An improved method for asteroid impact probability due to swarm intelligence algorithms

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Introduction

- This research explores two fundamental question regarding the orbital dynamics of potentially hazardous objects (PHOs):
  - (1) given the best orbit determination solution, i.e. a state and uncertainty at a specific time, what is the closest that asteroid ever gets to the Earth when propagated forwards in time?
  - (2) how can the computationally expensive process of running a Monte Carlo simulation, with potentially thousands or millions of samples, be improved?

Method

- pose the PHO close approach problem as a trajectory optimization problem
- objective function set equal to perigee radius

$$J = r_p = \left[r_x^2(t_p) + r_y^2(t_p) + r_z^2(t_p) \right]^{1/2}$$

- decision vector defined as an orbital state with constraints defined as the +/- 3 sigma state uncertainties for each element

$$\mathbf{x} = \begin{bmatrix} a & e & i & \Omega & \omega & M \end{bmatrix}$$

$$\mathbf{x_{ub}} = 3 \begin{bmatrix} \sigma_a & \sigma_e & \sigma_i & \sigma_\Omega & \sigma_\omega & \sigma_M \end{bmatrix}$$

$$\mathbf{x_{lb}} = -3 \begin{bmatrix} \sigma_a & \sigma_e & \sigma_i & \sigma_\Omega & \sigma_\omega & \sigma_M \end{bmatrix}$$

Method

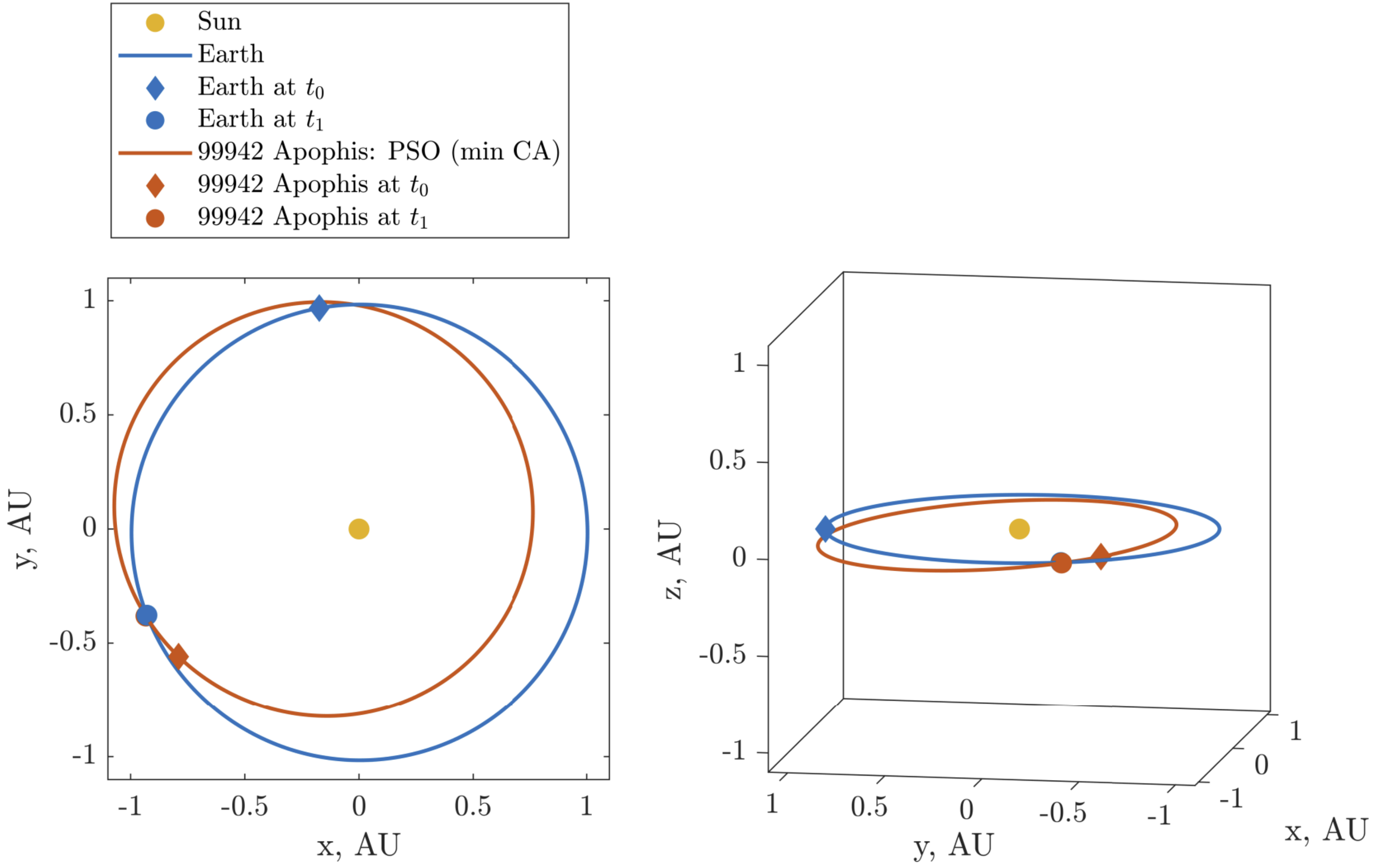
- Particle Swarm Optimization (PSO) – a swarm intelligence algorithm
- Generate random initial population of particles in n-dimensional search box – just like a Monte Carlo
    - n=6 since the search space is a 6-element orbit state
- Particles have a position vector for its location in the feasible n-dimensional search box and an associated score based on some cost function
    - Cost function is the perigee radius when that state is propagated until Earth close approach

