Black Hole Binaries with Advanced Detectors

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Current status of estimation: enormous uncertainty

	$\dot{N}$ (yr	$\dot{N}$ (yr	$\dot{N}_{high}$ (yr	$\dot{N}_{max}$ (yr
NS-NS	0.4	40	400	1000
NS-BH	0.2	10	300	
BH-BH	0.4	20	1000	
IMRI into IMBH			10	300
IMBH-IMBH			0.1	1

Abadie et al. 2010 ("Rate" paper by LIGO Scientific Collaboration)

How compact binaries are produced?

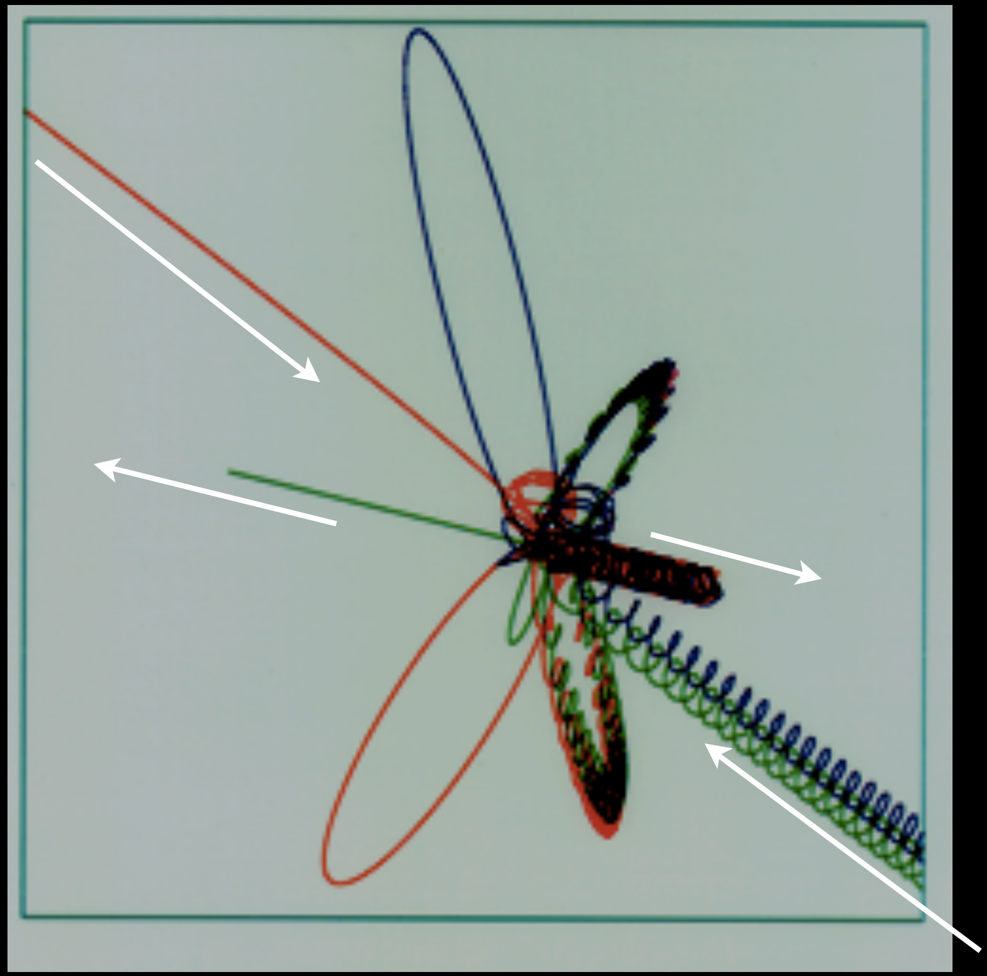
- Evolution of primordial binaries
  - Each component has to be massive
  - Should be proportional to the number of stars
- Dynamical Formation: More sensitive to density than the total amount of stars
  - 3-body processes
    - Globular Clusters: Banerjee et al., 2010; Bae et al. 2014, MNRAS in press; Kim et al., 2014, in preparation
  - Capture by gravitational radiation (2-body processes)
    - Nuclear Clusters: O'Leary et al. 2009; Hong & Lee 2014, in prep.

