Dense Star Clusters
as
Binary Black Hole Factories

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Northwestern University

Dense Star Clusters

Open Clusters
Globular Clusters
Nuclear Star Clusters

M30
(NASA/ACS Survey)

Globular Clusters

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

M30
(NASA/ACS Survey)

47 Tuc
(NASA/HST)

Globular Clusters

- Found in almost all galaxies

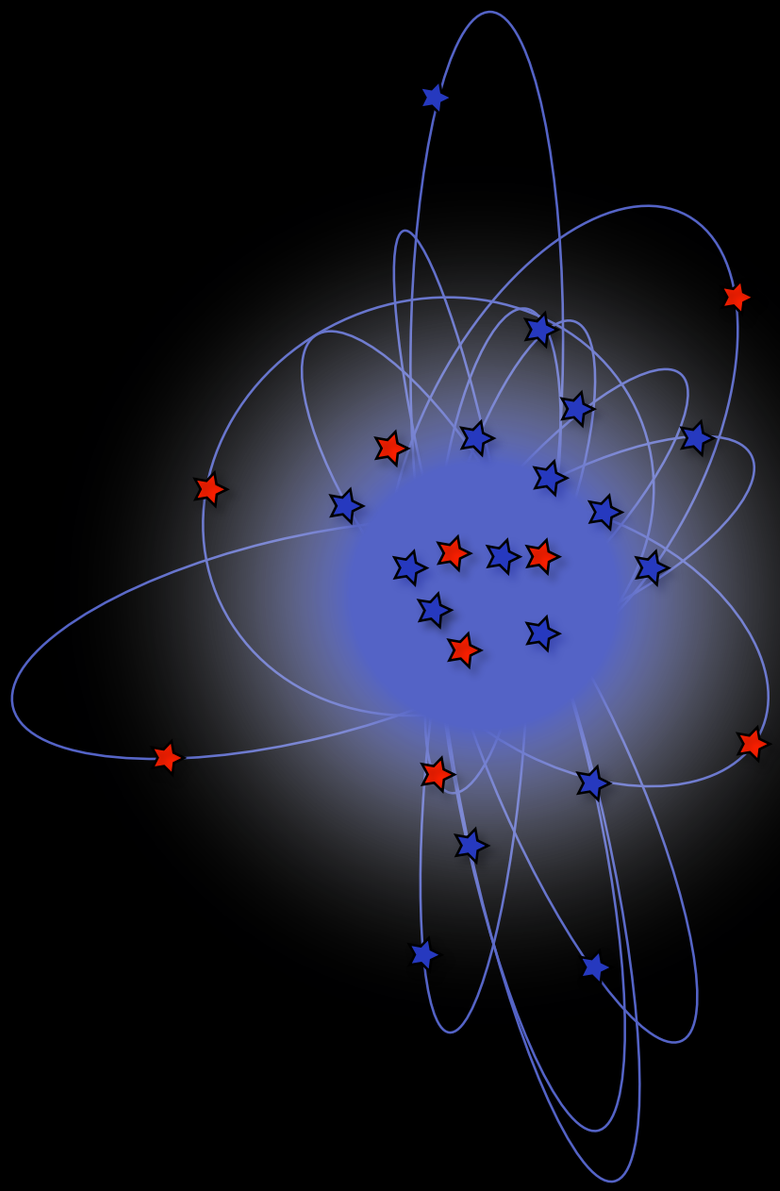
Milky Way

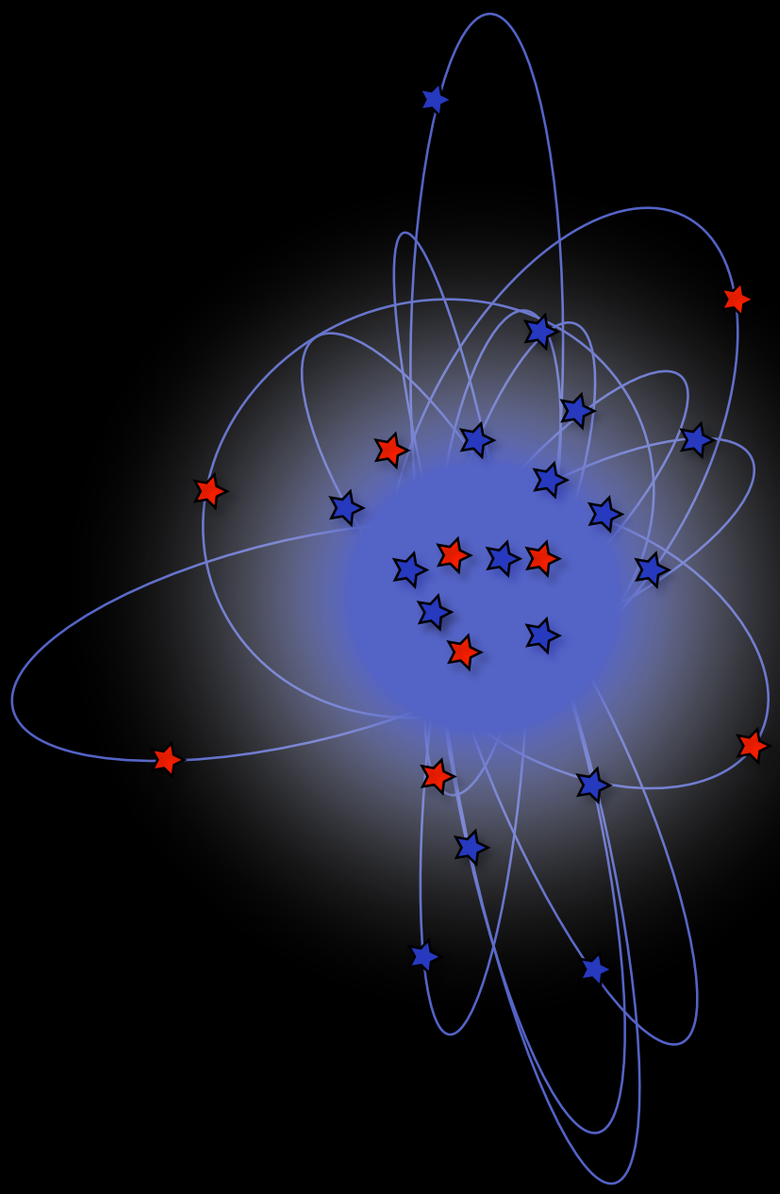
NASA/Adler/U. Chicago/Wesleyan/JPL-Caltech

