THE BLACK HOLES OF THE GRAVITATIONAL UNIVERSE

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Amaldi Research Centre
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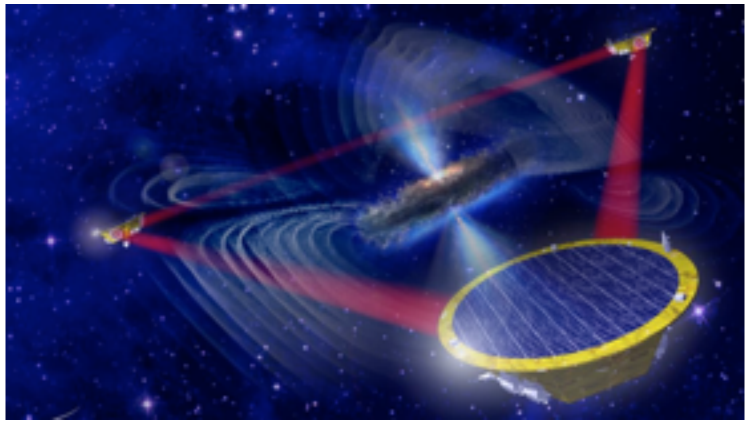
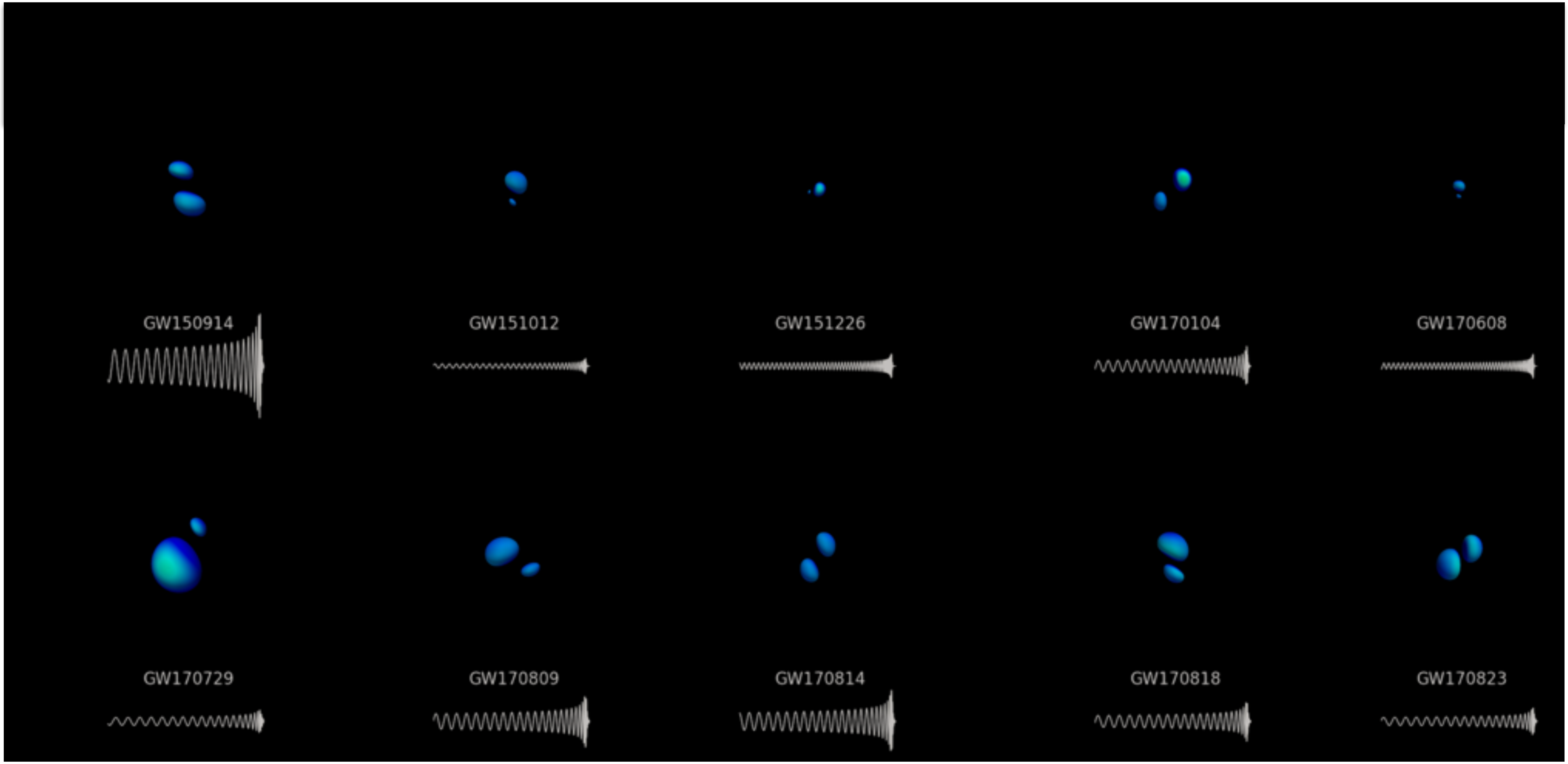




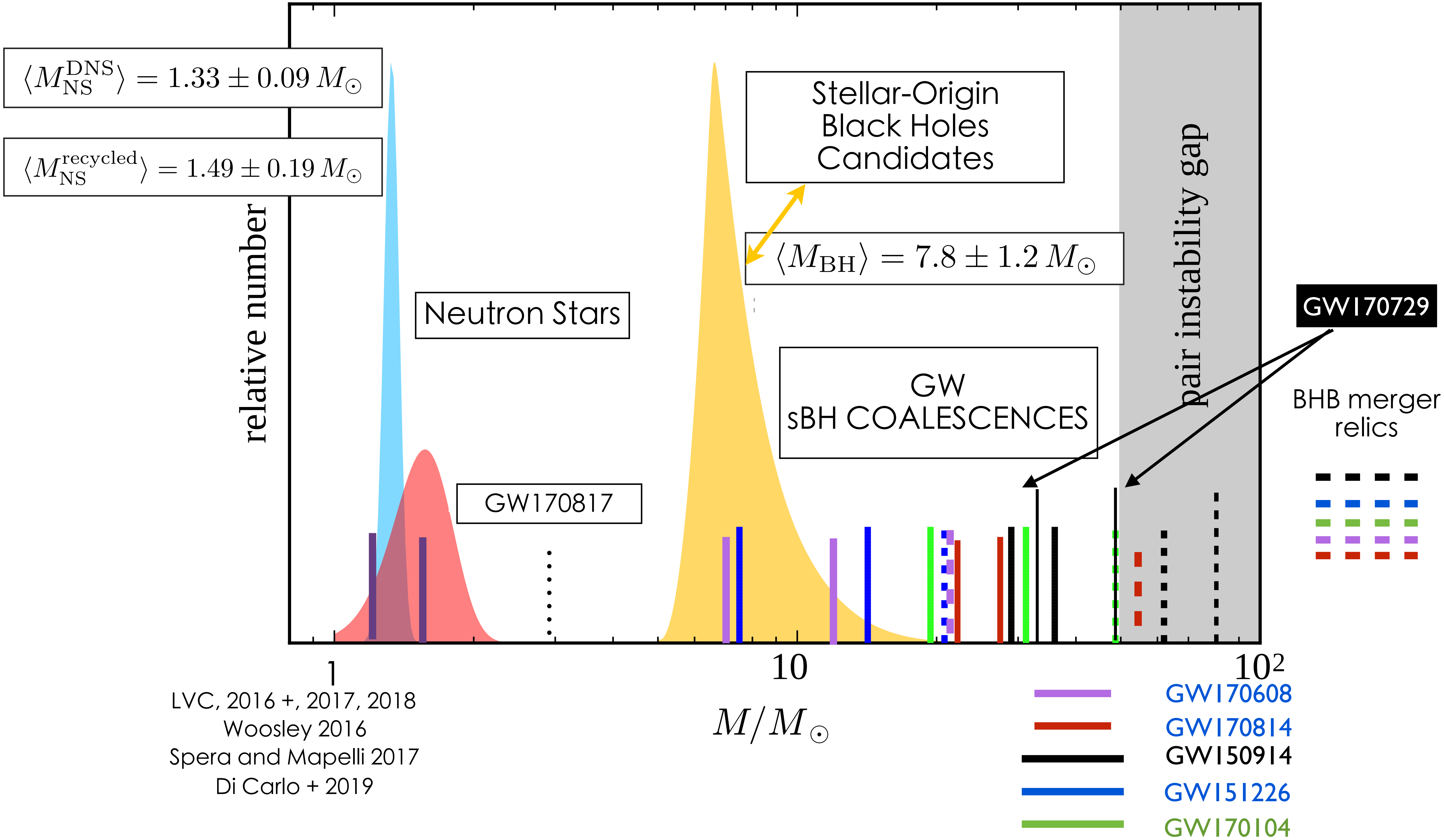
LVC 2018

LIGO-VIRGO

Fulvio RICCI +

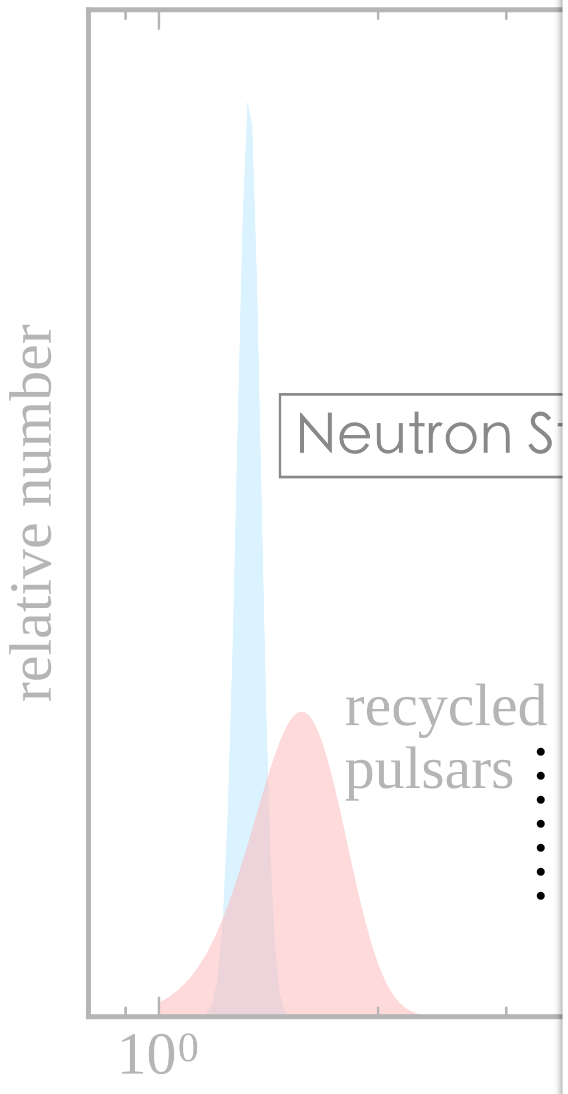
Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_eff	$M_\mathrm{f}/\mathrm{M}_\odot$	a_f	$E_\mathrm{rad}/(\mathrm{M}_\odot c^2)$	$\ell_\mathrm{peak}/(\mathrm{erg\,s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

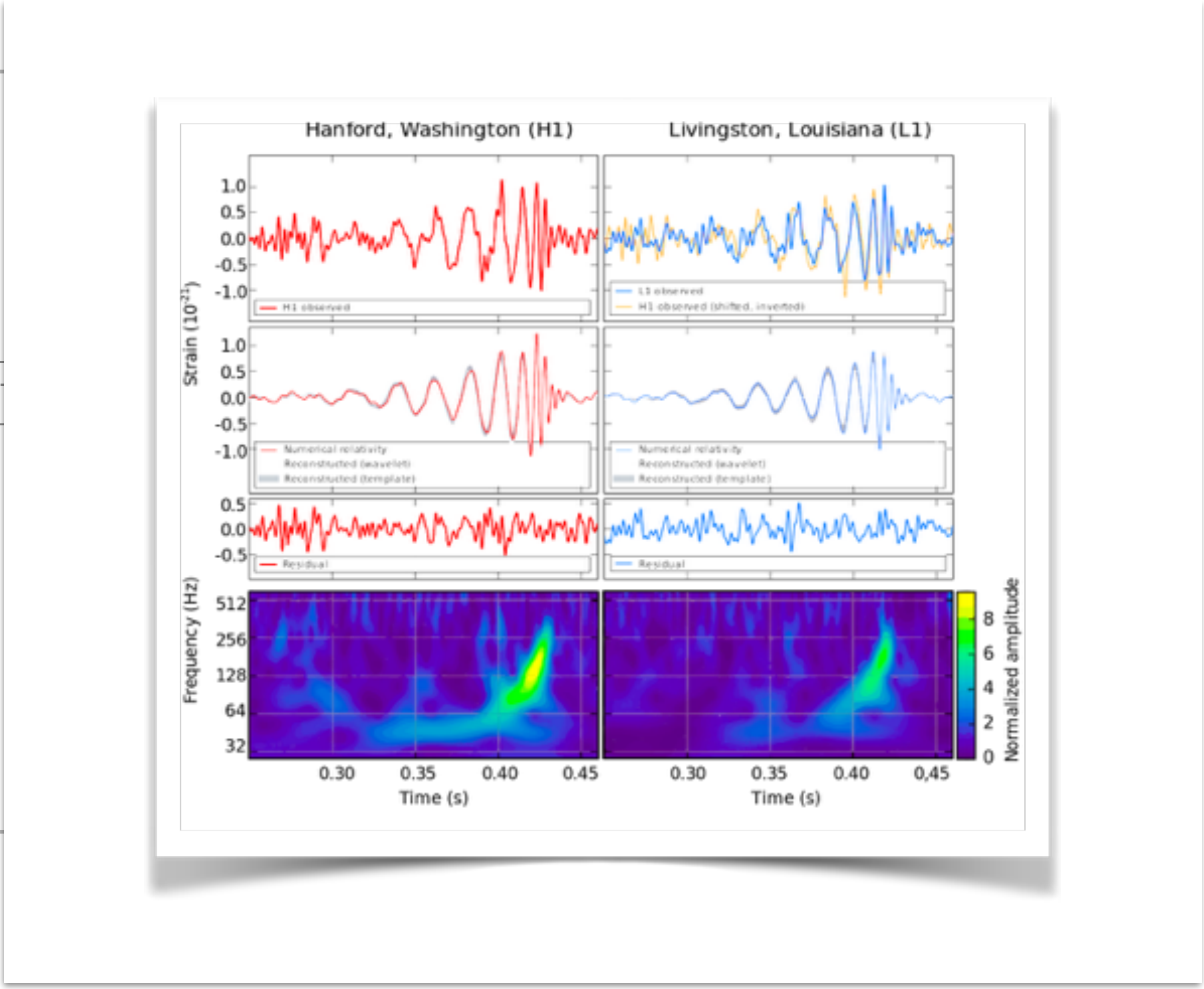
- wider black holes mass spectrum - lower metallicity



LVC, 2016 +, 2017, 2018
Woosley 2016
Spera and Mapelli 2017
Di Carlo + 2019

- LIGO-VIRGO - With these historical discoveries, the strongest evidence of the existence of "STELLAR BLACK HOLES" for which we have a "leading order theory" on the physics of their formation
- era of precision in experimental gravity

