An alternative scenario for Gaia BH3 as a binary black hole-star system

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Abstract: This work is about Gaia BH3, a binary system formed by a 0.76 $M_\odot$ star orbiting a 32.7 $M_\odot$ black hole. The work focuses on evaluate the possibility of having a inner binary system of black holes instead of a single black hole. It has been performed through analytical analysis. We obtained that it cannot be ruled out this possibility and that, if it host a binary system of black holes, we would not be able to detect it with a probability greater than 77%, for coplanar orbits. The method developed in this work may apply to other systems and be thus useful for future discoveries.
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SDGs: 4) Quality education, 8) Economic growth, 9) Innovation and 17) Alliance for goals

I. INTRODUCTION

Stellar black holes (BH) are unique objects in Universe. They are a very compact object as a result of the death of massive stars $M \geq 15M_\odot$. Due to BHs high density, not even light can escape from them. Hence, BHs are elusive objects, very difficult to detect but with some exceptions. Among these, *Dormant BHs* are a peculiar class of BHs that we have been able to discover even in our Galaxy. Dormant BHs are a peculiar type of BHs that are found in binary systems with a companion visible star. These system consist of a star orbiting a BH, but far enough to prevent interactions and accretion of the star on the BH. Because of this, there is no X-ray emission. Dormant BHs are detected by seeing that the visible companion is in orbit with a non-visible object. Hence, high-precision astrometry data is needed. Astrometry is the observational astronomy technique that measures the position and movement of visible astronomical objects. GAIA is the most valuable resource for this task, providing highly accurate astrometric and spectroscopic data. Spectroscopic data allow us to know the distribution of the electromagnetic radiation that comes from a visible object and to know, for example, its metallicity. Also, astrometric data of GAIA is helpful in making clear which region of our Galaxy the dormant BH belongs to. GAIA also provide the metallicity of the system via its visible companion star. One can obtain a robust estimate of the BH mass, infer on the formation mechanism, and know the distance. For computing BH mass two proper motions are needed: from astrometry and from radial velocity with spectroscopy of the star.

Thanks to the satellite GAIA, so far three dormant BHs have been discovered in our Galaxy: Gaia BH1 a 0.93$M_\odot$ star and 9.6$M_\odot$ BH at 480 pc [6], Gaia BH2 a 1$M_\odot$ star and 8.9$M_\odot$ BH at 1160 pc [7] and Gaia BH3 a 0.76$M_\odot$ star orbiting around a 32.7$M_\odot$ BH at 590 pc [3]. In this work we focus on the latest system found, Gaia BH3. The BH in Gaia BH3 is the most massive stellar BH that has been found in our Galaxy and the most massive dormant BH found so far. Similar masses have been found only in extragalactic regions through gravitational waves (GWs). Gaia BH3 is the first system associated with a cluster and found in the halo of the Milky Way where metallicity is generally low; on the contrary Gaia BH1 and BH2 have been found the disk in the field of the Galaxy, in isolation, and in a metal rich environment, not even associated with a cluster [3]. Gaia BH3 is also the first confirmation that such massive BHs are associated with metal-poor stars. Three possible scenarios have been proposed to explain the large mass of Gaia BH3 — a single massive BH, a binary black hole (BBH), or a binary hosting a BH and a compact object. In this work, we will focus on the second scenario.

In section II we present the equations used to learn how the mass of the BH in Gaia BHs are computed and to do the analysis of Gaia BH3 as a triple system. In section III we derive the mathematical relations that allow us to put constrains on the inner BBH. In section IV we present the results of the work and in section V we draw the overall conclusions.

II. BACKGROUND

GAIA compute the function mass (in $M_\odot$) as: [3]

$$f_M = \left(\frac{a_0}{\varpi}\right)^3 \left(\frac{1\,\mathrm{yr}}{P_*}\right)^2 = \frac{|F_1 M_2 - F_2 M_1|^3}{(F_1+F_2)^3 (M_1+M_2)^2} \quad (1)$$

Where a_0 is the angular semi-major axis of photocentre orbit, P_* the period and ϖ the parallax. Index 1/2 is for the most/less bright object. F and M are respectively the photometric flux and mass (in $M_\odot$). The first equality is always valid and the second is for binaries.

