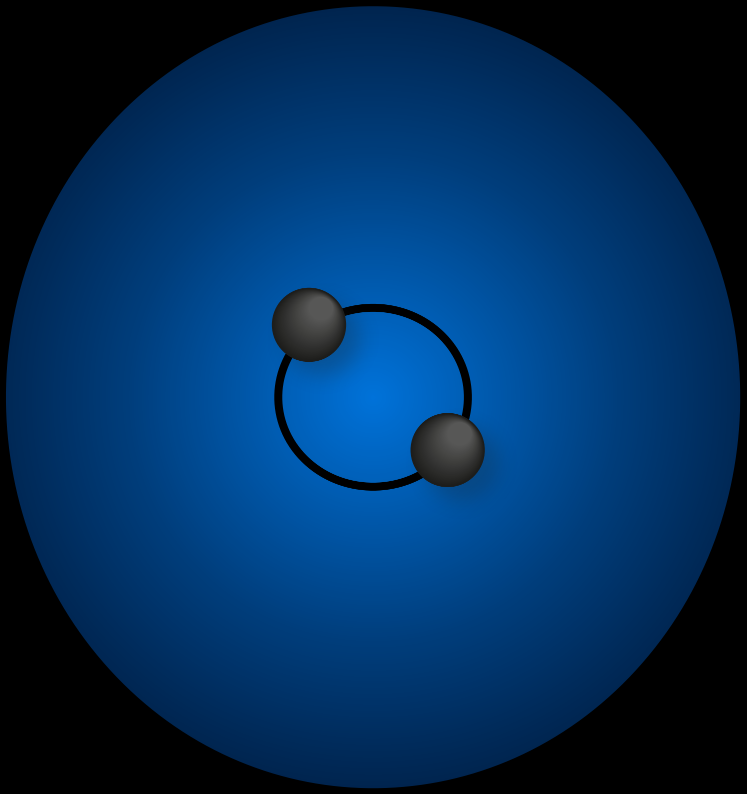

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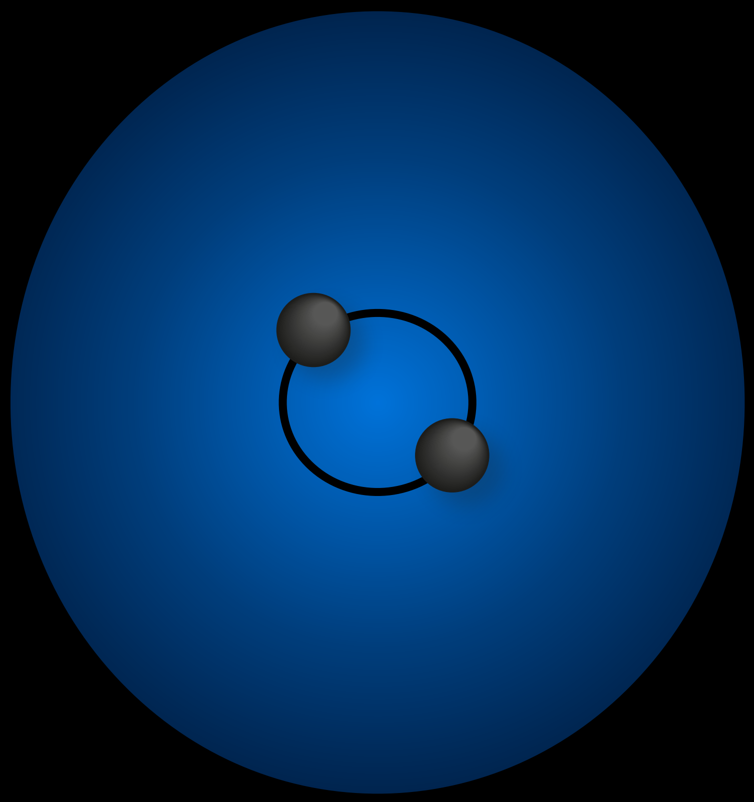

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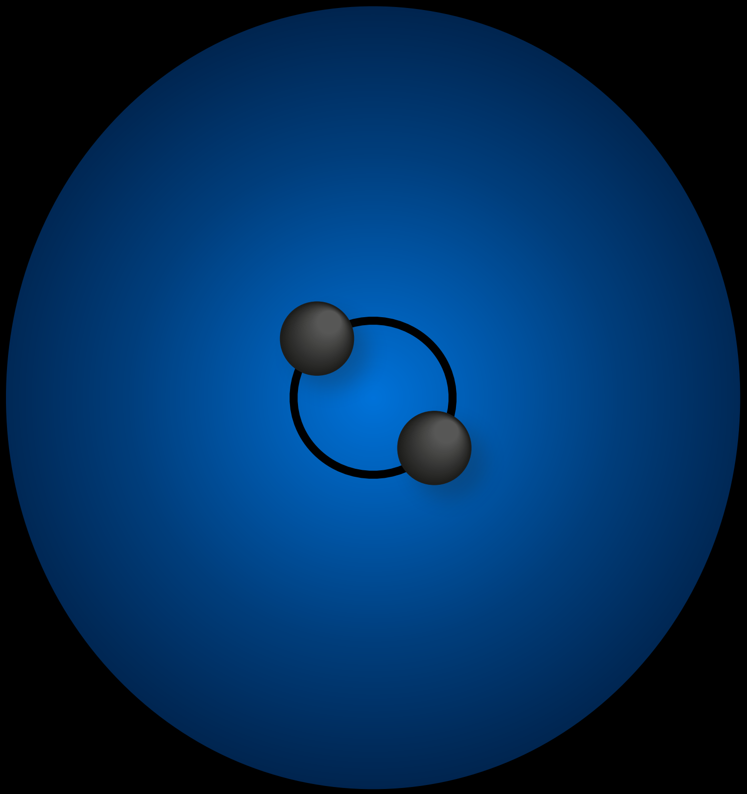

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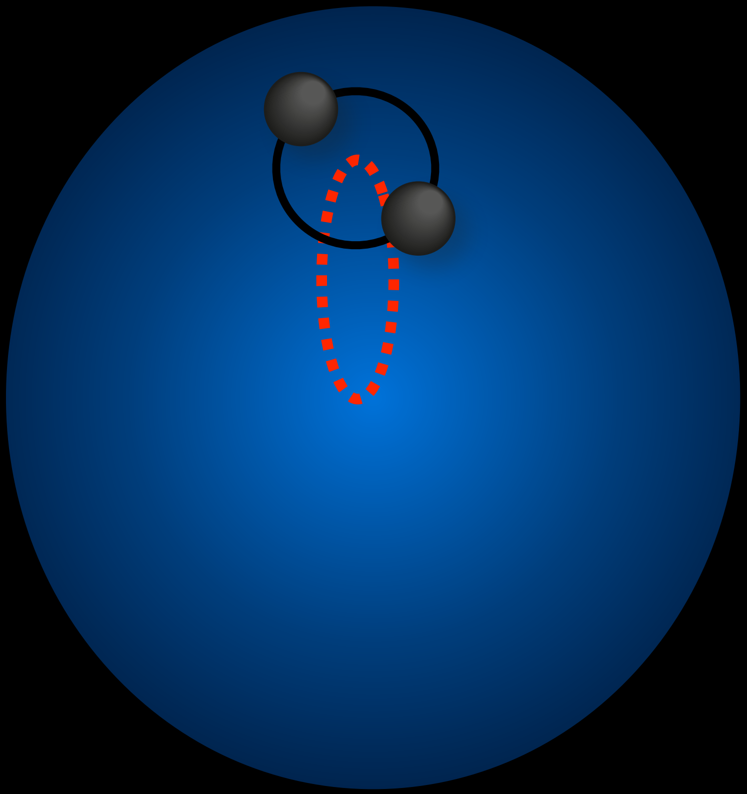

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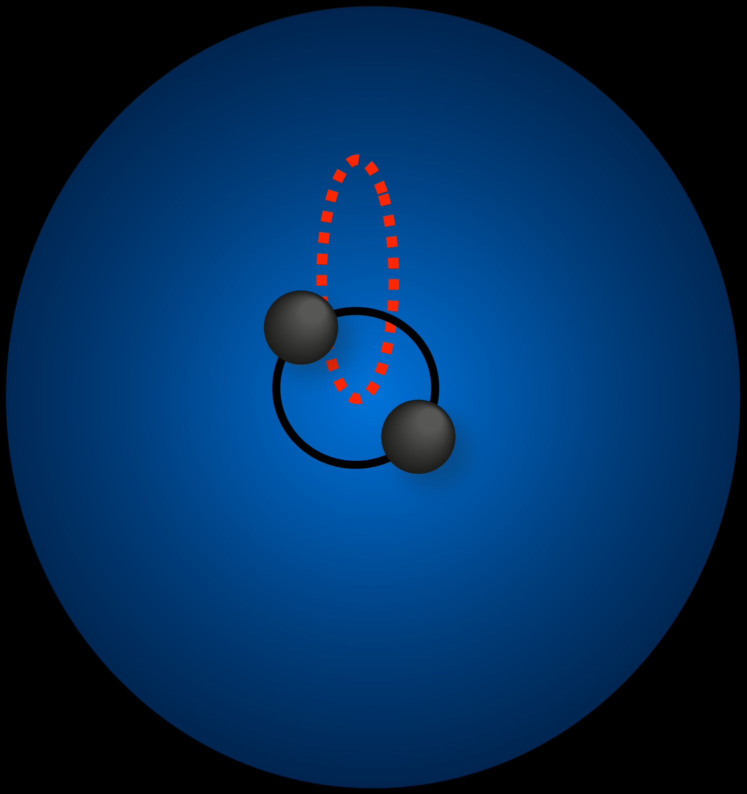

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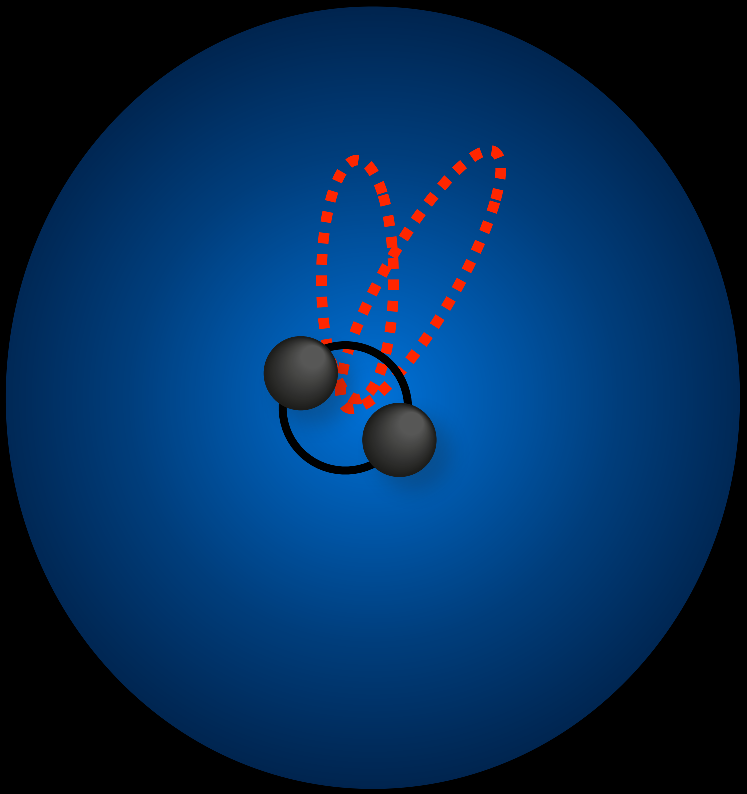

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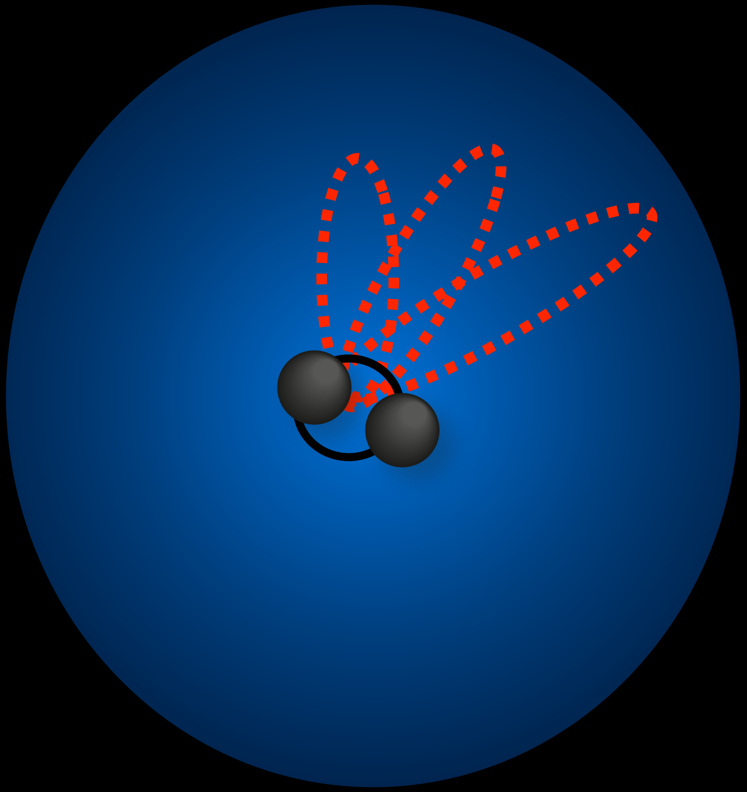

