Study and analysis of the role of the Moon in asteroid deflection

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Introduction

The risk associated with asteroid impacts is becoming increasingly apparent, particularly now that telescope surveys are discovering really close approaches every year. There is no need to appeal to the famous mass extinction occurred 65 million years ago [1], recent events like the Tunguska [2] or Chelyabinsk [3,4] remind us how vulnerable we are to such an event. In the last few years, asteroid deflection proposals have been proliferating (e.g., Kinetic Impactor, Ion Beam Deflection, Gravity Tractor…), yielding promising approaches in order to avoid potential asteroid collisions with the Earth [5,6].

In the context of a Potentially Hazardous Asteroid (PHA) deflection, we study the role that the Moon might play in this scenario, and discuss the possible outcomes that a failed deflection strategy involving a direct collision with the Moon could have in terms of future encounters with the Earth. To do so, we first perform a set of numerical simulations considering a simple Sun-Earth-Moon toy model, and compare the evolution of the asteroids' orbits depending on the system's configuration. Secondly, we address the hypothetical 2021 PDC impact scenario by calculating the necessary deflection that yields an impact with the Moon. From this, we evaluate the possible consequences of failed orbit deflections, and the effect of their subsequent close encounter with the Moon.

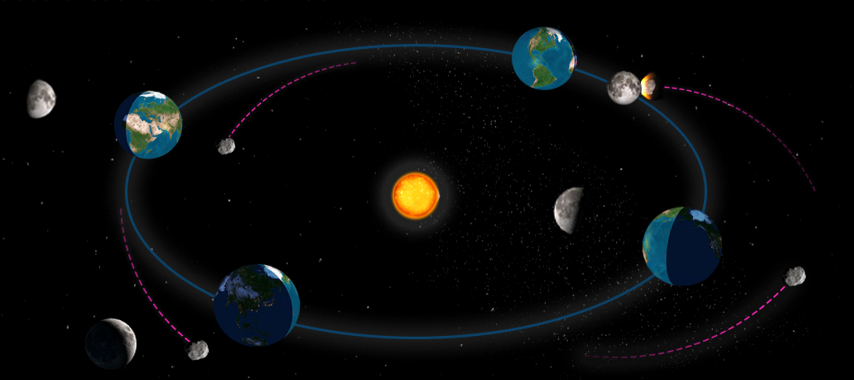

Fig. 1 - Conceptual illustration of different Earth-Moon-asteroid encounters to be analyzed.

Methodology

To carry out our first set of simulations, we build a coplanar toy model of the Sun-Earth-Moon system, where the initial positions and velocities for each of the three bodies are extracted from the bicircular model [7]. This particularly allows us to place the Moon in a specific configuration with the respect to the Sun-Earth line (see Figure 2).

Based on this general configuration, we analyze a test case where we force a close encounter between the Moon and a set of asteroids passing through certain crossing points of interest (see Figure 2). Specifically, we select 200 crossing points linearly spaced above the Earth-Moon line corresponding to a Lunar angular position of -30°.

The eccentricities of the asteroids' orbits are fixed to a constant value of $e = 0.5$, while the semi-major axis of each orbit is 1.5 times bigger than the distance between the corresponding crossing point and the Sun. The resulting system is then integrated over 50 years using the IAS 15 integrator implemented in the REBOUND package [8], and the positions of all particles are recorded 100000 times along the time considered.

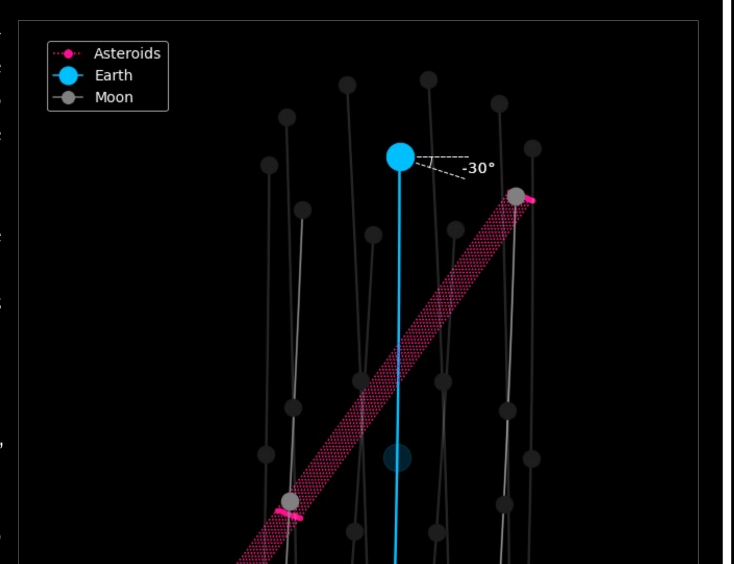

Fig. 2 - Earth-Moon and asteroid clones' encounters.

