The astrophysical origin of GW150914

Tomek Bulik
University of Warsaw

with
Chris Belczynski, Michal Dominik, Dan Holz, Richard O' Shaughenessy, Mirek Giersz, Dorota Rosinska, Grzegorz Wiktorowicz, Magda Szkudlarek

The recent breakthrughs

- Detection of gravitational waves
- Detection of a black hole
- Detection of black hole binary
- Evidence for BHs with masses of 30 and and up to 60 solar masses
- Possibility to test General Relativity
- Possibility to test Quantum Gravity(?)
- The brightest source ever seen in the sky:

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

Where does it fit into broad astrophysical picture?

- Evolution of binaries in the field
- Formation in dense clusters
- Population III stars

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

Evolution of binaries in the field

Evolution of binaries in galaxies with typical densities. Probability of collisions between binaries negligible.

Use the *StarTrack* code:

- developed over last 18 years

- well tested to model various types of binaries

- used extensively to investigate properties of compact object binaries

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

Krzysztof Belczynski,[1,2,3,4] Vassiliki Kalogera,[1,2] and Tomasz Bulik[3]

Received 2001 November 22; accepted 2002 February 18

2002

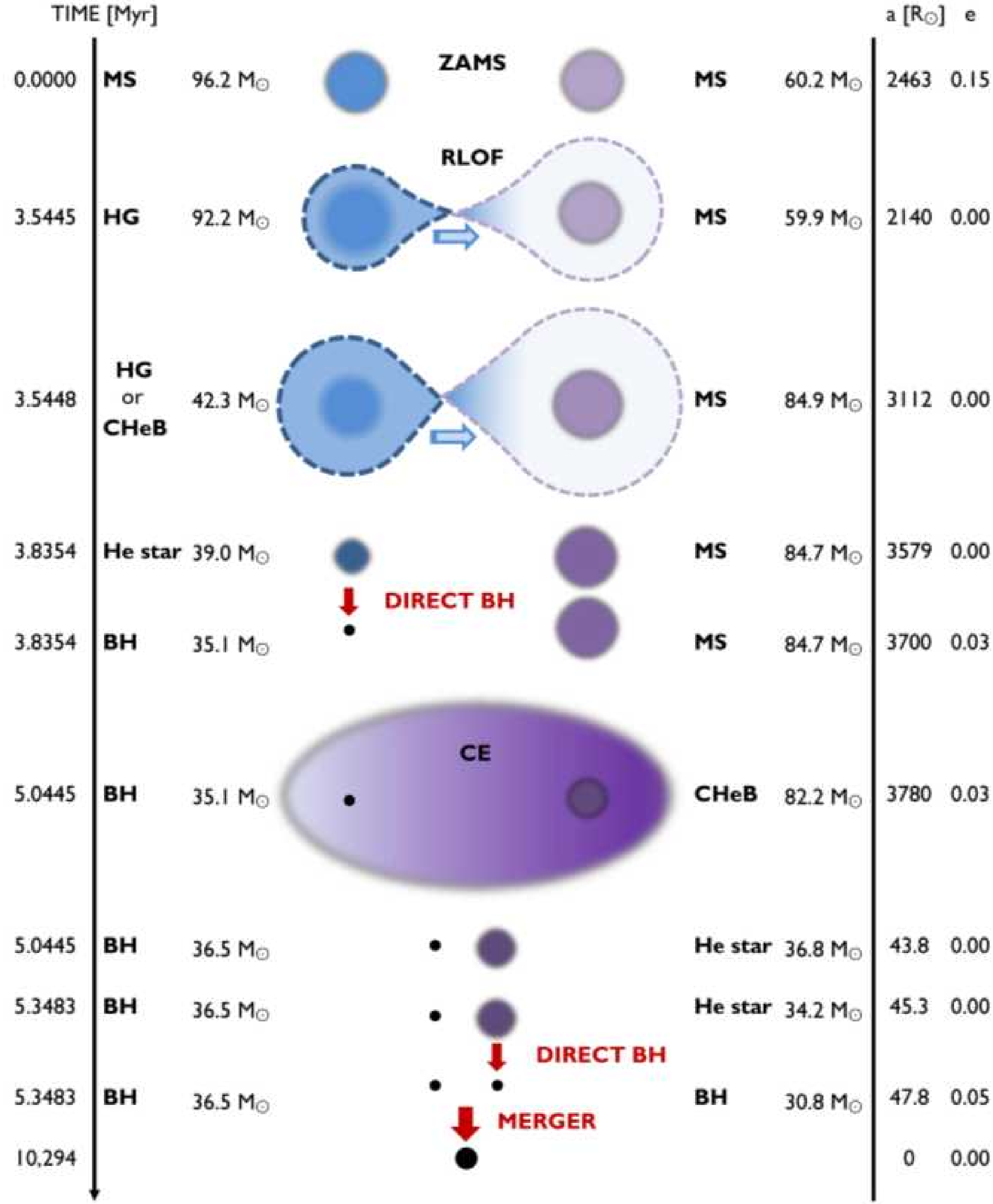
COMPACT OBJECT MODELING WITH THE STARTRACK POPULATION SYNTHESIS CODE

Krzysztof Belczynski,[1,2] Vassiliki Kalogera,[3] Frederic A. Rasio,[3] Ronald E. Taam,[3] Andreas Zezas,[4] Tomasz Bulik,[5] Thomas J. Maccarone,[6,7] and Natalia Ivanova[8]

Received 2005 November 29; accepted 2007 May 28

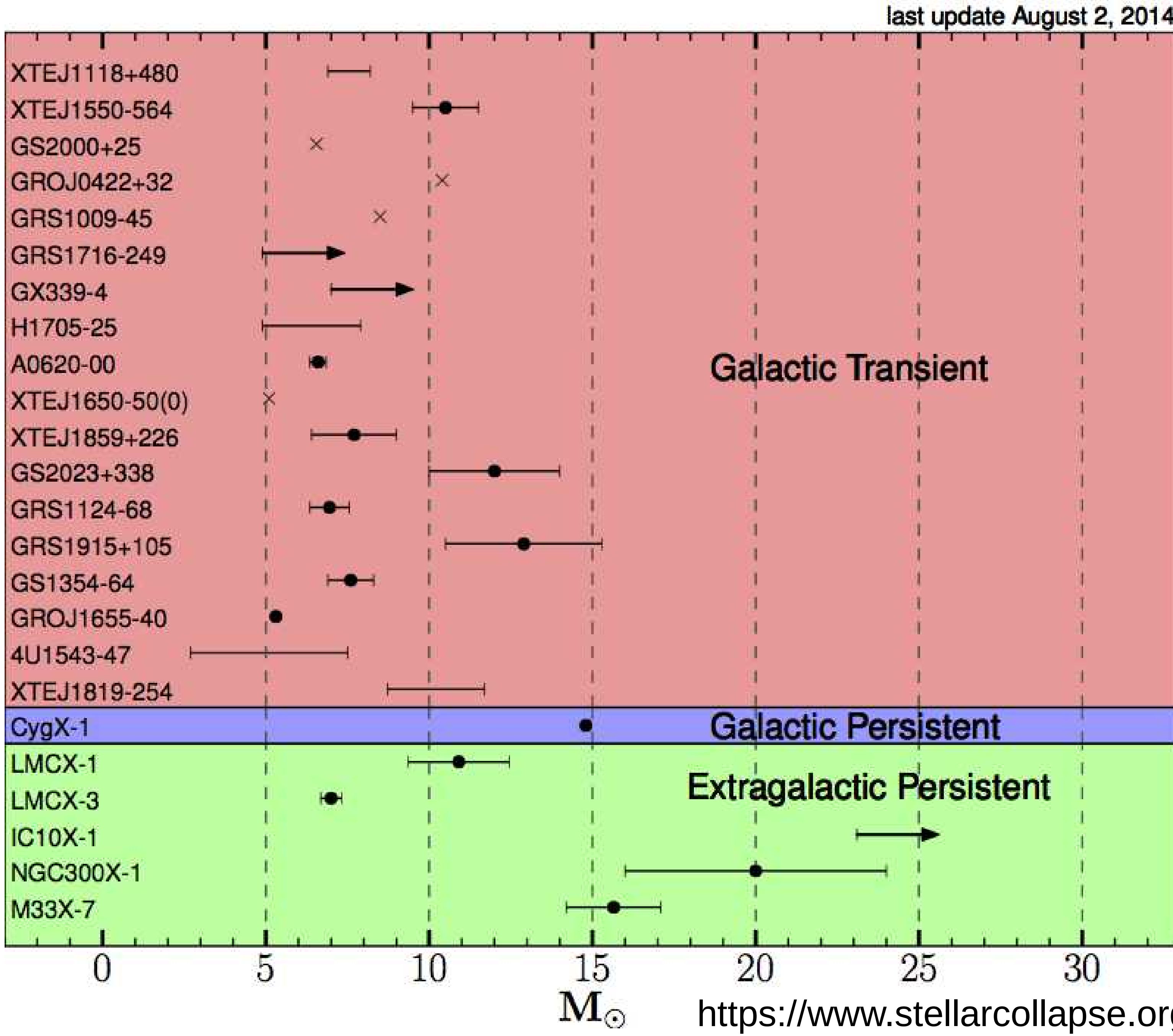
2008

Evolutionary scenario



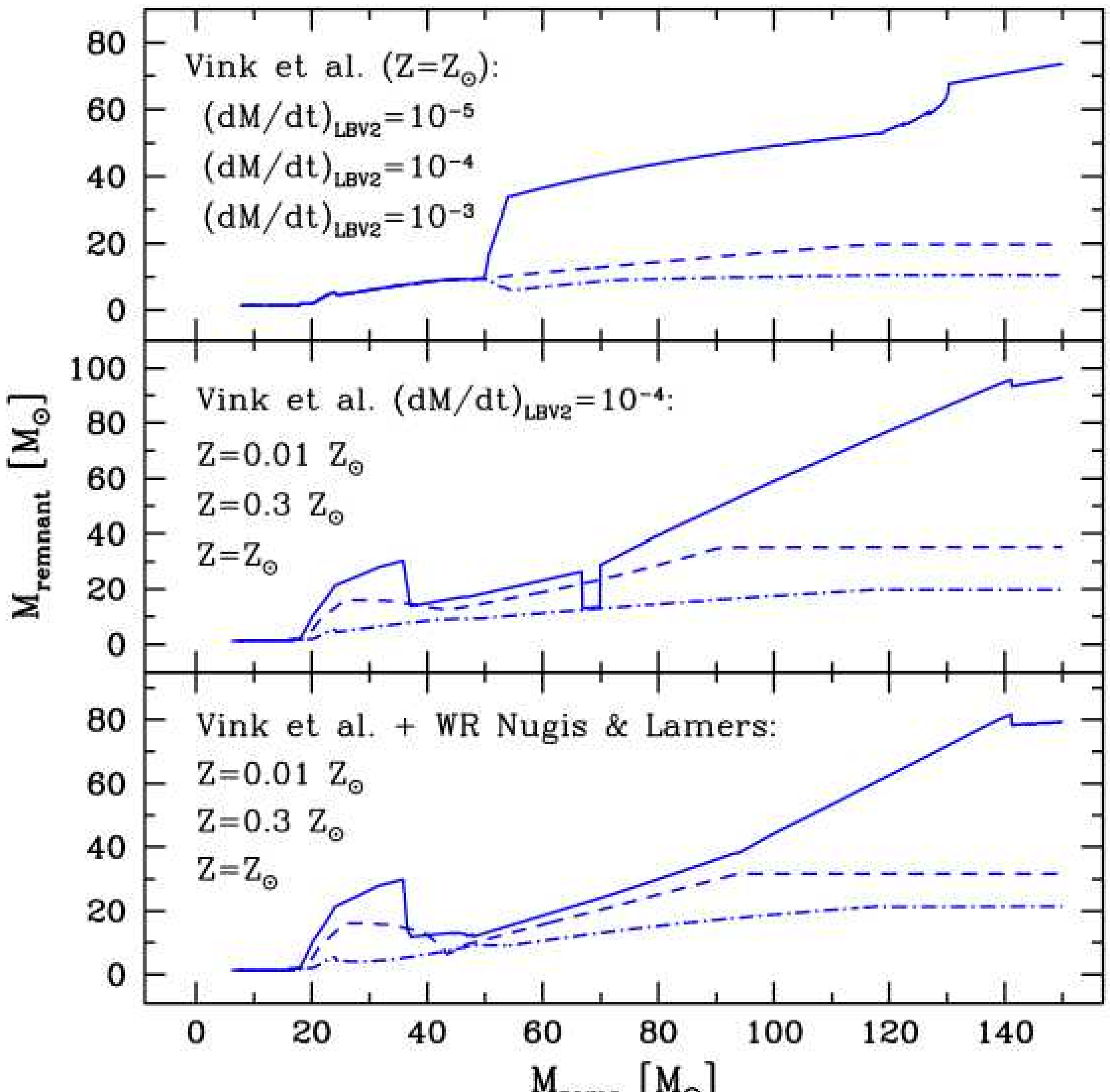
Credit: Wojtek Gładysz

BH formation: masses and kicks



https://www.stellarcollapse.org/bhmasses

Black hole masses



Black holes with masses up to 80 solar masses can form easily in low metallicity environment

