formation and coalescence sites of the first GW events

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FIRST
THE FIRST STARS AND GALAXIES

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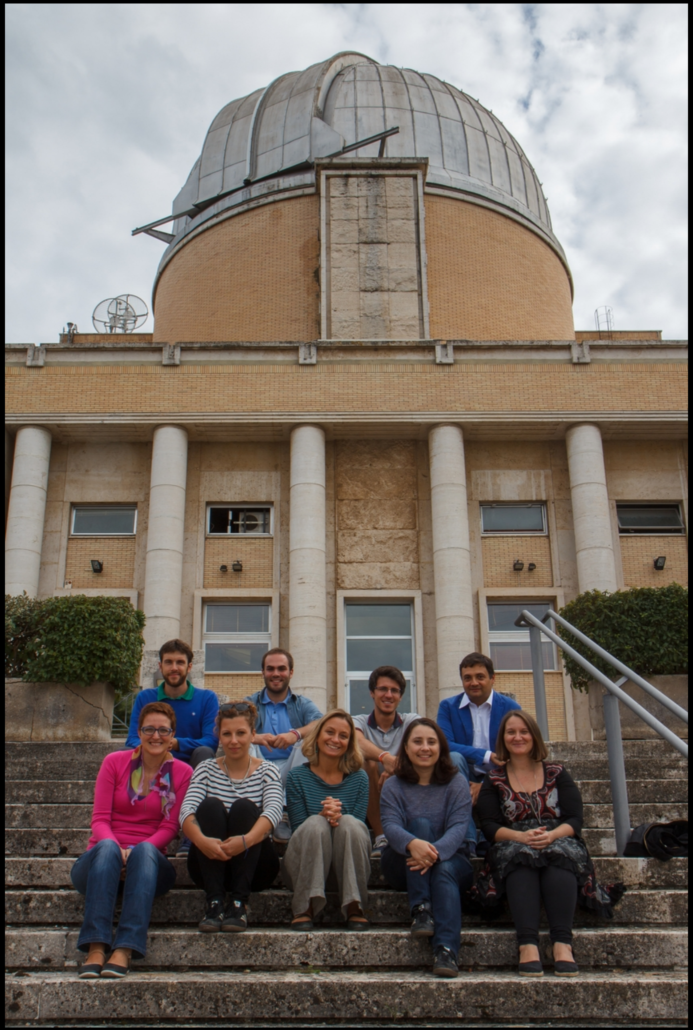


detected GW events

Abbott+2016a, Abbott+2016b, Abbott+2016c, Abbott+2016d, Abbott+2017

	name	m_{BH1} [M_{sun}]	m_{BH2} [M_{sun}]	redshift	$M_{source,f}$ [M_{sun}]	χ_{eff}
O_1	GW150914	$36.2^{+5.2}_{-3.8}$	$29.1^{+3.7}_{-4.4}$	$0.09^{+0.03}_{-0.04}$	$62.3^{+3.7}_{-3.1}$	$-0.06^{+0.14}_{-0.14}$
	GW151226	$14.2^{+8.3}_{-3.7}$	$7.5^{+2.3}_{-2.3}$	$0.09^{+0.03}_{-0.04}$	$20.8^{+6.1}_{-1.7}$	$0.21^{+0.2}_{-0.1}$
	LVT151012	23^{+18}_{-6}	13^{+4}_{-5}	$0.20^{+0.09}_{-0.09}$	35^{+14}_{-4}	$0.0^{+0.3}_{-0.2}$
O_2	GW170104	$31.2^{+8.4}_{-6.0}$	$19.4^{+5.3}_{-5.9}$	$0.18^{+0.08}_{-0.07}$	$48.7^{+5.7}_{-4.6}$	$-0.12^{+0.21}_{-0.30}$

$R_{O1} = 9 – 240\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

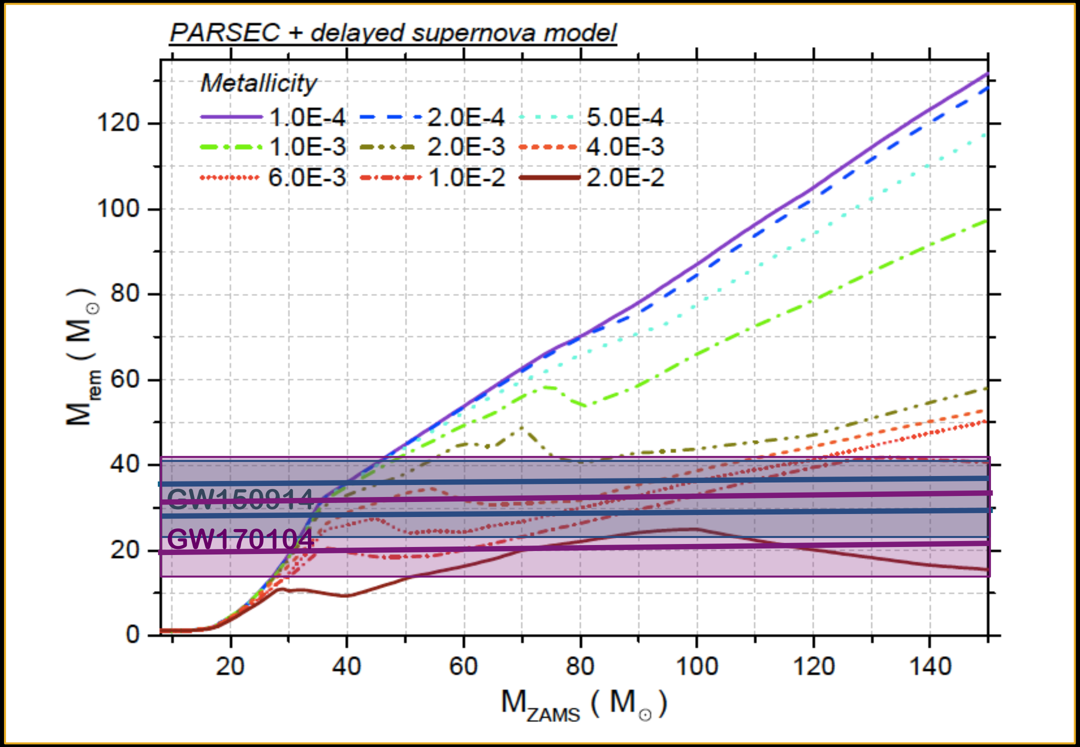
$R_{O1+O2} = 12 – 213\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

the observed properties do not allow to discriminate among different binary BHs formation channels

astrophysical implications

“ Given our current understanding of BH formation from massive stars, using the latest stellar wind, rotation, and metallicity models, we conclude that the GW150914 BBH most likely formed in a low-metallicity environment: below 1/2 Z_{sun} and possibly below 1/4 Z_{sun}” Abbott et al. (2016)

“Given the mass of the primary black hole, the progenitors of GW170104 likely formed in a lower metallicity environment $Z \lesssim 0.5\ Z_{sun}$” Abbott et al. (2017)



$Z \leq 0.3\ Z_{sun}$

$Z \leq 0.5\ Z_{sun}$

Spera et al. (2015)

formation & coalescence rates

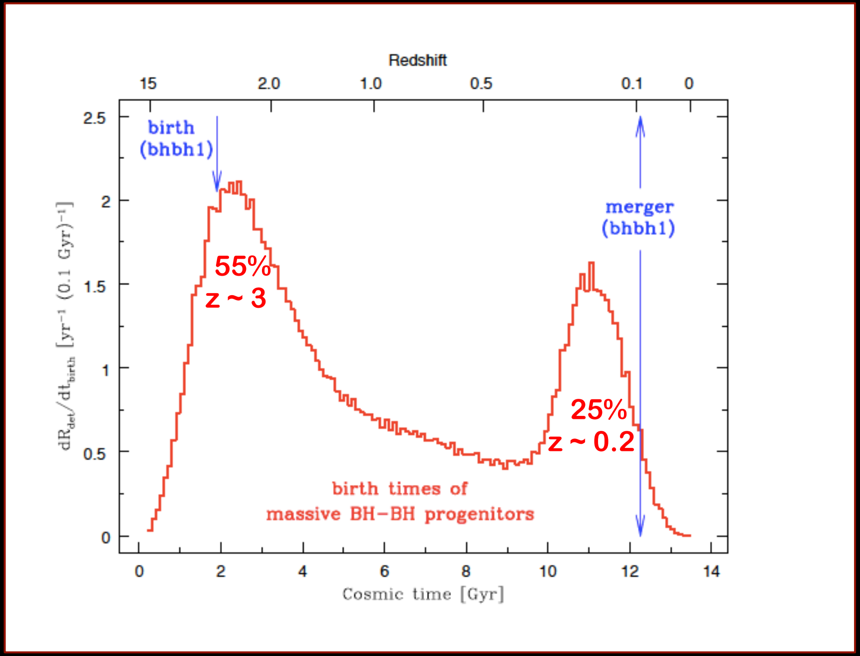
Schneider et al. 2001; Regimbau 2011; Marassi et al. 2011; Dominik et al. 2013; Dvorkin et al. 2016

StarTrack binary population synthesis to generate synthetic BH binaries with different initial Z

