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

Lawrence Livermore National Laboratory

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.

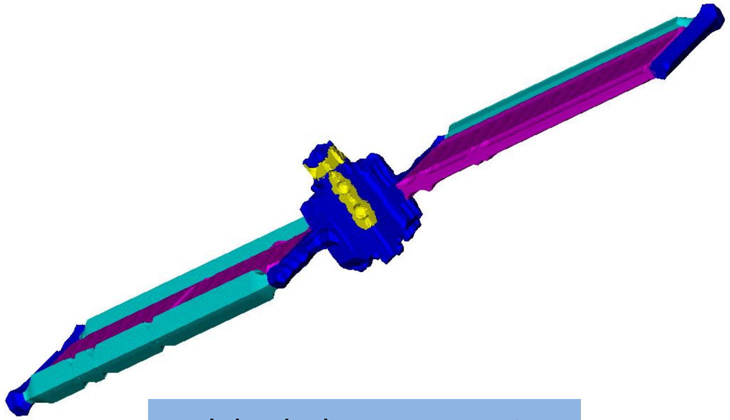
- Multiple codes used to model the problem: Spheral (ASPH) and CTH (AMR Eulerian).

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

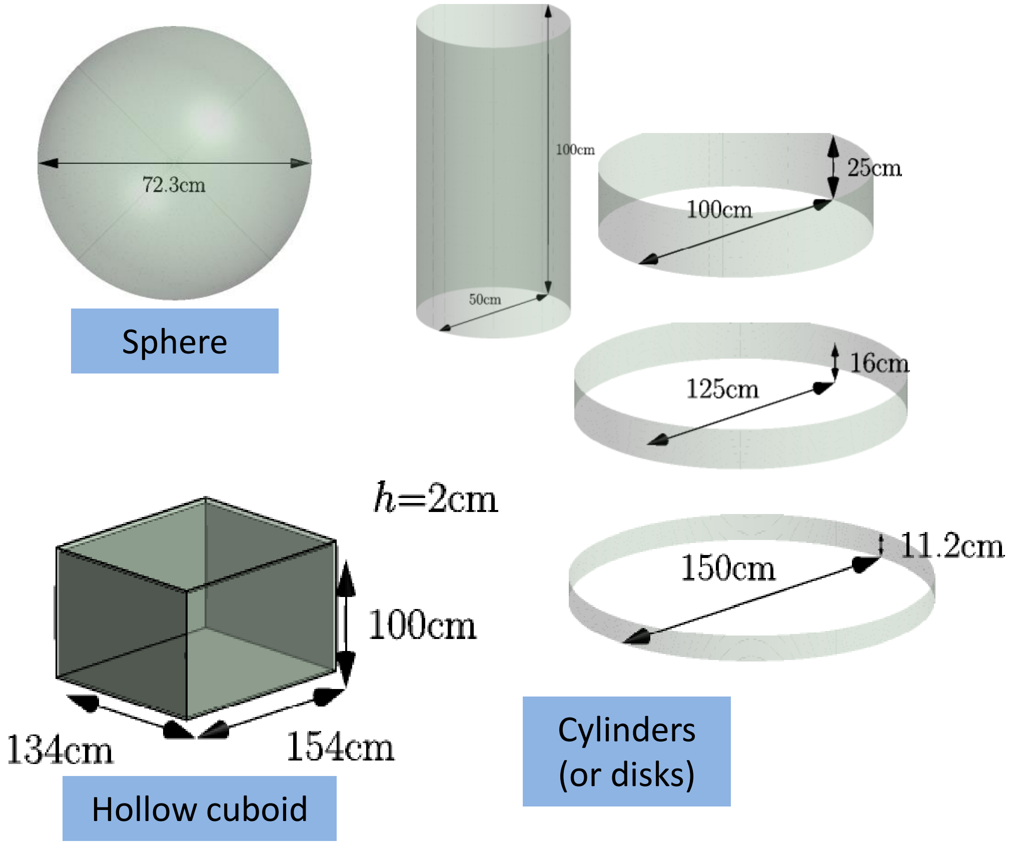
DART geometry rendering



Polyhedral reconstruction in Spheral (materials)

