7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Session 7b: Deflection & Disruption Testing

Chairs: Patrick Michel | Angela Stickle | Megan Syal

Presenters: M. Burkey | A. Stickle | C. Raskin |
M. DeCoster | M. Owen

Progress on Developing a Simplified Model of X-Ray Energy Deposition for Nuclear Mitigation Missions

Planetary Defense Conference, April 28th 2021

Mary Burkey

Rob Managan, Kirsten Howley, Nick Gentile,
Megan Bruck Syal, Mike Owen

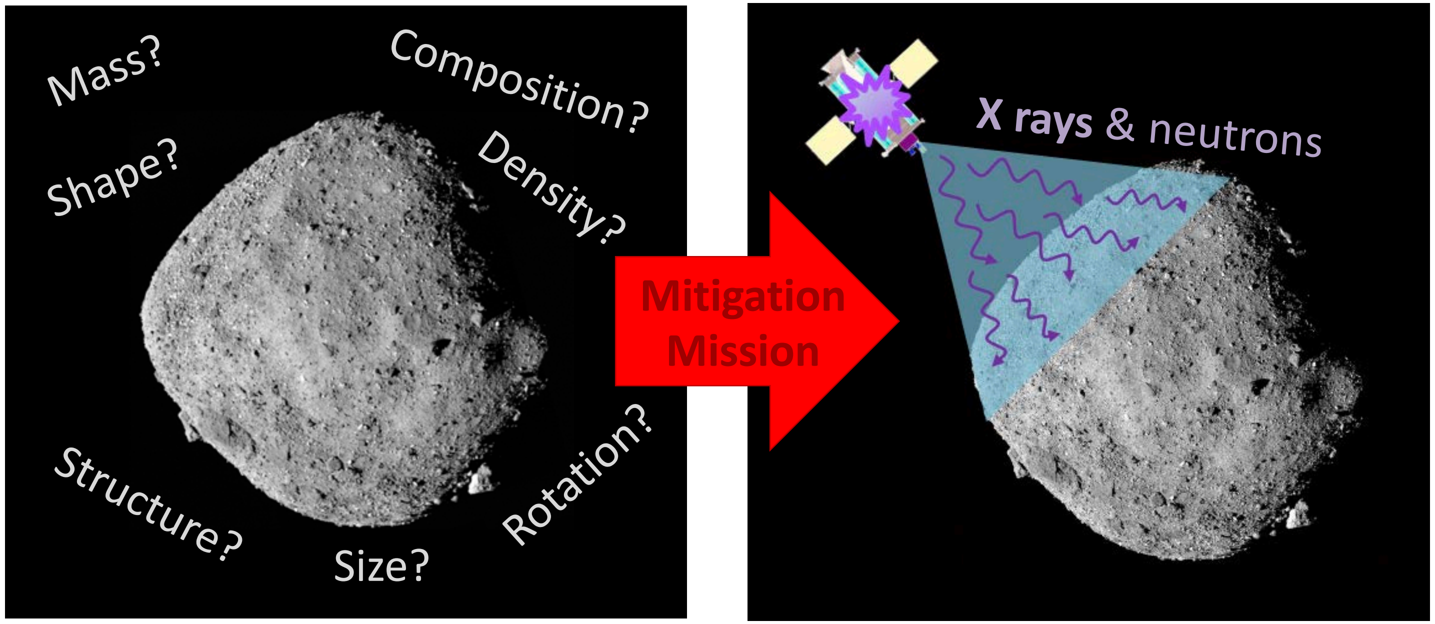
LLNL-PRES-821486

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

An Option for Planetary Defense: Nuclear Deflection/Disruption

- A nuclear mitigation mission is dependent on many asteroid properties that may be poorly constrained before launch.



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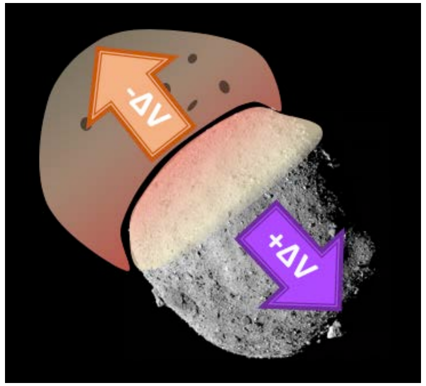
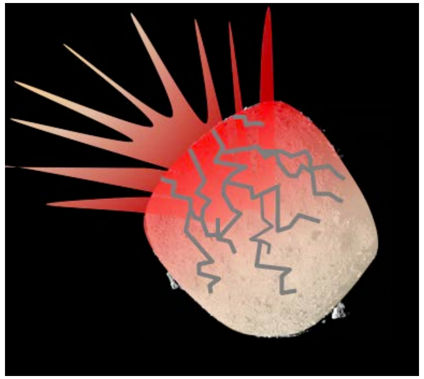


Successful Deflection Mission: asteroid remains intact and misses Earth

X

Failed Mission: asteroid breaks into slow-moving fragments that could hit Earth

✓



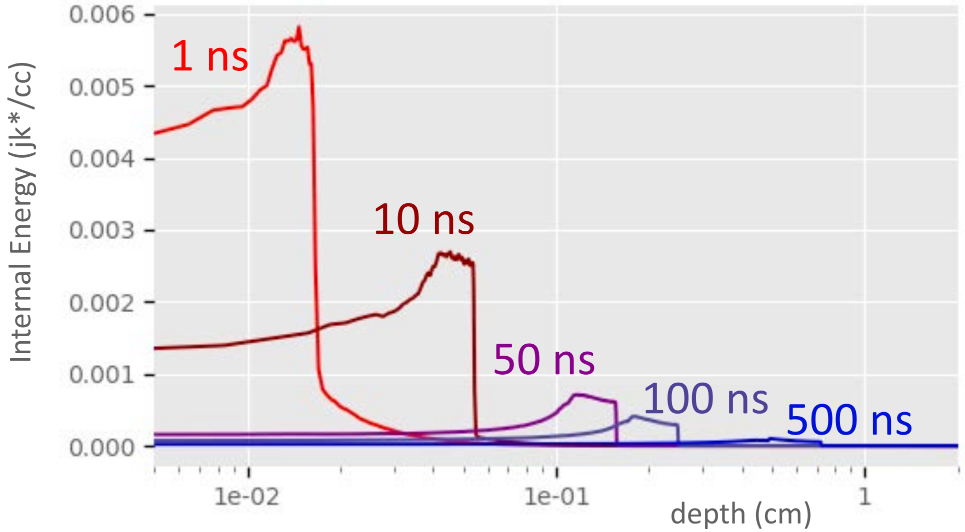
Successful Disruption Mission: asteroid is blasted into many small, fast-moving fragments

Bennu: photo from the NASA OSIRIS-REx mission

A problem with two parts

X-Ray Energy Deposition

- X rays penetrate 1 µm – 1 cm into the material, causing heating and ionization. Some energy re-radiates away.
- Only a full radiation-hydrodynamics code can cover all the physics that is happening in this process.



Hydrodynamics

- Everything that happens after the energy deposition.
- The deposited energy causes material to begin moving and expanding.
- At this point, only a standard hydrocode is needed to follow the material's movement and energy.

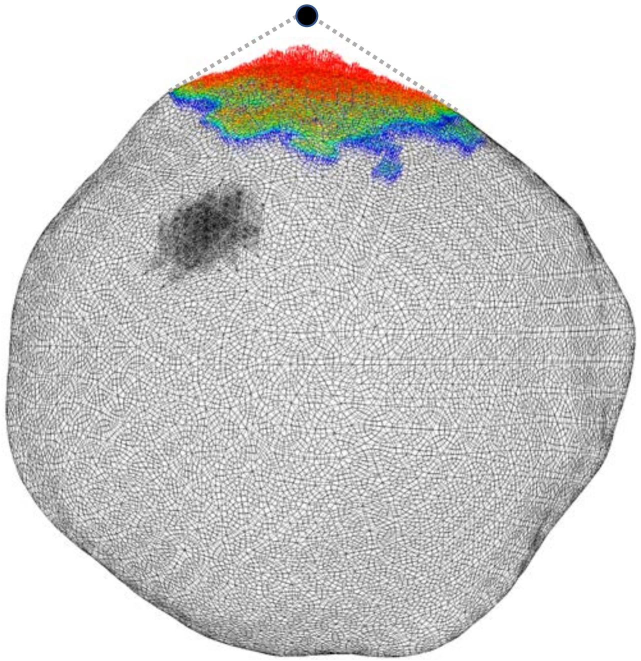


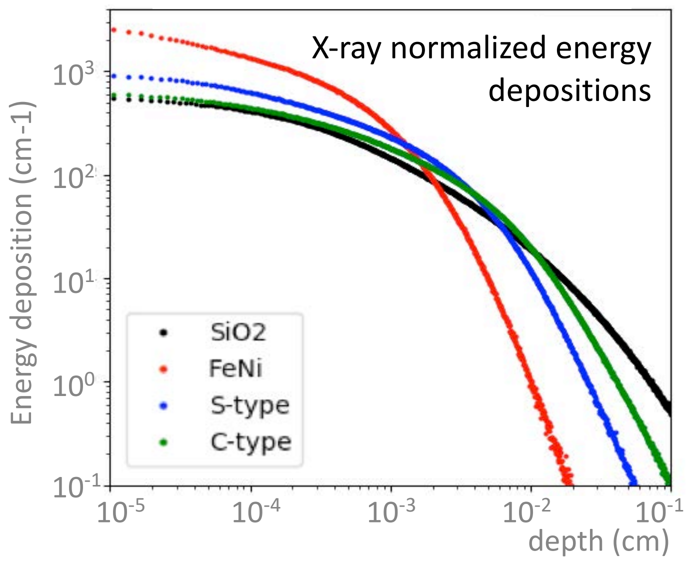
Image credit: Megan Bruck Syal
*1 jerk = 1e16 ergs

Nuclear Deflection/Disruption Modeling: X-ray Energy Deposition

Old Way: Mercury

Mercury is a Monte Carlo particle transport code, which works well for neutron energy deposition

- ✓ Easy-to-fit energy depositions
- ✓ profiles can be easily scaled by yield and angle of incidence
- ✗ Cold opacities assumed
- ✗ **No re-radiation**
- ✗ **No radiation-hydrodynamics coupling**

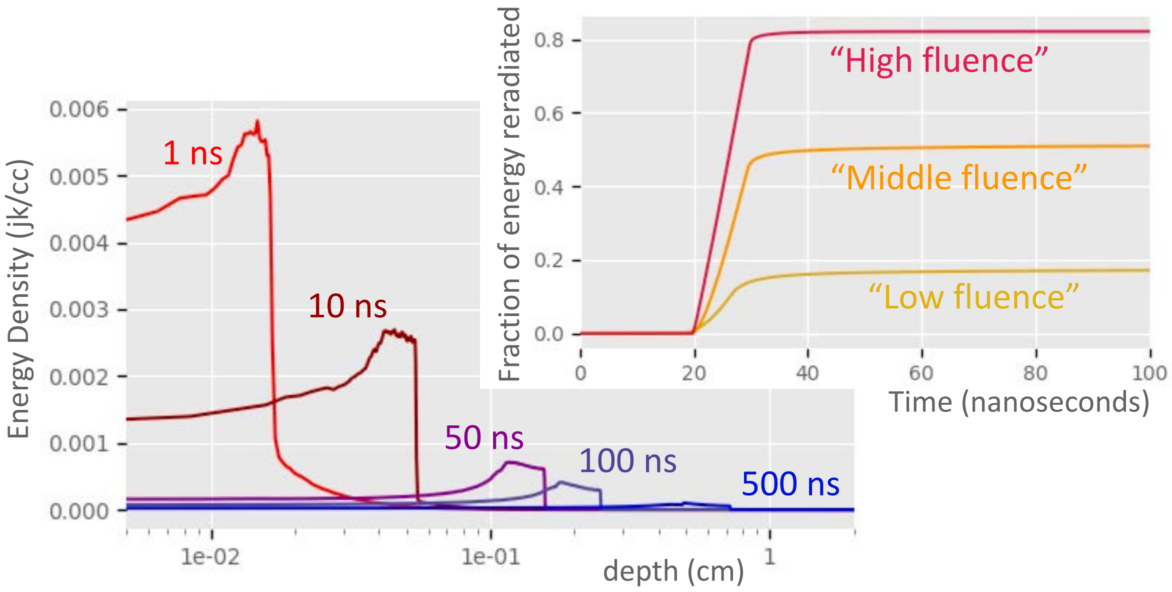


$$f(x,\chi) = \frac{1}{\cos(\chi)} \sum A_i \exp\left(\frac{-x}{\lambda_i \cos(\chi)}\right)$$

New Way: Kull

Kull is a mesh-based radiation-hydrodynamics code that was developed for High Energy Density Physics

- ✓ Includes re-radiation and rad-hydro effects!
- ✓ Uses best-available opacities
- ✗ No more easy fits



1D Kull Energy Deposition Tests:

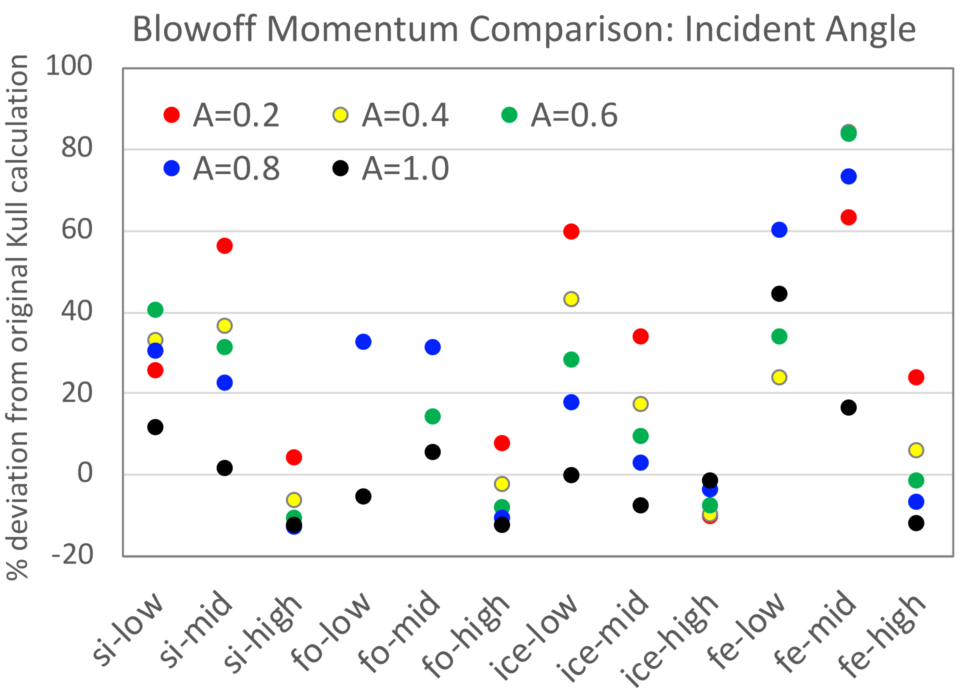
Scope of Study:

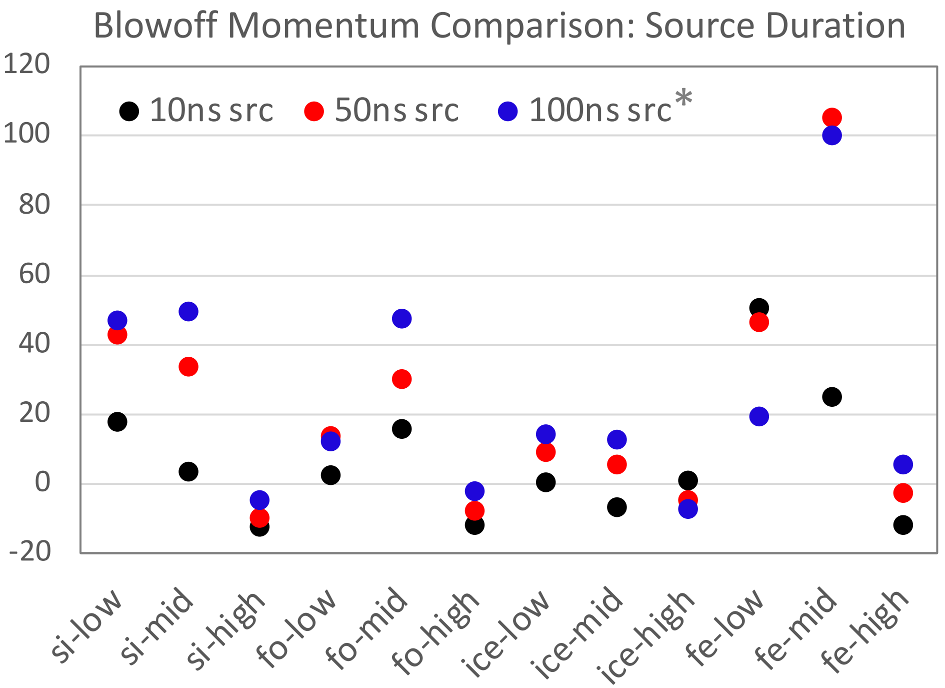
Materials
Silicon Dioxide (SiO_2)
Forsterite (Mg_2SiO_4)
Ice (H_2O)
Iron (Fe)

Source
1 keV Black Body at 4 Fluences:
Low – 1e-4 kt/m^2
Mid – 2.5e-3 kt/m^2
Mid-High – 0.12 kt/m^2
High – 1 kt/m^2

Test Asteroid/Case:
R=150m, Standoff=50m

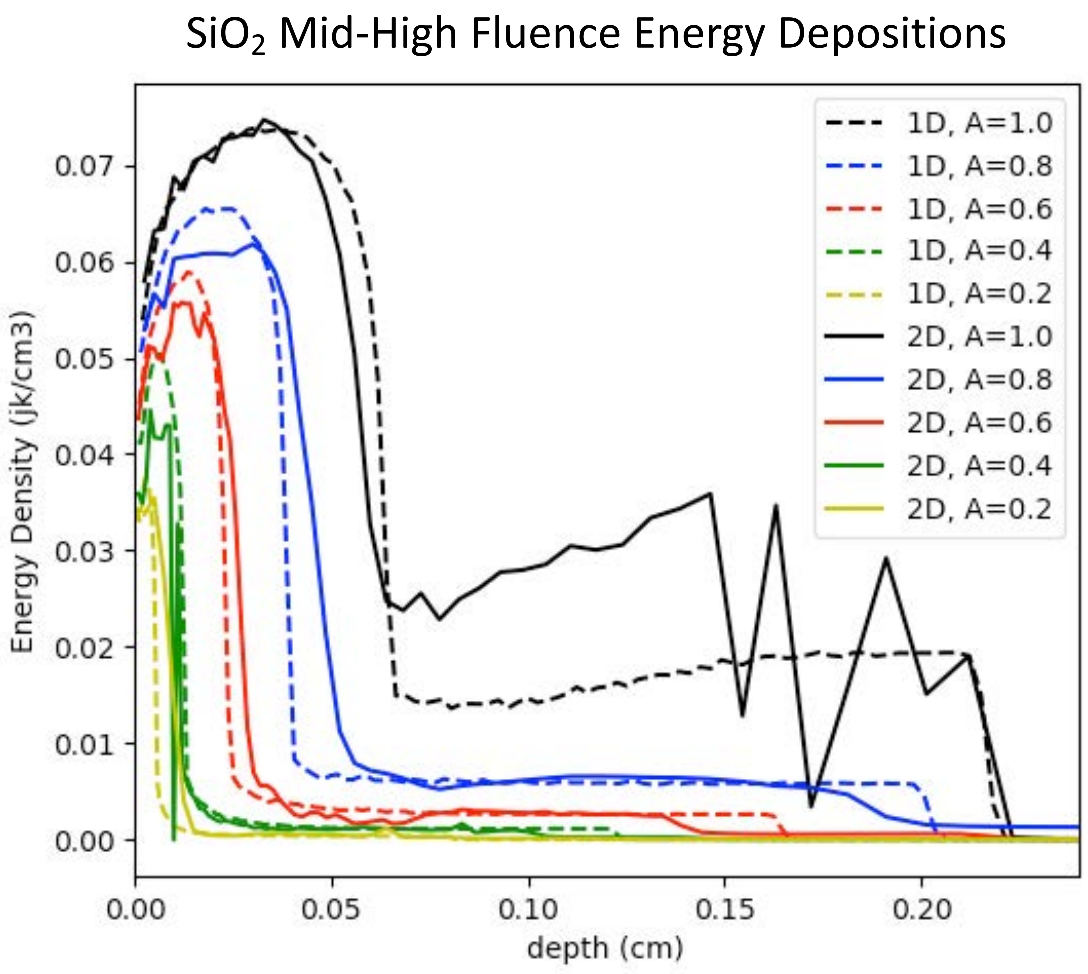
Can we initialize Kull with a Kull-generated energy profile at a specific time and get roughly the same answer as a normal Kull simulation?





We can in most cases reproduce the pure Kull blowoff momentum to within ±50%.

Level Up: 2D Kull Energy Deposition Tests

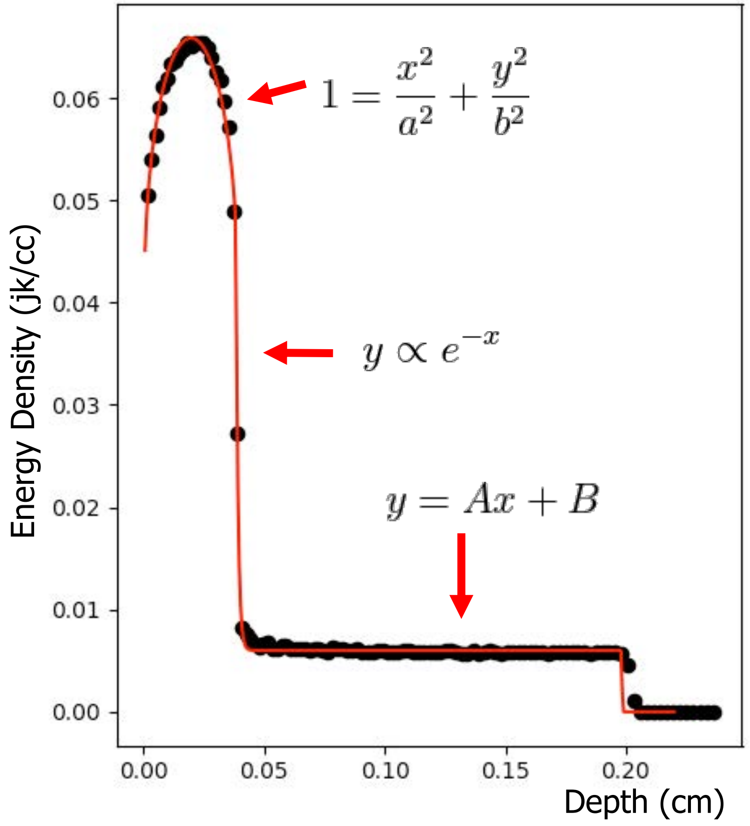


Fluence Level	Low	Mid	Mid-High	High
2D blowoff momentum (g cm/µs)	4.66e6	3.81e7	4.65e8	1.98e9
1D integrated blowoff momentum (g cm/µs)	4.74e6	3.92e7	4.55e8	1.91e9
Time after "detonation" (µs)	1.36	5.0	3.48	2.19

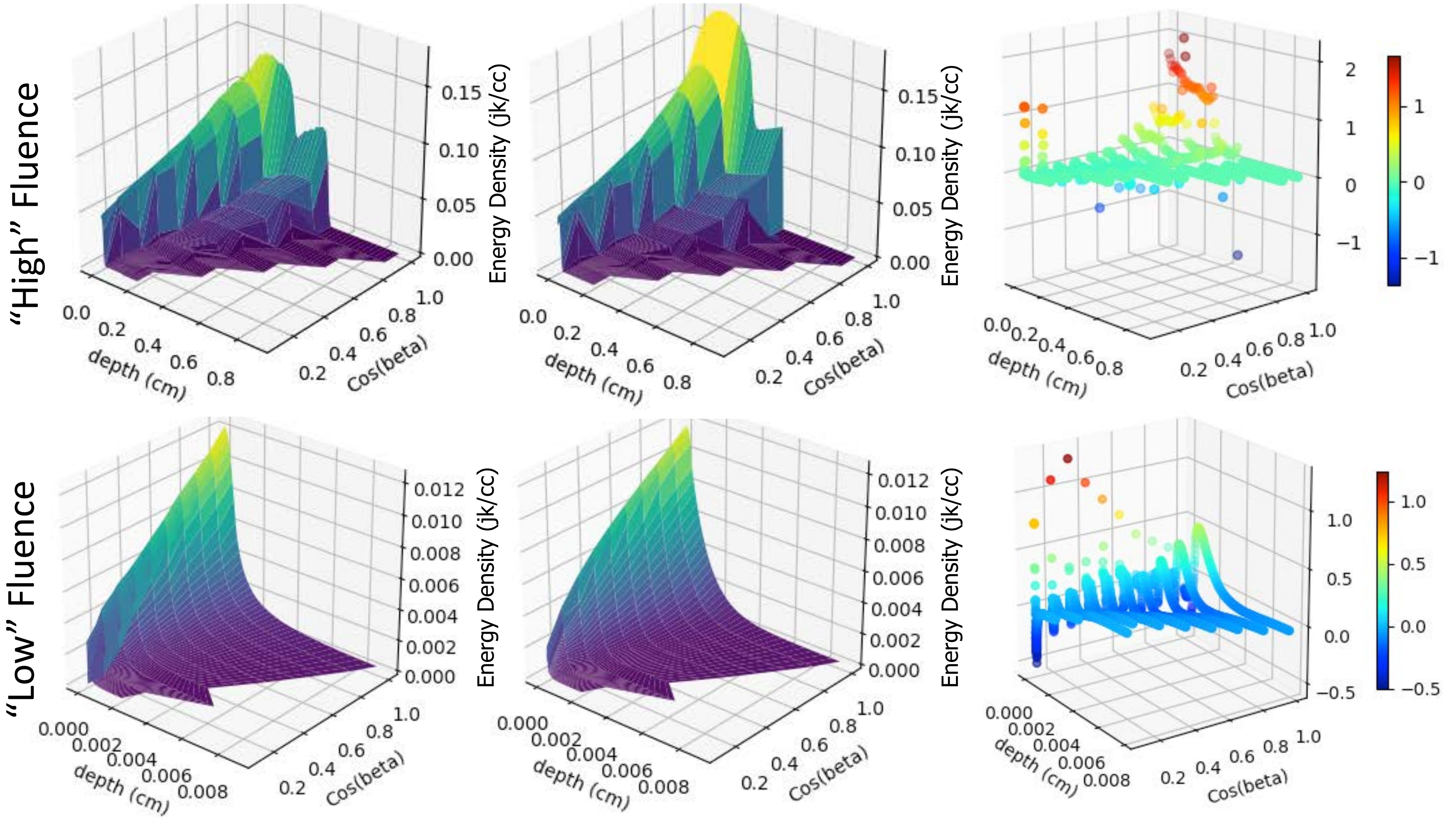
- The 1D and 2D blowoff momentum results from pure Kull simulations match closely
- The energy deposition profiles also match reasonably well…
  - …And will improve when a time-dependent source is implemented into the 1D simulation.
- We will use the "cleaner" 1D data for fitting an angle-dependent function.

