Orbits of black holes in galactic triaxial potentials

Juan Barbosa

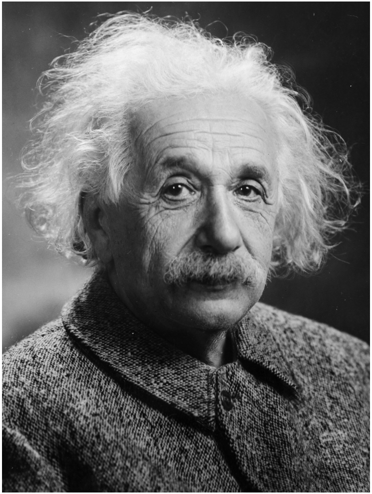
Jaime Forero
Advisor

Departamento de Física
Facultad de Ciencias
Universidad de los Andes

Overview

Introduction

Introduction



- Theory of General Relativity, 1916
- More than 100 years have passed since the publication of the theory
- Today there are gaps in the understanding and implications of Einstein's equations

Introduction

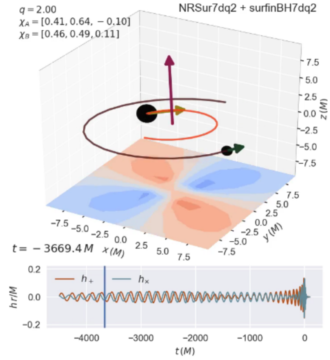


Figure: Binary black hole merger simulation

Vijay Varma, Leo C Stein, and Davide Gerosa. "The binary black hole explorer: on-the-fly visualizations of precessing binary black holes". In: *arXiv preprint arXiv:1811.06552* (2018)

Objectives

Study the effect of different triaxial potentials, and initial velocities, on the times required by black holes to return to their initial position, after experiencing a recoil, as well as to quantify how chaotic its trajectory is

- Obtain probability distributions for the return properties of the black holes, based on the magnitude and direction of the initial velocity
- Study the chaotic behavior of orbits using Lyapunov exponents

Methodology

Galactic setup

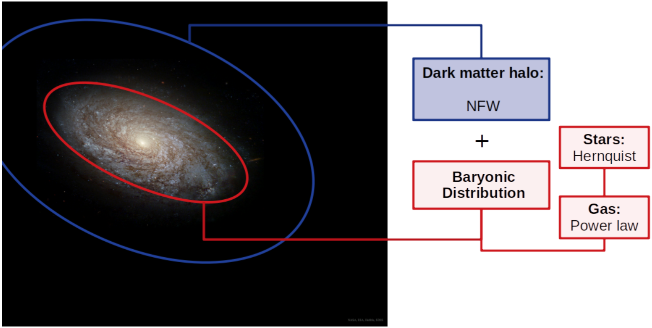


Figure: NGC4414 galaxy as seen by the Hubble telescope.

Mass distributions

1. Dark matter (NWF):

$$\rho_{\mathrm{DM}}(r) = \frac{\rho_0^{\mathrm{DM}}}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2} \tag{1}$$

2. Stellar density (Hernquist):

$$\rho_s(r) = \frac{f_s f_b M_T \mathcal{R}_s}{2\pi r(r + \mathcal{R}_s)^3} \tag{2}$$

3. Gas density (Dobule power law):

$$\rho_{\mathrm{gas}}(r) = \frac{\rho_0^{\mathrm{gas}}}{\left(1 + \frac{r}{r_0}\right)^n} \tag{3}$$

Equation of motion

Trajectories of the kicked black holes are obtained by numerically solving the equation of motion.

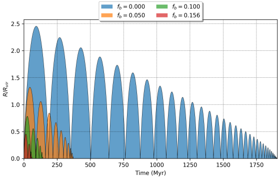
$$\ddot{\vec{x}} = -a_{\text{grav}}(\vec{x})\hat{x} + \left(a_{\text{DF}}(\vec{x}, \dot{\vec{x}}) - \dot{x}\frac{\dot{M}_\bullet(x, \dot{x})}{M_\bullet} \right) \hat{\dot{x}} \tag{4}$$

where $M_\bullet$ is the black hole mass

- Dark matter, stars and gaseous materials from the medium interact with the black hole adding a drag force
- The black hole accretes matter from the surroundings

