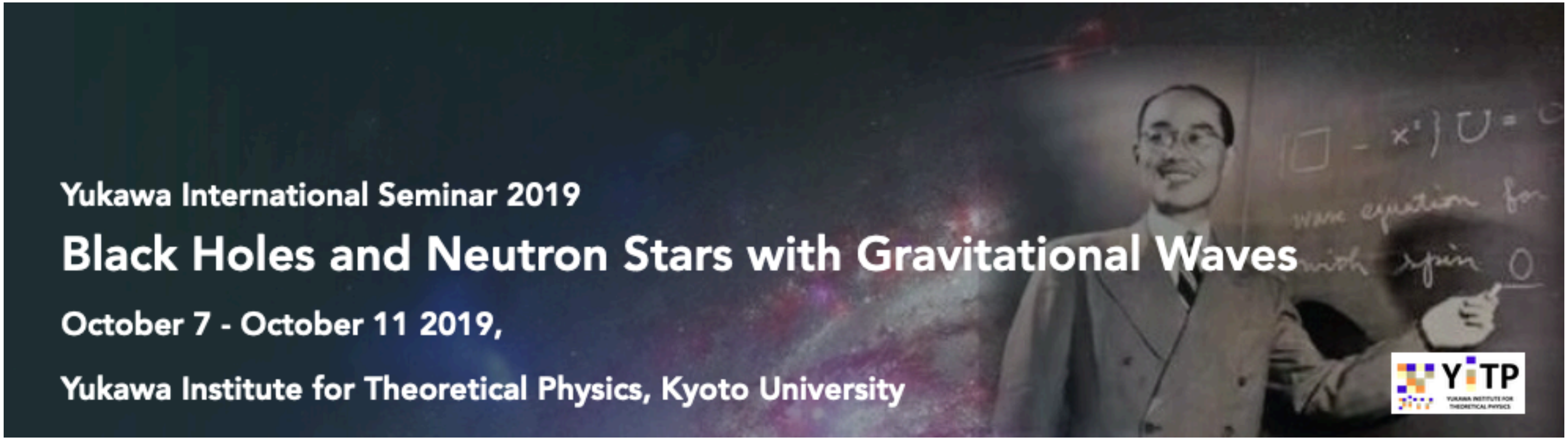


black hole archaeology with gravitational waves

Raffaella Schneider
Sapienza Università di Roma

http://www.roma1.infn.it/amaldicenter/home.html

Monica Colpi (Milano Bicocca University)

Francesco Conte (Heidelberg University)

Luca Graziani (ARC, Sapienza University)

Marco Limongi (INAF/OAR)

Stefania Marassi (Sapienza University)

Michela Mapelli (Padova University)

Kazuyuki Omukai (Tohoku University)

Mario Spera (Northwestern University)

Rosa Valiante (INAF/OAR)

Marta Volonteri (IAP, Paris)

and many others…

astrophysical implications of known black hole masses

masses of known black holes and of their merger product

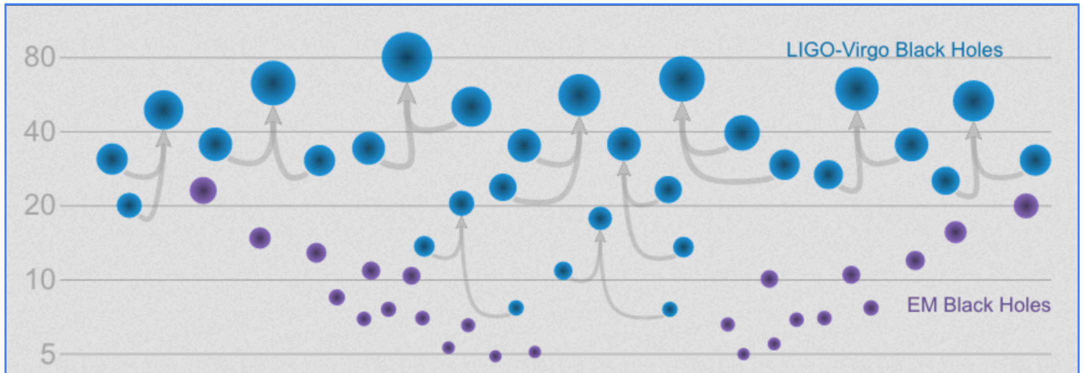
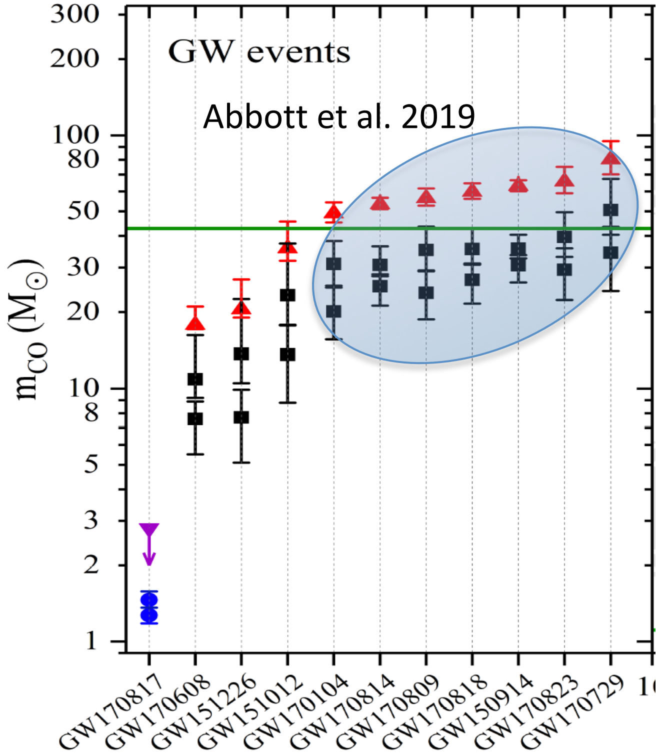
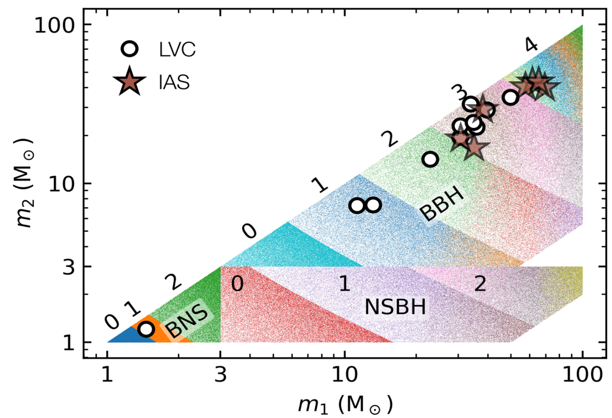


Image credit: LIGO-Virgo / Frank Elavsky / Northwestern



O2: Six New Events in Banks 3 and 4



Name	Bank	$\mathcal{M}^{\rm det}(M_\odot)$	$\chi_{\rm eff}$	z	GPS time[a]	$\rho^2_{\rm H}$	$\rho^2_{\rm L}$	$\mathrm{FAR}^{-1}(\mathrm{O2})$[b]	$\frac{W(\mathrm{event})}{\mathcal{R}(\mathrm{event}\mid\mathcal{N})}$ (O2)	$p_{\rm astro}$
GW170121	BBH (3,0)	29^{+4}_{-3}	$-0.3^{+0.3}_{-0.3}$	$0.24^{+0.14}_{-0.13}$	1169069154.565	29.4	89.7	2.8×10^3	> 30	> 0.99
GW170304	BBH (4,0)	47^{+8}_{-7}	$0.2^{+0.3}_{-0.3}$	$0.5^{+0.2}_{-0.2}$	1172680691.356	24.9	55.9	377	13.6	0.985
GW170727	BBH (4,0)	42^{+6}_{-6}	$-0.1^{+0.3}_{-0.3}$	$0.43^{+0.18}_{-0.17}$	1185152688.019	25.4	53.5	370	11.8	0.98
GW170425	BBH (4,0)	47^{+26}_{-10}	$0.0^{+0.4}_{-0.5}$	$0.5^{+0.4}_{-0.3}$	1177134832.178	28.6	37.5	15	0.65	0.77
GW170202	BBH (3,0)	$21.6^{+4.2}_{-1.4}$	$-0.2^{+0.4}_{-0.3}$	$0.27^{+0.13}_{-0.12}$	1170079035.715	26.5	41.7	6.3	0.25	0.68
GW170403	BBH (4,1)	48^{+9}_{-7}	$-0.7^{+0.5}_{-0.3}$	$0.45^{+0.22}_{-0.19}$	1175295989.221	31.3	31.0	4.7	0.23	0.56

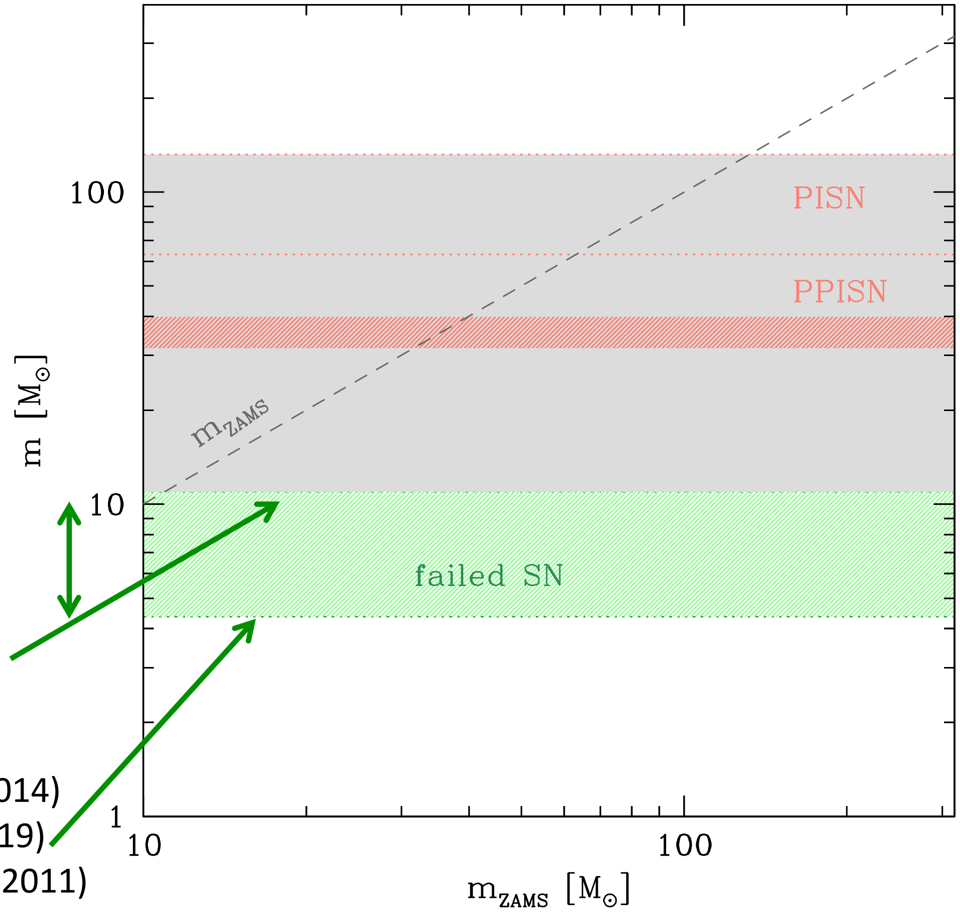
(O2 = 118 days)

Venumadhav et. al., (2019)

outline

- how do massive black holes form?
- when and where do they form?
- can we explore cosmic dawn with GWs?

Do we know the maximum black hole mass formed by a single isolated massive star?



when do massive stars explode?

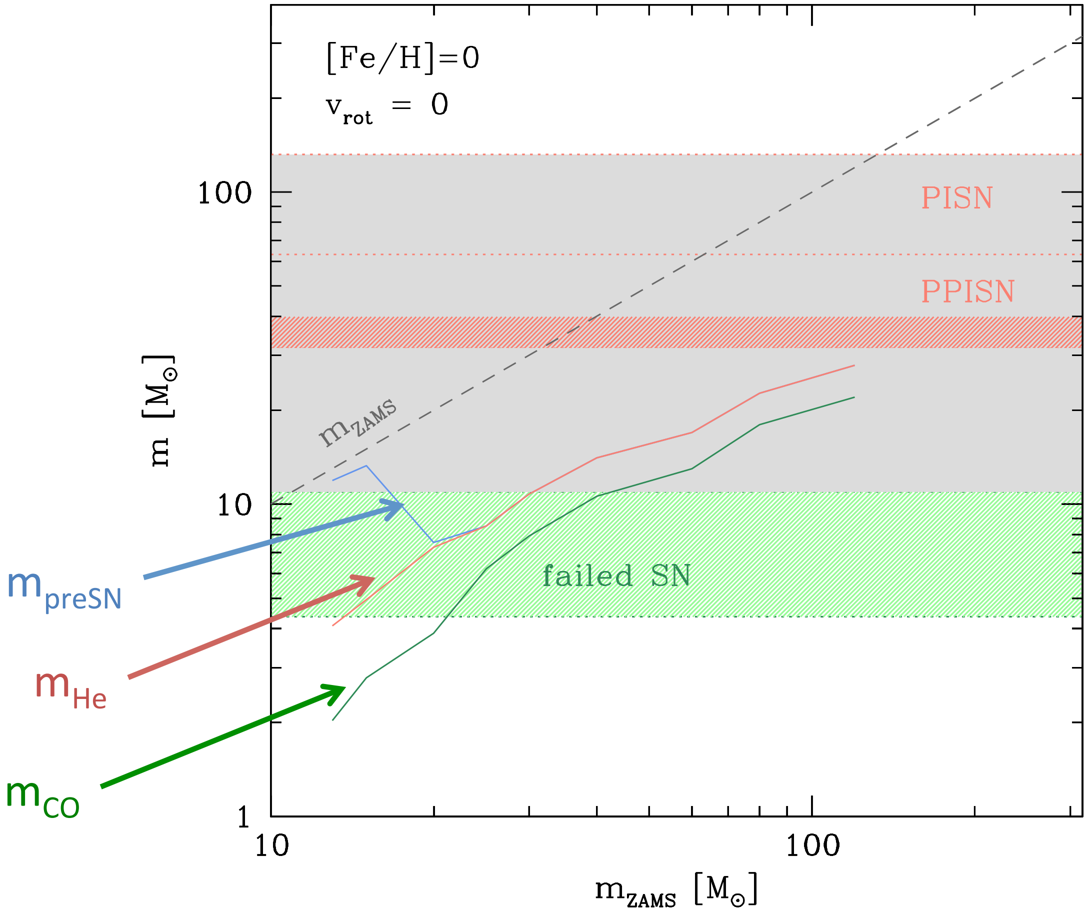
when mco ≥ 11 M_{sun}
(Fryer et al 2012)
when the compactness
$\xi_{2.5} > 2.5$ (Horiuchi et al. 2014)
$\xi_{2.5} > 3.0$ (Mapelli et al. 2019)
$\xi_{2.5} > 4.5$ (O'Connor & Ott 2011)

when do massive stars become pair-unstable ?

when mHe ≥ 33 M_{sun}
(Woosley 2017)
when mHe ≥ 40 M_{sun}
mco ≥ 32 M_{sun}
(Heger & Woosley 2002)
(Georgy et al. 2017)
(Limongi & Chieffi 2018)
when mHe ≥ 40 M_{sun}
(Leung et al. 2019)

see Nomoto's talk tomorrow

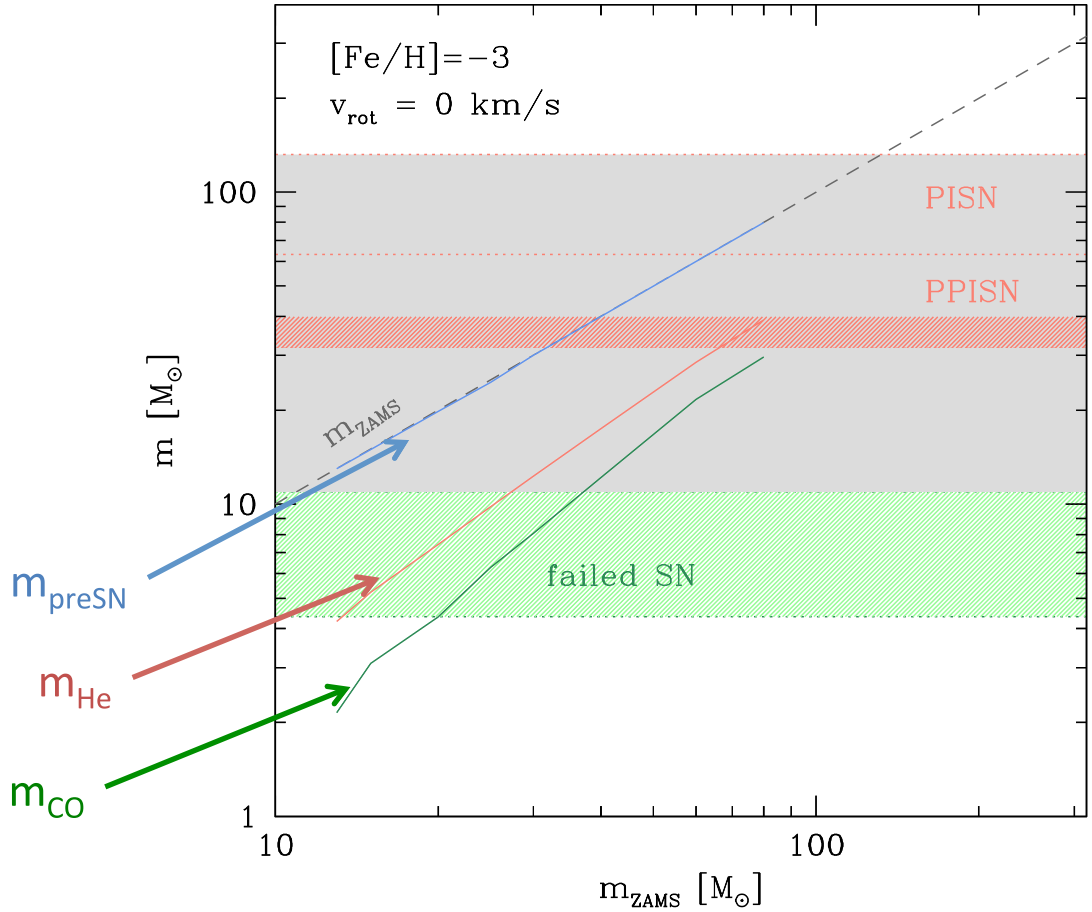
Do we know the maximum black hole mass formed by a single isolated massive star?



massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

13 $M_{sun} \leq m_{zams} \leq 120\ M_{sun}$ [Fe/H] = 0, -1, -2, -3 v_{rot} = 0, 150 km/s, 300 km/s

Do we know the maximum black hole mass formed by a single isolated massive star?



