Hydrocode Simulations of Robust Asteroid Disruption via Hypervelocity Impacts

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Overview: Planetary defense from asteroids via deflective means alone does not offer viable solutions in terminal scenarios where there is little warning time before impact. The PI method of planetary defense enables operation in terminal interdiction modes where there is little warning time prior to impact, but can also operate in the same extended time scale interdiction modes as made possible by traditional deflection techniques, which results in a versatile, multi-modal planetary defense capability. The method is also practical and cost-effective since it relies solely on launch vehicles and penetrator materials already available today, and thus presents itself as a logical and competitive option for planetary defense. The method involves an array of small hypervelocity kinetic penetrators that completely or partially fragment the threat. In terminal interdiction modes, the bolide fragments of maximum ~ 10 m diameter airburst in the atmosphere, with the primary channel of energy going into spatially and temporally de-correlated shock waves.

6 modes of operation:

1. Short warning time terminal defense mode with robust disruption: 1 – 10-day intercept of 15 – 100 m threats. Fragments burn up in Earth's atmosphere resulting in de-correlated shock waves which cause little damage. Sum of optical pulses remains below combustion limit of paper/dry grass.

2. Moderate warning time mode with robust disruption: 10 – 60-day intercept of 100 – 500 m diameter threats, ex. Apophis, Bennu.

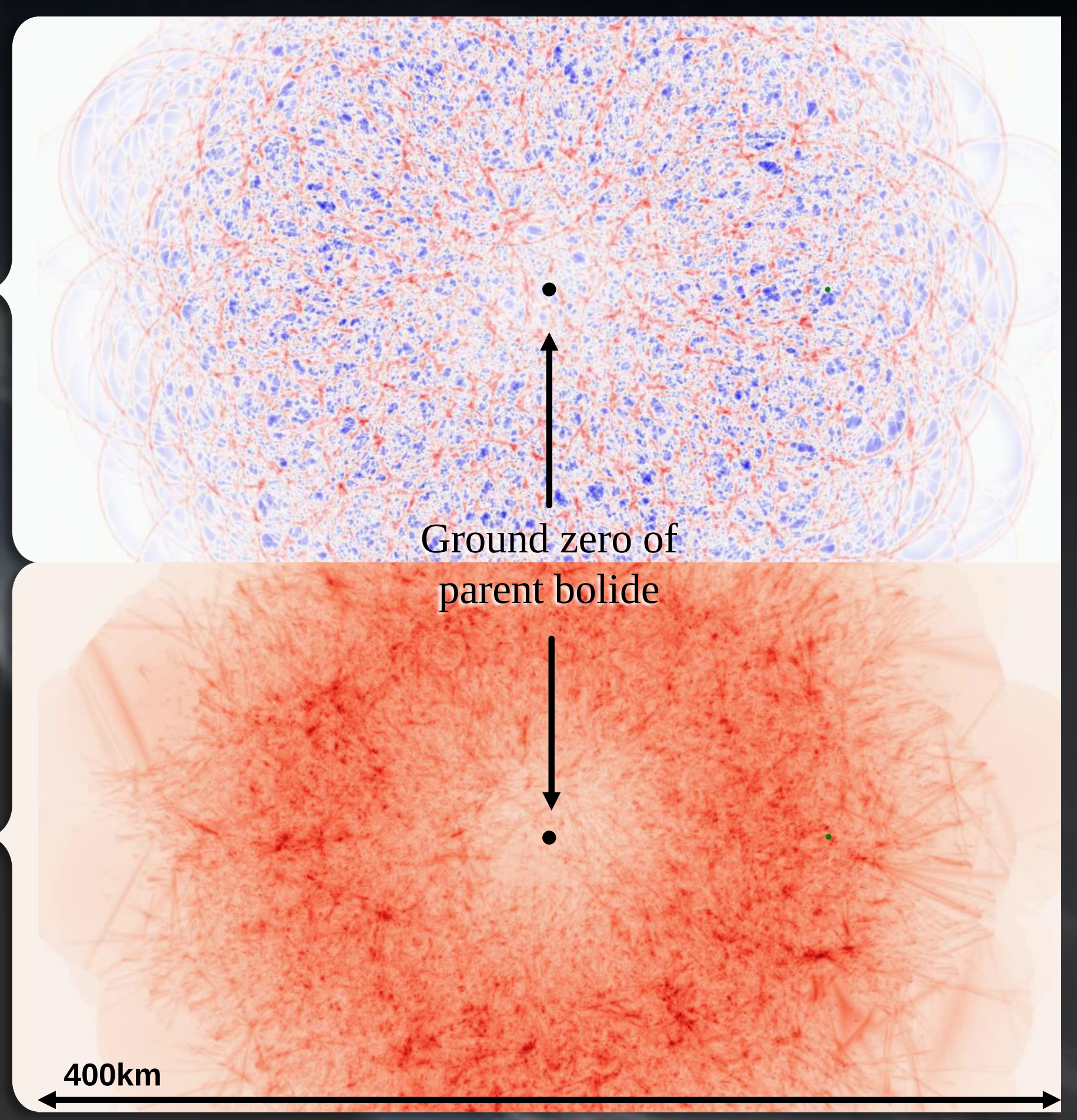
3. Low warning time mode with robust disruption: > 75-day intercept of 500 – 1000 m diameter threats. Fragments spread out to miss Earth and threat is permanently removed. This mode would generally use NED penetrators.

