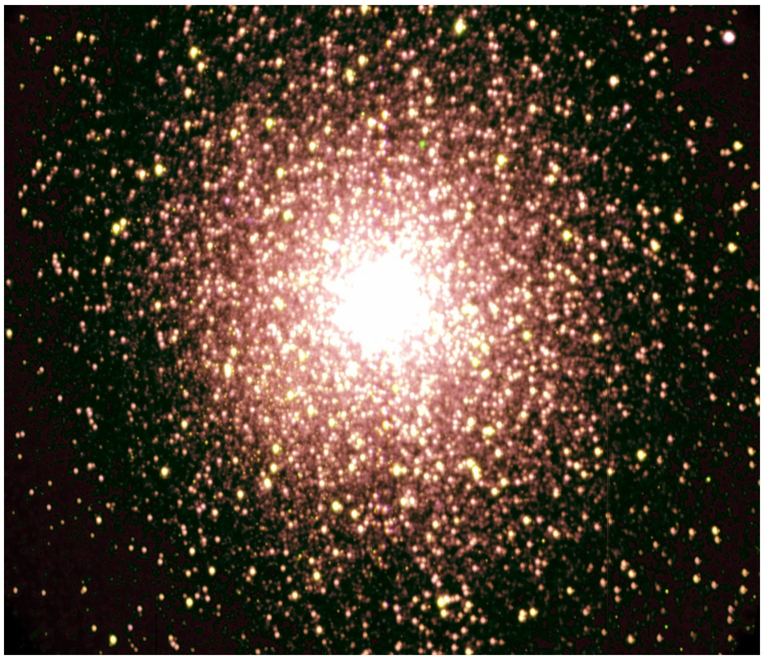
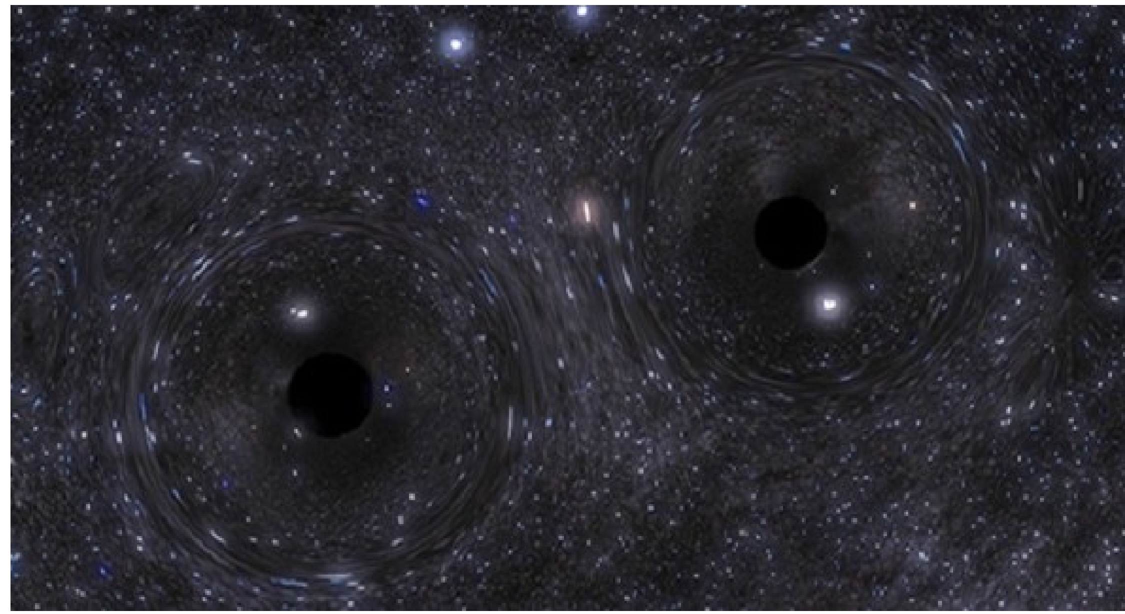
Coalescing binary black holes originating from globular clusters





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A. Askar, M. Szkudlarek,D.Gondek-Rosinska, M.Giersz,T.Bulik, 2017,MNRAS

INNOVATIVE ECONOMY
NATIONAL COHESION STRATEGY
FNP Foundation for Polish Science
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

The recent breakthroughs

- 2015 - detection of gravitational waves by aLIGO → GW Astronomy, a new window onto the Universe
- Detection of black hole binaries: GW150914,GW151226, GW170104 and LVT151012
- Observation evidence that BBHs merge within Hubble time
- Evidence for BHs with masses of 30 and up to 60 solar masses (their formation requires an origin from low metallicity environments (Belczynski et al. 2010, 2016))
- GW150914 - the “brightest” source ever observed

$$L_{GW} = 200^{+30}_{-20} \mathrm{M}_{\odot} s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\ s}^{-1}$$

Expect a lot of discoveries in near future by Advanced LIGO/VIRGO detectors !!!

Where does it fit into broad astrophysical picture?

-evolution of binaries in the field (Belczynski et al. 201

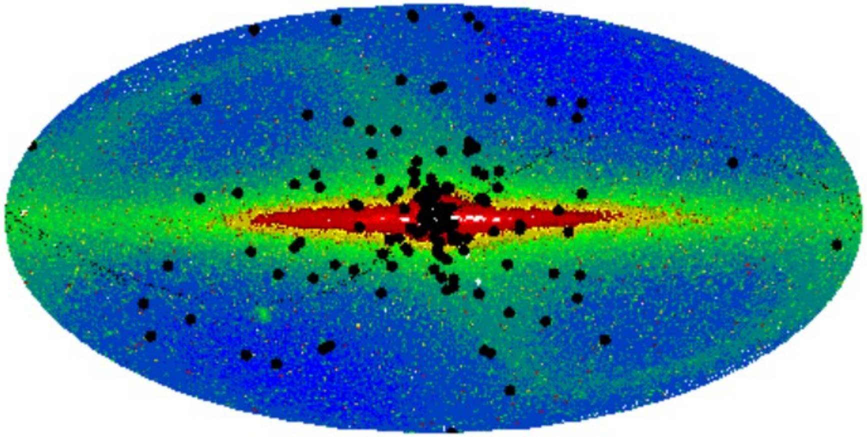
-formation of binaries in dense clusters

-population III

Globular Clusters

- Spherical collections of stars that orbits a galactic core as a satellite. More than 1000 extragalactic GC (HST) up to 375 Mpc. ~157 GC in Milky Way (Harris catalog)
- GC contain 10000 to milions stars
- Most of stars are old Population II (metal-poor) stars
- Stars are clumped closely together, especially near the centre of the cluster --> close dynamical interactions → tight binary systems containing compact objects
- Globular Clusters in the Milky Way are estimated to be at least 10 billion years old. 50% GC within 5kpc, the most distant 130 Mpc

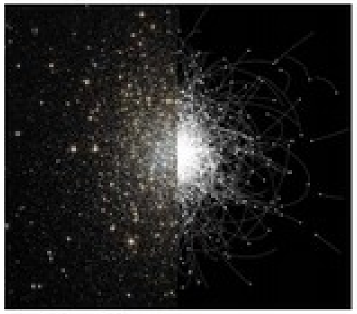
NGC 104 aka 47 Tucanae



Credit: Benacquista & Downing, 2011, the distribution of 157 globular clusters in the MW from Harris catalog

Stellar dynamics and Globular Clusters

- Stellar dynamics describes systems of many point mass particles whose mutual gravitational interactions determine their orbits.
- Globular clusters are excellent laboratories for stellar dynamics.
- Evolution of star clusters can be numerically modelled using sophisticated *N-body* and Monte Carlo codes.
- Dynamical evolution of such collisional system is governed by a number of physical processes that include
  - 2-body Relaxation of Stars
  - Stellar Evolution
  - External Tidal Fields
  - Binary Formation and Interactions



- MOnte Carlo Cluster simulAtor (MOCCA): Code to evolve real size globular clusters (Giersz et al. 2013) - http://moccacode.net/
  - Based on the application of the Monte Carlo method to star clusters, known as Hénon's Method (1971).
  - Precision and detailed output of MOCCA simulations is comparable to N-body
  - codes, but MOCCA is much faster (can simulate the evolution of a cluster with million stars up to a Hubble time within a day).

Globular clusters and gravitational waves

- Binary/Stellar evolution produces a number of interesting objects and exotic binary systems in globular clusters.
- Dense stellar environments of globular clusters are conducive to forming hard binaries with evolved compact objects.
- Dynamical interactions in globular clusters can eject a lot of binary systems that could be potential sources of gravitational waves.
- Numerous studies have used star cluster evolution codes to predict the number of gravitational wave events (mostly BBH mergers) originating from Globular Clusters.
    - Monte Carlo Codes: Downing et al. (2011), Rodriguez et al. (2015) and Rodriguez, Chatterjee & Rasio (2016), Askar et al. (2016).
    - Direct N-body Codes: Banerjee, Baumgardt & Kroupa (2010), Tanikawa (2013), Bae, Kim & Lee (2014) and Mapelli (2016).

Code description

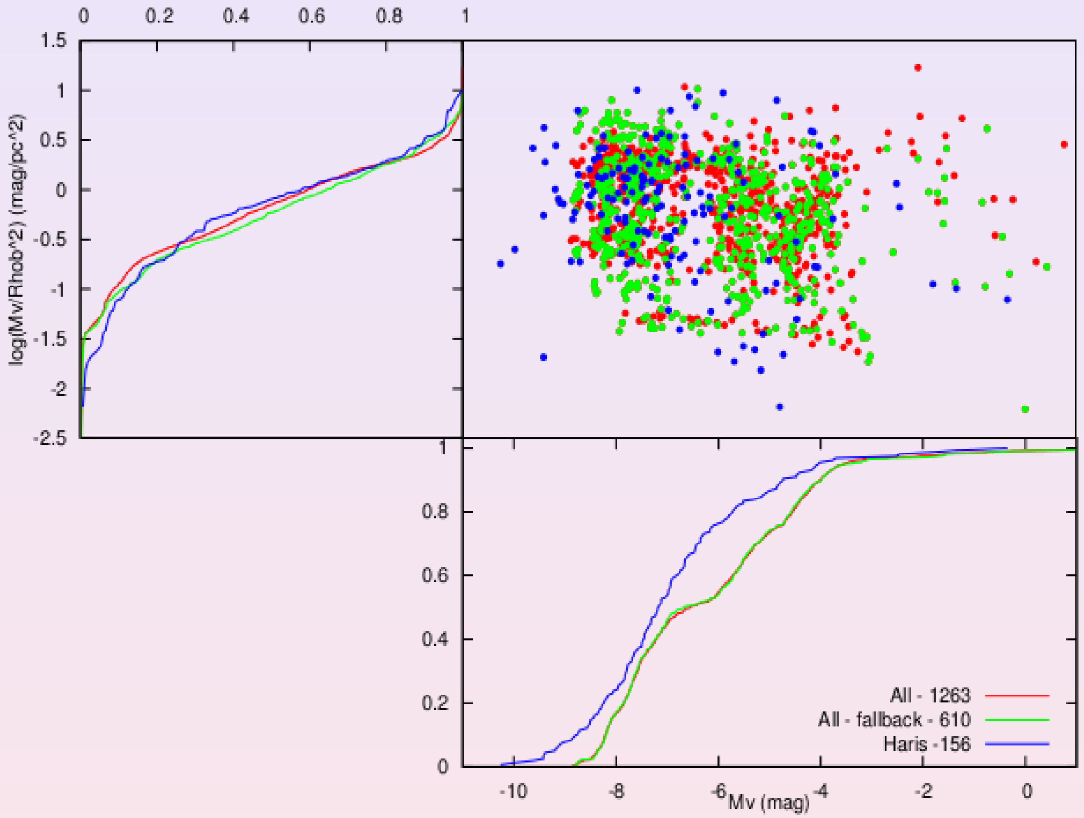
- We use the MOCCA Monte Carlo code developed by Mirek Giersz, Henon (1971), Stodolkiewicz (1982), Similar to the code used by the Northwestern group.
- Well tested, allows to investigate individual interactions, while ensuring that the evolution of cluster is accurate and computationally efficient.
- BIGSURVEY – 2000 MOCCA models, range of metallicities and sizes to match the population of GCs in the Milky Way
- Matches Milky Way but is not a fit. Many degeneracies.

