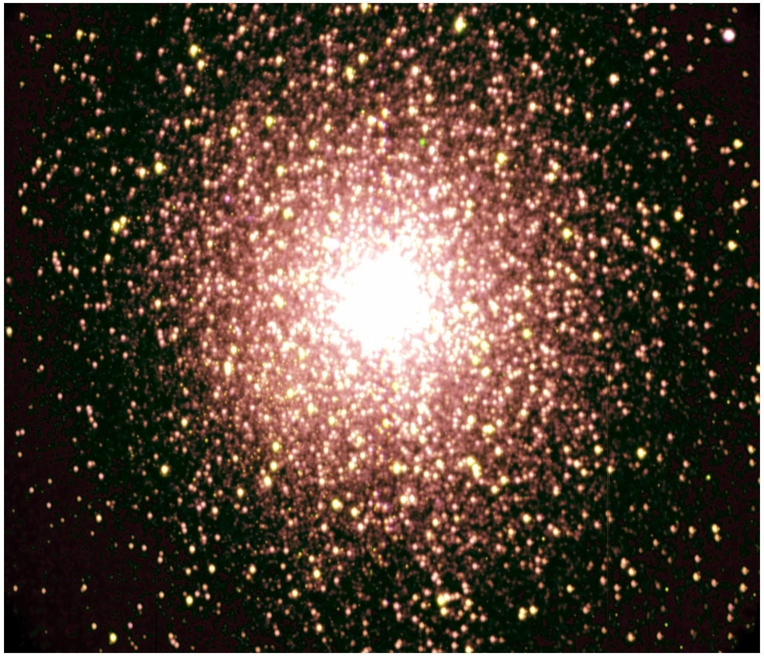
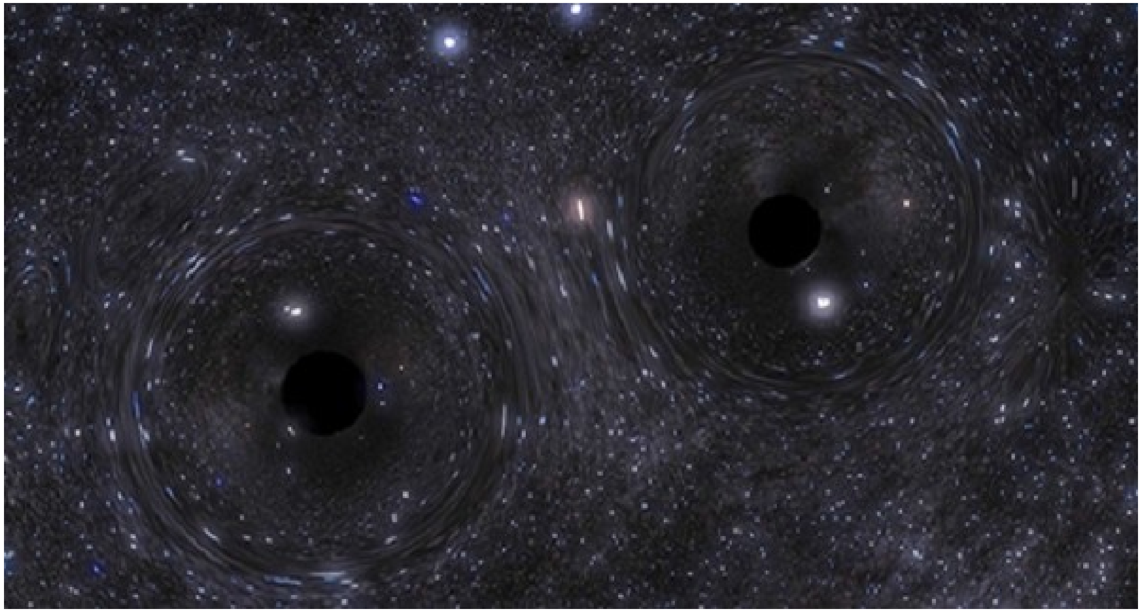
Coalescing binary black holes originating from globular clusters





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A. Askar, M. Szkudlarek,D.Gondek-Rosinska,
M.Giersz,T.Bulik, 2016,MNRAS

The recent breakthroughs

- 2015 - detection of gravitational waves by aLIGO → GW Astronomy, a new window into the Universe
- Detection of black hole binaries: GW150914,GW151226+LVT151012
- Evidence for BHs with masses of 30 and up to 60 solar masses
- GW150914 - the “brightest” source ever seen in the sky:

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

- Expect a lot of discoveries during O2 starting in a few weeks !!!
- Merging BBH the most important sources of gravitational waves
- Where does it fit into broad astrophysical picture?

-evolution of binaries in the field

-formation of binaries in dense clusters

-population III

Globular Clusters

- Massive spherical collection of 10000 to
  10 million stars.
- Typically old stellar systems (about 13 Gyr)
- Stars are clumped closely together especially near the centre (core) of the cluster (very dense systems).
- Contain 1% of mass of a galaxy

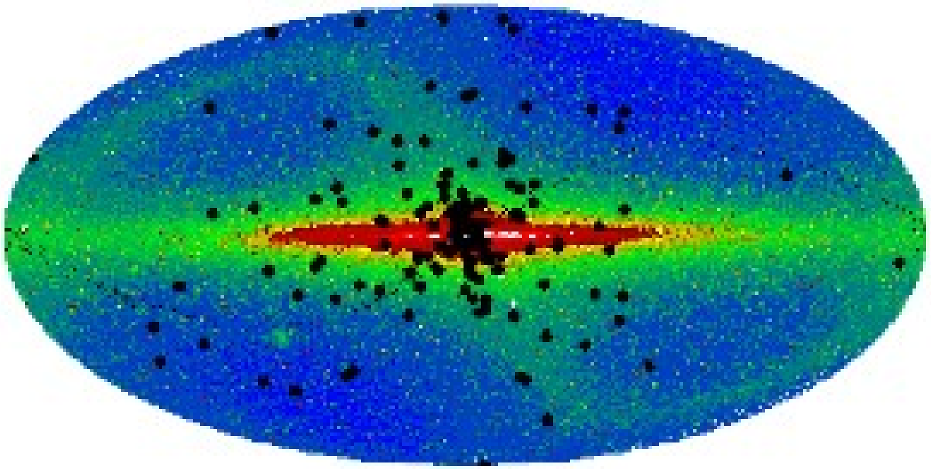
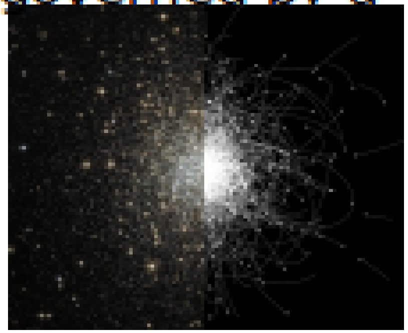


Figure1 GC distribution about Milky Way from M. Benacquista & J. Downing 2011, positions of 157 GC from Harris catalog

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*** or **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

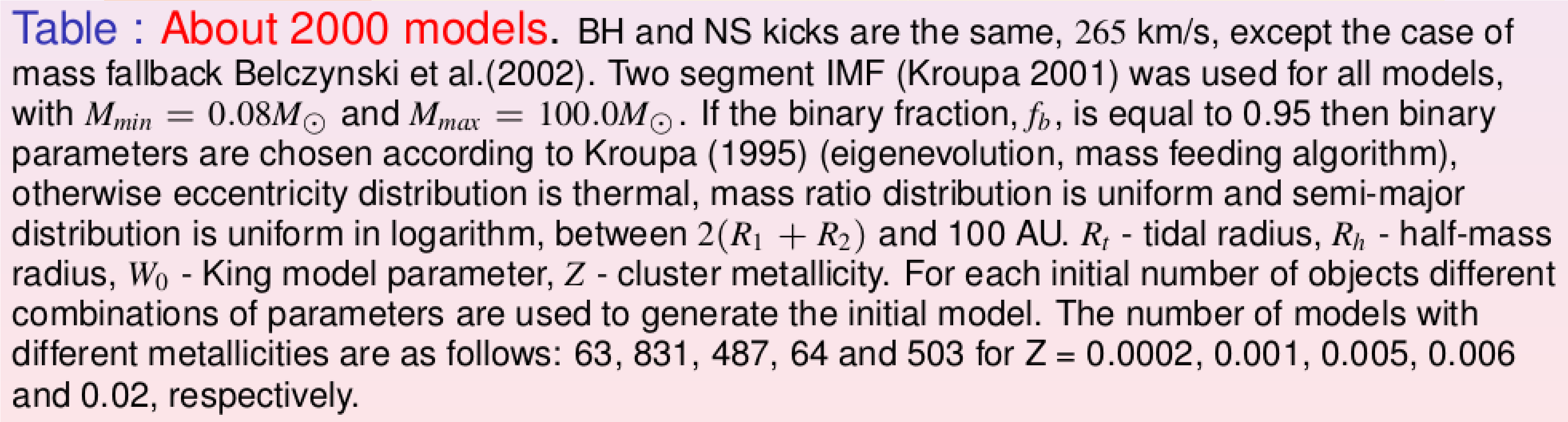
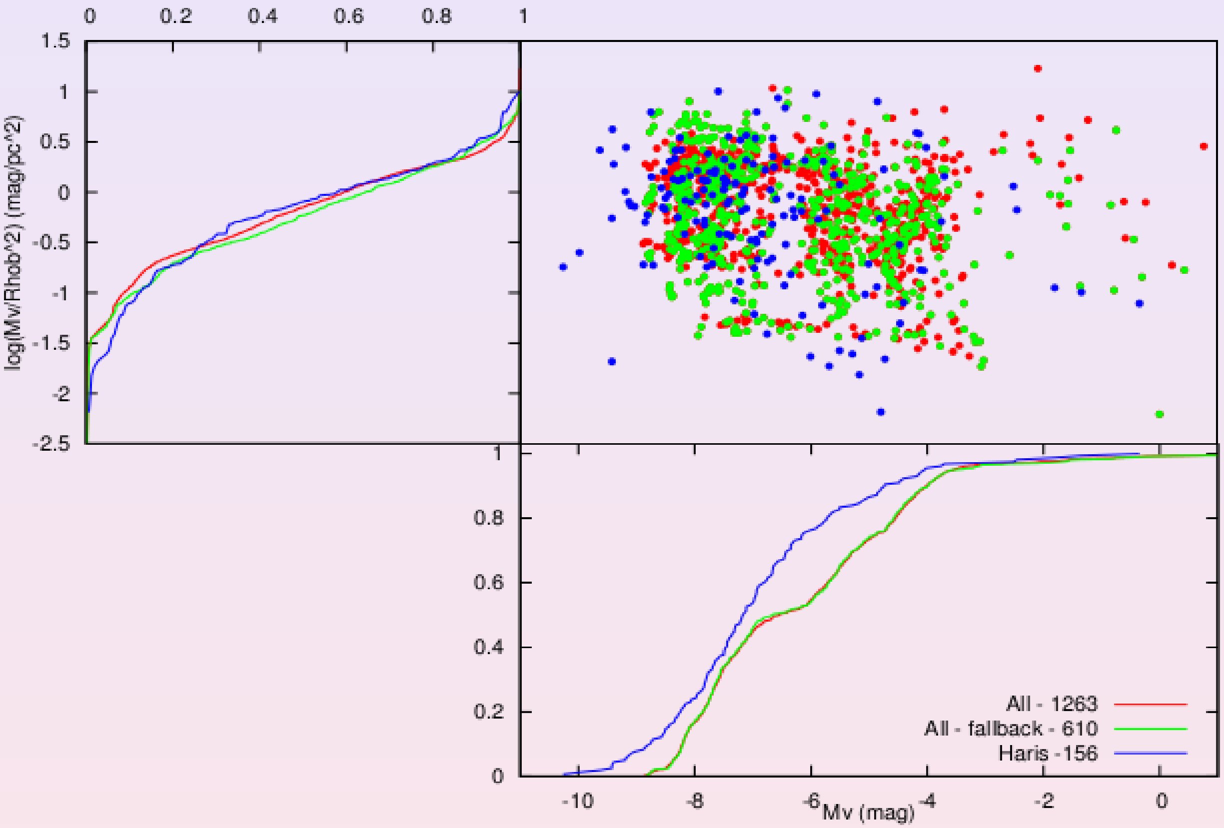


