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

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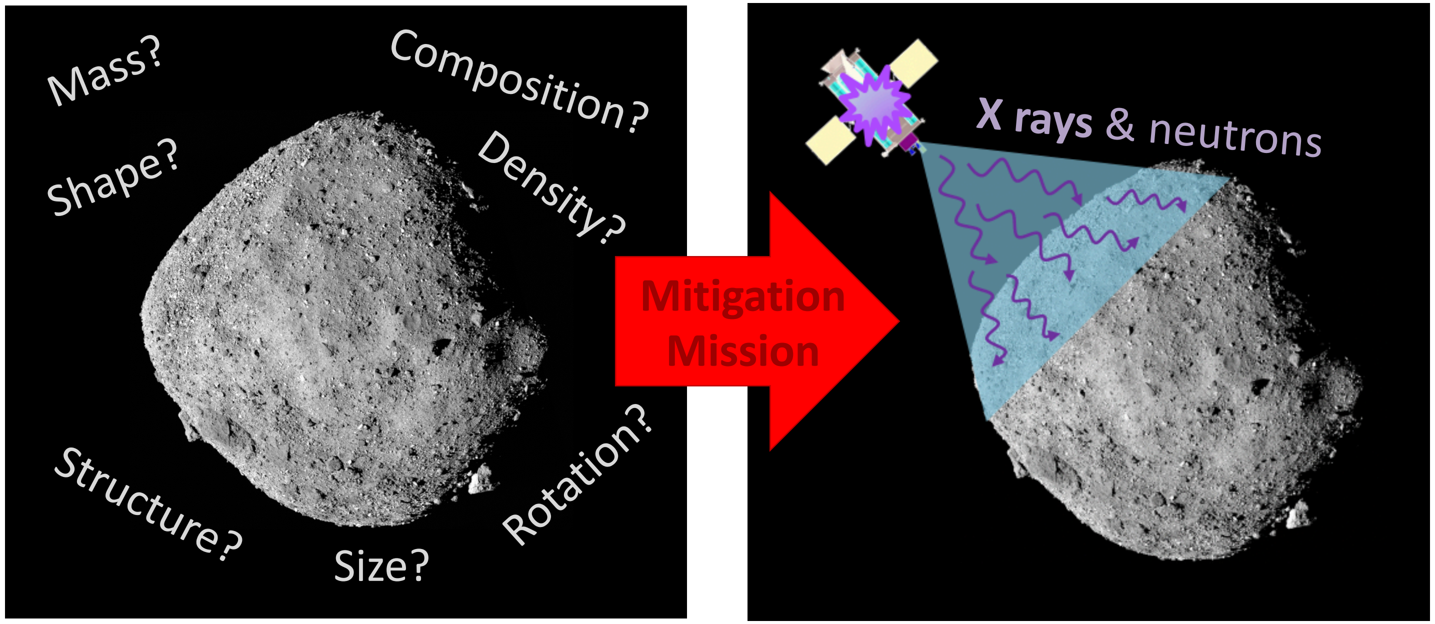
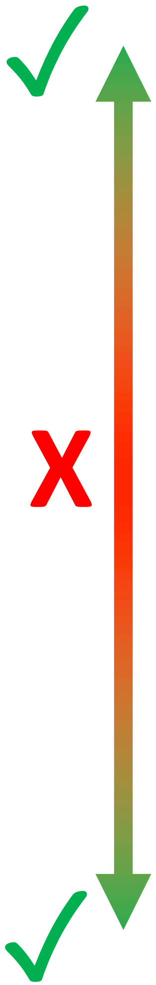
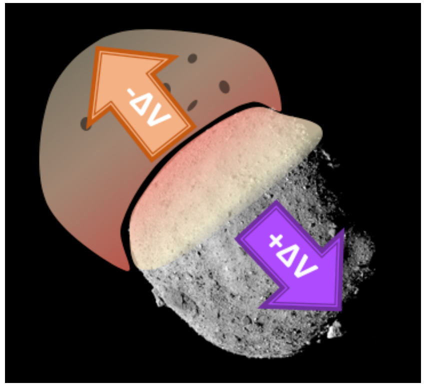
An Option for Planetary Defense: Nuclear Deflection/Disruption