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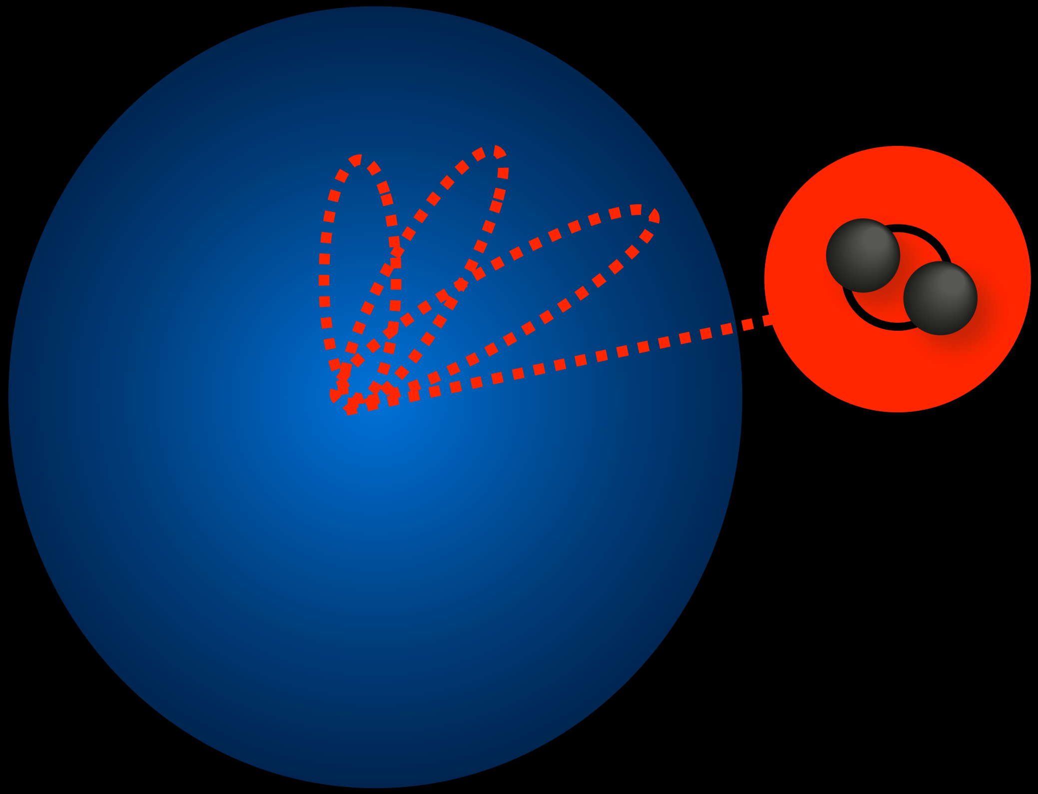

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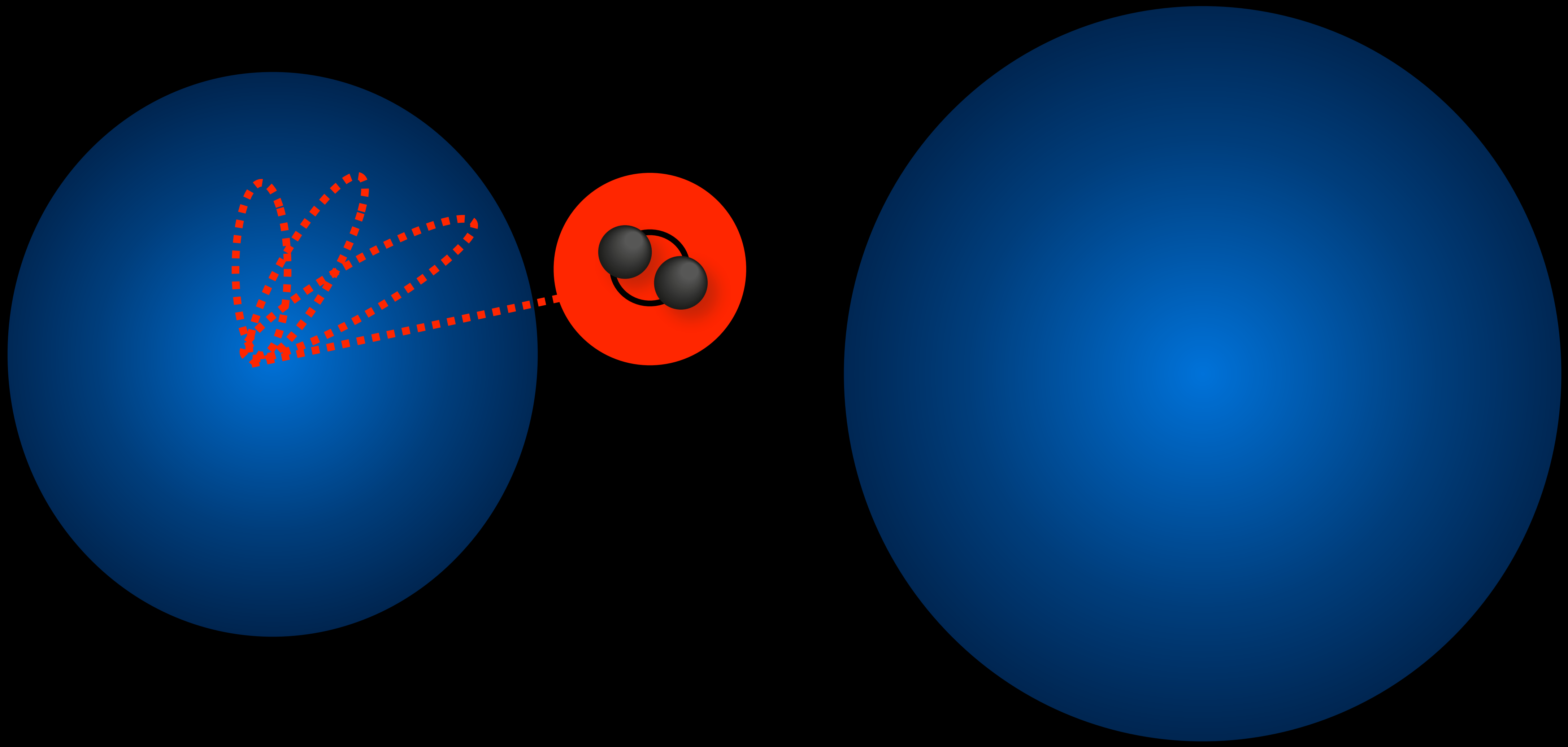

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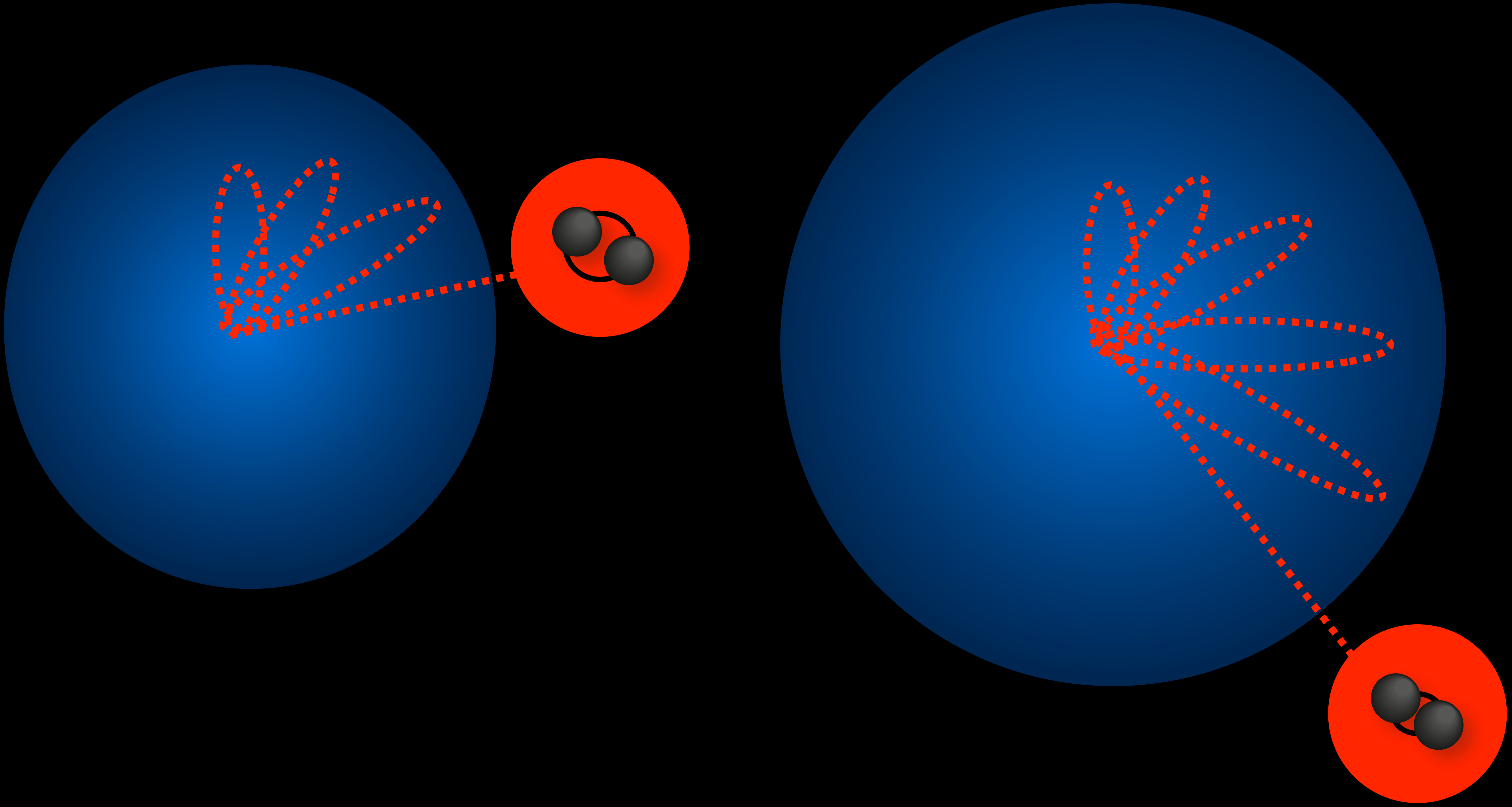

