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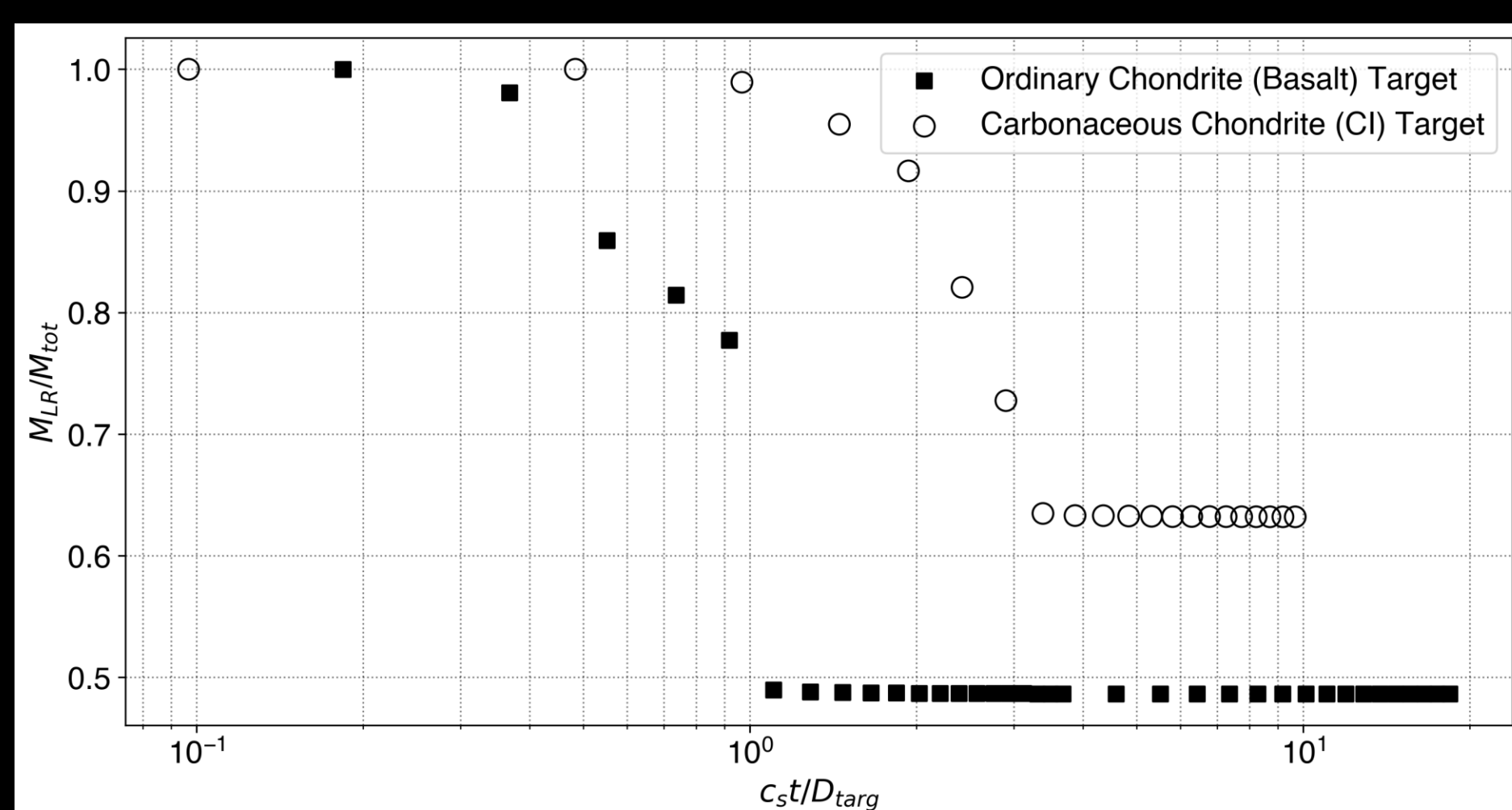
## What are the limits of kinetic impactors?

NASA's DART mission successfully altered the orbit of a 160-m-diameter asteroid, demonstrating kinetic impact technology for Planetary Defense [1]. While successful, the DART mission also raised new questions about the extent at which kinetic impactors could be used in real scenarios. In particular, kinetic impacts on 50- 100 m-diameter NEAs could lead to a disruption event, rather than a deflection. In such an event, it is not yet clear that the threat would be adequately mitigated, or if the threat would be exacerbated by multiplying the number of potential Earth-bound impactors. Here, we study the outcomes of impacts in the catastrophic disruption regime of small (50-100 m) coherent asteroids to better understand the limits at which kinetic impactors could be used for asteroid mitigation.

