

Binary Black Holes and Globular Clusters

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- Broad-brush picture of evolution of BH subsystem
- Order of magnitude estimates
- Numerical results
 - ◆ Direct N -body of globular cluster
 - ◆ Introduction to *Fewbody*
 - ◆ Monte-Carlo of BH subsystem
 - ◆ Direct N -body of BH subsystem

Broad-brush picture

- Globular cluster, stars form
- Heavy stars ($\gtrsim 20M_{\odot}$) become BHs ($t \sim 10$ Myr)
- BHs mass segregate into cluster core ($t \sim 100$ Myr)
- BH system decouples dynamically and begins to evolve independently from the rest of the cluster
 - ◆ if no primordial binaries, they are formed as BH system core collapses
 - ◆ BHs do not interact with other cluster stars
 - ◆ BH system destroys itself, ejecting tight binaries ($t \lesssim 1$ Gyr)

Order of magnitude estimates

Kulkarni, Hut, & McMillan (1993), Sigurdsson & Hernquist (1993)

- Assuming a reasonable IMF, $N_{\text{BH}} \sim 10^{-4} N$

- BH birth kicks unknown, but perhaps

$$v_{\text{BH}} \approx \frac{m_{\text{NS}}}{m_{\text{BH}}} v_{\text{NS}} \ll v_{\text{esc}}$$

Fryer & Kalogera (2001)

- Mass segregation timescale: $t_{\text{ms}} \approx \frac{\langle m \rangle}{m_{\text{BH}}} t_{\text{rh}} \approx 100 \text{ Myr}$

Fregeau, Joshi, Portegies Zwart, & Rasio (2002)

- Spitzer mass stratification instability:

$$\left(\frac{M_{\text{BH}}}{M_{\text{clus}}} \right) \left(\frac{m_{\text{BH}}}{\langle m \rangle} \right)^x \approx 10^{-4} \left(\frac{m_{\text{BH}}}{\langle m \rangle} \right)^{x+1} \approx \begin{cases} 0.21 \\ 3.4 \end{cases} \gtrsim \begin{cases} 0.16 \\ 0.32 \end{cases}$$

Watters, Joshi, & Rasio (2000)

- Relaxation timescale of BH system:

$$t_{\text{r,BH}} \approx 1 \text{ Myr} \left(\frac{\sigma}{10 \text{ km/s}} \right)^3 \left(\frac{m_{\text{BH}}}{15 M_{\odot}} \right)^{-1} \left(\frac{\rho}{10^5 M_{\odot}/\text{pc}^3} \right)^{-1}$$

Order of magnitude estimates (cont'd)

- Upper limit on sub-cluster evaporation time:

$$t_{\text{evap}} \lesssim 10 \times 300 t_{\text{rh,BH}} \approx 1 \text{ Gyr}$$

Kalogera, King, & Rasio (2003)

- Properties of ejected binaries

- ◆ Thermal eccentricity distribution: $dP(e)/de = 2e$

- ◆ Semimajor axis: $E_b \gtrsim 10^3 kT$, so $a \lesssim 0.1 \text{ AU}$

Hut, McMillan, & Romani (1992)

- GW merger timescale:

$$300 \text{ Myr} \left(\frac{\mu M^2}{M_{\odot}^3} \right)^{-1} \left(\frac{a}{R_{\odot}} \right)^4 (1 - e^2)^{7/2} \sim 1 \text{ Gyr}$$

Peters (1964)

Numerical results: Portegies Zwart & McMillan (2000)

- Performed direct N -body simulations of $\sim 2 - 4 \times 10^3$ total stars with $\sim 20 - 40$ primordial BHs of mass $10M_{\odot}$
- Of 204 total BHs in 9 simulations:
 - ◆ 62 ($\sim 30\%$) ejected in binaries
 - ◆ 124 ($\sim 61\%$) ejected as single BHs
 - ◆ 1 ($\sim 1\%$) ejected in binary with low-mass companion
 - ◆ 17 ($\sim 8\%$) retained by cluster
- Ejected with $E_b \sim 10^3 - 10^4 kT$
- Roughly thermal eccentricity distribution, with large e slightly overrepresented
- Ejected within first few Gyr