Binary interaction with others

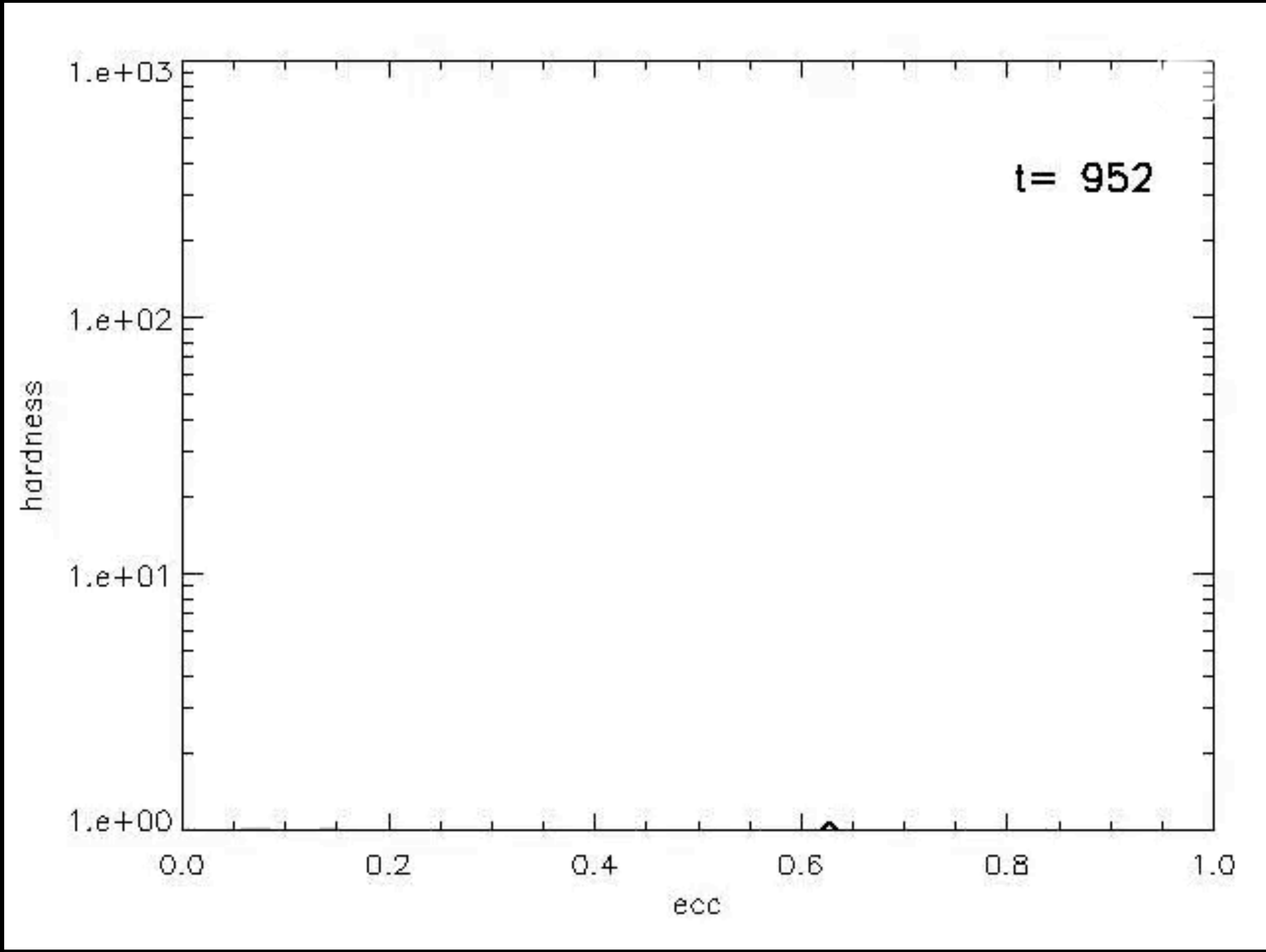
- Binaries become tighter as a result of interaction
  - Endothermic, and provides recoil energy
- Ejection occurs when recoil energy is greater than escape energy:

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

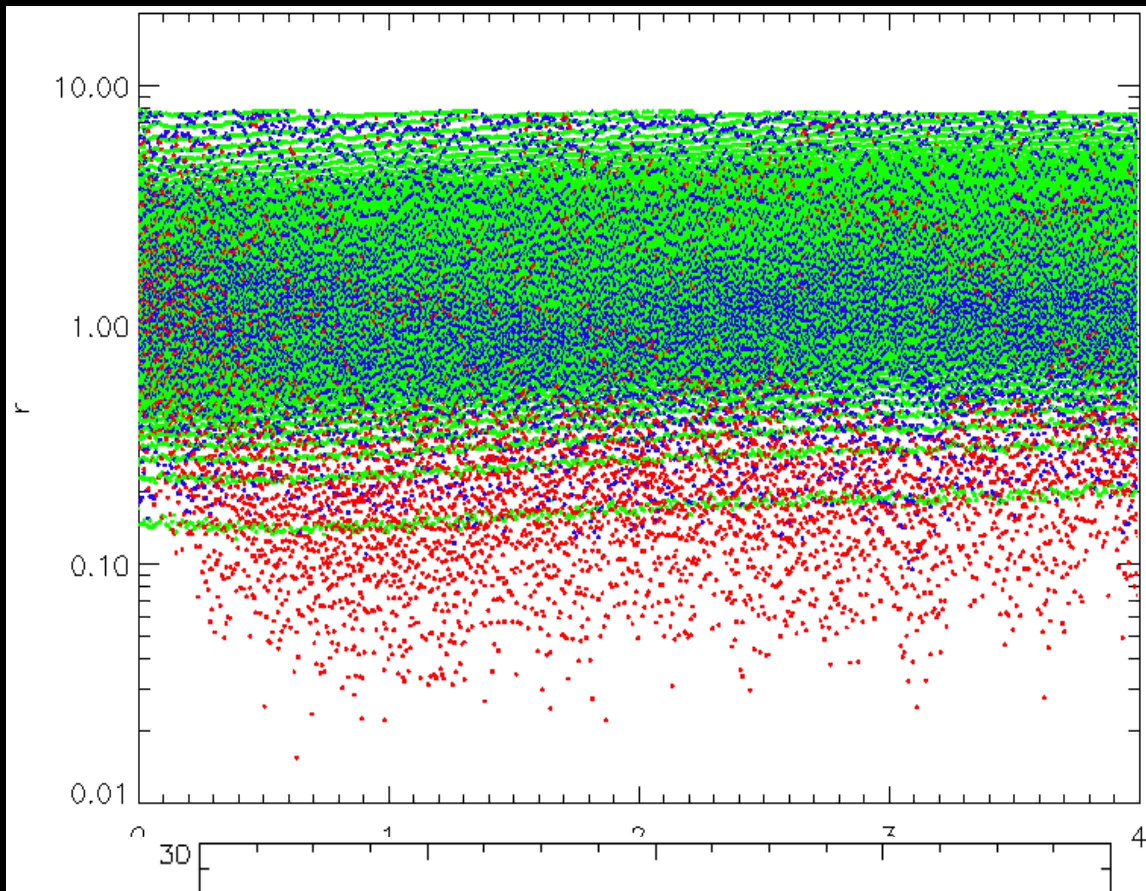
- The distribution of eccentricity: *f(e)de = 2e de.*