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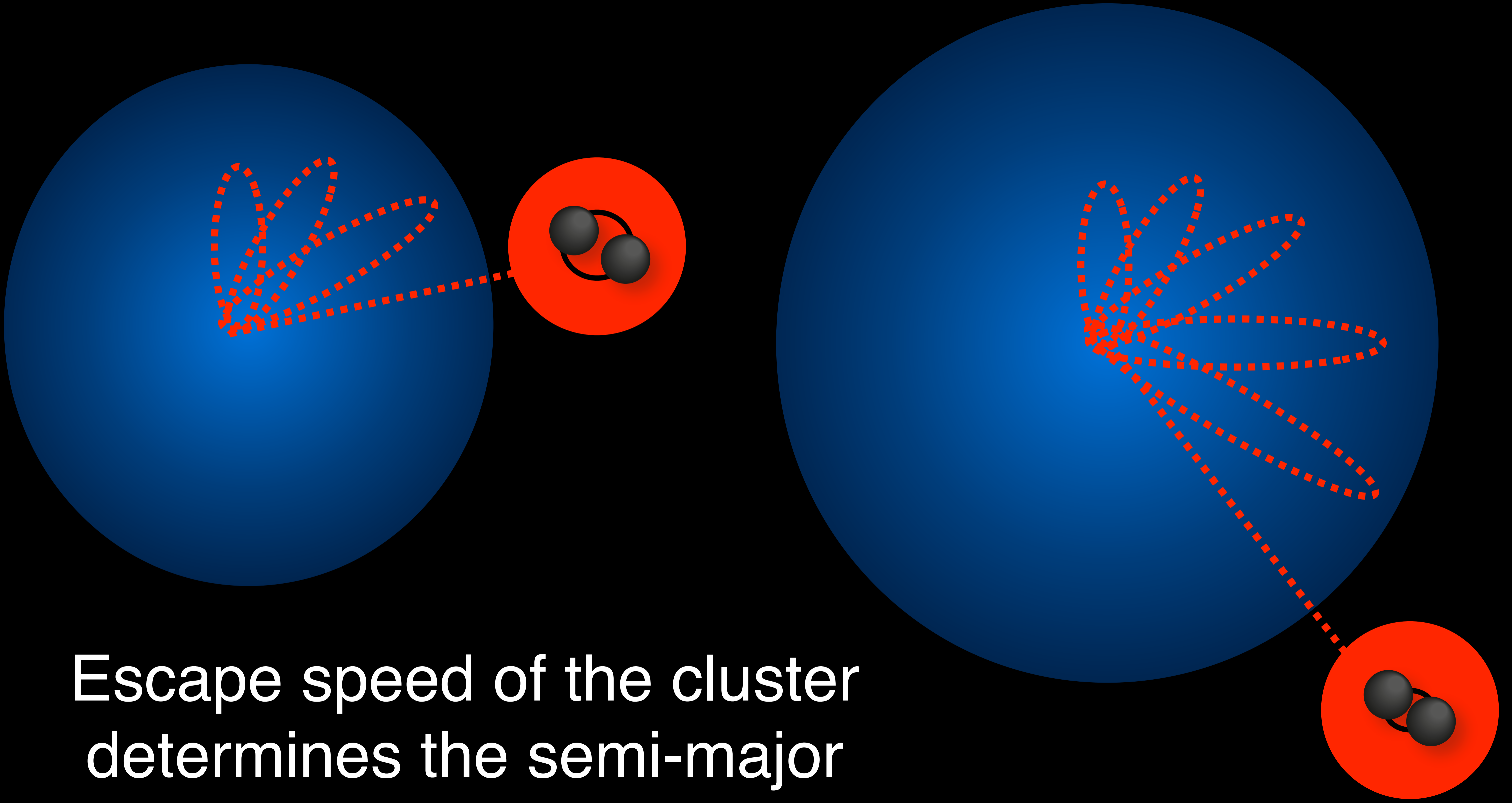
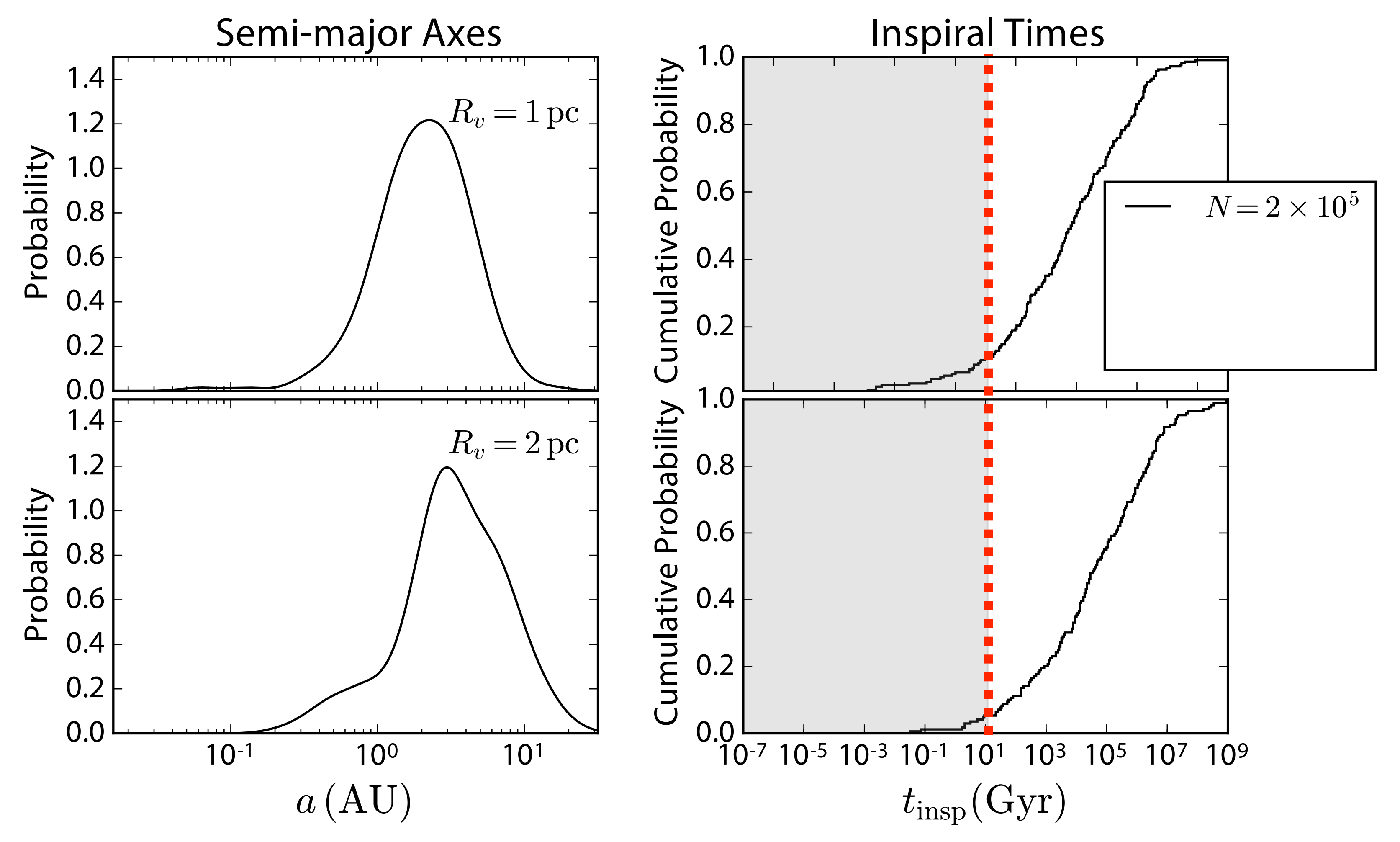


Escape speed of the cluster determines the semi-major axis of the ejected binaries

Chaotic Interactions



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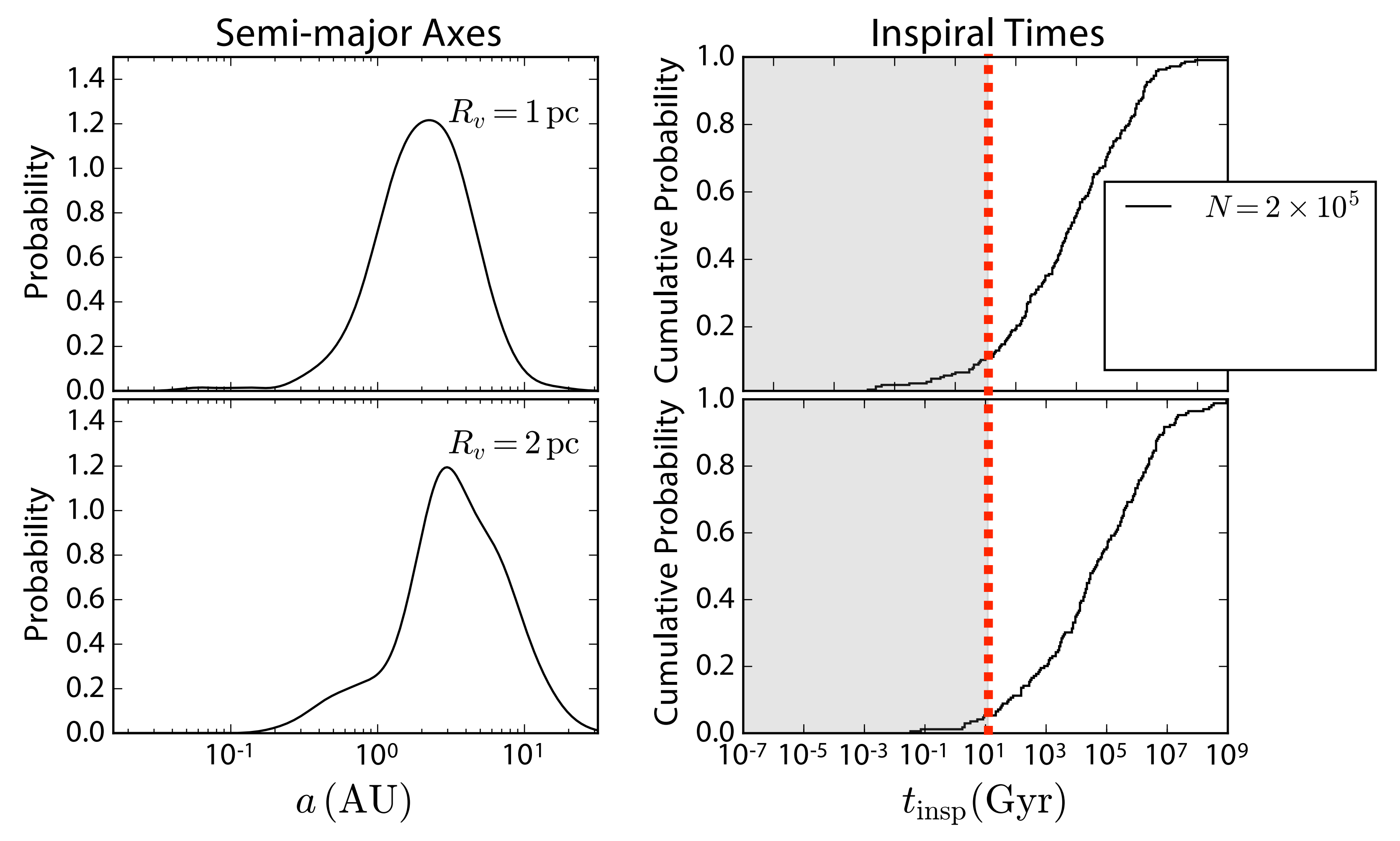
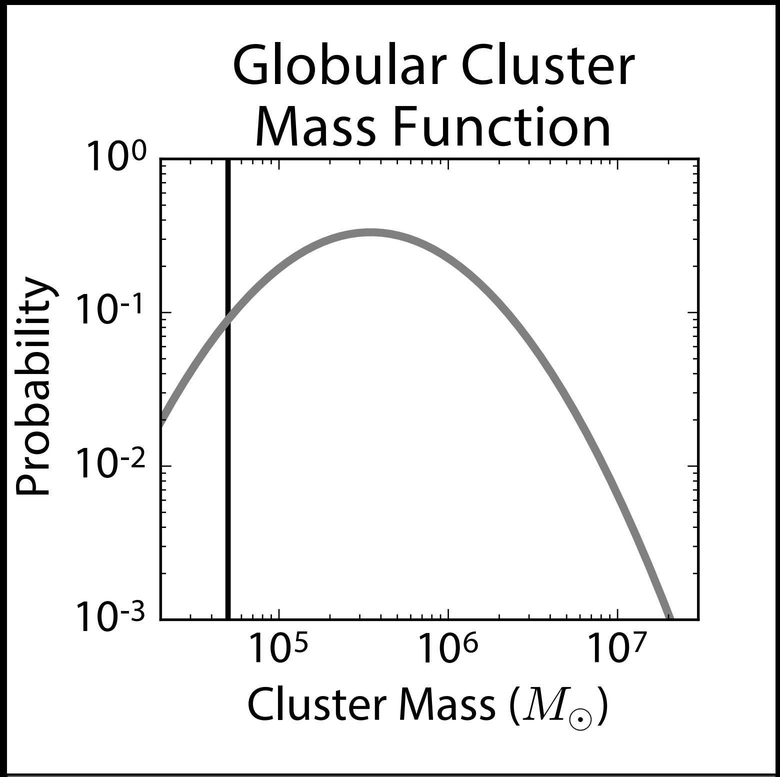


from Harris, 2014



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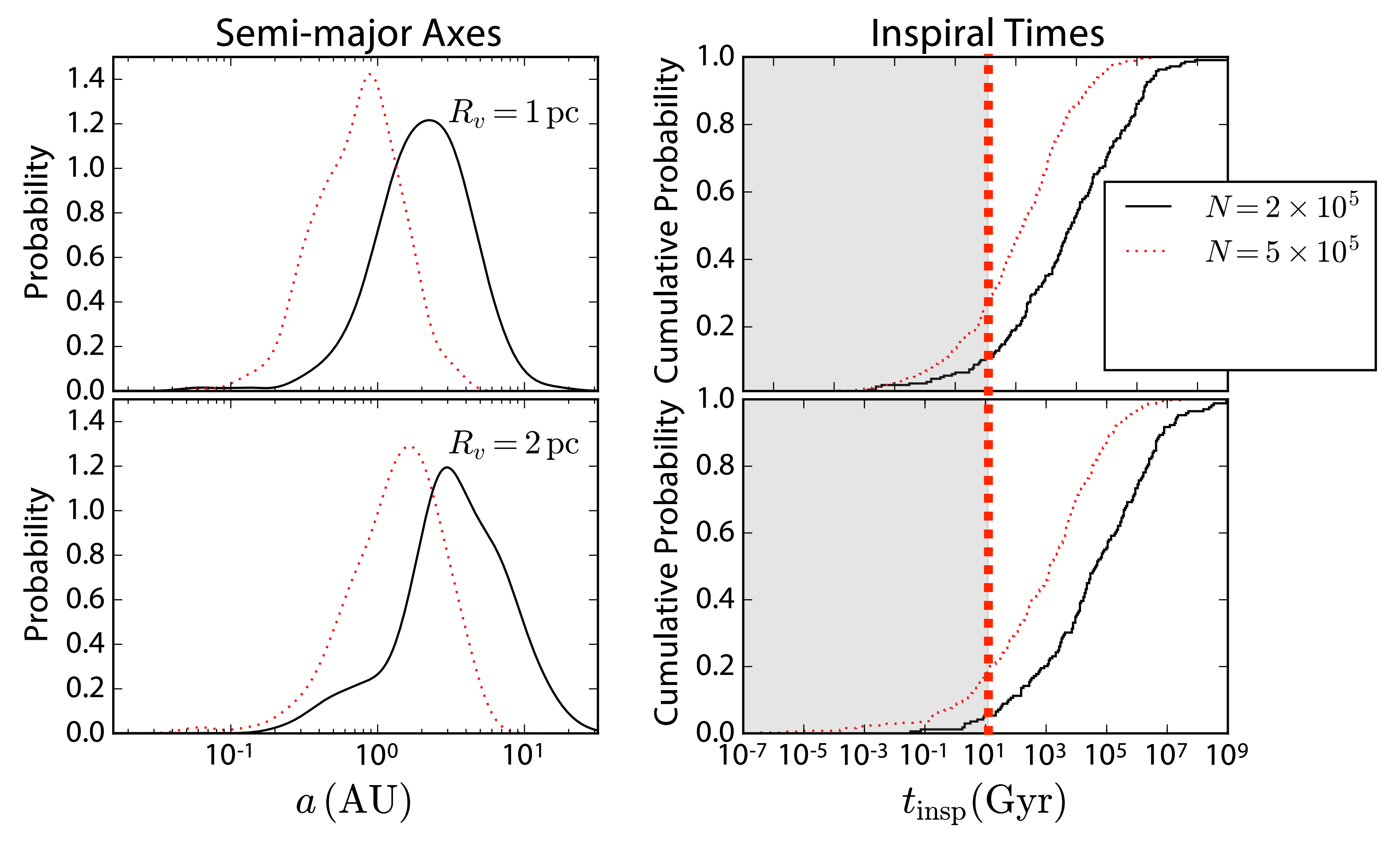