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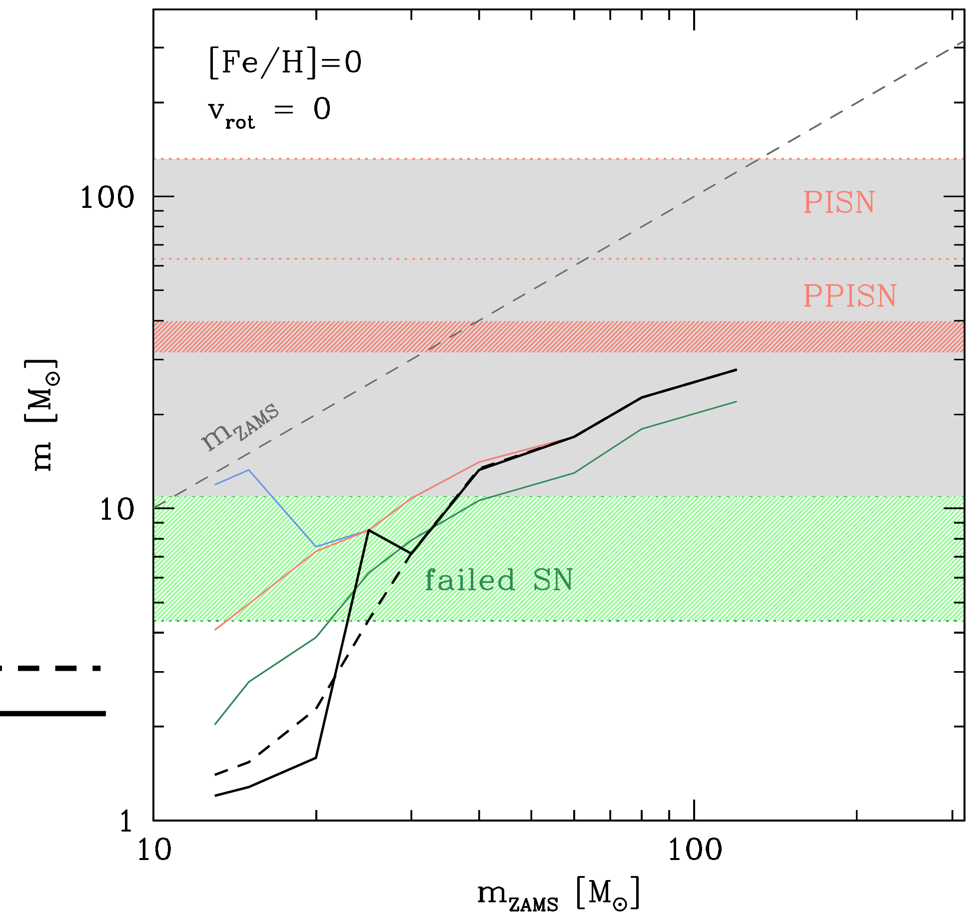

delayed SN
prompt SN
(Fryer et al. 2012)

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

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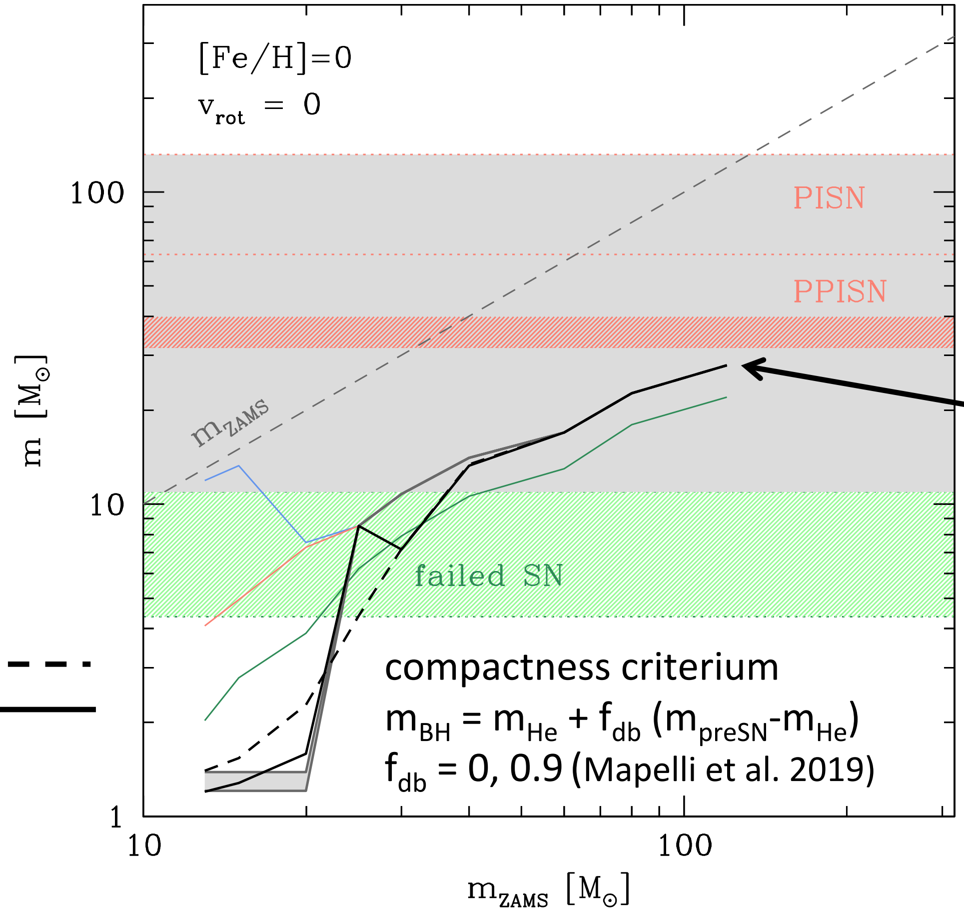

$m_{bh,max}$ = 28 M_{sun} set by mass loss

delayed SN
prompt SN
(Fryer et al. 2012)

compactness criterium

$m_{BH} = m_{He} + f_{db} (m_{preSN} - m_{He})$

f_{db} = 0, 0.9 (Mapelli et al. 2019)

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

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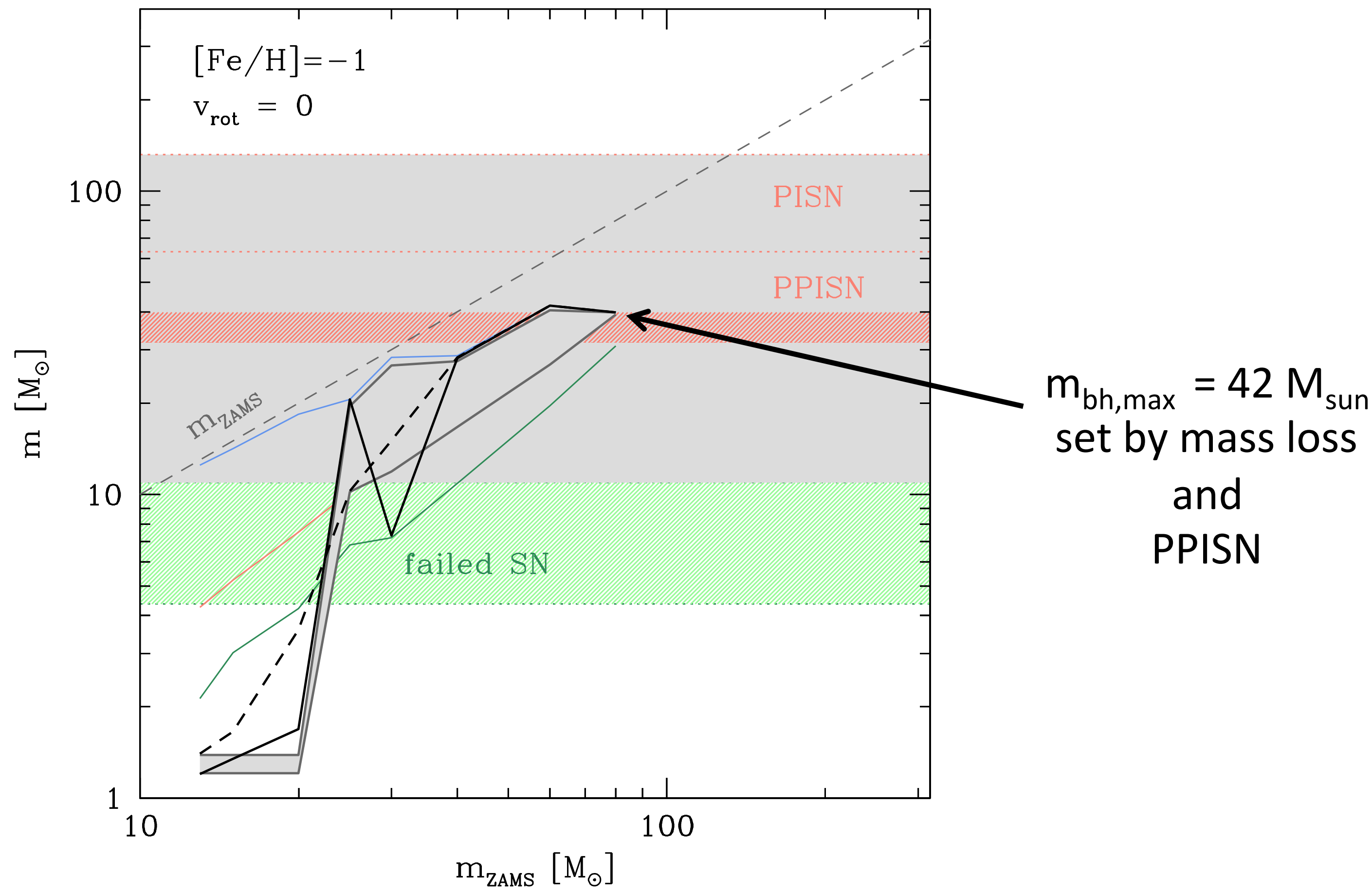

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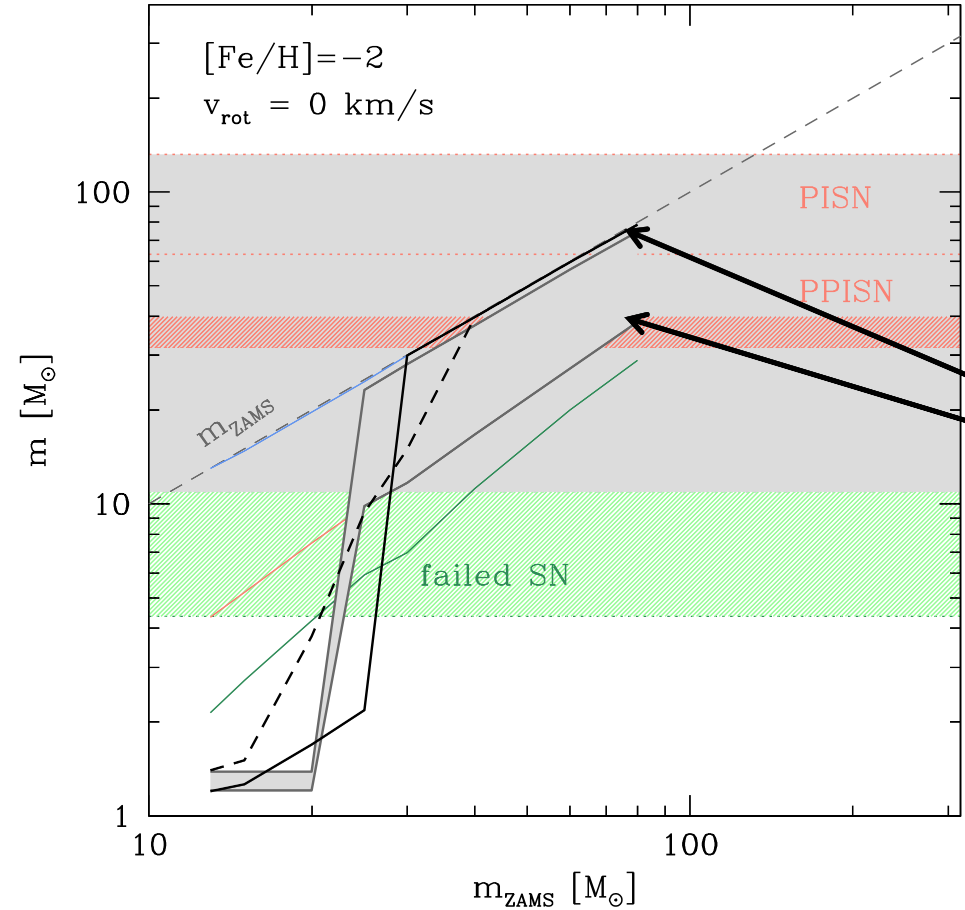

$m_{bh,max}$ = 78.60 M_{sun}

$m_{bh,max}$ = 38.30 M_{sun}

set by PPISN and by f_{db}

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

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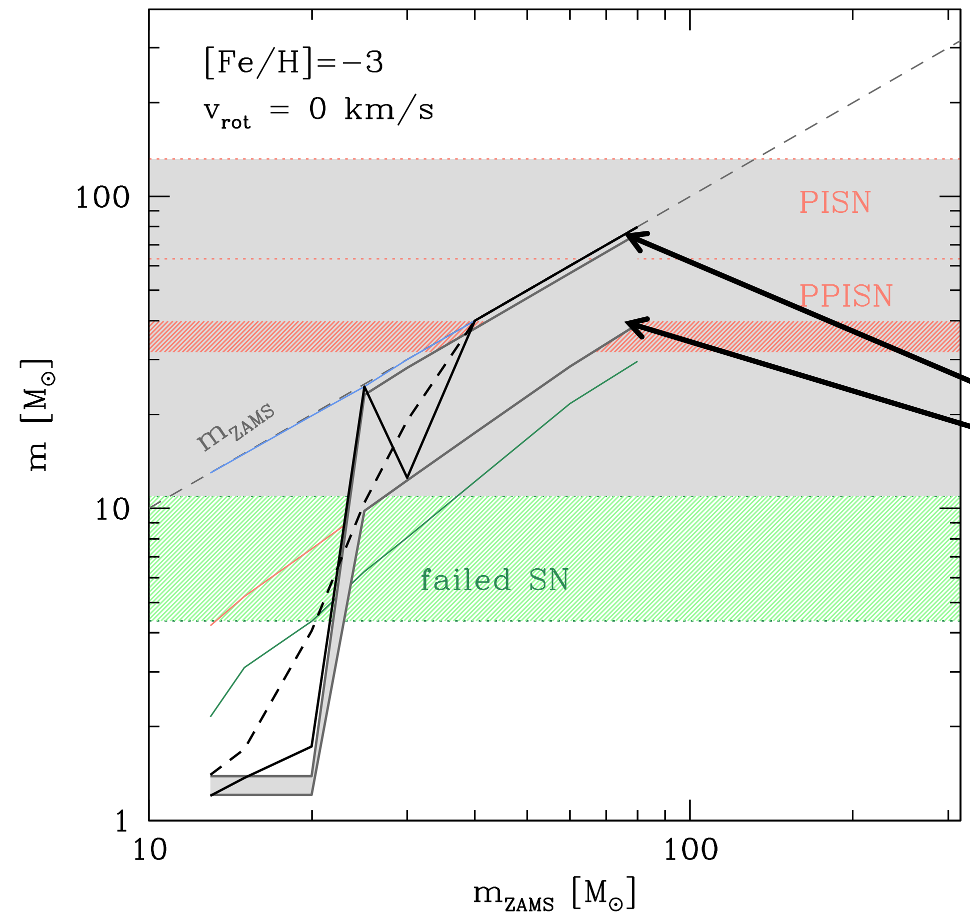

