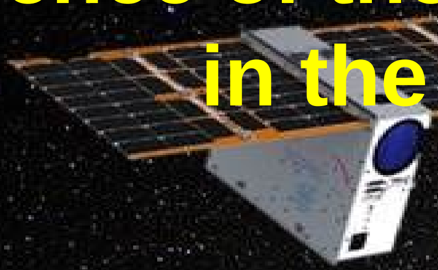
Influence of the body composition on the evolution of ejecta in the Didymos-Dimorphos binary system



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DART
Double Asteroid Redirection Test

LICIACube

Joint work with:
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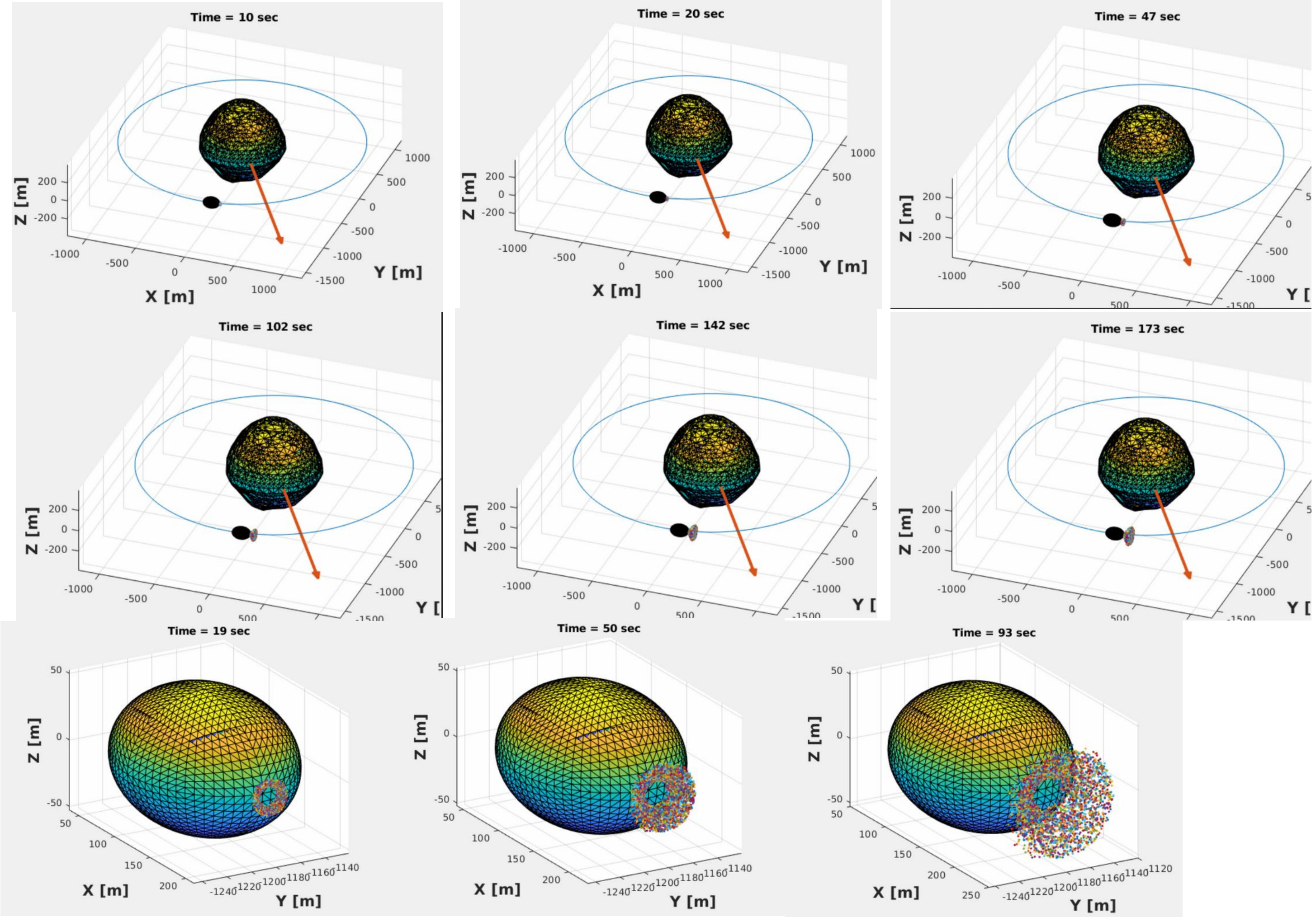
The goal of the present work is the fine tuning of the model developed in the framework of the LICIACube team for the simulation of the dynamics of the ejecta from the DART impact in the Didymos-Dimorphos system



$D_{Didymos}$ = 0.780 km (± 10%)
$D_{Dimorphos}$ = 0.163 ± 0.018 km
a_{orb} = 1.18 +0.04/-0.02 km

Input data on ejecta particles come from iSALE simulations performed by S. Raducan assuming different target compositions.
As a default, for the results shown in the next slides we considered a target with:

