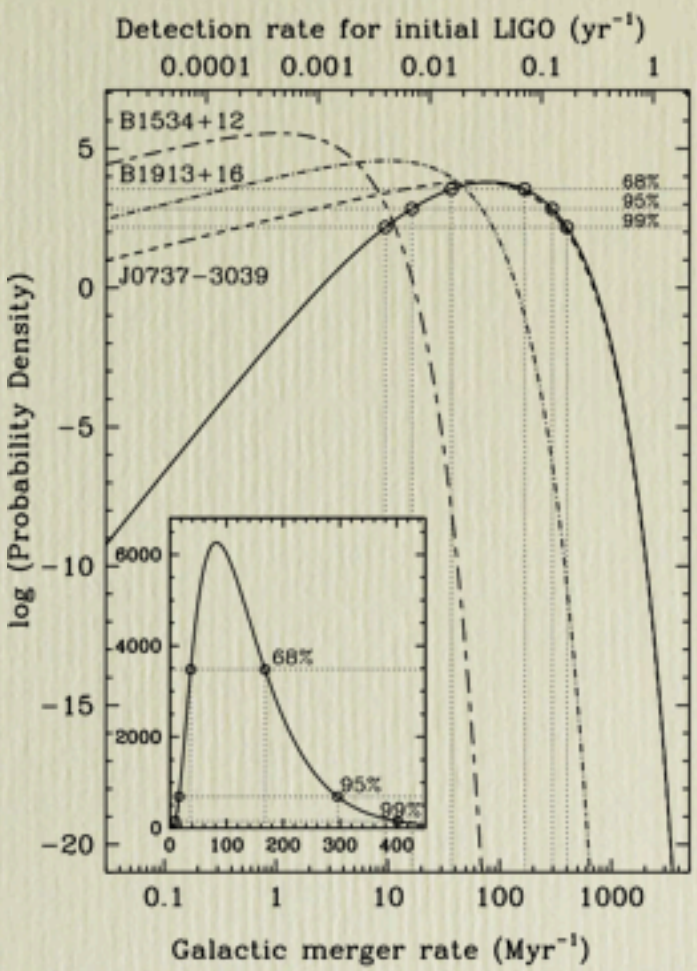
Compact Binaries Ejected from Globular Clusters as GW Sources

Hyung Mok Lee and Young-Bok Bae
Seoul National University

KITP Workshop
July 30-August 3, 2012

Question (and answer)

- How many compact binaries (NS-NS, BH-NS) have been formed in globular clusters?
  - 1.4-3 Myr^{-1} (cf, 100 Myr^{-1} for disk population, Kalogera et al. 2004; see also Kim et al.'s poster)
  - 0.08 -0.24 Myr^{-1} for BH-BH (cf, 0.005 Myr^{-1} , Abadie et al. 2010)



Kalogera et al. 2004

Pulsars in Globular Clusters

(http://www.naic.edu/~pfreire/GCpsr.html)

- 143 pulsars in 27 globular clusters are known
  - 23 millisecond pulsars are found in 47 Tuc alone
- Note that globular clusters are very old, and the pulsars in globular clusters should be 'recycled' pulsars → there should be many more 'neutron stars' which are not pulsars

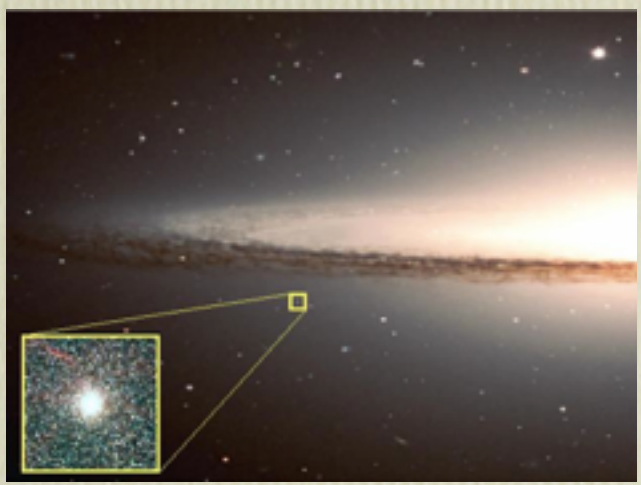
Neutron star kicks: how GCs contain neutron stars?

- Many pulsars are known to have large peculiar velocity, e.g., B1508+55 moves at 1100 km/sec (Chatterjee et al. 2005), with average kick velocity being ~400 km/s
  - Asymmetry of the supernova explosion?
- However, escape velocity from globular clusters is ~30 km/sec. How neutron stars remain in GC?
  - Neutron star kick velocity has bimodal distribution: one very high velocity of > 400 km/s (70%) and nearly zero (~30%) [Freyer et al. 1998]

