Properties of dynamically formed black hole binaries in globular clusters

Chunglee Kim (KASI)

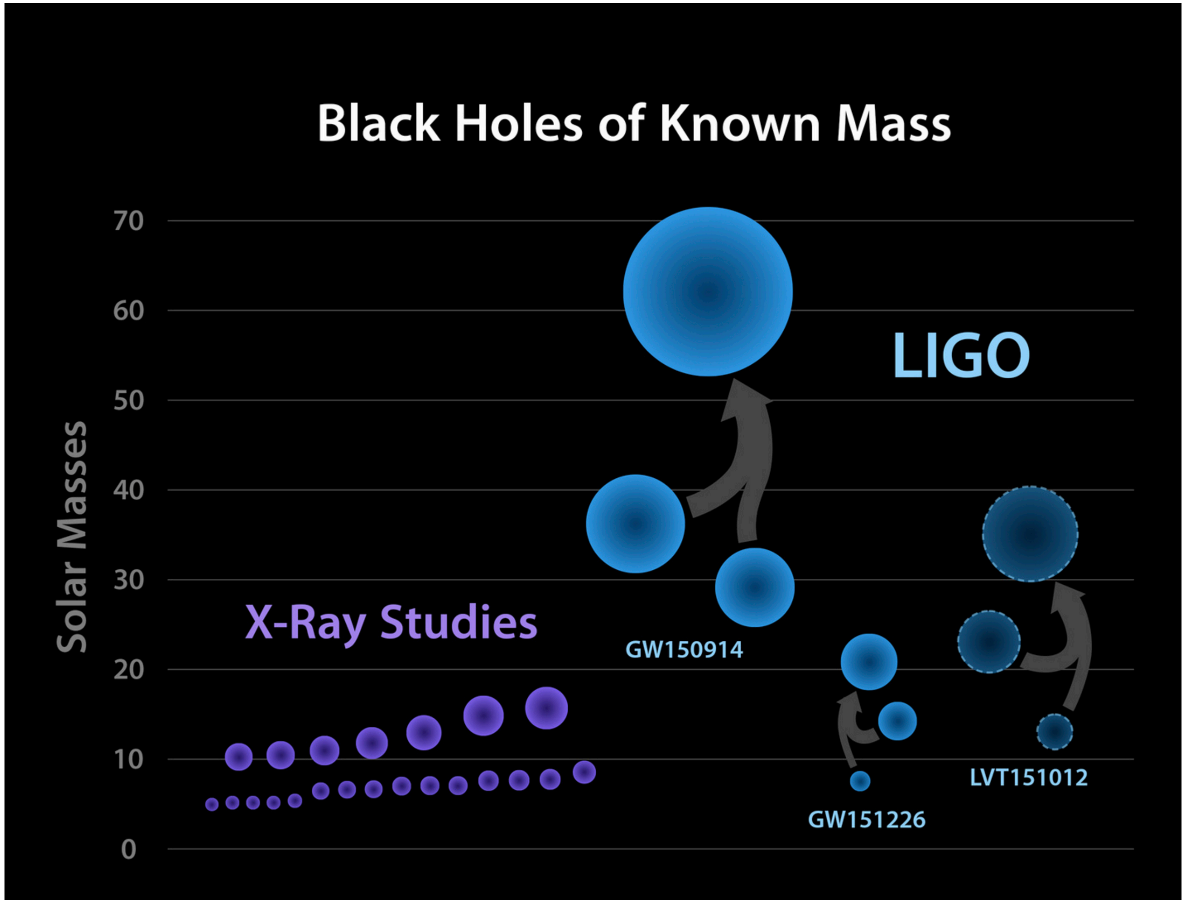
with Dawoo Park (SNU), Hyung Mok Lee(SNU), Yeong-Bok Bae (KASI),
and Chris Belczynski (Warsaw)

2017.5.31. GWPAW @ Annecy, France

aLIGO's GW detections prove

- Binary black holes (BBHs) exist
- Some BBHs do merge emitting GWs
- And, yes, there are BHs more massive than 10 M_{sun}.

BHs with $\mathcal{O}(100)$ M_{sun} can be explained by merger.



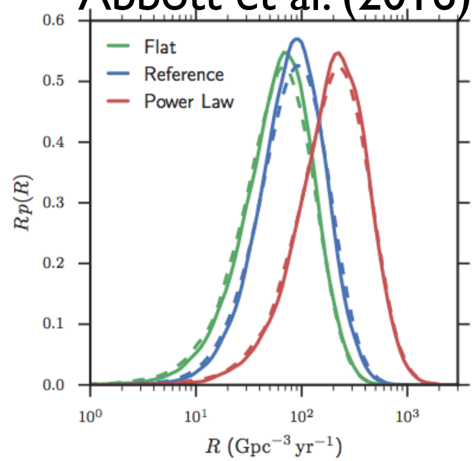
typical info from inspiral-dominant GW observation for a BBH (GW151226, Abbott et al. 2016)

Primary black hole mass	$14.2^{+8.3}_{-3.7} M_\odot$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_\odot$
Chirp mass	$8.9^{+0.3}_{-0.3} M_\odot$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_\odot$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_\odot$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_\odot c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	440^{+180}_{-190} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

and spin magnitudes.
- precessing/aligned spin templates
- one of the BH has $|s| > 0.2$ in GW151226

Binary Black Holes (BBHs) and GW detection with aLIGO-like sensitivity (f_{gw} > 10 Hz)

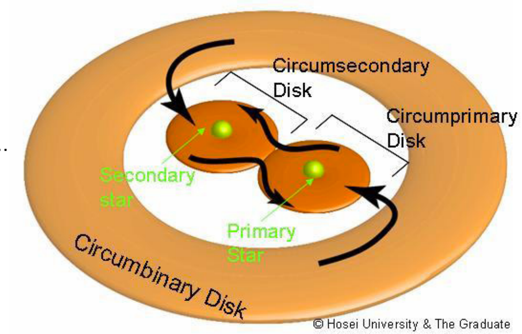
Abbott et al. (2016)



