COALESCING BLACK HOLES IN THE COSMIC LANDSCAPE

Deciphering the Astrophysics behind the Discovery

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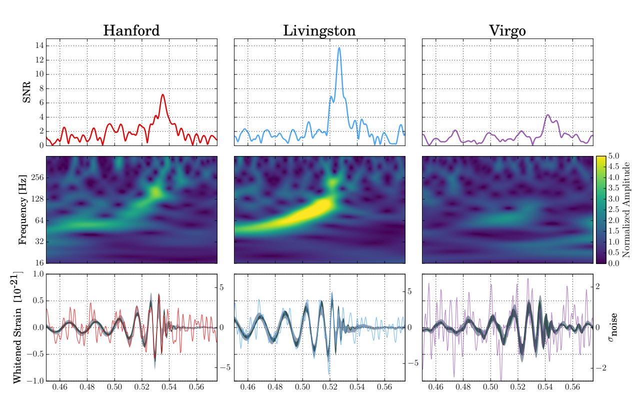
"AGN 13: THE BEAUTY AND THE BEAST"

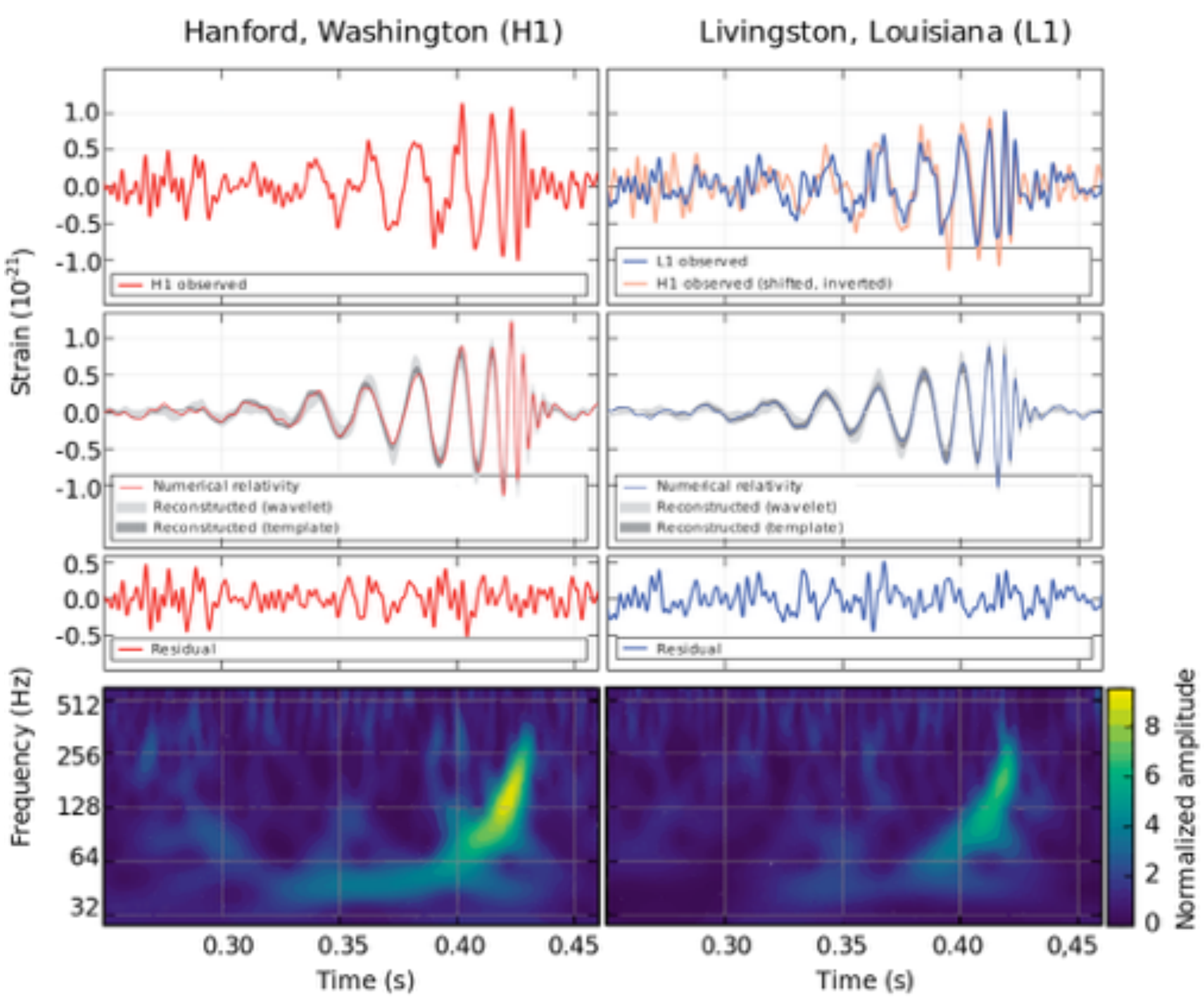
9-12 October 2018

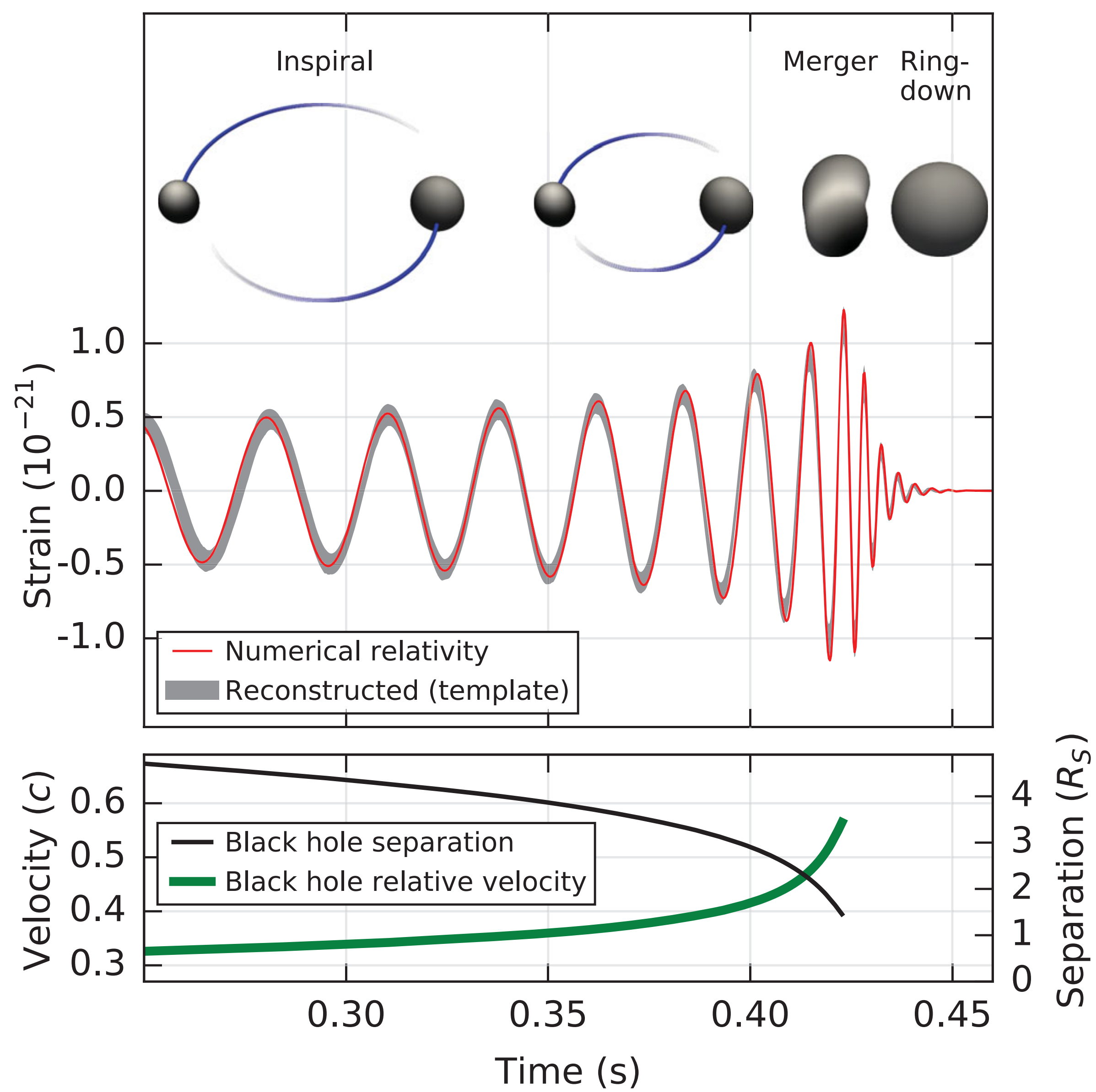


GW150914

HERE IS THE BEAUTY !

THE MERGER OF TWO PURELY GEOMETRICAL OBJECTS





$$3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg/s}$$

$$3.0^{+0.5}_{-0.5} M_{\odot} c^2$$

The LIGO and VIRGO Scientific Collaboration

BLACK HOLE COALESCENCE - UNIVERSALITY - SIMPLICITY

initial state

external parameters

final state

$m_{\rm BH,1}$

$m_{\rm BH,2}$

$q \equiv m_{\rm BH,1}/m_{\rm BH,2}$

$\mathbf{S}_{\rm BH,1}$ $\mathbf{S}_{\rm BH,2}$

spins and mass ratio can vary widely in LISA sources

distance

sky position

orientation of the orbit

polarization

Φ

$t_{\rm coal}$

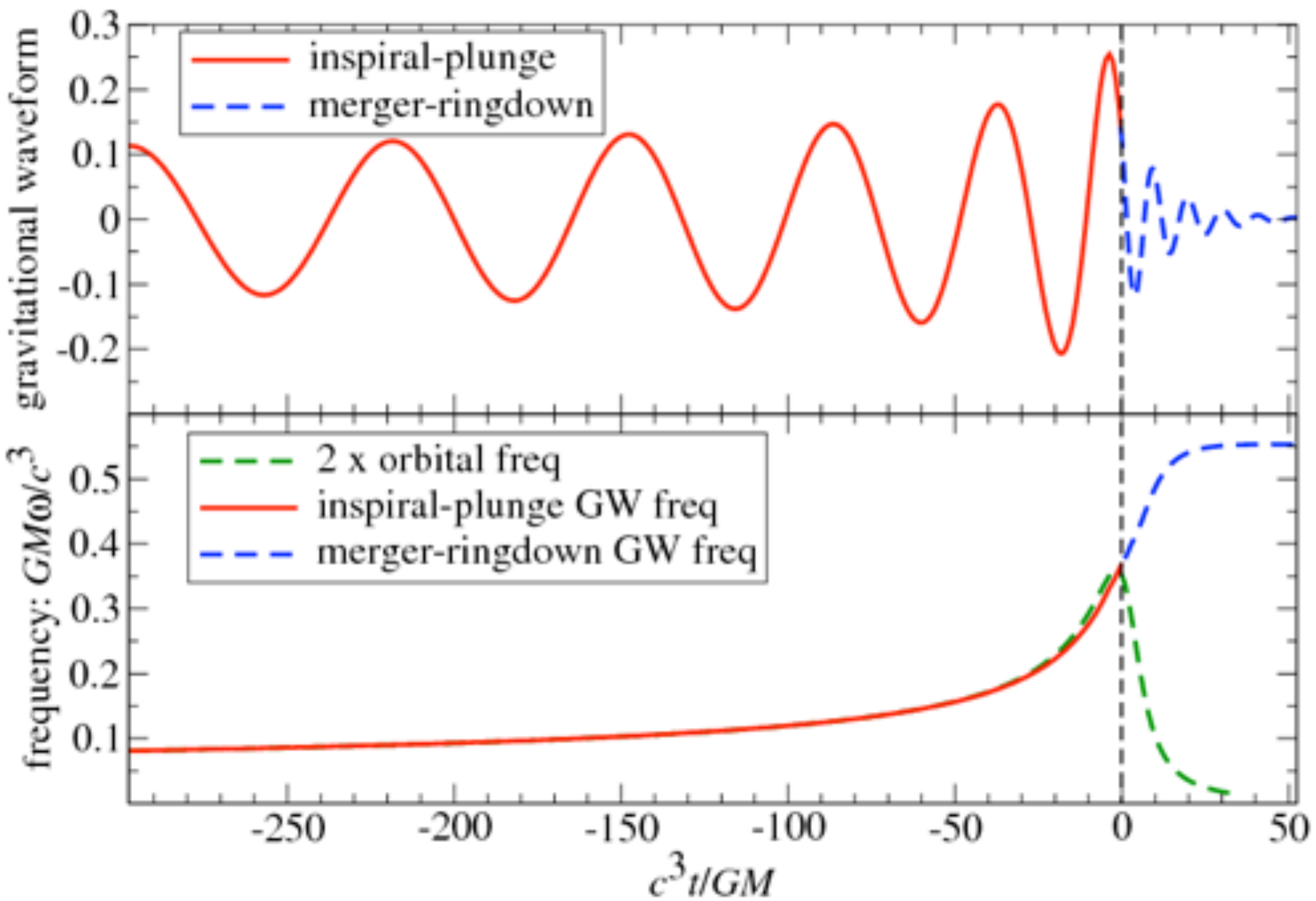
$M_{\rm BH,f}, \mathbf{S}_{\rm BH,f}$

15-dimensional parameter space

BLACK HOLE COALESCENCE - HYDROGEN ATOM (classical!)

$$(10^6, 10^6)\, M_\odot \qquad 10^4\, M_\odot c^2$$

THE COALESCENCE OF MASSIVE BLACK HOLES



$$f_{\rm gw} = \frac{1}{\pi}\left(\frac{GM}{a}\right)^{1/2}$$

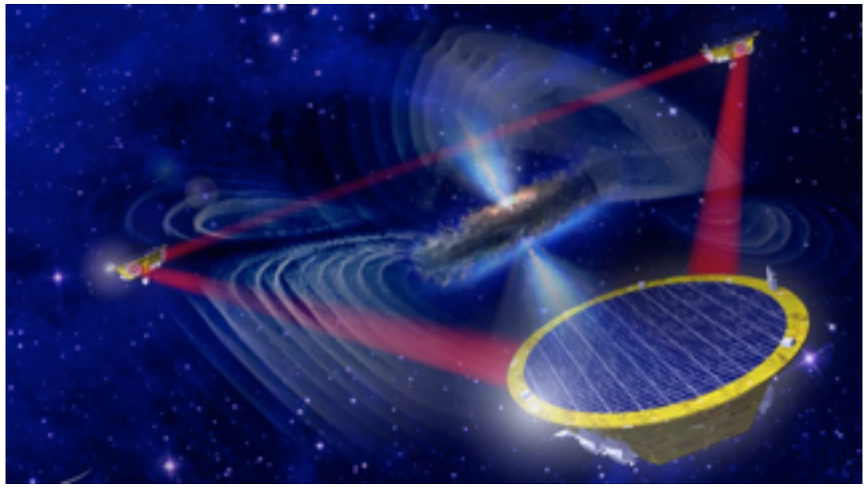
$$f_{\rm coal} = \frac{1}{(\pi 6^{3/2})}\frac{c^3}{GM}$$