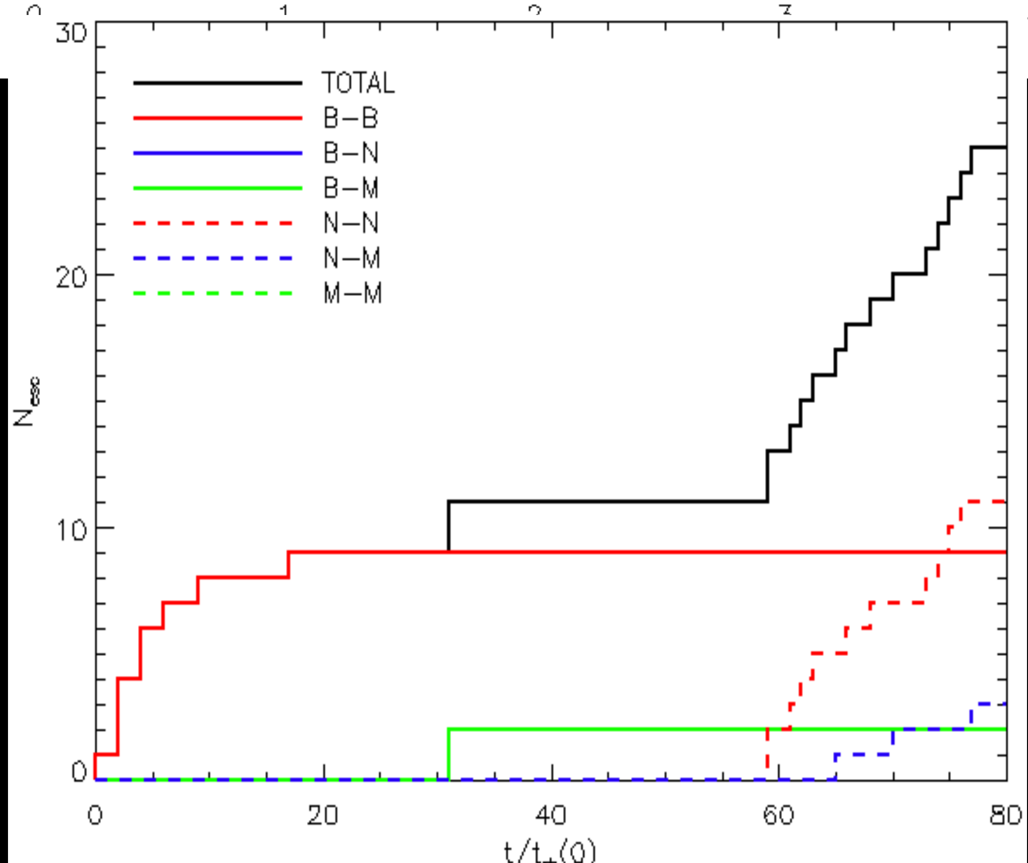


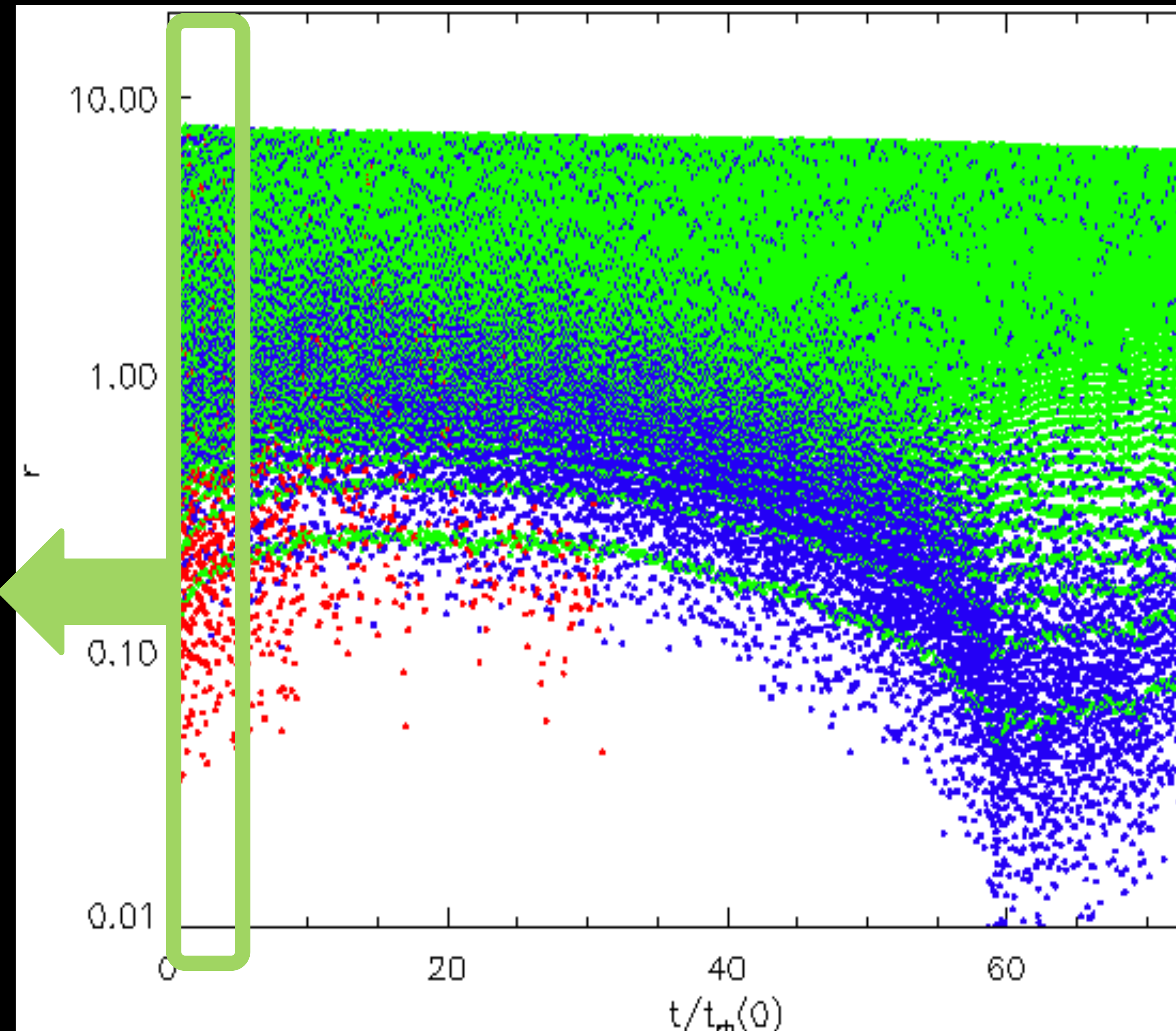
Evolution of binary parameters: example



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







Red: BH
Blue: NS
Green: Normal

Summary of Simulations

- Almost all black holes evaporate in short time, and neutron stars escape from GCs later.
- 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 they are easily destroyed (but it depends on the binary parameters)

Estimation of merger rate

- We assume the following number fractions
  - 0.5 % NS (but 10% of this remains)
  - 0.01 % in BH
- 15% of these objects escape in the form of compact binaries
- We used 142 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
- Results (uncertainties from retention rate [~4], and surviving GC population [~2], etc.)
  - NS-NS: 0.05 - 0.5 /Myr NS-NS ➡ 0.01- 0.1 /yr (cf. field pop. ~40 /yr)
  - BH-BH 0.03 – 0.25 Myr ➡ 8 - 60 /yr (cf. field pop. ~ 20 /yr)

