Entry Angle Effects on the Ground Signature of the Chelyabinsk Superbolide

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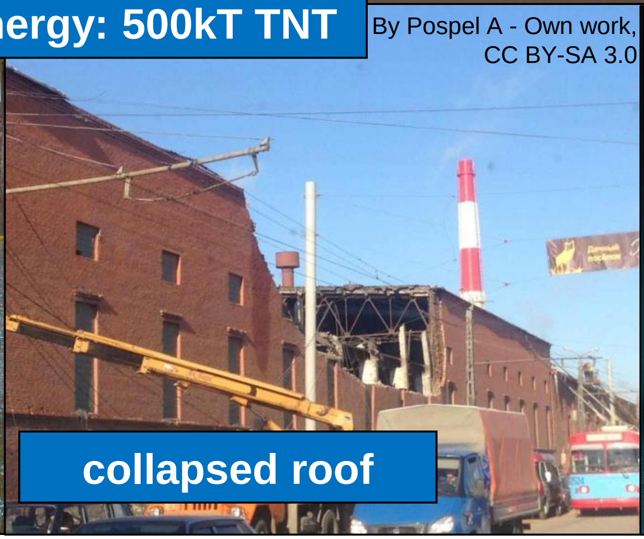
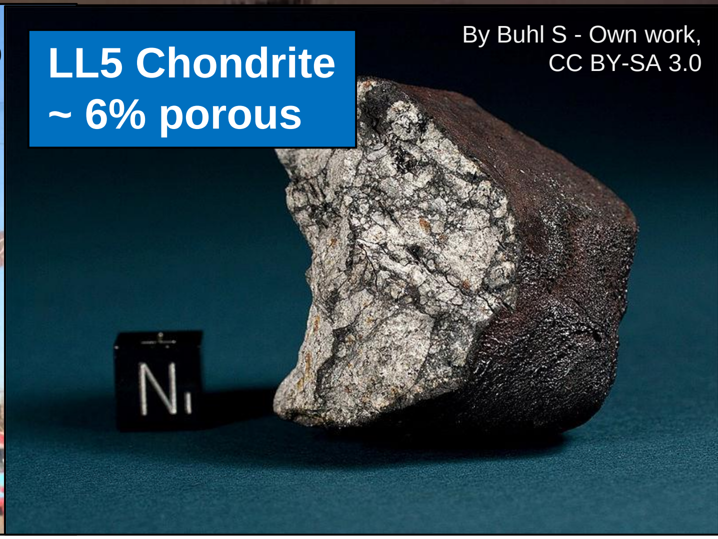
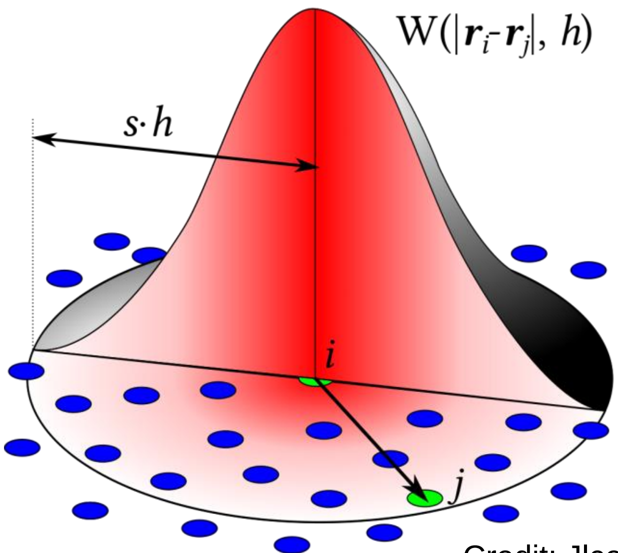
Chelyabinsk Superbolide





Smoothed Particle Hydrodynamics

- SPH is a Lagrangian mesh-free approach to solving PDE's.
- Nodes interact with a dynamic neighbor set through a smoothing kernel.