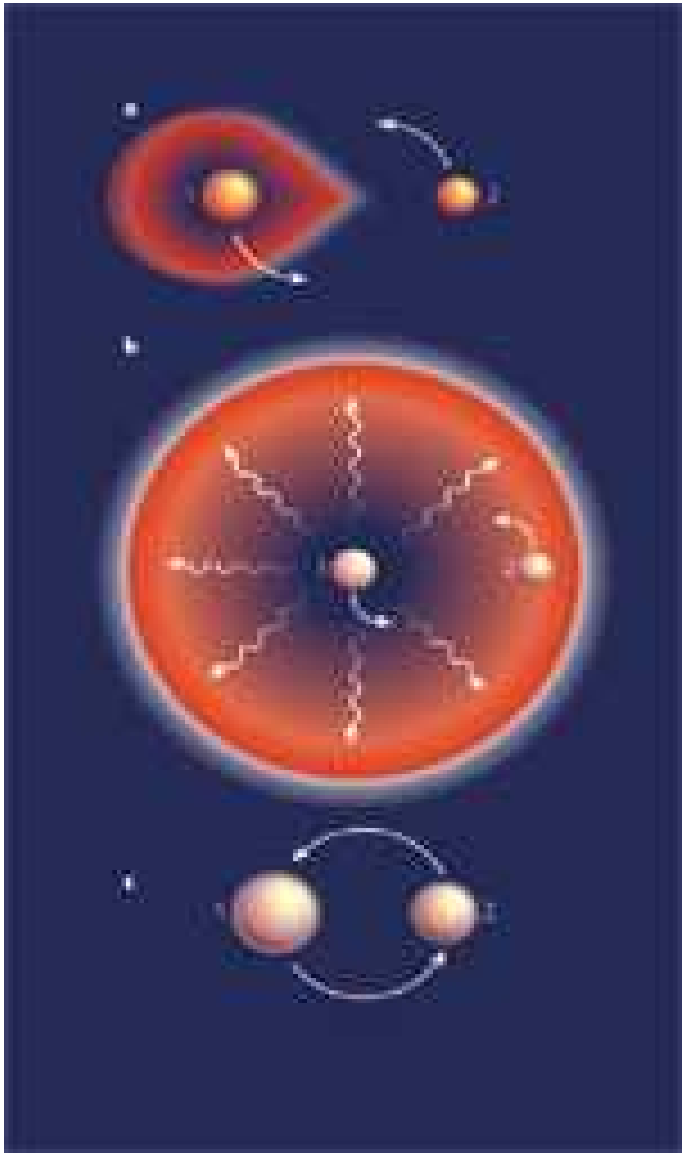
BH formation kicks

- Neutron star receive kicks, do black holes?
- X-ray binary selection effects
- Theoretical expectations
- Influence on the formation scenario
- Kicks quench formation of BHBH binaries
  - Note that it is the first kick that counts, the second can be large

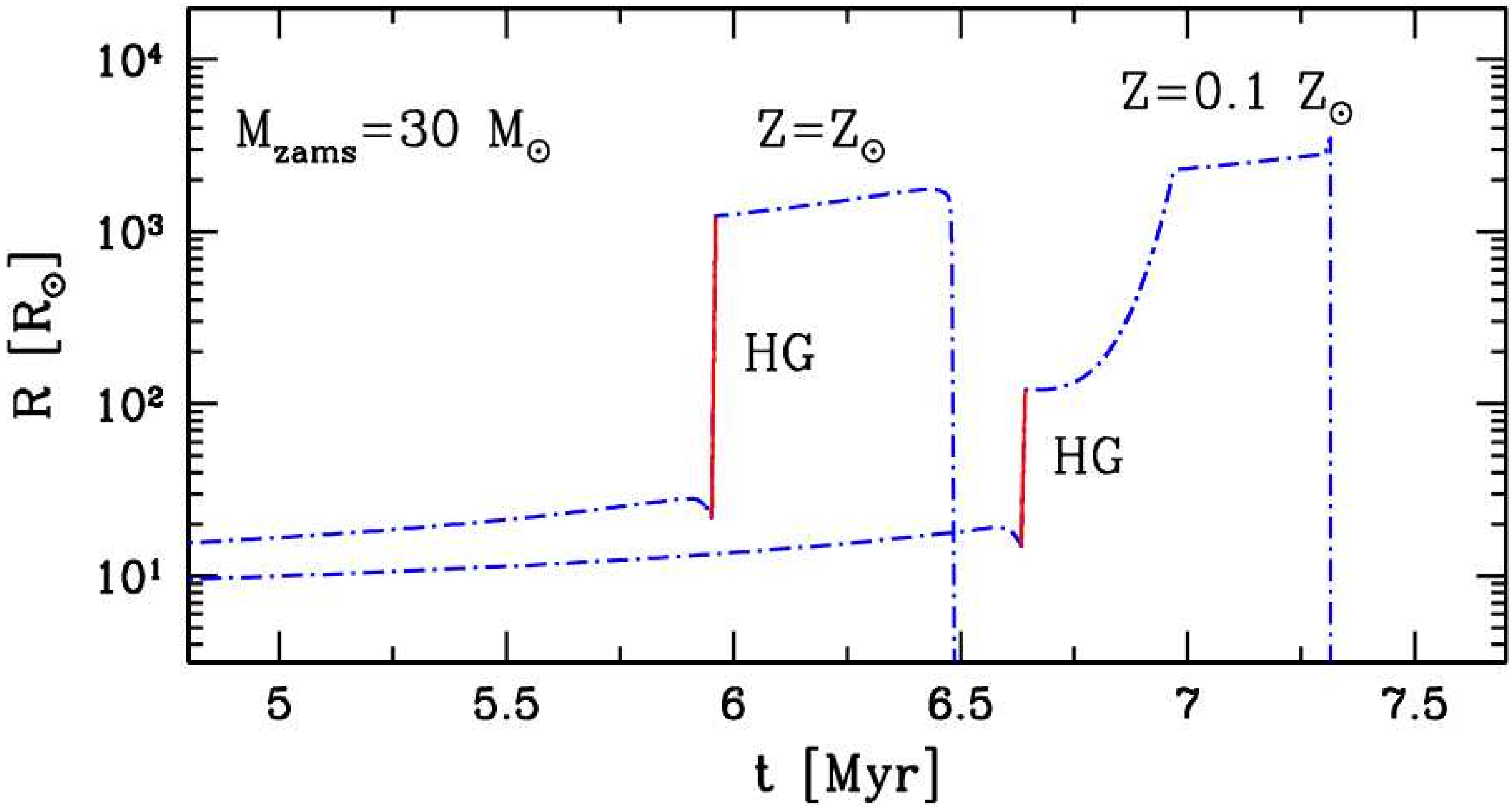
Common envelope

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

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

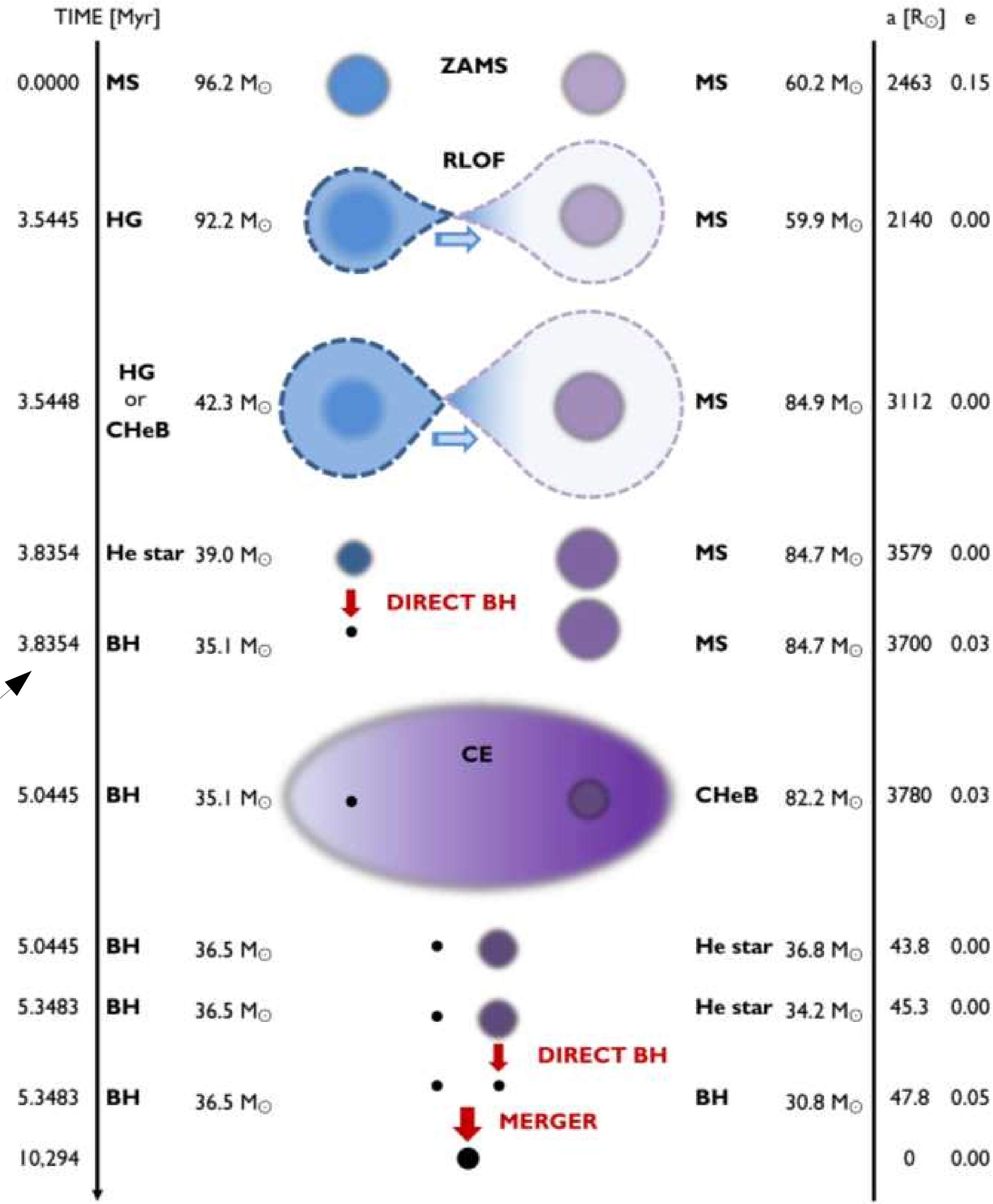


The role of metallicity in common envelope



Low metallicity star are typically smaller. Hertzsprung Gap smaller

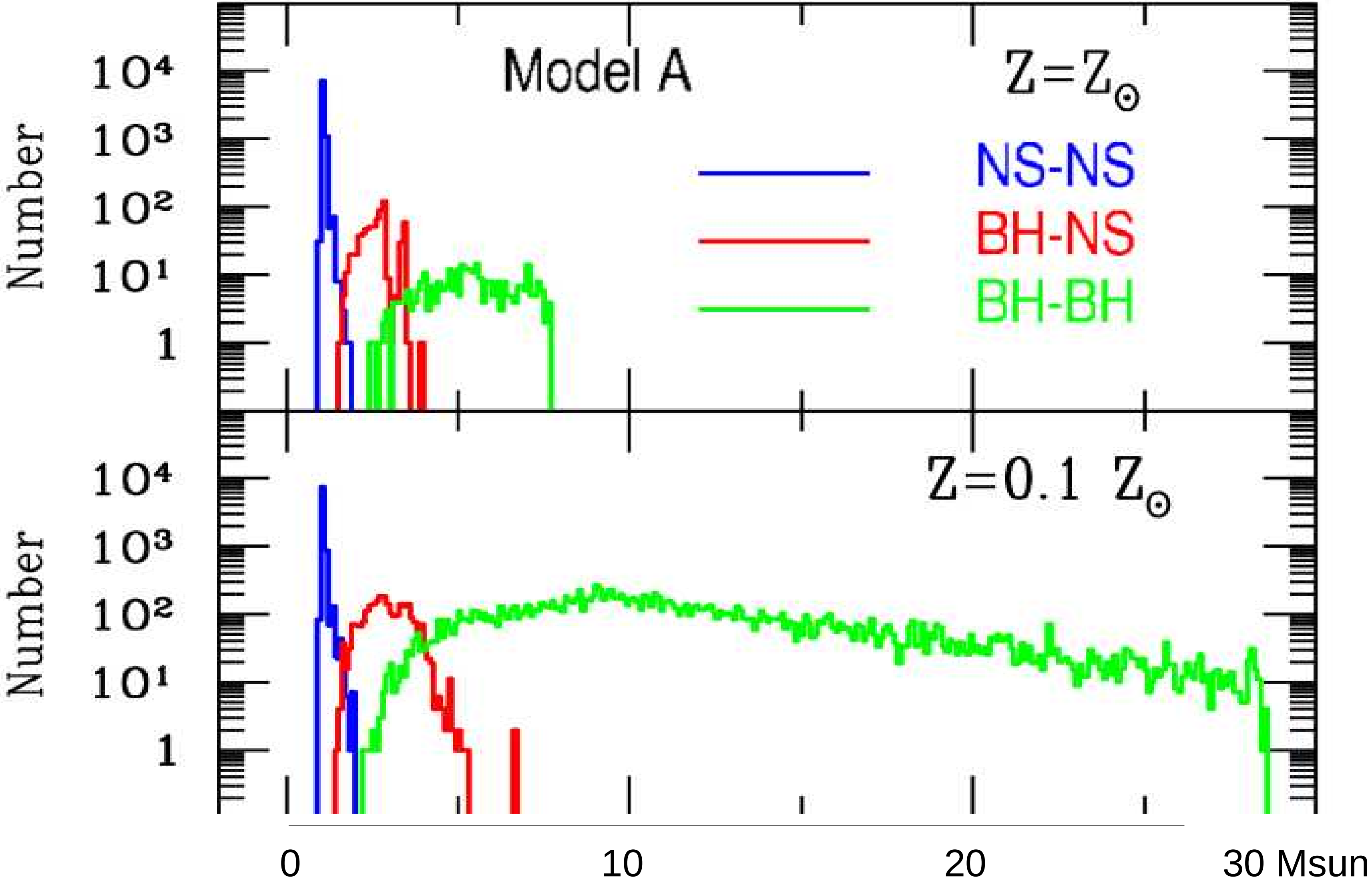
Metallicity is crucial for formation of binary BHs