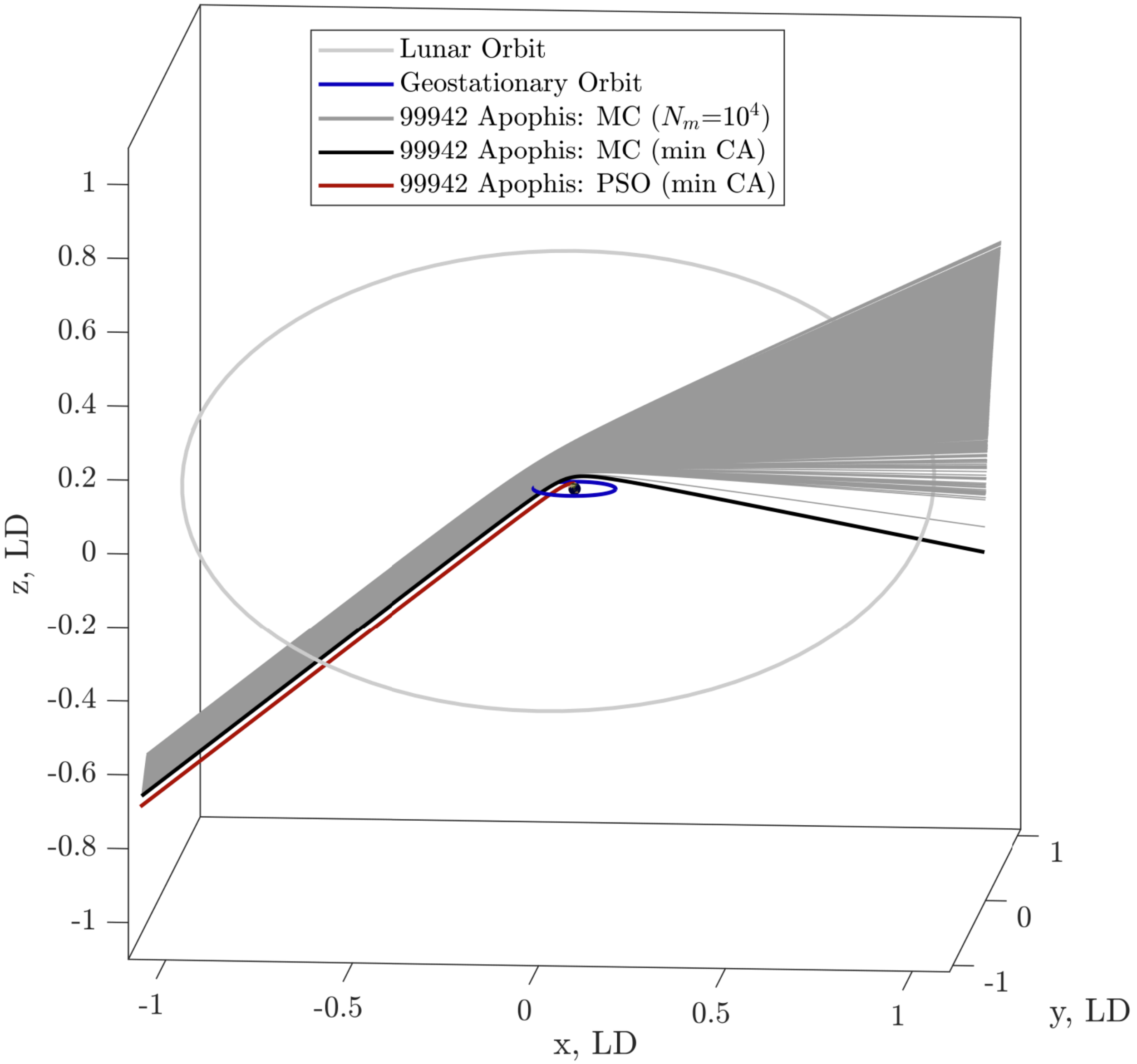
Method

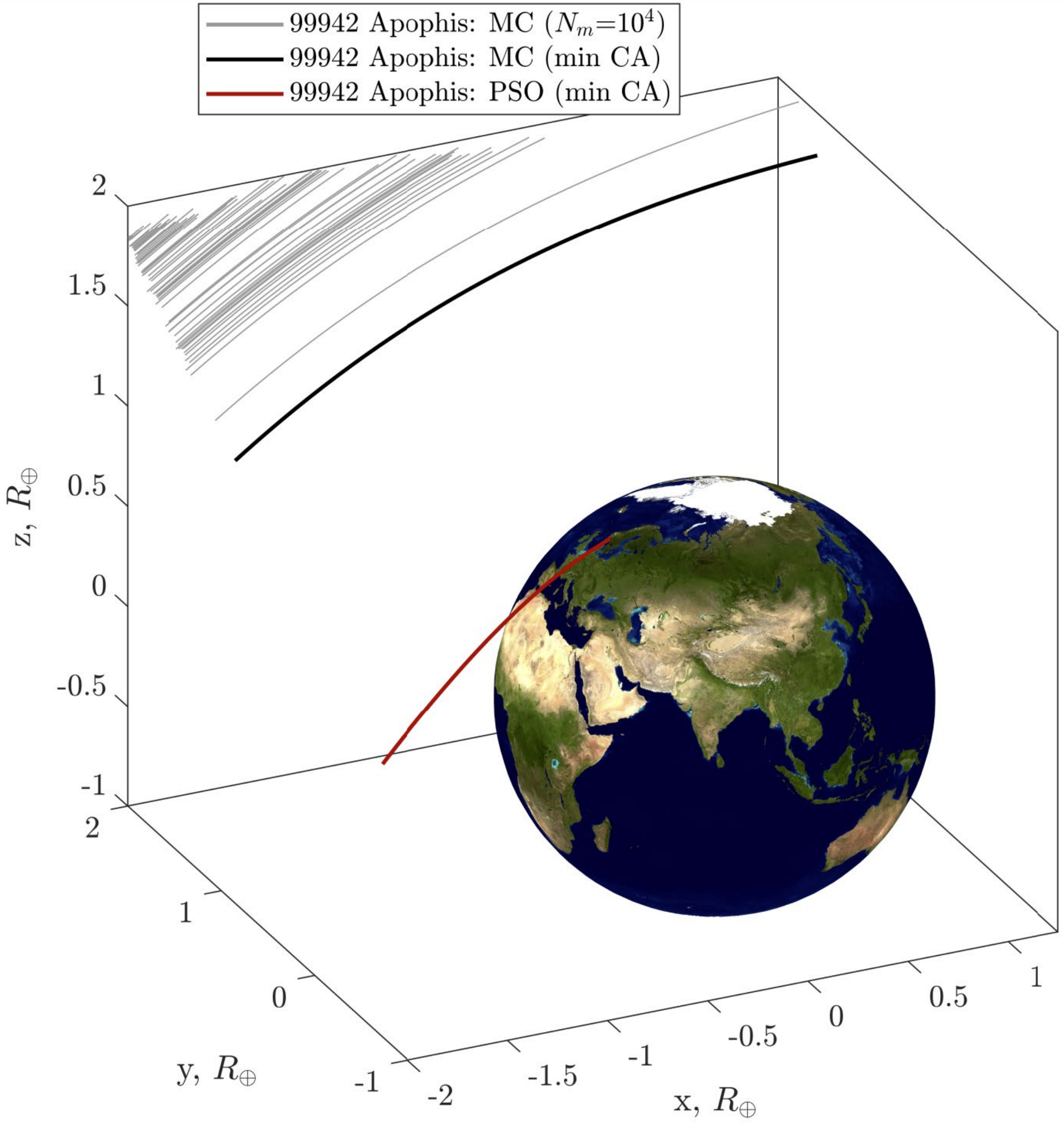
- PSO iterates, updating the position vector of each particle based upon three components with associated weighting coefficients:
  - *Inertial*: biases each particle to continue moving in the direction it was moving in during the previous iteration
  - *Cognitive*: biases the particle to move towards the best position that it has experienced (its personal best fitness)
  - *Social*: biases the velocity towards the global best fitness found by any particle in the population

