Impact Simulations Provide Critical Information to Constrain Dimorphos's Material Properties and Better Understand the DART Impact

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DART

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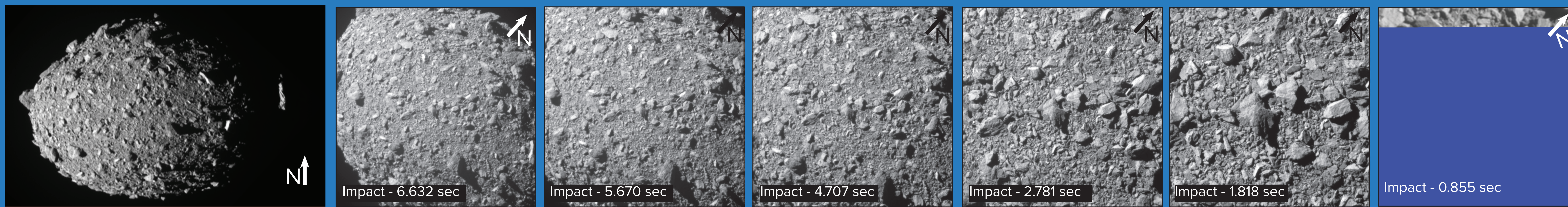
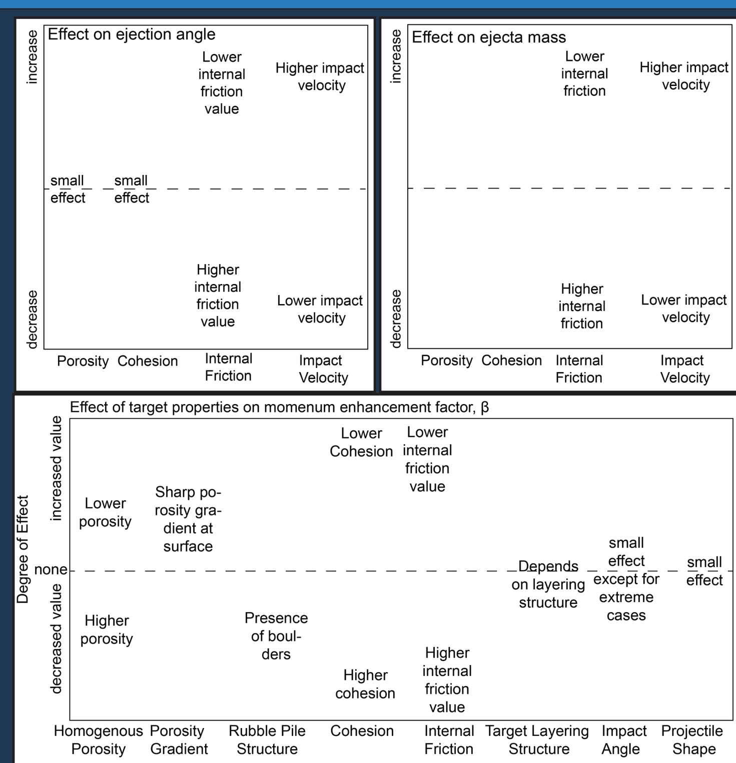


Pre-impact Predictions

The DART Impact Modeling Working Group examined a variety of material properties and ejecta parameters that could affect results of the DART impact. The most important material properties for ejecta behavior and momentum enhancement (β) are: material yield strength (cohesion), internal friction angle, porosity, and target structure. [Stickle et al., 2022]