Extragalactic Globular clusters

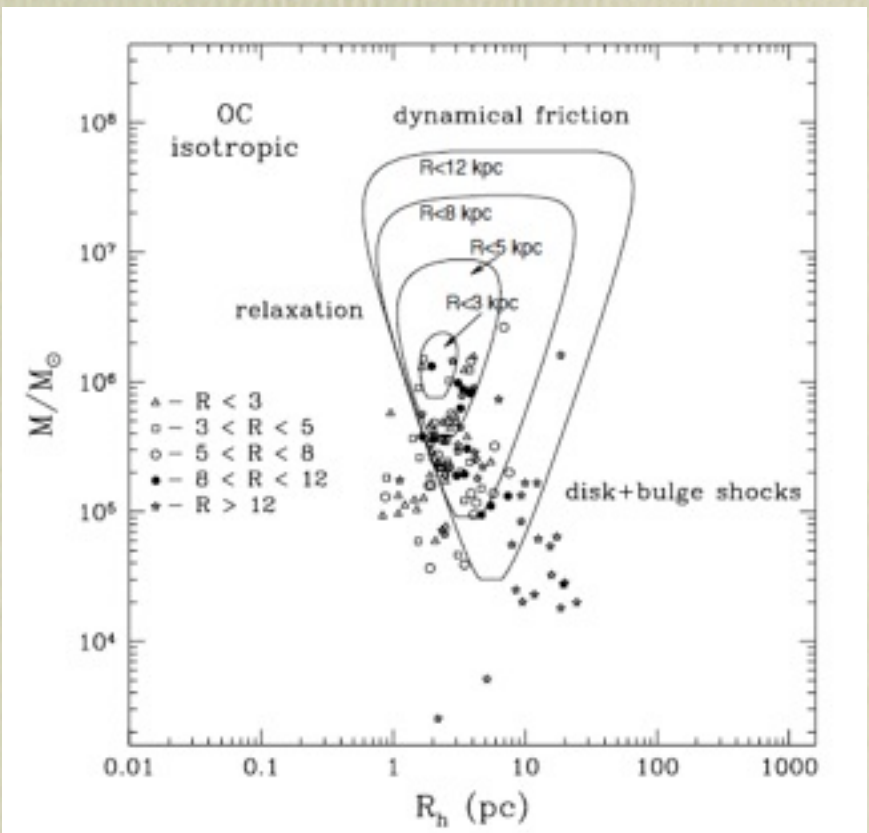
- All galaxies with $M_V<-15$ have at least one GC
- ~400 in M31
  > 10,000 in some ellipticals
- S_N (Specific frequency): number of clusters per unit luminosity

  S_N (spirals)< S_N(ellipticals)



Globular Clusters are Fragile!

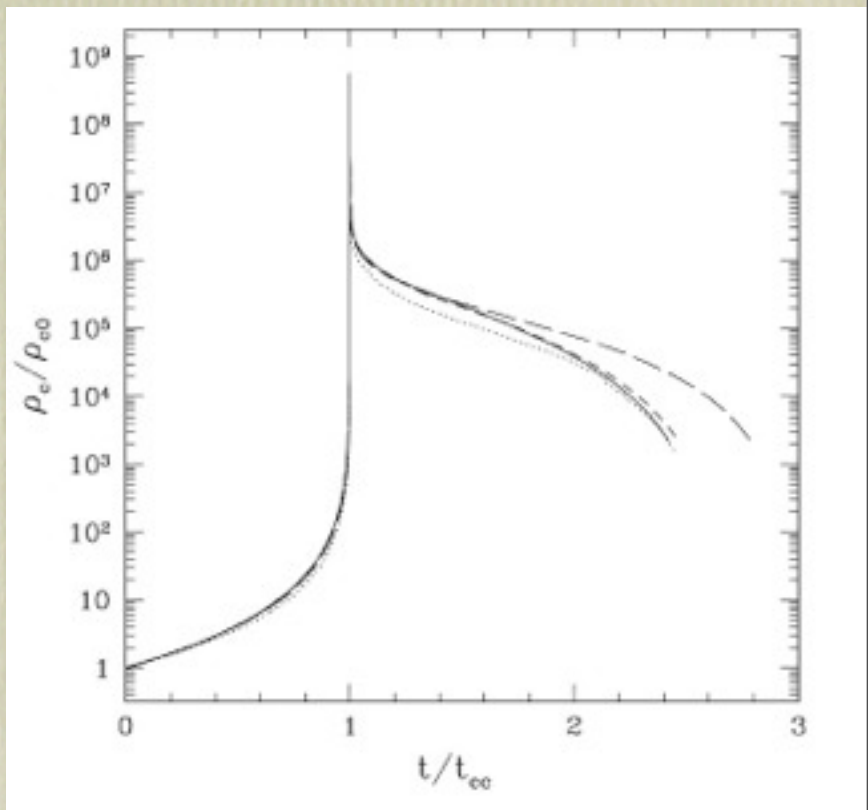
- Stars evaporate from the cluster due to several reasons:
  - Galactic tidal field
  - Tidal shock
- Clusters can be completely destroyed in time shorter than Hubble time
  - What you see today may be some fraction of the original population



Gnedin & Ostriker 1997

Dynamical Evolution: Core collapse and expansion

Gnedin, Lee & Ostriker (1999)



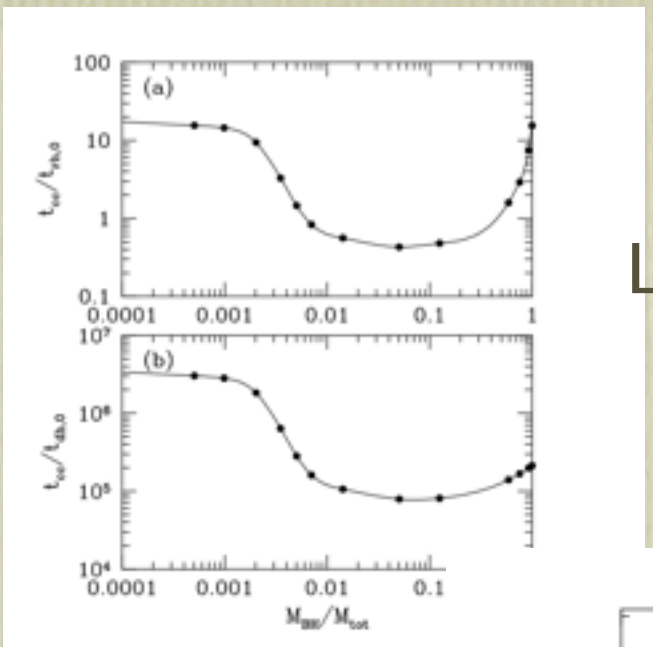
- Self-gravitating systems undergo 'core-collapse' and expansion by binary heating
- The time scale for core-collapse is ~10 t_{rh}

$$t_{rh} = 5.4 \times 10^8 \left(\frac{M}{10^7 M_\odot}\right)\left(\frac{r_h}{1\mathrm{pc}}\right)\left(\frac{M_\odot}{m}\right) \text{ years}$$

