Gravitational waves: a new messenger to explore the Universe

30 March - 1 April 2021

THE MASSIVE BINARY BLACK HOLE POPULATION ACROSS COSMIC TIME SEEN UNDER A SEMI-ANALYTICAL PERSPECTIVE

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

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OUTLINE

* Introduction : Massive black holes and massive binary black holes

* The model used to study the massive (binary) black holes in a cosmological context

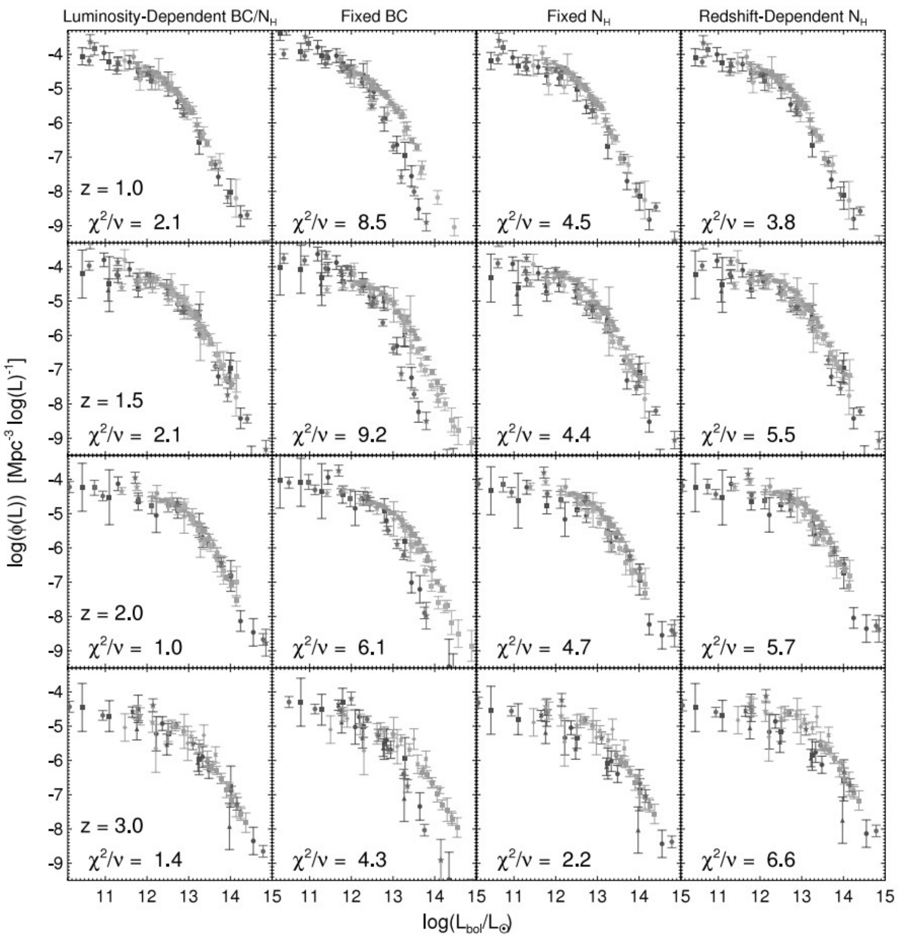
* Results

* Conclusions

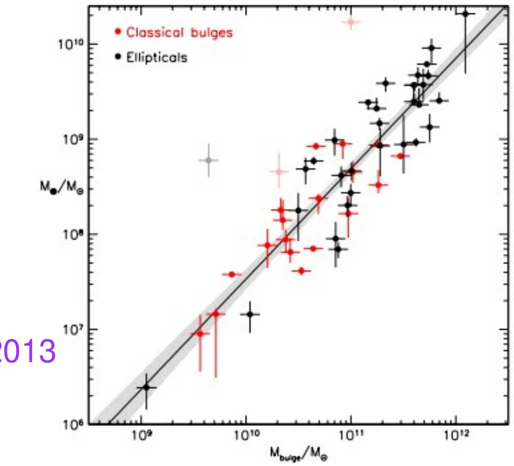
INTRODUCTION

* Our relationship with massive black holes started in 1963 when Schmidt M. found the first quasar

* More and more people studied the population of quasars: Luminosity functions, scaling relations …