Always maintaining the same asteroids' orbits and crossing points, the simulation is carried out for 75 different angular positions of the Moon uniformly distributed along a full Lunar rotation (Figure 2). By doing this, we not only intend to study the evolution of the asteroids' orbits when experiencing a close encounter with the Moon, but also compare the observed behavior with the results obtained for the rest of the configurations in which the Moon is placed farther away from the potential impactors.

In our second experiment we compute the deflection of the hypothetical asteroid PDC 2021 that yields its impact with the Moon, in order to study the consequences that a failed orbit correction, and hence a close approach with the Moon, could involve in terms of future hazardous close encounters with the Earth. To find the appropriate deflection at the time of discovery, we use Monte Carlo simulations by generating random variations of the velocity vector and propagating each clone to its closest encounter with the Moon. This process is iteratively repeated converging to the optimal one-impulse lunar correction by evaluating the minimum distances and reducing the variation range in each step.

Making use of the obtained asteroid deflection, we then modify the resulting ΔV in order to generate an array of 1800 possibly miscorrected asteroids contained in the same plane (Figure 3). The resulting orbits are spaced 833 km apart from each other and cover a distance at the time of the first close encounter of $1.5 \cdot 10^6$ km. Relying again on the REBOUND package, we finally propagate this set of particles up to 50 years, taking also into account all the planets in the Solar System and identifying which asteroids initially had a close encounter with the Earth or the Moon, and whether this was inward or outward. As a result, we evaluate the Moon's gravitational influence when the failed lunar impact deflection occurs.

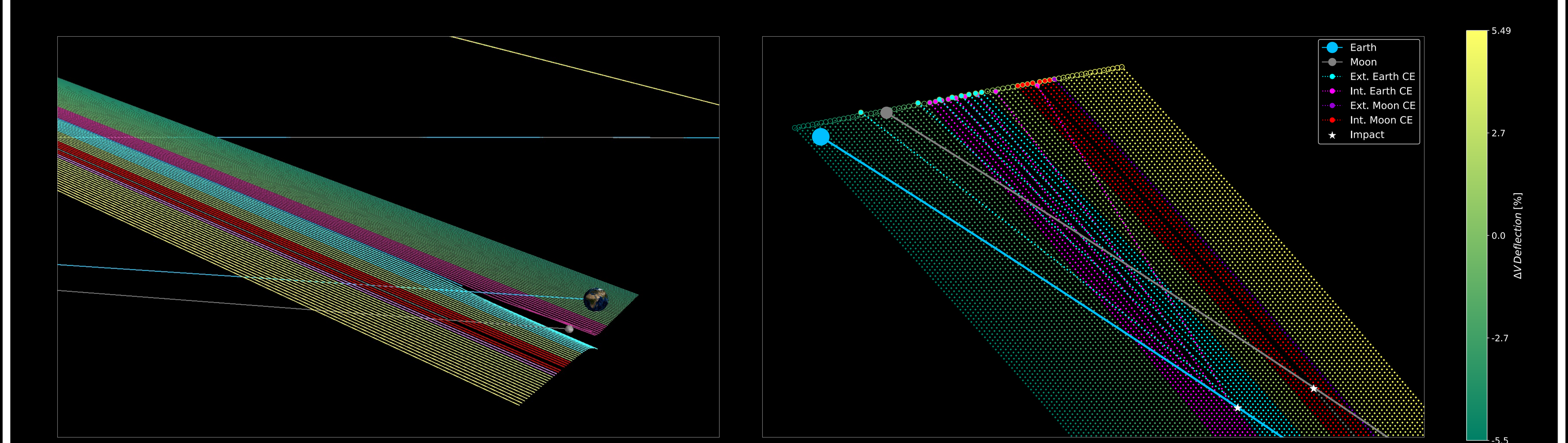

Fig. 3 - The approach of the clones with slightly different separation distances generated from failed lunar impact deflections.

