

# JACOBI CAPTURES : A FIRST STEP IN THE FORMATION OF OFF-CENTERED MASSIVE BLACK HOLE BINARIES IN DWARF GALAXIES

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**Abstract.** The discovery of early-time supermassive black holes by JWST has rekindled interest in black hole mass assembly. Additionally, simulations and observations suggest a substantial population of off-centered intermediate-mass black holes in dwarf galaxies, potentially impacting black hole mass assembly, provided their capacity to merge beyond galactic cores. This study examines off-centered black hole dynamics in dwarf galaxies with cored dark matter haloes which can lead to long infall times and core stalling. By integrating off-centered black holes into the gravitational potential of a dwarf galaxy and exploring the phase space of initial conditions, we quantify the number of captures, which are a crucial step in off-center black hole mergers. Our analysis indicates captures in about 11% of cases. Such captures could be maintained over time within structures such as stripped nuclei or globular clusters.

Keywords: black hole physics - galaxies: dwarf - galaxies: kinematics and dynamics - software: simulations.

## 1 Introduction

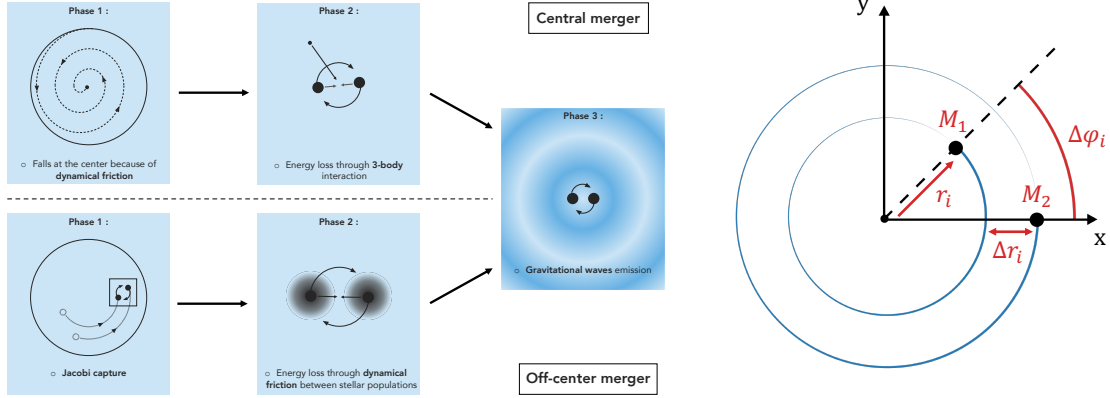
Over the last decades, black holes have been discovered at the centers of both massive and dwarf galaxies, suggesting a shared history between them and their hosts (e.g., Gebhardt et al. 2000; Reines et al. 2013). The conventional picture of black hole mergers involves a three-phase process starting by their infall towards the galaxy center due to dynamical friction (cf. top panel of Fig. 1). However, this picture may not hold in low-density systems like dwarf galaxies, where the infall time can significantly exceed the Hubble time or black holes may be halted by core stalling (Kaur & Sridhar 2018; Banik & van den Bosch 2021), which would result in a large population of off-centered intermediate mass black holes (Bellovary et al. 2019, 2021; Pfister et al. 2019; Reines et al. 2020). Hence, it is essential to inquire whether merging beyond the central region is possible, as this could bear notable consequences for the assembly of black hole mass. We investigate the first anticipated step of this process: the Jacobi capture, namely the capture between the two black holes when they enter their sphere of influence (cf. lower panel of Fig. 1, and Francois et al. in prep., for more details). In this effect, we integrate two off-centered black holes in a dwarf galaxy gravitational potential. Our study aims to provide simplified yet general insights applicable to various scenarios, paving the way for more complex simulations.

## 2 Method

We use a simplified setup where we integrate two black holes on coplanar circular orbits in an external gravitational potential representing the dark matter halo of a dwarf galaxy. We explore the 5-parameter space of the encounter (cf. Fig. 1 right) to quantify the occurrences of capture, investigating how the different parameters affect this process. We then focus on core stalling as the cause for off-centering, reducing the parameters to 3 ( $M_1, M_2, \Delta\varphi_i$ ). Subsequently, we employed a semi-analytical model to generate merger trees (Jiang et al. 2021), yielding a representative sample of black hole masses which enables us to derive a merger probability in the case of black holes stemming from major mergers.

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**Fig. 1. Left:** Top panel: classical black holes merger scenario in the galactic centre. Bottom panel: anticipated scenario for an off-center merger. **Right:** Parameters of an initial configuration :  $r_i$  the initial radius of the inner BH,  $\Delta r_i$  the radial separation between BHs,  $\Delta \varphi_i$  the phase difference and  $M_1, M_2$  the two masses.

### 3 Results

The general 5-parameter case highlights a preference for capture when the outer black hole surpasses the inner one in mass. We find bonding bands in terms of initial separation between the orbits ( $\Delta r_i$ ); below these bands (small radial separation between black holes), either initial proximity enables binding, or insufficient orbital frequency difference hinders the catch-up with the initial phase difference, preventing binding. Conversely, beyond these bands (associated with larger radial separations), the black holes remain too distant for binding. Core stalling typically places the BHs at very close radii, namely in the regime of small radial separations, where BHs bind when their initial separation is small enough. This results in a moderate mass disparity (closely matched masses are synonymous with closely matched stalling radii) and a low phase difference. Subsequently, using merger trees to sample masses, we derived a capture probability of 11% when BHs stem from major mergers.

### 4 Conclusions

In this study, we explored the possibility for black holes to merge outside galactic centers in dwarf galaxies. Using an idealized setup, we quantified the probability of Jacobi capture, a fundamental step in forming an off-centered binary and examined the effects of various parameters. We find that capture occurs in about 11% of cases. This result carries significant implications for the assembly of black hole masses, especially if these captures can be prolonged over time through dissipative forces. Further investigations into the effectiveness of these forces, particularly within stripped nuclei or globular clusters, are warranted. These findings shed light on the importance of captures in these environments and are perhaps an important step in the ongoing quest to understand the origins and growth of black holes in the Universe.

### References

- Banik, U. & van den Bosch, F. C. 2021, ApJ, 912, 43  
 Bellovary, J. M., Cleary, C. E., Munshi, F., et al. 2019, MNRAS, 482, 2913  
 Bellovary, J. M., Hayoune, S., Chafra, K., et al. 2021, MNRAS, 505, 5129  
 Francois, T. L., Boily, C., Freundlich, J., et al. in prep.  
 Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJ, 539, L13  
 Jiang, F., Dekel, A., Freundlich, J., et al. 2021, MNRAS, 502, 621  
 Kaur, K. & Sridhar, S. 2018, ApJ, 868, 134  
 Pfister, H., Volonteri, M., Dubois, Y., Dotti, M., & Colpi, M. 2019, MNRAS, 486, 101  
 Reines, A. E., Condon, J. J., Darling, J., & Greene, J. E. 2020, ApJ, 888, 36  
 Reines, A. E., Greene, J. E., & Geha, M. 2013, ApJ, 775, 116