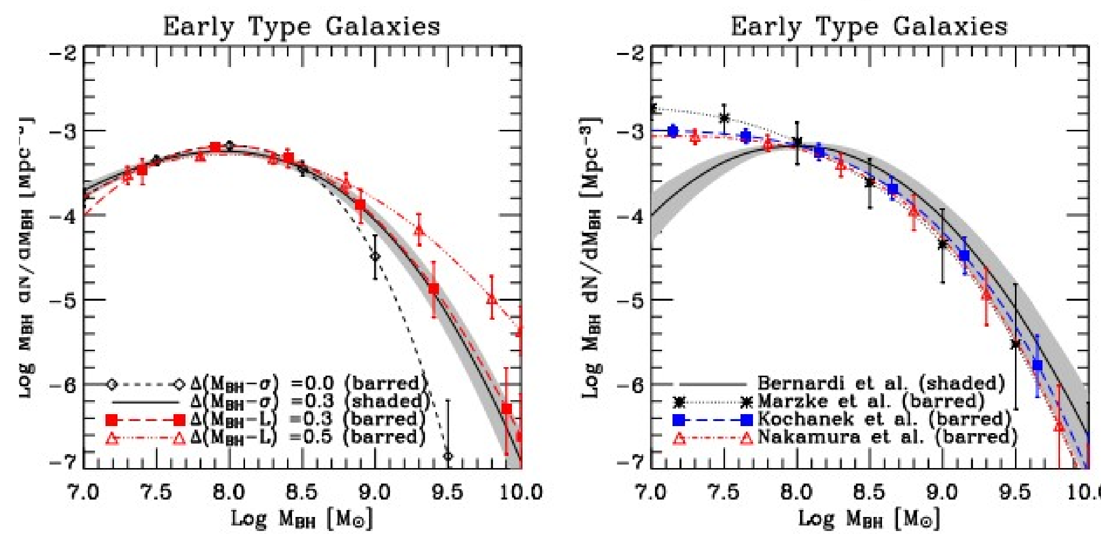


Hopkins et al. 2009



Kormendy & Ho et al. 2013

Marconi et al. 2004



* We reached the <u>CONCLUSION</u> that

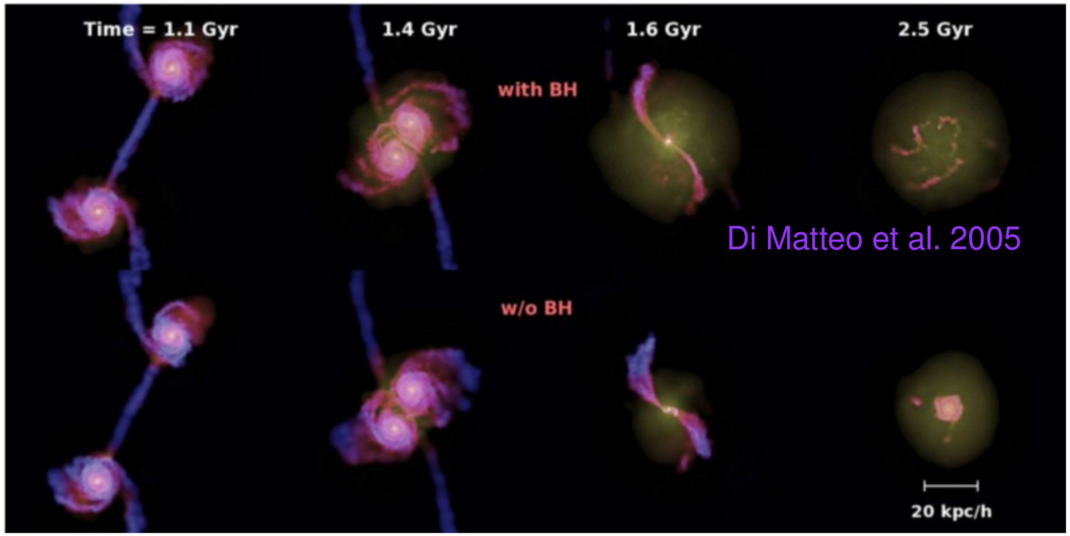
MASSIVE BLACK HOLES (>10^6 M_{sun}) ARE UBIQUITOUS IN ALL GALAXIES

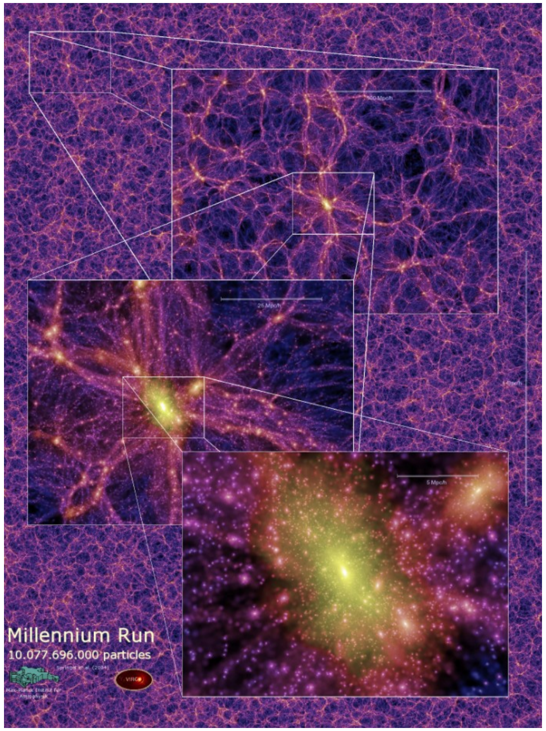
INTRODUCTION

* MASSIVE BLACK HOLES (>10^6 M_{sun}) ARE UBIQUITOUS IN ALL GALAXIES

HIERARCHICAL GROWTH OF THE STRUCTURES:

Mergers are one of the main drivers of galaxy evolution





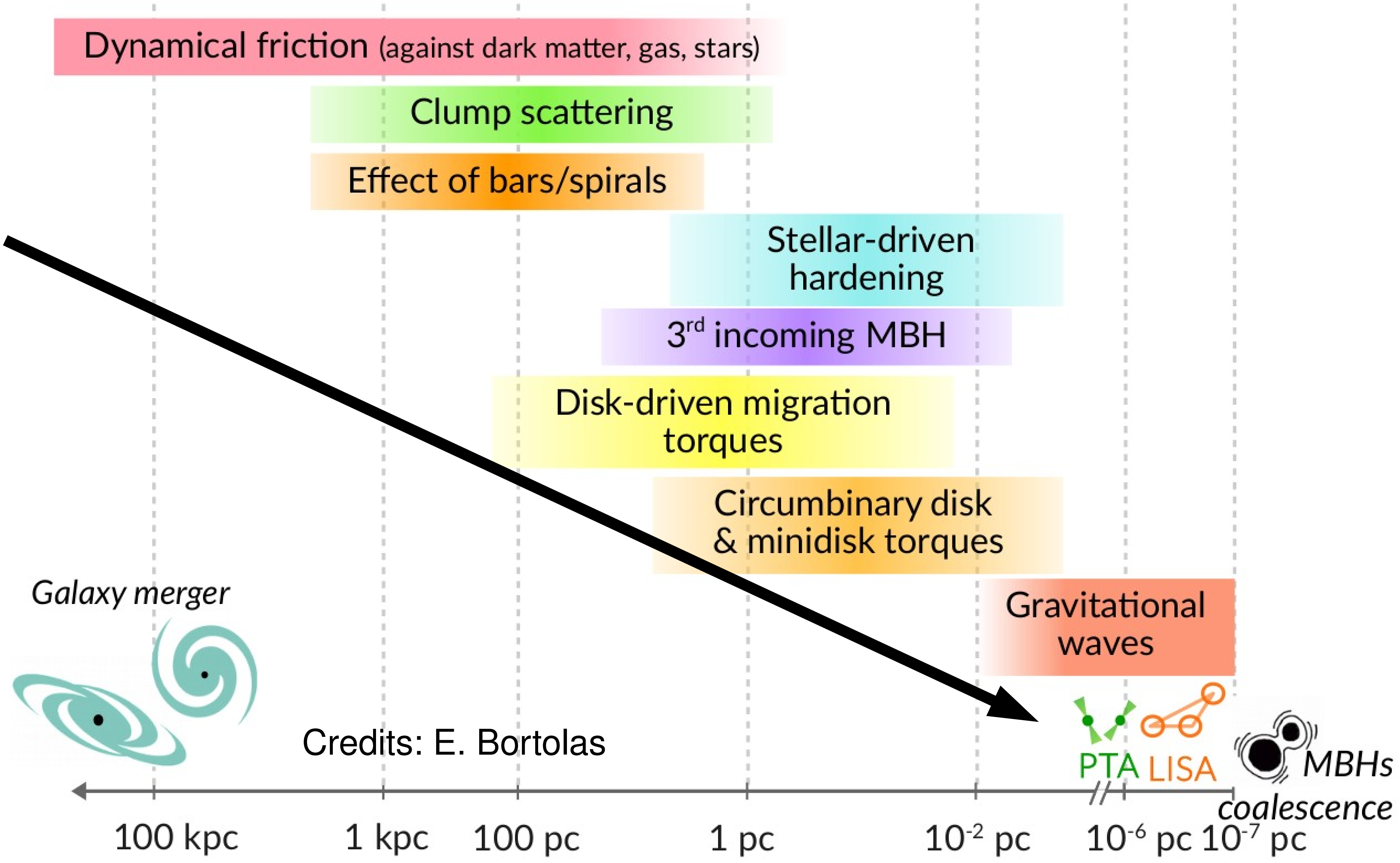
GALAXIES MIGHT HOST **MORE** THAN ONE MASSIVE BLACK HOLE

BLACK HOLES ARE DEPOSITED FAR AWAY (> kpc)

IS POSSIBLE BRING THE TWO BLACK HOLES TOGETHER (~pc) ?