When two massive BHs are in close orbit, their orbit shrinks over time due to loss of energy and angular momentum via GW emission. Eventually the system will merge and remain just one BH. Because of this, due to just GW emission, a binary system of two point masses M_1 and $M_2 > M_1$ suffers a change in semi-major axis, a, over time given by: [1]

$$\left\langle \frac{da}{dt} \right\rangle = -\frac{64}{5}\frac{G^3}{c^5}\frac{qM^3}{(1+q)^2}\frac{1+\frac{73}{27}e^2+\frac{37}{96}e^4}{a^3(1-e^2)^{7/2}} \quad (2)$$

Where $q = \frac{M_1}{M_2}$ being the mass ratio, M the total mass, $M = M_1 + M_2$, e is the eccentricity of the orbit, G is the gravitational constant and c is the speed of light. $\langle\rangle$ indicates average value because we don't know the exact position of the two masses at time t.

In a 3-body system, due to the presence of a inner binary of q mass ratio, the outer body undergoes to changes in its radial acceleration seeing as wobbles in its near-keplerian trajectory. For Gaia BBH the visible companion semi-major axis is much bigger than the inner system, $a_{\text{in}} << a_*$. With this condition the perturbative term, δU_{RV} is: [2]

$$\frac{\delta \dot{U}_{\text{RV}}}{3\delta \cdot \Omega_{\text{in}}^2} = -2\sin(\Omega t) + 4\sin(2\Omega_{\text{in}} t) + e_{\text{in}}(-12\sin(\Omega_{\text{in}} t) + 4\sin(3\Omega_{\text{in}} t) + + e_*(-6\sin(2\Omega t) + 16\sin(2\Omega_{\text{in}} t)) \quad (3)$$

Where $\delta = \frac{q/8}{(1+q)^2}\left(\frac{a_{\text{in}}}{a_*}\right)^4 a_{\text{in}}$. $\Omega = \sqrt{\frac{G(M+M_*)}{a_*^3}}$ and $\Omega_{\text{in}} = \sqrt{\frac{GM}{a_{\text{in}}^3}}$ are respectively the frequency of the outer star and inner binary. Note $\Omega_{\text{in}} >> \Omega$ since $a_{\text{in}} << a_*$. This is assumed in expression (3). Also, e_{in} and e_* are, respectively the eccentricity of the inner binary and the visible star. $\delta \dot{U}_{\text{RV}}$ expression if for coplanar orbits. For inner and outer circular orbits but mutually inclined, the perturbative term on acceleration, $\delta \dot{W}_{\text{RV}}$, is: [2]

$$\frac{4\delta \dot{W}_{\text{RV}}}{3\delta \cdot \Omega_{\text{in}}^2} = 2(3 - 7\cos^2 i)\sin(\Omega t) + - 10\sin(3\Omega t)(1-\cos^2 i) + + 4\sin(2\Omega_{\text{in}} t)[(1+\cos i)^2 - (1-\cos i)^2] \quad (4)$$

Where i is the inclination angle between inner and outer orbit. Both (4) and (3) short-period velocity variations are detectable with high resolution and are a sign of a inner binary system.

For mutually inclined orbits $i \neq 0$, inner binary can also be noticed through the changes in inclination due to precession of the orbital plane of the outer star, the nodal precession effect. This are long-term variations on visible companion velocity. Using [11] expressions for the case $I_{\text{los}} = \pi/2$ (line of sight) for simplicity, the difference of maximum and minimum velocity semi amplitudes, Δ, is:

$$\Delta = V_0(1 - |\cos(\bar{i})|) \quad (5)$$

Where, $\bar{i} = \tan^{-1}\left(\frac{\xi \sin(i)}{1+\xi\cos(i)}\right)$ and ξ is:

$$\xi = \frac{q}{(1+q)^2}\frac{M}{M_*}\sqrt{\frac{1-e_{\text{in}}^2}{1-e_*^2}}\left(\frac{P_{\text{in}}}{P_*}\left(1+\frac{M_*}{M}\right)\right)^{1/3} \quad (6)$$

Where P_* and P_{in} are, respectively, the period of the star and the inner BBH. $P_{\text{in}} = \sqrt{\frac{GM}{4\pi^2 a_{\text{in}}^3}}$. M_* is star mass and

$$V_0 = \frac{1}{\sqrt{1-e_{\text{out}}^2}}\left(\frac{2\pi G M^3}{(M+M_*)^2 P_*}\right)^{1/3} \quad (7)$$