4. Longer warning time/existential threat mode: > 100-day intercept of 1 – 15 km diameter threats. Fragmentation via nuclear explosive device (NED) penetrator array results in fragment cloud spreading large enough to miss Earth for virtually all fragments.

5. Asymmetrical fragmentation and enhanced deflection mode: > 1-year intercept which internally generates momentum relative to the original center of mass via fragmentation and ejection. Equivalent to a very large β.

6. Longer warning time classical deflection: > 1-year intercept and momentum transfer via kinetic impactors for full multimodal use of PI method.

Ground effects:



Blast waves generated by 2,000 individual fragments from a 100 m diameter parent bolide interfering in the ground plane of the Earth at t = 150 seconds after the first fragment airburst. Our model follows each fragment and computes the resulting acoustic blast wave and the optical signature produced for any observer on the Earth. The model inputs the parent diameter, speed, density distribution, angle of attack, yield strength, and the fragmentation distribution. The results show that the peak blast wave pressures remain below the point of residual window breakage (~ 3 kPa) and the optical pulses remain below the combustion point of dry grass/paper (< 0.2 MJ/m^2).

Student involvement:

We have a significant undergraduate presence in our UCSB lab, and there are already 10 students working on various aspects of the **π** program, primarily on blast wave and optical pulse simulations.