$$t_\circ = \frac{GM}{c^3}$$

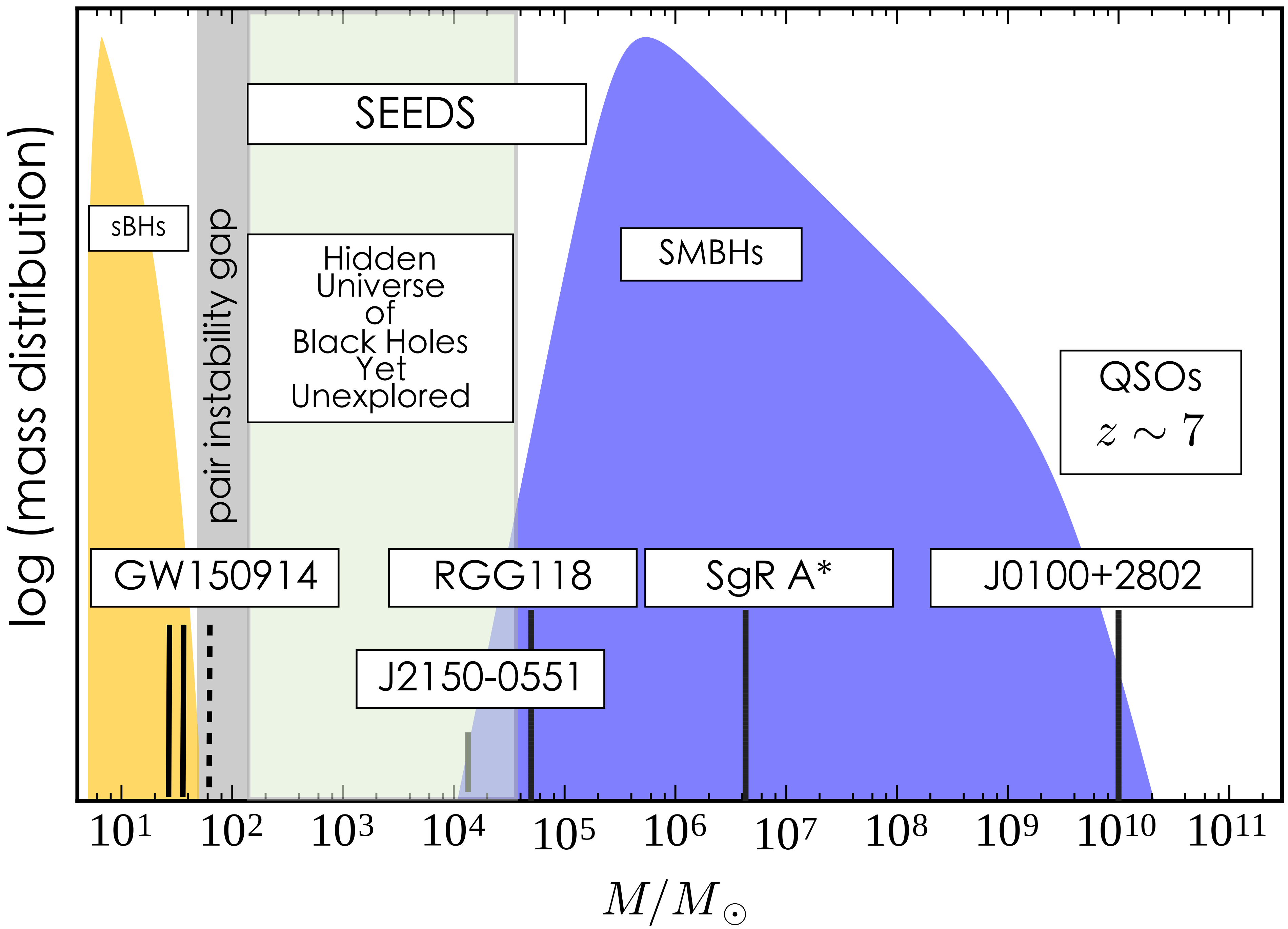
$$f_\circ = \frac{c^3}{GM}$$

The Gravitational Universe

- What is the origin of the supermassive black holes and how fast do they grow
- Do "seed black holes" exist?

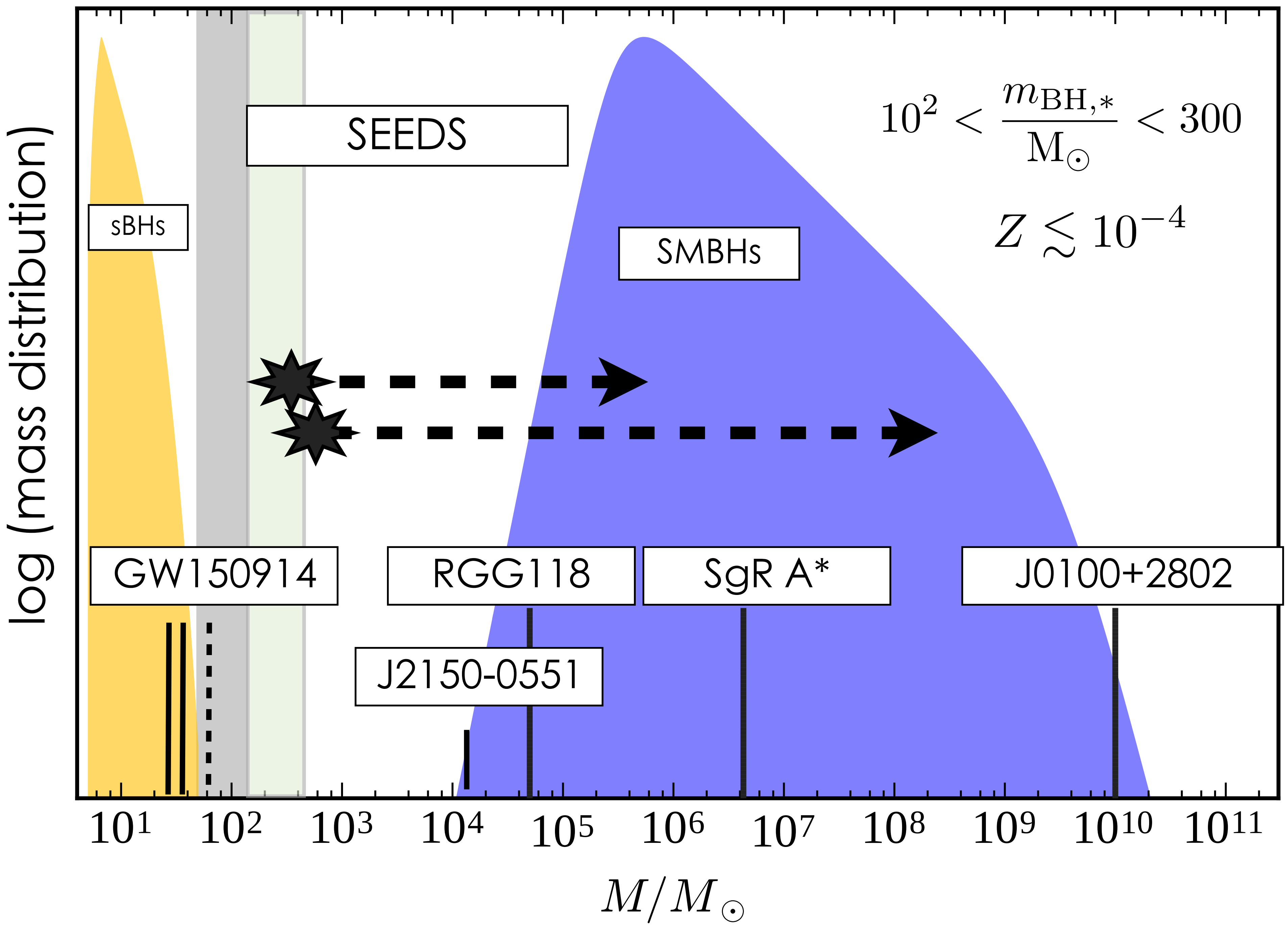


Black Holes - Universe



a fil rouge (only stars make black holes) ?
genetic divide?

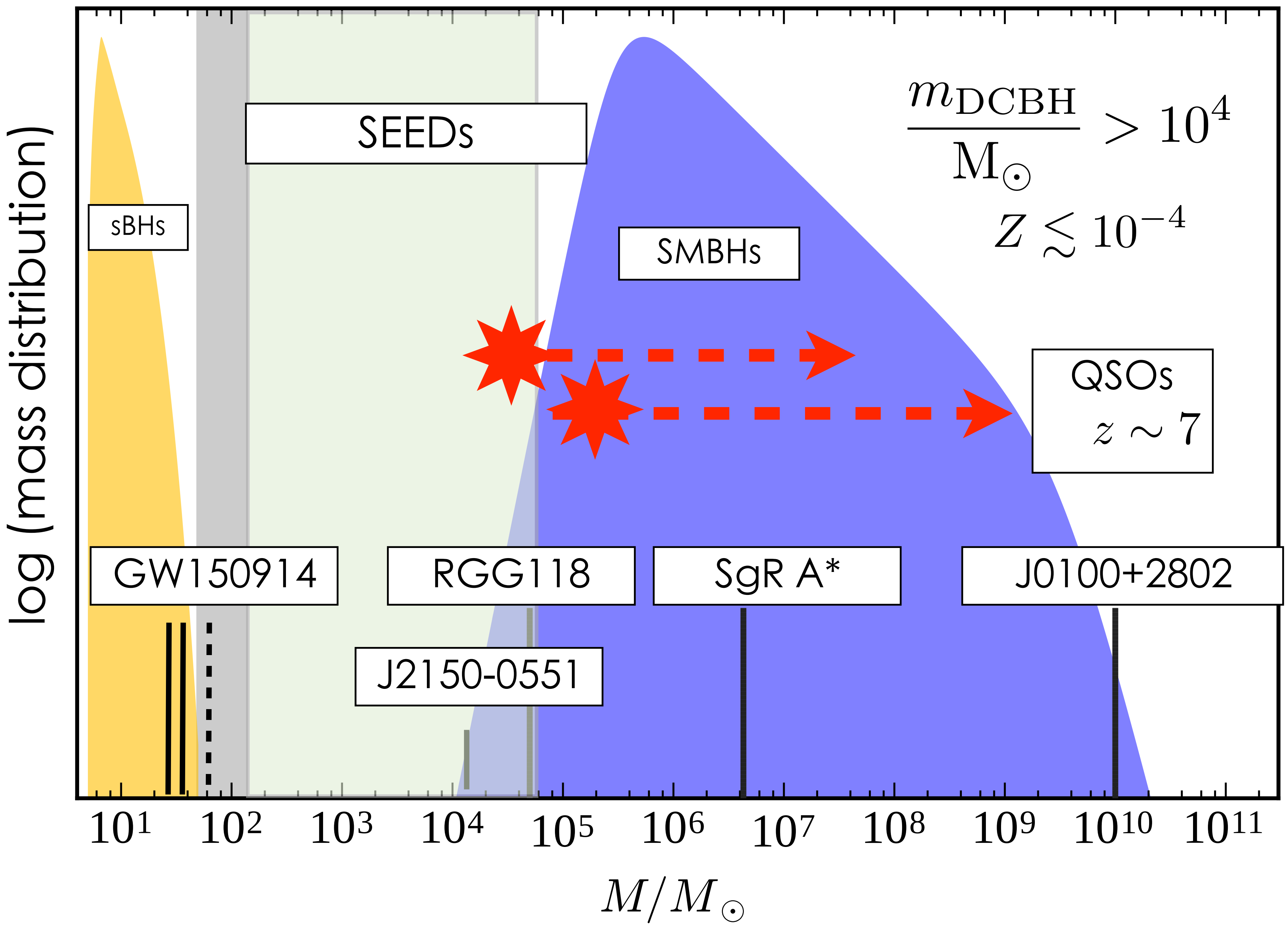
Black Holes in the High Redshift Universe - POP III relics - “LIGHT SEEDS”



do they pair in close binaries in situ?

Black Holes - new, yet unseen objects - “HEAVY SEEDS”

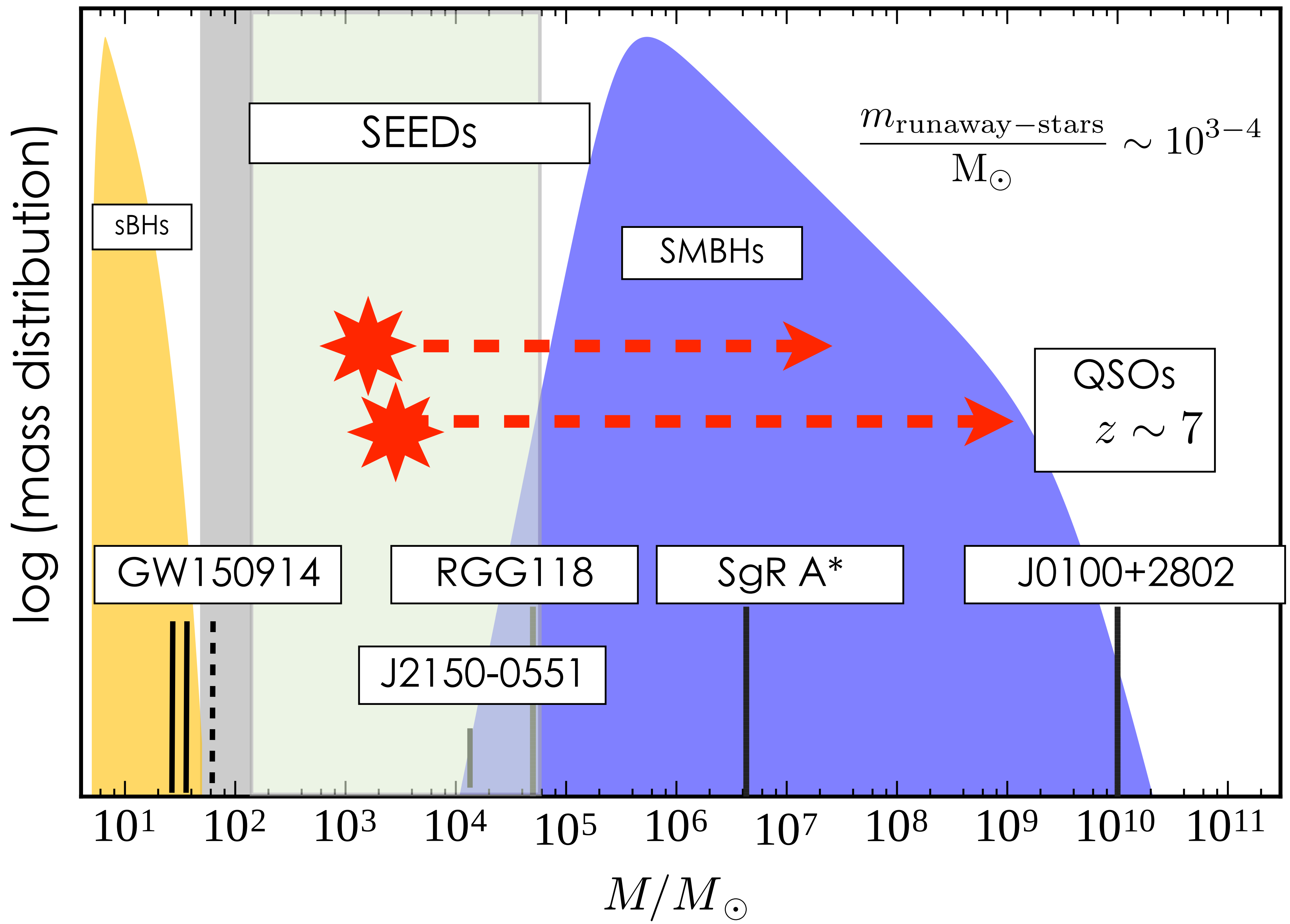
$$T_{\rm GR} = 4\times10^{9}\left(\frac{M_\odot}{10^4}\right)\,{\rm K} \qquad \rho_{\rm GR} = 2\times10^{4}\left(\frac{M_\odot}{10^4}\right)^{7/2}\,{\rm gr\,cm^{-3}}$$



Agarwal 2018
Haemmerlé+2018
Schleicher+2013
Hosokawa+2913
Pezzulli_2016
Omukai 2001

Direct monolithic collapse of Pop III supermassive stars in atomic cooling halos illuminated by UV radiation

