# The Stochastic Evolution of Supermassive Black Hole Binaries in Galaxy Mergers

Leevi Mänttäri

22.04.2026

The coalescence of supermassive black hole (SMBH) binaries in galaxy mergers is the primary source of gravitational waves (GWs) at low frequencies. The complex nature of SMBH coalescence requires numerical methods to make quantitative predictions for current and future observational programmes, such as Pulsar Timing Arrays (PTAs) and Laser Interferometer Space Antenna (LISA). Because the eccentricity ($e$) of the SMBH binary significantly affects both the merger timescale and the emitted GW spectrum, it is important to understand how accurately it is captured in numerical simulations when predicting and interpreting GW observations.

Following Rawlings et al. (2023), we study SMBH binary eccentricity in equal-mass galaxy mergers in $N$–body simulations with the KETJU code, which combines the GADGET-4 fast multipole gravity solver with accurate regularized integration and post-Newtonian corrections around SMBHs. Our simulations model idealized galaxy mergers with no gas and no dark matter, in which stochasticity in SMBH binary merger orbits is primarily caused by finite resolution effects that are inversely proportional to the square root of the total number of particles. Nasim et al. (2020) argued that the scatter in SMBH binary eccentricity is due to poor resolution, implying that with sufficient numerical resolution the eccentricity would become a reliably predictable quantity. However, we find that in simulations with realistic, high-eccentricity merger orbits, the binary eccentricity is a non-linear function of the deflection angle in the SMBH orbit during the nearly radial close encounter between the SMBHs before they form a bound binary. This mapping appears to be independent of particle resolution in our simulations, with resolutions ranging from $1 \times 10^5$ to $8 \times 10^6$ particles per galaxy. In these high-eccentricity major merger configurations, the non-linear mapping is sensitive to small perturbations in the merger orbit, producing binary eccentricities that span almost the full range from $e = 0$ to $e = 1$.

In low-eccentricity merger configurations, the lack of radial close encounter between the SMBHs before they form a bound binary leads to less scatter, and in this case the stochasticity is mainly due to the finite resolution effects and decreases with increasing number of stellar particles. In real galaxies, perturbations from gas and substructure in the merger orbit are likely to be large enough for the binary eccentricity to be effectively random. Our results show that the scatter in SMBH binary eccentricity arises from physical sensitivity to small perturbations in the final radial plunging trajectory of the SMBHs before becoming bound. At least in the equal-mass case, the stochasticity of the binary eccentricity is therefore an unavoidable physical feature of realistic galaxy mergers. Thus, rather than giving an exact prediction for the SMBH binary eccentricity in a given merger, we must focus on predicting the distribution of eccentricities possible for a given merger configuration.

# References

Rawlings, A., M. Mannerkoski, P. H. Johansson, and T. Naab (Dec. 2023). "Reviving stochasticity: uncertainty in SMBH binary eccentricity is unavoidable". In: *Monthly Notices of the Royal Astronomical Society* 526.2, pp. 2688–2695. DOI: 10.1093/mnras/stad2891. arXiv: 2307.08756 [astro-ph.GA].

Nasim, I., A. Gualandris, J. Read, W. Dehnen, M. Delorme, and F. Antonini (July 2020). "Defeating stochasticity: coalescence time-scales of massive black holes in galaxy mergers". In: *Monthly Notices of the Royal Astronomical Society* 497.1, pp. 739–746. ISSN: 1365-2966. DOI: 10.1093/mnras/staa1896. URL: http://dx.doi.org/10.1093/mnras/staa1896.