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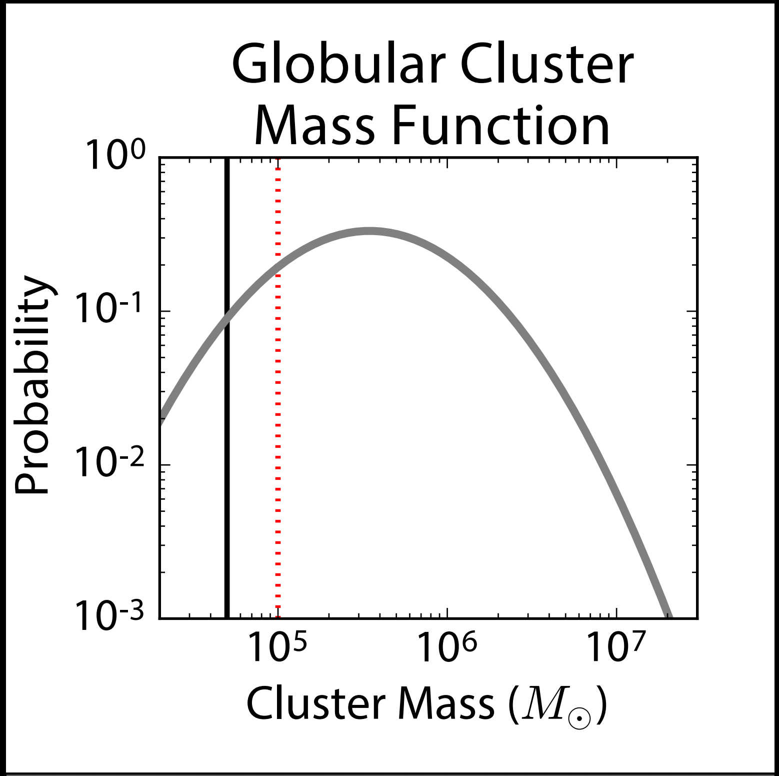

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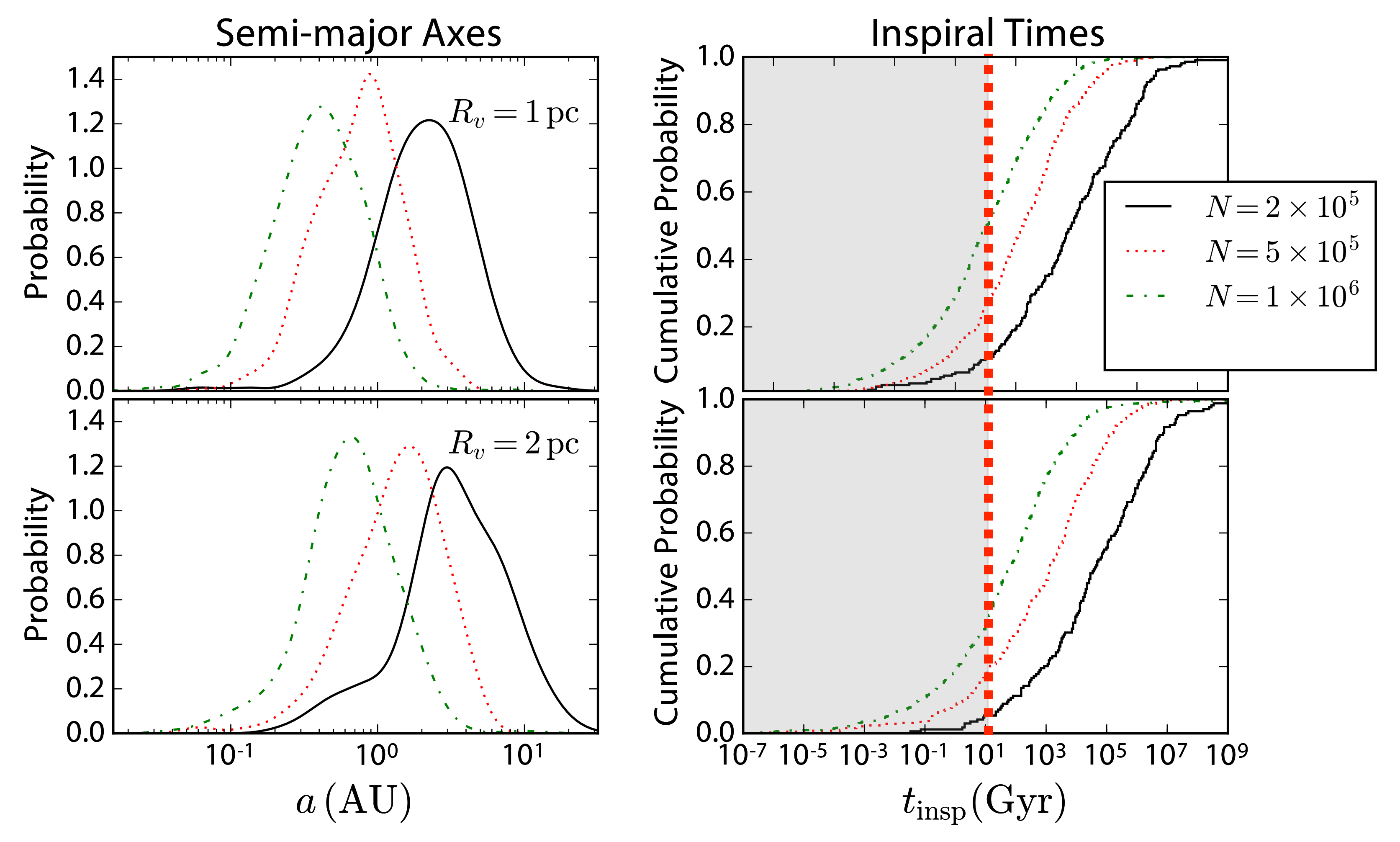

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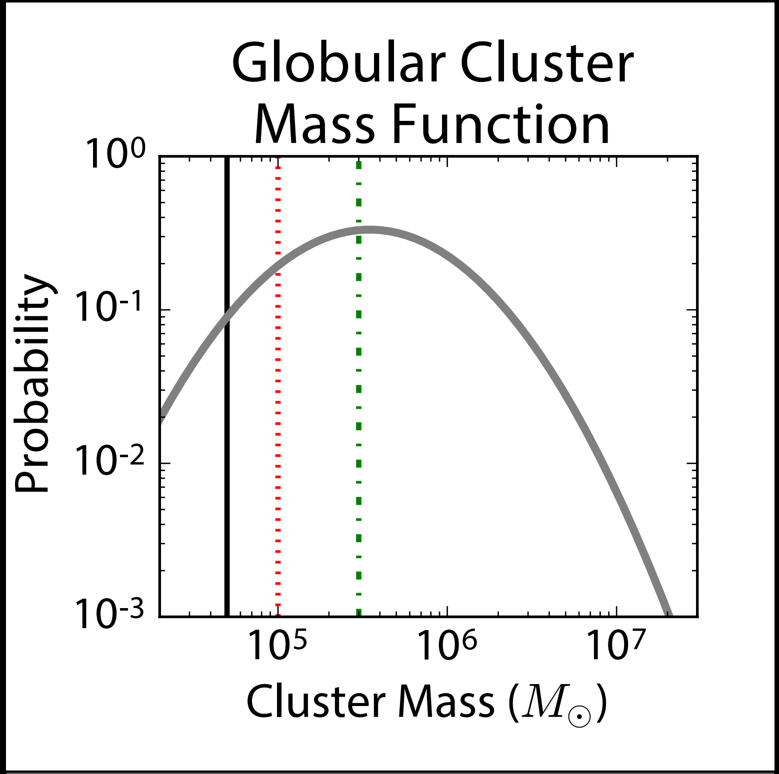

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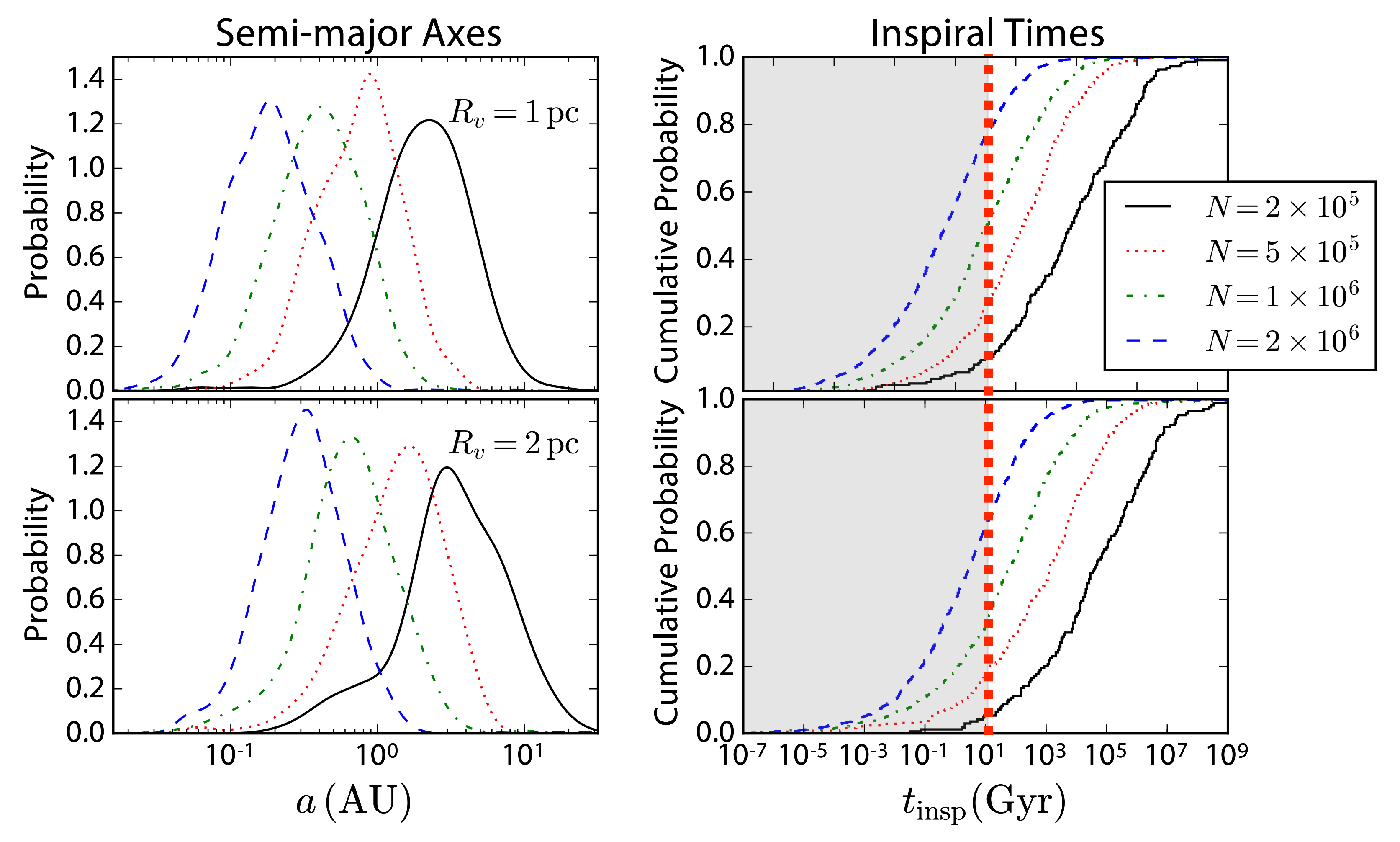