$m_{bh,max}$ = 79.90 M_{sun}

$m_{bh,max}$ = 38.90 M_{sun}
set by PPISN
and by f_{db}

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

13 $M_{sun} \leq m_{zams} \leq 120$ M_{sun} [Fe/H] = 0, -1, -2, -3 v_{rot} = 0, 150 km/s, 300 km/s

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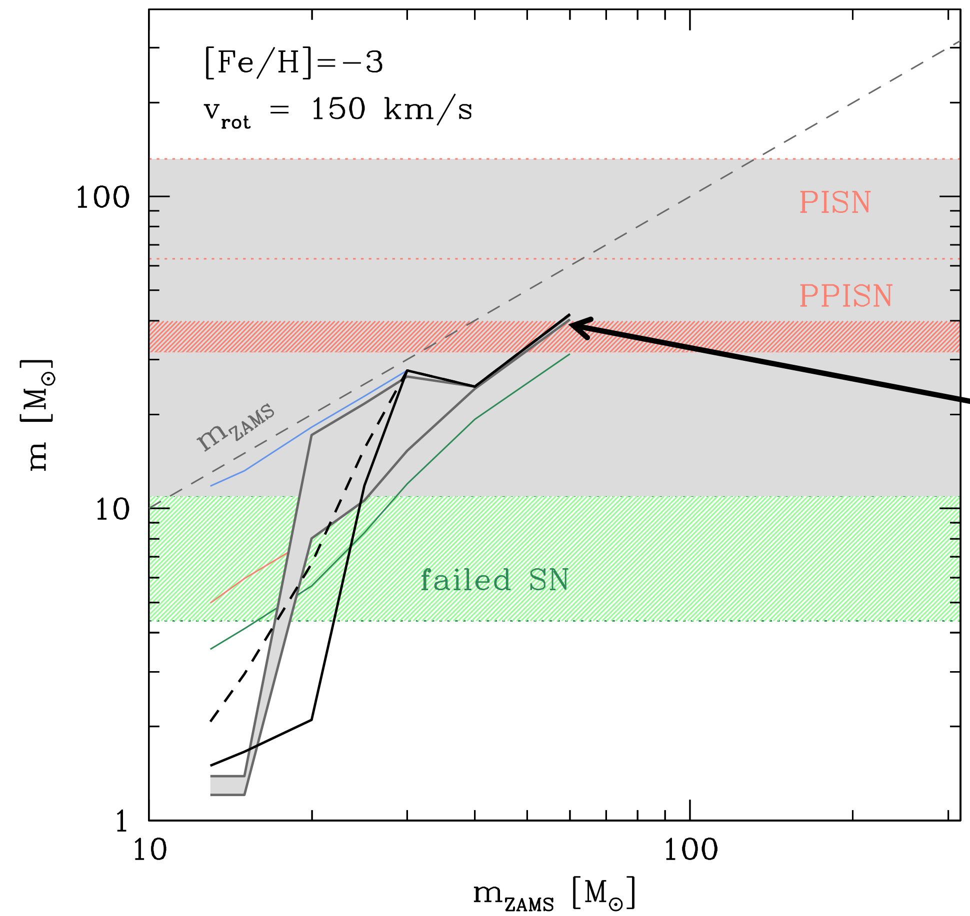
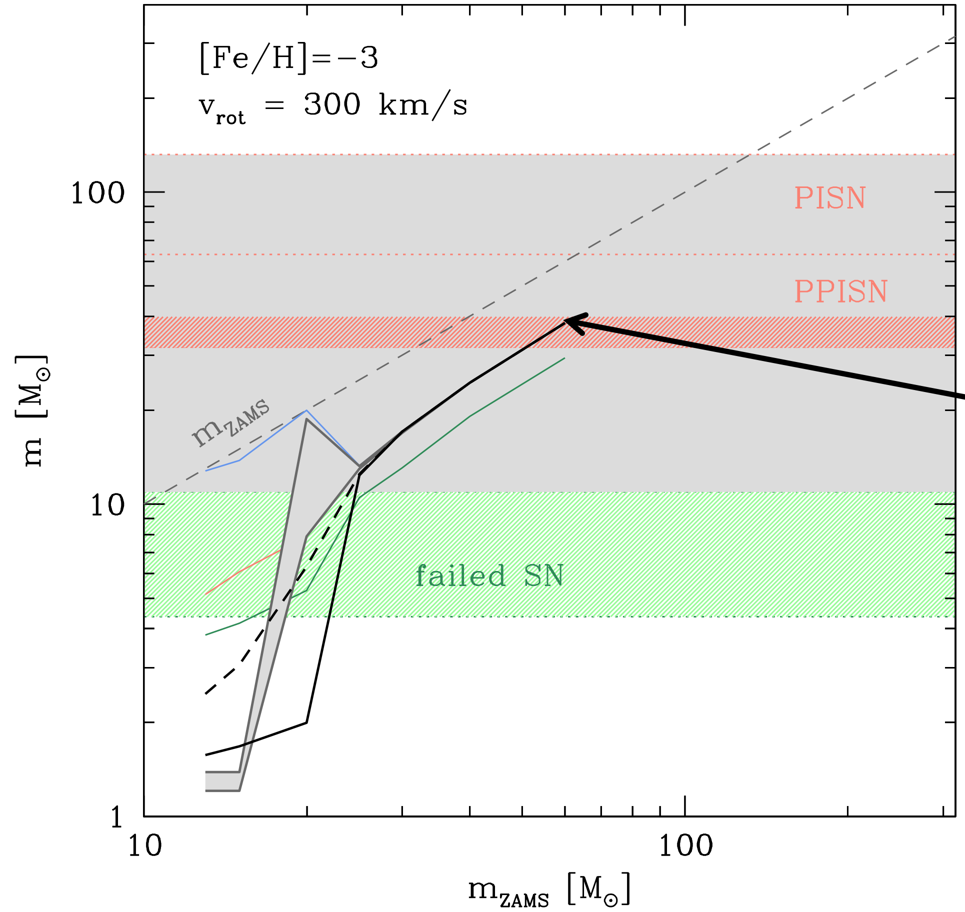


$m_{bh,max}$ = 41.9 M_{sun}
set by mass loss
and
PPISN

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

13 $M_{sun} \leq m_{zams} \leq$ 120 M_{sun} [Fe/H] = 0, -1, -2, -3 v_{rot} = 0, 150 km/s, 300 km/s

Do we know the maximum black hole mass formed by a single isolated massive star?



$m_{bh,max}$ = 38.1 M_{sun}
set by mass loss
and
PPISN

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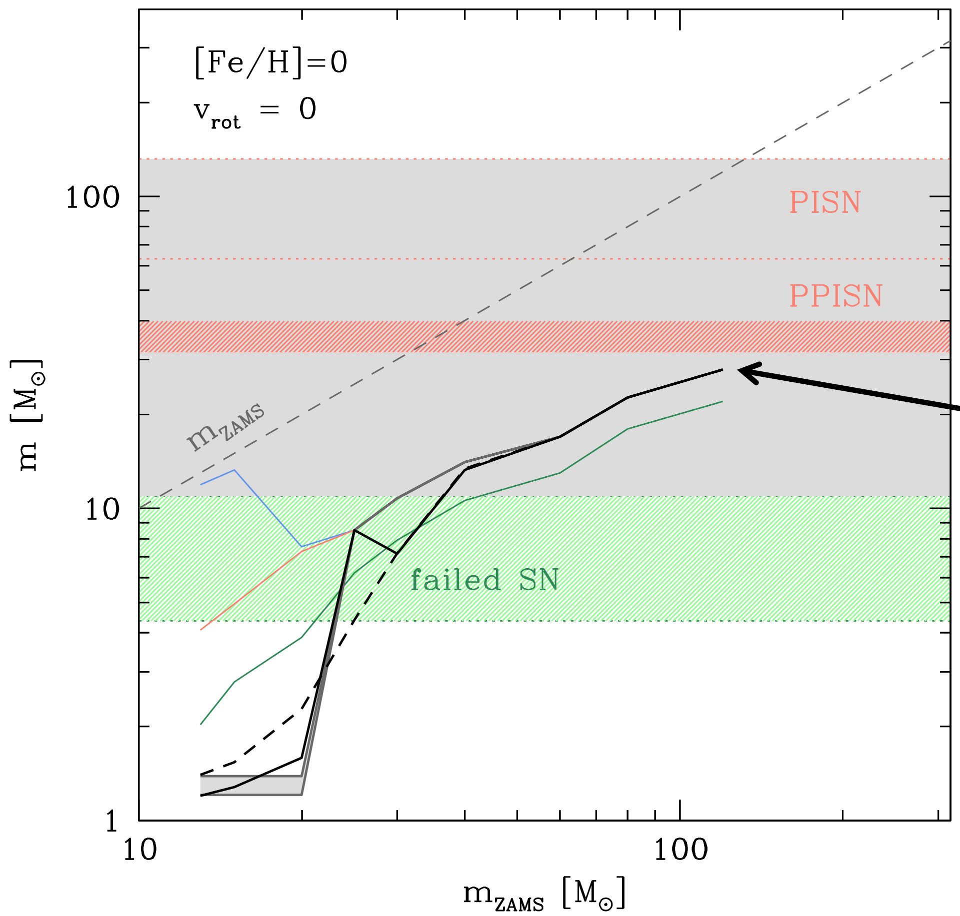

$m_{bh,max}$ = 28 M_{sun}
set by mass loss

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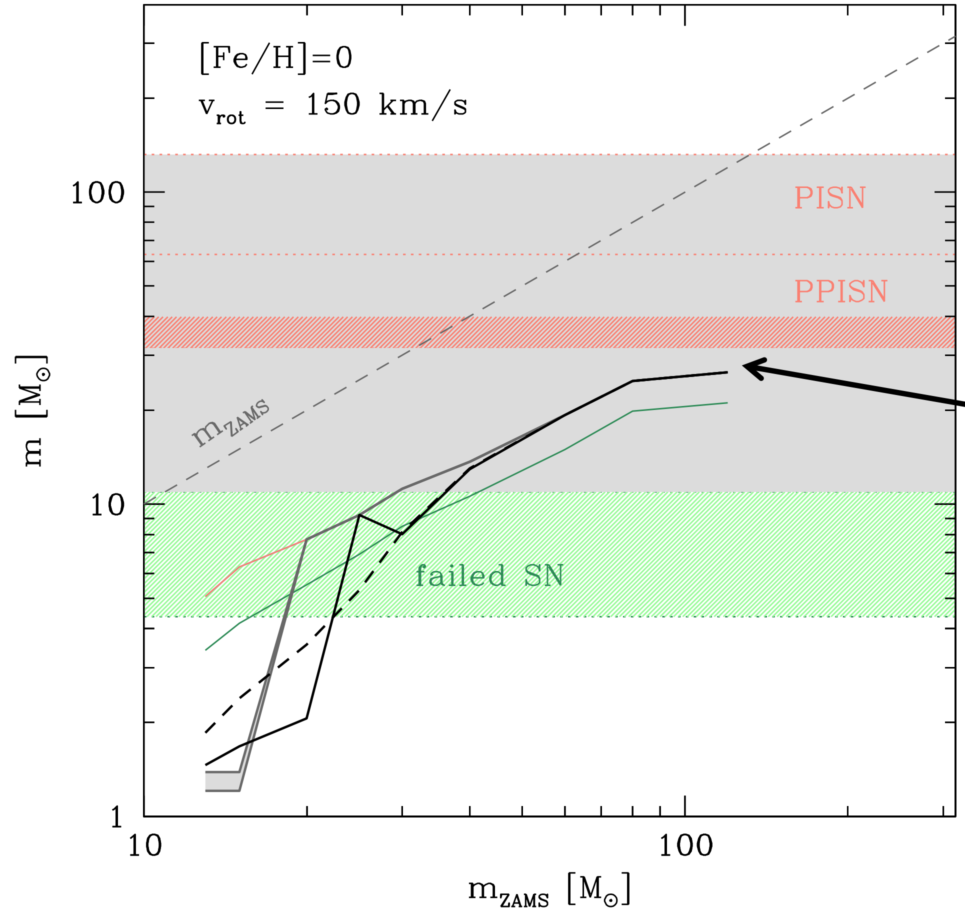

$m_{bh,max}$ = 26.5 M_{sun}
set by mass loss

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

13 M_{sun} ≤ m_{zams} ≤ 120 M_{sun} [Fe/H] = 0, -1, -2, -3 v_{rot} = 0, 150 km/s, 300 km/s

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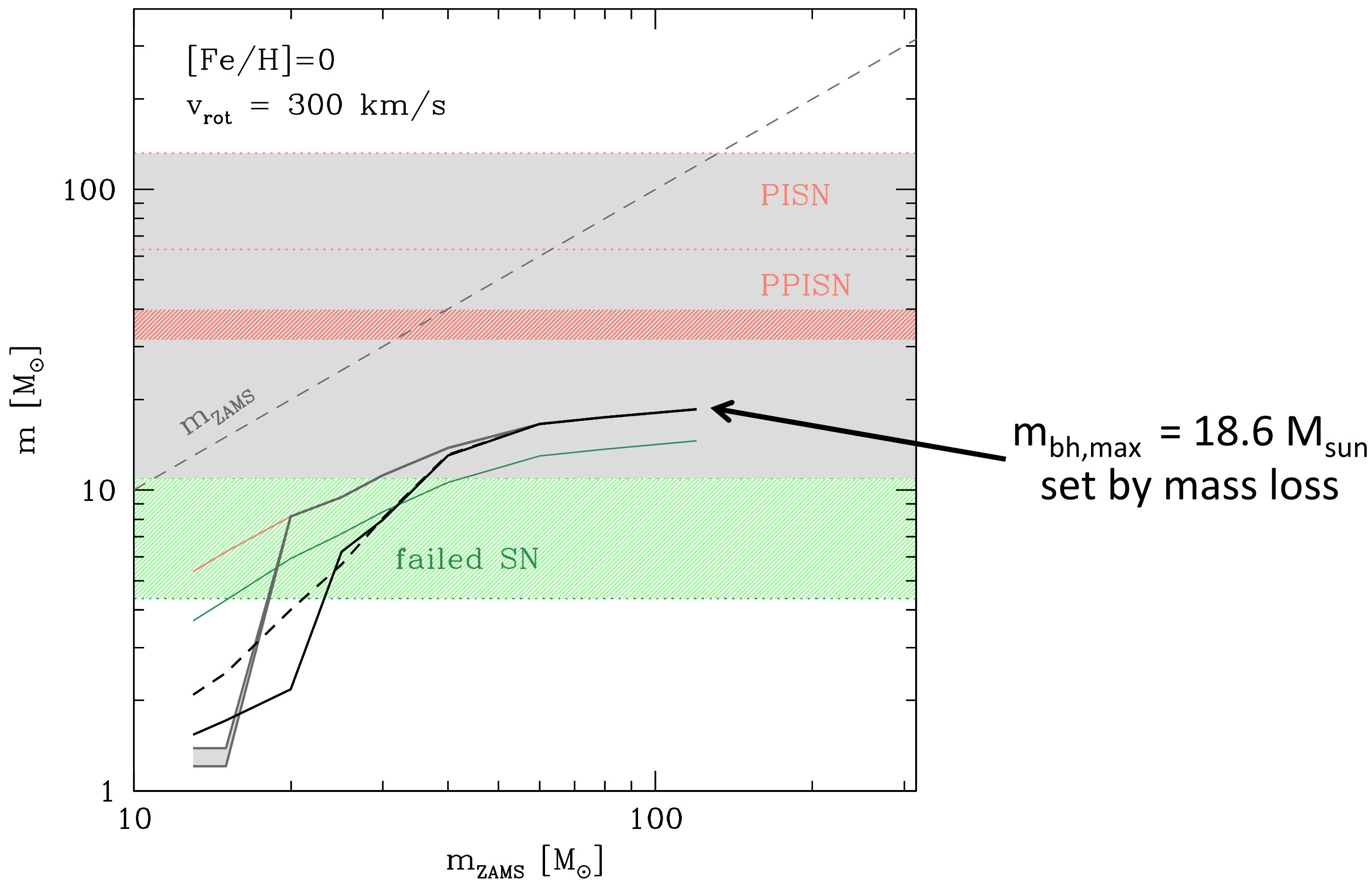