Dynamical friction mass segregation

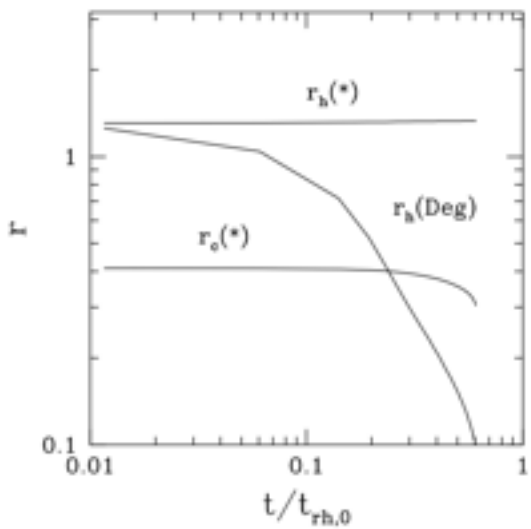
- The time scale for the collapse becomes much shorter if massive components exist

$$t_{cc,multi} \sim \left(\frac{m_{light}}{m_{heavy}} \right) t_{cc,single}$$



Lee (1995)

M_{heavy}/M_{total}



Lee (2001)

- Central part becomes completely dominated by massive components

Binaries in Star Clusters

- Binary orbits can be significantly affected by the interaction with other objects in dense environments: super-elastic scattering
- What kind of binaries?
  - Primordial
  - Three-body processes (Goodman & Hut 1984)
  - Tidal capture (Press & Teukolsky 1977, Lee & Ostriker 1986)
  - Gravitational wave capture: negligible (Lee 1995, 2001)

We should consider

- Mass function and energy equipartition
- Primordial Binaries
- Binary formation
- Binary-single interactions ➔ Hardening of binaries
- External tidal field (static or time varying)
- Stellar Evolution
- Evaporation of stars

