Footprints of celestial mechanics in N-body dynamics of galactic nuclei

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Introduction

Direct N-body modelling is a straightforward and versatile method to study the stellar dynamics in dense environments of galactic nuclei. On the other hand, the N-body problem exhibits chaotic behaviour and the calculations are heavily affected by round-off errors and time discretisation. As a result, the numerically obtained solutions of the equations of motion may be significantly different from the true ones (e.g., Boekholt & Portegies Zwart 2015). It is thus crucial to *understand why* the obtained results look in the way they do. Here, we demonstrate how the methods of celestial mechanics can provide insights for systems that show a certain degree of hierarchy in their configuration, such as the galactic nuclei.

Dynamical coupling of Keplerian orbits

The centre of our Galaxy hosts a number of young stars at distances $0.03\ \mathrm{pc} \lesssim r \lesssim 0.5\ \mathrm{pc}$ from the central supermassive black hole (SMBH). A significant subset of them apparently form a coherently rotating disc-like structure, the clockwise system (CWS; e.g., Levin & Beloborodov 2003, Yelda et al. 2014), while the rest is scattered more or less randomly around it. Observations also reveal a massive gaseous torus, the circumnuclear disc (CND; Christopher et al. 2005), with a characteristic radius of $\approx 2\ \mathrm{pc}$ that seems to be roughly perpendicular to the CWS (Paumard et al. 2006). Numerical N-body modelling of the dynamical evolution of the CWS under the perturbative influence of the CND (Haas et al. 2011a) shows that the inner, denser, part of the CWS tends to gradually change its orientation towards highly inclined with respect to the CND, keeping its coherence (see Fig. 1). On the other hand, the outskirts of the CWS are disrupted by the differential precession of the orbits. This behaviour can be understood by means of a simplified semi-analytical model (Haas et al. 2011b) that consists of two mutually interacting bodies on circular orbits around the SMBH and a distant source of axisymmetric gravitational potential (CND). It turns out that the interaction can be either strong with a synchronous precession of their orbits (Fig. 2, left) or weak, in which case the precession is independent (Fig. 2, right). In both cases, however, inclination of the inner orbit (red lines) increases.