Fitting to 1D Depositions (Preliminary):

Sample 1D Energy Deposition Fit



Energy Deposition Data | Energy Deposition Fit | (Fit – Data)/Avg(Data)

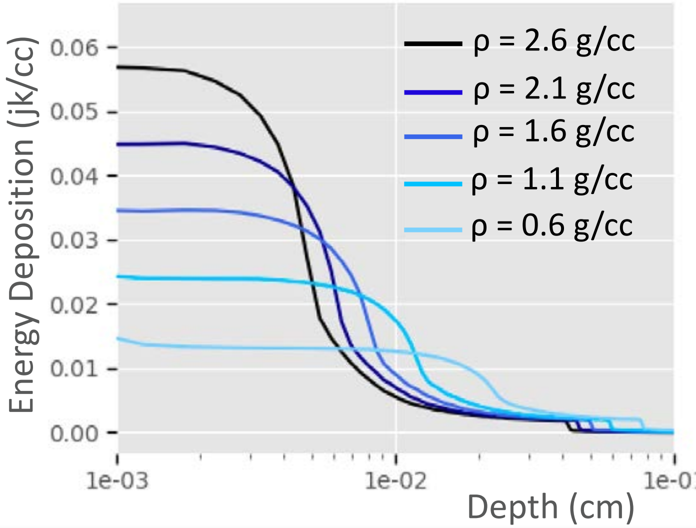


Preliminary Results and Still To Do

Fluence Level	Low	Mid	Mid-High	High	Exercise
2D Pure Kull momentum (g cm/μs)	4.66e6	3.81e7	4.65e8	1.98e9	1.17e8
2D Deposition Function momentum (g cm/μs)	4.98e6	4.92e7	4.77e8	1.81e9	1.73e8
Time after "detonation" (μs)	1.36	5.0	3.48	2.19	1.34

- Preliminary results are promising but should improve with better 1D data.
- Exercise: Asteroid diameter is 120m, material is SiO_2, and a "High" Fluence is applied (Yield = 1Mt, Standoff = 9m)

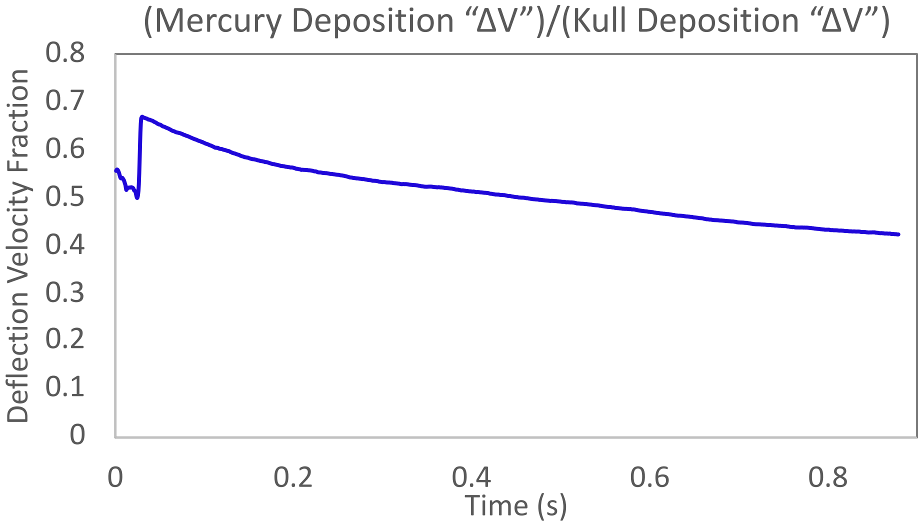
Deposition Shape vs Density/Porosity

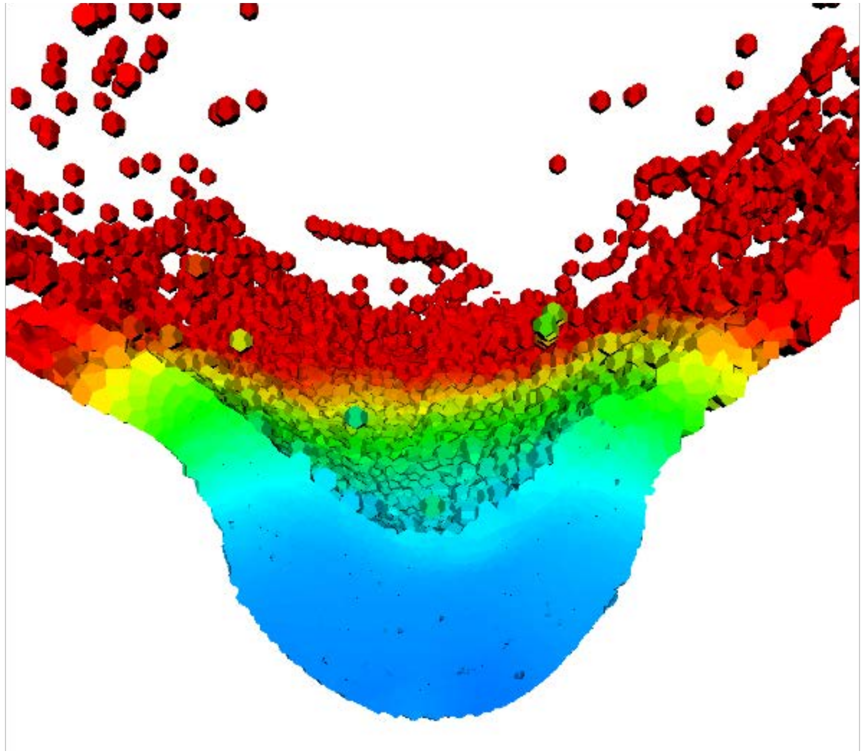


- Still lots to do:
  - Global fit over all fluences/source durations
  - Scaling based on density/porosity
  - Same analysis for remaining materials (Forsterite, Ice, and Iron)
  - Thorough study of model weaknesses/errors

Conclusions and Exercise Test with Spheral

- Modeling the x-ray energy deposition is complicated and requires a full rad-hydro simulation to get right.
- Our analytic deposition model is progressing quickly and shows promise.
- The PD community can use our model to more efficiently explore the vast space of potential scenarios and uncertainties.





Getting ΔV right requires rad-hydro simulations of the x-ray energy deposition.

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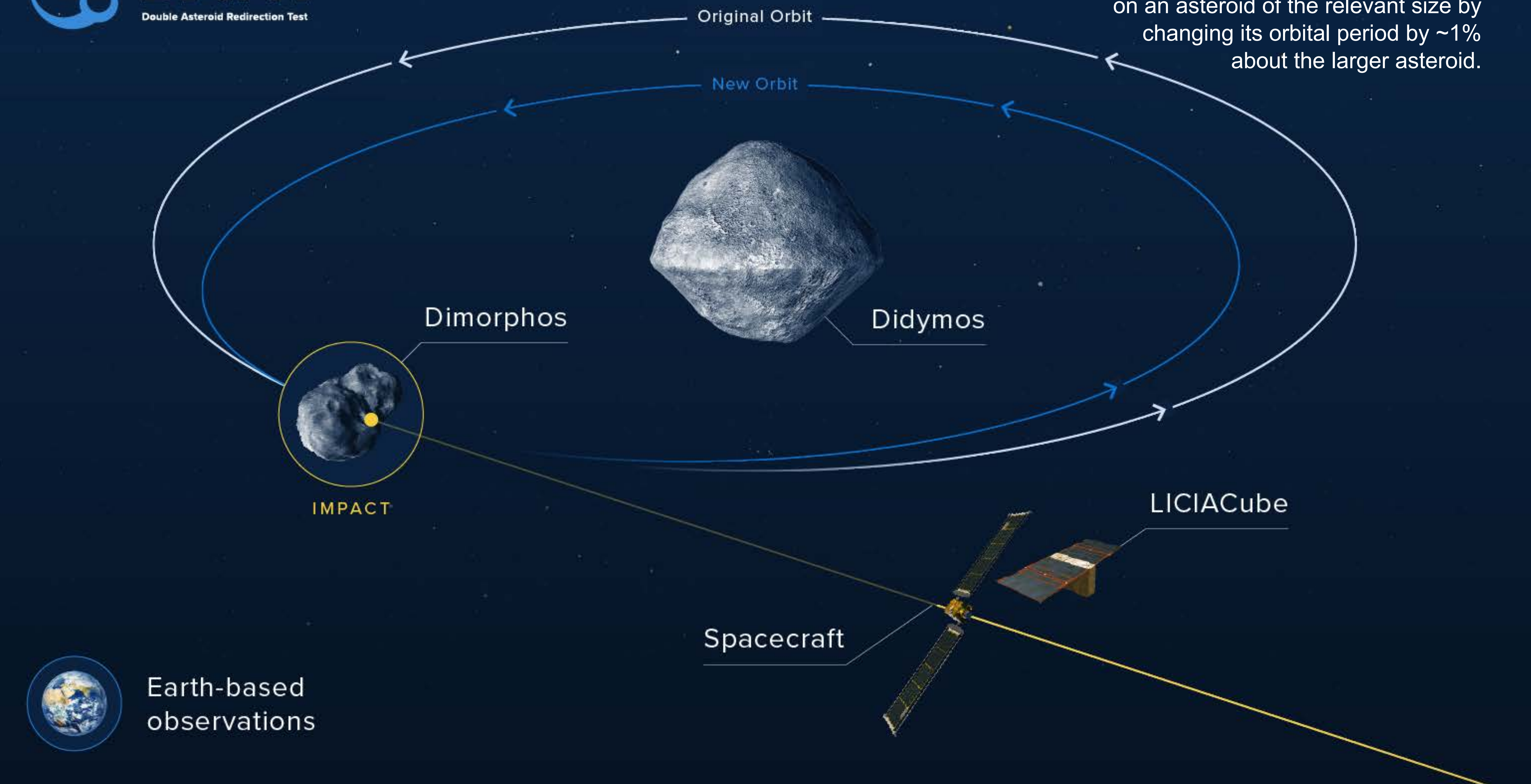
The Double Asteroid Redirection Test (DART) Impact Modeling Working Group Inverse Test

Angela M. Stickle, Megan Bruck Syal, Wendy K. Caldwell, Mallory DeCoster, Dawn Graninger, Martin Jutzi,Robert Luther, Mike Owen, Jason Pearl, Catherine S. Plesko, Sabina Raducan, Emma Rainey, Cody Raskin, Tane Remington, Andy Rivkin, and the AIDA/DART Impact Modeling Working Group

Planetary Defense Conference 2021
April 28, 2021

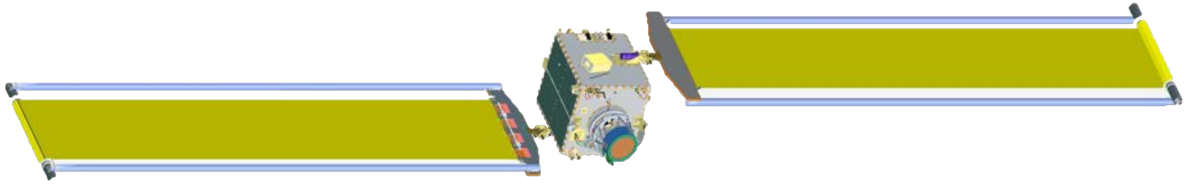
The Ideal Target

It allows a deflection demonstration on an asteroid of the relevant size by changing its orbital period by ~1% about the larger asteroid.

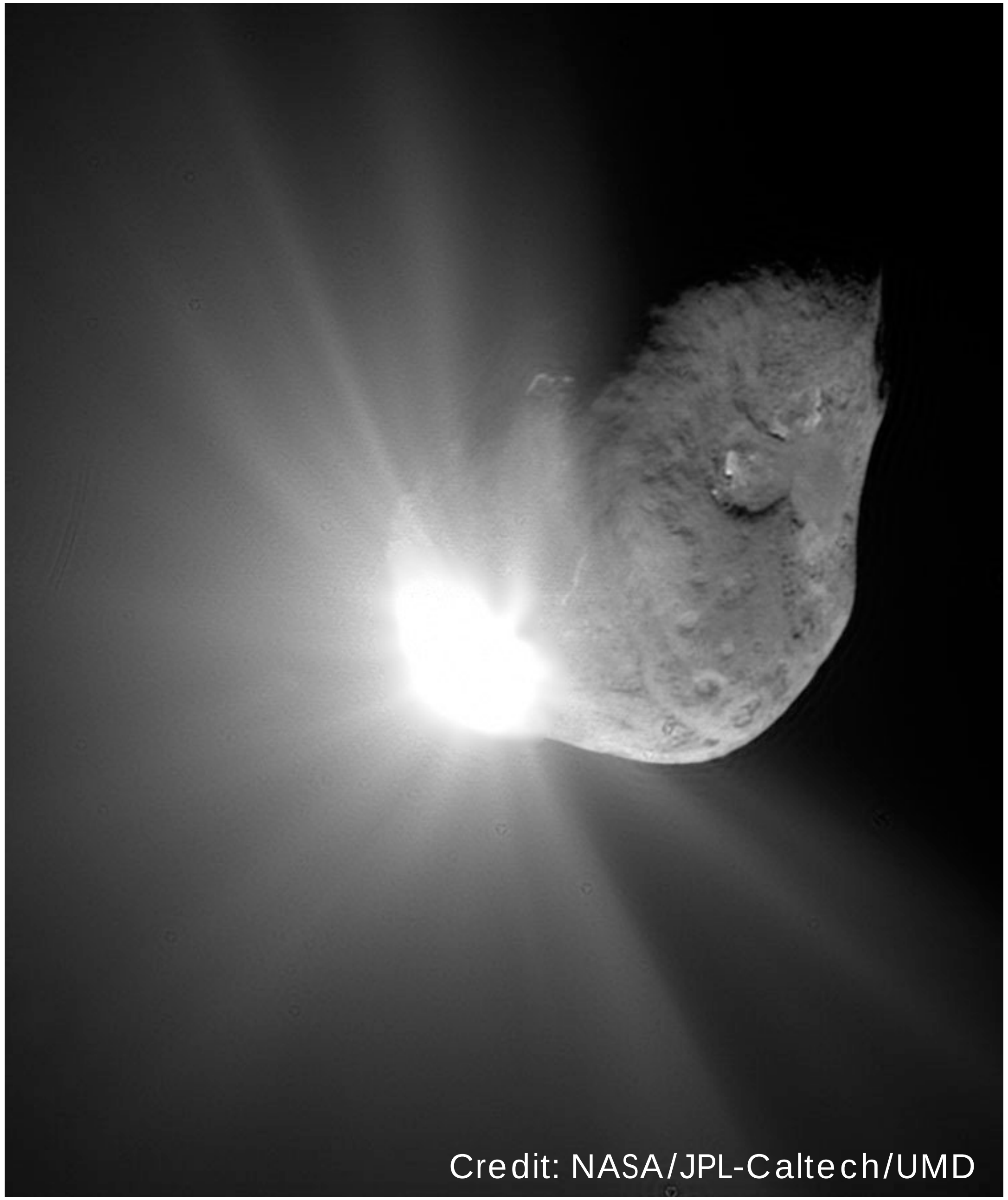


Planetary-scale Impacts Provide Partially Well-controlled Experiments

- The DART impact will join Deep Impact and LCROSS as planetary-scale impact experiments
  - Initial impactor parameters are well known



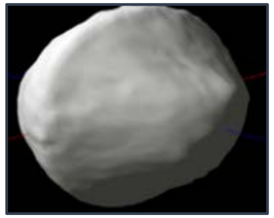
  - Physical properties of Dimorphos are not well constrained



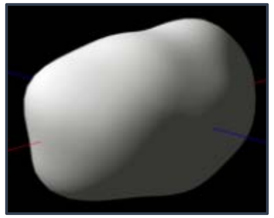
We know little about the object we are going to hit

Dimorphos

?



ID1: kw4a



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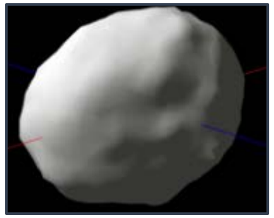
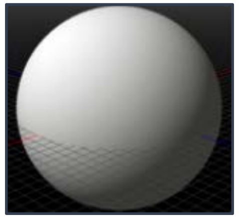
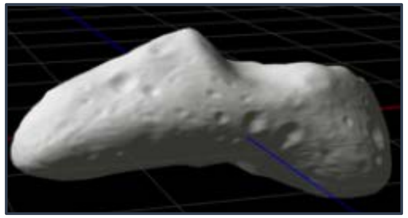


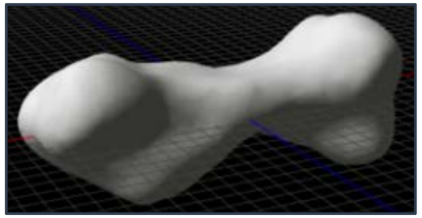
ID6: Rashalom



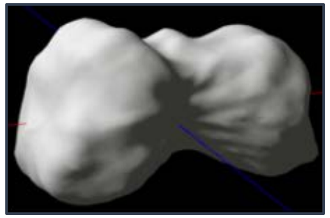
ID7: sphere 1



ID4: Eros



ID5: Kleo



ID3: Mithra

Planetary-scale Impacts Provide Partially Well-controlled Experiments

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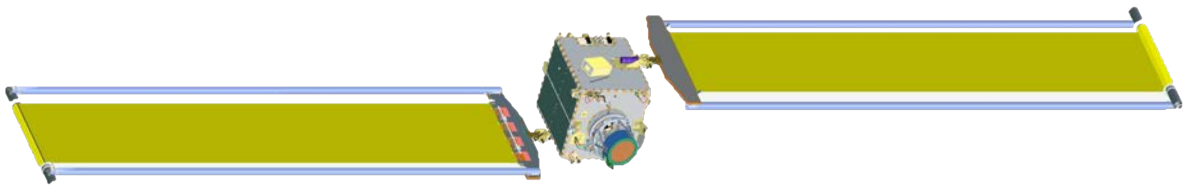
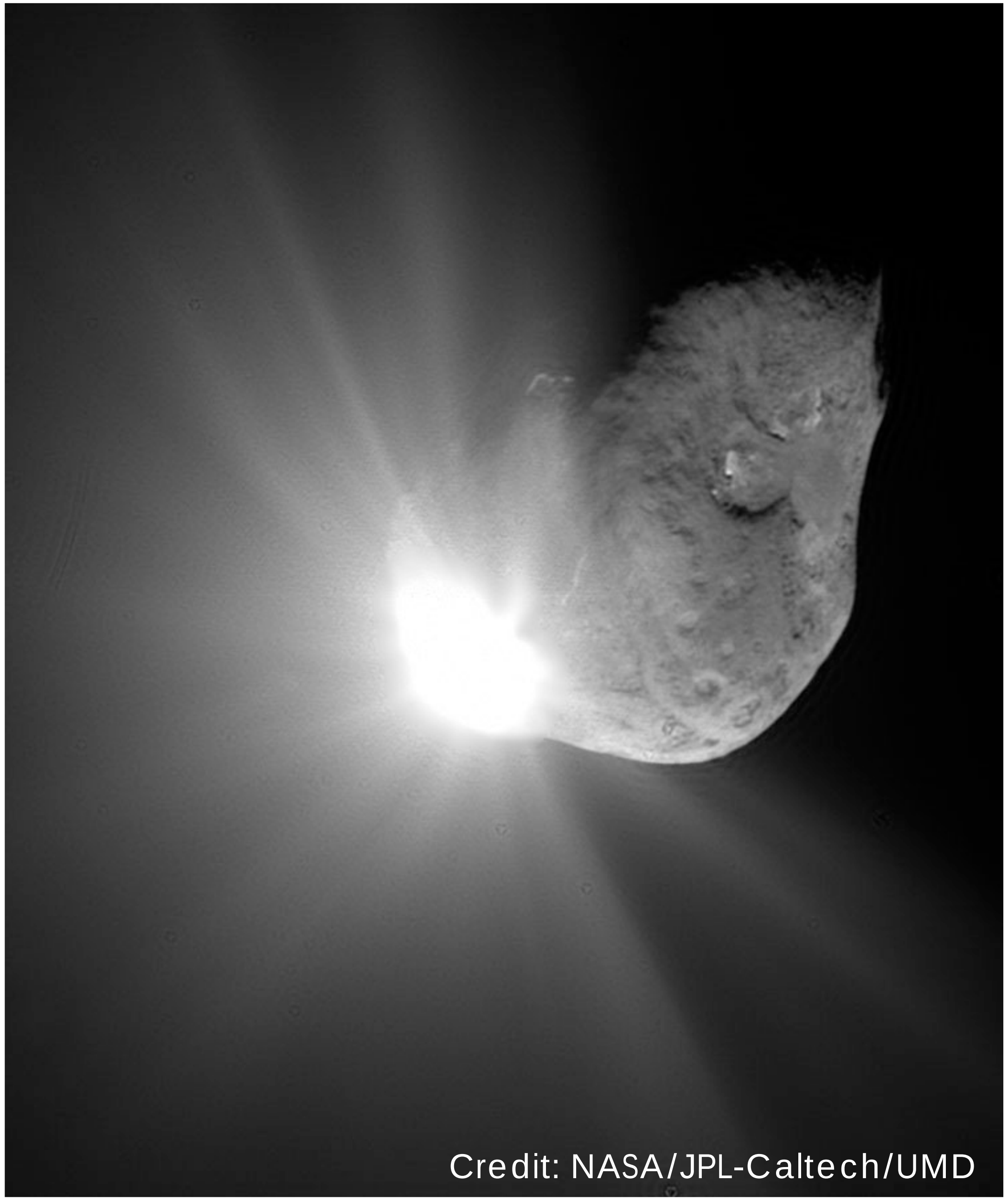
  - Initial impactor parameters are well known

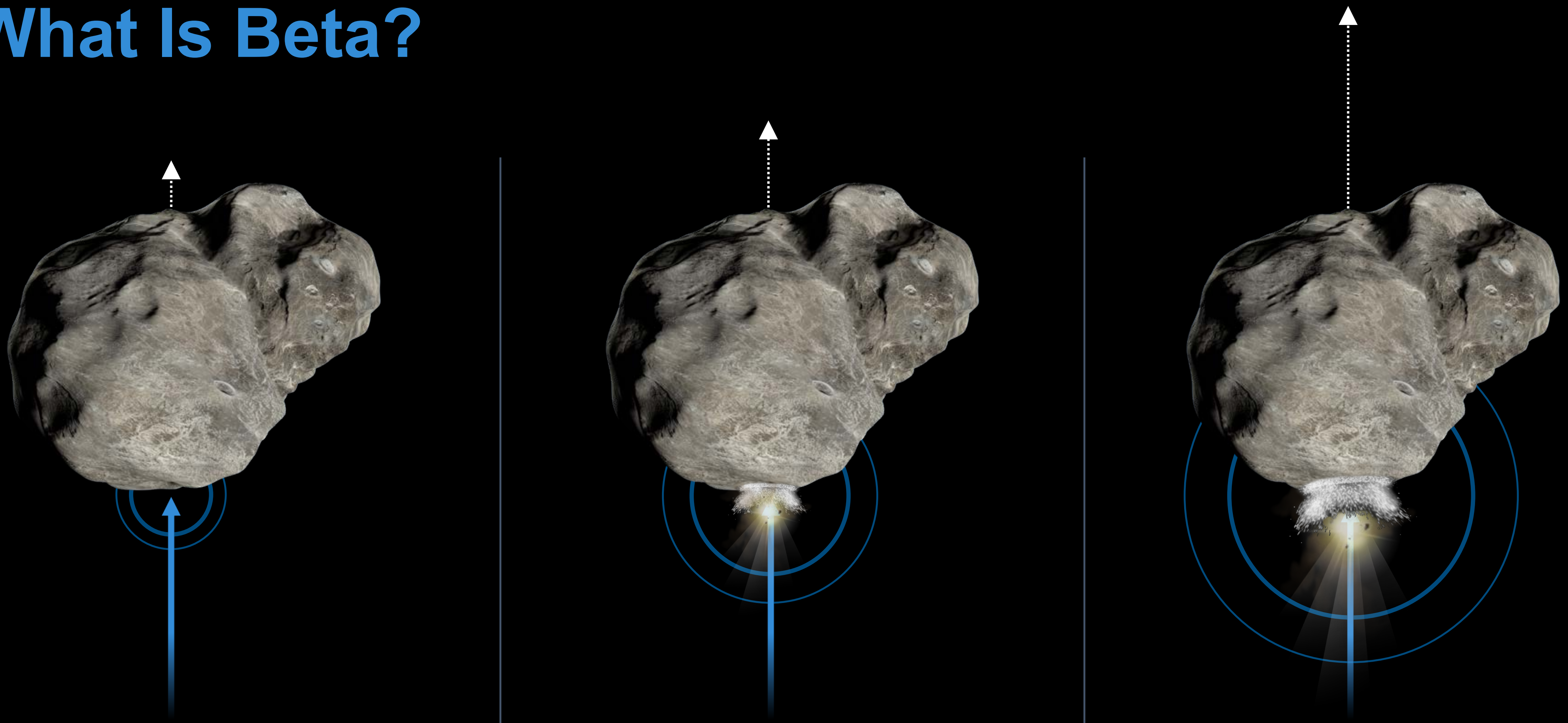


  - Physical properties of Dimorphos are not well constrained
- Understanding the conditions of the DART impact is essential for interpreting the ability of the kinetic impactor to deflect an asteroid (estimating β)



Credit: NASA/JPL-Caltech/UMD

What Is Beta?