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

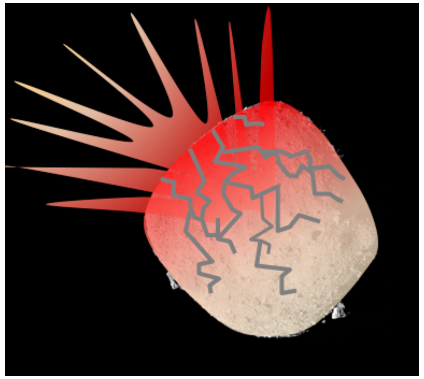






Successful Deflection Mission: asteroid remains intact and misses Earth

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



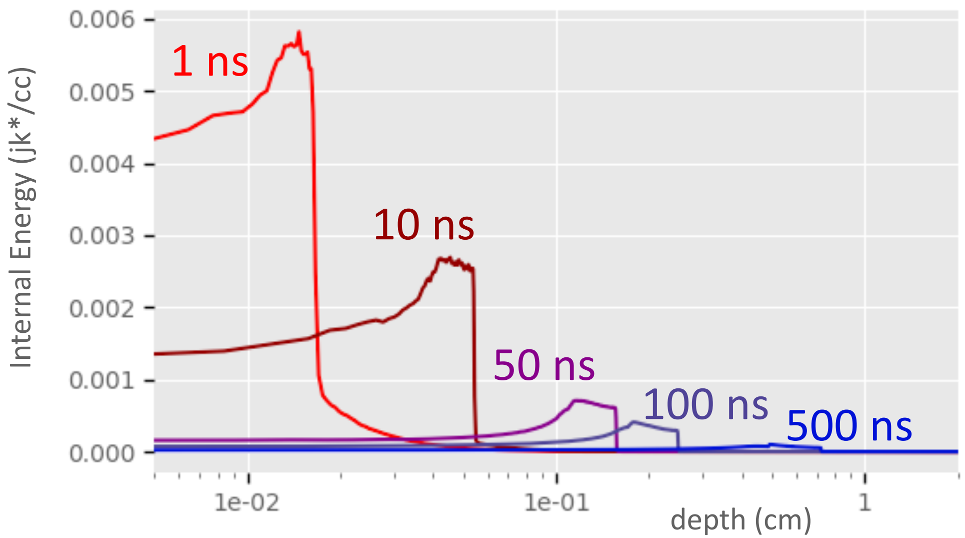
Successful Disruption Mission: asteroid is blasted into many small, fast-moving fragments

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.