We conducted hypervelocity impact experiments using the HyFire lab at the Hopkins Extreme Materials Institute (Fig 1). This includes a two-stage gas gun and a suite of diagnostic tools which include highspeed cameras capable of capturing the post-impact dynamics of fragments as a target is disrupted. We characterized the disruption characteristics of CI carbonaceous chondrite simulants (Fig. 2 and 3), that have similar characteristics to Bennu samples [2,3]. The experimental results are used to calibrate a SPH code, *miluphcuda* [5], which we use to perform larger-scale simulations of disruptive impacts on to 50-100 m-diameter targets by a kinetic impactor (Fig. 4 and 5).

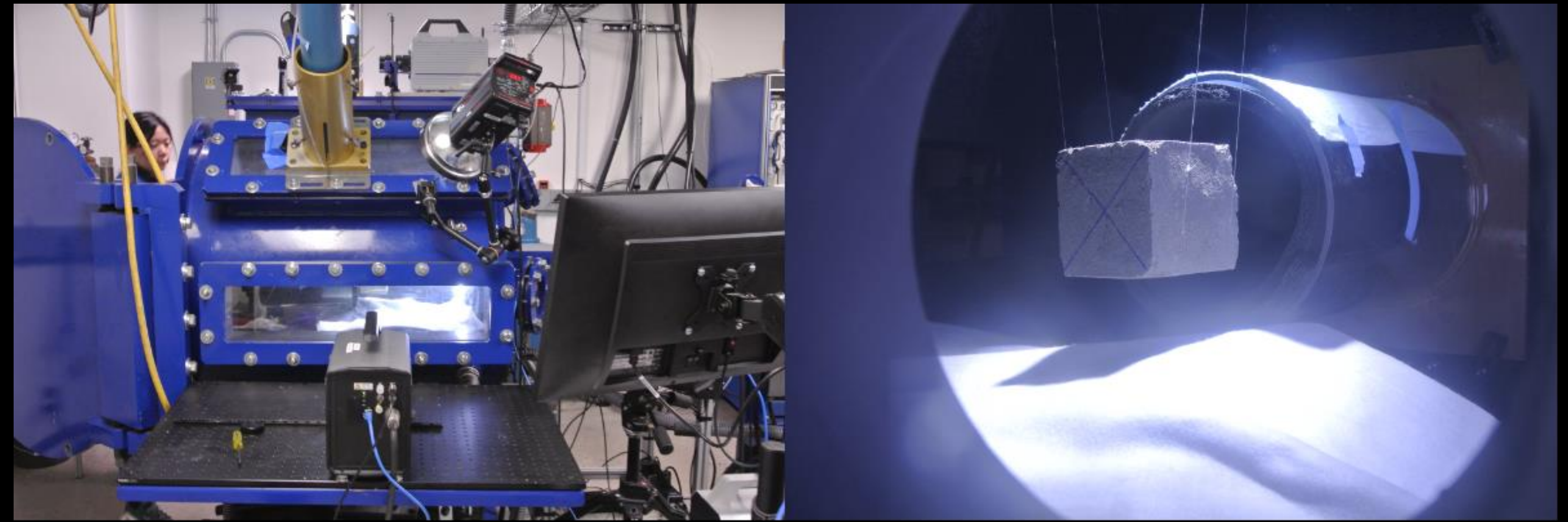
Here, we present simulation results into coherent 50-m-diameter blocks that have material properties similar to ordinary chondrites [4] and carbonaceous chondrites. These material types constitute the majority of known near-Earth asteroids at this size class. For either target, the simulations show that impacts close to the catastrophic disruption threshold, where the specific impact energy,  $Q=Q^*_D$ , results in the majority of target material (except for a small fraction of fast moving ejecta) to be deflected along the direction of impact (Fig. 5). Further work is needed to better characterize the relative efficiency of a single disruptive impact to multiple smaller kinetic impacts with  $Q \ll Q^*_D$ .

**References:** [1] Daly, R.T., et al. 2023, Nature 616, 443 [2] Metzger, P., et al. 2019, Icarus 321, 632. [3] Lauretta, D.S., et al. 2024, MAPS 59, 2453. [4] Benz, W., & Asphaug, E., Icarus 107, 98. [5] Schäfer, C., et al., 2016, A&A 590, A19. [6] Ryan, A., et al. 2025, in prep. [7] Nakamura, T., et al 2023, Science 379, 6634. **Acknowledgements:** R.-L. B. was supported by JHUAPL's JHU Sabbatical Program, and by NASA New Frontier's Data Analysis Program through grant 80NSSC22K1035. We thank the developers of *miluphcuda* for providing access to their code. We thank Justin Moreno of HEMI for supporting the impact experiments.