- The classic Monte Carlo method can be reframed as zeroth order PSO

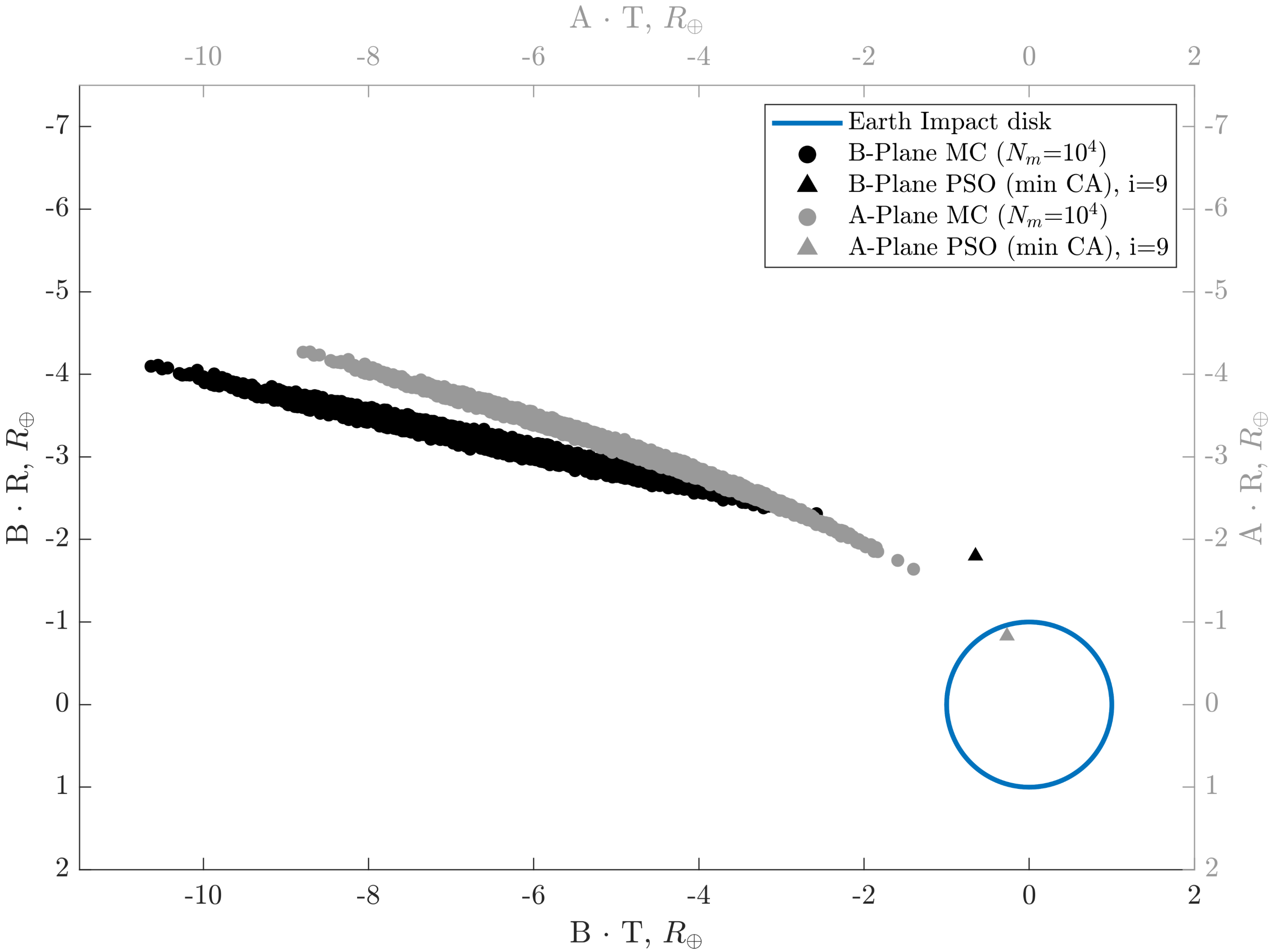
Case Study 1) Apophis



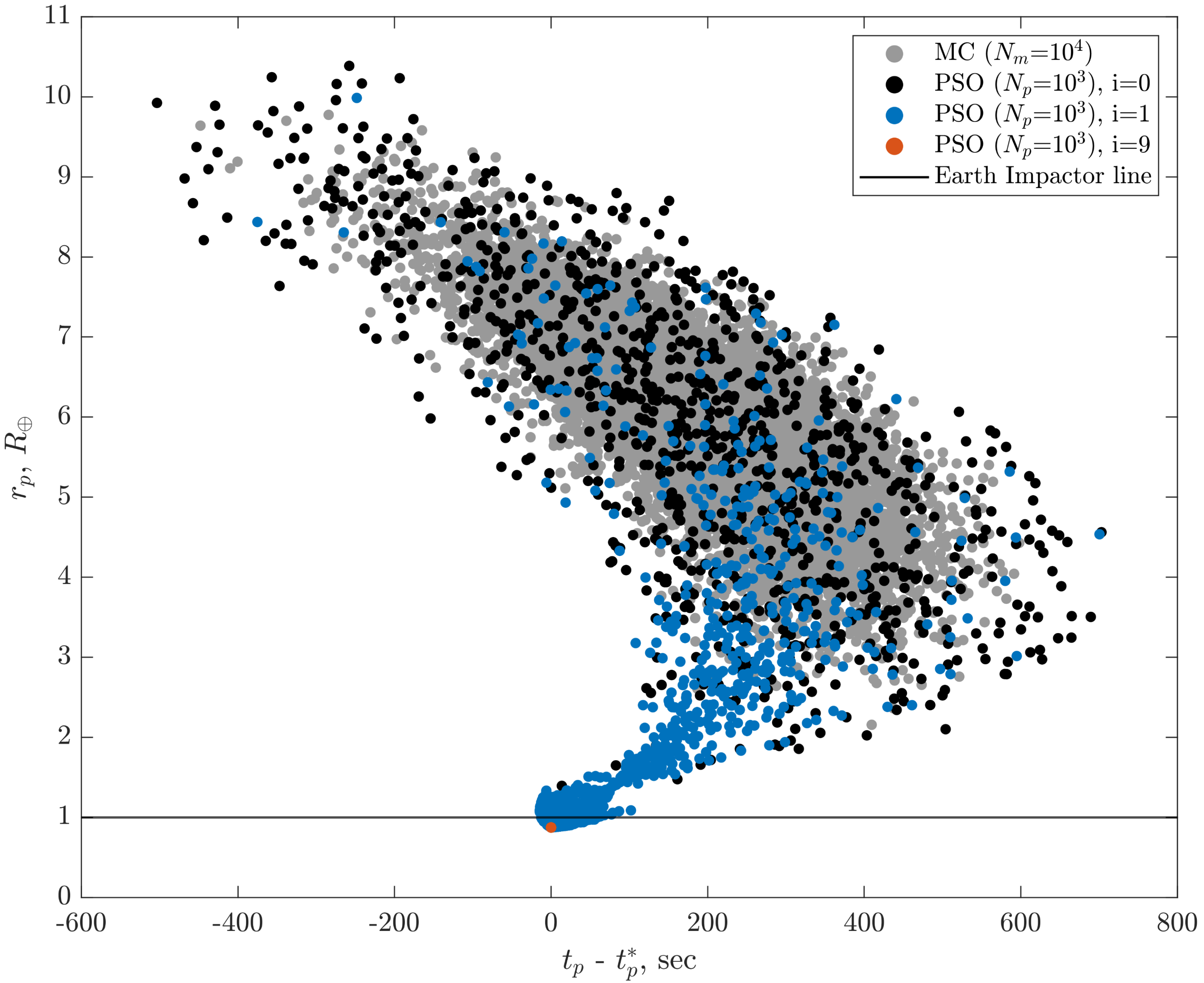

Lunar Orbit
Geostationary Orbit
99942 Apophis: MC (N_m=10^4)
99942 Apophis: MC (min CA)
99942 Apophis: PSO (min CA)
z, LD
x, LD
y, LD
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.5
0.5


99942 Apophis: MC (N_m=10^4)
99942 Apophis: MC (min CA)
99942 Apophis: PSO (min CA)
z, $R_\oplus$
y, $R_\oplus$
x, $R_\oplus$
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