Credit: Jlceros

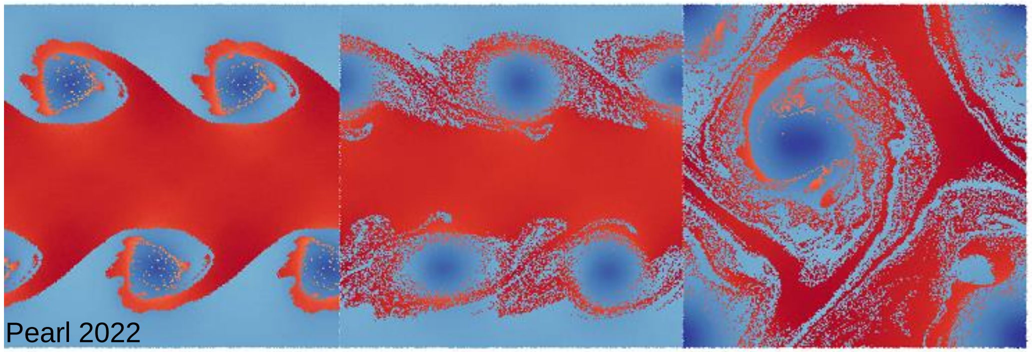
Our code Spheral++

Steerable, massively parallel, environment for particle-based simulation. Written in C++ with python wrapping.

github repo

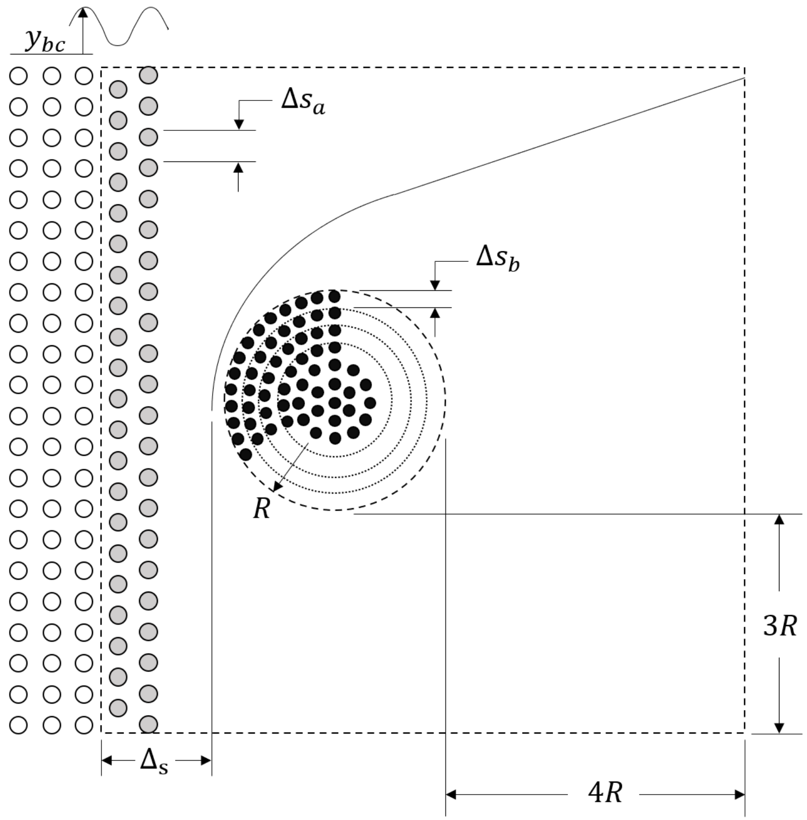
Spheral's FSISPH solver is used in this study. The solver was designed to model the highly dynamic interactions of dissimilar materials.