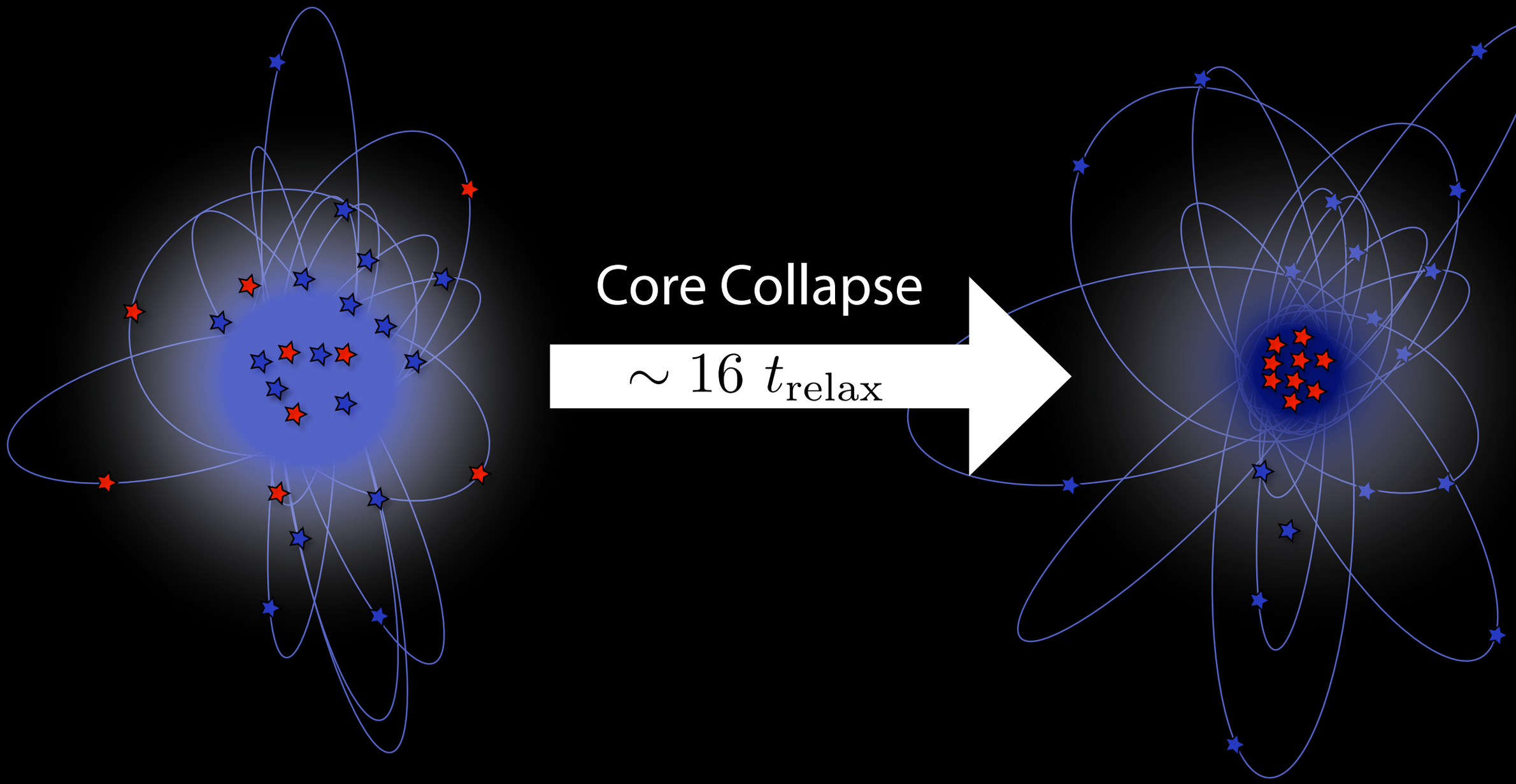
M87

Adam Block/Mt. Lemmon SkyCenter/U. Arizona

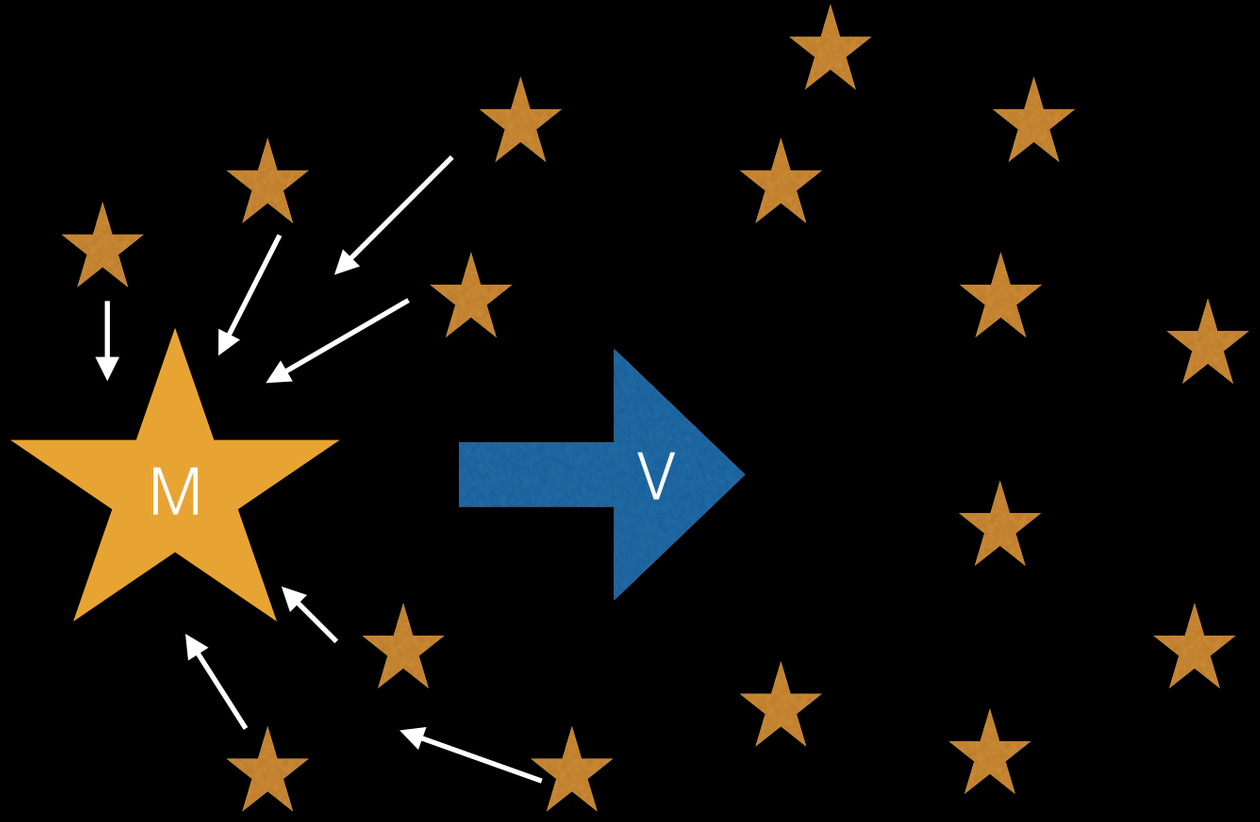
Globular Clusters



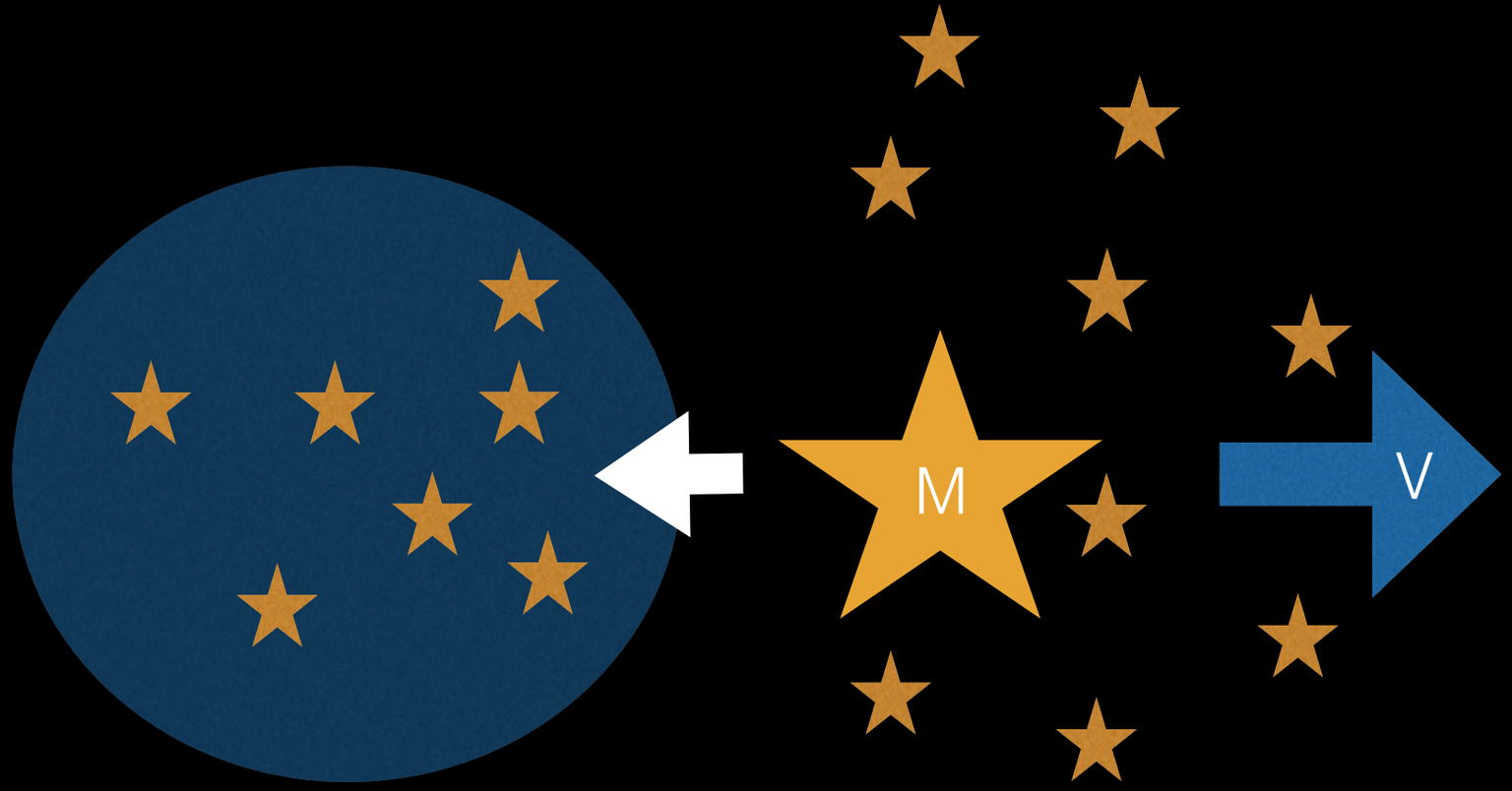



Core Collapse
$\sim 16\ t_{\rm relax}$

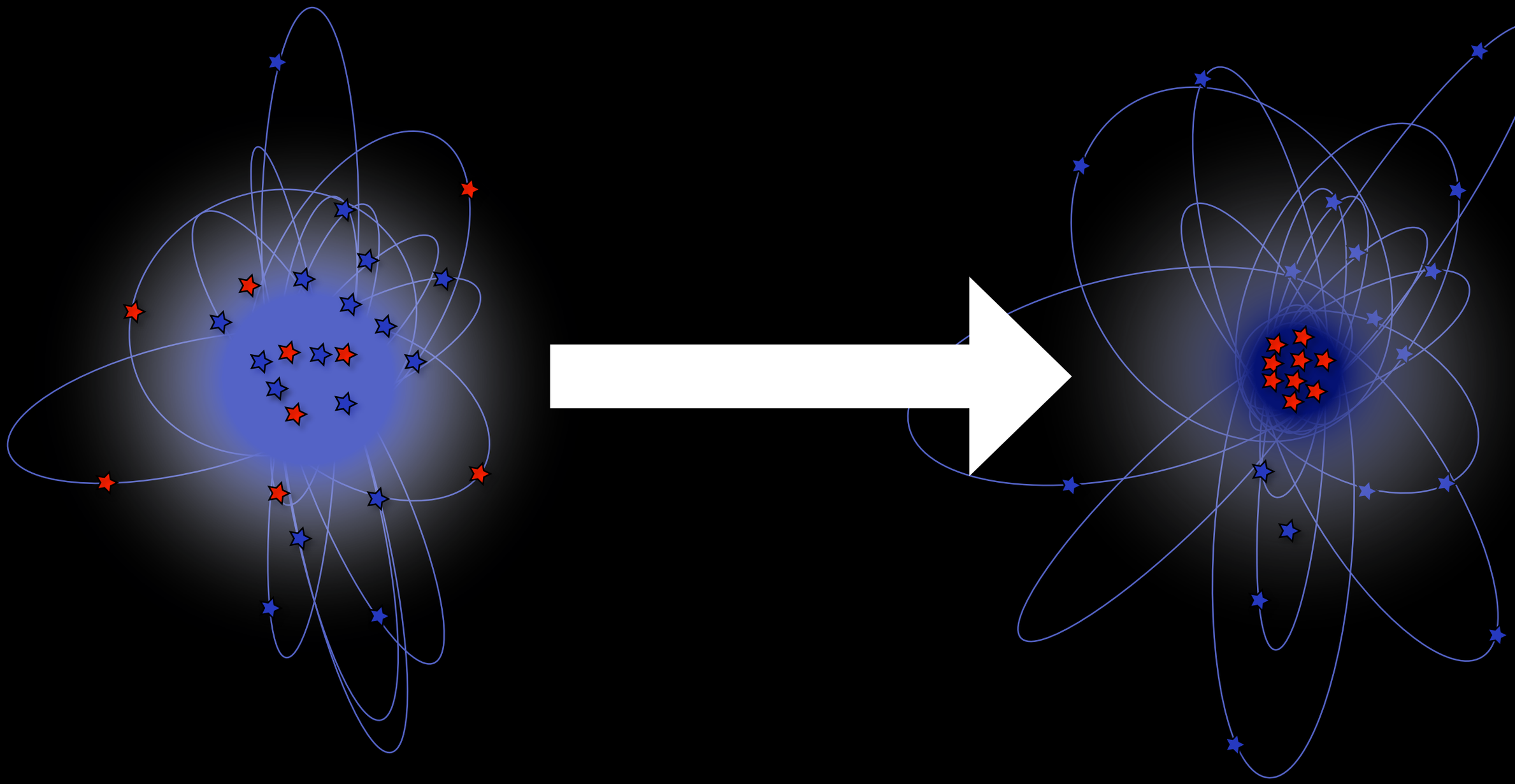
Dynamical Friction

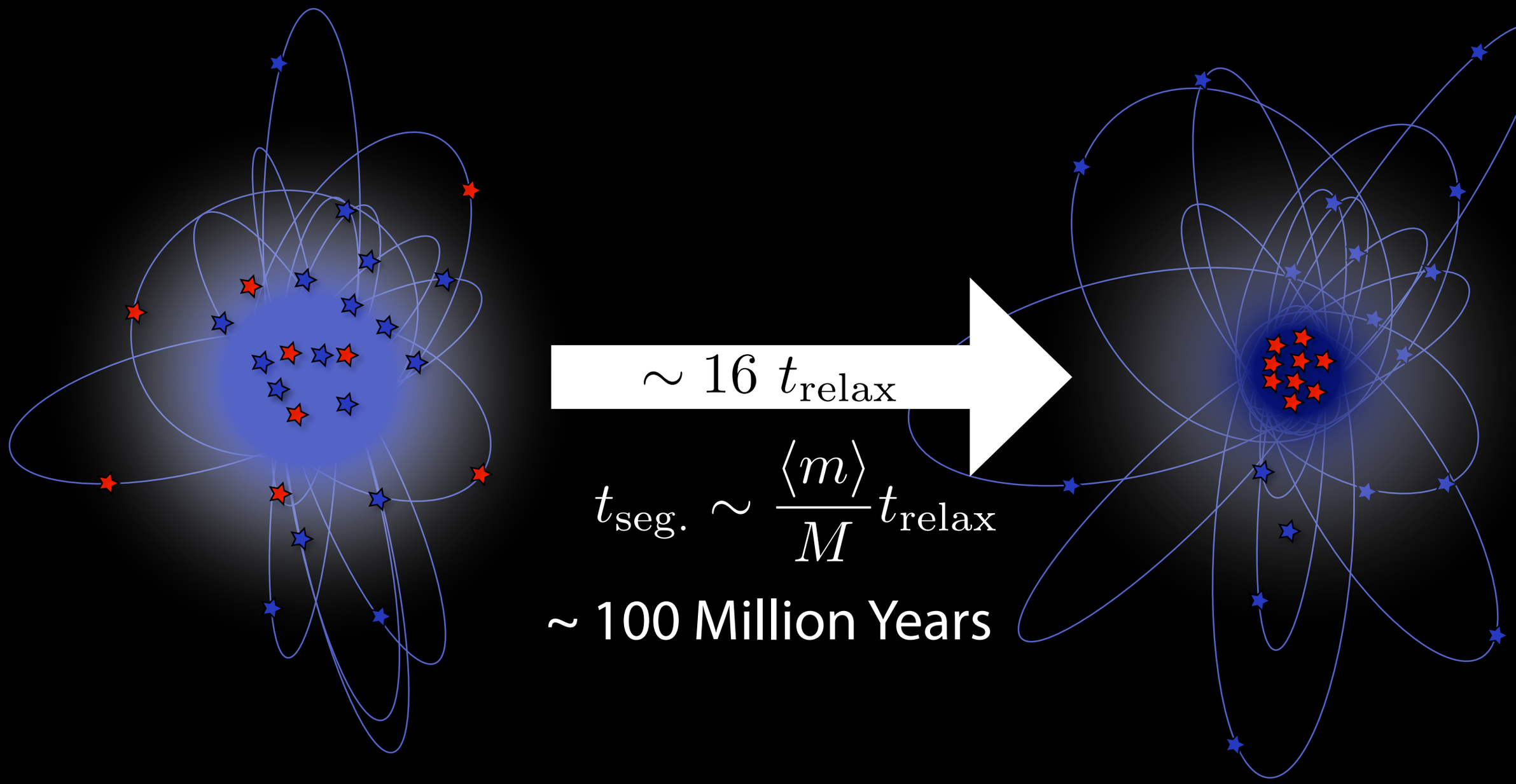


Dynamical Friction



Massive particles will “segregate” into center of the cluster




$\sim 16\ t_{\mathrm{relax}}$
$t_{\mathrm{seg.}} \sim \frac{\langle m \rangle}{M} t_{\mathrm{relax}}$
~ 100 Million Years

Black holes in Globular Clusters

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a

Black holes in Globular Clusters

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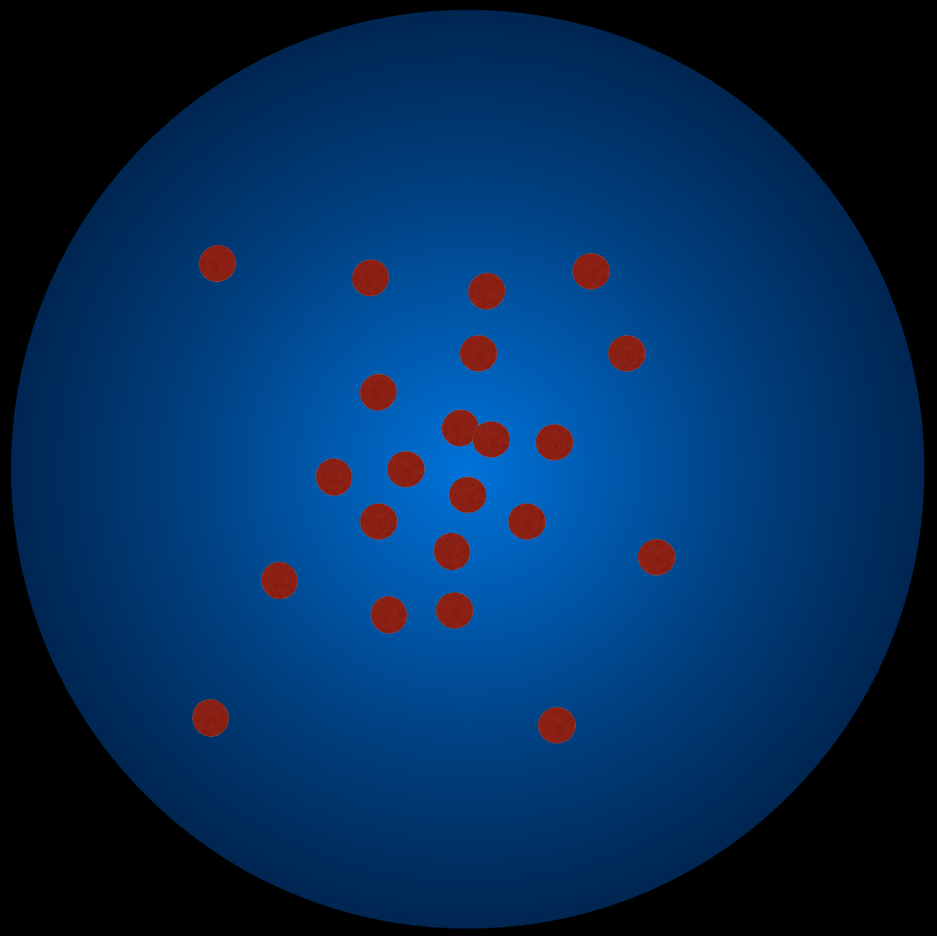

Black holes in Globular Clusters

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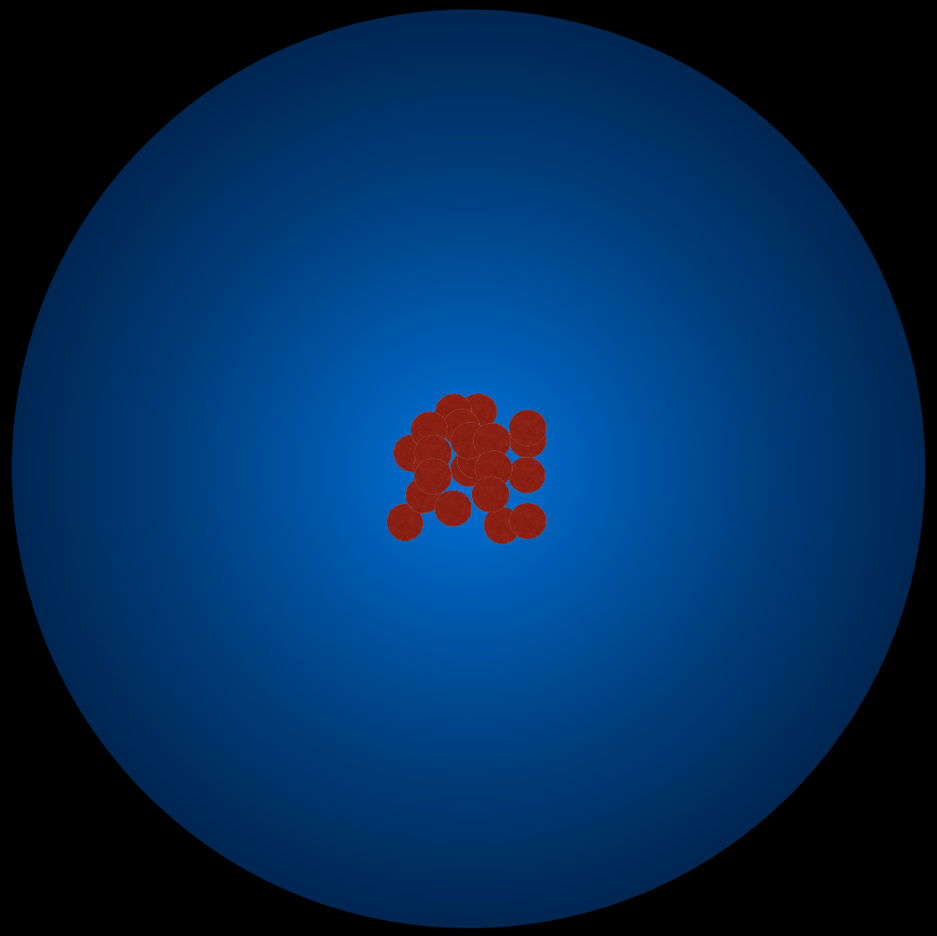