+

metallicity-corrected cosmic star formation rate density evolution

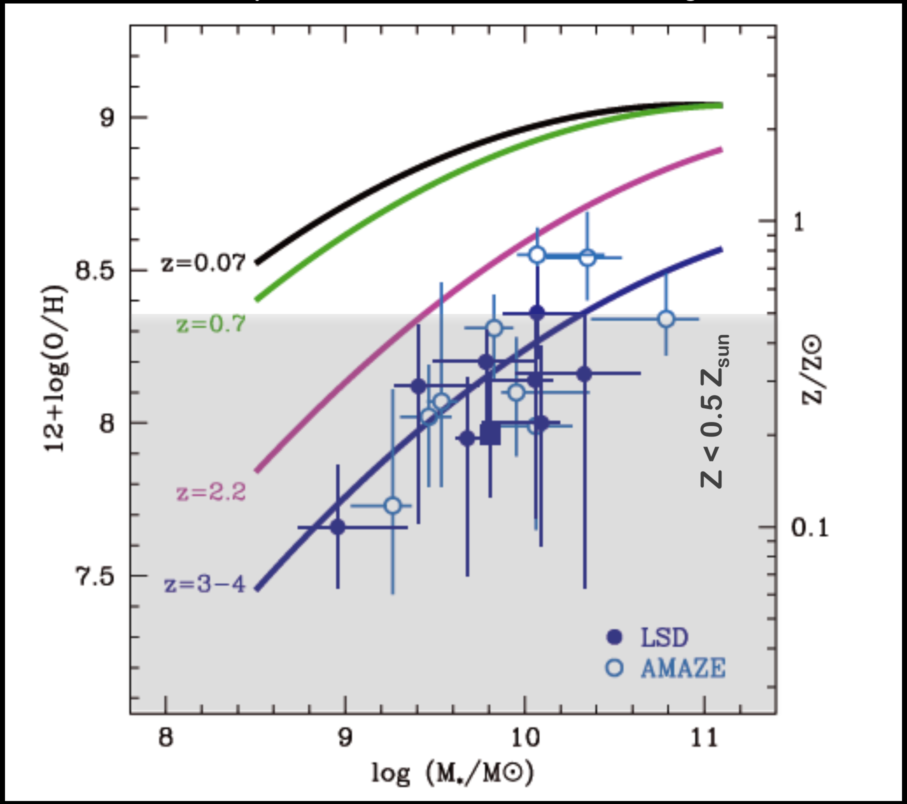
bimodal formation rate of GW150914-like systems



Belczynski et al. (2016)

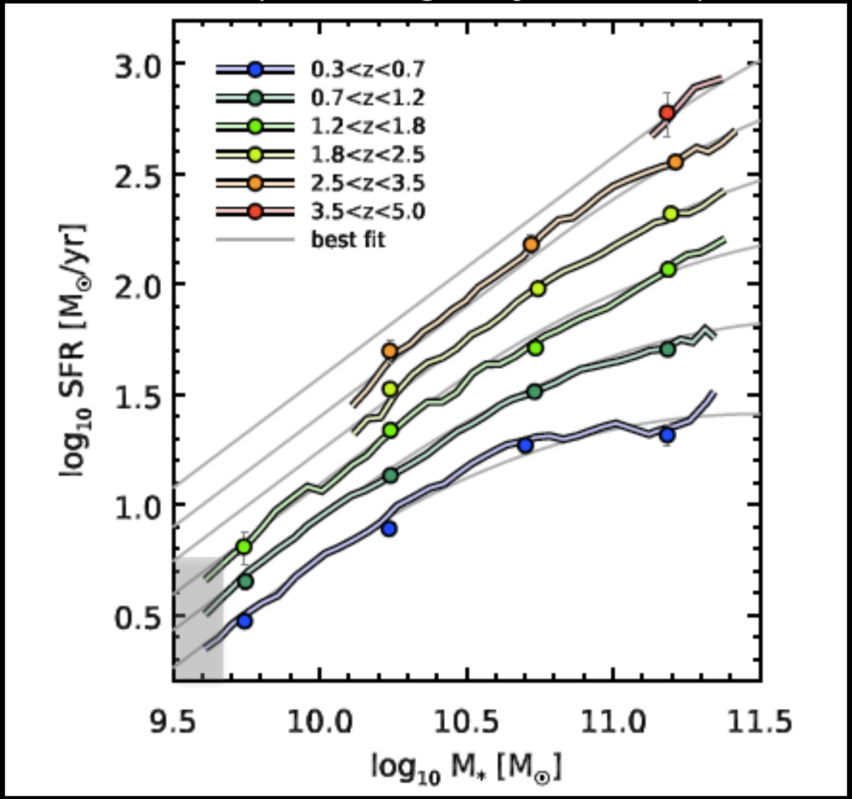
galaxy scaling relations

redshift-dependent mass-metallicity relation



Maiolino et al. (2008); Mannucci et al. (2009)

redshift-dependent galaxy main sequence



Schreiber et al. (2015)

stars with $Z < 0.5\ Z_{sun}$ form in low-mass galaxies at z < 1 at low rates or in galaxies with a broader range of stellar masses and SFRs at higher-z

from cosmic averages to individual formation/coalescence sites

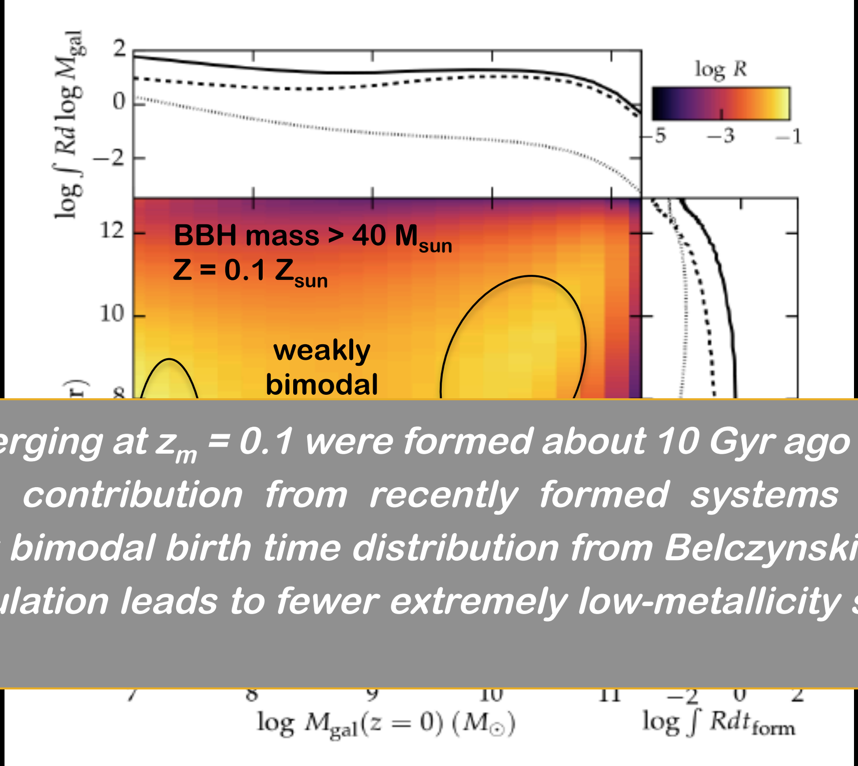
Lamberts et al. (2016); O'Shaughnessy et al. (2016); Ebert et al. (2017)

BSE binary population synthesis to generate synthetic BH binaries with initial Z = 0.3, 0.1, 0.01 Z_{sun}

+

observed galaxy scaling relations and analytical dark matter halo mass function

merger rate as a function of lookback time to the formation of the progenitor and different present day BBH merger host galaxy masses



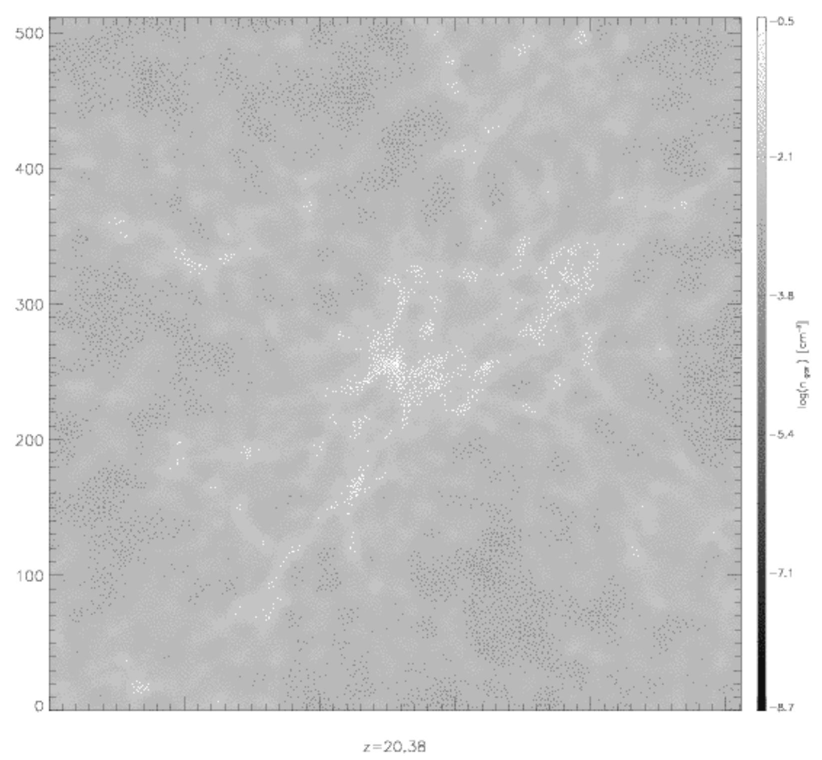
"Most of the BBH merging at z_m = 0.1 were formed about 10 Gyr ago (z_{form} ~ 1.5), at the peak of star formation. The contribution from recently formed systems is negligible. We do not recover the strongly bimodal birth time distribution from Belczynski et al. (2016) because our self-consistent calculation leads to fewer extremely low-metallicity stars compared with what they assumed"