FSISPH methods



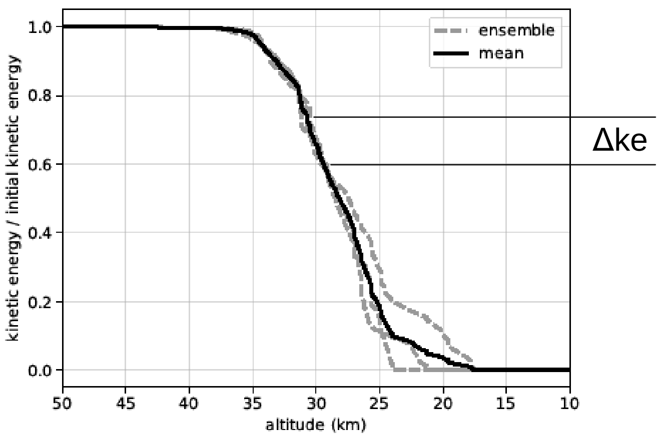
Entry Simulation Setup

- Material properties derived from available data for Chelyabinsk meteorites. (Zaytsev 2022, Kohout 2012). Material properties of granite used to fill gaps.
- Tillotson equation of state
- Elasticity, plasticity, and damage models based on Benz and Asphaug 1994 with modifications of Owen 2010, Owen 2022.
- Strain – porosity model of Wunnemann 2006 with thermal correction of Collins 2010.
- LEOS tabular data for air to model high-temperature effects.

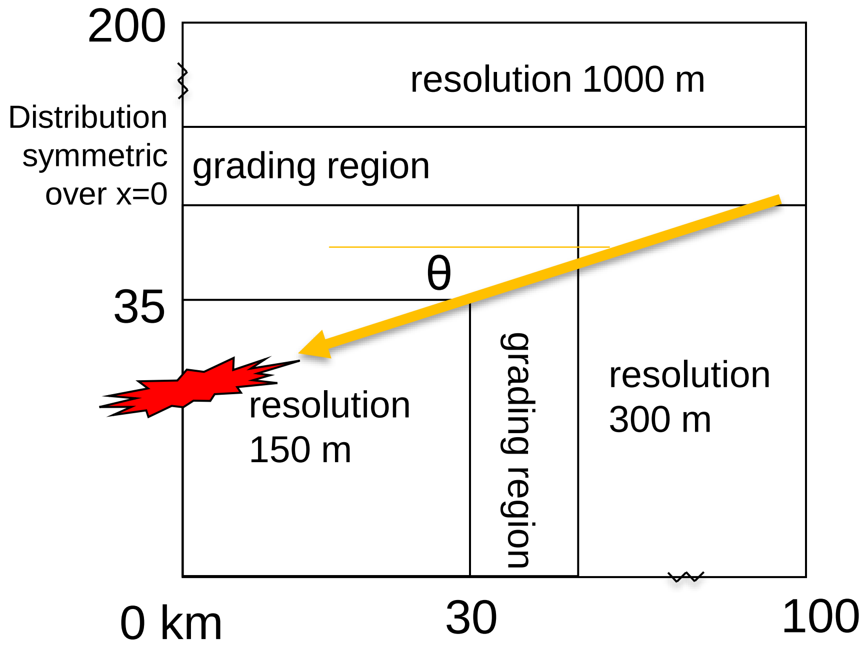


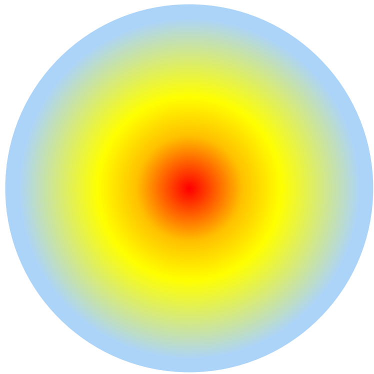
- Domain set in the bolide frame.
- Inlet conditions feeds particles in.
- Particles are volume-matched at the stagnation point on the material interface.