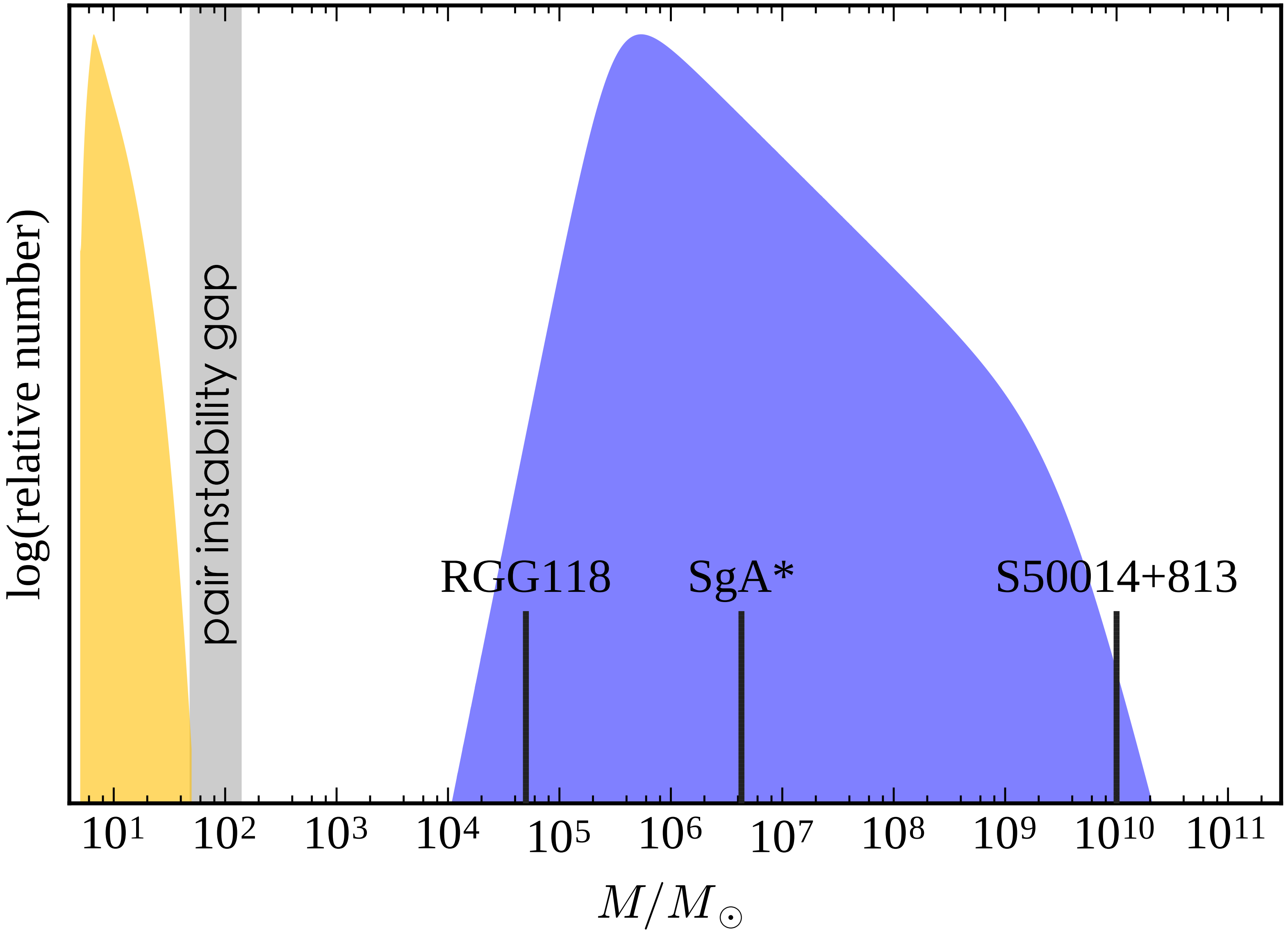




··· next run O3 ··· to detect (BH,NS) mergers

STELLAR ORIGIN BLACK HOLES

SUPERMASSIVE BLACK HOLES

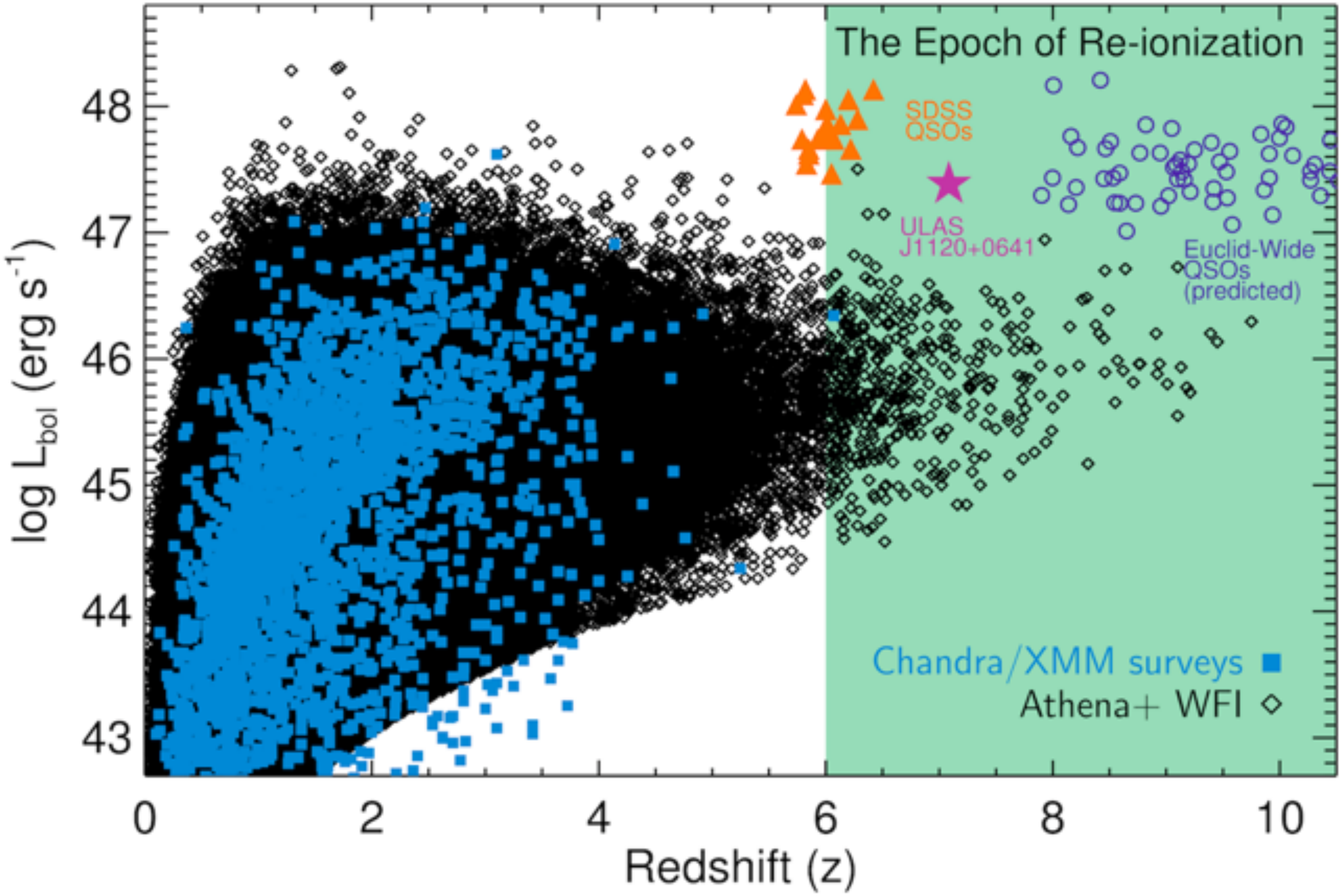


EM Observations

- Existence of **AGN - QSOs** - powered by accretion onto supermassive black holes of millions to billions suns
- Black Hole masses correlate with physical properties of galaxies —M-sigma relation — feedback from the AGN
- Less massive black holes live in less massive galaxies - correlation is highly scattered - nuclear star clusters
- Local census of supermassive black holes in spheroids
- Combining data from the unresolved X-ray background with those on the local census of silent black holes we learned supermassive black holes have grown mainly by radiatively efficient accretion during the last e-folding time below z~3 during the peak of the star formation rate
- Supermassive black holes weighing billion suns (QSOs) are in place @ z~7

- Supermassive black holes come to birth "light"
- Concept of "SEEDS" - "intermediate mass" black holes forming at high redshifts in high-sigma density peaks under extreme conditions (low or null metallicities)
- "seeds" are "transitional objects" — single epoch forming —grow through (merger induced) accretion and mergers
- Accretion & mergers erase information on their birth properties
- To recover their properties with need to have access to a huge cosmological volume — observe @z>10
- EM - low accretion luminosities

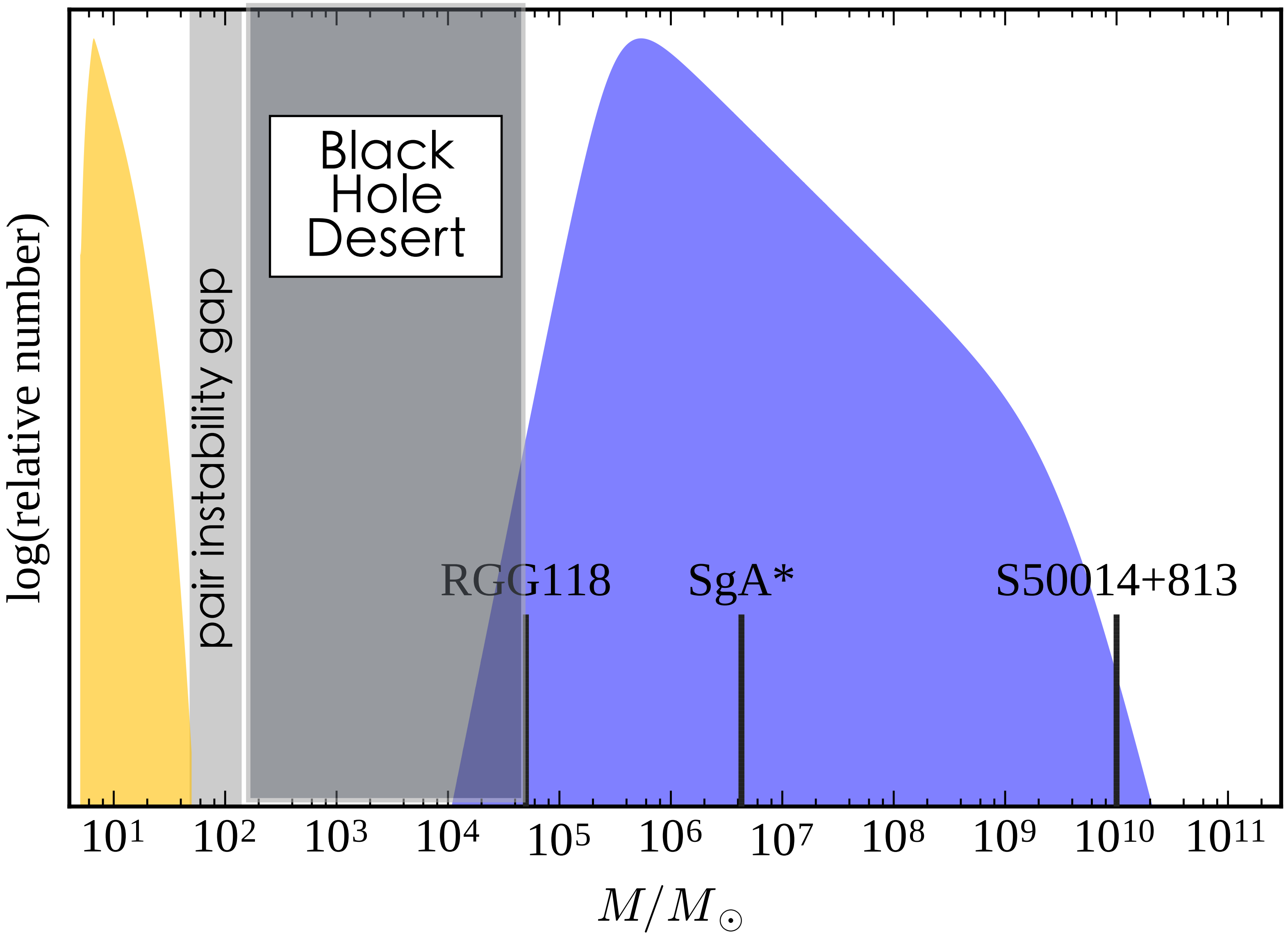
ELECTROMAGNETIC UNIVERSE
SUPERMASSIVE BLACK HOLES

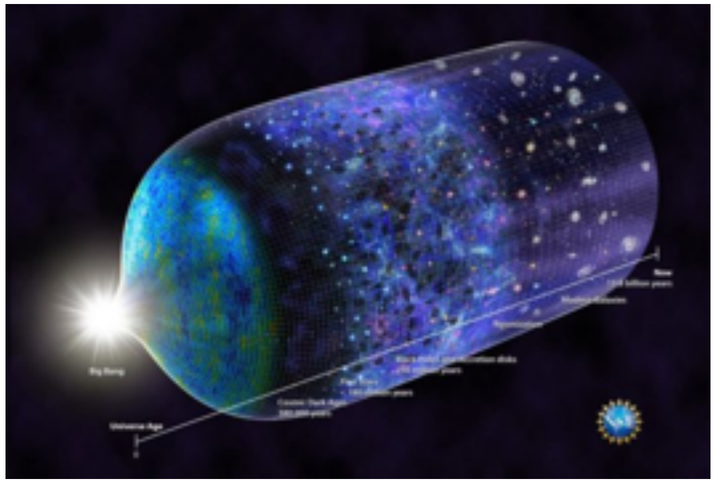


Athena white paper
2013

- Luminosity gives only lower limit on the mass
- Correlated studies in the optical to infer the mass from the dynamics of the BLR

Importance to measure their masses





unanswered questions

- HOW did supermassive black holes form? From the gravitational collapse of a yet unknown class of compact objects with mass in the hundred thousands ?
- Is there a deep PHYSICAL LINK between STELLAR and SUPERMASSIVE black holes? (only "stars" form black holes of any mass scale through accretion and mergers)
- WHEN - WHERE did the seeds form? (cosmology)
- HOW did they evolve - mass & spins ? (structure formation)

- “high redshift”
- “low metallicity environments”

H molecular cooling

light
seeds

Pop III

$$150 < \frac{m_{\rm BH,*}}{\rm M_\odot} < 10^3$$

RUNAWAY
star collisions
in dense nuclear
star clusters
at the centre
of forming disc
galaxies

$$300 < \frac{m_{\rm runway-BH}}{\rm M_\odot} < 3000$$

H atomic cooling

heavy
seeds

direct
collapse

$$10^4 < \frac{m_{\rm DCBH}}{\rm M_\odot} < 10^5$$

$$Z = Z_{\rm primordial} = 0$$

$$Z < Z_{\rm crit} \sim 10^{-4} {\rm Z_\odot}$$

$$T_{\rm vir} < 10^4\,{\rm K}$$

$$D_{\rm dust/gas} < 5 \times 10^{-9}$$

$$M_{\rm halo} \sim 10^6\,{\rm M_\odot}$$

Latif & Ferrara 2016, for a review

$$Z < Z_{\rm crit} \sim 10^{-4} {\rm Z_\odot}$$

$$J_{\rm LW} > J_{\rm crit}$$

$$T_{\rm vir} \simeq 10^4\,{\rm K}$$

$$M_{\rm halo} = 10^{7-9} {\rm M_\odot}$$

light
seeds

Pop III

$$150 < \frac{m_{\rm BH,*}}{\rm M_\odot} < 10^3$$

runaway
star collisions
in dense(nuclear)
star clusters
at the centre
of forming disc
galaxies

$$300 < \frac{m_{\rm runway-BH}}{\rm M_\odot} < 3000$$

heavy
seeds

direct
collapse

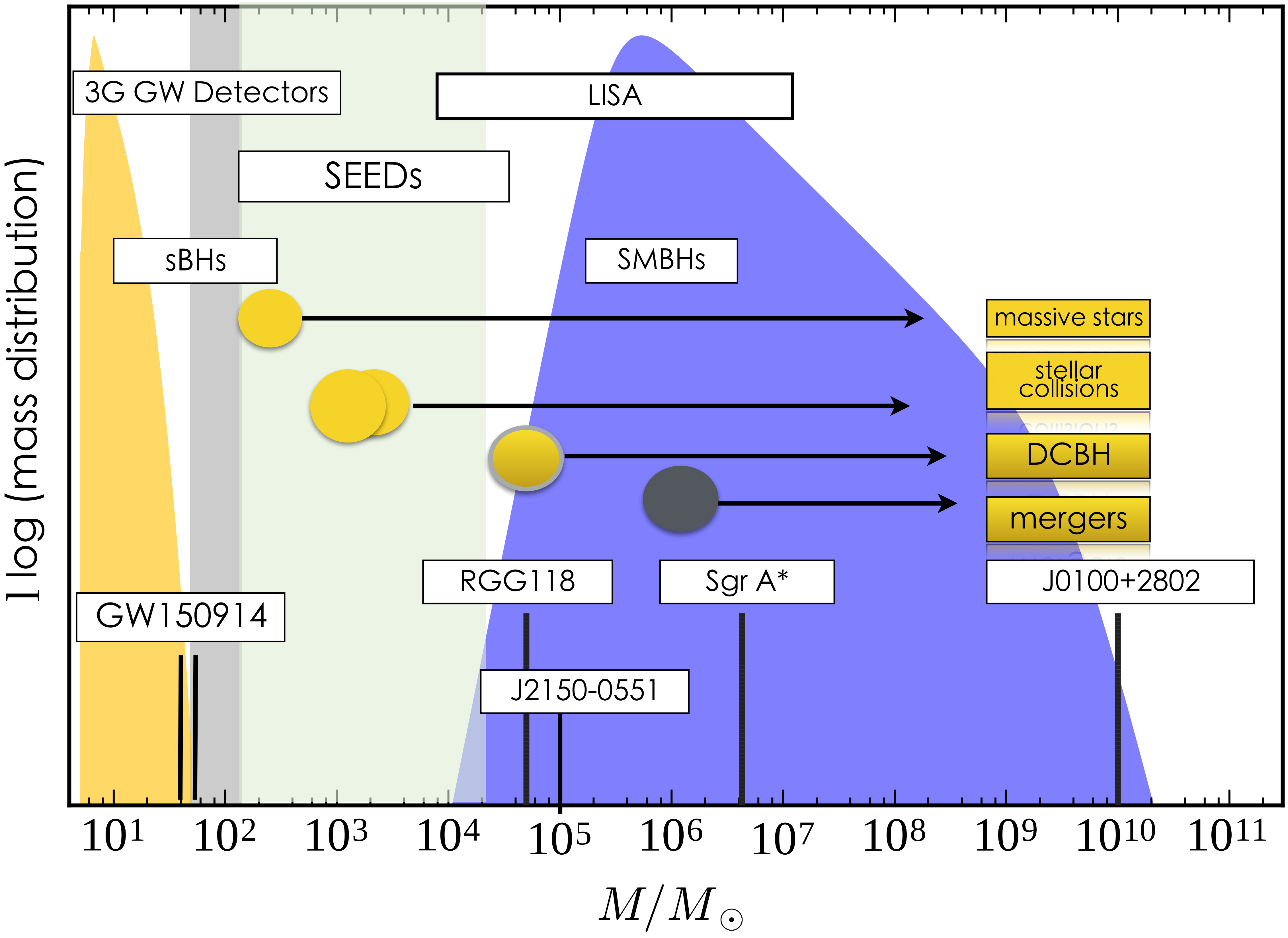
$$10^4 < \frac{m_{\rm DCBH}}{\rm M_\odot} < 10^5$$