Results and Discussion

As a result of the toy model simulations previously described, we record the positions of all particles along the 50 years of simulation, and subsequently extract the distance between the Earth and each of the 200 asteroids included in the system. In this regard, Figure 4 shows in pink the Earth-asteroid distance as a function of time in the case of a Moon angular position of 150°. In this scenario no significant variations between the asteroids' orbits are observed, and the close encounters with the Earth always take place at certain specific times mainly starting after approximately 25 years. On the other hand, Figure 4 shows in yellow the Earth-asteroid distance in the configuration where the planned close encounter with the Moon occurs (i.e., a Moon angular position of -30°, see Figure 2). In this case the asteroid's orbits are clearly affected by the Moon's presence, resulting in a wider variety of close encounters occurring also at earlier times along the integration time considered.

In order to further evidence this behaviour, for each of the 75 Moon configurations considered we compute the number of orbits that approach the Earth by less than 0.05 AU, corresponding to the limit commonly employed to define a potentially hazardous asteroid (PHA) [8]. In addition to this, we also count the total number of points in all orbits that fall below the same established PHA threshold. The resulting values are shown in Figure 5, where the number of potentially hazardous orbits and the total counts are represented by the yellow and blue straight lines, respectively. The green dashed line represents the minimum distance between the incoming asteroids and the Moon in each case, allowing us to record any other plausible Moon-asteroid encounters besides the one planned at -30°.

The right-hand plot, corresponding to the results taken over the full 50 years time span considered, shows some variations depending on the Moon's angular position, with no clear effect of the planned Moon-asteroid encounter. The results taken only over the first 20 years of simulation (left-hand plot), however, reveal two clear peaks coinciding with the configurations for which the Moon-asteroid distances are minimum. Let us note that, while the central peak is caused by the planned close encounter at -30°, the left-most peak is due to a previous close encounter between the incoming asteroids and the Moon at approximately -140°, as illustrated in Figure 2. This essentially demonstrates the same behaviour already observed in the two particular cases studied in Figure 4: While the unperturbed orbits present no close encounters during the first 20 years, the gravitational interactions with the Moon corresponding to the -30° and -140° cases perturb significantly the incoming asteroids, hence triggering numerous close encounters with the Earth taking place at earlier times.