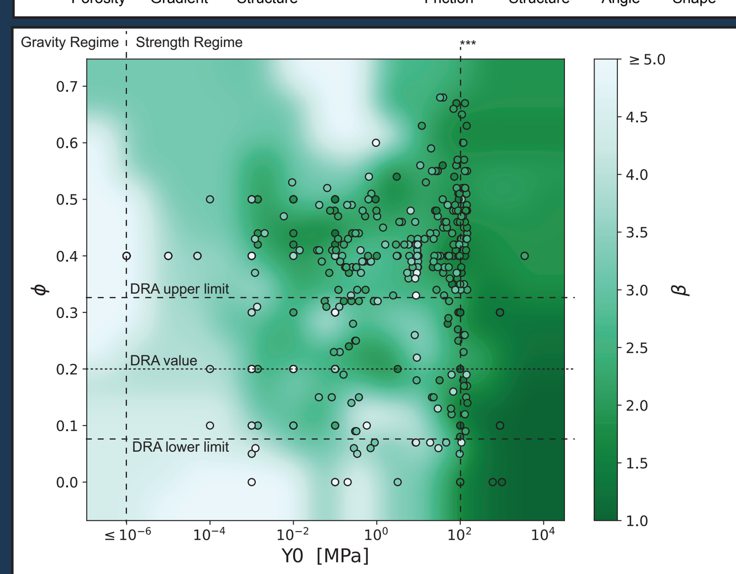


Summarizing over 5 years of modeling efforts, the DART Impact Modeling Working Group predicted:

1 < β < ~5

(right) Contour plot showing a subset of simulations and how β was affected by target yield strength (cohesion) and porosity.

*** meteorite strength [Cotto-Figueroa (2016)]

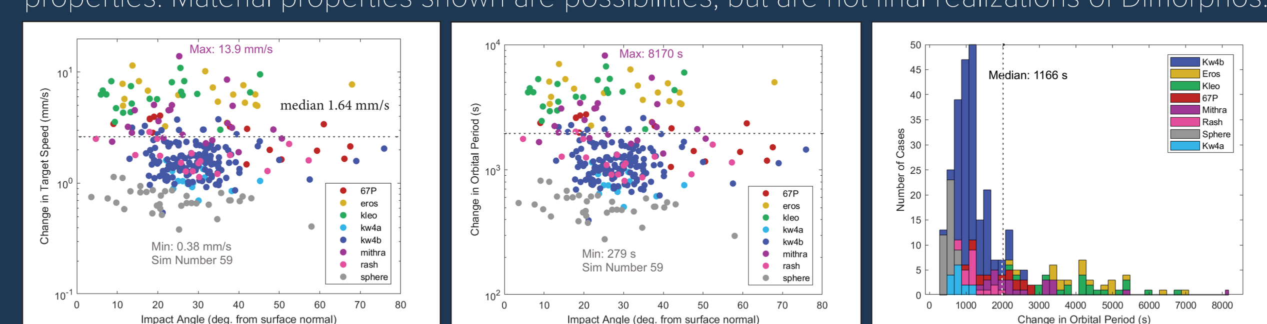


Pre-Impact Modeling Efforts Provide Intuition about Material Properties

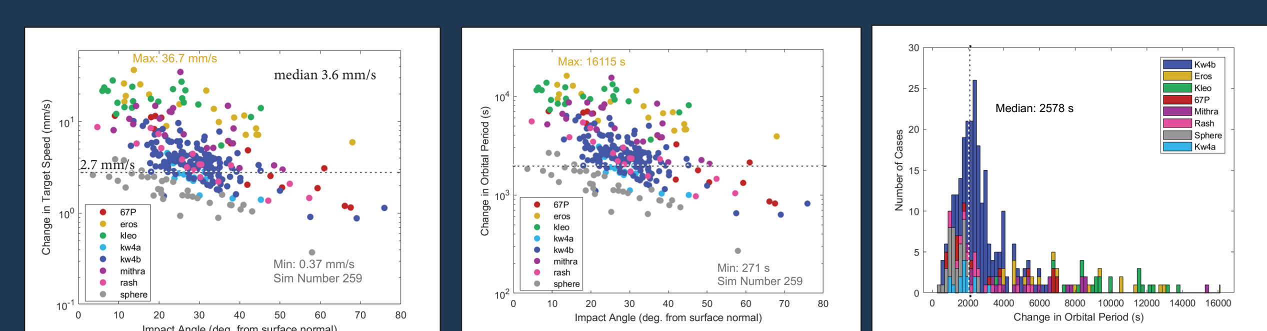
Prior to impact, The DART Impact Modeling Working Group performed a variety of simualtions to determine the momentum enhancement factor, β, as a function of material properties. Hundreds of simulations provided information about key material properties and their effects on momentum enhancement and ejecta behavior (left). These were used as starting points to understand the DART observations.