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.
    - Many SGRB seem to be present in the outer parts of galaxies
- Ellipticals have higher SN, and could be better places for these populations

KGWG Korean Gravitational-Wave Group

SEOUL NATIONAL UNIVERSITY

Nuclear Star Clusters (NCs)

Hubble image of the Sagittarius star cloud

- The densest stellar system
  - n ~ $10^5 M_\odot pc^{-3}$ (Schodel et al. 2009)

- SMBH at the center
  - e.g., Sgr A* in the Milky Way
    - M(SgrA*)~3-4 x $10^6 M_\odot$
  - Produces the central cusp

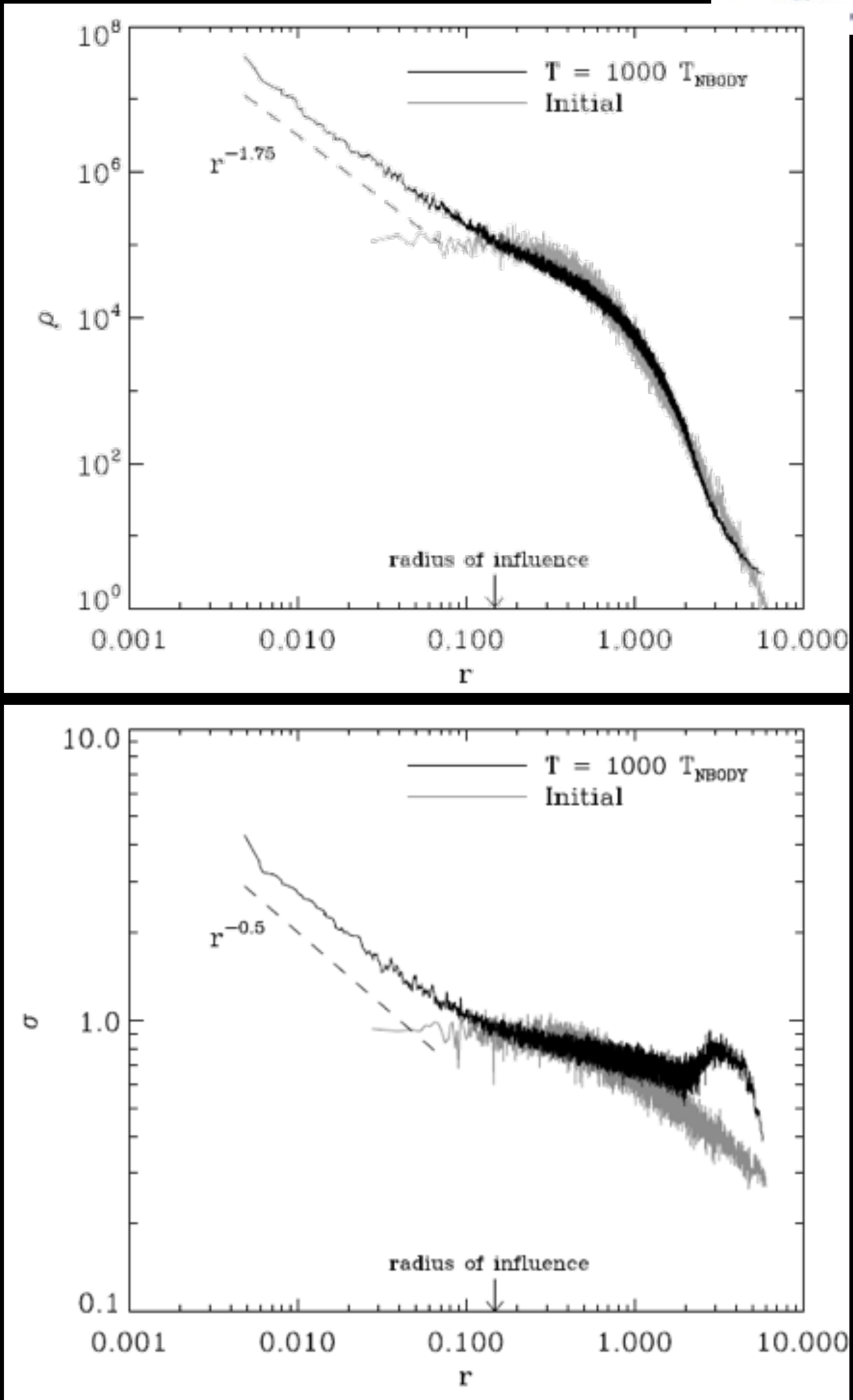
GW Sources in Nuclear Clusters

- Extreme mass ratio inspirals (EMRI)
    - Lightman & Shapiro (1977); Hopman & Alexander (2003, 2005, 2006); Merritt et al. (2011)
  - Compact stars spiraling in the massive black hole
  - low frequency