Table : About 2000 models. BH and NS kicks are the same, 265 km/s, except the case of mass fallback Belczynski et al.(2002). Two segment IMF (Kroupa 2001) was used for all models, with $M_{min} = 0.08M_\odot$ and $M_{max} = 100.0M_\odot$. If the binary fraction, f_b, is equal to 0.95 then binary parameters 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

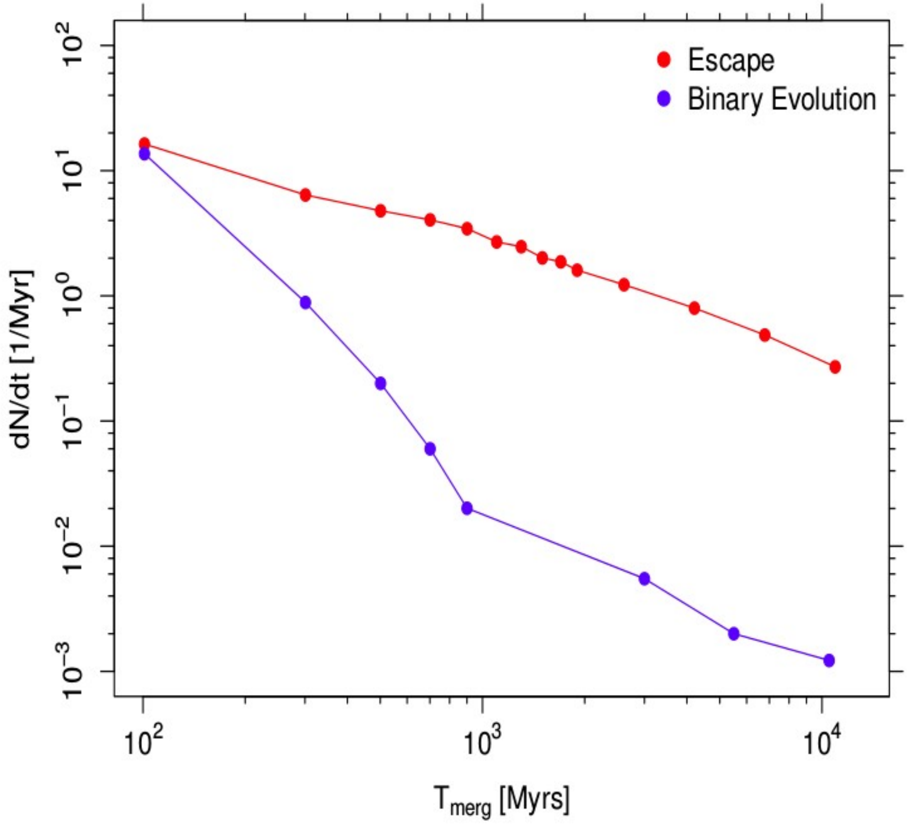


Models for the Survey were not selected to match the observed Milky Way GCs. Except for few bright (massive and intermediate mass) Galactic GCs, the agreement with the observational properties of Galactic GCs is quite good. Despite this agreement, any combination of global observational properties of 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.

Merging Binary Black Holes from Globular Clusters

Number of merging BBH binaries within Hubble time per unit time (1 Myr) and M_{BH} < 100Msun
BBH in GC: 3 000; BBH ejected from GC ~15 000,



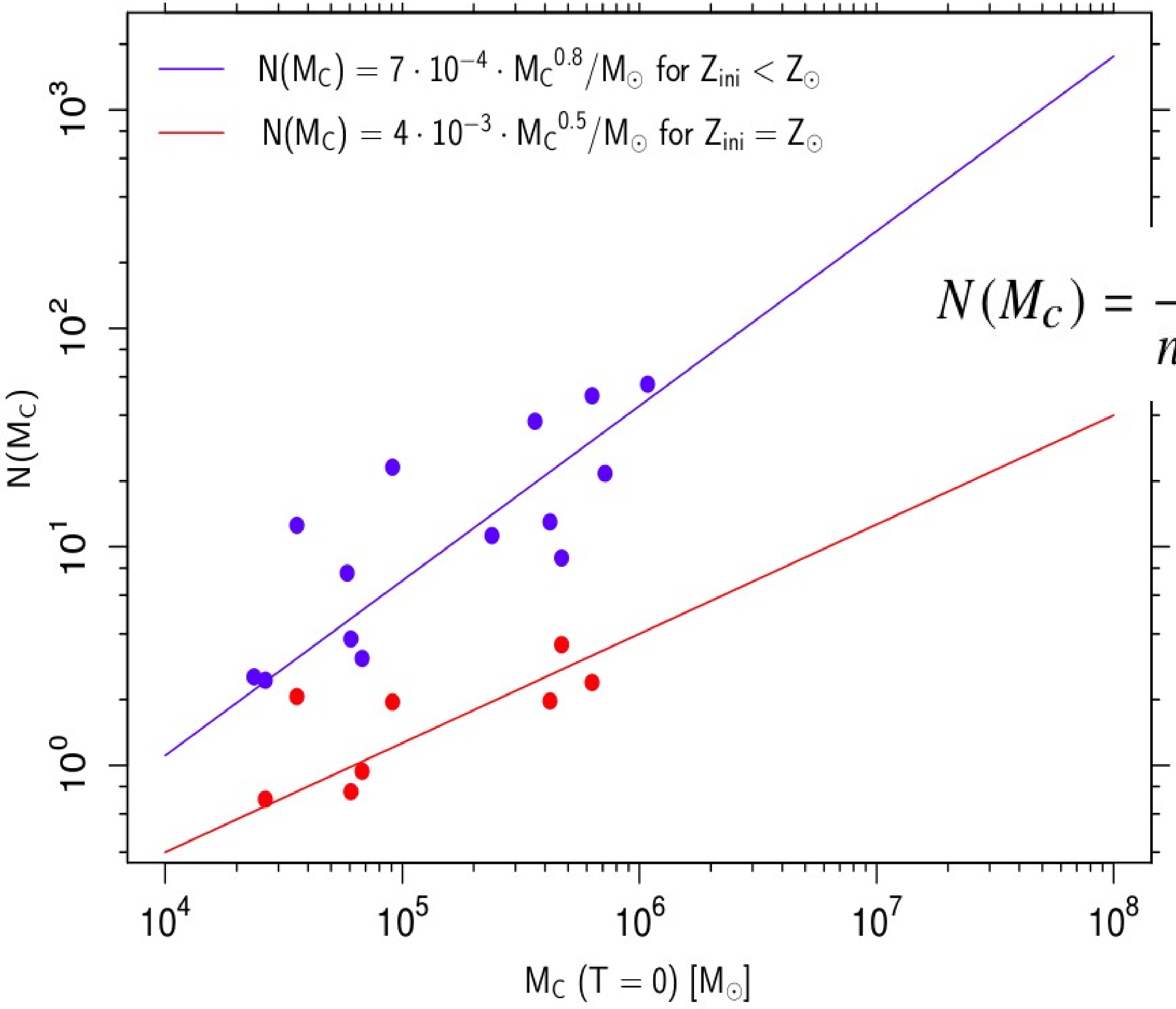
- Path to BBH

  - escaping binaries (dominating)