Handoff and Effects Simulation Setup



(1) Each timestep total energy/ momentum deposit determined from tabulated output from entry simulation.



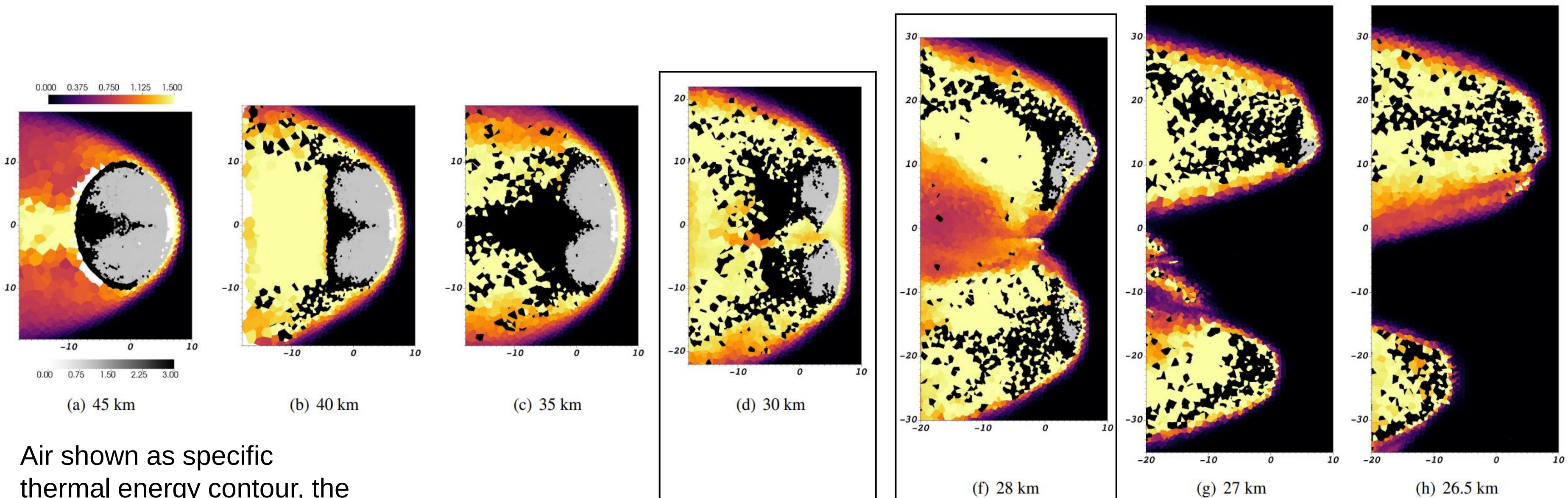


(2) energy/momentum distributed over a smoothing kernel.

(3) Deposited along the trajectory in a graded hydrostatic atmosphere as a time-dependent source.

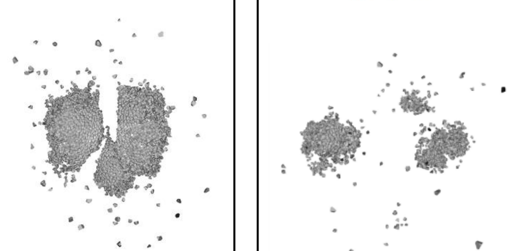
Tensile Strength and Fragmentation Affect Breakup Dynamics

- Fracture occurs near the rear and propagates forward
- Intact fragments pivot about stag. point, increase cross section
- Damaged debris is shielded in the wake
- Fragments separate and formerly shield debris is swept downstream
- Main fragments begin to break up
- Fragments full disrupted
- Debris cloud decelerates

