Probing disruption heuristics for kinetic deflection of asteroids

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Motivation

Impulsive methods of deflecting asteroids come with an inherent risk of partially fragmenting or disrupting the asteroid, potentially resulting in multiple hazardous fragments being on an impact trajectory with Earth. A common rule of thumb to avoid accidental disruption has been that any impulse should apply a velocity change, dV, to the asteroid of less than 10% of its escape velocity, v_{esc} (e.g., Miller and Dearborn, 2015, *Handbook of Cosmic Hazards and Planetary Defense*). For purposeful robust disruption, where the entire asteroid is broken down into small, fast-moving fragments, the rule of thumb is a velocity change of more than 10 times the asteroid's escape velocity.

Here, we analyze various disruption heuristics using hydrocode simulations of kinetic impacts into asteroids, using the NASA/FEMA Tabletop Exercise 5 (TTX5) and the 2025 Planetary Defense Conference (PDC25) hypothetical scenarios as case studies. Simulations were designed to look at information available early in each exercise when uncertainties were large. They demonstrate the importance of a reconnaissance mission ahead of a mitigation attempt.

Methodology

Spheral++ Github:

- TTX5:

	Diameter [m]	Density [kg/m³]	Mass [kg]
90th %ile	450	1993	9.54E+10
50th %ile	226	2006	1.21E+10
10th %ile	125	1992	2.04E+09

To deflect the 90th percentile object, using a Falcon Heavy to launch, keeping each individual impulse below 10% escape velocity with a β of 2, and launching as soon as possible, seven impactors would be required. The first impactor, modeled here, would be 10726 kg and have a closing velocity of 10.24 km/s.

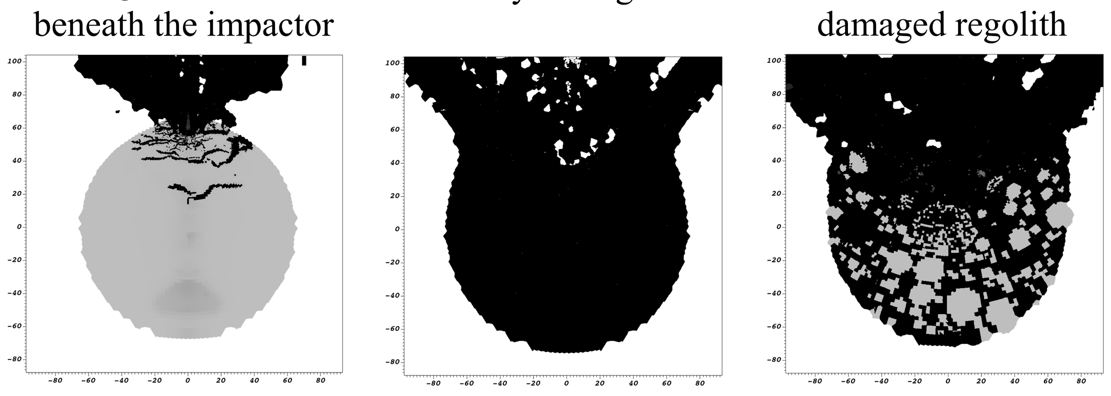
- PDC25:

	Diameter [m]	Density [kg/m³]	Mass [kg]
100th %ile	278	2794	3.13E+10
95th %ile	191	2417	8.84E+09
50th %ile	127	2062	2.21E+09
5th %ile	77	1886	4.52E+08