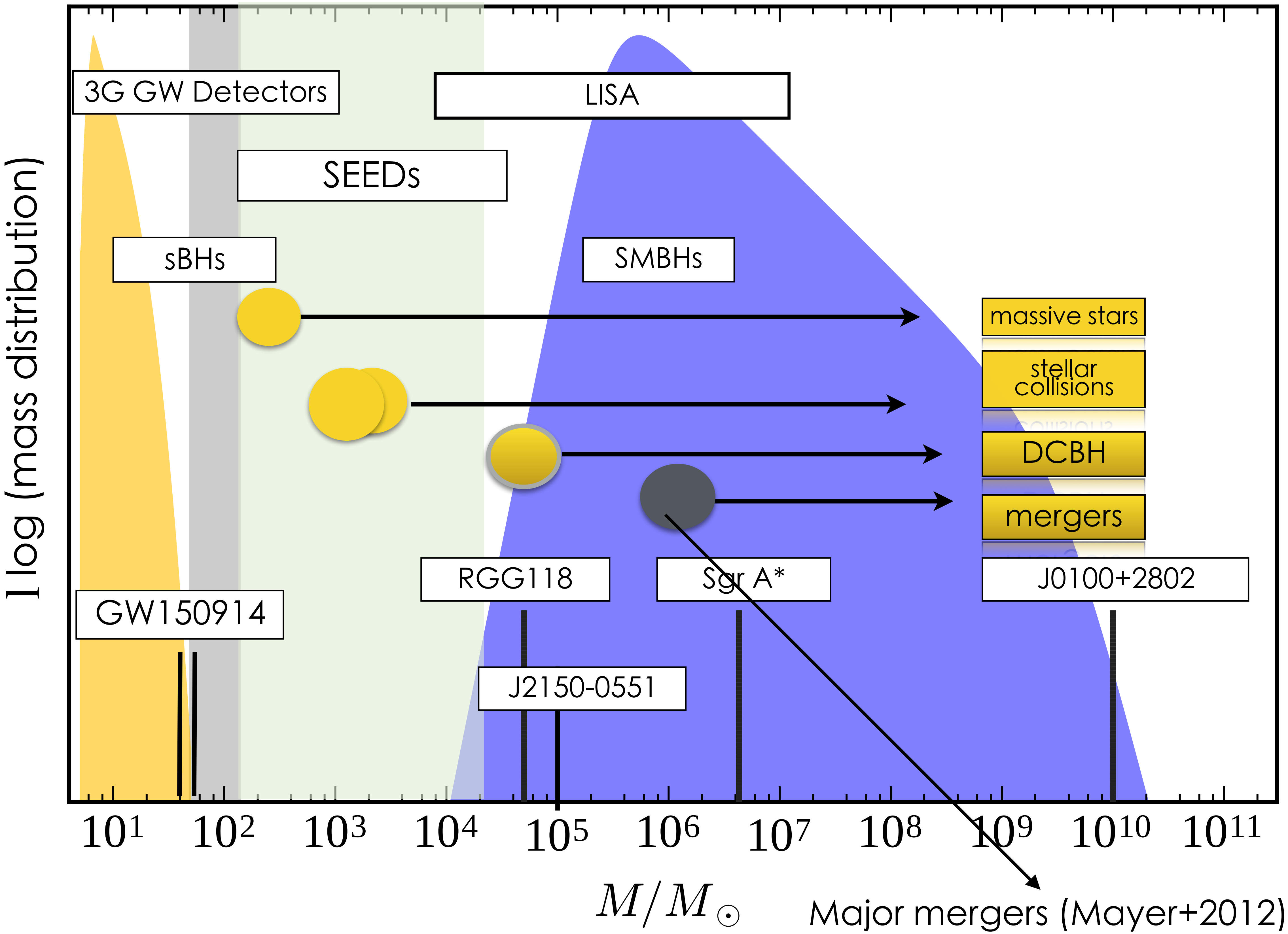
$$M_{\rm halo} = 10^{7-9}{\rm M_\odot}$$

$$Z < Z_{\rm crit} \sim 10^{-4}{\rm Z_\odot}$$

H atomic cooling

Devecchi + 2009,10,11
Reinoso, Schleicher +2018

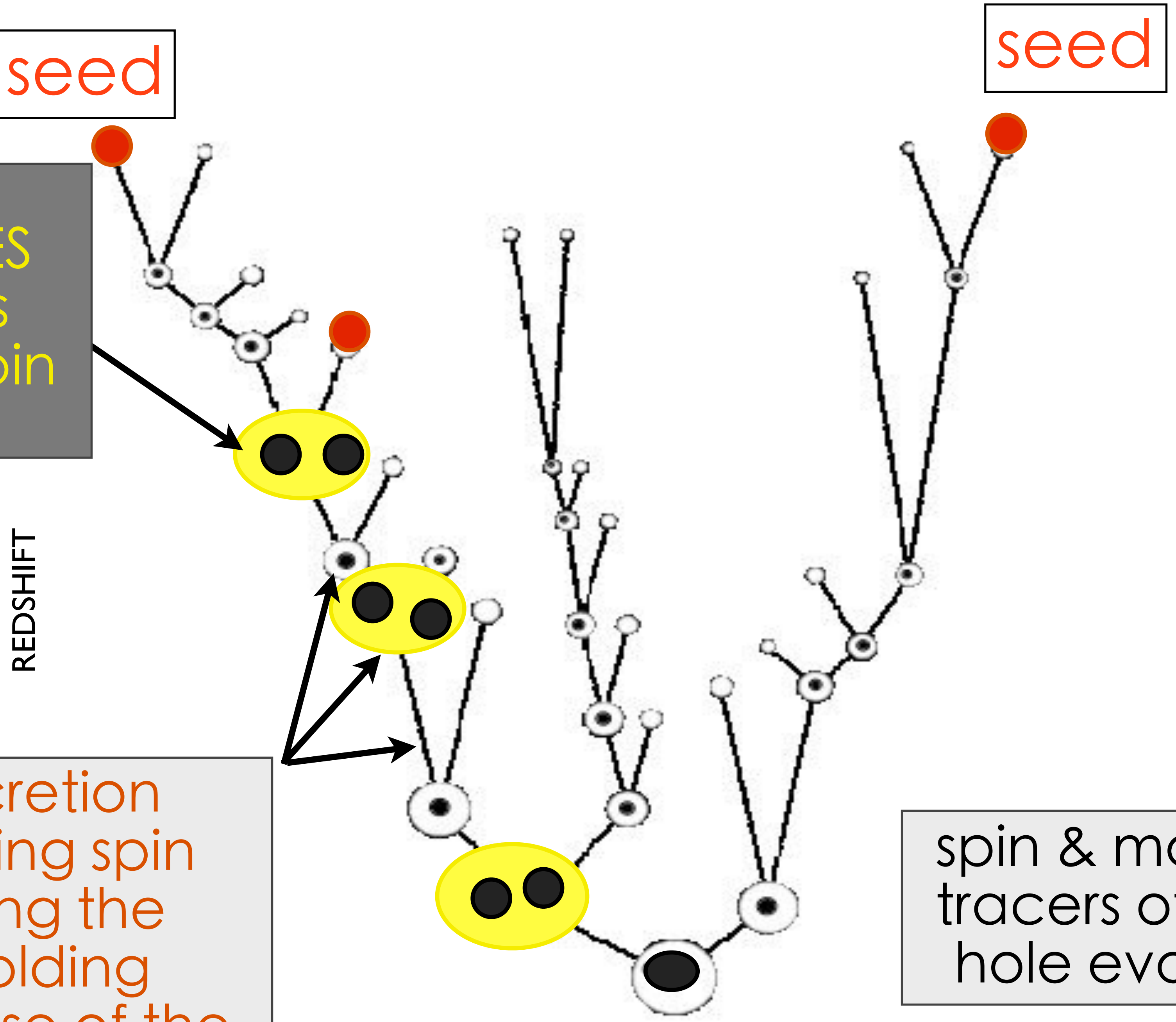

3G GW Detectors
LISA
SEEDs
sBHs
SMBHs
massive stars
stellar collisions
DCBH
mergers
RGG118
Sgr A*
J0100+2802
GW150914
J2150-0551
1 log (mass distribution)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
$M/M_\odot$



Major mergers (Mayer+2012)
New objects?????

- How to detect “seeds”?
- How to track their growth?

BLACK HOLE GROWTH DURING GALAXY ASSEMBLY COSMOLOGICAL DRIVEN MERGERS



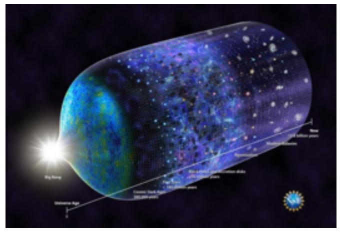
COLAESCENCES
doubling mass
changing the spin

accretion
shaping spin
during the
e-folding
increase of the
mass

spin & mass key
tracers of black
hole evolution

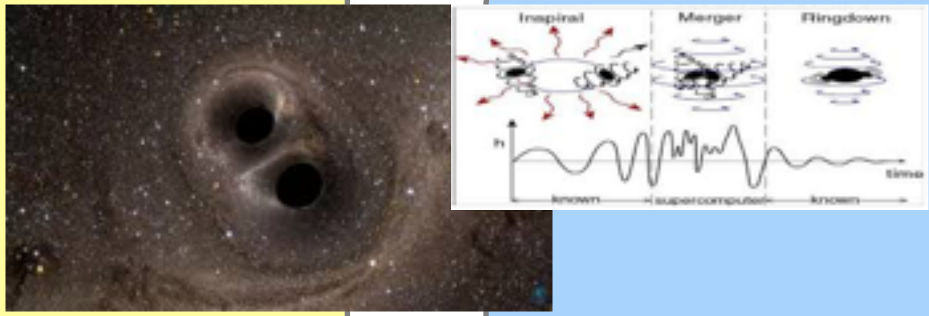
Volonteri 2010,
Amaro Seoane + 2014, Latif & Ferrara 2016, Colpi & Sesana 2017