Lamberts et al. (2016)

tracing BBH formation along the MW assembly with radiative and chemical feedback with GAMESH

GAMESH: GAMETE semi-analytical galaxy formation model + dark matter simulation coupled to the radiative transfer code CRASH

Graziani et al. 2015, 2017



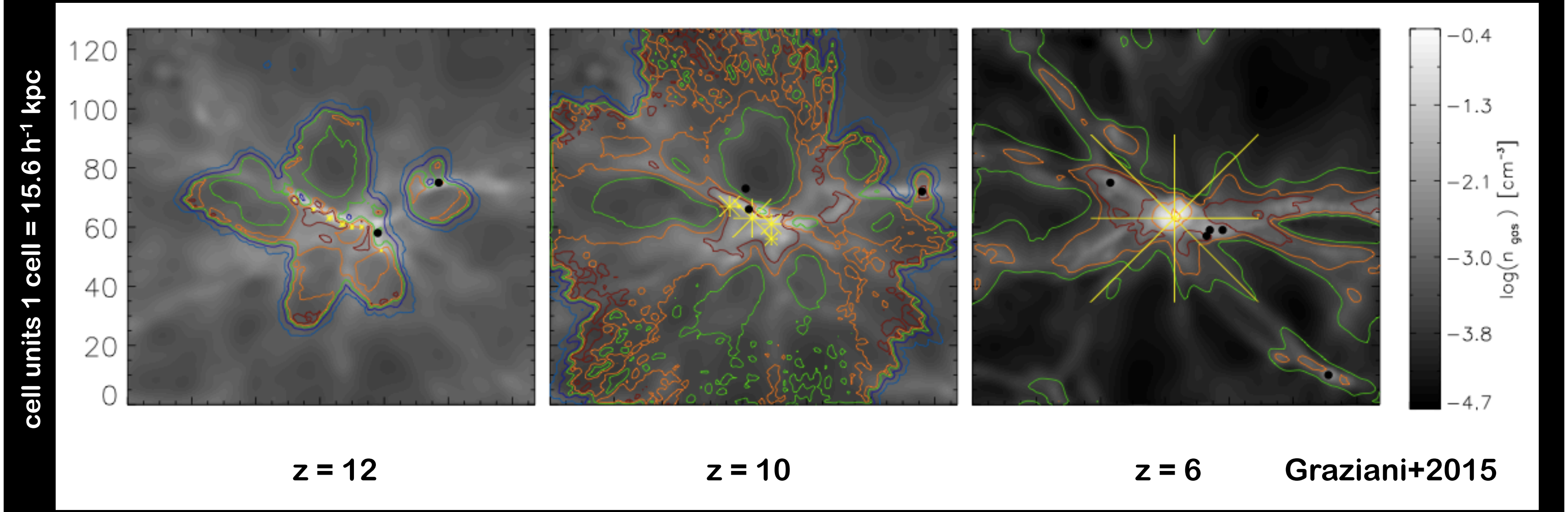
Dark matter simulation of the Milky Way galaxy in Planck cosmology GCD+ code with multi-resolution technique (Kawata & Gibson 2003):

Low-res spherical region of $R_l \sim 20\ h^{-1}$ Mpc taken from a low-res cosmological simulation

High-res spherical region of $R_h \sim 2\ h^{-1}$ Mpc with $M_p = 3.4 \times 10^5\ M_{sun}$

effects of inhomogeneous radiative feedback

suppression of star forming regions caused by gas photo-heating and photo-evaporation



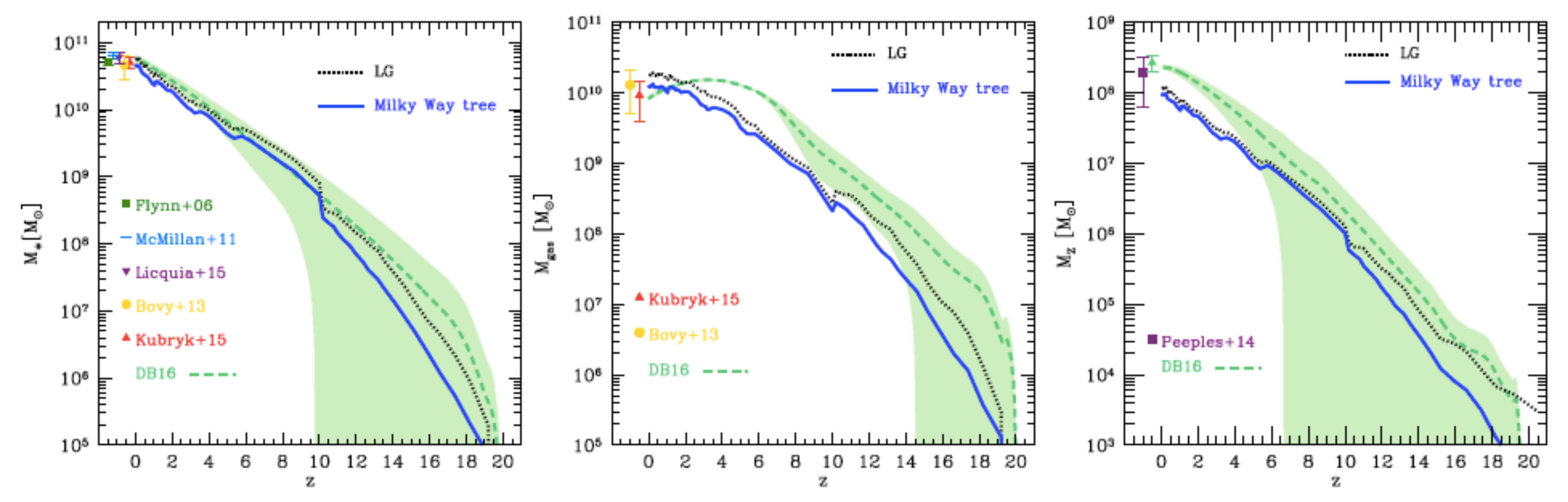
z = 12 z = 10 z = 6 Graziani+2015

Temperature contours:
T ~ 100 4 x 10^3 10^4 1.3 x 10^4 1.5 x 10^4 K

star forming regions in the plane are represented by yellow asterisks
black dots indicate regions where star formation is suppressed by radiative feedback

the history of dark and luminous galaxies in the Local Group

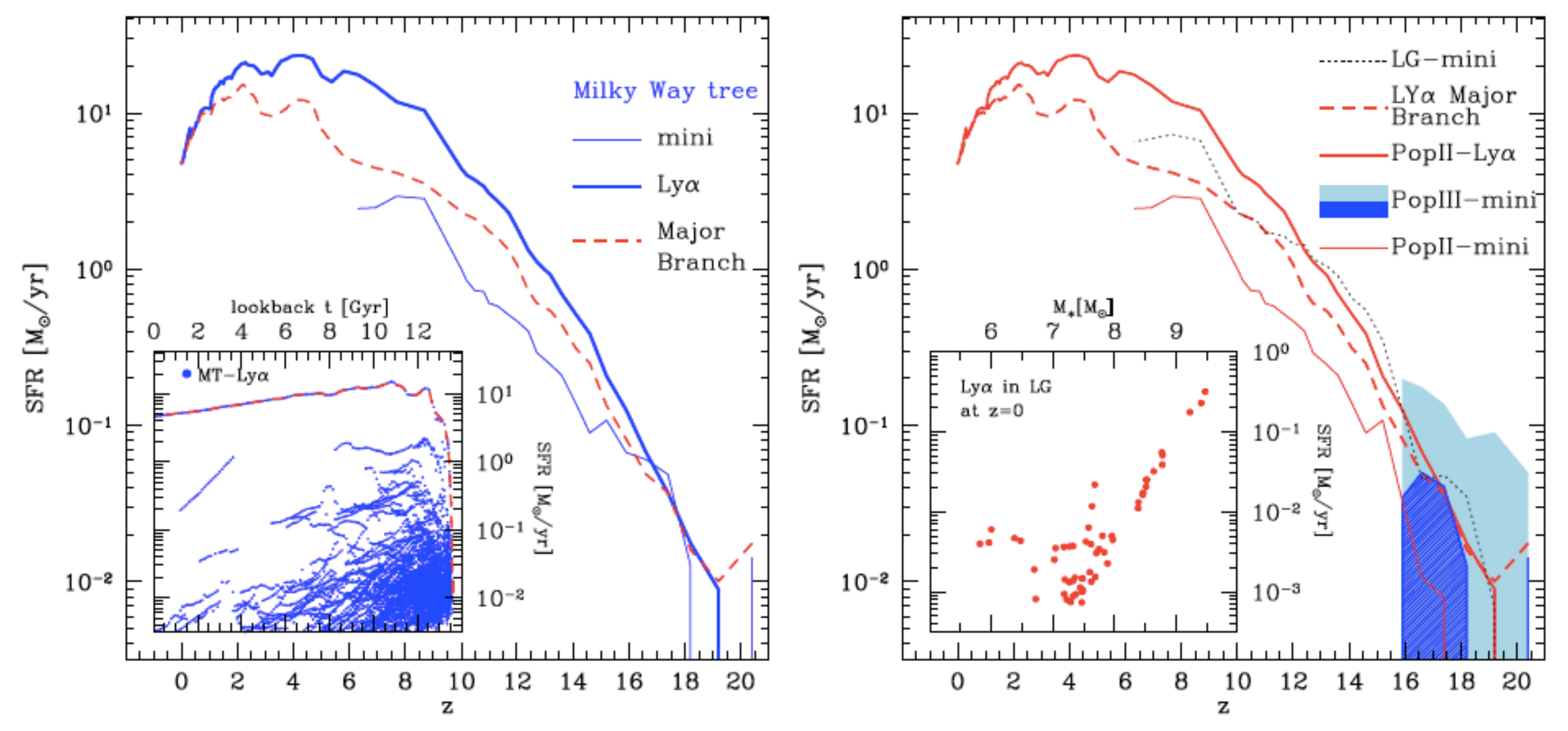
redshift evolution of the total mass in stars, gas and metals in the Local Group and in the MW