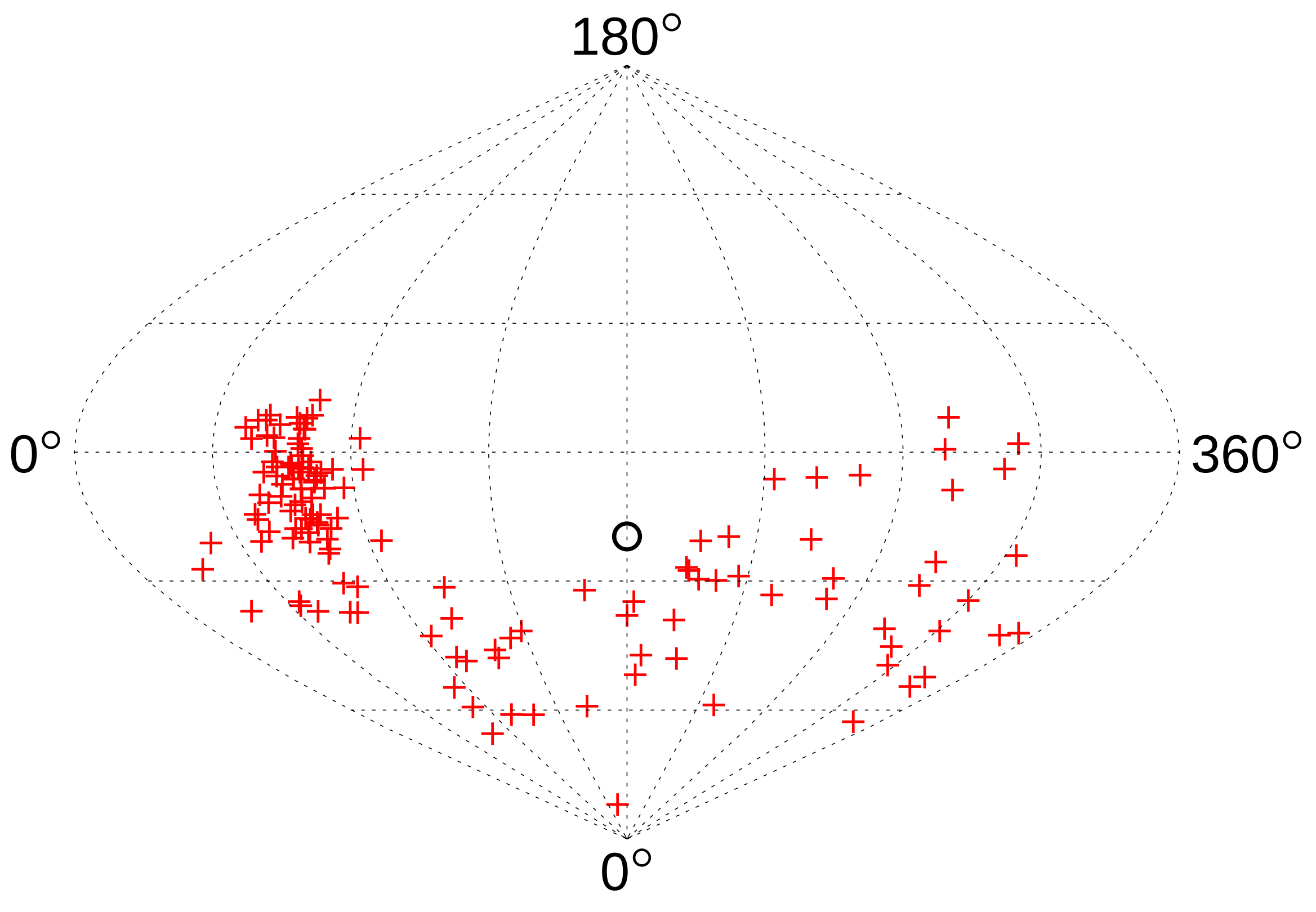

Figure 1: Normal vectors of individual orbits of the most massive stars in the N-body model of the CWS. Empty circle denotes the initial state, reference plane is the CND.

A generalisation of this model for a larger number of orbits reveals that some of them may dynamically couple together due to their strong interaction, effectively acting as a single super-orbit in the interaction with the rest of the system. In the N-body model, such a strongly bound group forms in the inner parts of the CWS, only weakly interacting with the outskirts.