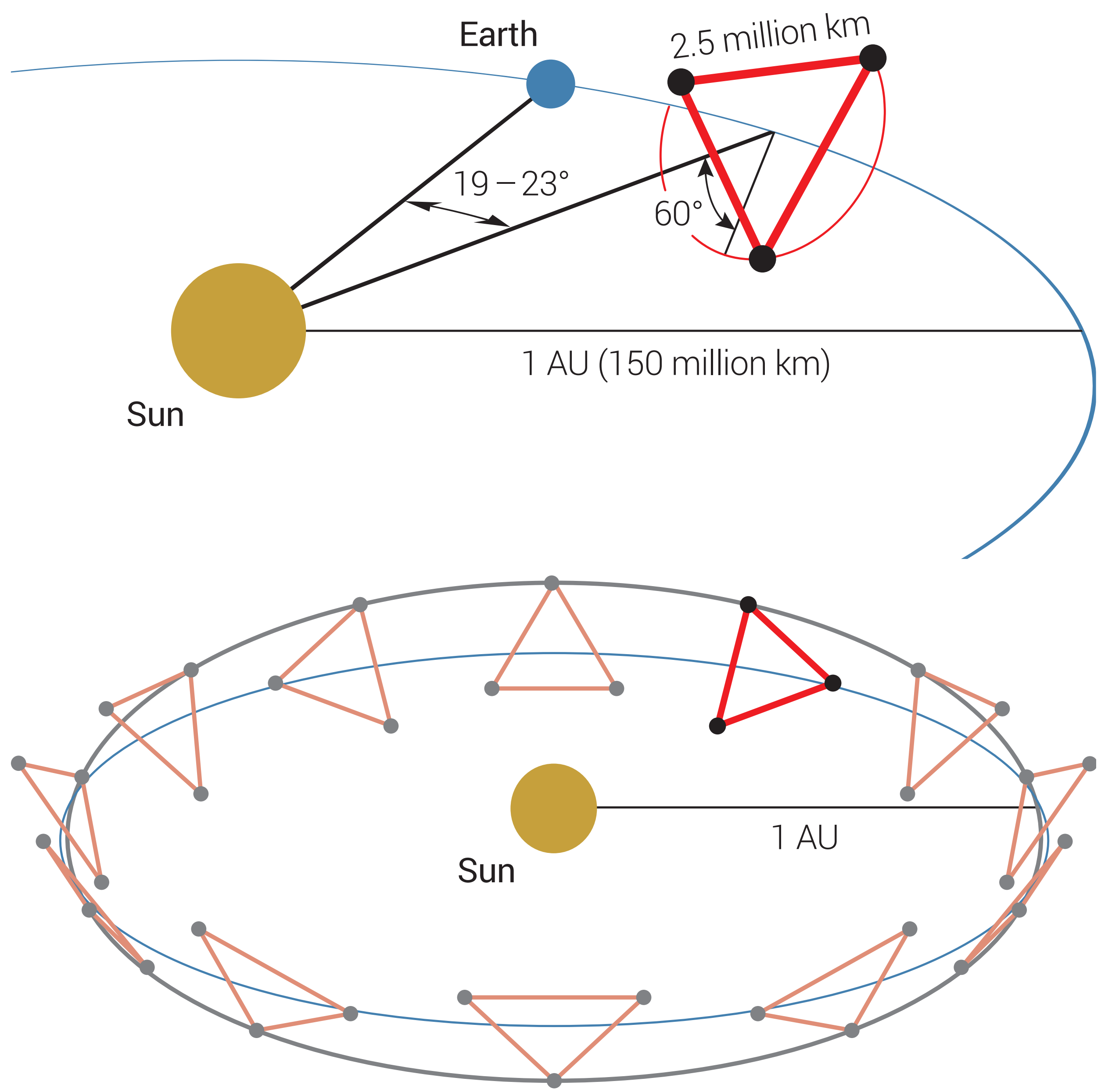
Black Holes: collisional runaway of stars, Pop II clusters @z~10



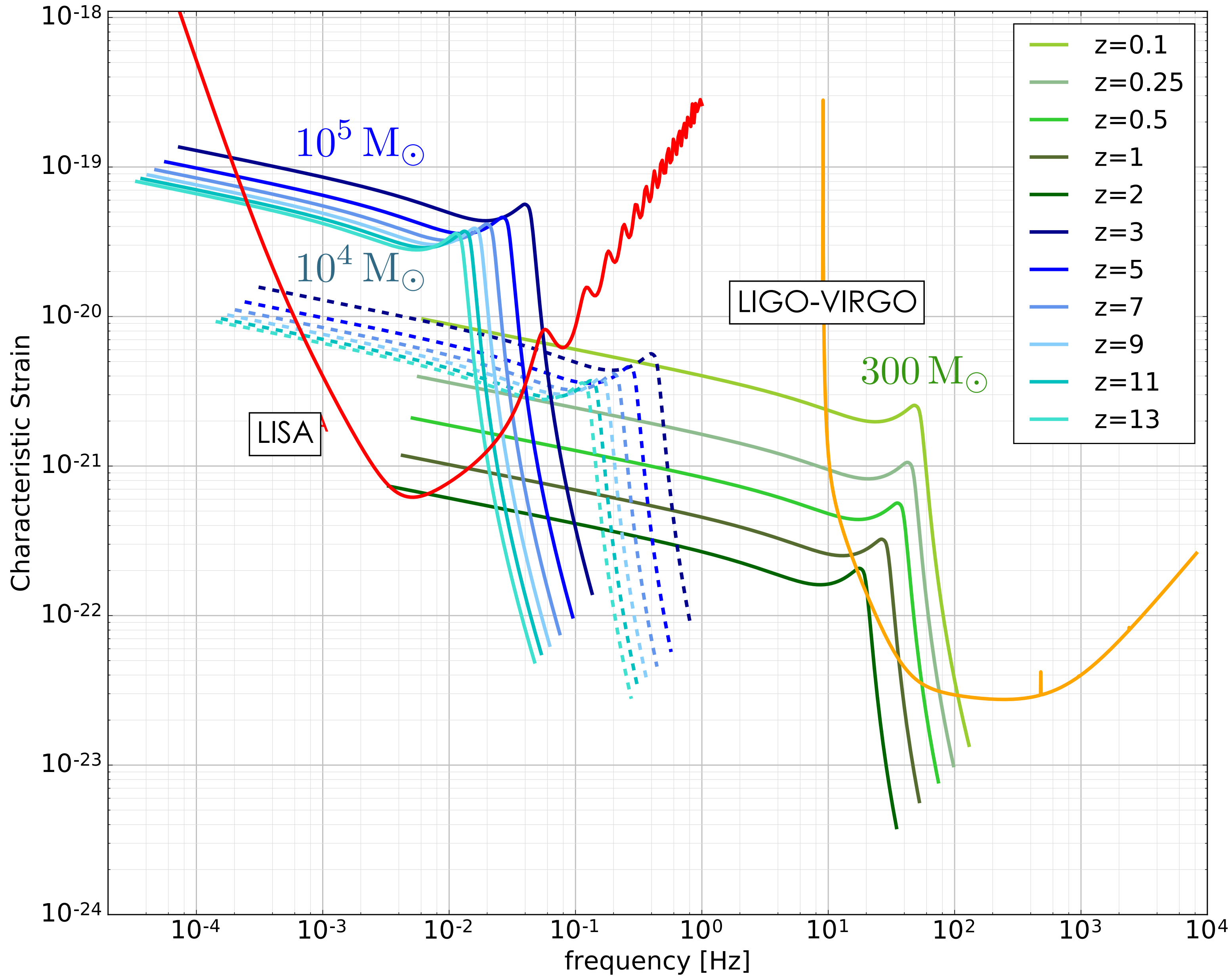
Katz 2018
Devecchi + 2012
Schleicher+2018

Formation of runaway stars in the stellar clusters

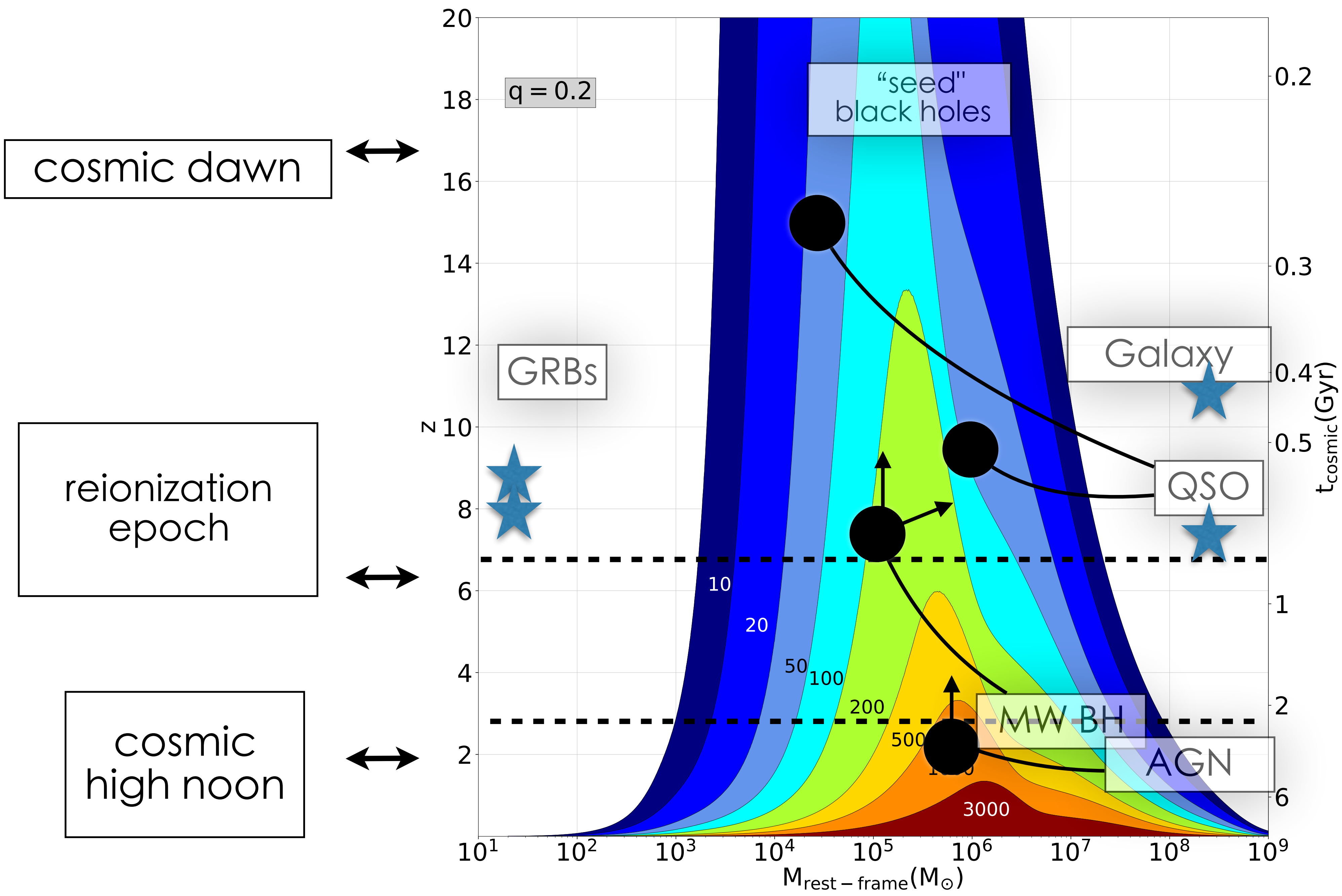
- LISA



$$\mathcal{M}_{\rm chirp}^{\rm obs} = (1+z) M_{\rm chirp}^{\rm source}$$

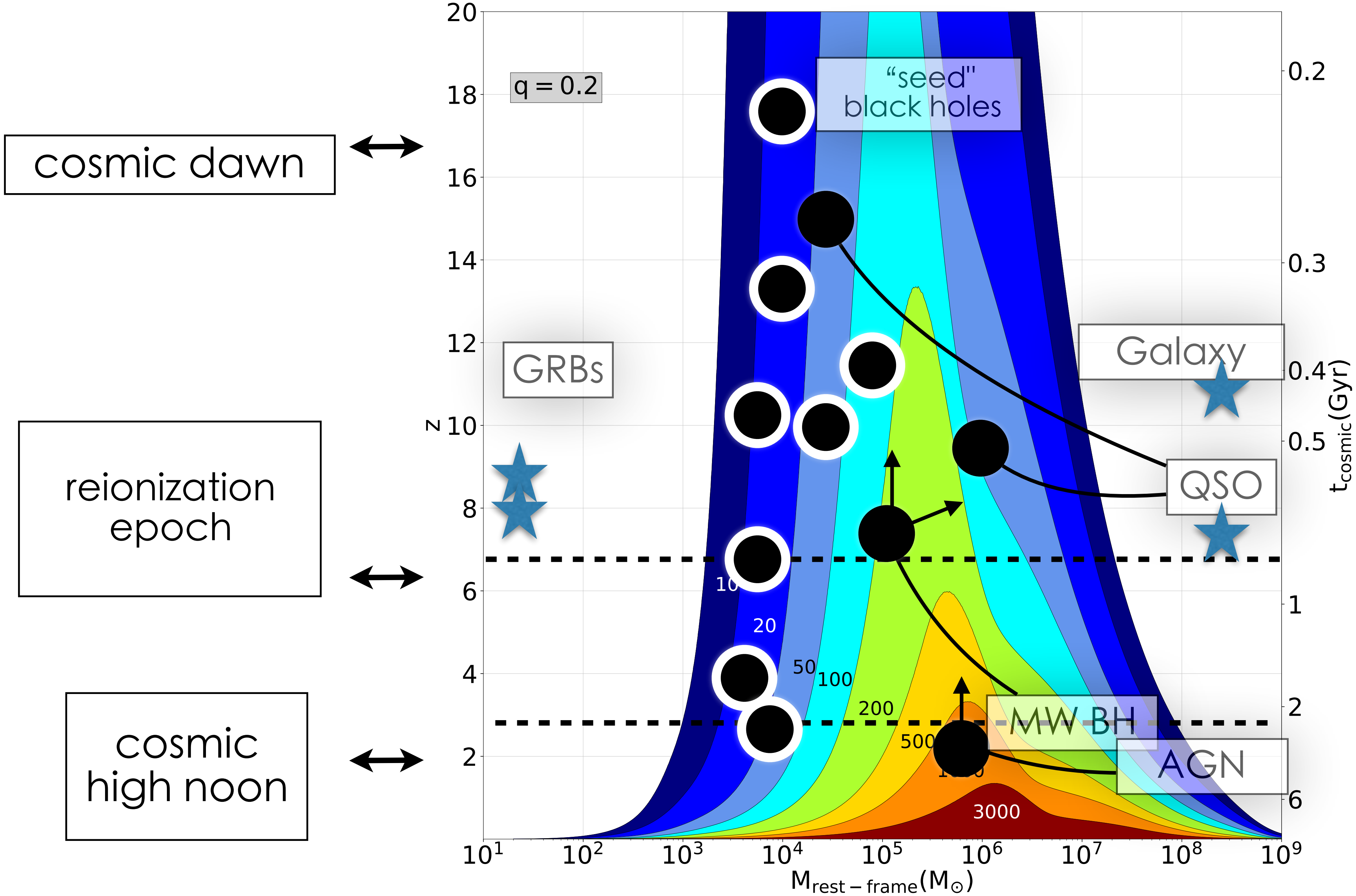


LISA HORIZON



- LISA horizon extends deep into the epoch of formation of the earliest black holes
- LISA traces the black hole cosmic swift drift to higher masses through accretion & mergers -low mass tail of the supermassive black holes
- spin and mass measurements are carried on with high precision

MOCK DATA



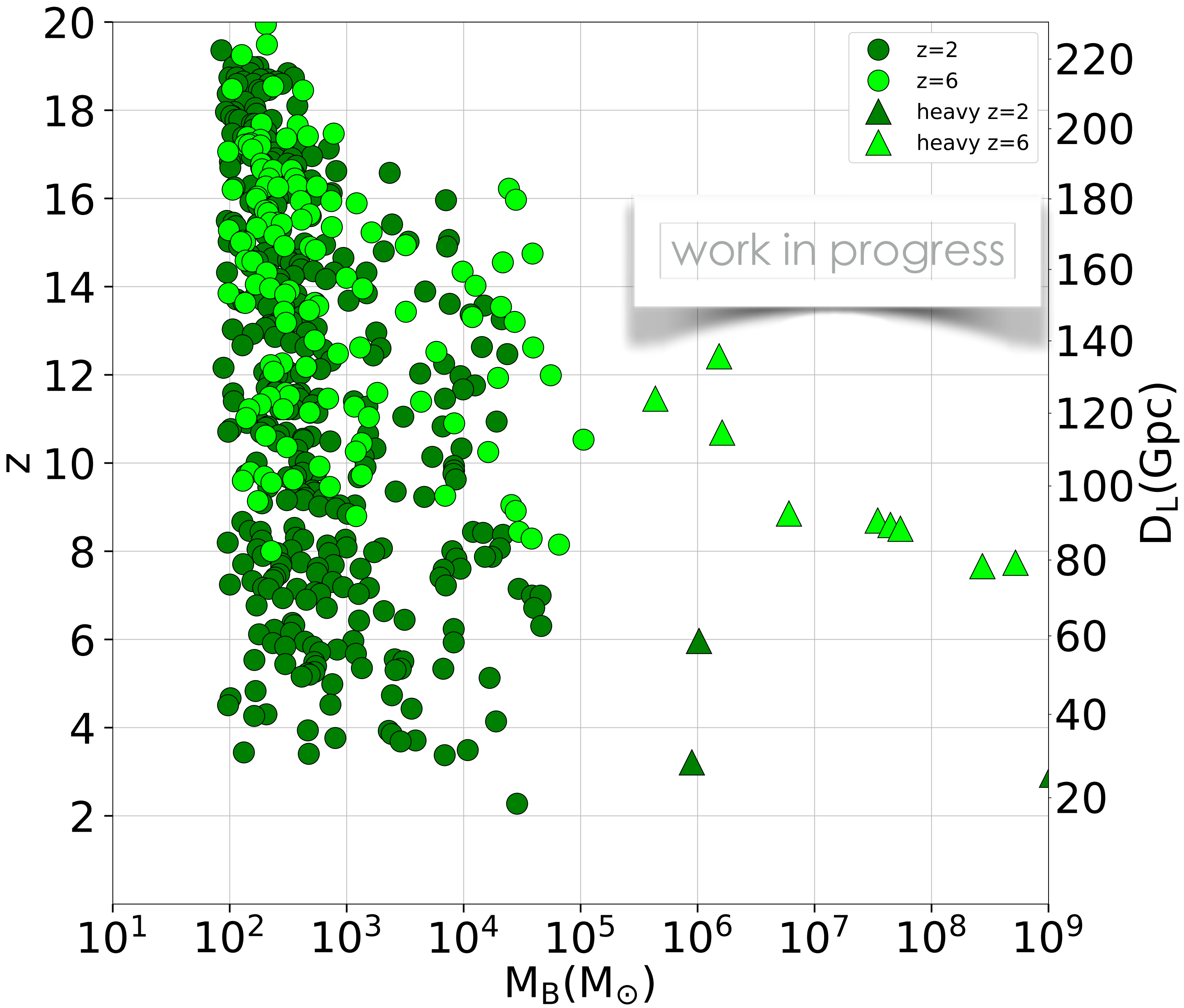
cosmic dawn
reionization epoch
cosmic high noon
q = 0.2
"seed" black holes
GRBs
Galaxy
QSO
MW BH
AGN
z
20
18
16
14
12
10
8
6
4
2
t_{cosmic}(Gyr)
0.2
0.3
0.4
0.5
1
2
6
10
20
50
100
200
500
3000
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
$M_{rest-frame}(M_\odot)$

How to interpret this MOCK DATA file ?