Beta = 1
No ejecta and small momentum increase

Beta = 2
Moderate ejecta and momentum increase

Beta = 4
Heavy ejecta and large momentum increase

The DART Impact Modeling Inverse Test

- Inverse problems tell us about parameters that we cannot directly observe
- Goal: determine the model parameters that best fit a given deflection observation
  - Trial and Error Method
  - Optimization algorithms (see Cody Raskin's talk, next)

Questions we want answered:

- What is the expected uncertainty on β estimates following the DART impact from simulations? How do target property choices affect the predicted values?
- How well can the impact scenario be recreated from limited information?
- Are current data analysis procedure and handoffs adequate or do new tools need to be developed?
- How long do these simulations take to provide answers and how many different simulations need to be run?

DART "Inverse Test" provides a different controlled experiment

Step 1: Set up "observations" → "The Game Masters"/Truth team

Test shape model and impact scene generated by ProxOps team

→ Pass to impact team

Impact models generate a Δv from a DART impact

→ Work with other working groups

Turn Δv into an "observed" Δp and period change

Step 2: Simulate post-impact modeling activities → "The Adventurers"

Receive shape model, mass estimate, period change, impact angle, simulated impact site image

→

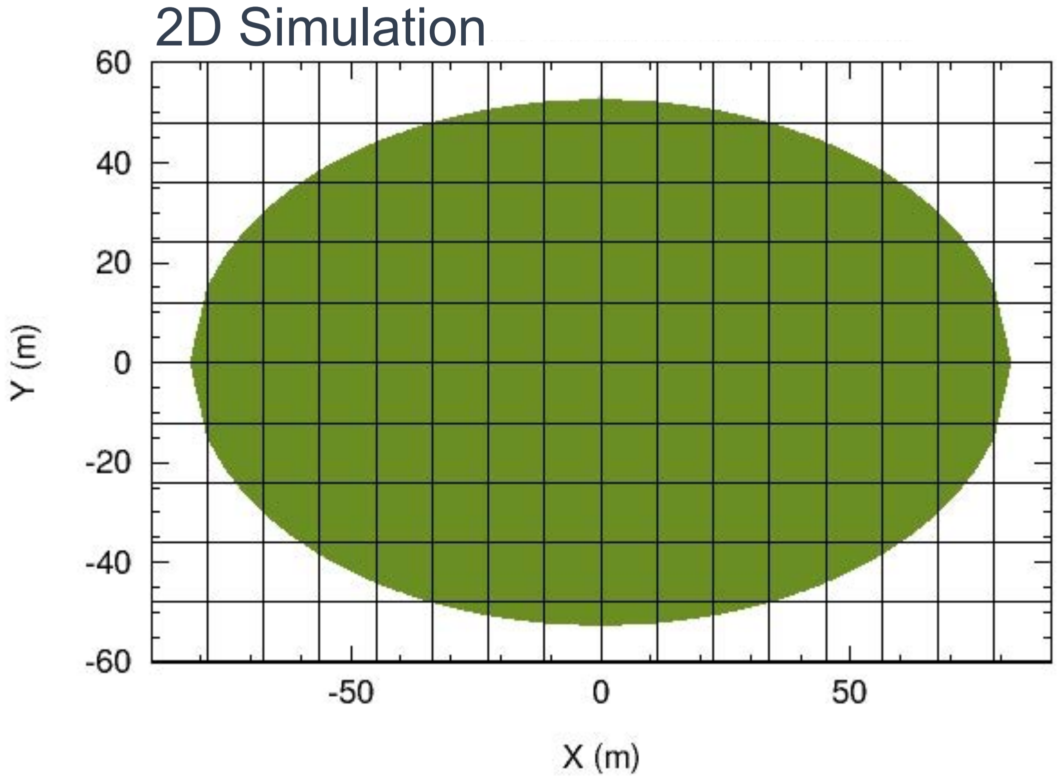
Use prediction simulations to identify range of possible material parameters

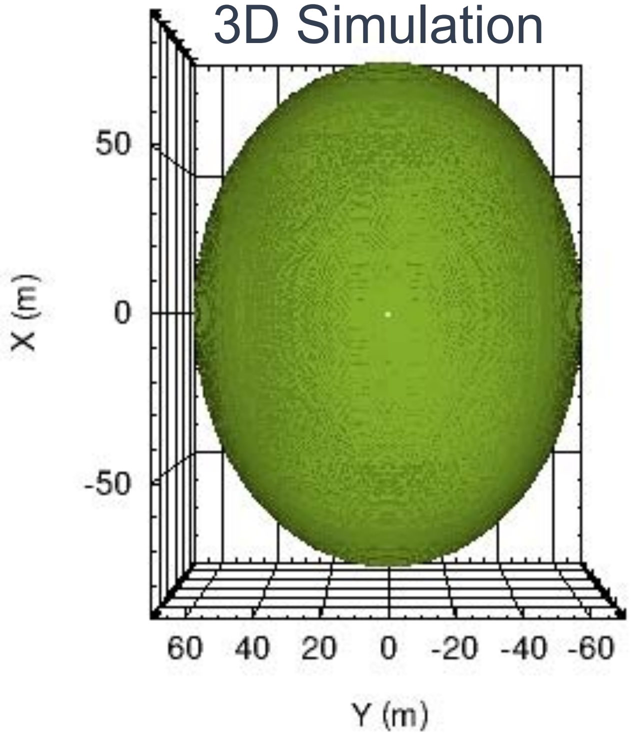
→

Turn Δv into a β with assumed material properties

DART Truth Model #1 – simple case

CTH Simulations run by Emma Rainey



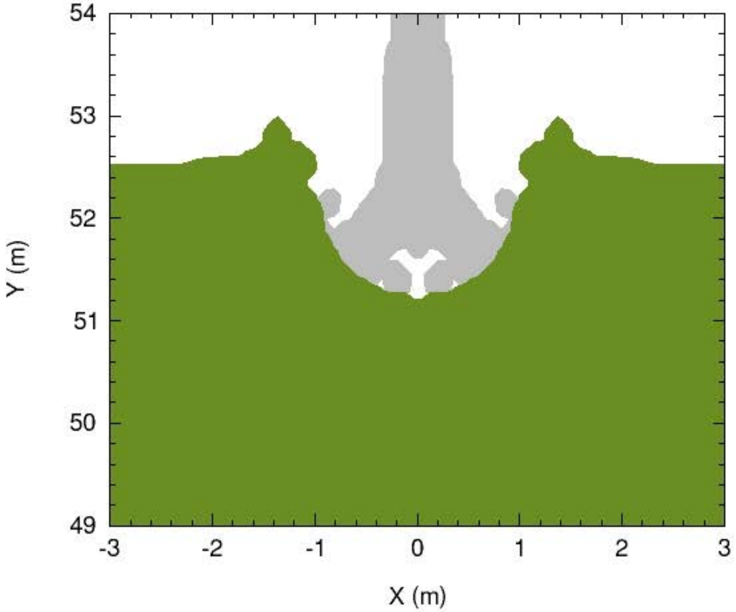


Impactor properties, limited target properties, impact geometry, and deflection velocity were provided to team

DART Truth Model #1 – simple case

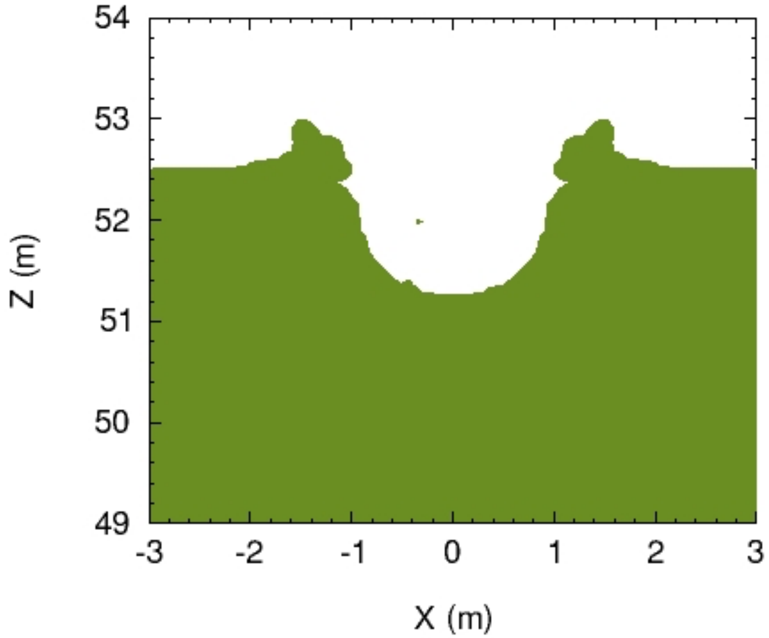
CTH Simulations run by Emma Rainey

2D Simulation



Δv = 0.096 ± 0.0029 cm/s

3D Simulation

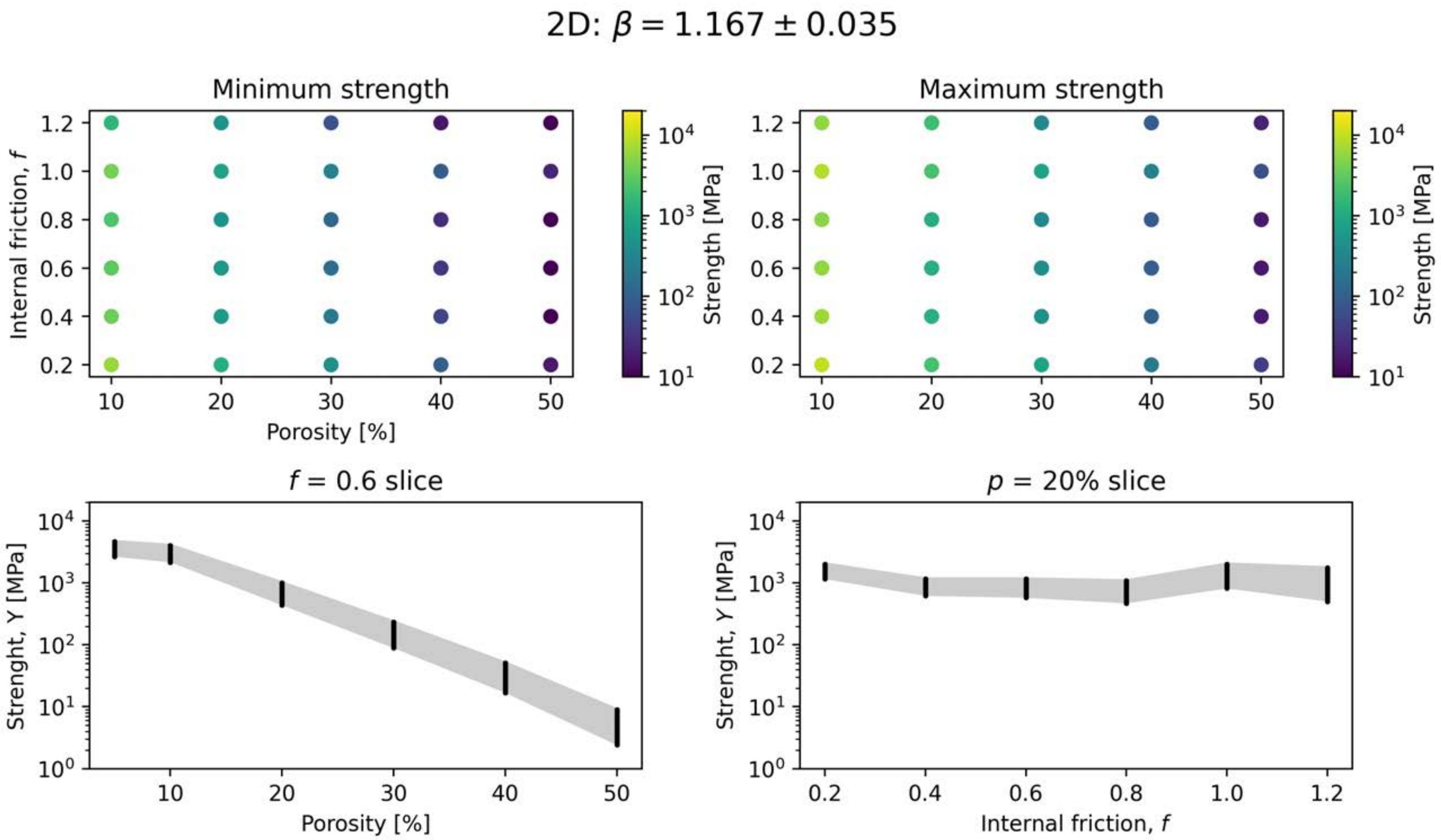


Width = 2.11 m
Depth = 1.20 m

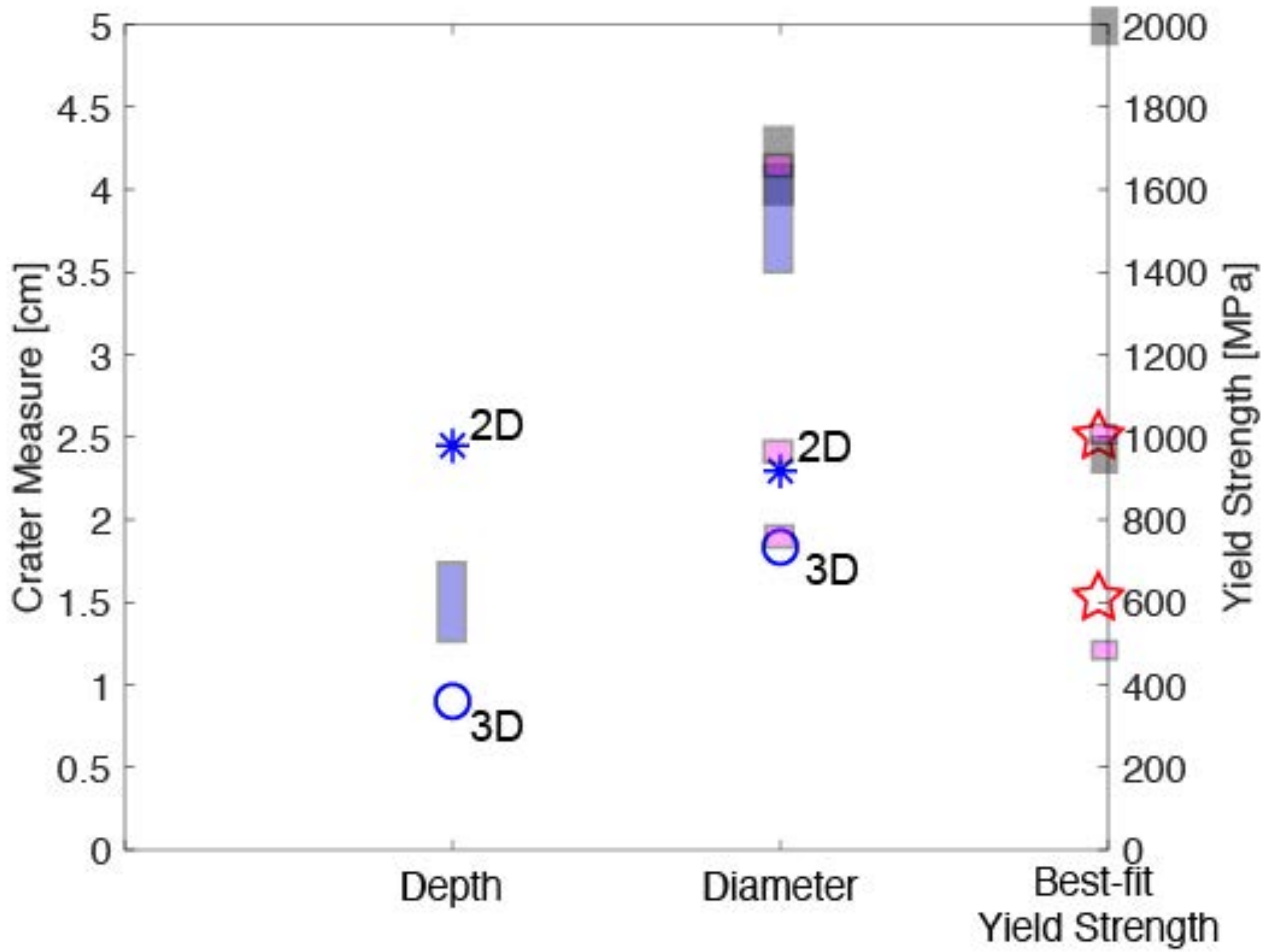
Δv = 0.115 ± 0.017 cm/s

Analytic model illustrates that a range of strength/porosity values can give you the same momentum enhancement

Model by Sabina Raducan



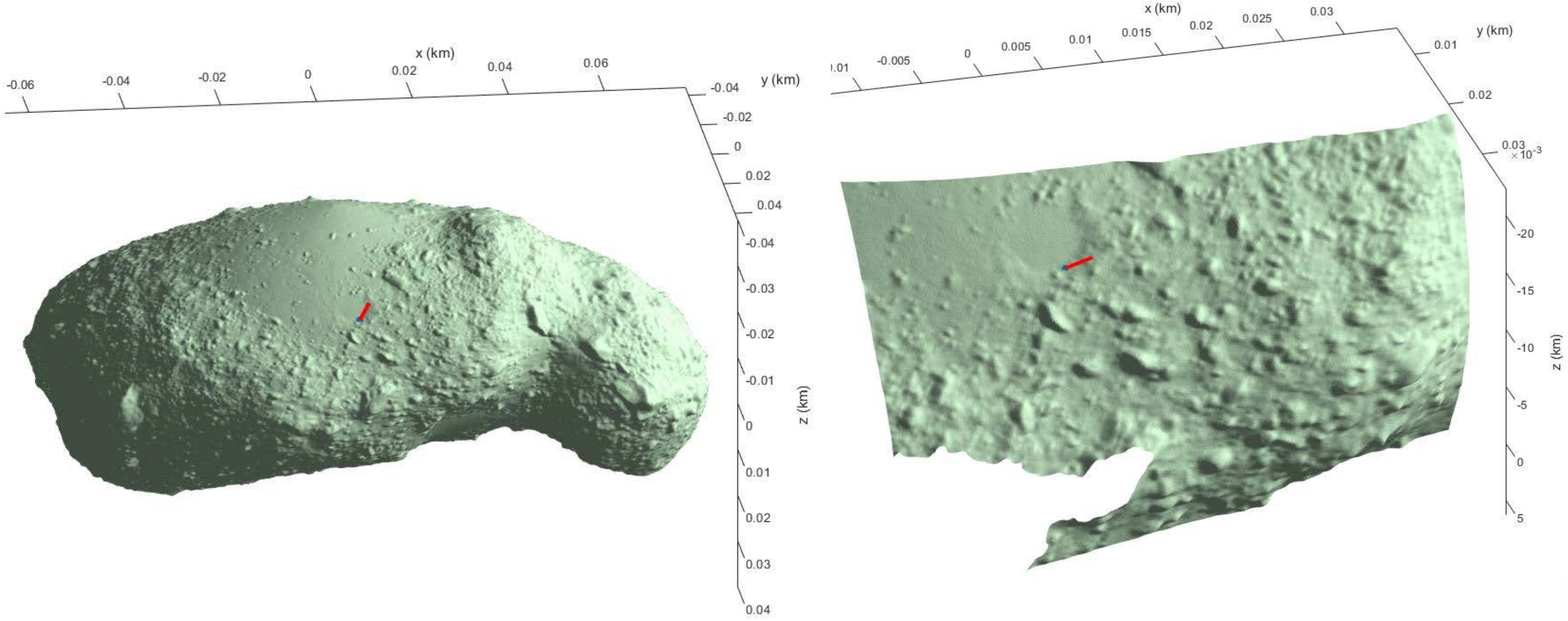
SL WCB diameter ~ 7.5 m



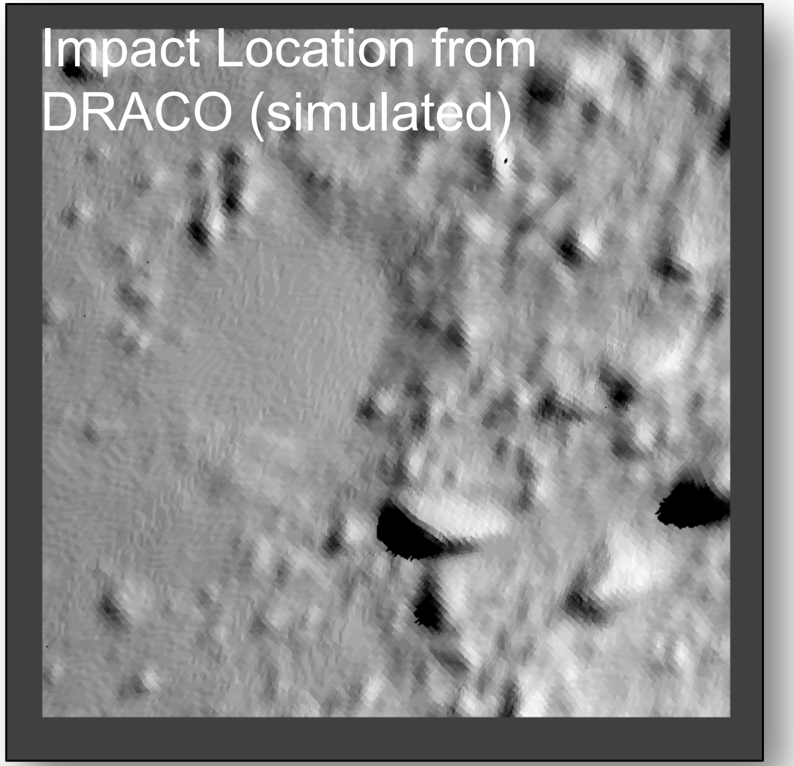
Models by Andy Cheng, Mallory DeCoster, Dawn Graninger, Robert Luther, Mike Owen, Jason Pearl Cody Raskin, Tane Remington

The second exercise provides a more stressing case

Beta will be estimated using procedure determined by DART team



Impact Location Plotted on STL



Truth models still in construction. Stay tuned!