The change of outer star velocity due to nodal precession is the relevant one in moderately inclined systems, $i < 50°$. The period of this variations are: [11]

$$P_\Omega = \frac{4q^3 P_*}{3(1+q)^6}\left(\frac{M}{M_*}\right)^2\left(1+\frac{M}{M_*}\right)^2 \cdot \cdot \frac{(1-e_{\text{in}}^2)^2}{\xi^3\cos(i_{\text{mut}})} \cdot \frac{1}{\sqrt{1+2\xi\cos(i_{\text{mut}})+\xi^2}} \quad (8)$$

The relevant long-term velocity variation in high-inclined triples, $i > 50°$, are ZKL oscillations. This oscillations refers to the eccentricity and inclination variations in triple systems. The time-scale of this variations are: [11]

$$\frac{T_{\text{ZKL}}}{P_*} = \frac{P_*}{P_{\text{in}}}\left(1+\frac{M}{M_*}\right) \quad (9)$$

Since ZKL oscillations are chaotic, there is no expression such as (5) to check for hidden binary inclination [11].

The stability condition of a 3-body system with mutually inclined orbits is: [11]

$$a_{\text{in}} < \frac{a_*/2.8}{1-0.3\frac{i}{180°}}\left[\left(1+\frac{M_*}{M}\right)\frac{1+e_*}{(1-e_*)^3}\right]^{-2/5} \quad (10)$$

Where i is in degrees. Note that it is valid for any value of the inner binary eccentricity, e_{in}, does not depend on q but on the total mass of the inner binary, M and that a_{in} maximum value is monotonically increasing with i.

To compute the fraction of expected BBH in Gaia BH3 we will use two different probability distributions of the number, N, of binary systems in our Universe. In literature the semi-major axis distribution of binaries in our Universe is $\sim a^{-n}$. From dynamics studies is seen that the number of binaries is uniform in energy of the binary, E. Since $E \propto a^{-1}$ it's suggested $n = 2$: [12]

$$\frac{dN}{dE} \sim \text{constant} \Longrightarrow \frac{dN}{da} \propto \frac{1}{a^2} \quad (11)$$

While observational data (Öpik's law) suggest $n = 1$ [13]:

$$\frac{dN}{da} \propto \frac{1}{a} \quad (12)$$

III. METHOD TO FIND A HIDDEN BBH

In this section we show that when computing BH mass there is no constrain on the number of BHs in Gaia BH3. Because of this, we show a methodology to find which hidden BBH could Gaia BH3 host. As the one

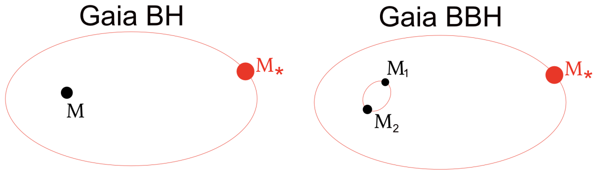

FIG. 1: Gaia BBH system with coplanar orbits, $i = 0°$, (right) compared to Gaia BH system (left). The visible star is represented in red circle and BHs in dark dots. Objects are indicated with its mass and ellipses are its trajectories.

		Single BH	**Binary BH**
star	a_* (AU)	16,17	16,17
	e_*	0,729	0,729
	M_* ($M_\odot$)	0,76	0,76
BH	$a_{\rm in}$ (AU)	∄	unkown
	$e_{\rm in}$	∄	unkown
	M ($M_\odot$)	32,7	$M_1 + M_2 = 32,7$

TABLE I: Basic orbital parameters and masses of the Gaia BH3 system as a single BH and as a binary BH. The orbital parameters of the visible star are the same in both systems. We do not consider uncertainties because doesn't have such impact in our purpose. *A priori* we do not have any information related to orbital parameters of the inner BBH. The sum of masses on BBH is the one from the single BH in Gaia BH (as explained in Section III A). The numerical values are from [3].

shown in Figure 1 and also mutually inclined orbits.