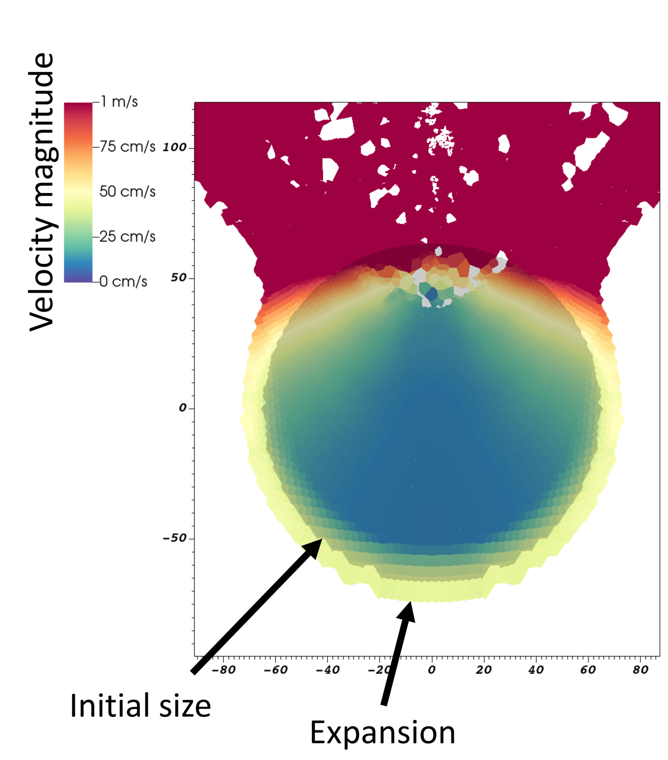
To deflect the 100th percentile object, using a Falcon Heavy to launch, keeping each individual impulse below 10% escape velocity with a β of 2, and launching as soon as possible, four impactors would be required. The first impactor would 4707 kg and have a closing velocity of 12.47 km/s.

- Simulations were performed in 3D using the smooth particle hydrodynamics code Spheral++ (Owen et al., 1998, *Astro. J*).
- The kinetic impactor was modeled as a solid aluminum sphere.
- The asteroid was modeled using a forsterite (Mg_2SiO_4) equation of state (M-ANEOS, Stewart et al., 2019, *Zenodo*).
- Each simulation included n-body self-gravity.
- The strength model for the asteroid was the Collins et al. (2004, *MPS*) pressure-dependent strength model. Parameters were varied to understand their affects on the outcome of the impact.
- The damage model describing fracture was adapted from Benz and Asphaug (1994, *Icarus*) with Weibull damage parameters tuned to match experiments on Aba Panu meteorite material.
- A model describing how porosity compacts was included for all simulations. Initial porosities of different materials were varied across simulations.
  - For TTX5, we used the strain-alpha porosity model of Wuennemann et al. (2006, *Icarus*) with the thermal correction of Collins et al. (2011, *IJIE*).
  - For PDC25, we used the P-alpha porosity model. Two different sets of parameters were explored, one approximating lunar regolith and one utilized by Raducan et al. (2024, *PSJ*) for models of a Dimorphos-like asteroid.
- The resolution of each simulation was set to be 10 cm at the impact site, with concentric shells of particles increasing in size by 2% in each shell.
- Several parameters were varied, including asteroid shape, cohesive strength of damaged material, crush curve, and initial geologic state.