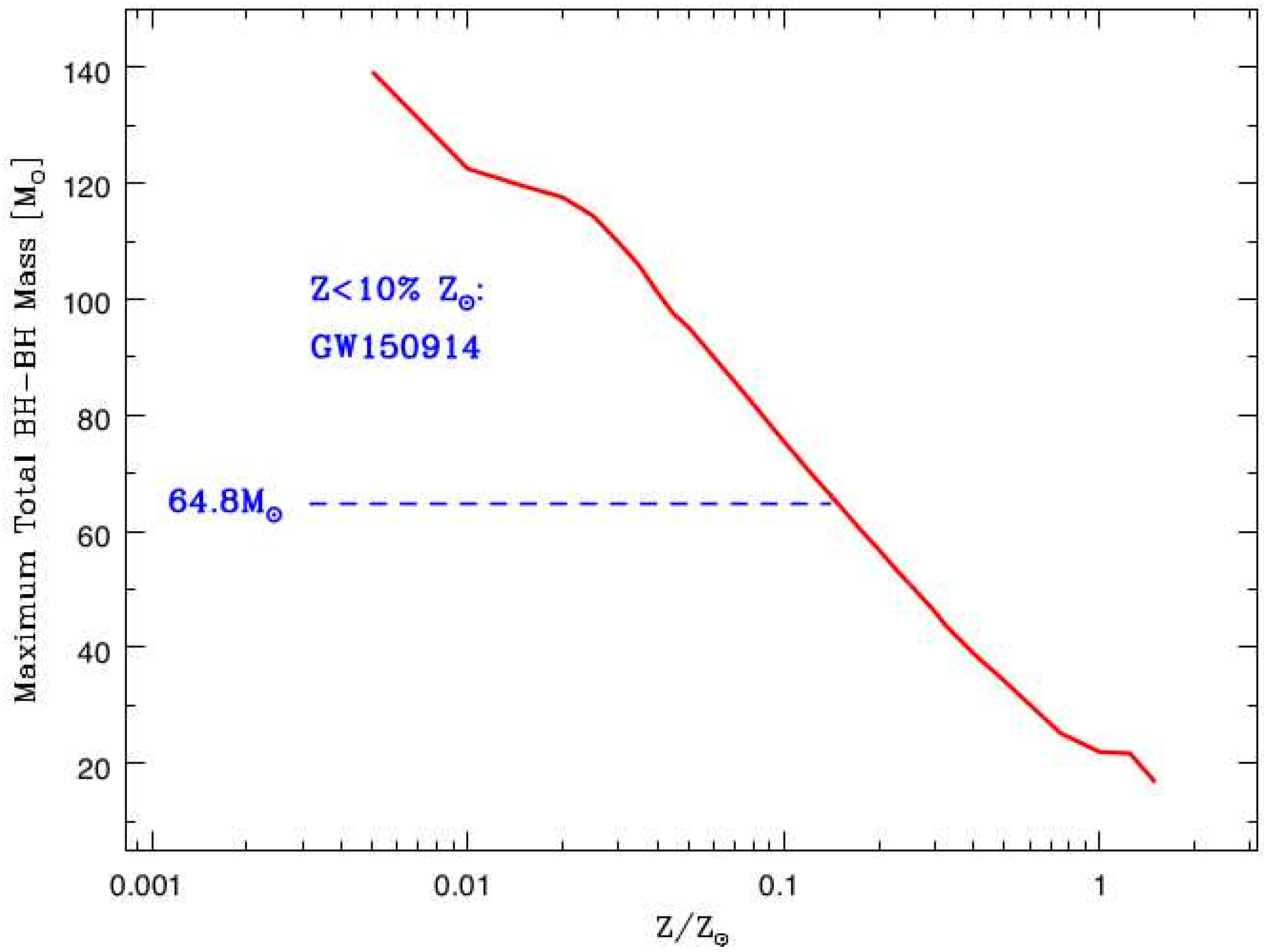
CE survival

BH masses

BHBH enhancement in low Z



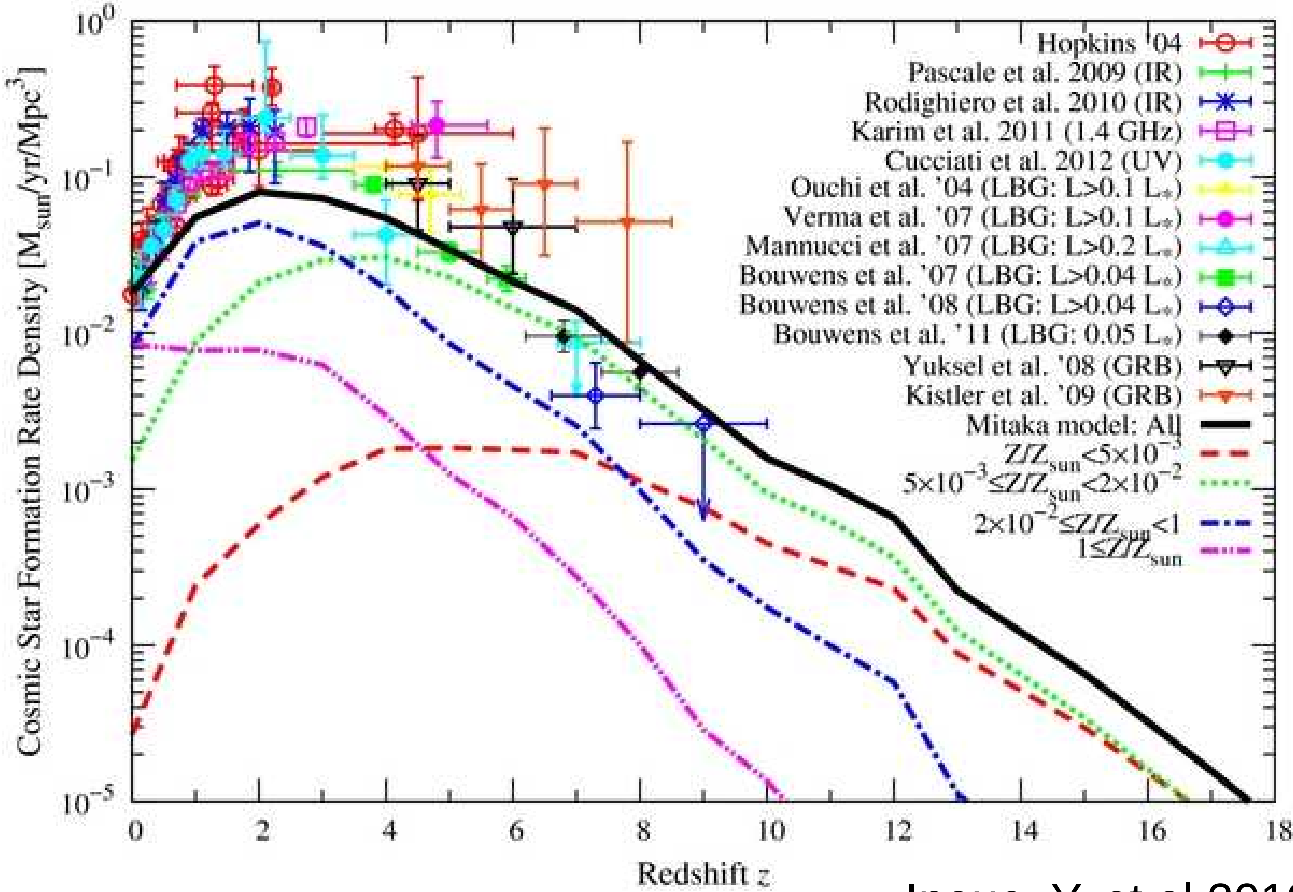
Maximum BHBH mass



GW150914 progenitors were low metallicity Z<10% Zsun.

What does it take to estimate the rates

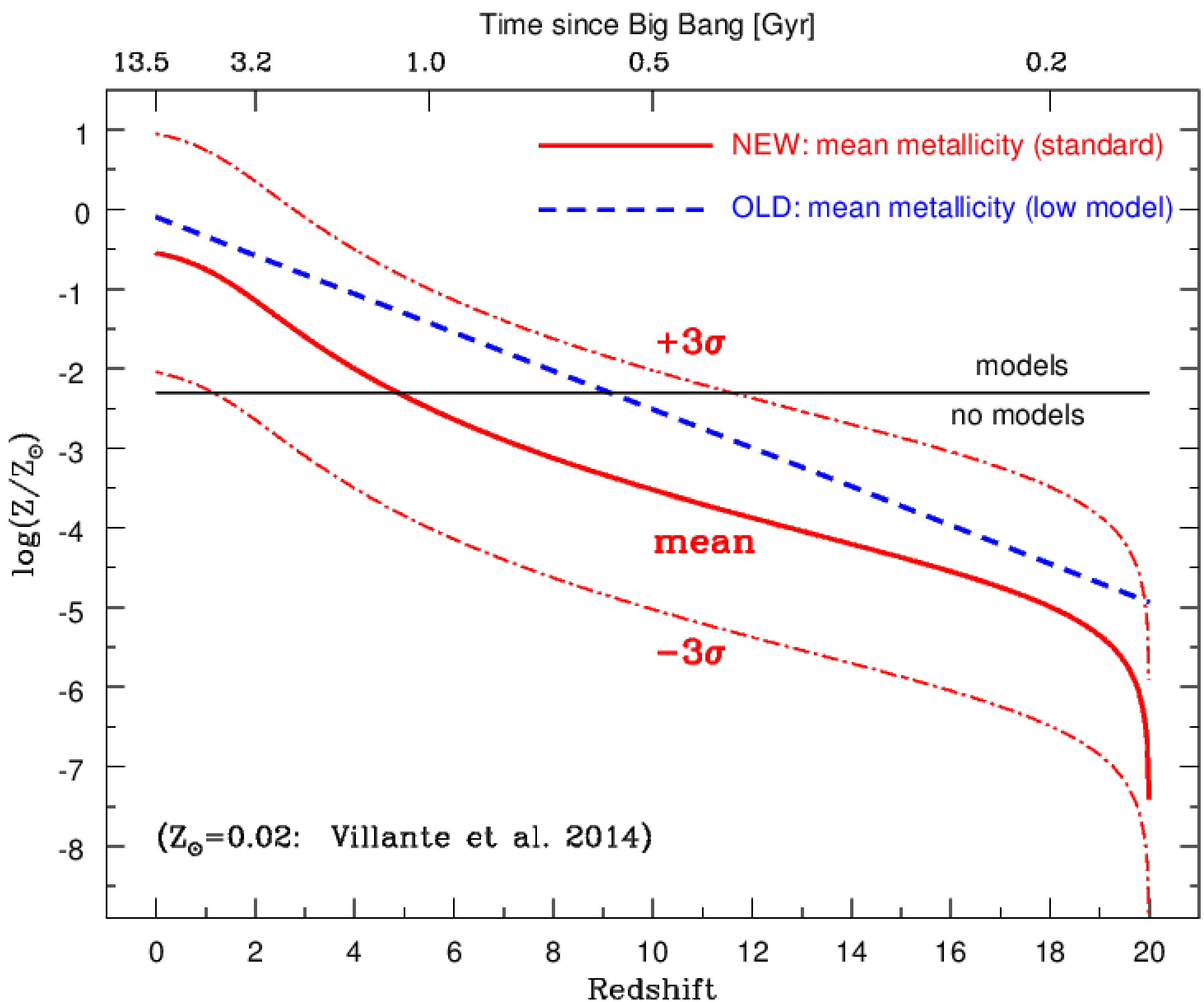
- SFR history
- Metallicity composition history
- Formation of BHBH, delays
- Remember about redshifting masses