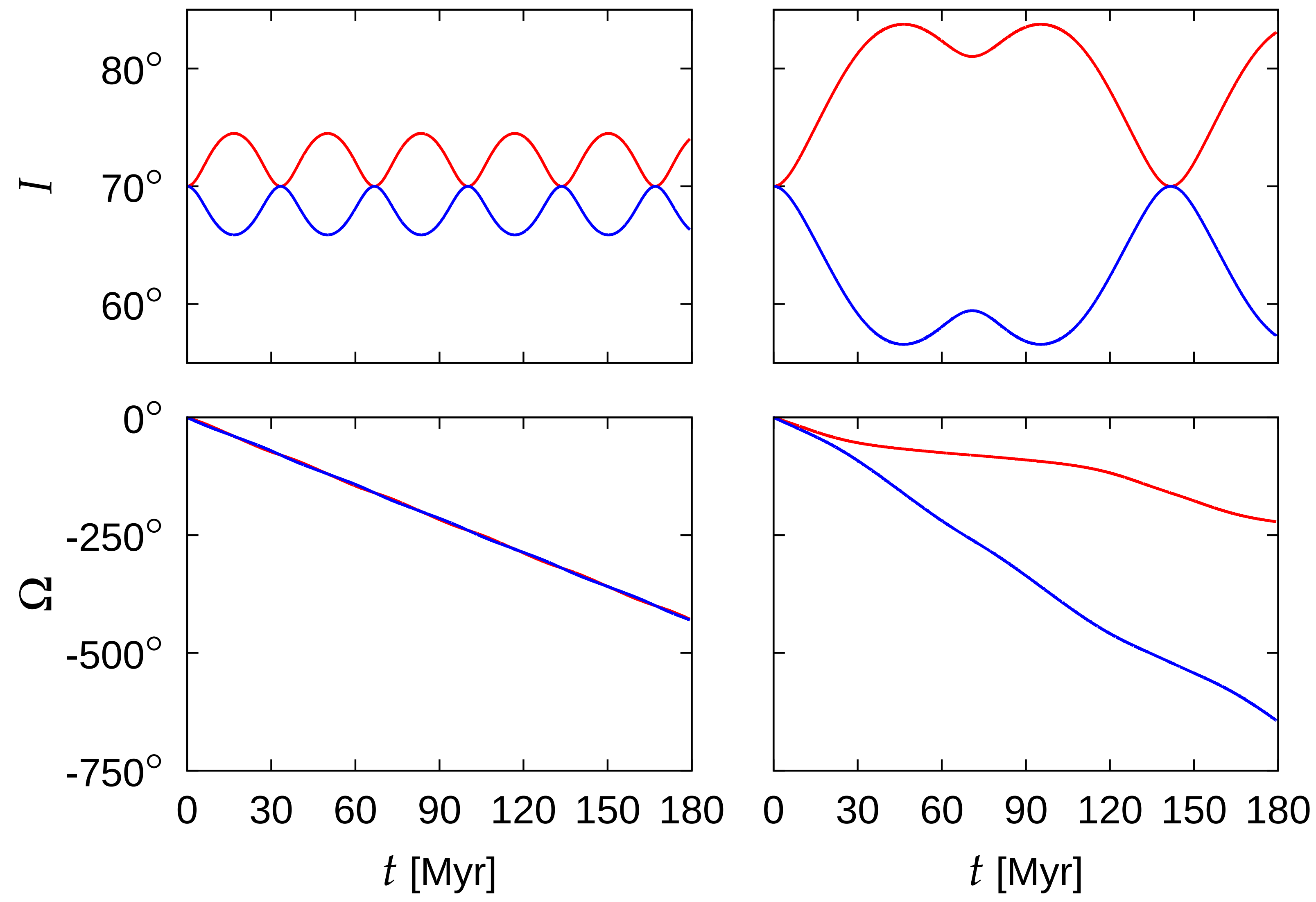

Figure 2: Evolution of inclination I and nodal longitude Ω in the semi-analytical model.

Kozai-Lidov dynamics

In another approximation, when the CND is neglected and the CWS is considered to be initially eccentric, its N-body modelling shows that a significant number of the stars are brought very close to the SMBH (Madigan et al. 2009). A more detailed analysis reveals that this is due to the secular evolution of their orbits in the eccentric gravitational potential of the CWS itself (Haas & Šubr 2016). An example of such an orbit is shown in Fig. 3. In this particular case, the orbit undergoes the so-called coplanar flip during which its eccentricity reaches values $e \to 1$. This phenomenon was discovered by Li et al. (2014) and represents a higher-order effect in the secular evolution of the inner binary in the hierarchical three-body problem if the orbit of the outer binary is eccentric (eccentric Kozai-Lidov cycles). Note that Kozai-Lidov dynamics within an eccentric disc that is embedded in an additional spherical potential is responsible for the oscillations of eccentricity observed in the N-body calculations of Madigan et al. (2009) who misinterpreted them as footprints of a so-called eccentric instability.