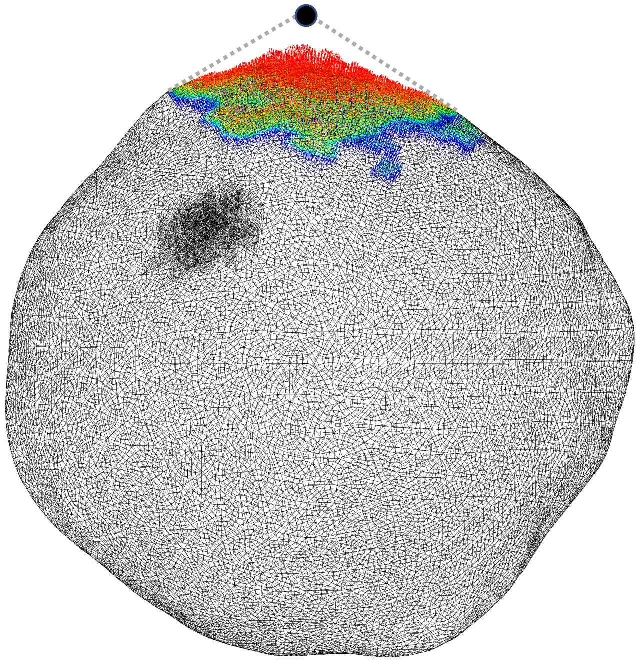


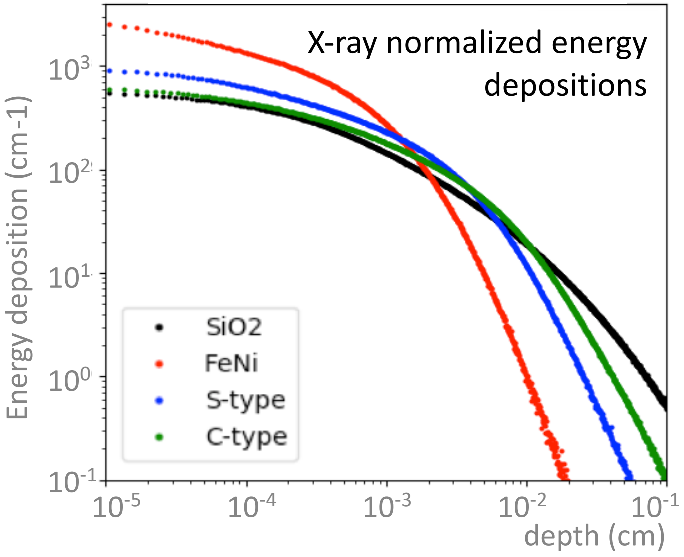
Image credit: Megan Bruck Syal
*1 jerk = 1e16 ergs

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**

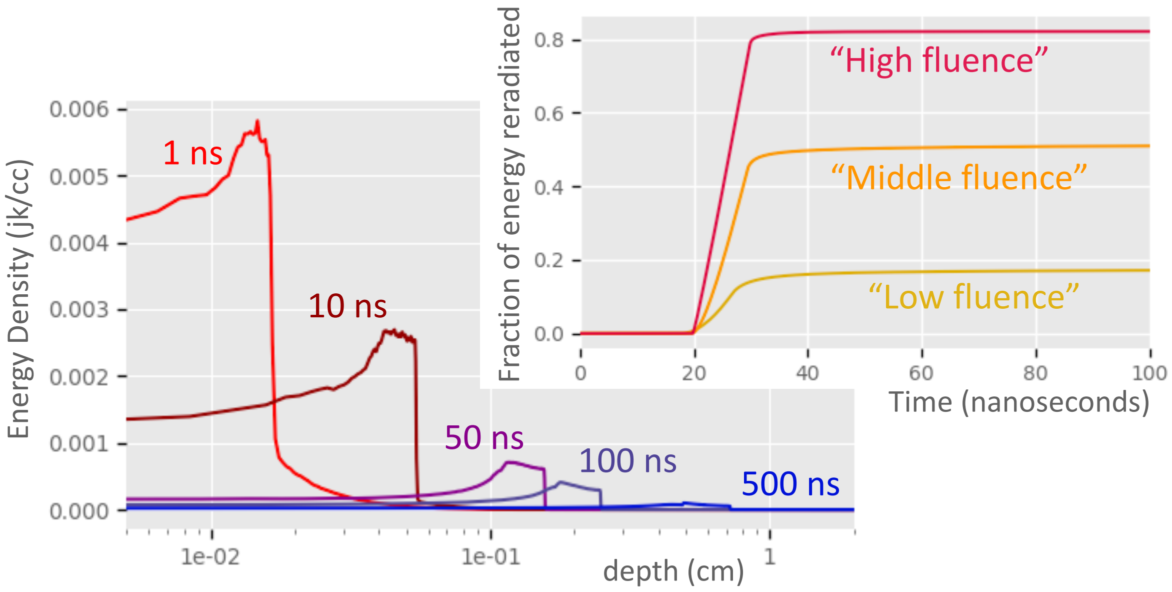


$$f(x,\chi) = \frac{1}{\cos(\chi)} \sum A_i \exp\left(\frac{-x}{\lambda_i \cos(\chi)}\right)$$