- Take a, e distributions to be representative
- Assume density of galaxies and star clusters in universe
- Obtain rate $R = 7.5 \times 10^{-8} h^3 \text{yr}^{-1} \text{Mpc}^{-3}$
- Estimate LIGO detection rate of $1.7 h^3 \text{yr}^{-1}$

- Mergers due to Kozai resonance in triples

Miller & Hamilton (2002b), Wen (2003)

- Formation of IMBH by runaway growth via mergers during BH subsystem collapse

Miller & Hamilton (2002a), Gültekin, Miller, & Hamilton (2003)

- Stable BH system remaining in cluster after BH subsystem disrupts may be dynamically important

Colpi, Possenti, & Gualandris (2002)

- Run-away growth before many BHs form?

Portegies Zwart, Makino, McMillan, Hut (1999), Gürkan, Freitag, & Rasio (2003)

- Designed for small- N dynamics
- Uses adaptive integrator, with optional pairwise K-S regularization Mikkola (1985)
- Binary trees for classification
- Mardling triple stability criterion to determine dynamical stability of full hierarchies Mardling & Aarseth (2001)
- Automatic calculation termination
- Binary trees for isolating unperturbed hierarchies from integrator
- Physical collisions in the sticky star approximation:
$$R_{\text{merger}} = f_{\text{exp}}(R_1 + R_2)$$

- Binary-single
- Binary-binary
- Triple-binary
- Cluster

- Treat BH system via Monte-Carlo
- Do binary interactions with *Fewbody*
- Between interactions, evolve binaries using Peters equations
- Check for Kozai-induced mergers in any stable triples formed

■ BHs

- ◆ $N_{\text{BH}} = 1024$
- ◆ $dN/dM \propto M^{-2}$
- ◆ $M \in [5, 15]M_{\odot}$
- ◆ 100% binary fraction, all hard binaries
- ◆ $p(q) \propto q$
- ◆ $p(a) \propto a^{-1}$
- ◆ $a \in [10, 10^4]R_{\odot}$