Summary of simulations

Metallicity	Total mass [10^6 Msun]	Mass range of clusters [10^6 Msun]	Number of models	Number of BHBH mergers
0.02	51.7	0.024-0.61	258	735
0.006	19.6	0.63	31	1857
0.005	49.4	0.024-0.61	243	3042
0.001	141	0.02-1.08	423	9169
0.0002	18.9	0.63	30	2276

Table : About 2000 models. BH and NS kicks are the same, 265 km/s, except the case of mass fallback Belczynski et al.(2002). Two segment IMF (Kroupa 2001) was used for all models, with $M_{min} = 0.08 M_\odot$ and $M_{max} = 100.0 M_\odot$. If the binary fraction, f_b, is equal to 0.95 then binary parameters are chosen according to Kroupa (1995) (eigenevolution, mass feeding algorithm), otherwise eccentricity distribution is thermal, mass ratio distribution is uniform and semi-major distribution is uniform in logarithm, between $2(R_1 + R_2)$ and 100 AU. R_t - tidal radius, R_h - half-mass radius, W_0 - King model parameter, Z - cluster metallicity. For each initial number of objects different combinations of parameters are used to generate the initial model. The number of models with different metallicities are as follows: 63, 831, 487, 64 and 503 for Z = 0.0002, 0.001, 0.005, 0.006 and 0.02, respectively.

Model vs Milky Way Globular Clusters

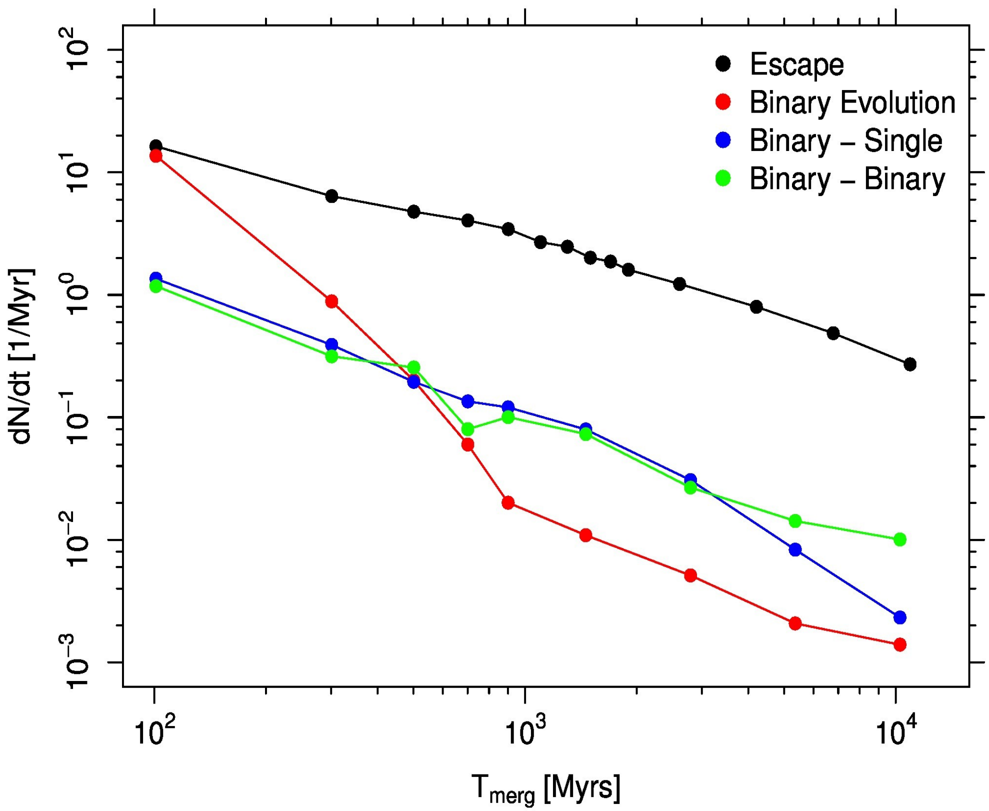


Models for the Survey were not selected to match the observed Milky Way GCs. Except for few bright (massive and intermediate mass) Galactic GCs, the agreement with the observational properties of Galactic GCs is quite good. Despite this agreement, any combination of global observational properties of GCs cannot be used to clearly distinguish between different cluster models because there is a strong degeneracy with respect to the initial conditions.

It can be assumed that the Survey cluster models are representative of the MW GC population.

BBH Mergers due GW radiation from Globular Clusters

Number of merging BBH binaries within Hubble time per unit time (1 Myr) as a function of merger time for black holes with $M_{BH} < 100M_{sun}$
BBH in GC: 3 000; BBH ejected from GC ~15 000,



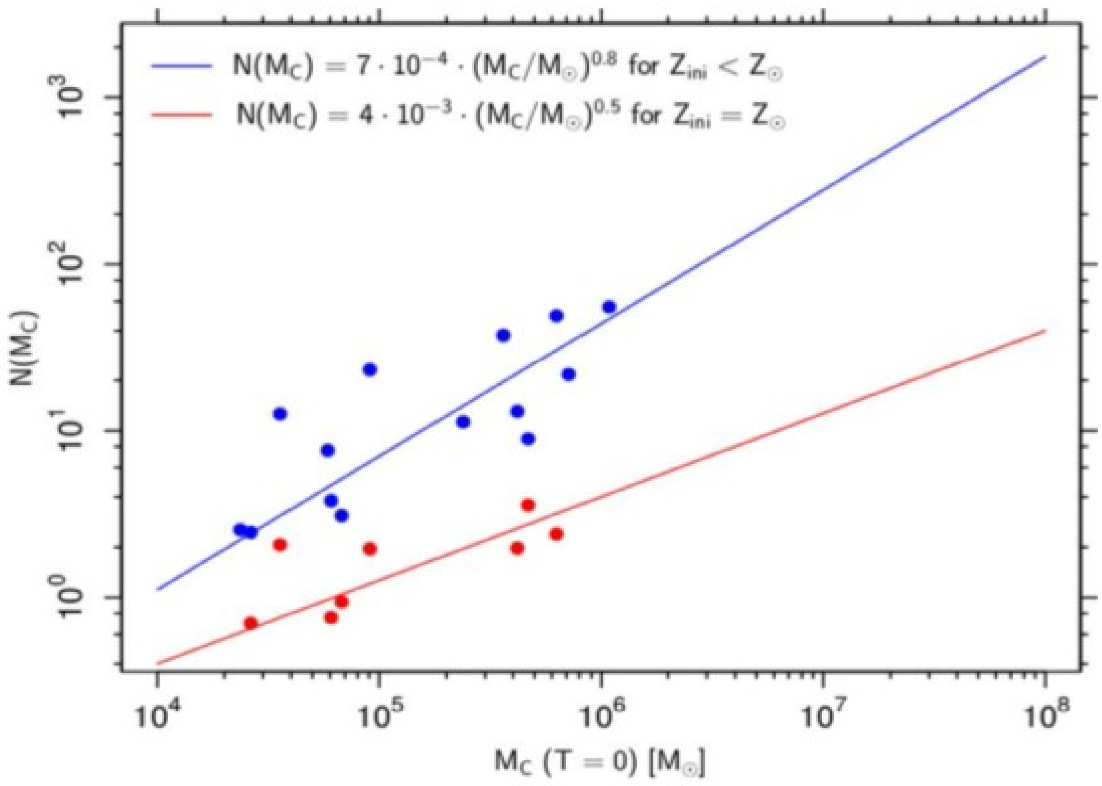
- Path to BBH

  - escaping binaries (dominating)

  -induced mergers inside GC
- Mass distribution?
- BBH production efficiency ?

Dependence on the cluster mass

- Analysis (cont) & Results



Normalized number of BBHs as a function of initial cluster mass M_c with fitted function $N(M_c)$ (BBH production efficiency).

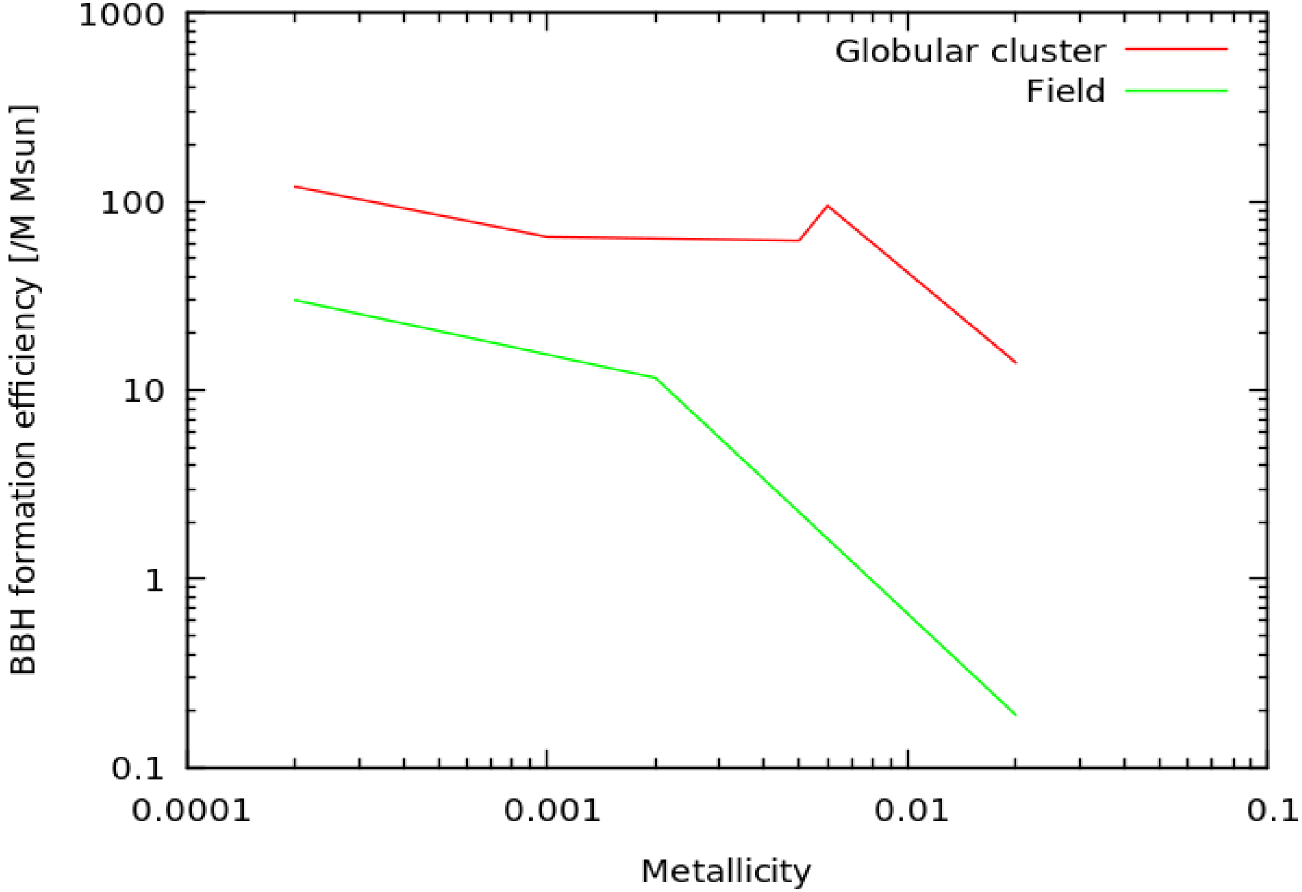
- Normalization function:

$$N(M_c) = \frac{n}{n_s \cdot M_c / 10^6 \, \mathrm{M}_\odot}$$

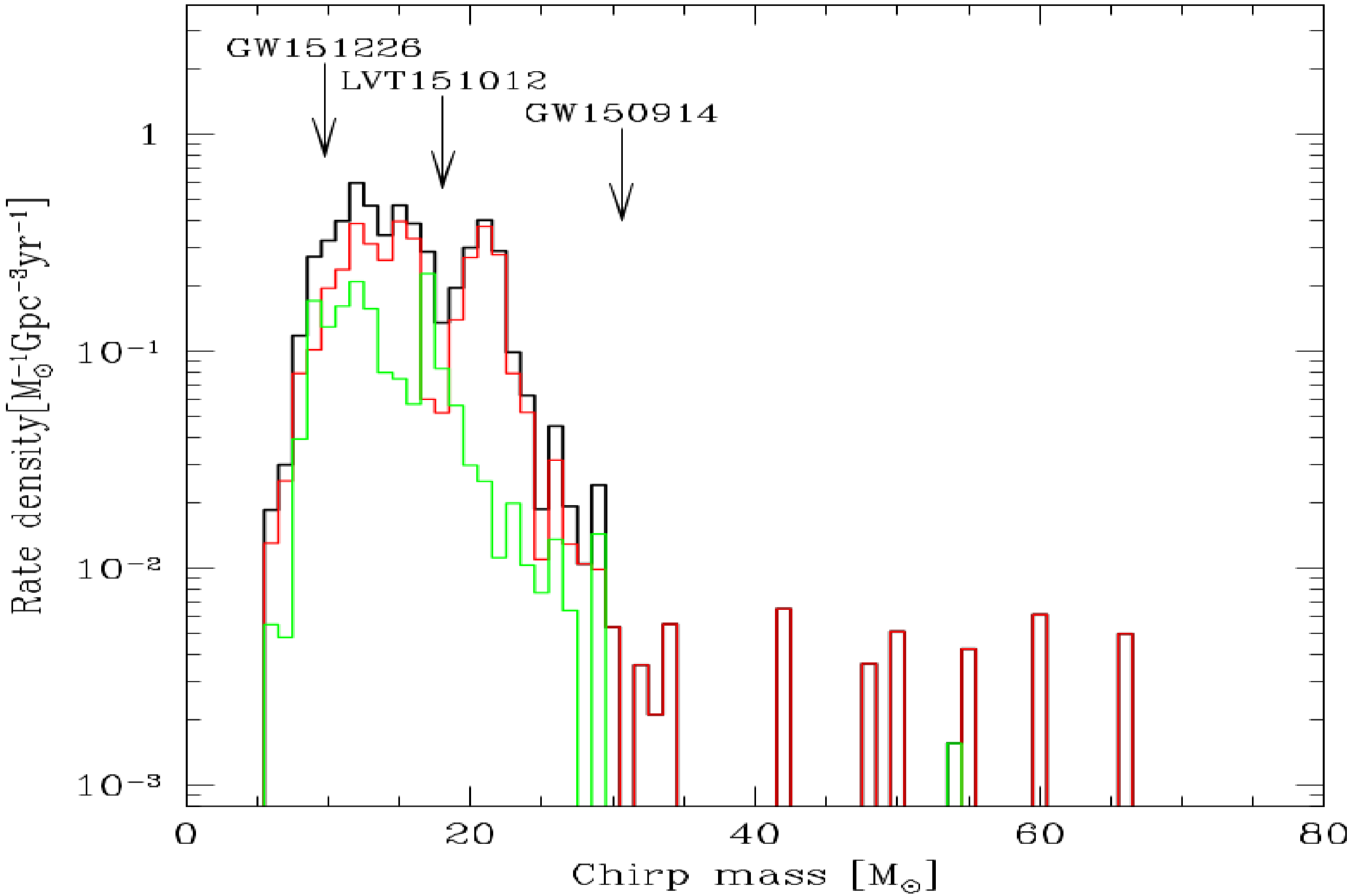
- $Z < 0.02$ – 17 269 merger events
  $Z = 0.02$ – 865 mergers
- Regardless of the metallicity, if the mass of a GC model is large, then the number of merging BBHs is higher.
- Low-metallicity clusters have a greater ratio of producing merging BBHs compared to higher metallicity cluster models.
- If clusters have larger initial masses then they will produce more merging BBHs.

BBH production efficiency:GC vs Field

Number of merging BBH binaries per 10^6 solar masses of stars.
Field data from Belczynski et al 2016



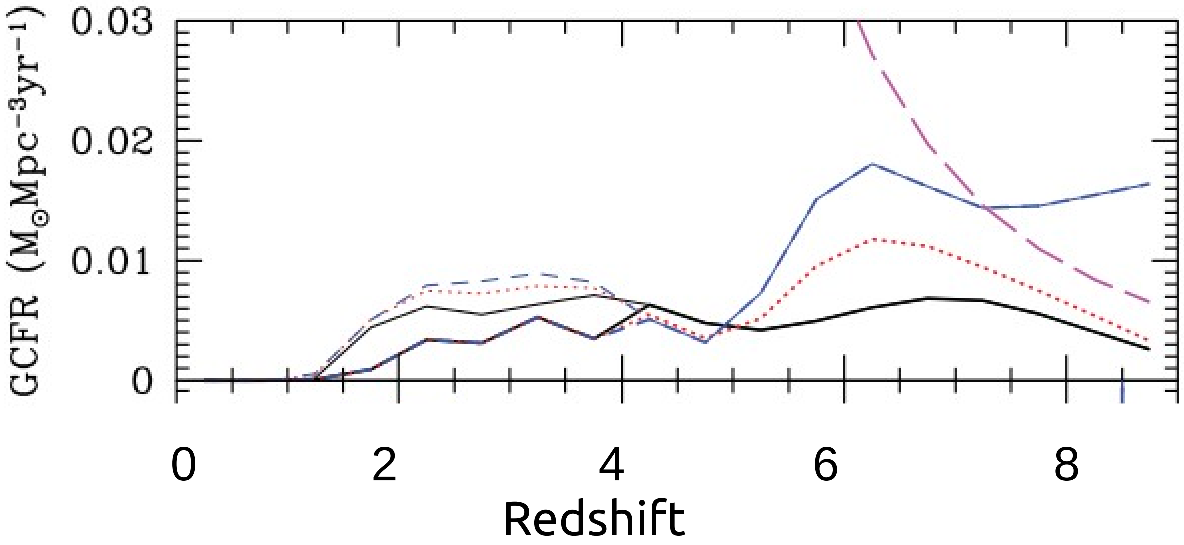
Local merger rate density for BBH merger
The dominant contribution – escaping BHBH



Merger rates in clusters

- Globular Cluster   formation rate

Katz & Ricotti 2013

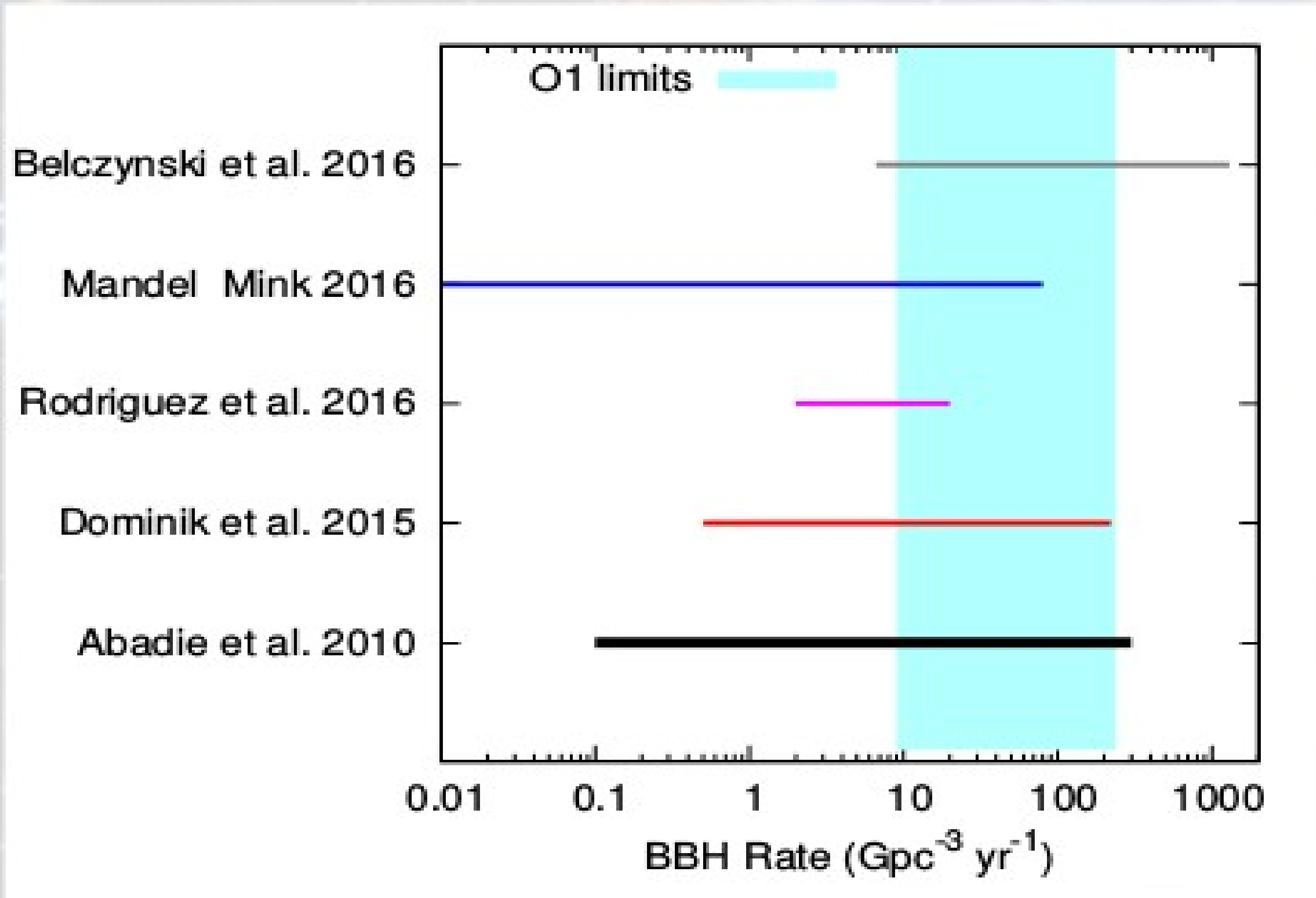


- GC mass composition
- GC metallicity
- The local merger rate (Abbas,Szkudlarek, Rosinska, Bulik, Giersz 2017)