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

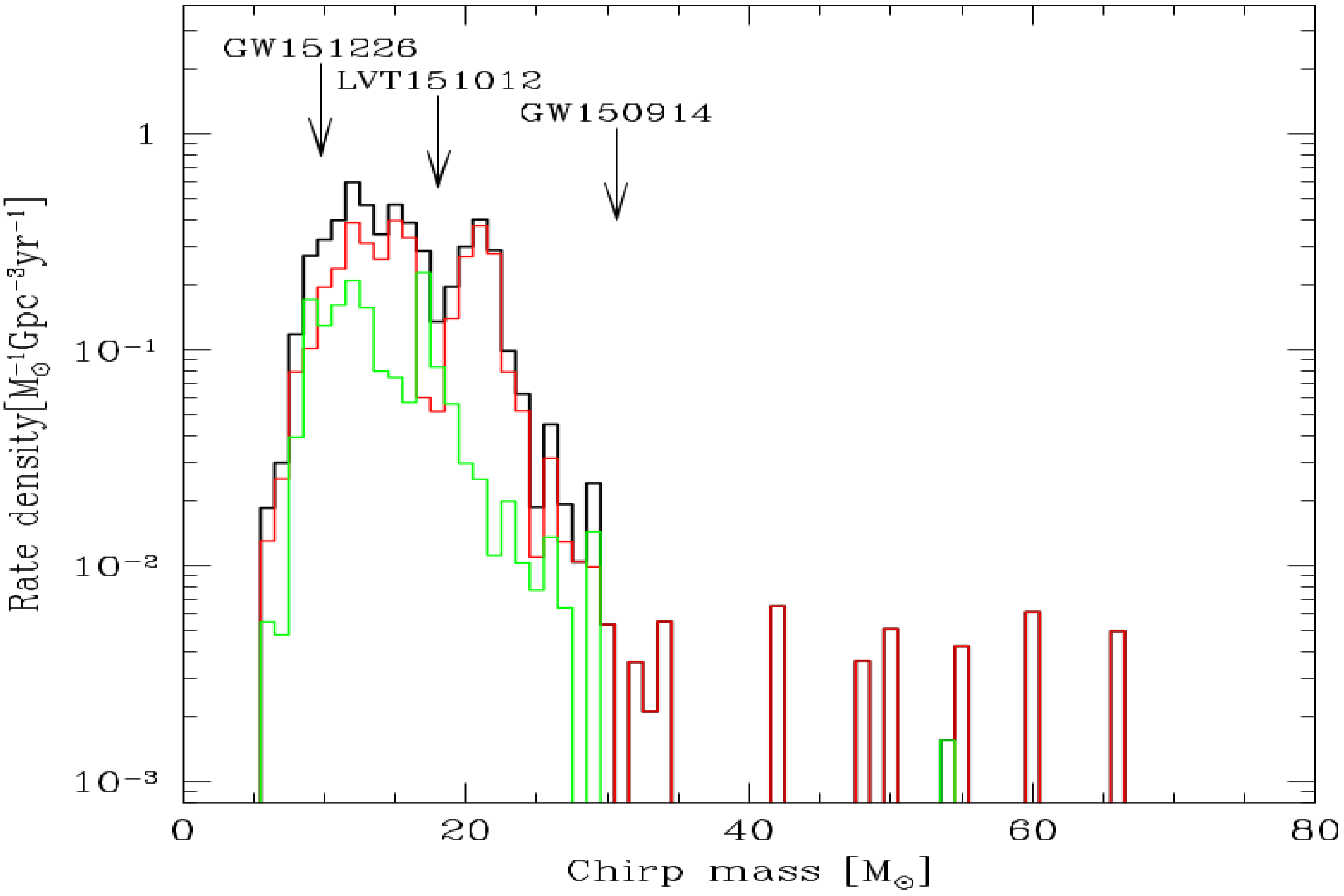
Dependence on the cluster mass

Zsun=0.02



$$N(M_c) = \frac{n}{n_s \cdot M_c/10^6 M_\odot}$$

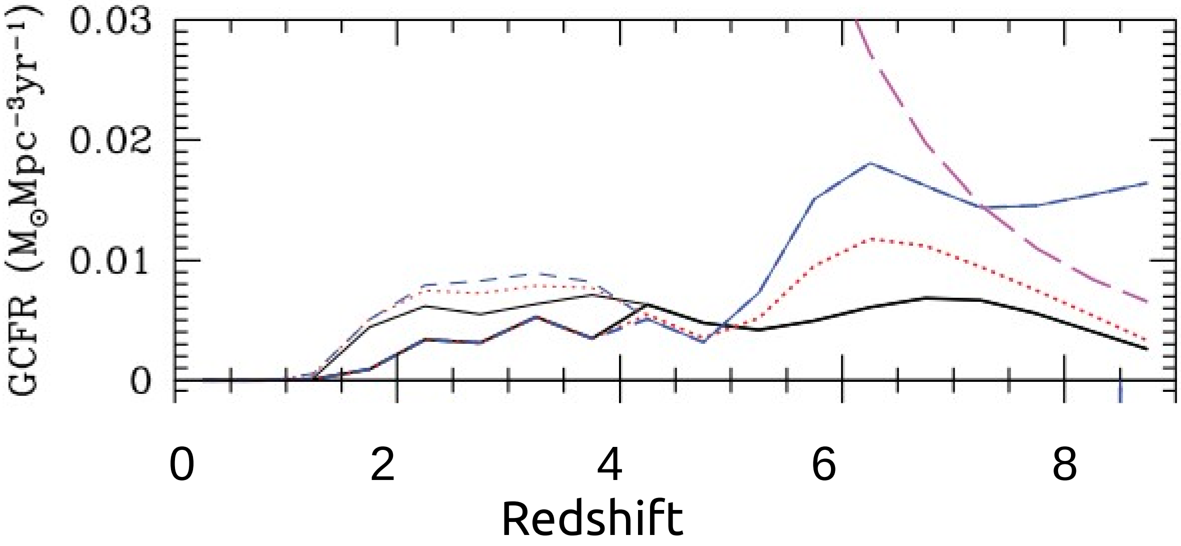
The dominant contribution – escaping BHBH



Merger rates in clusters

- Globular Cluster formation rate

Katz & Ricotti 2013



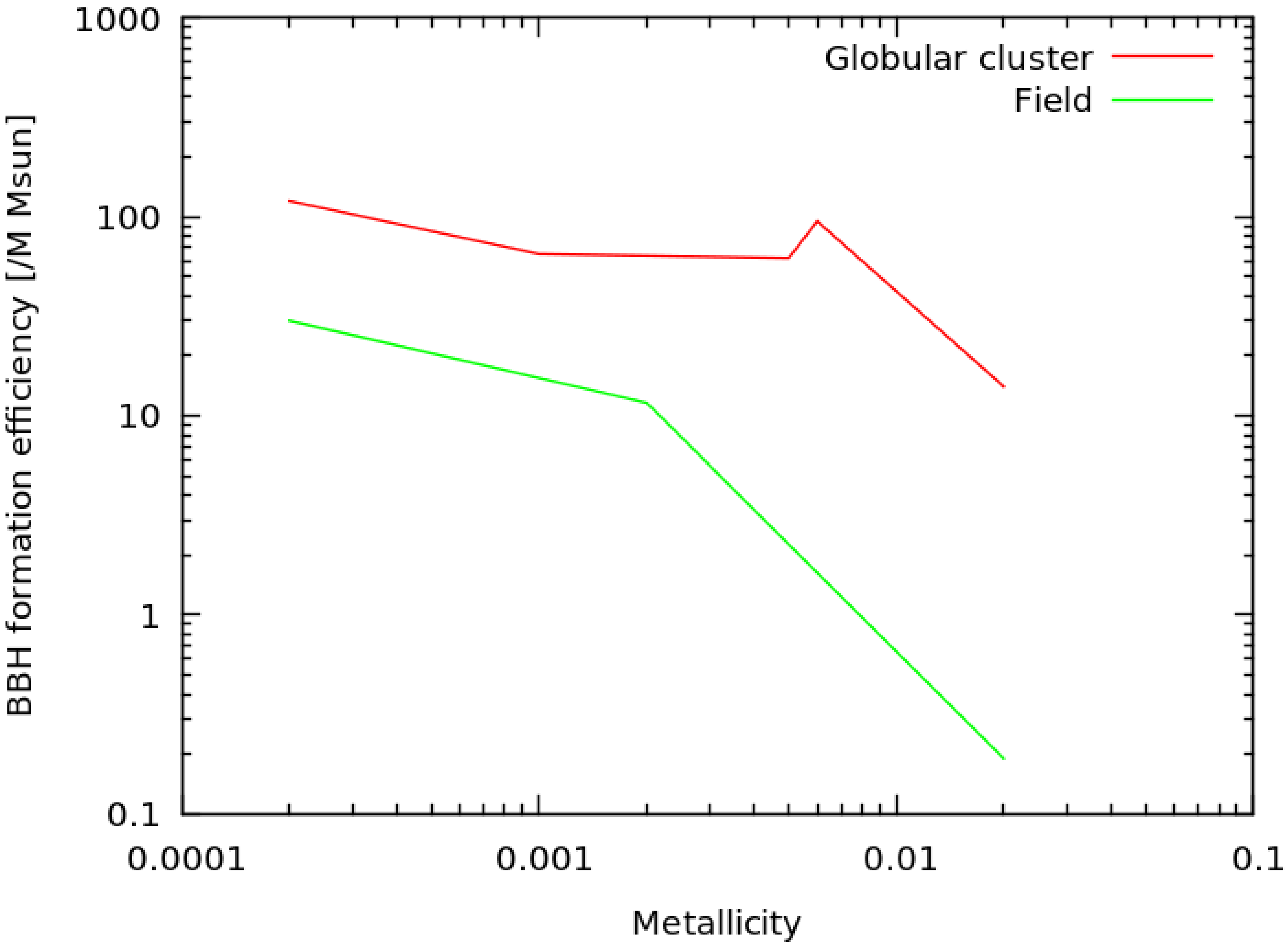
- GC mass composition
- GC metallicity
- The local merger rate

  - 5.4 Gpc^-3/yr

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

BH production efficiency

Number of merging BBH binaries per 10^6 solar masses of stars.