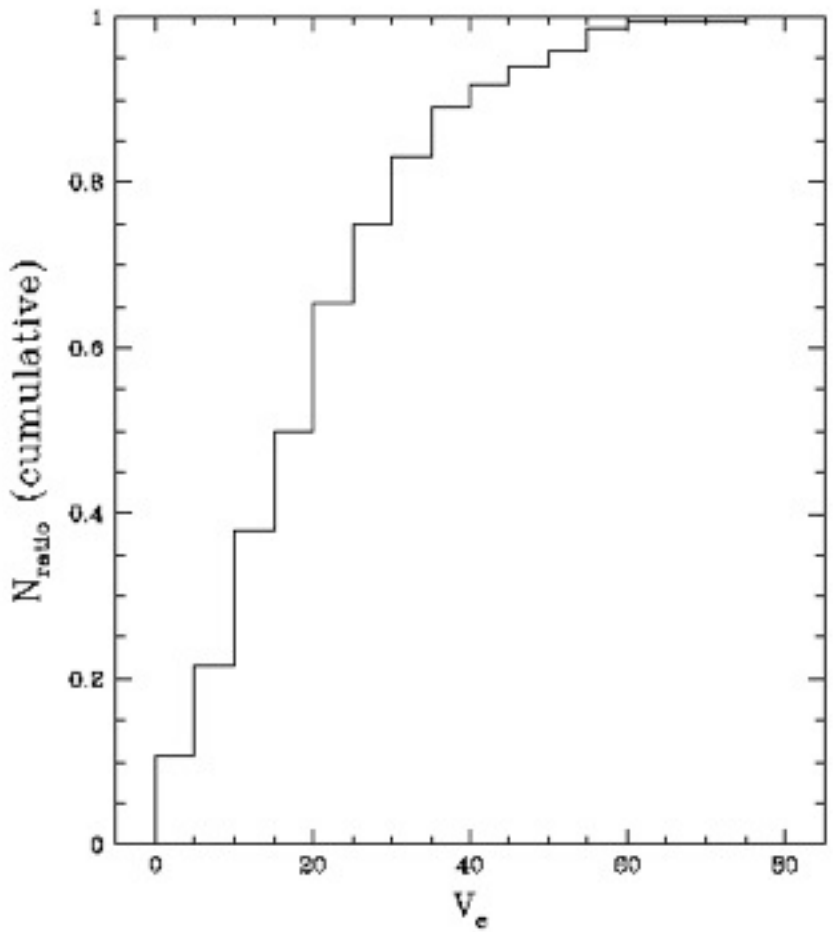
Hard binaries are ejected

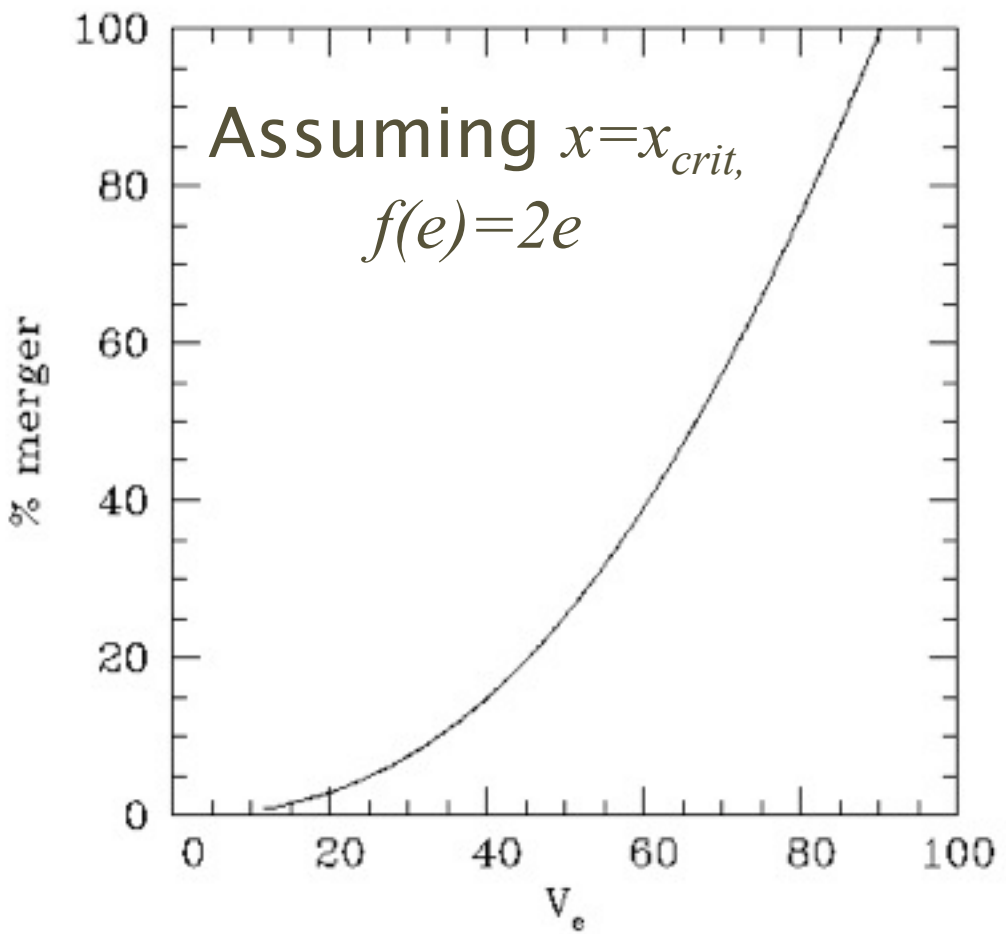
- Binaries become harder as a result of interaction
- Ejection occurs when recoil energy is greater than escape energy:

$$a < a_{crit} = \frac{Gm}{15v_{esc}^2}$$

- The distribution of eccentricity would be 'thermal', i.e., $f(e)de = 2e\,de$.

Galactic Globular Clusters





Median V_{esc} = 20 km/sec

Fraction of merger binaries within Hubble time

N-body Simulations

- pherical, non-rotating models in static tidal field
- Composed of two or three components:
  - 0.7 M_{sun}, representing stars below turn-off point
  - 1.4 M_{sun}, representing massive remnant stars (2-10% by mass)
  - 10 M_{sun}, representing stellar-mass black holes
- N=5,000 ~ 50,000
- Primordial binaries
- GPU version of Nbody6

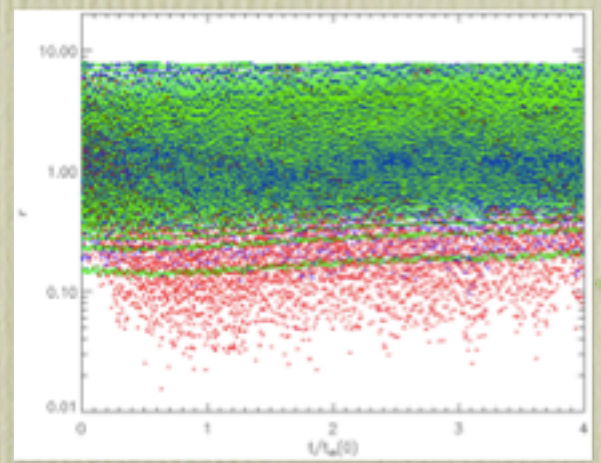
Limitations and Justifications

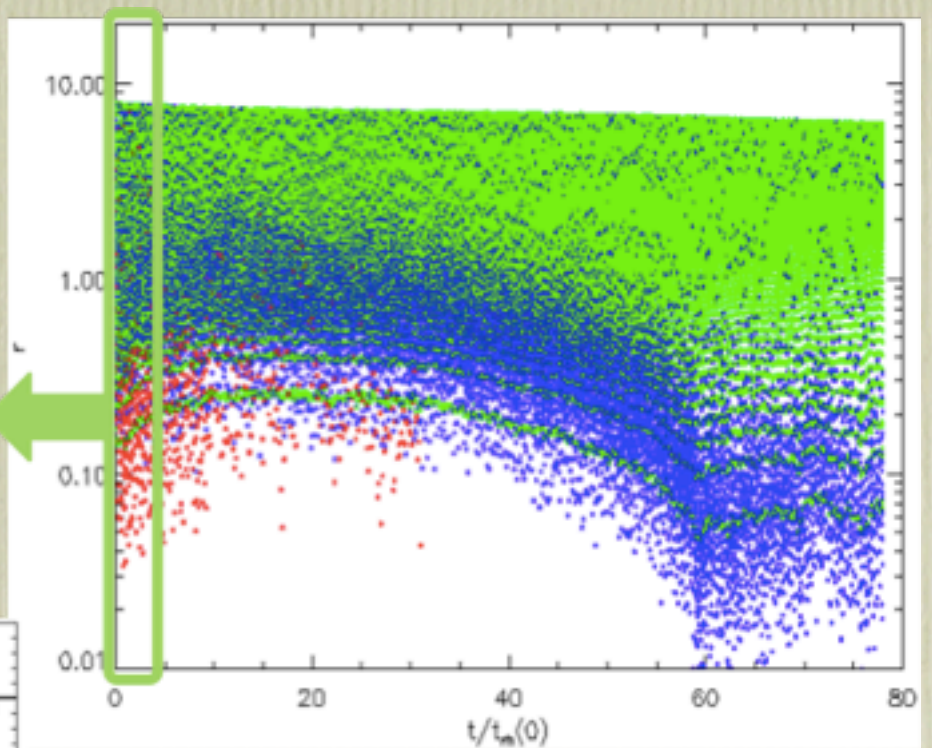
- Small N (typically 10,000, up to 5 x 10^4)
- Larger fraction of NS & BH than real clusters
- Primordial binaries are not treated realistically
- No stellar evolution
  - The purpose is not to have 'realistic' evolution, but to extract some general results.