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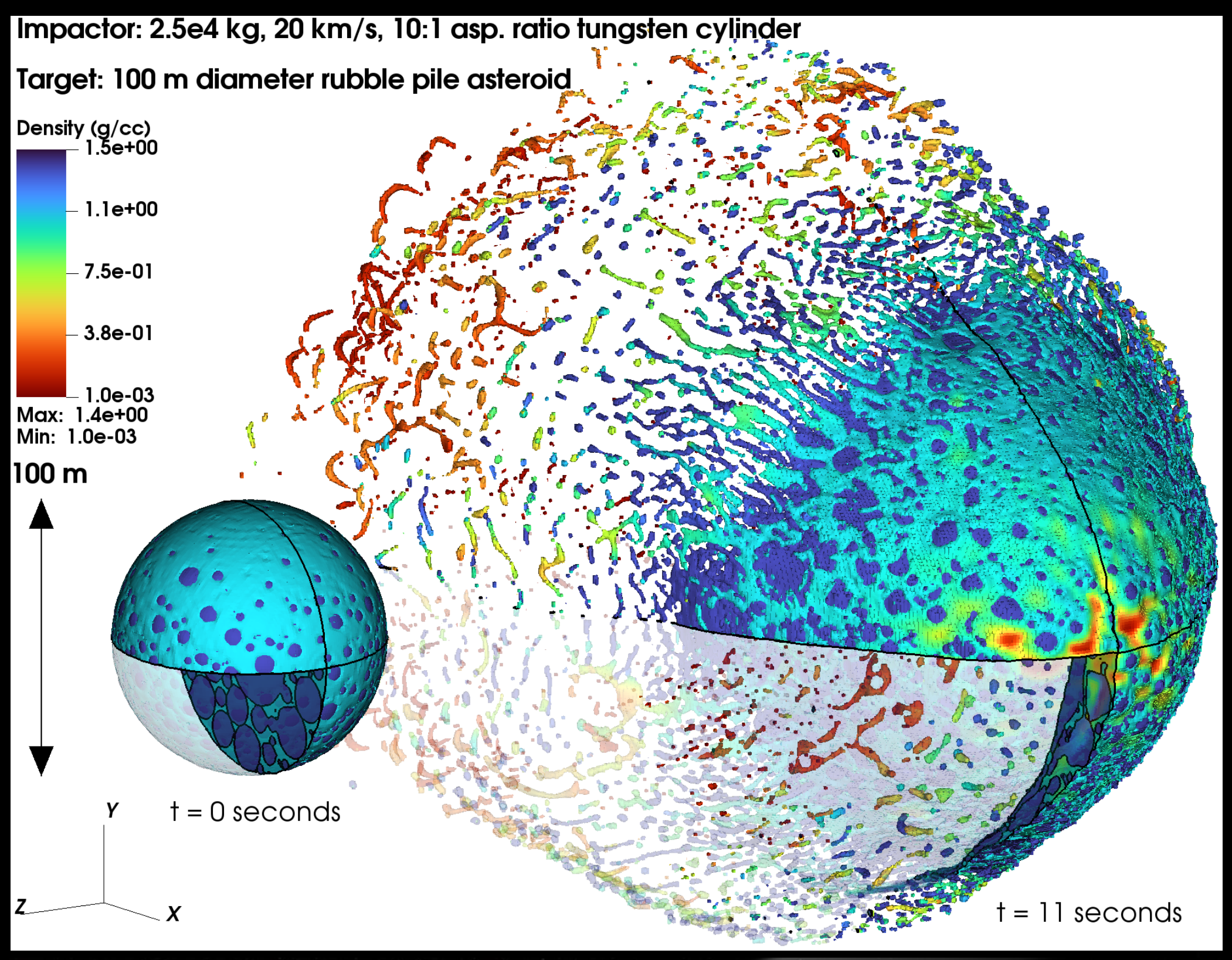
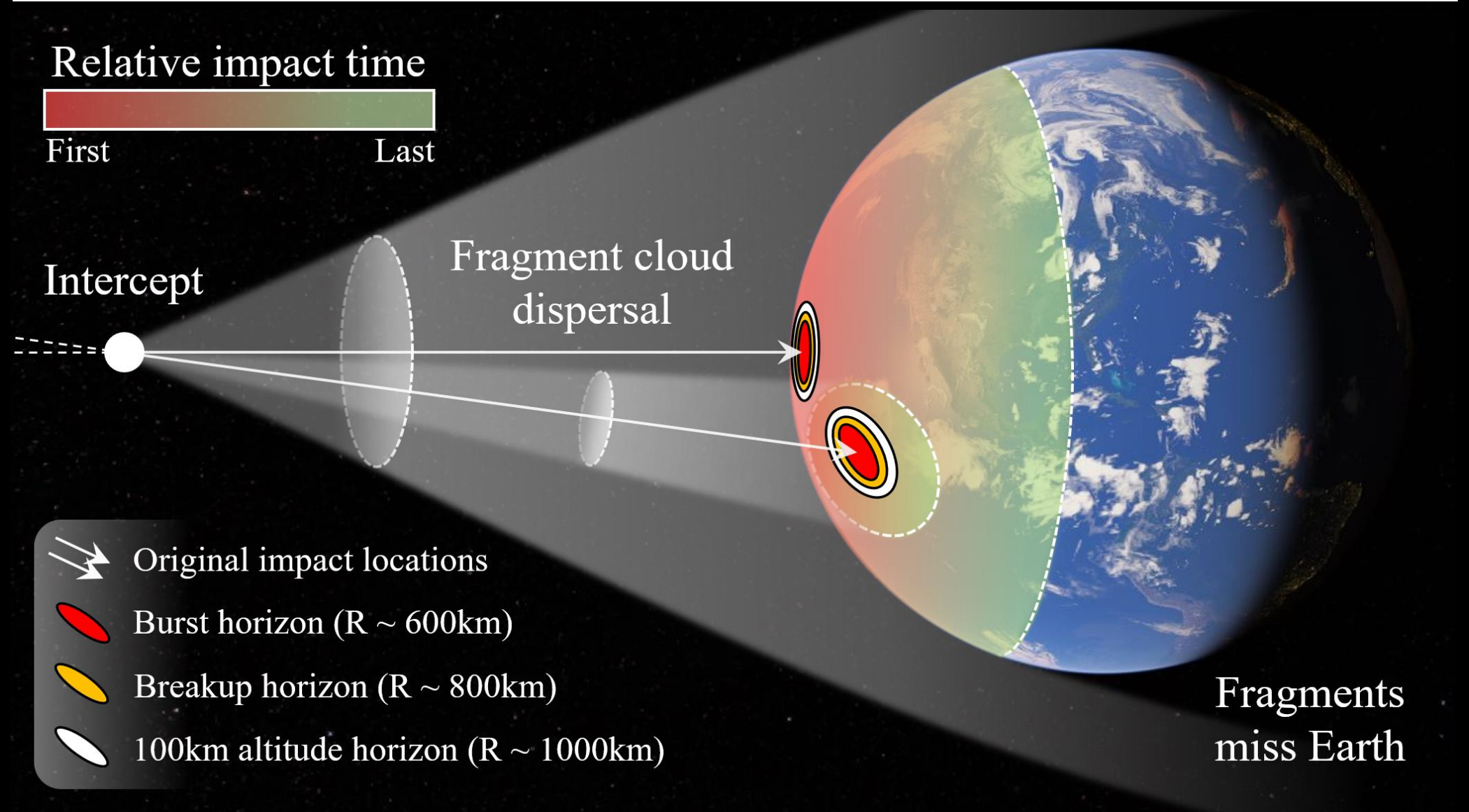
Hypervelocity interception: With the LLNL arbitrary Lagrangian-Eulerian (ALE) hydrodynamics code ALE3D using the High-End Computing Capability (HECC) at NASA Ames Research Center, we model hypervelocity impact dynamics using extreme equation-of-state material models. This informs the design of more efficient mitigation missions. Our simulation campaign also aims to better understand the effect of material properties on the generation of a fragment cloud upon total disruption. In previous work, we investigated 20 km/s impact events with asteroid targets in the 20 – 100 m diameter range with 100 and 500 kg 10:1 aspect ratio cylindrical tungsten penetrators. Extending the penetrator mass to > 2 metric tons enables robust disruption of asteroid targets in the 20 – 150 m diameter range. Such modest penetrator mass enables a "single-launcher solution" for threats of this size by utilizing the maximum payload capacities of common launch vehicles. Ropbust disruption of much larger threats can be achieved with the use of NEDs. However, unlike the deflection of an asteroid via the standoff detonation of an NED (where only a fraction of the total radiative output from the NED is incident upon the surface of the asteroid), here the NED is delivered a significant depth below the surface via a series of sequential hypervelocity penetrators. The first set of penetrators drills a tunnel inside of which the final penetrator delivers and detonates an NED.