Determining Dimorphos's Material Properties

Measured period change, Δv, β, are in line with pre-impact simulations using a variety of material properties. Material properties shown are possibilities, but are not final realizations of Dimorphos.

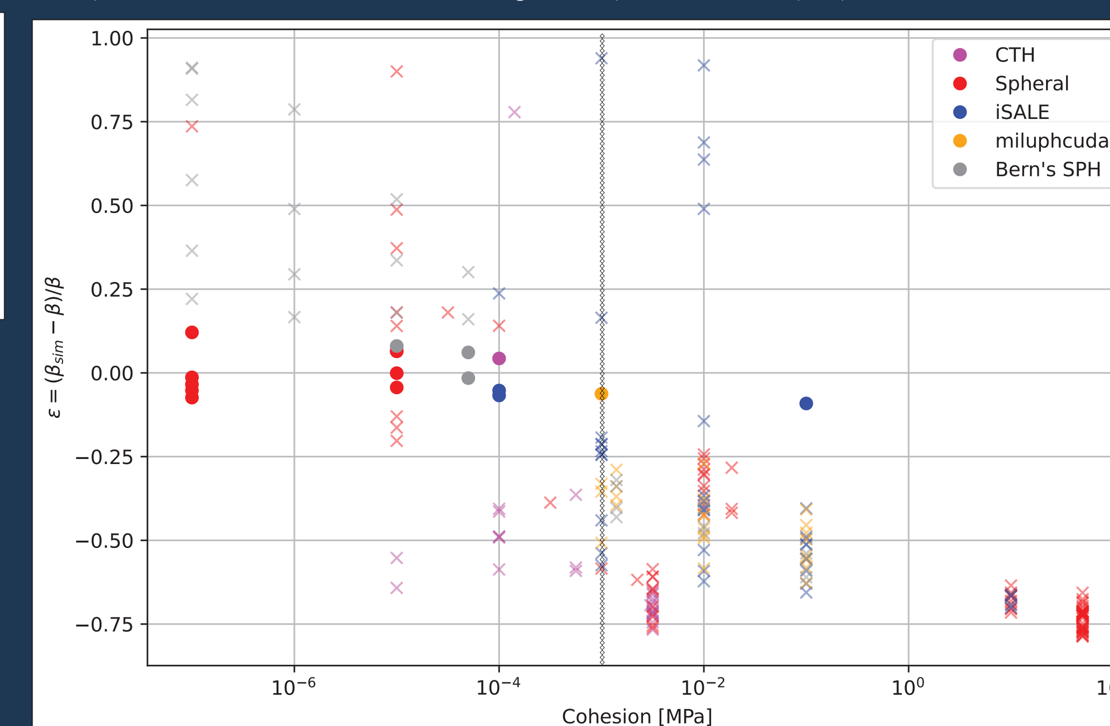


Spacecraft mass = 557 kg, asteroid density = 2170 kg/m³ (~24% porosity), designed as low ejecta end member



Spacecraft mass = 557 kg, asteroid density = 2820 kg/m³; designed as "lots of ejecta" end member