- Stellar mass black holes binaries (BH-BH, ~10$M_\odot$)
  - Can be formed by gravitational radiation capture (Hansen 1972; Quinlan & Shapiro 1987, 1989)
  - Cusp around supermassive black hole provides favorable environment for the capture
  - 1~10% SBHs in galactic nuclei (Hopman & Alexander 2006b) due to mass segregation
    - Initially 0.1% of BHs (Alexander 2005)

N-body Realizations

- Stellar cusp (Bahcall & Wolf 1976)
  - $\rho(r<r_{inf}) \sim r^{-1.75}$
- Keplerian velocity dispersion near MBH
  - $\sigma(r<r_{inf}) \sim r^{-0.5}$
- Nearly isothermal velocity dispersion at $r>r_{inf}$
- Velocity dispersion bump at $r\sim40\ r_{inf}$ due to the external potential well



Distribution of a and e

- Parabolic approximation and equal mass (Quinlan & Shapiro 1987, 1989)

$$\Delta E = -\frac{85\pi G^{7/2} m^{9/2}}{12 c^5 r_p^{7/2}} \quad r_{p,max} = \left(\frac{85\pi}{6}\right)^{2/7} \frac{Gm}{c^{10/7} v_\infty^{4/7}} \approx \frac{3Gm}{c^{10/7} v_\infty^{4/7}}$$

- $r_p / r_{p,max}$: uniform distribution
- v_∞ : 1D Gaussian distribution

Before capture

$$a = \frac{Gm}{v_\infty^2}$$

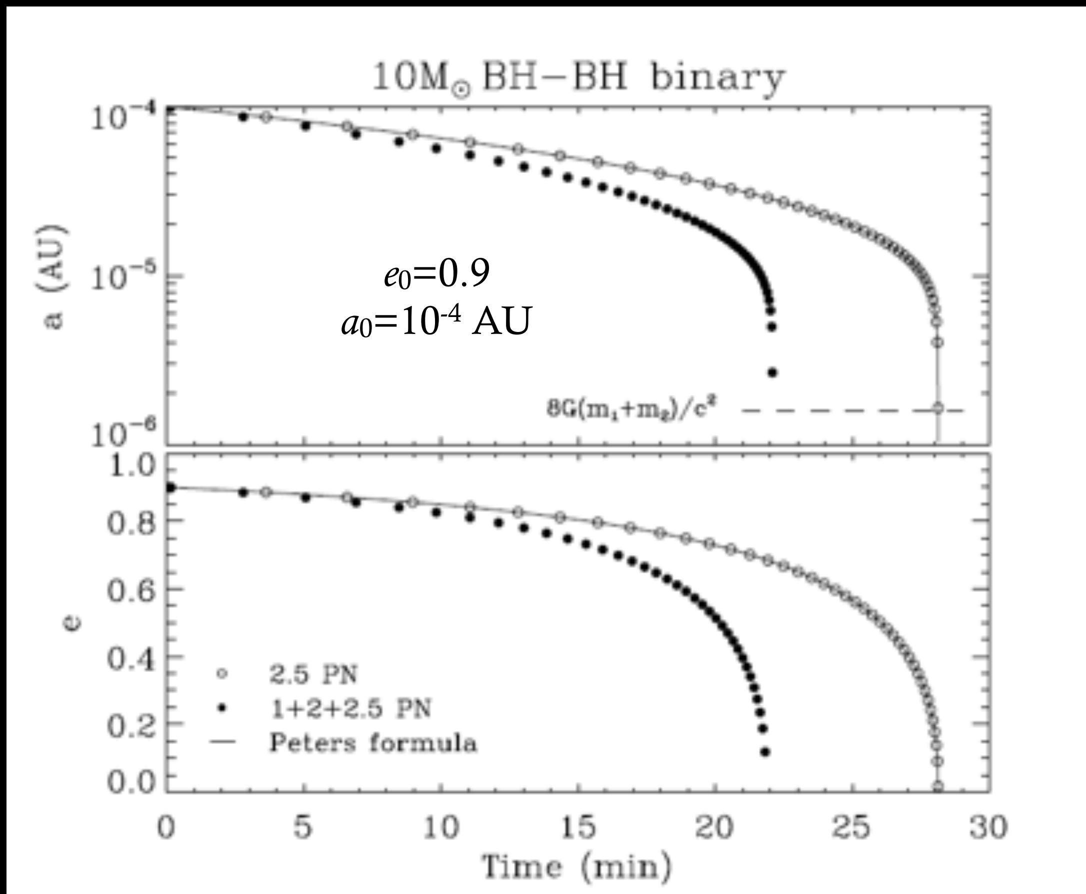
$$e \approx 3\left(\frac{v_\infty}{c}\right)^{10/7}\left(\frac{r_p}{r_{p,max}}\right) + 1$$