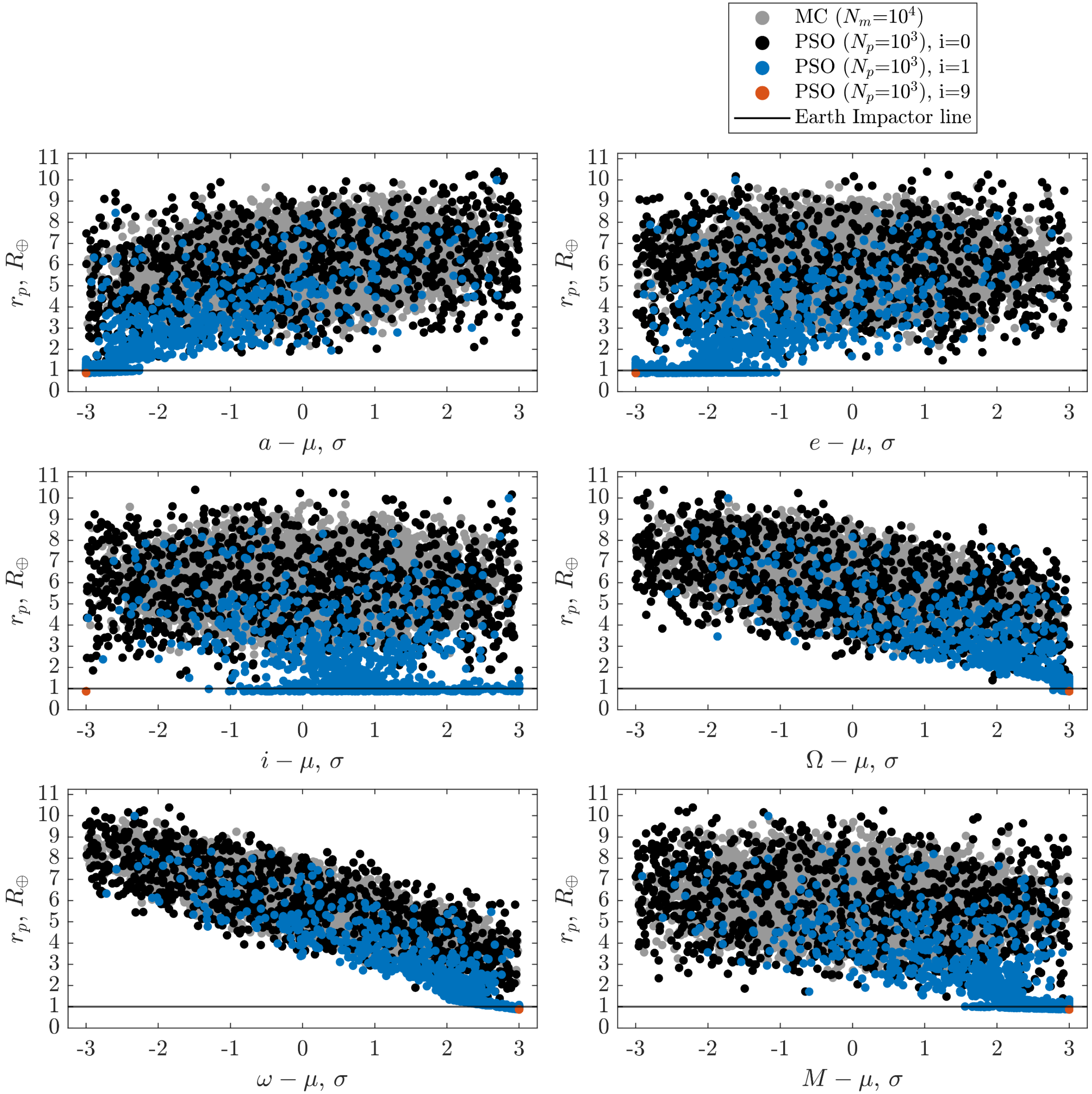
Case Study 1) Apophis



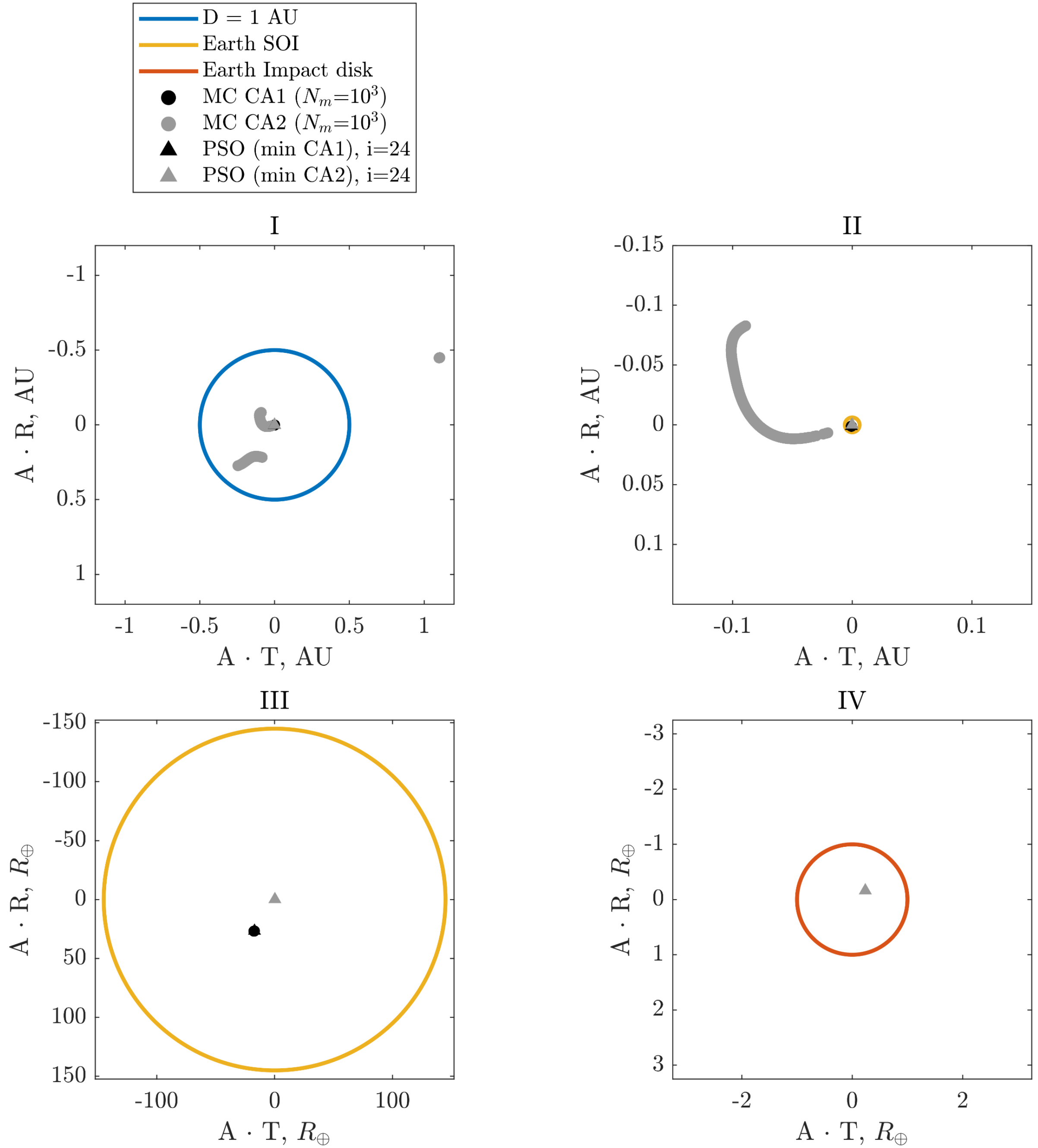
Case Study 1) Apophis



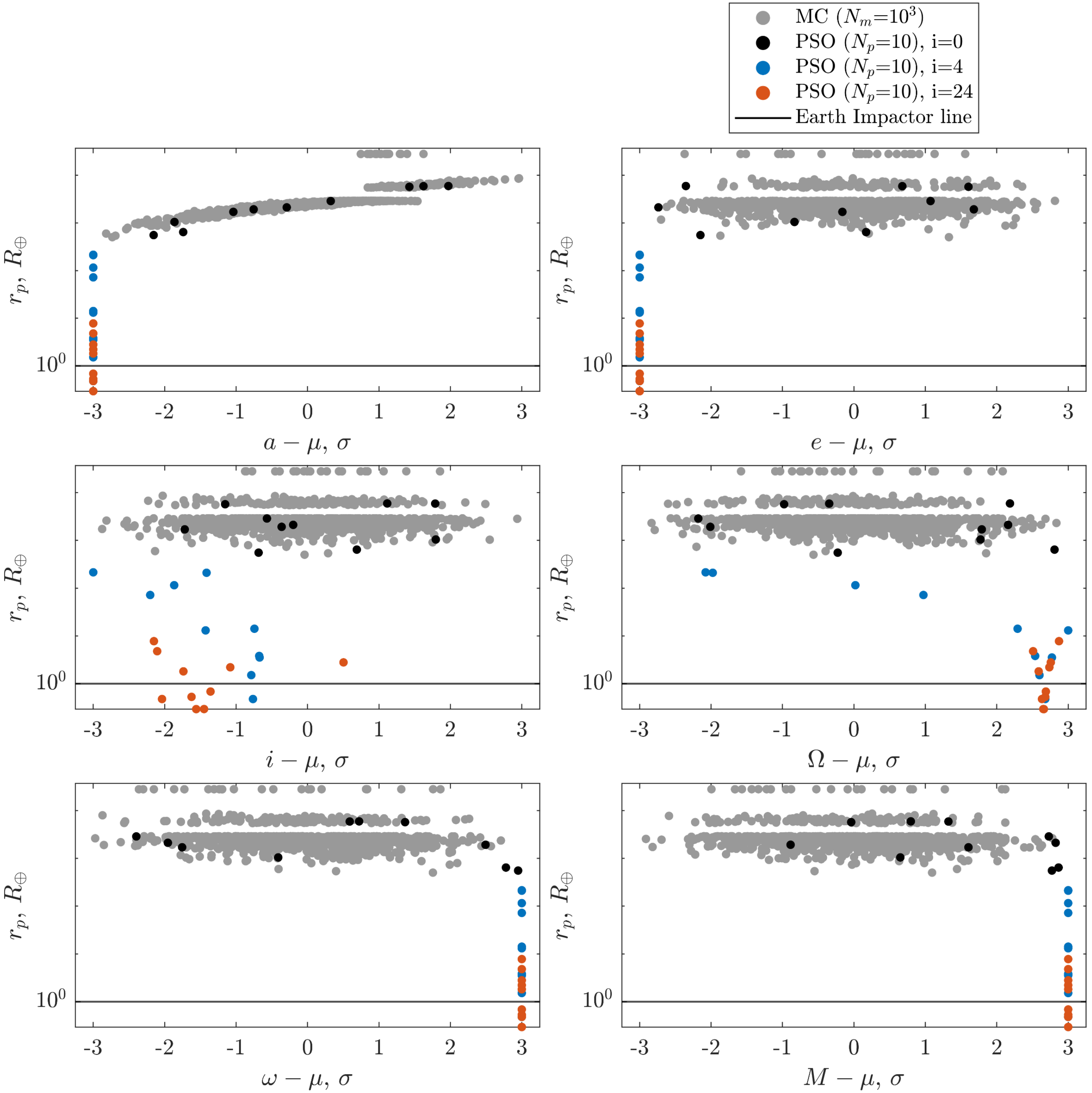
Case Study 1) Apophis