  - 5.4 Gpc^-3/yr

  - 30 Gpc^-3/yr if we include GC with 10^7 Msol,
- Systematic uncertainties to be understood

BBH merger rate:
9 - 240 Gpc^{-3} yr^{-1}



Local Merger Rate Density of BBH Mergers

- Calculated local merger rate density can be 3 to 5 times higher:
  - Uncertainties in initial cluster mass: In order to reproduce the more massive and bright observed GCs, we will need to have initial cluster masses larger than what were simulated in the survey models. (up to $10^7\ M_\odot$)
  - Recall the production efficiency:

$$Z = 0.02 \rightarrow N(M_c) = 4 \times 10^{-3} \cdot (M_c/M_\odot)^{0.5} \qquad Z < 0.02 \rightarrow N(M_c) = 7 \times 10^{-4} \cdot (M_c/M_\odot)^{0.8}$$

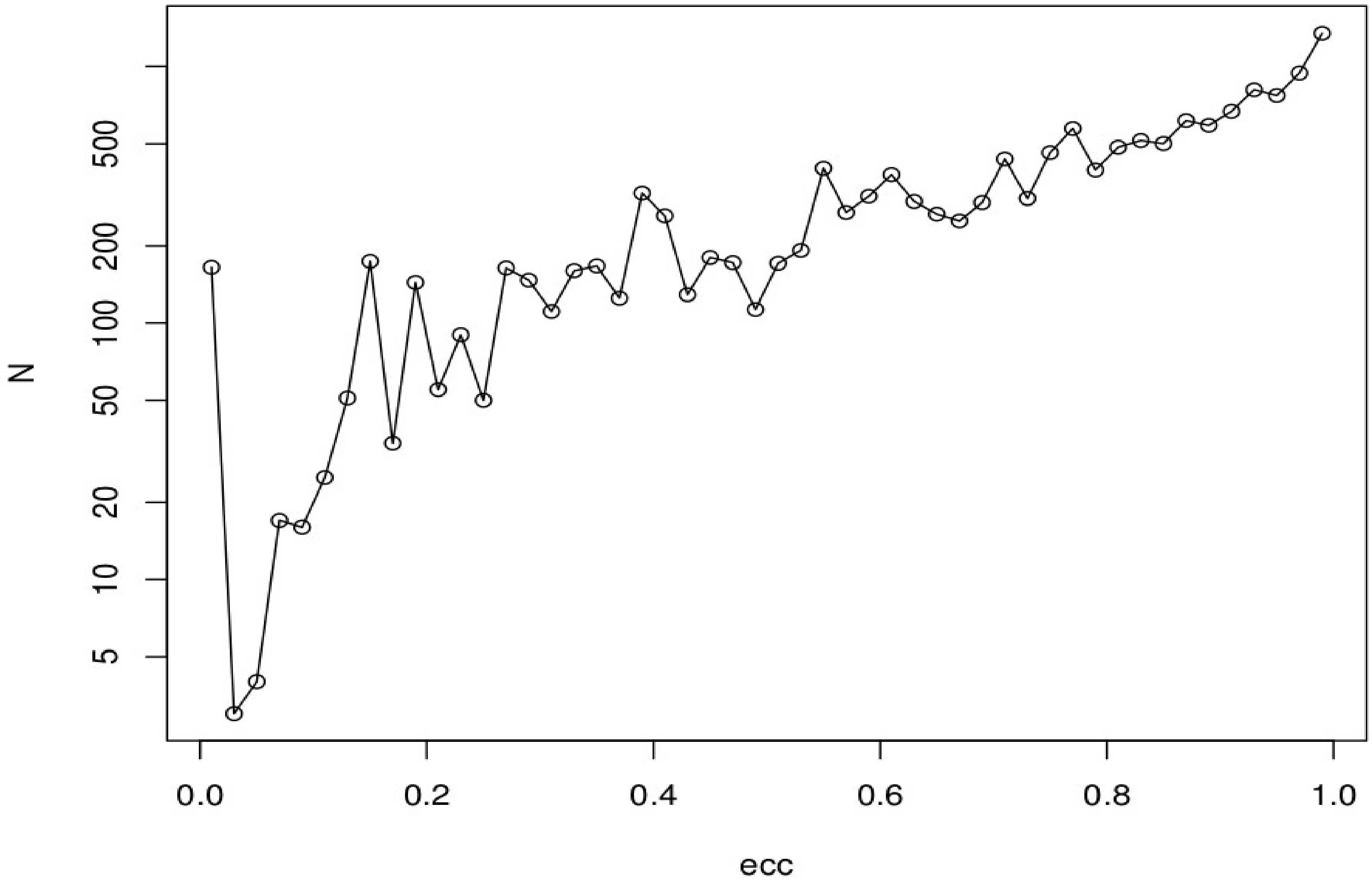
  - Additionally, the uncertainty in the metallicity composition of GCs in early galaxies and the uncertainties connected with stellar IMF and the maximum stellar mass may also introduce an additional increase in the merger rate.
- Expected rate of events in the first LIGO observing run (O1):
  - 0.36 to 1.8 detections
  - In agreement with Rodriguez, Chatterjee & Rasio (2016).

Field vs Globular Clusters

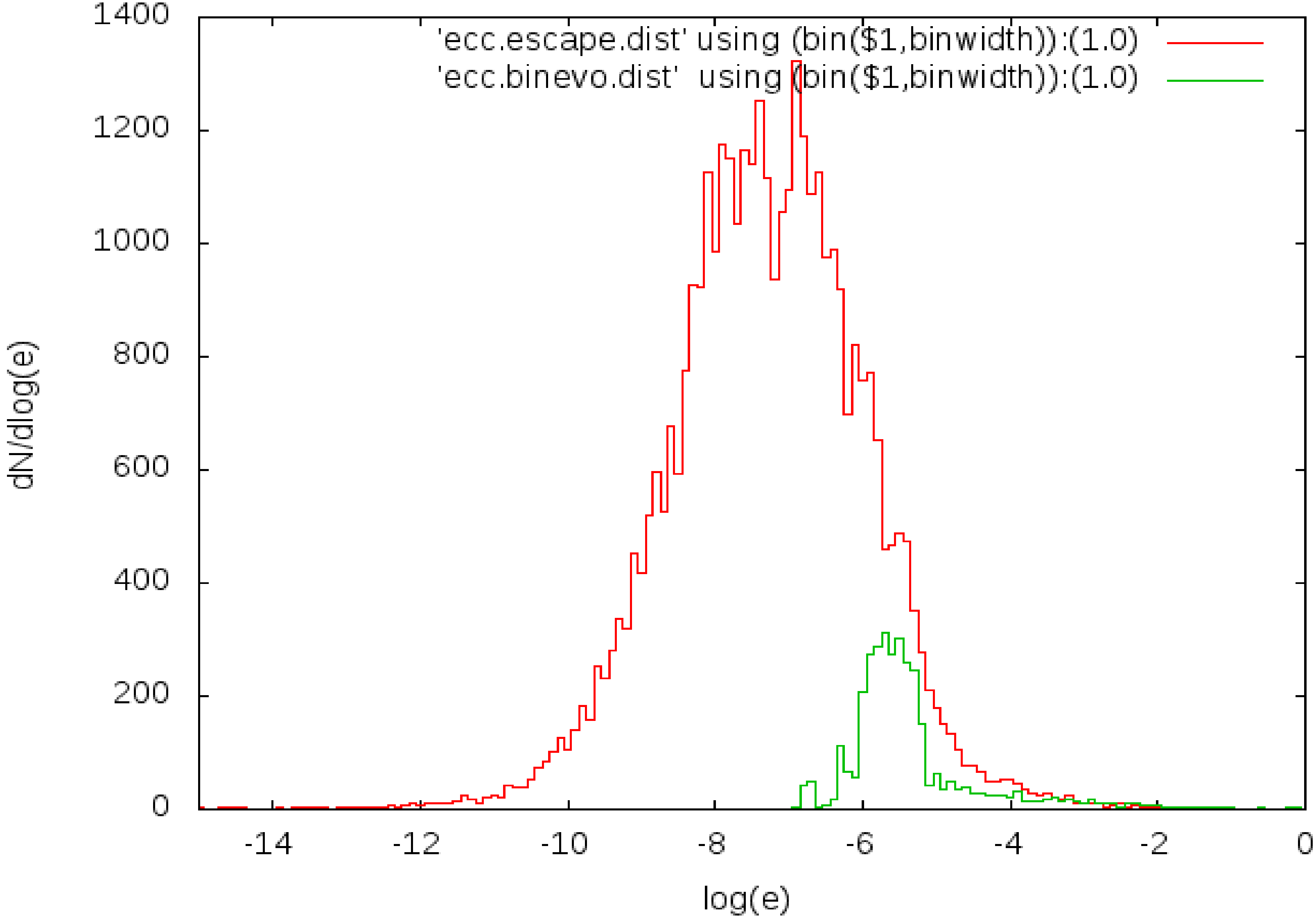
- Can we use spins to distinguish the two?
- GC formation – exchanges, non aligned spins
- Are spins aligned in field evolution?

- Can we use eccentricities to distinguish the two?
- In the field only 0.1% with $e > 0.01$ (Kowalska et al. 2011)
- In GC, dynamically-formed binaries highly eccentric ?