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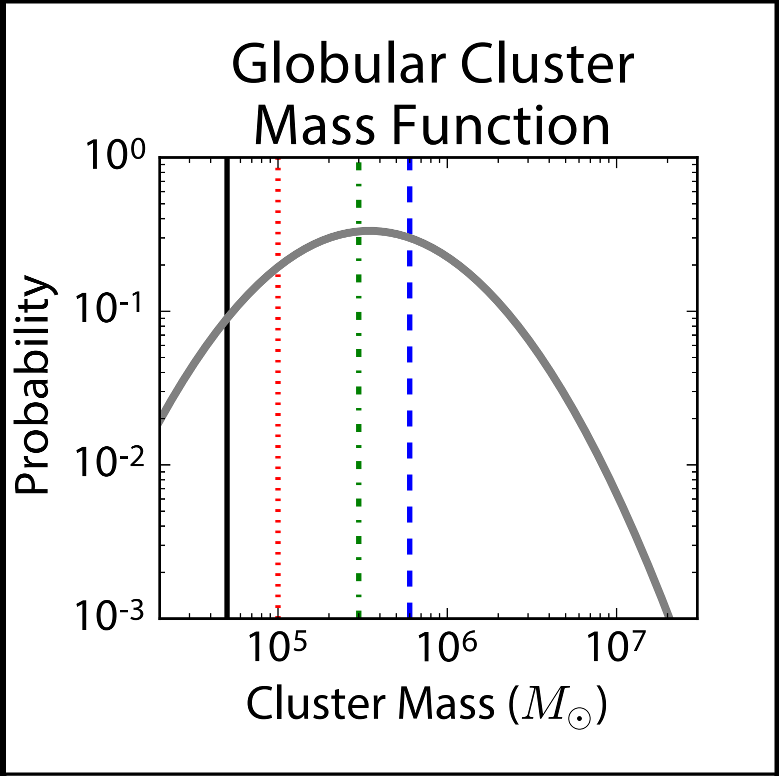
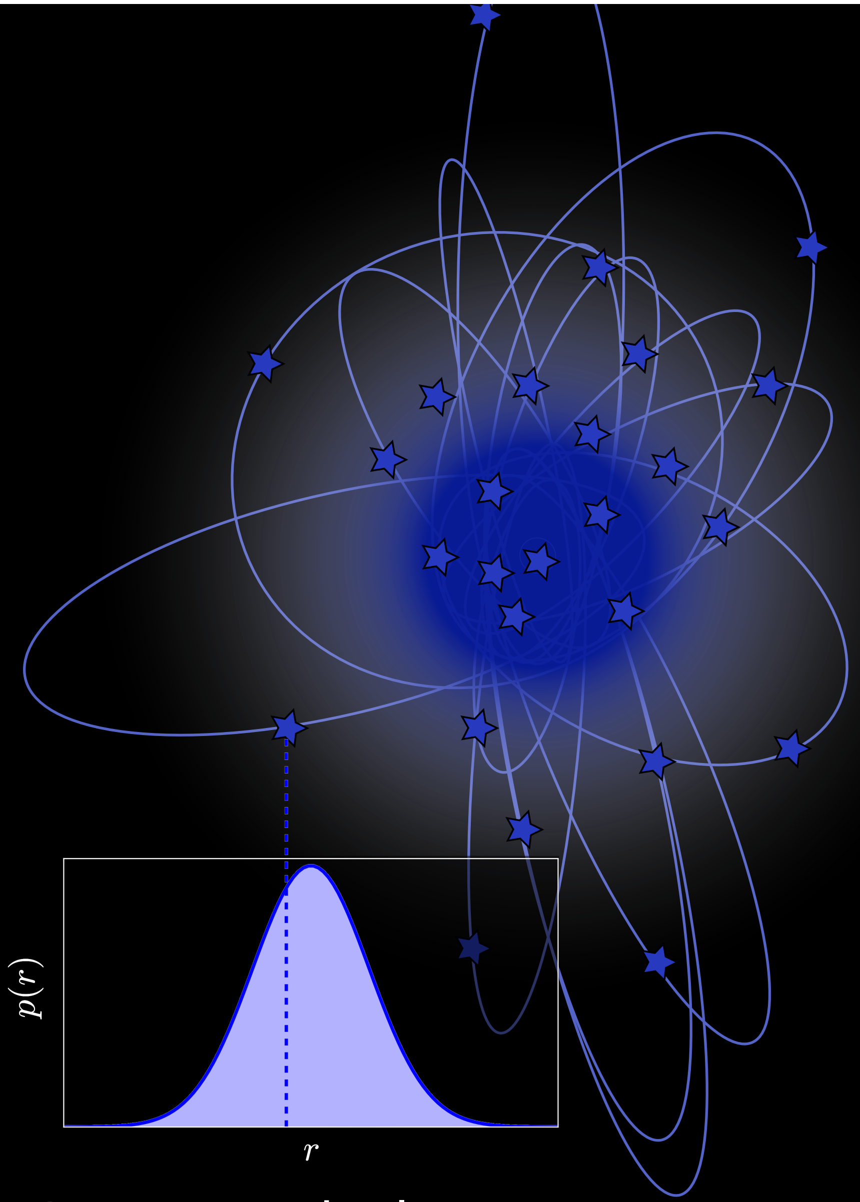
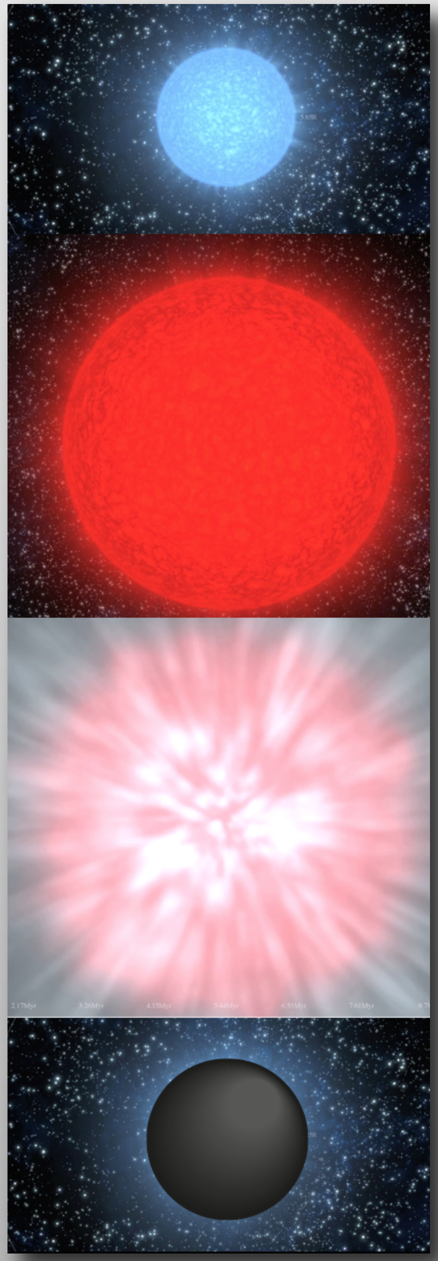


Monte Carlo Method



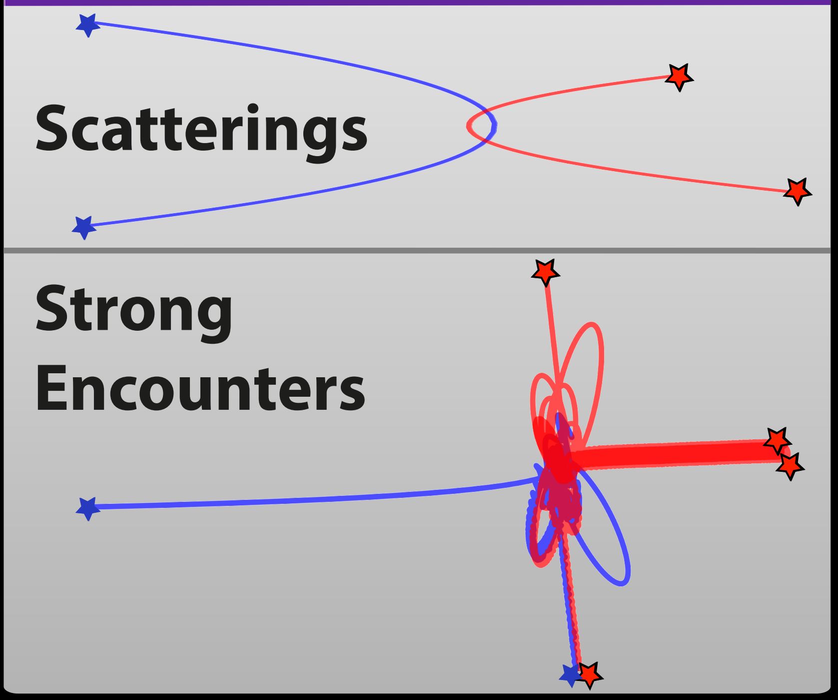
Positions and velocities determined by sampling orbits in a spherical potential

Stellar Evolution



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

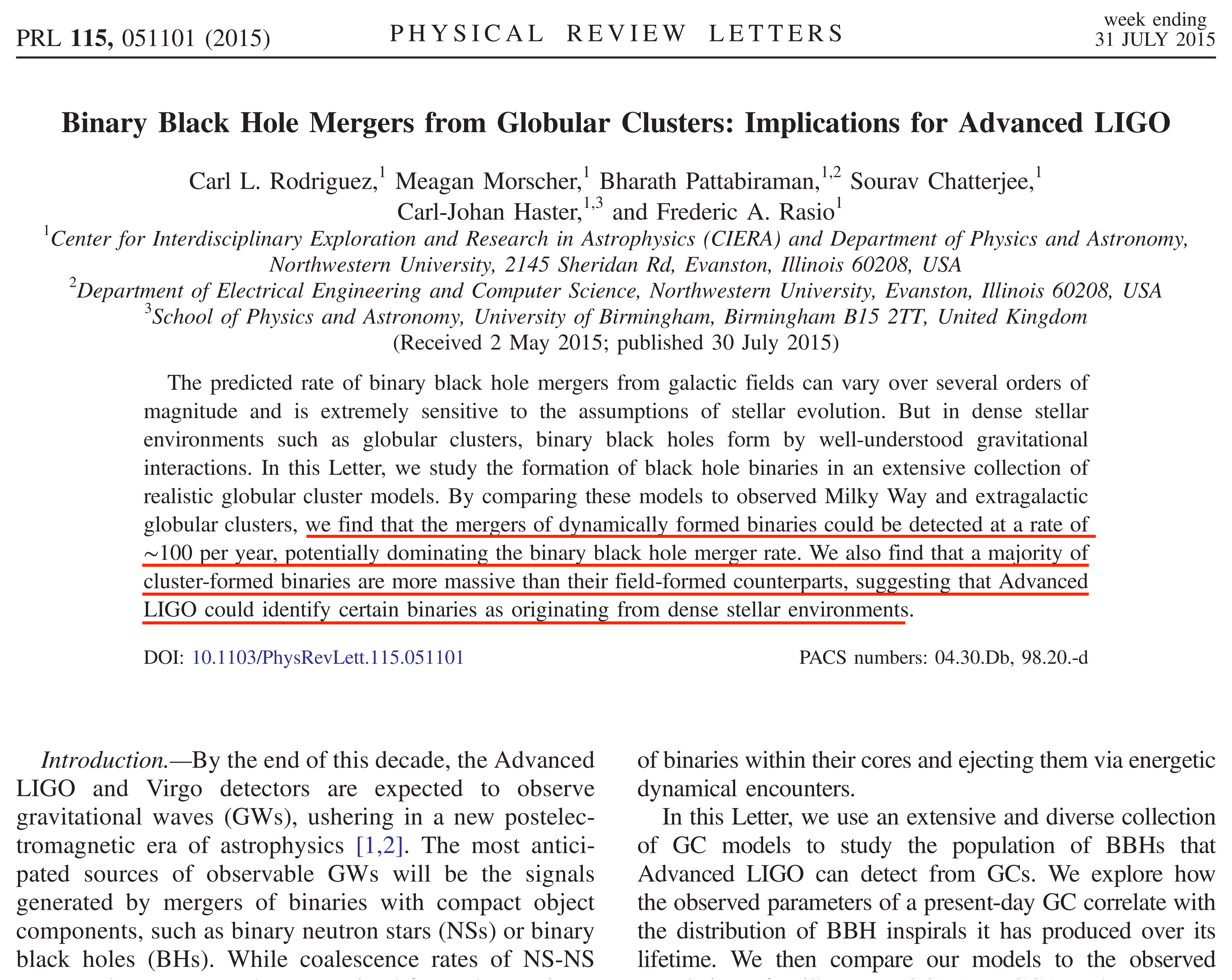
Dynamical Interactions



Theoretical Expectations for Dynamically Produced LIGO Sources

- For many years theorists have predicted that dense star clusters could play a key role in producing merging black hole binaries
  (Portegies Zwart & McMillan 2000, ApJL)

- Our most detailed predictions for LIGO came out just before the first detection…
  (Rodriguez et al. 2015, PRL)



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

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

Carl L. Rodriguez,[1] Meagan Morscher,[1] Bharath Pattabiraman,[1,2] Sourav Chatterjee,[1]
Carl-Johan Haster,[1,3] and Frederic A. Rasio[1]
[1] *Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Rd, Evanston, Illinois 60208, USA*
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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.