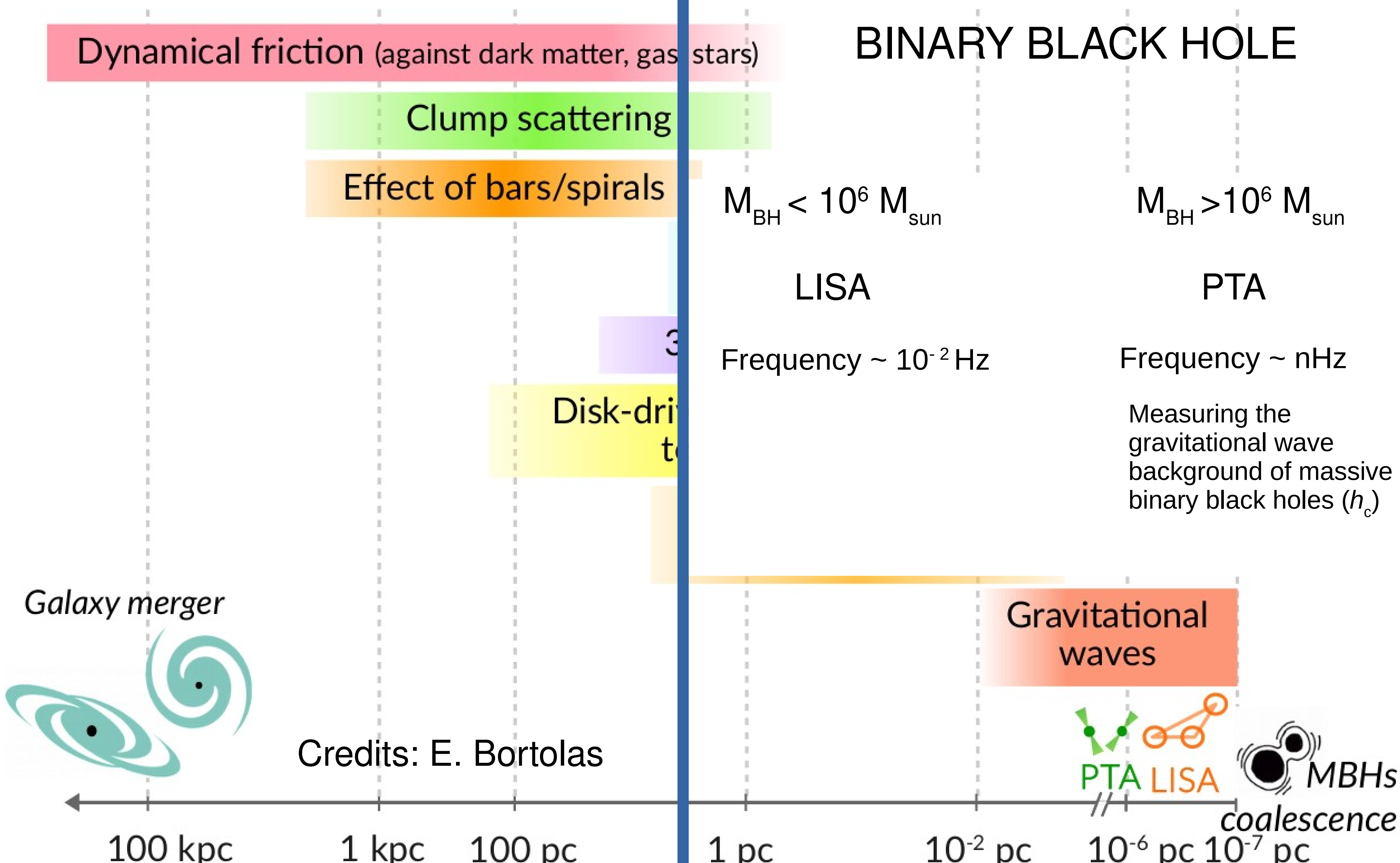
INTRODUCTION

Many works have tackled this problem...