Graziani+2017

the history of dark and luminous galaxies in the Local Group

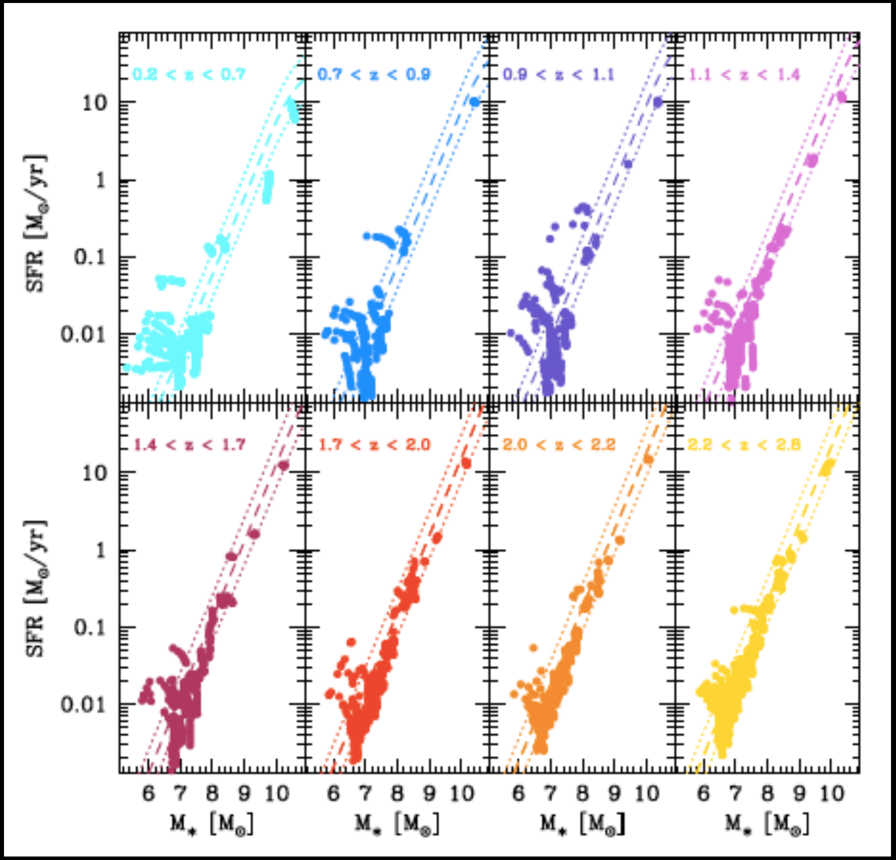
star formation histories of the MW and Local Group galaxies

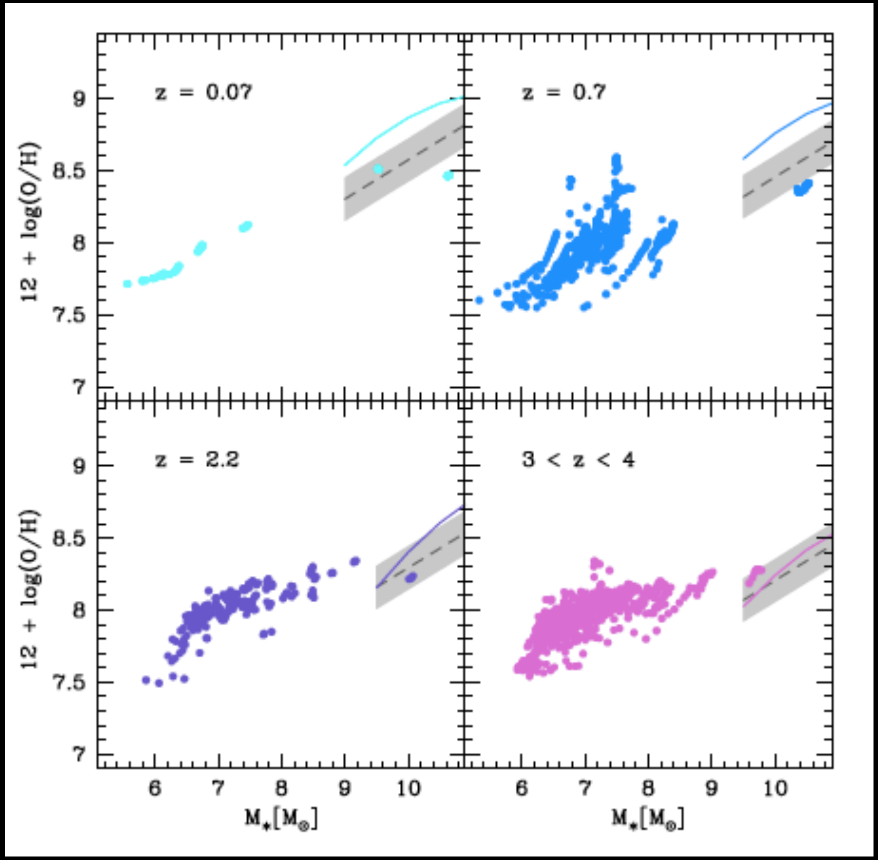


Graziani+2017

the history of dark and luminous galaxies in the Local Group

mass metallicity relation and main sequence of star formation





Graziani+2017

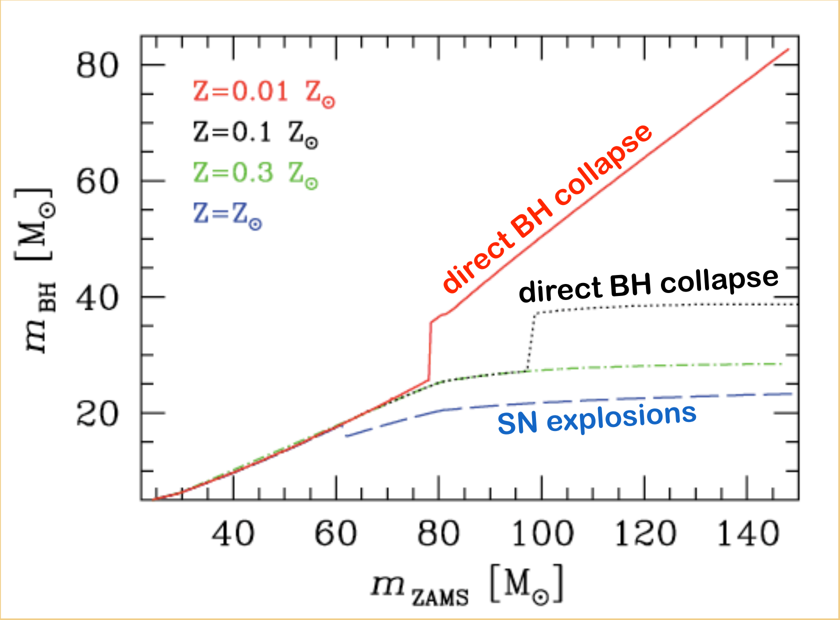
field BH binary formation

binary population synthesis code SeBa
(Portegies Zwart & Verbunt 1996; Nelemans, Yungelson & Portegies Zwart 2001)

+

metallicity-dependent prescriptions for stellar evolution, stellar winds and remnant formation
(Mapelli et al. 2013)