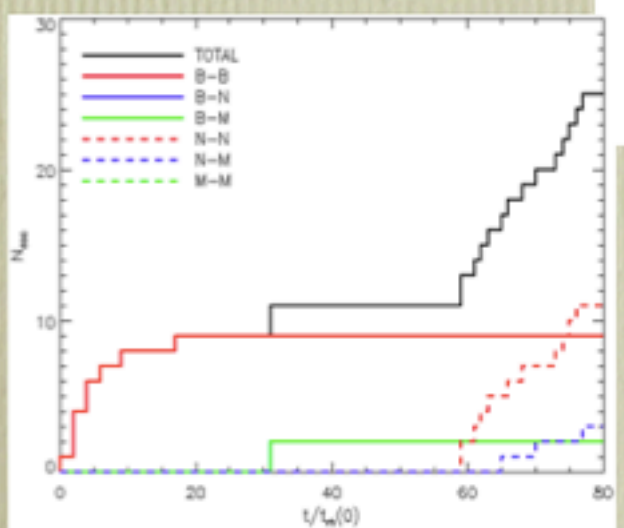
Summary of N-body Simulations

- Almost all black holes evaporate in fraction of core-collapse time, and 80-90% of neutron stars escape from GCs in a few core-collapse time
- 30% of these objects are in the form of compact binaries (BH-BH or NS-NS) →The number of ejected binaries is 15% of the total.
- BH-NS binaries are very rare
- The presence of primordial binaries does not change the results, since the ejection mechanism is the same