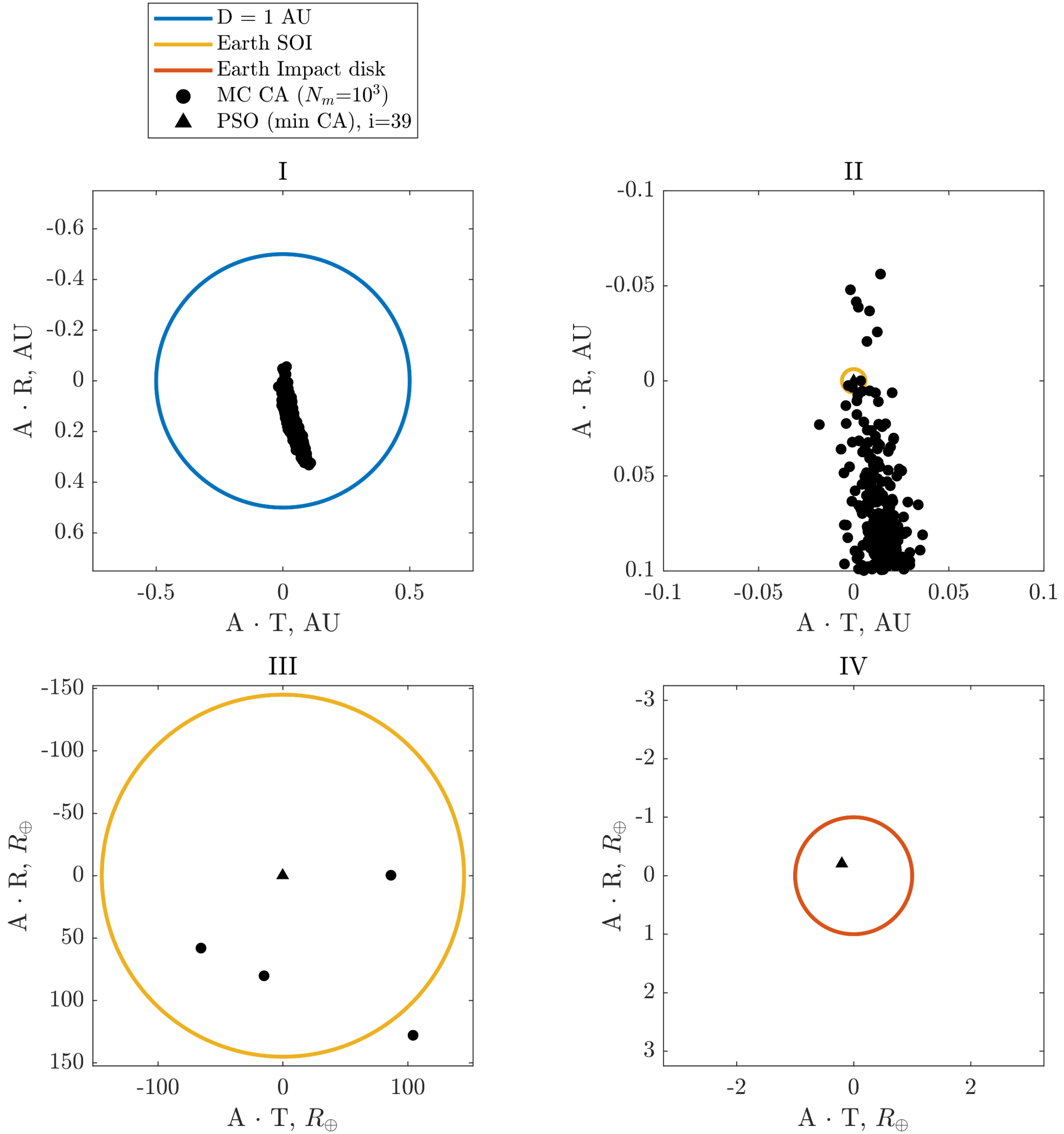
Case Study 2) Bennu



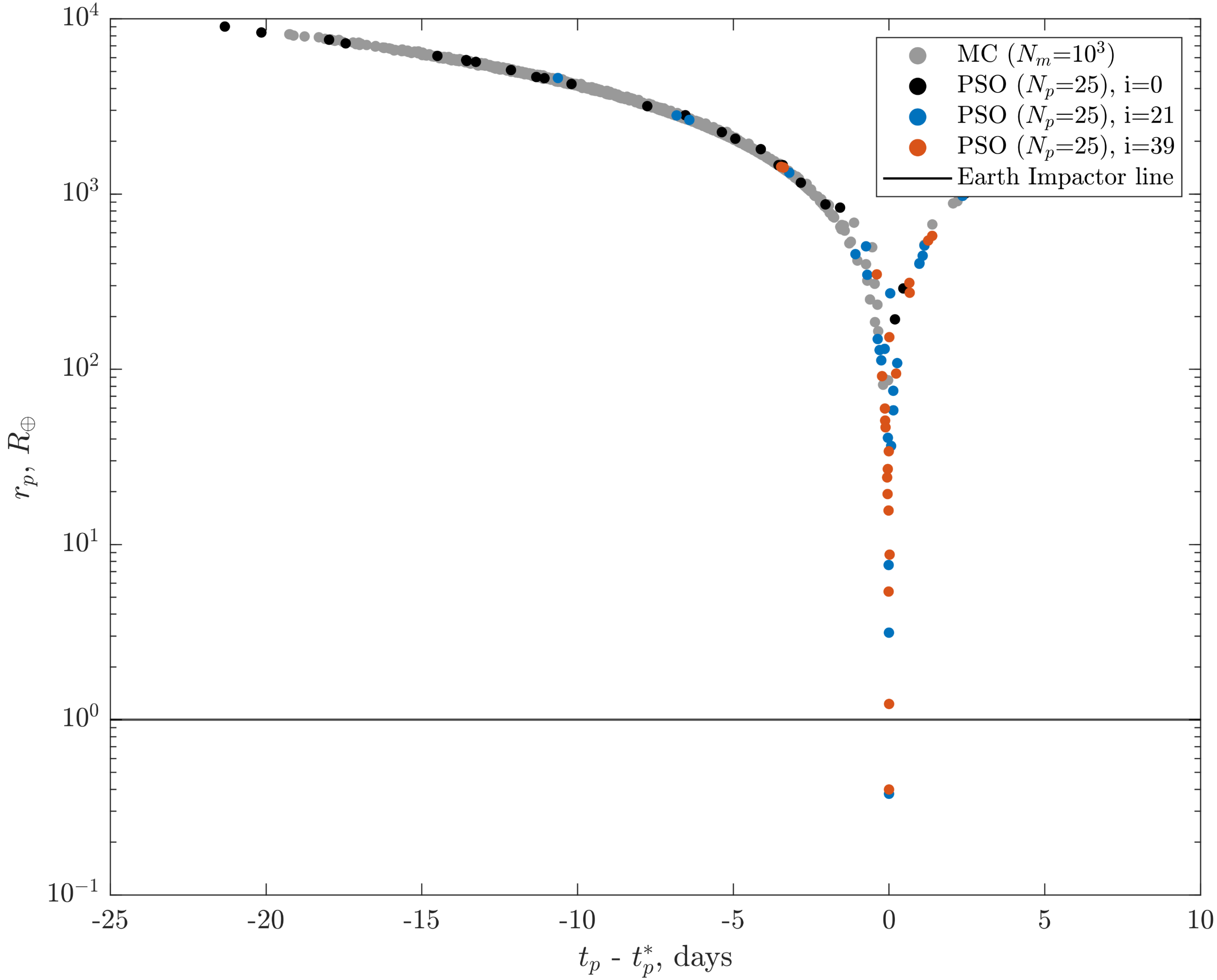
Case Study 2) Bennu



Case Study 3) Swift-Tuttle



Case Study 3) Swift-Tuttle



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