Black holes in Globular Clusters

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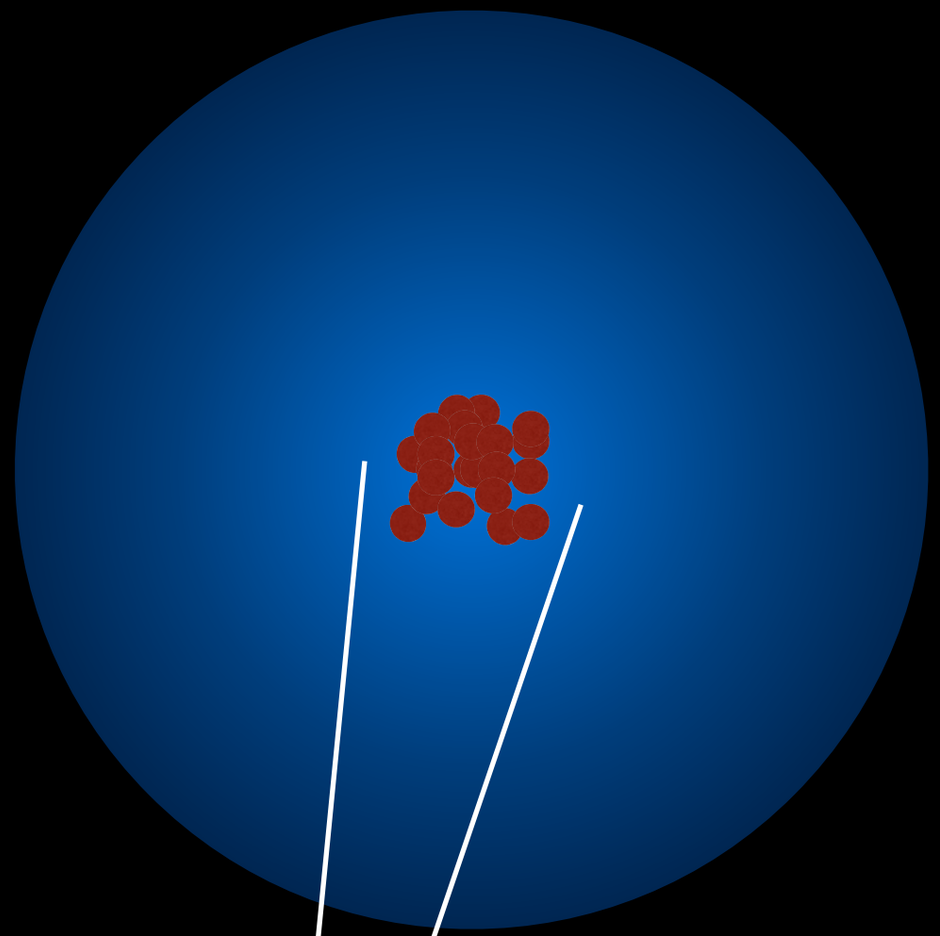

$$t_r^{BH} << t_{rh}$$

Black holes in Globular Clusters

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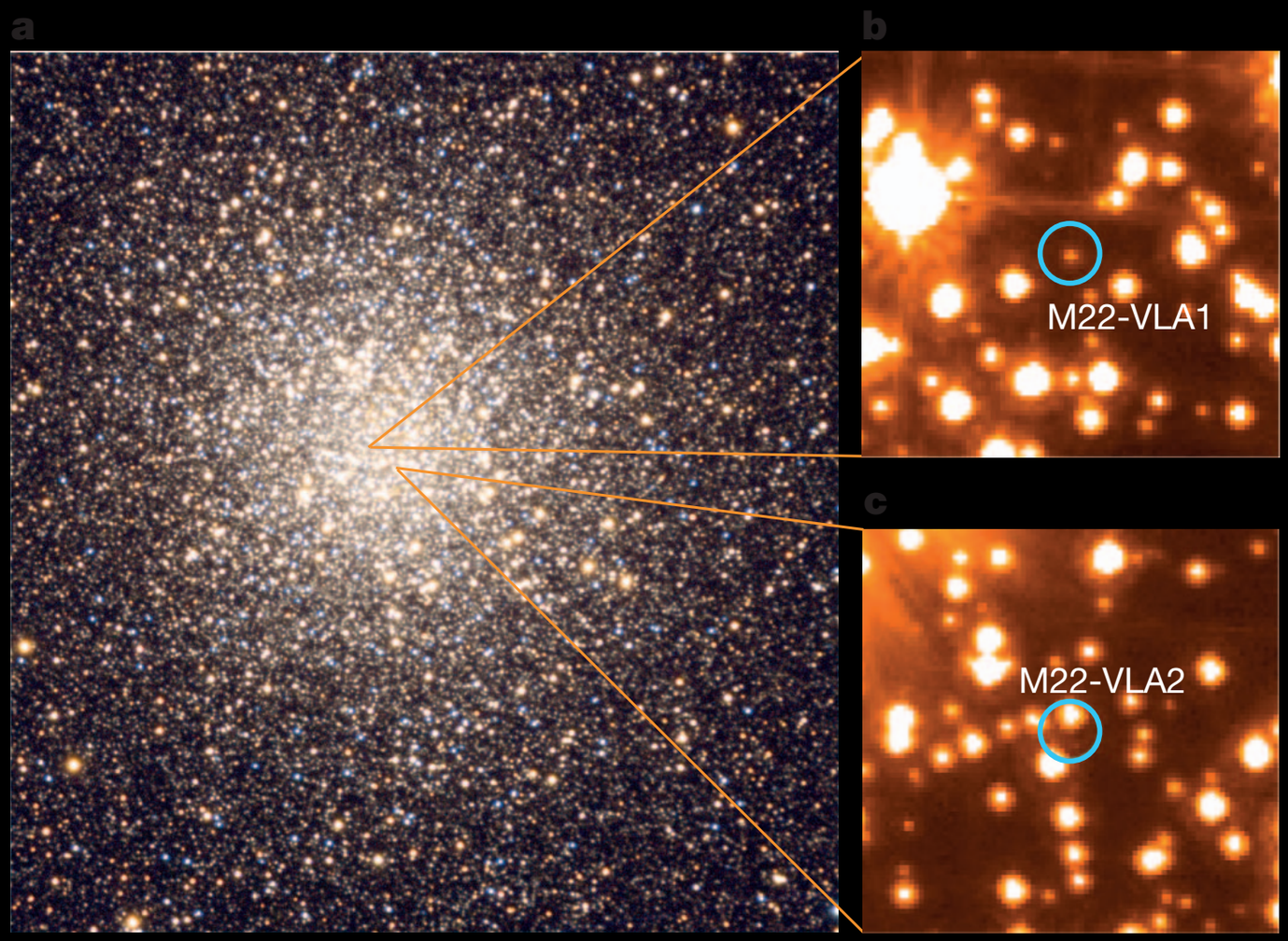
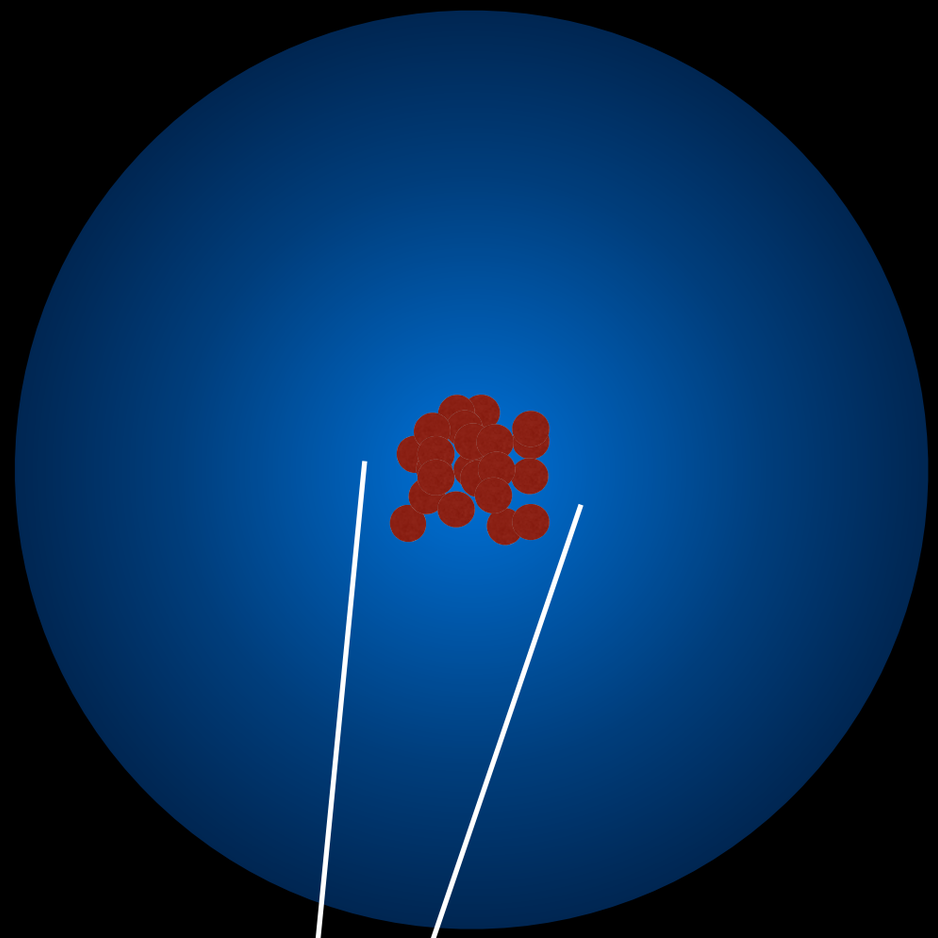
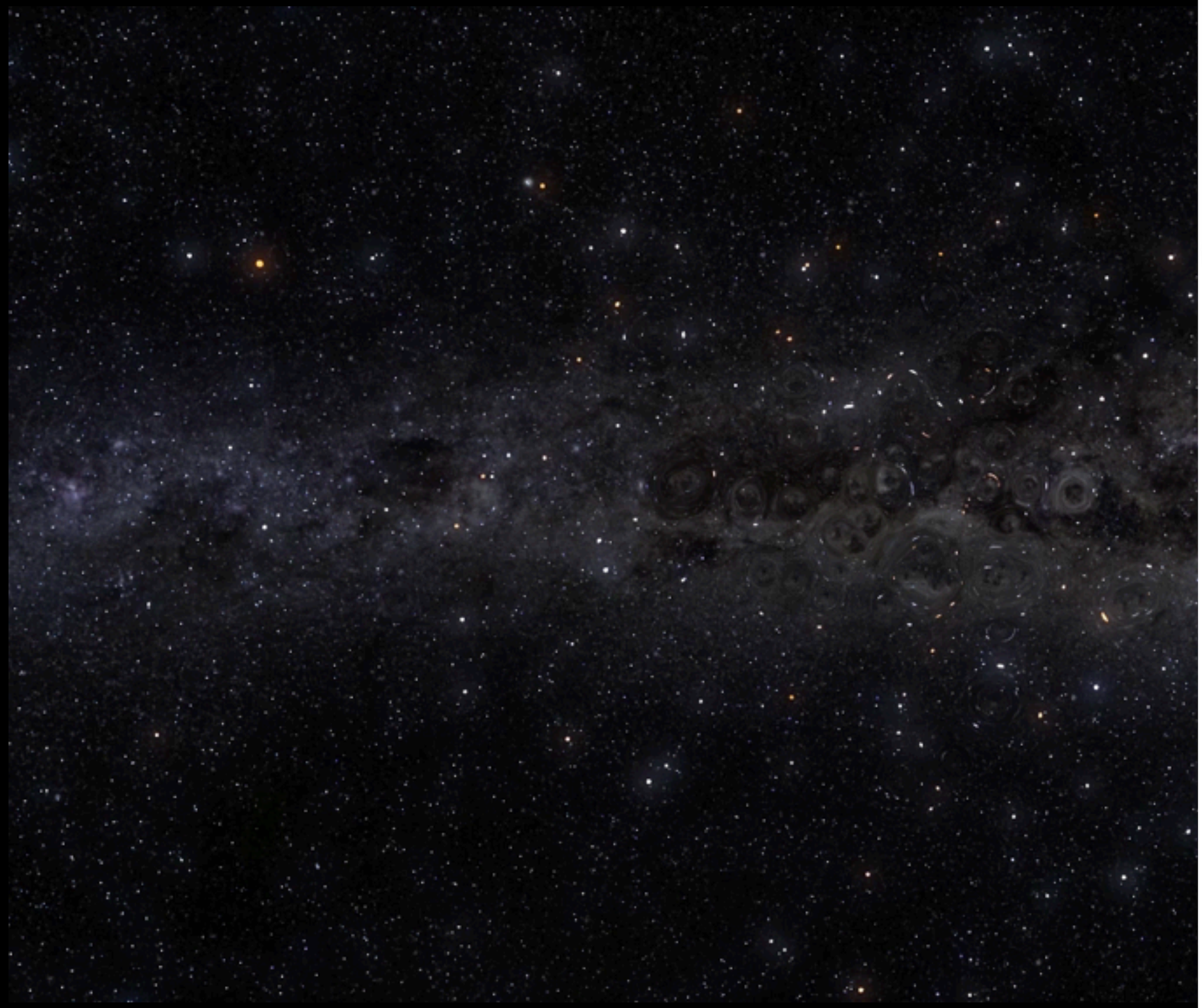
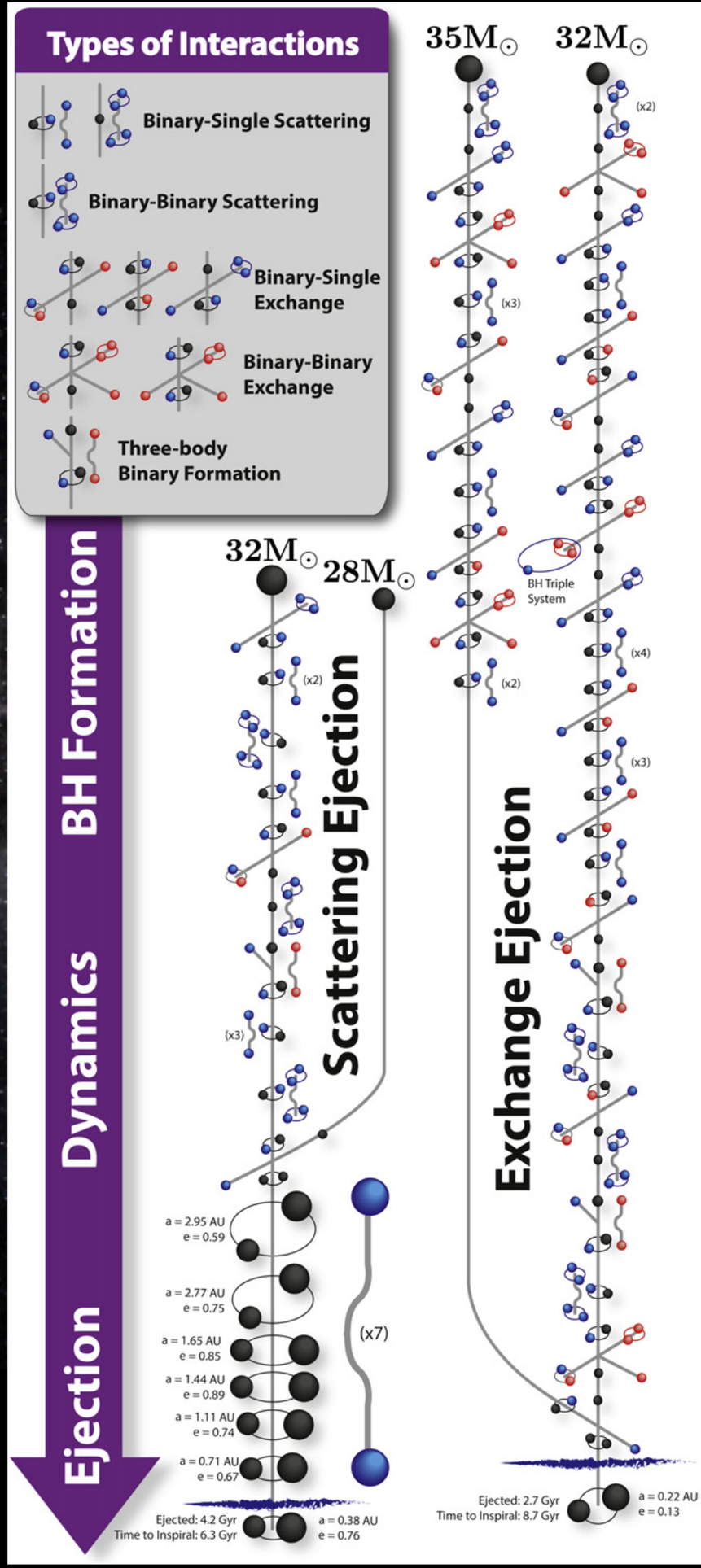