N=20,000, NS=140 BH=60

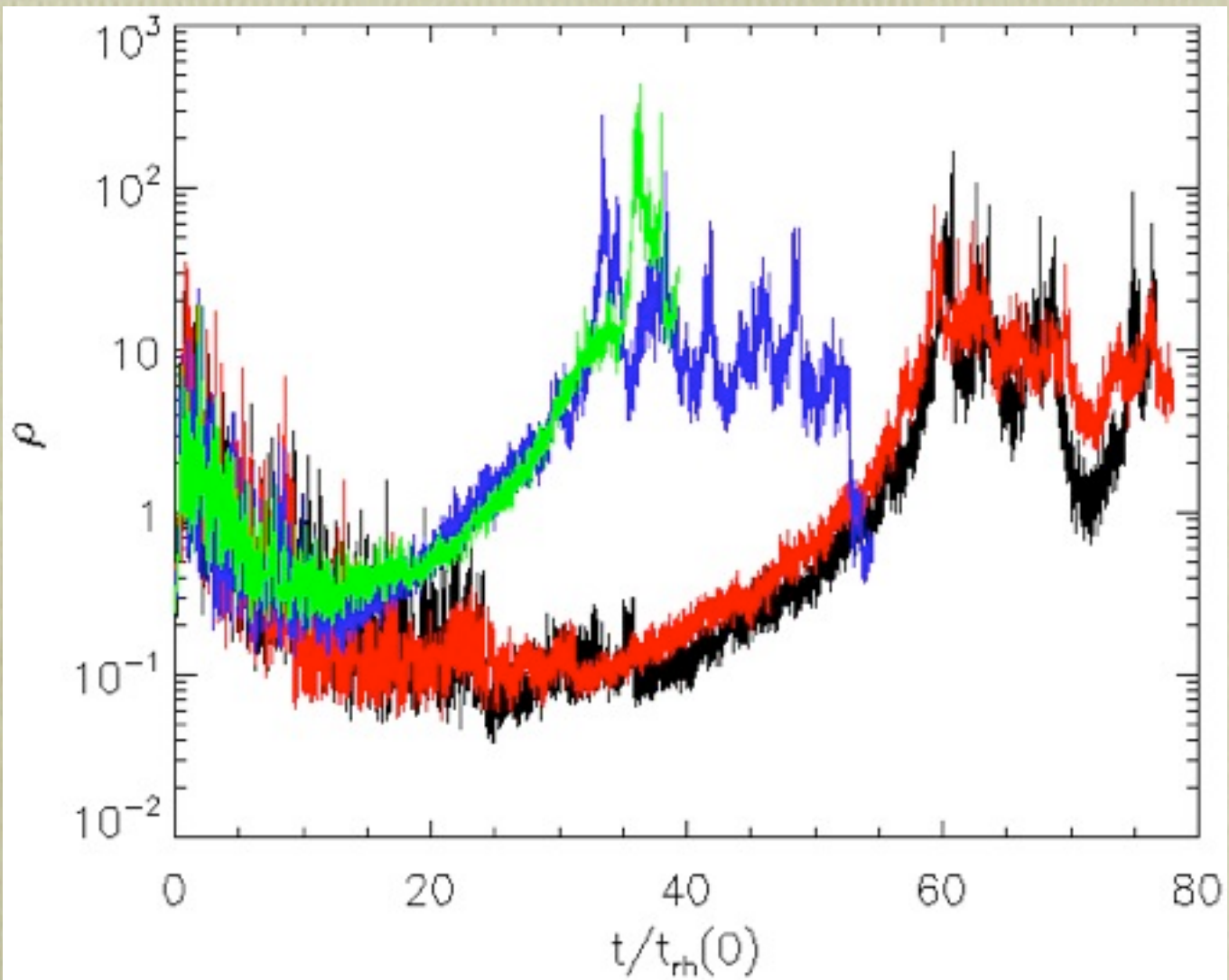






Red: BH
Blue: NS
Green: Normal

Central density



N=20k, NS-280, BH-60
N=20k, NS-140, BH-60
N=20k, NS-280, BH-40
N=40k, NS-280, BH-60

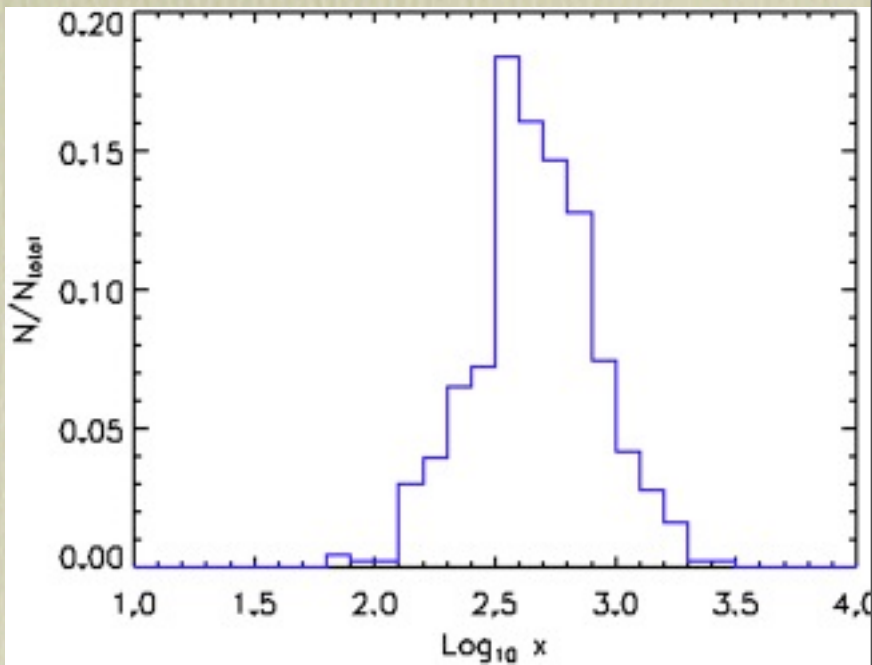
How can we use the N-body results?

How can we use the N-body results?

- The distribution of orbital separation depends only on the escape velocity

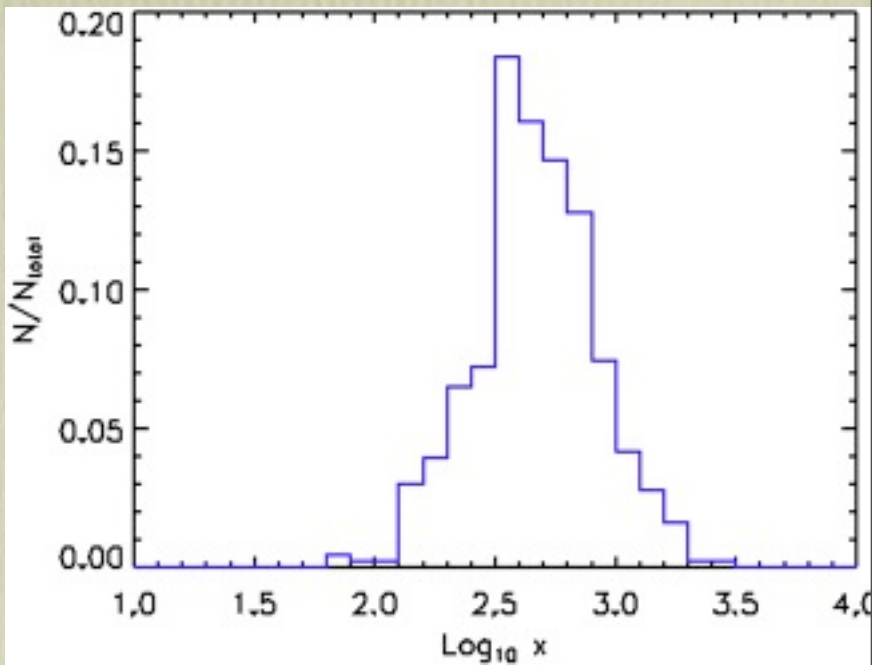
How can we use the N-body results?