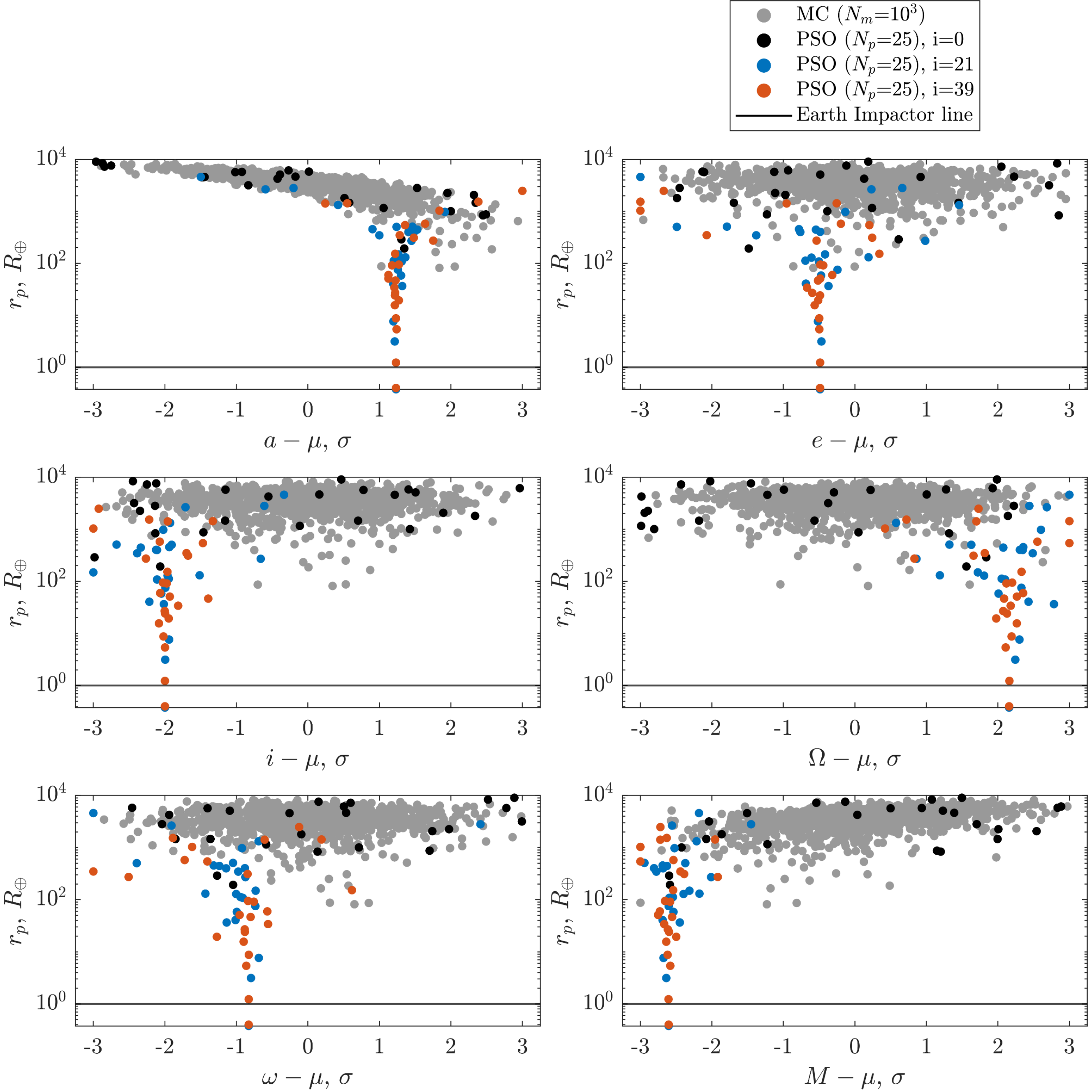

Conclusions

- The introduced method is an improvement in computational efficiency and effectiveness at finding virtual impactors that are not detected in a Monte Carlo simulation.

- The PSO PHO close approach method accurately and efficiently predicts the "worst-case scenario" for a given potentially hazardous object and its orbit determination solution.