To compute the mass of a BH in a Gaia BH we adapt expression (1) for dormant BHs and we get:

$$f_M = M\left(1 + \frac{M_*}{M}\right)^{-2} \tag{13}$$

Because in dormant BHs $F_{BH} = 0$. From GAIA astrometric data of Gaia BH3 [3] (no uncertainties): $P_* = 4194.7$ days, $\varpi = 1.6747$ mas and $a_0 = 27.07$ mas. This results in a mass function of $f_M = 32.03$ $M_\odot$ using expression (1). Using the above expression this results in a BH of $M = 32.7$ $M_\odot$ BH. Recall $M_* = 0,76$ $M_\odot$. Note that this method is valid for inner binary, tertiary, quadruple, etc system of BHs. In this cases M would be sum of the BH masses. Therefore, there is no constrain on the number of BHs innit. Hence, could host a BBH.

From know on we present the conditions that must satisfy the inner BBH in Gaia BH3 in order to exist but not be detectable. We use four criteria:

Since we are looking for a BBH, we have to avoid those which that have merged and are now a single BH. To determine the timescale decay of the inner binary system of mass ratio q due to GW radiation leading to collapse, that is $T = \frac{a(e)}{\langle \dot{a}(e)\rangle}$, we use (2) and we obtain:

$$T = \frac{a(e)^4}{\beta(q)} f(e) \rightarrow a(e) = \left(\frac{\beta(q)T}{f(e)}\right)^{1/4} \tag{14}$$

Where $f(e) = \frac{(1-e^2)^{7/2}}{1+\frac{73}{27}e^2+\frac{37}{96}e^4}$ and $\beta(q) = \frac{64}{5}\frac{G^3}{c^5}\frac{qM^3}{(1+q)^2}$. q and T are our free-parameters since M is well-known. For values of semi-major axis lower than the above expression the binary has merged and therefore is a single BH from a merger.

A inner BBH can be hidden from observational data if the short-term velocity variations are smaller than the resolution. We assume that when at least the maximum value of this perturbations, $\delta V_{\rm RV}$, are $\approx 2\delta V_{\rm res}$, twice the resolution of the instrument used, it can be noticed a difference from a keplerian orbit. And therefore, a sign of a inner binary system. In (3) and (4) we have presented this pertubations with eccentricity, $\delta \dot{U}_{\rm RV}(e_{\rm in}, e_*)$, and inclination, $\delta \dot{W}_{\rm RV}(i)$, dependence separated. To unify this dependence, we will use as the total velocity pertubations on eccentric and inclined triple system the following:

$$\delta V_{\rm RV} \approx \delta U_{\rm RV}(e_{\rm in}, e_*) + \delta W_{\rm RV}(i) - \delta W_{\rm RV}(i = 0°) \tag{15}$$

To find $\max(\delta V_{\rm RV}) \equiv \delta\bar{V}$, we integrate the above expression, find the maximum and obtain:

$$\begin{aligned}\frac{4\delta\bar{V}}{3\Omega_{\rm in}^2\delta} &= 4\frac{32e_{\rm in}}{3} + 4e_*\left(\frac{3}{\Omega} - \frac{8}{\Omega_{\rm in}}\right) \\ &- \frac{2(3-7\cos^2 i)}{\Omega} + \frac{10}{3\Omega}(1-\cos^2 i) + \\ &+ \frac{2}{\Omega_{\rm in}}[(1+\cos i)^2 - (1-\cos i)^2]\end{aligned} \tag{16}$$

The constant of integration is 0 because we put the initial condition on $\delta V_{\rm RV}(t^*)$, where t^* is the time that allows the constant to be 0. Applying $\Omega_{\rm in} >> \Omega$, entering the assumed condition $\delta\bar{V} = 2\delta V_{\rm res}$ and isolating $e_{\rm in}$ we have:

$$e_{\rm in} = \frac{3\Omega_{\rm in}}{128}\left(\frac{4\cdot 2\delta V_{\rm res}}{3\Omega_{\rm in}^2\delta} - \frac{12e_*}{\Omega} + \frac{8-32\cos^2 i}{3\Omega}\right) \tag{17}$$

Recall $\Omega_{\rm in}$ has $a_{\rm in}$-dependence. q and $\delta V_{\rm res}$ are our free-parameters. We will use a uncertainty of $\delta V_{\rm res} = 10$m/s.