- The distribution of orbital separation depends only on the escape velocity



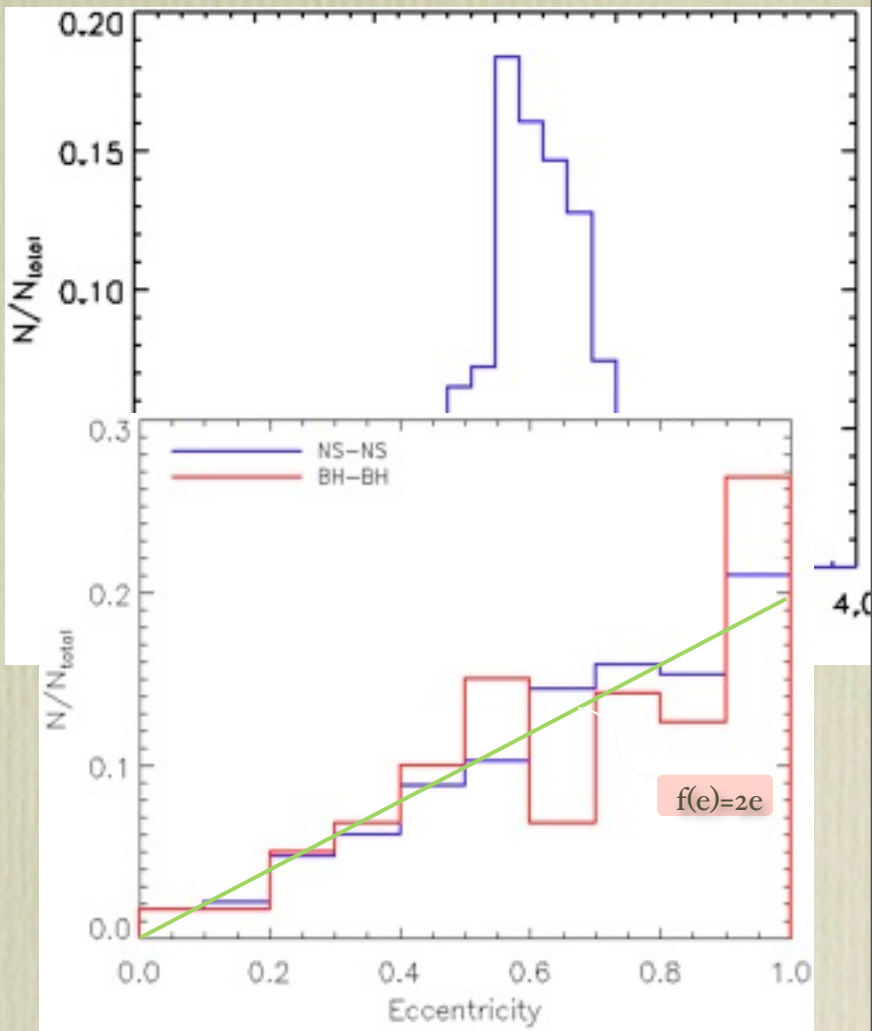
How can we use the N-body results?

- The distribution of orbital separation depends only on the escape velocity
- The eccentricity distribution is almost invariant of any parameters (i.e., thermal distribution)



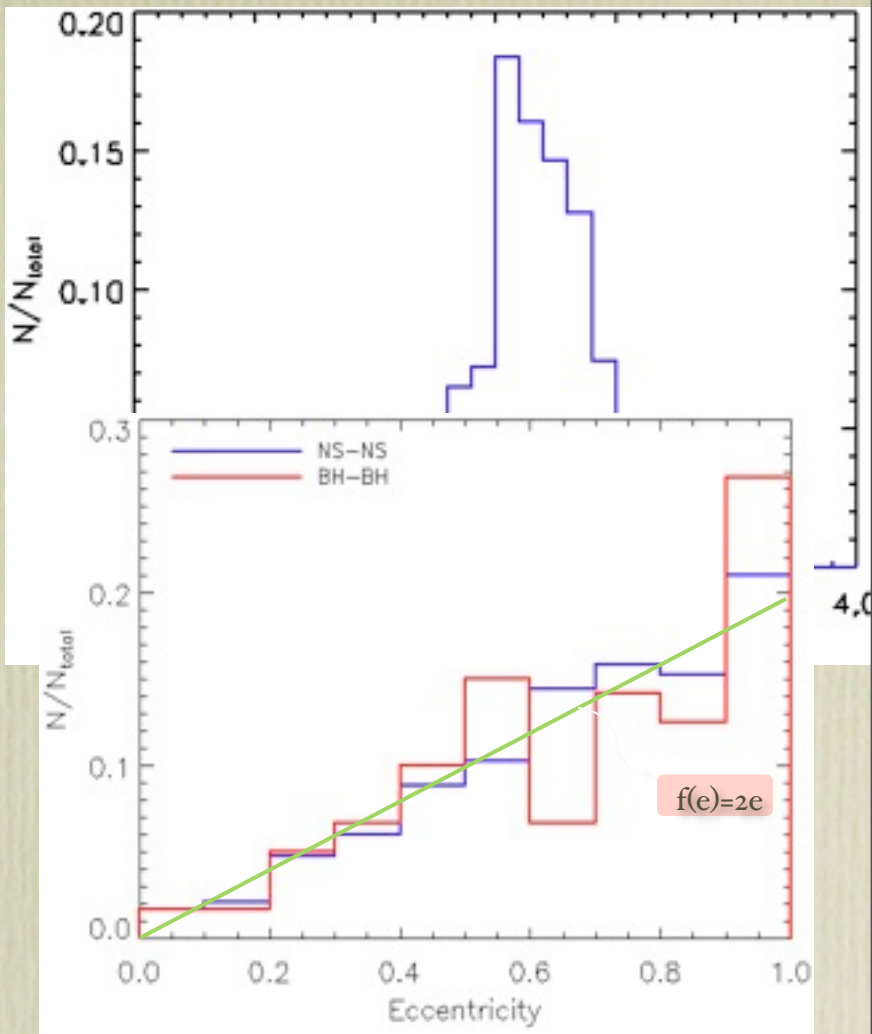
How can we use the N-body results?