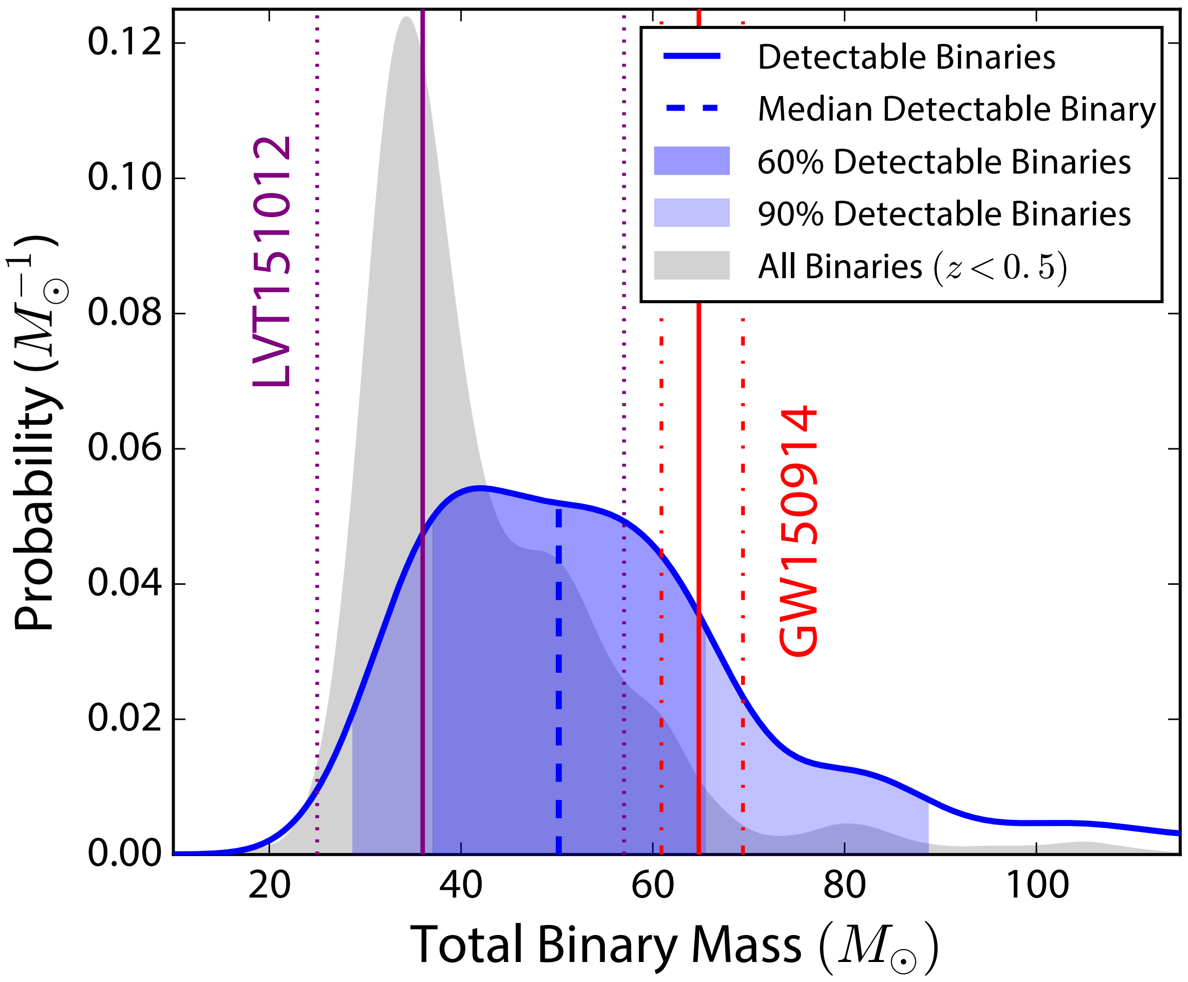
DOI: 10.1103/PhysRevLett.115.051101 PACS numbers: 04.30.Db, 98.20.-d

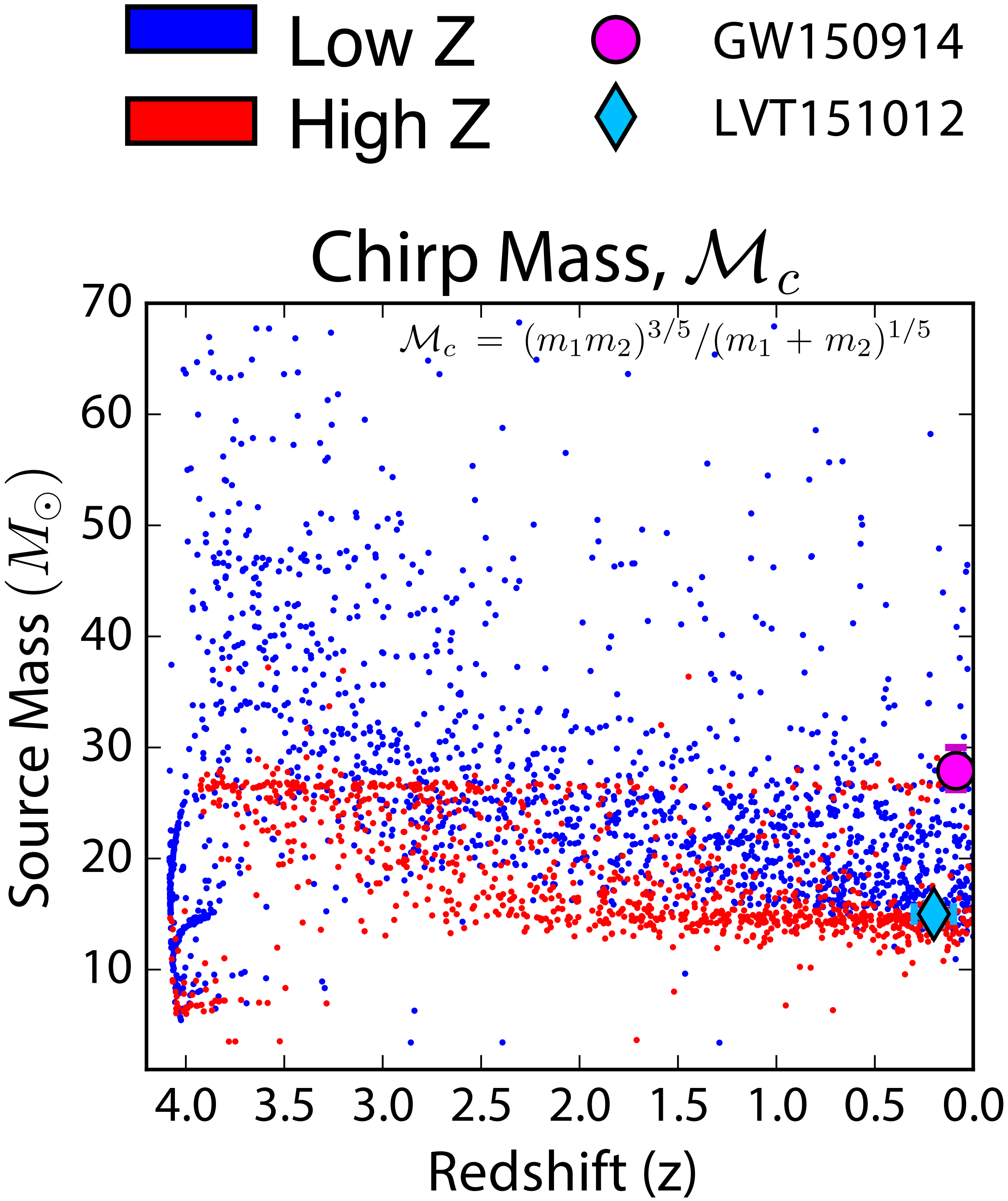
Introduction.—By the end of this decade, the Advanced LIGO and Virgo detectors are expected to observe gravitational waves (GWs), ushering in a new postelectromagnetic era of astrophysics [1,2]. The most anticipated sources of observable GWs will be the signals generated by mergers of binaries with compact object components, such as binary neutron stars (NSs) or binary black holes (BHs). While coalescence rates of NS-NS

of binaries within their cores and ejecting them via energetic dynamical encounters.

In this Letter, we use an extensive and diverse collection of GC models to study the population of BBHs that Advanced LIGO can detect from GCs. We explore how the observed parameters of a present-day GC correlate with the distribution of BBH inspirals it has produced over its lifetime. We then compare our models to the observed

Binary Masses

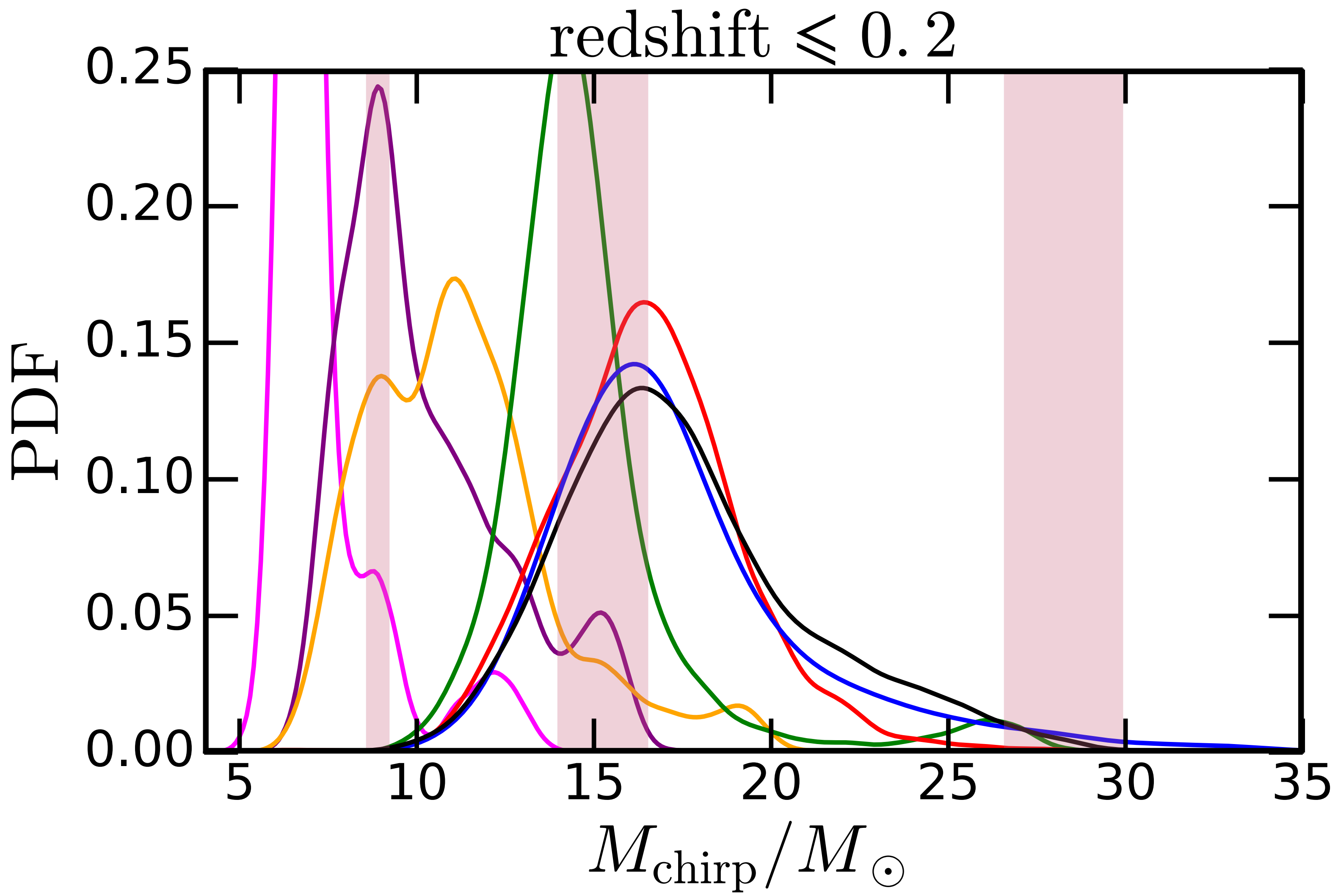




Rodriguez et al. 2016 ApJL

Binary Masses

Lower mass systems form easily in younger, higher metallicity clusters…



Chatterjee et al. 2016 ApJL, submitted

Merger Rates

Mergers	**Pessimistic**	**Realistic**	**Optimistic**
O1 (Detections / 16 Days)	0.05	0.2	0.7
O1 (Detections / 50 Days)	0.2	0.5	2
O2 (Detections / Year)	4	15	60
Design Sensitivity (Detections / Year)	30	100	400