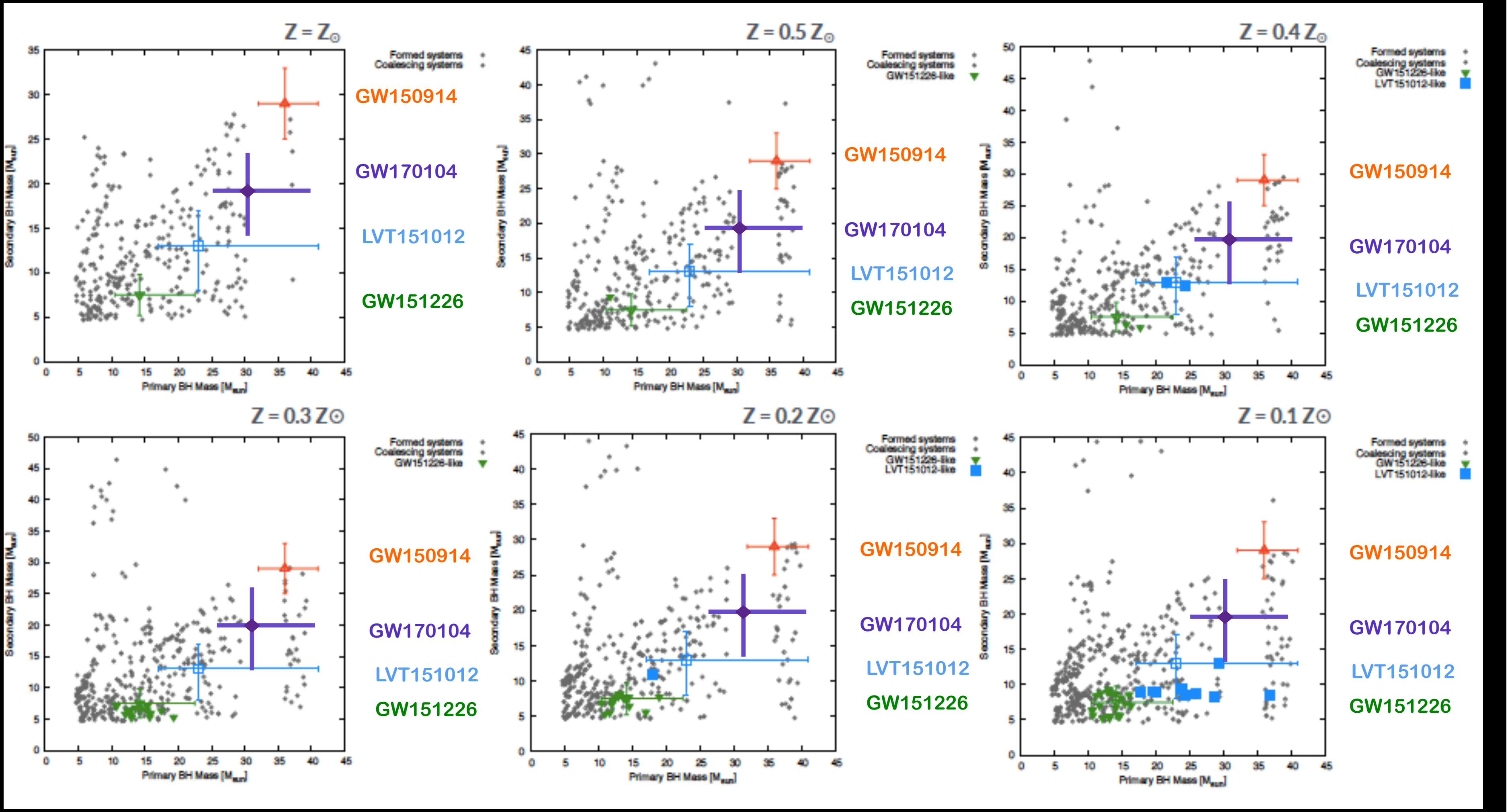
mass of the BHs versus ZAMS mass of the progenitor star
for isolated stellar evolution



field BH binary formation

we run 11 simulations with N = 2 10^6 binaries with metallicities in the range 0.01 $Z_{sun} \leq Z \leq Z_{sun}$

distributions of BBH masses at different Z: in colors merging BBHs with masses in the range of GW events



Courtesy of M. Alparone

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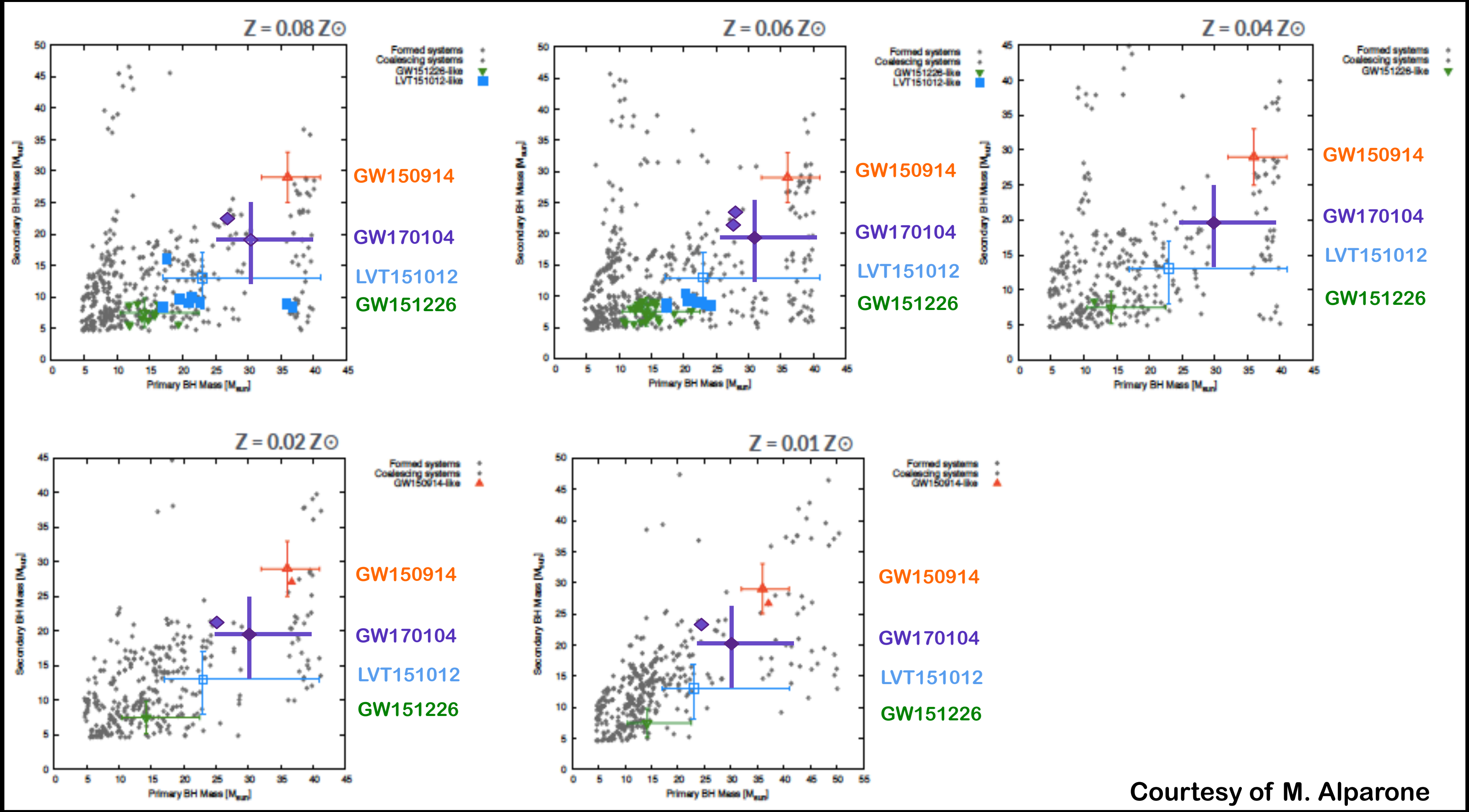
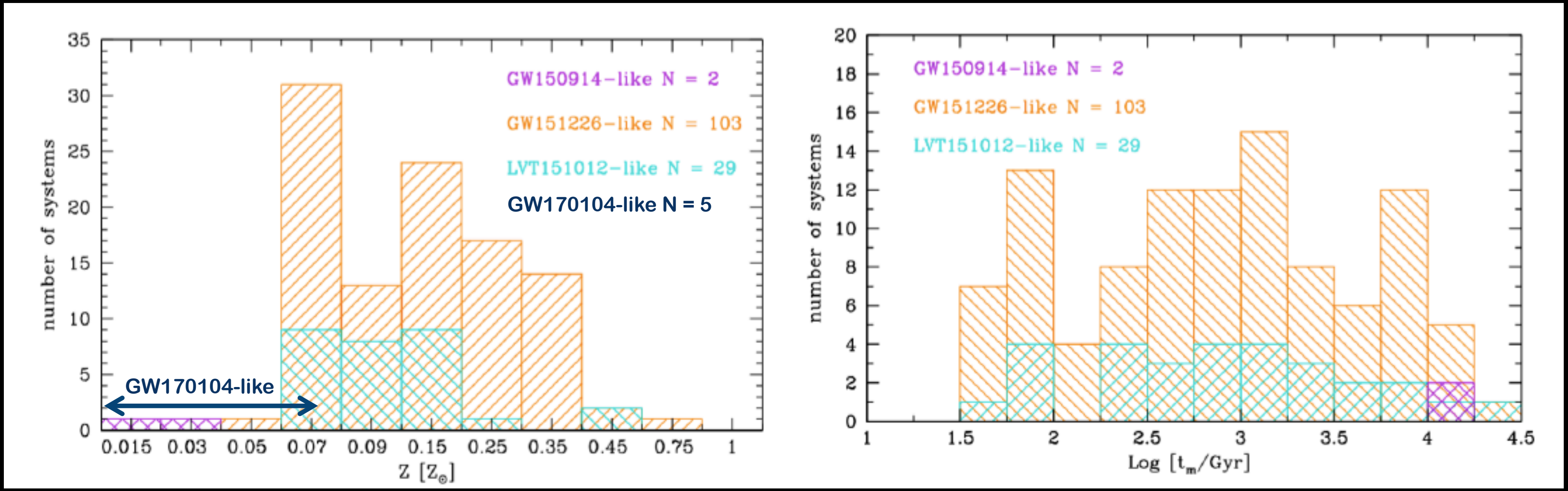


Courtesy of M. Alparone

field BH binary formation

number of GW events predicted by SeBa as a function of metallicity and merger time



Schneider, Graziani, Marassi, Spera, Mapelli, Alparone, de Bennassuti 2017

GW150914 BBH candidates have low metallicities, $Z \leq 0.05\ Z_{sun}$, and long merger times, $3.87 \leq \text{Log}\ t_m/\text{Gyr} \leq 4.12$