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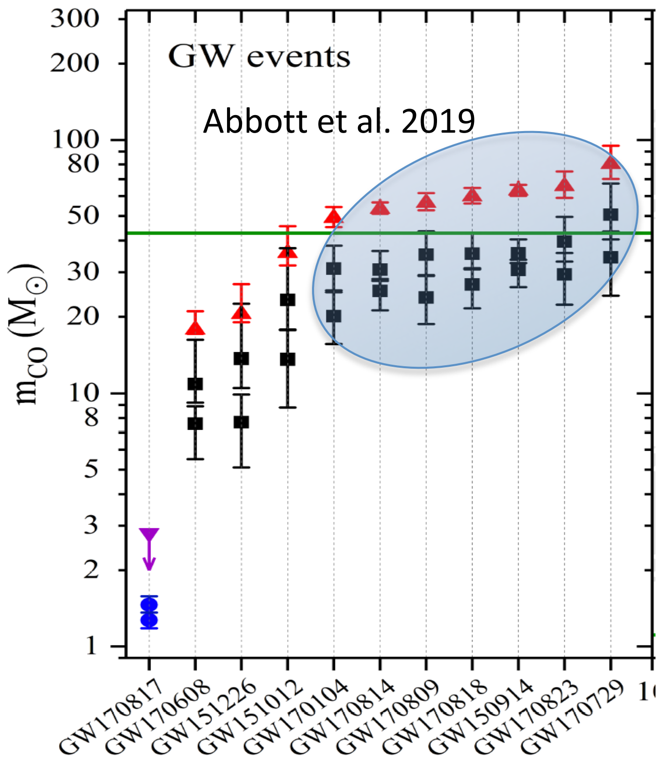
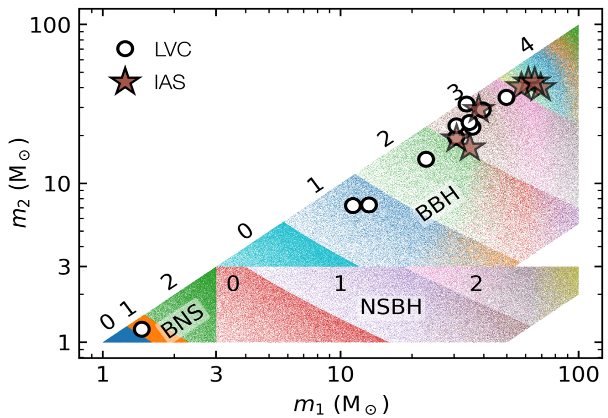
astrophysical implications of known black hole masses

Given our current understanding of massive stellar evolution:

- ✓ At solar metallicity it is hard to form black holes with masses > 30 M_{sun}
- ✓ Black holes with masses > 50 M_{sun} can form at very low Z (≤ 10^{-2} Z_{sun})
- ✓ Non rotating very metal poor stars can form ≈ 80 M_{sun} black holes



O2: Six New Events in Banks 3 and 4



Name	Bank	$\mathcal{M}^{\rm det}(M_\odot)$	$\chi_{\rm eff}$	z	GPS time[a]	$\rho^2_{\rm H}$	$\rho^2_{\rm L}$	FAR^{-1}(O2)[b]	$\frac{W(\rm event)}{\mathcal{R}(\rm event\|\mathcal{N})}$ (O2)	$p_{\rm astro}$
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(O2 = 118 days)

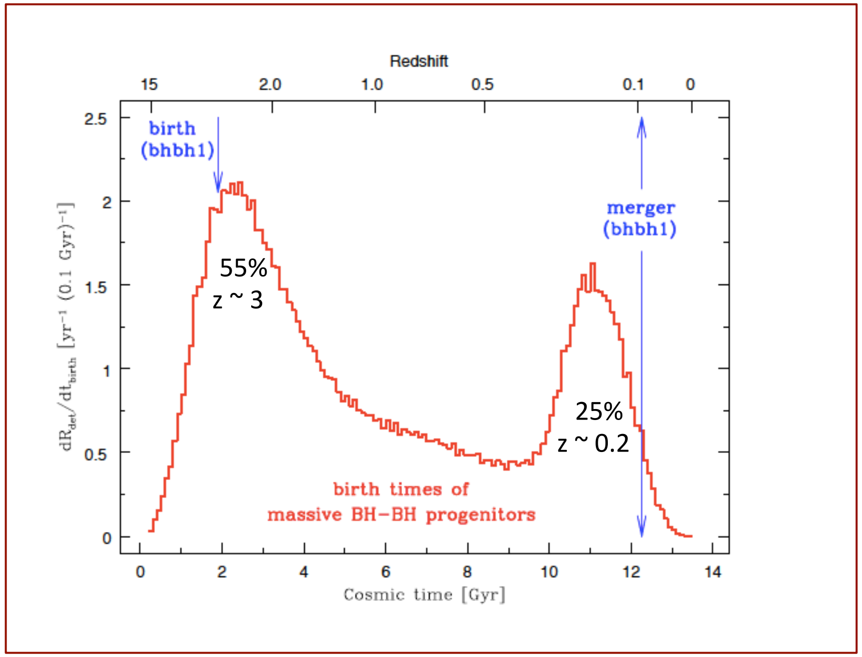
Venumadhav et. al., (2019)

the formation environment of field black hole binaries

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

binary population synthesis to generate synthetic BH binaries with different initial Z
+
metallicity-corrected cosmic star formation rate density evolution

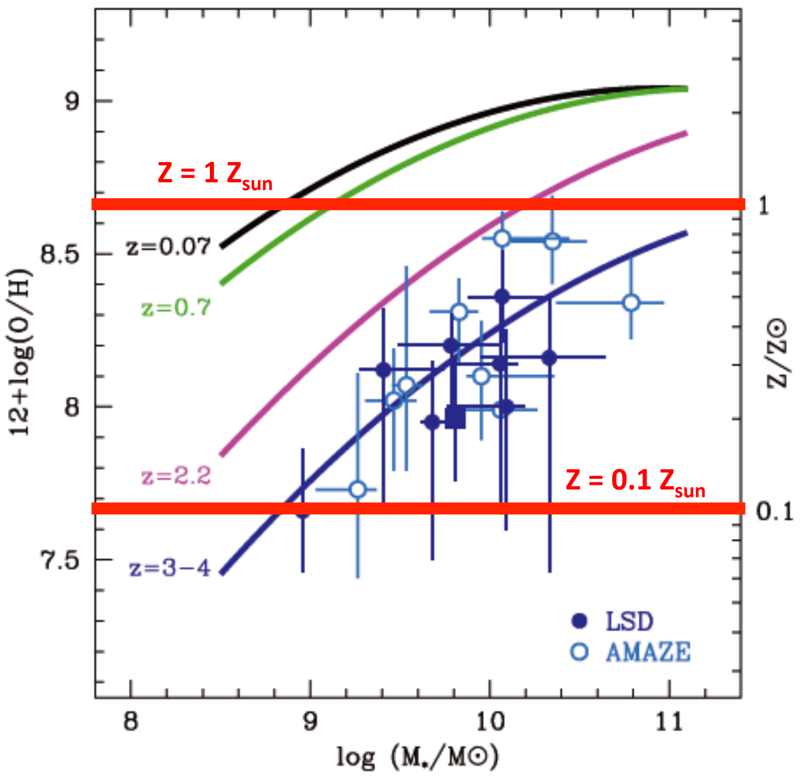
bimodal formation rate of GW150914-like systems



Belczynski et al. (2016)

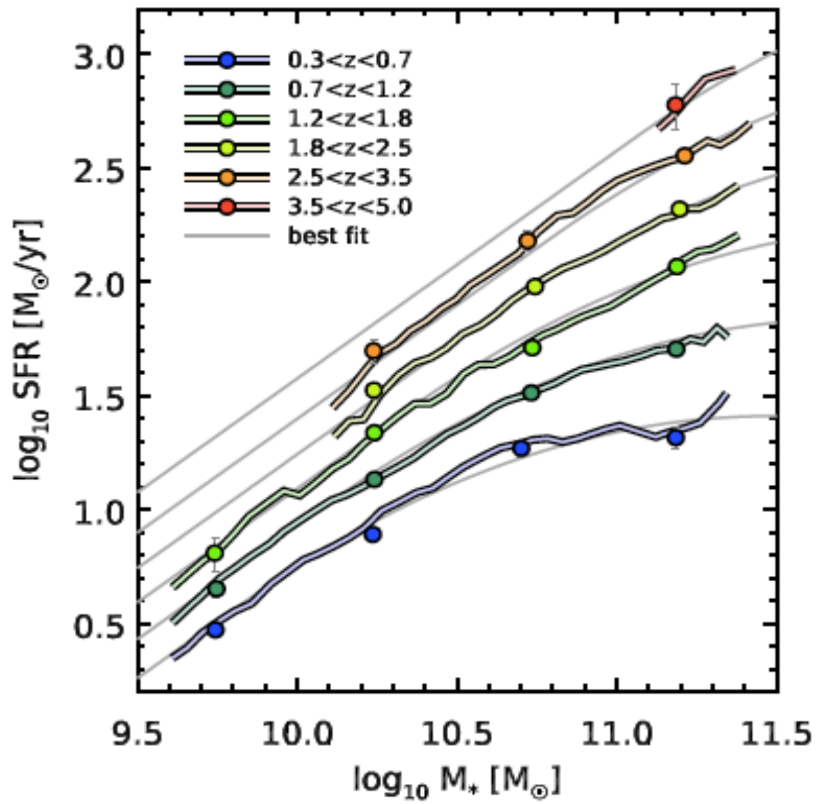
observed galaxy scaling relations

redshift-dependent mass-metallicity relation



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

redshift-dependent galaxy main sequence



Schreiber et al. (2015)

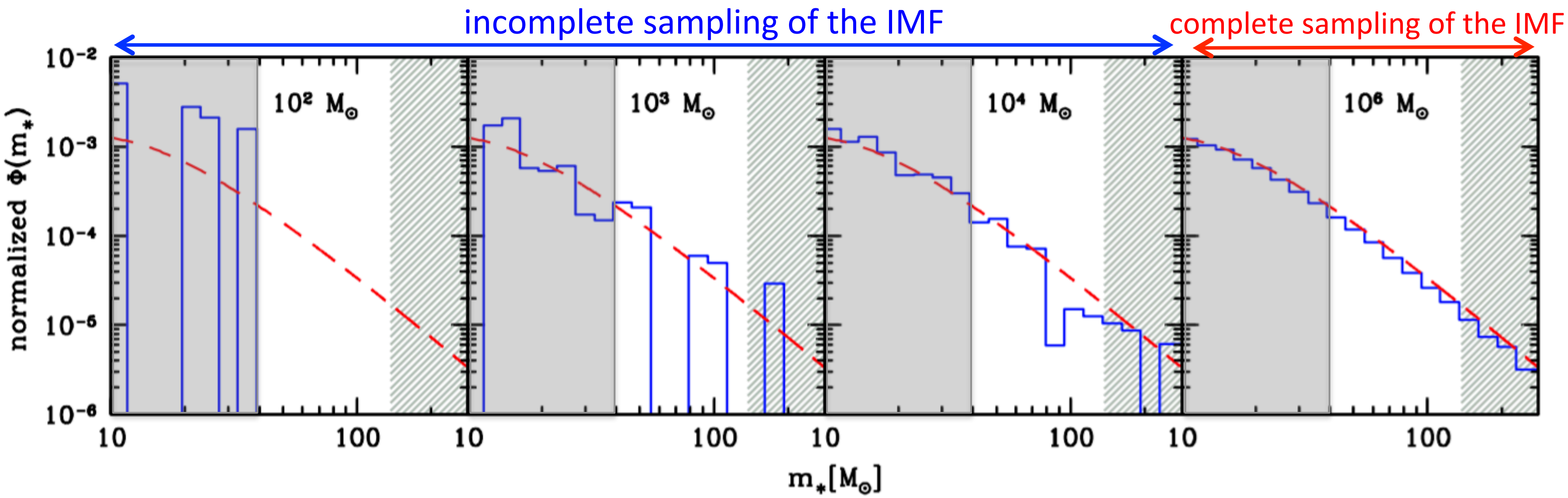
stars with $Z < 1\ Z_{sun}$ form in low-mass galaxies at $z < 1$ at low rates or in galaxies with a broader range of stellar masses and SFRs at higher-z

stars with $Z < 0.1\ Z_{sun}$ form in low-mass, low SF galaxies at all redshifts

In low star forming regions there is a low probability to form massive stars

$$\Phi(m) = \frac{dN}{dm} \propto m^{\alpha-1}\exp\left(-\frac{m_{ch}}{m}\right)$$

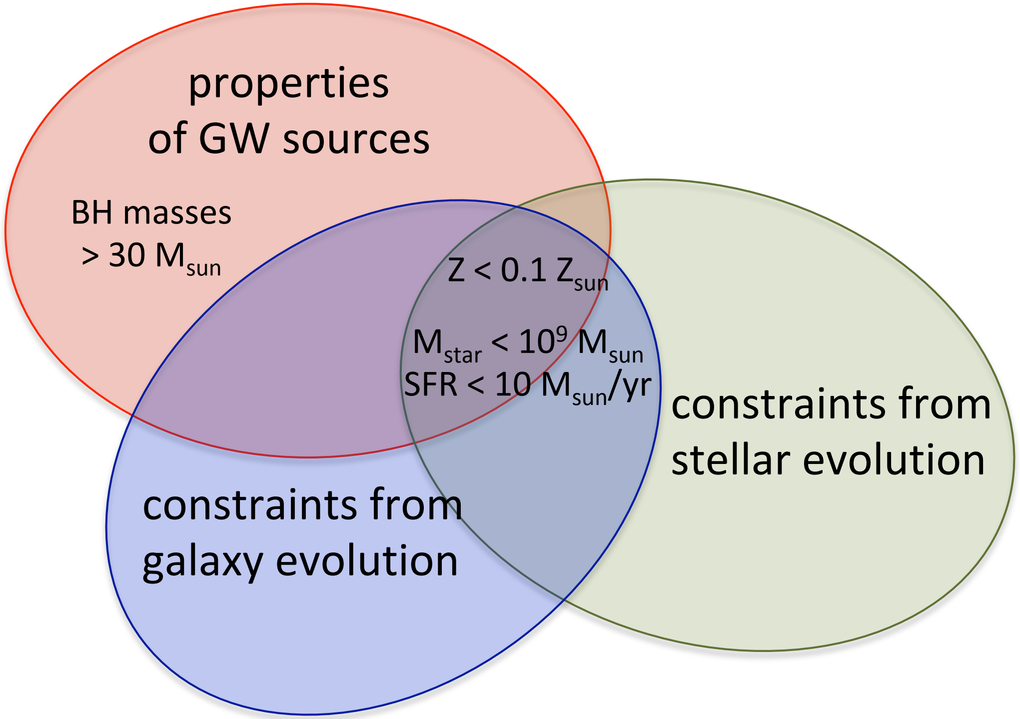
$m_{ch} = 20\ M_{sun}$ $\alpha = 1.35$ $m_* = [10 - 300]\ M_{sun}$



Valiante+2016; de Bennassuti+2016

→ Large number of massive binary stars are required to extract potential heavy black hole binary systems

the road ahead: from cosmic averages to individual formation sites



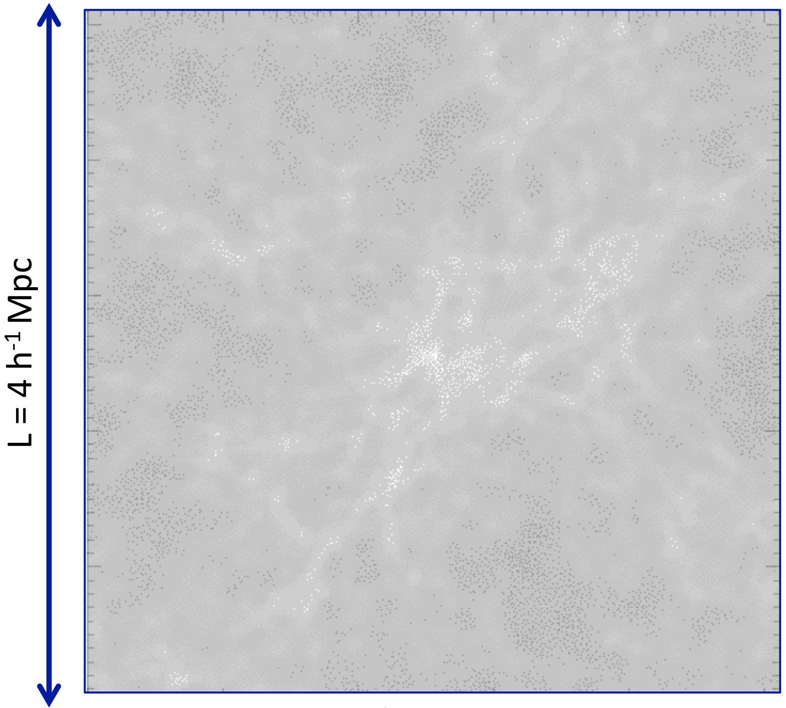
see also posters by
Mandhai and Chruślińska

- make tailored predictions for specific classes of GW sources
- use GW observations to improve stellar and galaxy evolution models