After capture

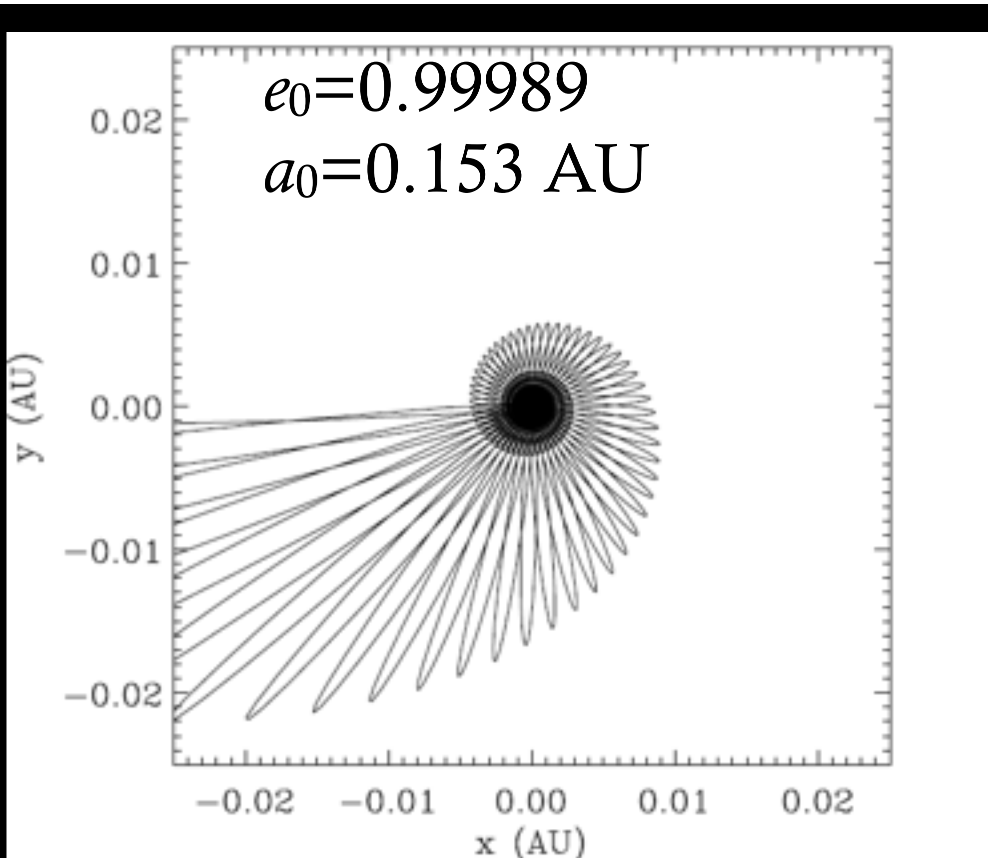
$$a' = \frac{Gm}{v_\infty^2}\left(\left(\frac{r_{p,max}}{r_p}\right)^{7/2} - 1\right)^{-1}$$