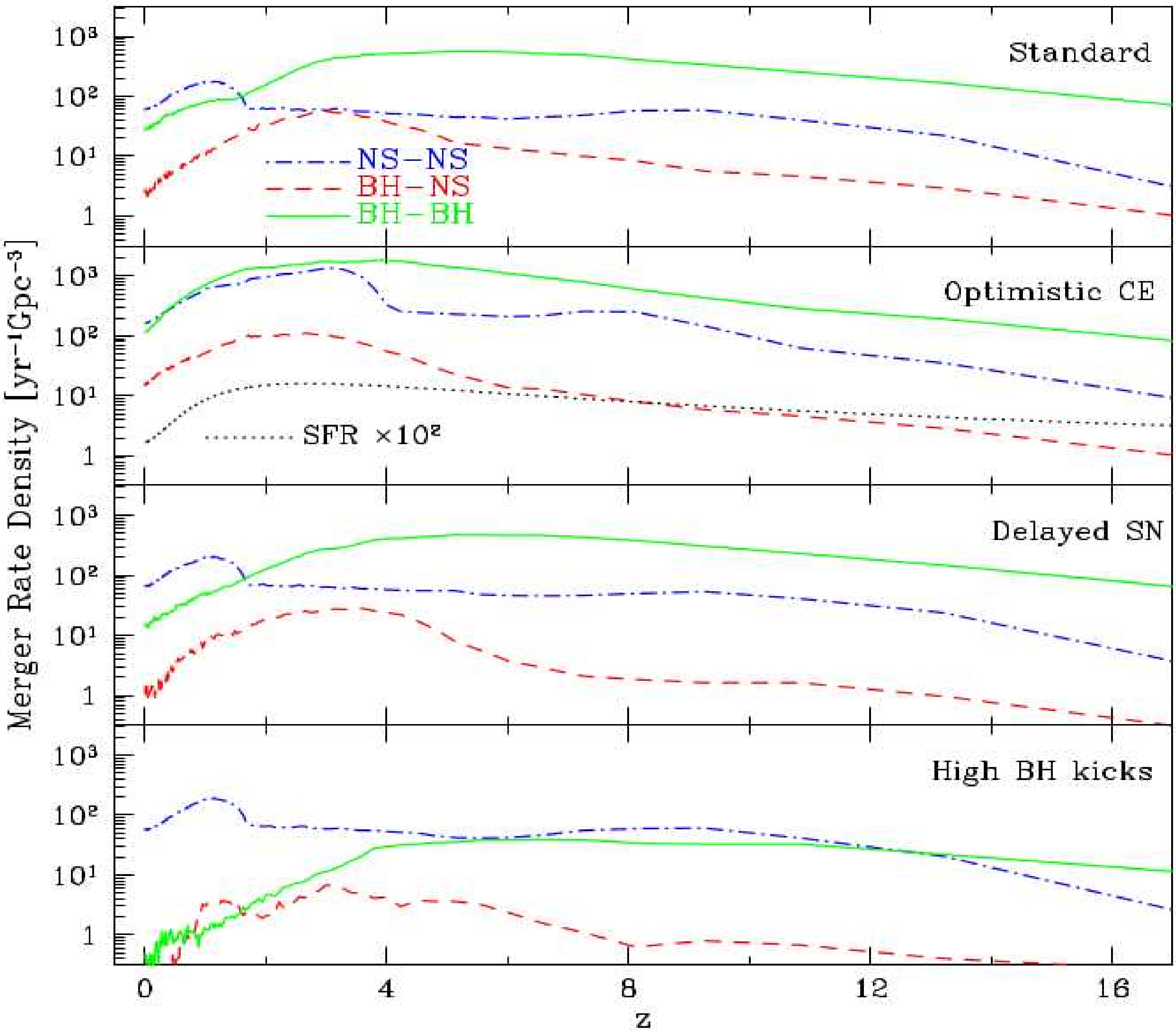
Inoue, Y, et al 2013

Binary → Formation of BBH → Delay → Merger → GW propagation → Observer

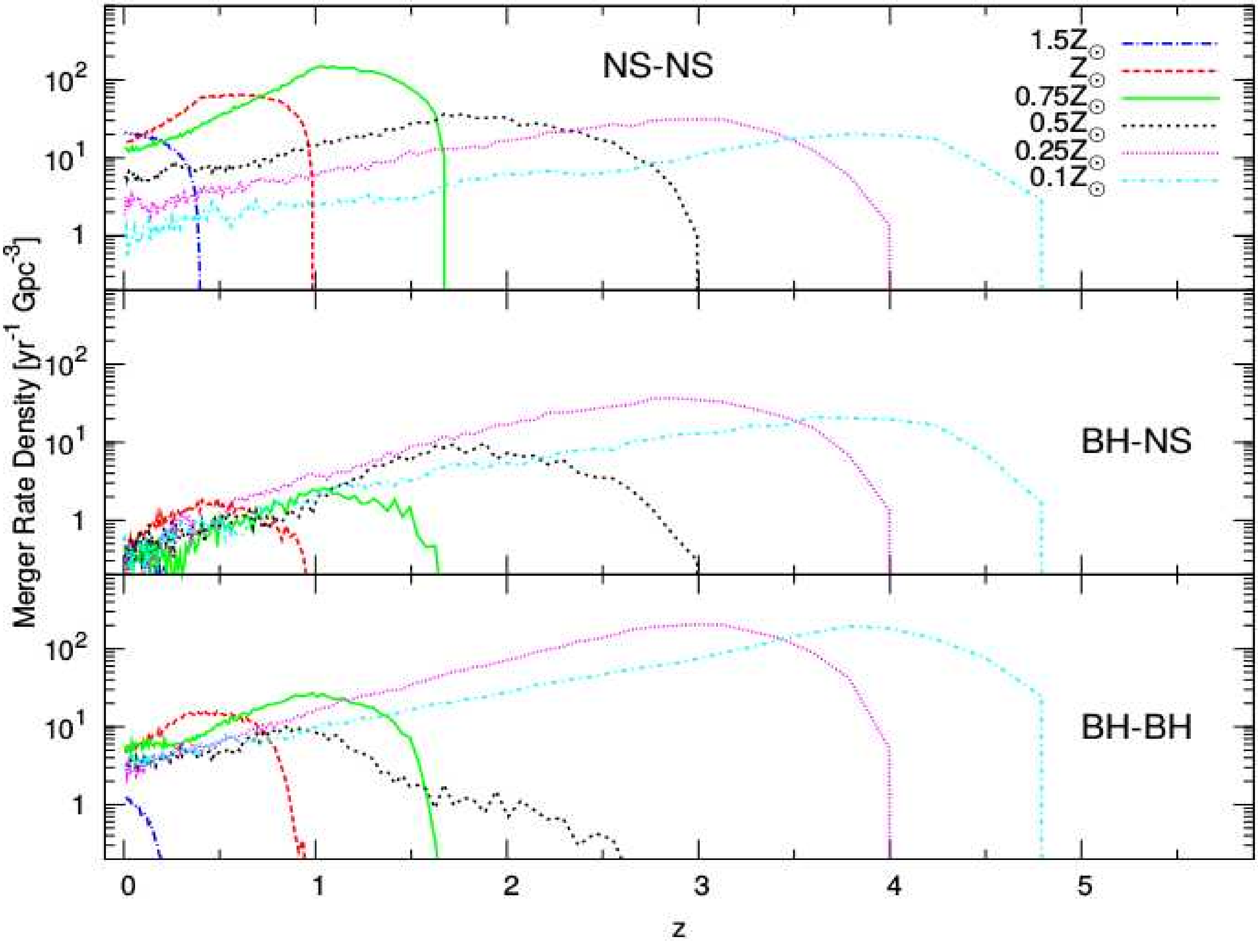
Metallicity evolution model



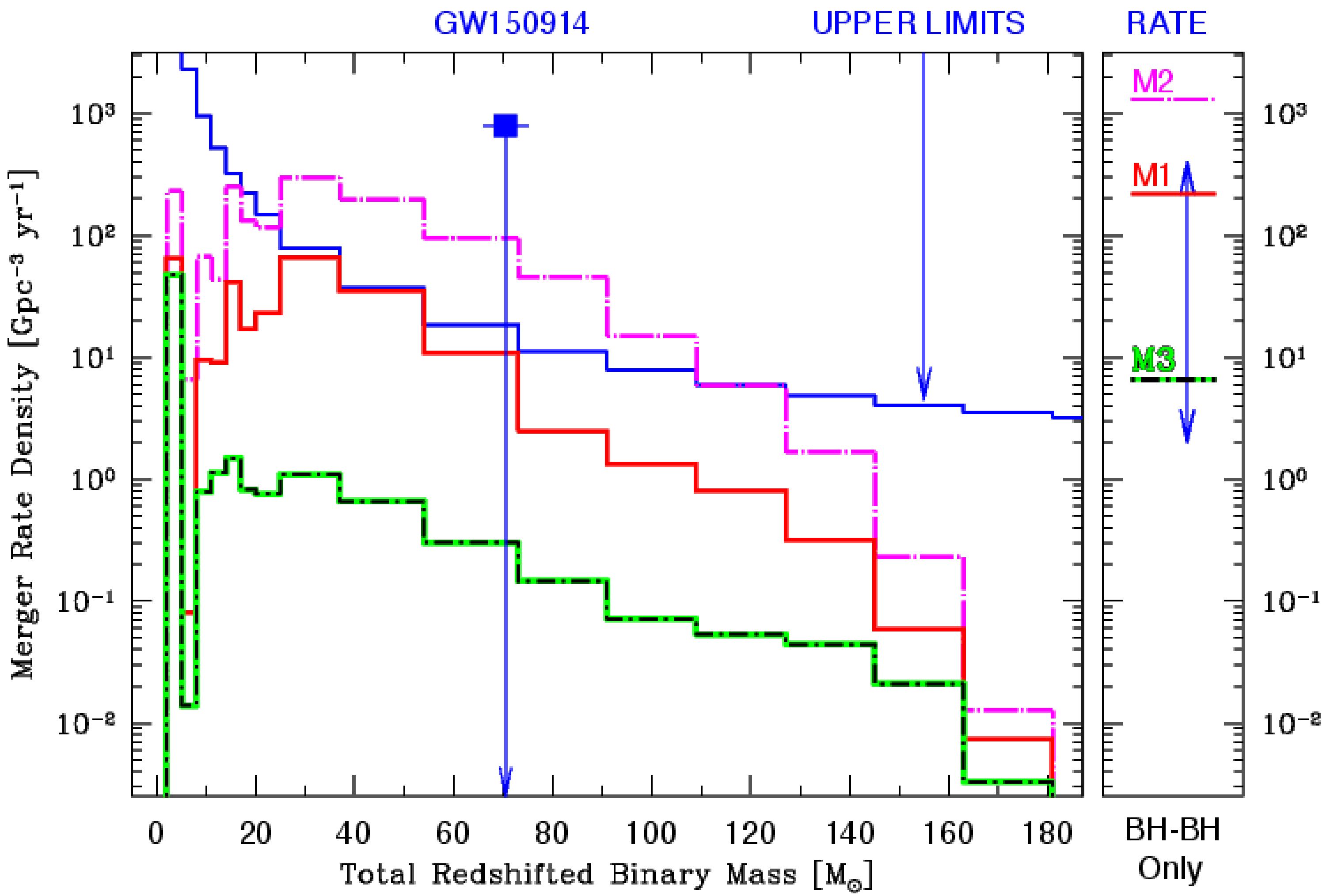
Merger rate density history



Merger rate history - metallicity



Expected mass distribution



When was it formed

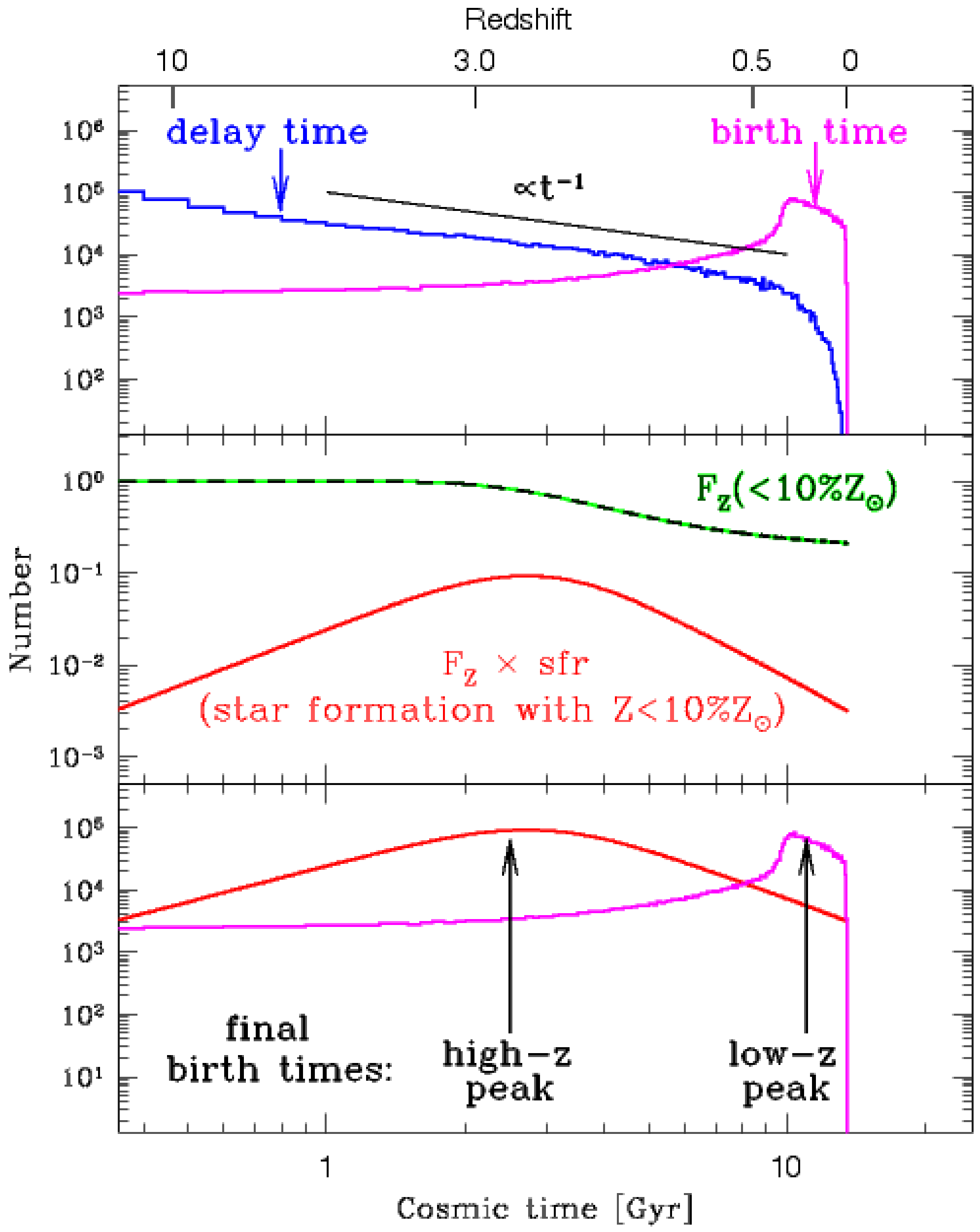
A combination of:

- metallicity evolution
- delay times

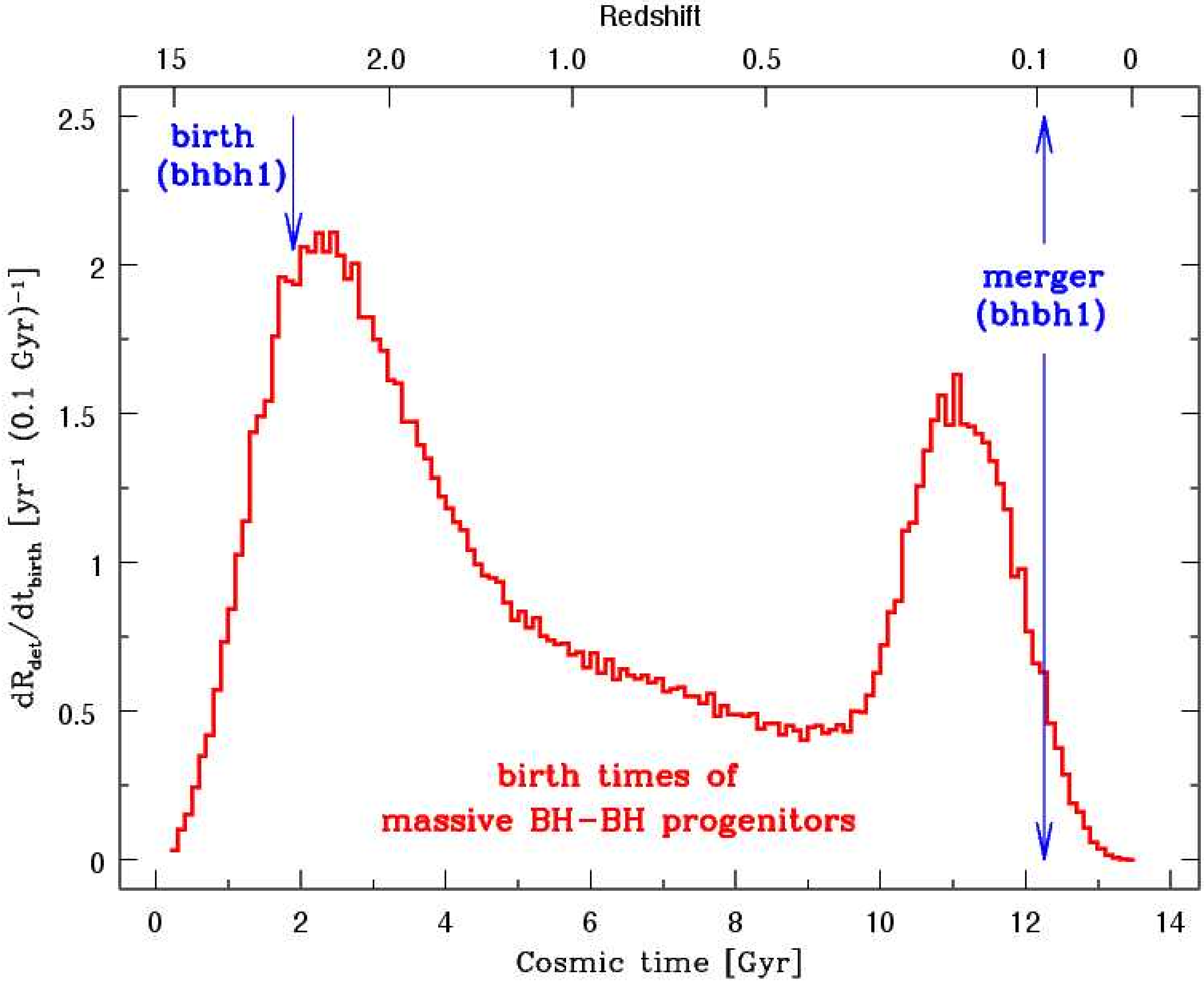
Two possible scenarios

Recent event

Very old event



Formation time probability



Progenitors?

IC10 X-1

- *MBH=23-33 Msun???*
- M_{WR}=17-35 Msun
- P=35h
- Host metallicity=0.3

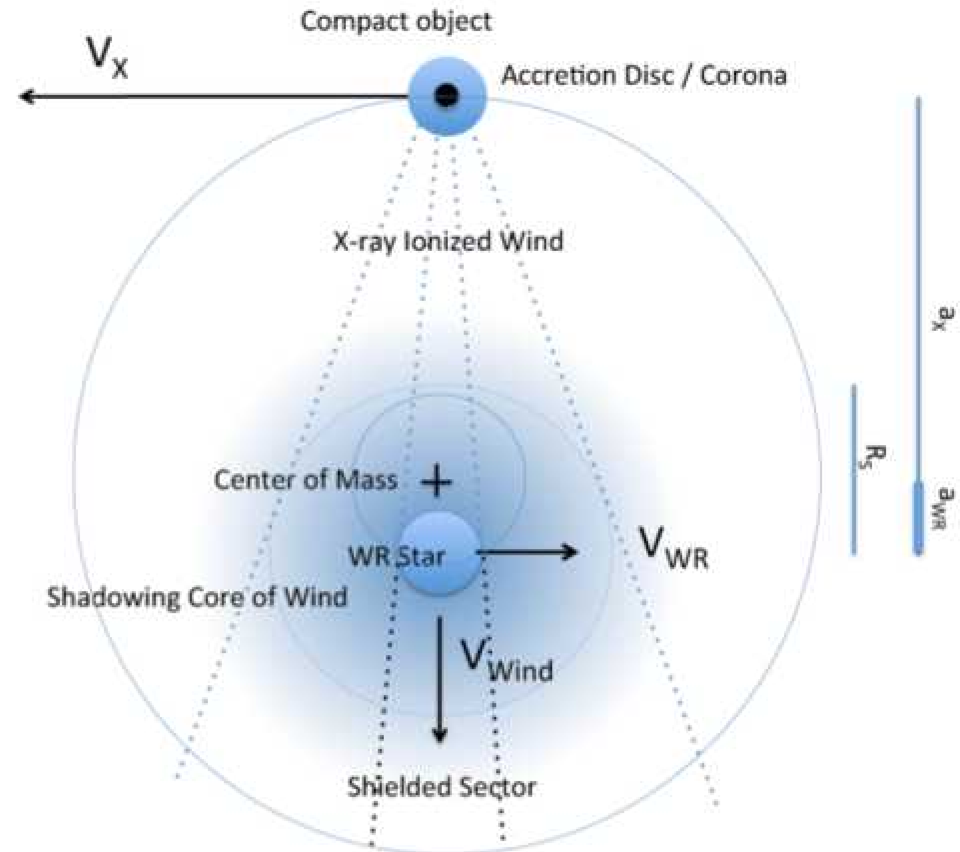
NGC300 X-1

- M_{BH}=14.5-20 Msun
- M_{WR}=15-26 Msun
- P=32h