- **BH mass function** more or less
(caution for observational biases)

- **BBH birthplace** spin & e, signal search in low f
(galactic disk vs globular cluster vs galactic center)

- **multi-messenger astronomy for BBHs?** "environment"
  important for astrophysics/cosmology
  detectability is in question

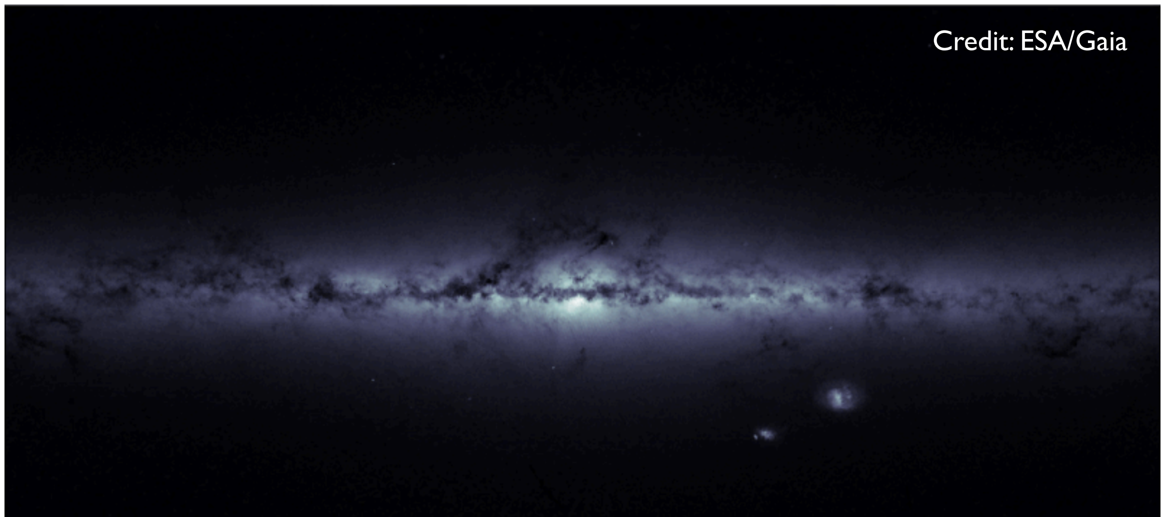


BBHs formed in a galactic disk

- **field or disk population**
  follows a standard stellar binary evolution scenario
  (progenitors are more massive than those of NS-NS binaries)

- **population synthesis:**
  mass transfer/common envelope, (SN kicks) are important

- **signature of field BBHs:**
  aligned spins, almost circular orbits,
  broader mass func. than cluster population (metallicity effects)
  pop III contribution? (in high redshift)

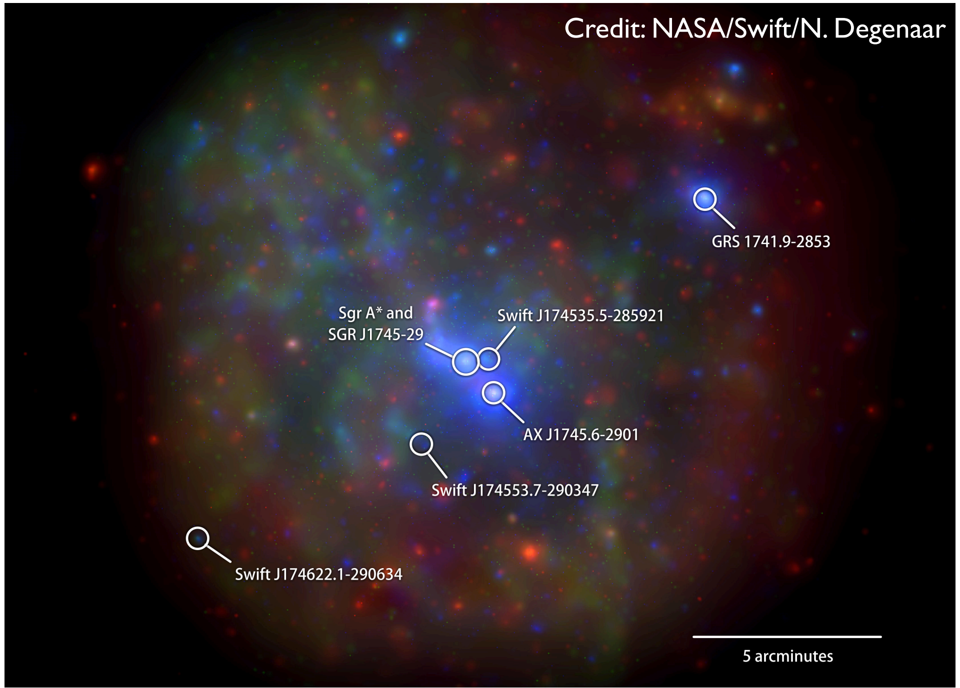


BBHs formed in dense stellar environments

- **Globular Clusters “GC" (cluster population)**
- Galactic Center

- **N-body, Monte Carlo simulations:**
  dynamics plays an important role in binary evolution
  [assumption] initial stellar/binary properties: similar to field population

- **signature of dynamically formed binaries:**
  isotropic spin directions, broad e [0,1], low metallicity effects in BH mass



N-body simulations of BBHs formed in a GC

- **paper I** Bae, CK, Lee, MNRAS (2014)
  1.4 M_{sun} NS, 10 M_{sun} BH

- **paper II** Park, CK, Bae, Lee, Belcznski (2017, arXiv:1703.01568)
  5, 10, 20 M_{sun} BH only,
  BH mass distribution from C. Belczynski's popsyn results