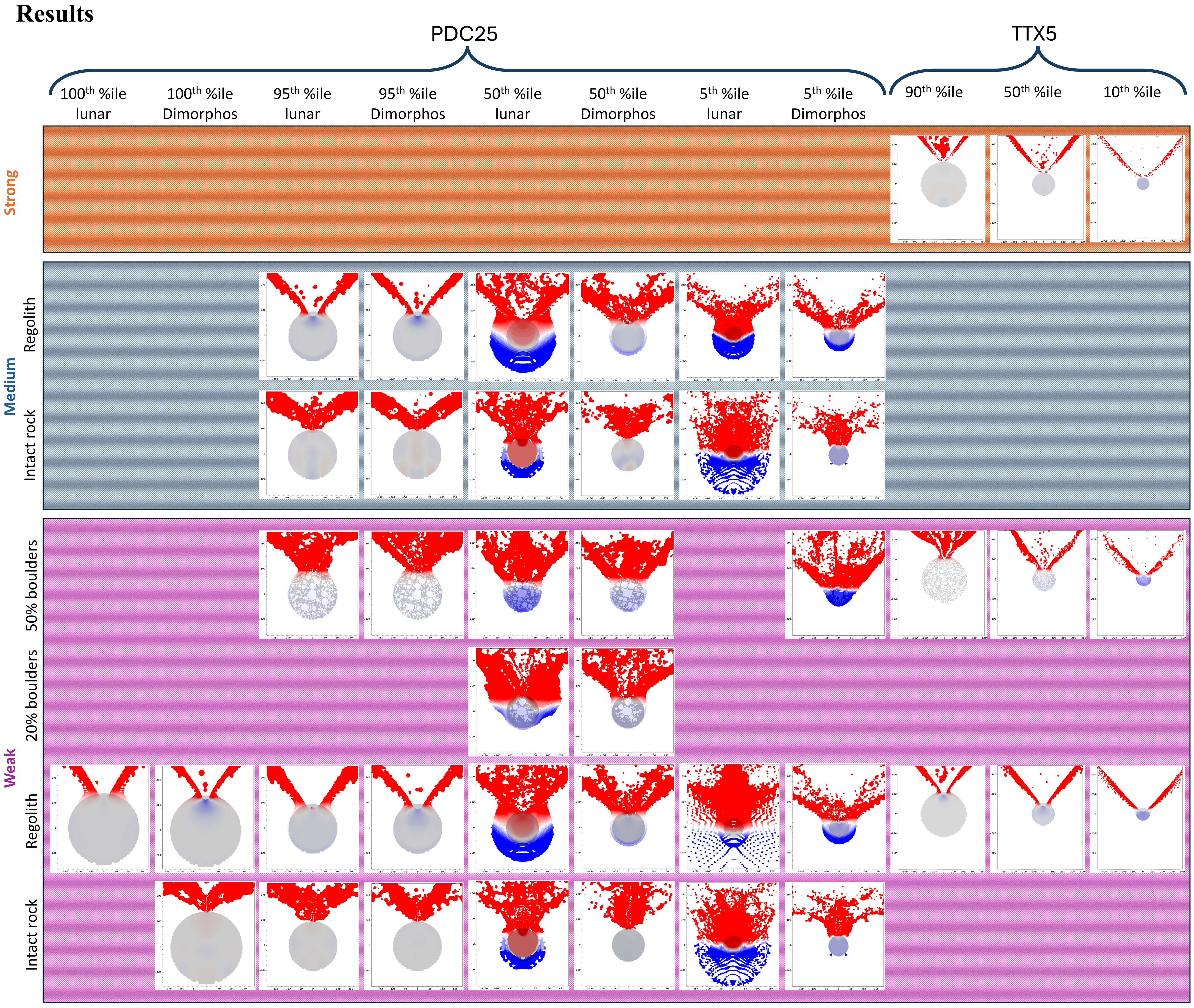
Intact rock is initially undamaged and fractures beneath the impactor | **Regolith** is initially fully damaged | **Rubble piles** are intact boulders + damaged regolith