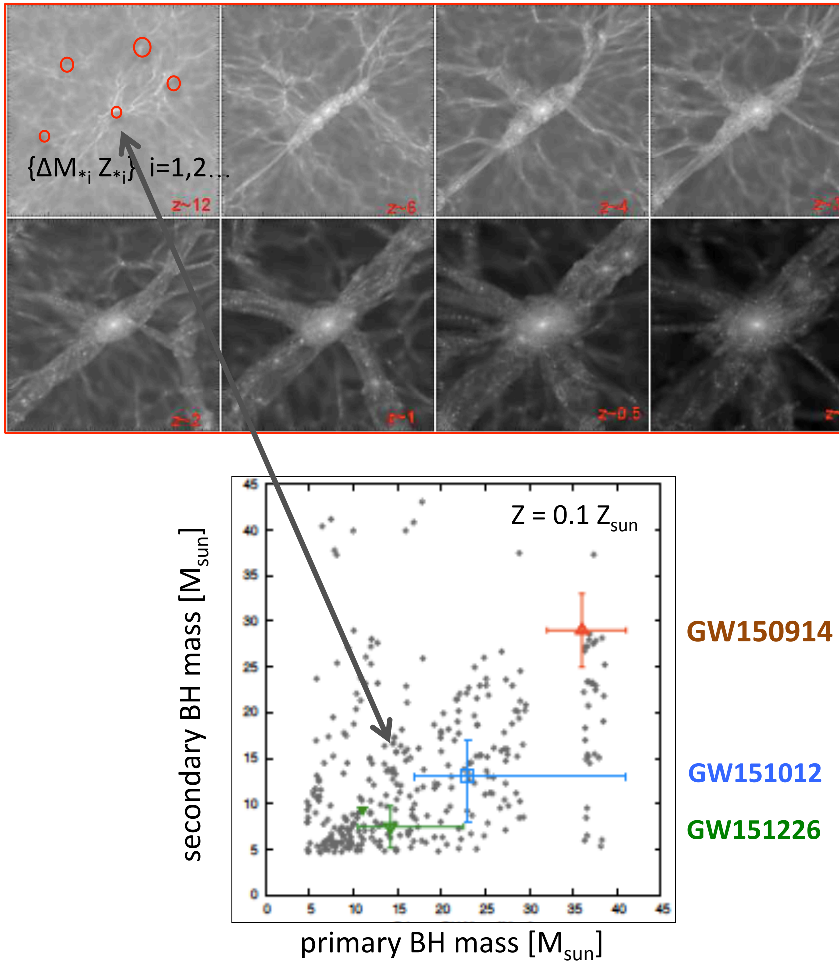
Lamberts et al. (2016); O'Shaughnessy et al. (2016); Ebert et al. (2017); RS et al. (2017); Chakrabarti et al. 2017; Mapelli et al. (2017, 2018); Marassi et al. (2019); Artale et al. (2019); Toffano et al. (2019); Belczynski et al. (2019); Chruślińska & Nelemans 2019

the formation and coalescence sites of the first GW events

cosmological simulation of a Local Group – like region



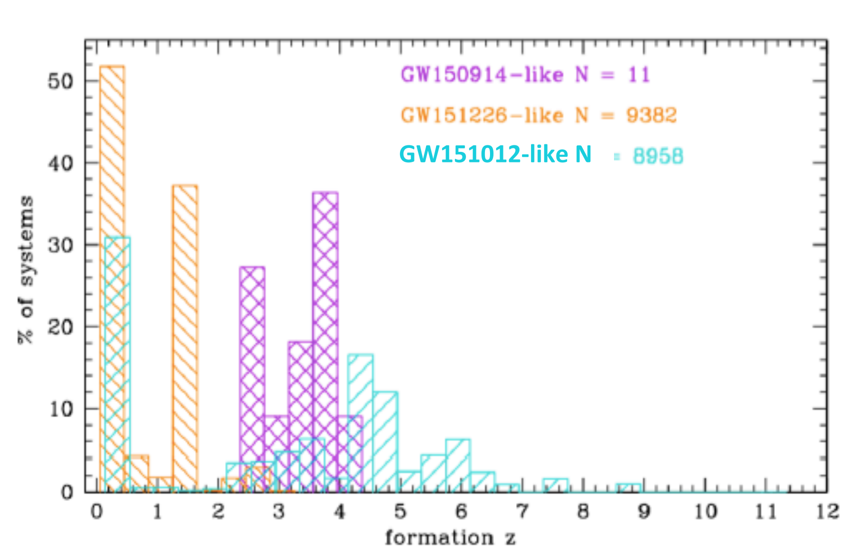
Graziani et al. 2015, 2017



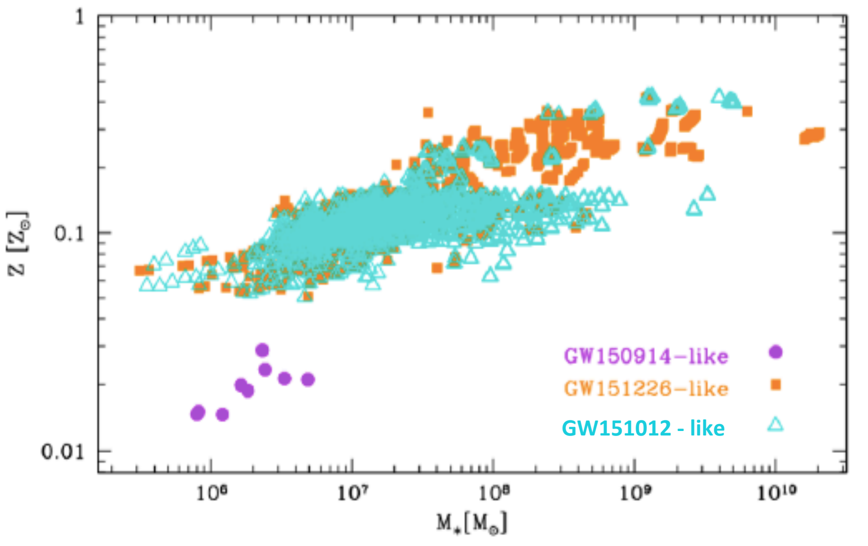
RS, Graziani, Marassi, Spera, Mapelli, Alparone, de Bennassuti 2017

the formation sites of the first GW events

distribution of formation redshifts



properties of formation sites



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

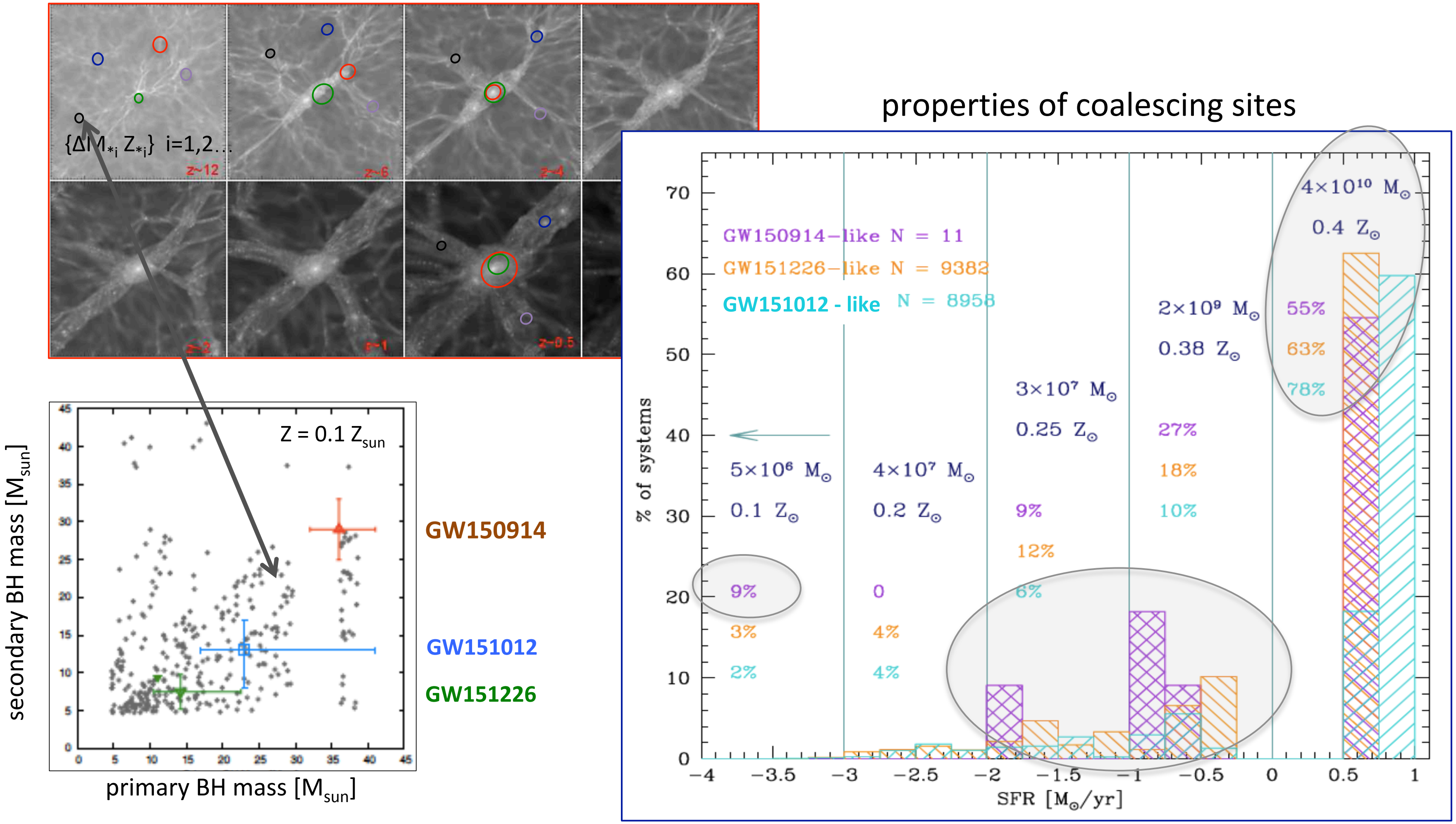
90% of GW151226-like systems form at $z_f < 2$ in galaxies with $M_* > 10^8\ M_{sun}$

70% of GW151012-like systems have $z_f > 2$, 50% have $z_f > 4$, and 6% have $z_f > 6$
70% of GW151012-like systems form in galaxies with $M_* > 10^8\ M_{sun}$

the formation sites of GW150914 are not resolved in large $(100\ h^{-1}\ cMpc)^3$ cosmological simulations (Illustris, Eagle)

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

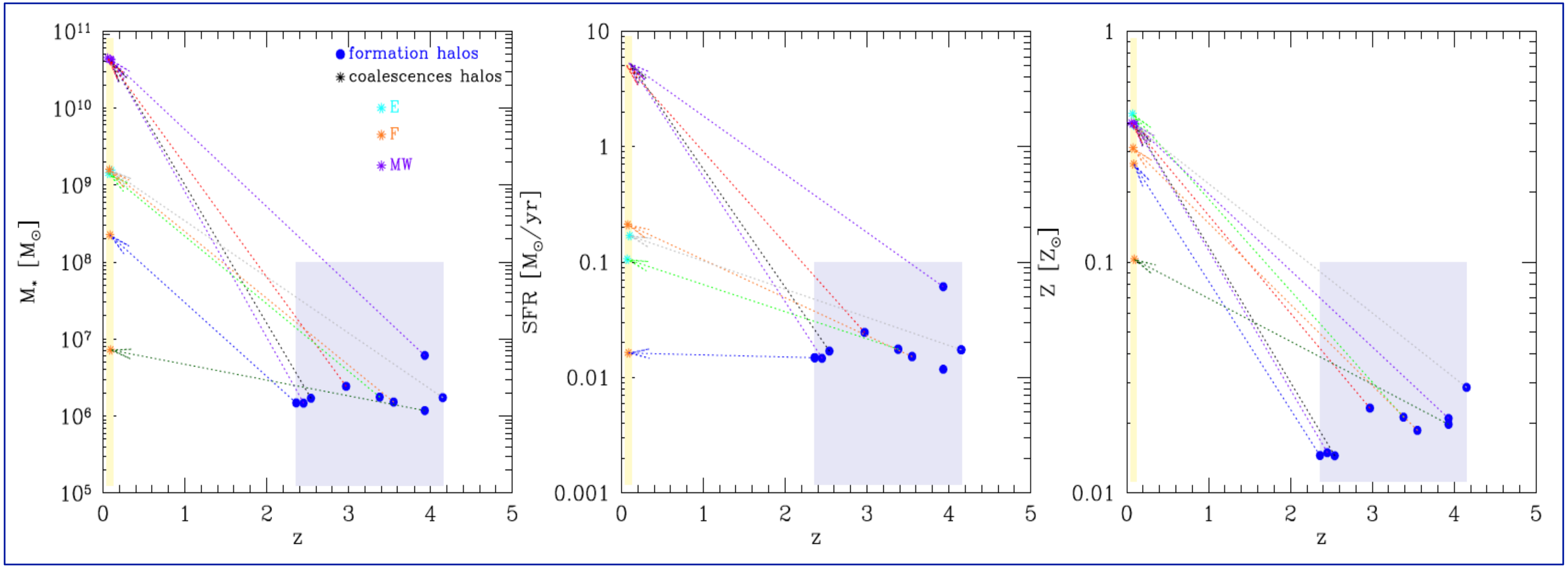
the coalescence sites of the first GW events



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

evolution of dwarf galaxies hosting GW150914-like events

individual evolutionary histories



MW: GW150914-like events in the most-massive MW-like progenitor galaxy

F: GW150914-like events in dwarf satellites of the MW

E: GW150914-like events in isolated dwarf galaxies

$2.36 \leq z_f \leq 4.15$

$0.06 \leq z_m \leq 0.12$

Marassi, Graziani, Ginolfi, RS, Mapelli, Spera, Alparone 2019

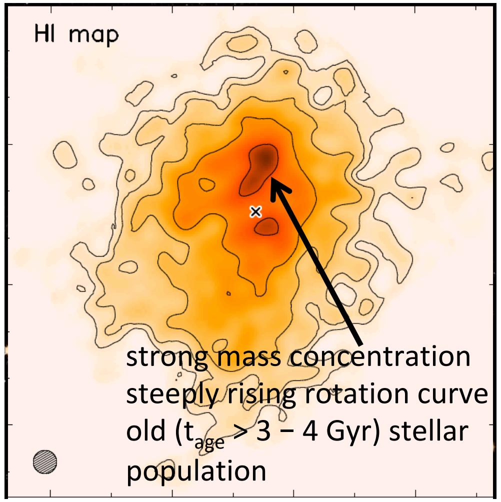
evolution of dwarf galaxies hosting GW150914-like events

observed analogues of (E and F) GW150914 hosts in DGS and ALLSMOG surveys

(gID) Obs.	$z_c \rightarrow z_s; z_{obs}$	Z [12+log(O/H)]	log($M_\star$) [$M_\odot$]	log(SFR) [$M_\odot$/yr]
(F1) UGC4483 [b]	$\mathbf{0.095 \rightarrow 0.0}$; 0.0005	$\mathbf{7.53 \rightarrow 7.68}$; 7.46 ± 0.02 [d]	$\mathbf{6.86 \rightarrow 6.87}$; 6.89 ± 0.22	**(-)→(-)**; -2.21 ± 0.18
(E1) PGC1446233 [a]	$\mathbf{0.072 \rightarrow 0.02}$; 0.023	$\mathbf{7.48 \rightarrow 8.39}$; 8.38 [c]	$\mathbf{9.15 \rightarrow 9.19}$; 9.11 ± 0.09	$\mathbf{-0.98 \rightarrow -1.05}$; -0.94 ± 0.28

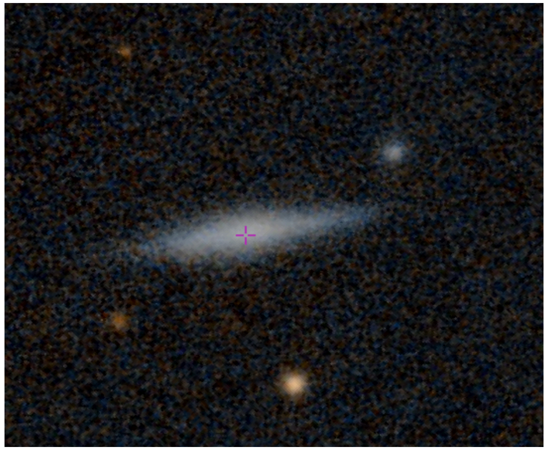
[a] Cicone et al. (2017). [b] Rémy-Ruyer et al. (2015). [c] Calibration from Marino et al. (2013). [d] Rémy-Ruyer et al. (2013).