■ Cluster

◆ Core-halo model

$$◆ n_c = 10^5 \text{pc}^{-3}$$

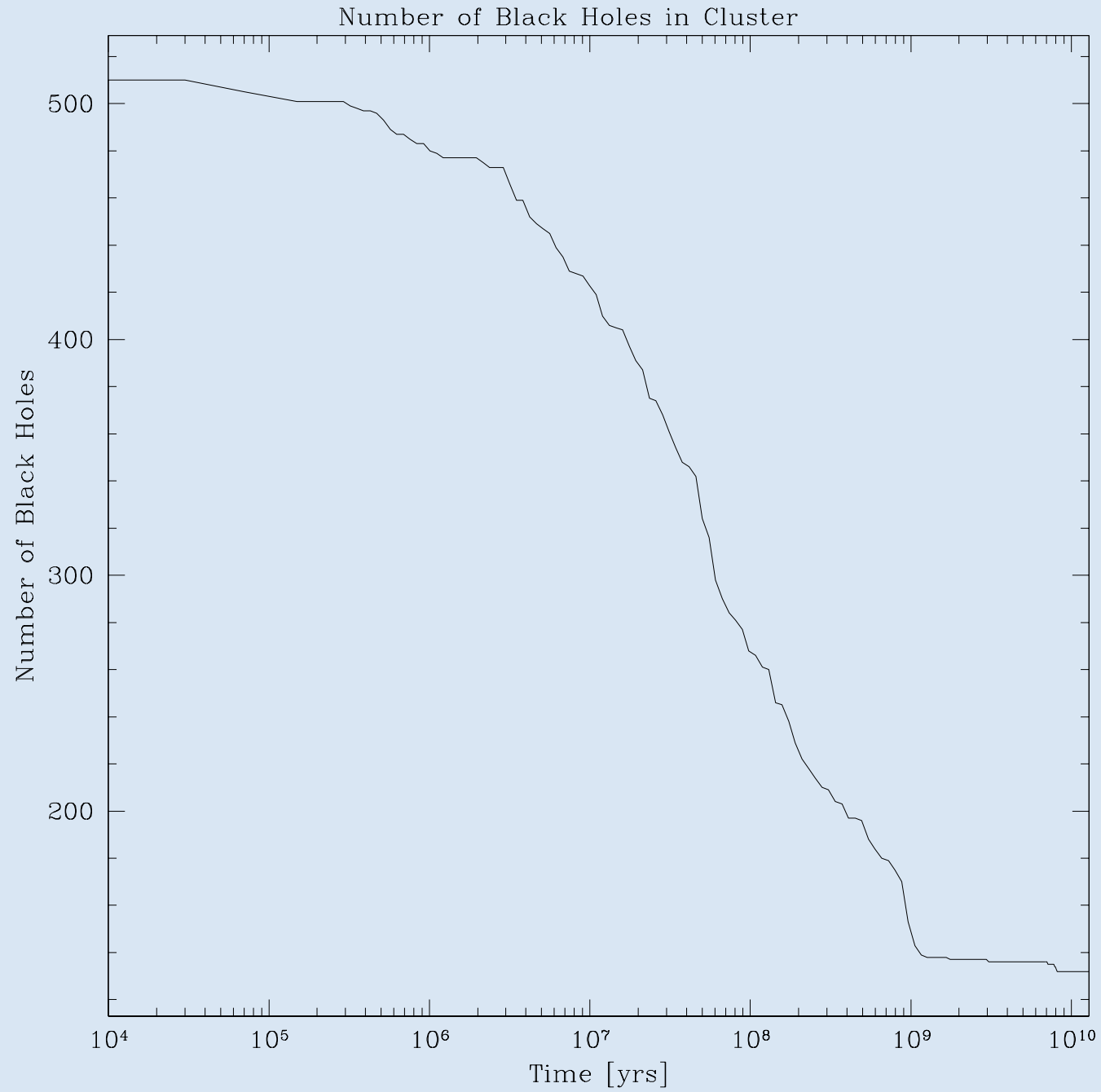
$$◆ v_{\text{esc,core}} = 30 \text{ km/s}$$