Credits: E. Bortolas

INTRODUCTION

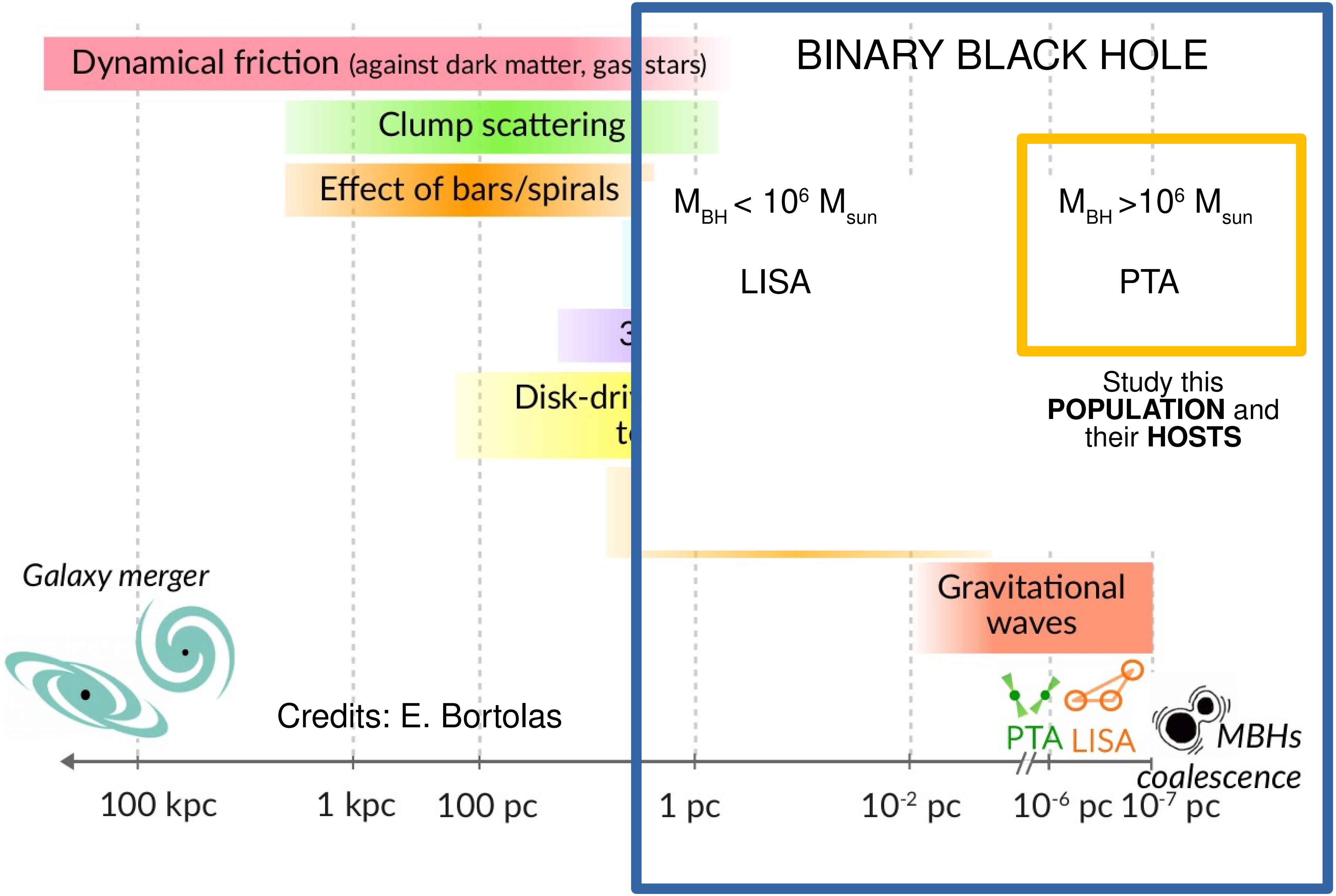


Credits: E. Bortolas

BINARY BLACK HOLE

$M_{BH} < 10^6 M_{sun}$	$M_{BH} > 10^6 M_{sun}$
LISA	PTA
Frequency ~ 10^{-2} Hz	Frequency ~ nHz
	Measuring the gravitational wave background of massive binary black holes (h_c)

INTRODUCTION



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THE MODEL

In order to study the population and hosts of massive binary black holes (>10^6 M_{sun}) we need several ingredients

RELIABLE GALAXY POPULATION

RELIABLE BLACK HOLE POPULATION

MODEL FOR THE BINARY POPULATION

THE MODEL

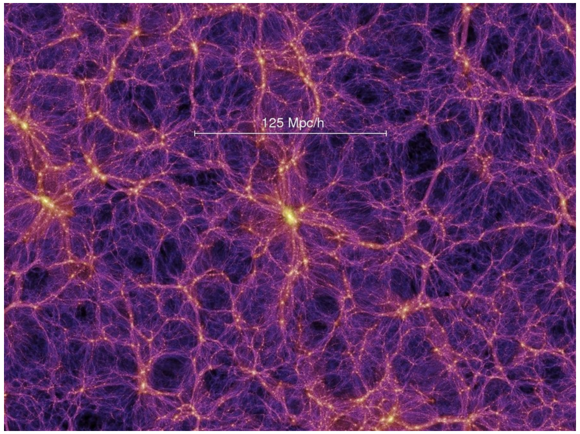
In order to study the population and hosts of massive binary black holes ($>10^6$ M_{sun}) we need several ingredients

RELIABLE GALAXY POPULATION | RELIABLE BLACK HOLE POPULATION | MODEL FOR THE BINARY POPULATION

1) MILLENNIUM SIMULATION Springel et al. 2005

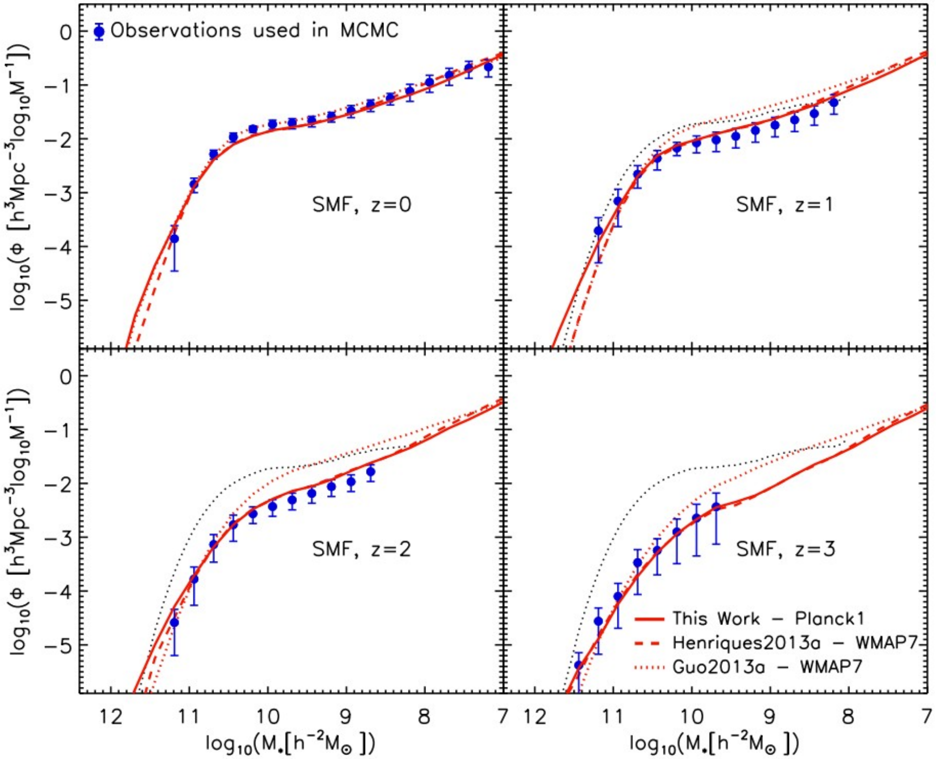
L_{box} = 500 Mpc / *h*

M_{halo} ~ 1.7×10^{10} M_{sun}



Proof of concept

Evolution of the *STELLAR MASS FUNCTION*



Henriques et al. 2015

2) SEMI-ANALYTICAL MODEL

L-Galaxies, Munich Galaxy Formation Model

Guo et al. 2011, Henriques et al. 2015

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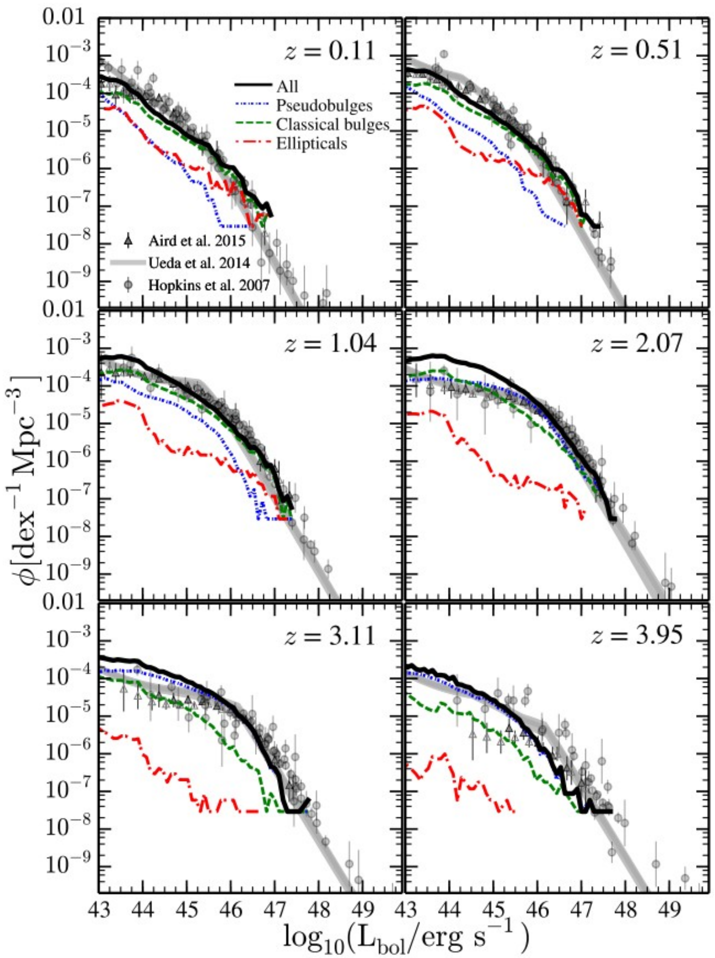
1) MILLENNIUM SIMULATION