- Porosity of 20 %
- Friction coefficient: f = 0.6
- Cohesive strength: 10 Kpa

The simulation model includes:

- Gravity field from a rotating primary body computed with:
  - Analytical formulation for a triaxial ellipsoid (e.g., MacCullagh, 1844; Murray & Dermott, 1999)
  - Polyhedron model from Werner and Scheeres, *CMDA*, 1997

- Solar gravity perturbation

- Secondary body gravity perturbation
  - (ellipsoidal shape, rotating) analytical perturbation, direct and indirect terms

- Solar Radiation Pressure (SRP) with shadow:
  - The ejecta particles have ellipsoidal shape and different cases can be simulated:
    - Particles with a given same shape and dimension, read from an input file
    - Particles with shapes and dimensions extracted from a distribution (e.g., as derived from impact experiments)
  - The ejecta particles are rotating ellipsoids, leading to a different A/M at each time step:
    - Regular rotation around the principal axis with a fixed assigned period
    - Regular rotation around the principal axis with a period extracted, for each particle, from a Maxwellian distribution
    - Random tumbling

The orbit integration

- The integration is performed in Cartesian coordinates with the RADAU integrator (Everhart, 1985)

- The ejecta orbit integration is performed in a *frame centered on Dimorphos* and later on the results are brought back (and shown in the following plots) in the *Didymos-centered frame*.

- The time evolution of the ejecta cloud is studied on different time scales to identify the driving effects and perturbations.

- The impact against the primary and secondary ellipsoidal bodies are recorded

- The integrations are carried out until a distance of twice the Hill radius of Didymos is achieved. After that distance the particle is considered *escaped* and is not followed further.

The simulation campaign

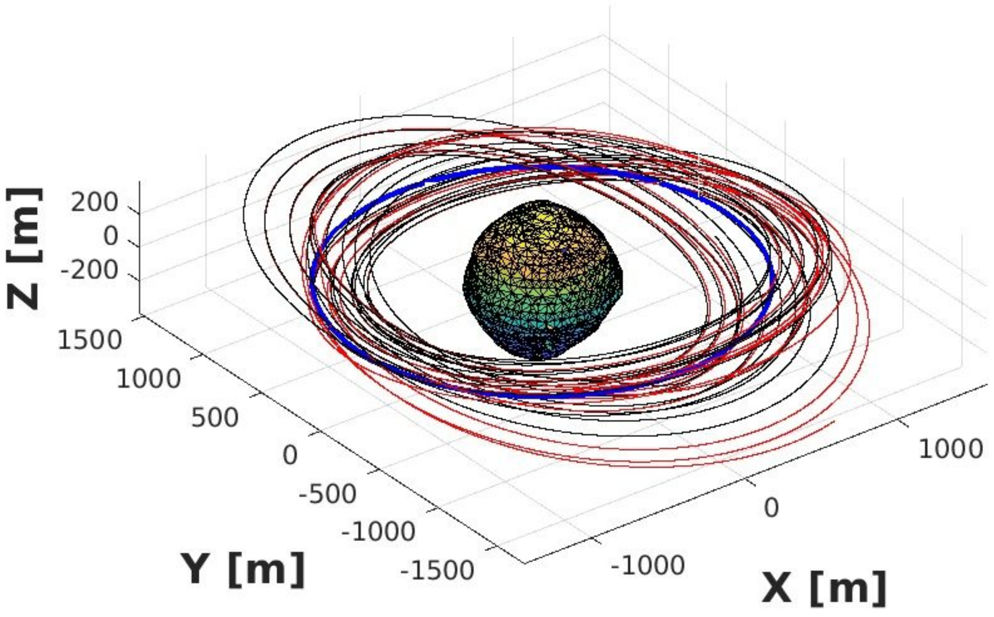
- A large set of simulation was performed and is under analysis
- The main purpose of the campaign is to validate the model and the software and to assess the most relevant effects
- The simulated cases include:
  - Polyhedron vs analytical gravity
  - Solar radiation pressure models (eg. Spherical vs. ellipsoidal particles, different rotation,…)
  - Different particles sizes and distributions
  - Different iSALE inputs (i.e., different target materials)
  - Different ejection velocities
  - Different impact location
  - Different time scales:
    - The analysis is pushed farther in time w.r.t. the LICIACube pass, to explore the possibility of the existence of stable particles left in the binary system at the arrival epoch of HERA.

Polyhedron vs analytical gravity

4 of particles were integrated using the primary (Dimorphos) gravity field given by the “official” polyhedron model and by an analytical computation of a triaxial ellipsoid potential (MacCullagh, J., 1844; Murray and Dermott, 1999).

- The particles integrated with the polyhedron (red lines) display a similar behavior w.r.t. those integrated with the analytical potential (black lines).