Strader et al., 2012



$$t_r^{BH} << t_{rh}$$




Types of Interactions
Binary-Single Scattering
Binary-Binary Scattering
Binary-Single Exchange
Binary-Binary Exchange
Three-body Binary Formation
BH Formation
Dynamics
Ejection
35M⊙
32M⊙
(x2)
(x3)
(x2)
BH Triple System
(x4)
(x3)
32M⊙
28M⊙
(x2)
(x3)
Scattering Ejection
a = 2.95 AU
e = 0.59
a = 2.77 AU
e = 0.75
a = 1.65 AU
e = 0.85
a = 1.44 AU
e = 0.89
a = 1.11 AU
e = 0.74
a = 0.71 AU
e = 0.67
(x7)
Ejected: 4.2 Gyr
Time to Inspiral: 6.3 Gyr
a = 0.38 AU
e = 0.76
Exchange Ejection
Ejected: 2.7 Gyr
Time to Inspiral: 8.7 Gyr
a = 0.22 AU
e = 0.13

Chaotic Interactions

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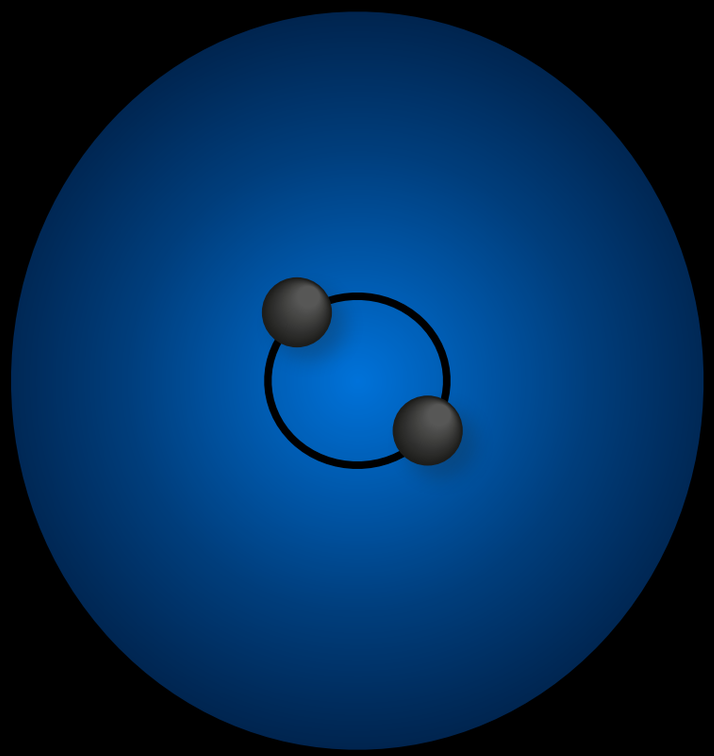

Chaotic Interactions

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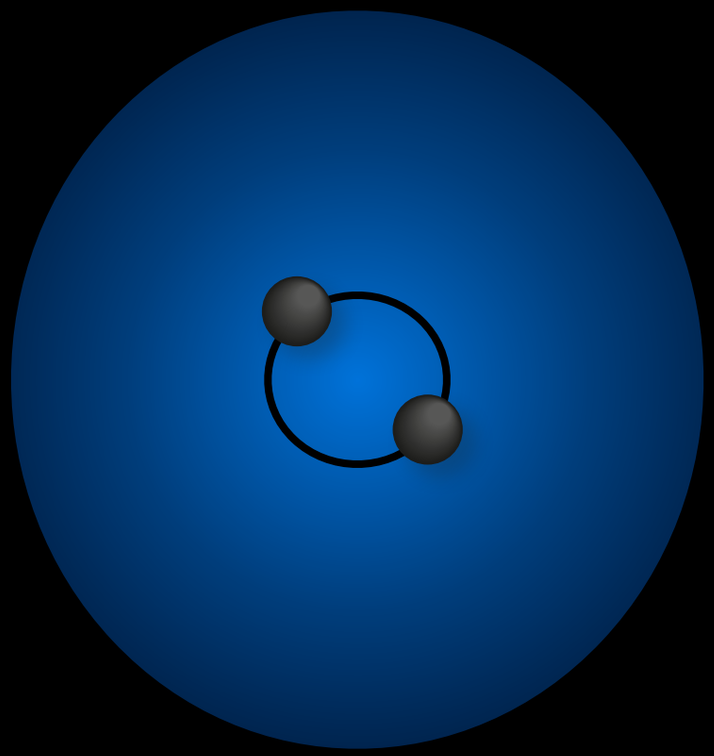

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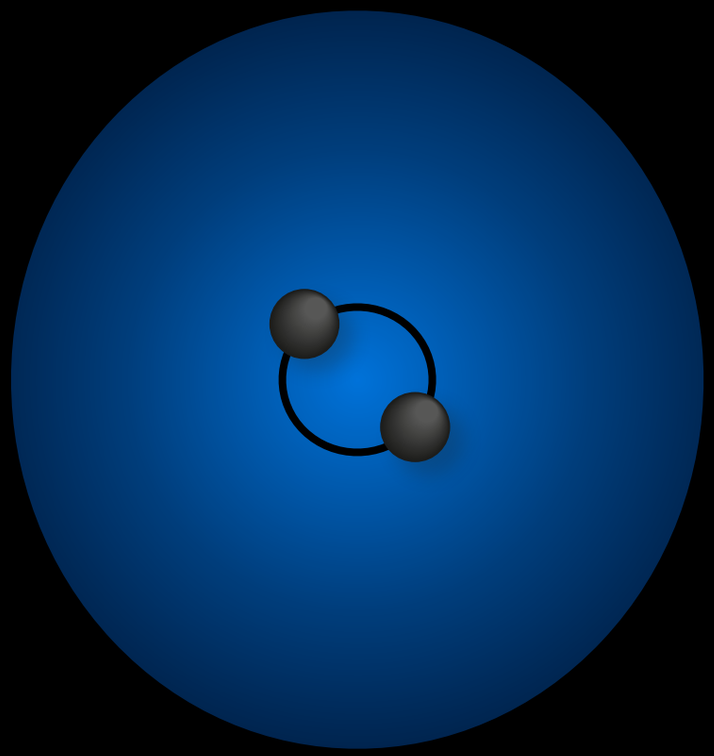

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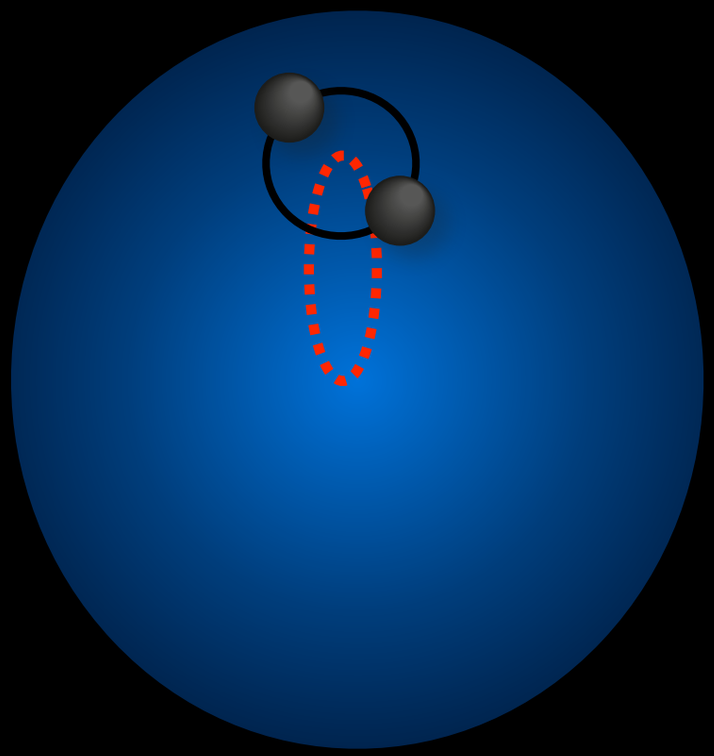

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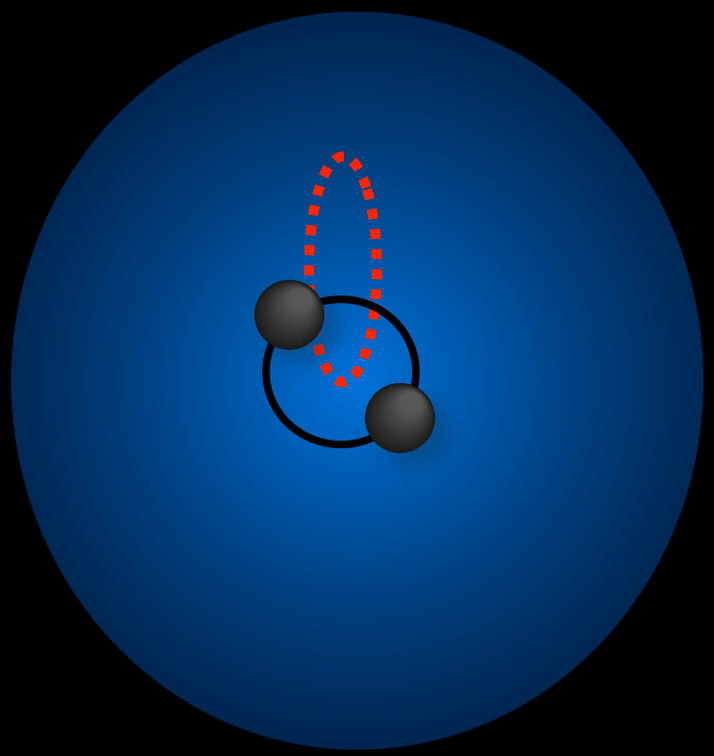

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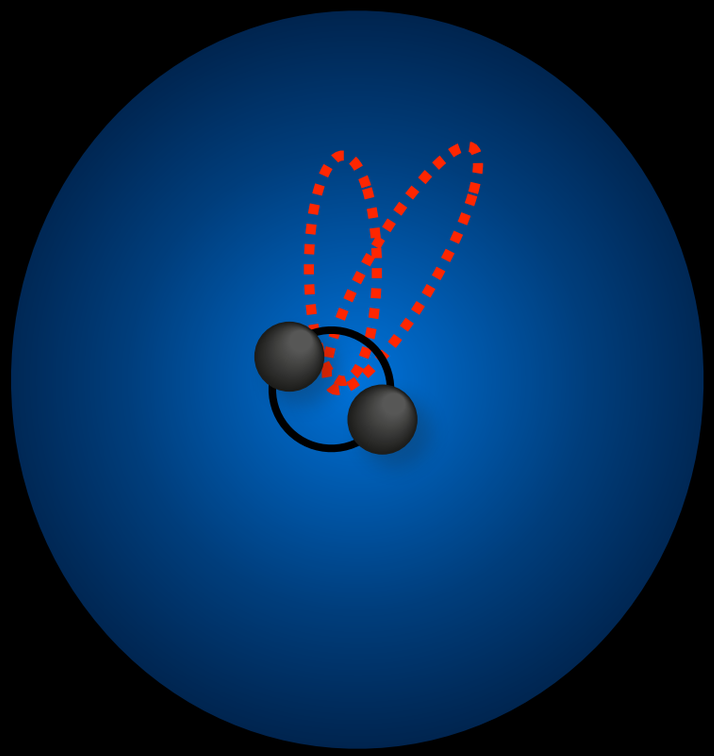

Chaotic Interactions

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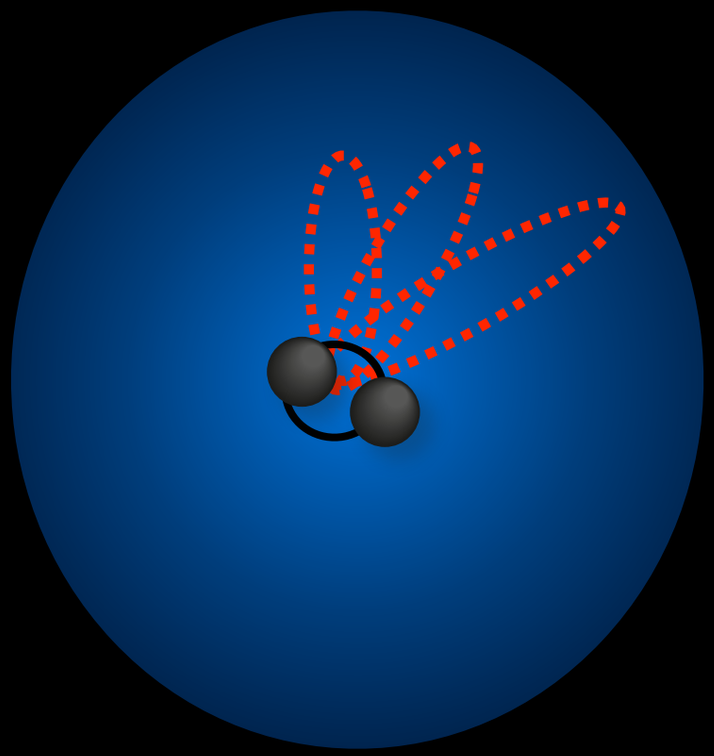