2) SEMI-ANALYTICAL MODEL

- Growth → Mergers & Disk instabilities
- Spin evolution → Link with the bulge formation and evolution
- Recoil velocities
- Wandering black holes

Izquierdo-Villalba et al. 2020

Evolution of the *QUASAR BOLOMETRIC LUMINOSITY FUNCTION*



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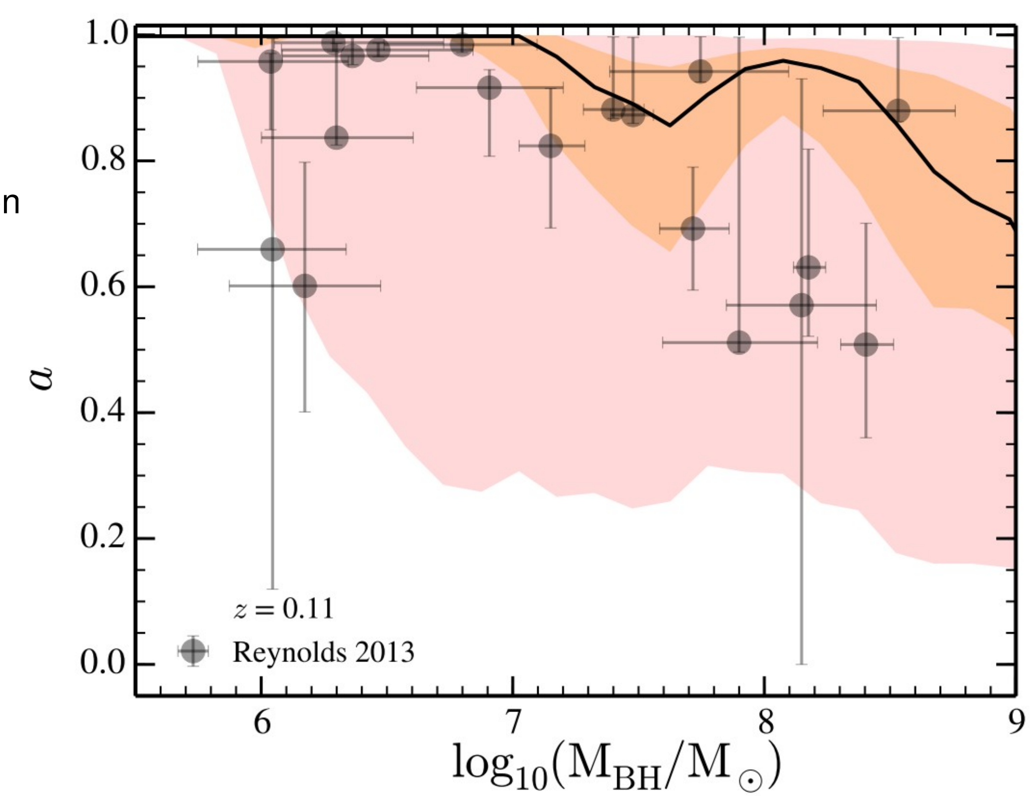
SPIN PARAMETER AT z = 0



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- Hardening phase

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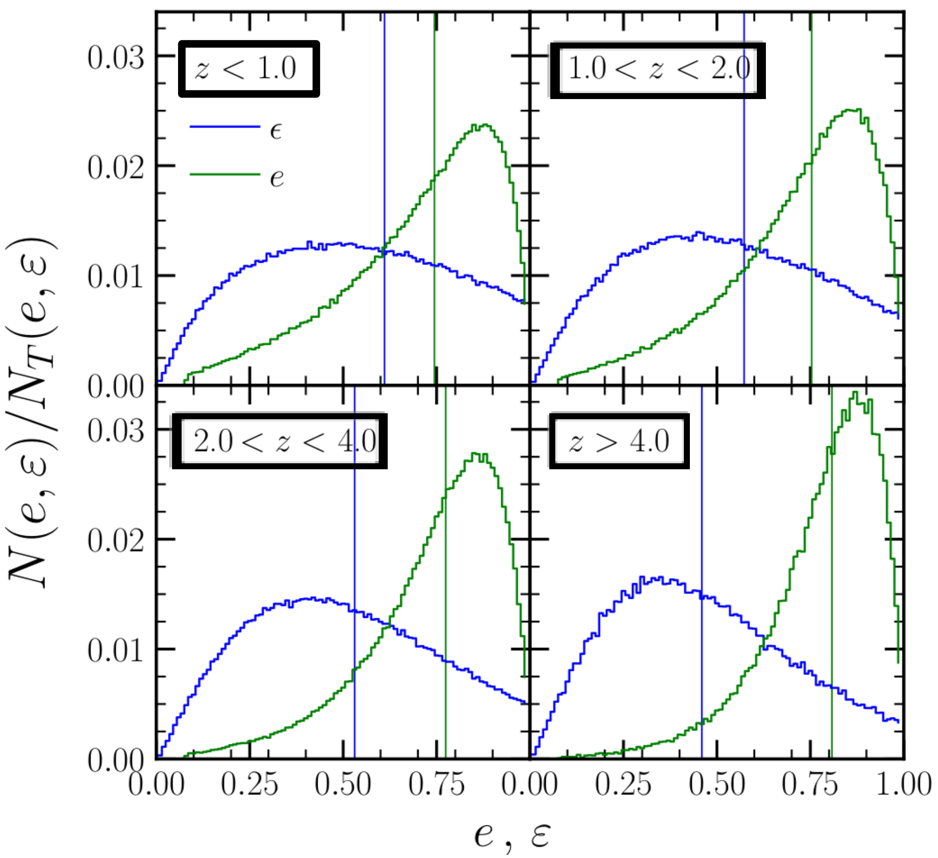
- Dynamical friction phase

$$t_{\rm dyn}^{\rm BH} = 19\, f(\varepsilon) \left(\frac{r_0}{4\,{\rm kpc}}\right)^2 \left(\frac{\sigma}{200{\rm km/s}}\right) \left(\frac{10^8\,{\rm M}_\odot}{{\rm M}_{\rm BH}}\right) \frac{1}{\Lambda}\ [{\rm Gyr}]$$

CIRCULARITY of the black hole orbit → Computed form the circularity of the **GALAXY ORBIT**