- Host metallicity=0.6

Tight binaries with a massive BH(??) accreting from a WR star in a low metallicity region

On the nature of the compact object in IC10 X-1

- The role of ionized wind
- X-ray eclipses vs. Velocity proile
- Radial velocity vs wind velocity
- Observations point toward a low mass object
- Looks like that is not it, but



PS. Winds also play a significant role in NGC300 X-1 (Binder et al. 2015)

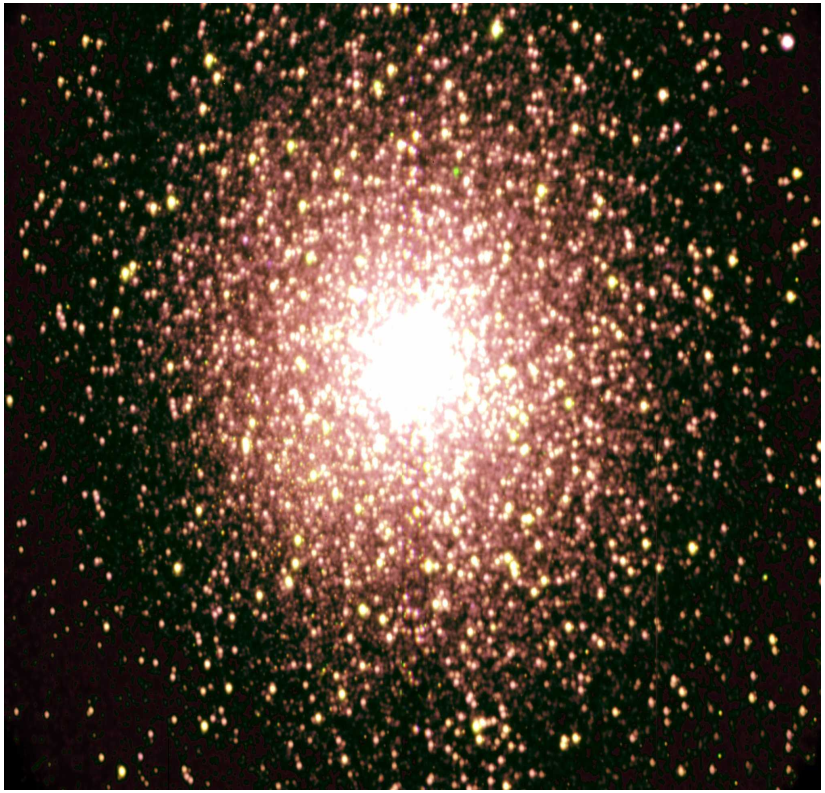
Origin of IC10 X-1

- Analysis of population of binaries in 0.3Zsun environment.
- Companions of 17Msun WR, accreting,
- Could not find a single system with a low mass companion
- Only BHs in the mass range 18-22 Msun
- Is there something more to the story?

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

Globular cluster origin



→ BH – BH ?