Results

Spherical potentials



⟵ Baryonic fraction

- Stellar fraction

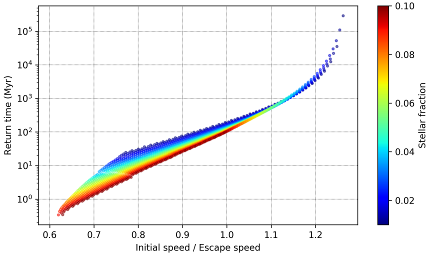
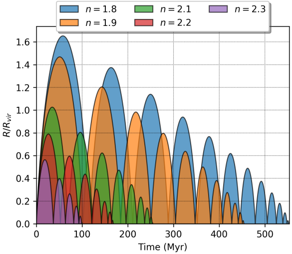


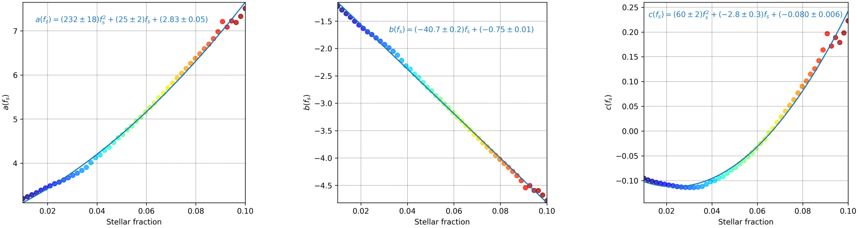
Figure: Return time for different initial speeds



⟵ Power law exponent

Effect of the stellar fraction

$$\log_{10}(T_{\mathrm{return}}) = [a(f_s)v + b(f_s)] + \frac{c(f_s)}{v - 1.3} \tag{5}$$



$$a(f_s) = 232f_s^2 + 25f_s + 2.83 \tag{6}$$

$$b(f_s) = -40.7f_s - 0.75 \tag{7}$$

$$c(f_s) = 60f_s^2 - 2.8f_s - 0.080 \tag{8}$$

Effect of the stellar fraction

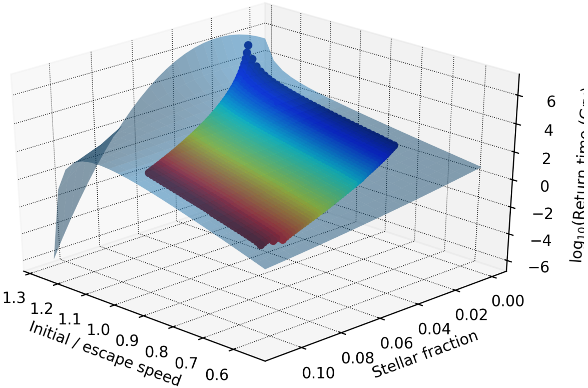
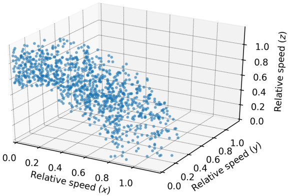
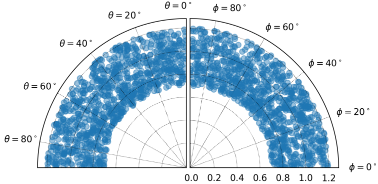


Figure: Generated surface with the proposed fitting curve

Initial conditions



(A) Cartesian



(B) Polar

Figure: Distributions of initial speeds for the triaxial lunches. θ describes the polar angle and ϕ the azimuth.

Triaxial: Initial conditions

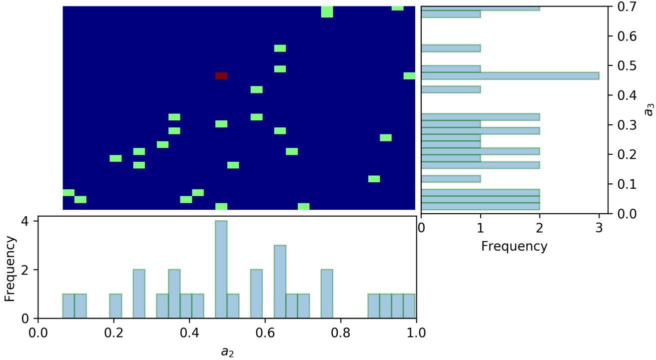


Figure: Distribution of the 28 pair of values for the y and z semiaxis.