Chaotic Interactions

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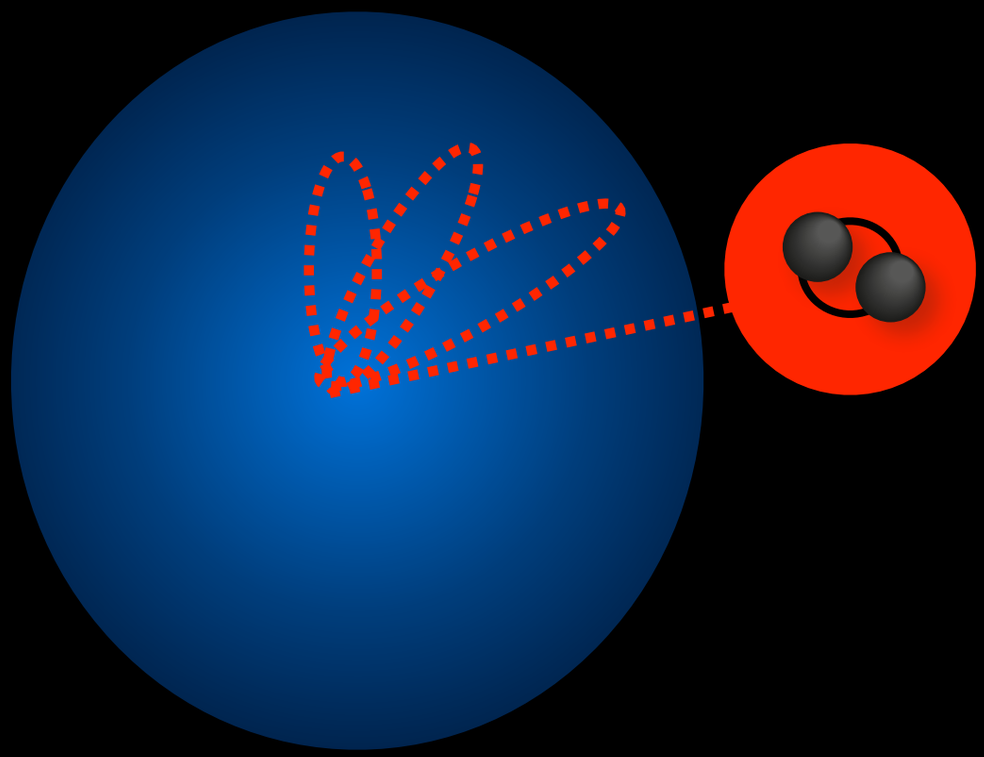

Chaotic Interactions

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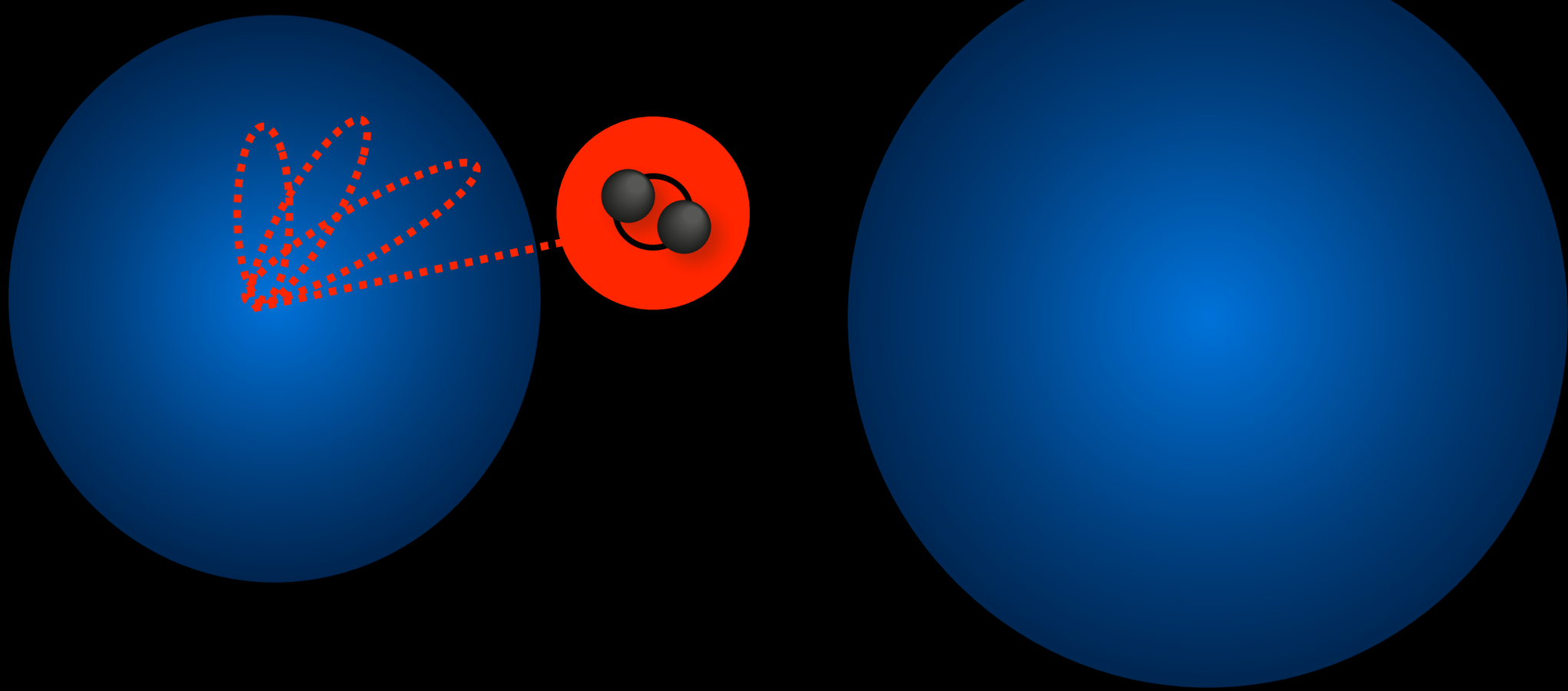

Chaotic Interactions

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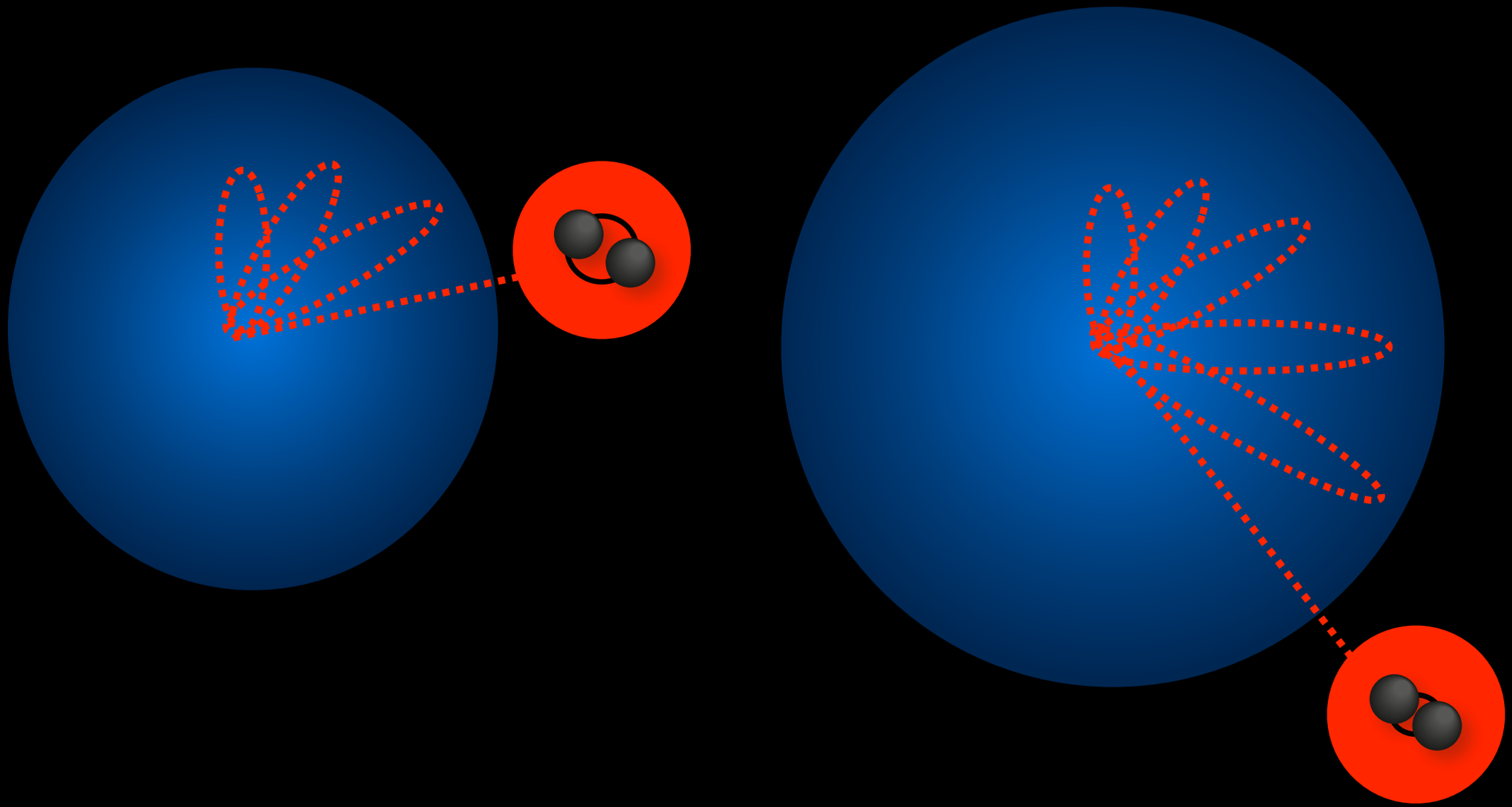

Chaotic Interactions

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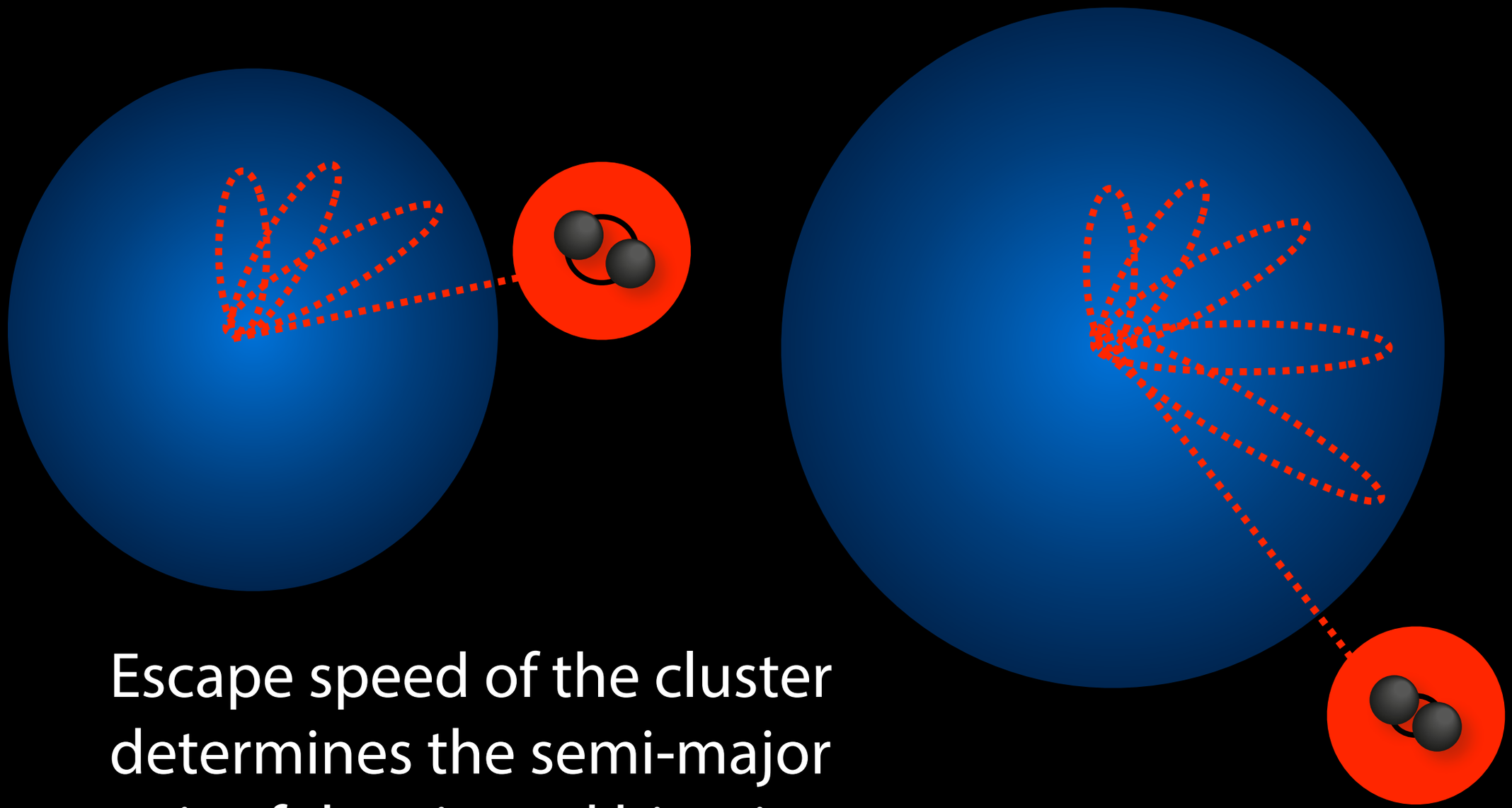
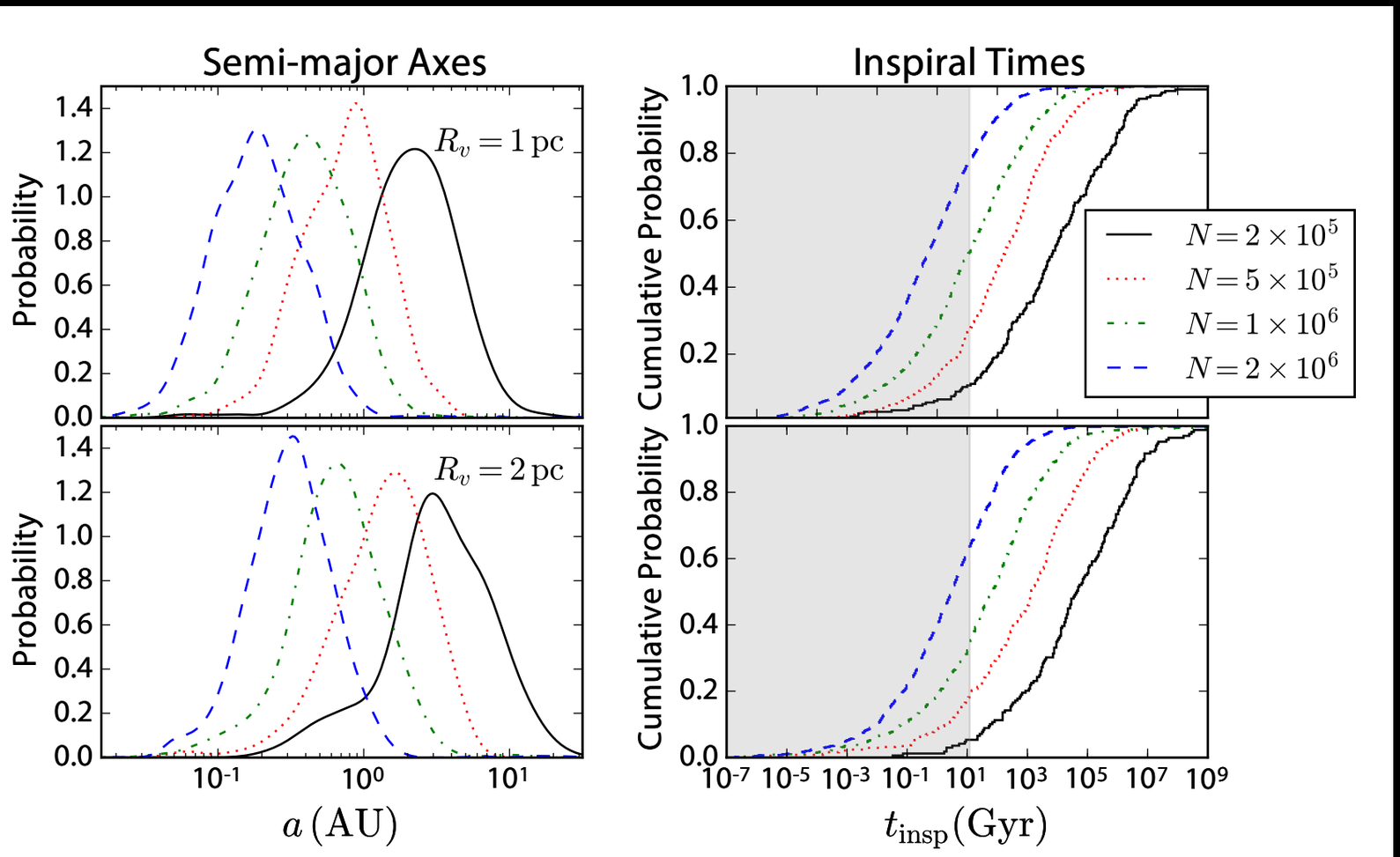
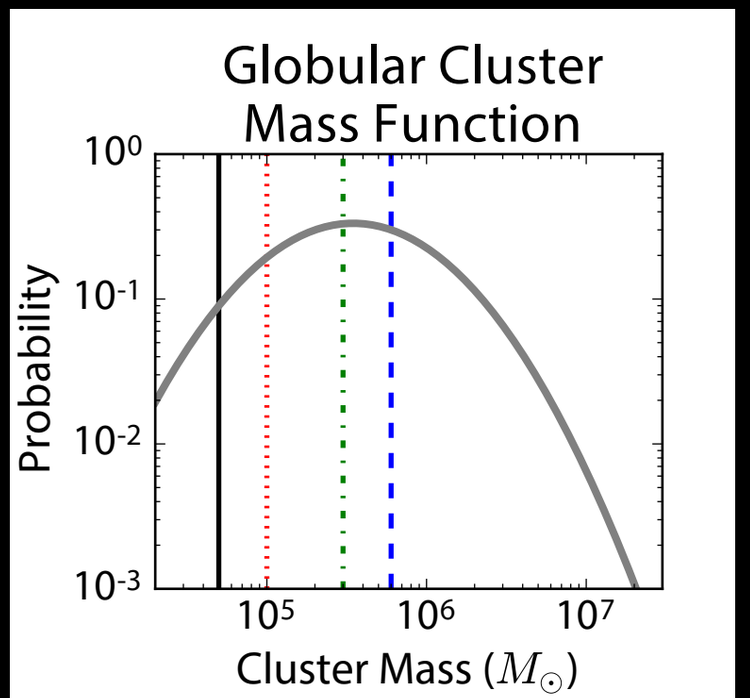