$$◆ v_{\text{esc,clus}} = 60 \text{ km/s}$$

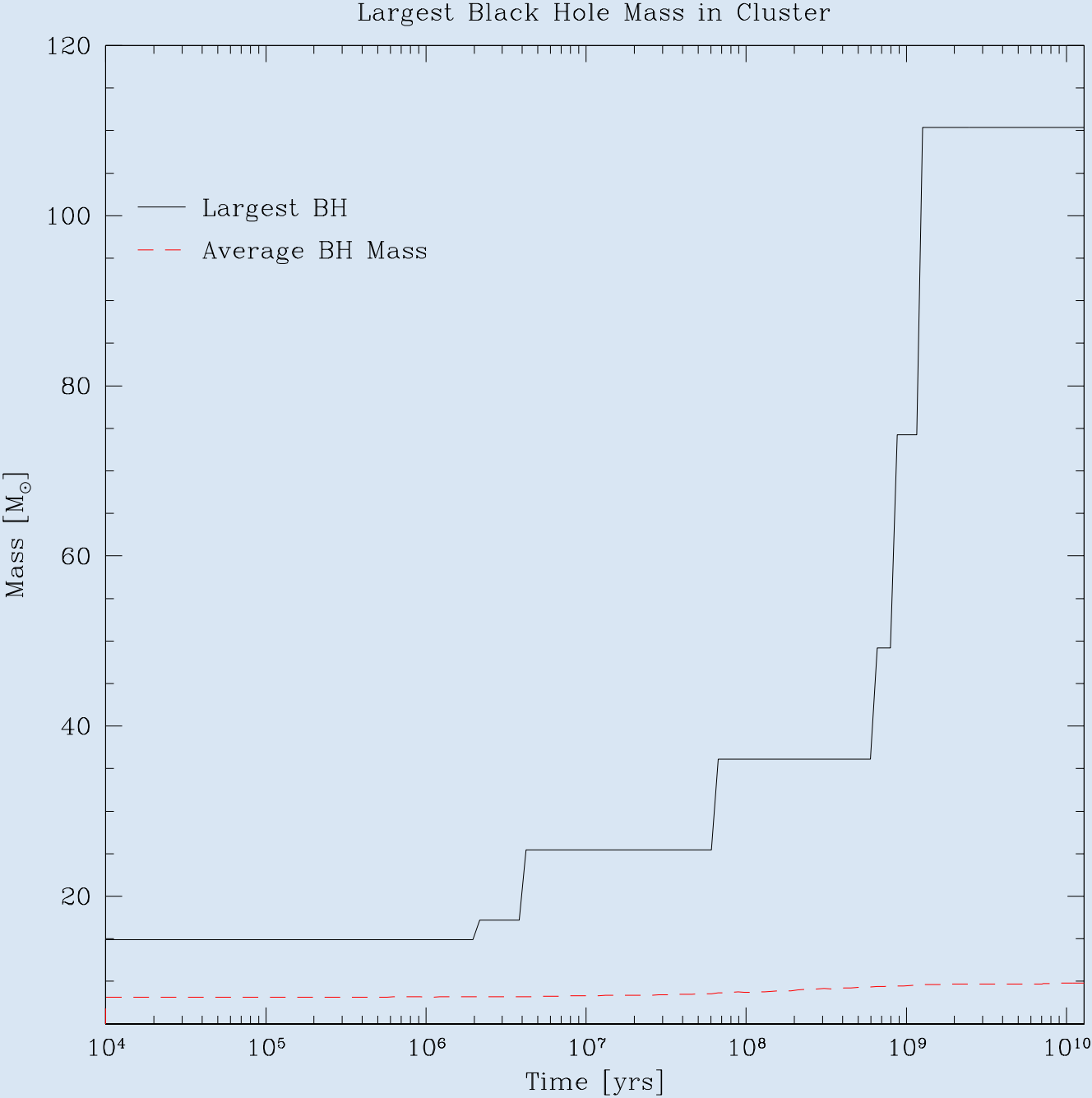
$$◆ t_{\text{rh}} = 1 \text{ Gyr}$$

$$◆ t_{\text{ms}} = \frac{\langle m \rangle}{m_{\text{BH}}} t_{\text{rh}}$$

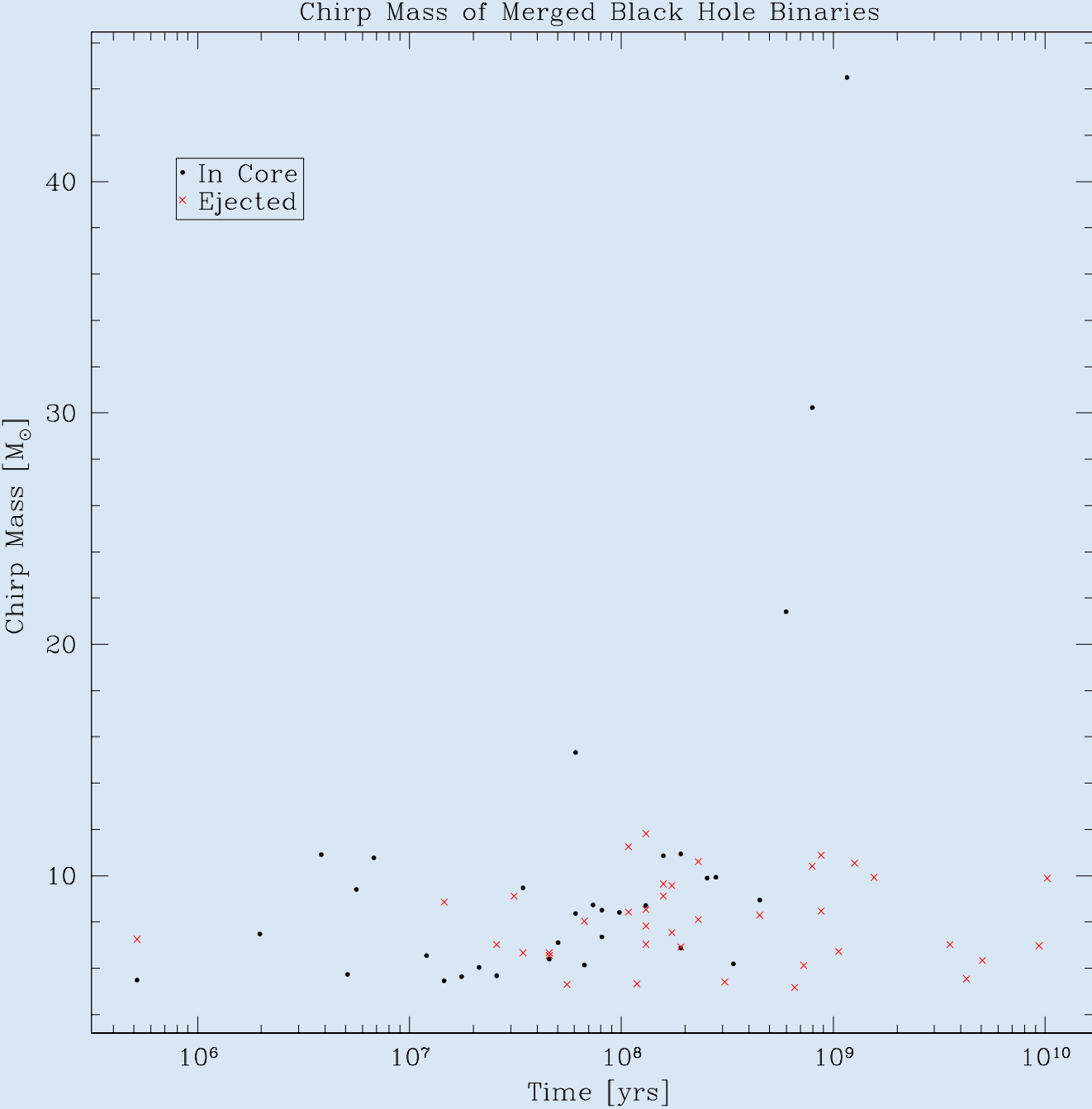
Number vs. time



Run-away growth



Relevance for LIGO



- Use *Fewbody* to do BH subsystem
- Add potential of globular cluster (static Plummer model for now)
- Add dynamical friction on BHs due to cluster stars