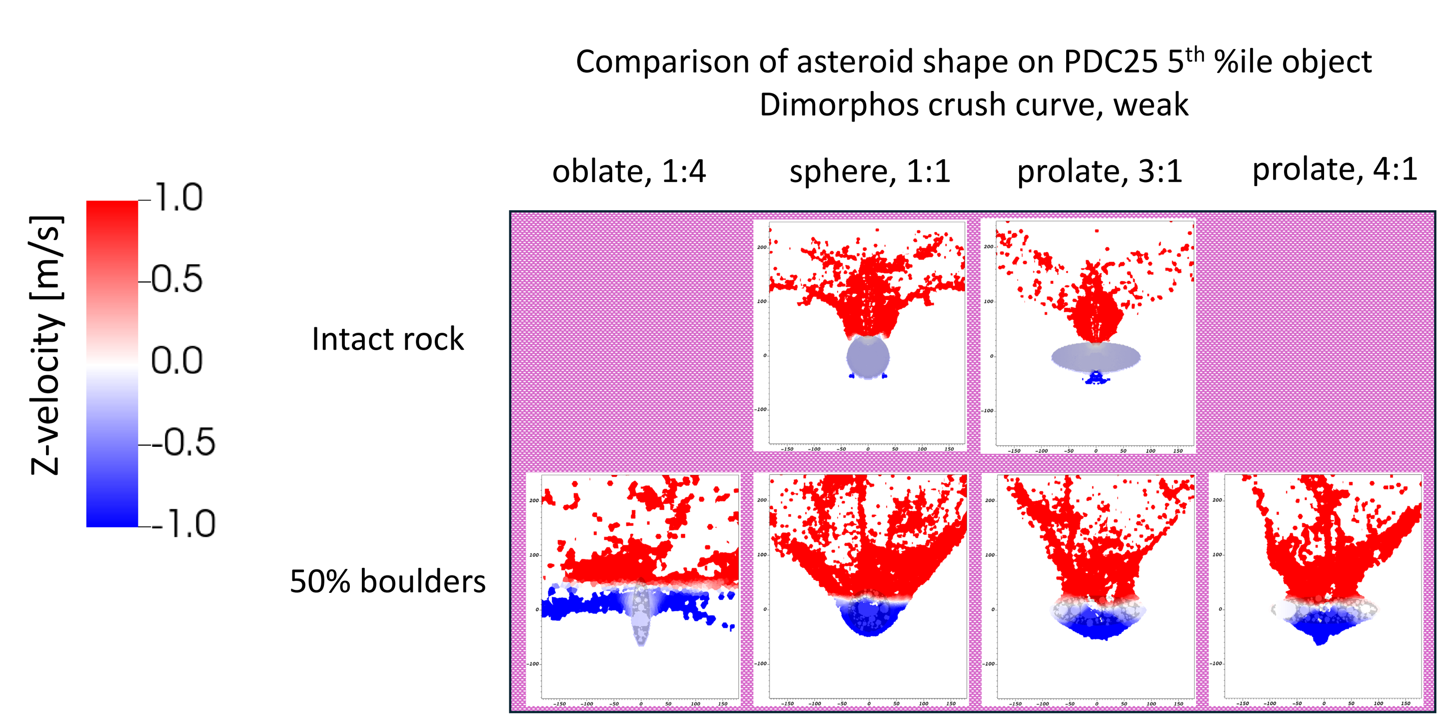


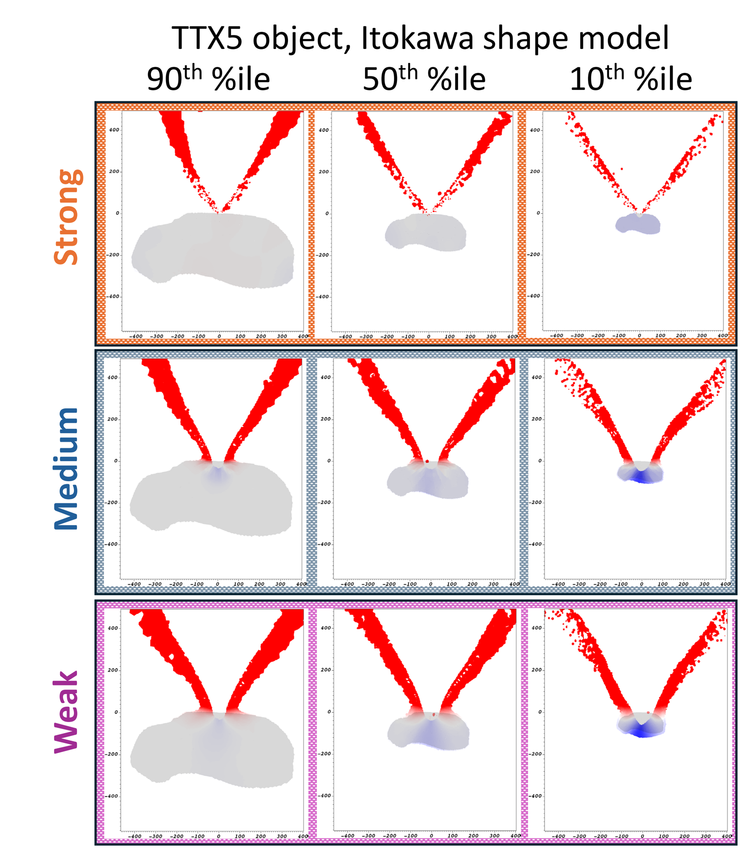
- Simulations were halted prior to reaching post-impact equilibrium due to computational cost. Therefore, disruption in this study is defined as a qualitative assessment of whether the asteroid is expanding compared with its initial shape, particularly in regions away from the impact site.