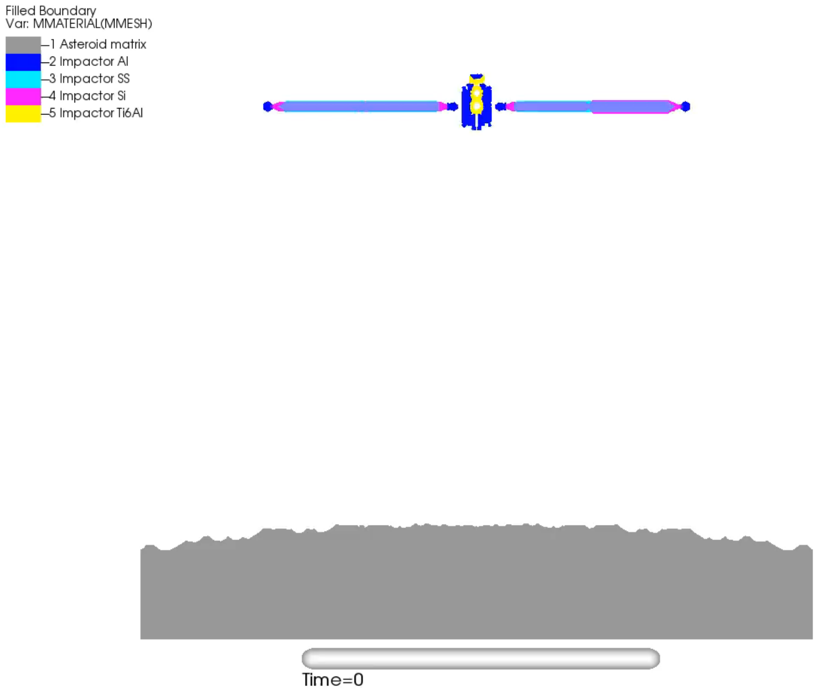
We consider a variety of idealized impactor geometries for comparison with the high fidelity DART model.

- 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%.



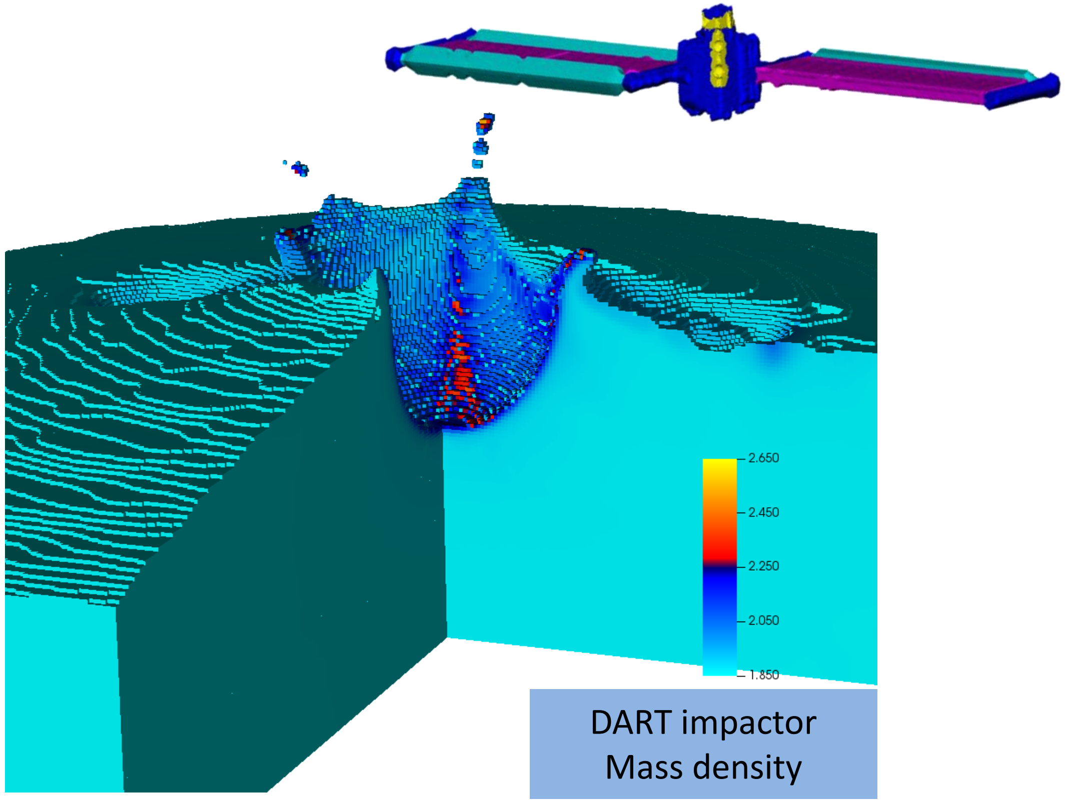
The full DART model impactor results in a fairly complex crater, with evident side craters due to the solar arrays and booms.