UGC 4483 ← → F system



Lelli et al. 2013

PGC1446233 ← → E system



Cicone et al. 2017

MW: GW150914-like events in the most-massive MW-like progenitor galaxy
F: GW150914-like events in dwarf satellites of the MW
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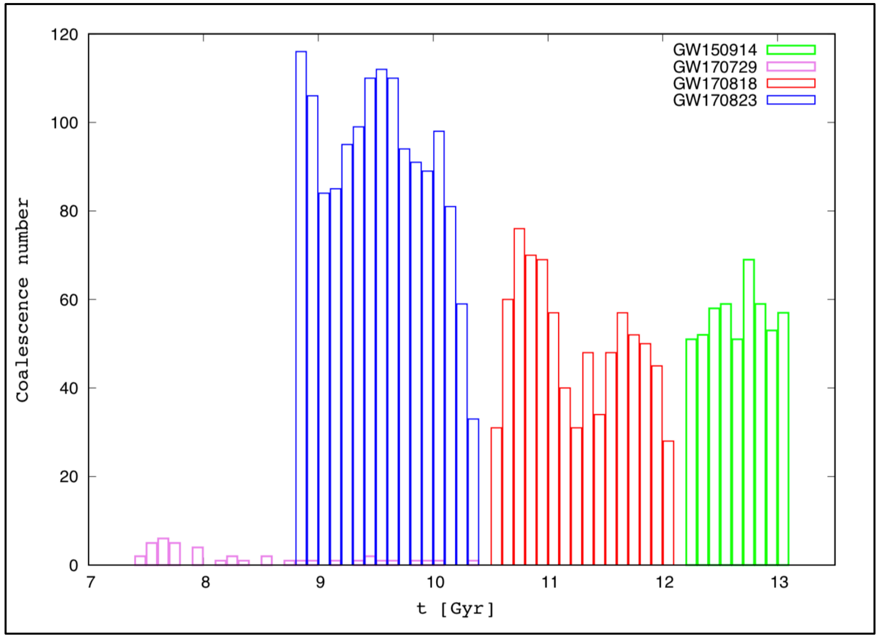
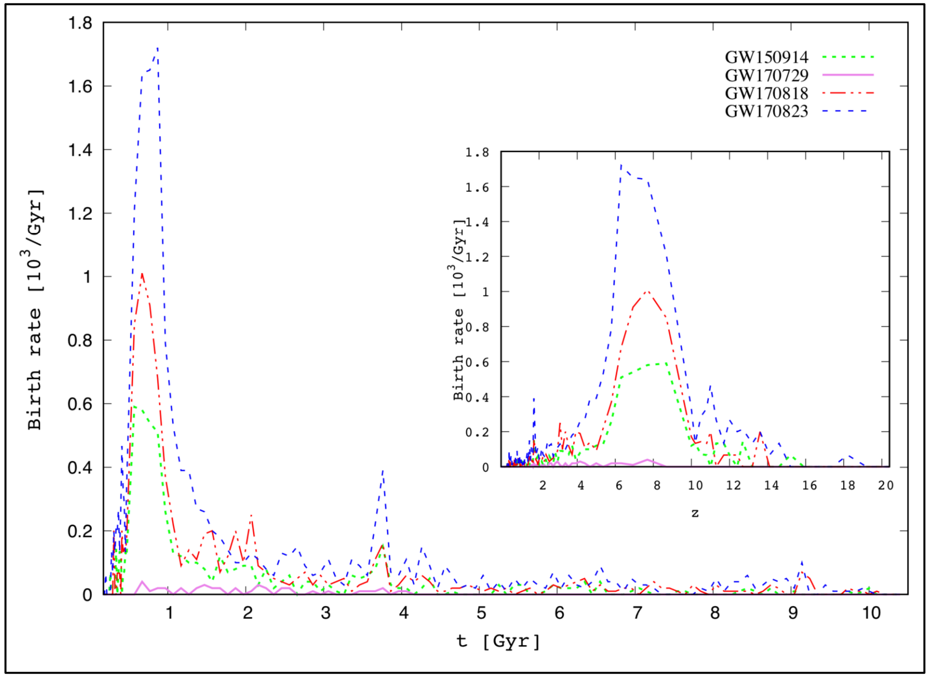
Marassi, Graziani, Ginolfi, RS, Mapelli, Spera, Alparone 2019

fossils of the pre-reionization epoch

selection of the 4 heaviest BH-BH in O1+O2



birth-rate of the 4 heaviest BH-BH in O1+O2



Graziani et al. in prep

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$M_f/M_\odot$	d_L/Mpc	z
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$63.1^{+3.3}_{-3.0}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$80.3^{+14.6}_{-10.2}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$59.8^{+4.8}_{-3.8}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$65.6^{+9.4}_{-6.6}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$

Summary (I)

- models suggest that the maximum BH mass formed from single stellar evolution can be as large as 80 Msun if the star has [Fe/H] = -3 and it is not rotating

- the heavy black hole binaries observed in O1 and O2 require low metallicity in their formation environment

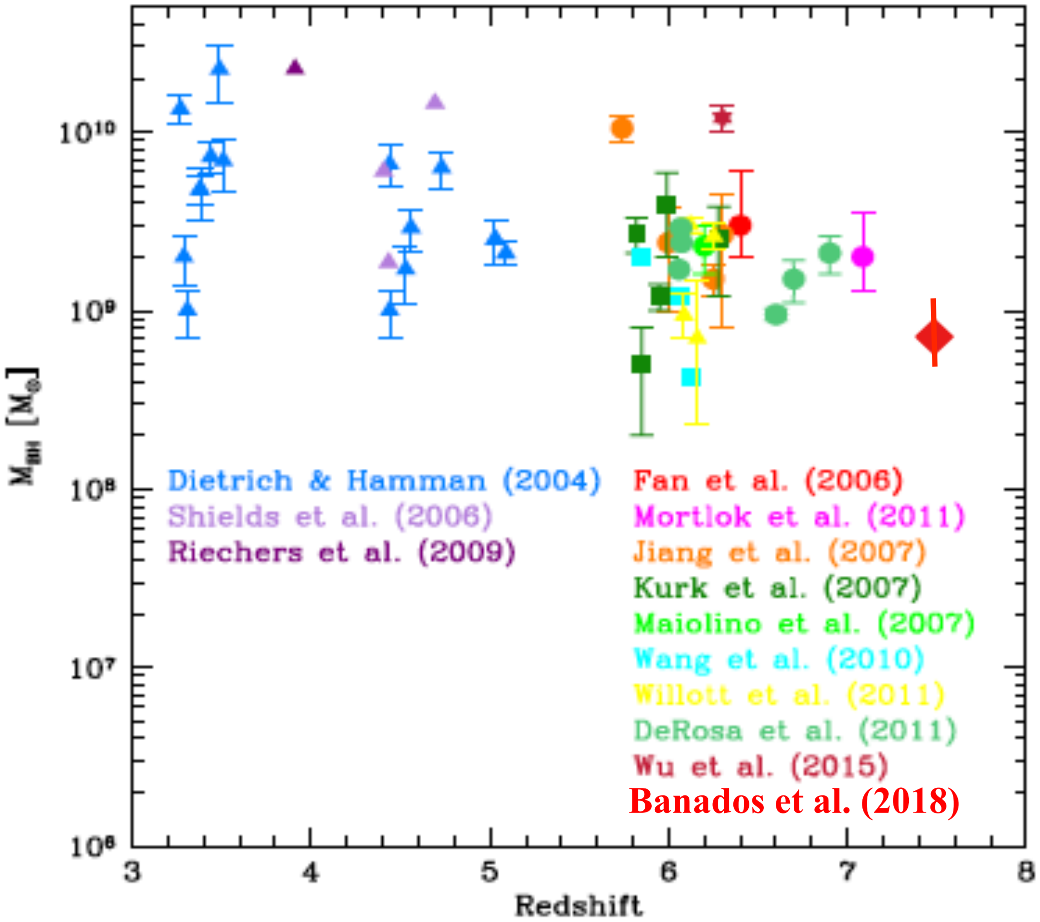
- low metallicity star forming regions are preferentially hosted in dwarf-like galaxies at high-z → low star formation rates → low statistics of the most massive stellar binaries

- the heaviest BHBH in O1 and O2 could have formed prior to cosmic reionization (peak formation at $6 < z < 8$)

these heavy BH-BH are fossils of stellar populations that can not be detected by current and future telescopes

the most distant supermassive BHs

a subsample of high-z SMBHs



Valiante et al. 2017

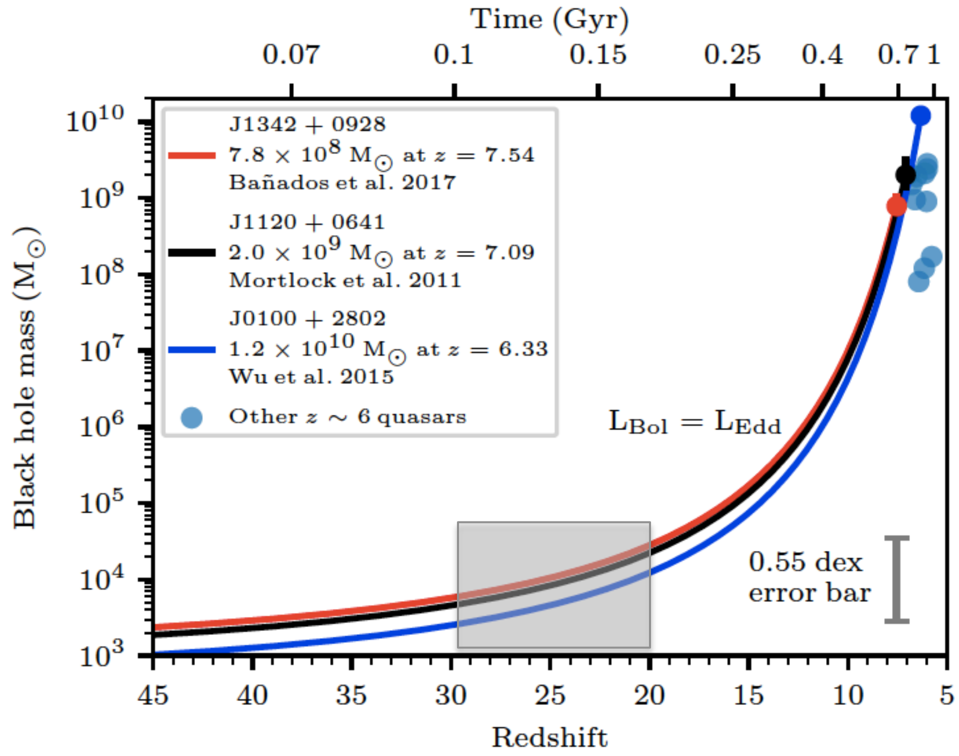
Decarli, priv comm:

~ 340 quasars at z>5.5 ~ 190 at z > 6.0 41(+6) at z > 6.5 5(+1) at z > 7.0

the first super-massive black holes

How do these SMBHs grow in less than 1 Gyr?

$M_{SMBH}(t) = M_{seed}(t_{form})\ e^{[(1-\varepsilon)/\varepsilon]\Delta t/tEdd}$ $\varepsilon = 0.1$ $t_{Edd} = 0.45$ Gyr



Banados et al. 2018

models of SMBH growth require massive seeds (> 10^3 - 10^5 M_{sun}) and/or episodes of super-Eddington accretion

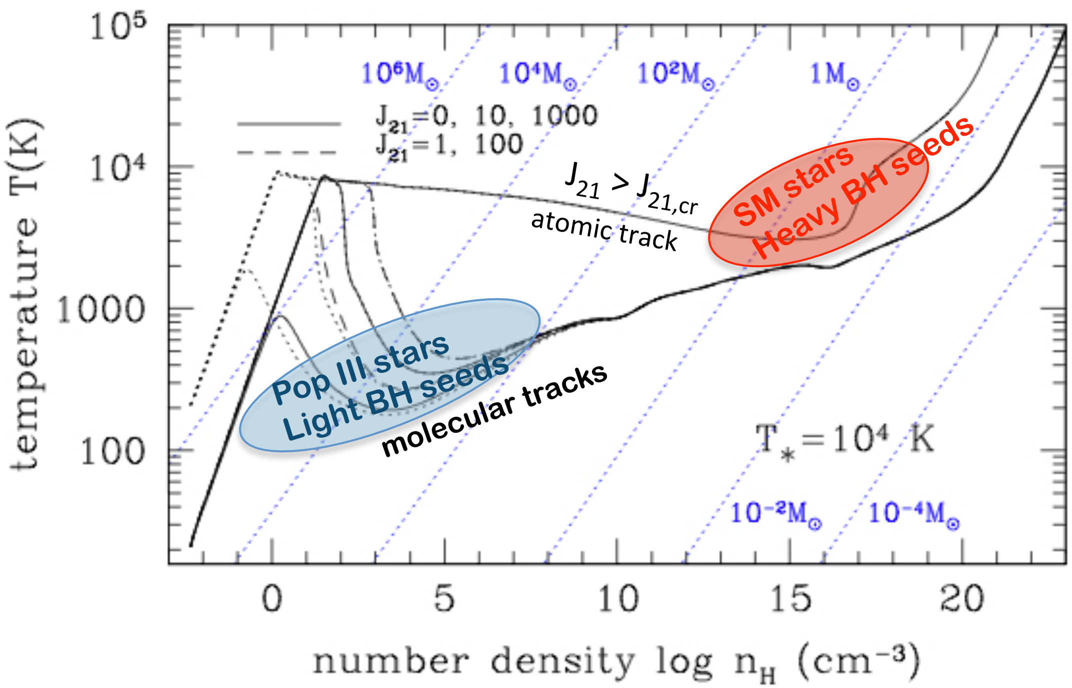
seed black holes

their nature is set by the environmental conditions

H_2 photo-dissociation from UV photons in the Lyman-Werner band: (11.2 – 13.6) eV

$J_{21} = J_{LW} / 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}

collapsing metal free gas clouds



Omukai, RS, Haiman (2008)

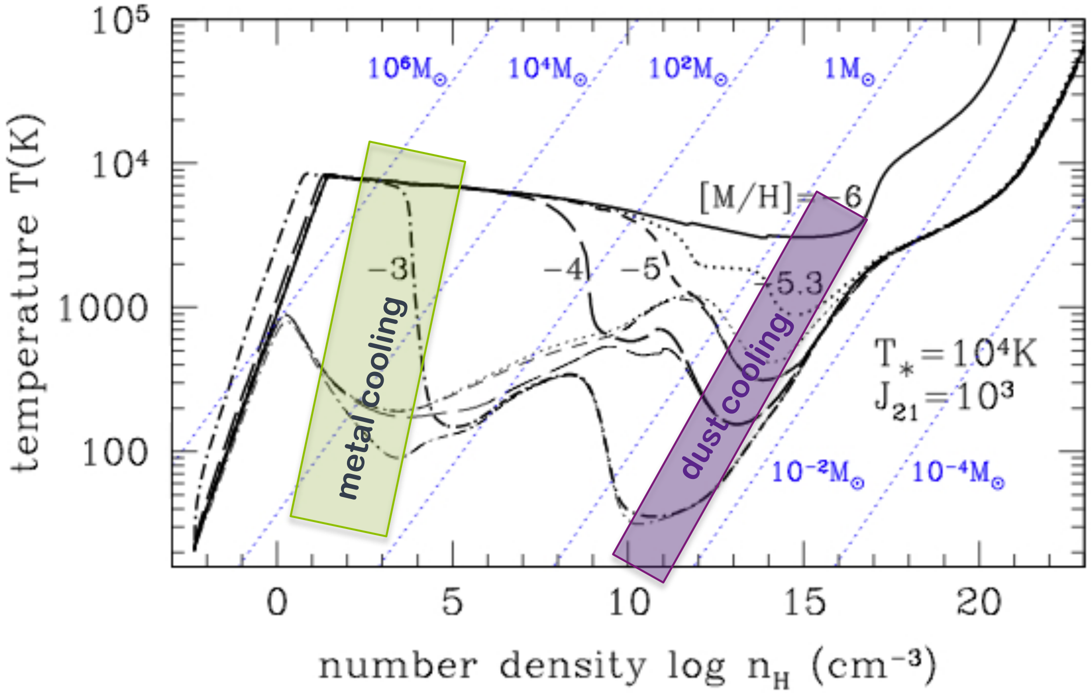
see also Omukai 2001; Oh & Haiman 2002; Bromm & Loeb 2003; Omukai+2008; Agarwal +2012; Latif+2014; Sugimura+2014, 2015; Agarwal +2015; Latif & Volonteri 2015; ; Regan & Haehnelt 2009; Hosokawa+2012; Latif+2013,2014, 2016; Prieto+2013; Regan+2014; Inayoshi+2014;Choi +2015; Becerra +2015, 2018

seed black holes

their nature is set by the environmental conditions

metal line cooling and dust cooling lead to fragmentation

collapsing metal enriched gas clouds irradiated with $J_{21} > J_{21,cr}$



Omukai, RS, Haiman (2008)