NBODY6 (Aarseth 2003)

initial density profile of a cluster: King model (King 1966)

total number of particles: 25k -100k per model

NS/BH mass fraction ~ 1.35-5 %

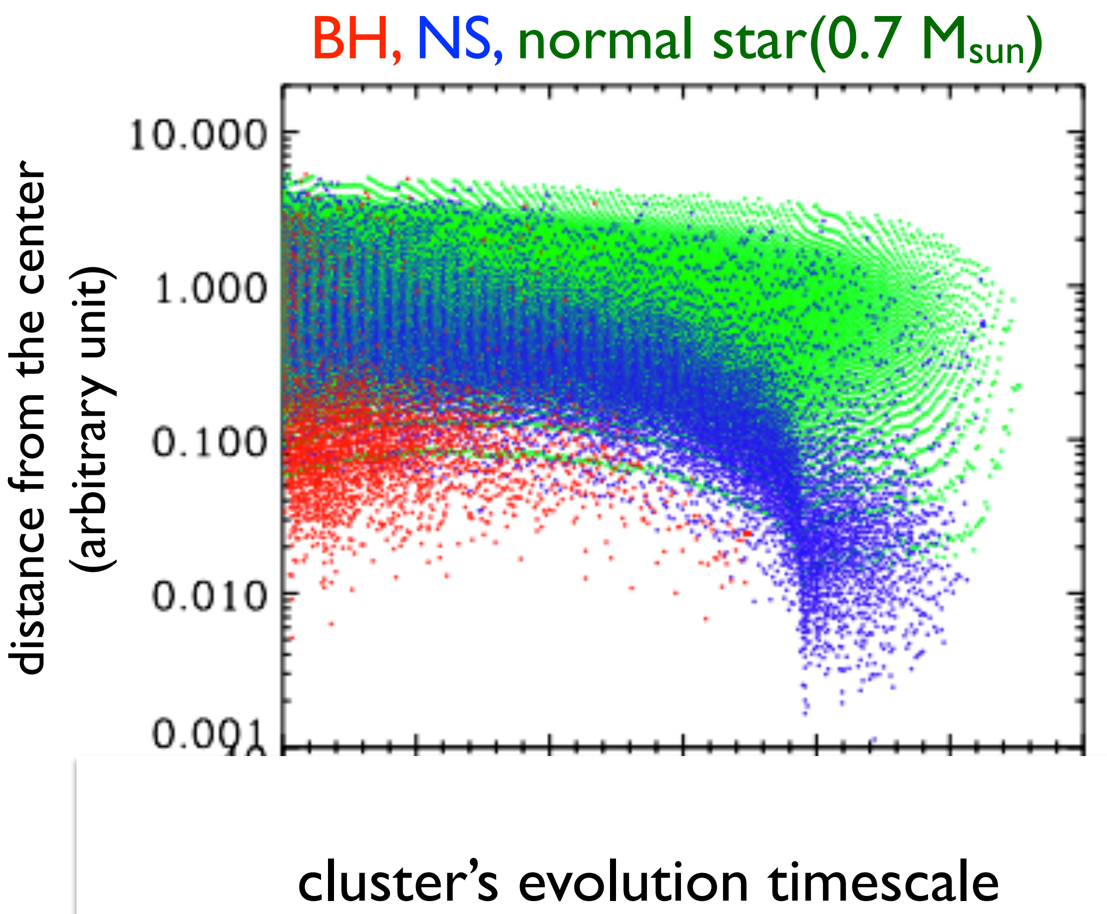
cf) MW GCs ~ 10^{6-7} stars

Model Assumptions (conservative)

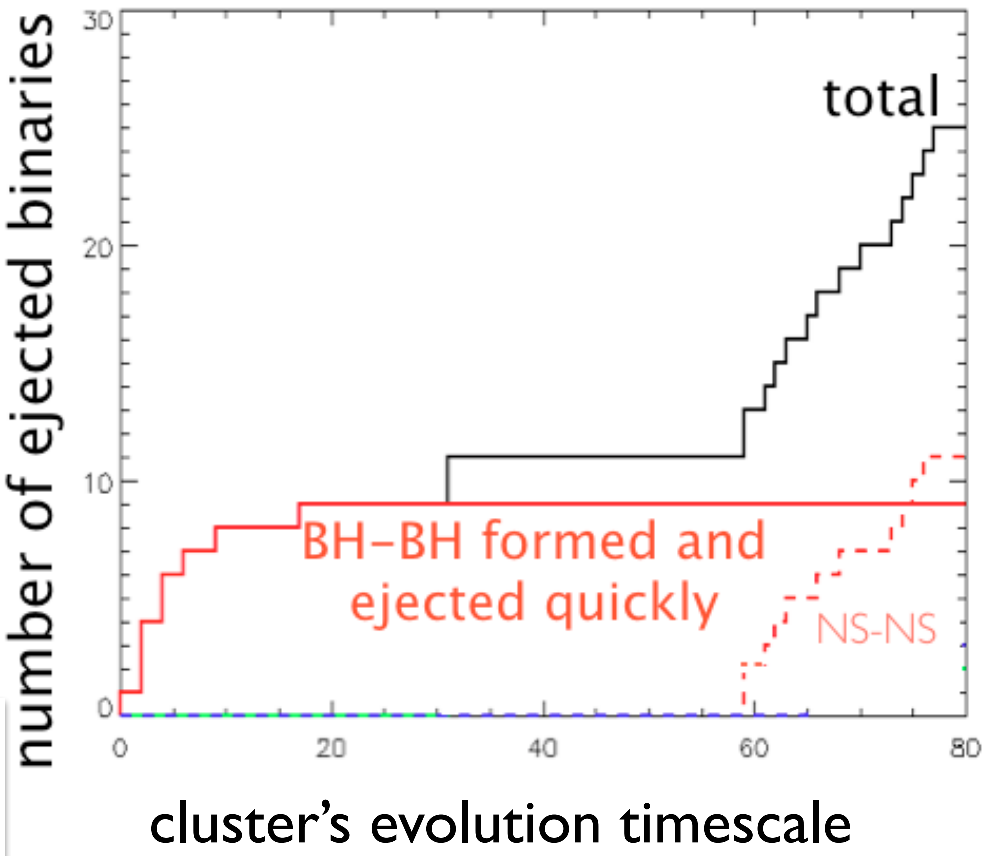
- no primordial binaries
- no SN kicks
- 3-body interactions only (no gravitational radiation capture)
- no stellar evolution involved
(but we adopt a mass function from popsyn for lower Z)
- no cluster evolution (young clusters rotate faster)

core-collapse and formation of CBCs from a globular cluster

- Core-collapse results in 3-body interactions (the heaviest first)
- Almost all compact objects are ejected from a cluster
- ~1/3 of ejected compact objects are in binaries
- unequal-mass binaries are rare