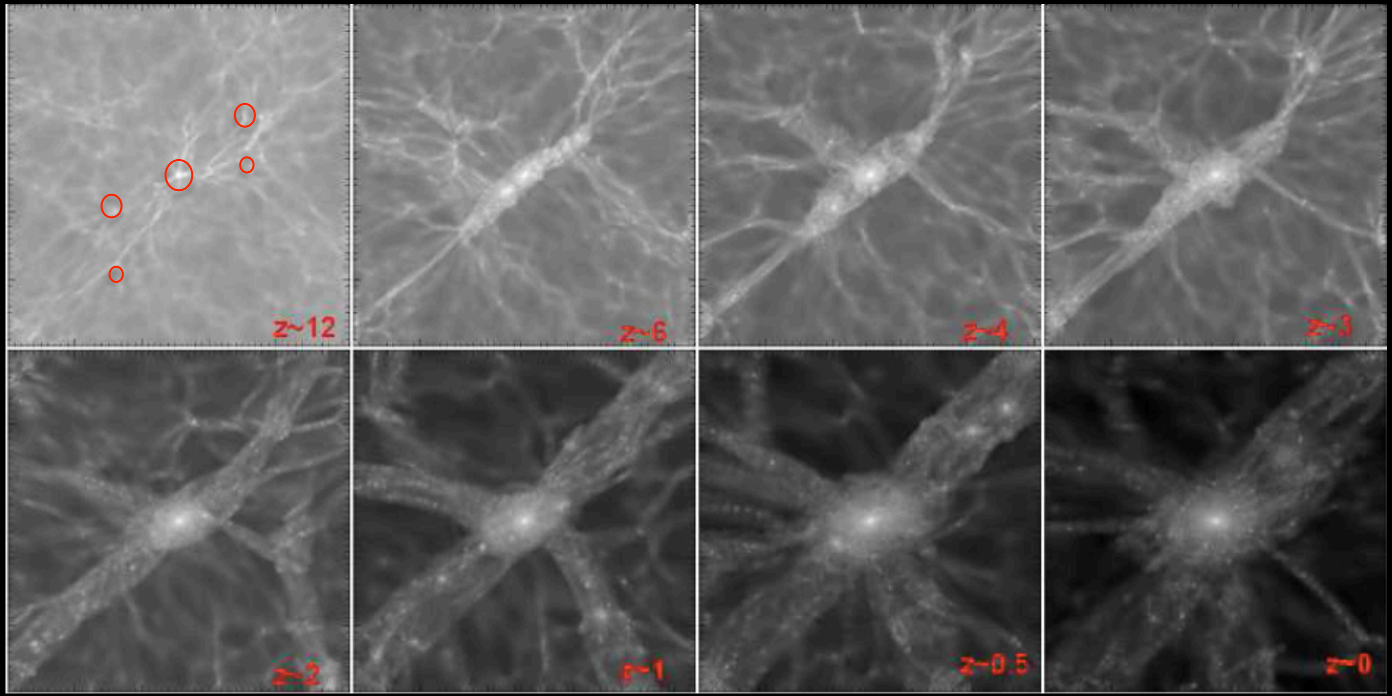
GW151226 candidates are more common, have metallicities $0.05\ Z_{sun} \leq Z \leq 0.75\ Z_{sun}$

most of LVT151012 candidates have metallicities $0.07\ Z_{sun} \leq Z \leq 0.25\ Z_{sun}$

both GW151226 and LVT151012 follow a flat distribution in merger times with $1.37 \leq \text{Log}\ t_m/\text{Gyr} \leq 4.25$

GW170104 is a heavy BBH and it requires low metallicities $Z < 0.07\ Z_{sun}$ and long t_m

modeling the formation sites



for each galaxy we know SFR and Z: we assume stellar progenitors of compact binaries to have the metallicity of the gas in which they form and we randomly extract from the SeBa output with the closest metallicity a number of binary systems until we reach the total mass of newly formed stars

↓

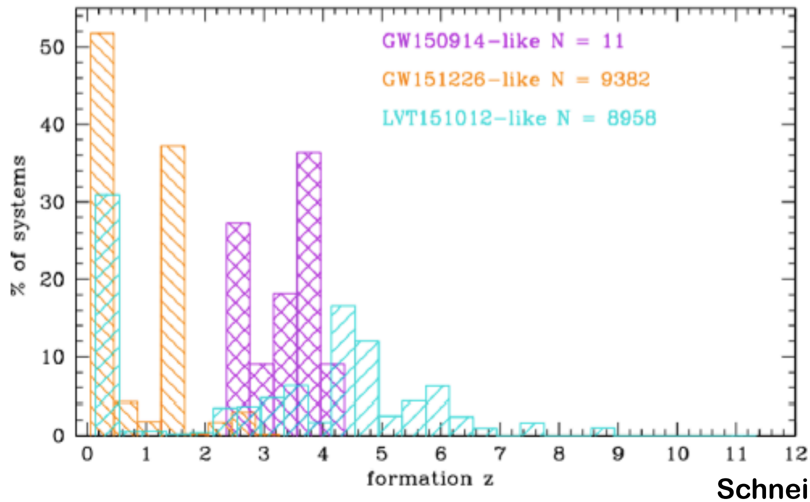
self-consistent metallicity-dependent birth and merger rates

modeling the formation sites

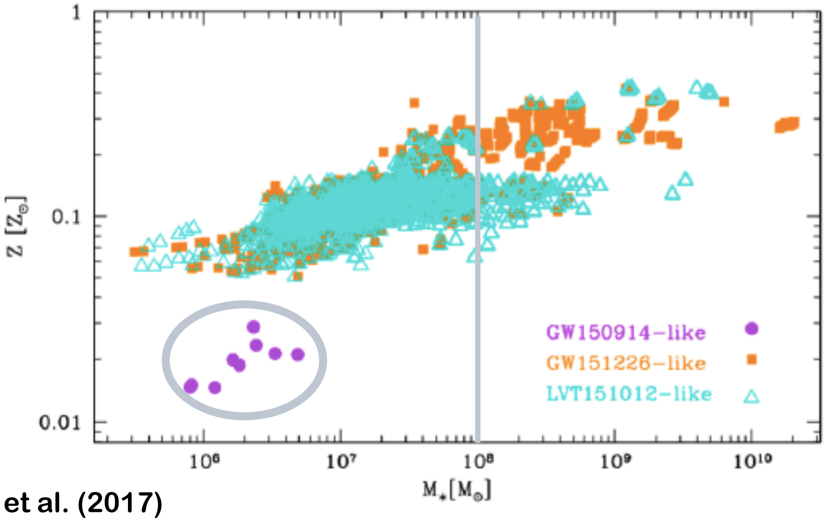
among all the simulated binary systems, we select GW150914, GW151226 and LVT151012 candidates:

- primary and secondary BH masses in the observed range
- merger occuring in the observed redshift range

distribution of formation redshifts



properties of formation sites



Schneider et al. (2017)

GW150914-like systems form at $2.36 \leq z_f \leq 4.15$ in low-metallicity dwarf galaxies with $7\ 10^5\ M_{sun} < M_* < 5\ 10^6\ M_{sun}$

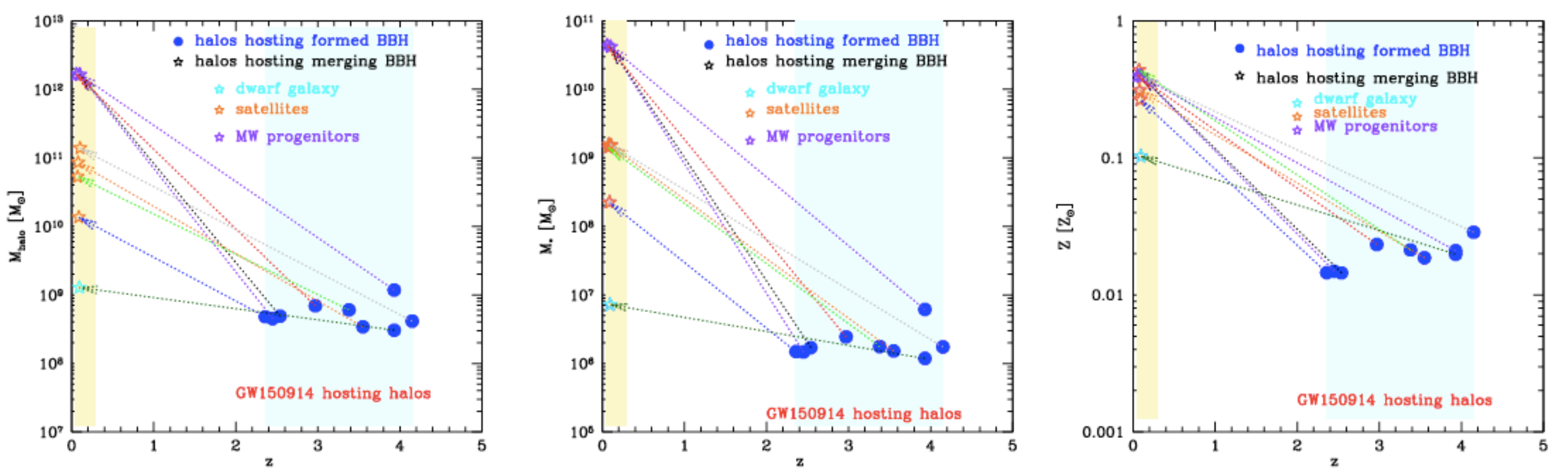
only 6% of GW151226-like systems form at $z_f > 2$ and 88% form in galaxies with $M_* > 10^8\ M_{sun}$

among LVT151012-like systems 67% have $z_f > 2$, 48% have $z_f > 4$, and 6% have $z_f > 6$, and 70% form in galaxies with $M_* > 10^8\ M_{sun}$

tracking the systems to coalescence

we track each GW150914, GW151226 and LVT151012 candidate BH system from formation to coalescence using a particle-based merger tree and we identify the galaxy where it resides when the merger event occurs