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:

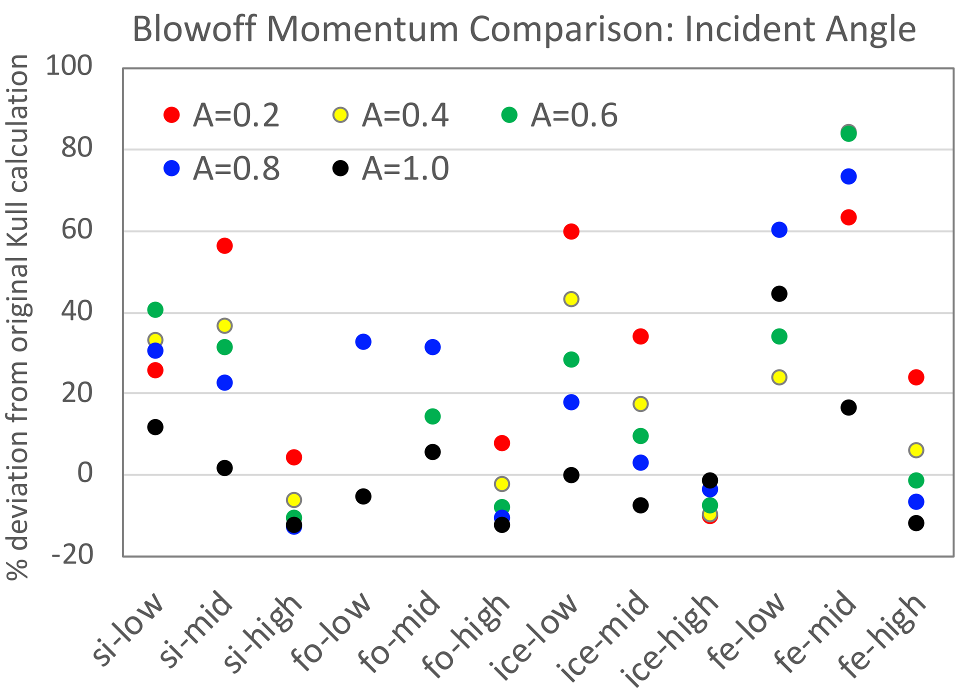
Scope of Study:

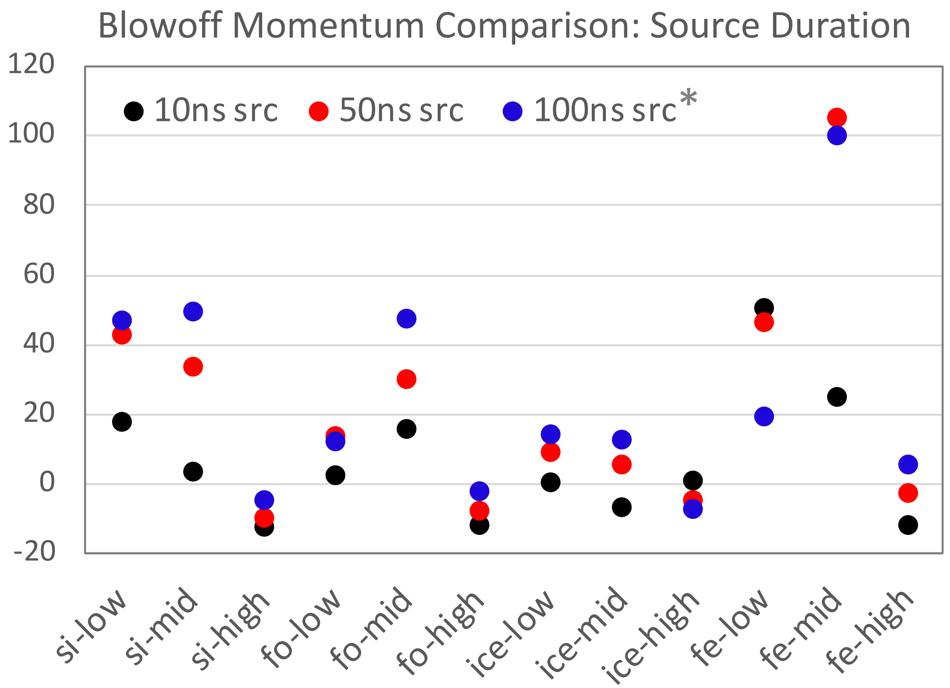
Materials
Silicon Dioxide (SiO_2)
Forsterite (Mg_2SiO_4)
Ice (H_2O)
Iron (Fe)