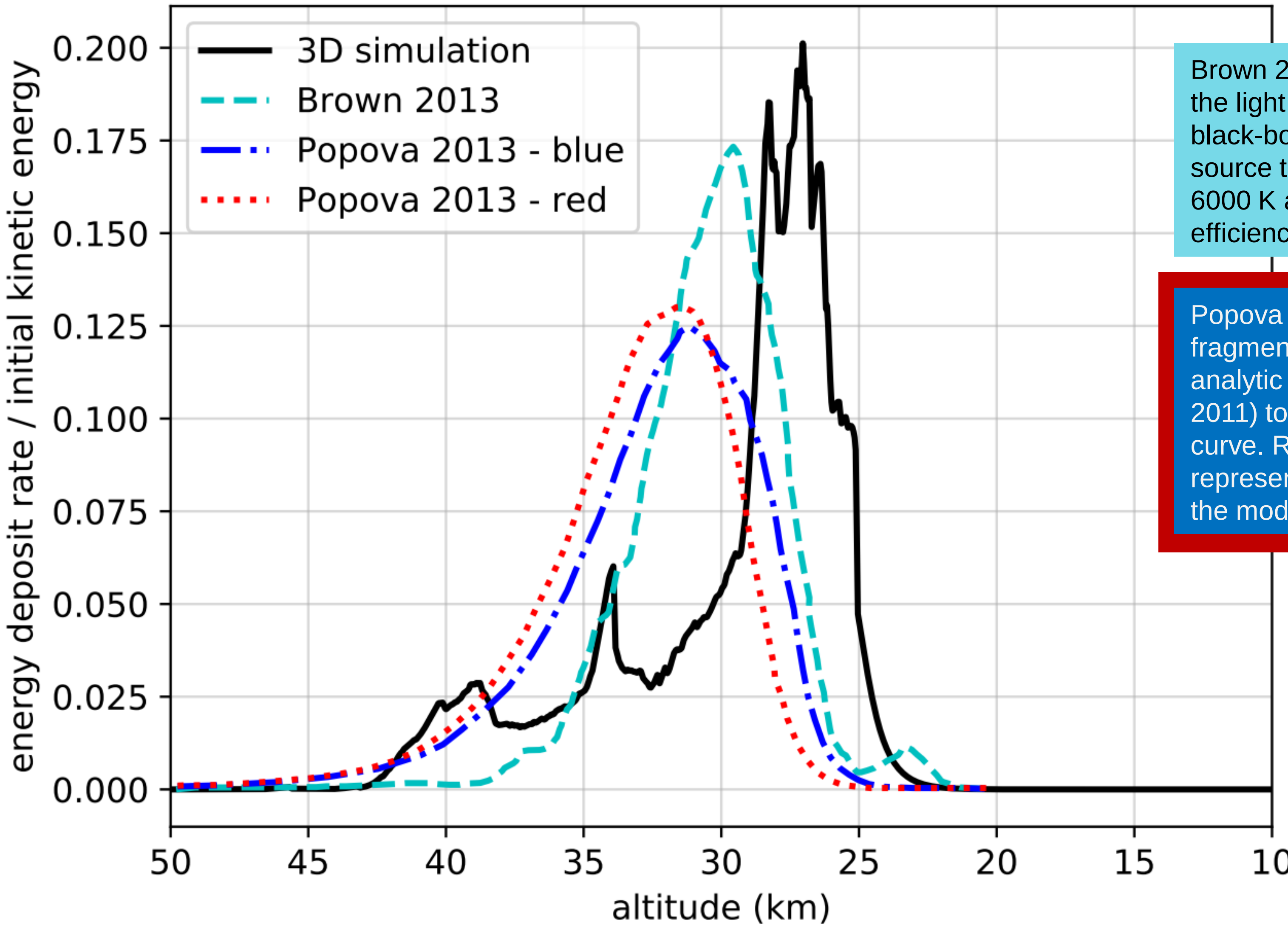


Air shown as specific thermal energy contour, the bolide as the damage trace.