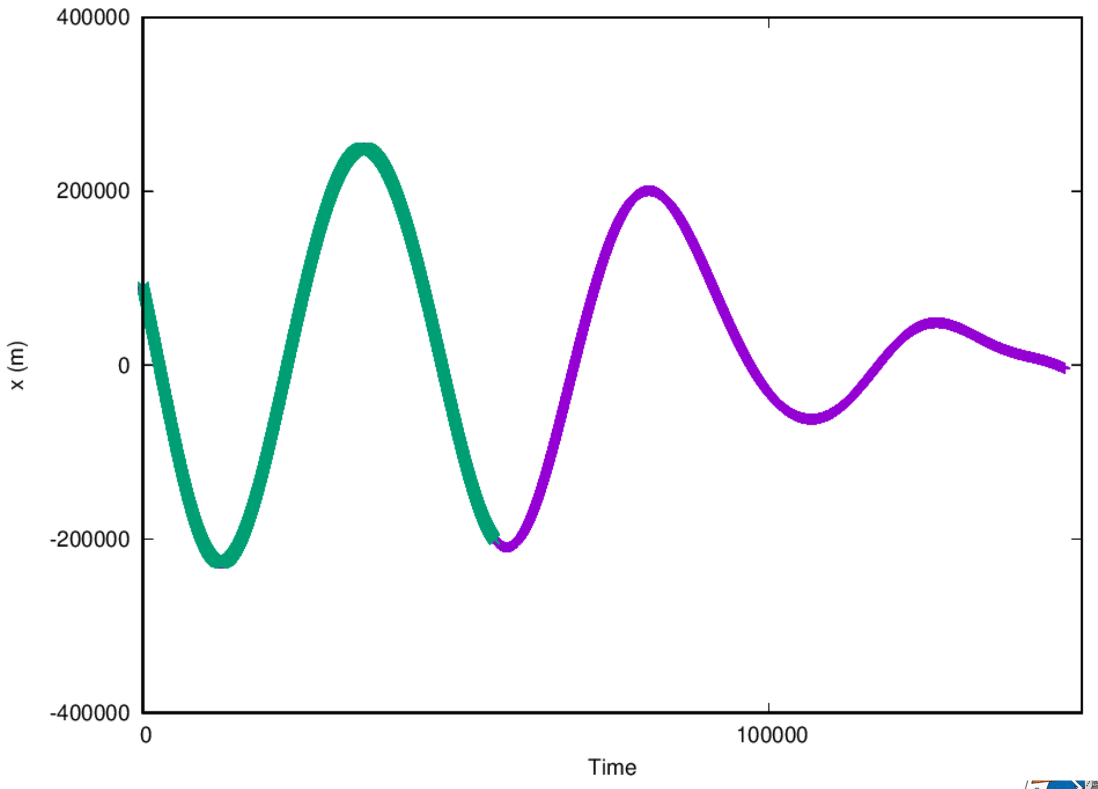
- In the case shown here the official model of Dimorphos is *de-facto* a triaxial ellipsoid and the simulations show that the analytical model reproduces very well the behavior of the, much more CPU consuming, polyhedral model for a similarly shaped body.



Polyhedron vs analytical gravity

4 of particles were integrated using the primary (Dimorphos) gravity field given by the "official" polyhedron model and by an analytical computation of a triaxial ellipsoid potential (MacCullagh, J., 1844; Murray and Dermott, 1999).

- Given the good results of the analytical ellipsoid, once a more complex model of Dimorphos will be available, we will be able to switch from the demanding polyhedral model (green line) to an analytical ellipsoid (purple line) once the particles have left the close proximity of the central body.



Solar Radiation Pressure

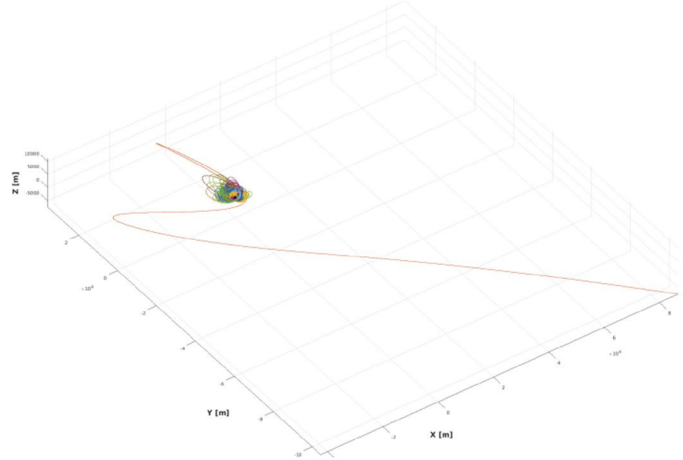
- The instantaneous area over mass ratio of each particle is computed at each time step according to the different rotation models adopted.