Results

Table: Parameters of the fitted gaussians

	Spherical	Triaxial
μ (10^5 $M_\odot$)	1.08	1.34
σ^2 (10^5 $M_\odot$)^2	3.7×10^{-4}	1.7×10^{-2}

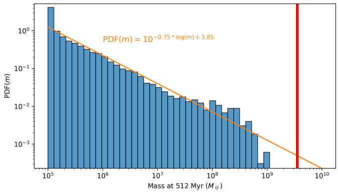


Figure: Mass distributions at $t = 512$ Myr

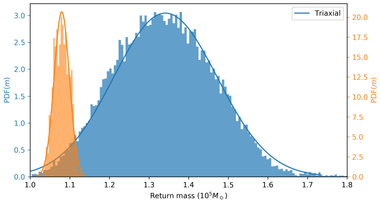


Figure: Mass distributions of the returned black holes

Results

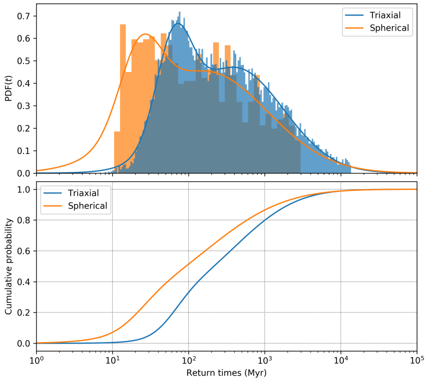


Figure: Return time distributions

Table: Fitted values

	Spherical	Triaxial
μ_1 log(Myr)	2.22	2.60
σ_1 log(Myr)	0.81	0.64
μ_2 log(Myr)	1.36	1.81
σ_1 log(Myr)	0.27	0.23
α	4.5×10^{-4}	3.5×10^{-4}
β	1.1×10^{-4}	1.2×10^{-4}

Results

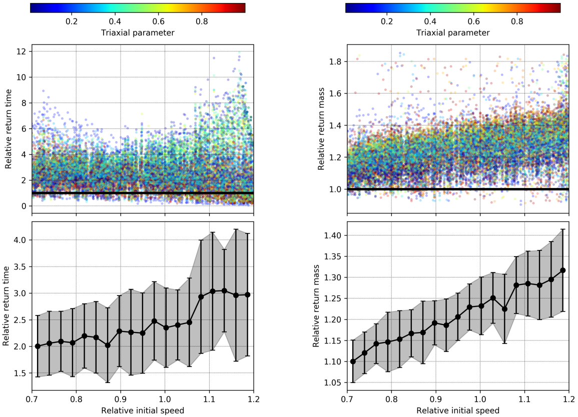


Figure: Distributions of the relative return properties.

Results

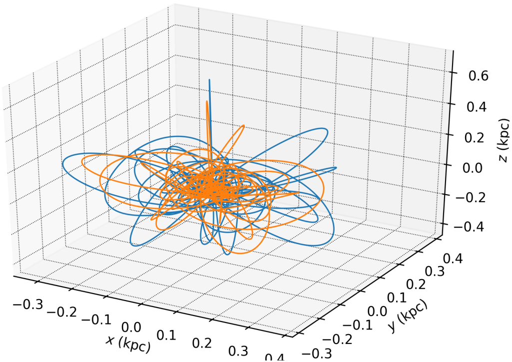
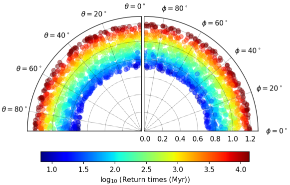
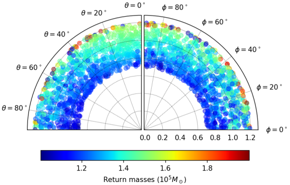


Figure: Orbits with a difference in the initial conditions of 1.9 %.

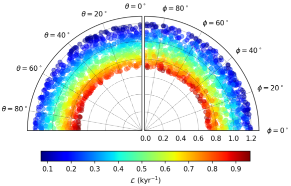
Spherical galaxy



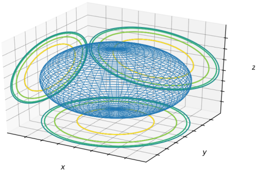
(A) Return times



(B) Return masses



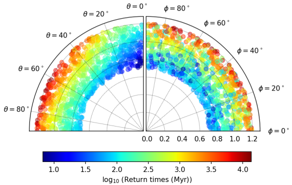
(C) Lyapunov exponent



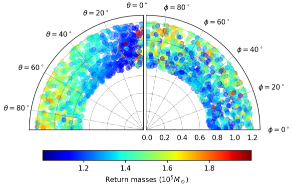
(D) Geometry

Figure: Distribution of the different properties for the galaxy with $a_1 = 1$, $a_2 = 9.6 \times 10^{-1}$, $a_3 = 7.0 \times 10^{-1}$.