Escape speed of the cluster determines the semi-major axis of the ejected binaries

Chaotic Interactions



from Harris, 2014

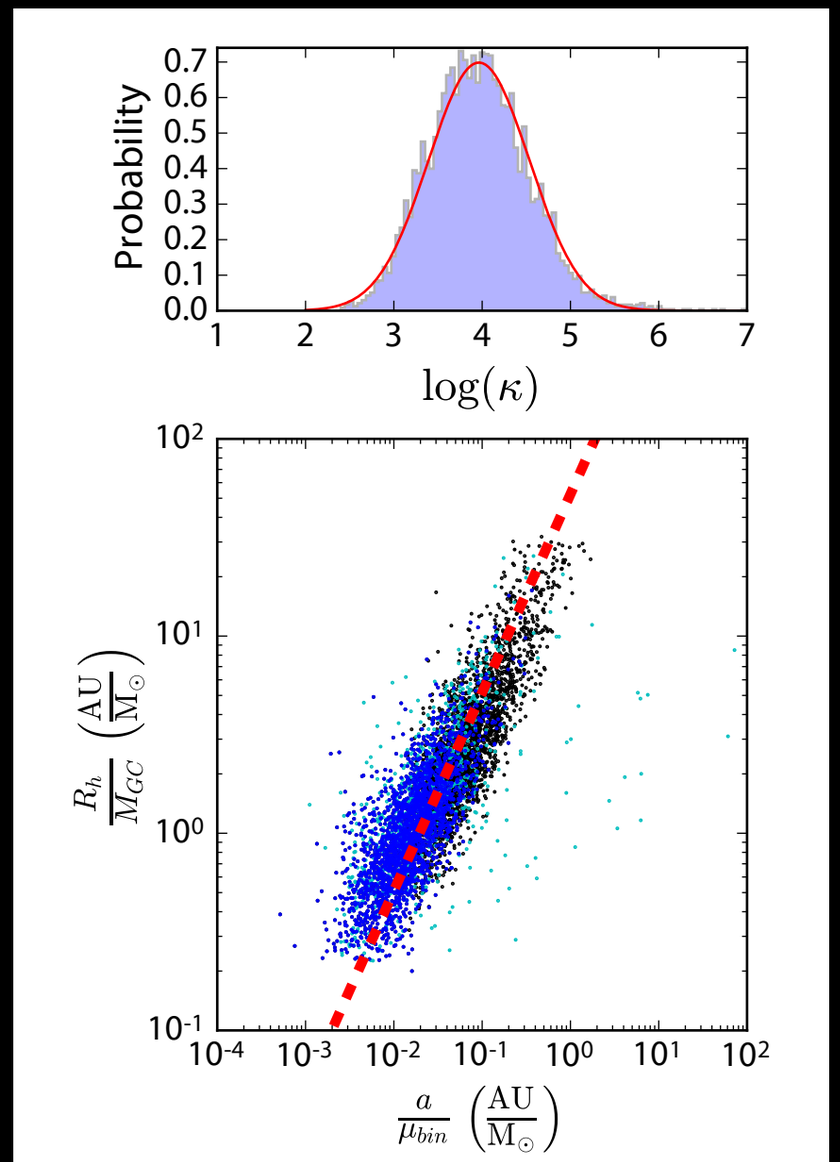


Chaotic Interactions

$$\frac{M_{GC}}{R_h} \propto \frac{\mu_{\rm bin}}{a}$$

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

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



Binary Masses

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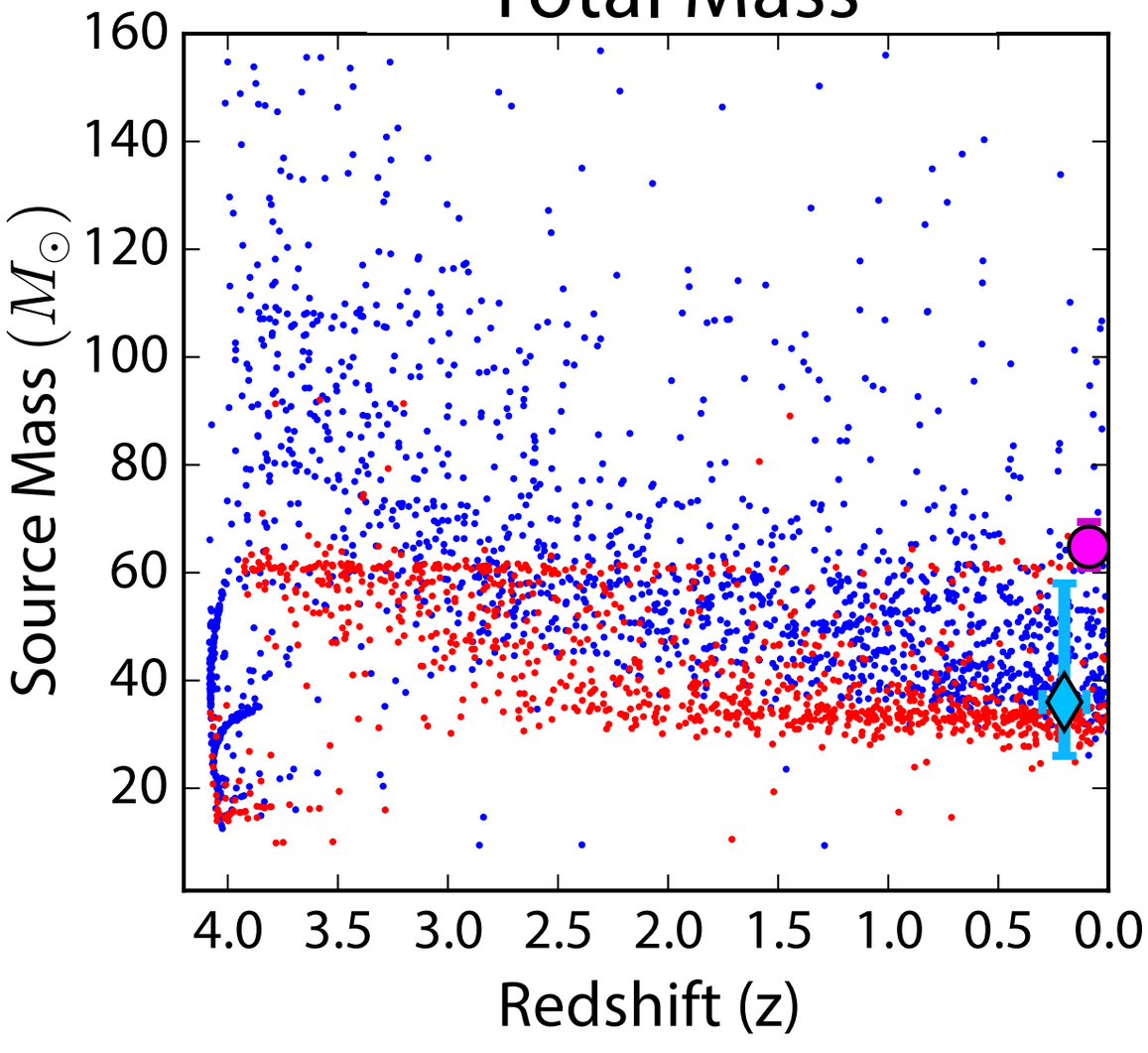
Low Z