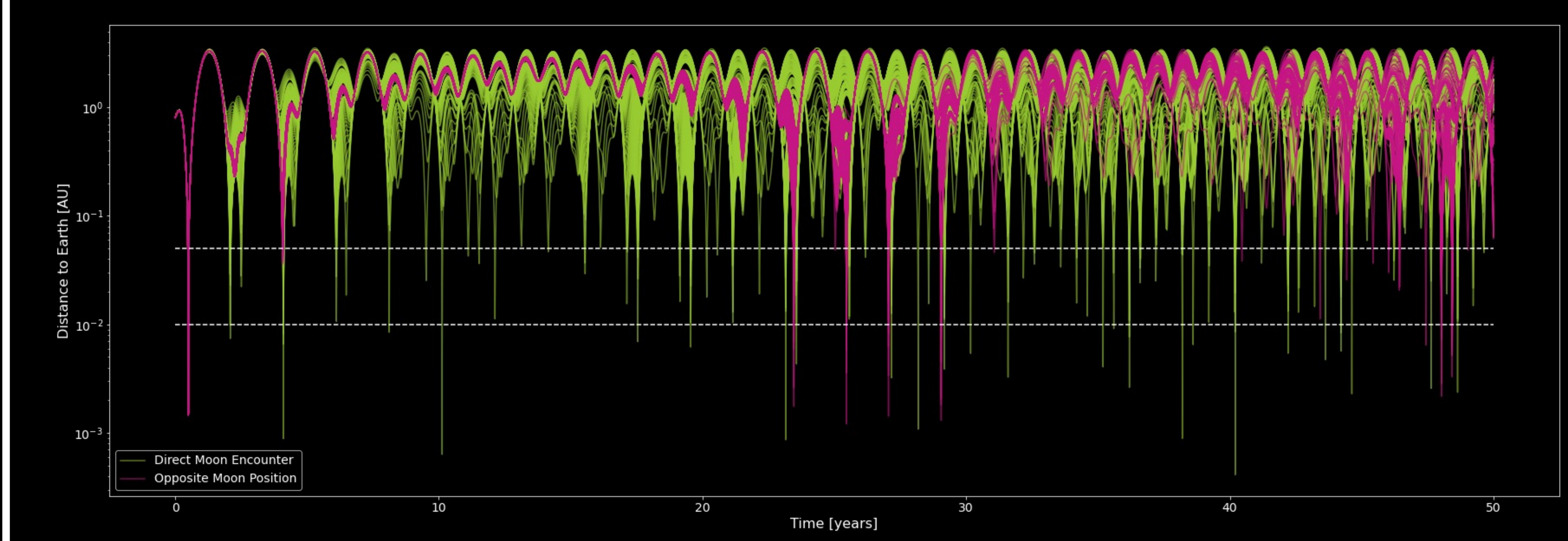

Fig. 4 - Distances from the asteroid set to the Earth for the planned encounter (yellow) and for the opposite Moon position (pink).

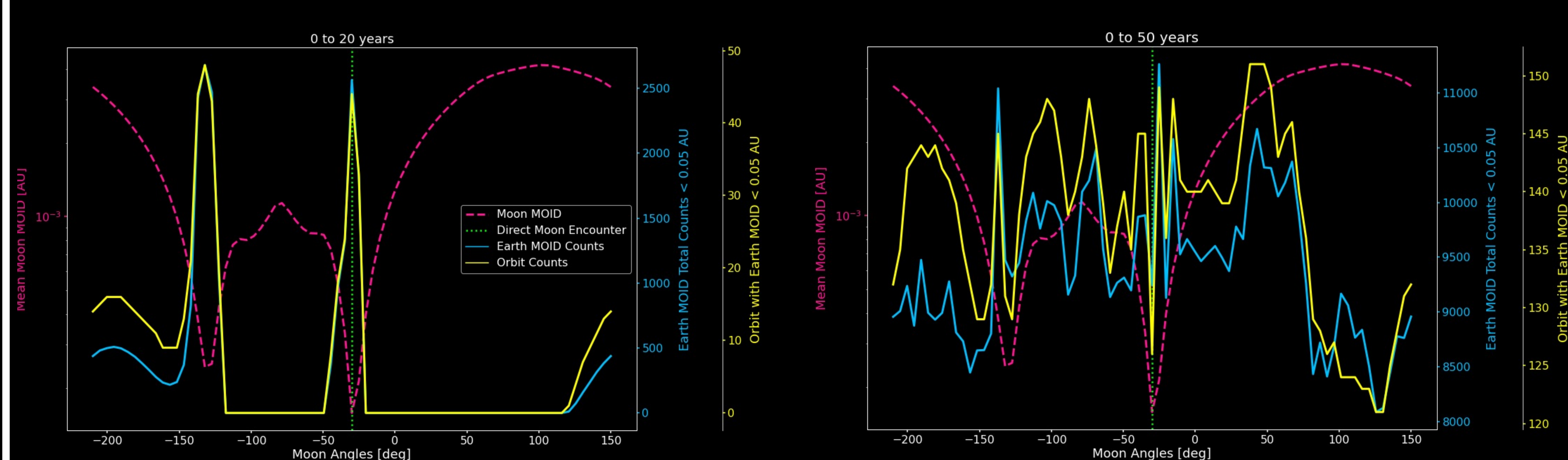

Fig. 5 – Close encounter counts for different Moon angle variations in ranges 0 to 20 years (left) and 0 to 50 years (right).

The deflection analysis for the hypothetical 2021 PDC scenario is shown in Figure 6. We propagate the clones by evaluating the distance to the Earth and classifying them according to their position at the first encounter: far from the Earth and the Moon (top), close to the Earth distinguishing interior and exterior encounters (middle) and close to the Moon distinguishing interior and exterior encounters (bottom). It is noticeable that the asteroid hazard increases in future encounters when it passes close to the Moon or the Earth, regardless of whether the close encounters are interior or exterior.