- 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.

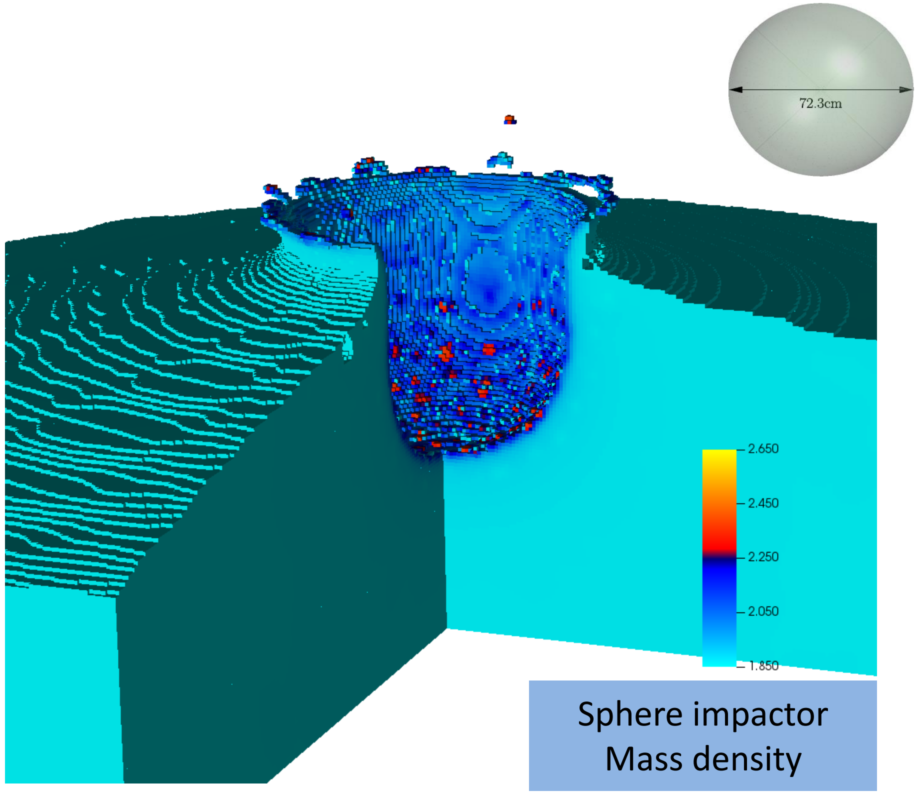


The effect of the CAD geometry on the crater is evident compared with the spherical impactor.