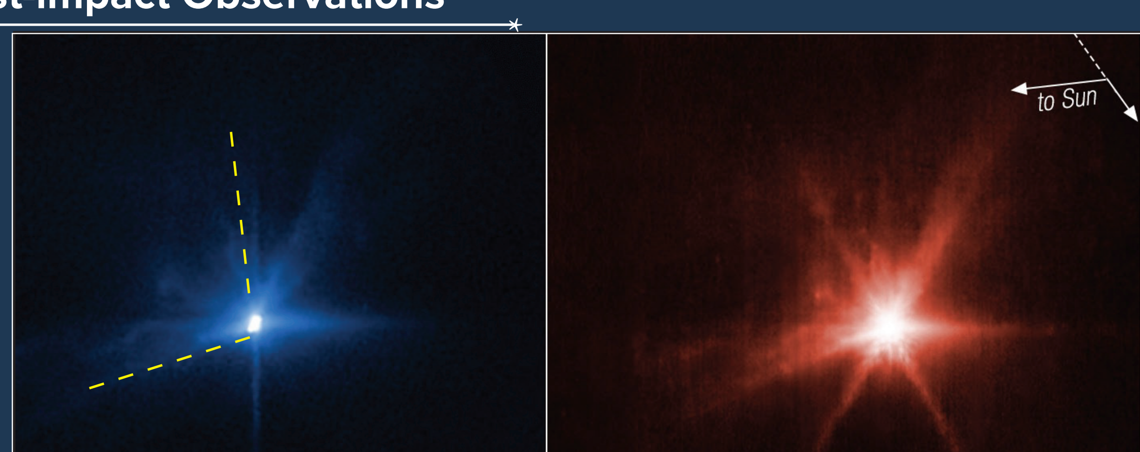
Evaluating results from pre-impact simulations against DART mission observations can provide first cuts at understanding Dimorphos material properties



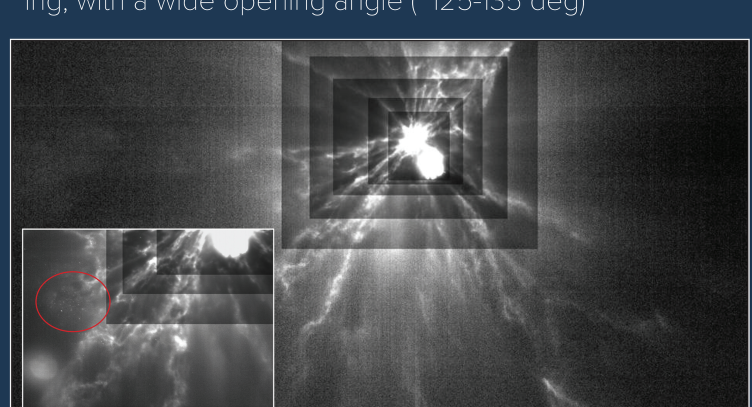
The mismatch between simulated (β_{sim}) and observed β-value as $\varepsilon=(\beta_{sim}-\beta)/\beta$ as a function of individual material properties.

No clear dependence of ε on friction coefficient or target porosity is apparent. There is a clear negative correlation between ε and the cohesion (yield strength of the target at zero pressure). Simulations that predict a β-value consistent with the DART outcome to within 2σ used target cohesion of ≤ 1 kPa

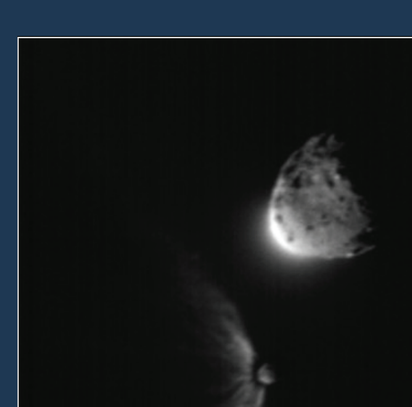
Post-impact Observations



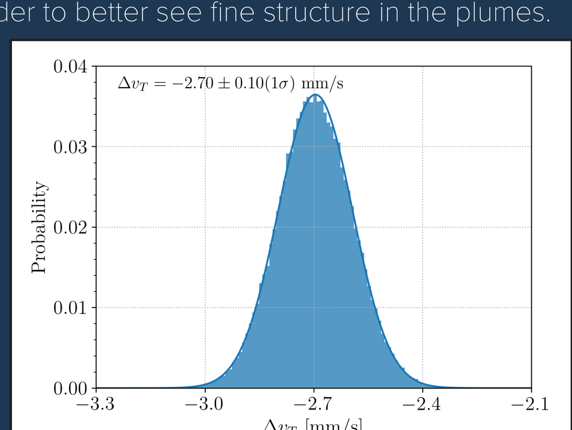
Hubble (left) and JWST (right) images following DART's impact show ejecta cone expanding, with a wide opening angle (~125-135 deg)