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?



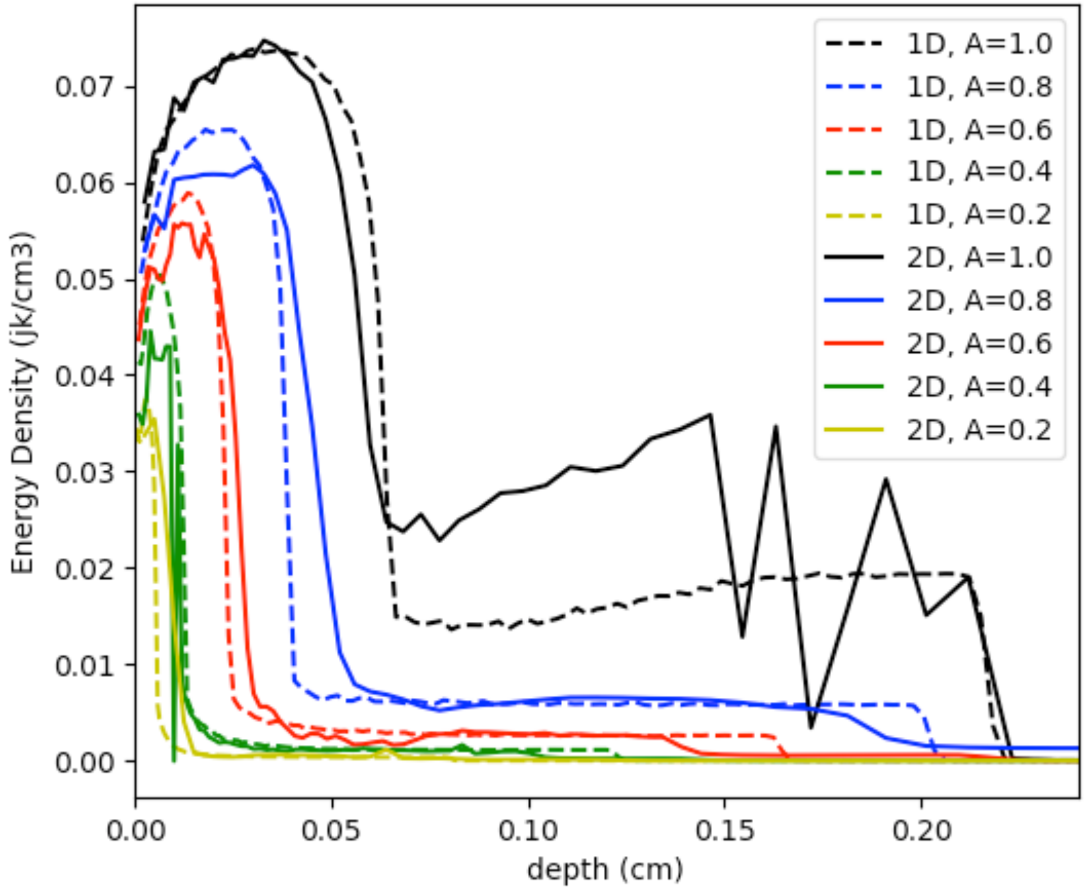


We can in most cases reproduce the pure Kull blowoff momentum to within ±50%.