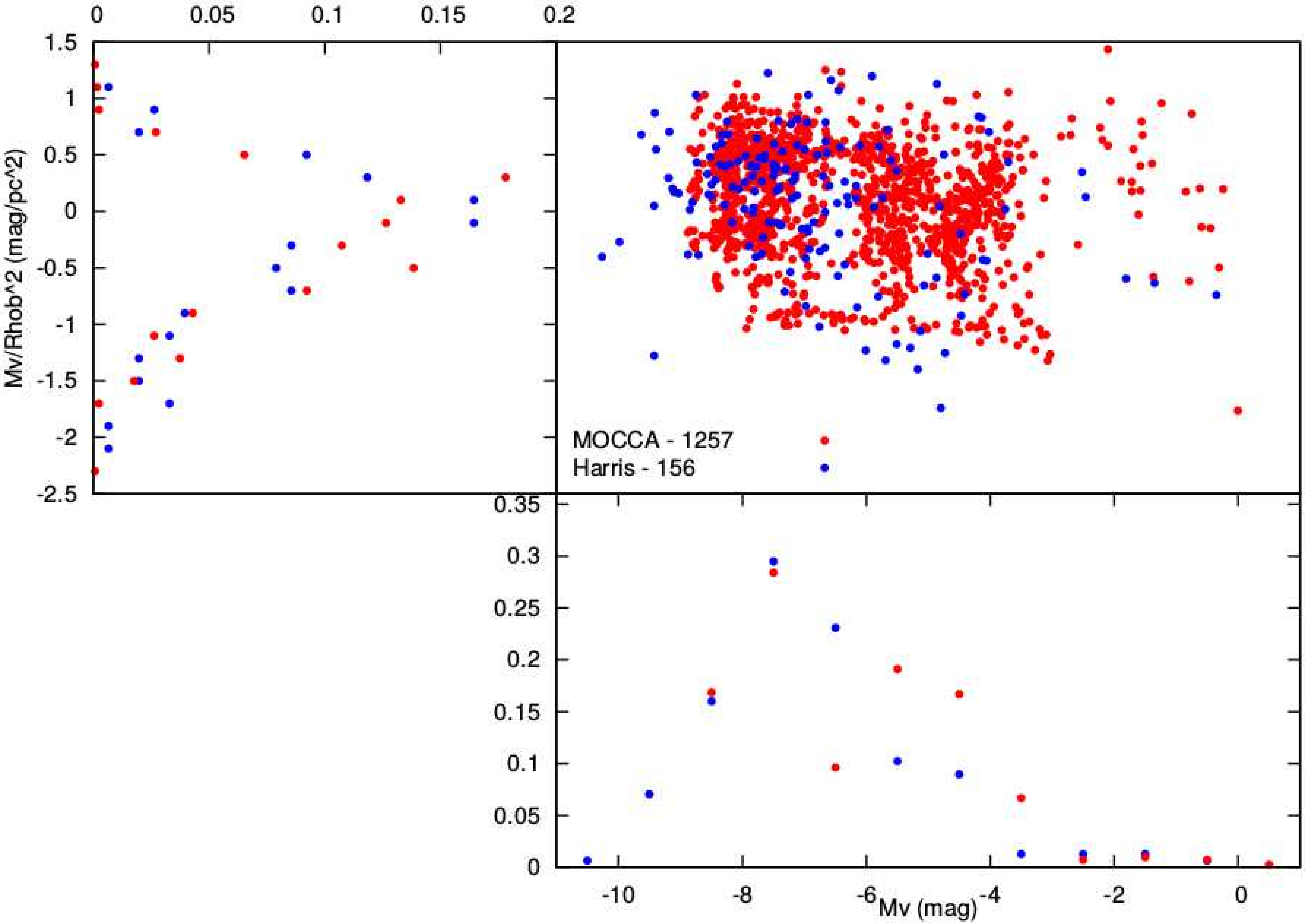
Code description

- 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

Model vs Milky Way GCs

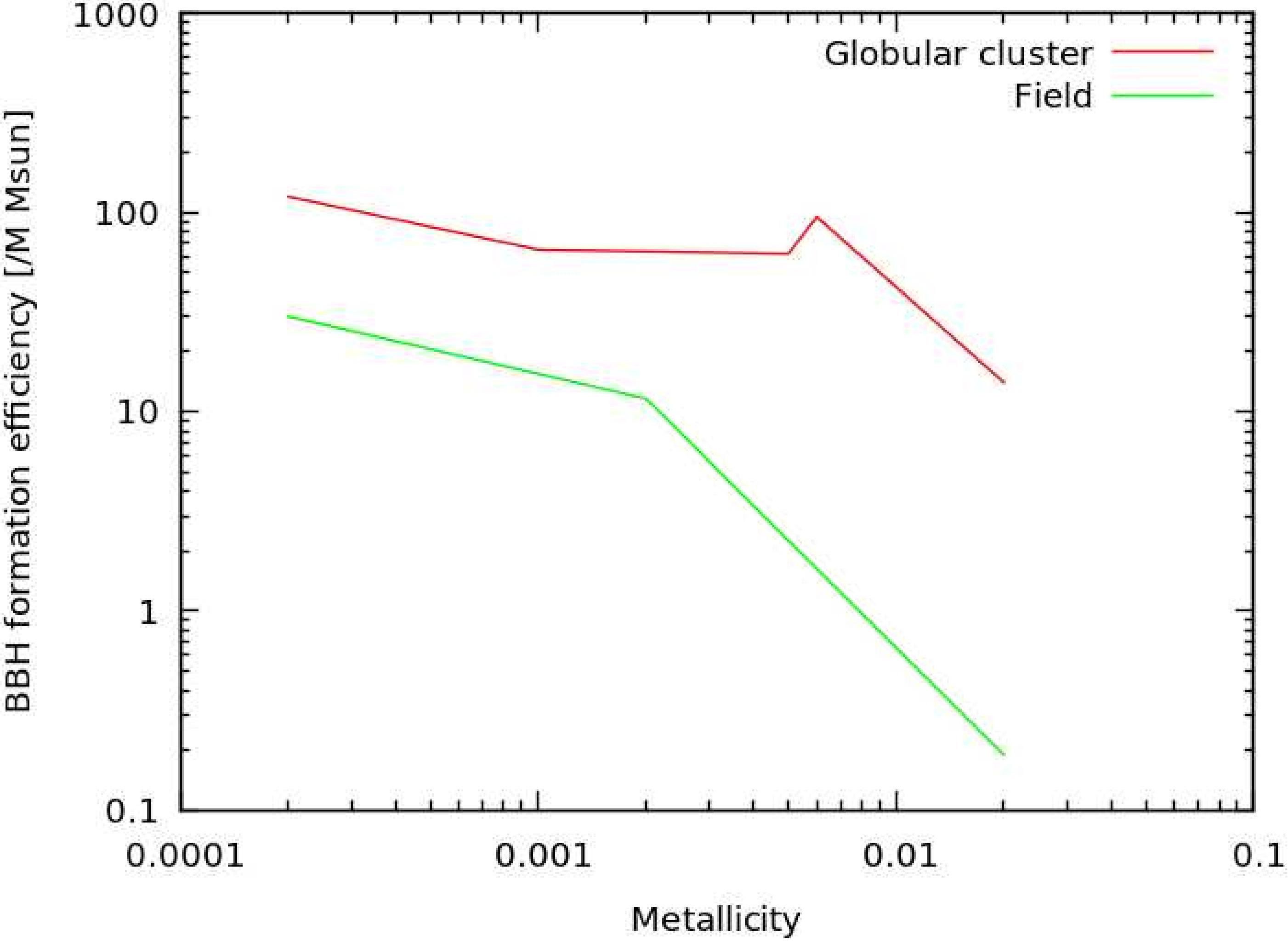


Results

- Paths to BHS
  - Escaping binaries (dominating)
  - Induced mergers inside GC
- Mass distribution
- BH production efficiency