High Z

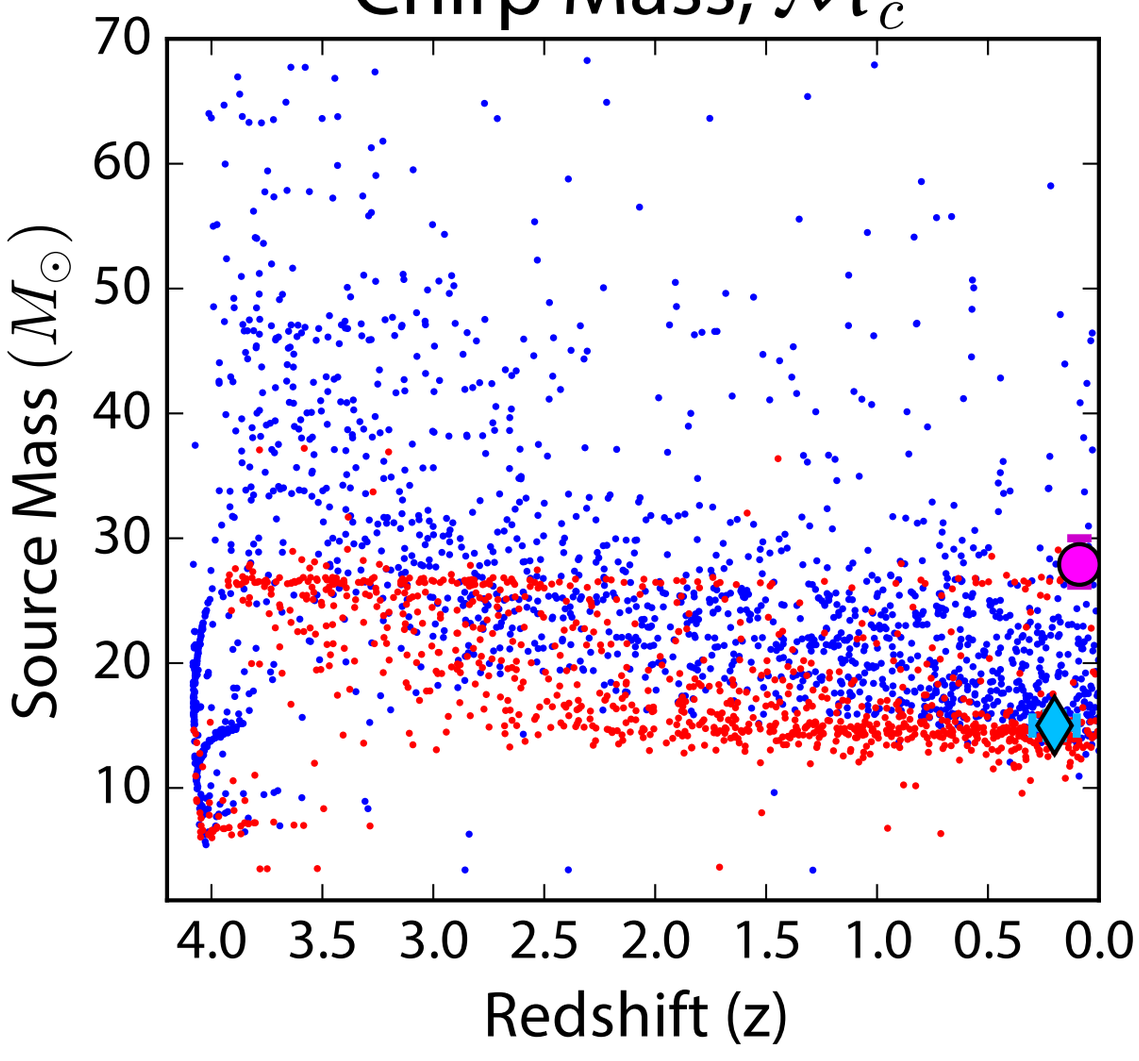
GW150914

LVT151012

Total Mass



Chirp Mass, $\mathcal{M}_c$



Merger Rates

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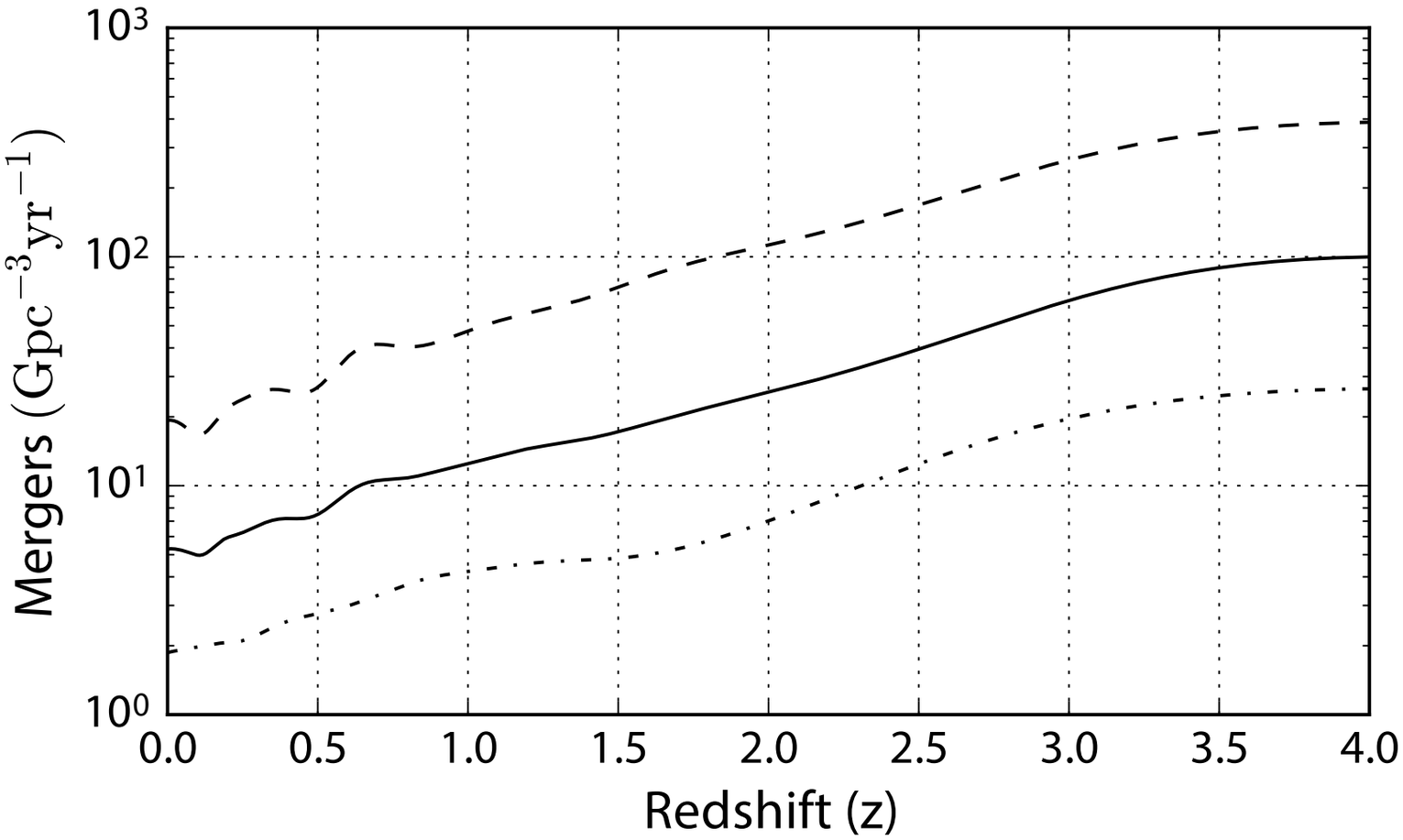
Mergers	Pessimistic	Realistic	Optimistic
O1 (Detections / 16 Days)	0.05	0.2	0.7
O1 (Detections / 50 Days)	0.2	0.5	2
O2 (Detections / Year)	4	15	60
Design Sensitivity (Detections / Year)	30	100	400



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

Nuclear Star Clusters

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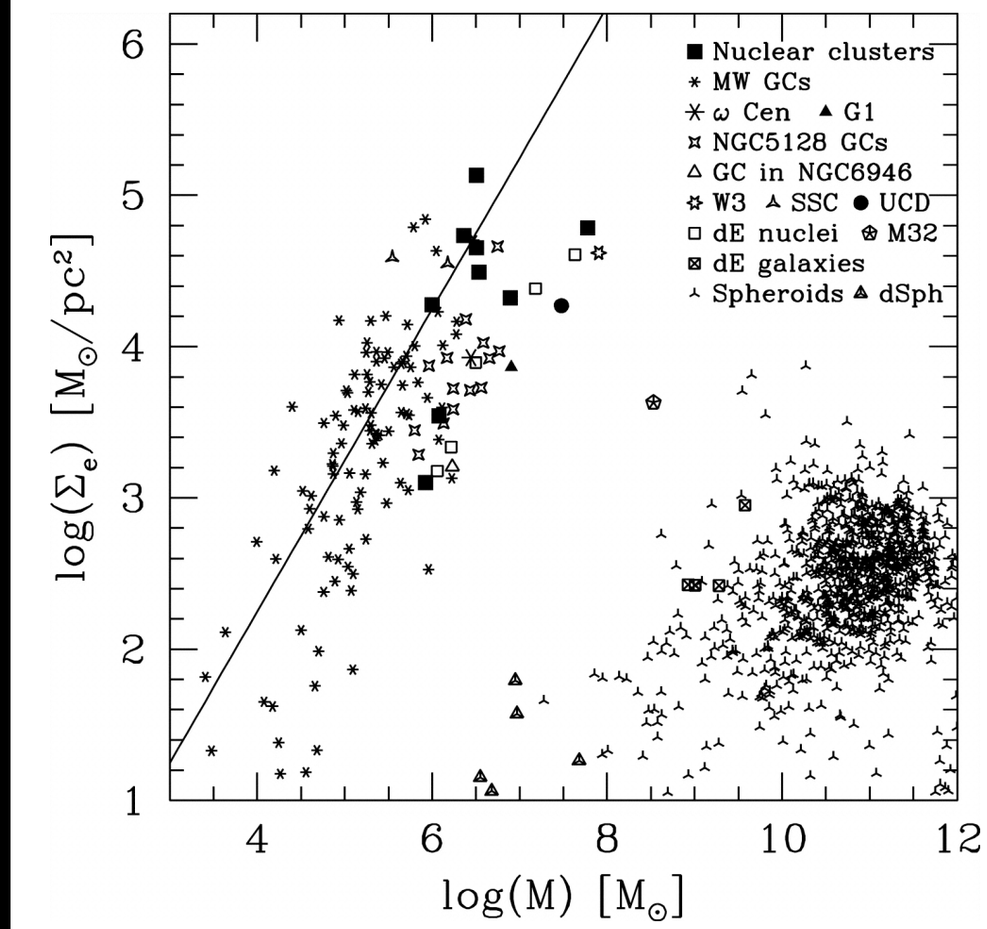
- **Extremely** Massive ($10^7 - 10^8$ stars)
- Compact
- Continuous star formation
- ~~Central massive black hole (sometimes)~~



Boker 2008

Nuclear Star Clusters

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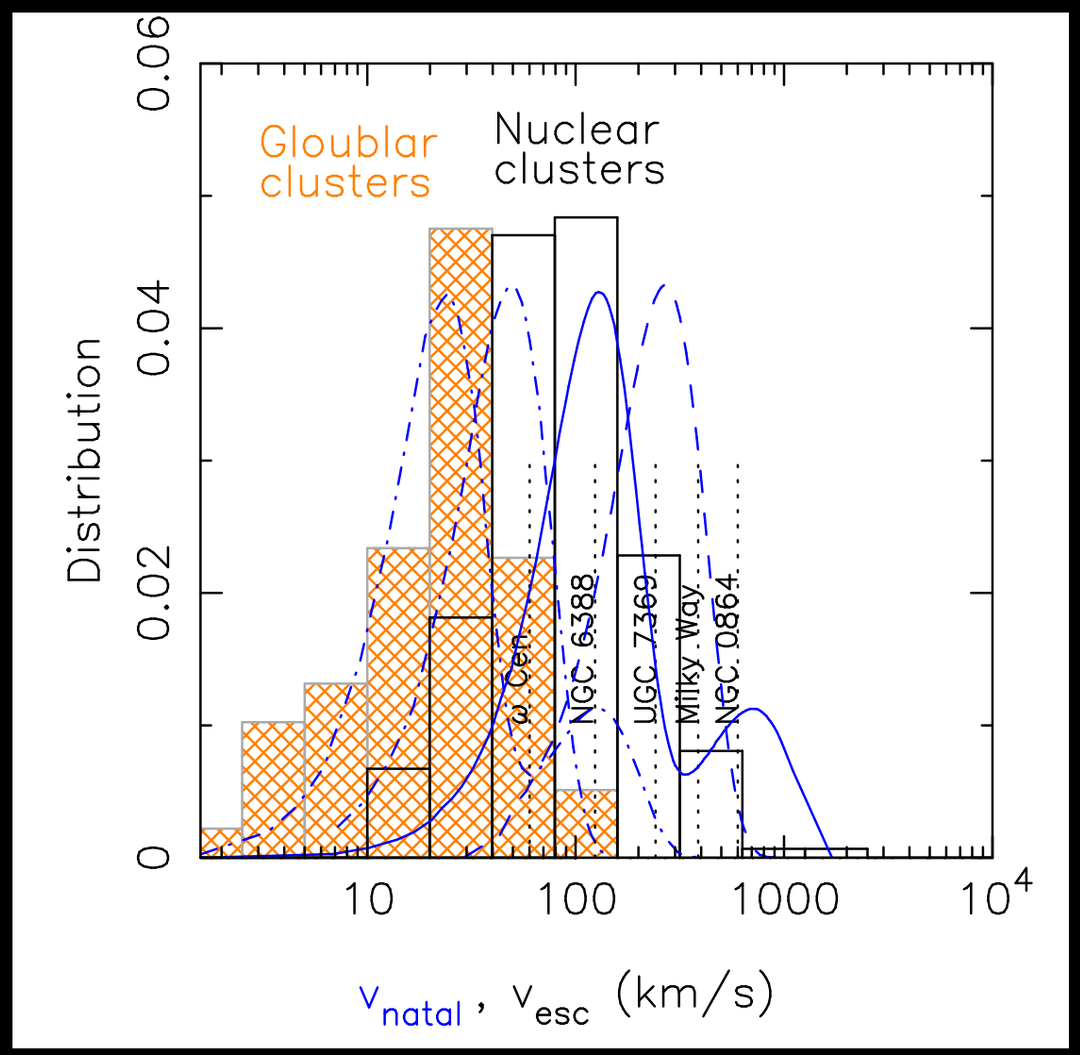
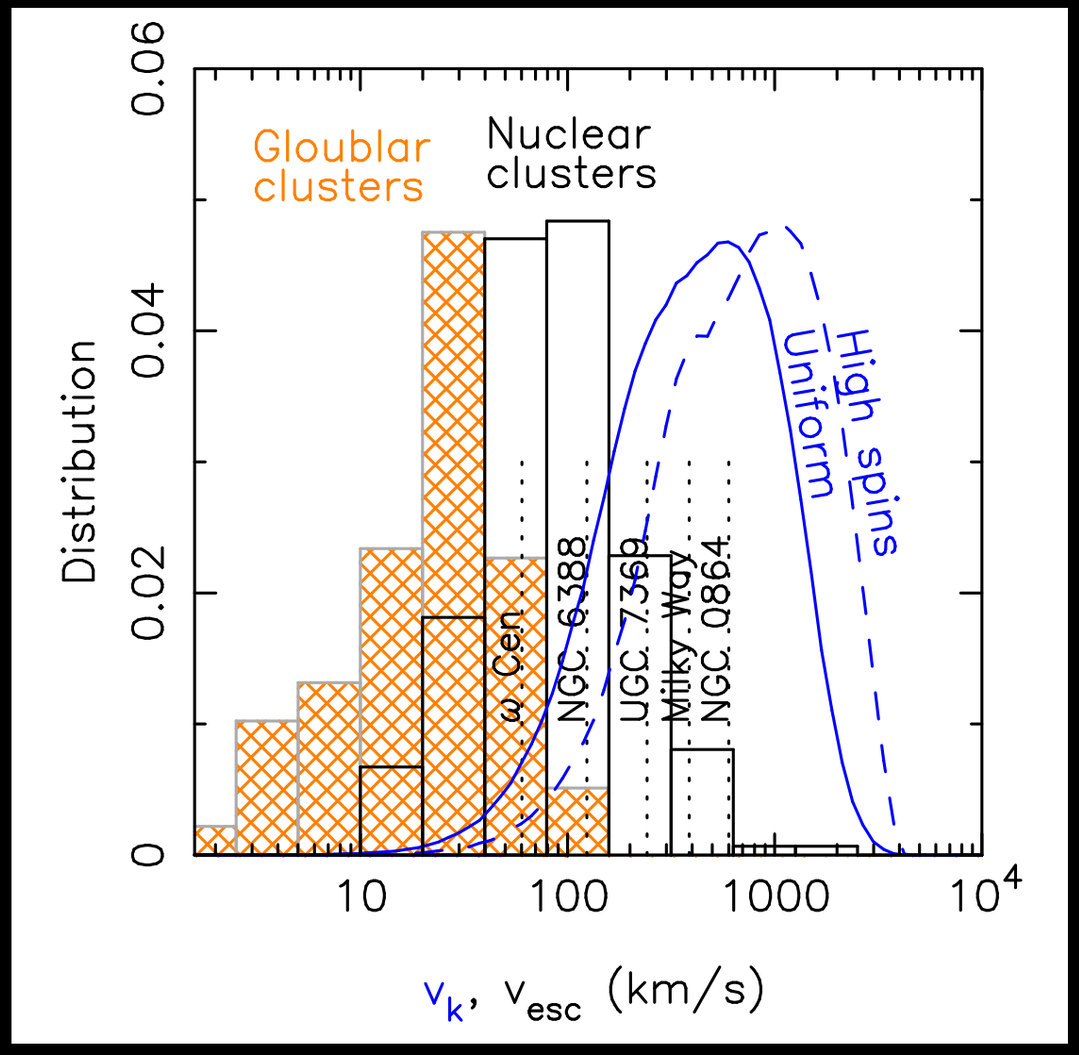
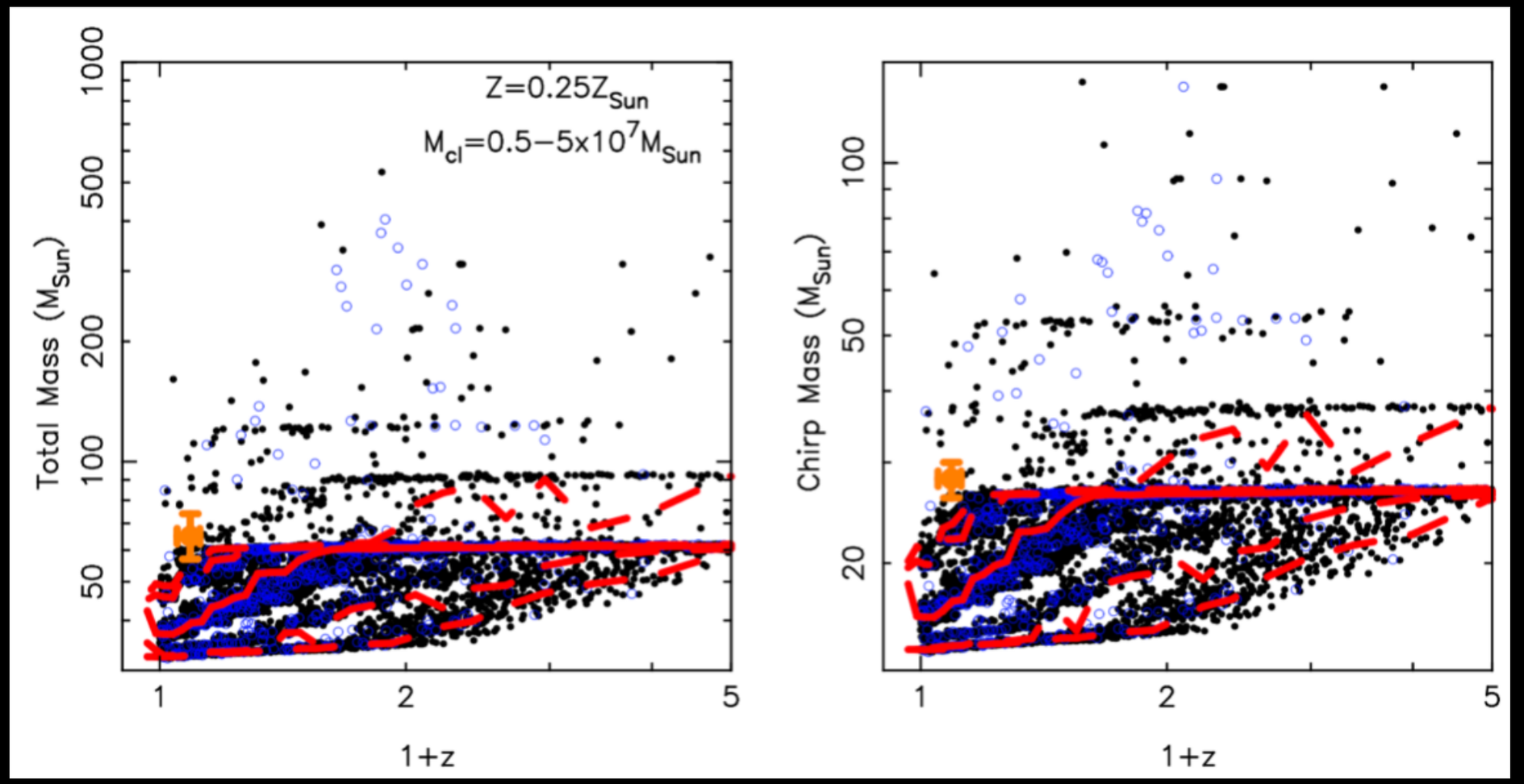