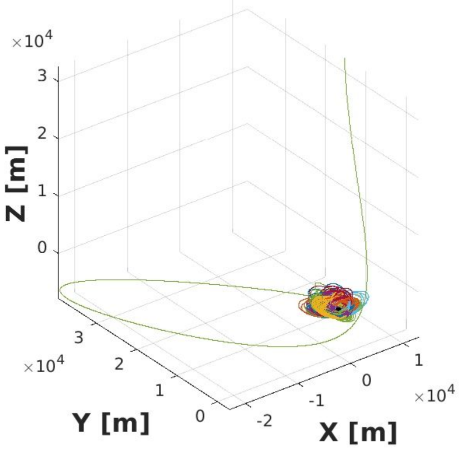
- 48 particles, 5 cm sized, were integrated with the following models:
  - Ellipsoids with random rotation (aspect area randomly changing at each time step from A_{min} to A_{max} of the given ellipsoid)
  - Ellipsoids with regular rotation around the principal axis with a fixed period (~ 30 seconds)
  - Spherical particles

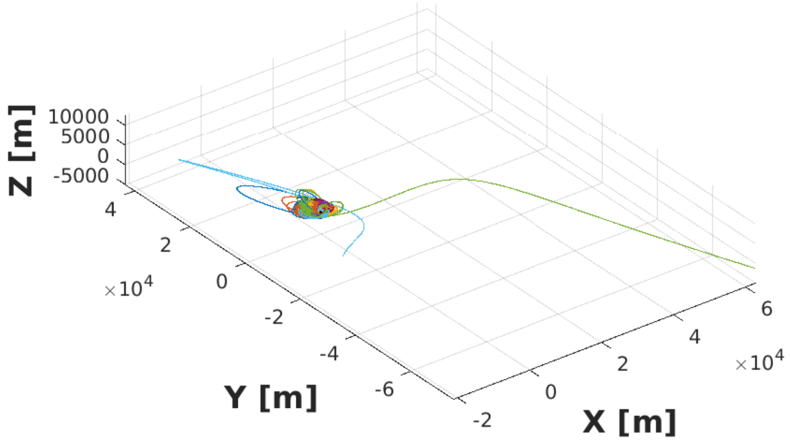
  - In the next slide the orbits of the 48 particles in 3 cases are shown. The panels in the TOP line show all the 48 particles, while the BOTTOM line shows a detail with all the particles which remain in the system.
  - All the particles, IN ALL THE 3 CASES, either impact or (a few of them) escape within, at most, 46 days in the investigated scenarios.
  - The impacts are on Didymos in the 80 % of the case for REGULAR, in 72 % of the cases for RANDOM and in 64 % of the case for SPHERICAL. The rest of the impacts are against Dimorphos.