Eccentricity of BBH at ejection



Eccentricities of BBH at f_{GW} =10 Hz



Summary

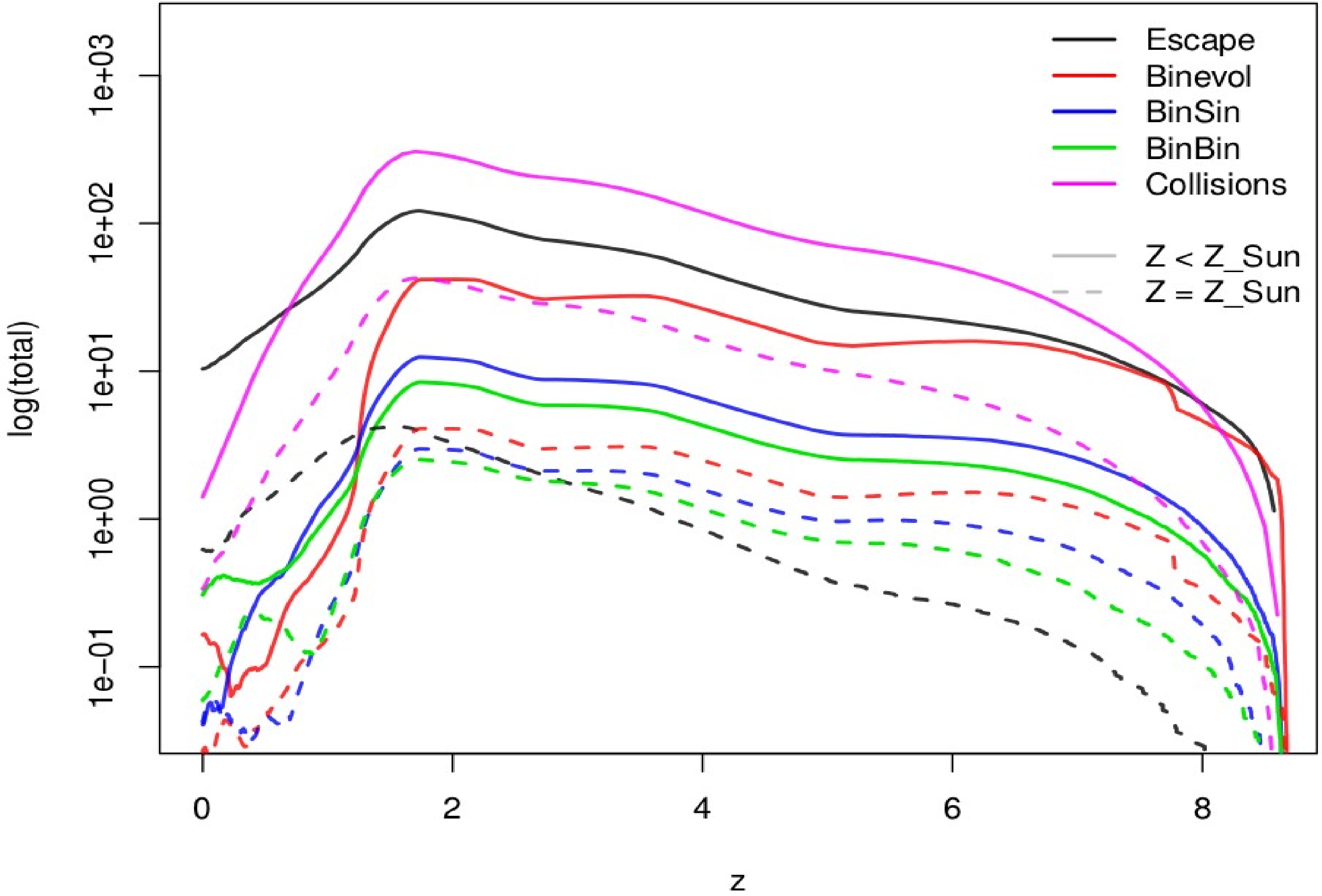
- We have explored mergers of BBHs from 1000 GC using MOCCA code.
- The dominant contribution is from ejected BBH and low metalicity models
- The local merger rate density of BBH from globular cluster is

  5.4-30 Gpc^-3/yr (Abbas,Szkudlarek,Rosinska,Bulik,Giersz 2017)
- Rates are in the low end of the observed values
  - Depends on assumptions on cluster mass and metallicity distribution
- Mass distribution of BBH consistent with aLIGO observations

  -Predict a tail of higher mass object merging inside clusters
- eccentric BBH systems ejected from clusters or merged in GC will not be a significant source for Advanced LIGO (..but BH in triple systems etc)
- Expect a lot of discoveries in near future !!!

Work in progress

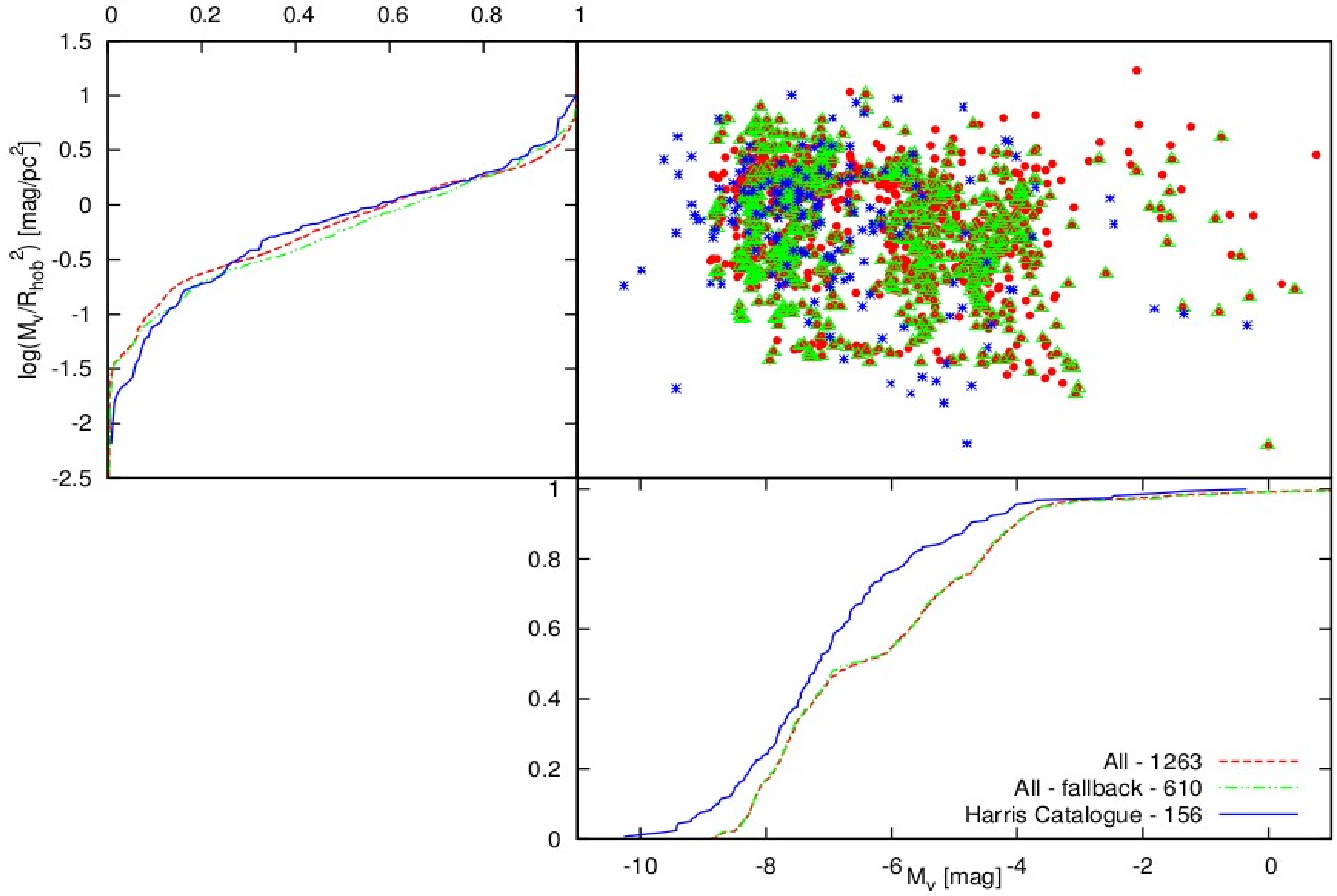
25 % of globular cluster models contain IMBHs, 100-10000Msol (Giersz et al. 2015).
One of formation scenario: built up BH mass due to mergers in dynamical interactions and mass transfer in binaries



Summary

- Field evolution sufficiently explains the origin of GW150914
- Globular Cluster origin is also likely
- Both require low metallicity environment
- Population III stars – maybe..

Model vs Milky Way Globular Clusters



Population III origin?

Mon. Not. R. astr. Soc. (1984) **207,** 585–609

Gravitational waves from a population of binary black holes

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THE ASTROPHYSICAL JOURNAL, 608:L45–L48, 2004 June 10

THE FIRST STELLAR BINARY BLACK HOLES: THE STRONGEST GRAVITATIONAL WAVE BURST SOURCI

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Received 2004 March 15; accepted 2004 April 26; published 2004 May 10

ABSTRACT

The evolution of the first populations of massive metal-free and metal-poor binary stars is followed. Such stars may form with large initial masses and evolve without significant mass loss. Stellar evolution at low metallicity may lead to the formation of intermediate-mass black holes (~100–500 $M_{\odot}$) in the early universe, in contrast to the much lower mass black holes (~10 $M_{\odot}$) formed at present. Following the assumption that some of these Population III stars have formed in binaries, we present the physical properties of the first stellar binary black holes. We find that a significant fraction of such binary black holes coalesce within the Hubble time. We point

Population III summary

- Masses in a similar range as other models
- Rates peak at $z \sim 10$
- Very uncertain population model
- Are they a separate class?