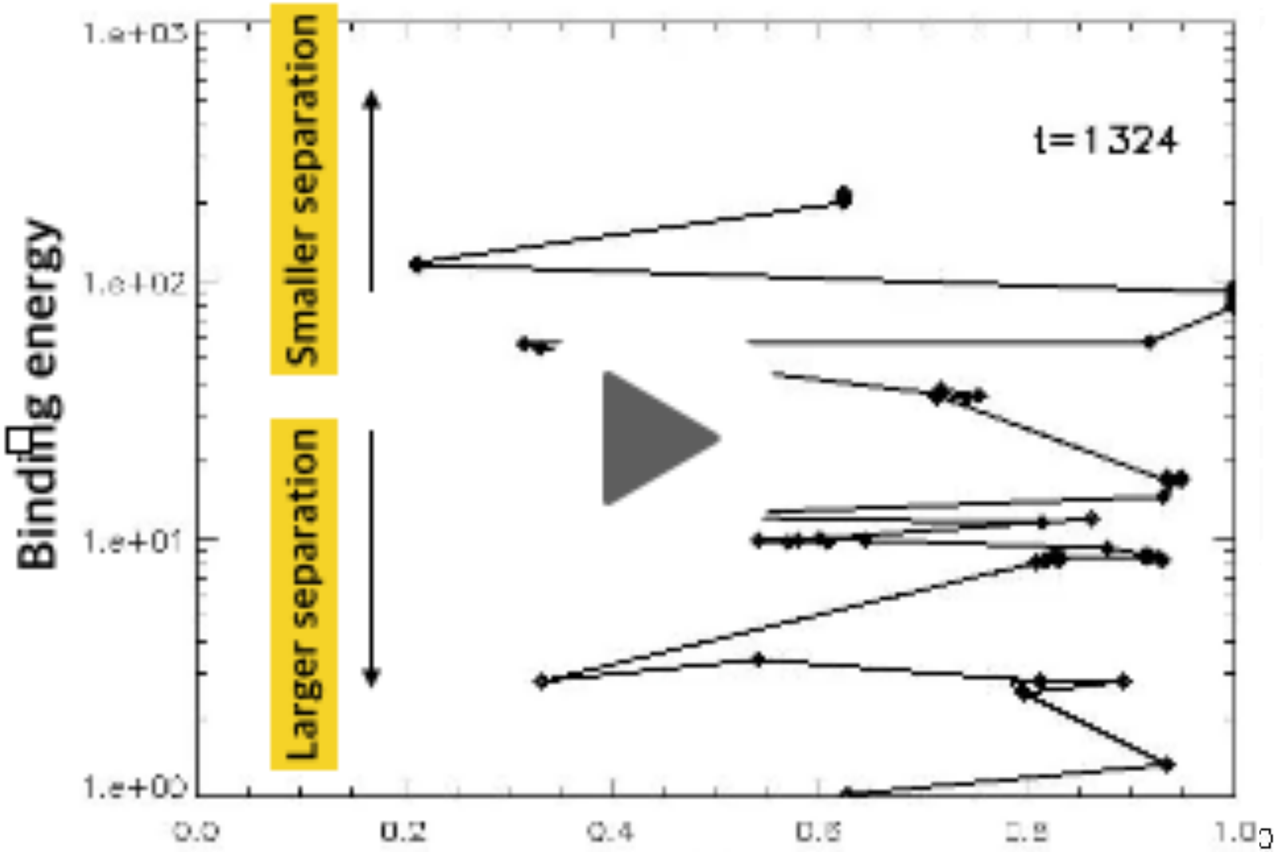


paper I



example of BH-BH interactions in globular clusters

$$a < a_{\rm crit} \approx \frac{Gm}{15 v_{\rm esc}^2} \approx 2.2 \times 10^{13}\,{\rm cm} \left(\frac{m}{1\,{\rm M}_\odot}\right)\left(\frac{20\ {\rm km\ s^{-1}}}{v_{\rm esc}^2}\right)^2 .$$



binary eccentricity

movie made by Y.-B. Bae

Consequences of 3-body interactions (=binary - single)

- initially: wide BBH + a single BH
- large cross section for interaction
- orbits get tighter, binaries become harder

“hard” binaries:
binary’s orbital velocity >> cluster’s velocity dispersion

Eventually, a BBH gets ejected from a cluster when its velocity becomes larger than v_{esc}

- binary’s e varies widely

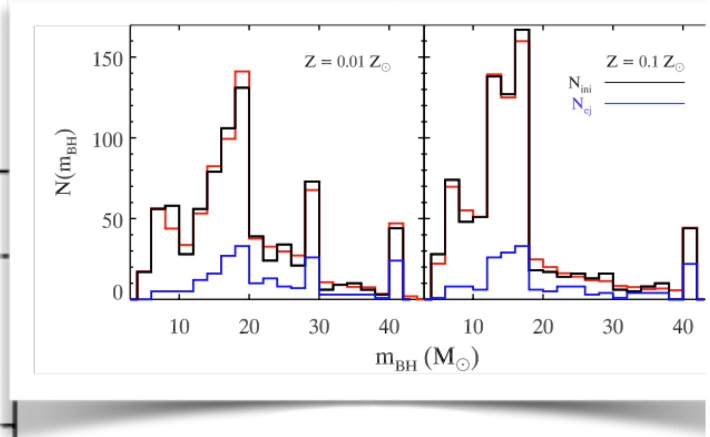
Properties BBHs formed in a GC
1. efficiency of massive binary formation