Extending the GWverse to "all" Frequencies



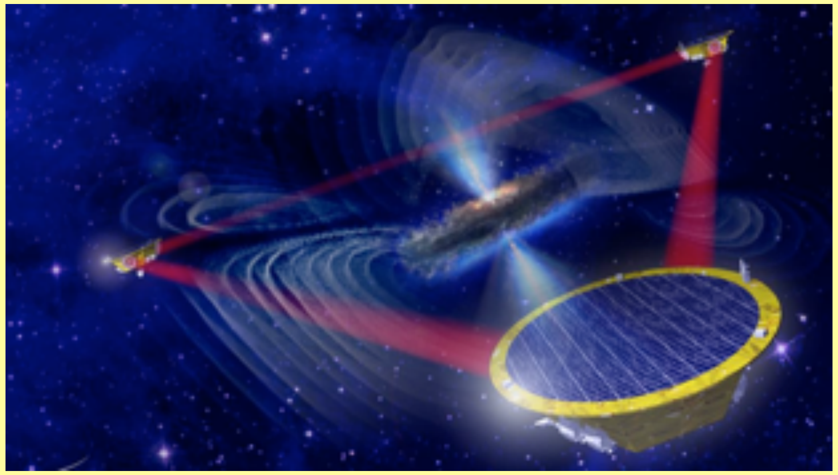
cosmologica redshift

20
15
10
9
8
7
6
5
4
3
2
1



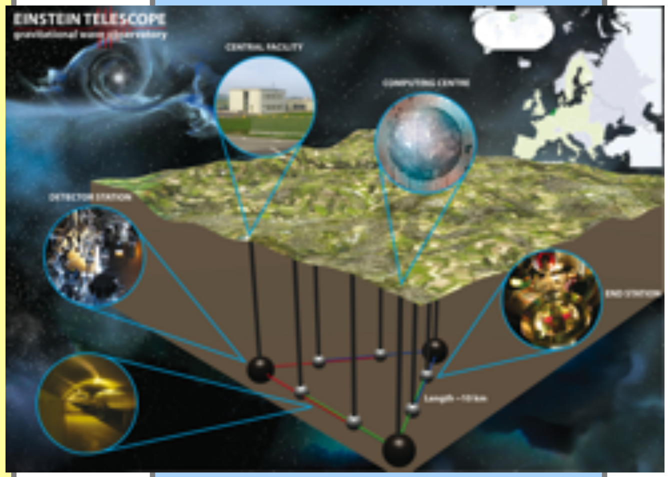
LISA

0.1 mHz-100 mHz

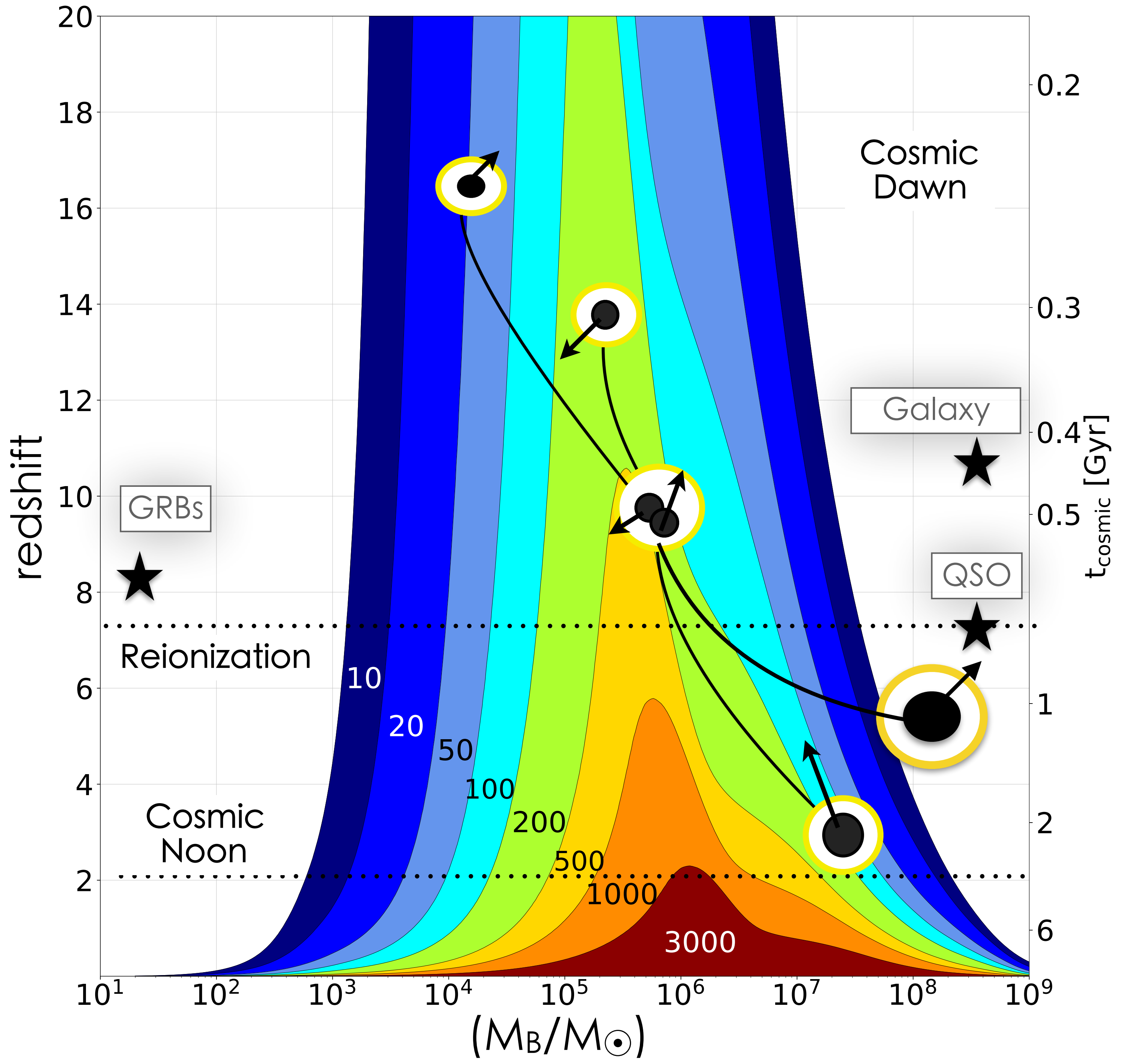


ET

3 Hz - 5 kHz

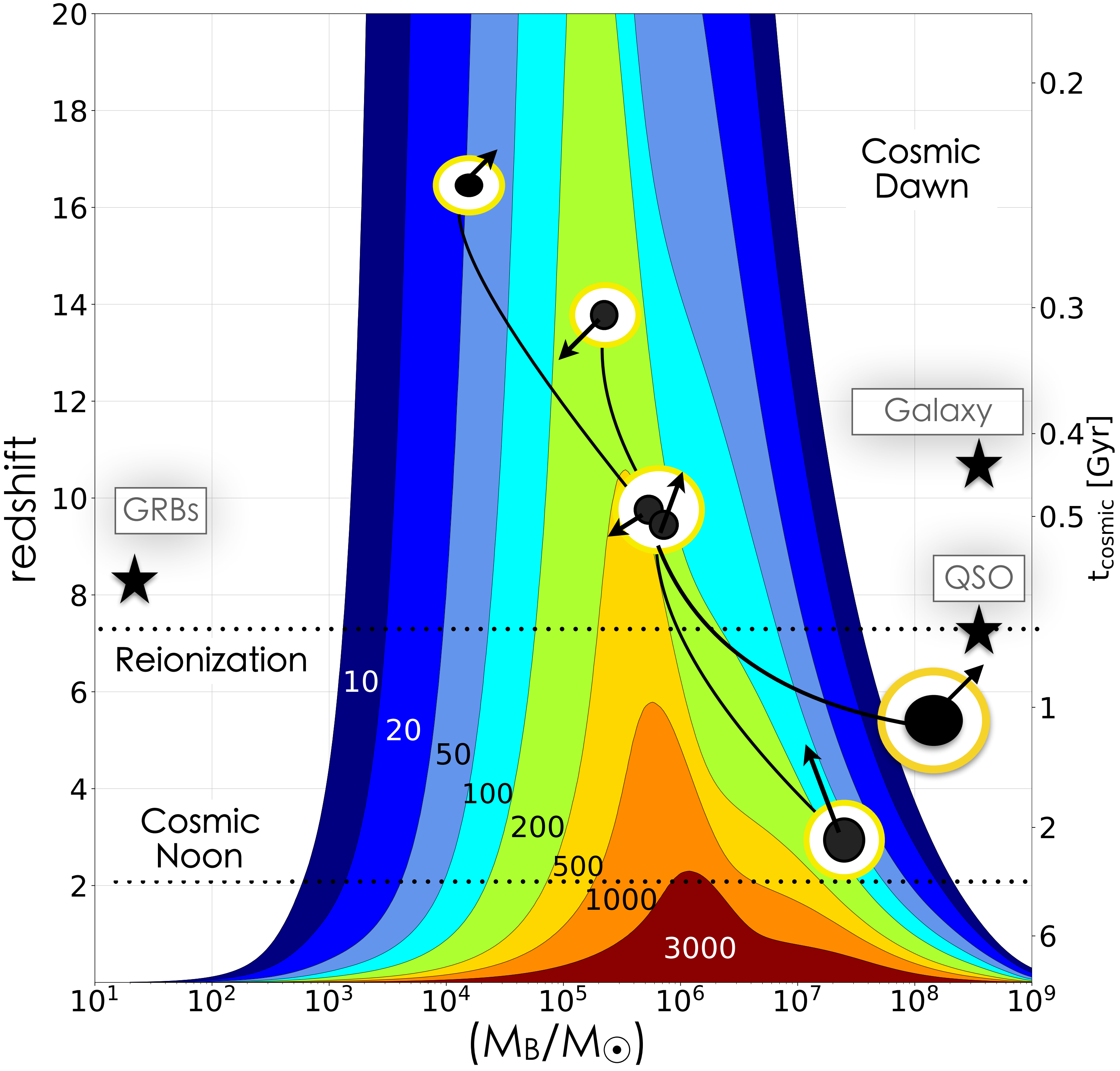


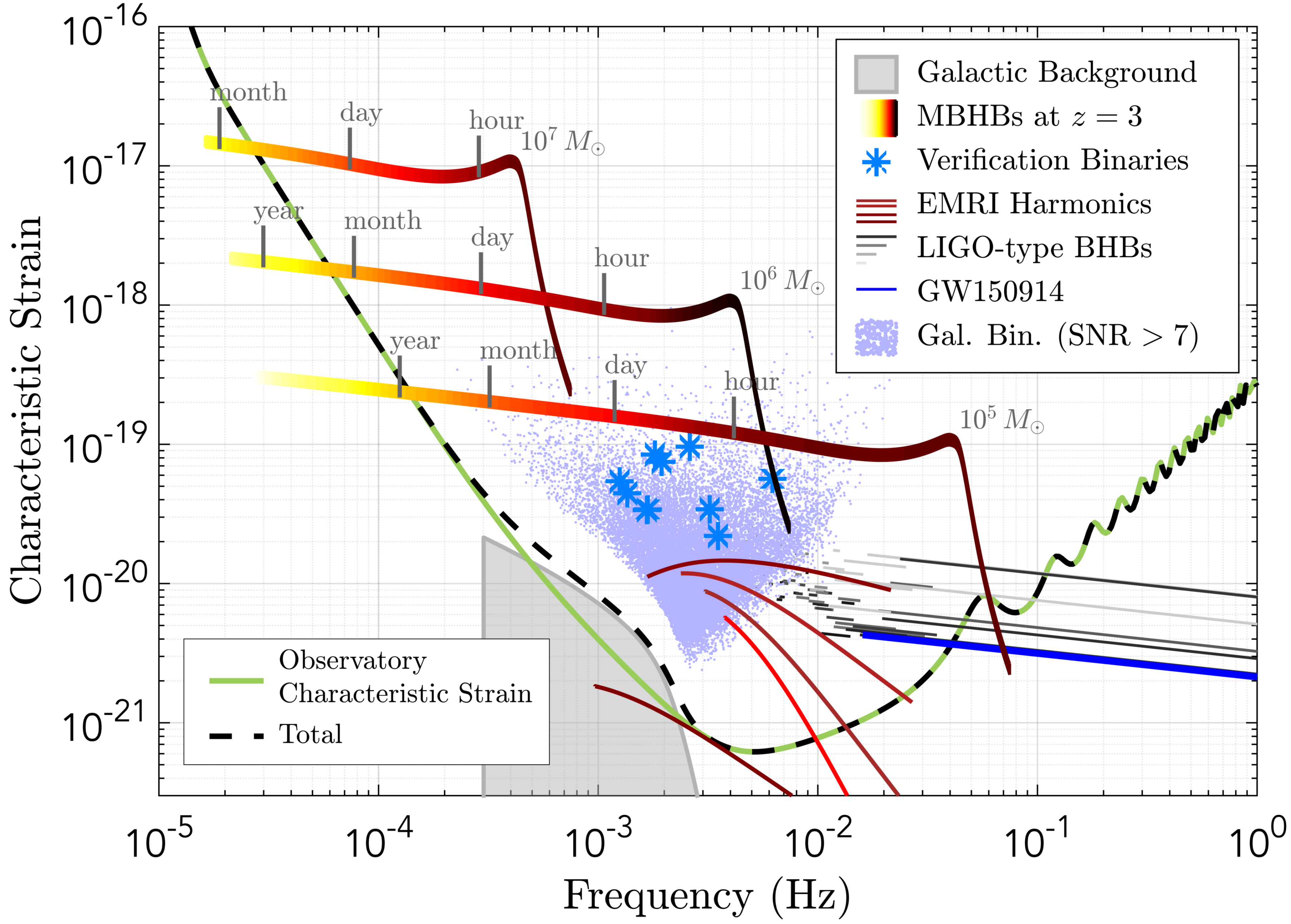
- LISA cosmic horizon for massive black holes is the entire universe



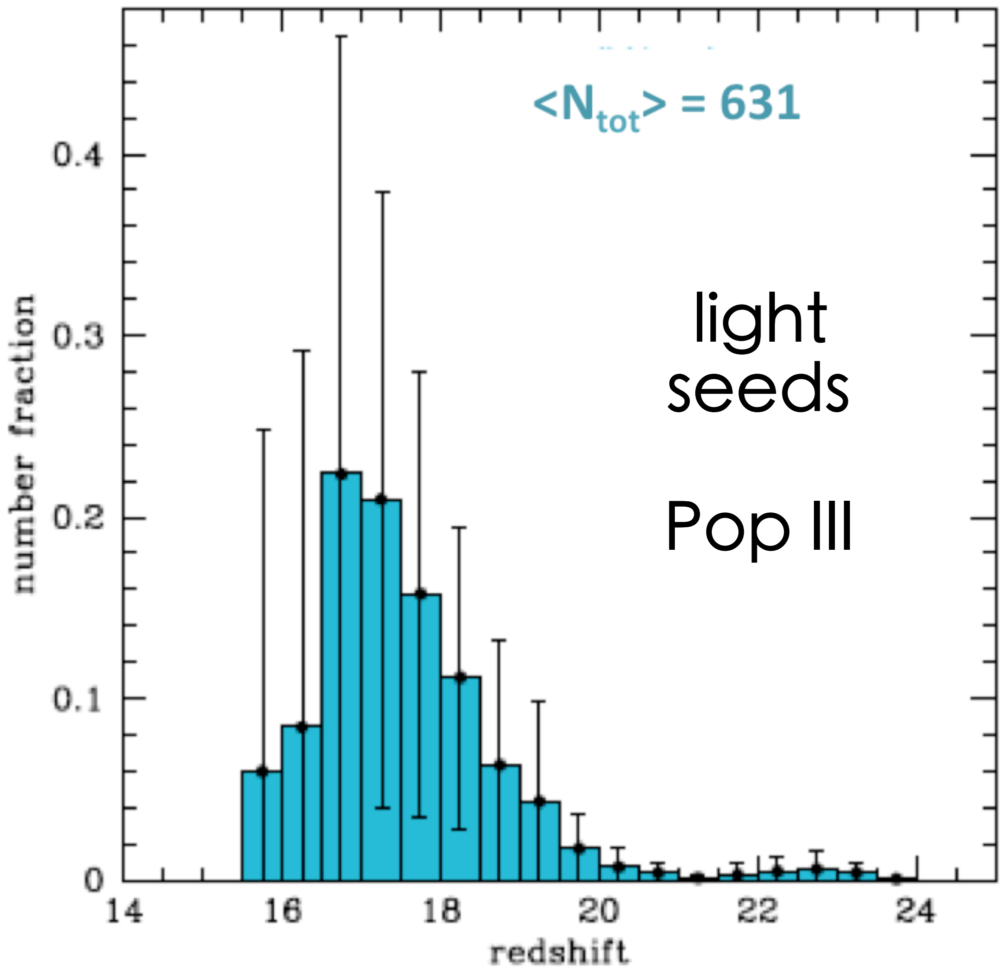
LISA white paper 2017

- Accretion might alone explain high z QSOs but accretion is likely modulated by halo-halo mergers - halo dynamics leads to black hole binary formation



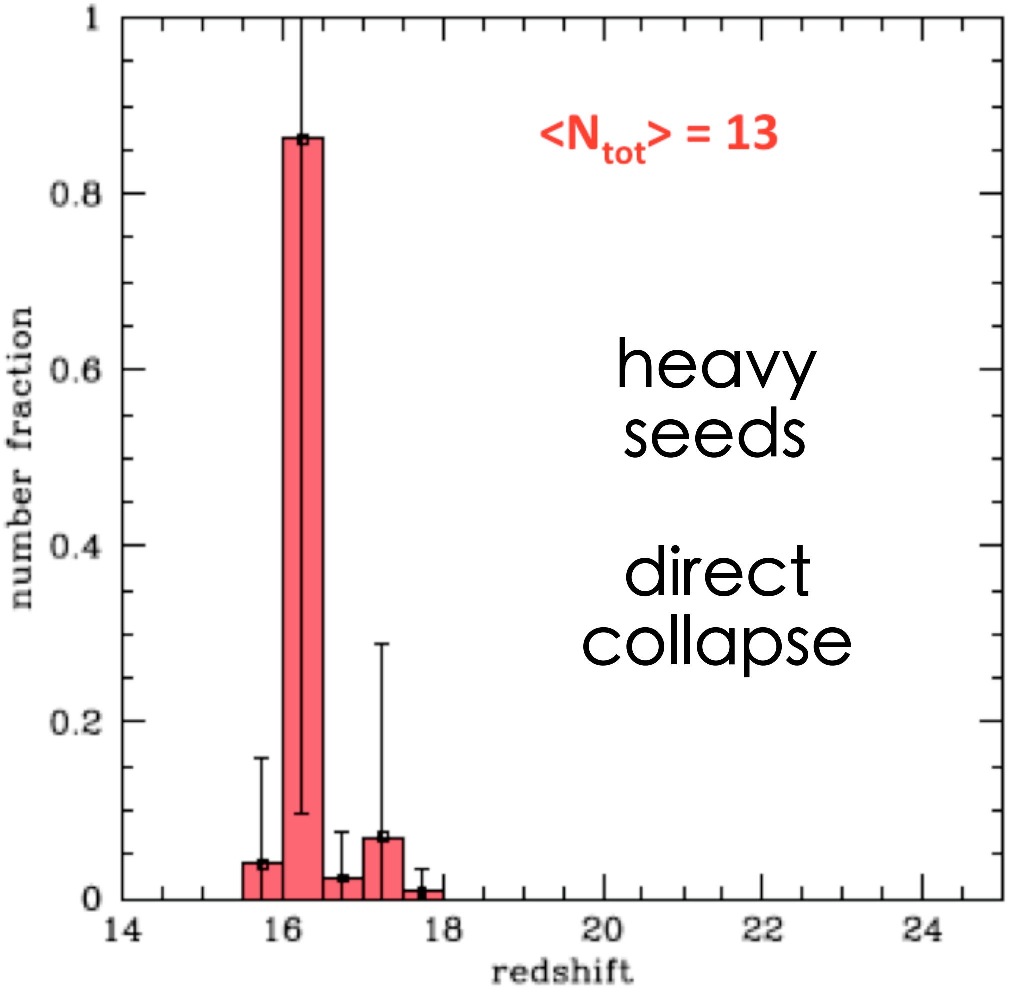

Characteristic Strain
Frequency (Hz)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
month
day
hour
$10^7\ M_\odot$
year
month
day
hour
$10^6\ M_\odot$
year
month
day
hour
$10^5\ M_\odot$
Galactic Background
MBHBs at $z = 3$
Verification Binaries
EMRI Harmonics
LIGO-type BHBs
GW150914
Gal. Bin. (SNR > 7)
Observatory Characteristic Strain
Total

Seed black holes in the cosmological context



light seeds

Pop III



heavy seeds

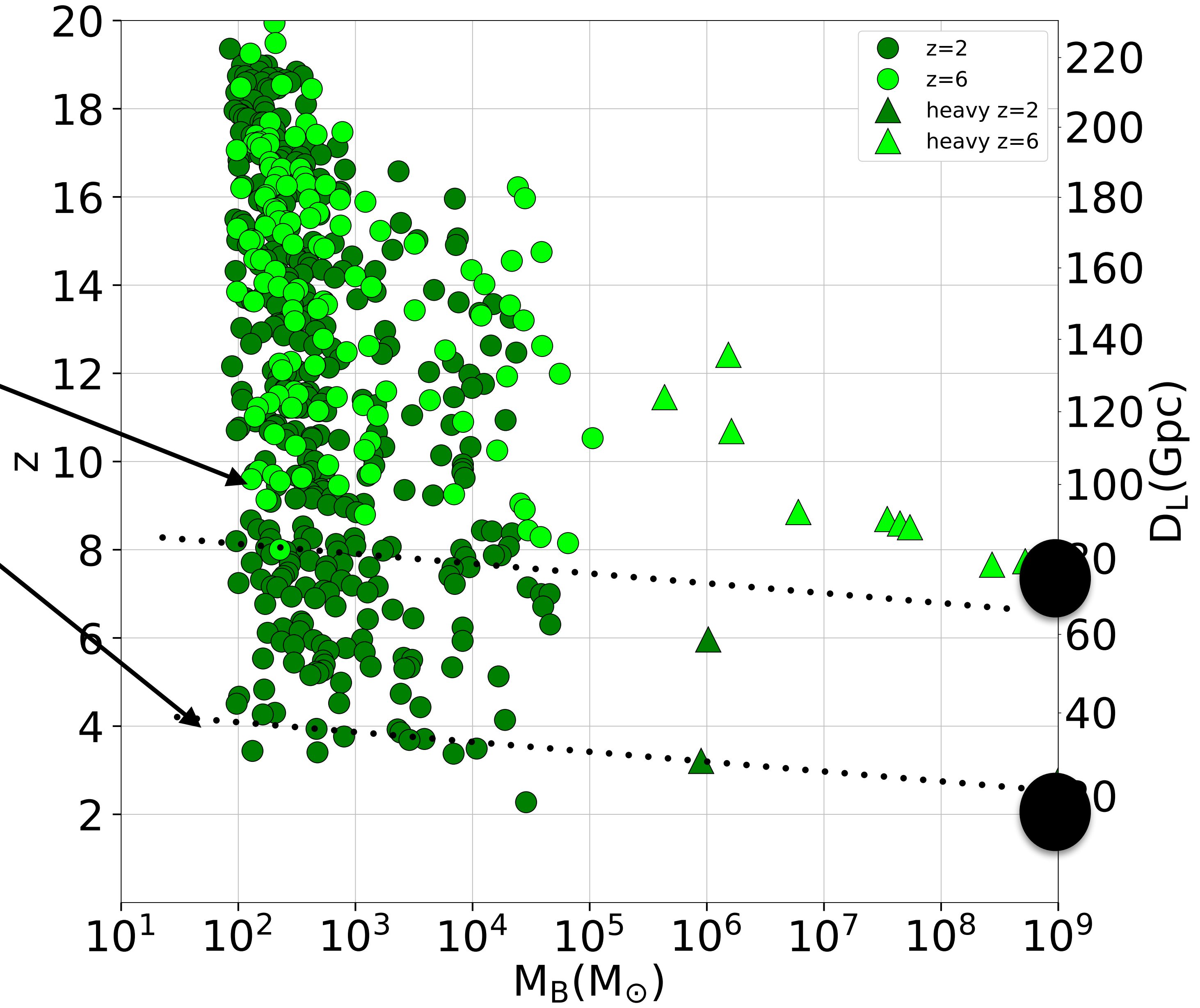
direct collapse

- distribution in redshift of light (selected as the most massive black hole present in a halo) and heavy seeds