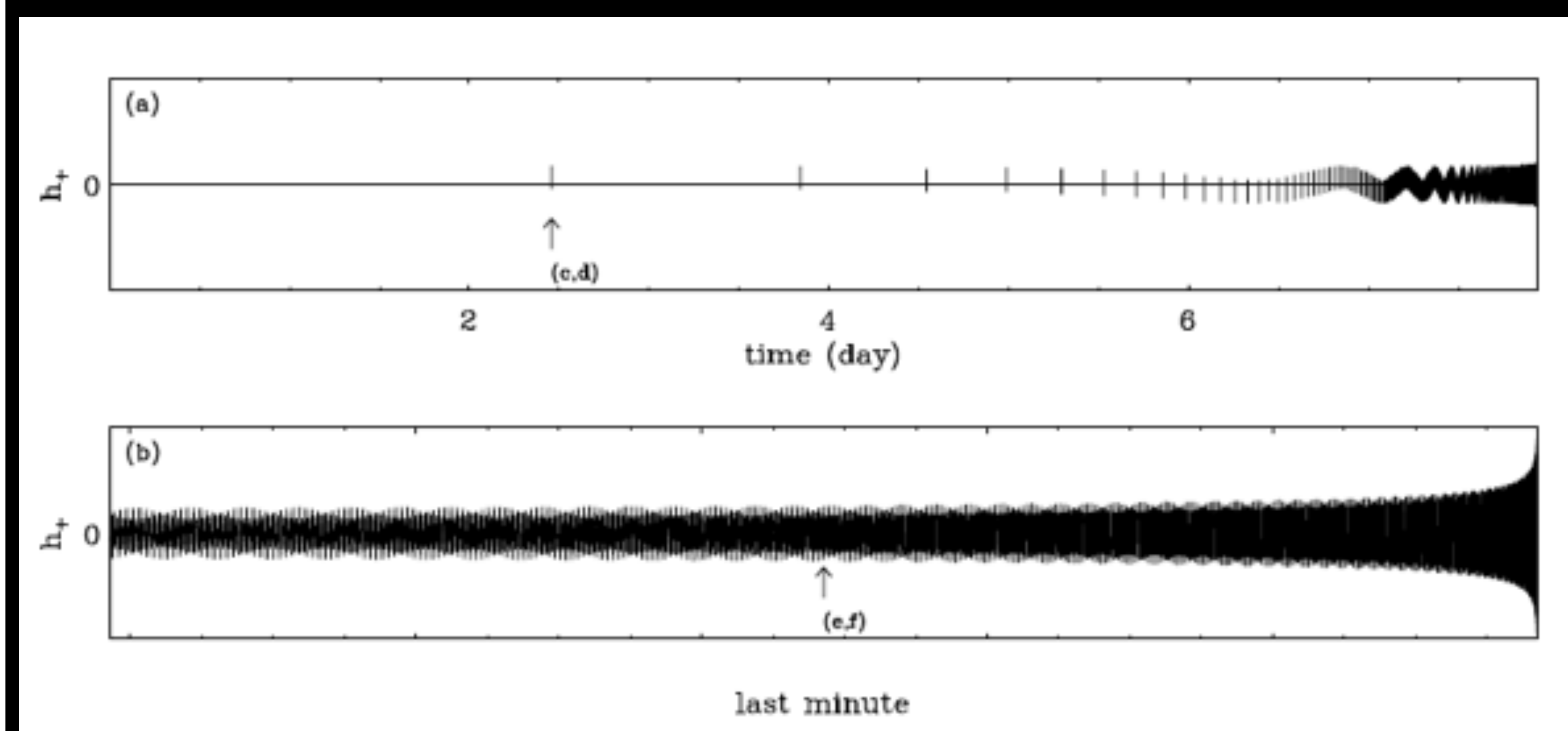
$$e' \approx 1 - 3\left(\frac{v_\infty}{c}\right)^{10/7} \frac{r_p}{r_{p,max}}\left(\left(\frac{r_{p,max}}{r_p}\right)^{7/2} - 1\right)$$

Orbital evolution and waveforms



- Precession should be taken into account for the calculation of the merging time.
- Binaries remain eccentric until they enter LIGO/Virgo band.
  - Waveforms are different from circular binaries





Expected Detection Rates for Adv. LIGO

Models	$M_{\rm MBH}/M_{\rm cl}$	$\Gamma_{\rm mer,MW}$ ($\rm Myr^{-1}$)	$\mathcal{M}^a_{\rm BH}$	$D_{\rm h}$ (Mpc)	$\mathcal{R}^b_{\rm det,l}$ ($\rm yr^{-1}$)	$\mathcal{R}^c_{\rm det,re}$ ($\rm yr^{-1}$)	$\mathcal{R}^d_{\rm det,h}$ ($\rm yr^{-1}$)
				986^e	0.06	0.44	2.99
1-4	0.2	3.33×10^{-4}	0.44	$\sim 1100^f$	0.09	0.64	4.32
				$\sim 1900^g$	0.27	2.00	13.5
				986^e	0.02	0.19	1.25
5-7	0.1	1.39×10^{-4}	0.44	$\sim 1100^f$	0.04	0.27	1.80
				$\sim 1900^g$	0.11	0.83	5.62

e: Abadie et al. 2010, SNR=8
f: Baker et al. 2007, SNR=10
g: Reiswig et al. 2009, SNR=8

- BH-BH Detection rates: 0.02-10 $\rm yr^{-1}$
  - 1-100 $\rm yr^{-1}$ (Fokker-Planck simulations for Galactic nuclei; O'Leary et al. 2009)
    - c.f. 1-2 $\rm yr^{-1}$ (field population synthesis; Belczynski et al. 2007, higher values in more recent works), 15-40 $\rm yr^{-1}$ (dynamical formation and hardening in GC)

Summary

- **Globular Clusters**
  - Both NS-NS and BH-BH binaries can be formed by three-body processes
  - They will become mergers well outside of the cluster (and halo)
  - NS-NS contribution may be smaller than disk populations, but BH-BH could be similar (or larger)
- **Nuclear Clusters**
  - BH-BH binaries are likely to be formed by capture process
  - They become mergers in very short time (days to a 1000s years)
  - They will remain eccentric until they enter LIGO/VIRGO bands
  - Rate is uncertain, but likely to be much smaller than disk/globular cluster contribution (< 1 per year)