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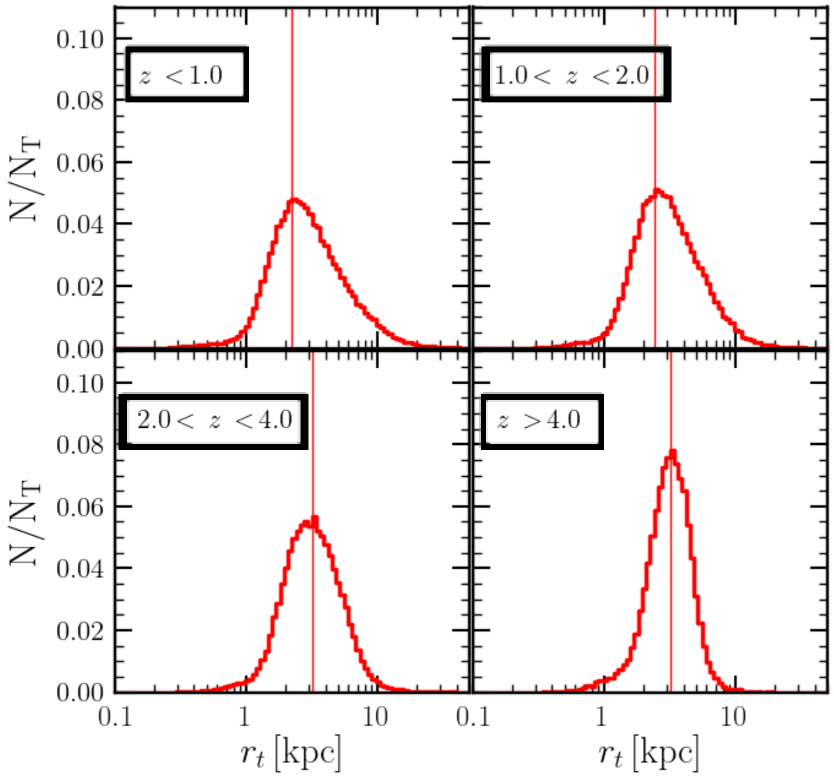
INITIAL POSITION of the black hole → Computed according to the galaxy **TIDAL RADIUS**

- Hardening phase

$$r_t = \left(\frac{G\,\rm M_{sat}}{\omega^2 - d^2\Phi/dr^2}\right)^{1/3}$$



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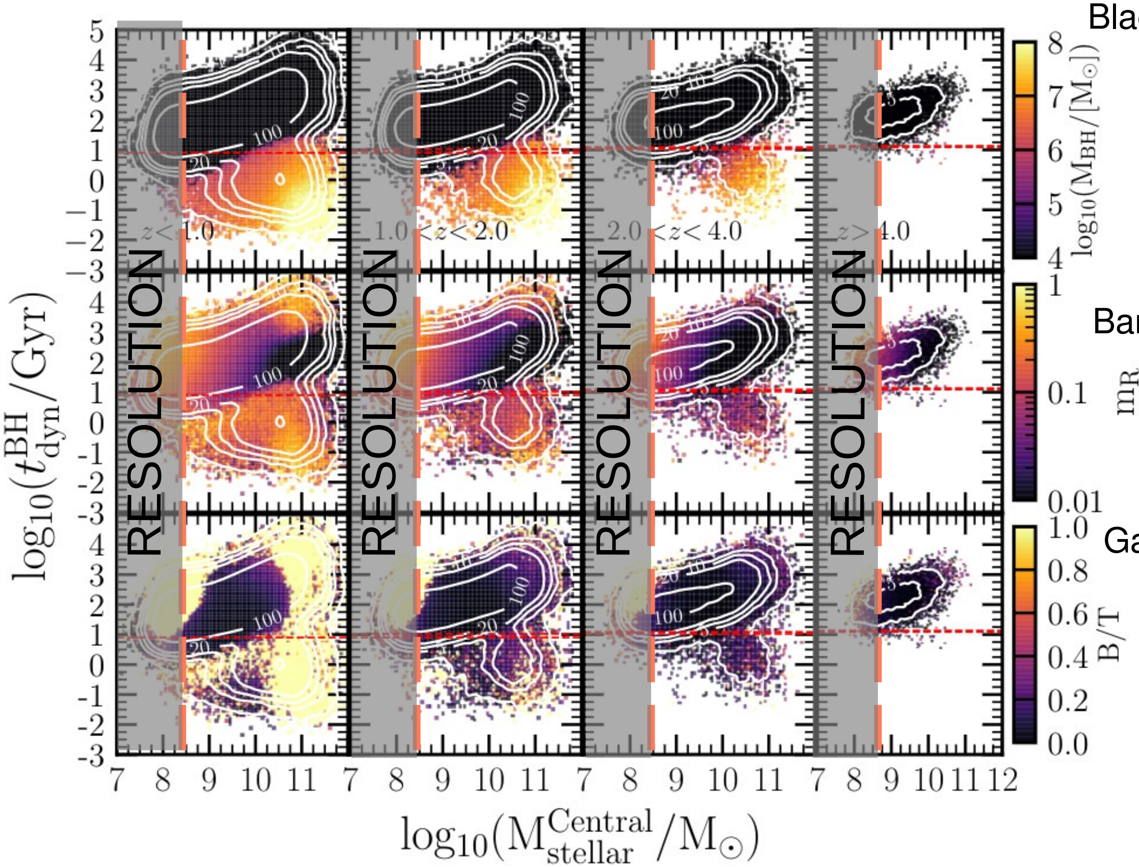
REDSHIFT

Black hole mass

Baryonic merger ratio

Galaxy morphology



$t_{dyn}^{BH} < t_H$ when:

- Massive black holes (>10^6 M_{sun})
- Large merger rations
- Typically in elliptical galaxies

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RELIABLE GALAXY POPULATION | RELIABLE BLACK HOLE POPULATION | MODEL FOR THE BINARY POPULATION

- Dynamical friction phase

- Hardening phase: We have assumed a **Sércic model profile**

$$\rho_B(r) = \rho_0 \left(\frac{r}{R_e}\right)^{-p} e^{-b\left(\frac{r}{R_e}\right)^{1/n}}$$