For resolution criteria on velocity variations due to nodal precession we will also assume that when this variations are $\approx 2\delta V_{\rm res2}$ ($\neq 2\delta V_{\rm res}$) the inner binary is detectable. When computing the value of V_0 from (7) expression with Gaia BH3 data it is seen that $V_0 = 68,2$ km/s, which is much bigger than standard velocity uncertainties. So, putting the assumed condition, $2\delta V_{\rm res} = \Delta$, and using the approximation that $\delta V_{\rm res2}/V_0 << 1$ we isolate ξ from (5) and we obtain:

$$\xi^{-1} = \sin(i)\cdot\left(\frac{V_0}{2\delta V_{\rm res}}\right)^{1/2} - \cos(i) \tag{18}$$

By isolating $a_{\rm in}$ from ξ expression in (6) we obtain:

$$a_{\rm in} = \xi^2\left(\frac{GM^2P_*}{4\pi^2(M+M_*)}\right)^{1/3}\left(\frac{(1+q)^2}{qM/M_*}\right)^2\frac{1-e_*^2}{1-e_{\rm in}^2} \tag{19}$$

Where q, i and $\delta V_{\rm res2}$ are our free-parameters. Now we will use a uncertainty of $\delta V_{\rm res2} = 100$ m/s. Because since long data collection is needed (as we will explain) maybe not the best instruments can be used for this purpose. We analyze the $i = 7°$ case since stronger inclinations than that will not cause any problem to be detected with enough long time data collection.

Finally, the triple system needs to be stable in order to exist. For stability criteria we use expression (10) with Table I data. For Gaia BH3 we obtain that the inner BBH semi-major axis needs to be less than: $a^{\rm max}_{\rm cop} = 0,956\,$AU and $a^{\rm max}_{90} = 1,128\,$AU for coplanar orbits and $i = 90°$ orbits, respectively.

IV. RESULTS

Fig. 2 shows for which semi-major axis and eccentricity we can hide a BBH in Gaia BH3 assuming expression (14) for GW merging, expression (17) for data resolution, expression (10) for stability of the triple system and expression (19) for data resolution for nodal precession.

In Fig. 2 the grey area is where the system would have merged because of GW emission, within T=10 Gyr. Hence, we don't have a inner BBH, we have a single BH. The white region on $q = 1$ is the $a_{\rm in}$ and $e_{\rm in}$ combination that make inner BBH detectable, for $i = 0°$. The red region is where the triple system would be unstable, for $i = 0°$ and $i = 90°$. The green region is the main result of our work, is where the system is: stable, not spiralling in (in 10 Gyr) and not detectable due to short-term variations. This region is the combination of semi-major axis and eccentricity of the inner BBH that are compatible with Gaia BH3 observations. Specifically, the green area on Fig. 2 is for coplanar orbits. Purple line is the maximum value that $i = 90°$ system can have and not be detected. Therefore, all values above this line define the undetectable area for $i = 90°$.
We can see that $q = 1$ is easy to detect than $q = 0.1$, as expected. The latter is undetectable with this resolution for any value of its eccentricity, semi-major axis and inclination. To have at least one detectable system, resolution needs to be less than 2.5m/s ($i = 0°$).

Purple line on Fig. 2 is above the green area. Because of this, the undetectable area for $i = 90°$ is bigger than the $i = 0°$ area. From this, we see that the more mutually inclined the inner BBH and the outer star are, the bigger the undetectable area. That means, inclined systems are more complicated to be detected with short-term perturbations on velocity of the outer star.

For $q = 0.1$ inclinations of $i < 11°$ can be hidden for nodal precession analysis in 100 m/s resolution during the needed timescale analysis. When $i \geq 11°$ inner BBH is completely detectable for 100 m/s resolution. For 10 m/s resolution (the other one used) there is no