Implications for DART

- Values provided to the team and specific hand-off procedures are vital to test before impact
- We know that β is not uniquely tied to one set of material parameters
  - Other information (e.g., crater size) is vital to limit range of possible values
  - Modeling work group simulation library provides important limits and starting points for parameters
- Given a deflection velocity, the adventurers were able to reproduce β values within ~10-15% of the "truth" value
  - This is comparable or better than variability due to different codes and/or users [Stickle et al. 2020]
  - Crater size has a larger range, depending on values chosen for strength
- In simple case, all adventurers were able to determine parameters similar to truth
- "Trial and error" methods can reproduce β in this simple case
  - More complex optimization methods could provide more robust answers if more complicated simulations are required? → See Cody Raskin's talk for descriptions of these types of simulations from LLNL
- Inverse test #2 will require more complicated models and provide better constraints on expected uncertainty in post-impact β calculations

DART

Double Asteroid Redirection Test

Accelerated Root Finding for the DART Inverse Test Using Machine Learning Decision Trees

April 23, 2021

Cody Raskin, Tane Remington, Jason Pearl

Lawrence Livermore National Laboratory

LLNL-PRES-821561

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

The DART Inverse Test

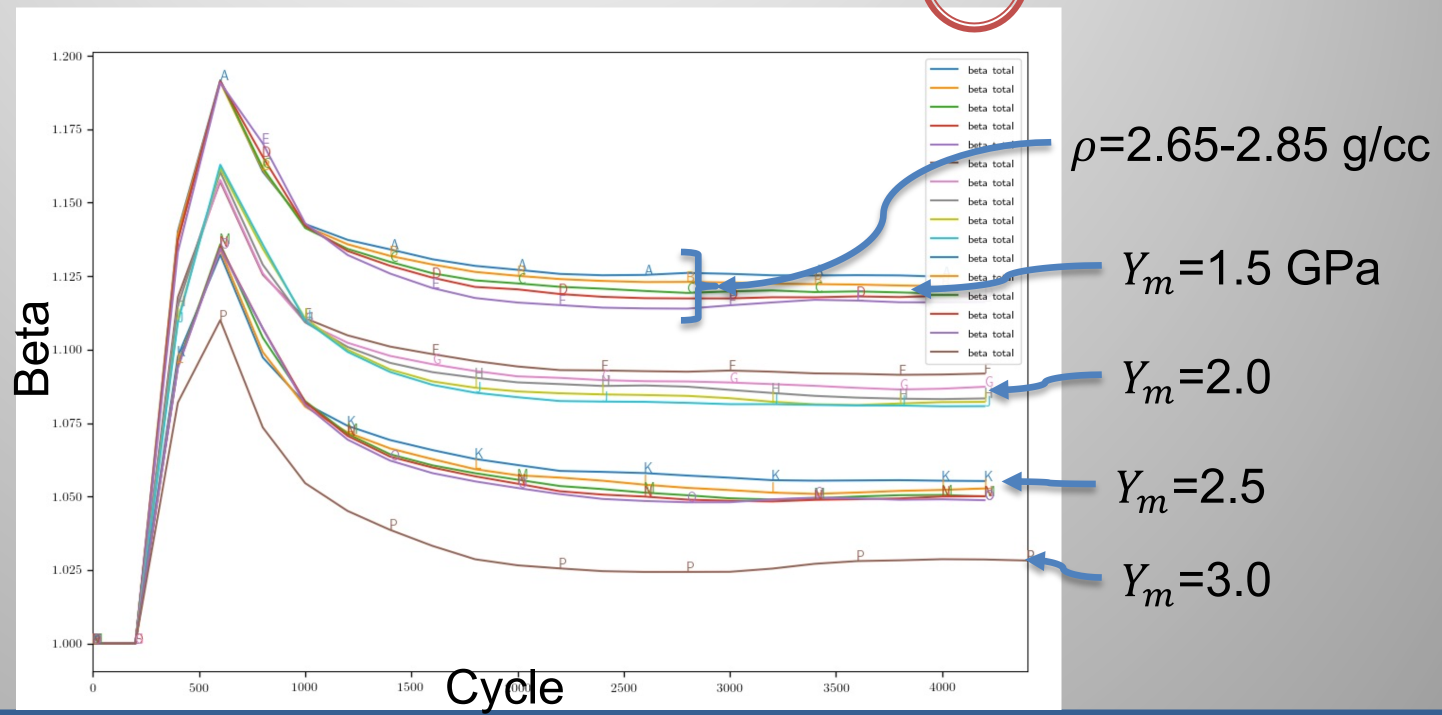
- Triaxial, rocky body
  - Uniform, constant density
  - No porosity
- Spherical impactor mass = 570 kg
  - Impactor momentum = $3.42\text{E}11 \text{ g cm/s}$
  - No impact angle (head on)
- Vary the yield strength and density parameters to drive to $\Delta v = 0.115 \text{ cm/s}$

3D Calculations

- SPH with Tillotson EOS
  - No damage model
    - Damage in all cases pushed beta much too high for this exercise
- Monolithic material (no boulder-like inclusions)
- 10cm resolution at impact site
- Assuming no information about total mass (or density) of Dimorphos – fixing only the triaxial dimensions (volume)

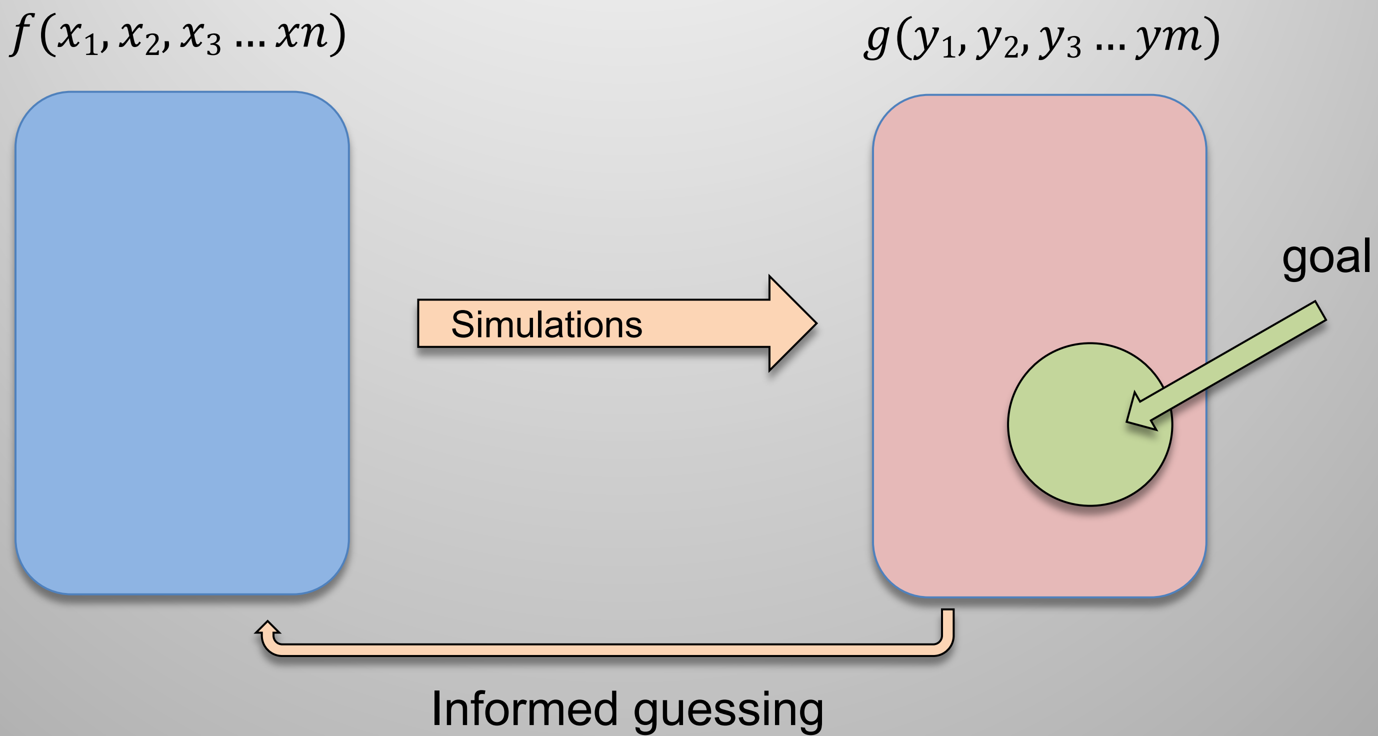
The Simulation Outputs Group Into Families

- Varying density and yield strength together results in families of Δv or β, grouped by the choice of maximum yield stress. $Y_i = Y_0 + \frac{\mu_i P}{1+\mu_i P/(Y_m - Y_0)}$



Inverse Problems are Typically Time-Consuming

- Repeated guessing and checking or running thousands of simulations and hoping for a "hit"



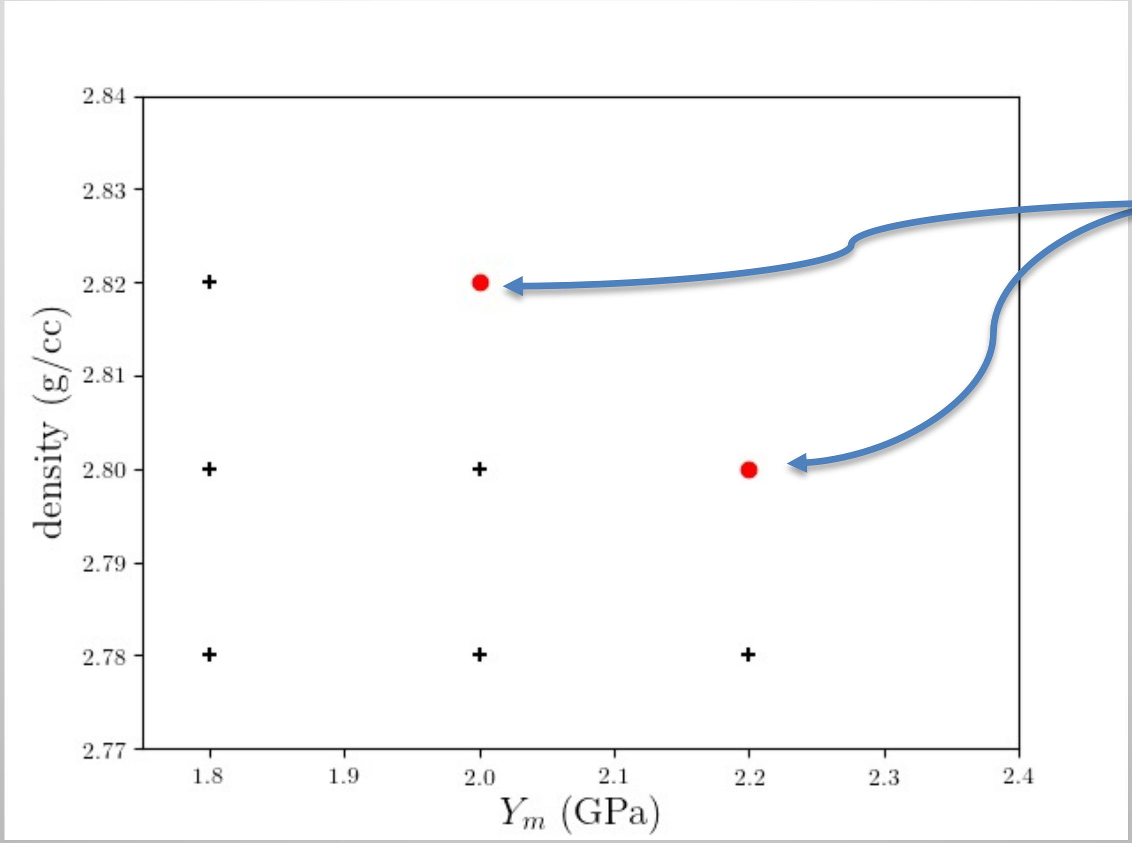
Decision Tree Regressor

- Most popular fast, supervised machine learning algorithm
- Non-parametric
  - Makes no assumptions about the parametric form of the output functor (good)
  - Generally requires large datasets to be accurate (bad)
- Steerable (good)
- Naïve (bad)

Is this Overkill?

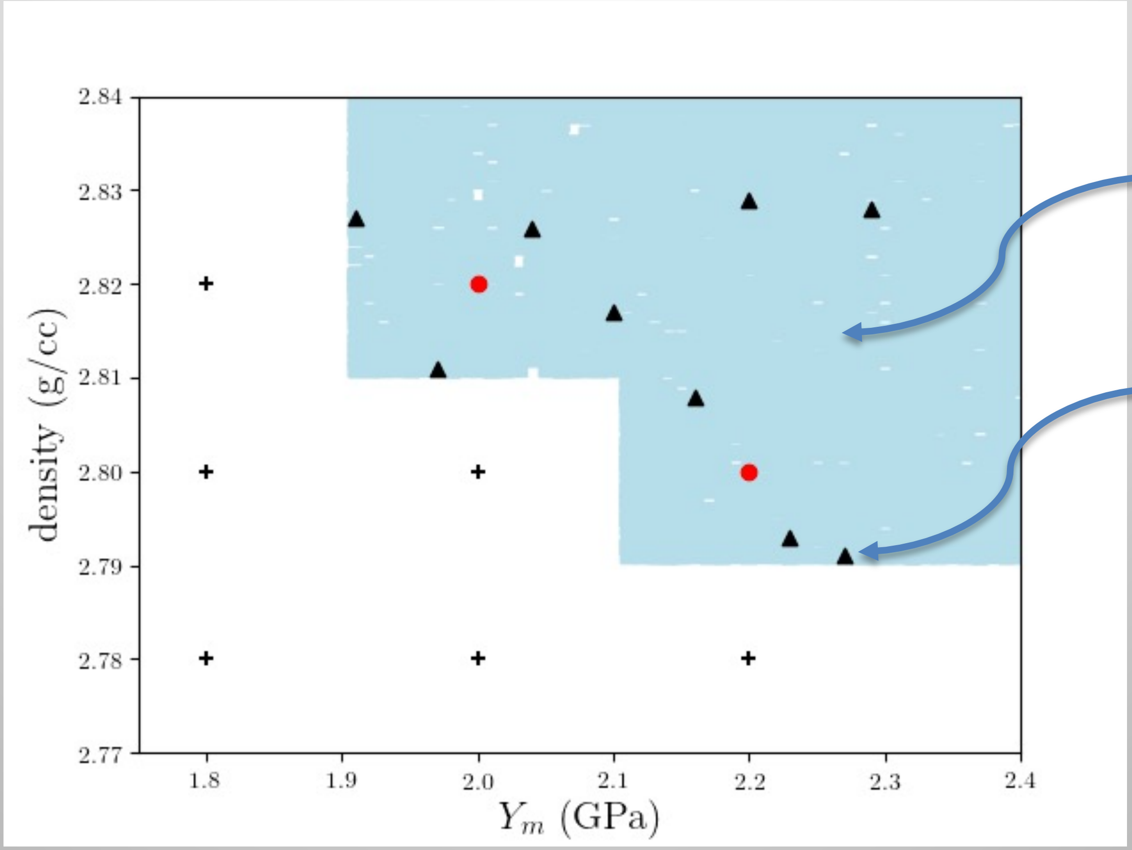
- Future trials may involve many more input and output parameters
  - Difficult for humans to find trends
  - Easy for computers
- Computer cycles are cheap – Human cycles are not
- "Going too far is half the fun of getting nowhere."
  - Bill Griffith

An Initial Scan of the Parameter Space Already Found Two Successes



$\Delta v = 0.115$ cm/s

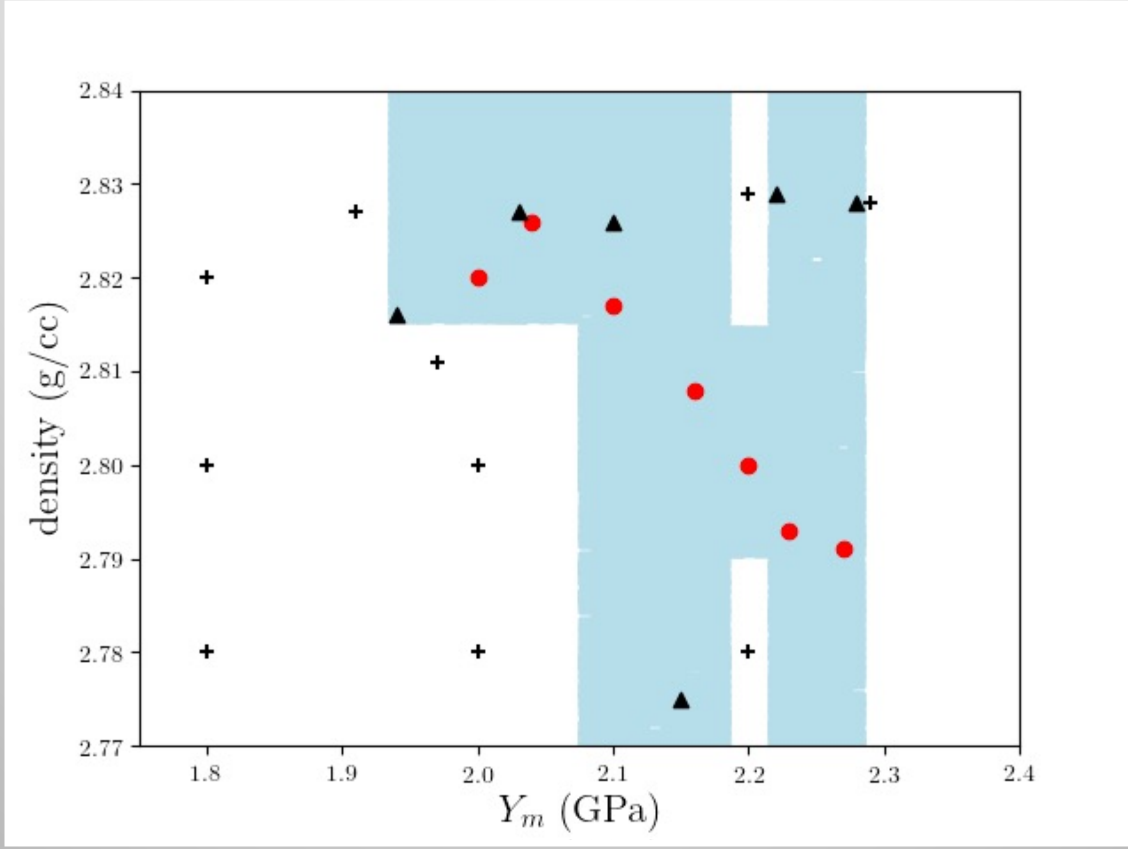
ML Algorithm Chooses the Next Parameter Set From the Prediction Space



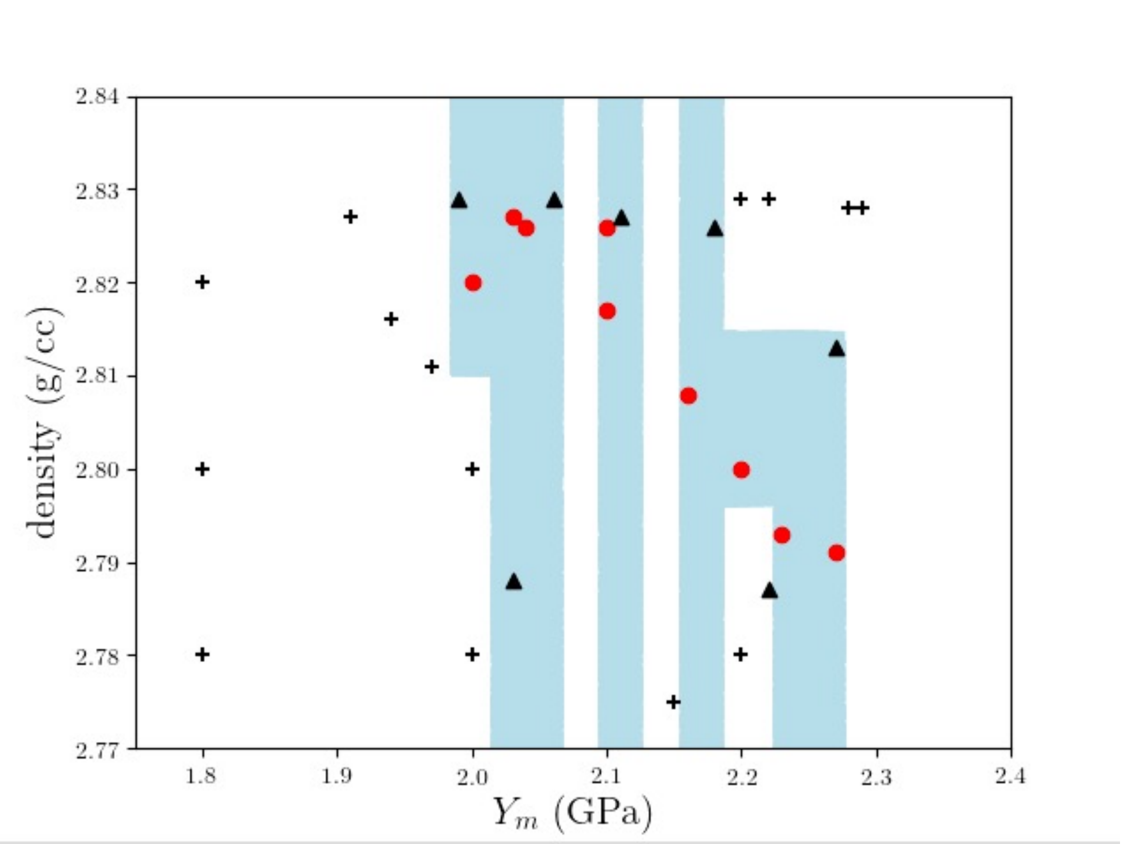
Prediction space

Mitchell's Best Sampling choice

ML Algorithm Refines the Prediction Space and Chooses More Samples

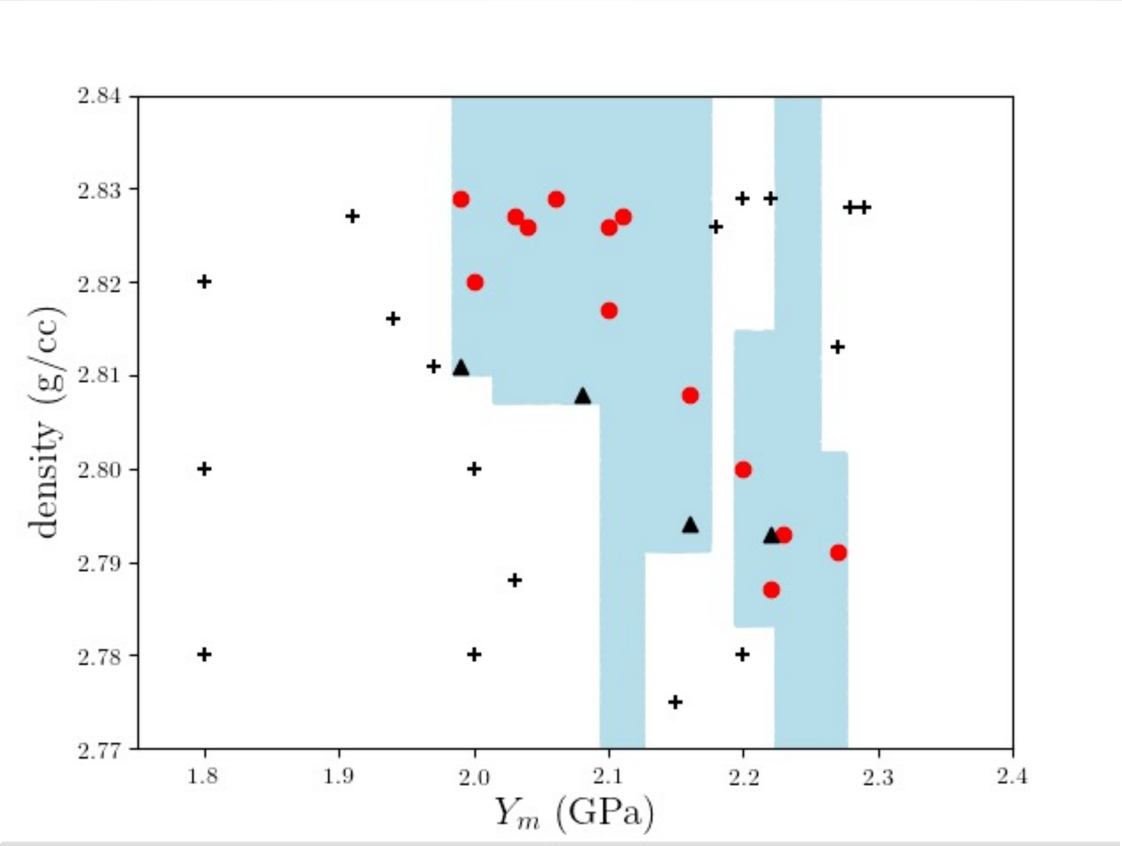


Enhance…



2.84
2.83
2.82
2.81
2.80
2.79
2.78
2.77
density (g/cc)
1.8
1.9
2.0
2.1
2.2
2.3
2.4
Y_m (GPa)

Enhance!!!



2.84
2.83
2.82
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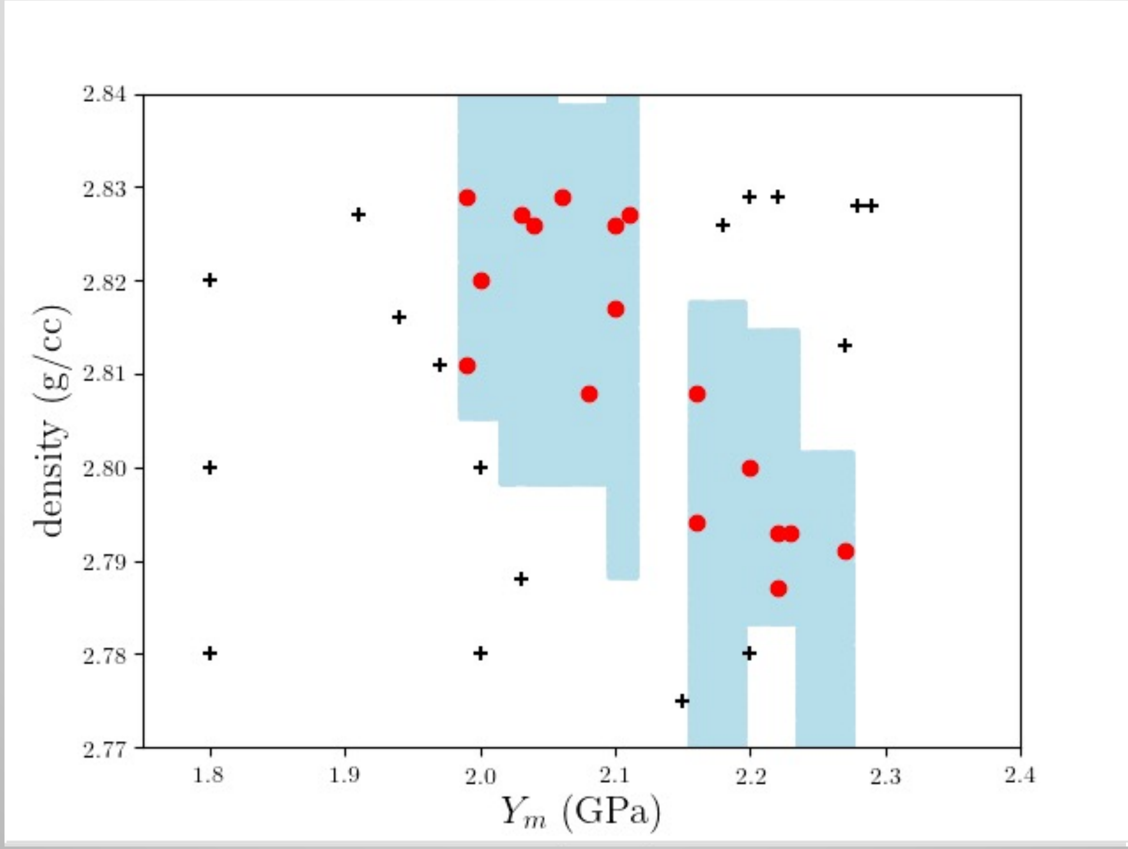
2.79
2.78
2.77
density (g/cc)
1.8
1.9
2.0
2.1
2.2
2.3
2.4
Y_m (GPa)

Several Candidate Parameter Sets Found in Short Order



Key judgments from the Exercise

- The synthetic observations are most consistent with a uniform, non-porous, single-density body with $\rho \approx 2.79 - 2.83$ g/cc and $Y_m \approx 2.3 - 2.0$ GPa.

- Including any damage model would require tuning the damage parameters to something akin to no damage, or tuning the density and yield strength to something very unlike rock.

- We did not assess the effects of porosity as this would not drive the Δv results in a helpful direction. Additionally, guidance from the Red Team briefing suggested bulk densities that are inconsistent with porous granite. It is still possible for a highly porous, metallic body to result in a similar Δv.