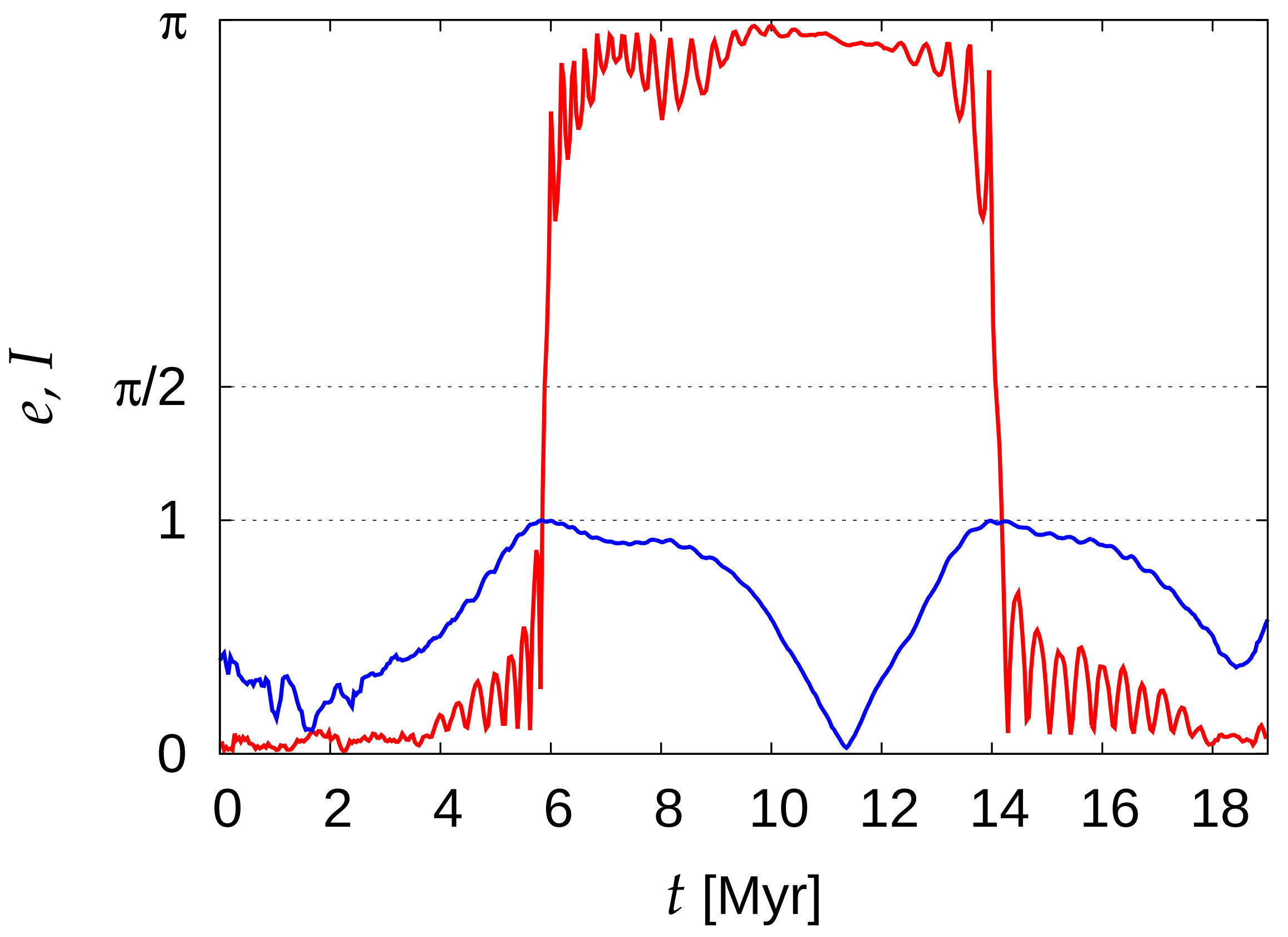

Figure 3: Evolution of eccentricity e (blue) and inclination I (red; in radians) during the coplanar flip.

References and Acknowledgements

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