Analogous to the results of the toy model, failed lunar deflections with close encounters with the Earth or the Moon have further close encounters earlier in time due to the scattering of the orbits caused by the gravitational influence. Although the total close encounter counts over 50 years are homogeneous despite the deflection (Figure 7), this advance of the approaches due to the initial close encounter increases the threat of impact. Earlier close encounters pose more risks as uncertainties (less chance of orbit perturbation) and our ability to respond are reduced. Since it is preferable to delay as much as possible the first encounters, in this case it would be desirable to design a deflection strategy that avoids its approach to the Moon.

Consequently, when using a kinetic impactor like e.g., *DART* NASA mission [10], it is particularly relevant to analyse how close the target would pass from the Earth and the Moon, and what would be the role of the latter in terms of future encounters. Many unknowns in the mechanical response and structure of the asteroid target can make difficult to predict the exact ΔV deflection outcome [11].

In Figure 7, it can be seen a range of deflection between 4 and 5 % change in ΔV that produces a valley in the total close encounter counts, pointing to a safe zone of interest to deflect the asteroid's orbit. Note that a deflection of 0 % corresponds to the impact with the Earth.

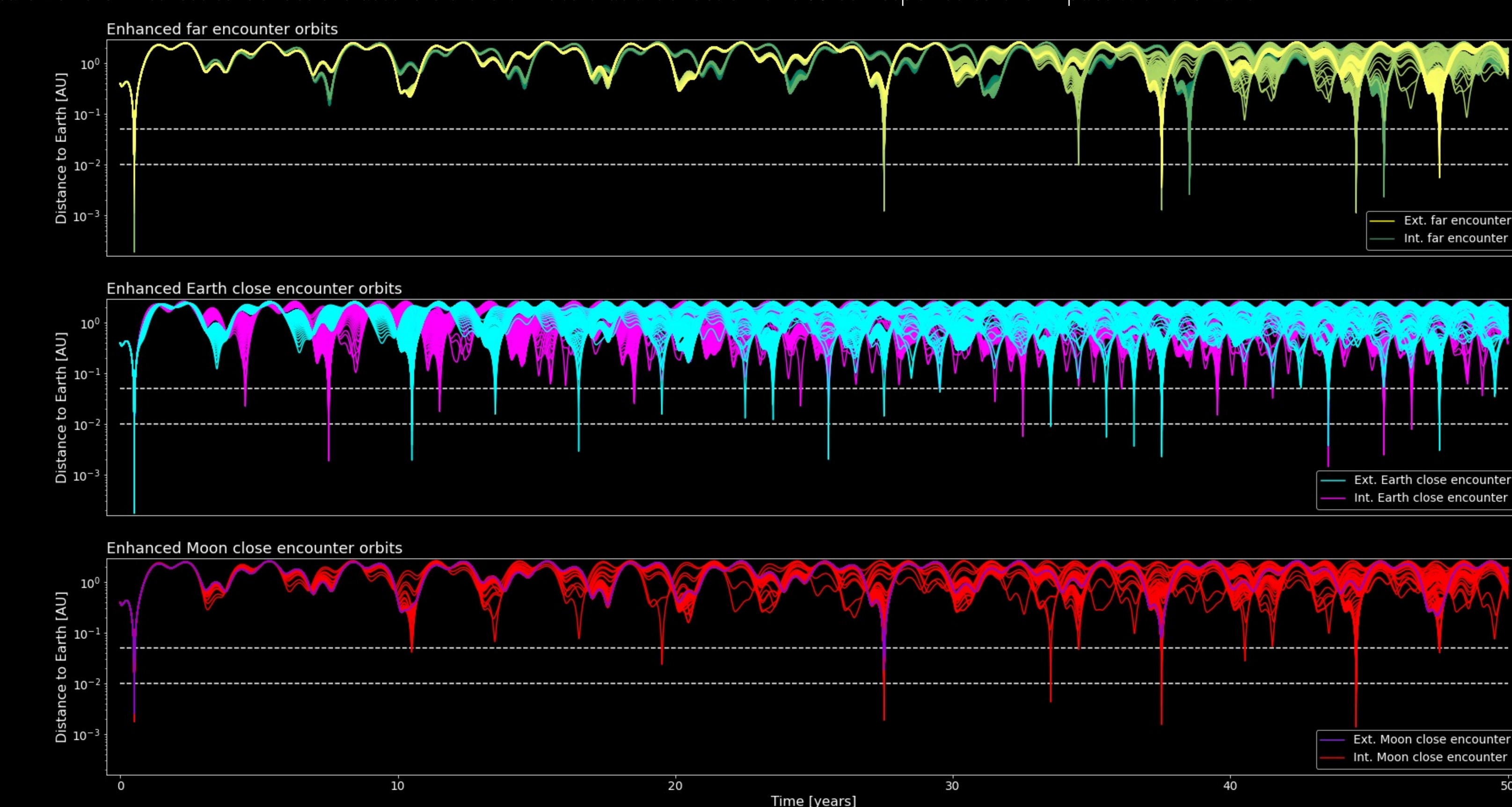

Fig. 6 - Distances from deflected clones PDC asteroid to Earth, where the minima mark the closest approaches.