Major Caveats / Things to Try Next

- ρ and Y_m alone are probably not a sufficient input parameter set
  - A <u>*curve*</u> of possible input choices yield the same output
  - Y_0 and porosity could also drive the decision tree
  - Lack of damage model is simplifying, but unrealistic
- Δv need not be the only output parameter
  - Crater size
  - Velocity dispersion of the debris
  - Flavor profile of the caramelized debris…
- I made no mention of the error analysis
  - And I'm not going to

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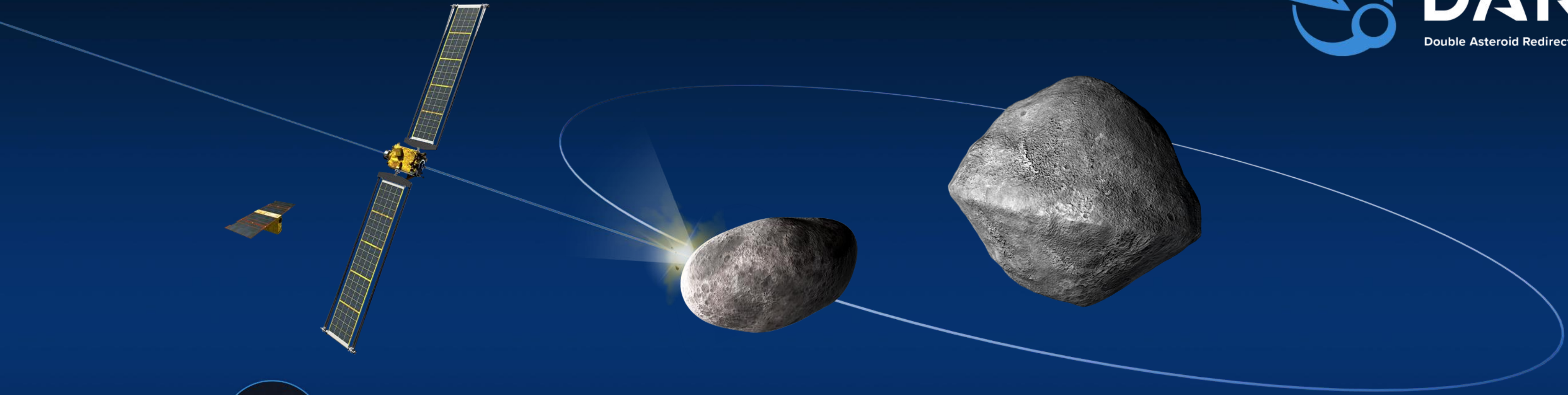

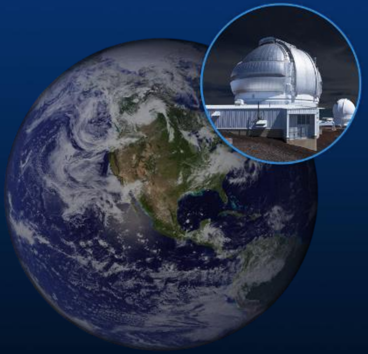

DART
Double Asteroid Redirection Test

Projectile Geometry Effects on Momentum Enhancement of Hypervelocity Impact Simulations

Mallory E. DeCoster,[1] Dawn Graninger,[1] Emma Rainey,[1] Michael Owen,[2] Angela Stickle, [1]

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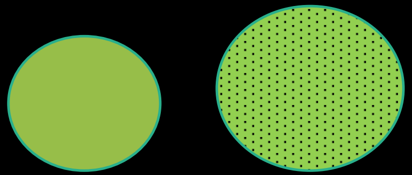
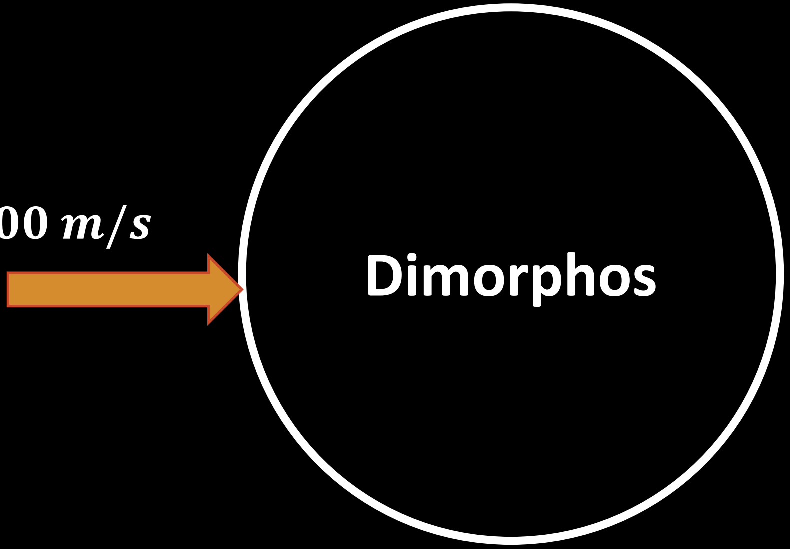
Is momentum enhancement (β) tied to the efficiency of the projectile to generate ejecta during crater formation? If so, is a simplified point source solution accurate for efficiently modeling the DART intercept?

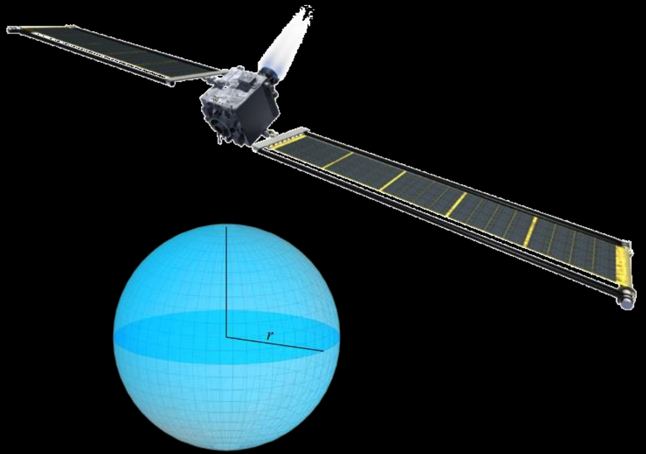
2D

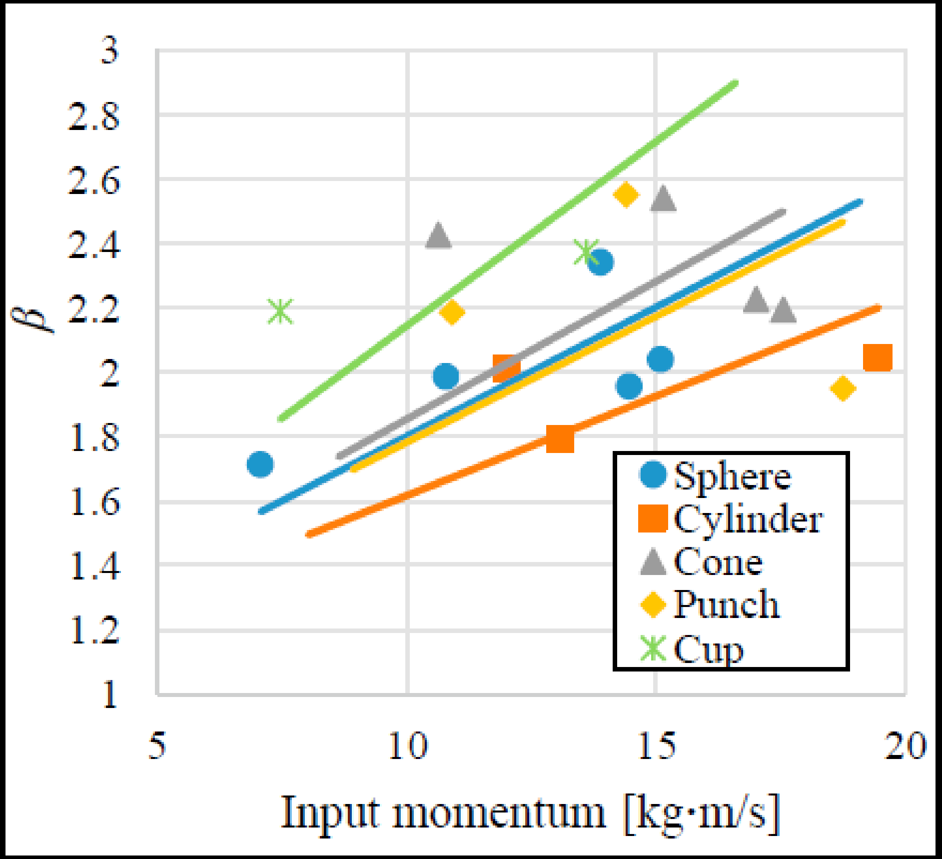


$V_{impact} = 6500\ m/s$



3D

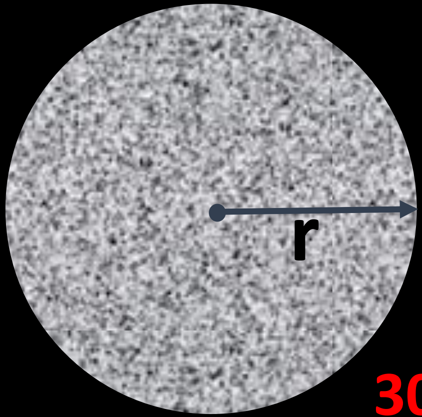




Ikeda *et al.*, Procedia Engineering 204 (2017) 138-145

The simulation parameters defined for the 3D CTH tests were adapted from the benchmarking study and standardized across the different codes. This time we used a more realistic target material of 30% porous basalt.

Dimorphos (Target) Shape



Sphere

Radius (r) = 80 m

Mass = 1.3×10^9 kg

Material

30% porous basalt

Asteroid Equation of State: Sesame

Bulk density = 2.65 g/cc

Porous density = 1.8536 g/cc (30% porosity)

Pore compaction pressure = 280 MPa

P-alpha describes pore crushing process

Base Asteroid Strength

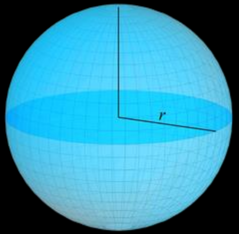
Model: Brittle Damage with Localized Thermal Softening (BDL-Basalt)

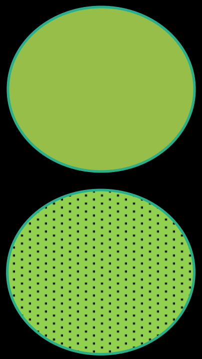
Cohesion of intact material: 90 MPa

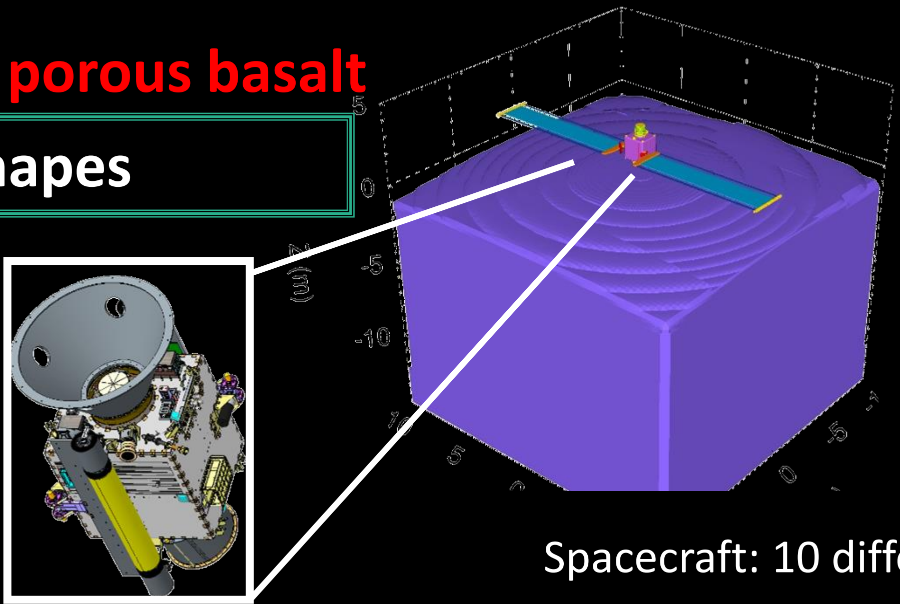
Limiting strength: 3.5 GPa

Tensile/spall strength: -10 MPa

2D/3D Impactor Shapes







Impactor Properties

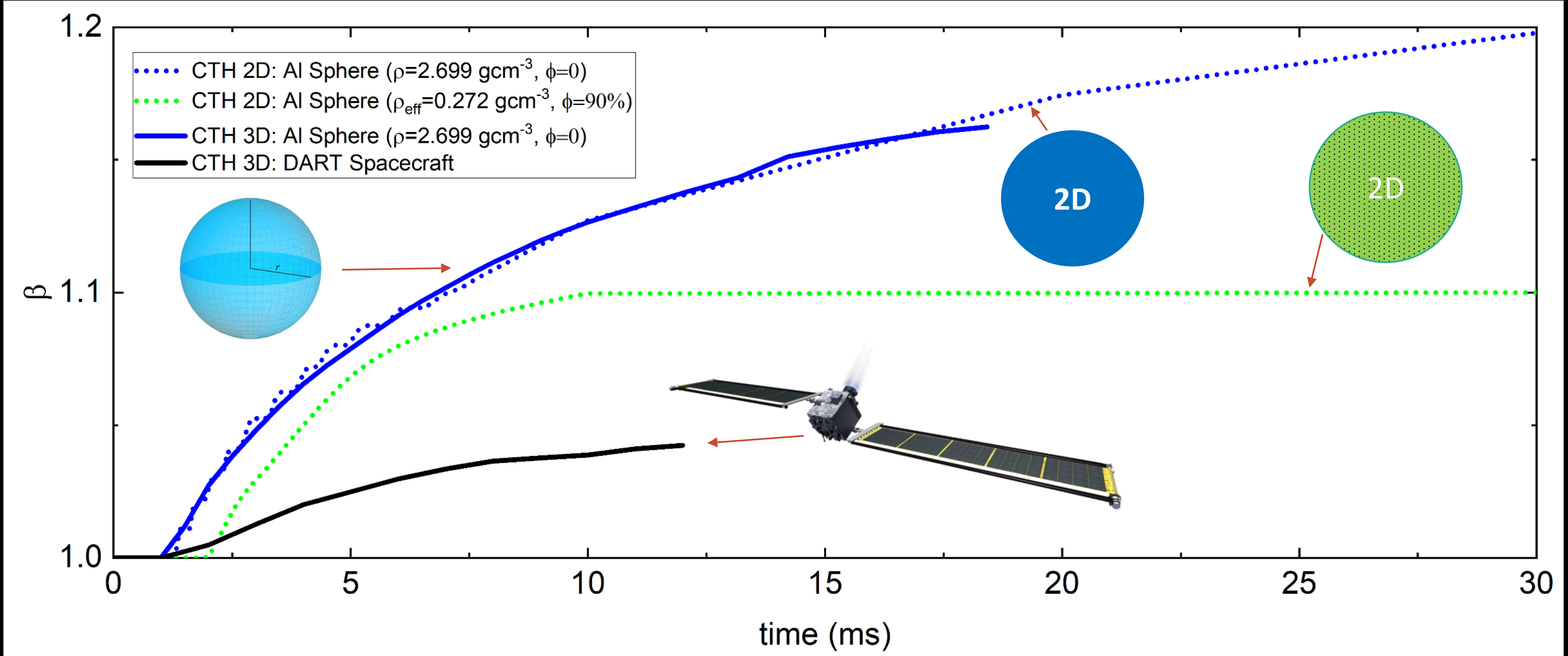
Mass = 550 kg

Velocity = 6.65 km/s

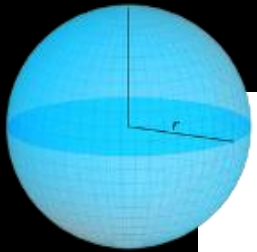
Simple shapes: Fully dense Aluminum

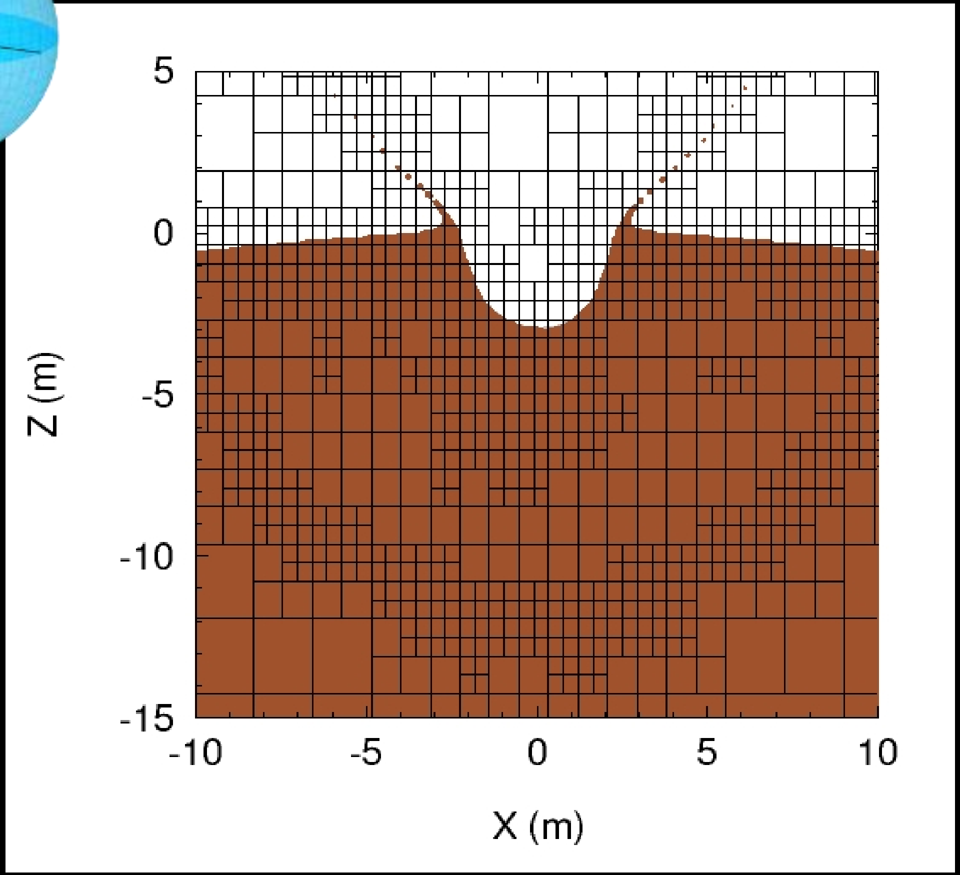
Spacecraft: 10 different materials (Al, Al alloys, steel, oxides, water, xenon)

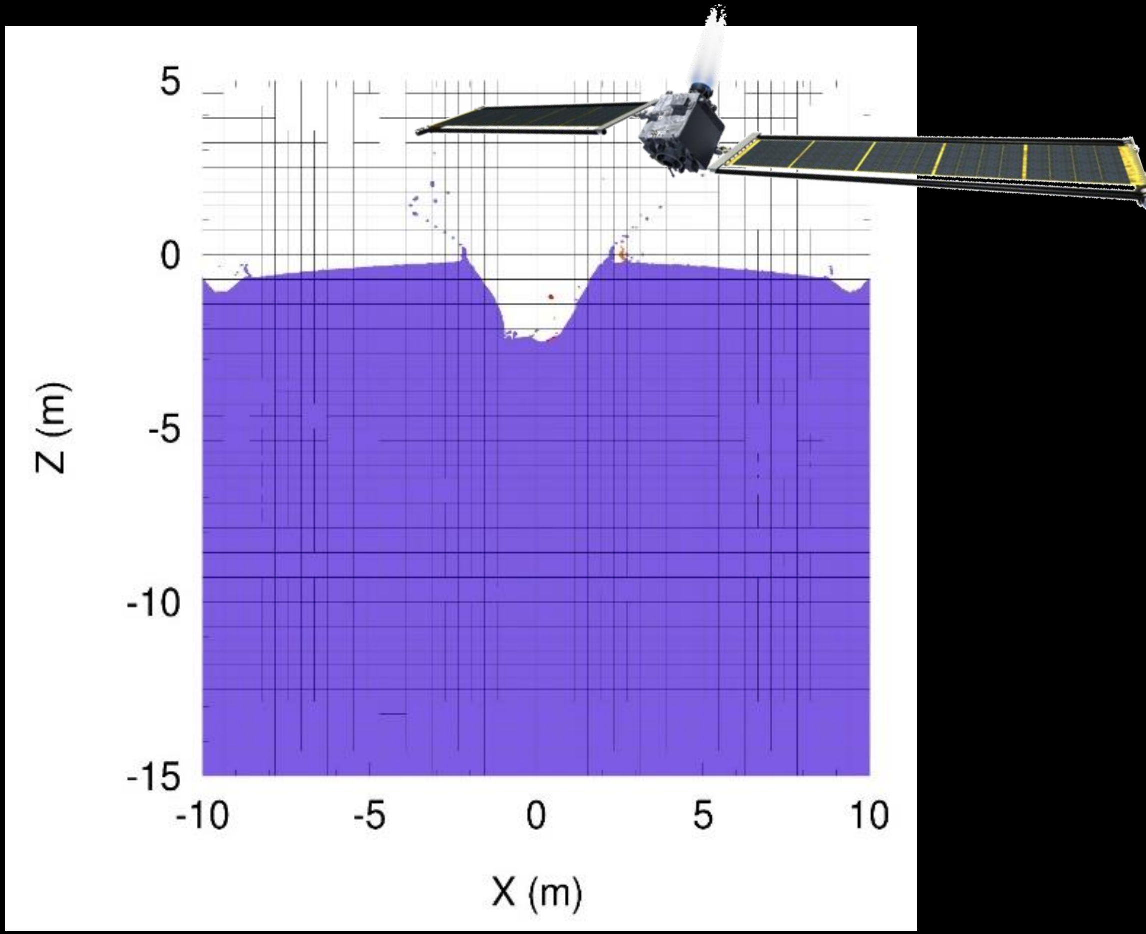
The temporal evolution of β for the 2D and 3D spheres are very similar. The momentum enhancement for the 3D sphere over predicts the spacecraft β by ~10%.



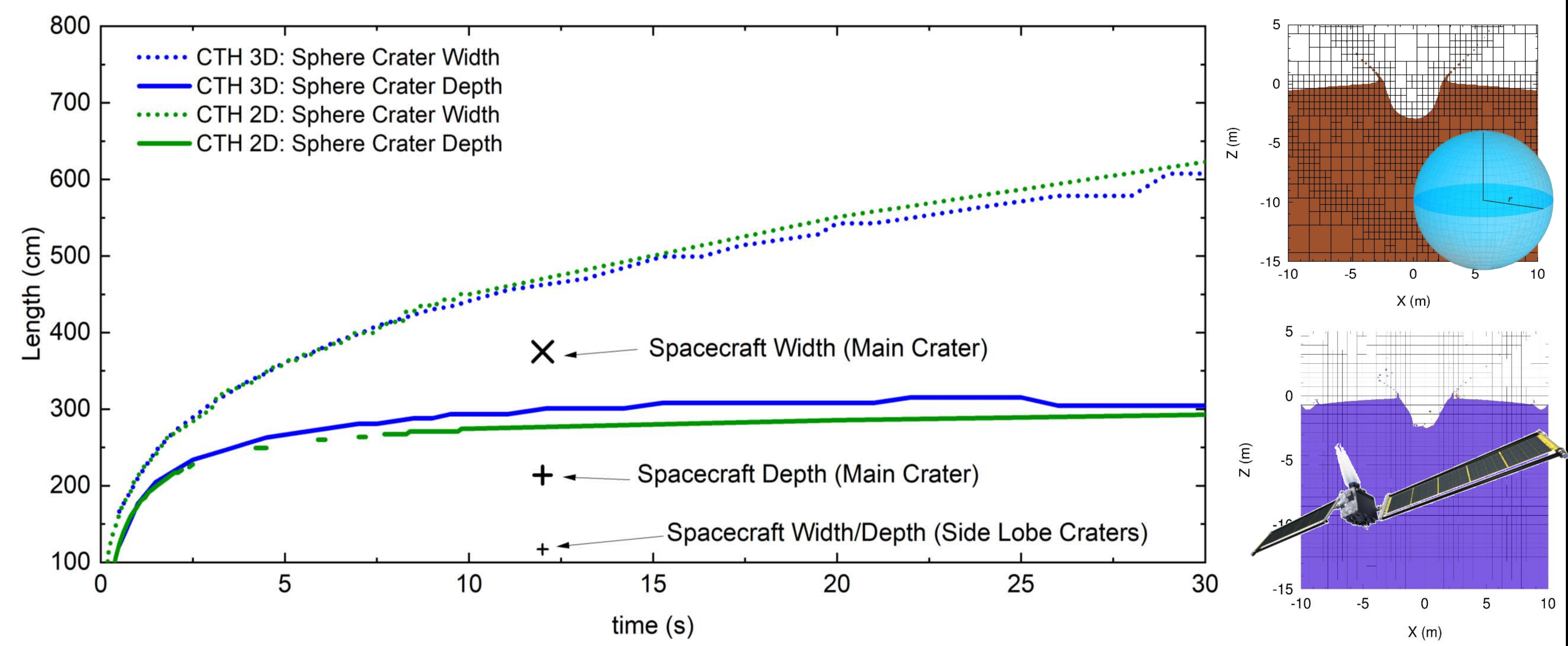
The temporal crater evolution of the 3D spacecraft is much different than the 3D sphere. In contrast to a singular transient crater that is wider than it is deep, the spacecraft produces a very complex-looking crater shape with side lobes.