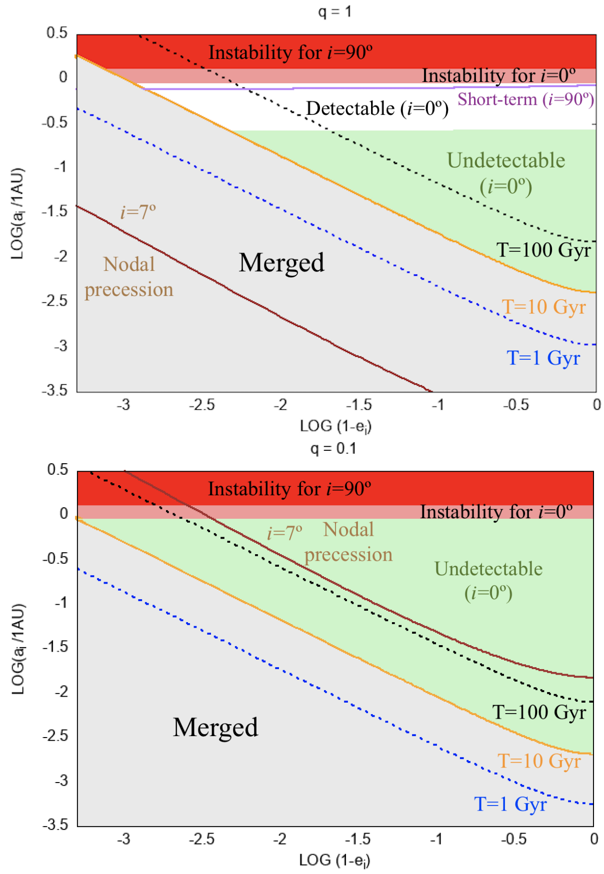

FIG. 2: $\log_{10}$ of initial semi-major axis of the inner binary orbit (in AU) as function of function of the eccentricity, for $q = 1$ (top) and $q = 0.1$ (bottom). With $\delta V_{\rm res} = 10$ m/s and $\delta V_{\rm res2} = 100$ m/s. The red areas are the instability criteria $\log(a) > \log(a^{\rm max}_{\rm cop}) = -0.042$ for coplanar orbits (transparent red) and $\log(a) > \log(a^{\rm max}_{90}) = 0.052$ for $i_{\rm mut} = 90°$ orbits (solid red). The blue, orange and black lines are the relation (14) for the three timescales that appear near to each line. The grey area is the area above T=10 Gyr line. The green area consist on values below the short term velocity variations criteria (17), for the case $i = 0°$, but above $T = 10$ Gyr line. The brown line is the long term velocity variations criteria due to nodal precesion, for $i_{\rm mut} = 7°$. And the pruple line is the short term velocity variations criteria (17) for $i = 90°$.

inclination that can be hidden. In $q = 1$ even with 100 m/s resolution and low inclination, cannot be hidden.

Green area on Fig. 2 has always inclination degeneracy, since $\forall i \geq 0°$ this region is undetectable. Because of this, the best option to break the degeneracy is by looking at nodal precession effect (for $i < 50°$) or ZKL oscillations (for $i > 50°$). Both cases with good enough resolution and long duration data collection will not be such a trouble to detect it. With expression (9) we compute the needed timescale of this data in order to see ZKL oscillations. For Gaia BH3 in the green area we obtain $T_{\rm ZKL} \in [0.028, 370]\,$Myr. Which is extremely large. For nodal precession on $i = 11°$, is: $P_\Omega = 662,24\,\mathrm{Myr}\cdot\frac{q^3(1-e_{\rm in}^2)^2}{(1+q)^6}$. Recall that increases with inclination, see (8) & (6). Also extremely large. Because of this extreme large time needed, Fig. 2 can be used in similar to Gaia BH3 systems to establish a lower limit on the mutual inclination of the inner BBH with the star. For example, if we apply this method to another Gaia BH system and we find out it has no green area (it is below the merged area). We can find the first inclination that appears to have a undetectable area and establish this as lower limit on inclination.

To compute the fraction of expected binaries in the undetectable region, we procedure as follows. For $q = 1$ and $e_{\rm in} = 0$, BBH is undetectable at $a_{\rm in} \in [0.0033, 0.266]$ AU but detectable at $a_{\rm in} \in [0.266, 0.956]$ AU. Knowing this and using dynamics (11) and Öpik's (12) distributions we obtain the following fractions:

$$f^{\rm dynamics} = \frac{\int_{0.0033\,\rm AU}^{0.266\,\rm AU} a^{-2}\,da}{\int_{0.0033\,\rm AU}^{0.956\,\rm AU} a^{-2}\,da} = 0.991 \tag{20}$$

$$f^{\rm \ddot{O}pik} = \frac{\int_{0.0033\,\rm AU}^{0.266\,\rm AU} a^{-1}\,da}{\int_{0.0033\,\rm AU}^{0.956\,\rm AU} a^{-1}\,da} = 0.774 \tag{21}$$

Therefore, if Gaia BH3 have a inner BBH both distributions suggest that the most likely semi-major axis values are the ones in the green area of Figure 2. This value will be lower for $e_{\rm in} > 0$ because the number of undetectable BBH systems decreases with $e_{\rm in}$ as one can see in Figure 2. And also dynamics distribution on eccentricity is skewed to high e, $dN/de \sim e$ [12].