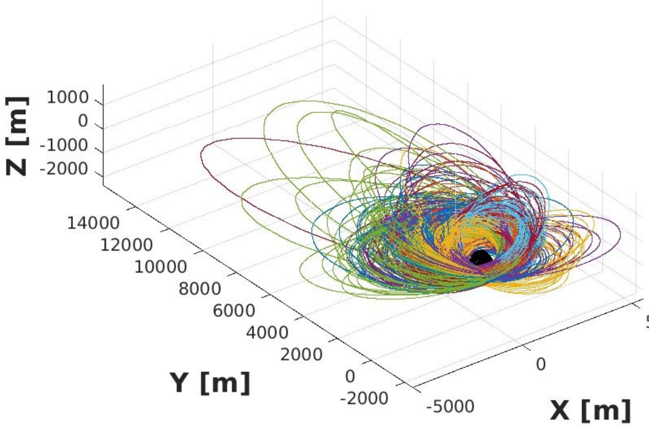
Solar Radiation Pressure

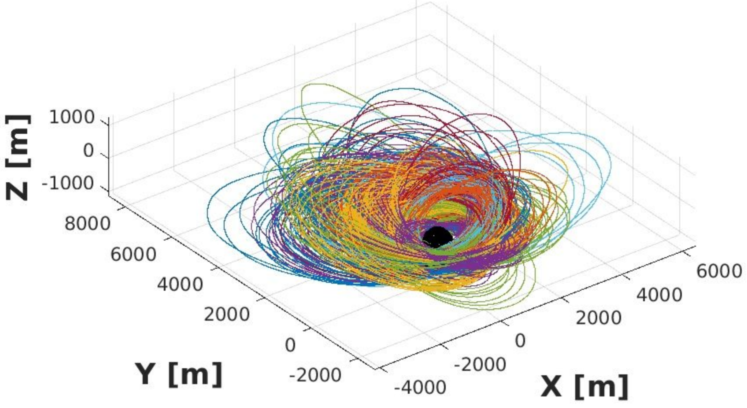
- RANDOM REGULAR SPHERICAL

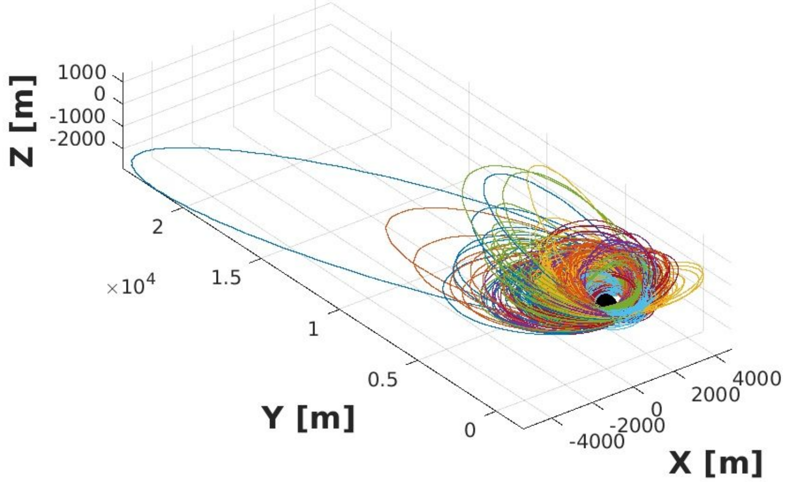












Solar Radiation Pressure

- It is difficult to disentangle the different contributions of the SRP models given the fact that the system is highly chaotic due to the repeated close approaches with Didymos and Dimorphos.
- Slight changes in the pre-encounter coordinates lead to completely different evolution of the particles orbit.
- A more detailed investigation of this aspect is undergoing by looking closely at the orbital elements time histories of the single particles.

Ejection velocities and target composition

- Several different target compositions were initially tested, coming from iSALE simulations.
- These simulations (Raducan 2019, 2020) explored a wide range of:
  - friction coefficient (from 0.2 to 1.2)
  - Cohesive strength (from 1 to 100 KPa)
  - Porosity (from 10 % to 50 %)

- It turns out that, in such high cohesion bodies, to detach from the surface, the particles need to be ejected with high velocities usually largely in excess of the body escape velocity (~ 10 cm/sec for Dimorphos). Hence, in all the explored cases, all the particles tend to quickly leave the system.

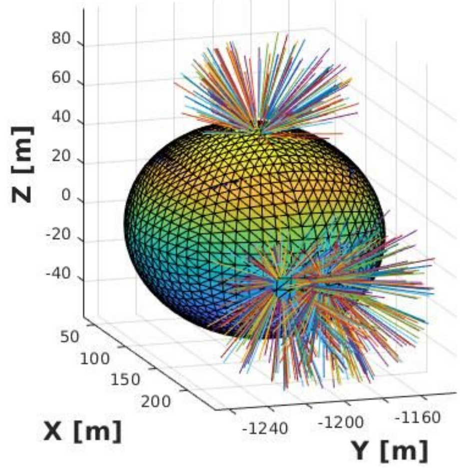
- To explore in depth the dependence of the ejecta evolution from the target composition, data for different (*softer*) targets shall be exploited in the near future.
- For the simulations shown in this presentation, the velocity vectors coming from the iSALE simulations were used keeping the original *versors*, while the magnitudes were re-scaled (lowered below the escape velocity threshold).
- Therefore, firm conclusions on the influence of the target composition on the ejecta evolution will be part of a future work stemming from different impact simulation data.

Impact locations

- 13 different impact locations where simulated, beside the nominal one (i.e., center front impact).
- 11 locations where chosen in a circular region within about 10 degrees in latitude and longitude from the nominal location
- 2 locations where displaced North (~75 degrees above the equator of Dimorphos) and South (~45 degrees)
- 200 particles of 5 cm in diameter were propagated in each scenario. The time span was abut 10 days.

Looking at the persistence of the particles in orbit around the system:

- In all the 11 proximity cases a percentage between 65-85 % of the particles re-impact one of the bodies: more than 95 % of the impacts are against Didymos
- In the two N & S locations there is a tendency (*to be confirmed*) of longer lifetimes, possibly related to more stable higher inclination orbits, with the following re-impact rates:
  - For the Northern location, about ~50% of the particles re-impact, with more (~14 %) re-impacts on Dimorphos
  - For the Southern location, about ~60 % (~ 5 % on Dimorphos).



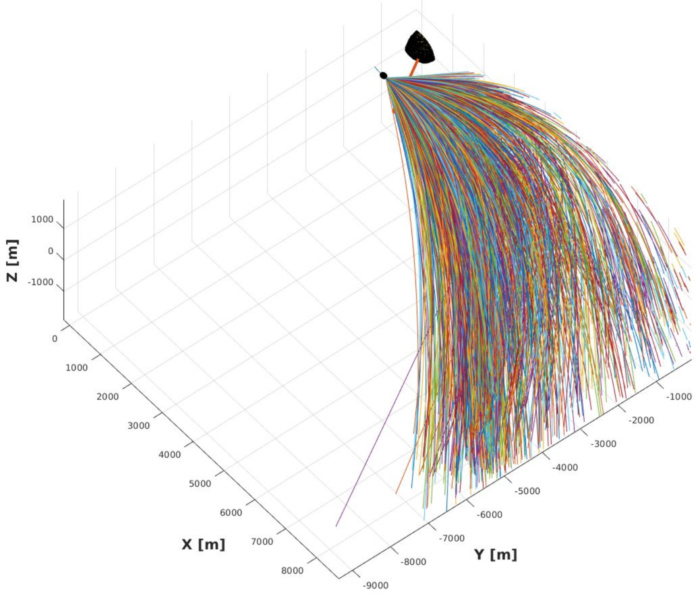
Longer time spans are under examination, limited to a subset of locations.