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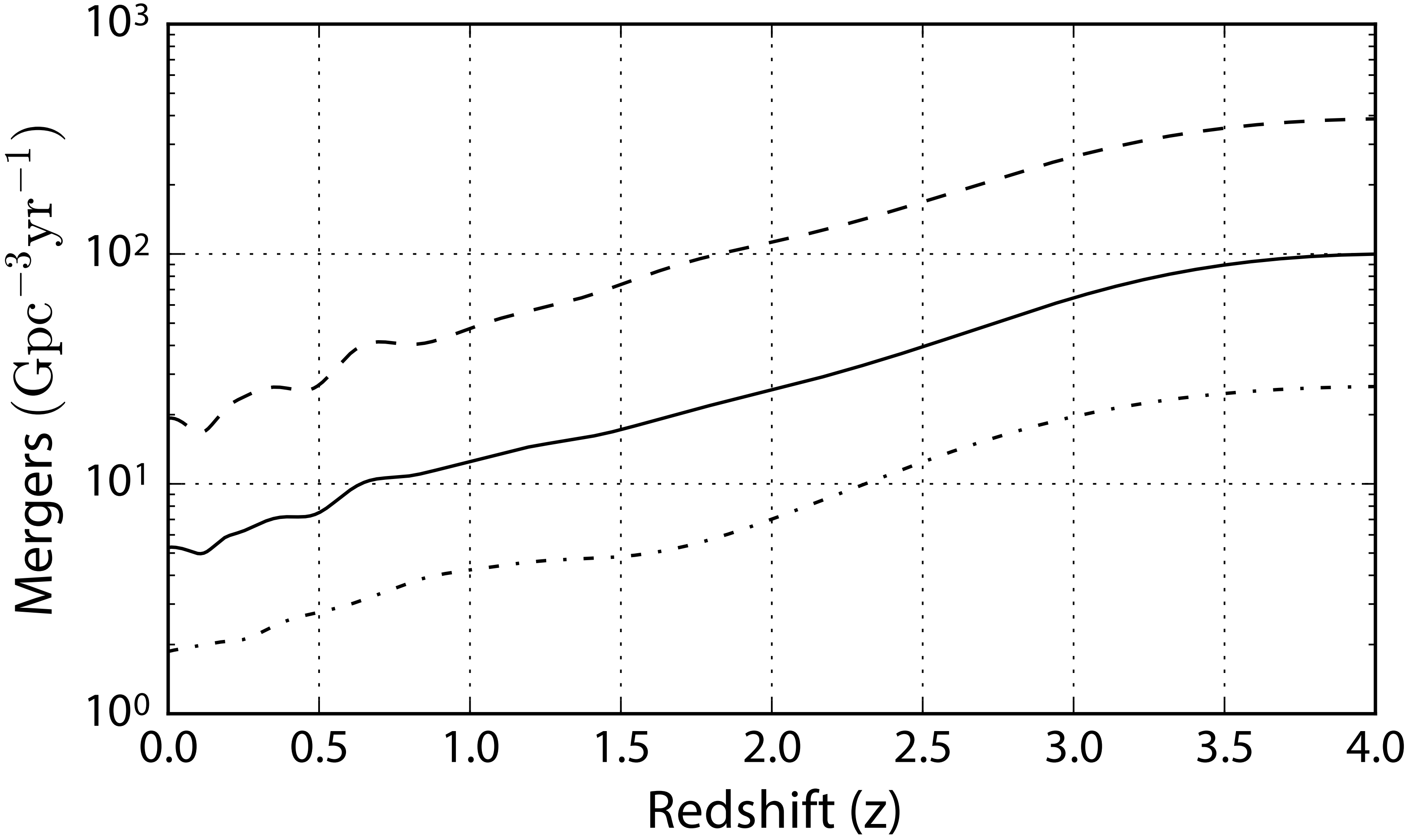

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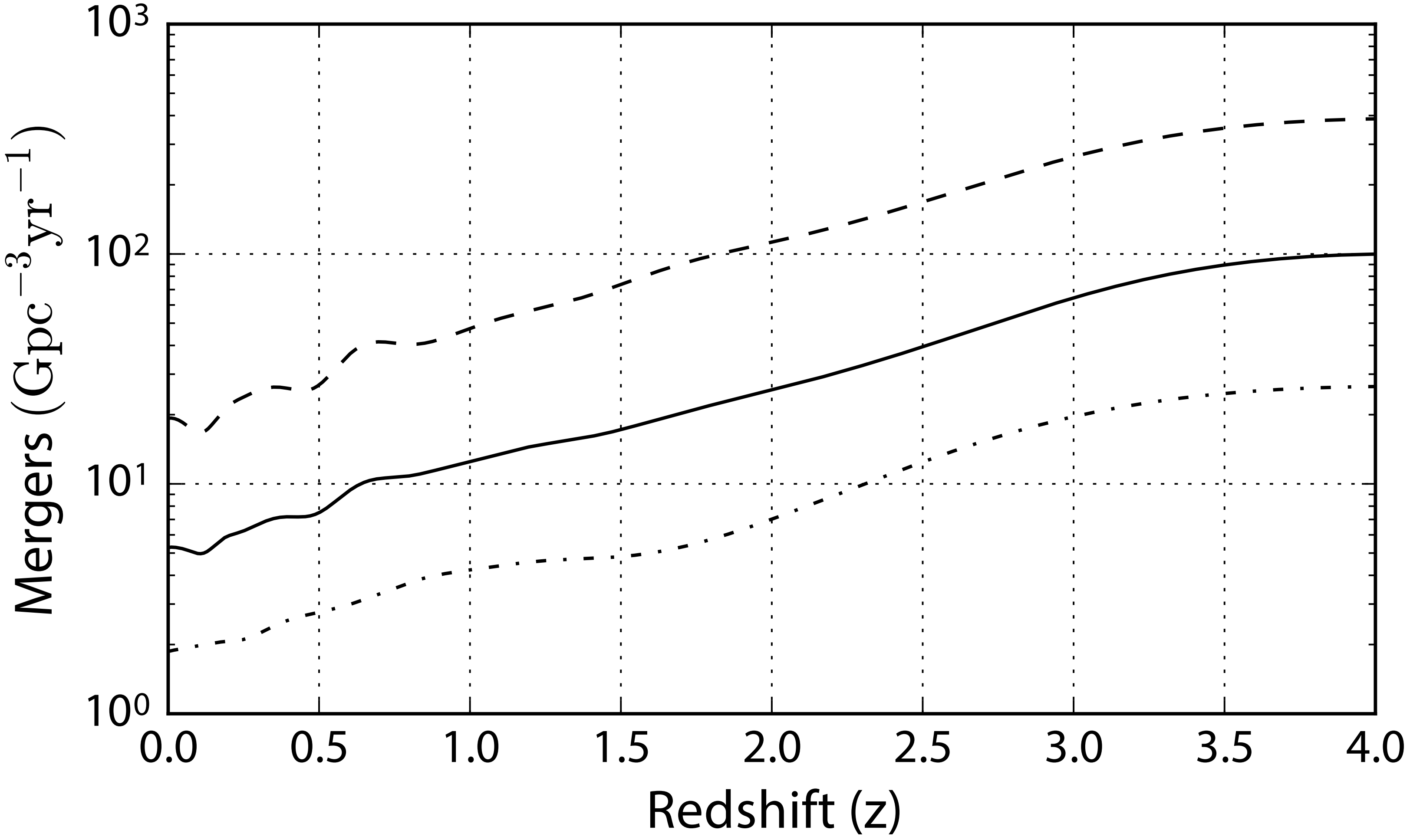

$$5\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

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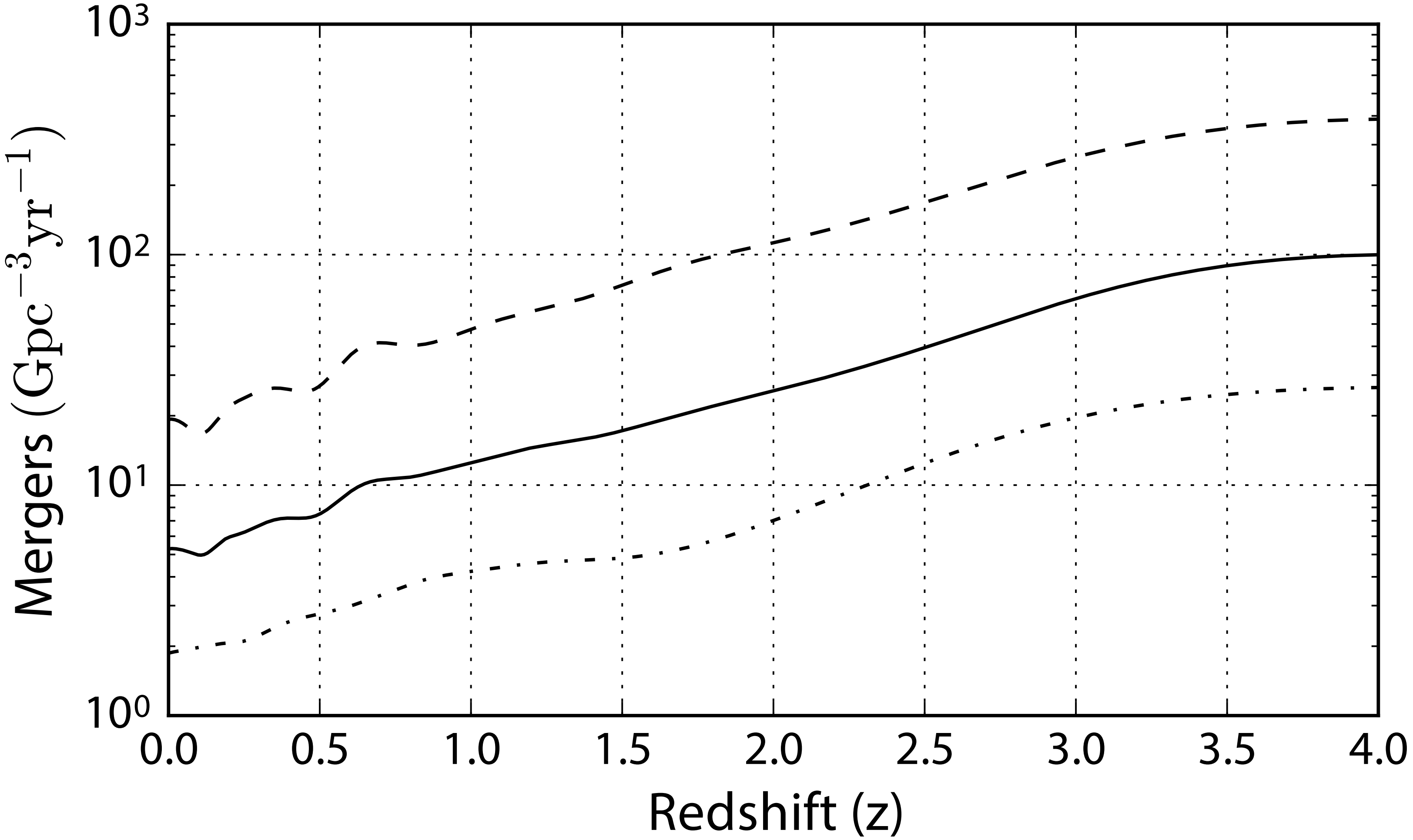

$$5\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

(agrees with Askar et al. 2016
— in next talk!)

Binary Evolution vs Dynamics

Binary Evolution vs Dynamics

- Masses and mass ratios <– not promising

  (Chatterjee et al. 2016, in prep)

Binary Evolution vs Dynamics

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- Eccentricity <– need LISA! not with LIGO
  (Breivik et al. 2016, ApJ, in press)

Binary Evolution vs Dynamics

- Masses and mass ratios <– not promising

  (Chatterjee et al. 2016, in prep)
- Eccentricity <– need LISA! not with LIGO

  (Breivik et al. 2016, ApJ, in press)
- Spins <– most promising!

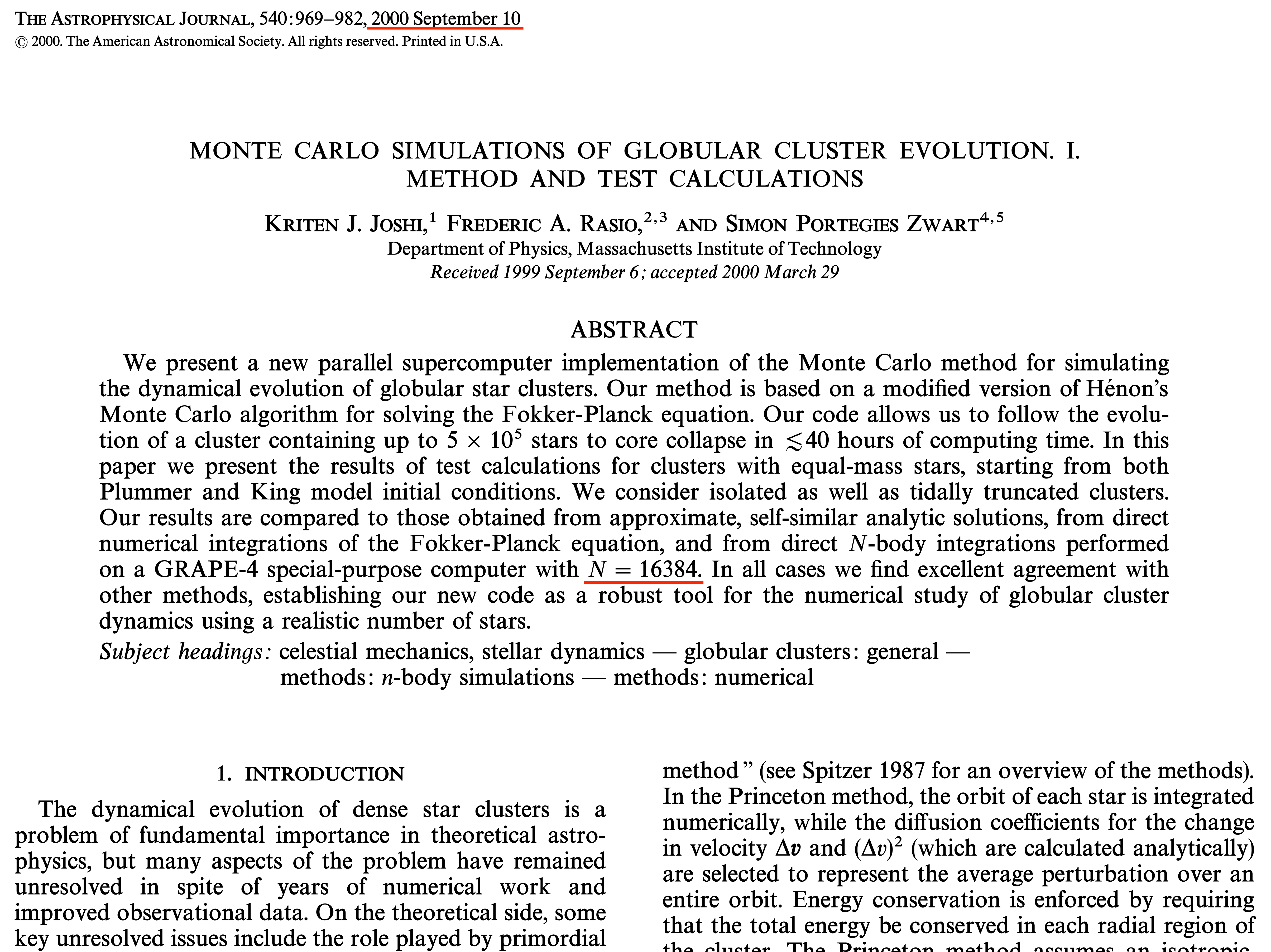
  (Rodriguez et al. 2016, ApJL, submitted)

Ask me about:

- Triples and Kozai captures (Antonini et al. 2016; Silsbee & Tremaine 2016)
- More massive star clusters: galactic nuclei, UCDs etc. (Antonini & Rasio 2016)
- Neutron stars (and NS-BH or NS-NS mergers from star clusters)

Conclusions

- Stellar dynamics in dense star clusters produces black hole binaries that merge at high rates in the local universe
- More massive systems preferentially made in old, massive globular clusters
- Less massive systems can be made in younger, higher-metallicity clusters
- Formation through stellar dynamics is easier to model and has fewer uncertainties than massive binary evolution
- The (near-)future of GW astrophysics looks very exciting!