- 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

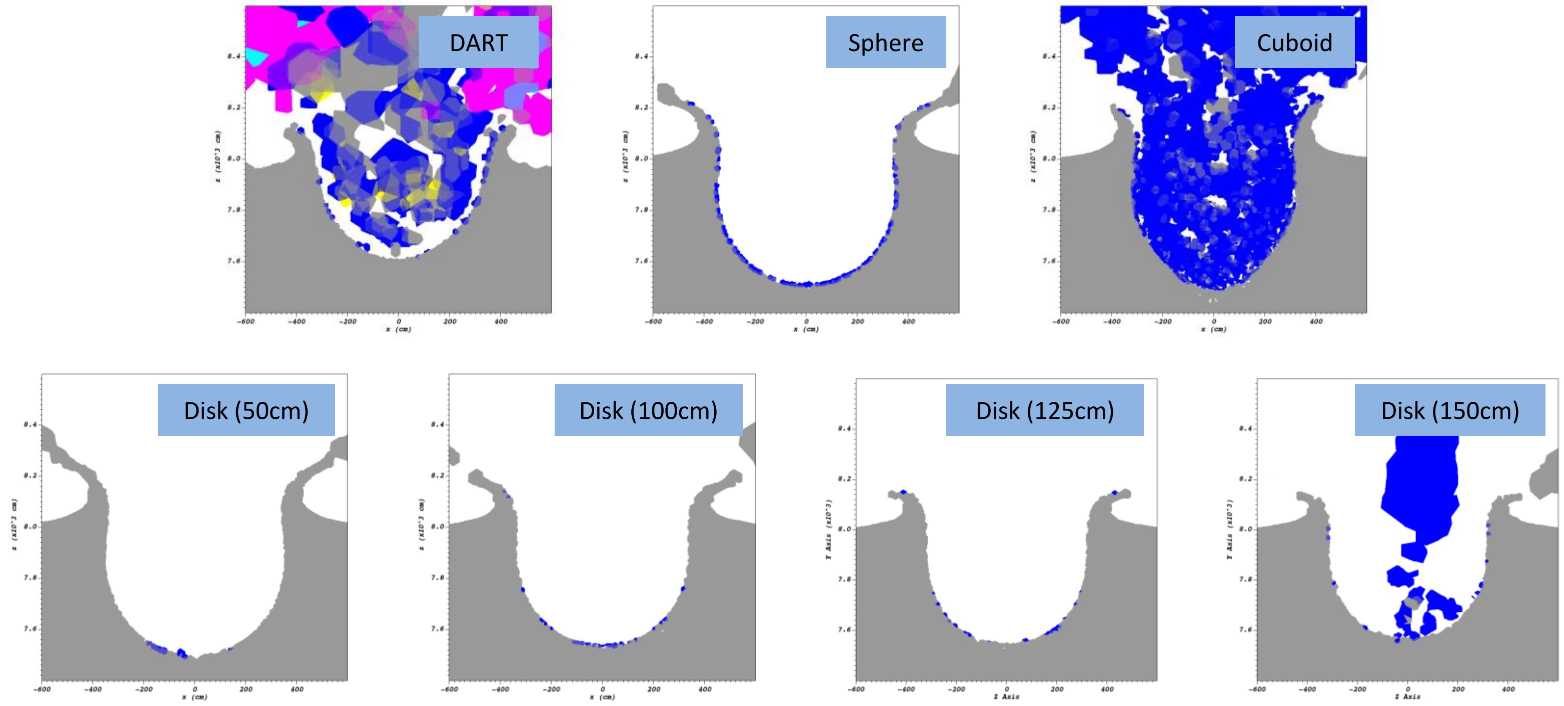


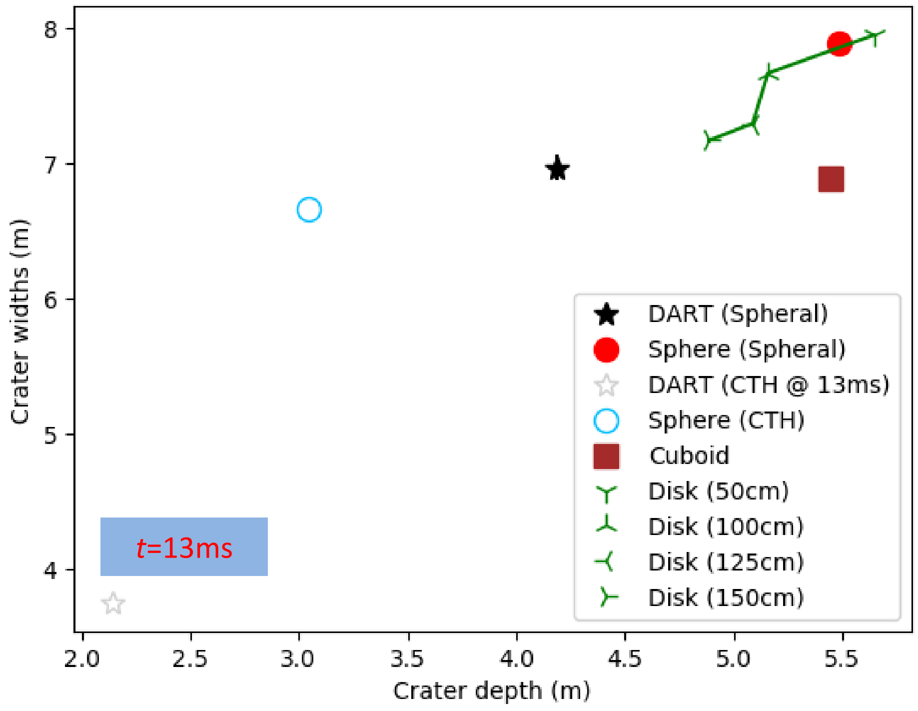
Sphere impactor
Mass density

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.