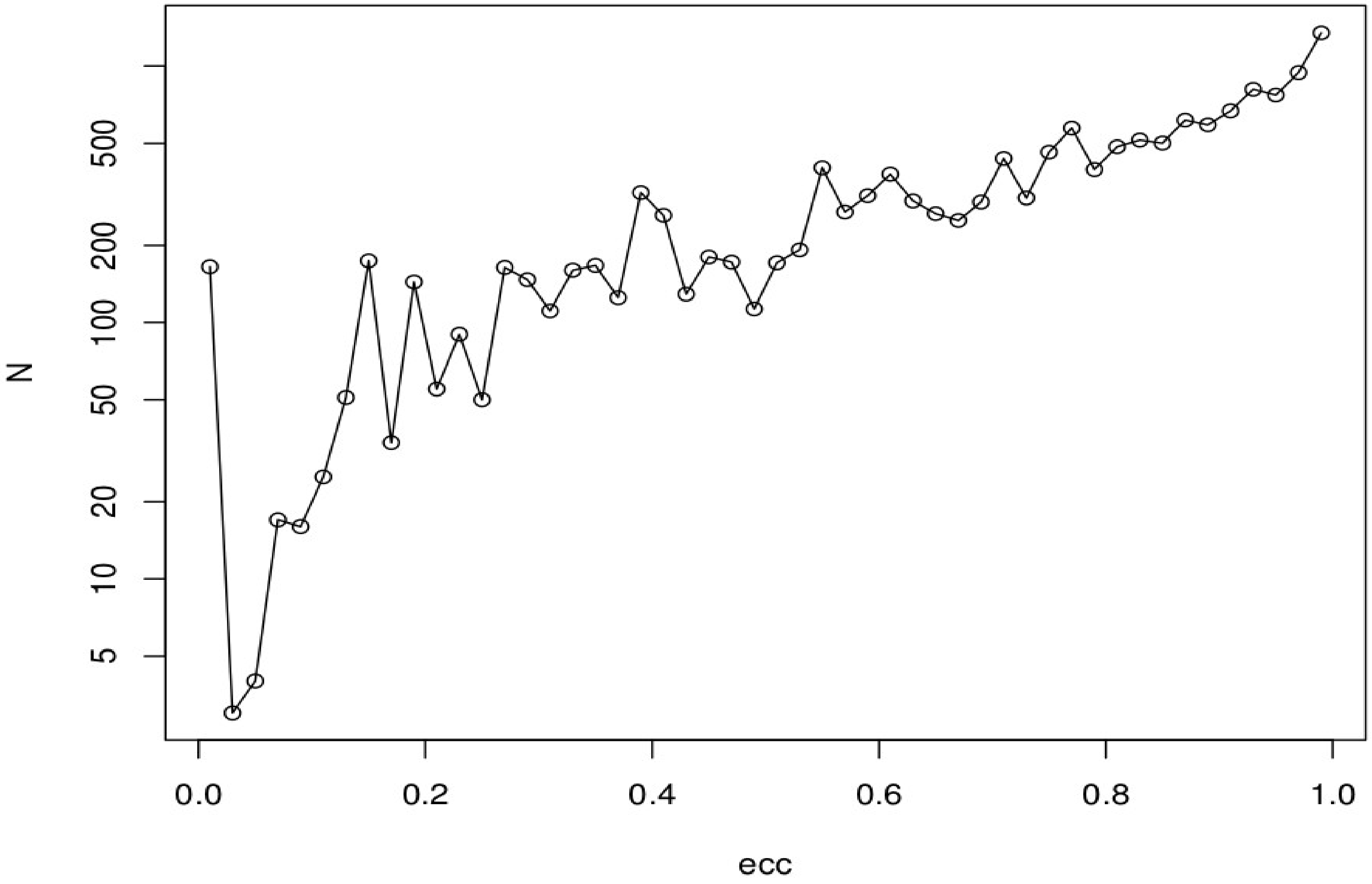


Field vs Globular Clusters

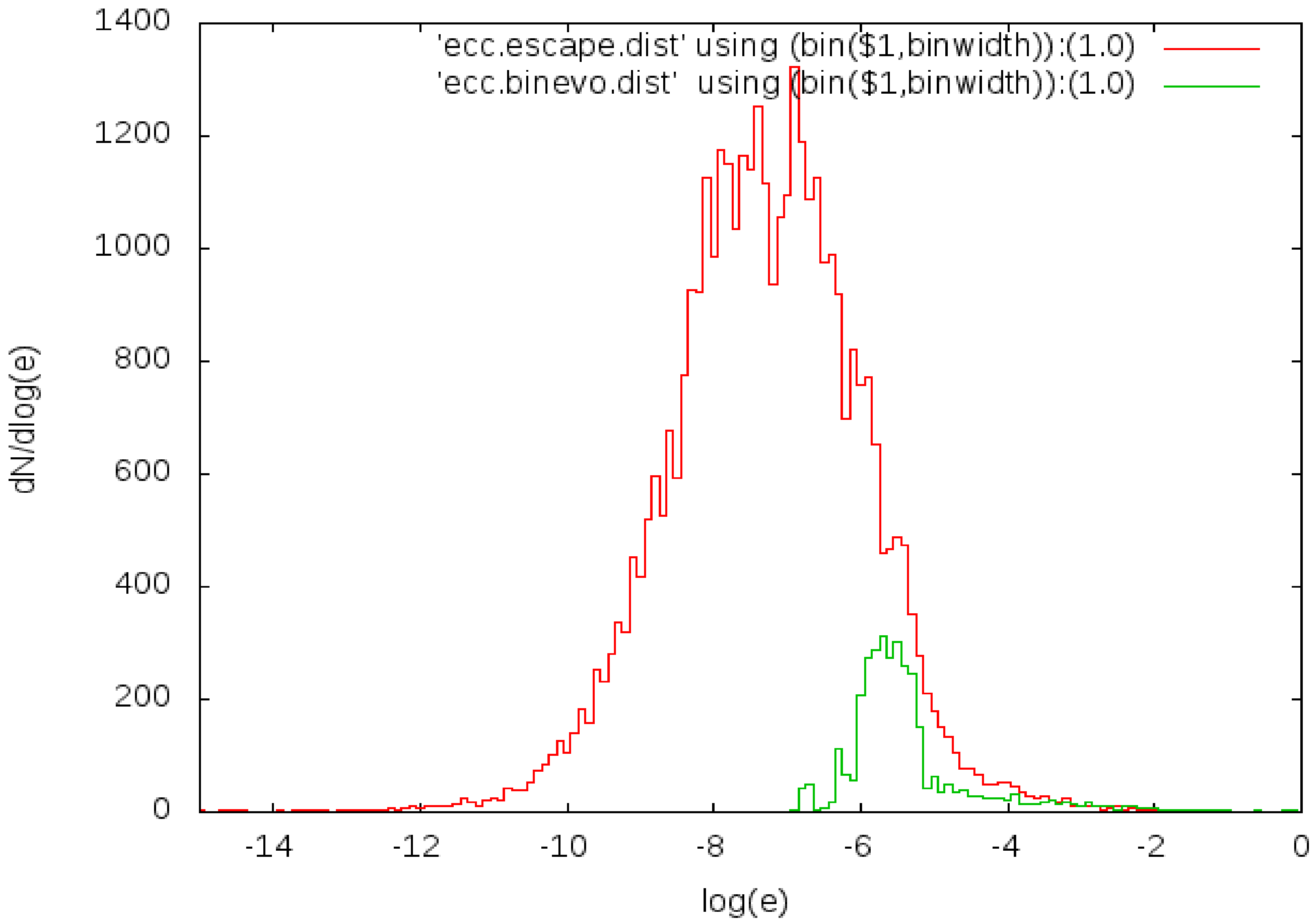
- Can we use spins to distinguish the two?
- GC formation – exchanges, non aligned spins
- Are spins aligned in field evolution?

- 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

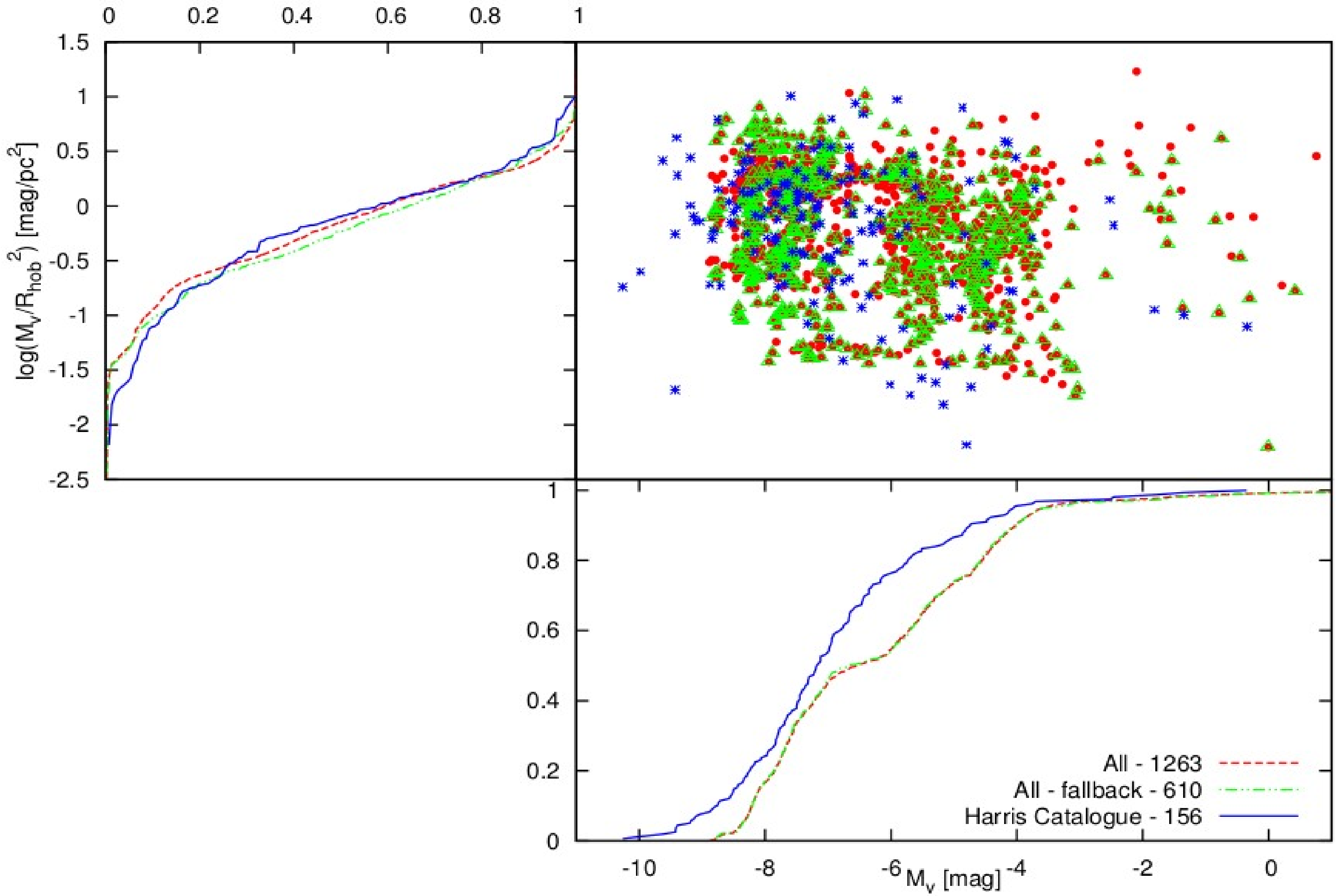
- We have explored mergers of BBHs from GC using MOCCA code.
- The dominant contribution from ejected BBH and low metalicity models
- The local merger rate density of BBH from GC is 5.4-30 Gpc^-3/yr
- Rates are in the low end of the observed values
  - Depends on assumptions on cluster mass and metallicity 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 the fall with O2 !!!

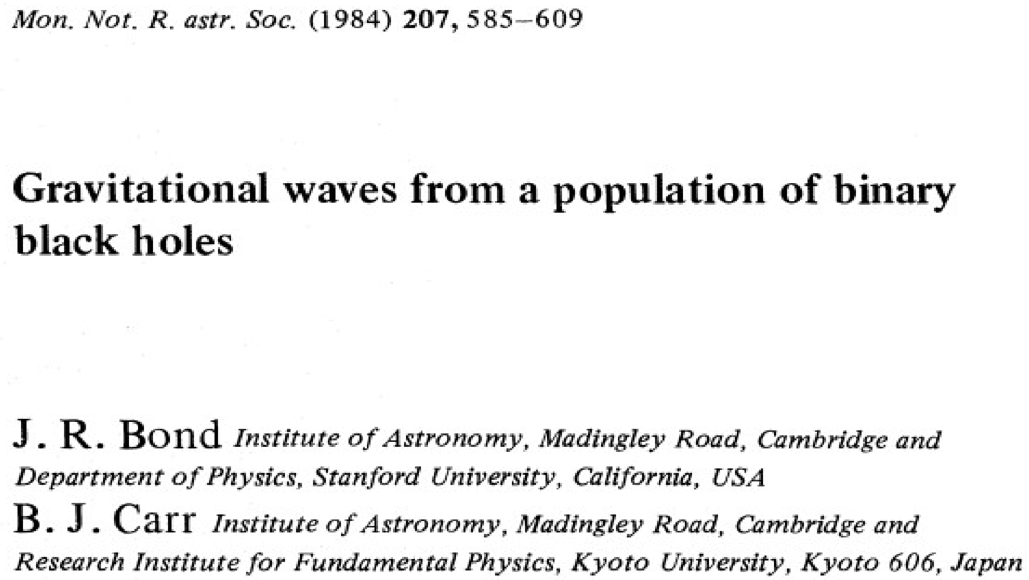
Summary

- Field evolution sufficiently explains the origin of GW150914
- Globular Cluster origin is also likely
- Both require low metallicity environment
- Population III stars – maybe..
- Expect a lot of discoveries in the fall with O2 !!!