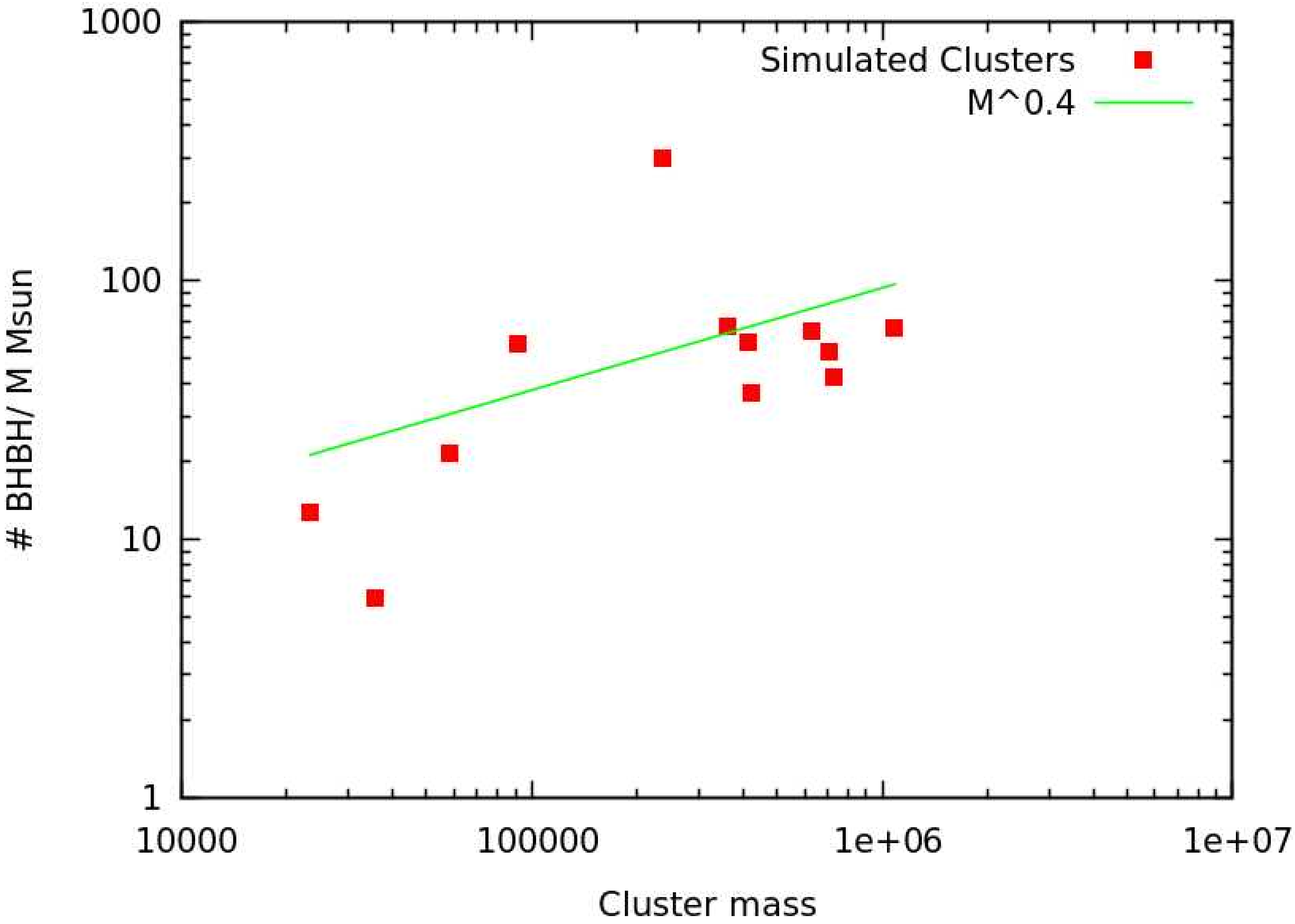
BH production efficiency

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

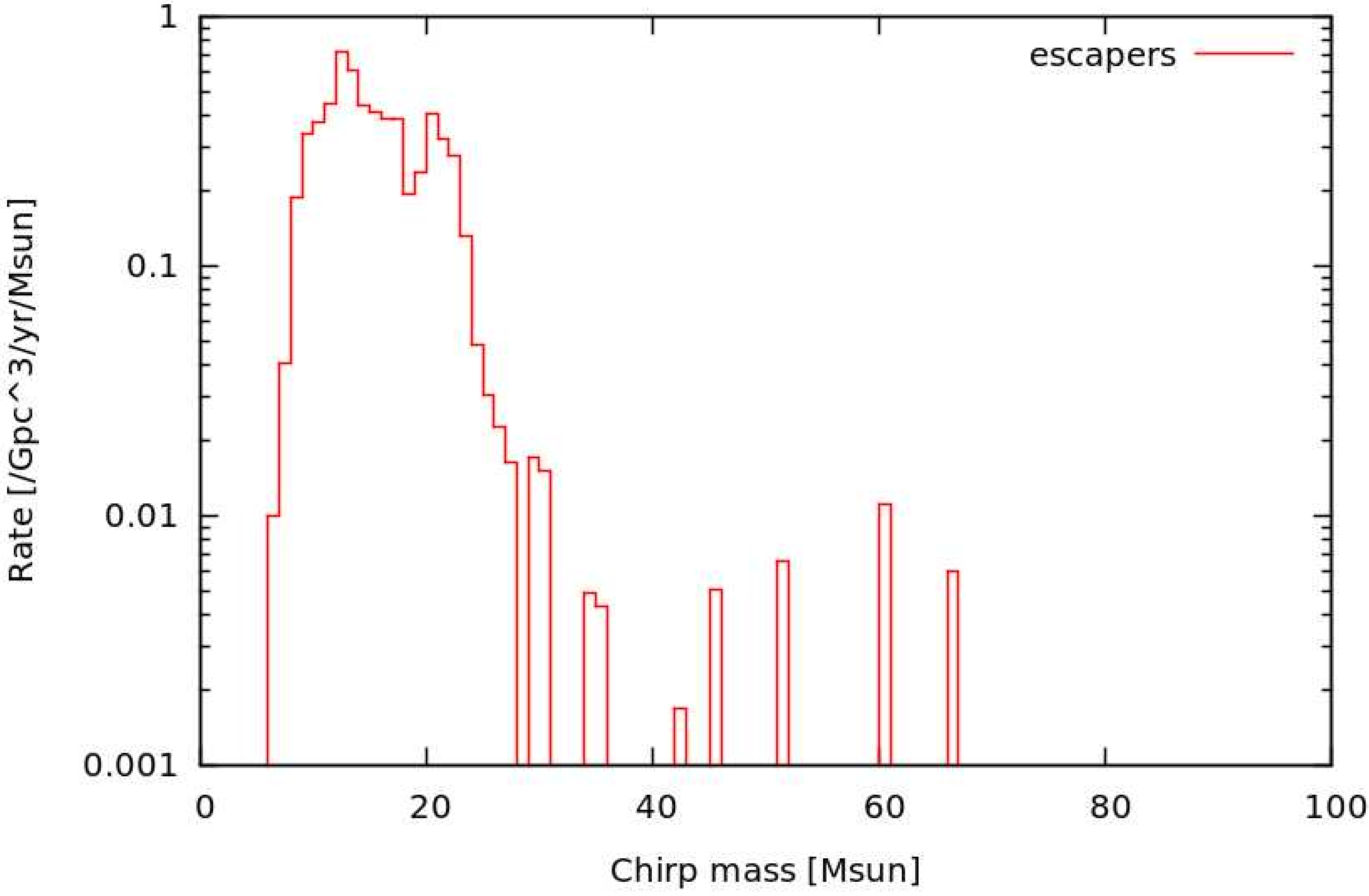


Dependence on the cluster mass

Z=0.001 (5% Zsun)

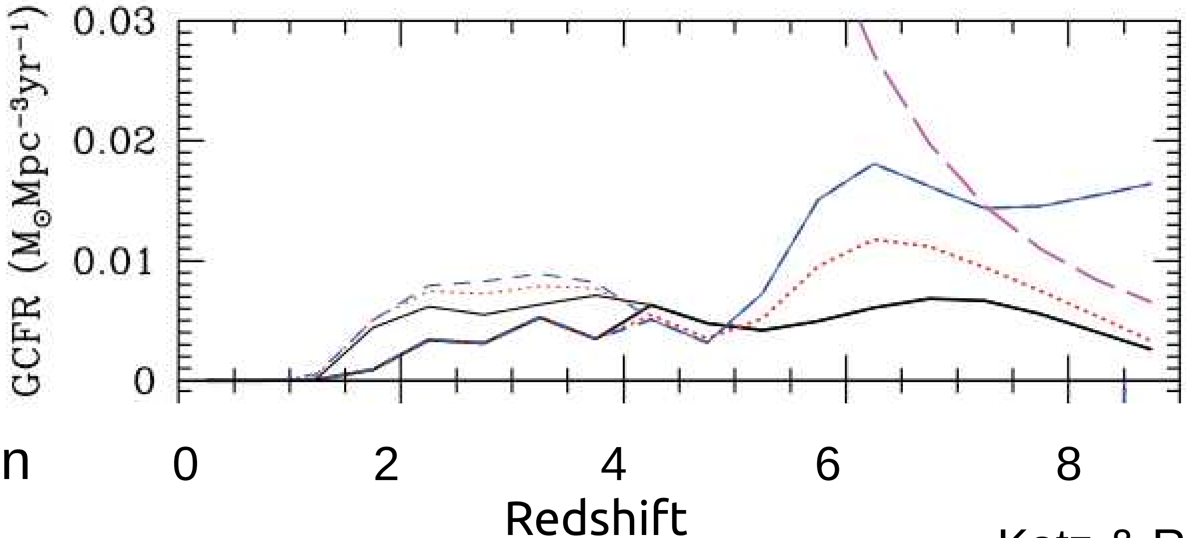


The dominant contribution – escaping BHBH



Merger rates in clusters

- GC cluster formation rate



Katz & Ricotti 2013

- GC mass composition
- GC metallicity
- Total merger rate $6.5 - 20\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Systematic uncertainties to be understood

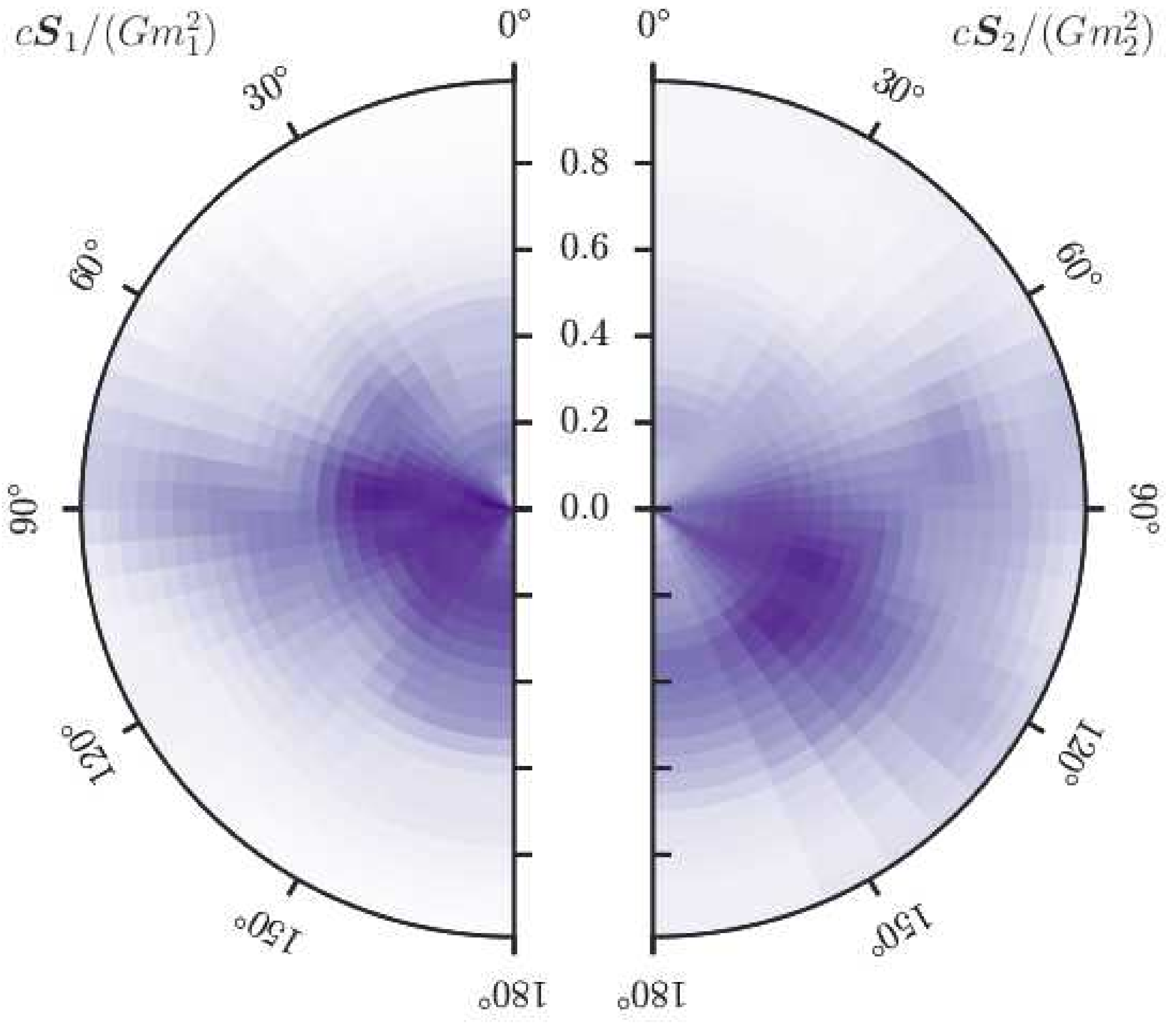
Second set of conclusion

- GC population also a likely origin
- Mass distribution consistent with observations
- Rates are in the low end of the observed values
  - Depends o assumptions on cluster mass and metallicity distribution
- Predict a tail of higher mass object merging inside clusters

Field vs GC

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

Basic parameters: spins



Spin evolution

Initial spins

Accretion, possible alignement of spin 2

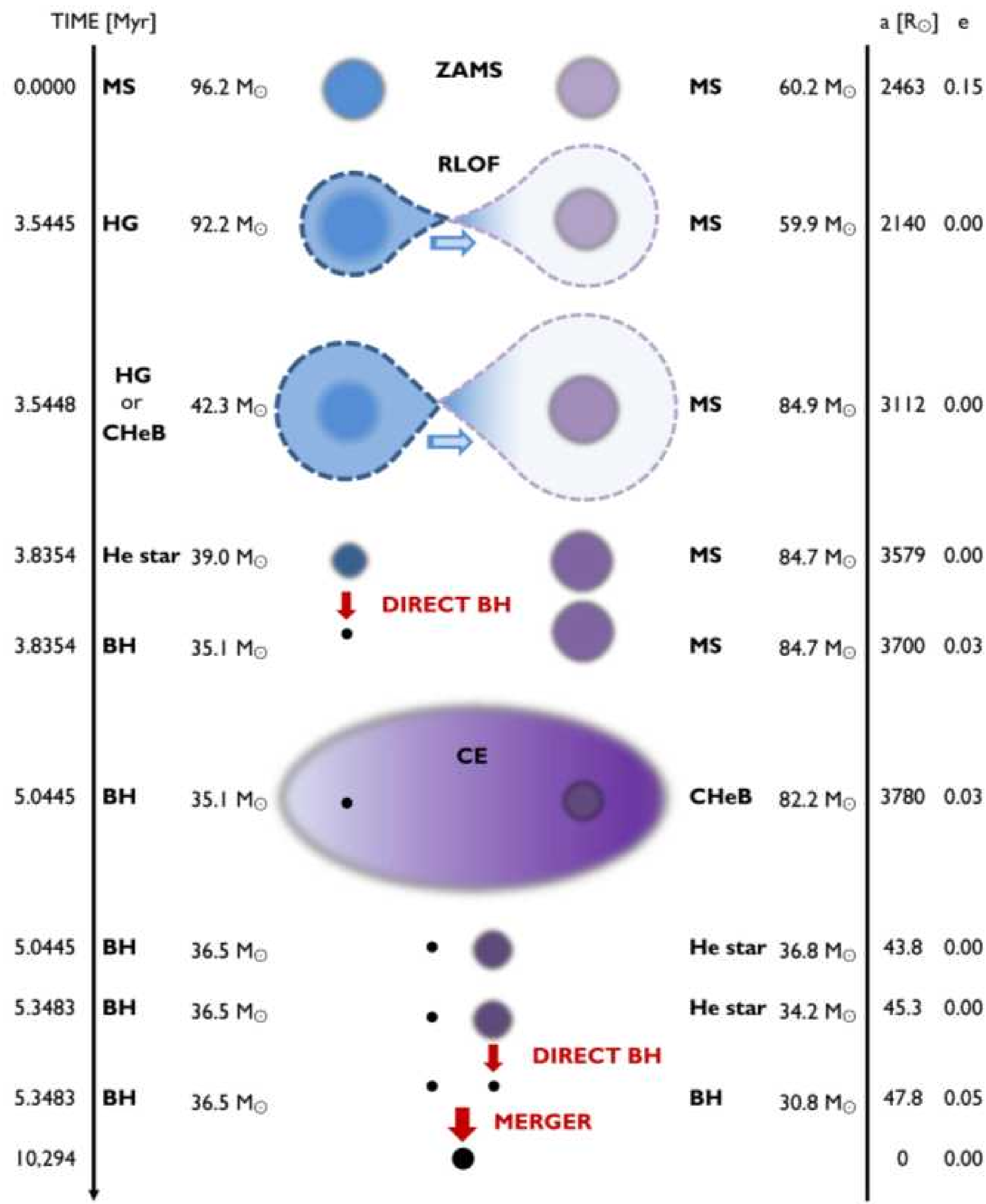
BH formation, kick?

CE – too short too affect

BH formation, kick?

Kicks are small.

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



Population III origin?