- DOMINATED BY THE DEGENERACY OF MODELS
- REAL HEAVY SEEDS?
- LIGHT SEEDS (POP III) + ACCRETION?
- RUNAWAY STELLAR COLLISIONS?

ET + LISA can break this degeneracy

Black Holes in the Cosmological Framework

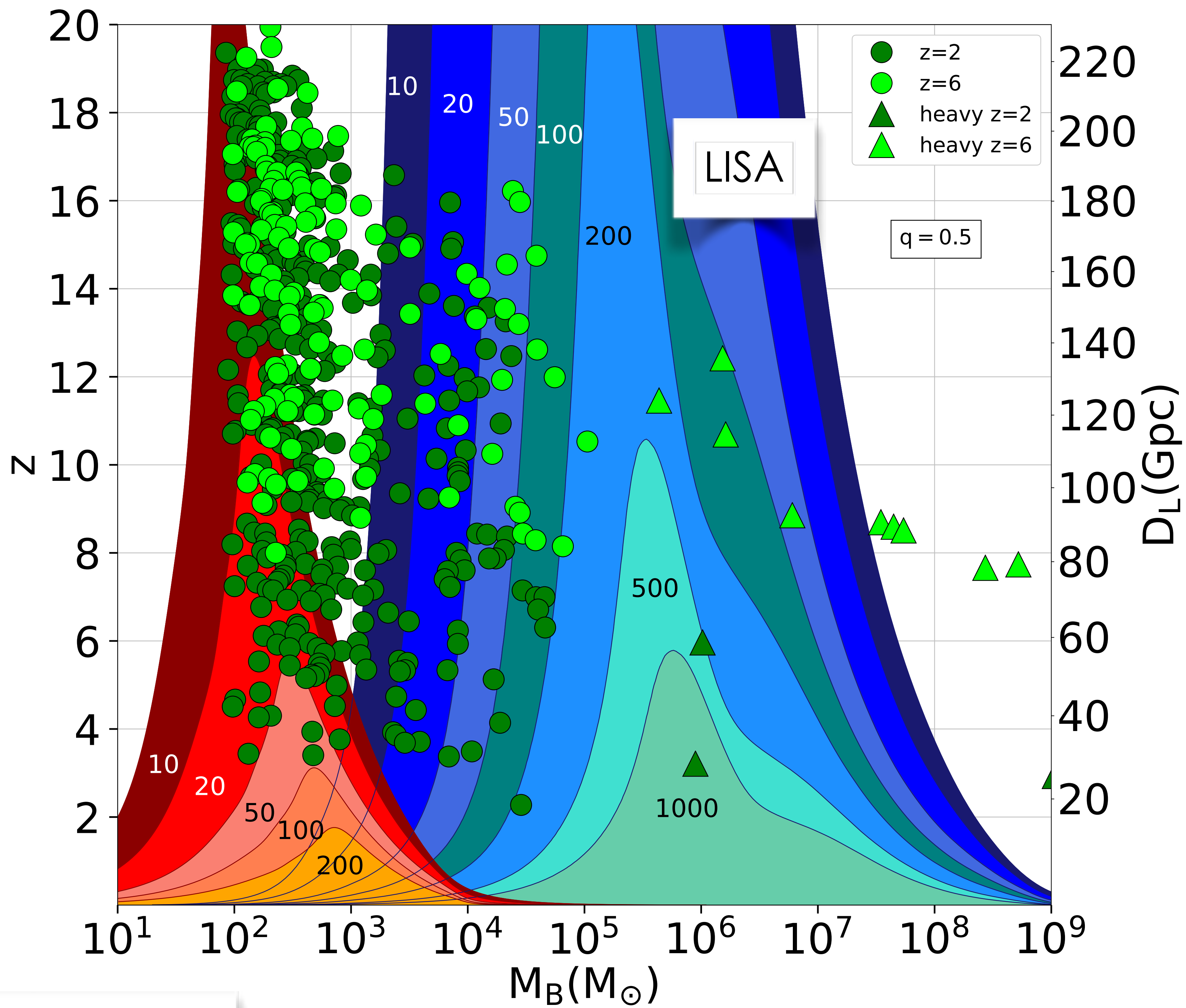


$M_{\rm halo} = 10^{13} M_\odot$

Black holes forming in pristine halos and pairing during halo-halo mergers
"cosmologically-driven mergers"
NO DELAY is included here

Valiante + 2018

Gravitational Universe



Einstein Telescope

work in progress

Valiante+2016,17,18
Pezzulli + 2017
Valiante + in prep.

SPIN

- mass and spin are modeled by accretion and merger
  - Spin increases from 0 to 1 after accreting (for prograde accretion) $\sqrt{6}M_{\rm BH,initial}$
  - Spin decrease from 1 to 0 after accreting (for retro-grade accretion) $\sqrt{3}/2M_{\rm BH,initial}$
  - Accretion torques lead to fast re-orientation of BH (disc-spin alignment)
  - Isotropic versus coherent accretion shape the spins in relation to the environment and feeding process
  - Mergers make two coalescing black hole spin up to 0.6578

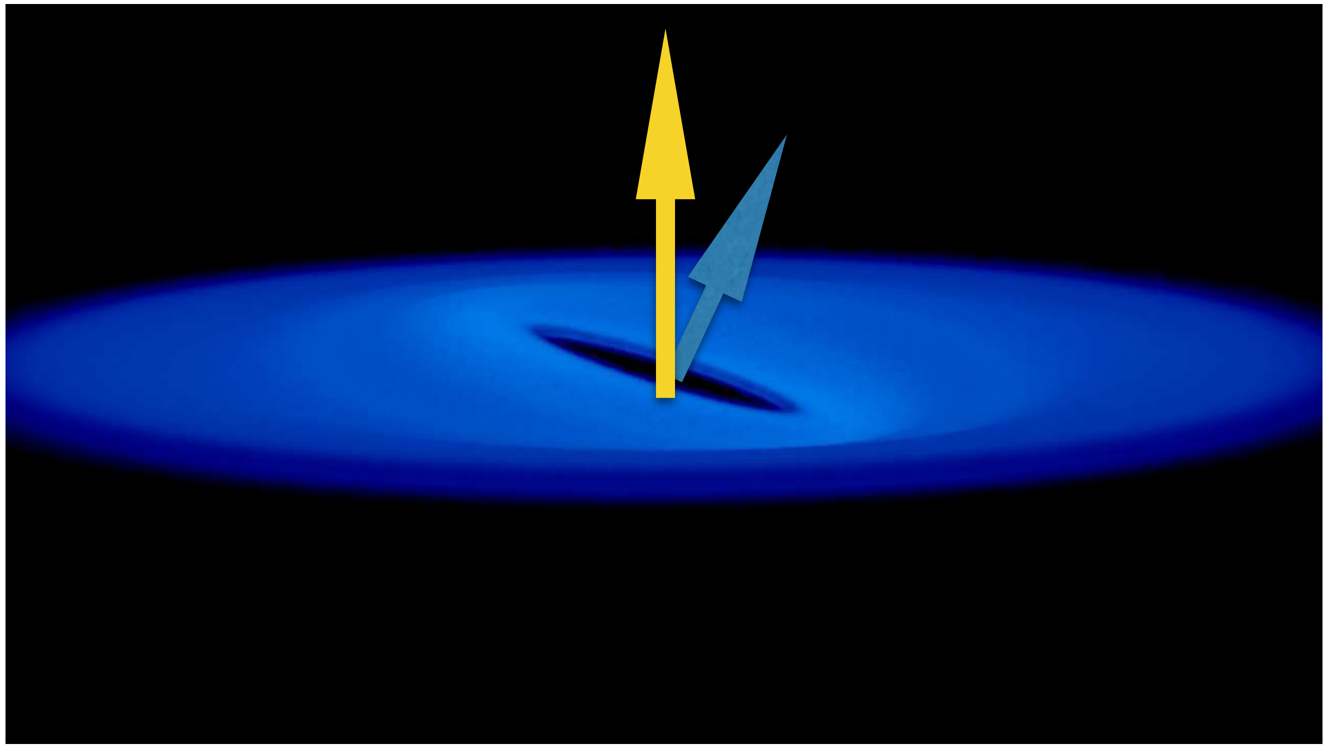
COLPI & SESANA 2016 for a review

$$\frac{dM_{\rm BH}}{dt} = (1-\eta)\dot{M}c^2 = (1-\eta)\left(\frac{f_{\rm Edd}}{\eta}\right)\frac{M_{\rm BH}}{\tau_{\rm S}},$$

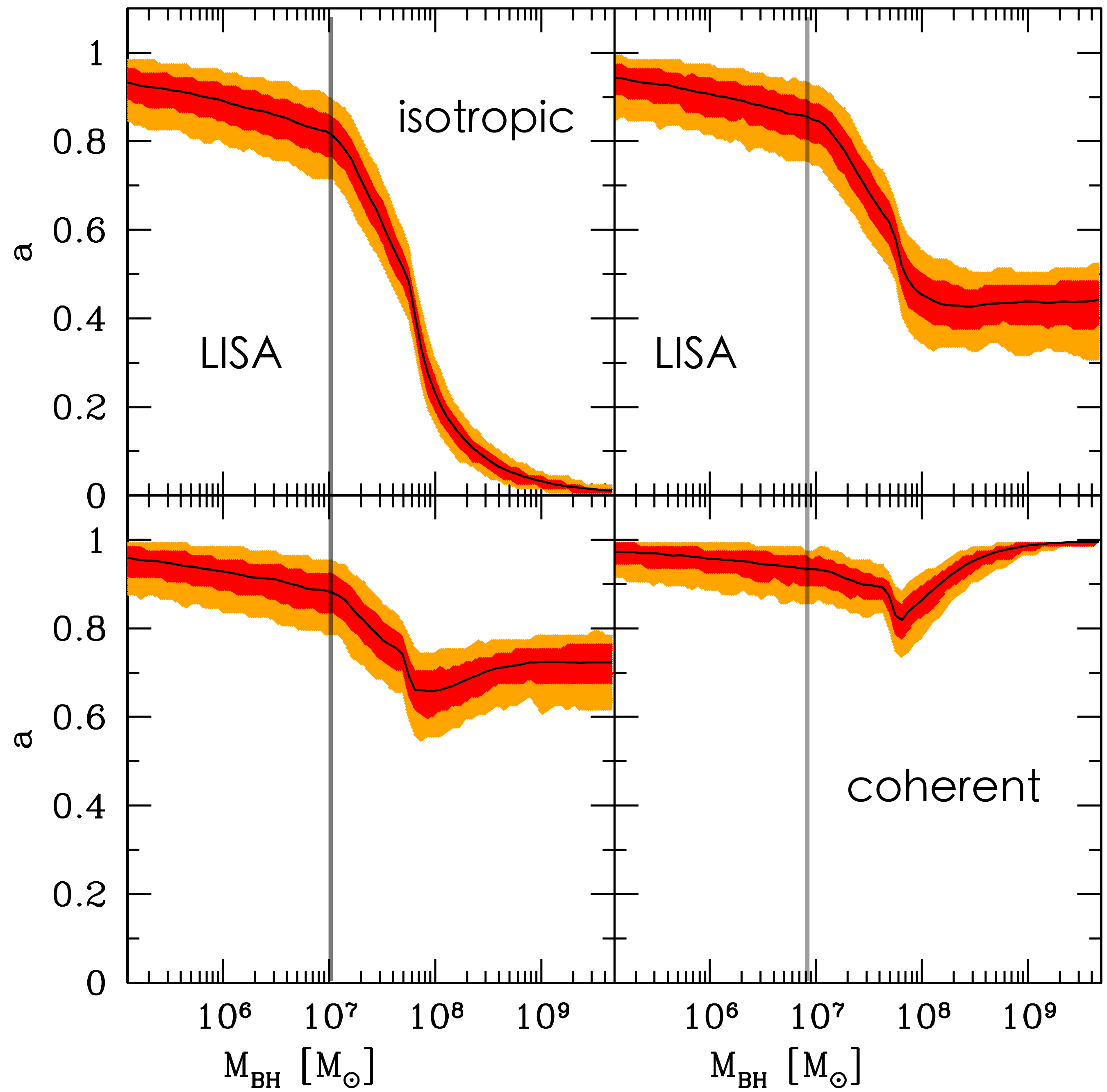
$$\tau_{\rm S} = 45\varepsilon_{0.1}\ \mathrm{Myrs}$$

$$\frac{d\mathbf{J}_{\rm BH}}{dt} = \dot{M}\frac{GM_{\rm BH}}{c}\Lambda_{\rm isco}\hat{\mathbf{l}}(R_{\rm ISCO}) + \frac{4\pi G}{c^2}\int_{\rm disk}\frac{\mathbf{L}\times\mathbf{J}_{\rm BH}}{R^2}dR,$$

$\mathbf{J}_{\rm disk}/\mathbf{J}_{\rm BH}$



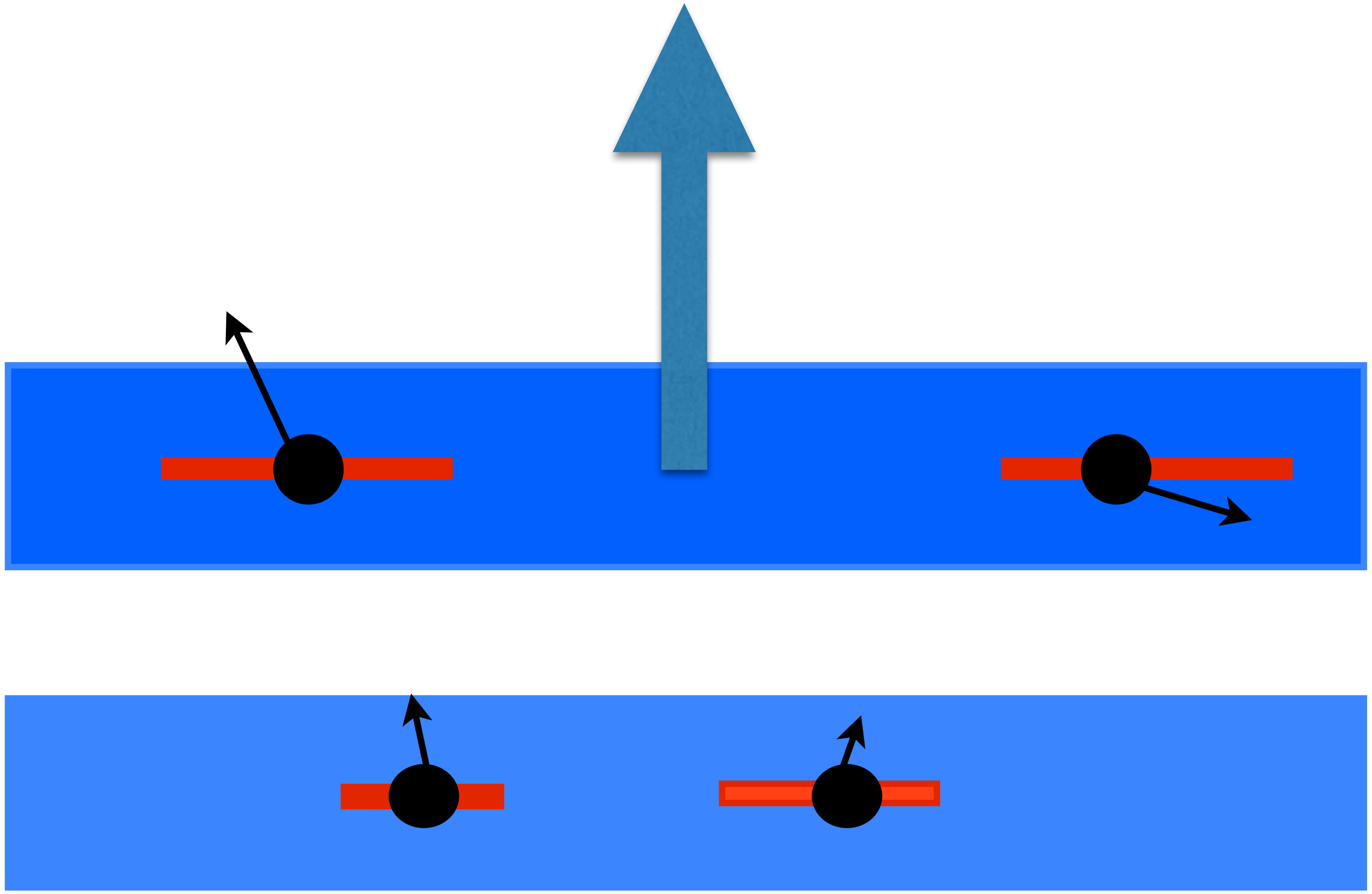
$$\tau_{\rm warp} < \tau_{\rm al} < \tau_{\rm acc} < \tau_{M_{\rm BH}} \sim \tau_{\rm spin}.$$