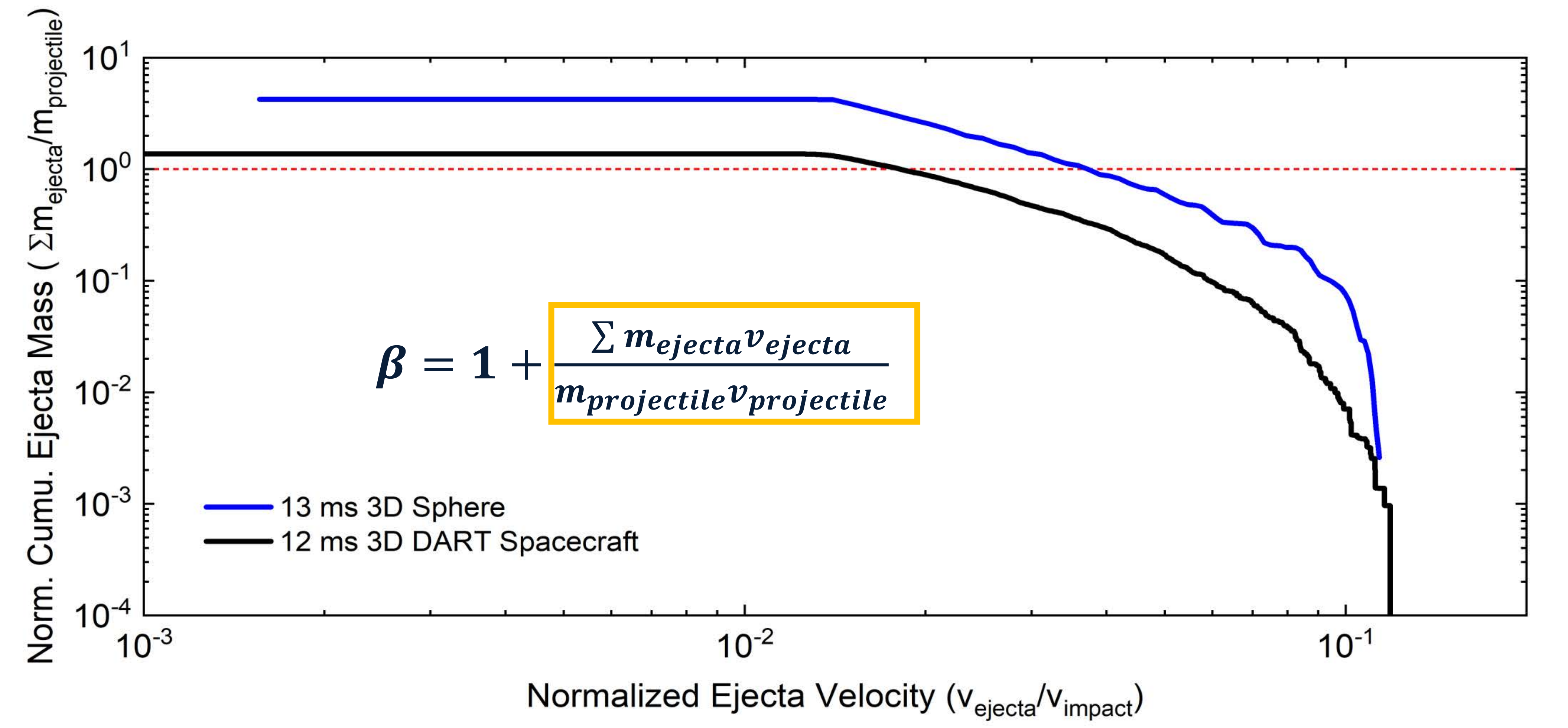




All impactors produce craters that are wider than they are deep. The sphere's crater is symmetrical while the spacecraft results in a more complex crater that is not as deep or wide as the sphere.

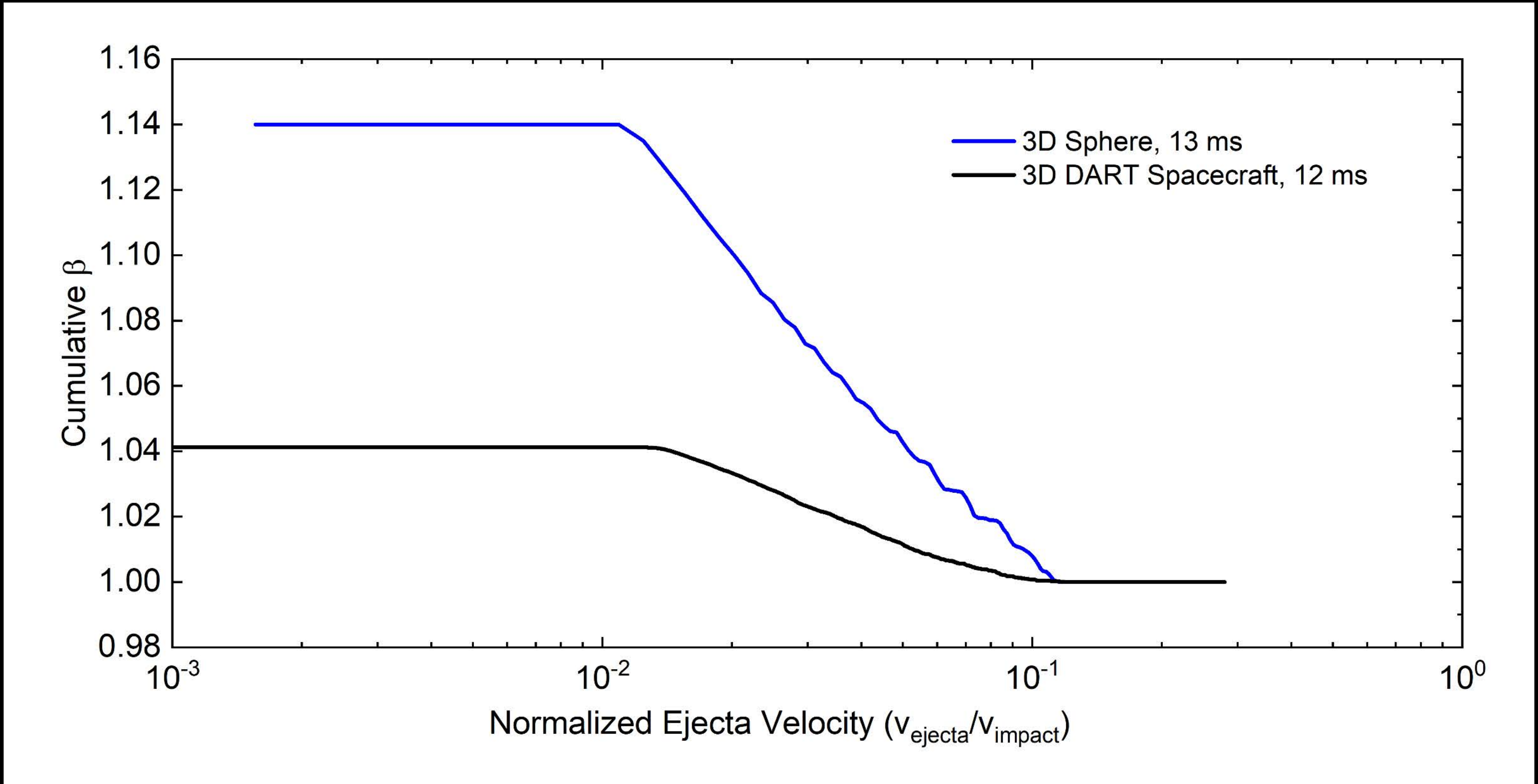


The 3D DART spacecraft produces ~3x less ejecta mass than the sphere, which is responsible for the smaller β. Our results suggest a fully dense Al sphere projectile excessively over predicts β for the DART intercept event.

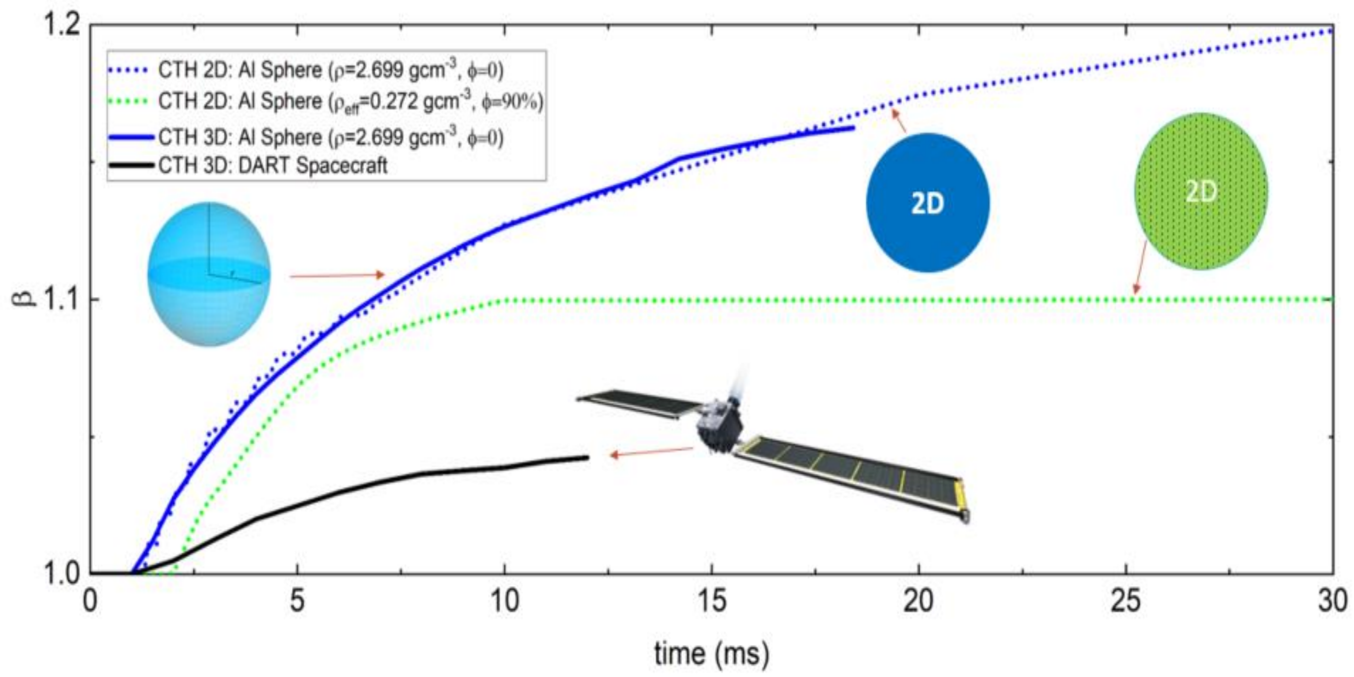


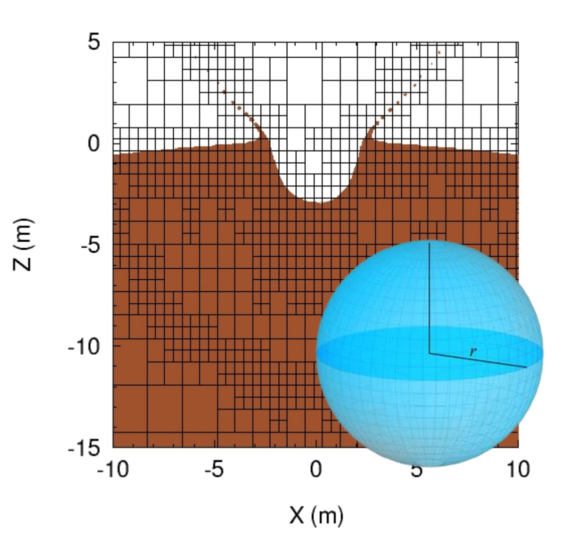
$$\beta = 1 + \boxed{\frac{\sum m_{ejecta} v_{ejecta}}{m_{projectile} v_{projectile}}}$$

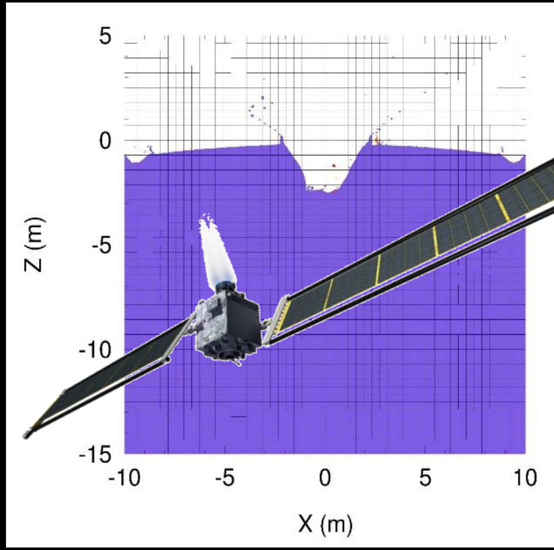
The sphere projectile creates a very different ejecta cloud compared to the spacecraft. While the range of ejecta velocities are similar, the ejecta formed from the sphere has a higher population of fast moving material.



Conclusion: The results show that a simplified model of the projectile over predicts β by ~ 10%. The sphere is a more efficient projectile resulting in more total ejecta mass and a larger population of fast moving material.







This study investigates the effects of projectile geometry on the momentum enhancement factor (β) for efficiently simulating the DART hypervelocity impact.

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Planetary Defense Conference

PROTECTING EARTH FROM ASTEROIDS

Session Date and Time:

Wednesday, 28 April, 2021

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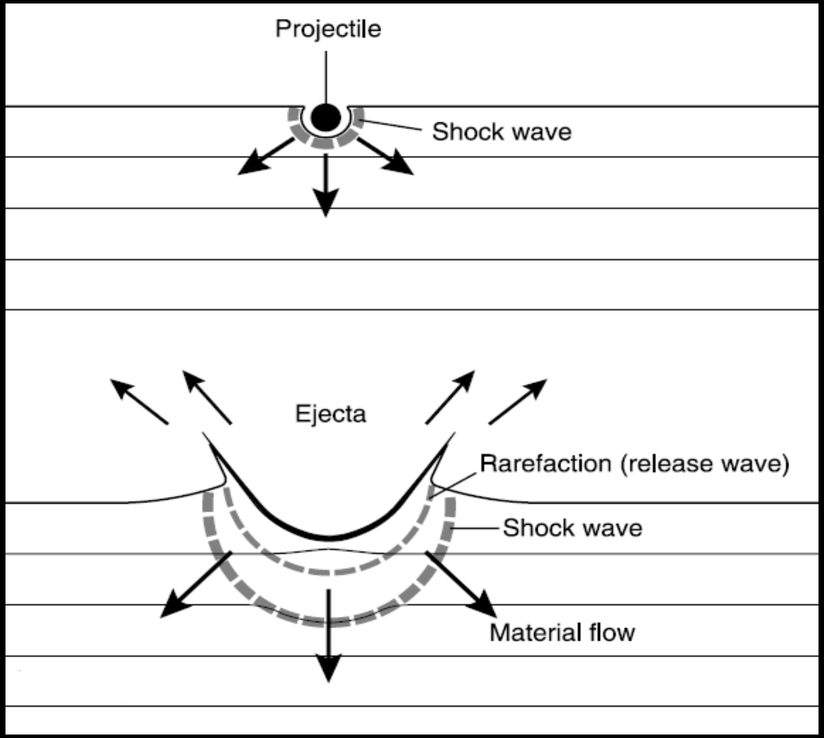
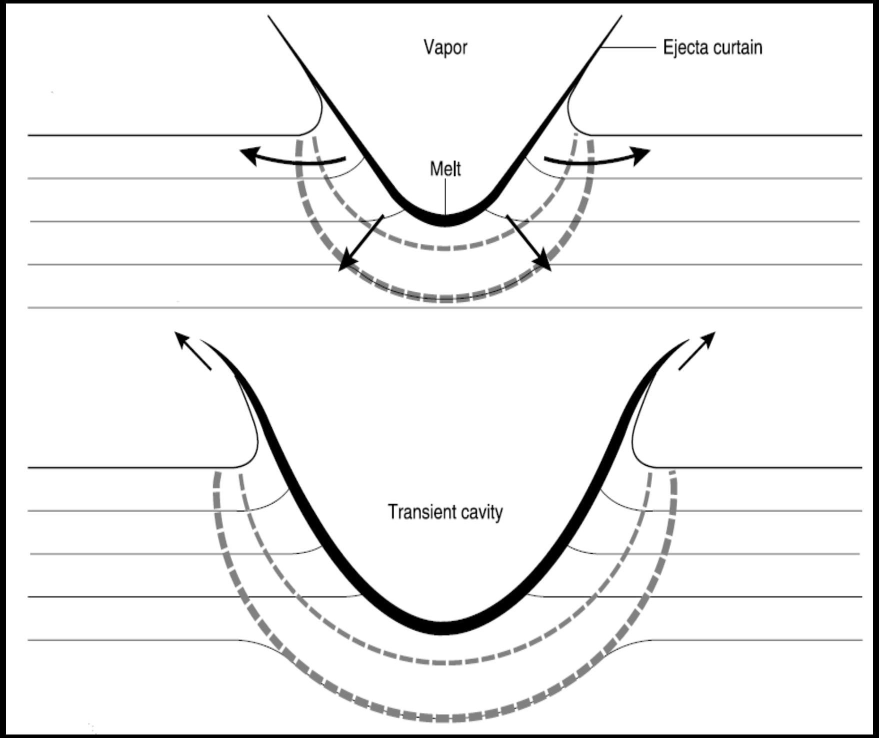
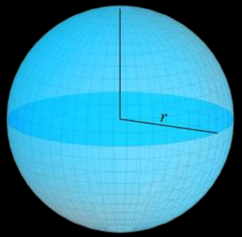
Backups

The processes which form large impact craters resulting from hypervelocity impacts are not fully known. We'd like to understand if the projectile can be represented as a simplified point source to make modeling more efficient.





is

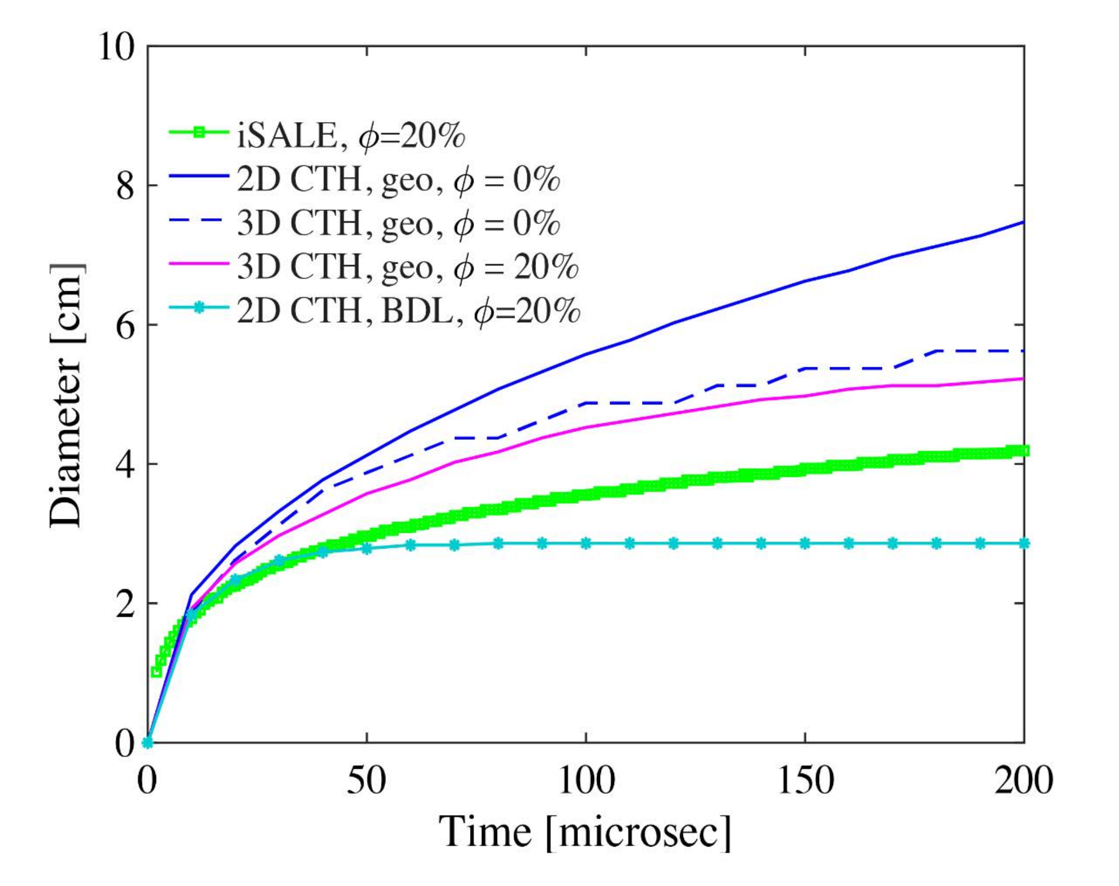


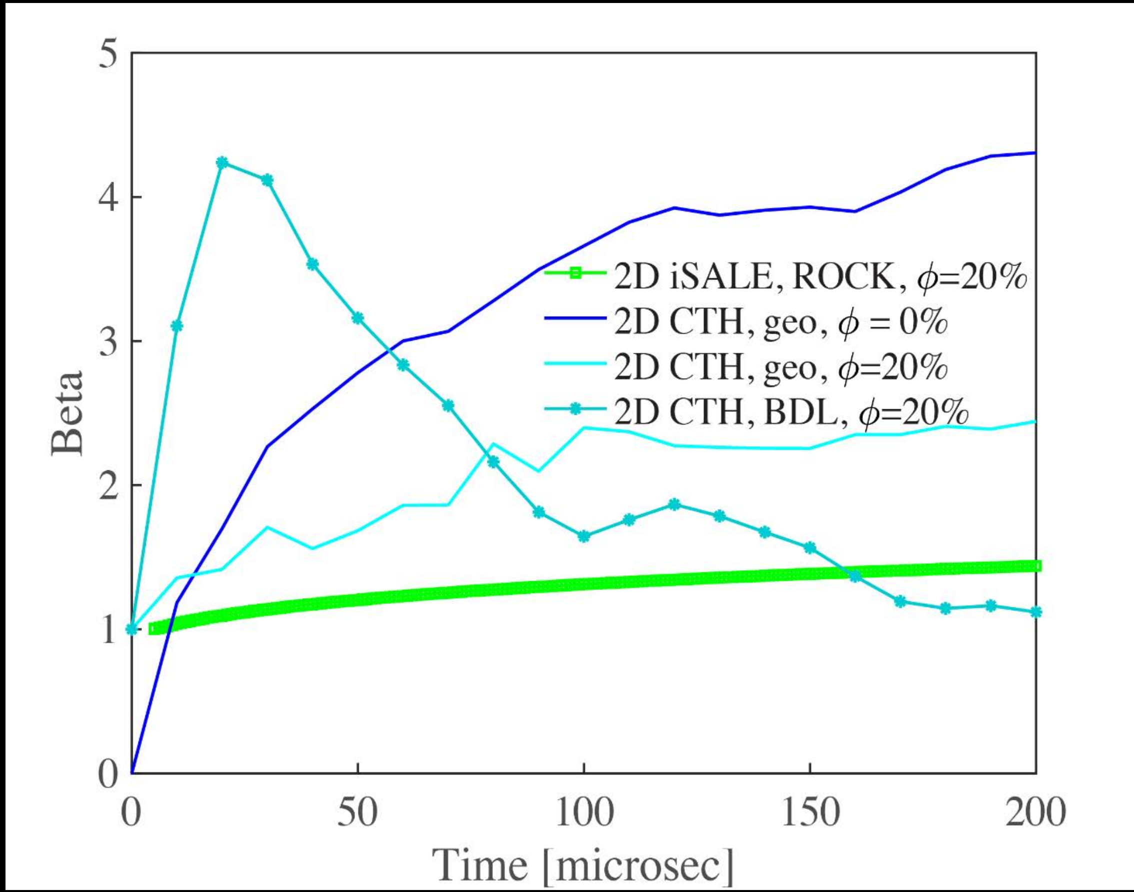
≈

Contact/Compression Stage **Excavation Stage** **?**

French, *Traces of Catastrophe*, Lunar and Planetary Institute (2003).

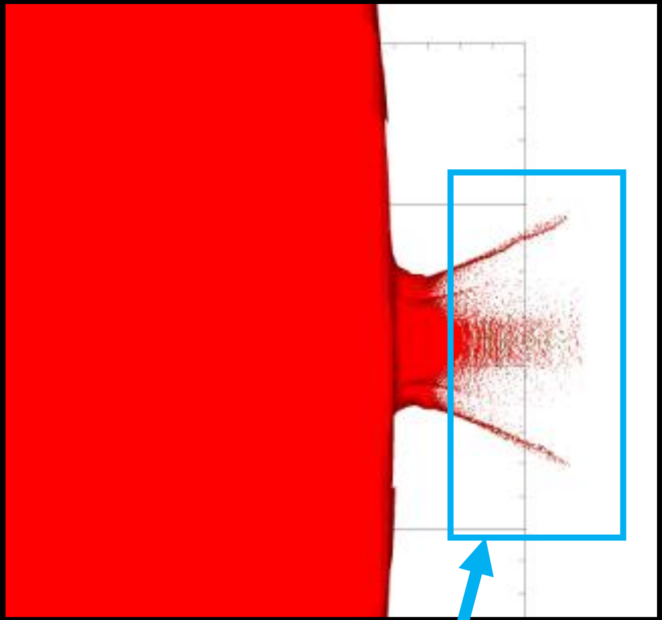
DART benchmarking studies show the propagation of error associated with variables in the phase space. The strength model and material parameters produce the largest uncertainty (~ 20%) in the prediction of crater size and momentum enhancement.