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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Department of Physics, Stanford University, California, USA
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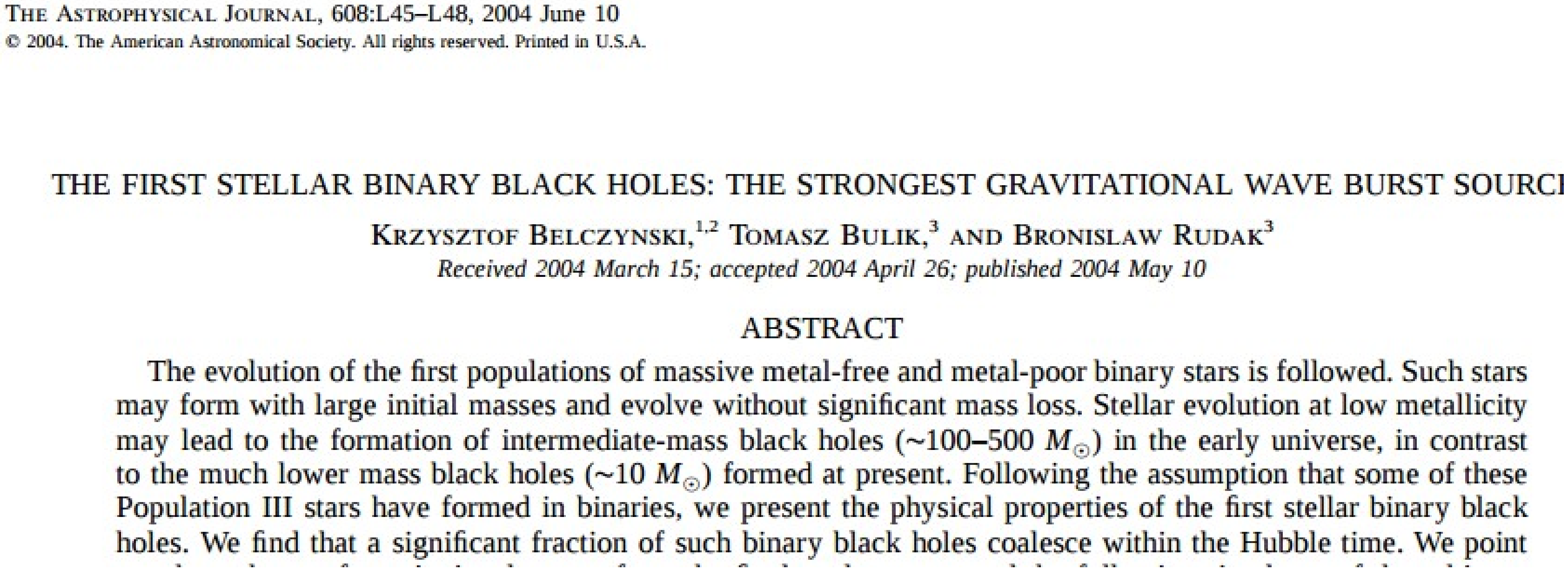


THE ASTROPHYSICAL JOURNAL, 608:L45–L48, 2004 June 10

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

KRZYSZTOF BELCZYNSKI,[1,2] TOMASZ BULIK,[3] AND BRONISLAW RUDAK[3]
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~10
- Very uncertain population model
- Are they a separate class?

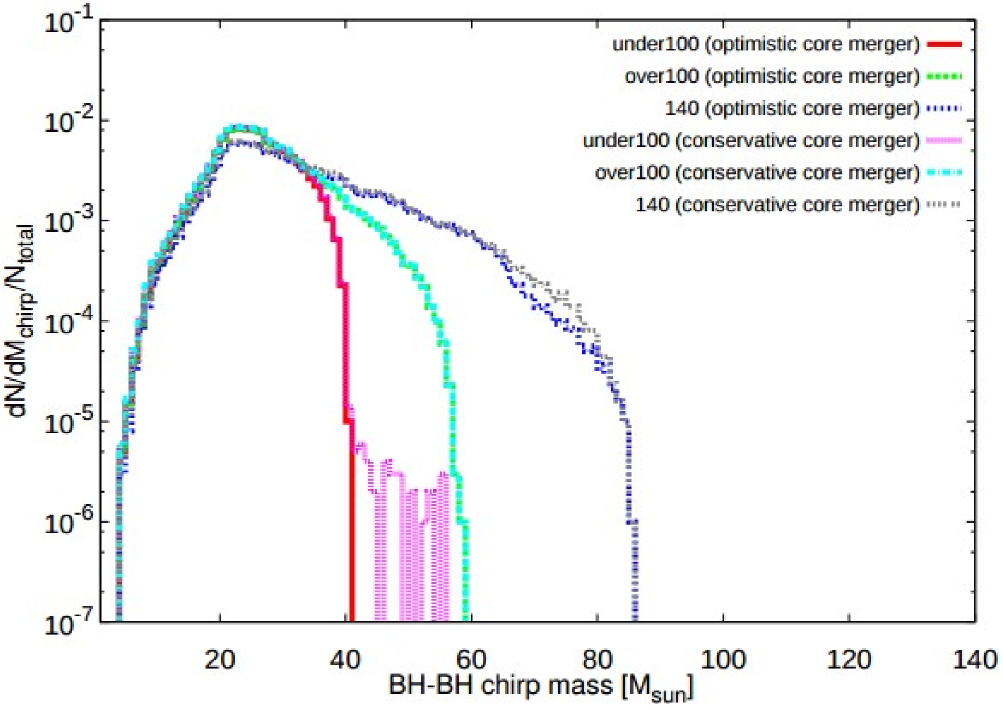
Population III

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



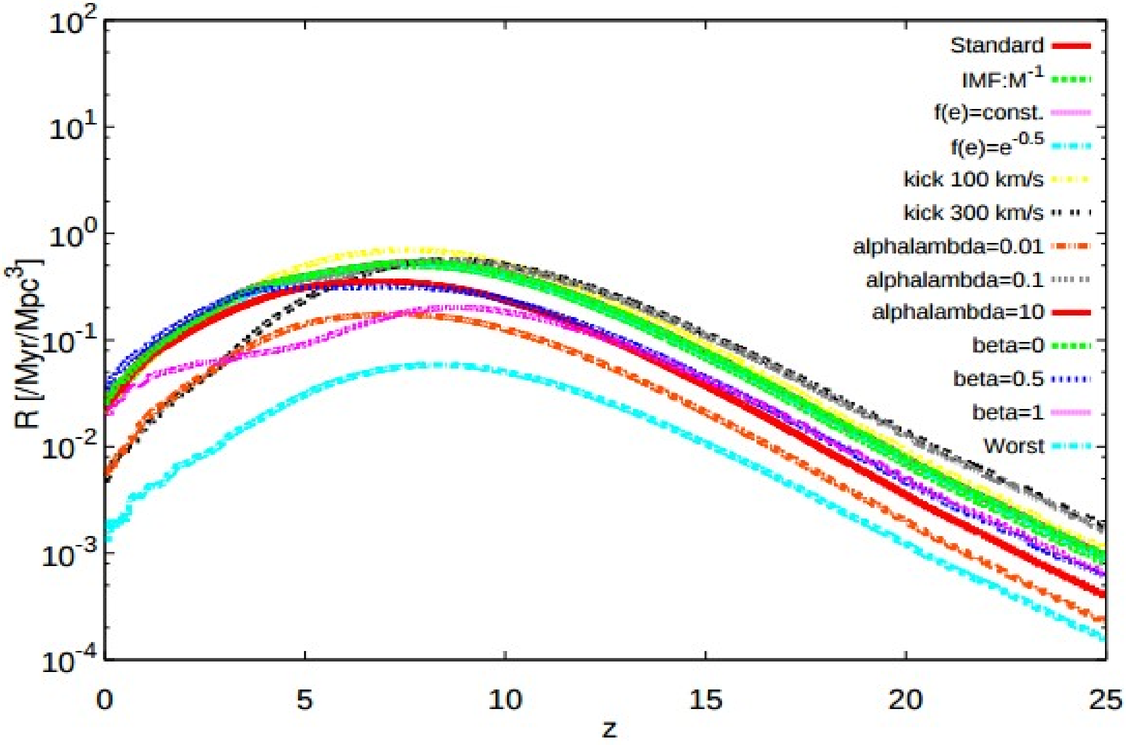


Figure 24. The merger rate densities

Spin evolution

Initial spins

Accretion, possible alignement of spin 2

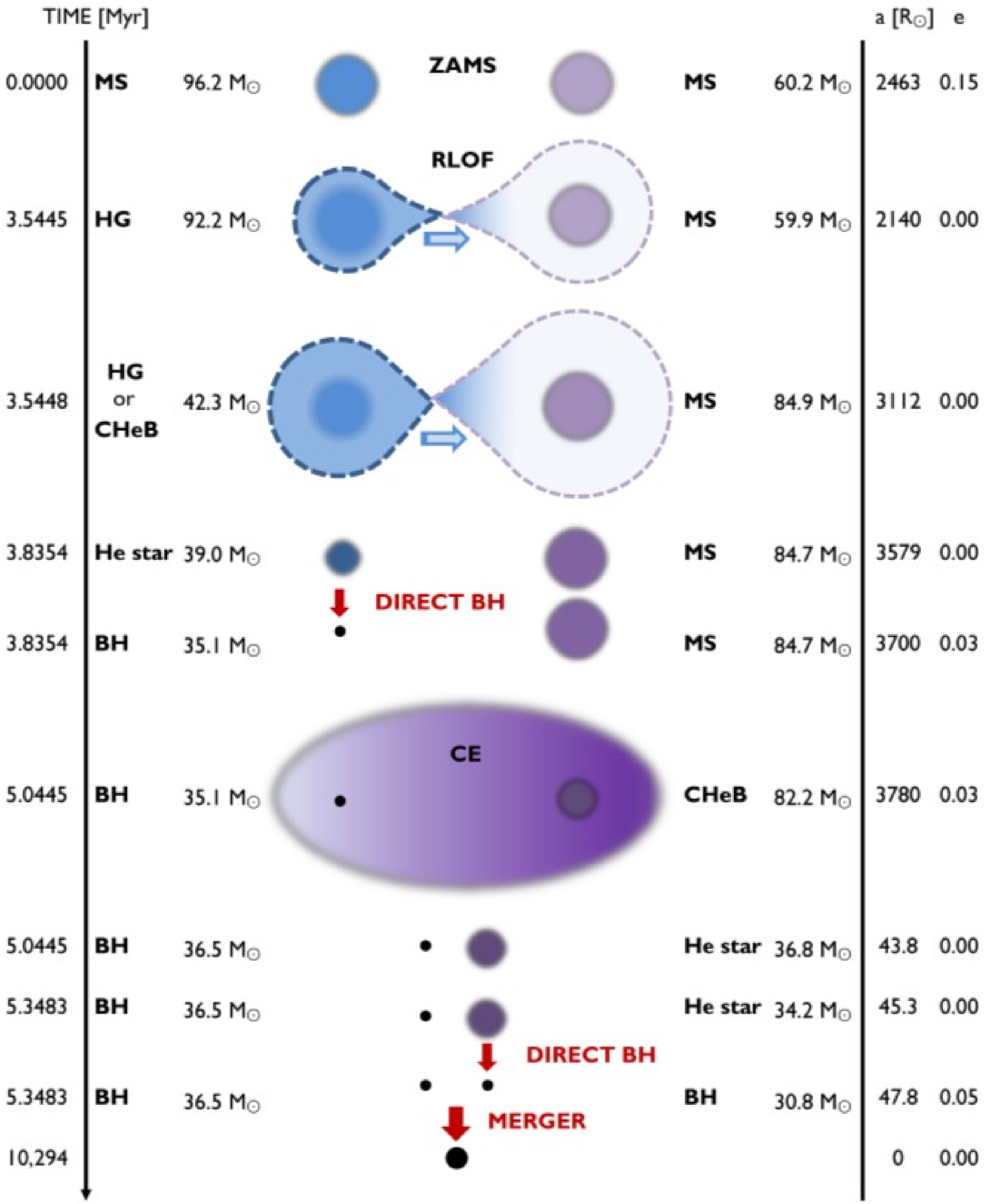
BH formation, kick?