*Source duration estimates taken from Glasstone, 1977

Level Up: 2D Kull Energy Deposition Tests

SiO_2 Mid-High Fluence Energy Depositions

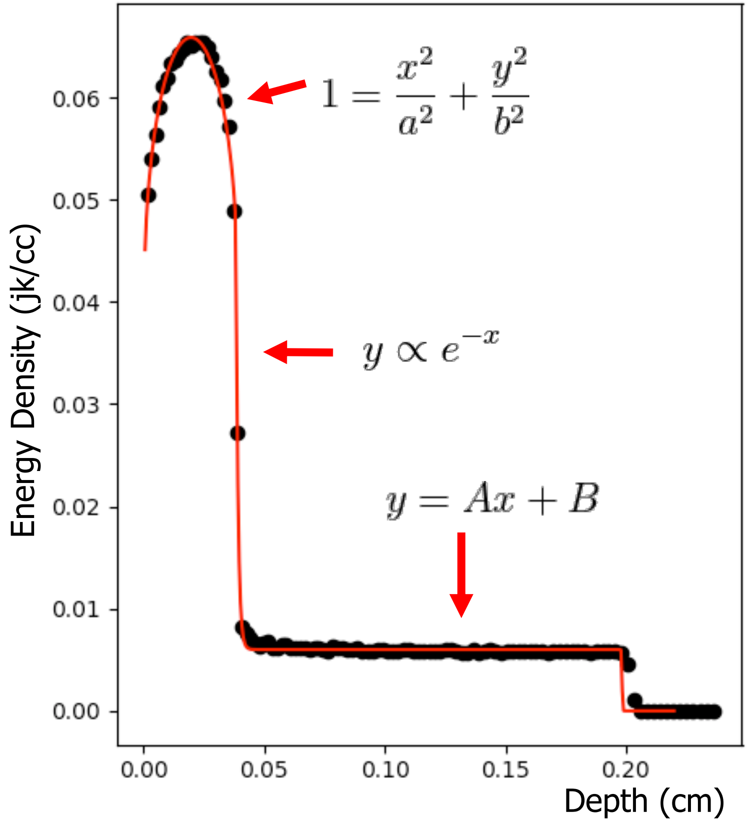


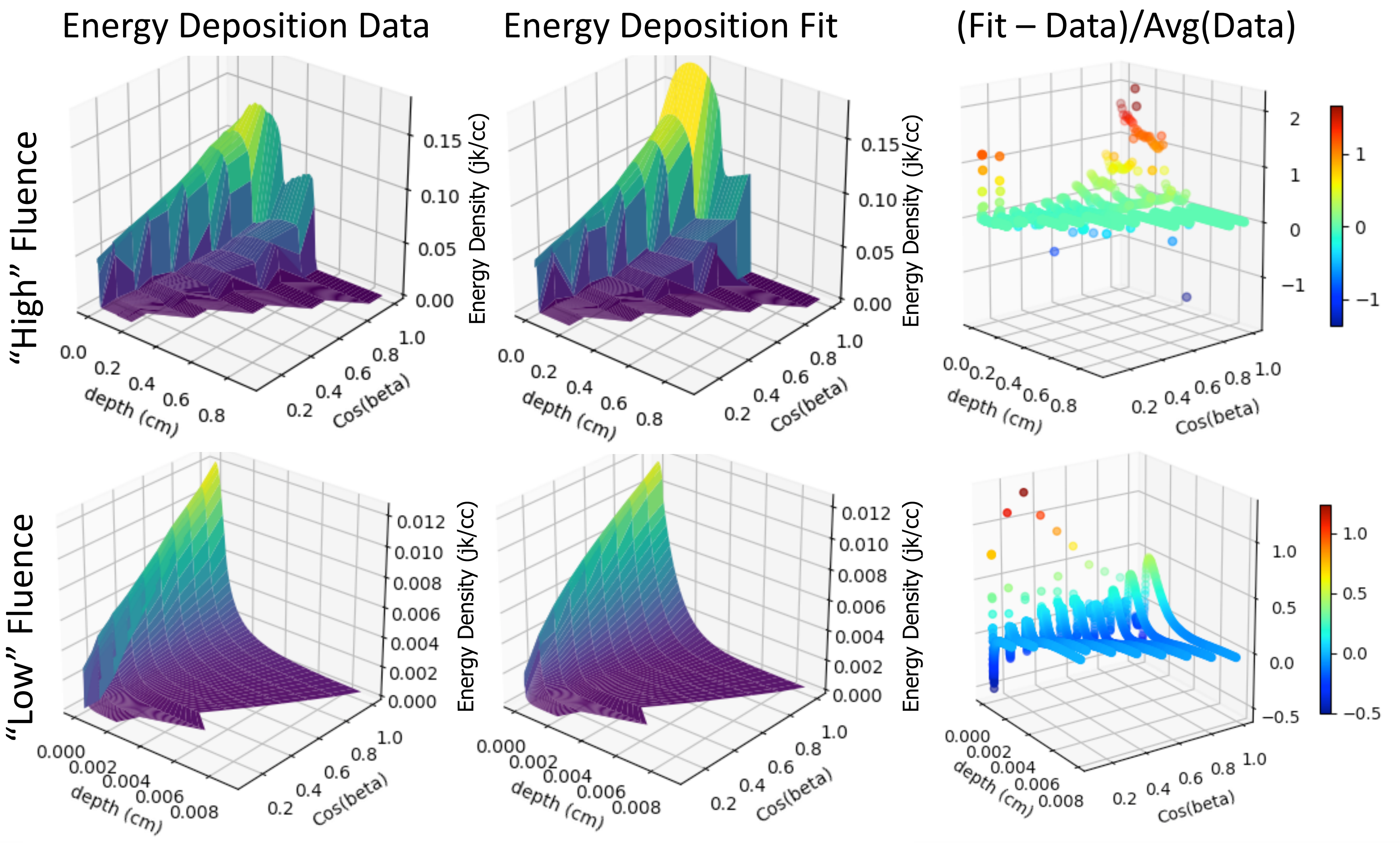
Fluence Level	Low	Mid	Mid-High	High
2D blowoff momentum (g cm/µs)	4.66e6	3.81e7	4.65e8	1.98e9