LISA black holes might be highly spinning regardless the accretion mode

Dotti, Colpi+ 2013
Sesana+ 2015

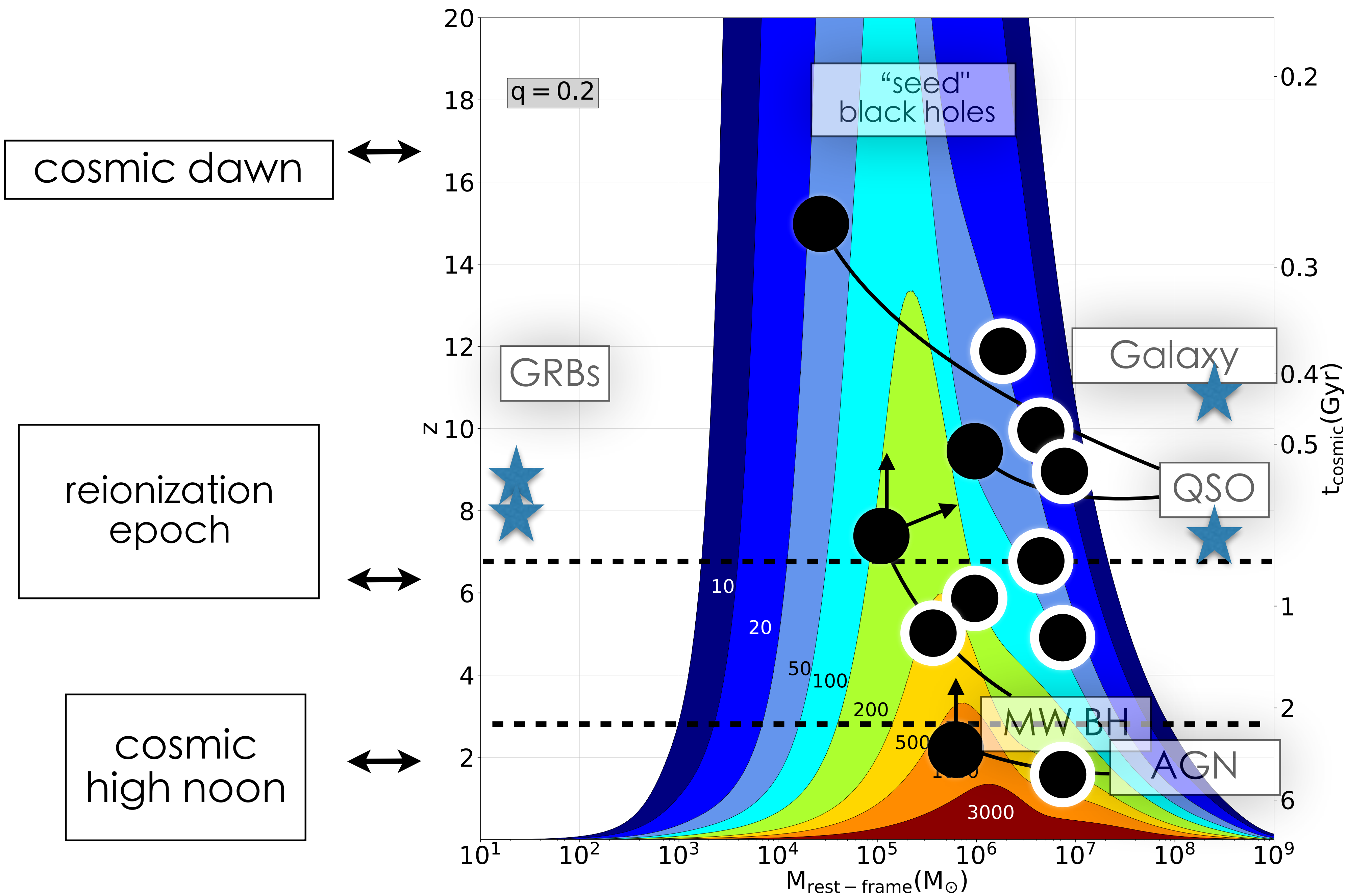
BINARY SPIN-SPIN ALIGNMENT



Tendency to align with the angular momentum of the circum- nuclear disc

DOTTI et al. 2010
PEREGO et al. 2009

MOCK DATA



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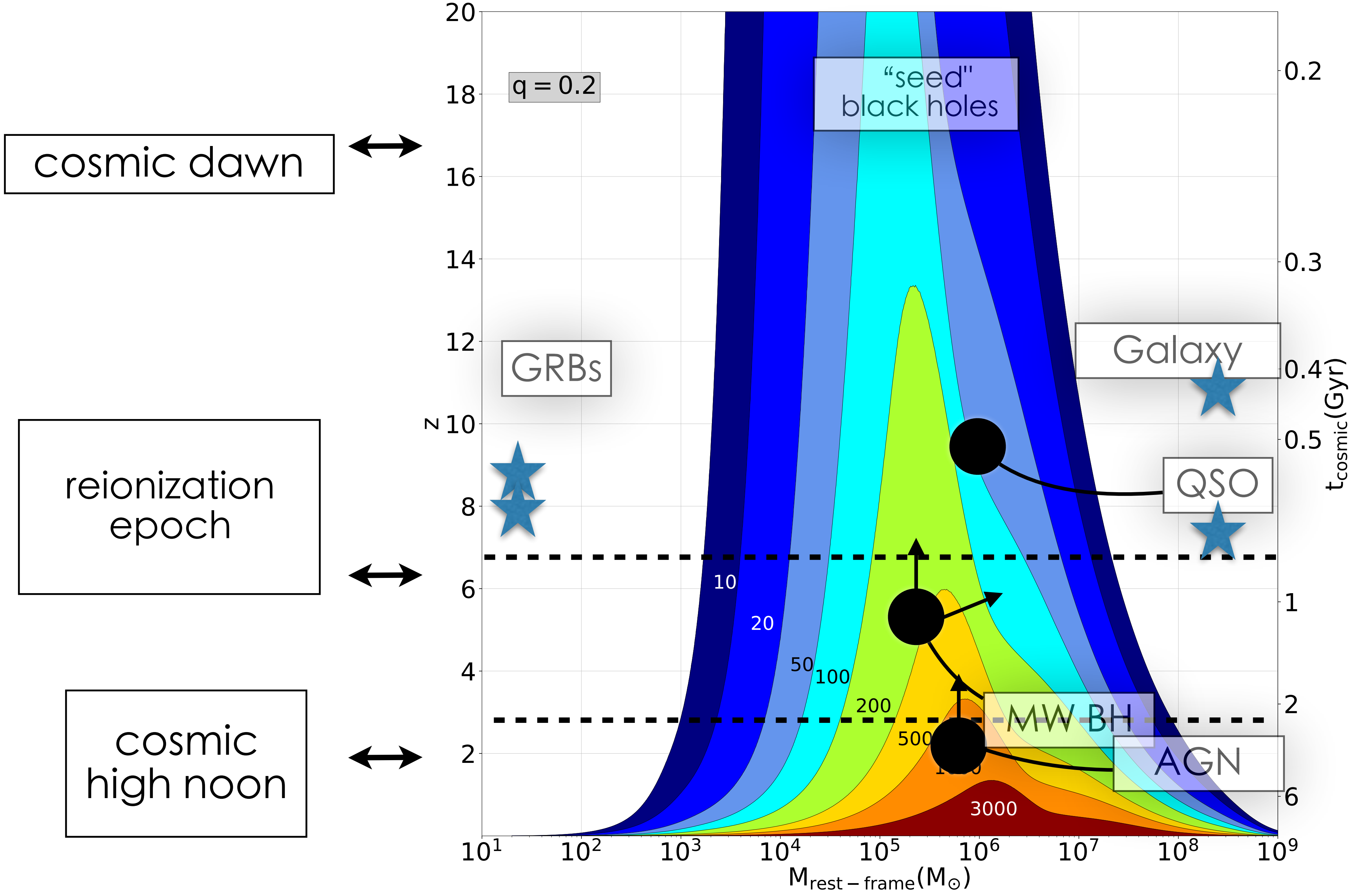
t_{cosmic}(Gyr)
0.2
0.3
0.4
0.5
1
2
6
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
$M_{rest-frame}(M_\odot)$

MOCK DATA



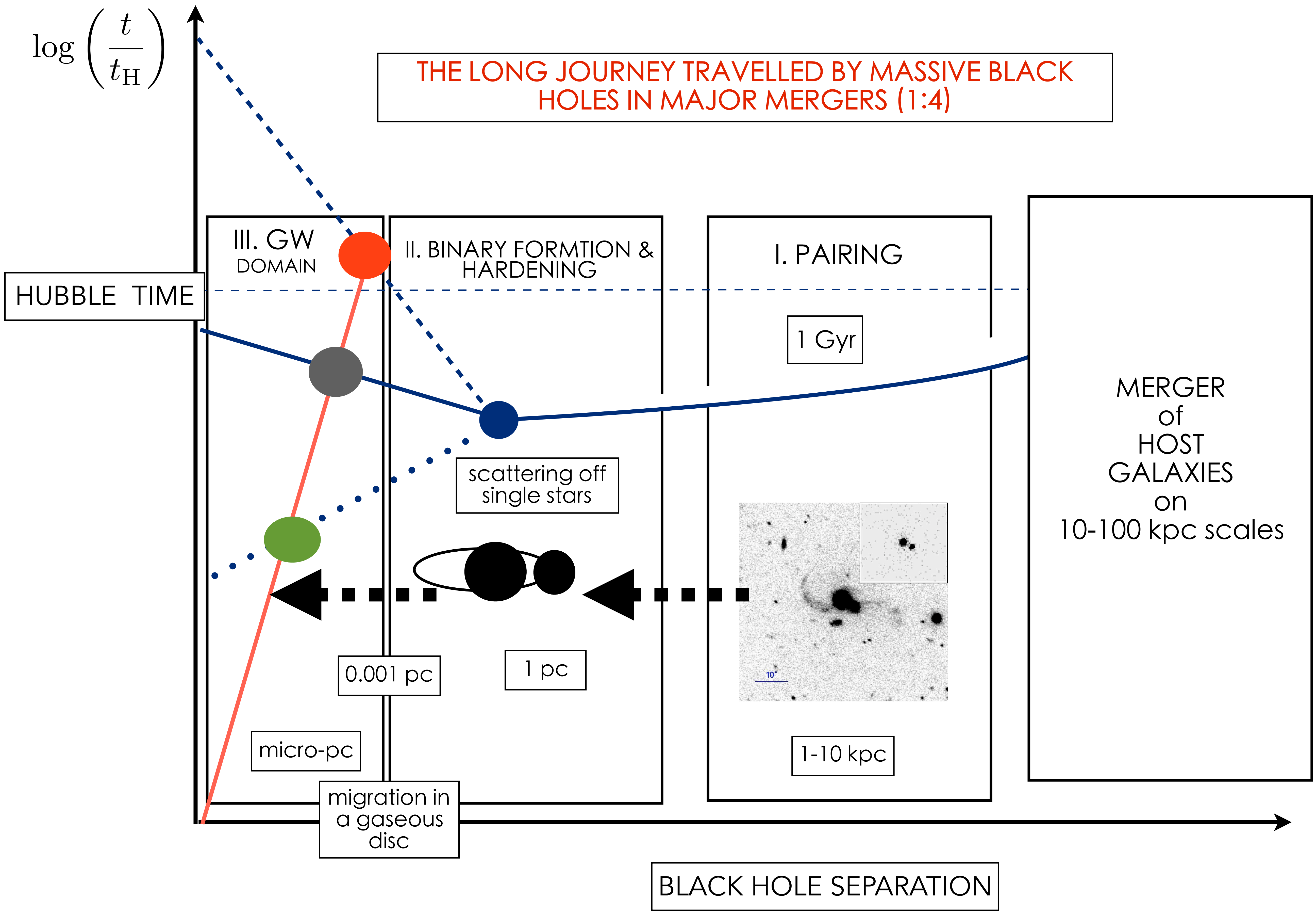
LOW REDSHIFT EVENTS

- the scale of gravitational-wave-driven inspiral is minuscule compared to galactic dimensions
- delays between formation of the binary and coalescence

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

$z = 15$ $t_{\rm cosmic} = 0.27\,{\rm Gyr}$	$M_{\rm B} = 10^5\, M_\odot$	$M_{\rm B} = 10^6\, M_\odot$
$a_{\rm GW}$	$\nu^{1/4} 2.5 \times 10^4\, R_{\rm G}$ $0.25\,{\rm mparsec}$	$\nu^{1/4} 1.4 \times 10^4\, R_{\rm G}$ $1.4\,{\rm mparsec}$
$z = 3$ $t_{\rm cosmic} = 2.16\,{\rm Gyr}$	$M_{\rm B} = 10^5\, M_\odot$	$M_{\rm B} = 10^6\, M_\odot$
$a_{\rm GW}$	$\nu^{1/4} 4 \times 10^4\, R_{\rm G}$ $0.4\,{\rm mparsec}$	$\nu^{1/4} 4.8 \times 10^4\, R_{\rm G}$ $5\,{\rm mparsec}$