V. CONCLUSIONS

We studied the possibility that Gaia BH3 host a inner BBH through analytical analysis of the system. Our main finding are summarized below:

- It cannot be discarded that Gaia BH3 is actually the first Gaia BBH system, the Gaia BBH1. Because for $q = 1$ and $q = 0.1$ we have obtained many compatible hidden BBH. Also, $q = 1$ expected binaries fraction tell us that for low eccentricities we have high probabilities to not be able to find the inner BBH. For $q = 0.1$ the probability is 100%.

- Since $q = 1$ and $i = 0°$ are, respectively, the easiest mass distribution and inclination to detect, we can say that if Gaia BH3 has a inner coplanar BBH, we will not detect it with a probability $\geq 77,4\%$ with Öpik's distribution and $\geq 99,4\%$ with dynamics semi-major axis distribution. With $\delta V_{\rm res} = 10\,\mathrm{m/s}$.

Although we just have worked with Gaia BH3, the described method is very useful for future high-mass Gaia BHs discoveries to check quickly if it's possible/plausible to have a hidden inner BBH instead of a single BH, as a first order. Later, to say it with certainty, a more detailed and complete analysis is needed, like the ones described in [2], [8], [9], [10], [11].

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Un escenari alternatiu per a Gaia BH3 com un sistema terciari d'una estrella i dos forats negres

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Resum: Aquest treball és sobre Gaia BH3, un sistema binari format per una estrella de 0.76 $M_\odot$ orbitant un forat negre de 32.7 $M_\odot$. El treball se centra en avaluar la possibilitat de tenir un sistema binari de forats negres en comptes d'un sol forat negre. S'ha fet mitjançant una anàlisi analítica. Hem obtingut que aquesta possibilitat no pot ser descartada i que, en cas que s'hi allotgi un sistema binari de forats negres, no el podríem detectar amb una probabilitat superior a 77% per a òrbites coplanars. El mètode desenvolupat en aquest treball es pot aplicar a altres sistemes i ser útil per futurs descobriments.
Paraules clau: forats negres latents - funció massa - Gaia BBHs - fusió gravitatòria - sistema de tres cossos - llei d'Öpik
ODSs: Aquest TFG està relacionat amb els Objectius de Desenvolupament Sostenible (SDGs)

Objectius de Desenvolupament Sostenible (ODSs o SDGs)

1. Fi de la es desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	
3. Salut i benestar		12. Consum i producció responsables	
4. Educació de qualitat	X	13. Acció climàtica	
5. Igualtat de gènere		14. Vida submarina	
6. Aigua neta i sanejament		15. Vida terrestre	
7. Energia neta i sostenible		16. Pau, justícia i institucions sòlides	
8. Treball digne i creixement econòmic	X	17. Aliança pels objectius	X
9. Indústria, innovació, infraestructures	X		

El contingut d'aquest TFG, part del grau universitari de Física a la Universitat de Barcelona, es relaciona amb l'ODS 4, i en particular amb la fita 4.4, ja que contribueix a l'educació en l'àmbit universitari. També es relaciona amb l'ODS 9, perquè en aquest treball es presenten eines matemàtiques i físiques que poden contribuir a innovacions dins del camp de l'astrofísica. Addicionalment es relaciona amb l'ODS 8, i en particular amb la fita 8.2, perquè un objectiu d'aquest treball és estalviar temps d'observació; valorar si val la pena recollir més dades sobre un sistema i emprar el temps guanyat a altres observacions més prioritàries. Contribuint d'aquesta manera a una major productivitat científica i econòmica. Finalment, també es relaciona amb l'ODS 17, ja que amb aquest treball es busca millorar la comprensió científica i també es busca desenvolupar la capacitat científica del redactor i dels lectors. l'ODS 17 també es relaciona amb aquest treball perquè hem col·laborat mútuament amb la Clàudia García Diago i el seu TFG titulat *The origin of Gaia BH3 in the progenitor cluster of ED-2 stream*, tutoritzat per Daniel Marín Pina, Sara Rastello i Mark Gieles. Ambdós ens hem dedicat a investigar sobre el Gaia BH3 des de perspectives diferents i la col·laboració ens ha sigut molt profitosa per desenvolupar millor els nostres treballs.