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

Gravitational waves from a population of binary black holes

J. R. Bond *Institute of Astronomy, Madingley Road, Cambridge and Department of Physics, Stanford University, California, USA*
B. J. Carr *Institute of Astronomy, Madingley Road, Cambridge and Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan*

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

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

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

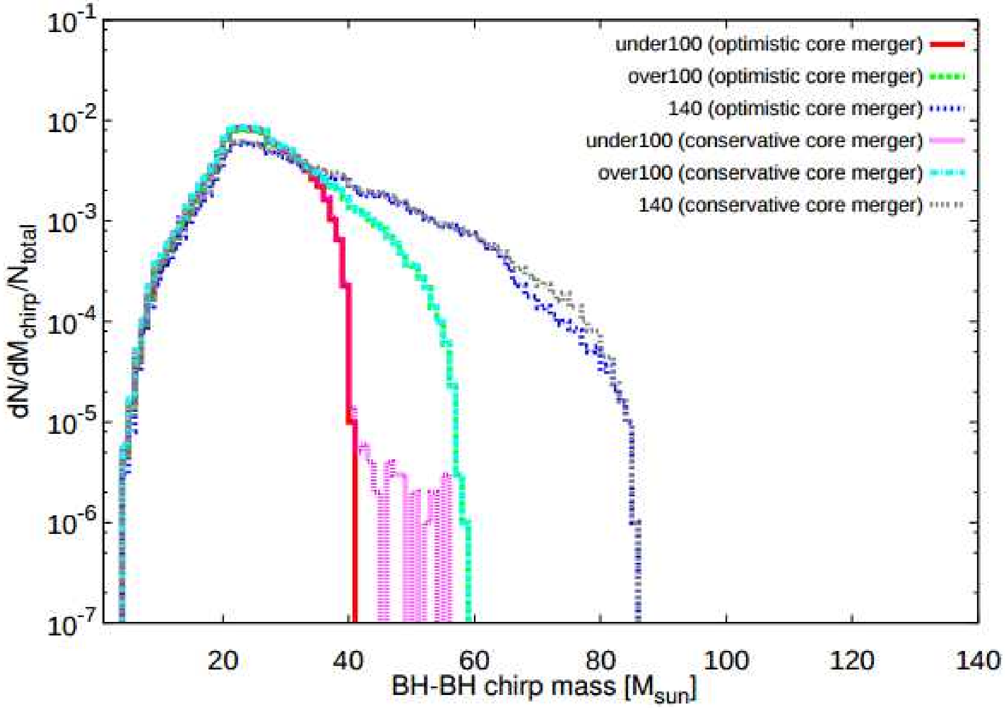
Population III

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



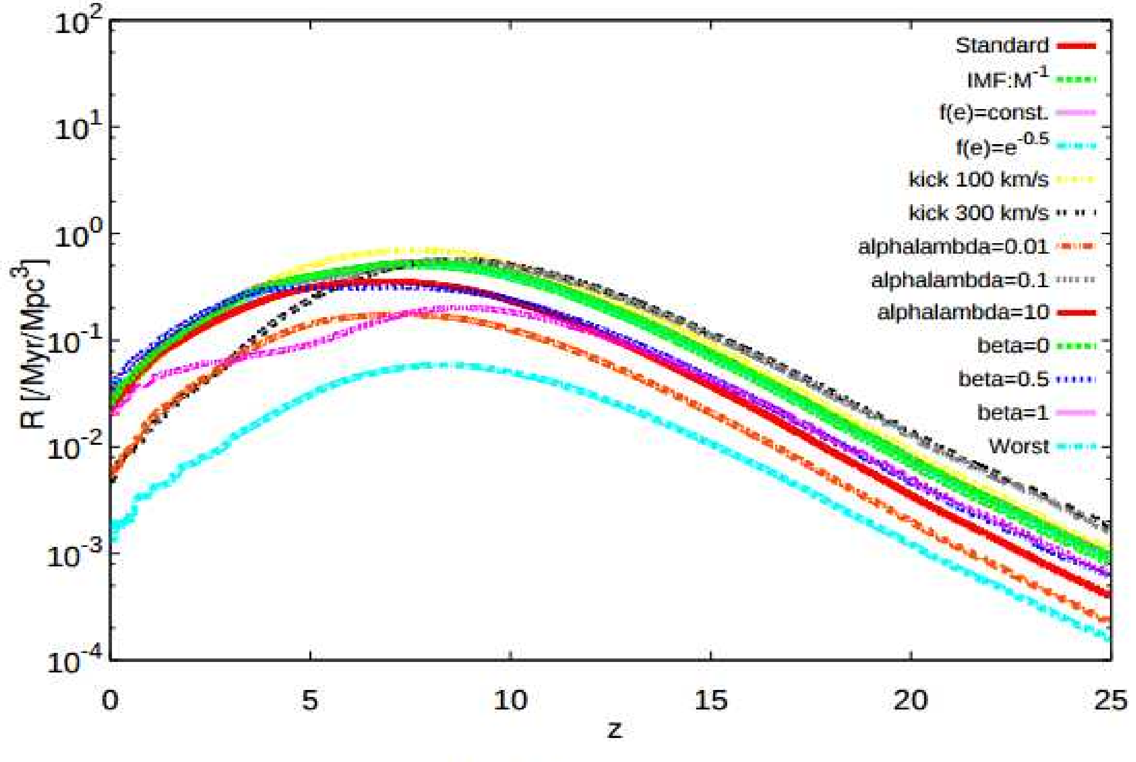
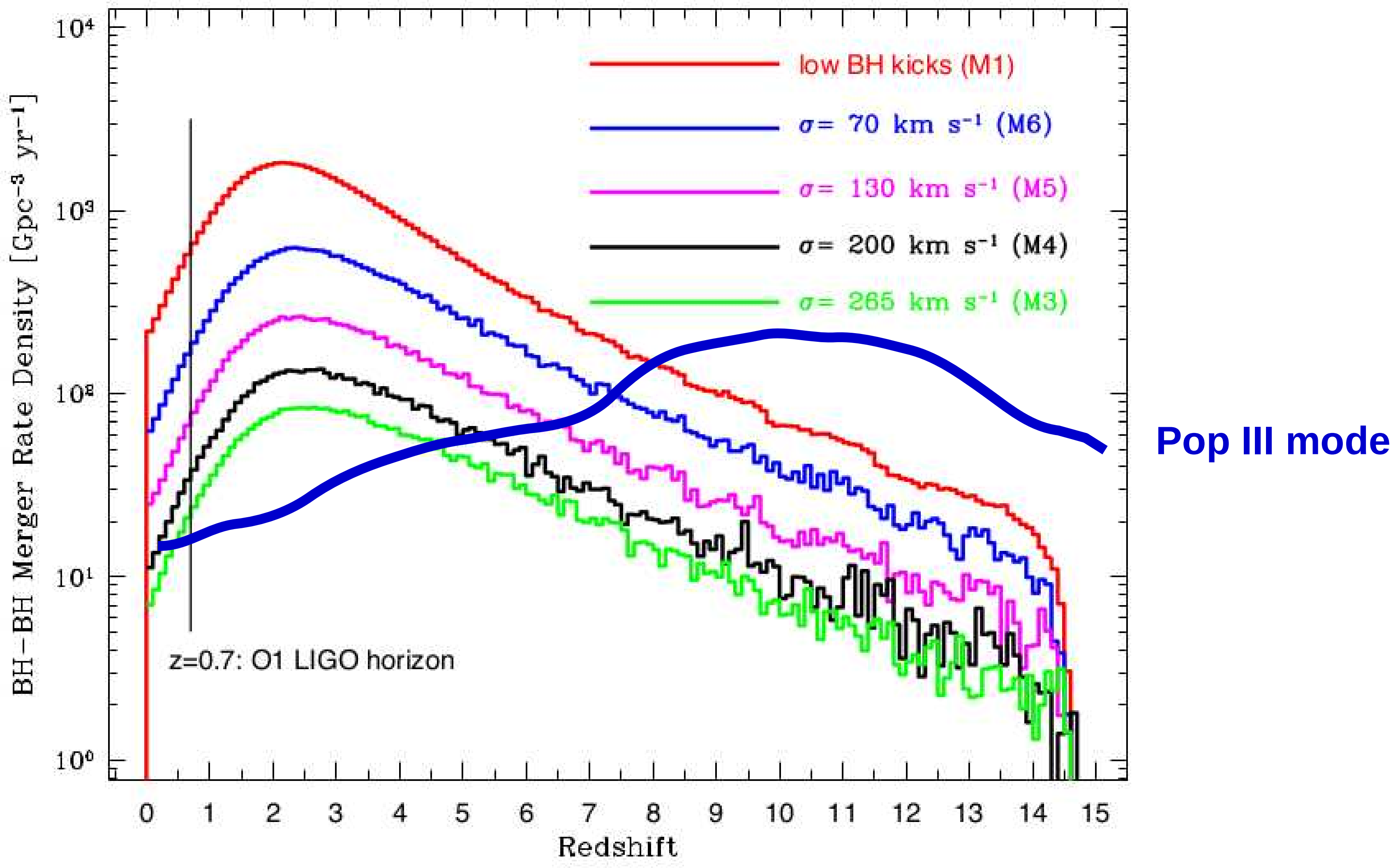


Figure 24. The merger rate densities

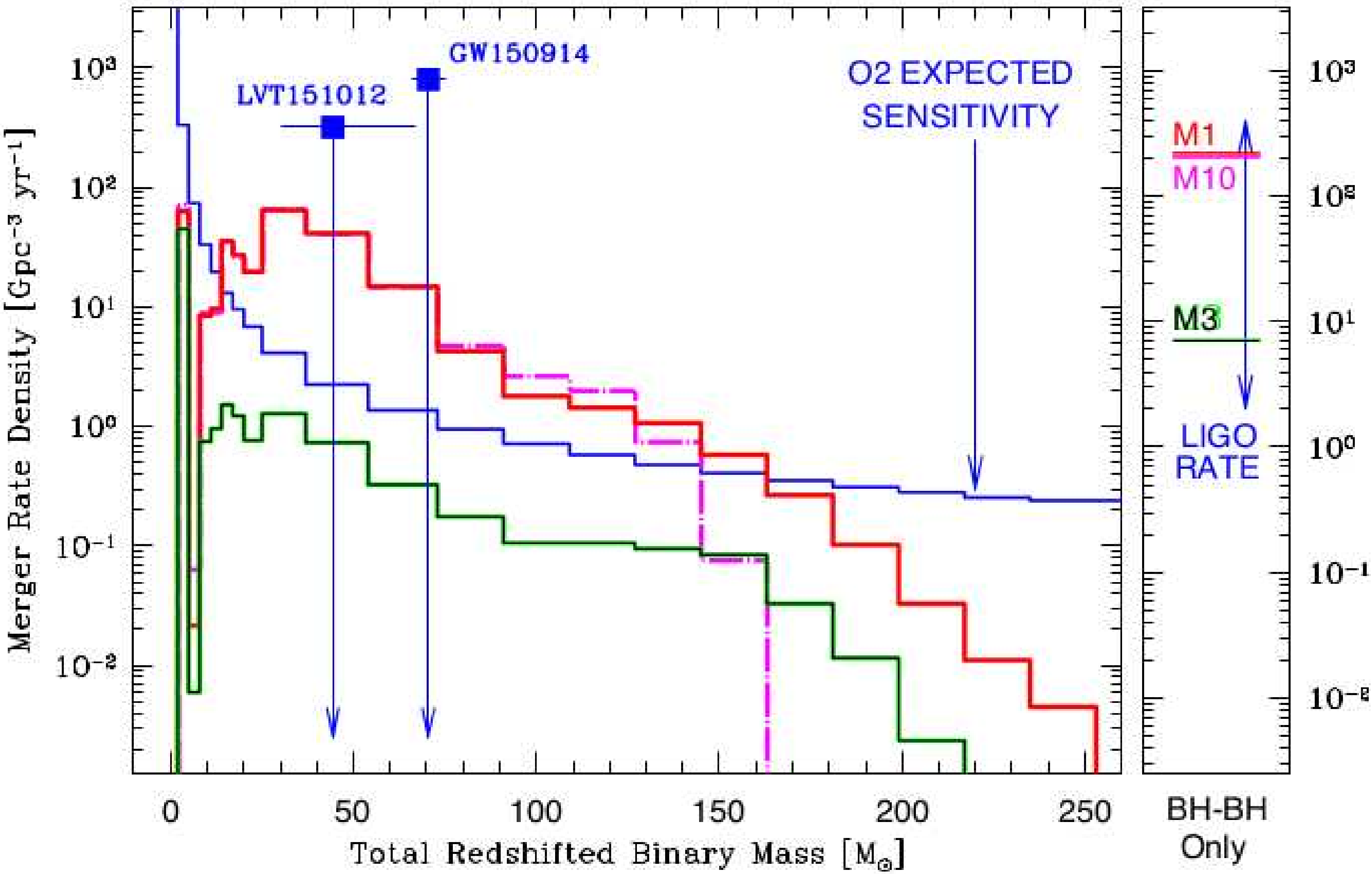
Population III summary

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

Merger rate as a function of distance



Prospects



GW150914
LVT151012
O2 EXPECTED
SENSITIVITY
M1
M10
M3
LIGO
RATE
Merger Rate Density [Gpc⁻³ yr⁻¹]
Total Redshifted Binary Mass [M⊙]
BH-BH
Only
10³
10²
10¹
10⁰
10⁻¹
10⁻²
0
50
100
150
200
250

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 !!!

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