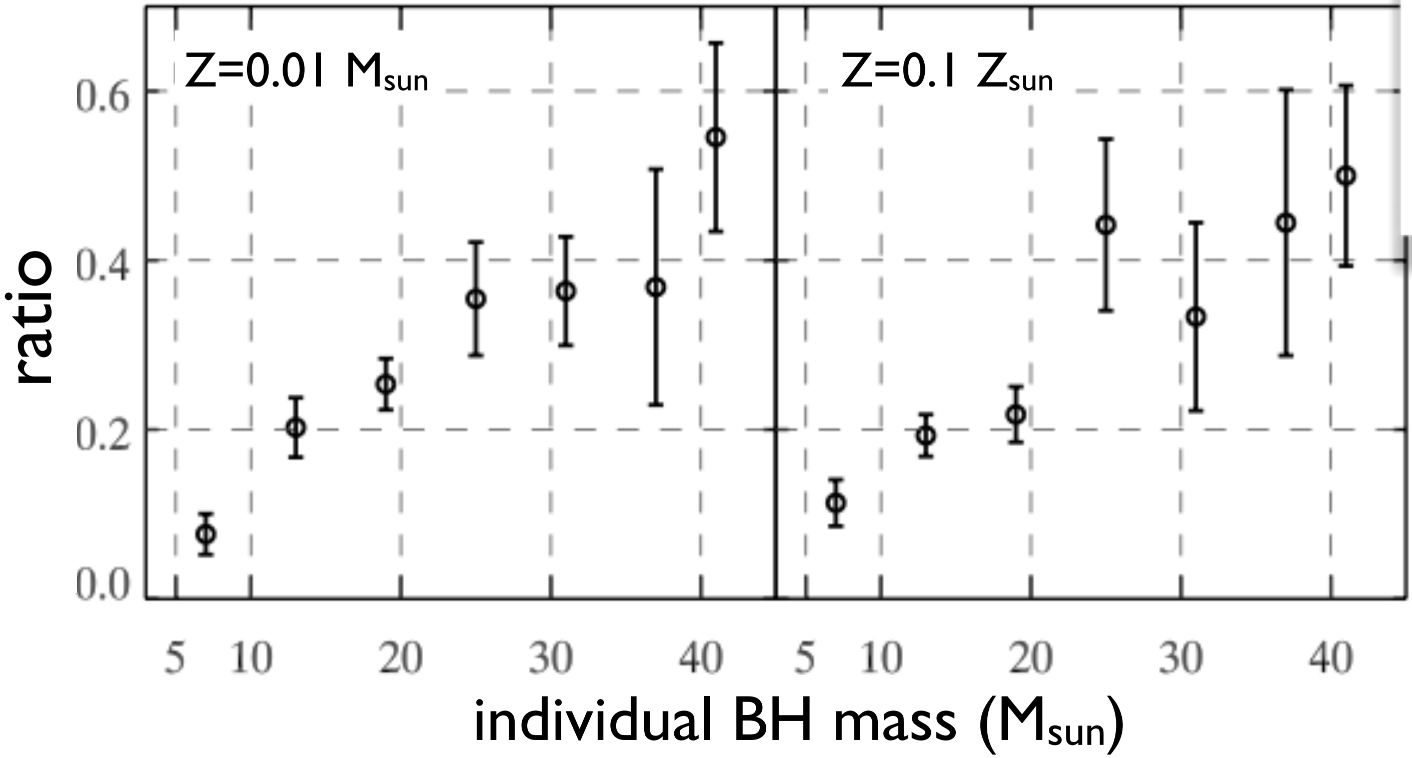
For a given BH mass function and cluster model,