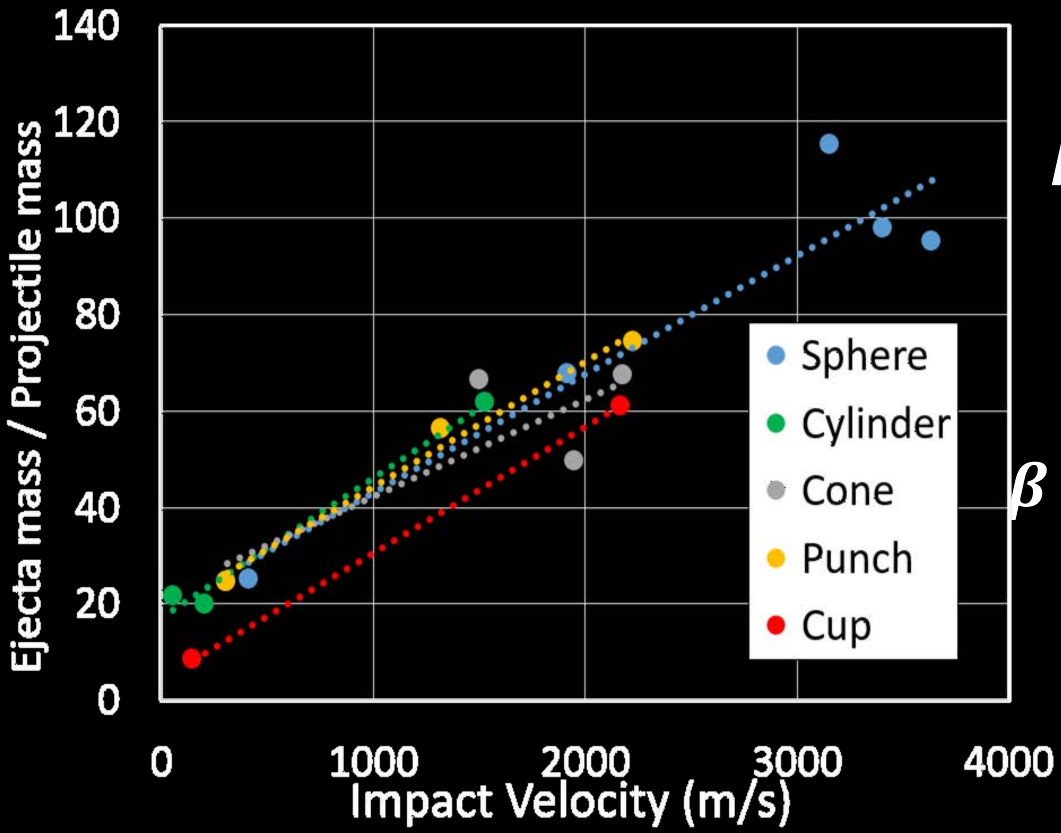


Stickle *et al.*, Icarus 338 (2020) 113446

While it has been shown that β is directly linked to the target material properties, the effects of the projectile geometry on momentum enhancement are relatively unknown. Due to the extra boost provided to β by escaping crater ejecta, it has been suggested that projectile configurations that promote large amounts of ejecta excavation will be more efficient impactors.



Ejecta = any material with mass above 80 cm of impact plane (1% target radius) with positive velocity normal to the impact plane, and a volume fraction < 1.



Ikeda *et al.*, Procedia Engineering 204 (2017) 138-145

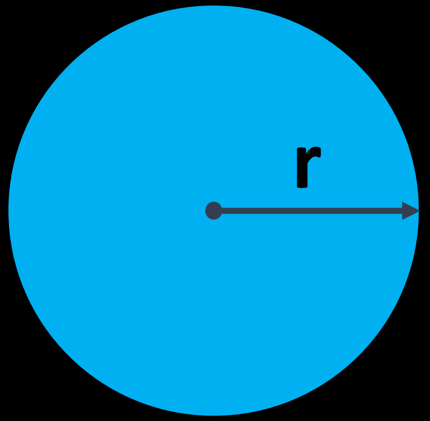
$$\beta = \frac{\Delta P_{Dimorphos}}{m_{projectile} v_{projectile}}$$

$$\beta = 1 + \frac{Total\ Ejecta\ Momentum}{m_{projectile} v_{projectile}}$$

β > 1, maybe >> 1

The simulation parameters defined for the initial 2D CTH tests were adapted from the benchmarking study and performed with no porosity in the basalt target.

Dimorphos (Target) Shape



Sphere

Radius (r) = 80 m

Mass = 1.3×10^{9} Kg

Material

Fully dense basalt

Cohesion=90 MPa (strong target)

Asteroid Equation of State: Sesame

$$F(V,T) = \phi_0(V) + F_{ion}(V,T) + F_{el}(V,T)$$

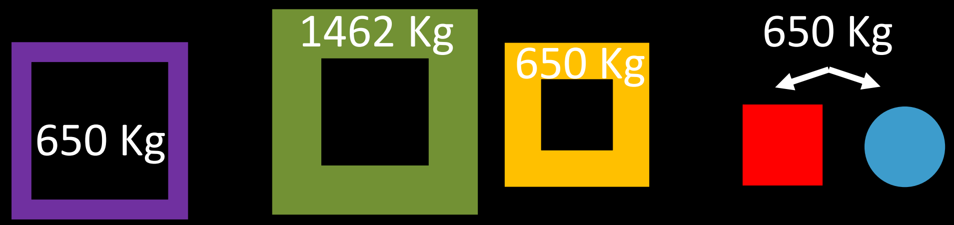
Bulk density = 2.648 g/cc

Base Asteroid Strength

Model: Brittle Damage with Localized Thermal Softening (BDL)

Damage is evolved in Asteroid

2D Impactor Shapes



10 cm wall

15 cm wall

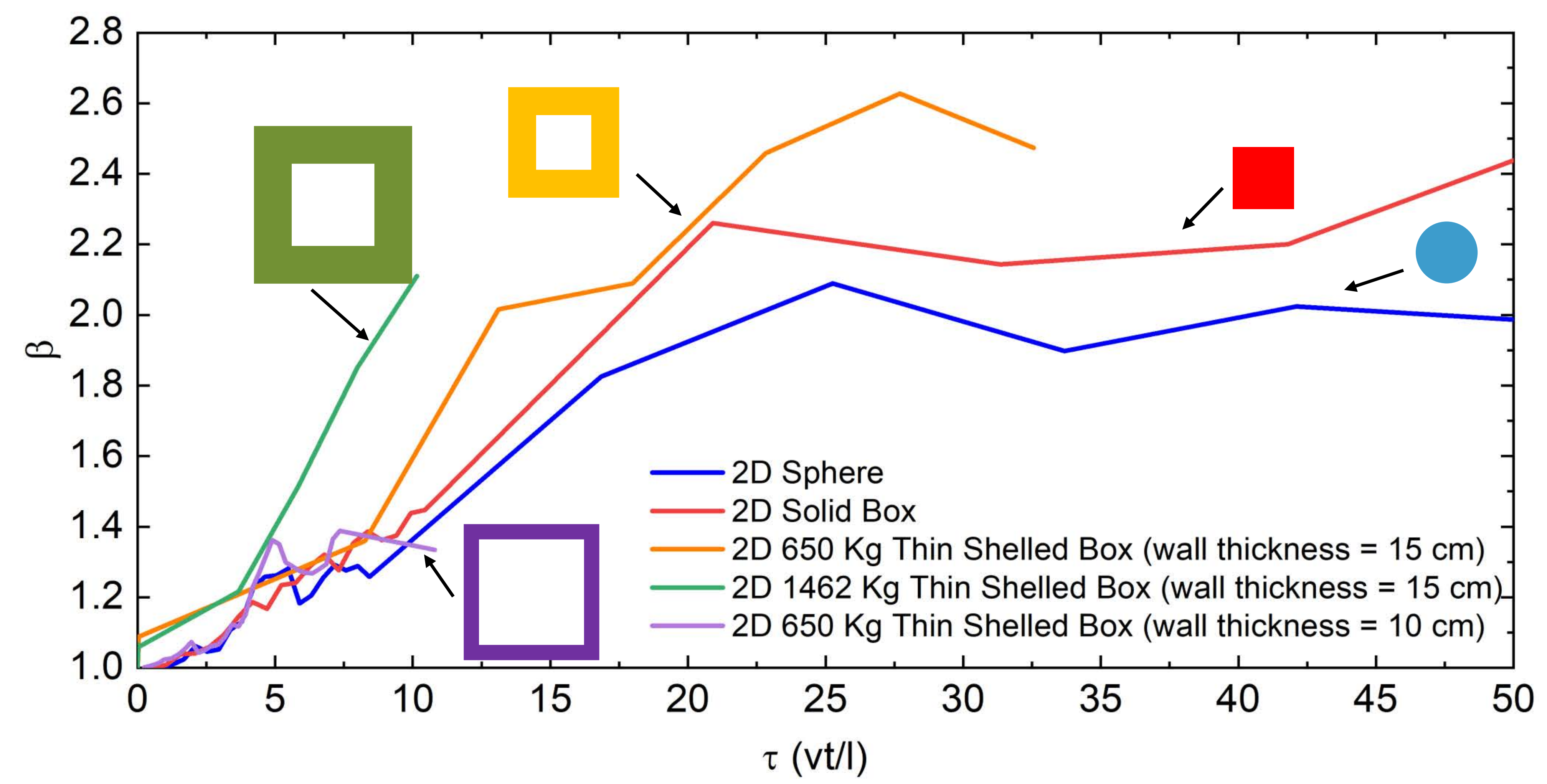
Impactor Properties

Composition: Fully dense Aluminum

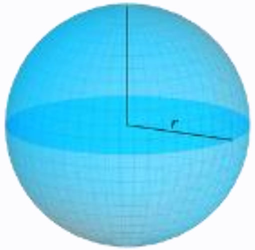
Mass = 650 - 1462 Kg

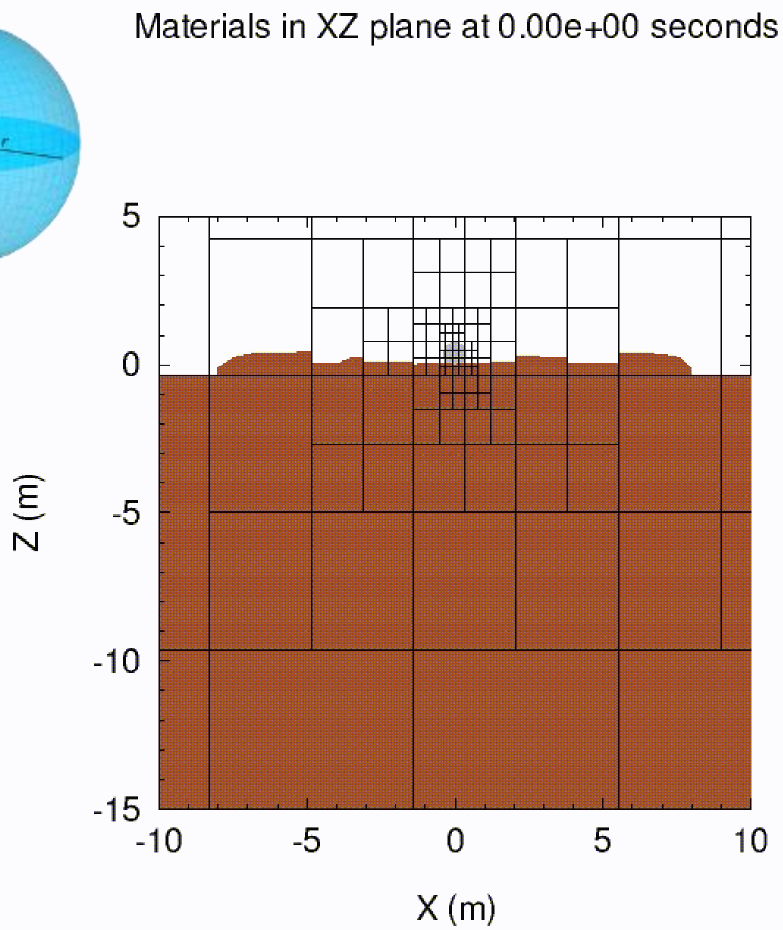
Velocity = 6.65 km/s

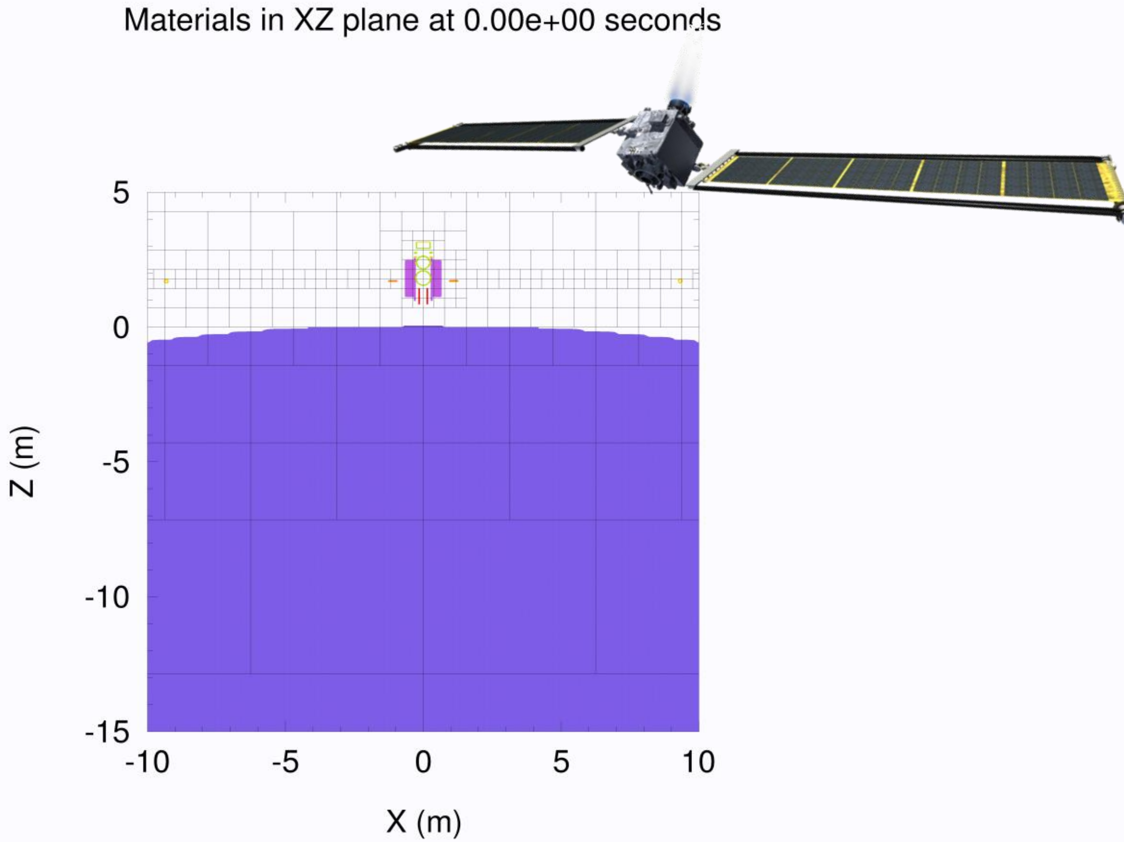
The 2D results show that there is not a strong dependence between β and projectile shape when the projectile mass is evenly distributed during impact. A natural question to ask is how does this translate to a more complex projectile shape, like the full spacecraft model with deployed solar panel wings?



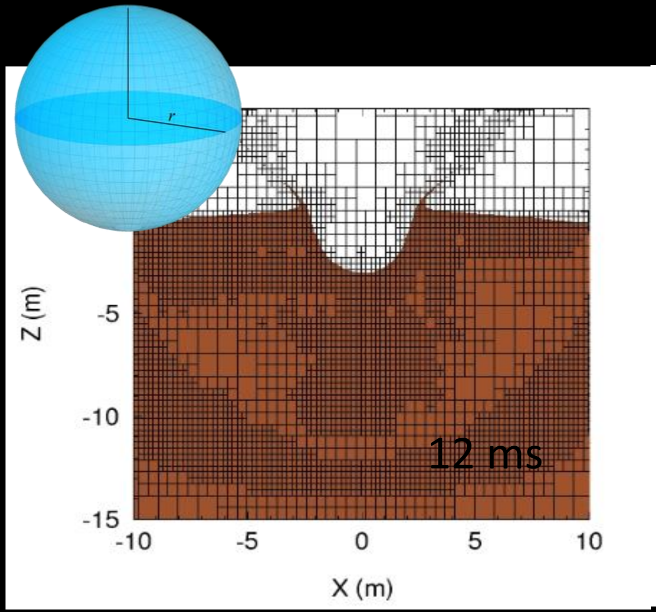
The temporal crater evolution of the 3D spacecraft is much different than the 3D sphere. In contrast to a singular transient crater that is wider than it is deep, the spacecraft produces a very complex-looking crater shape.

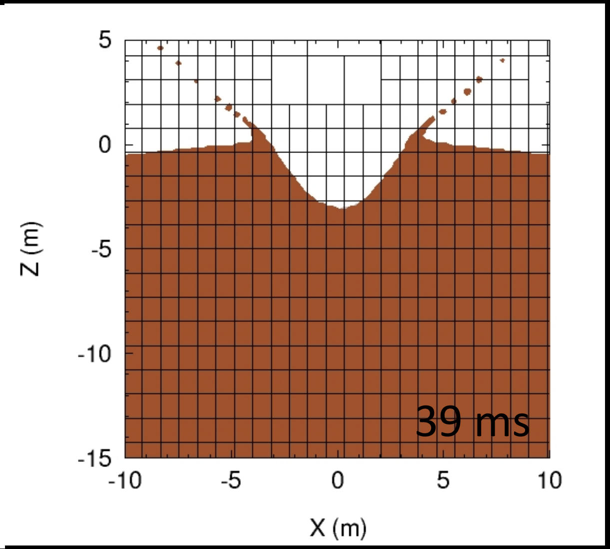


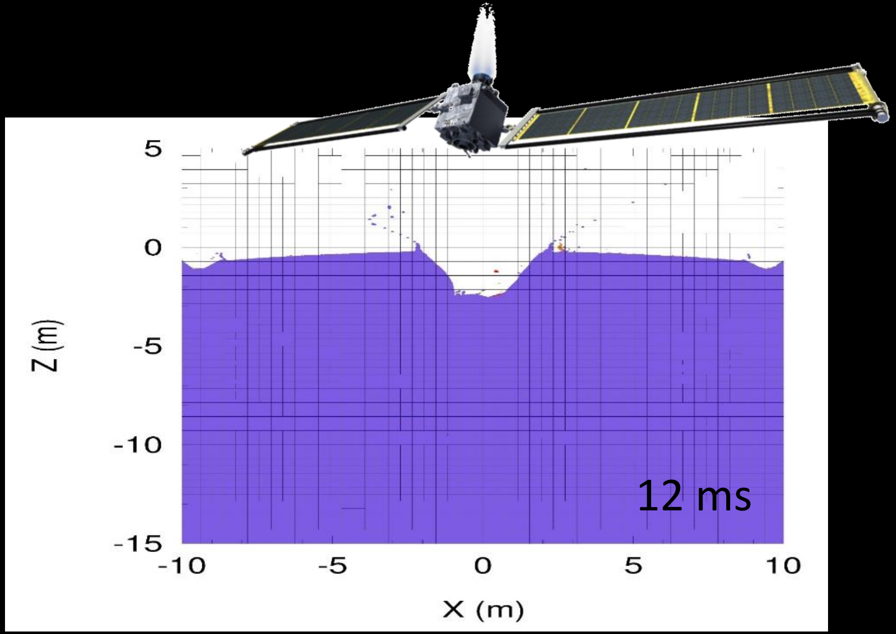




A much more complex crater is created by the spacecraft, as the solar panels contribute to the coupling of the spacecraft to the target .







Spacecraft Geometry Effects on Cratering and Deflection in the DART Mission

Presented at the 2021 Planetary Defense Conference

J. Michael Owen[1], Mallory DeCoster[2], and Dawn Graninger[2]
[1]Lawrence Livermore National Laboratory, *mikeowen@llnl.gov*
[2]Johns Hopkins University/Applied Physics Laboratory

April 28, 2021

LLNL-PRES-821498
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

At the 2019 PDC we presented early work looking at spacecraft geometry effects.

- We compared models using spheres, cubes, and a spacecraft model based on DAWN.
  - We found the impactor geometry could affect β by 10%-15% (lowest for the spacecraft model, highest for symmetric impactors like the sphere).
  - The crater morphology was also affected:
    - Diameters and depths varied by roughly a meter (10%), again with the larger/deeper craters for simple symmetric impactors like the sphere and smaller craters due to the most realistic spacecraft model.

- This year we would like to finalize this study with several improvements over our prior study:
  - Improved material modeling, with damaged rock behaving more like granular material rather than a strengthless fluid (in Spheral – CTH already had this model).
  - Higher fidelity models of the spacecraft scenario:
    - Realistic materials (previously just used Si and Al).
    - Real CAD based geometry with true geometry, components, panels, and voids.
      - Prior simulations relied on full density solid impactor models, implying we shrank the spacecraft volume in order to match the true mass.

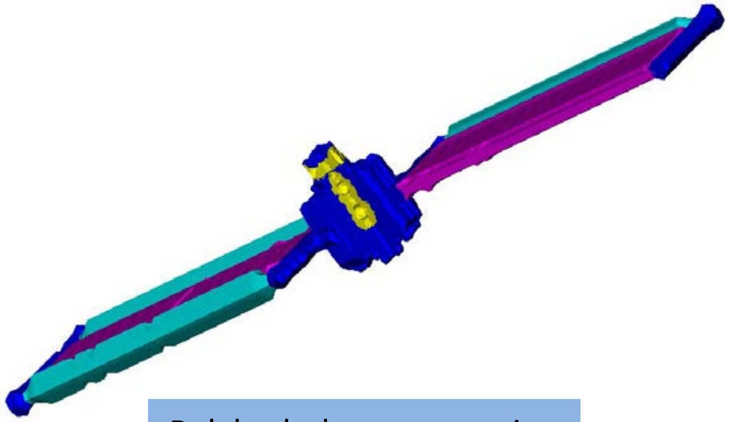
- Multiple codes used to model the problem: Spheral (ASPH) and CTH (AMR Eulerian).

The spacecraft model is based on a simplified DART CAD model.

- We use STL models for each part in a simplified model
  - Roughly 50 individual components (panels, camera, struts, etc.)
  - We use one of 4 material models for each component in the model: Al, Ti-6Al, Stainless Steel, and Si.
- Spheral fills each STL part model with ASPH (Adaptive SPH) points, while CTH paints in each component on an AMR mesh.
- The total spacecraft mass is 535kg, which is distributed between the materials as:

Material	Mass
Al	377kg
Si	57.3kg
Ti-6Al	41.35kg
Stainless Steel	59.35kg

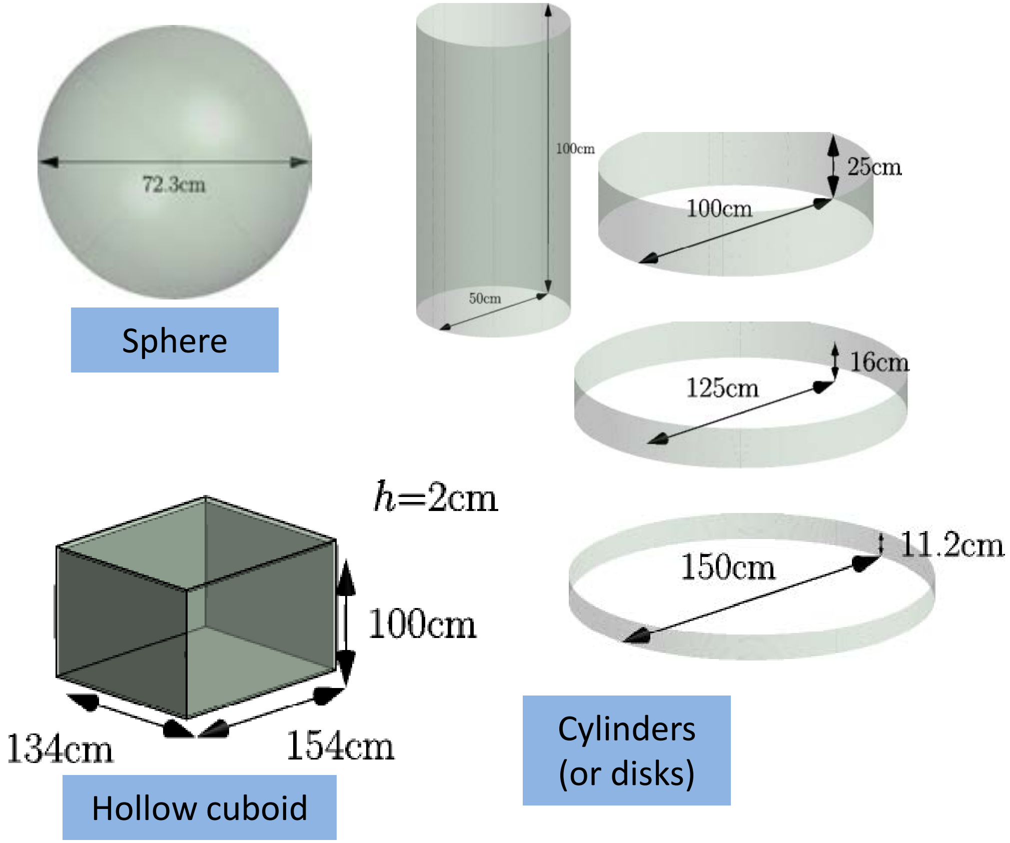
DART geometry rendering



Polyhedral reconstruction in Spheral (materials)

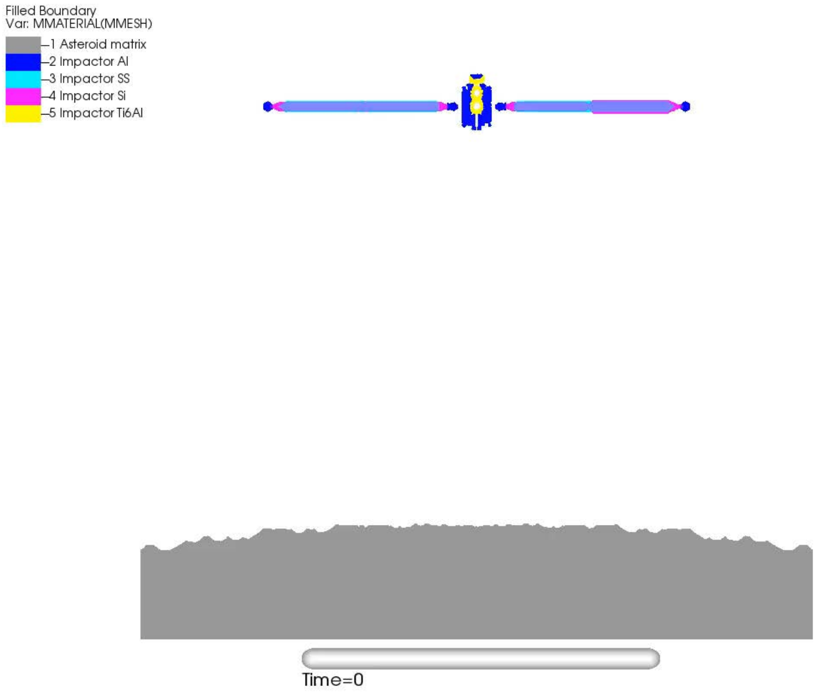
We consider a variety of idealized impactor geometries for comparison with the high fidelity DART model.