Valiante+2016

MERGER TREE OF HIGH z QSOs

“failed”
non-evolved
Seeds



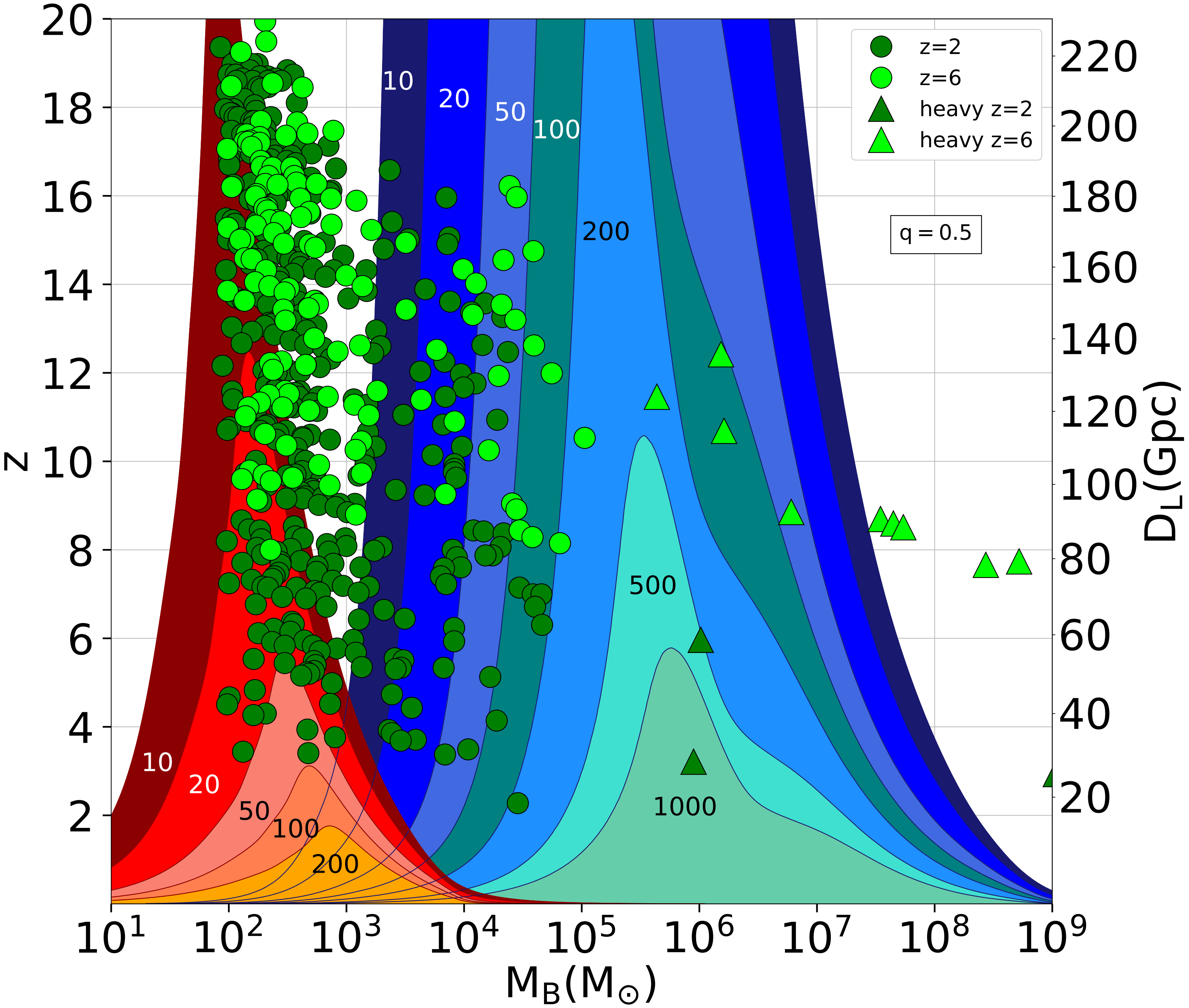
Black holes forming
in pristine halos and
pairing in
“cosmologically-
driven mergers”

Valiante +
In preparation

$M_{\rm halo} = 10^{13} M_\odot$

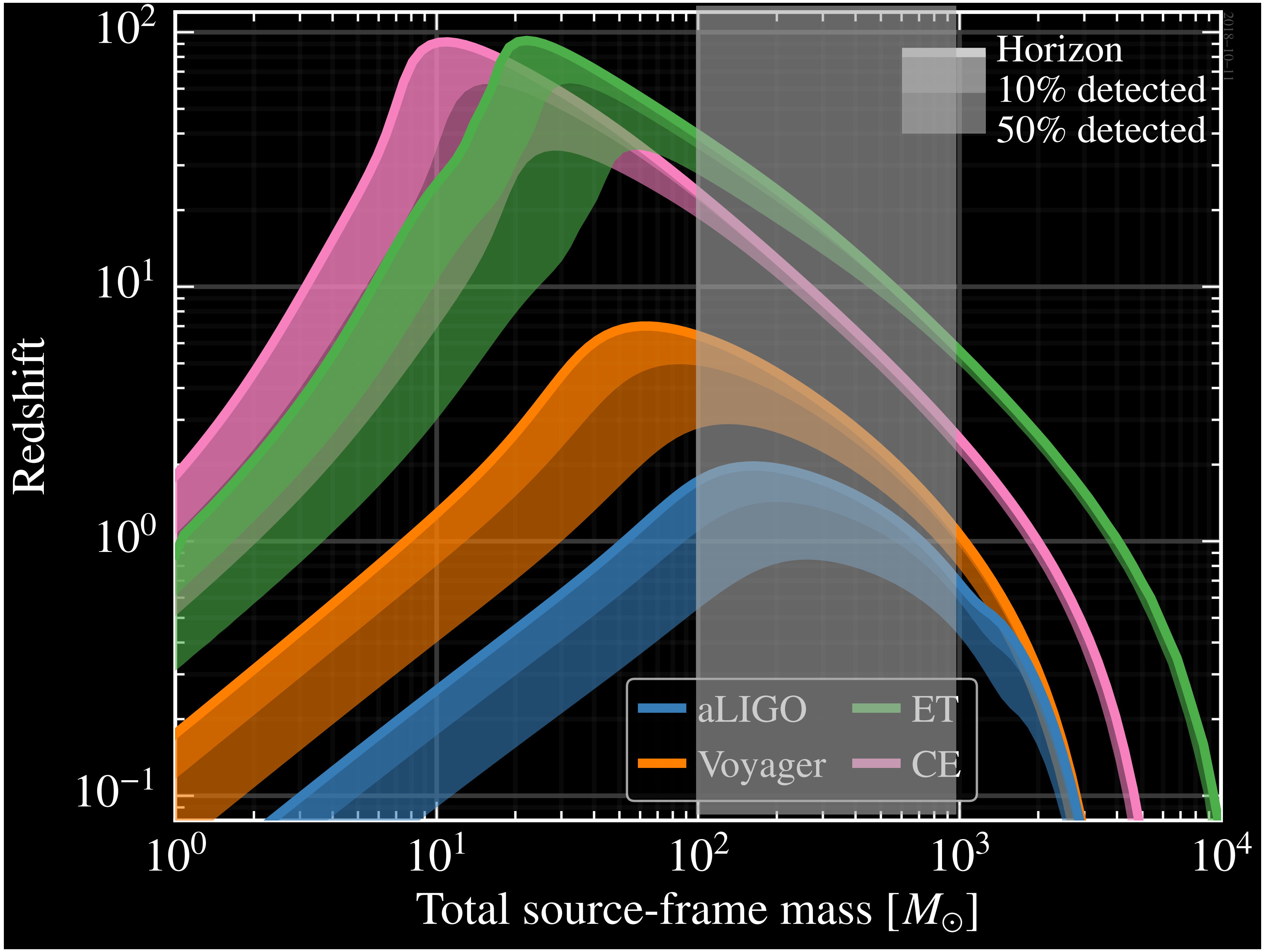
- dot= halo+halo merger with two nuclear light seeds merging

Black Holes in the Gravitational Universe

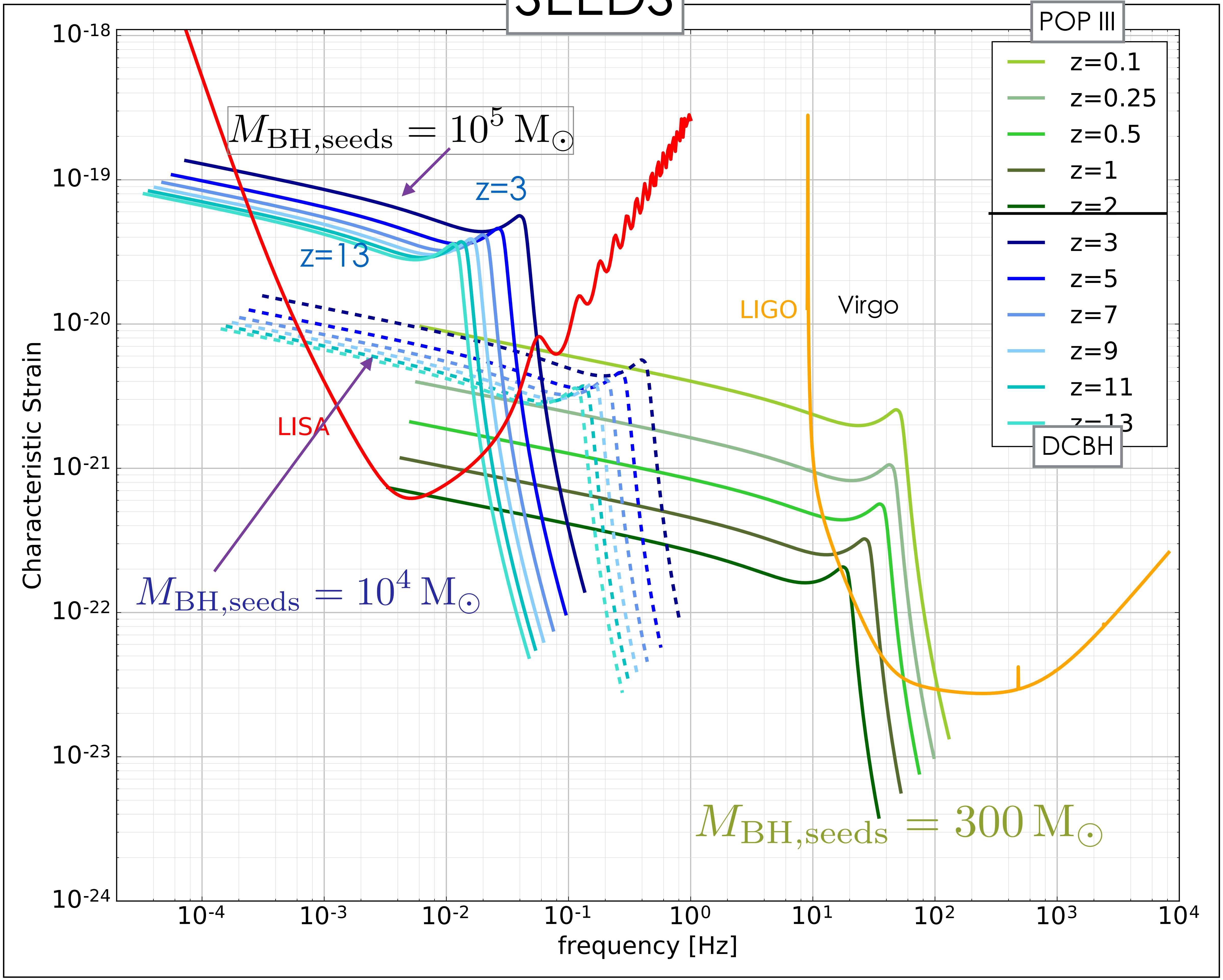


Valiante + 2019 in Preparation

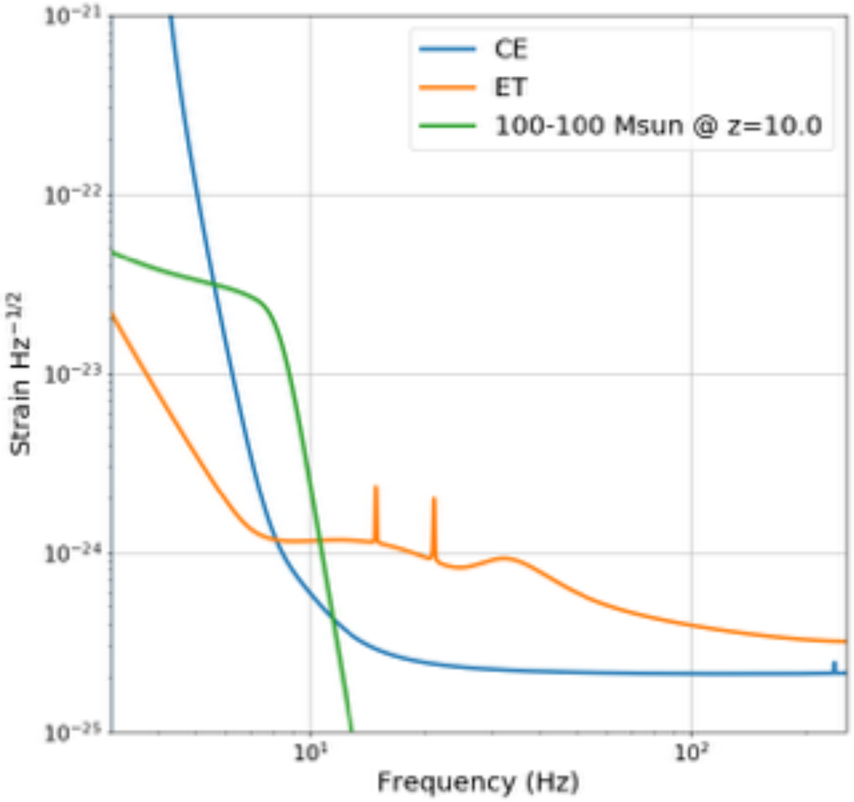
Waterfall plot for non spinning black holes: PhenomC
ET_D sensitivity curve + LISA

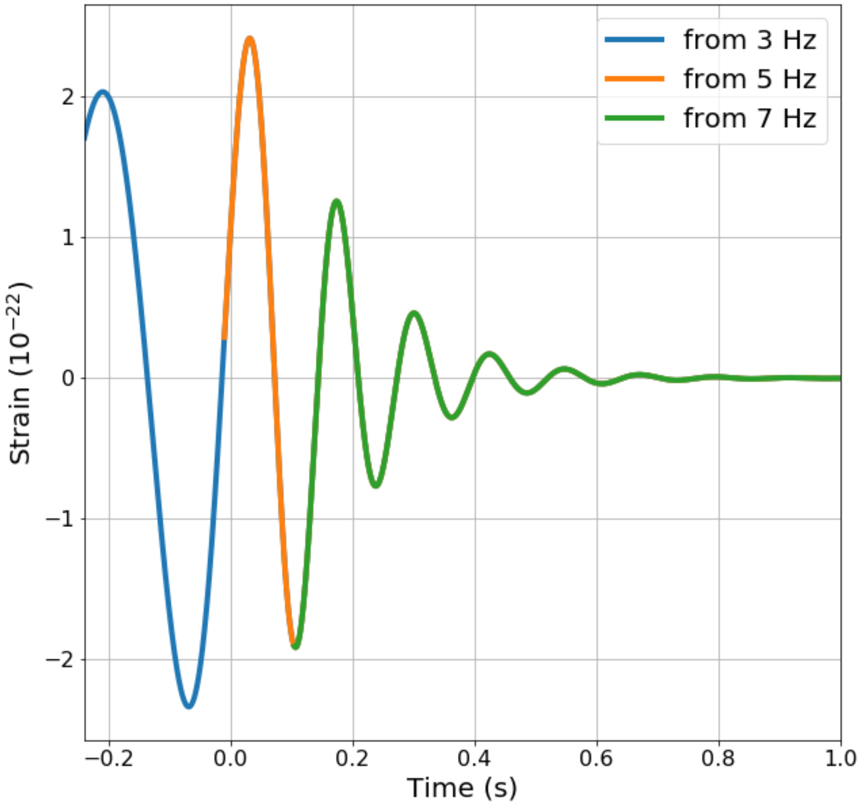

Horizon
10% detected
50% detected
aLIGO
Voyager
ET
CE
Redshift
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3
10^4
Total source-frame mass [$M_\odot$]
2018–10–11

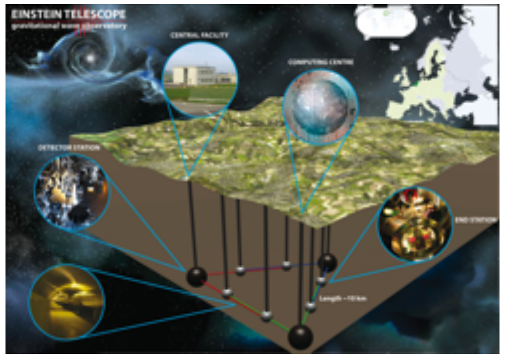
SEEDS


POP III
z=0.1
z=0.25
z=0.5
z=1
z=2
z=3
z=5
z=7
z=9
z=11
z=13
DCBH
$M_{\rm BH,seeds} = 10^5\,{\rm M}_\odot$
z=3
z=13
$M_{\rm BH,seeds} = 10^4\,{\rm M}_\odot$
LISA
LIGO
Virgo
$M_{\rm BH,seeds} = 300\,{\rm M}_\odot$
Characteristic Strain
frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

- Key role of Einstein Telescope
- Detecting ‘failed seeds” will be a challenge
- the only avenue to unveil the ‘seed’ and weight their mass !







courtesy of S. Fairhurst

- How do black holes pair ?
- How fast do they coalesce?
- Rates?