- The distribution of orbital separation depends only on the escape velocity
- The eccentricity distribution is almost invariant of any parameters (i.e., thermal distribution)



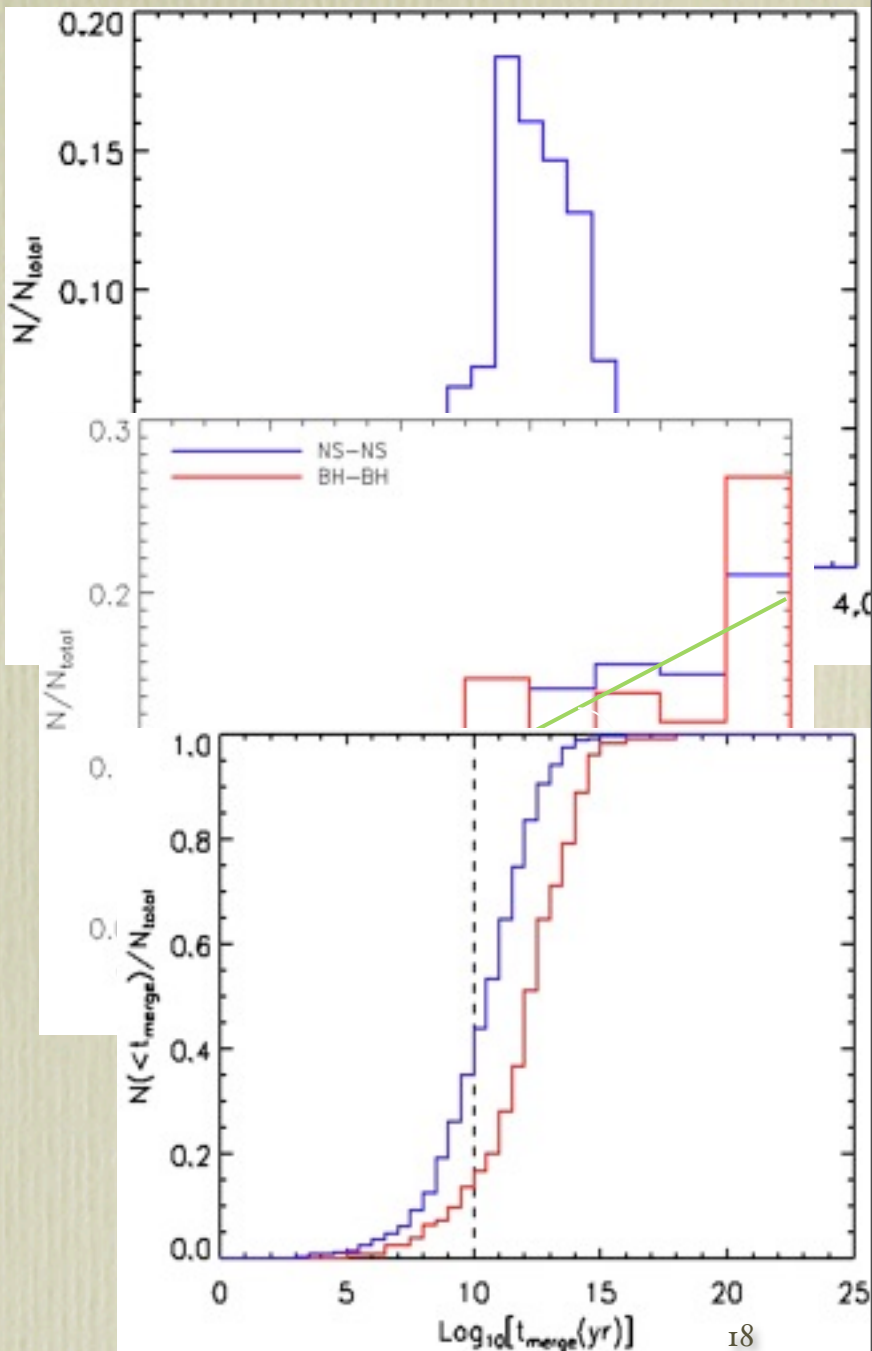
How can we use the N-body results?

- The distribution of orbital separation depends only on the escape velocity
- The eccentricity distribution is almost invariant of any parameters (i.e., thermal distribution)
- The 'merging time' distribution depends on central velocity dispersion (provided v_{esc}/σ is a constant)



How can we use the N-body results?

- The distribution of orbital separation depends only on the escape velocity
- The eccentricity distribution is almost invariant of any parameters (i.e., thermal distribution)
- The 'merging time' distribution depends on central velocity dispersion (provided v_{esc}/σ is a constant)



Estimation of merger rate

- We assume the following number fractions
  - 0.5 – 1% NS
  - 0.06 -0.2 % in BH
- 15% of these objects escape in the form of compact binaries
- We used 56 clusters in the catalogue by Harris (2010) with mass and velocity dispersion http://physwww.mcmaster.ca/~harris/Databases.html
- We computed the number of binaries whose merging time is shorter than Hubble time for each cluster and add them up

→ 1.5 - 3 Myr^{-1} for NS-NS and 0.08 – 0.25 Myr^{-1} for BH-BH

Uncertainties

- All the results depend on the number of NS and BH formed and retained in GC: BNS down, BBH OK?
- We used 56 clusters with known parameters, but there are 157 known clusters in the Galaxy with expected number being ~200: up
- Only ~20% (Djorgovski 1993) of the clusters have short time scale for production and ejection of compact binaries: down
- There should have been many clusters which are already disrupted (Lee & Goodman 1995, Gnedin & Ostriker 2000): up

Other properties

- We do not expect any merger inside the cluster
- Relative velocity to the host cluster
  1.8 v_{esc} for NS-NS binaries
  1.4 v_{esc} for BH-BH binaries

→Offset from the home cluster could be more than 10 kpc when they merge.

- Ellipticals have higher S_N, and could be better places for these populations