1D integrated blowoff momentum (g cm/µs)	4.74e6	3.92e7	4.55e8	1.91e9
Time after "detonation" (µs)	1.36	5.0	3.48	2.19

- 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





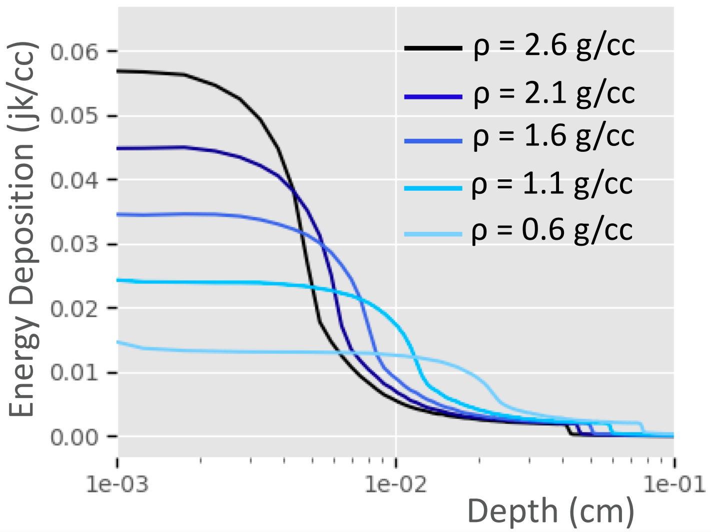
Preliminary Results and Still To Do

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)