most massive BHs — mostly in binaries

less massive BHs — singles > binaries

expected from 3-body interactions

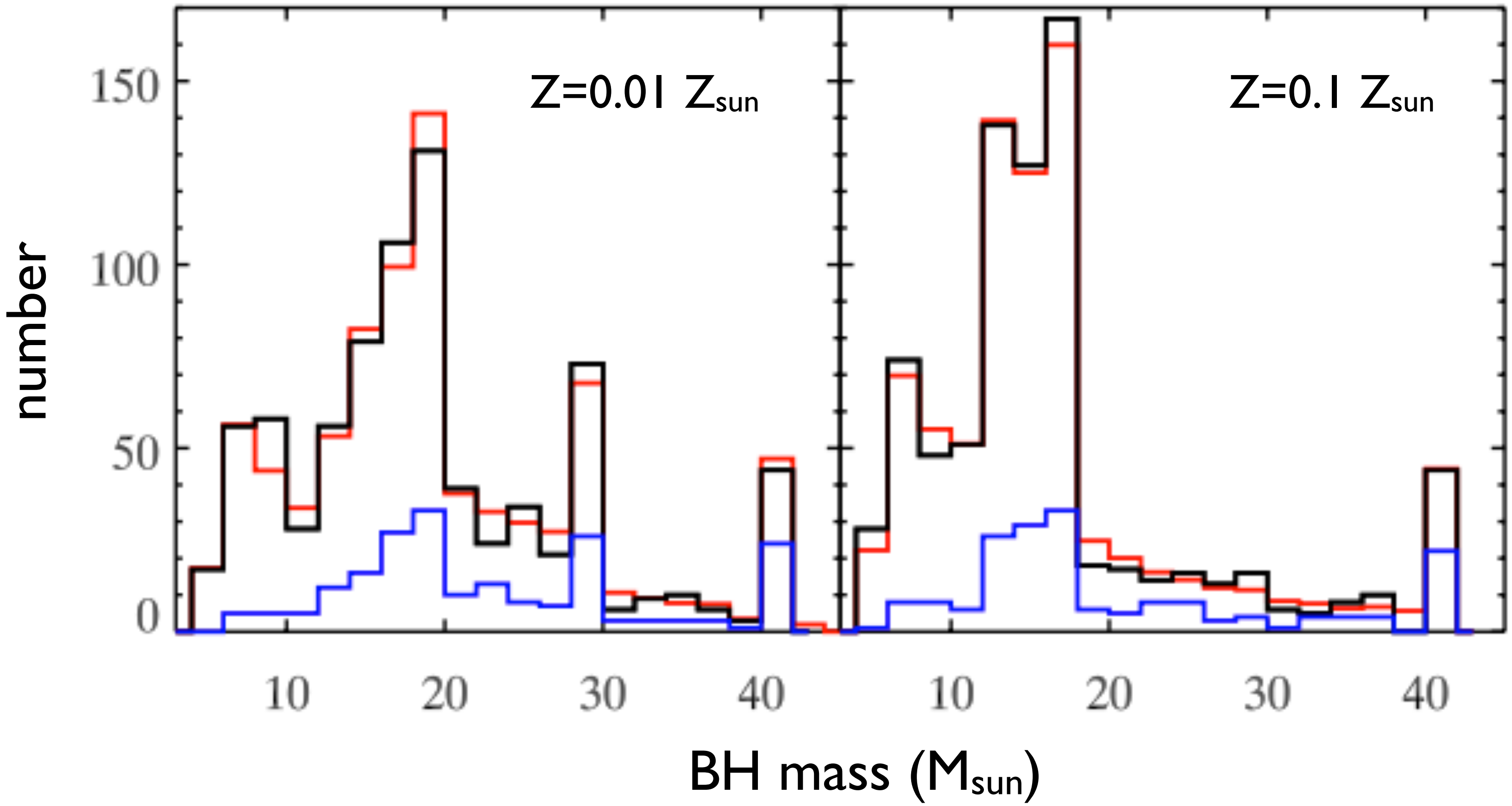




results for a continuous mass function from popsyn (paper II)

Properties BBHs formed in a GC
2. mass function (single BHs vs BBHs)

Model	N_{total} (×1,000)	BH fraction(%)	BH mass range	Assumed [Fe/H]	N_{run}
Belc01	50	$4.4 \sim 5.1$	$5 - 41.5$	-1	8
Belc001	50	$4.6 \sim 5.7$	$5 - 41.5$	-2	8



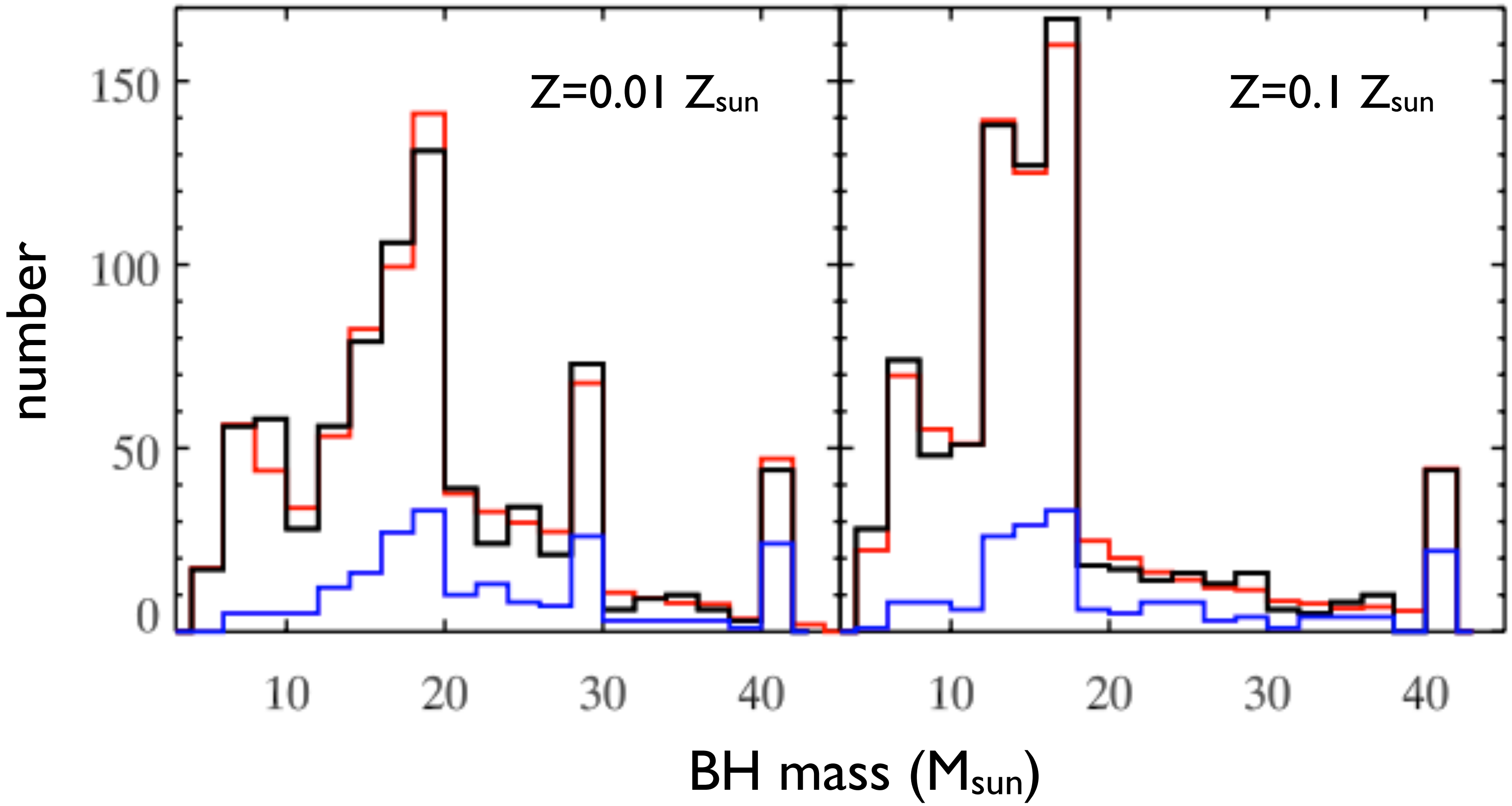
(results from paper II)

popsyn results
initially single BHs
ejected merging BBHs

Properties BBHs formed in a GC
2. mass function (single BHs vs BBHs)

BH mass distribution is "broad"

Observed BBH mass func. can have significant deficit of "lighter" BHs (single BHs would be missing in known sample!)