**Figure 4.** For each SPH simulation, we use a friends-of-friends algorithm [4] to isolate fragments in the target. Here, we show that disruptive simulations of impacts into 50-m-diameter targets of different material types at 5.3 km/s are run sufficiently long that the mass of the largest remnant ( $M_{LR}/M_{tot}$ ) converges. The black squares (basalt target) and white circles (CI target) show the evolution of  $M_{LR}/M_{tot}$  as a function of a  $p$ -wave crossing time,  $c_s t / D_{targ}$ , where  $c_s$  is the material sound speed,  $t$  is simulation time, and  $D_{targ}$  is the target diameter.

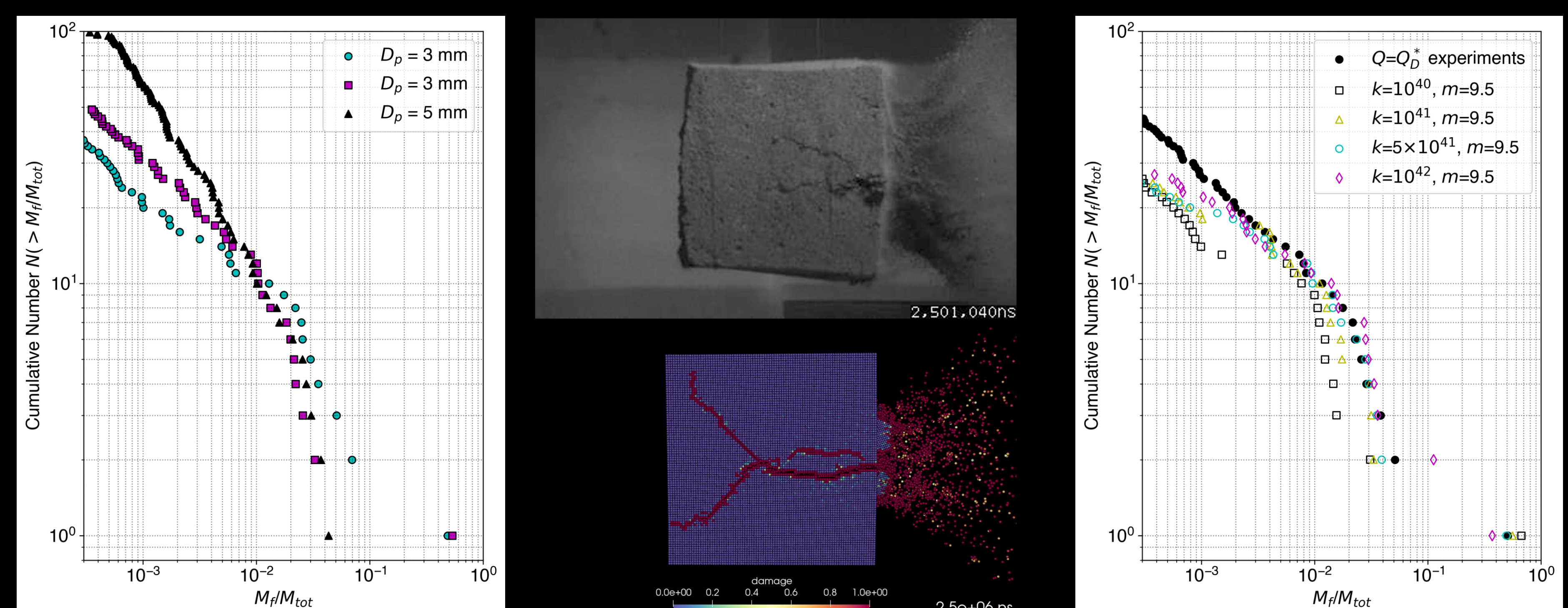
## We conducted hypervelocity impact experiments on blocks of carbonaceous chondrite simulant to characterize their disruption behavior



**Figure 1.** *left*, the impact chamber and diagnostics setup at Johns Hopkins University's Hopkins Extreme Materials Institute's HyFire facility. *right*, the CI block targets were suspended on fishing wire in order to better assess post-impact fragment velocity.