Results



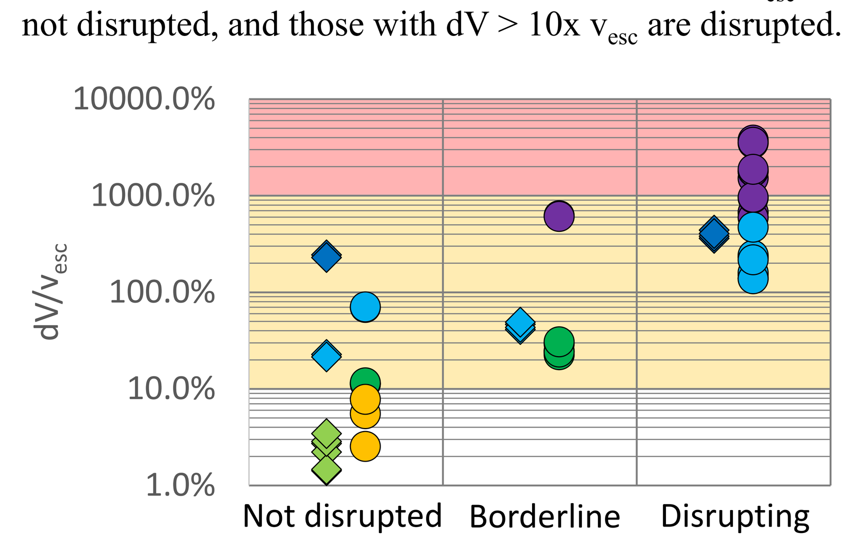




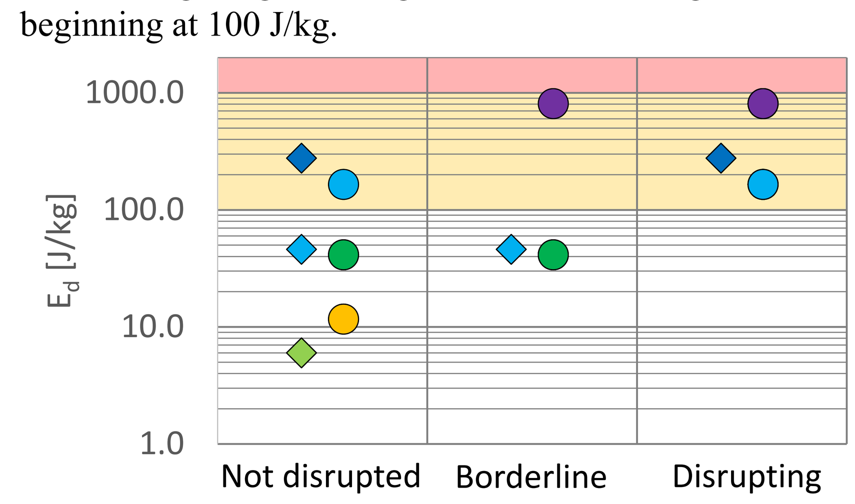
Summary: Comparisons of simulation results to disruption heuristics

TTX5: ◆ 10th %ile ◆ 50th %ile ◆ 90th %ile **PDC25:** ● 5th %ile ● 50th %ile ● 95th %ile ● 100th %ile