CE – too short too affect

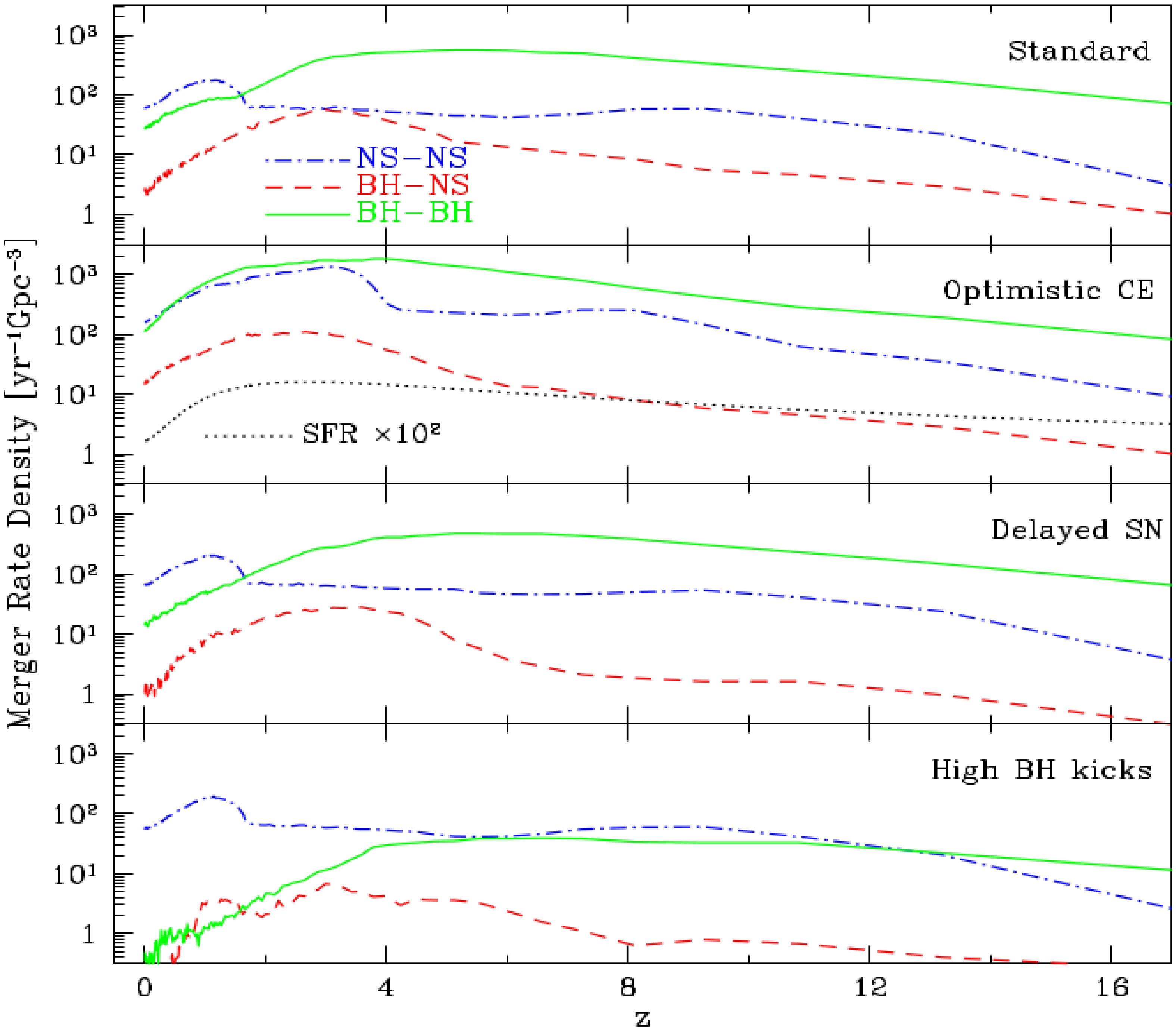
BH formation, kick?

Kicks are small.

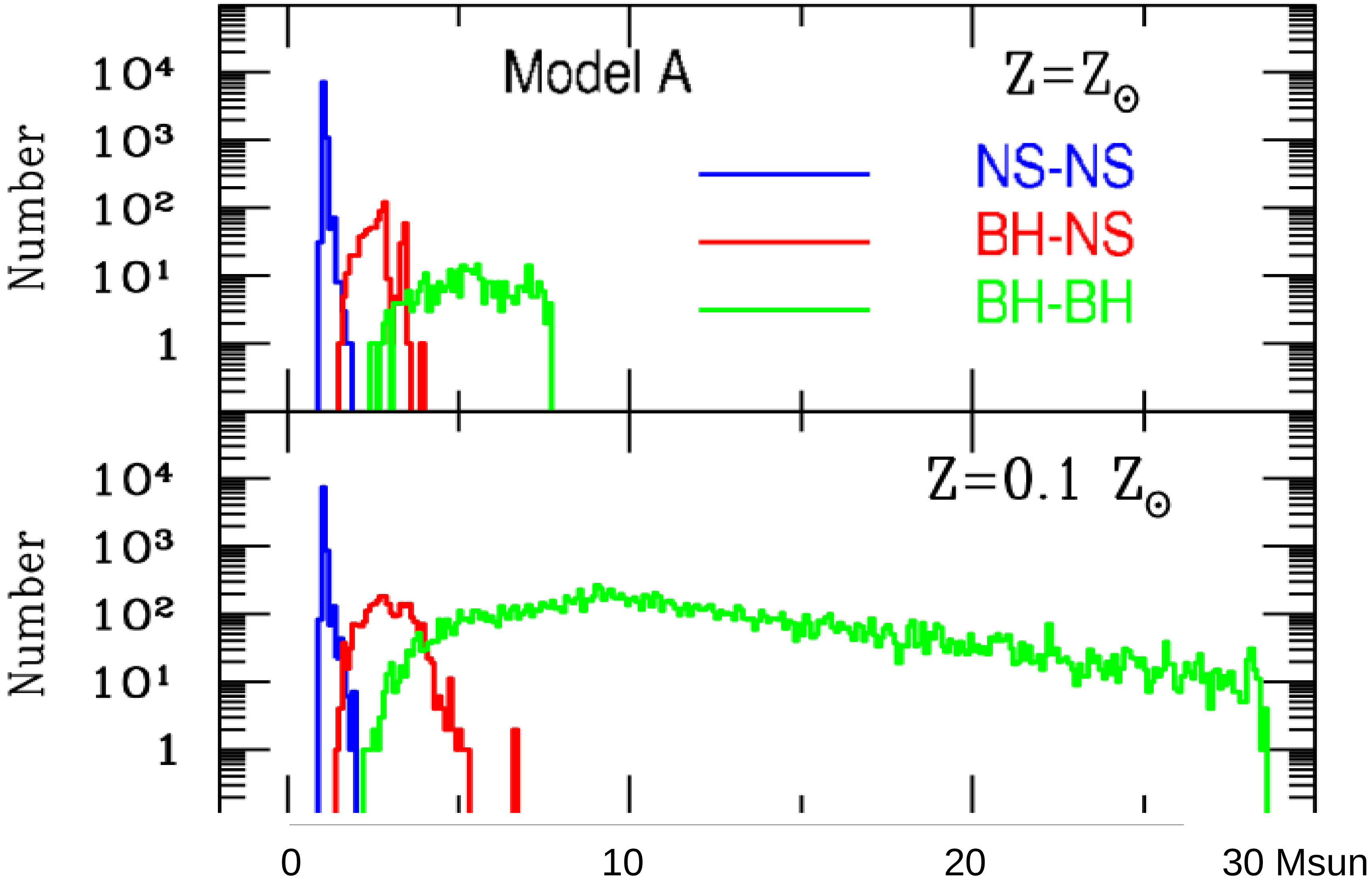
Final spins close to initial.
See *Albrecht et al 2014*
The BANANA Project.