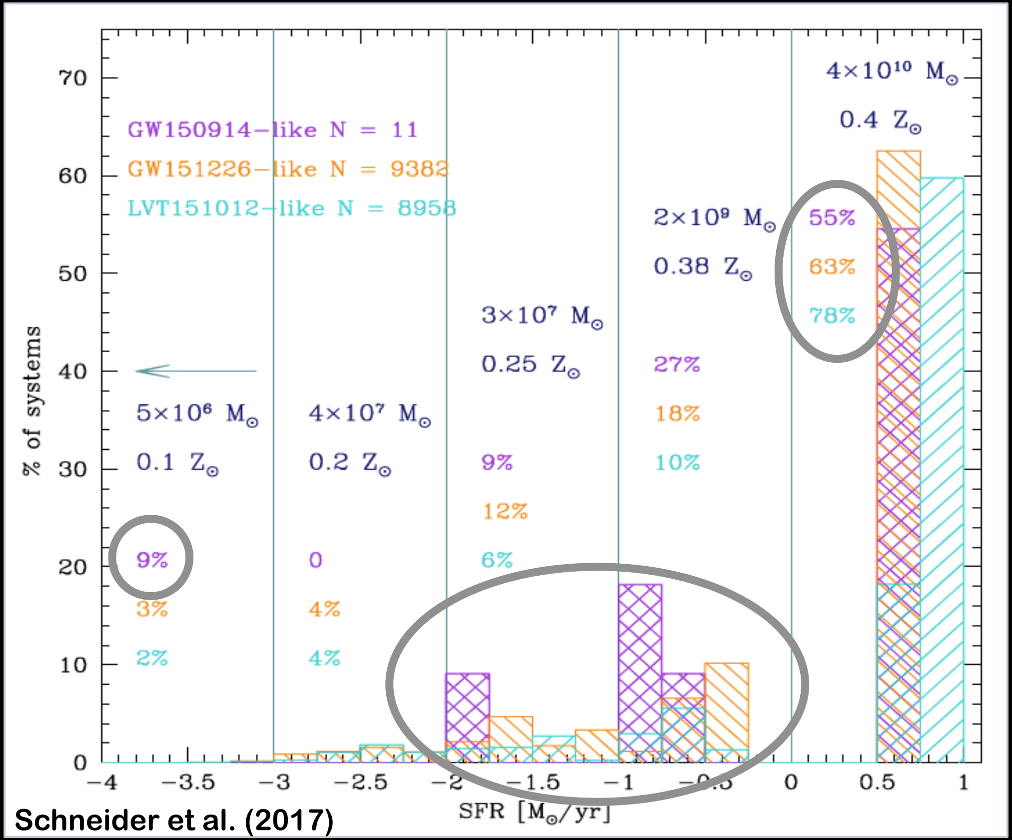
1:1 relation between formation and coalescence sites for GW150914 candidates



Marassi et al. in prep

properties of coalescence sites

SFRs, masses and metallicities of host galaxies



Schneider et al. (2017)

~ 10% of GW150914-like systems may be hosted in very small galaxies ($M_* < 5\ 10^6$ M_{sun}) where SFR ~ 0 due to radiative feedback effects

→ smallest dwarf spheroidals or ultra-faint dwarfs

galaxies with $M_* \sim 4\ 10^{10}$ M_{sun},, Z ~ 0. 4 Z_{sun} and SFR ~ 5 M_{sun}/yr have the largest probability to host GW150914, GW151226 and LVT151012-like events

smaller galaxies, with properties similar to LMC, SMC and dwarfs, have a smaller probability to have hosted the first three GW events

the mass spectrum of BH remnants of Pop III stars

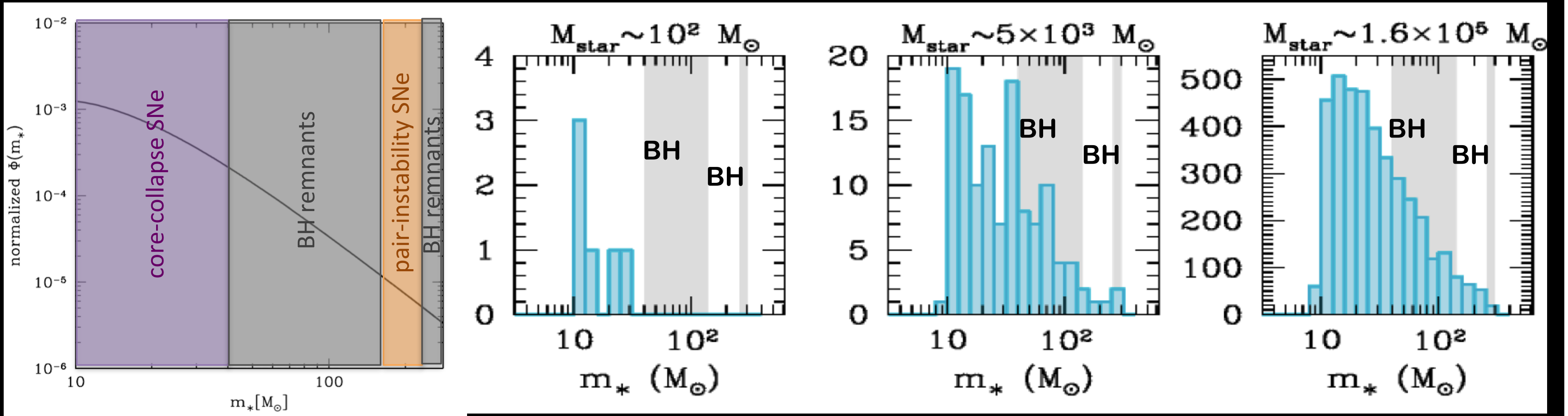
Pop III stellar mass spectrum is still very uncertain: stars form from 10s to 1000s of M_{sun}
(Hosokawa et al. 2011; Hirano et al. 2014, 2015; Susa et al. 2014; Stacy et al. 2016; Hosokawa et al. 2016)

empirically motivated Pop III IMF from stellar archeology data (de Bennassuti et al. 2016)

$$\Phi(m_*) \propto m_*^{\alpha-1}\; e^{-m_*/m_{\rm ch}},$$

with $\alpha = -1.35$, $m_{\rm ch} = 20\ M_\odot$ and $10\ M_\odot \leqslant m_* \leqslant 300\ M_\odot$

effective mass distribution of Pop III stars and BH remnants (Valiante et al. 2016)



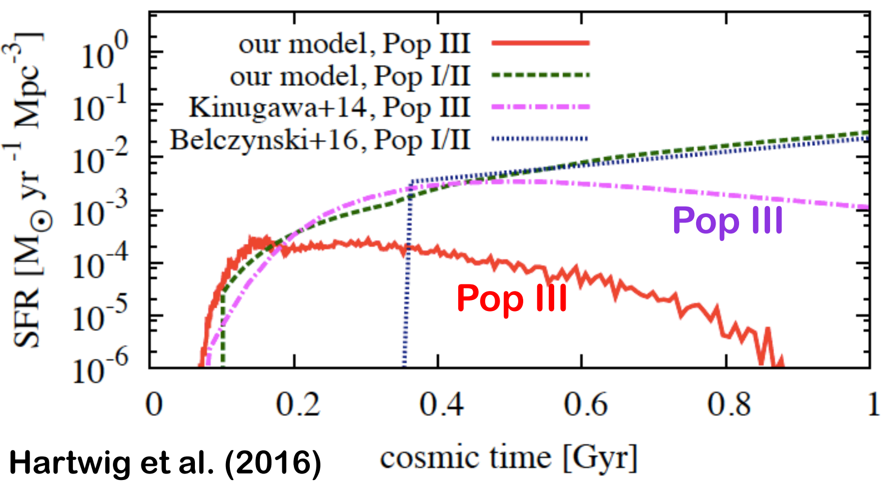
Pop III BH mass spectrum depends on the efficiency of star formation in the first mini-halos at high z

Pop III binary evolution

Stacy & Bromm 2014; Kinugawa et al. 2014; Hartwig et al. 2016

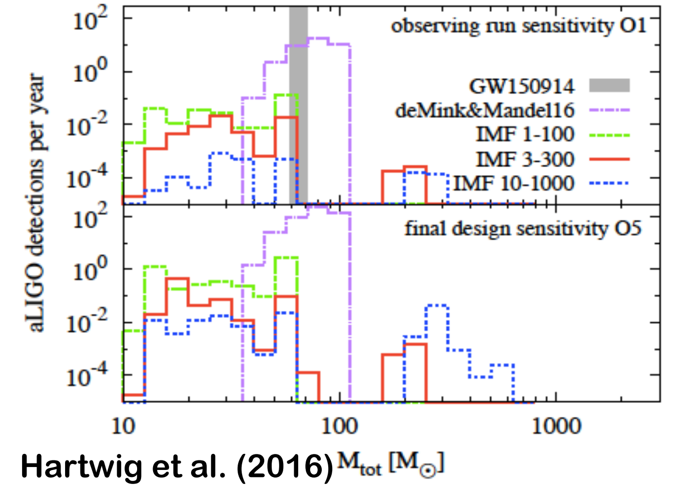
large uncertainties on the Pop III binary evolution modeling

time evolution of the star formation rate density



Hartwig et al. (2016)

BBH detectios as a function of the BBH total mass



Hartwig et al. (2016)