Right top: Catastrophic disruption of a 100 meter diameter asteroid via the 20 km/s impact of a 2.5 metric ton, 10:1 aspect ratio tungsten cylinder penetrator. The bolide prior to impact is shown on the left, and the aftermath of the impact at 11 seconds is shown on the right. The color plot shows the material density in grams per cubic centimeter.

Right bottom: Illustration of the dispersal of the fragment cloud after a disruptive intercept. Observer horizons for the fragment burst and breakup altitudes are also shown.





Enhanced deflection of large threats: Mitigation of km-scale threats can also be achieved on longer timescales via the enhanced deflection mode of PI. Unlike momentum transfer methods which have demonstrated momentum enhancement factors on the order of $\beta \approx 3$ to 4, the enhanced deflection mode maximizes the kinetic energy transferred from the penetrator to the target. This generates a significantly higher momentum enhancement effect due to the large mass of ejected material, as can be seen in the sequence of images below. The momentum enhancement effect of a particular intercept scenario can be estimated with $\beta = M\,\Delta V/mv$, where M is the target asteroid mass, ΔV is the change in speed of the target asteroid, m is the penetrator mass, and v is the penetrator closing speed.

Two enhanced deflection scenarios are shown in the figure below, with the sequence of frames progressing in time from top to bottom. The 3D plots show the material speed in cm/μs at 0.1, 1, 10, and 60 seconds after impact. The inset 2D figures show the material damage parameter $0 \leq D \leq 1$. After 1 second, the material damage distribution remains mostly static in both cases. On the left is a simulation of the enhanced deflection of a 500 m diameter rubble pile asteroid model via the impact of a 10 metric ton, 10:1 aspect ratio tungsten cylinder at 20 km/s. On the right is a similar 20 km/s impact of a 100 metric ton penetrator upon a 1 km diameter rubble pile asteroid model. At 60 seconds after impact for the 500 m case, we calculate that the momentum enhancement factor achieved is $\beta_{500m} \approx 81.6$. Similarly, at 60 seconds after impact for the 1 km case, we calculate that the momentum enhancement factor achieved is $\beta_{1km} \approx 41.3$. These are extremely high β values. For reference, the estimated β value for the DART mission was ~ 3.61, which delivered ~ 570 kg of spacecraft mass to impact the asteroid Dimorphos at ~ 6.6 km/s.