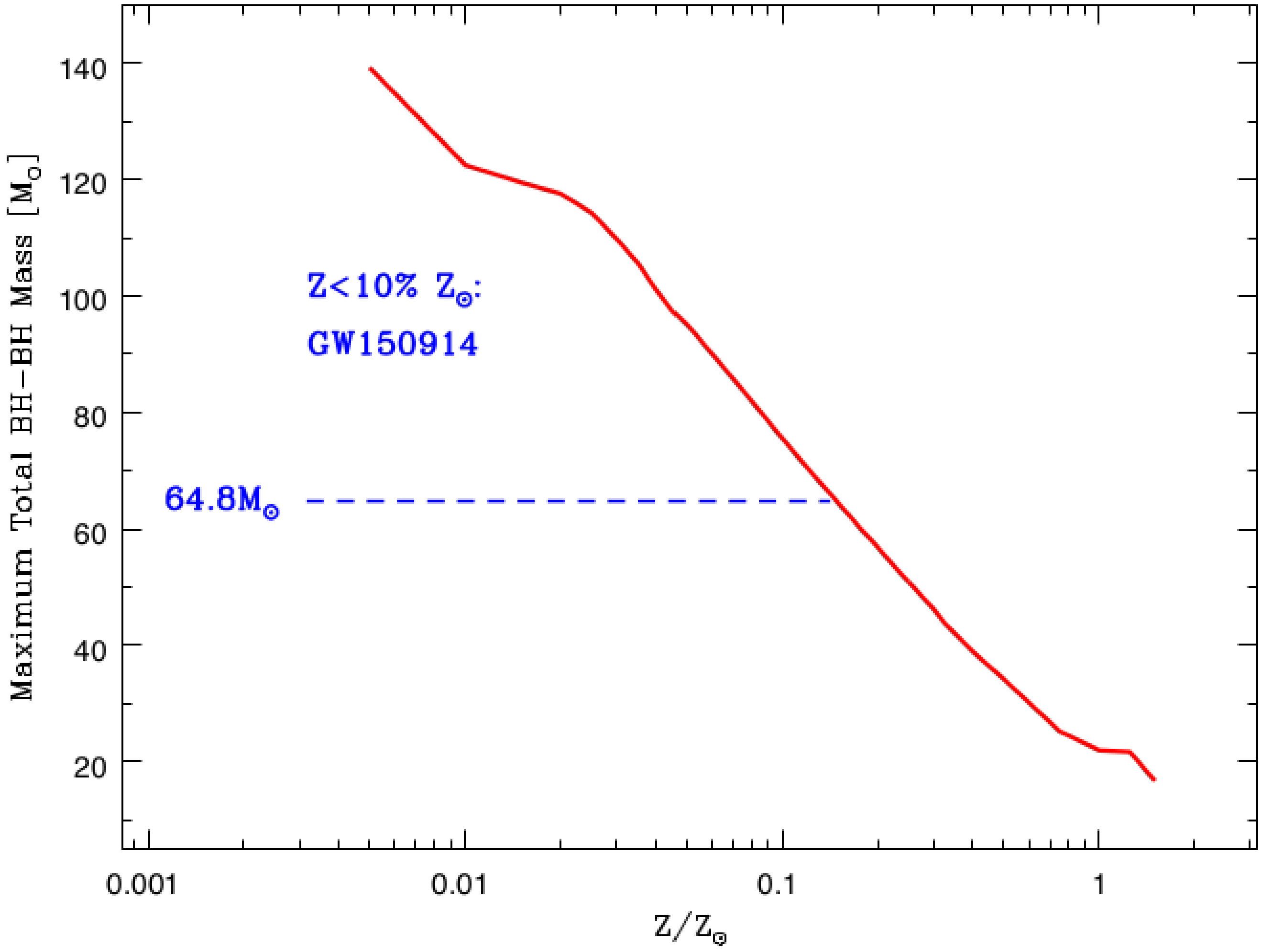
Merger rate density history



BHBH enhancement in low Z



Maximum BHBH mass



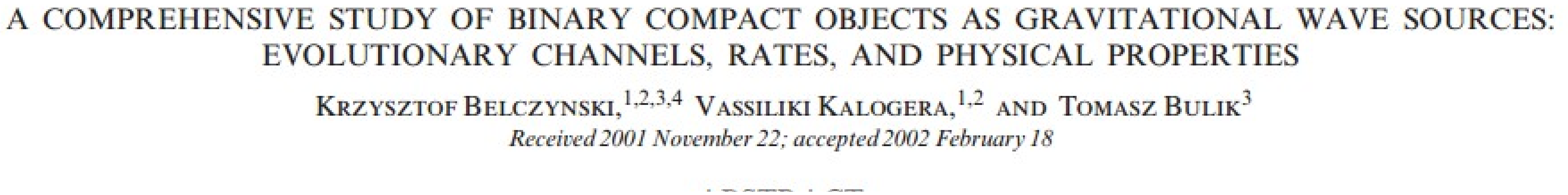
GW150914 progenitors were low metallicity Z<10% Zsun.

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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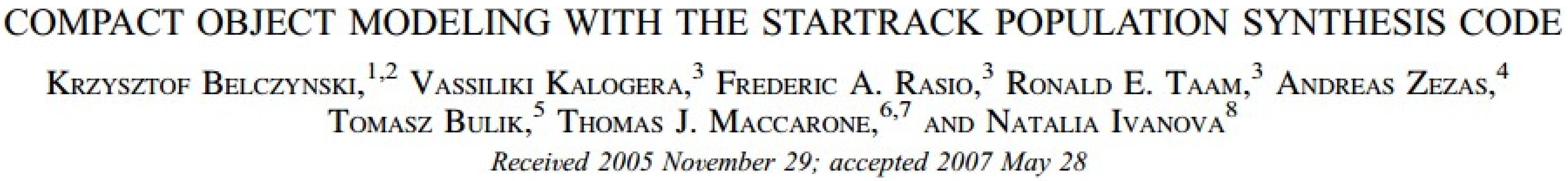
2002



COMPACT OBJECT MODELING WITH THE STARTRACK POPULATION SYNTHESIS CODE

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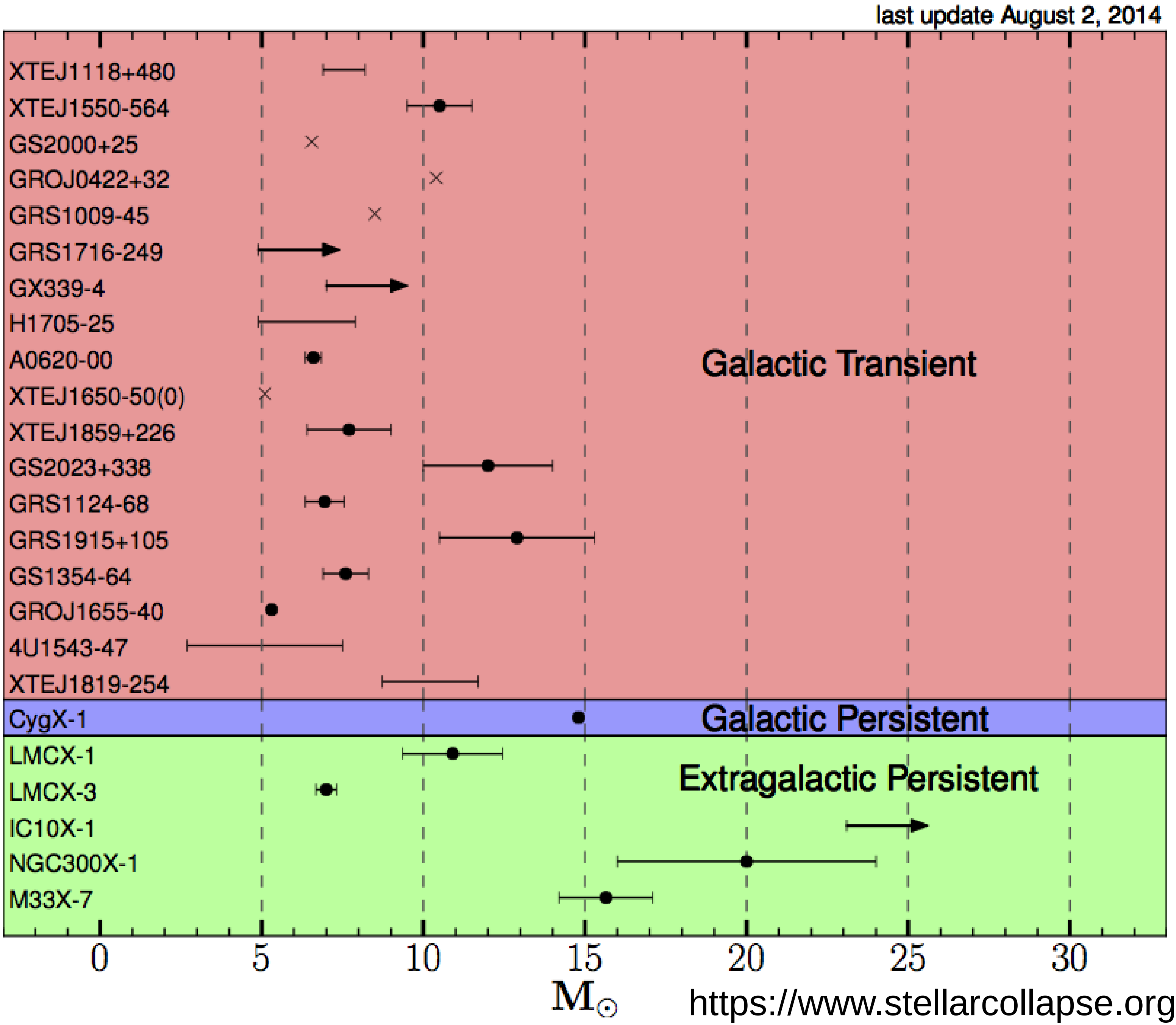
Received 2005 November 29; accepted 2007 May 28