Biava et al. 2019

1) Gas rich mergers : Disk torques driven the binary merge

$$t_{delay} = R_c \frac{G(M_{BH,1} + M_{BH,2})}{\sigma_{inf}^2}$$

2) Gas poor mergers : The stellar background drives the binary merge Sesana & Khan 2015

$$\frac{da_{BH}}{dt} = \left(\frac{da_{BH}}{dt}\right)_{Hard} + \left(\frac{da_{BH}}{dt}\right)_{GW} = -\frac{GH\rho_{inf}}{\sigma_{inf}} a_{BH}^2 - \frac{64G^3(M_{BH_1} + M_{BH_2})^3 F(e)}{5c^5(1+q)^2 a_{BH}^3}$$

$$\frac{de}{dt} = a_{BH} \frac{G\rho_{inf} HK}{\sigma_{inf}} - \frac{304}{15} \frac{G^3 q (M_{BH_1} + M_{BH_2})^3}{c^5 (1+q)^2 a_{BH}^4 (1-e^2)^{5/2}} \left(e + \frac{121}{304} e^3\right)$$

a) The initial eccentricity is assumed to be random between [0,1]

b) The initial separation is computed as $M_{Bulge}(< a_0) = 2M_{BH,2}$

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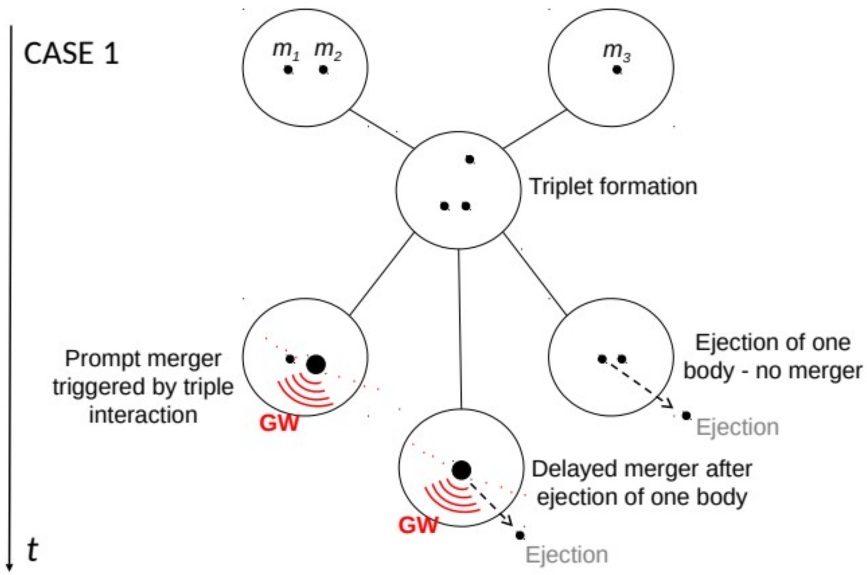
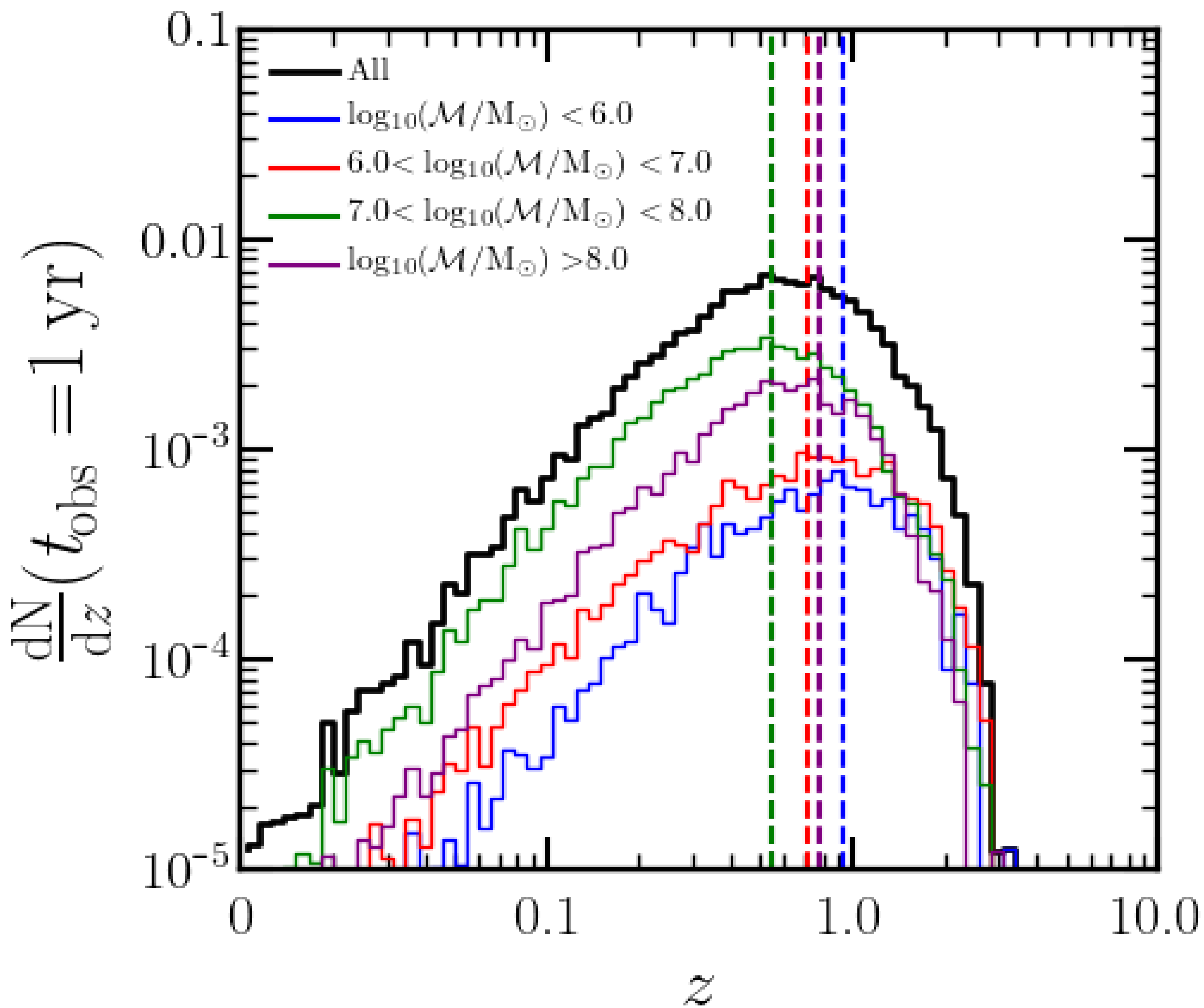
- Hardening phase
- Merger caused by intruder massive black hole (Bonetti et al. 2018)