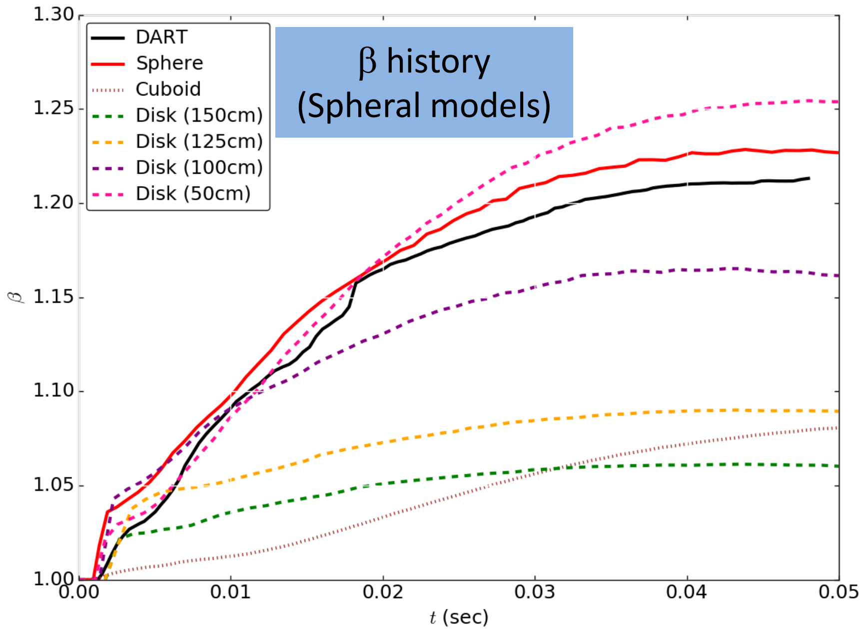


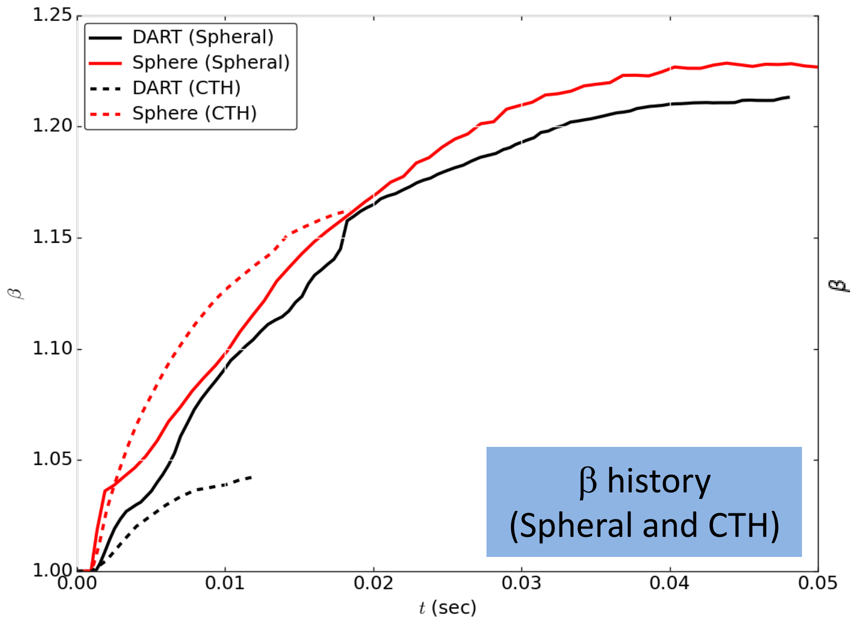
The ejecta momentum enhancement (β) shows trends with impactor geometry, though Spheral finds the sphere fortuitously matches DART reasonably in this quantity.

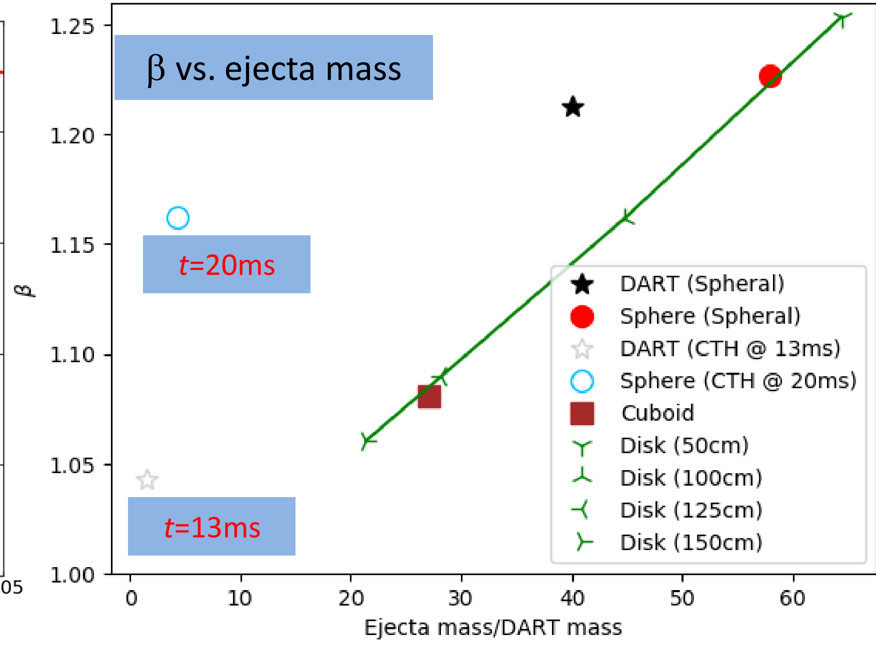
- Spheral and CTH agree reasonably on β for the sphere, with Spheral somewhat higher.
  - This despite CTH finding less ejecta mass and a smaller crater volume compared with Spheral (note, both CTH models at earlier time).
  - Both find the DART model β to be reduced (CTH more so).

- 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.