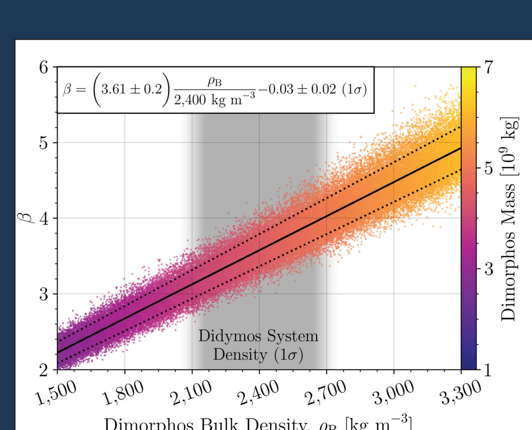


Enhanced LICIACube image following DART's impact shows complex ejecta and potential ejected boulders. Each rectangle represents a different level of contrast in order to better see fine structure in the plumes.



LICIACube image just after closest approach, showing the ejecta structure from behind

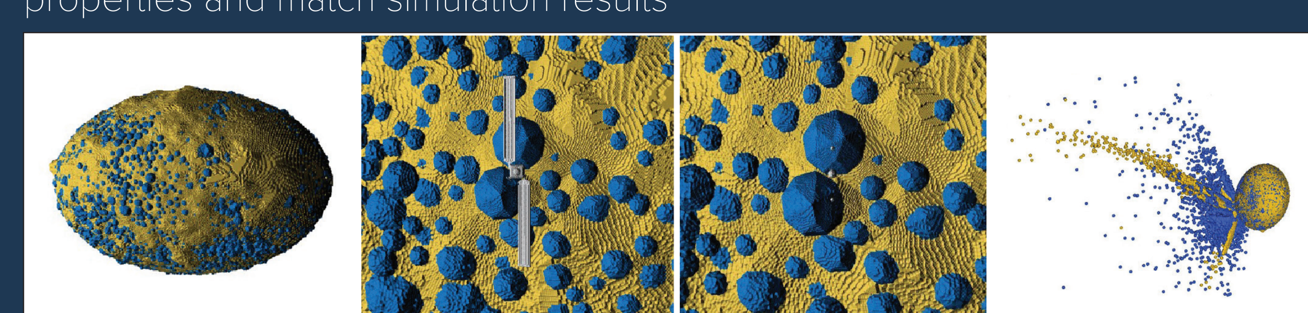




Post-DART simulations provide estimates for a mean vT of -2.70 mm/s ±0.10 mm/s (left), and a model for beta as a function of density (right) [Cheng et al. 2023].

Post-Impact Impact Modeling Efforts

The DART Impact Modeling Working Group is currently running a variety of simualtions to determine the momentum enhancement factor, β, and to constrain the material properties of Dimorphos by matching observations. Constraints outside of β and Δv are required to fully constrain Dimorphos material properties and match simulation results



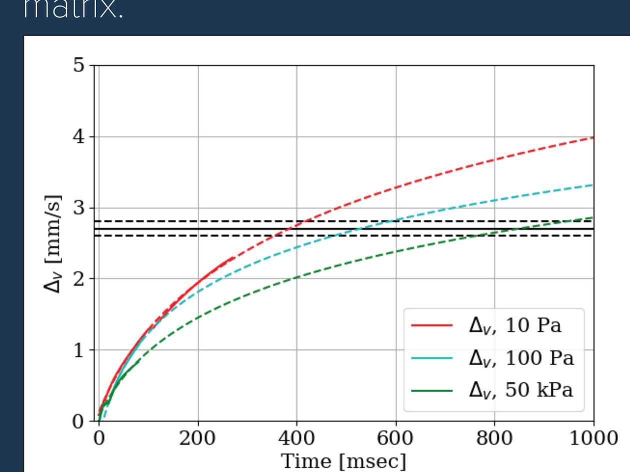
Impact simulations with realistic geometry, boulder fields, and reasonable material properties re-produce many of the DART observations