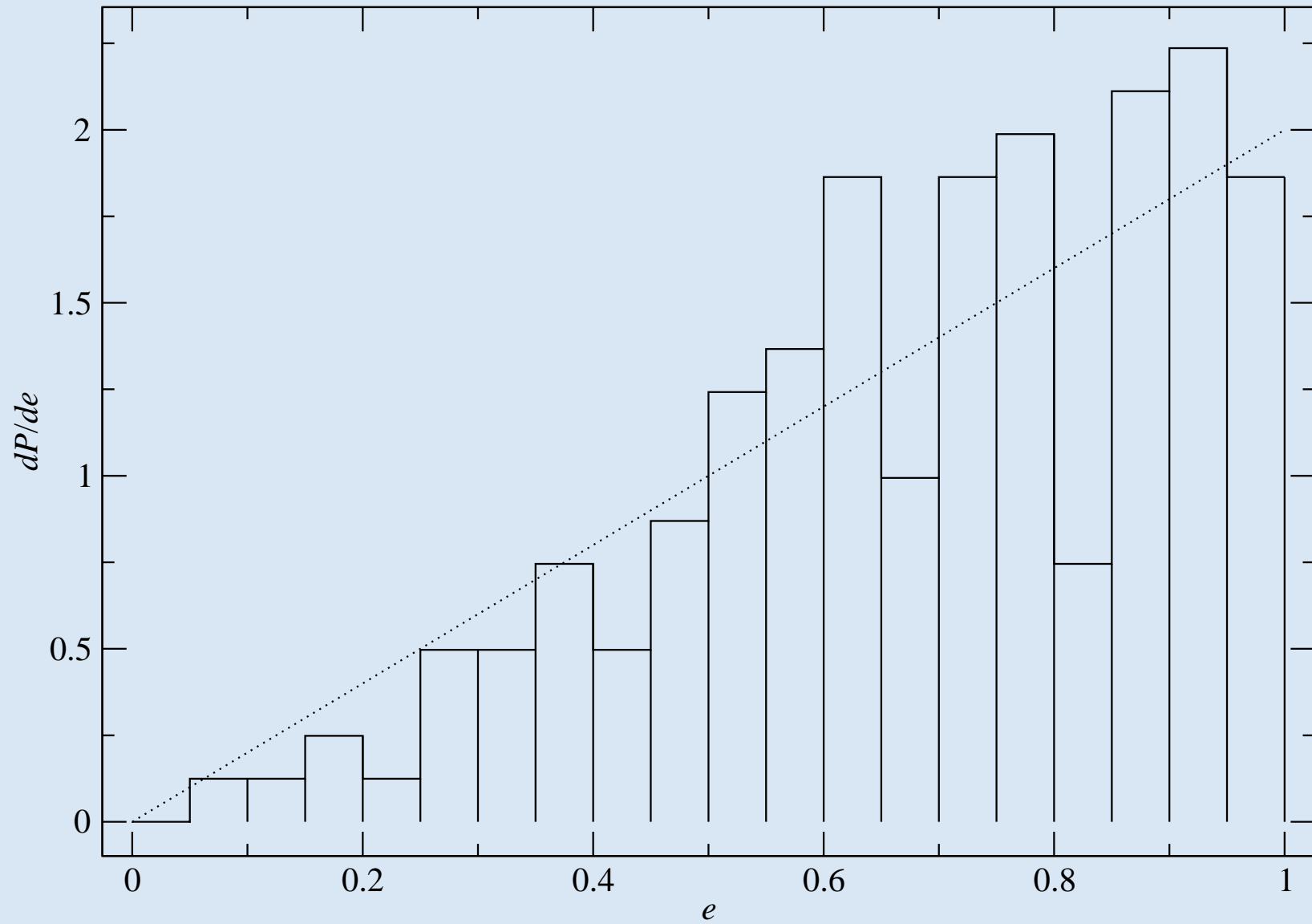
Initial conditions

- 25 BHs of mass $20M_{\odot}$
- Cluster mass of $10^5 M_{\odot}$
- Cluster core density of $10^5 M_{\odot}/\text{pc}^3$
- BH positions and velocities drawn from cluster distribution function, out to a limiting radius of r_h , to mimic primordial mass segregation