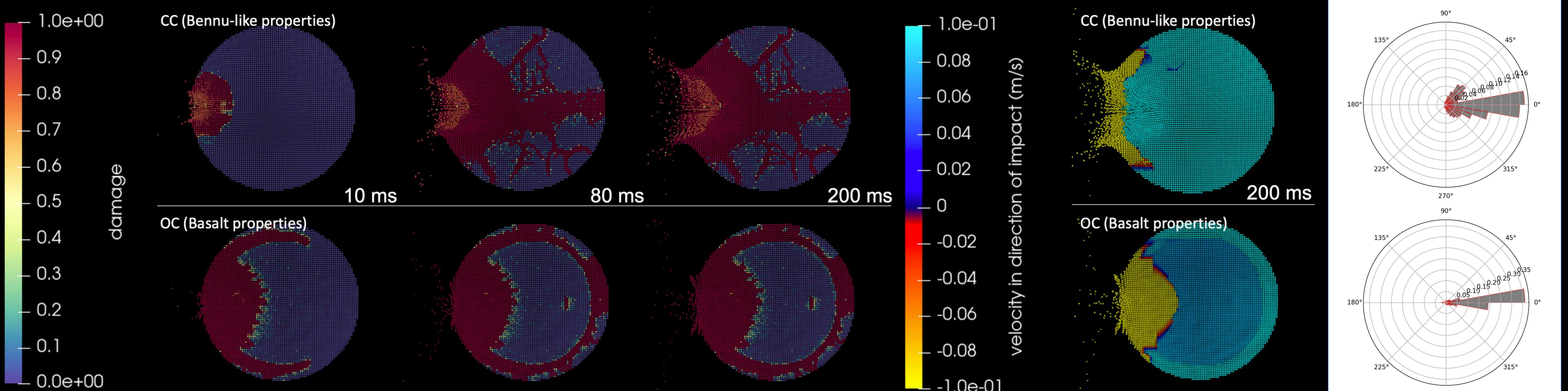


**Figure 2.** For targets, we use 9 x 9 x 9 cm blocks of CI carbonaceous chondrite simulant prepared by Space Resource Technologies [Metzger+2019] as these are the closest analog to Bennu material [Lauretta+2024]. We conducted 3 head-on impact experiments at 5.3 km/s using aluminum projectiles with diameters,  $D_p = 3$  and 5 mm. These sequence of images over 2.3 ms show the case of a 5-mm diameter projectile.



**Figure 3.** *left*, We collected and measured post-impact fragment masses. The cumulative mass frequency distribution (MFD) of these experiments show that the  $D_p = 3$  mm are close to the disruption limit,  $Q=Q^*_D$ , where the mass of the largest fragment is half the total mass ( $M_{LR}/M_{tot} = 0.5$ ). *middle*, We use our experimental results to calibrate an SPH code, *miluphcuda* [5], which uses a  $p$ -alpha porosity model and a Tillotson equation of state (EOS). We use the results of physical characterization of the simulant [2], Bennu samples [6], and Ryugu samples [7] for EOS parameters. The figure shows a comparison of a disruptive impact experiment (top) to a SPH simulation (bottom) at 2.5 ms after impact. *right*, We conduct 1:1 impact-to-experiment simulations and vary the Weibull parameters,  $m$  and  $k$  (e.g., [4]), and compare the MFD results of simulations to the experiments, finding a best correspondence for  $m = 9.5$  and  $k = 5 \times 10^{41} \text{ cm}^3$ . The number of SPH particles in each simulation is  $\sim 700,000$ .

## Simulations of disruptive hypervelocity impacts onto coherent 50-m targets show that the majority of the target mass is deflected along the impact trajectory



**Figure 5.** *left*, Results of SPH simulation of 5.3 km/s disruptive impact (final mass of largest remnant shown in Fig. 4) on to a 50-m-diameter coherent carbonaceous chondrite (CC, *top*), and a 50-m-diameter coherent ordinary chondrite (OC, *bottom*), which show the propagation of damage in the interior of the target with time. The number of SPH particles in each simulation is  $\sim 300,000$ . The different physical properties of the targets lead to unique fragmentation patterns across the targets. A deep transient crater and linear fractures forms in the CC target. Spallation feature and the retention of an undamaged core are features of the OC target, consistent with previous observations [4]. *middle*, Despite the difference in physical properties, the majority of the mass in the CC and OC targets is deflected along the trajectory of the impactor at approximately 10 cm/s. The impactor mass in both cases was approximately 2,000 kg. *right*, a wind diagram showing the distribution of directions that particles that make-up the target travel along post-impact. The radial units are in target mass. For both cases, the majority of mass are deflected at angle that does not deviate much from the impact trajectory (0 degrees).