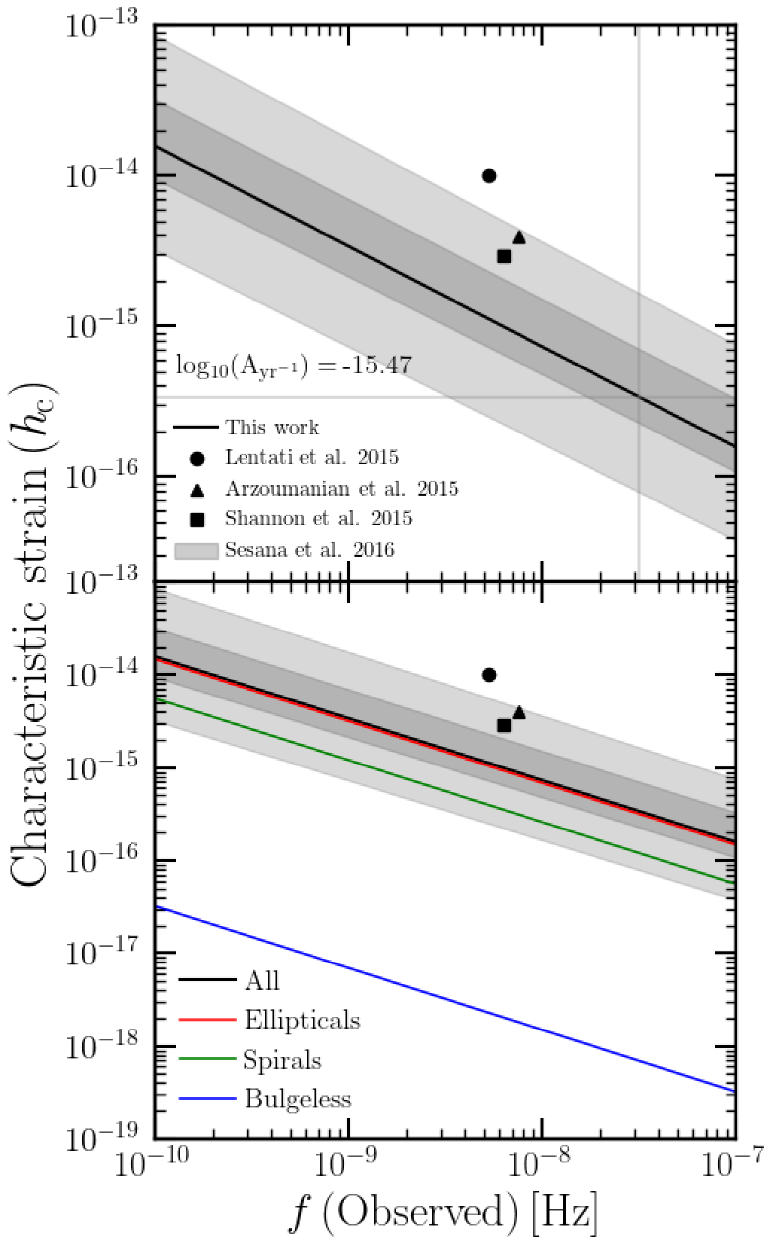
RESULTS

MERGER RATE



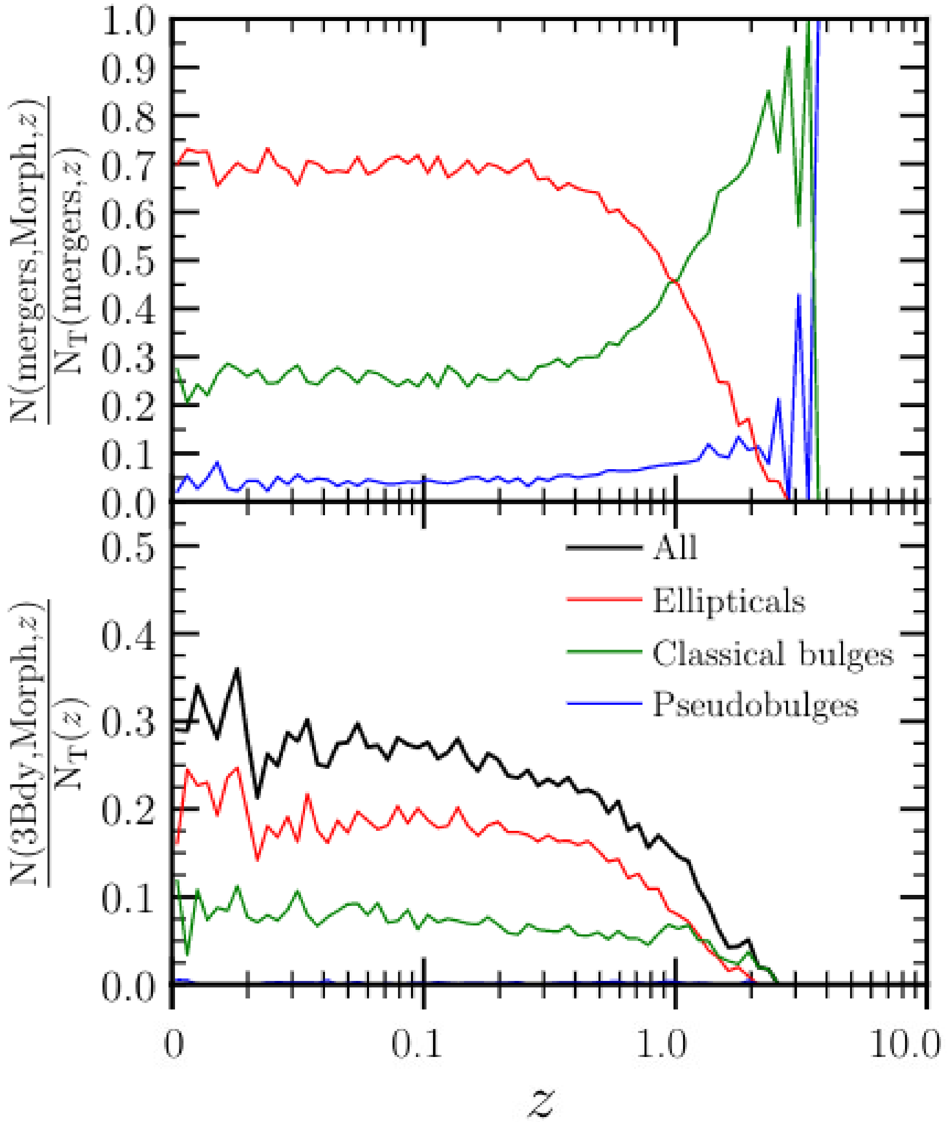
RESULTS

AMPLITUDE OF THE GRAVITATIONAL WAVE BACKGROUND IN THE PTA BAND



RESULTS

PROPERTIES OF THE GALAXIES HOSTING MERGING MASSIVE BLACK HOLES



CONCLUSIONS

* We have tackled the formation and evolution of massive black hole binaries (>10^6 M_{sun}) in the PTA band

  - Dark matter merger trees from N-body simulations
  - Semi-analytical model
  - Proper treatment of the growth and spin evolution

* For galaxies $M_{stellar}$ > 10^9 M_{sun} only black holes >10^6 M_{sun} can reach the nucleus of its central galaxy
  - After baryonic merger with merger ratios > 0.1
  - Seems to have a correlation between the wandering time and the galaxy morphology

* The merger rate of binary black holes of >10^6 M_{sun} is quite low < 0.01 event per year

* The amplitude of the gravitational wave background at nHz is consistent with the expectations AND most of the signal comes form binary black holes merging in elliptical galaxies

* The encounter with an intruder black hole lead to the final coalescence of the
  ~30% of binary black holes in elliptical galaxies
  ~10% of binary black holes in spiral galaxies hosting a classical bulge
  ~0% of binary black holes in spiral galaxies hosting a pseudobulge

THANKS

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Evolution of the *BLACK HOLE MASS FUNCTION*