Antonini and Rasio 2016

Nuclear Star Clusters



Antonini and Rasio 2016

Multiple BH Mergers

Spins ~ 0.7

Highest Mass BHs

$1.5\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Nuclear Star Clusters
(with central MBHs)

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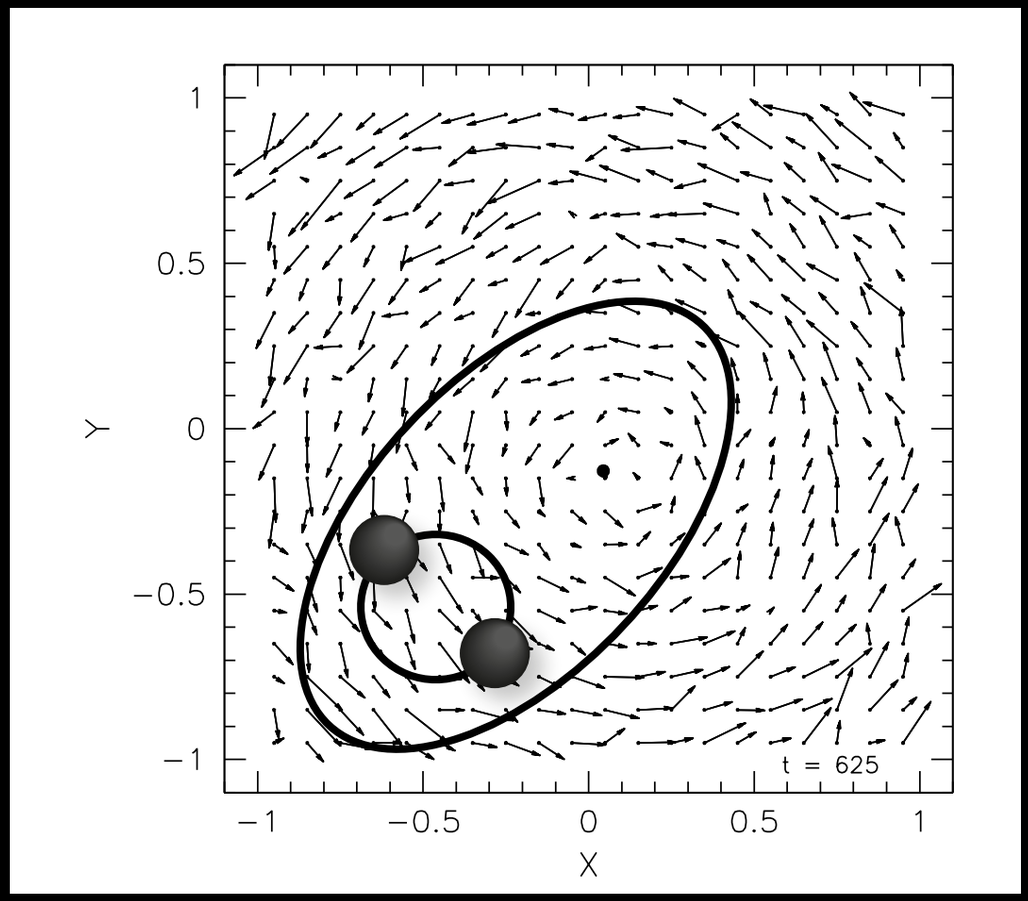
- Single-Single Capture
  - $0.001 - 0.01\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- AGN disk induced inspiral
  - $3\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- Lidov-Kozai driven merger

  $100\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ (?!)



Gualandris and Merritt 2011

Tsang 2013, Stone 2016, VanLandingham 2016

Field vs. Clusters

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- Masses
- Mass ratios
- Eccentricity
- Spins

Field vs. Clusters

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- Masses
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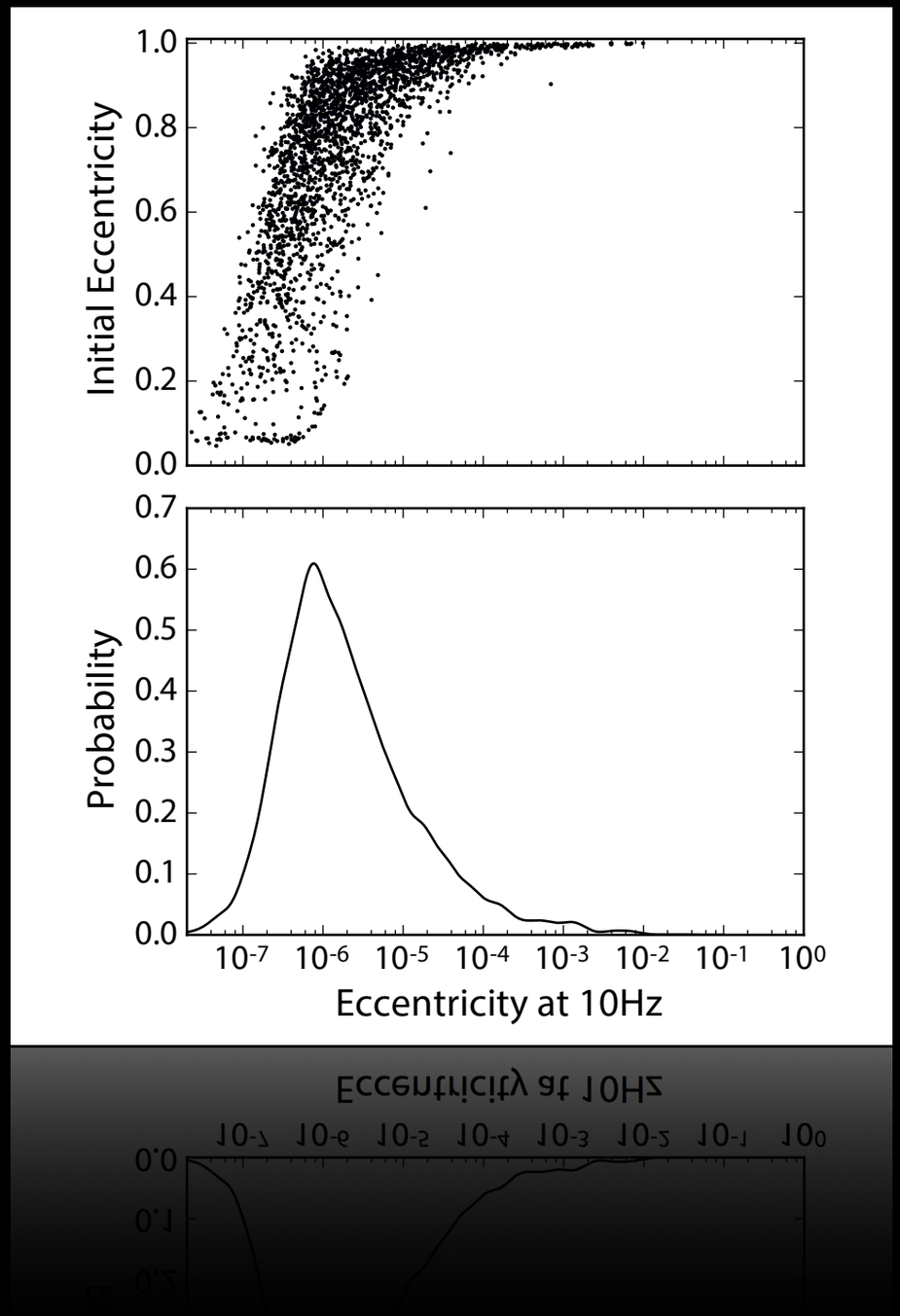

Field vs. Clusters

- Masses
- Mass ratios
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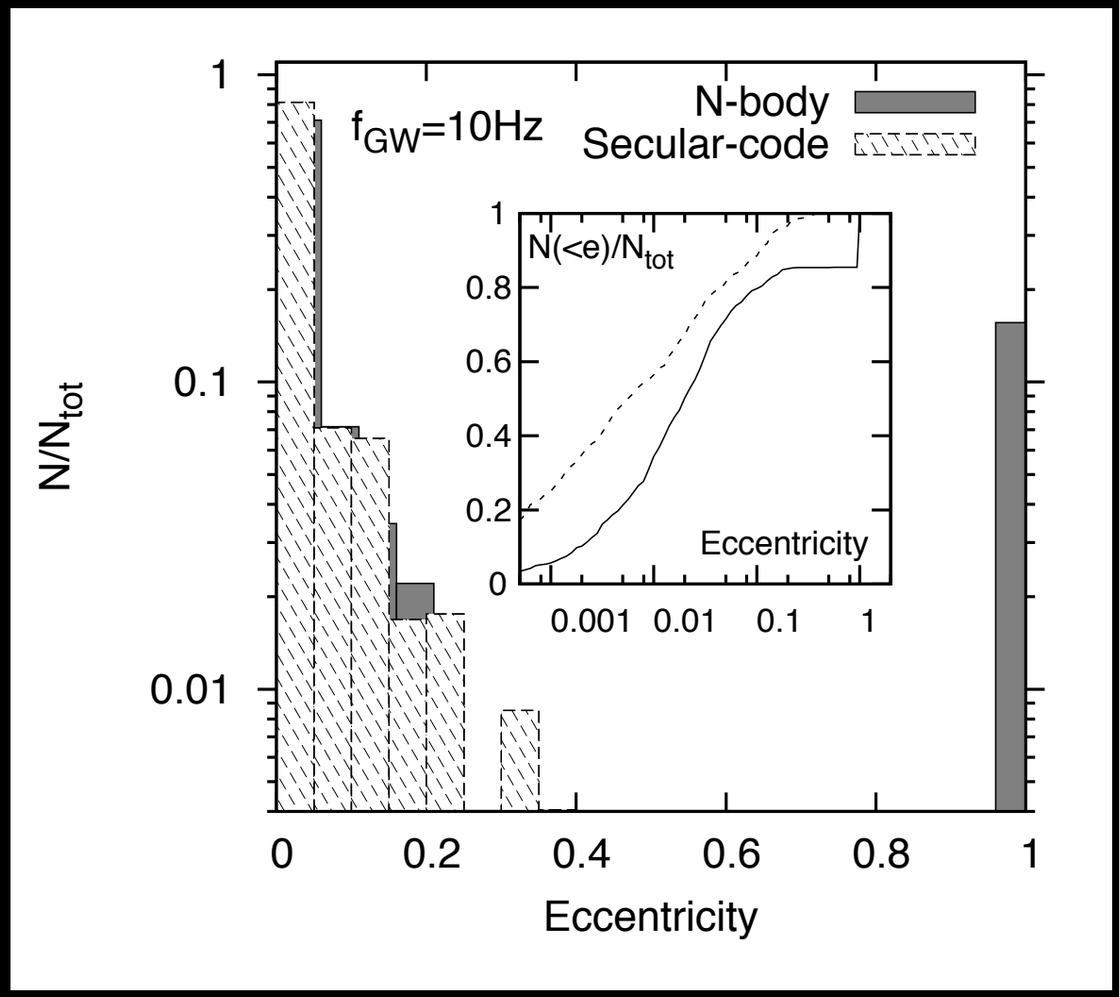

Antonini et al. 2015

What is the field?

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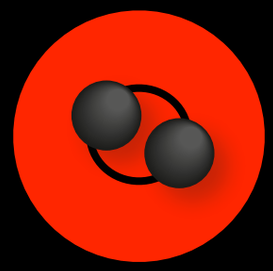
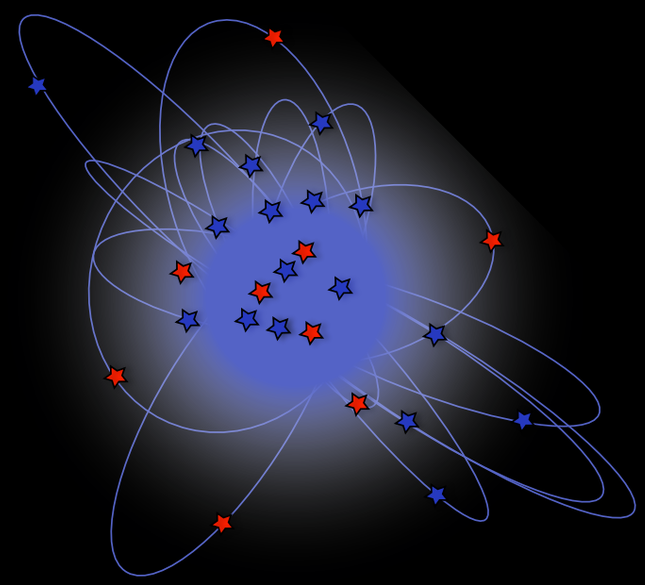
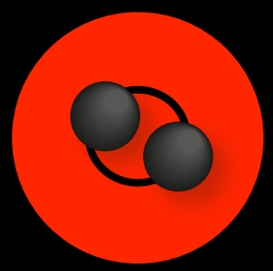
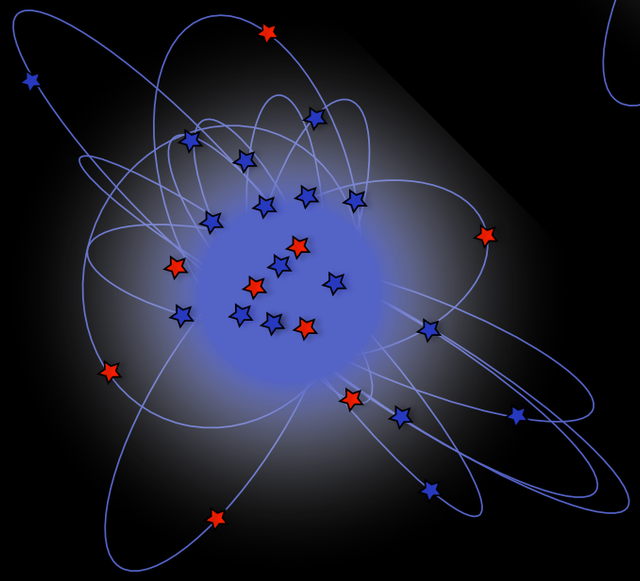
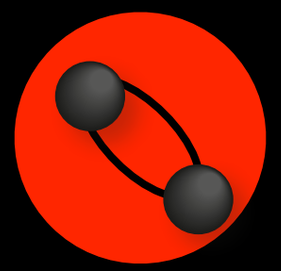


vs.









Disrupting open clusters? $3.5\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ Ziosi et al., 2014