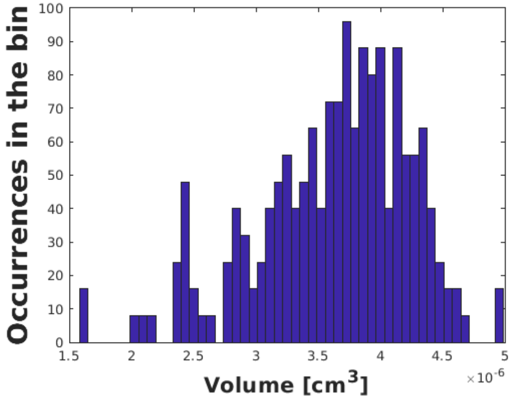
Small particles: 0.1 mm

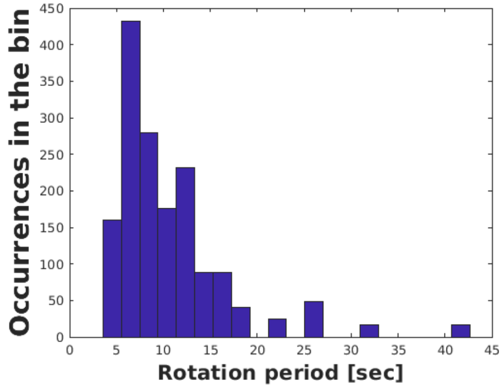
1600 rotating ellipsoidal particles ~ 0.1 mm in size

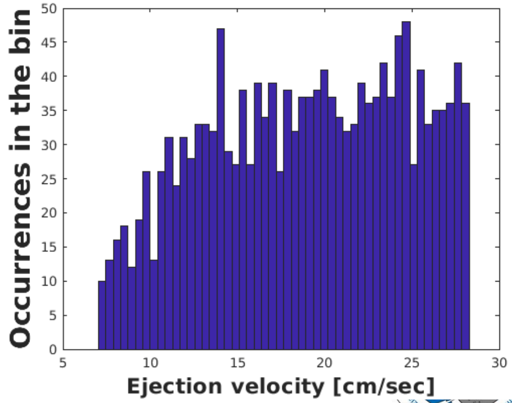
- Note: for this small sized particles the SRP becomes the dominant effect (w.r.t. the GM of the body) at about 4.4 Didymos radii.

- All the particles escape within 2 days from impact, quickly “blown away by SRP.