2008

BH formation: masses and kicks

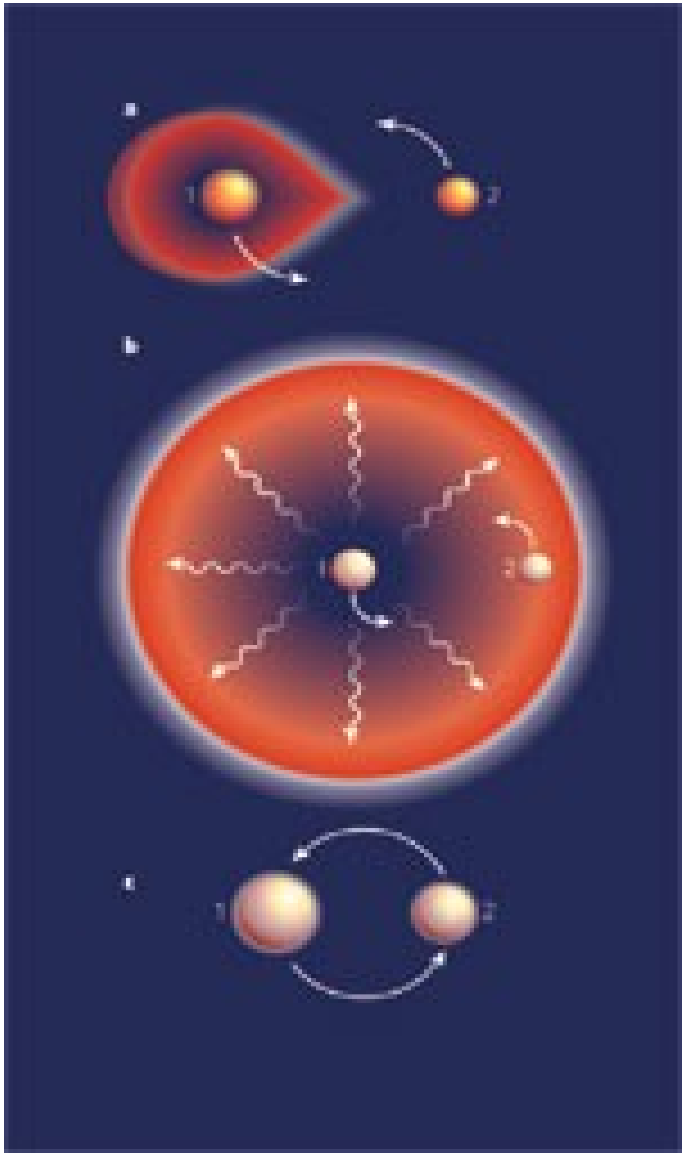


https://www.stellarcollapse.org/bhmasses

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

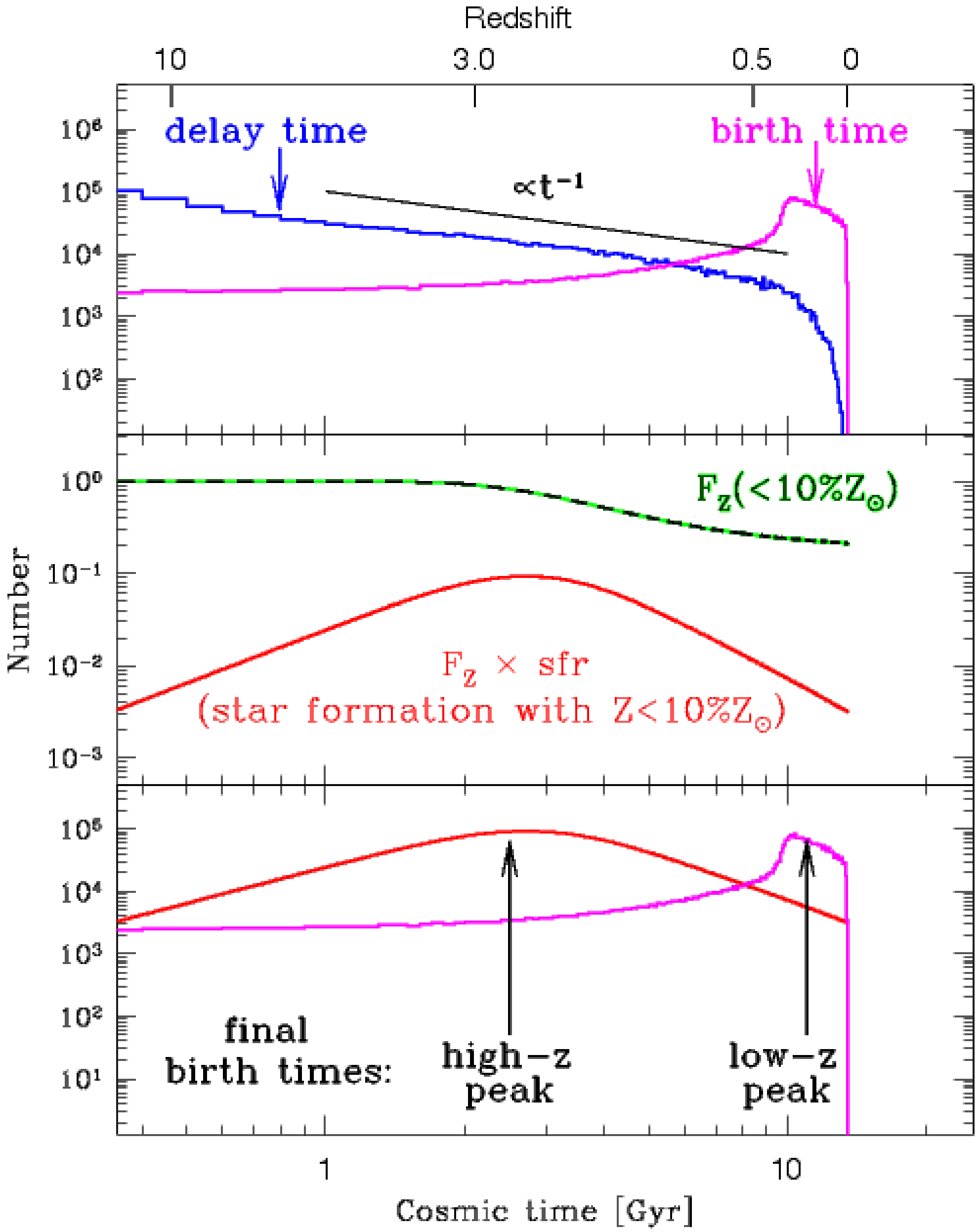
A combination of:

- metallicity evolution
- delay times

Two possible scenarios

Recent event

Very old event



Expected rates

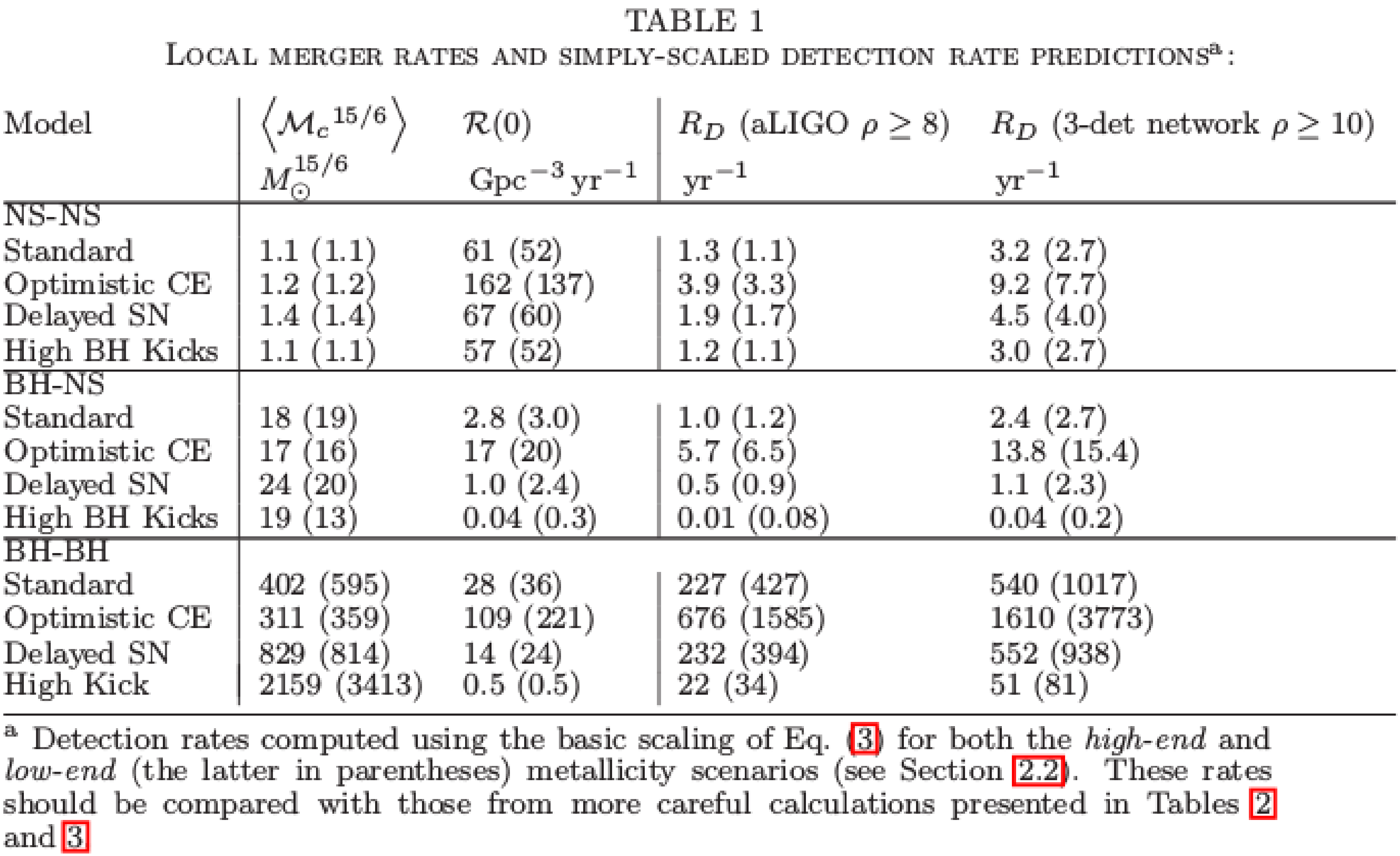


TABLE 1

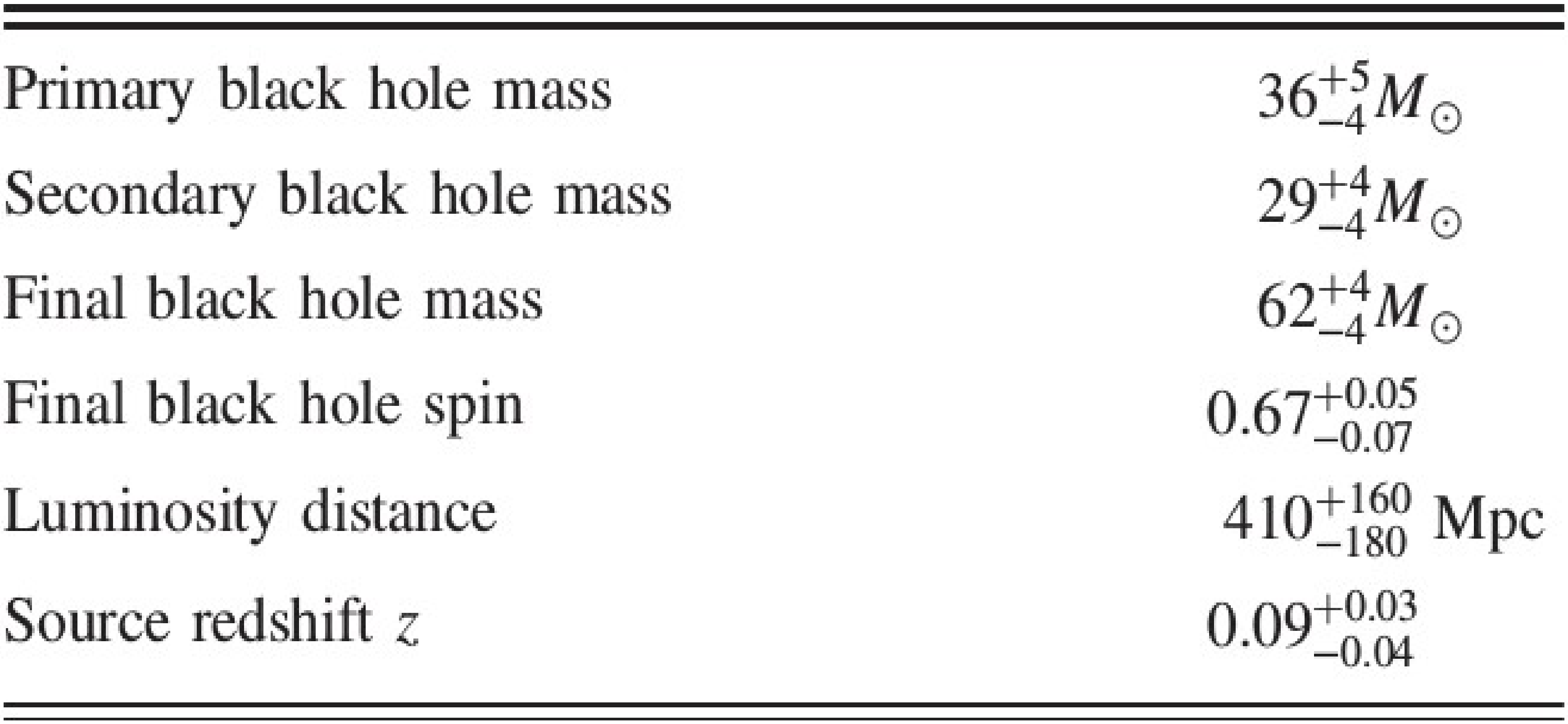
LOCAL MERGER RATES AND SIMPLY-SCALED DETECTION RATE PREDICTIONS[a]:

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