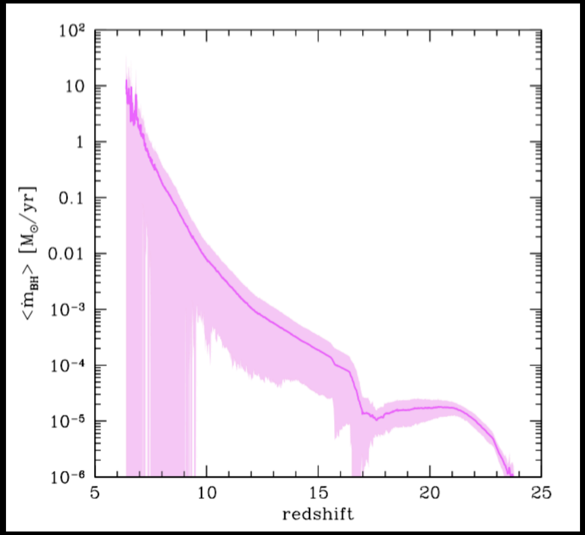
GW150914 has a 1 % probability to originate from Pop III star

up to 5 detections per year with aLIGO at final design sensitivity originate from Pop III BBHs

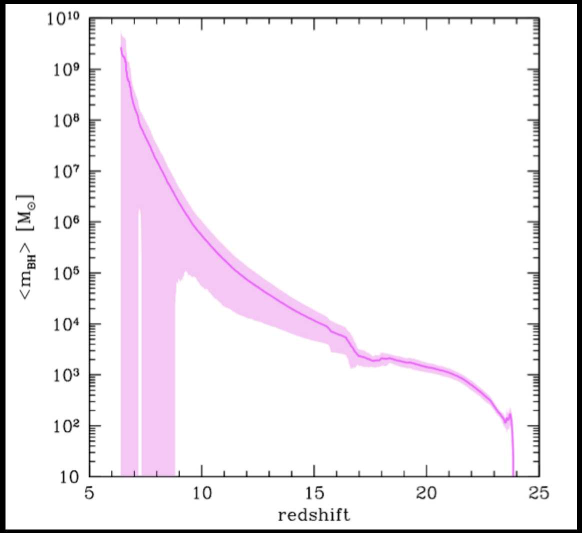
growing the first SMBHs

Valiante et al. 2011, 2014, 2016; Pezzulli et al. 2016, 2017

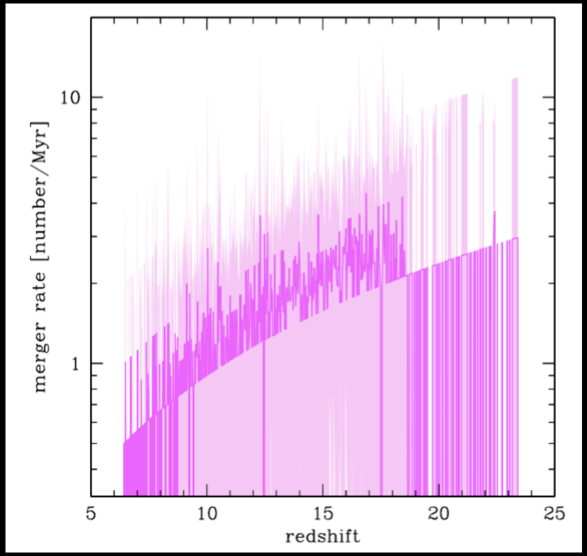
mean Eddington-limited accretion history



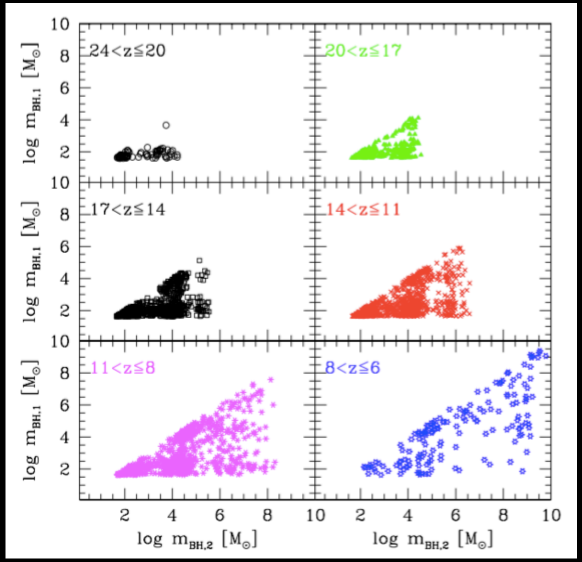
mean Eddington-limited BH mass evolution



mean rate of BHBH mergers



mass spectrum of BBHs at different z

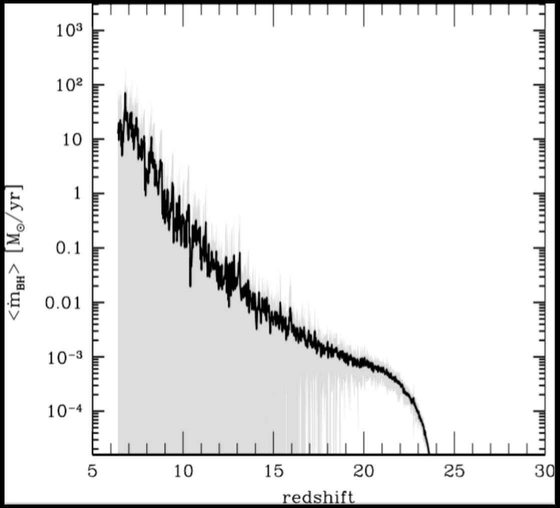


courtesy of
Rosa Valiante

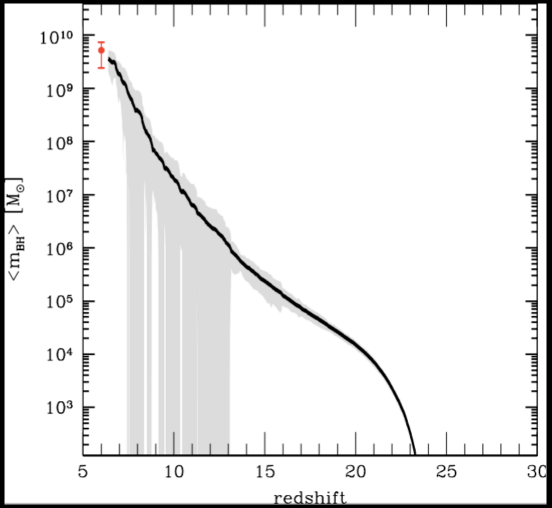
growing the first SMBHs

Valiante et al. 2011, 2014, 2016; Pezzulli et al. 2016, 2017

mean super-Eddington accretion history



mean super-Eddington BH mass evolution



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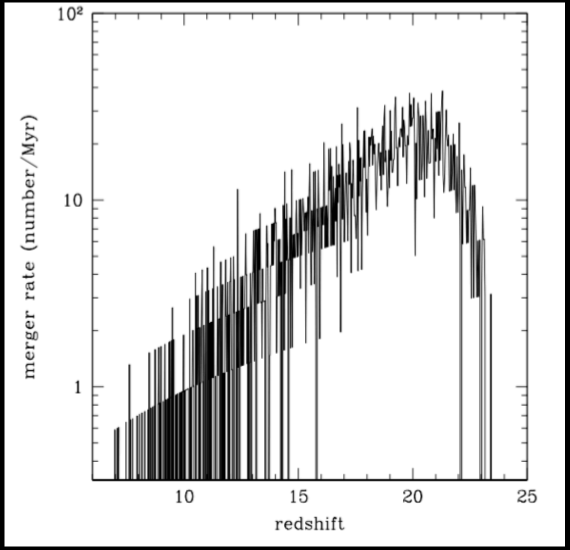
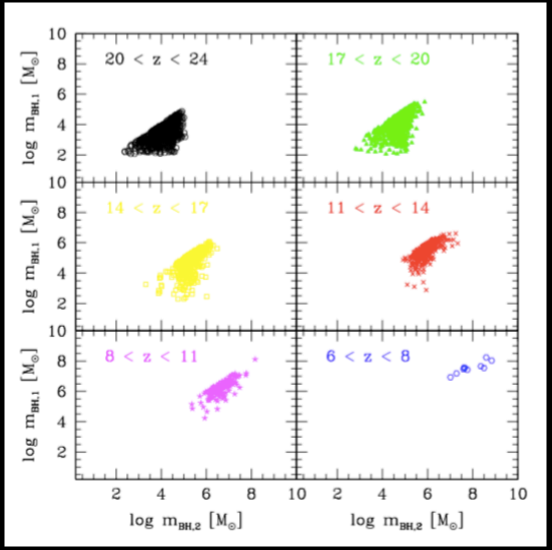


mass spectrum of BBHs at different z



courtesy of
Edwige Pezzulli

Summary

GW astronomy requires the development of theoretical frameworks that allow sampling of the model parameter space

GAMESH is novel theoretical model to characterize the formation and coalescence sites of compact binaries in a cosmological context

We find that more than 70% of GW151226 and LVT151012 candidates form in galaxies with stellar mass $M > 10^8 M_{sun}$ in the redshift range [0.06 - 3] and [0.14 - 11.3], respectively

All GW150914 candidates form in low-metallicity dwarfs with $M < 5 \; 10^6 \, M_{sun}$ at $2.4 < z < 4.2$

By the time they reach coalescence, the observed events are most likely hosted by star forming galaxies with $M > 10^{10} \, M_{sun}$

Due to tidal stripping and radiative feedback, a non negligible fraction of GW150914 candidates end-up in galaxies with properties similar to dwarf spheroidals and ultra-faint satellites

Pop III remnants mass spectrum depends on the poorly constrained Pop III IMF and on the efficiency of Pop III star formation

Formation scenarios for the first SMBHs at $z > 6$ may be tested by GW observations