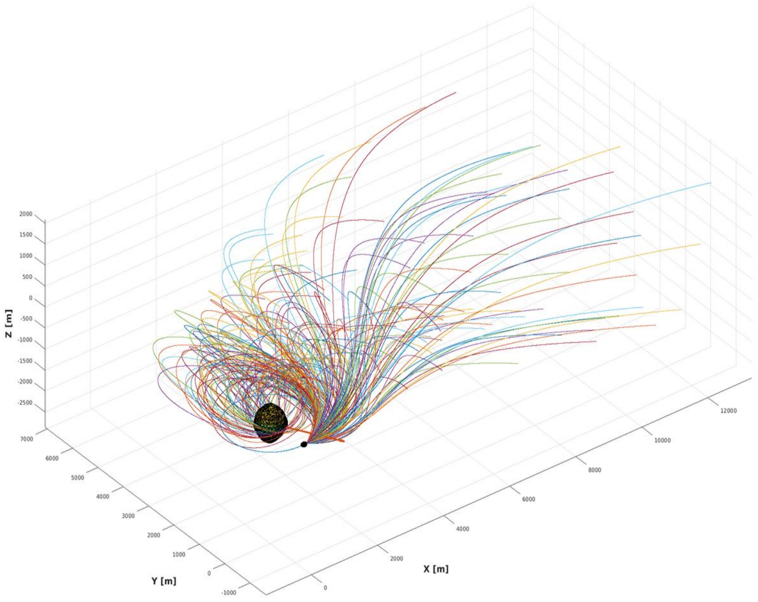


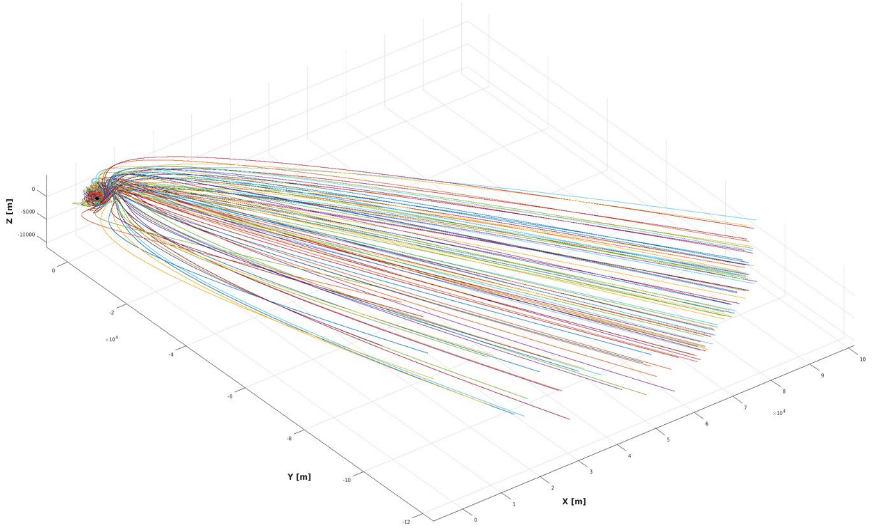




1 mm particles

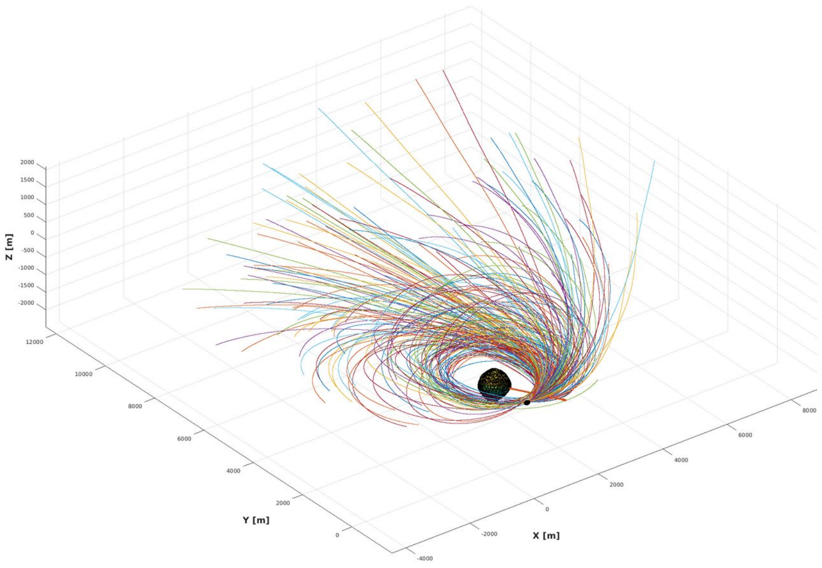
- 200 rotating ellipsoidal particles, ~ 1 mm
- Only ~ 18 % of the particles are left after ~ 6 days of integration
- ~ 50 % of the particles re-impact, all against Didymos
- ~ 22 % of the particles escape from the system
- *Longer time span under investigation*
- *1.1 day after impact* *~ 6 days after impact*