THE ASTROPHYSICAL JOURNAL, 540:969–982, 2000 September 10

MONTE CARLO SIMULATIONS OF GLOBULAR CLUSTER EVOLUTION. I. METHOD AND TEST CALCULATIONS

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Received 1999 September 6; accepted 2000 March 29

ABSTRACT

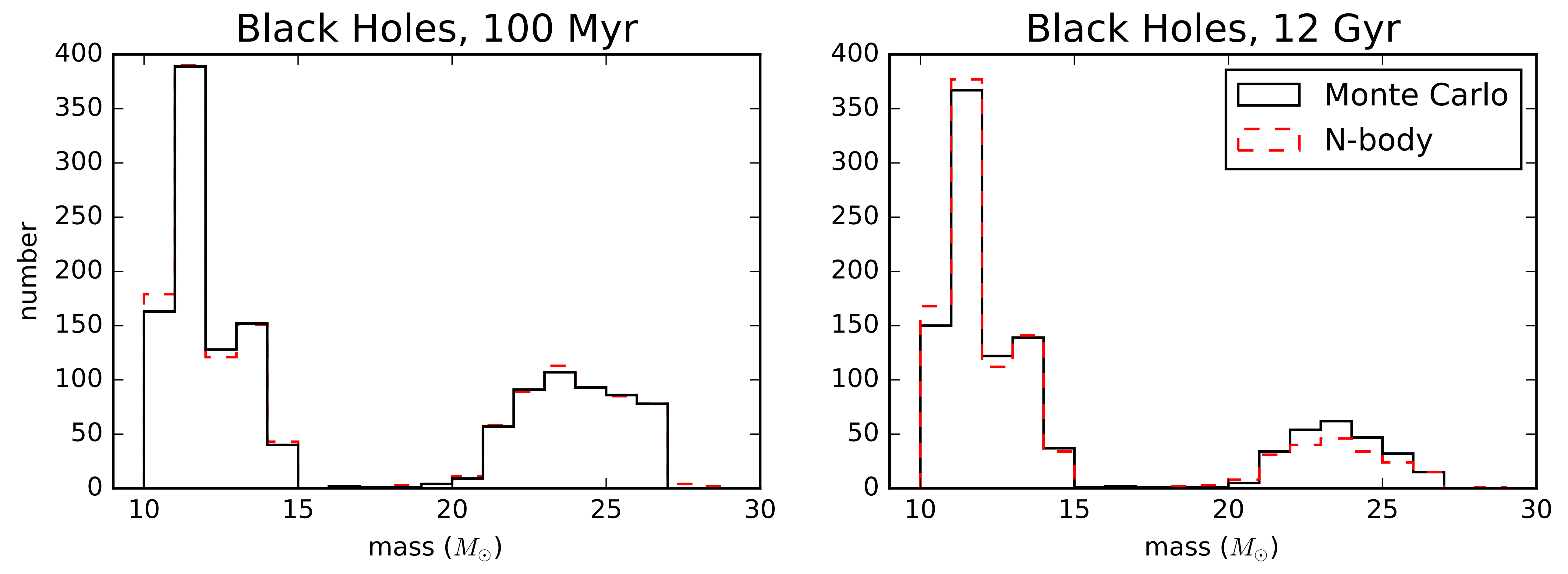
We present a new parallel supercomputer implementation of the Monte Carlo method for simulating the dynamical evolution of globular star clusters. Our method is based on a modified version of Hénon's Monte Carlo algorithm for solving the Fokker-Planck equation. Our code allows us to follow the evolution of a cluster containing up to 5×10^5 stars to core collapse in $\lesssim 40$ hours of computing time. In this paper we present the results of test calculations for clusters with equal-mass stars, starting from both Plummer and King model initial conditions. We consider isolated as well as tidally truncated clusters. Our results are compared to those obtained from approximate, self-similar analytic solutions, from direct numerical integrations of the Fokker-Planck equation, and from direct N-body integrations performed on a GRAPE-4 special-purpose computer with $N = 16384$. In all cases we find excellent agreement with other methods, establishing our new code as a robust tool for the numerical study of globular cluster dynamics using a realistic number of stars.

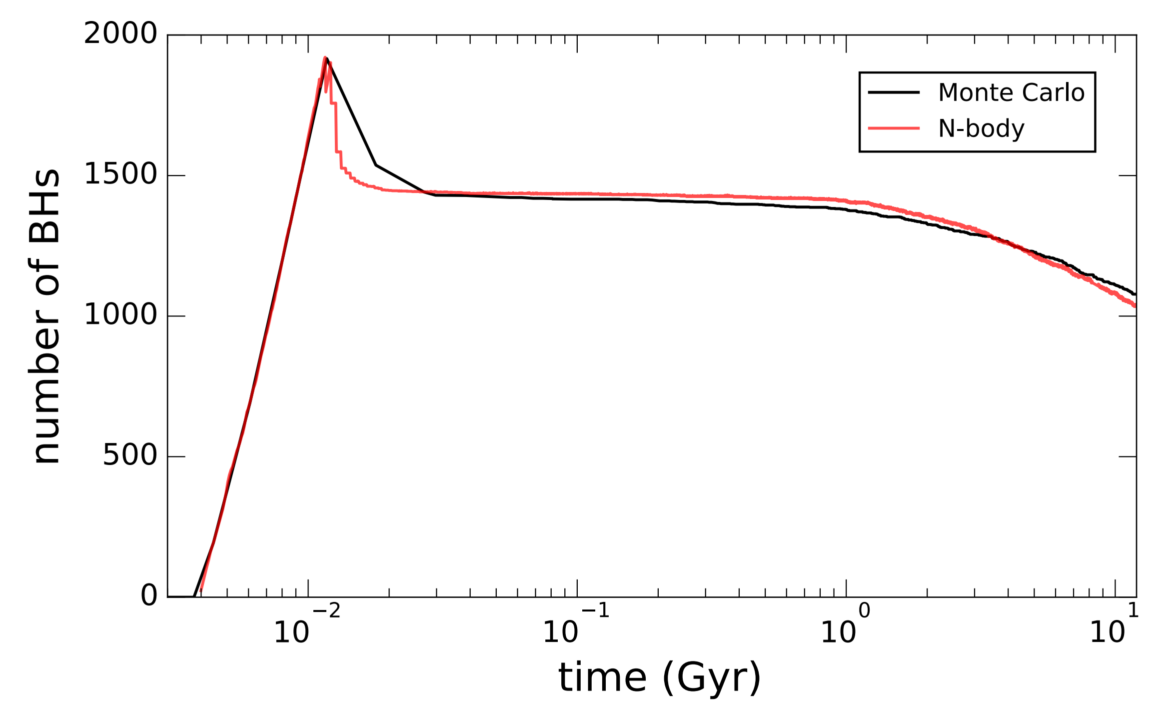
Subject headings: celestial mechanics, stellar dynamics — globular clusters: general — methods: n-body simulations — methods: numerical

1. INTRODUCTION

The dynamical evolution of dense star clusters is a problem of fundamental importance in theoretical astrophysics, but many aspects of the problem have remained unresolved in spite of years of numerical work and improved observational data. On the theoretical side, some key unresolved issues include the role played by primordial

method" (see Spitzer 1987 for an overview of the methods). In the Princeton method, the orbit of each star is integrated numerically, while the diffusion coefficients for the change in velocity $\Delta \boldsymbol{v}$ and $(\Delta v)^2$ (which are calculated analytically) are selected to represent the average perturbation over an entire orbit. Energy conservation is enforced by requiring that the total energy be conserved in each radial region of the cluster. The Princeton method assumes an isotropic

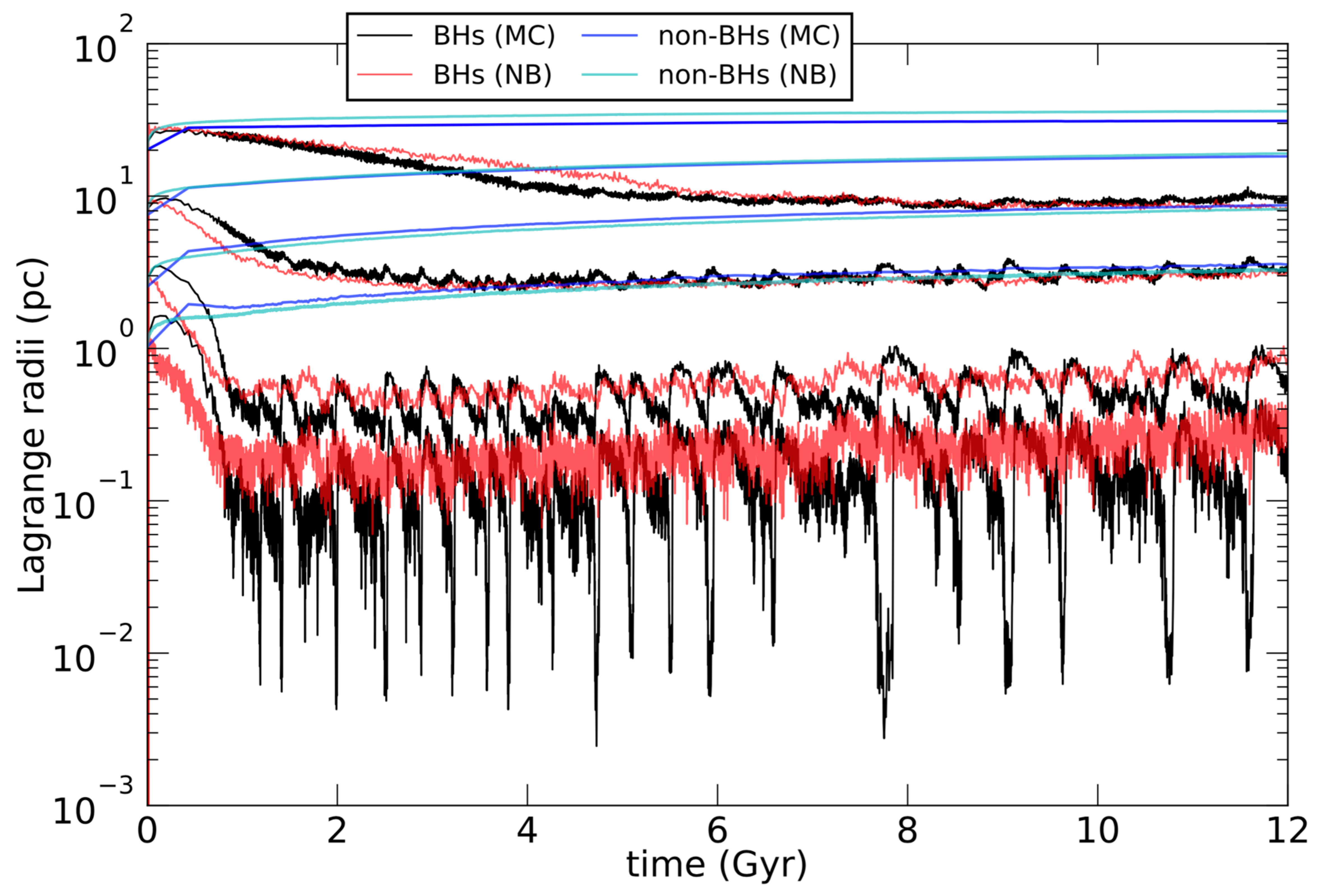




Rodriguez et al. 2016, MNRAS, in press

Comparison between CMC and Direct N-body code for cluster model with N=10^6 (NBODY6++GPU run lasting about 1 year!)

But nothing is perfect…



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Rodriguez et al. 2016, MNRAS, in press