- The game here is to maintain the same impactor mass (535 kg) and impact velocity (6.65 km/sec), while varying the geometry.
- In both Spheral and CTH we compare two impactor geometries: DART and a sphere.
- In Spheral we have also modeled a few more cases:
  - A hollow cuboid with the same moment of inertia as DART.
  - A series of solid cylinders (or disks), with diameters in the range *D*=[0.5, 1, 1.25, 1.5] meters.
- All cases model Dimorphos as a uniform SiO_2 sphere of 160 m diameter and bulk porosity ϕ=30%.



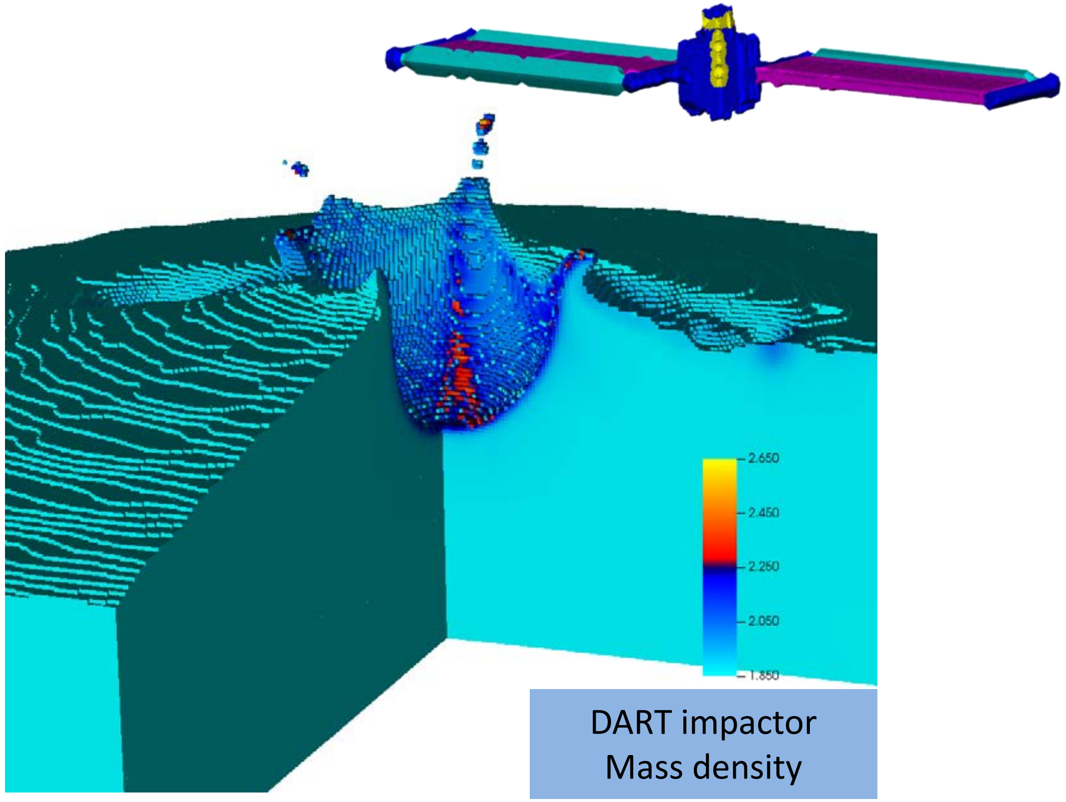
The full DART model impactor results in a fairly complex crater, with evident side craters due to the solar arrays and booms.

- In these models we impact with solar arrays parallel to Dimorphos' surface.
- This animation shows the materials in Spheral's polyhedral reconstruction.
- This is a slice through the simulation, run to 50 milliseconds final time.
- The crater is not a simple bowl: the solar panel structures (primarily the stainless steel booms and rollers) result in shallow craters on both sides of the primary crater.

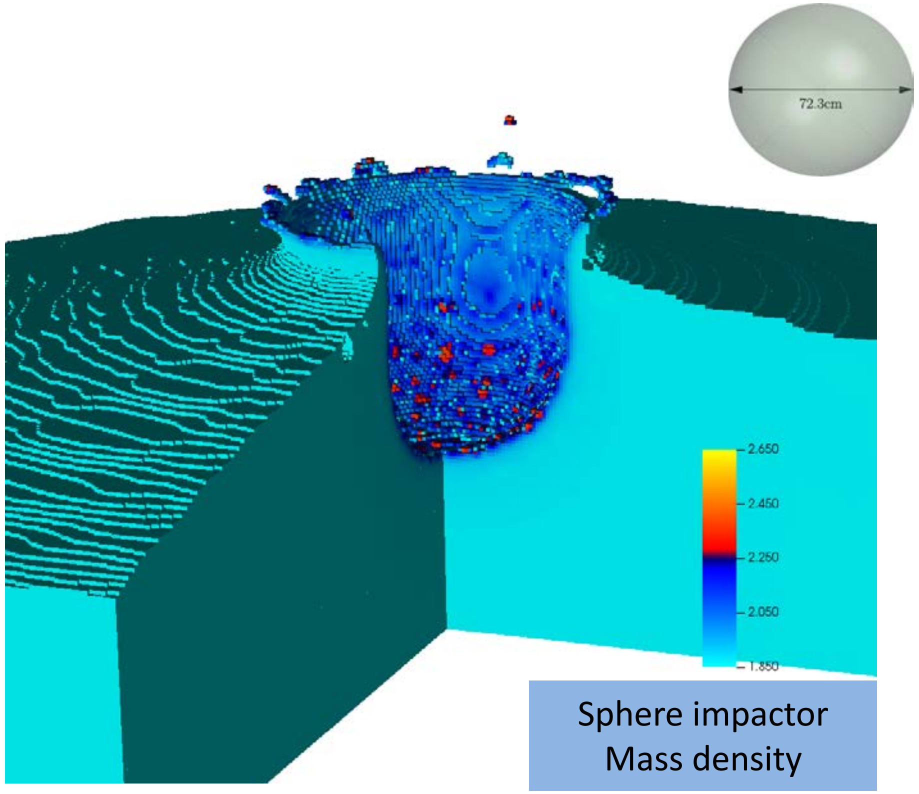


The effect of the CAD geometry on the crater is evident compared with the spherical impactor.

- In these mass density images we can clearly see the imprint of full DART geometry at 50 ms.
  - Compared with the spherical impactor the central crater is shallower and not as wide.
  - The side craters are evident from the solar arrays (at least for this simple monolithic target at early time).



DART impactor
Mass density

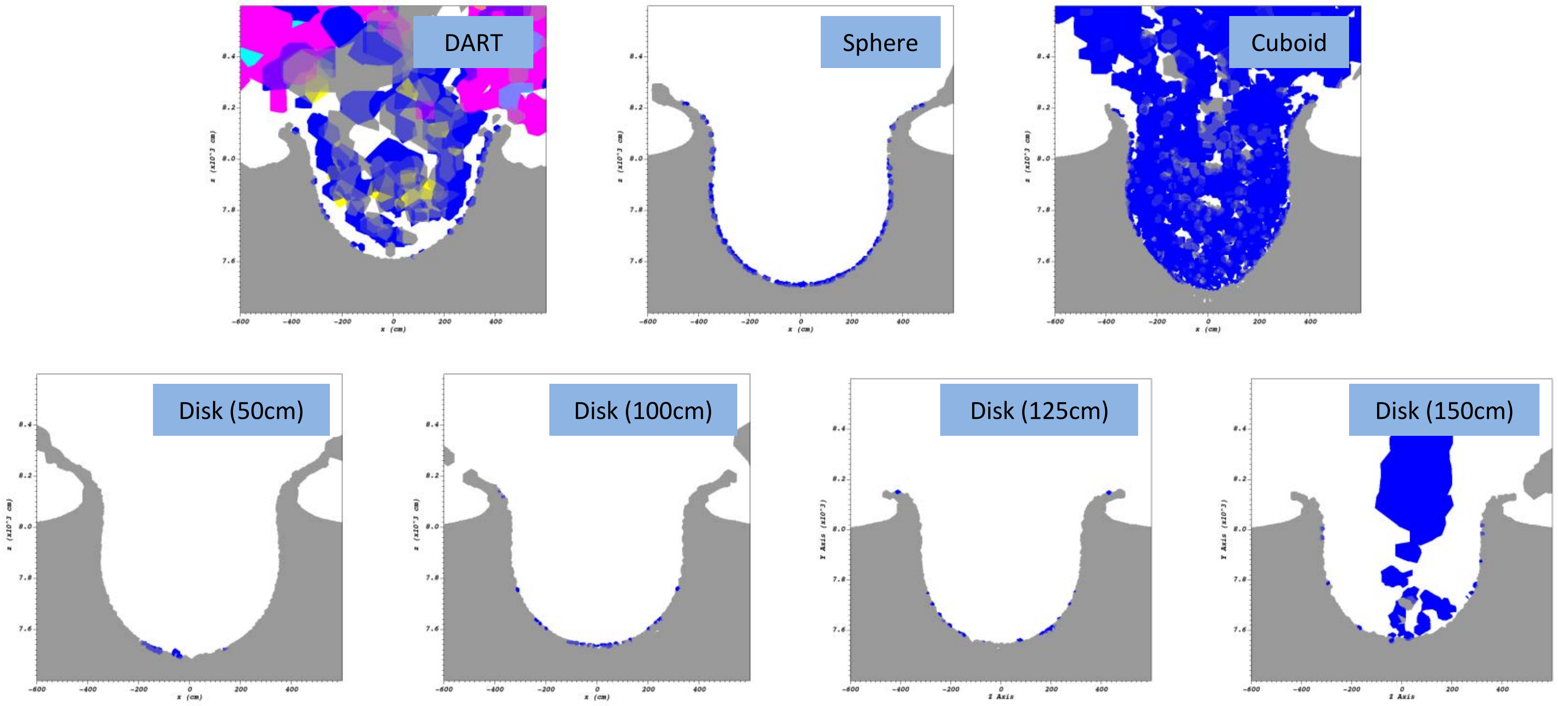


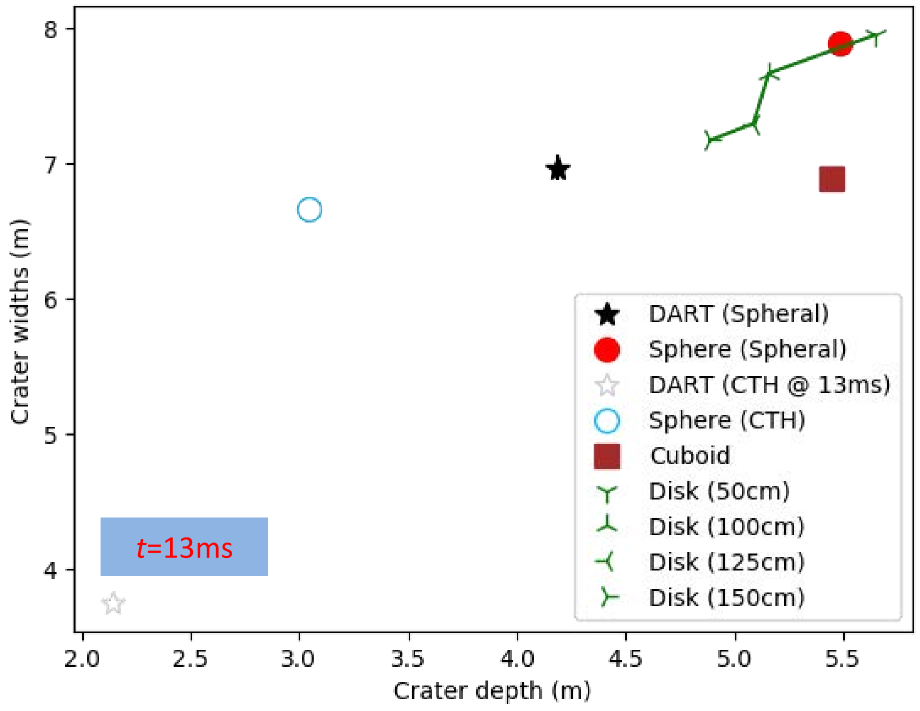
Sphere impactor
Mass density

The crater tends to be smaller for more complex impactor shapes that do not penetrate as well.

- This is particularly clear for the cylinder/disk impactors: the wider/thinner the disk, the shallower and narrower the crater.

- CTH tends to find smaller crater volumes than Spheral.
  - Note, the CTH DART model is shown at 13 ms (not 50 ms), and so may grow with time still.



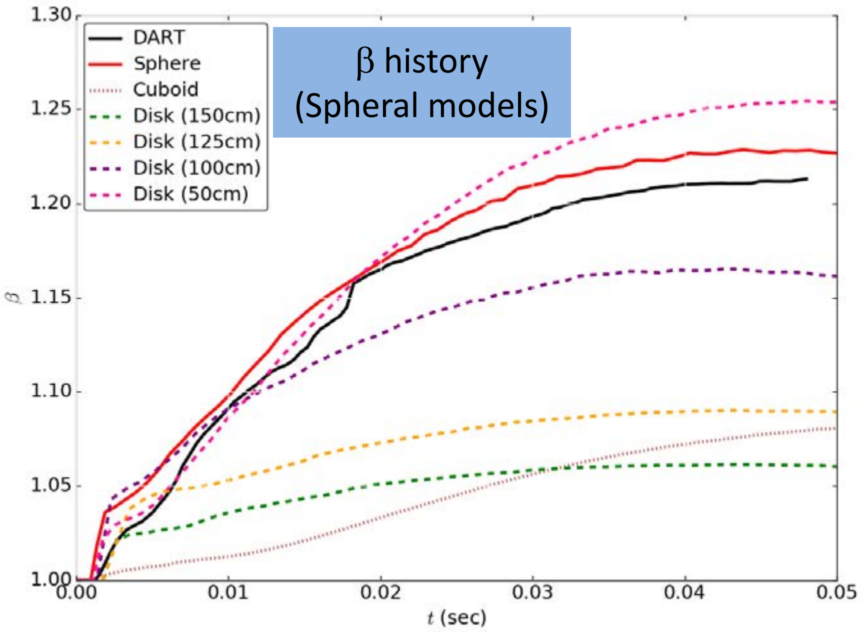


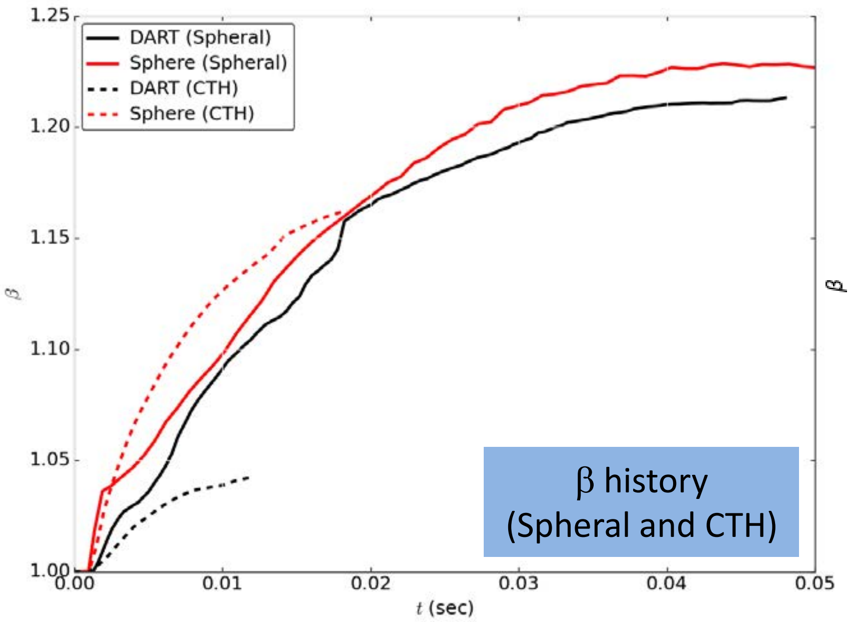
The ejecta momentum enhancement (β) shows trends with impactor geometry, though Spheral finds the sphere fortuitously matches DART reasonably in this quantity.

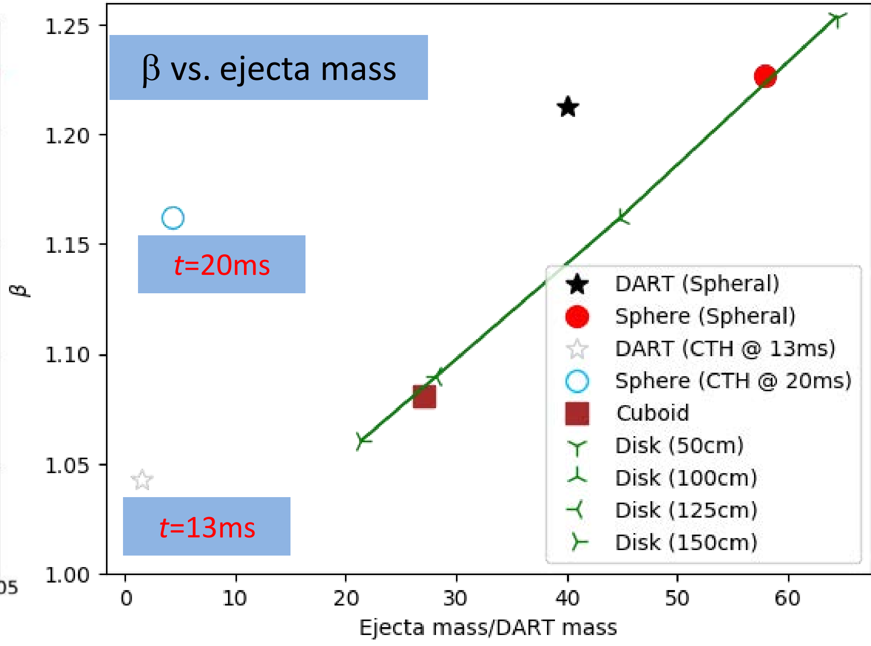
- Spheral and CTH agree reasonably on β for the sphere, with Spheral somewhat higher.
  - This despite CTH finding less ejecta mass and a smaller crater volume compared with Spheral (note, both CTH models at earlier time).
  - Both find the DART model β to be reduced (CTH more so).

- The disk/cylinder models show a clear pattern in β -- penetrating rods produce higher β.

- The idealized impactors follow a tight correlation of ejecta mass vs. β.
  - The DART model is an outlier in this plot, producing more β per ejecta mass.



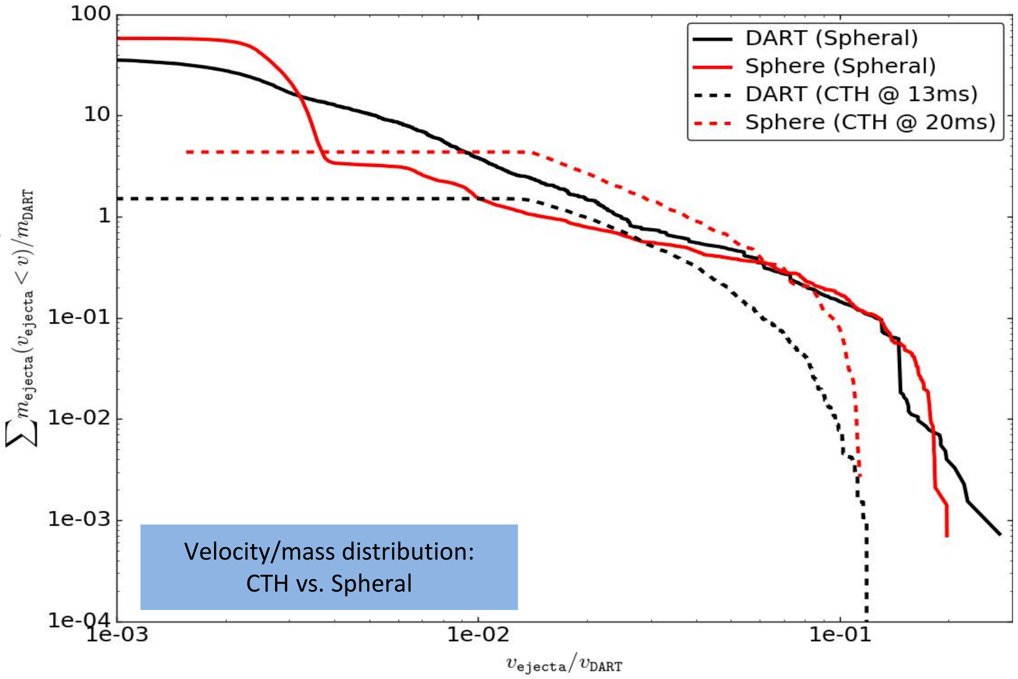


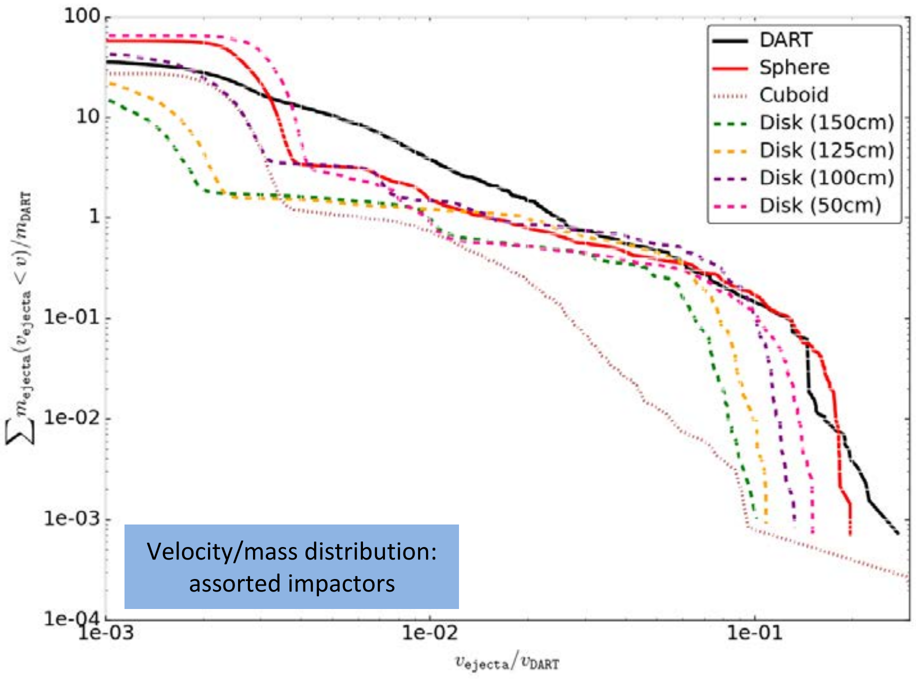


The ejecta velocity distribution is also affected by impactor geometry, though again the sphere and DART agree reasonably.

- The shapes of the ejecta distributions are similar for the sphere vs. DART.
  - Spheral finds the magnitudes of the two case are close, though the mass of slow ejecta is reduced for DART.
  - CTH shows the DART distributions are similar in shape but reduced in magnitude vs. the sphere.
  - Recall though the CTH calculations are at earlier times (20ms for the sphere, 13ms for DART).

- The disk/cylinder models show consistent effects:
  - Ejecta from flat disks is systematically lower at all velocities.
  - The rod shows the most ejecta/highest β of all cases.





Overall we find the impactor geometry can affect the measurable quantities in kinetic impactors.

- In terms of crater geometry, we see a roughly 15% effect in the main crater dimensions:
  - 7m wide for DART vs. 8m for the sphere; 4.5m deep for DART vs. 5.5m deep for the sphere
- The ejecta shows some large differences, with the sphere producing significantly more ejecta mass: 2x @ 50ms, with the sphere ejecta mass still climbing (consistent with the different crater volumes).
  - CTH finds a 3x ejecta mass discrepancy.
- This effect is somewhat mitigated in β, as the DART model produces slightly more ejecta at moderate velocities vs. the sphere.
  - The sphere still produces a larger β in the end, but not by quite as much as the difference in ejecta mass would suggest. CTH finds this discrepancy between the sphere and DART to be even larger (10% in β).
- We find that varying the impactor geometry in a systematic way (varying cylinders for instance) produces measurable and predictable changes in β and crater dimensions.
  - The sphere, cylinders, and cuboid produce distinct ejecta cloud properties, but fall on a single linear relation when we plot β vs. total ejecta mass.
  - The DART model does not fall on this trend however.
- Gratifyingly, the broad conclusions comparing the spherical impactor vs. DART are consistent between CTH and Spheral, the two codes discussed in this study.

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Q&A

Session 7b: Deflection & Disruption Testing

7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Break

Up next: Session 8b - Mission & Campaign Design