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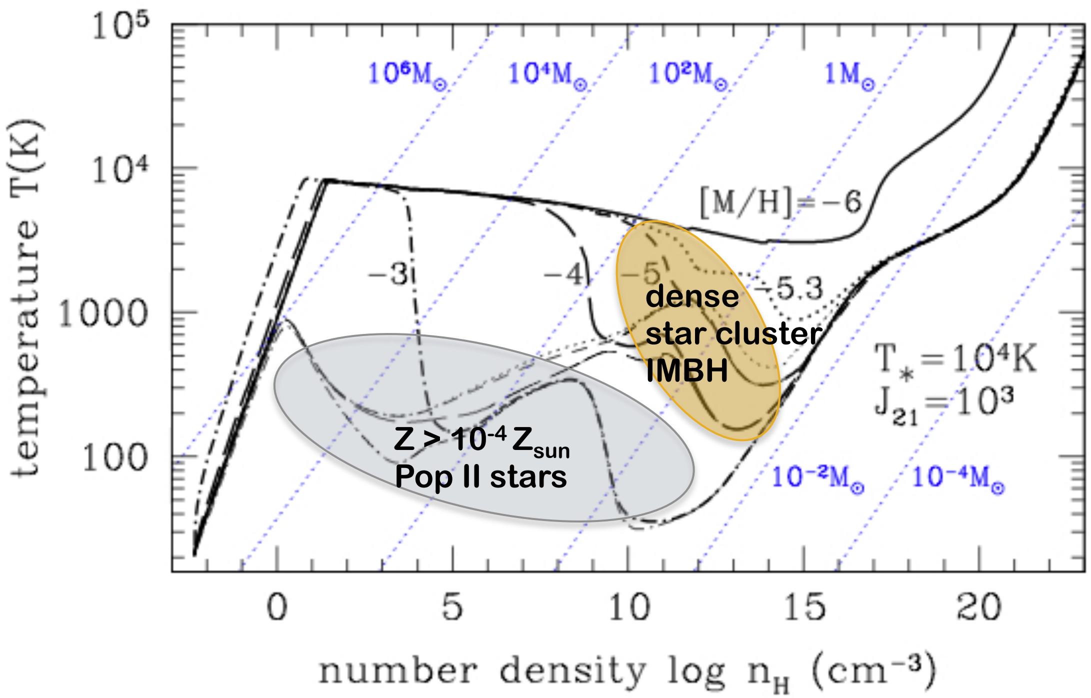
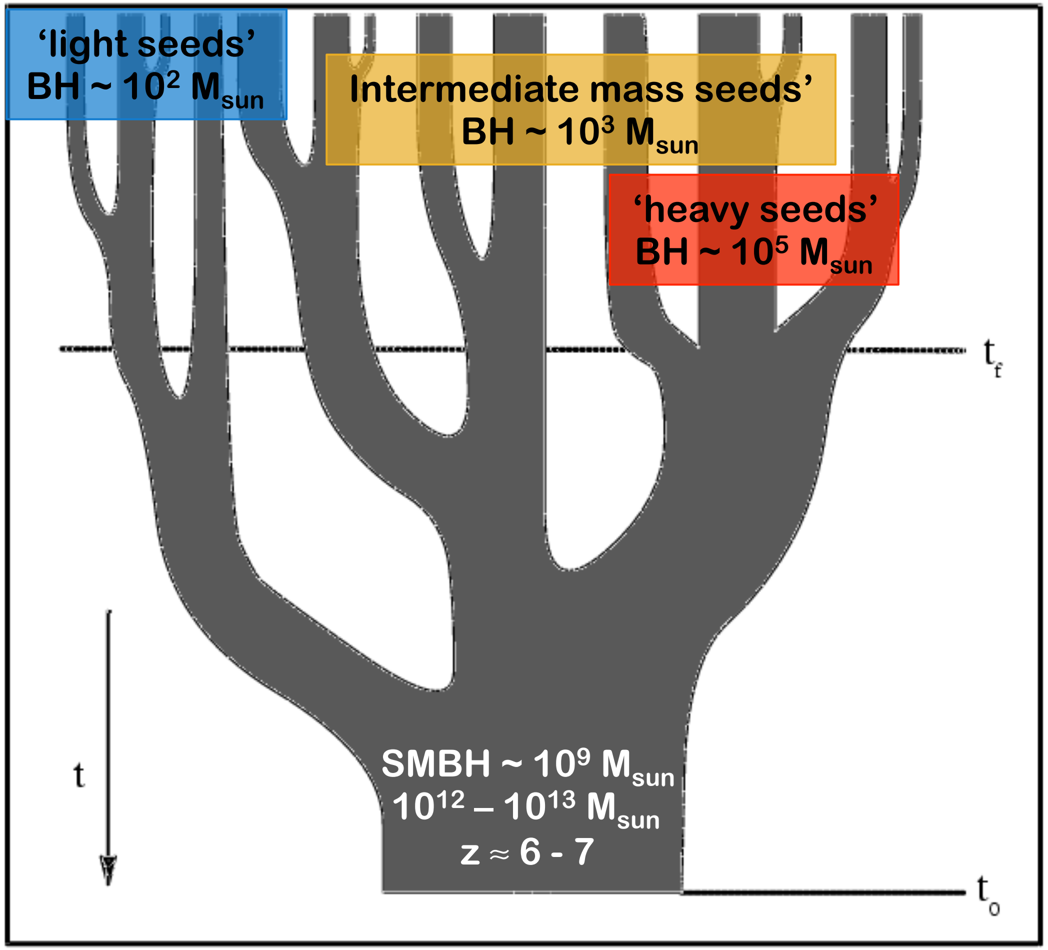


Omukai, RS, Haiman (2008)

the formation of the first SMBHs: planting and growing seeds in a highly biased region

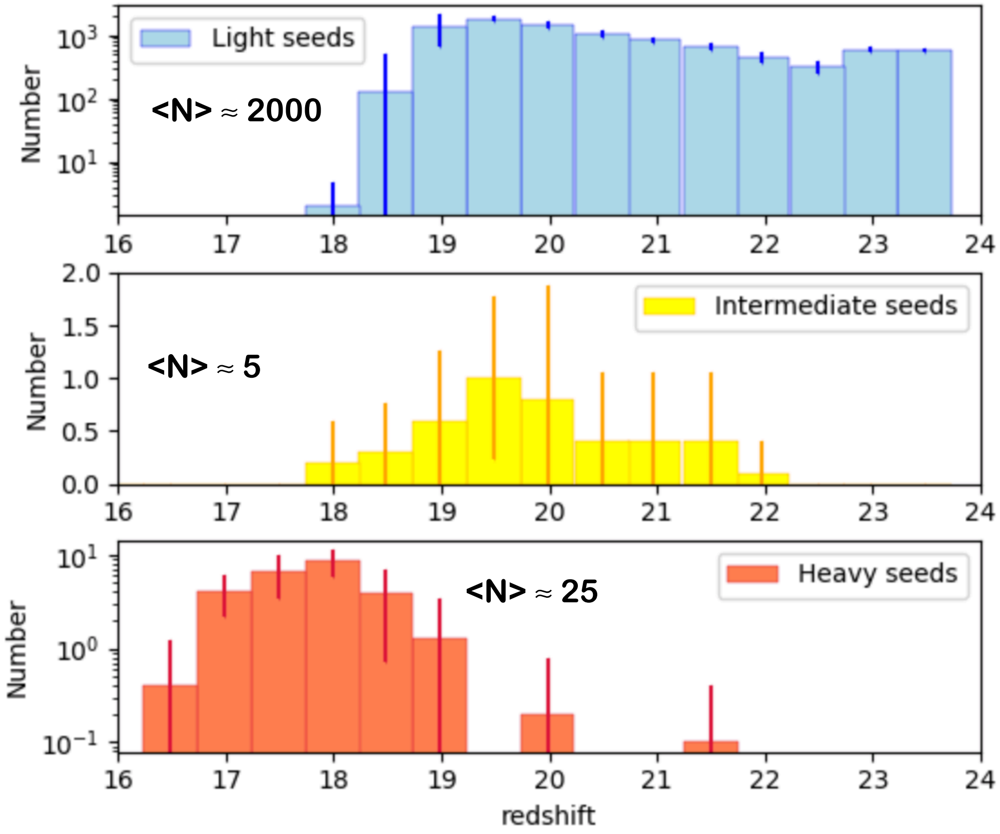


Haiman & Loeb 2001, Volonteri et al. 2003, Wyithe & Loeb 2003, Haiman 2004, Menci et al. 2004, 2008, Shapiro 2005, Yoo & Miralda-Escude' 2004, Bromley et al. 2004, Volonteri & Rees 2005, Li et al. 2007, Pelupessy et al. 2007, Sijacki et al. 2009, Tanaka & Haiman 2009, Lamastra et al. 2010, Valiante et al. 2011, Petri et al. 2012; Valiante et al. 2015; 2016, 2017, 2018; Pezzulli et al. 2016, 2017; Sassano et al. 2019

a census of BH seeds progenitors

data-constrained models (GQd): >10^9 M_{sun} BH @ z = 6 in 10^{13} M_{sun} DM halos

redshift distribution averaged over 10 independent simulations



$J_{21} < J_{21,cr}$
$Z < Z_{cr}$
$D < D_{cr}$

$T_{vir} > 10^4$ K
$J_{21} > J_{21,cr}$
$Z < Z_{cr}$
$D > D_{cr}$

$T_{vir} > 10^4$ K
$J_{21} > J_{21,cr}$
$Z < Z_{cr}$
$D < D_{cr}$

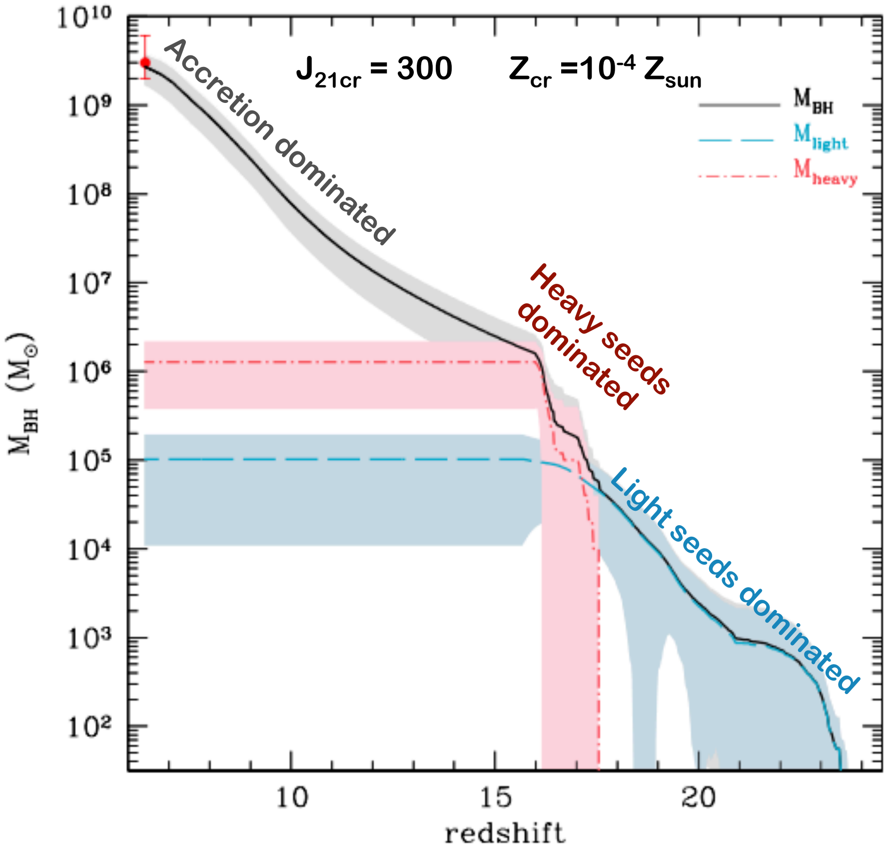
Sassano et al. 2019

- inhomogeneous metal enrichment
- inhomogeneous Lyman Werner radiation
- $Z_{cr} = 10^{-4} Z_{sun}$, $D_{cr} = 4.4\ 10^{-9}$, $J_{21,cr} = 1000$

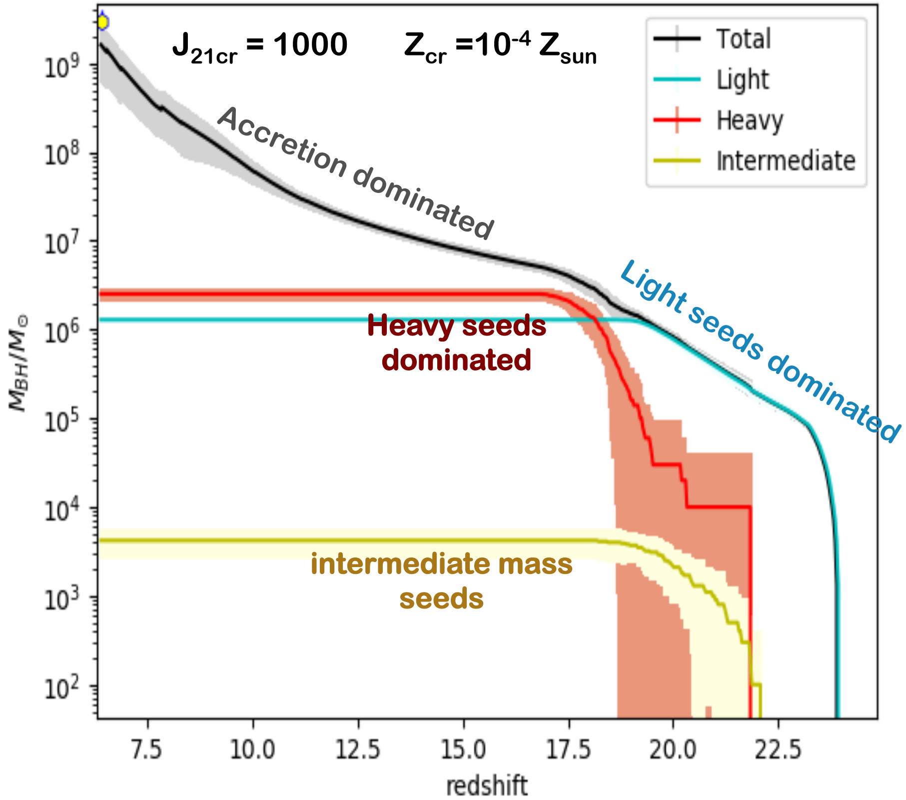
growing the first SMBHs

data-constrained models (GQd): >10^9 M_{sun} BH @ z = 6 in 10^{13} M_{sun} DM halos