- black holes are minuscule
- coalescing binary black holes are minuscule

$$R_{\rm G} = \frac{2GM}{c^2} = 0.1\left(\frac{M_{\rm BH}}{10^6\,M_\odot}\right)\,\mu\text{parsec}$$

$$t_{\rm coal} = \frac{5}{256}\frac{c^5}{G^3}\mathcal{G}(e)(1-e^2)^{7/2}\frac{a^4}{\nu\,M_{\rm B}^3}$$

$$\nu = \frac{\mu}{M} = \frac{q}{(1+q)^2} \qquad\qquad M_{\rm B} = M_{\rm BH,1} + M_{\rm BH,2}$$

$z = 15$ $t_{\rm cosmic} = 0.27\,{\rm Gyr}$	$M_{\rm B} = 10^5\,M_\odot$	$M_{\rm B} = 10^6\,M_\odot$
$a_{\rm GW}$	$\nu^{1/4}2.5\times10^4\,R_{\rm G}$ $0.25\,{\rm mparsec}$	$\nu^{1/4}1.4\times10^4\,R_{\rm G}$ $1.4\,{\rm mparsec}$

Portrait of an isolated gas-rich major (1:4) merger

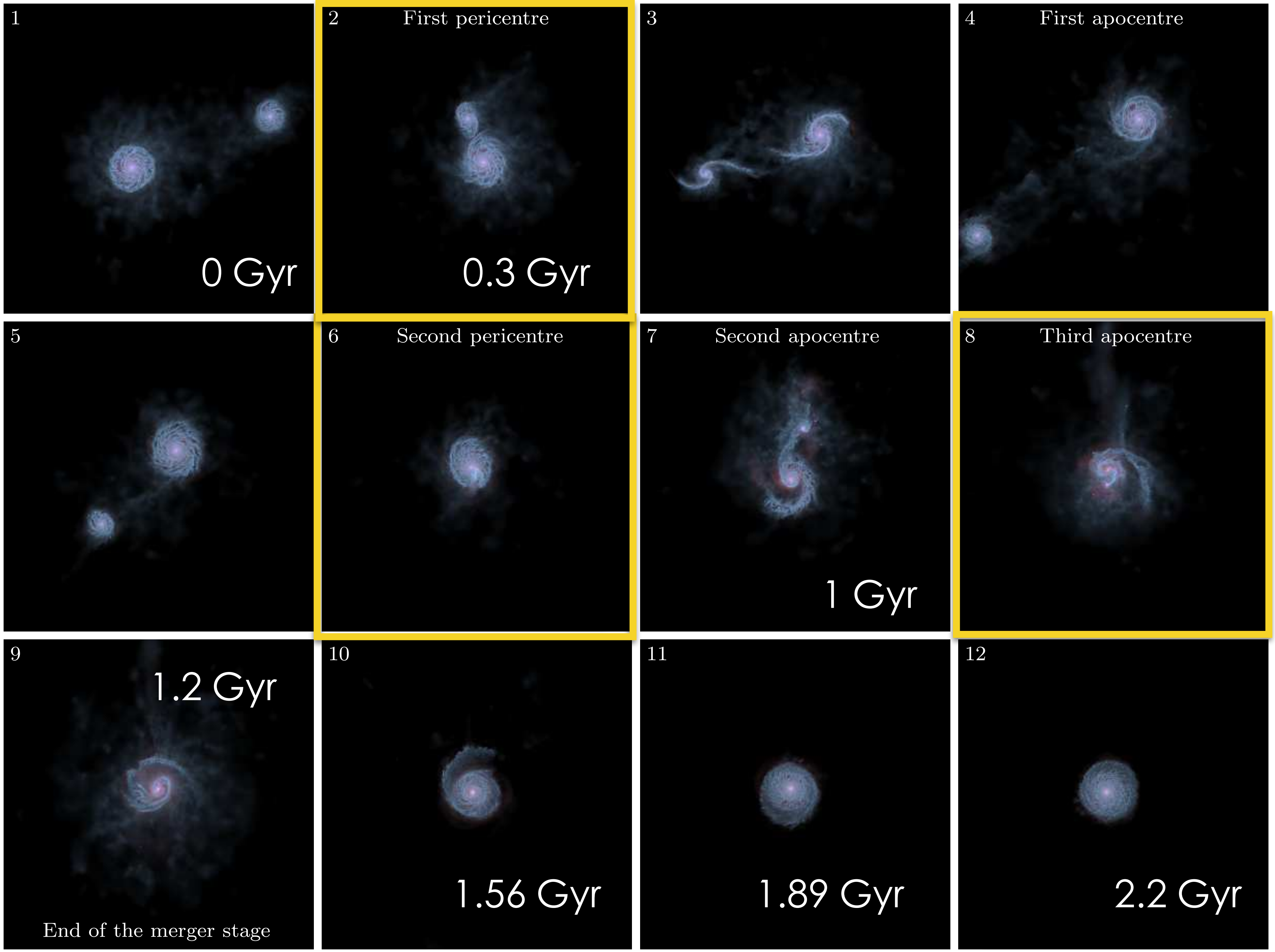
- Clock: time "zero"

$$M_{\rm BH,primary} = 3 \times 10^6\, M_\odot$$
$$M_{\rm halo} = 2.2 \times 10^{11}\, M_\odot;\, M_{\rm bulge} = 2 \times 10^9\, M_\odot$$
$$M_{\rm disc,*} = 6 \times 10^9\, M_\odot;\, M_{\rm disc,gas} = 3 \times 10^9\, M_\odot$$

70x70 kpc box

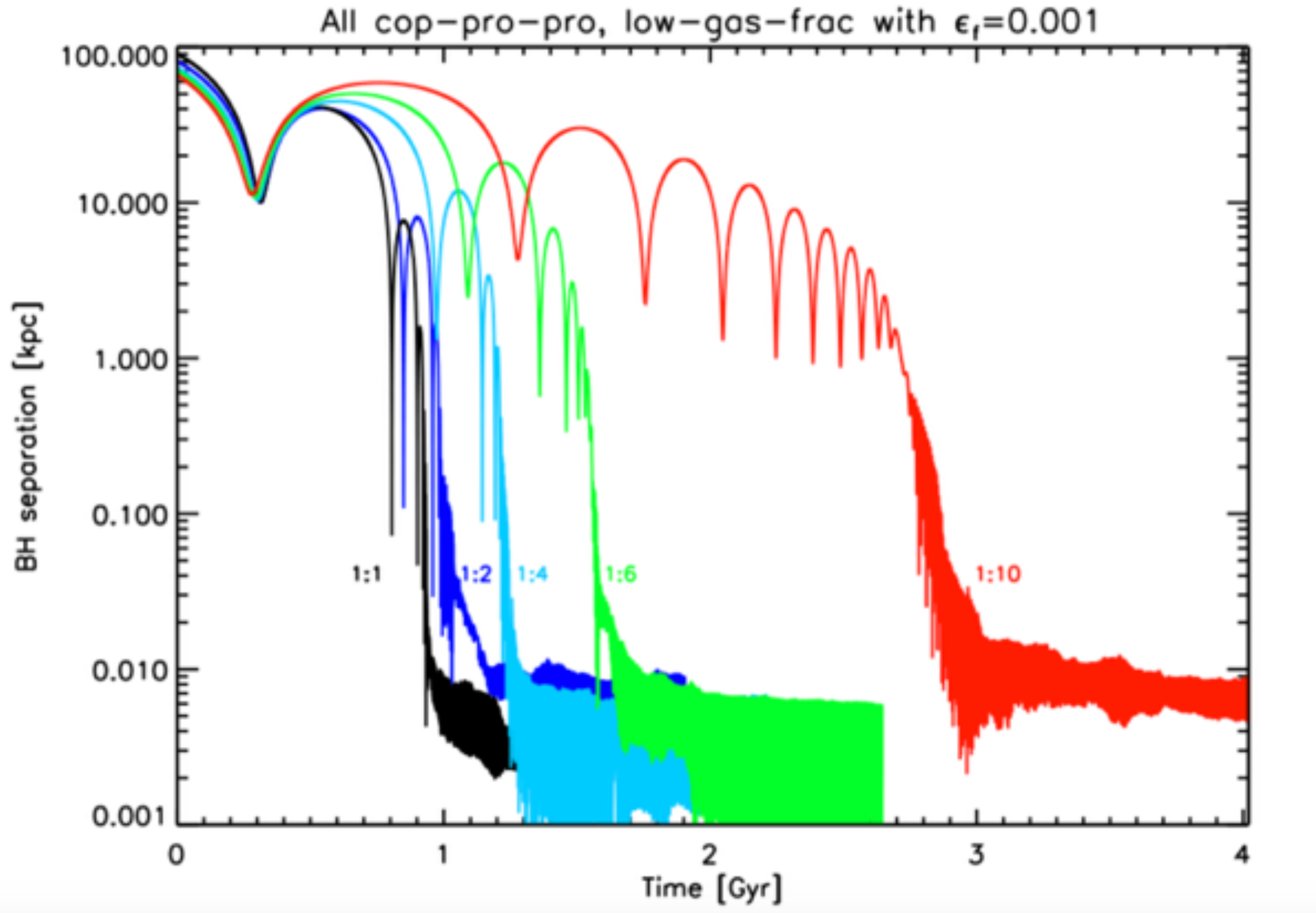
1:4 merger between two disc galaxies

gas fraction 30%



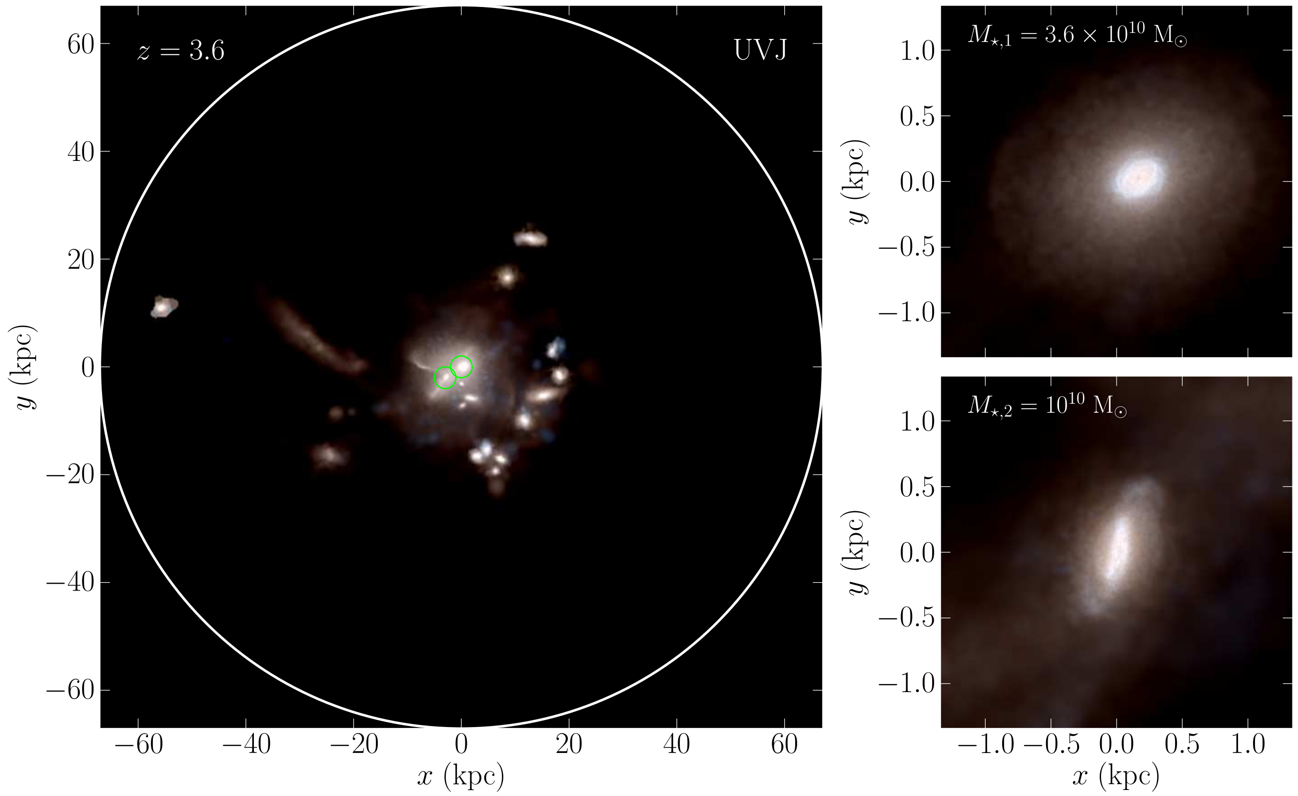
Capelo+2014

$$\mathbf{F}_{\rm DF}^{\rm stars} = -4\pi \ln \Lambda G^2 M_{\rm BH}^2 \rho_* \mathcal{F}\left(\frac{V_{\rm BH,orb}}{\sigma_*}\right) \frac{\mathbf{V}_{\rm BH,orb}}{V_{\rm BH,orb}^3}$$



$$a_{\rm binary} \sim \frac{G M_{\rm B}}{\sigma^2} \sim 1 \left(\frac{M_{\rm B}}{10^6\,{\rm M}_\odot}\right)\left(\frac{50\,{\rm km\,s^{-1}}}{\sigma}\right)^2 \text{ parsec}$$

Portrait of a cosmological merger



$$m_1^{\mathrm{BH}} = 10^8\,\mathrm{M}_\odot$$

$$m_2^{\mathrm{BH}} = 3 \times 10^7\,\mathrm{M}_\odot$$

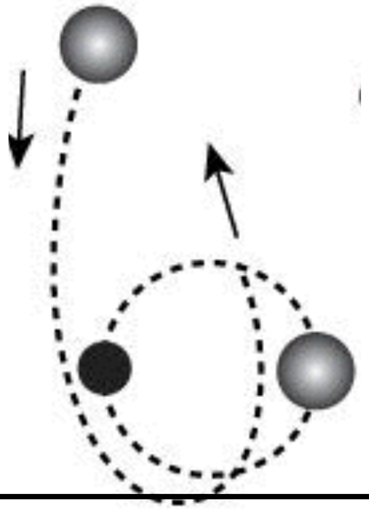
Khan, Mayer, Fiacconi 2016

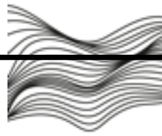
- first ab initio simulation of a galaxy group @ z=3.5 from Argo cosmological simulation
- identification of the two main spirals undergoing a major merger (1:3.6 mass ratio) on a nearly parabolic orbit with co-rotating stellar discs inclined by 67 degrees
- gas fractions of about 10%

$$M_{2,*} \sim 10^{10}\,M_\odot$$
$$M_{1,*} \sim 3.6 \times 10^{10}\,M_\odot$$
$$M_{\mathrm{halo}} \sim 10^{13}\,M_\odot \quad @ \quad z = 0$$