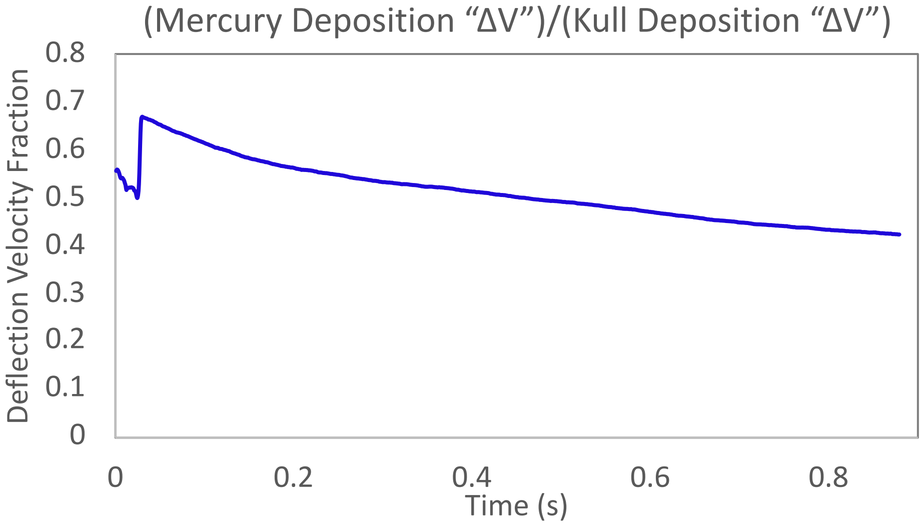
- Still lots to do:
  — Global fit over all fluences/source durations
  — Scaling based on density/porosity
  — Same analysis for remaining materials (Forsterite, Ice, and Iron)
  — Thorough study of model weaknesses/errors

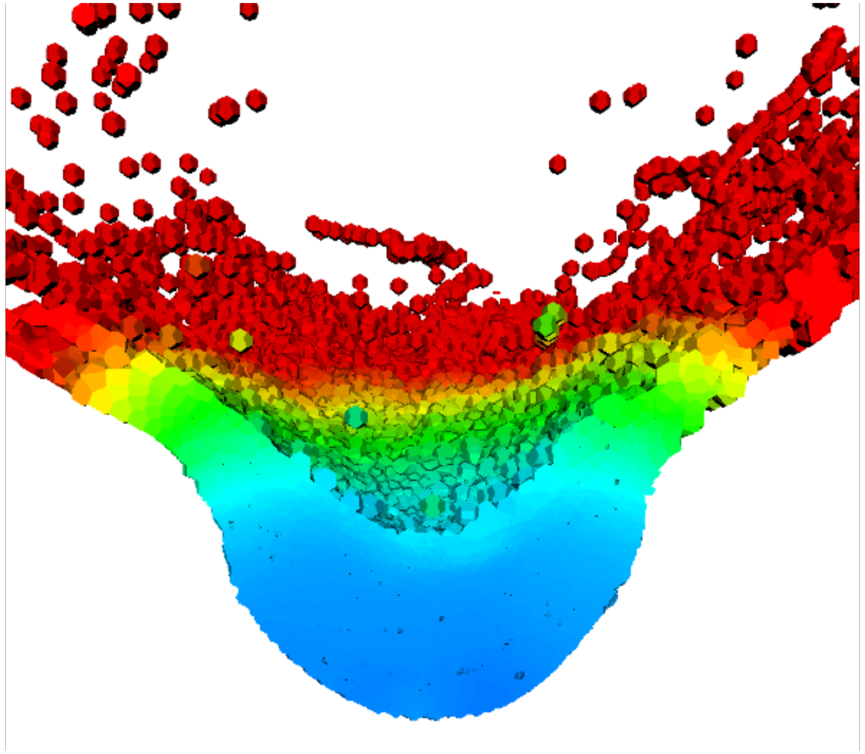
Deposition Shape vs Density/Porosity



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.