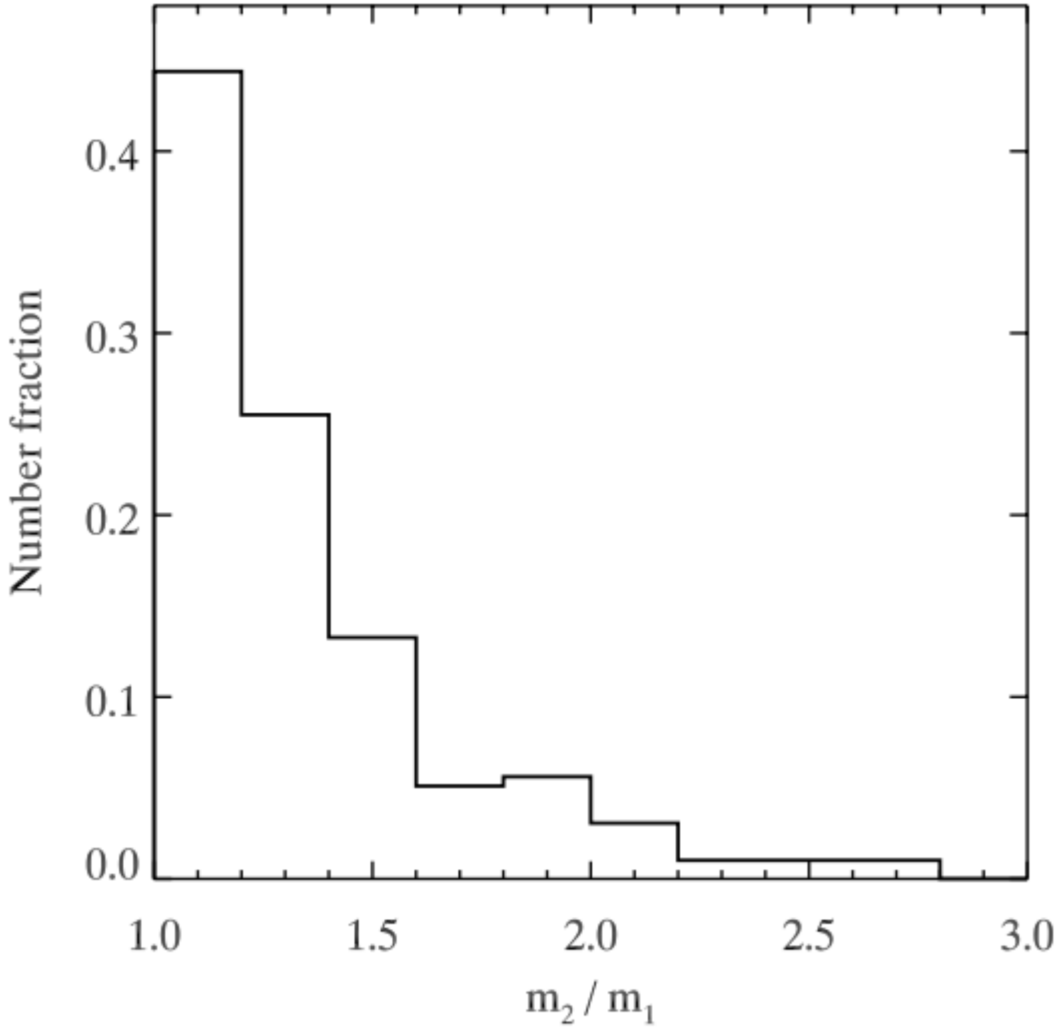


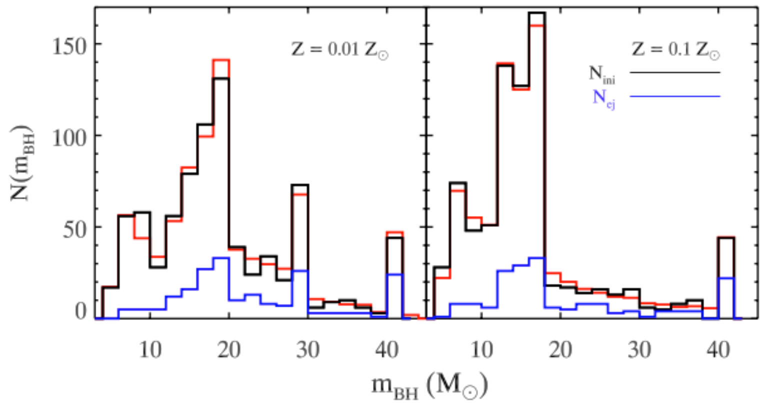
(results from paper II)

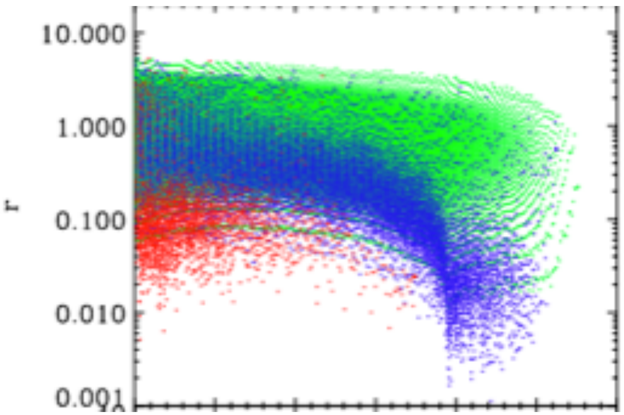
popsyn results
initially single BHs
ejected merging BBHs

Properties BBHs formed in a GC
3. mass ratio $q=m_2/m_1$

Cluster population still favors equal-mass BBHs with q < 3
note: NS-BH binaries would be extremely rare!