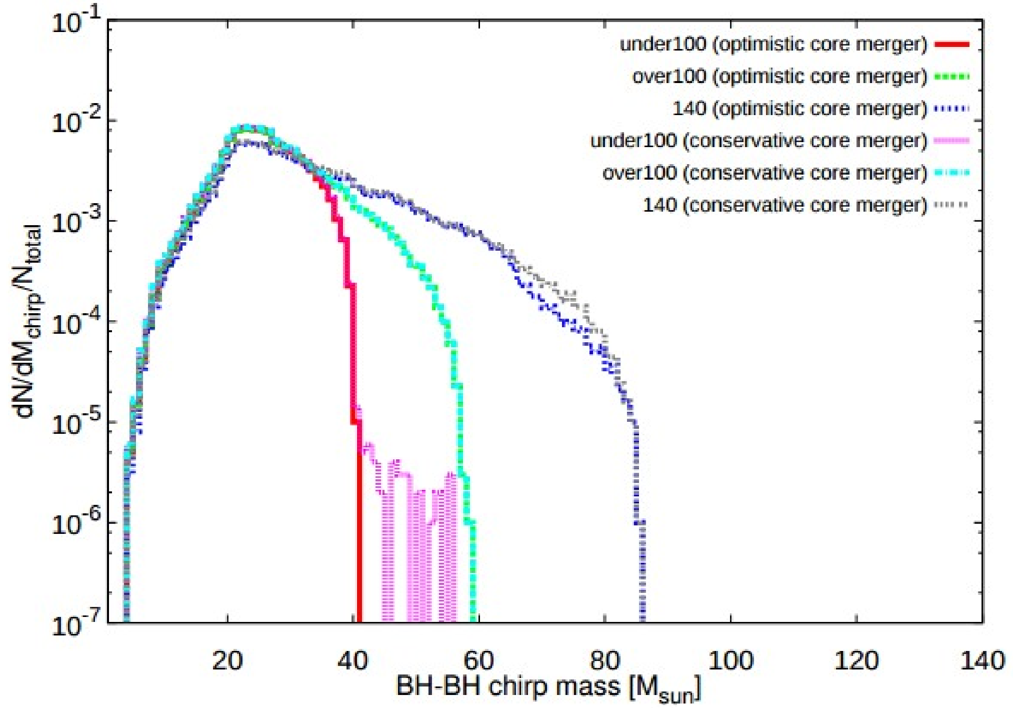
Population III

Recent study of Kinugawa et al. 2016:

Mass range similar to low metallicity stars

Local rates in the range of 1-100 /Gpc^3/yr

Rate density peaks at z=5-10



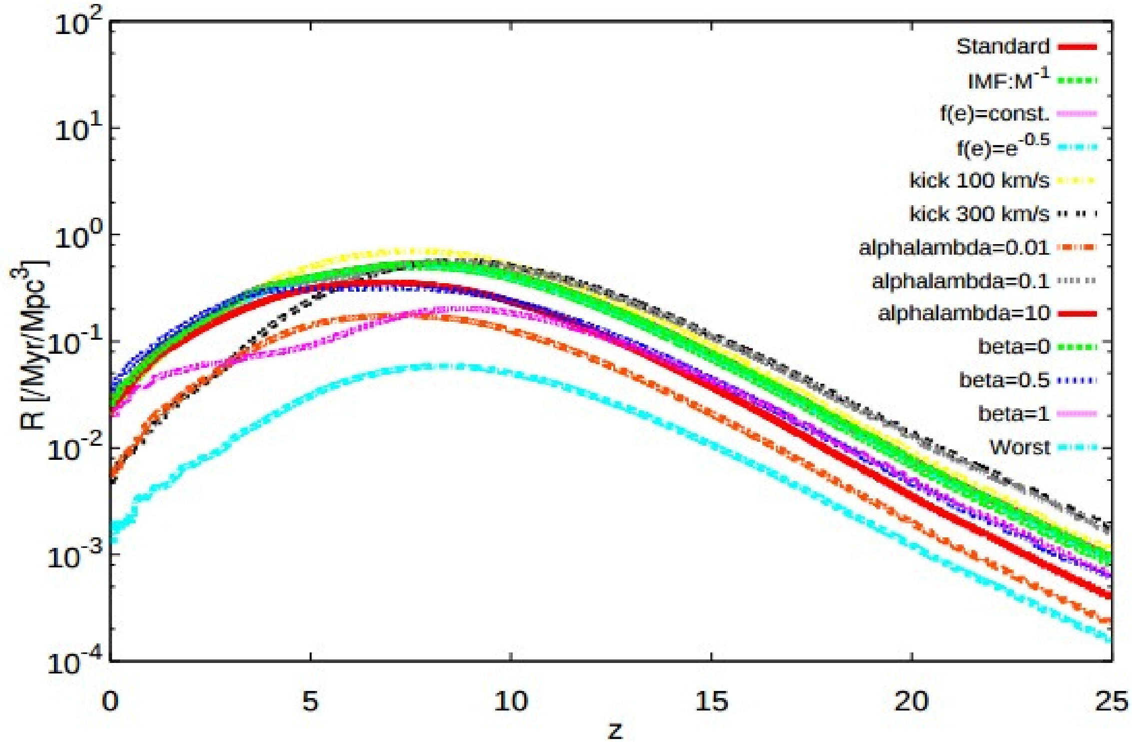


Figure 24. The merger rate densities

<u>Spin evolution</u>

Initial spins

Accretion, possible alignement of spin 2

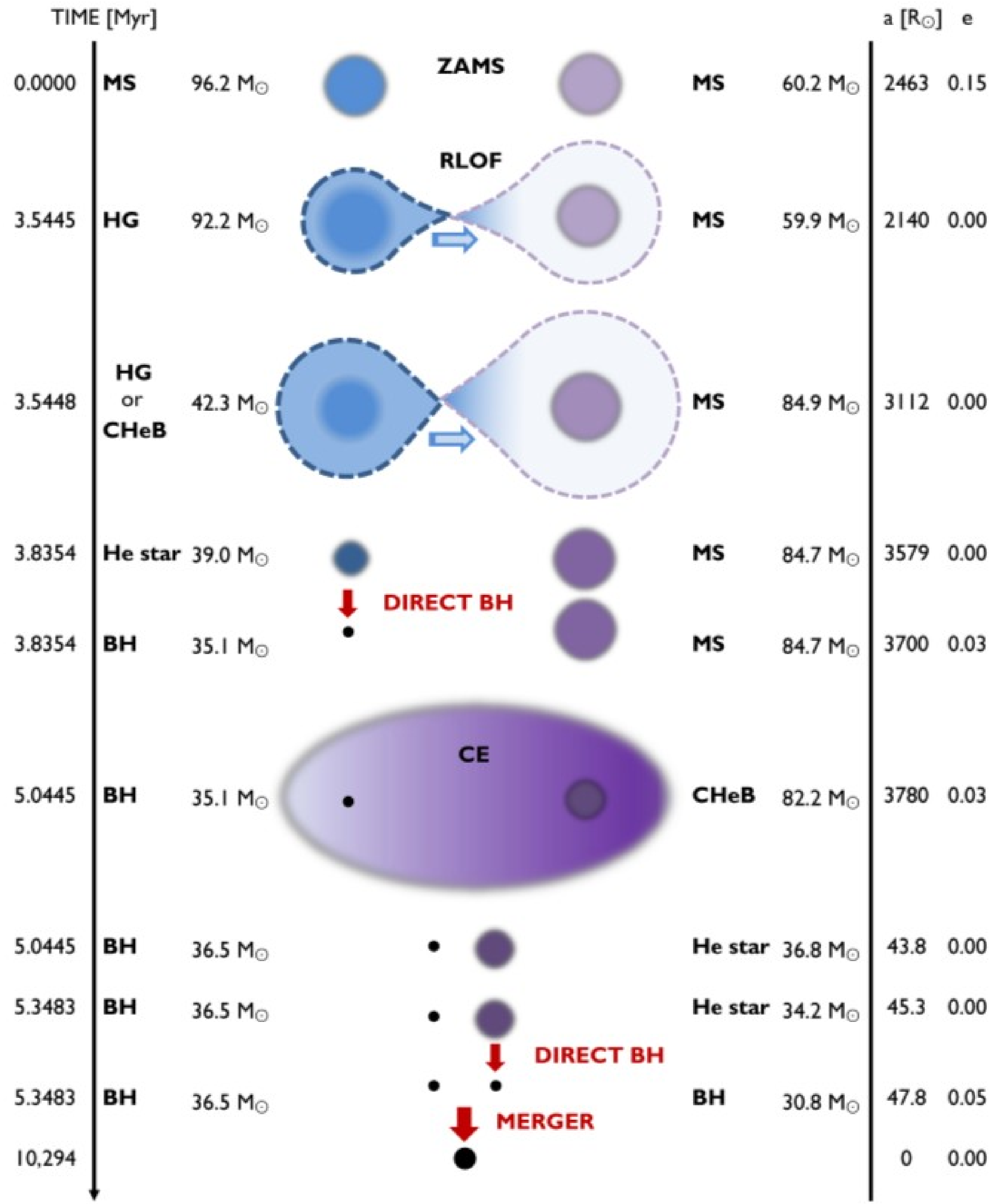
BH formation, kick?

CE – too short too affect

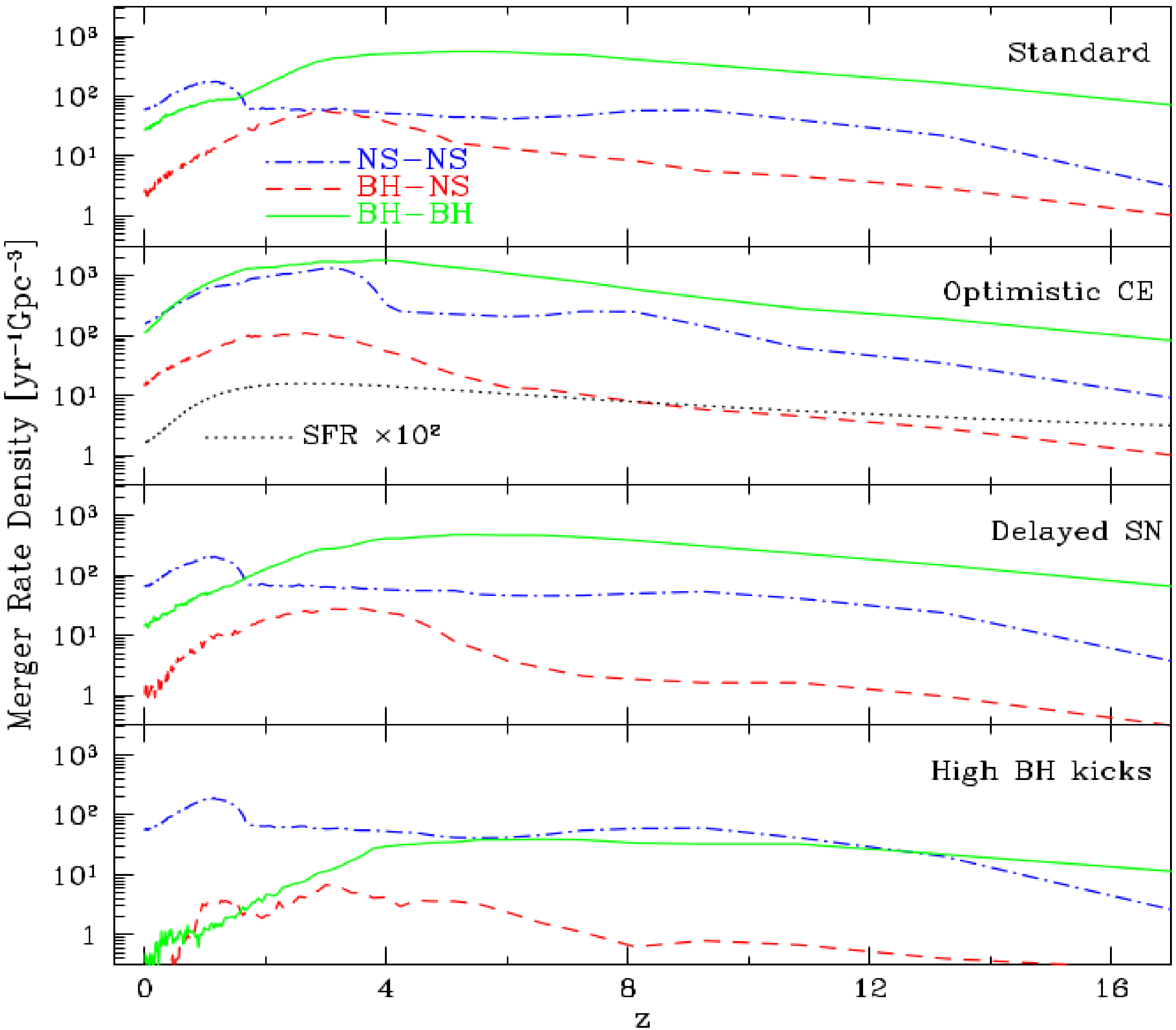
BH formation, kick?