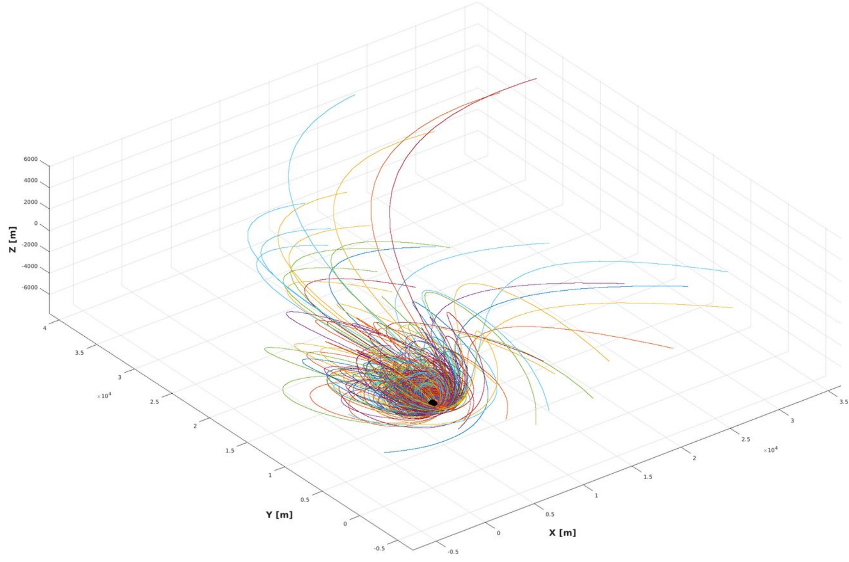




1 cm particles

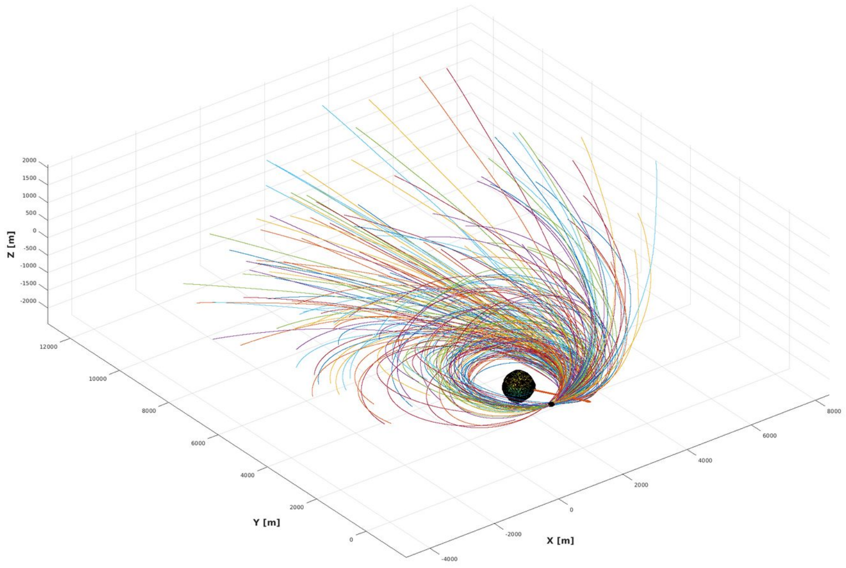
- 200 rotating ellipsoidal particles, ~ 1 cm
- ~ 15 % of the particles are left after ~ 8 days of integration
- ~ 75 % of the particles re-impact:
  - 98 % against Didymos
  - 2 % against Dimorphos
- *Longer time span under investigation*
- *~ 1.1 day after impact* *~ 8 days after impact*

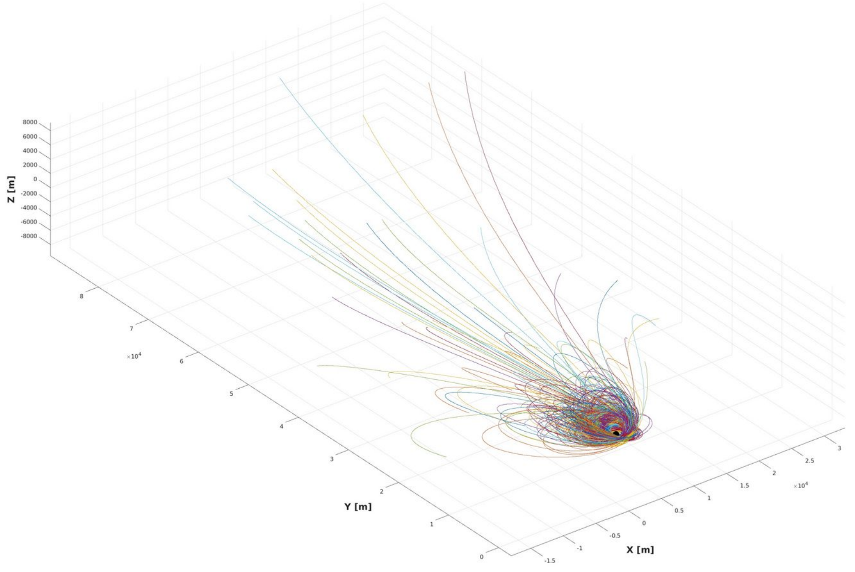




5 cm particles

- 200 rotating ellipsoidal particles, ~ 5 cm
- ~ 75 % of the particles are left after ~ 11.6 days of integration
- ~ 25 % of the particles re-impact:
  - 70 % against Didymos
  - 30 % against Dimorphos
- *Longer time span under investigation*
- *~ 1.1 day after impact* *~ 11.6 days after impact*





CONCLUSIONS and FUTURE WORK (1/2)

- A comprehensive model for the dynamics of the ejecta from the DART impact has been tested and validated. The model can be used for studying both short and long term ejecta dynamics.
- The main conclusions are:
  - The gravity potential computed with the polyhedron can be effectively substituted with the analytical formulation for nearly ellipsoidal bodies or when the distance from the central body is large enough to minimize the shape effects.
  - In order to explore the influence of the asteroid composition in the ejecta evolution, different impact simulations for less cohesive bodies (leading to smaller ejection velocities) shall be adopted.
  - Different models for the rotating particles in the SRP effect computation were tested. The three models give comparable results when looking at the global behavior over long time spans.
  - The dynamics of the particles appears extremely cahotic due to the repeated close encounters with either one of the asteroids.
  - Impact locations in the vicinity (around 10 degrees in latitude and longitude) of the default location lead to quite similar ejecta evolutions. Impacts in the Northern and Southern region appear to lead to more long lived particles (perhaps related to higher inclination orbits).

CONCLUSIONS and FUTURE WORK (2/2)

- The main conclusions are (Cont.ed):
  - Particles below 1 mm are quickly (~ 1 day) swept away by SRP .
  - Particles larger ≥ 1 mm show a growing percentage of longer living orbits.
  - Nonetheless, in the analyzed simulations, no particle survived in the system for more than ~ 45 days.

Future work will analyze:

- Different impact simulations
- Significantly longer time spans, looking also at the characterization of the observed chaotic behavior
- Orbital elements analysis of the surviving orbits to identify regions of stability (also in relation to the existing literature on the subject)

ACKNOWLEDGMENTS

This research was supported by the Italian Space Agency (ASI) within the LICIACube project
(ASI-INAF agreement AC n. 2019-31-HH.0).