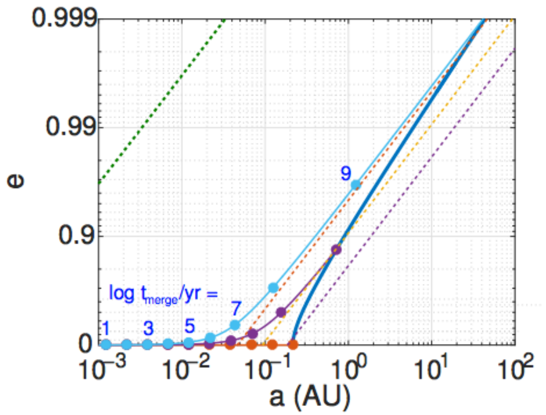


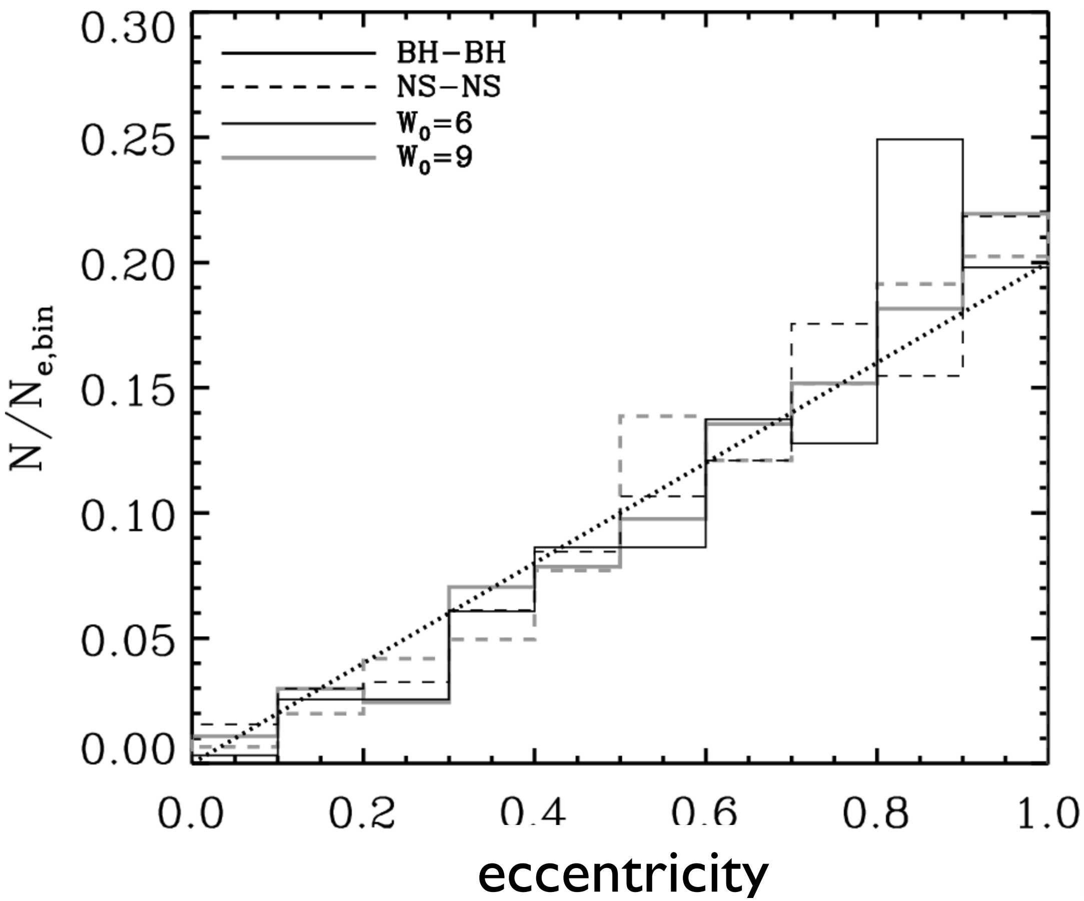
results from popsyn mass function (paper II)

Properties BBHs formed in a GC
4. eccentricity distribution

At the time of ejection, binary's eccentricity follows f(e) ~2e "thermal"

In f > 20 Hz, however, most binaries would look "circular" with low e





paper I

BH: 10 M_{sun}
NS: 1.4 M_{sun}

$N_{e,bin}$: total number of ejected BBH

Summary/comments

Almost all BBHs are expected to be ejected out of a host cluster.

Contribution from cluster BBHs would be comparable to that of field population: detection rates: ~ 0.5 - 40 yr^{-1}, works before GW150914
~ 5 Gpc^{-3} yr^{-1} Rodriguez et al. (2016),
Askar et al. (2016) MOCCA
~ 15 - 60 yr^{-1} for aLIGO-aVirgo (out work)
BBH event rate : ~2.5 - 10 per GC per yr (out work)

*** estimated detection rates: 3-40 Gpc^{-3} yr^{-1} (GW150914,151226)**

BH-NS is not expected from clusters

Mass function inferred from BBH observation biased for heavy BHs
(reasons: smaller detection volume + formation efficiency in clusters)

isolated (field) BBHs vs dynamically formed (cluster) BBHs are not very different. (best bet: recision PE for spin & e and statistics from inspirals)