$$a \propto \nu^{1/4} M^{3/4}$$

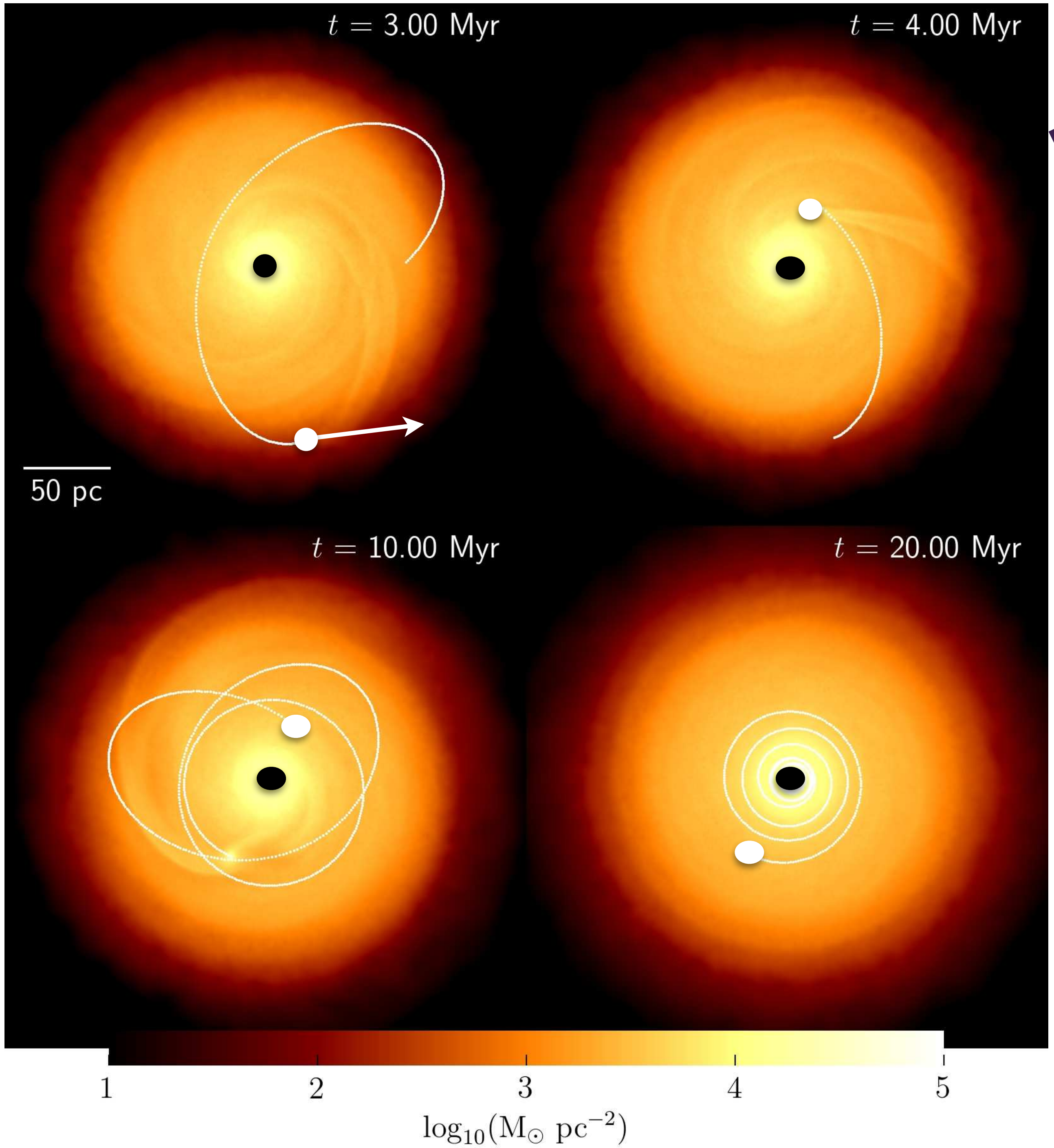


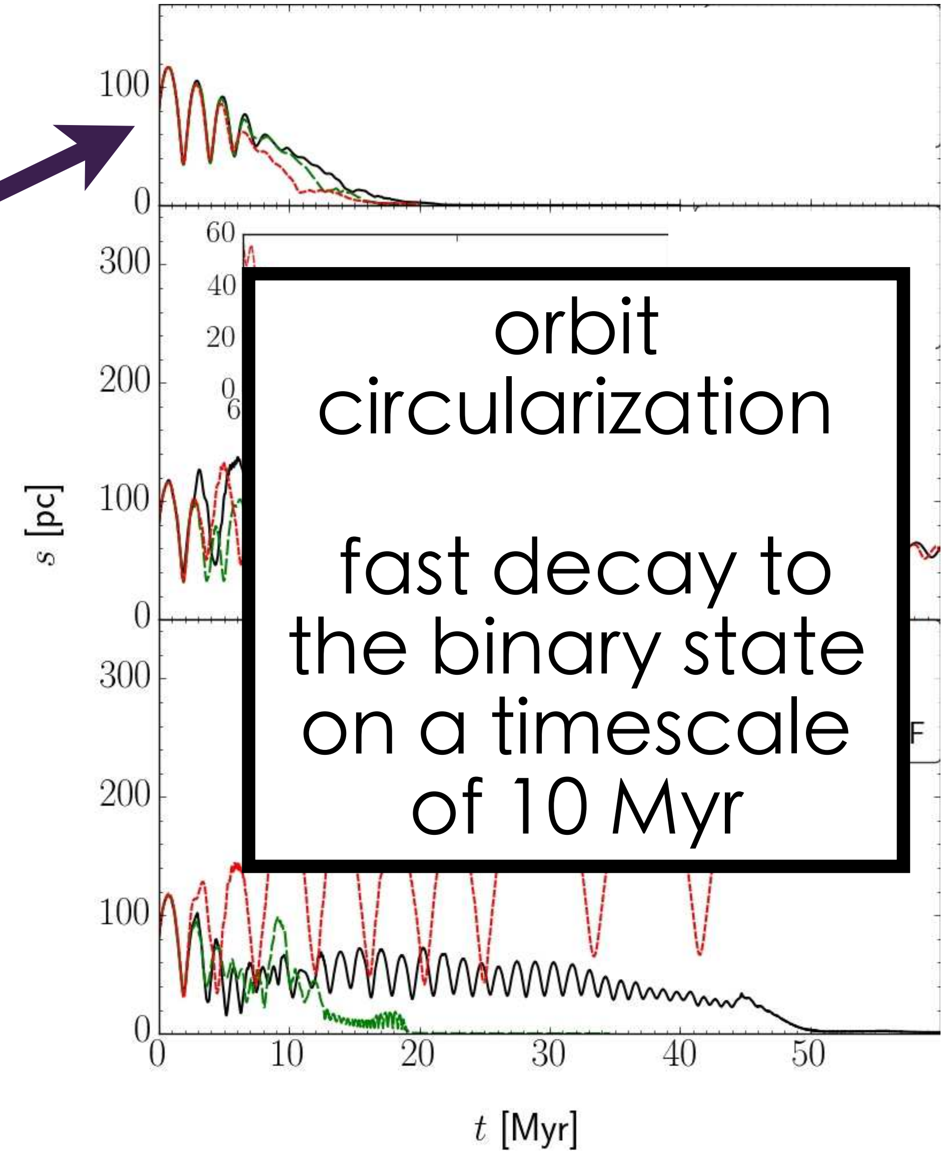
THE LONG JOURNEY TRAVELLED BY MASSIVE BLACK HOLES IN MAJOR MERGERS (1:4)
$\log\left(\frac{t}{t_{\rm H}}\right)$
HUBBLE TIME
III. GW DOMAIN
II. BINARY FORMTION & HARDENING
I. PAIRING
1 Gyr
scattering off single stars
MERGER of HOST GALAXIES on 10-100 kpc scales
0.001 pc
1 pc
1-10 kpc
micro-pc
migration in a gaseous disc
BLACK HOLE SEPARATION

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

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

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

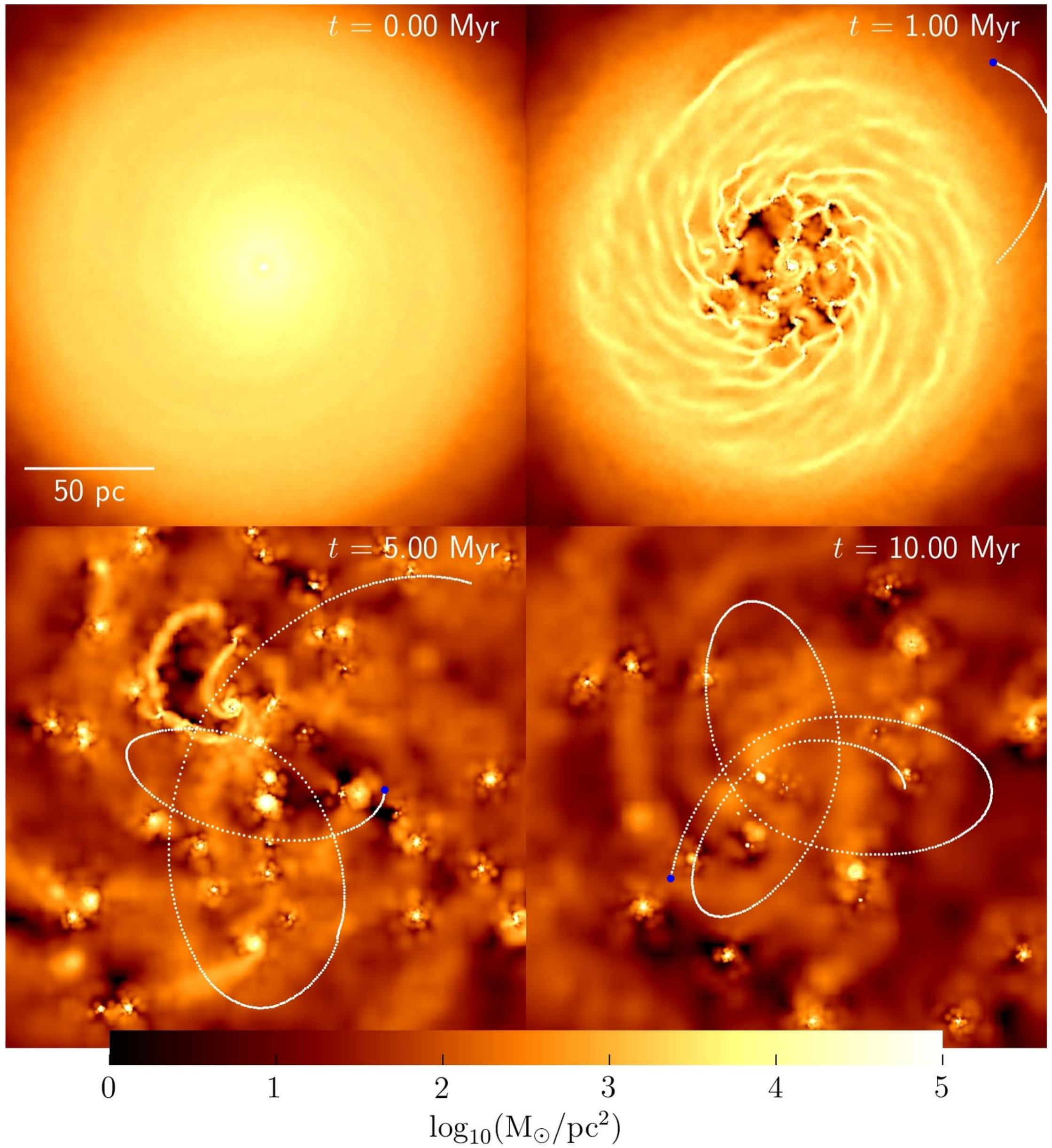




orbit circularization

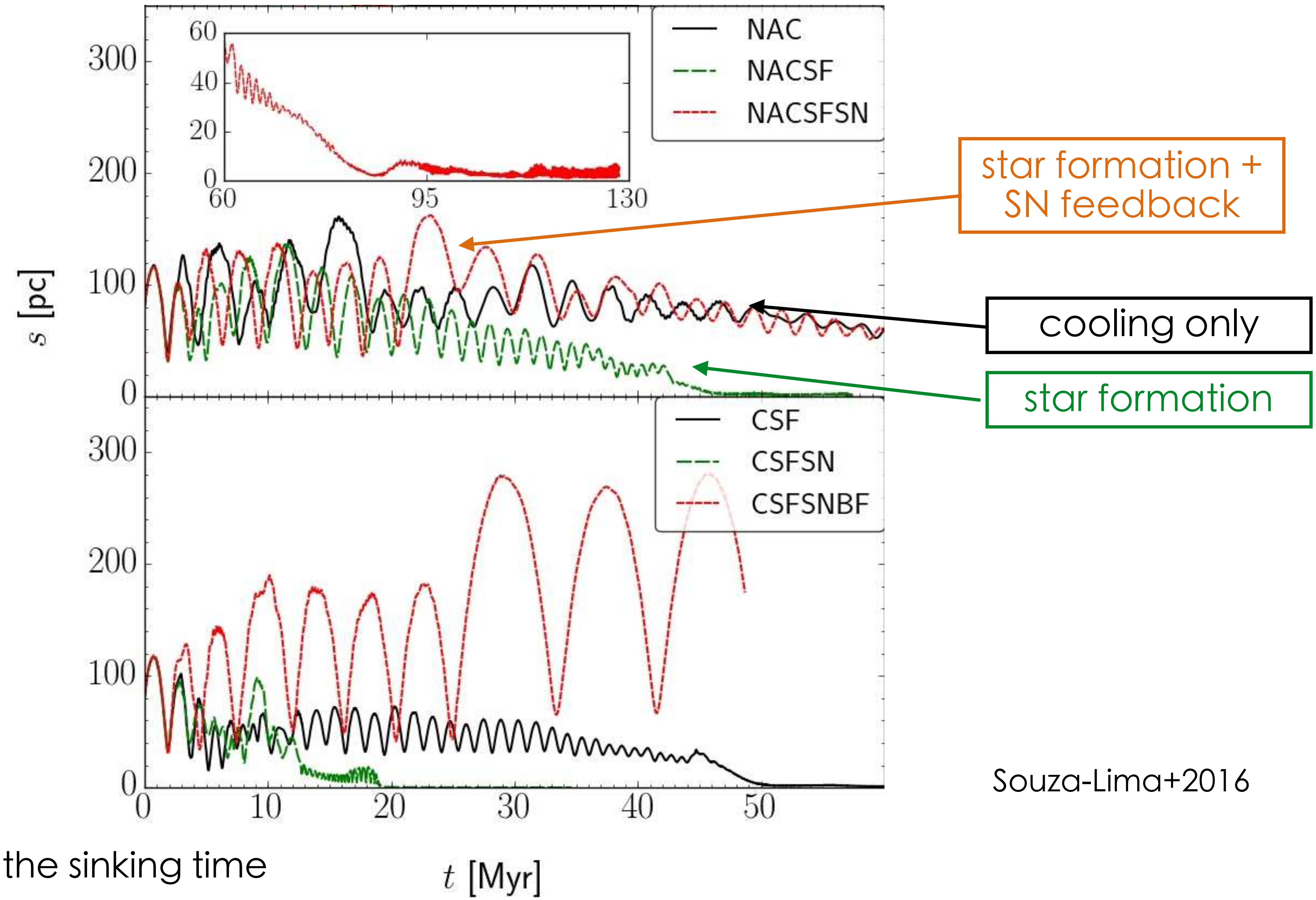
fast decay to the binary state on a timescale of 10 Myr

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

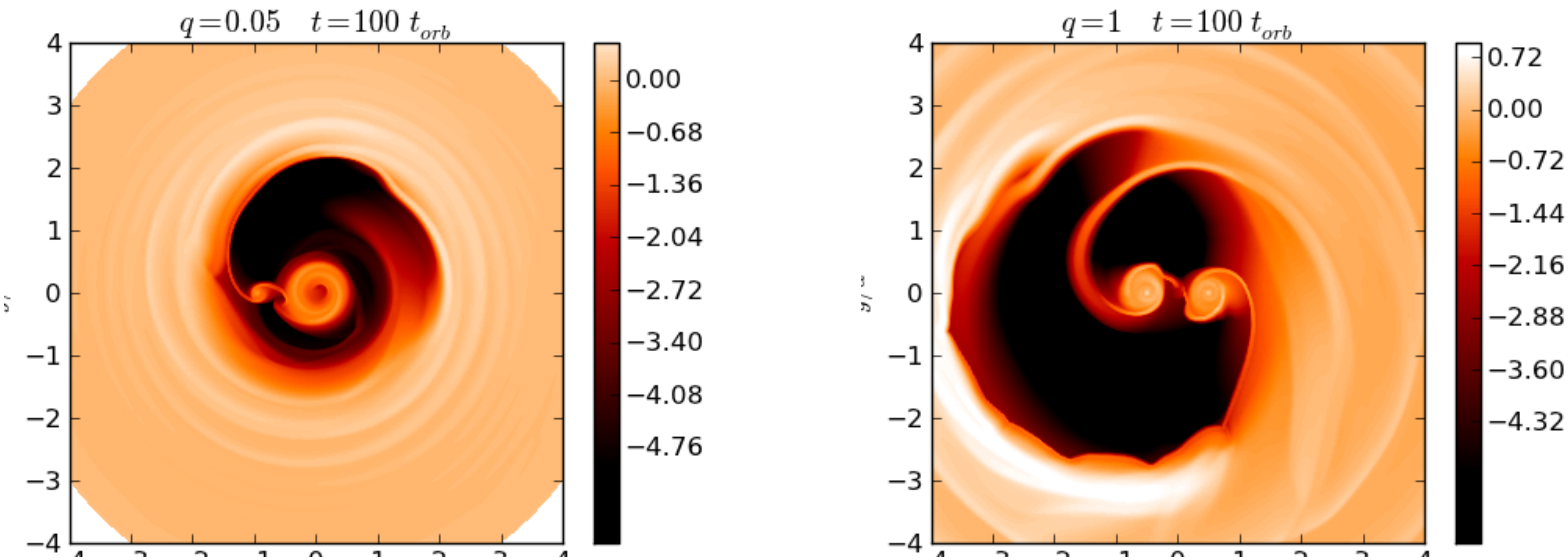
Souza Lima+2016, del Valle+2015, Fiacconi+2013