Kicks are small.

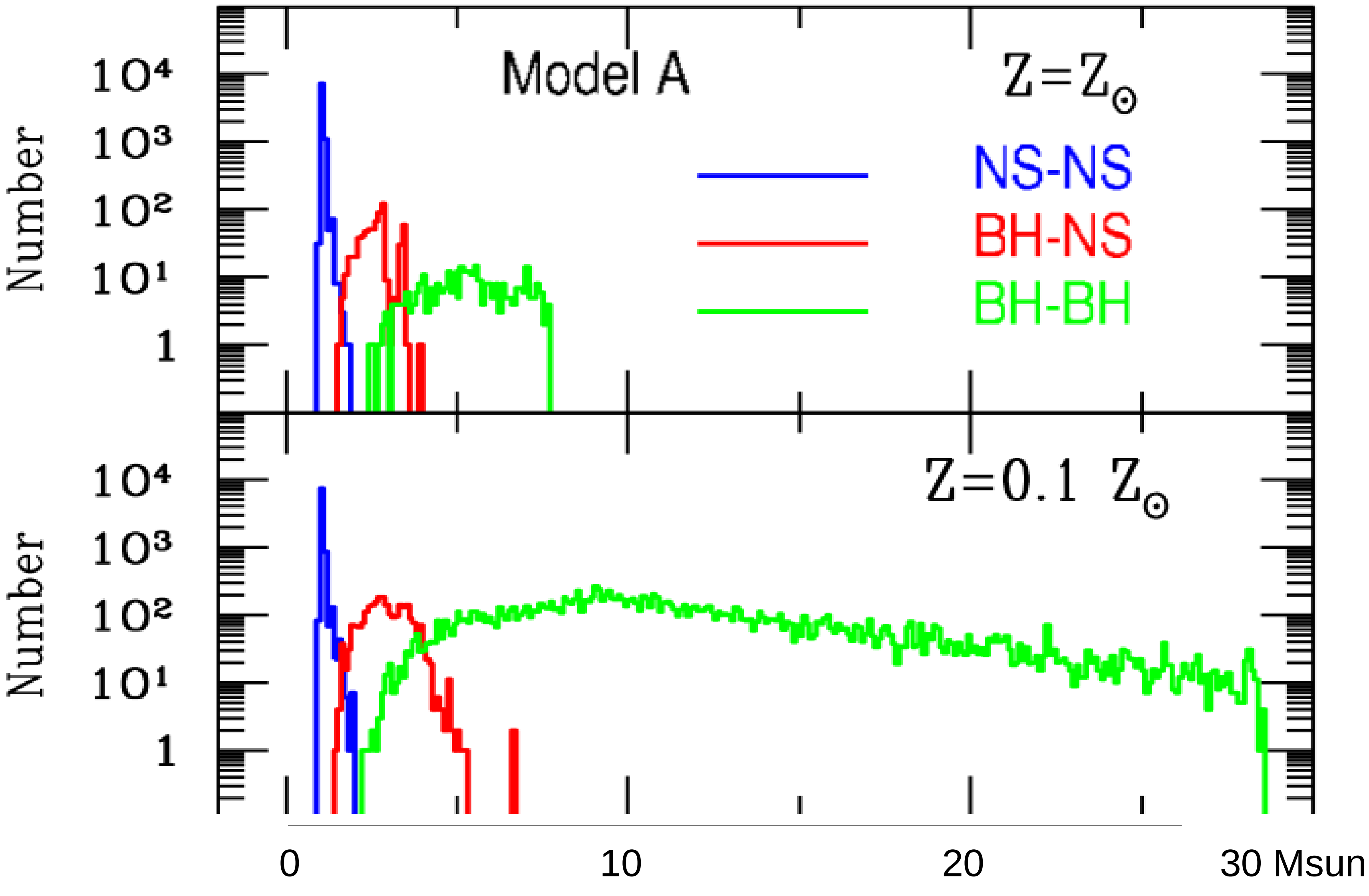
Final spins close to initial.
See *Albrecht et al 2014 The BANANA Project.*



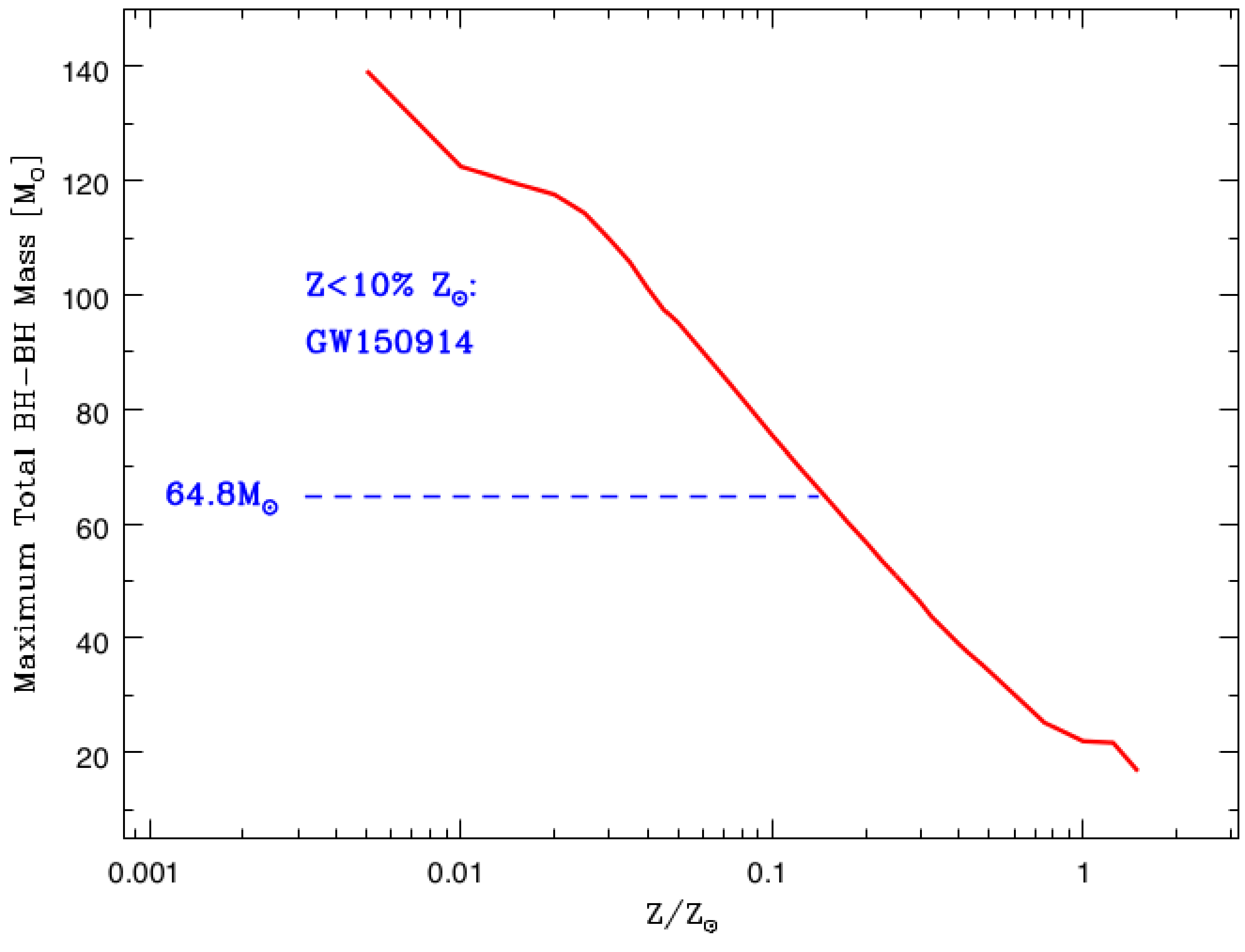
Merger rate density history



BHBH enhancement in low Z



Maximum BHBH mass



GW150914 progenitors were low metallicity Z<10% Zsun.

First set of conclusions

- GW150914 originated in low metallicity stars
- The masses are in the expected range
- Kicks in forming the BHs are low (<50km/s)
- Common envelope efficiency is typical $\alpha \approx 1$
- Formation time
  - Early Universe (z~3)
  - Recent (z~0.1-0.5)
- Progenitors of BHBH mergers: one gone, one left

StarTrack description, reference

- Initial parameters
- Stellar evolution
- Formation of compact objects: masses, kicks
- Mass transfers, common envelope treatment

A COMPREHENSIVE STUDY OF BINARY COMPACT OBJECTS AS GRAVITATIONAL WAVE SOURCES: EVOLUTIONARY CHANNELS, RATES, AND PHYSICAL PROPERTIES

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Received 2001 November 22; accepted 2002 February 18