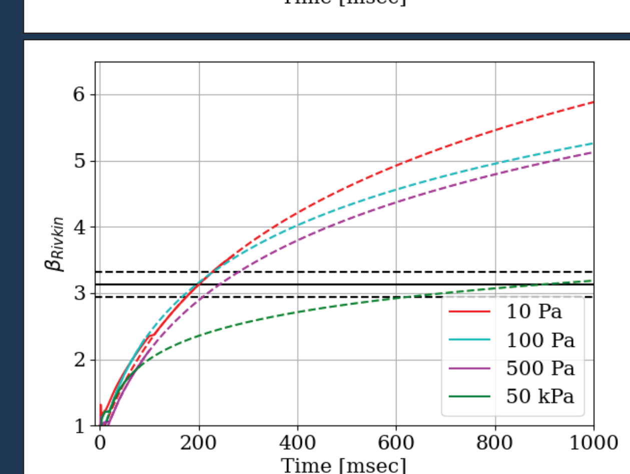
Key observations to help constrain parameters:

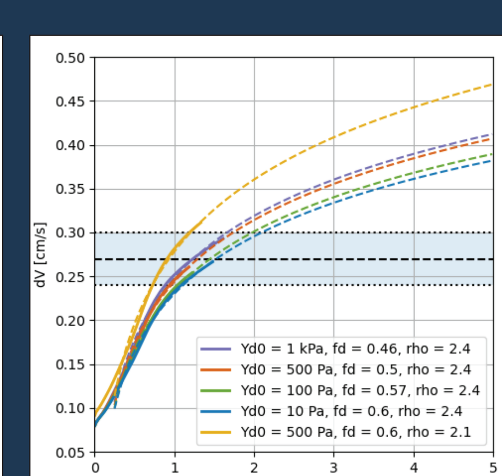
- Boulder strewn surface
- Wide Ejecta Cone
- Long-lived Ejecta formation
- Complex ejecta patterns
- Ejecta Rays
- Deflection Velocity and period change

Determining Dimorphos's Material Properties

A suite of initial simulations using "very" weak to "moderately" weak matrix material provides insight into potential strength of Dimorphos matrix.`