- increase in the sinking time
- no-circularization
- scattering off the disc plane - postponed merger
- rare cases in which the secondary black hole is drag inside a clump rapidly to the centre
- spread in the delay times (stochastic dynamics): 2–100 Myrs

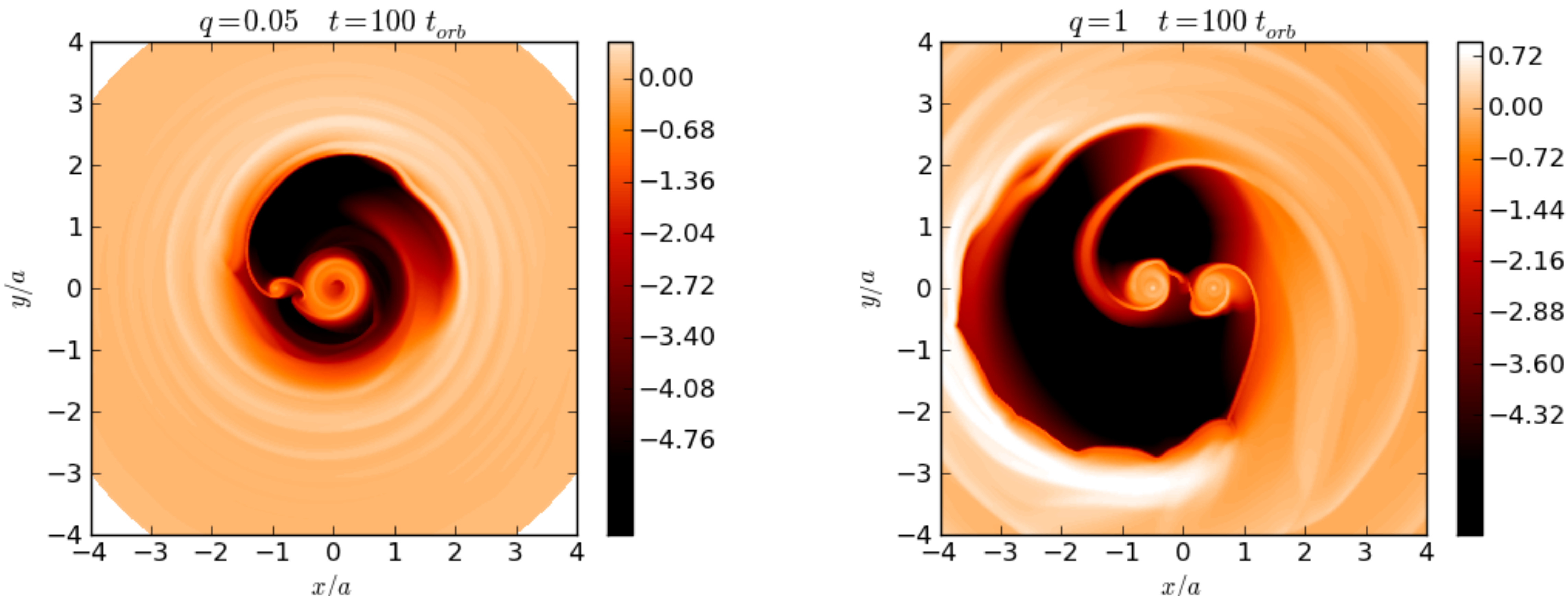
type II migration in a circum-binary disc

Courtesy by Zoltan Haiman +2017

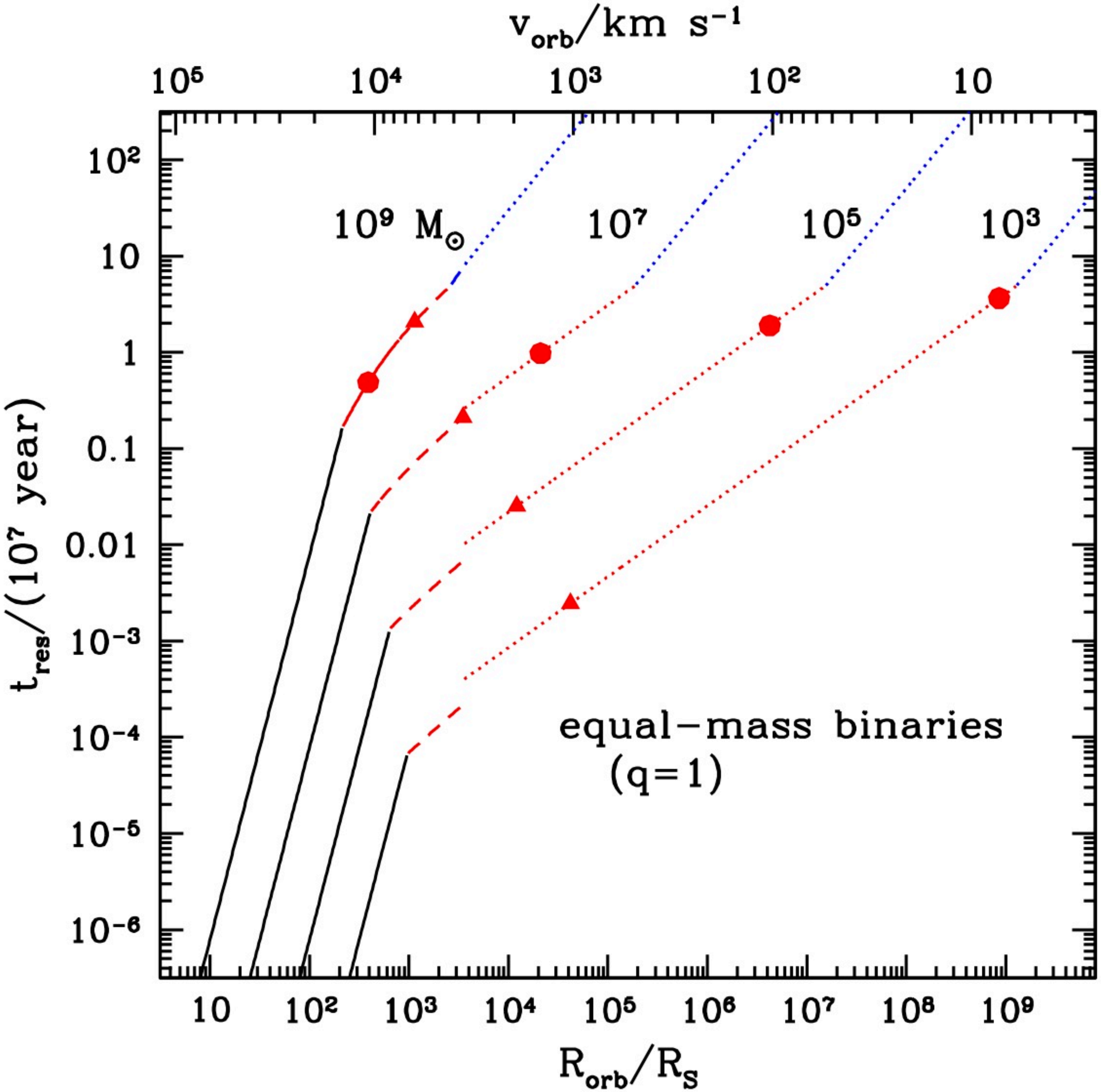


- black holes deposit orbital angular momentum exciting both leading and trailing spiral waves opening a gap of twice the size of the binary separation

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



- turbulence and gravitational torques maintain the contact between the disc and the black hole
- the two black holes “migrate” inwards
- the gap “follows” the binary
- mini discs and not empty cavity



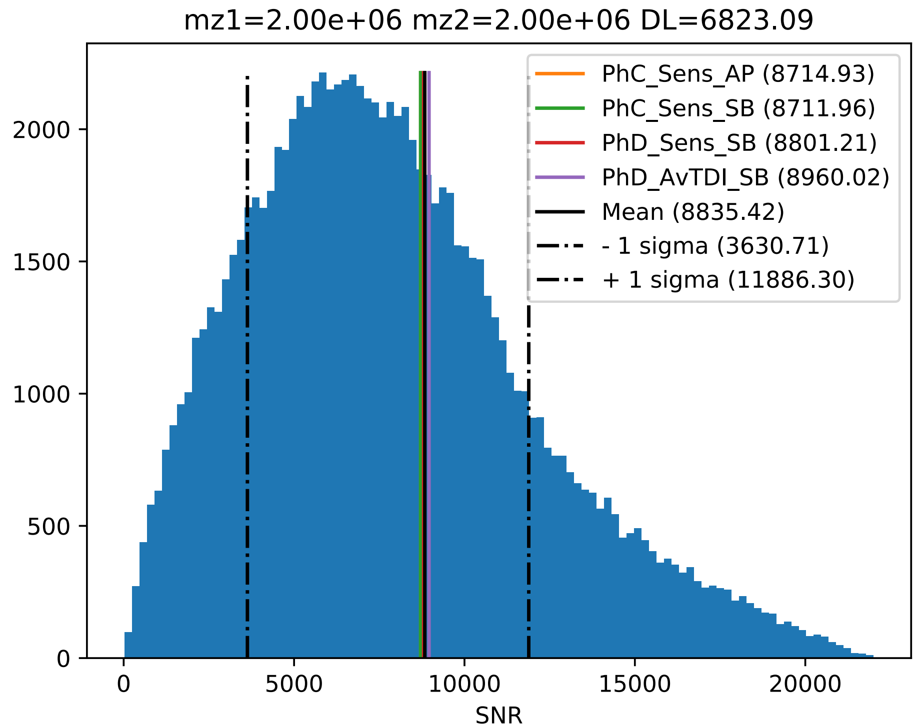
v_orb/km s^-1
10^5
10^4
10^3
10^2
10
10^2
10
1
0.1
0.01
10^-3
10^-4
10^-5
10^-6
t_res/(10^7 year)
10^9 M_⊙
10^7
10^5
10^3
equal-mass binaries
(q=1)
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
R_orb/R_S

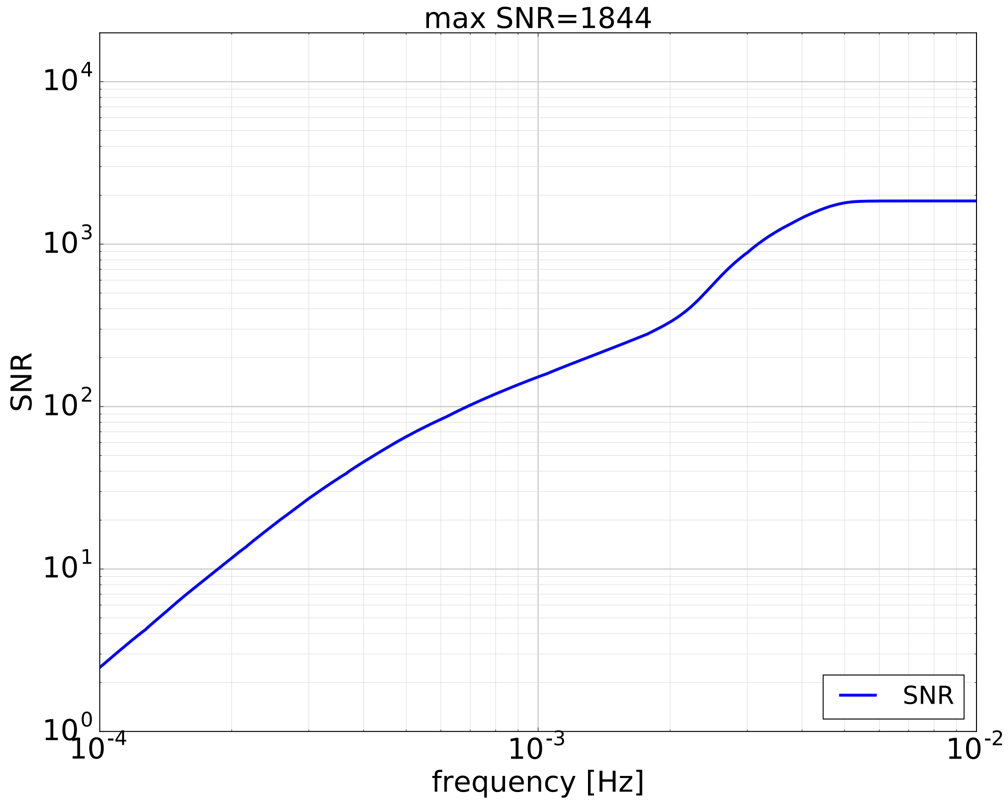
electromagnetic counterparts

- DUAL AGN (NGC6240)
- BINARY AGN long search for and still under search
- EM-counterpart @ coalescence -kseconds prior merging

$$\Delta\Omega \approx 0.5\,\mathrm{deg}^2\,\rho_3^{-7/4}$$

ρ_3 $--->$ $\mathrm{SNR} = 10^3$





Summary

- The gravitational universe promises many new discoveries
- New way of observing black holes: binary and GW signal
- Study of the EM signature of a binary coalescence events
- Search for strategies to recognize these transient events
- Search for synergies with Athen
- … please join the effort
- ………… please join the effort in understanding the dynamics critical for assessing the rate and the binary black holes mass spectrum

take home message

- black hole dynamics is a very complex problem
- presence of a massive stellar cusp leads to swift coalescence (z-dependent? wait until z~4-5?)
- presence of large inflows of gas produce scatter in the delay times
- setting the "clock" is both a cosmological and local problem
- it is still difficult to quantify the level of broadening of the time delay distribution in the formation of ET-LISA coalescing binary black holes: 10 Myrs - 4 Gyrs

- ANCILLARY SLIDES

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

- Clock: time "zero"

$M_{\rm BH,primary} = 3 \times 10^6 \, M_\odot$

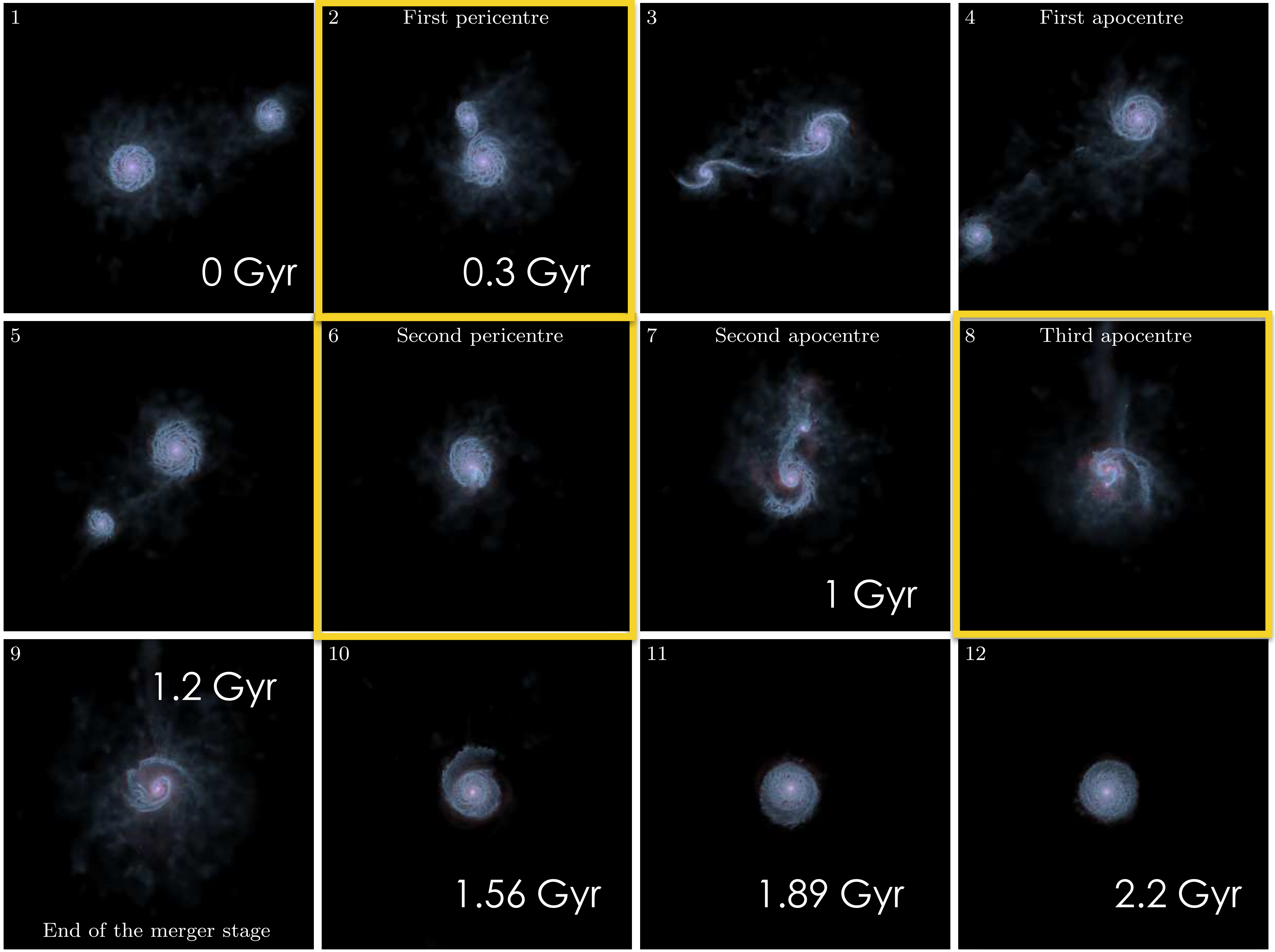
$M_{\rm halo} = 2.2 \times 10^{11} \, M_\odot; M_{\rm bulge} = 2 \times 10^9 \, M_\odot$