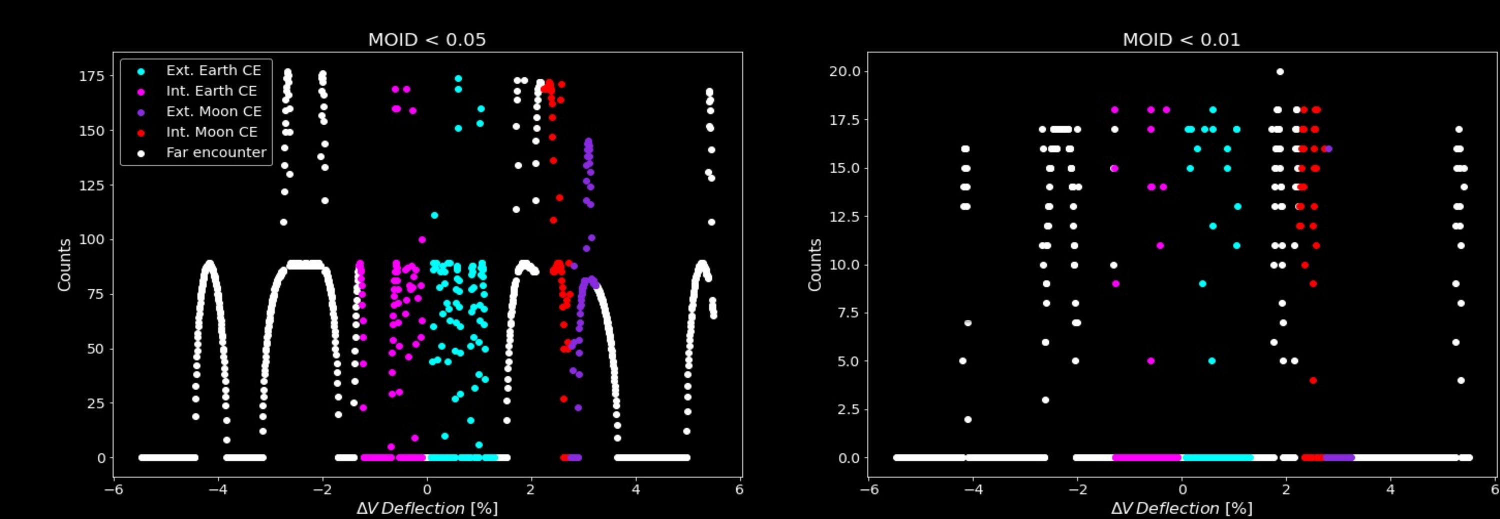

Fig. 7 - Close encounter total counts between the deflected PDC asteroids and the Earth.

Conclusions

- Making use of the IAS 15 integrator implemented in the *REBOUND* package, we have conducted several simulations to analyze the possible outcomes in the context of a failed deflection strategy based on a direct collision with the Moon.
- A close encounter with the Moon in our toy model could perturb significantly the asteroids' orbits, and potentially translate into the appearance of close encounters taking place at earlier times.
- Regarding the PDC 2021 hypothetical scenario, the asteroid orbits having close encounters with the Earth or the Moon are later scattered by their gravitational influence, hence covering a wider range of orbits and generating earlier close encounters that could pose a higher threat.
- Whether close encounters are interior or exterior to the Earth or the Moon in reference to their relative positions, in principle, does not influence the likelihood of future impacts.
- For the cases analyzed in this study, our results show that a deflection strategy based on a direct collision with the Moon could have an adverse outcome if the direct impact does not occur.
- As envisaged in our test configurations, the perturbations inflected by the Moon should therefore be carefully evaluated when designing deflection strategies.

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