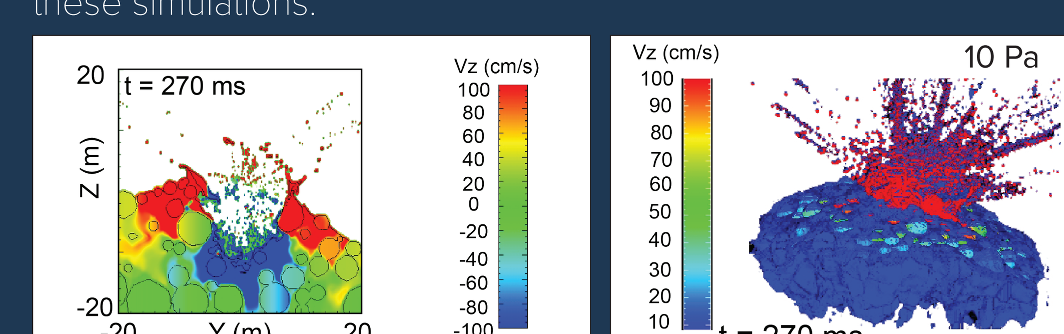




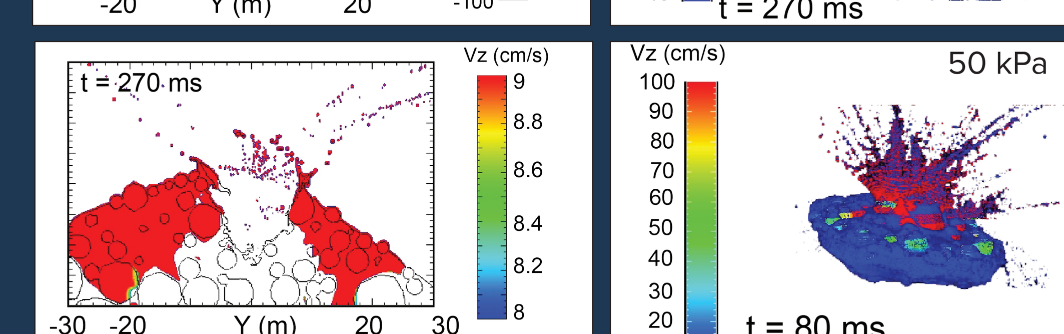
Here, matrix strength values < 10s kPa provide too large of a velocity change compared to DART observations. This trend is seen for the first few hundred milisec and out to later times. A strength of ~50 kPa provides a better fit to observations and β

Estimating Crater Size

Initial simulations can put an upper bound on expected crater size, which can be tested by Hera! Matrix strength of 10 Pa provides an appropriate upper limit to crater size for these simulations.



(top) All material with velocity > 1 m/s for 10 Pa matrix . Crater diam ~ 50-60 m



(bottom) All material with v > 1 m/s for a 50 kPa matrix, which matched Δv observations the best. Diameter is ~40m

Crater size is estimated by looking at all material moving away from Dimorphos faster than the escape velocity (~ 9 cm/s). (above) material is colored red that would escape.

Upper limits suggest crater diameter ~50 m

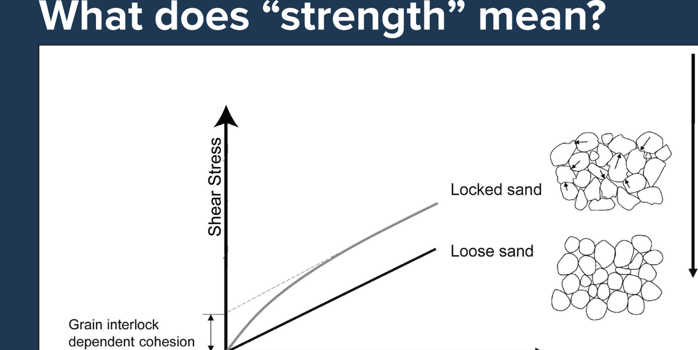
Interpreting Impact Simulations

Key observations to help constrain parameters:		Simulation Setup or Result:
Boulder strewn surface	✓ →	Simulated boulder strewn surface
Wide Ejecta Cone	✓ →	Result: Wide Ejecta Cone comes from boulder interaction and target curvature
Long-lived Ejecta formation	? →	Result: Nearly strengthless surfaces produce too large of a push
Complex ejecta patterns	✓ →	Result: Complex ejecta patterns result from boulders and irregular surface
Ejecta Rays	✓ →	Result: Ejecta Rays result from complex surface and boulders
Deflection Velocity and period change	? →	Result: Deflection Velocity and period change can be matched for "moderately" weak matrix material

Other Complicating Factors

- Structure/Boulders at and near the surface provide additional complications to unravel
- Boulder position and size can substantially affect the ejecta mass-velocity distribution and momentum transfer efficiency of the impact
- "Strength" is a nebulous word in impact cratering
- No evidence for fines at surface of Dimorphos
- What is the "strength" of the surface or boulders, then?
- The complex DART spacecraft geometry can influence cratering and alter momentum enhancement and ejecta properties

What does "strength" mean?



Irregular boulders on Dimorphos could lead to higher "strength" of material as they interact. The higher the degree of interlock, the higher the curvature of the strength envelope at low normal stress, and the higher the grain interlock-dependent cohesion [after Bahrani and Kaiser (2020)]

References: Stickle et al. (2022). *The Planetary Science Journal*, 3(11), 248.; Cotto-Figueroa, D., et al. (2016) *Icarus*, 277, pp.73-77. Bahrani and Kaiser (2020) *Journal of Rock Mechanics and Geotechnical Engineering*, 12(6), pp 1152-1170; Cheng et al. (2023) *Nature*