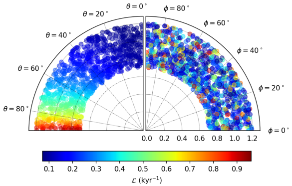
Disc galaxy



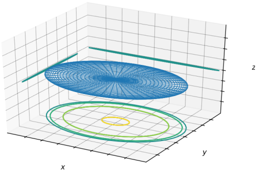
(A) Return times



(B) Return masses



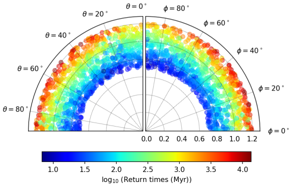
(C) Lyapunov exponent



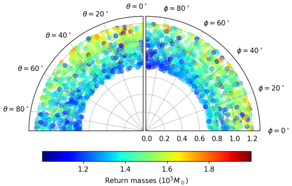
(D) Geometry

Figure: Distribution of the different properties for the galaxy with $a_1 = 1$, $a_2 = 6.9 \times 10^{-1}$, $a_3 = 1.2 \times 10^{-2}$.

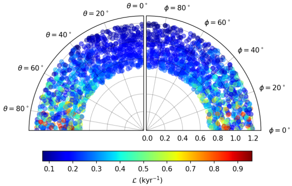
Bar galaxy



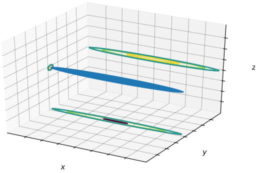
(A) Return times



(B) Return masses



(C) Lyapunov exponent



(D) Geometry

Figure: Distribution of the different properties for the galaxy with $a_1 = 1$, $a_2 = 6.6 \times 10^{-2}$, $a_3 = 6.1 \times 10^{-2}$.

Conclusions

Conclusions

- Including triaxiality in galaxies can shift the predictions from previous spherical studies
  - On average, return times for triaxial studies are 2.6 times longer than those expected in spherical galaxies
  - Masses, on the other hand, show an average increase of 24 %
- Correlation of the return properties (time and mass) has been quantified at 0.63
- The probability of finding a black hole such as the ULAS J1342+0928 quasar in the simulations is 0.34 %
- The baryonic fraction of the galaxy, the power law exponent of the gas profile, and the amount of stars drastically alter the return properties of a black hole

Conclusions

- Lyapunov exponents show that there is a dependency with the magnitude of the initial velocity
- More chaotic orbits are related with the highest potential axis (major semiaxis)

Thank you

References

- Varma, Vijay, Leo C Stein, and Davide Gerosa. "The binary black hole explorer: on-the-fly visualizations of precessing binary black holes". In: *arXiv preprint arXiv:1811.06552* (2018).
- Meier, David L. *Black hole astrophysics: the engine paradigm*. Springer Science & Business Media, 2012.
- Bassan, Massimo. "Advanced interferometers and the search for gravitational waves". In: *Astrophysics and Space Science Library* 404 (2014), pp. 275–290.
- Brügmann, Bernd. "Fundamentals of numerical relativity for gravitational wave sources". In: *Science* 361.6400 (2018), pp. 366–371.
- Hoyng, Peter. "Gravitational waves". In: *Relativistic Astrophysics and Cosmology: A Primer* (2006), pp. 133–154.
- Weber, Joseph. "Gravitational radiation". In: *Physical Review Letters* 18.13 (1967), p. 498.
- Abbott, BP et al. "LIGO: the laser interferometer gravitational-wave observatory". In: *Reports on Progress in Physics* 72.7 (2009), p. 076901.
- Acernese, Fausto et al. "Status of VIRGO". In: *Classical and Quantum Gravity* 25.11 (2008), p. 114045.
- Straumann, Norbert. *General relativity*. Springer Science & Business Media, 2012.