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

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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
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 …

We reached the CONCLUSION that massive black holes (\( >10^6 \, M_\odot \)) are ubiquitous in all galaxies.

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**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 …

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**CONCLUSIONS**

MASSIVE BLACK HOLES (\( >10^6 \, M_\odot \)) ARE UBIQUITOUS IN ALL GALAXIES.
INTRODUCTION

* Massive black holes (>10^6 M_\odot) 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...

Dynamical friction (against dark matter, gas, stars)
Clump scattering
Effect of bars/spirals
Stellar-driven hardening
3rd incoming MBH
Disk-driven migration torques
Circumbinary disk & minidisk torques
Gravitational waves

Galaxy merger

Credits: E. Bortolas

100 kpc  1 kpc  100 pc  1 pc  10^{-2} pc  10^{-6} pc  10^{-7} pc

PTA  LISA  MBHs

Coalescence
**INTRODUCTION**

Dynamical friction (against dark matter, gas, stars)

- Clump scattering
- Effect of bars/spirals

Galaxy merger

Credits: E. Bortolas

**BINARY BLACK HOLE**

- $M_{BH} < 10^6 \, M_{\text{sun}}$
- $M_{BH} > 10^6 \, M_{\text{sun}}$

**LISA**

Frequency $\sim 10^{-2} \, \text{Hz}$

**PTA**

Frequency $\sim \text{nHz}$

Measuring the gravitational wave background of massive binary black holes ($h_c$)

**Gravitational waves**

PTA

LISA

MBHs

coalescence

1 pc $\sim 10^{-2}$ pc $\sim 10^{-6}$ pc $\sim 10^{-7}$ pc

100 kpc 1 kpc 100 pc
INTRODUCTION

BINARY BLACK HOLE

Dynamical friction (against dark matter, gas, stars)
Clump scattering
Effect of bars/spirals
Disk-drift instabilities

$M_{\text{BH}} < 10^6 \, M_{\text{sun}}$
LISA

$M_{\text{BH}} > 10^6 \, M_{\text{sun}}$
PTA

Study this POPULATION and their HOSTS

Galaxy merger

Credits: E. Bortolas

100 kpc 1 kpc 100 pc

1 pc $10^{-2}$ pc $10^{-6}$ pc $10^{-7}$ pc

Gravitational waves

PTA LISA MBHs coalescence
### THE MODEL

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

- **Reliable Galaxy Population**
- **Reliable Black Hole Population**
- **Model for the Binary Population**
In order to study the population and hosts of massive binary black holes (>10^6 M_\text{sun}) we need several ingredients:

1) **MILLENIUM SIMULATION**
   - Springel et al. 2005
   - L_{\text{box}} = 500 \text{ Mpc} / h
   - M_{\text{halo}} \sim 1.7 \times 10^{10} M_\text{sun}

2) **SEMI-ANALYTICAL MODEL**
   - L-Galaxies, Munich Galaxy Formation Model
   - Guo et al. 2011, Henriques et al. 2015

Evolution of the **stellar mass function**

Proof of concept

Henriques et al. 2015
In order to study the population and hosts of massive binary black holes (>10^6 M_{\odot}) we need several ingredients:

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

1. RELIABLE GALAXY POPULATION
2. RELIABLE BLACK HOLE POPULATION
3. MODEL FOR THE BINARY POPULATION

1) MILLENNIUM SIMULATION
2) SEMI-ANALYTICAL MODEL
   - Growth → Mergers & Disk instabilities
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     Izquierdo-Villalba et al. 2020
In order to study the population and hosts of massive binary black holes ($>10^6 \text{ M}_{\text{sun}}$) we need several ingredients:

- Reliable galaxy population
- Reliable black hole population
- Model for the binary population

- Dynamical friction phase
- Hardening phase
In order to study the population and hosts of massive binary black holes (>10^6 M_\text{sun}) we need several ingredients.

- Dynamical friction phase

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

- Hardening phase

**CIRCULARITY** of the black hole orbit

Computed from the circularity of the GALAXY ORBIT

- 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_{\odot}) we need several ingredients

- Dynamical friction phase

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

**INITIAL POSITION** of the black hole

Computed according to the galaxy **TIDAL RADIUS**

- Hardening phase

\[ r_t = \left( \frac{G M_{\text{sat}}}{\omega^2 - d^2 \Phi/dr^2} \right)^{1/3} \]

**RESULTS**

**CONCLUSIONS**
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 involves:

- Dynamical friction phase
- Hardening phase

**RESULTS**

- Black hole mass
- Baryonic merger ratio
- Galaxy morphology

**CONCLUSIONS**

\[ t_{dyn}^{BH} < t_H \text{ when:} \]

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

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

- Dynamical friction phase

- Hardening phase: We have assumed a Sérsic 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

\[ t_{\text{delay}} = R_e \frac{G(M_{\text{BH,1}} + M_{\text{BH,2}})}{\sigma_{\text{inf}}^2} \]

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

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

\[ \frac{de}{dt} = a_{\text{BH}} \frac{G \rho_{\text{inf}} H K}{\sigma_{\text{inf}}} - \frac{304}{15} \frac{G^3 q(M_{\text{BH,1}} + M_{\text{BH,2}})^3}{e^5(1 + q)^2a_{\text{BH}}^4(1 - e^2)^{5/2}} \left( e + \frac{121}{304} e^3 \right) \]

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

b) The initial separation is computed as

\[ \tilde{M}_{\text{Bulge}}(< a_0) = 2M_{\text{BH,2}} \]
THE MODEL

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

- Dynamical friction phase
- 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

\[ \log_{10}(A_{\nu-1}) = -15.47 \]

- This work
- Lentati et al. 2015
- Arzoumanian et al. 2015
- Shannon et al. 2015
- Sesana et al. 2016

Characteristic strain vs. observed frequency.
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 from 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
The Model

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1) Millennium Simulation
2) Semi-Analytical Model
   - Growth → Mergers & Disk instabilities
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Evolution of the Black Hole Mass Function