2002

COMPACT OBJECT MODELING WITH THE STARTRACK POPULATION SYNTHESIS CODE

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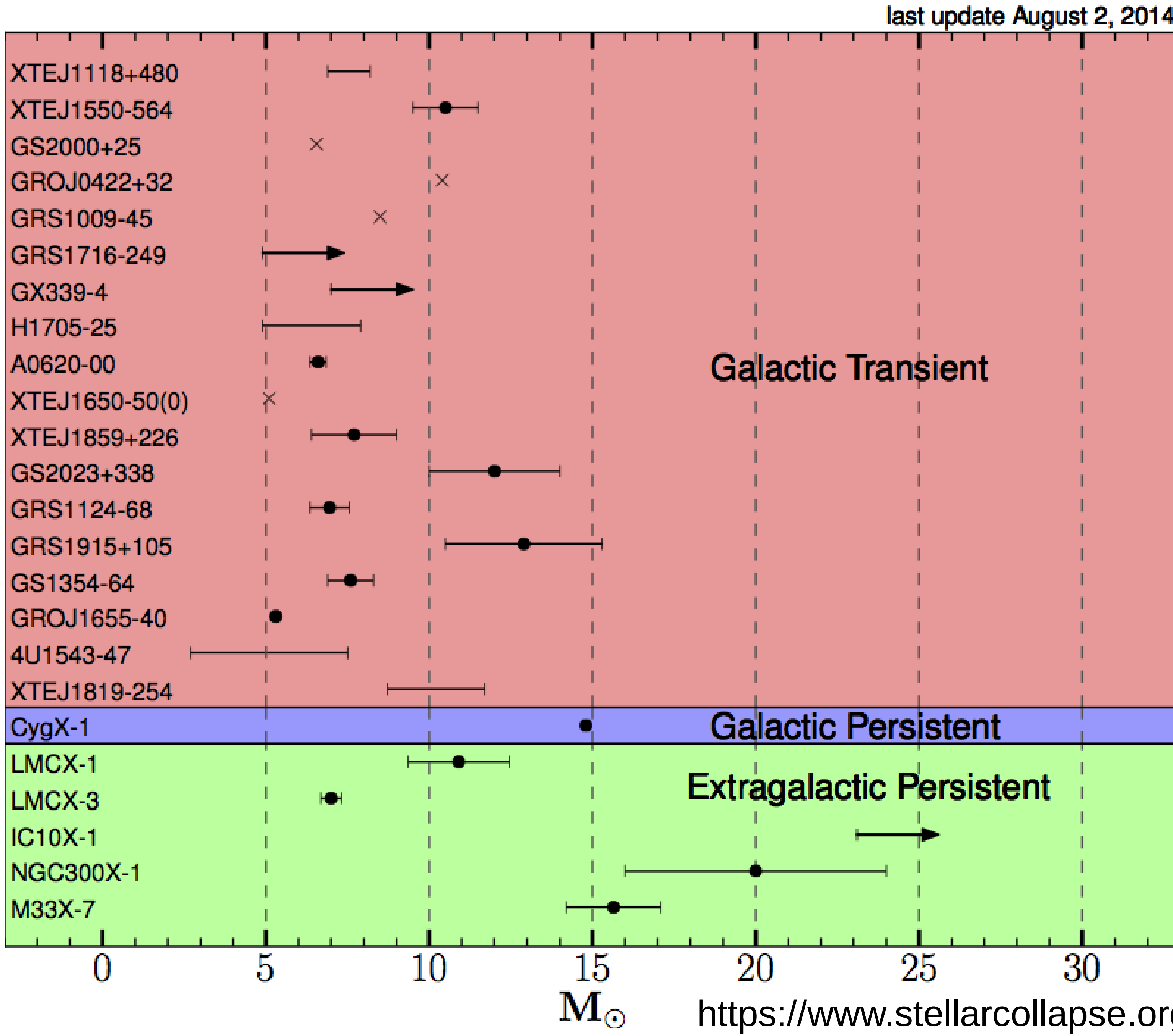
2008

BH formation: masses and kicks

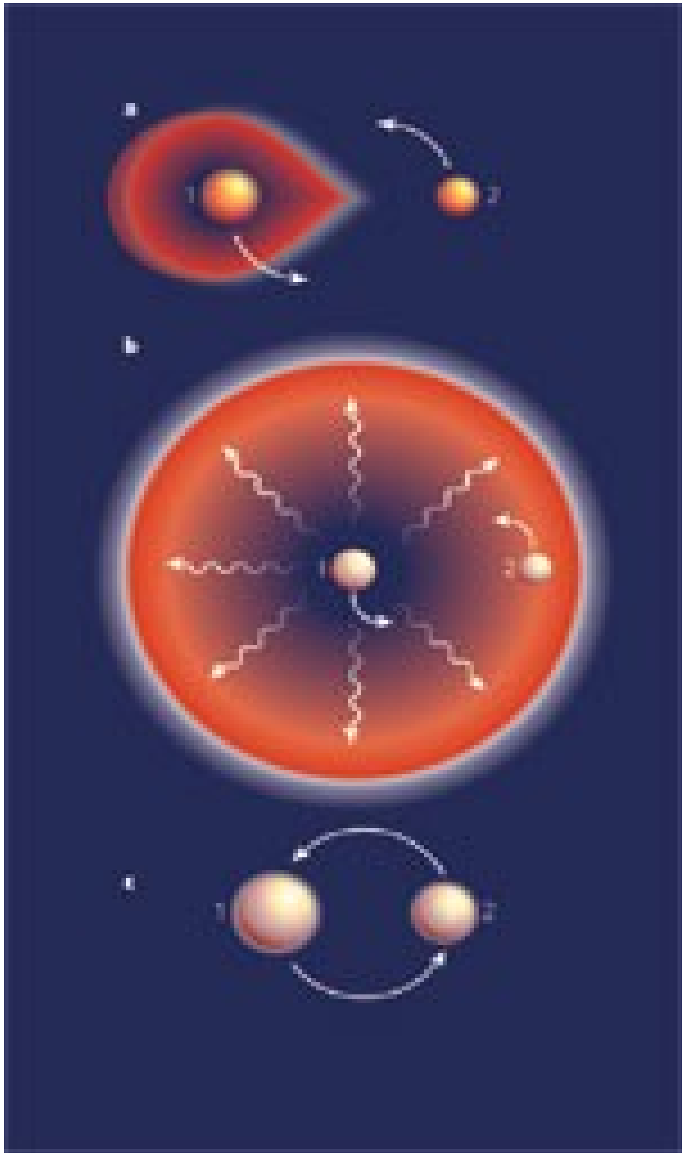


https://www.stellarcollapse.org/bhmasses

Common envelope

- What is it?
- Why it is a problem?
- Short timescale
- Non equlibrium evolution
- Core – envelope distinction
- Survival or merger?
- Parameterization:
  - Efficiency
  - Envelope binding

$$E_{bind} = \alpha E_{grav}$$



When was it formed

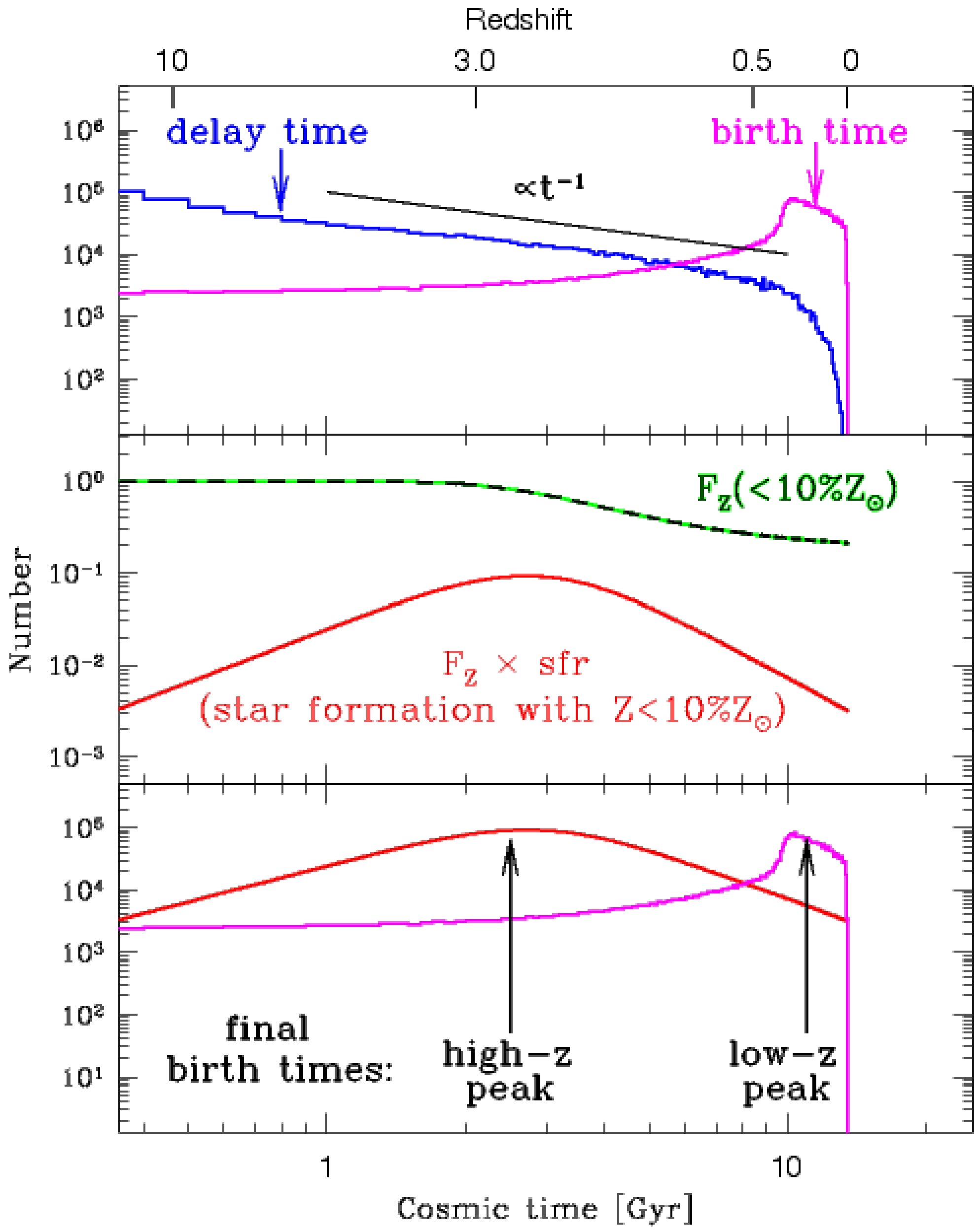
A combination of:

- metallicity evolution
- delay times

Two possible scenarios

Recent event

Very old event



Expected rates

TABLE 1
LOCAL MERGER RATES AND SIMPLY-SCALED DETECTION RATE PREDICTIONS[a]:

Model	$\langle \mathcal{M}_c{}^{15/6} \rangle$ $M_\odot^{15/6}$	$\mathcal{R}(0)$ $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$	R_D (aLIGO $\rho \geq 8$) yr^{-1}	R_D (3-det network $\rho \geq 10$) yr^{-1}
NS-NS				
Standard	1.1 (1.1)	61 (52)	1.3 (1.1)	3.2 (2.7)
Optimistic CE	1.2 (1.2)	162 (137)	3.9 (3.3)	9.2 (7.7)
Delayed SN	1.4 (1.4)	67 (60)	1.9 (1.7)	4.5 (4.0)
High BH Kicks	1.1 (1.1)	57 (52)	1.2 (1.1)	3.0 (2.7)
BH-NS				
Standard	18 (19)	2.8 (3.0)	1.0 (1.2)	2.4 (2.7)
Optimistic CE	17 (16)	17 (20)	5.7 (6.5)	13.8 (15.4)
Delayed SN	24 (20)	1.0 (2.4)	0.5 (0.9)	1.1 (2.3)
High BH Kicks	19 (13)	0.04 (0.3)	0.01 (0.08)	0.04 (0.2)
BH-BH				
Standard	402 (595)	28 (36)	227 (427)	540 (1017)
Optimistic CE	311 (359)	109 (221)	676 (1585)	1610 (3773)
Delayed SN	829 (814)	14 (24)	232 (394)	552 (938)
High Kick	2159 (3413)	0.5 (0.5)	22 (34)	51 (81)

[a] Detection rates computed using the basic scaling of Eq. (3) for both the *high-end* and *low-end* (the latter in parentheses) metallicity scenarios (see Section 2.2). These rates should be compared with those from more careful calculations presented in Tables 2 and 3

Dominik et al 2012

Basic parameters of the system

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Abbott et al. 2016