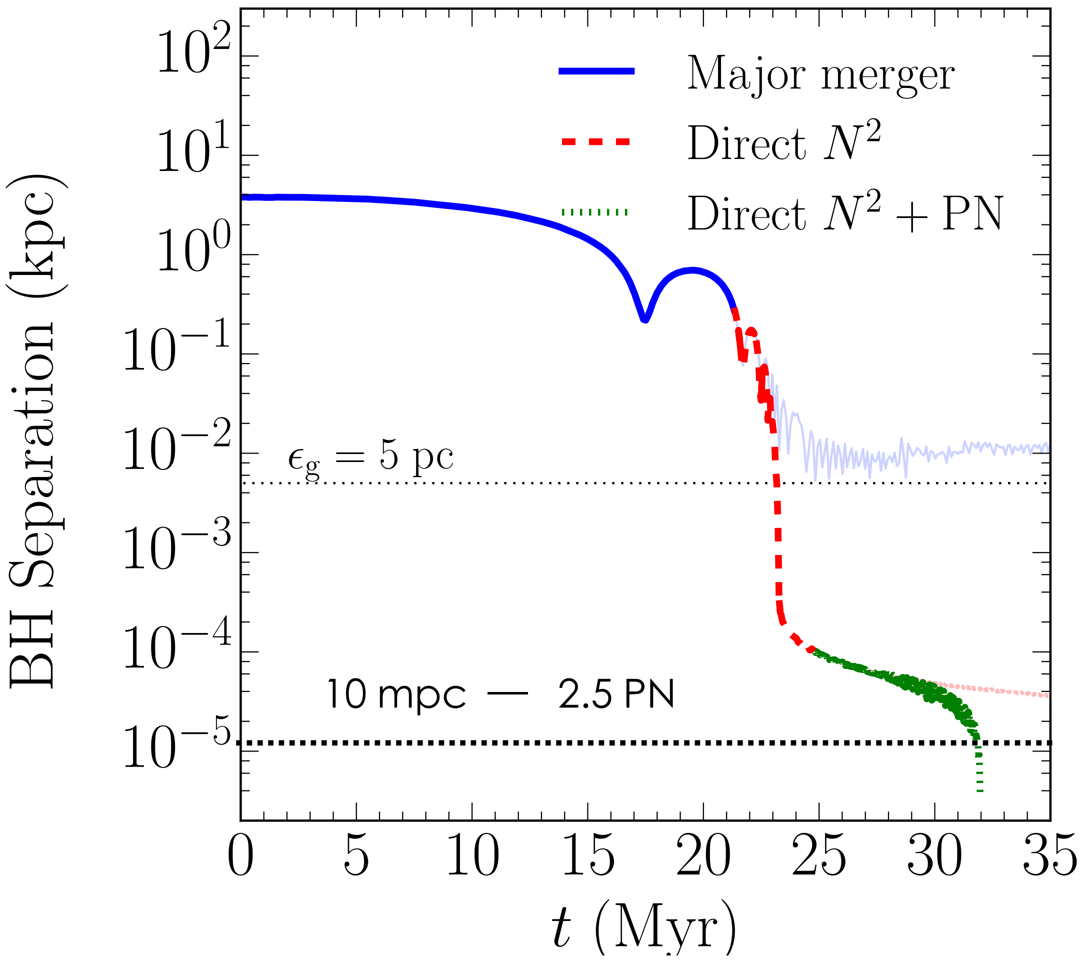
- gas inflows in the inner 500 pc from cosmological streams are conducive to an intense burst of star formation around the secondary black hole

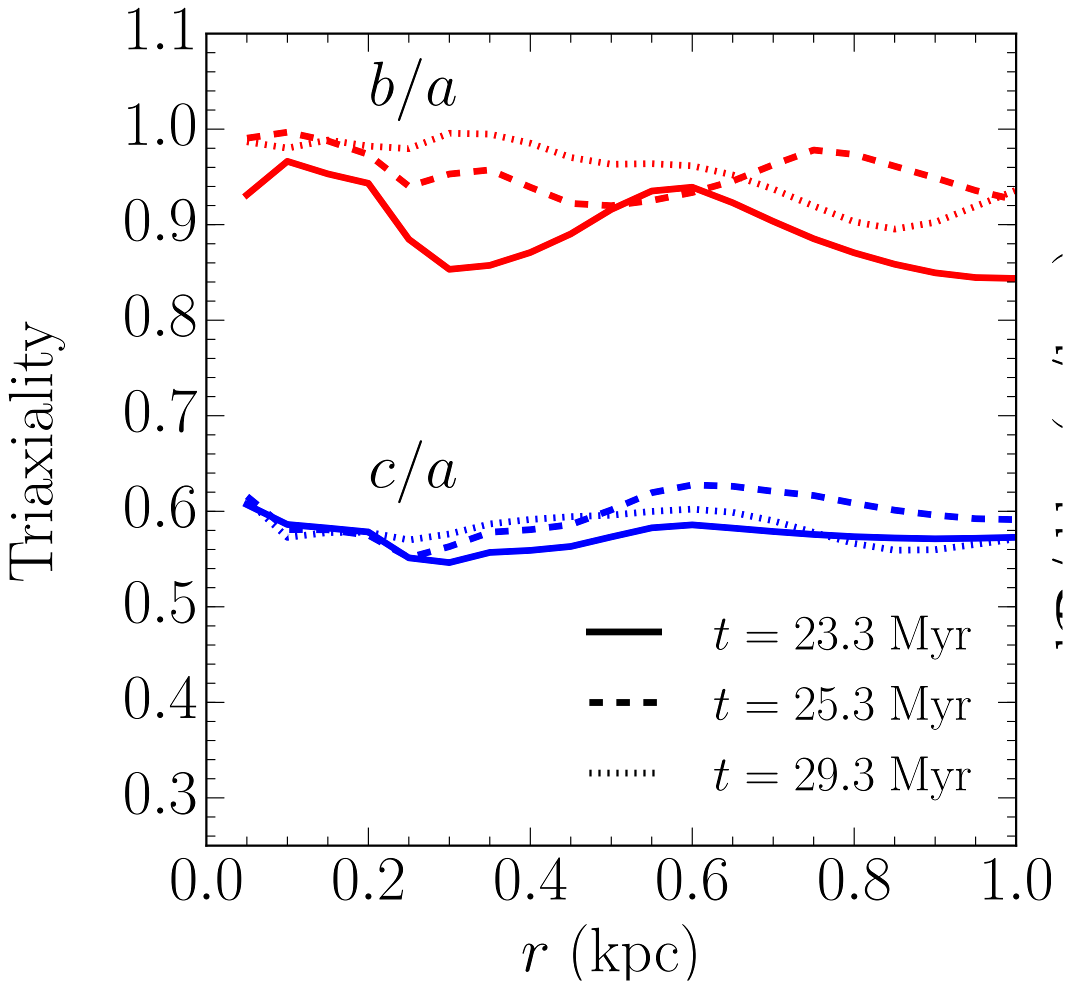
- the black holes are surrounded by a stellar cusp which enhances their "effective mass" - the orbital decay is governed by dynamical friction of the stellar cusps





- the binary hardens by the slingshot mechanisms with individual stars impugning on the binary form low-angular momentum orbits in a triaxial potential. The binary mergers 10 Myrs after the merger of the stellar cusps

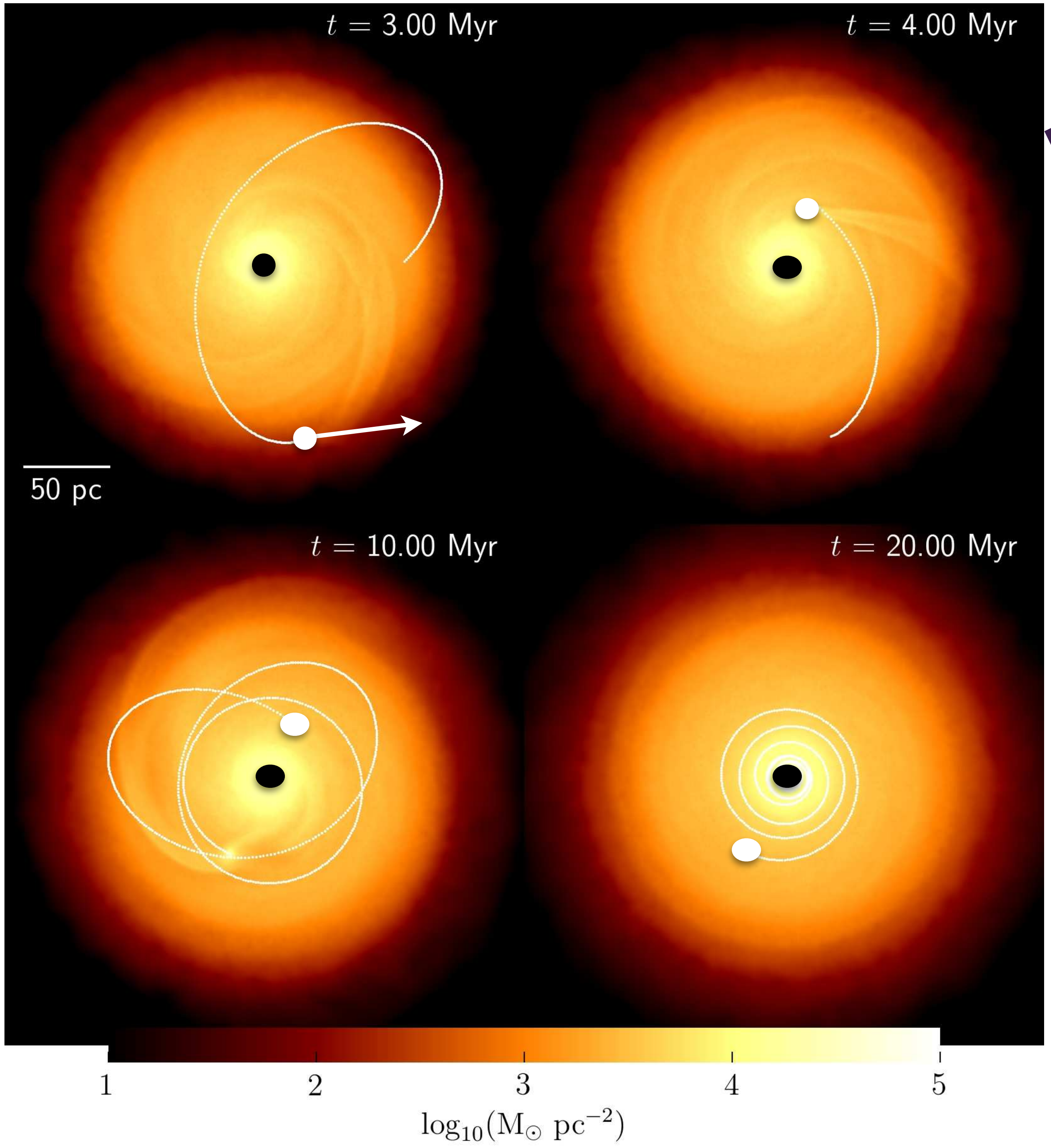


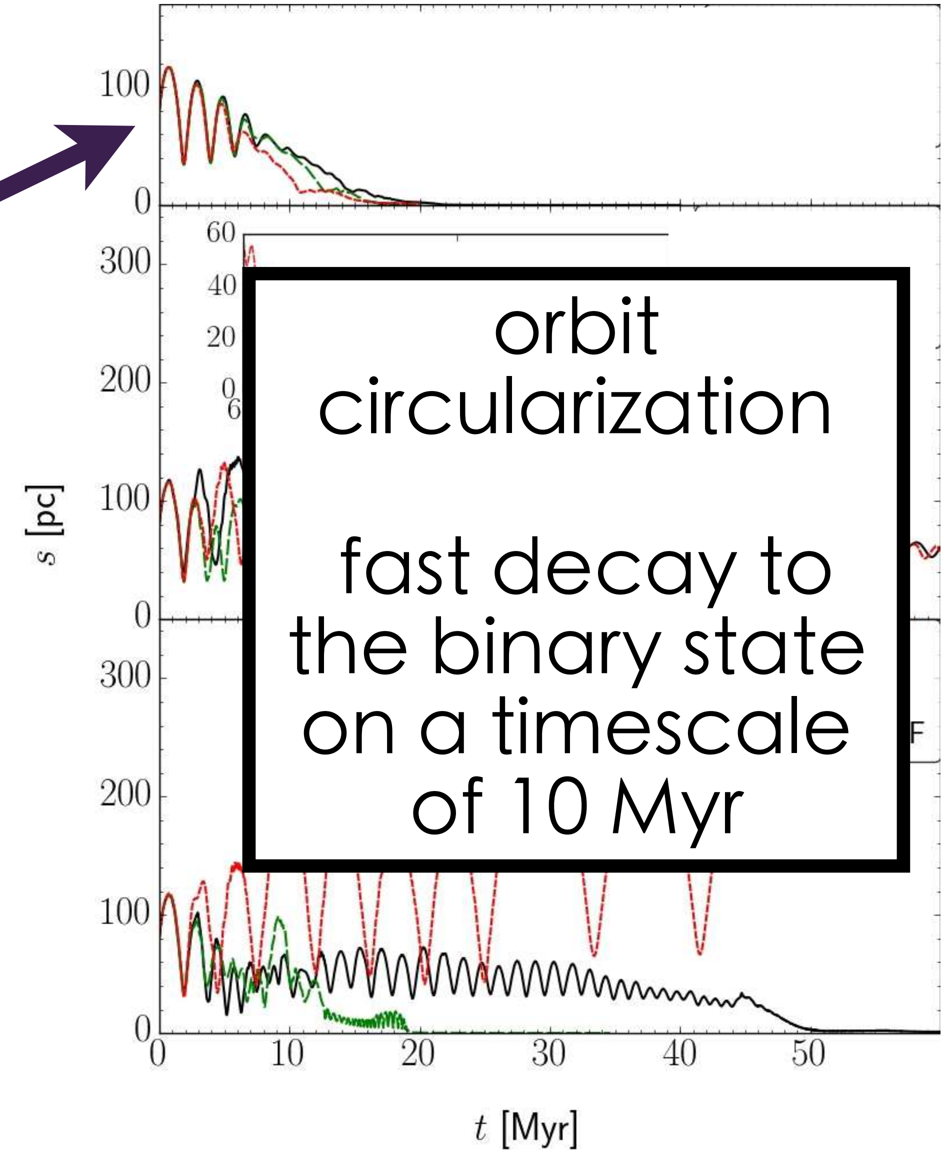


Black hole dynamics in massive circum-nuclear gas discs on ~(100 - 1)pc

$M_{\rm disc} = 10^8\, M_\odot$

$M_{\rm BH,1} = 10^7\, M_\odot$ $M_{\rm BH,2} = 5 \times 10^5\, M_\odot$

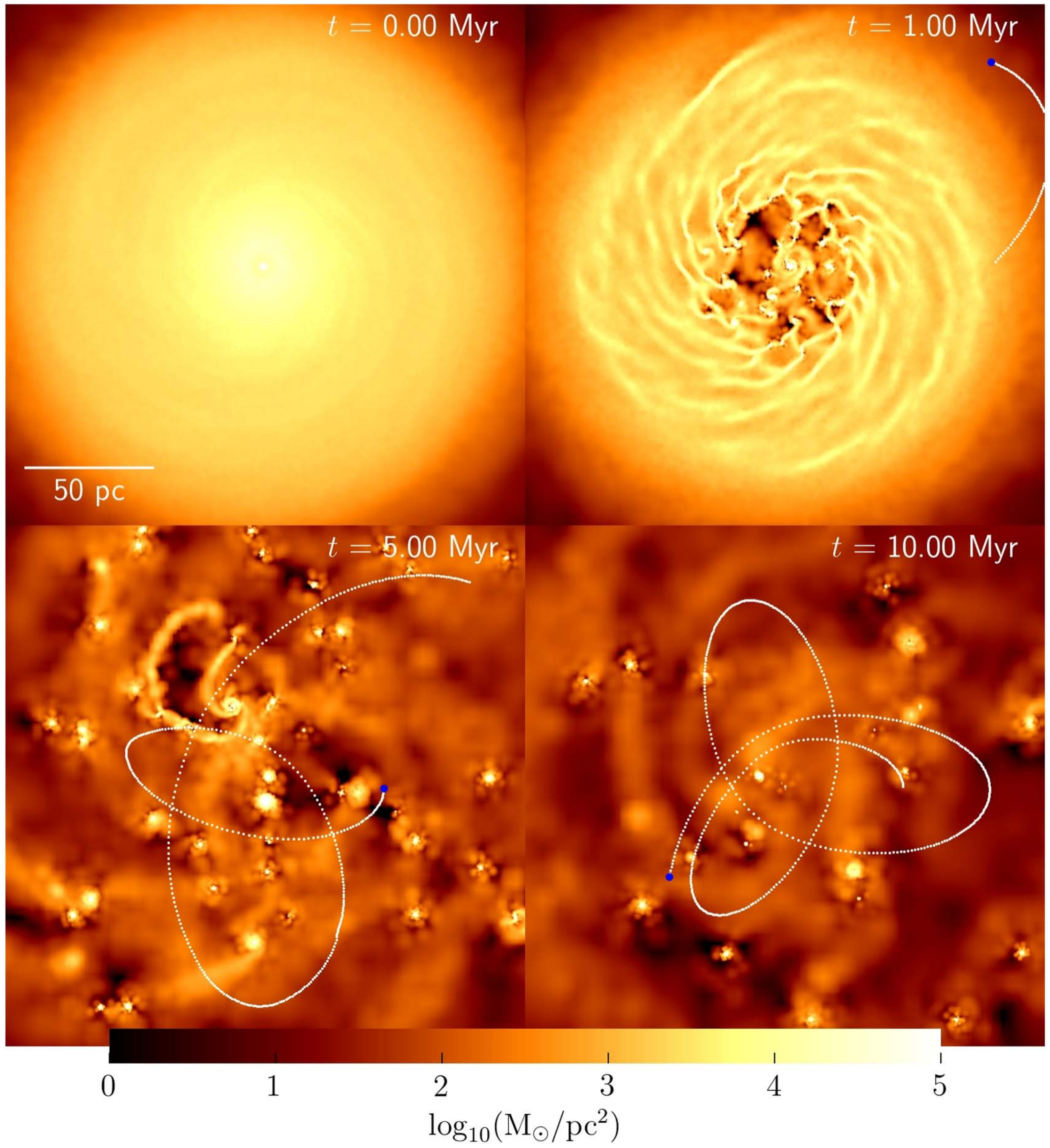




orbit circularization

fast decay to the binary state on a timescale of 10 Myr

Souza Lima+2016
Dotti+2007-2010
Fiacconi+2013
Lupi+2015
del Valle+2015,
Roskar+2015,
Tamburello+ 2016