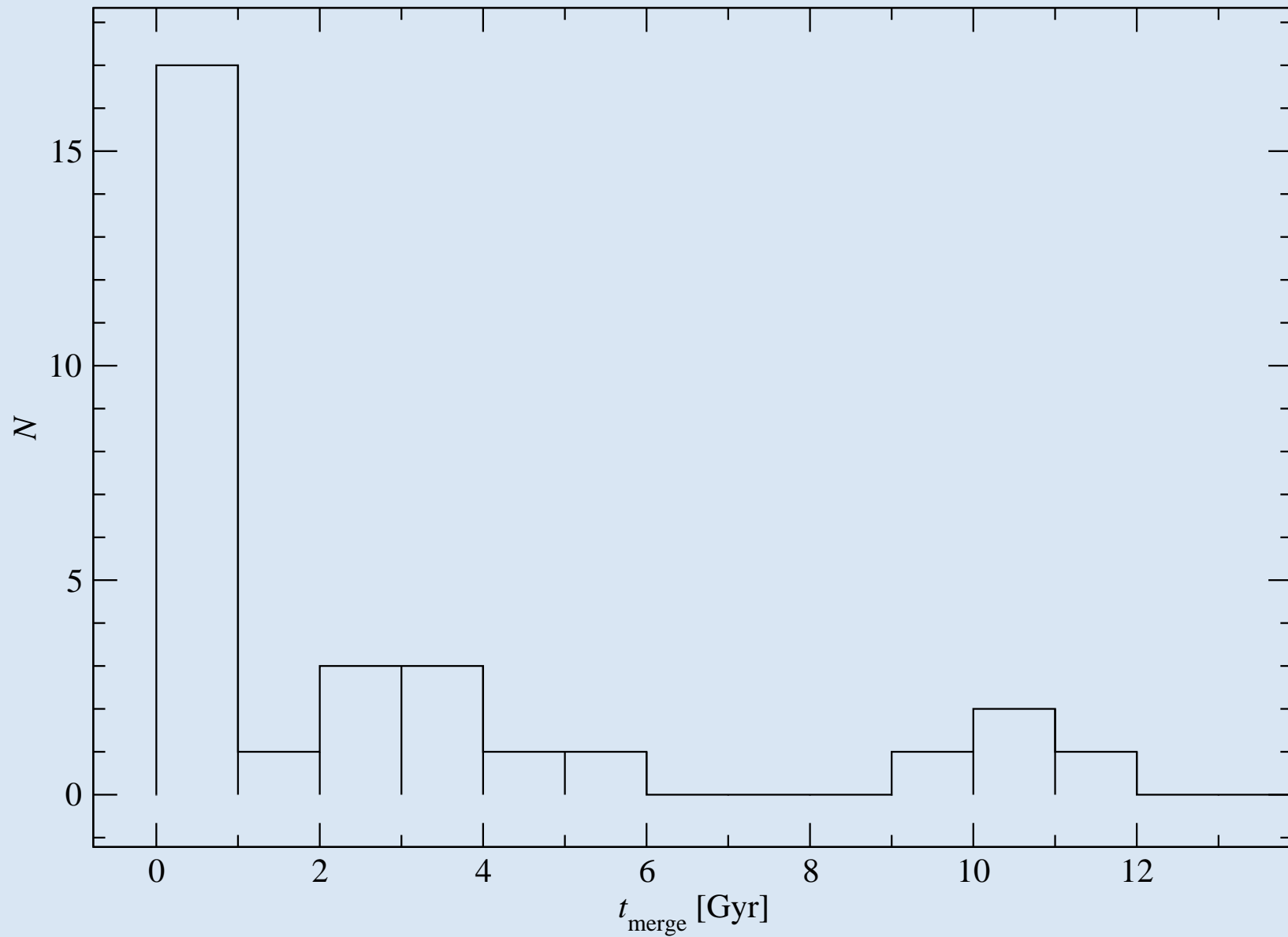
Direct N -body for BHs (cont'd)

- Of 775 total BHs in 31 simulations:
 - ◆ $\sim 40\%$ ejected as binary BHs
 - ◆ $\sim 45\%$ ejected as single BHs
 - ◆ $\sim 15\%$ retained by cluster, in the form of triples, etc.
- Roughly thermal eccentricity distribution
- Ejected before $\lesssim 1\text{Gyr}$

Distribution of eccentricities



Distribution of observable merger times



What's left?

- Usually a stable hierarchical triple ($\sim 80\%$ of the time)
- Triples retained in cluster core, never ejected
- Outer binary is wide ($a_{\text{out}} \sim 10^4$ AU), so triple is likely to be disrupted quickly by field stars

Summary

- BH subsystem evolves quickly (~ 1 Gyr)
- Equipartition between BHs and cluster stars not reached
- BH binaries ejected early ($\lesssim 1$ Gyr) with short (~ 1 Gyr) merger timescales
- Runaway merger scenario plausible, even without seed BH