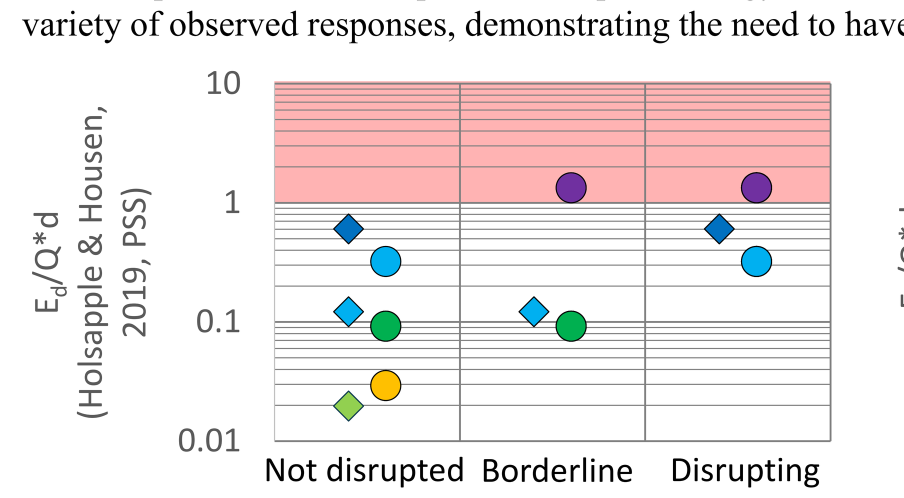
Comparing dV heuristics to our qualitative assessment of disruption suggests these metrics are conservative but accurate. Simulations with an asteroid dV < 10% v_{esc} are not disrupted, and those with dV > 10x v_{esc} are disrupted.

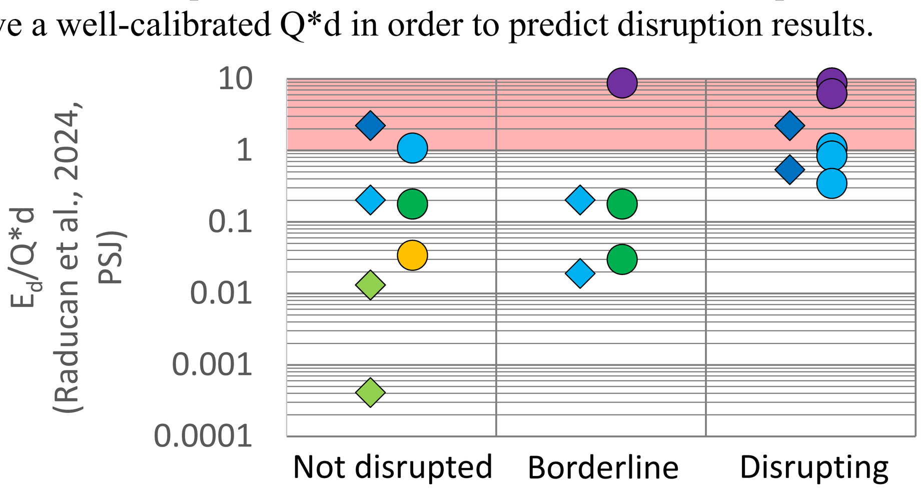


E_d is the specific energy of impact, i.e., the energy of the impactor per unit mass of the asteroid. If the specific energy exceeds 1000 J/kg, the asteroid is considered to have undergone global fragmentation, with fragmentation beginning at 100 J/kg.



Q*d is the specific disruption energy, i.e., the energy required to disrupt an asteroid per unit mass of that asteroid. There are multiple formulations for this value, typically functions of asteroid size and impact angle and calibrated to a set of asteroid properties. Here we examine two formulations: Holsapple and Housen's (2019, PSS) formulation for S-type asteroids and Raducan et al.'s (2024, PSJ) formulations for Dimorphos-like asteroids with appropriate boulder fills. If the specific energy of the impact exceeds the specific disruption energy, the asteroid is disrupted. Neither criterion examined here captures the variety of observed responses, demonstrating the need to have a well-calibrated Q*d in order to predict disruption results.





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