evolution of the total nuclear BH mass averaged over 10 simulations

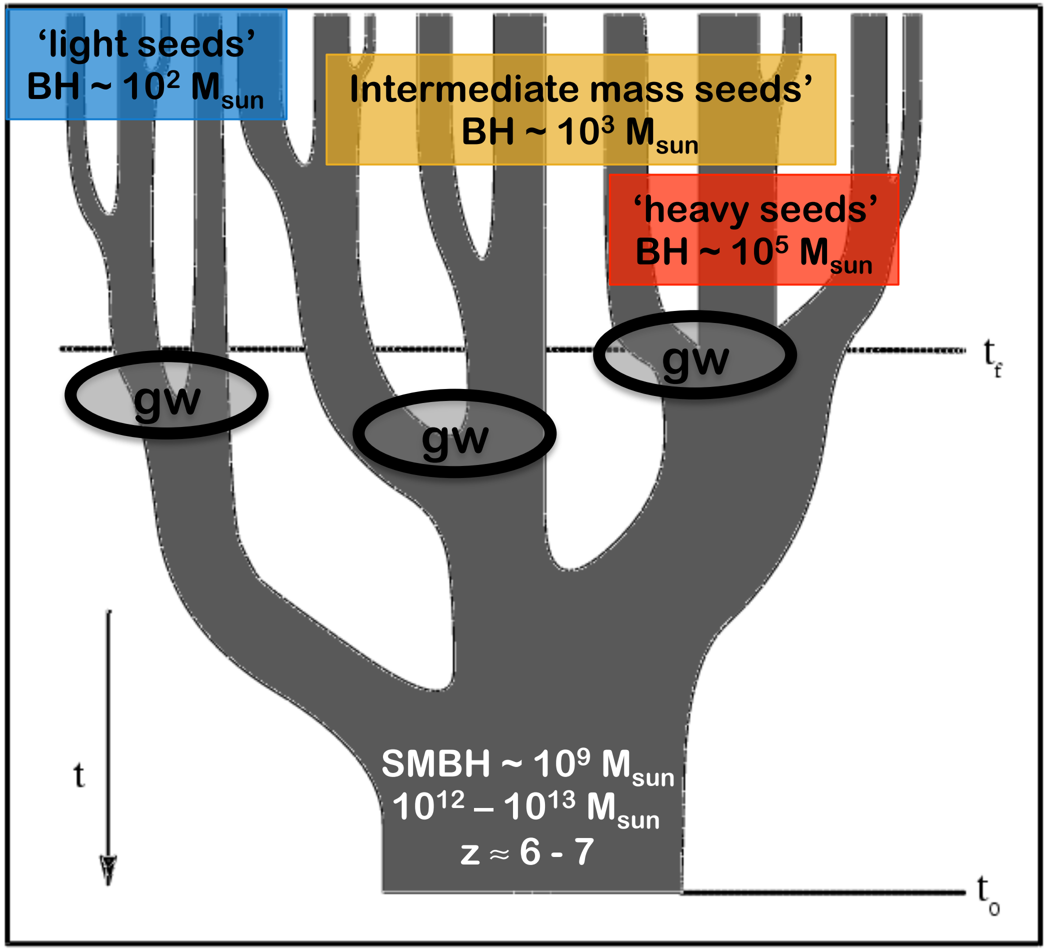


Valiante et al. 2016



Sassano et al. 2019

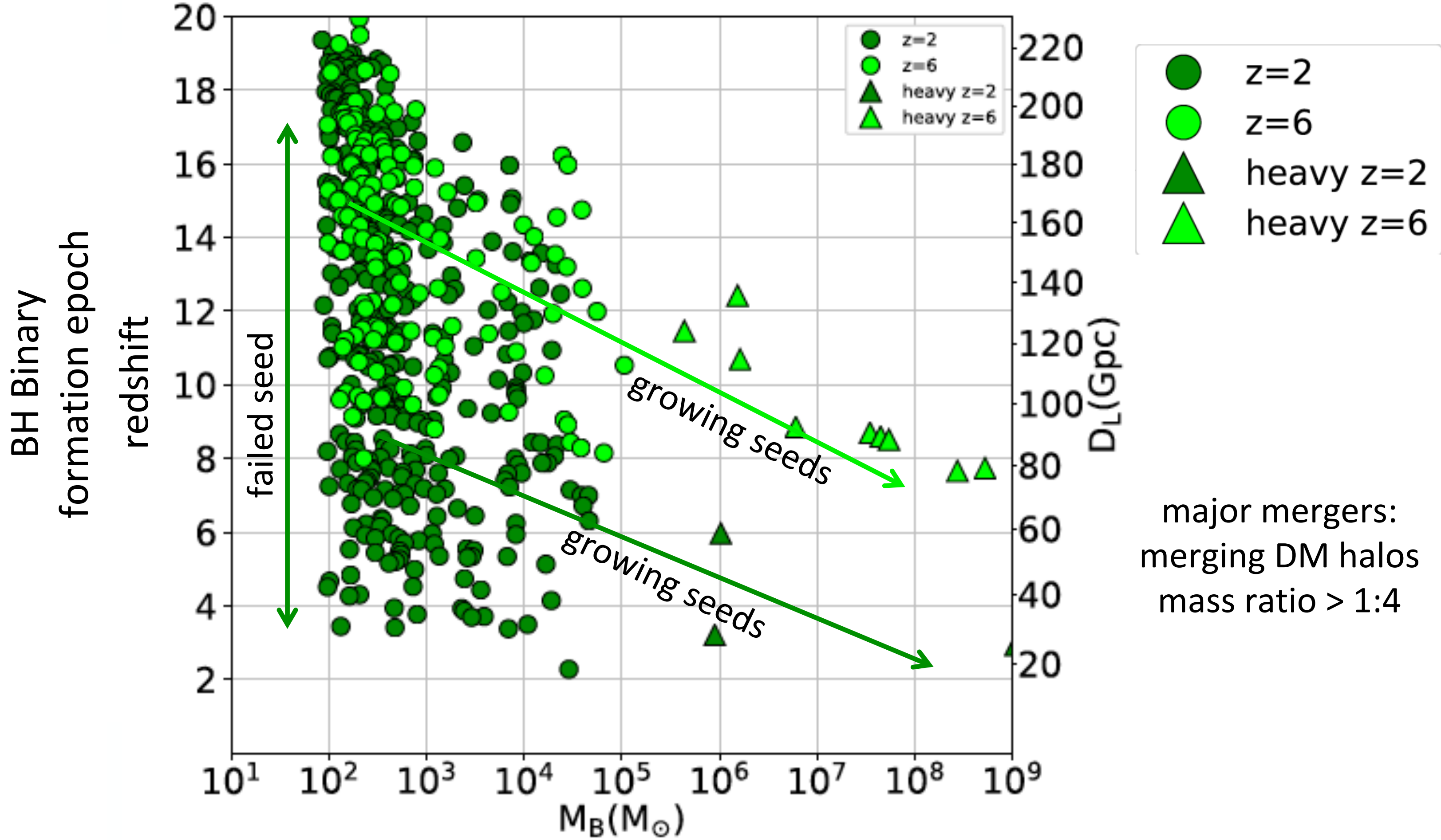
emission of gravitational waves during galaxy mergers



Haiman & Loeb 2001, Volonteri et al. 2003, Wyithe & Loeb 2003, Haiman 2004, Menci et al. 2004, 2008, Shapiro 2005, Yoo & Miralda-Escude' 2004, Bromley et al. 2004, Volonteri & Rees 2005, Li et al. 2007, Pelupessy et al. 2007, Sijacki et al. 2009, Tanaka & Haiman 2009, Lamastra et al. 2010, Valiante et al. 2011, Petri et al. 2012; Valiante et al. 2015; 2016, 2017, 2018; Pezzulli et al. 2016, 2017; Sassano et al. 2019

cosmological binary black hole mergers

data-constrained models (GQd): >10^9 M_{sun} BH @ z=2 or 6 in 10^{13} M_{sun} DM halos

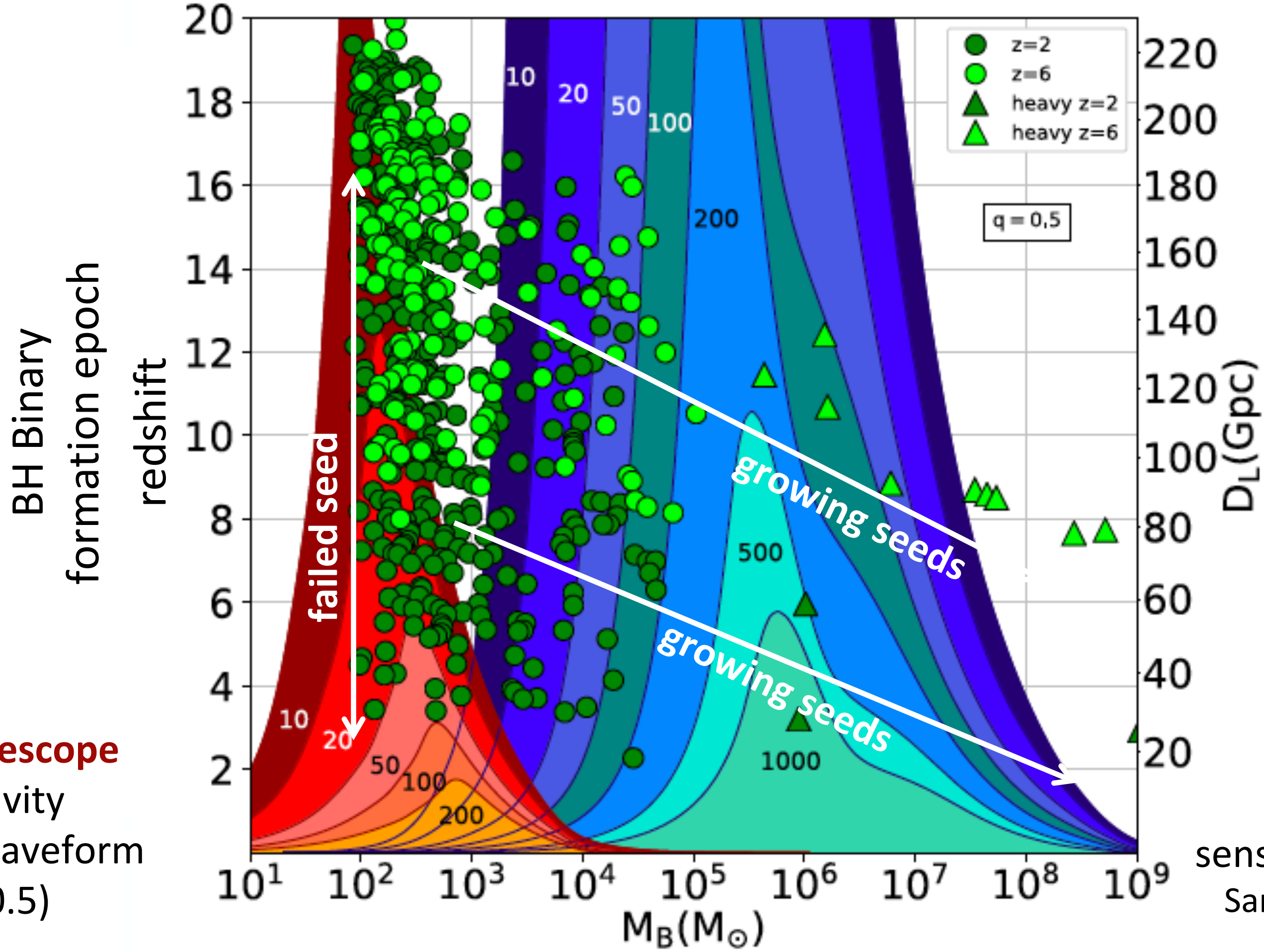


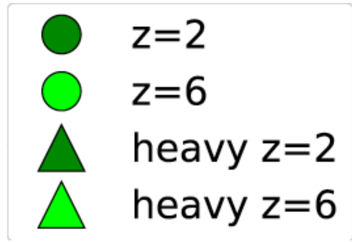
major mergers:
merging DM halos
mass ratio > 1:4

the black holes are assumed to merge with the hosts galaxies

cosmological binary black hole mergers

data-constrained models (GQd): >10^9 M_{sun} BH @ z=2 or 6 in 10^{13} M_{sun} DM halos





major mergers:
merging DM halos
mass ratio > 1:4

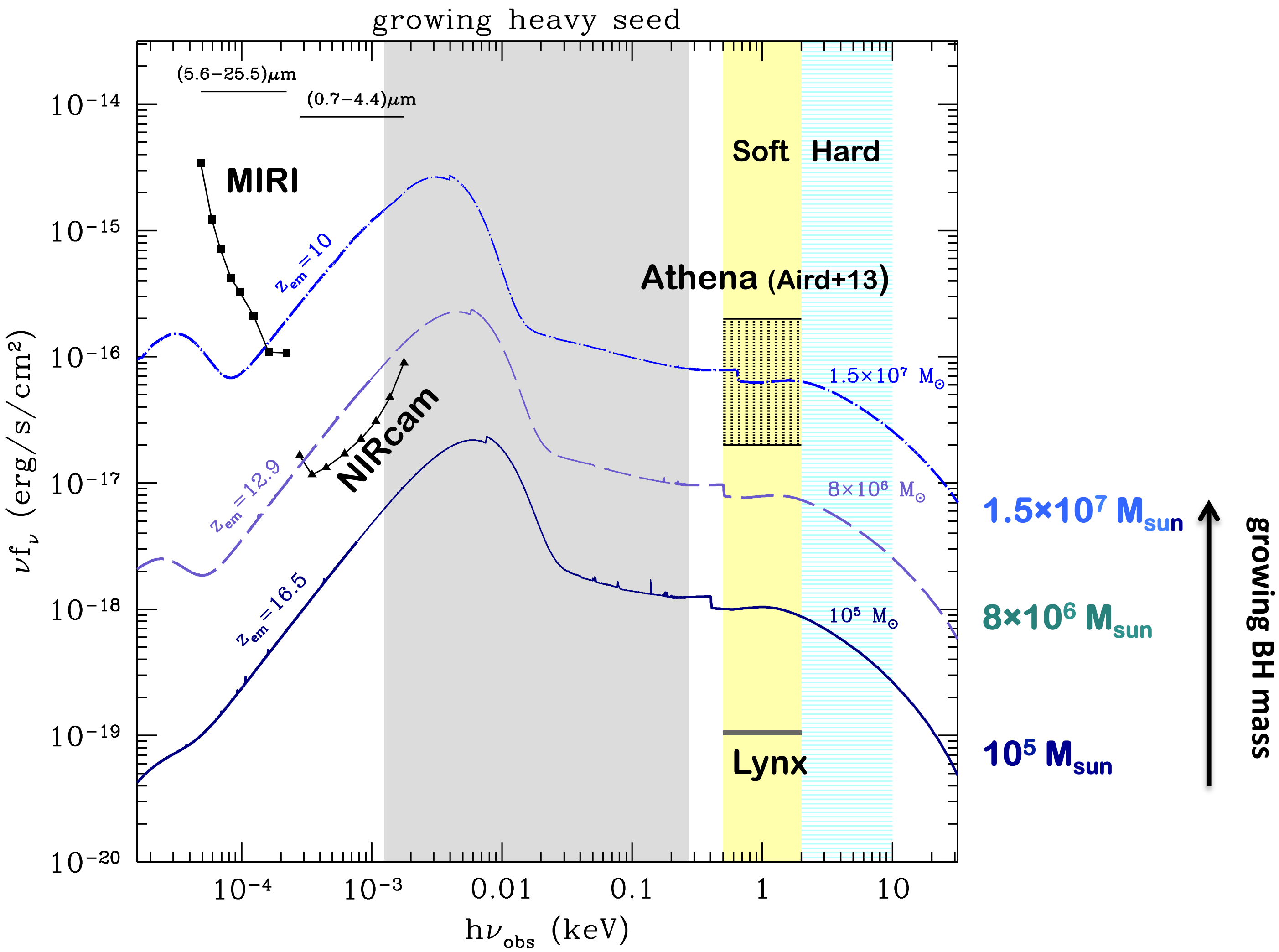
Einstein Telescope
ET_D sensitivity
PhenomC waveform
(spin=0, q=0.5)

LISA
sensitivity curve (q=0.5)
Santamaria et al (2010)

the black holes are assumed to merge with the hosts galaxies

Valiante, Margiagli et al. 2019

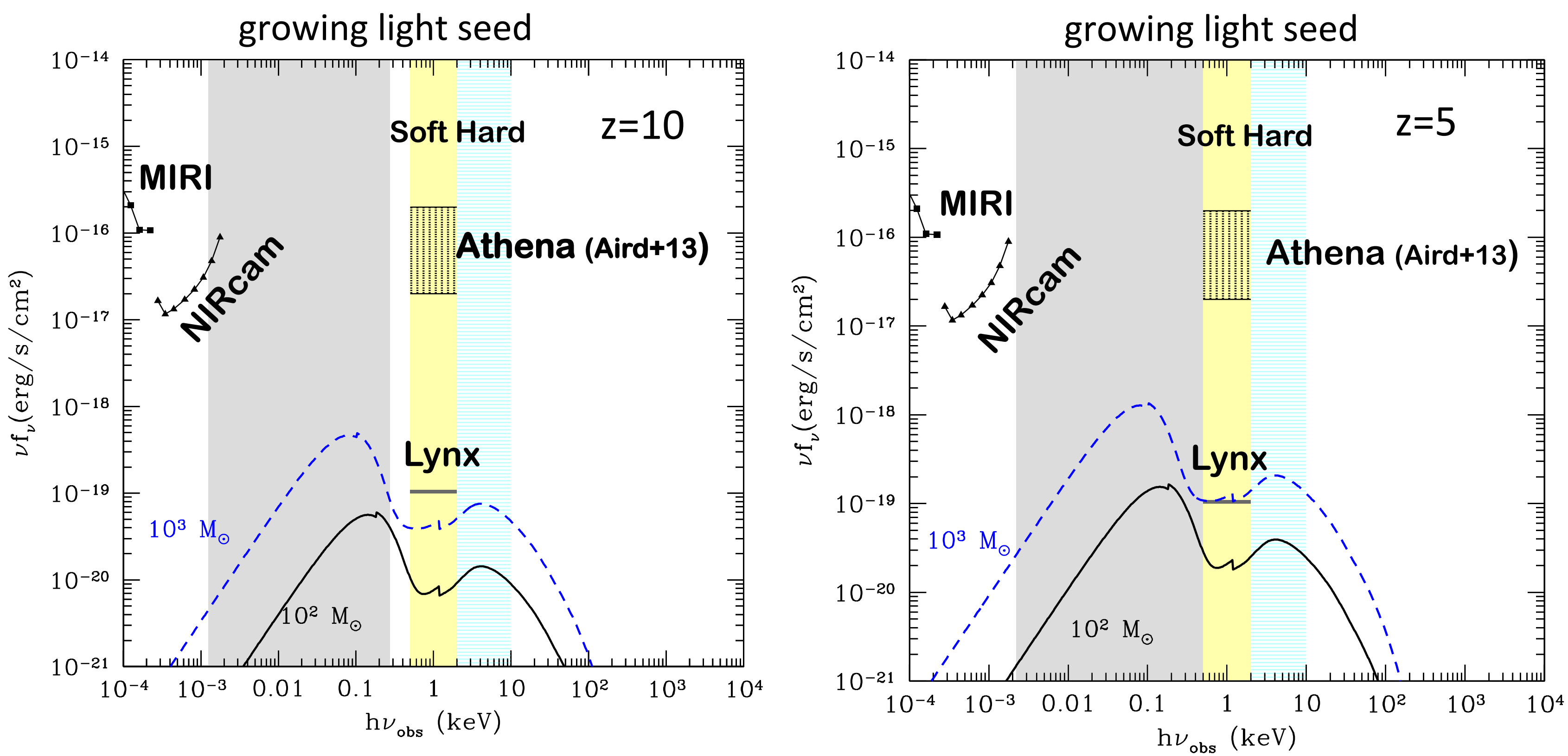
the EM emission from a growing heavy seed



JWST and Athena (and Lynx) will be able to detect the earliest accreting (massive) black holes out to z=13 (17)

Valiante, RS et al. 2018; Valiante, Margiagli et al. 2019

the EM emission from a growing light seed



accreting light seeds with masses 100 Msun, 1000 Msun will not be detectable with EM facilities
3G GW detectors will be the only way to detect them!

Valiante, RS et al. 2018; Valiante, Margiagli et al. 2019

Summary (II)

- BH seeds progenitors of the first SMBHs can form in a variety of flavours: light (100 M_{sun}), intermediate-mass (1000 M_{sun}) and heavy (10^4 – 10^5 M_{sun}) depending on environmental conditions

- JWST/Athena (LynX) will be able to detect active heavy seeds out to z = 13 (17) but will not detect active light seeds

- failed or growing BH seeds paired in halo mergers will be detectable by 3rd generation GW telescopes out to z = 20!

3G GW detectors will be able to probe the earliest phases of BH formation at cosmic dawn