$M_{\rm disc,*} = 6 \times 10^9 \, M_\odot; M_{\rm disc,gas} = 3 \times 10^9 \, M_\odot$

70x70 kpc box

1:4 merger between two disc galaxies

gas fraction 30%



Capelo+2014

take home message

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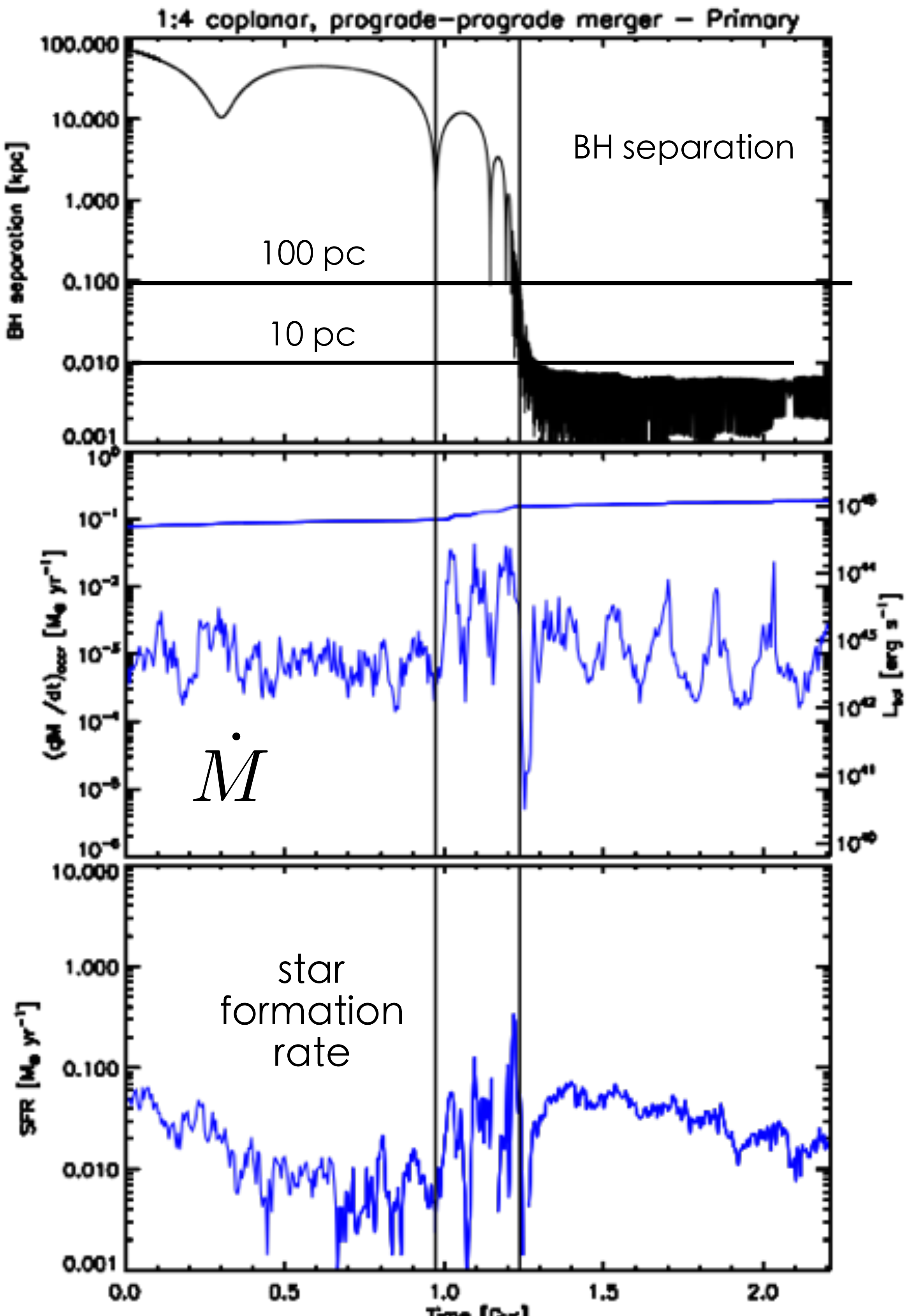
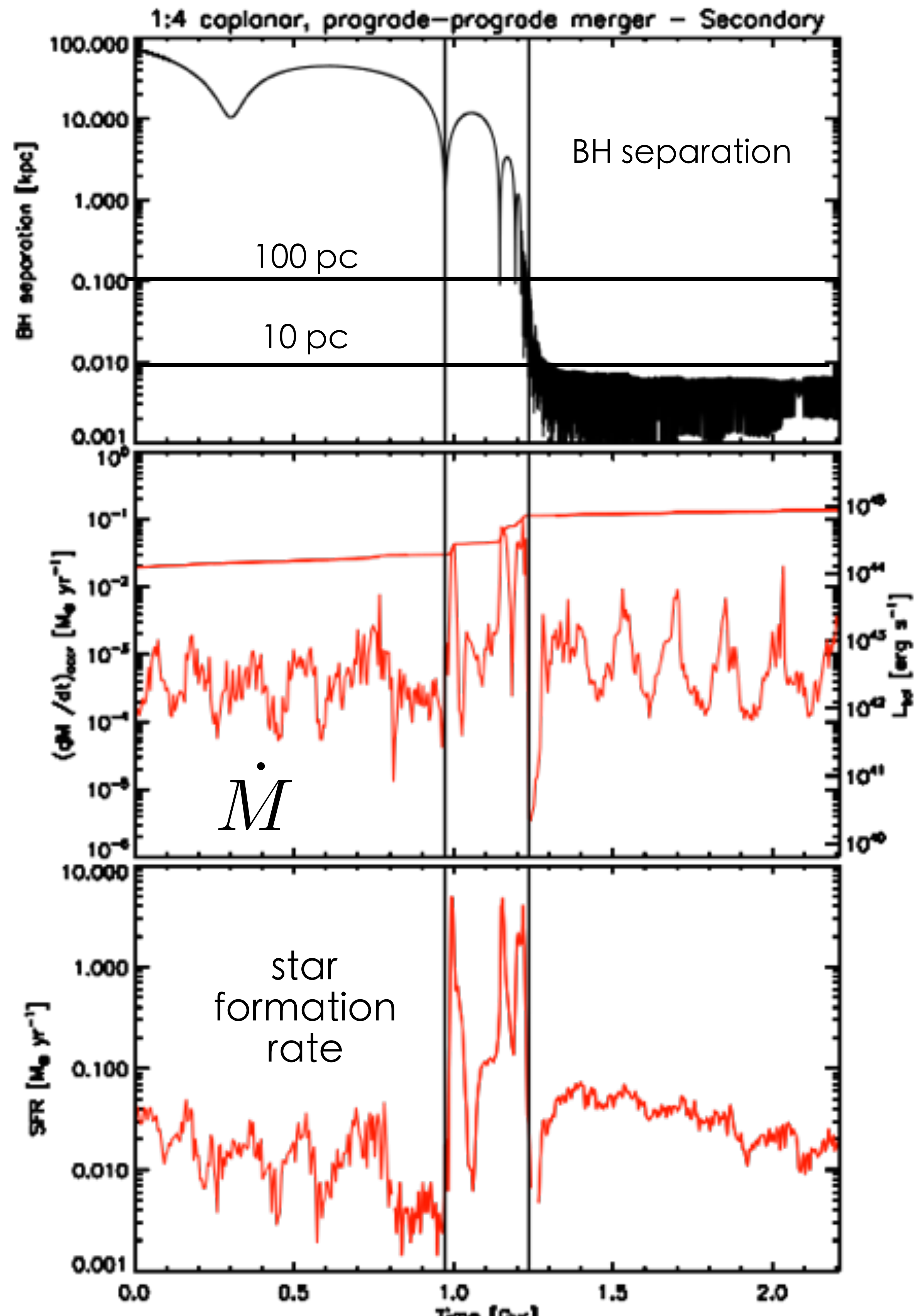
primary black hole

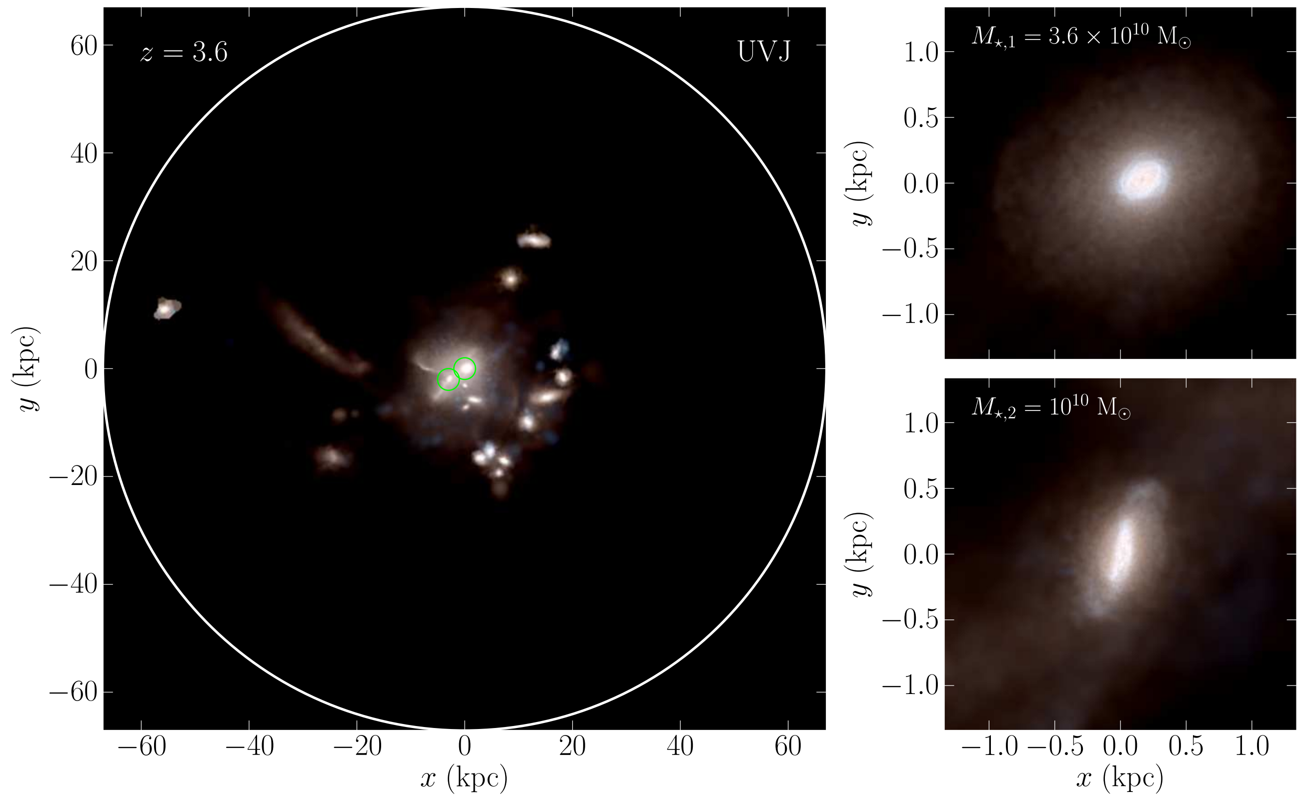


secondary black hole



Capelo+2014

portrait of a cosmological merger



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

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

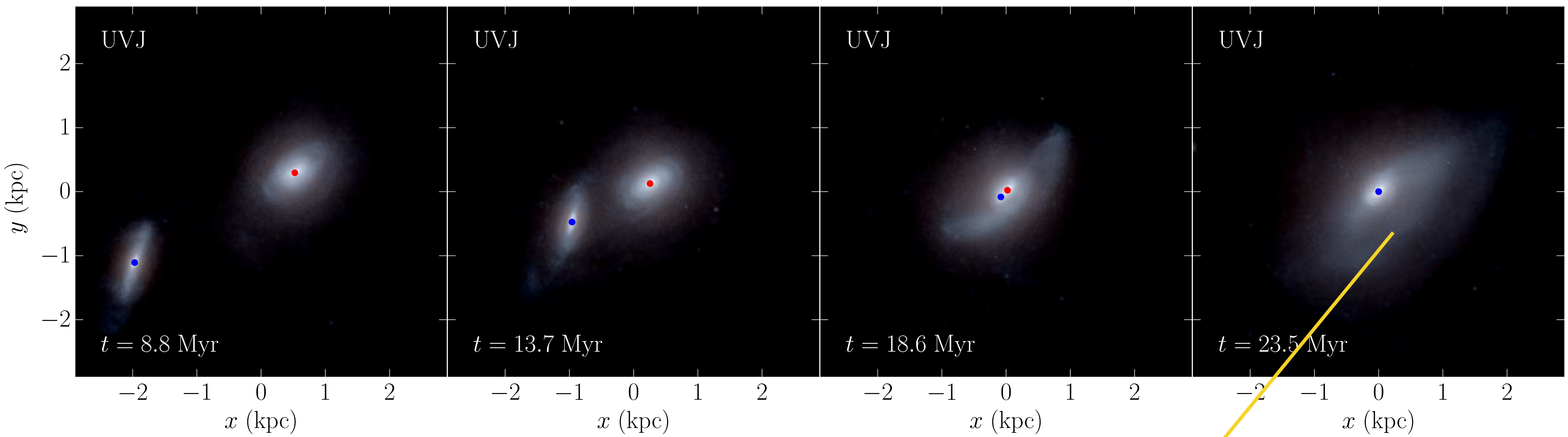
Khan, Mayer, Fiacconi 2016

- 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%
- splitting procedure to attain a force resolution of 5 pc - Direct N-Body code
  (mass resolution 6000 gas,10,000 stars, 100,000 dark matter)

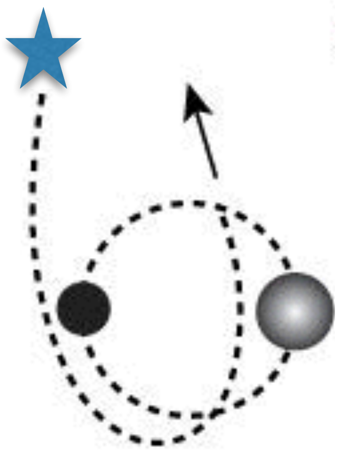
$$M_{2,*} \sim 10^{10}\ M_\odot$$
$$M_{1,*} \sim 3.6 \times 10^{10}\ M_\odot$$
$$M_{\mathrm{halo}} \sim 10^{13}\ M_\odot \ \ @\ \ z = 0$$

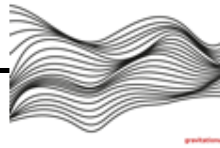
II. (a) pairing phase

- gas inflows in the inner 500 pc from cosmological streams are conducive to intense bursts 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



effective black hole mass enhanced by an episode of star formation





Take home message

- nuclear inflows of gas and episodes of star formation in the vicinity of the black holes are instrumental in creating the conditions for rapid pairing as they enhance the effective mass of the black hole and thus the dynamical friction drag
- provide the reservoir of stars for the slingshot mechanism to become effective in the triaxial potential of the new galaxy
- stars are “key players” for the merger to stay on clock with the “help” of gas: having a higher degree of dissipation/ability to loose angular momentum gaseous stream lead to formation of stellar cusps
- just a single simulation with “massive” black holes