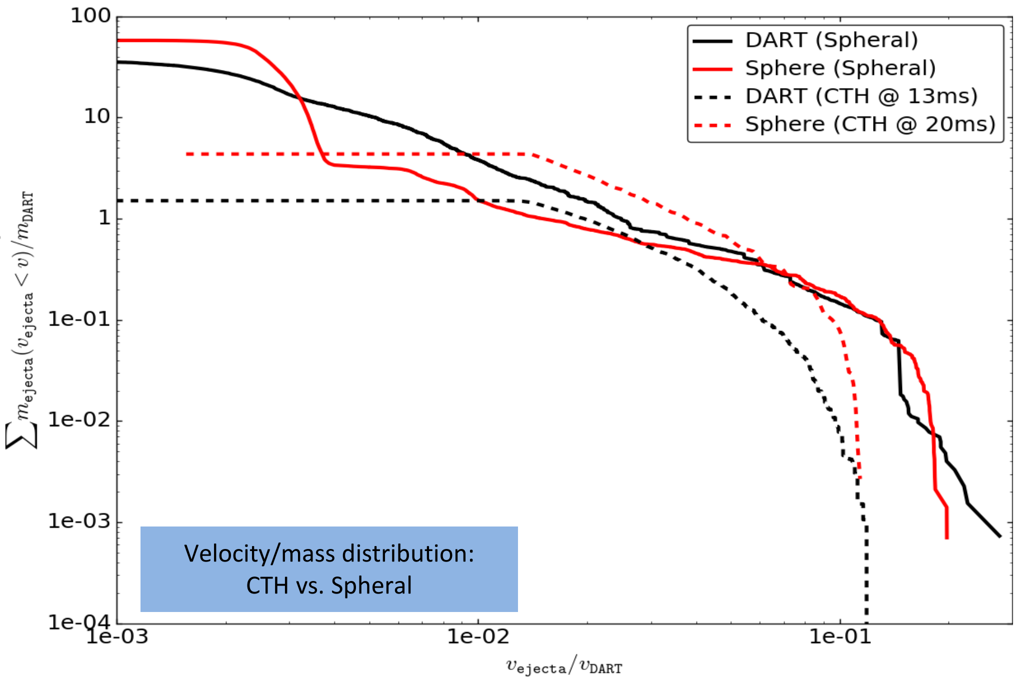


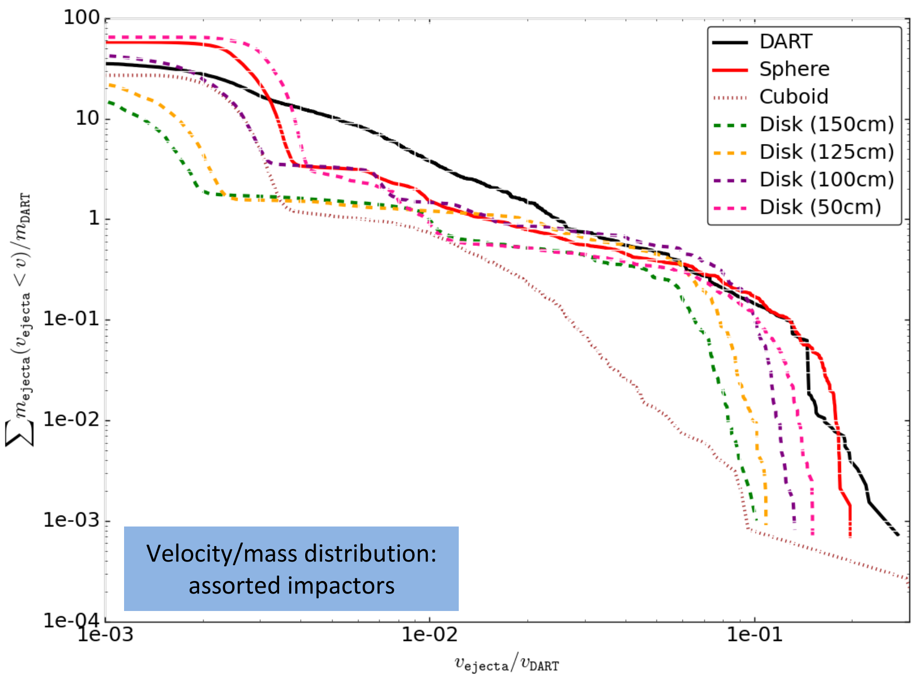


The ejecta velocity distribution is also affected by impactor geometry, though again the sphere and DART agree reasonably.

- 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.

Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.