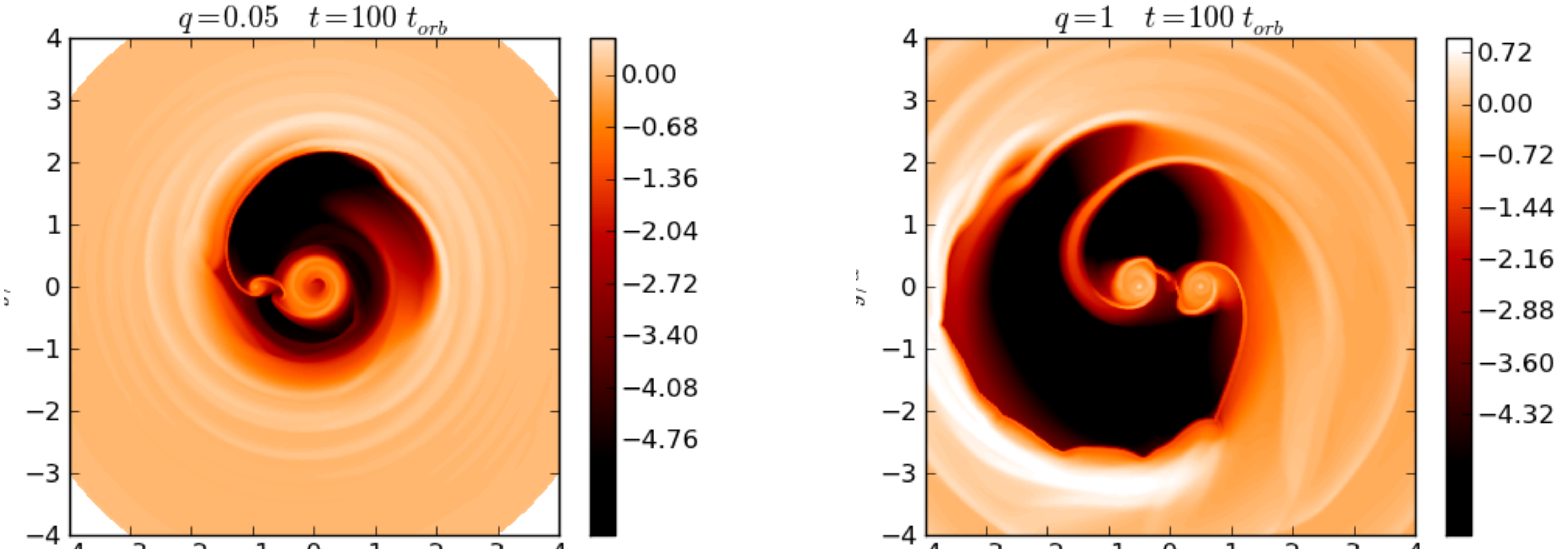


- fragmentation from inside out occurs on a timescale smaller than the orbital decay time
- dense gaseous clumps form, interact, merge to form fewer and larger clump, and migrate to the centre
- clumps can have masses comparable or larger than the black hole masses
- high density contrast leading to a completely different dynamics

Souza Lima+2016, del Valle+2015, Fiacconi+2013

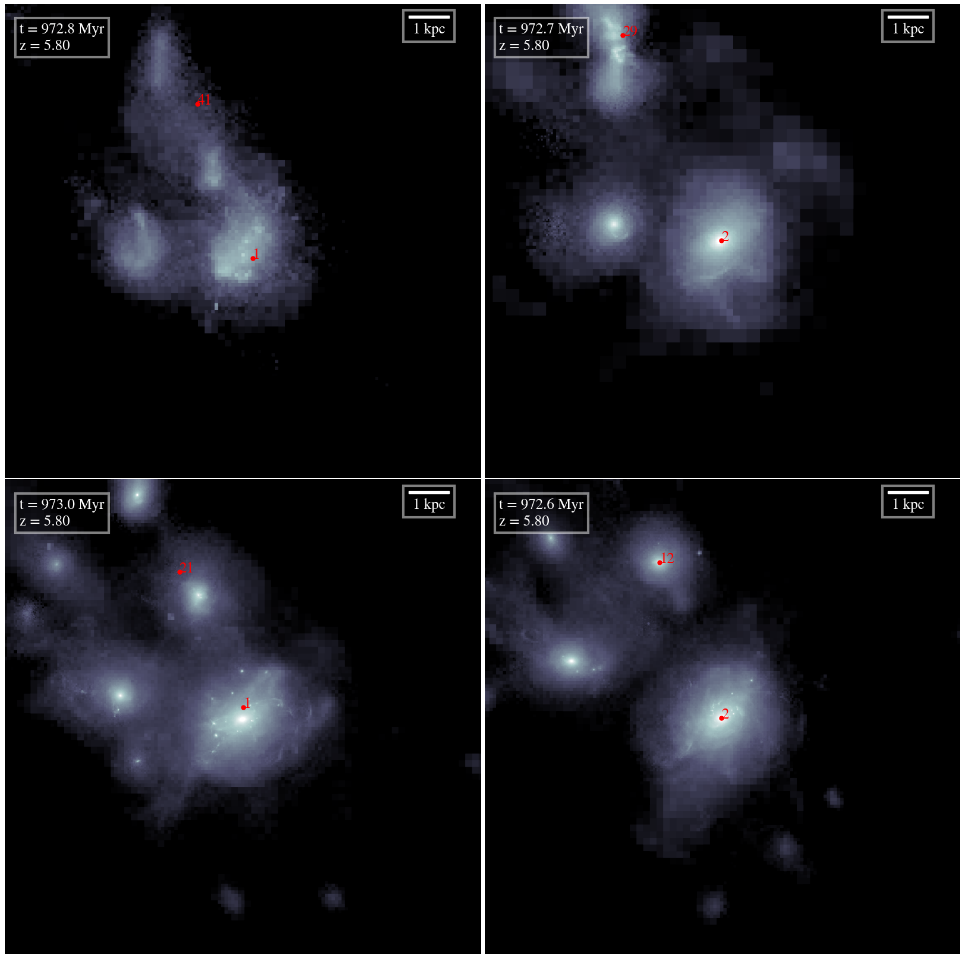
Type II migration in a circum-binary disc

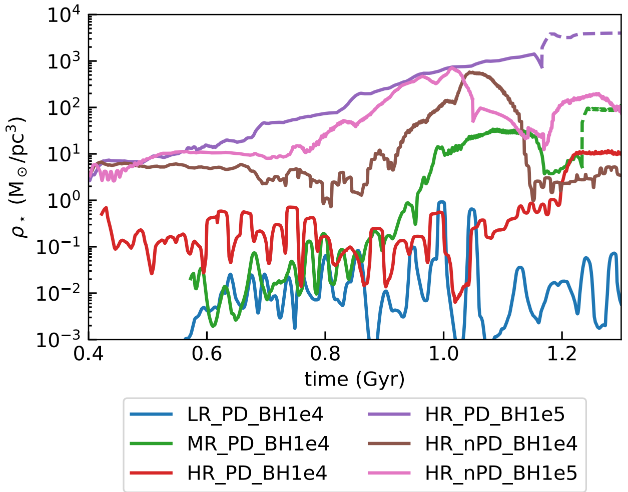
Courtesy by Zoltan Haiman +2017

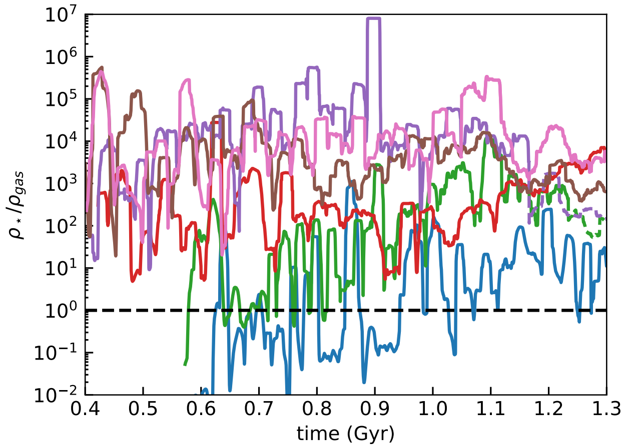


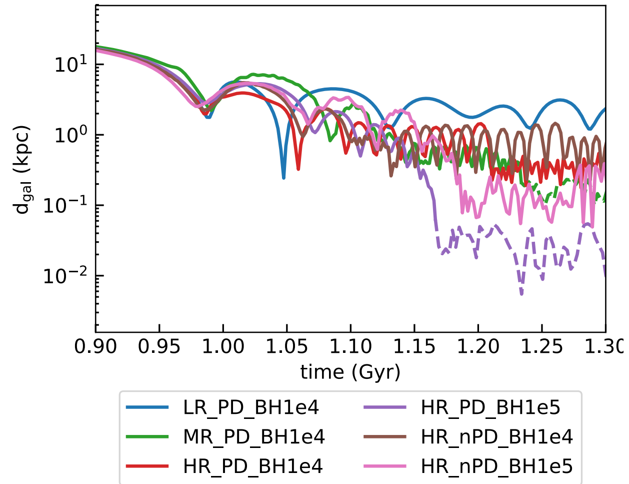
- black holes deposit orbital angular momentum exciting both leading and trailing spiral waves opening a gap of size twice the size of the binary separation

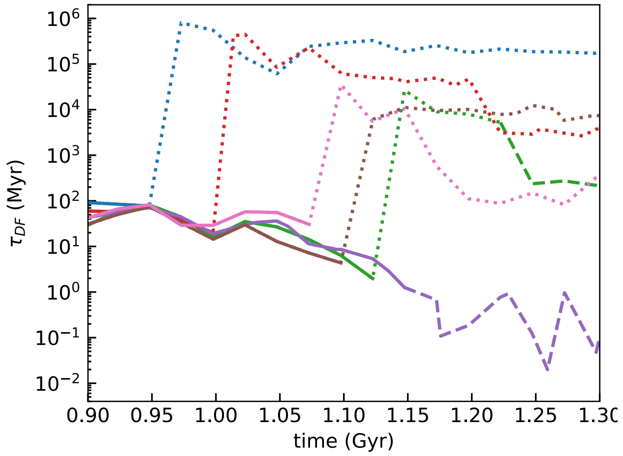
Kocsis+ 2007,2012; MacFadyen+2008; Roedig et al. 2011,12,14; D' Orazio et al. 2013; Farris et al. 2015; Dunhill et al. 2015; Tang et al. 2017; Maureira-Fredes 2018; Dotti+2015







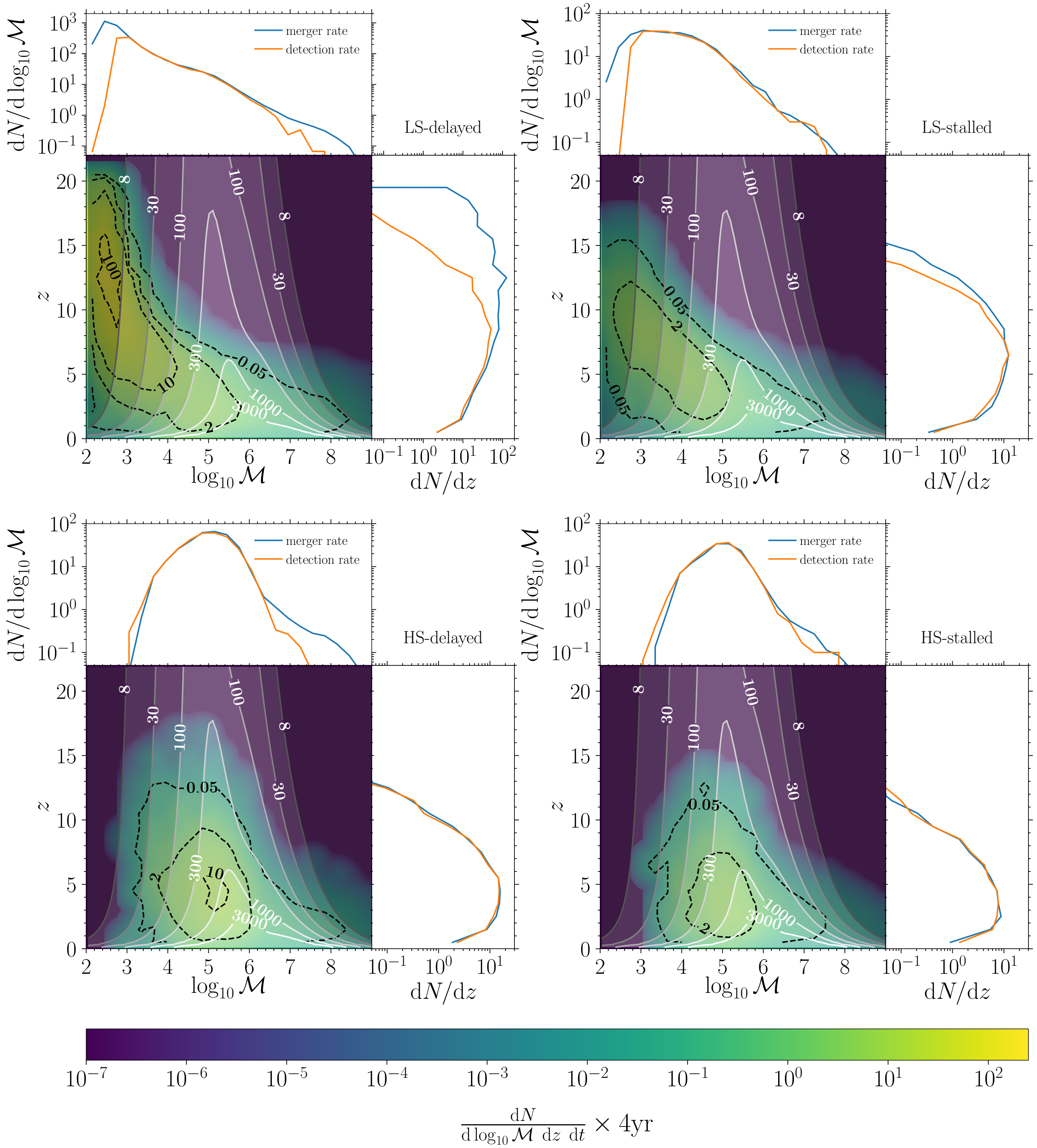




Pfister+ 2019 submitted

- z=9 zoom -in simulation of merging halos
- stars have a stabilizing role in the dynamics of black holes
- in high z mergers also the stellar distribution create e fluctuating background which randomize the black hole dynamicst
- need of sufficient “heavy seeds”

- Inside a relic asymmetric galaxy
- Stalling of the binary due to loss of stars
- Triple interaction with a third black holes
- Kozai resonances
- Chaotic three body interaction



Bonetti+2018

summary

- Detecting coalescing binary black holes across cosmic ages and over a wide range of masses, which implies detecting low and high frequency gravitational waves will lead to a deep understanding on the origin and evolution of the black holes of the universe
- understanding the nature of massive black holes is of extreme importance
- the two main avenues — light versus heavy—- may not be the only possible and we need to critically study formation and dynamical processes to establish their role
- only LISA and III generation of ground based telescopes will let us understand black holes
- the gravitational universe promises many discoveries