Intact Fragments viewed from downrange



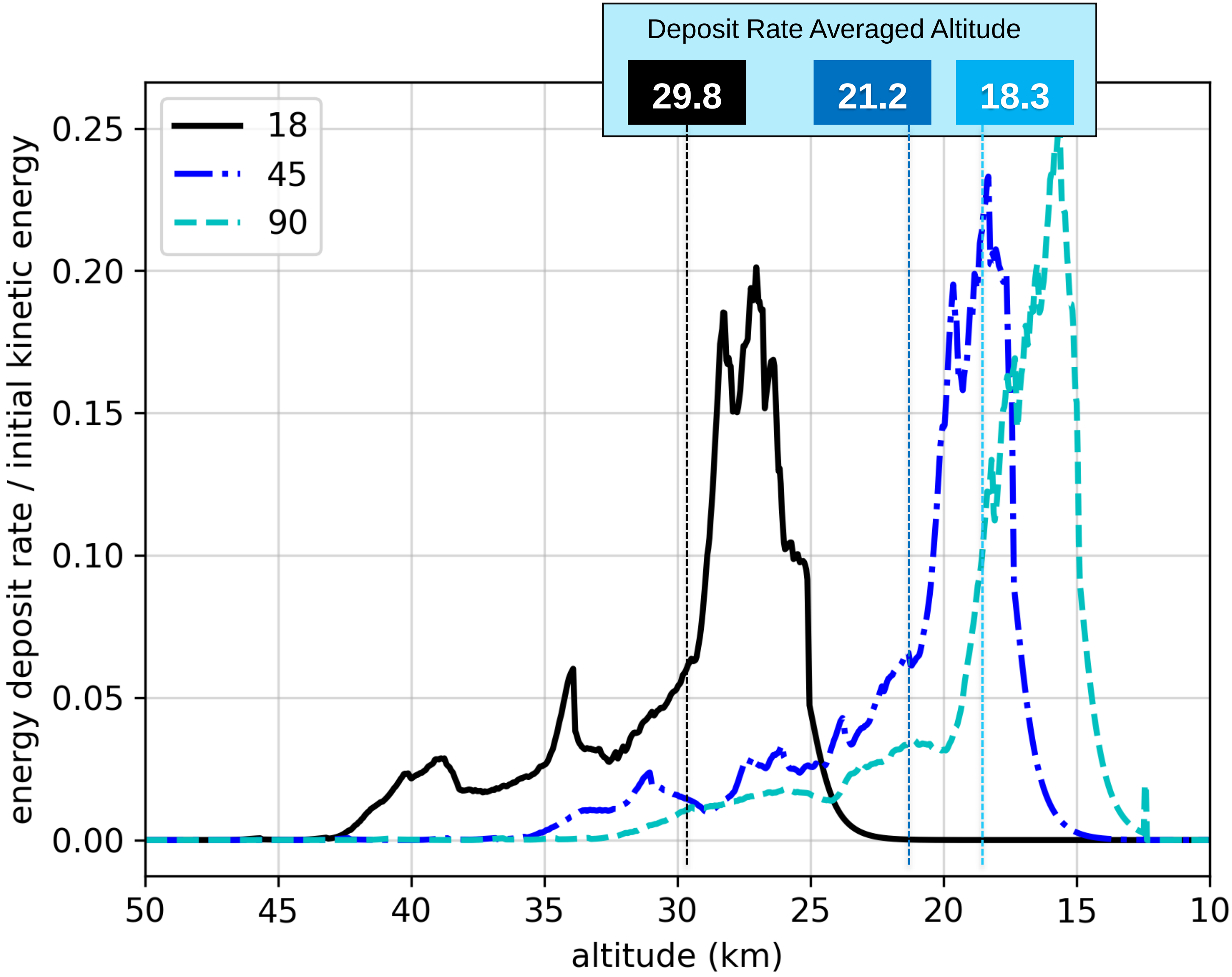
Simulated Energy Deposit Compared to Observation-Derived



Brown 2013 derived from the light curve assuming a black-body emission with a source temperature of 6000 K and a bolometric efficiency of 17%.

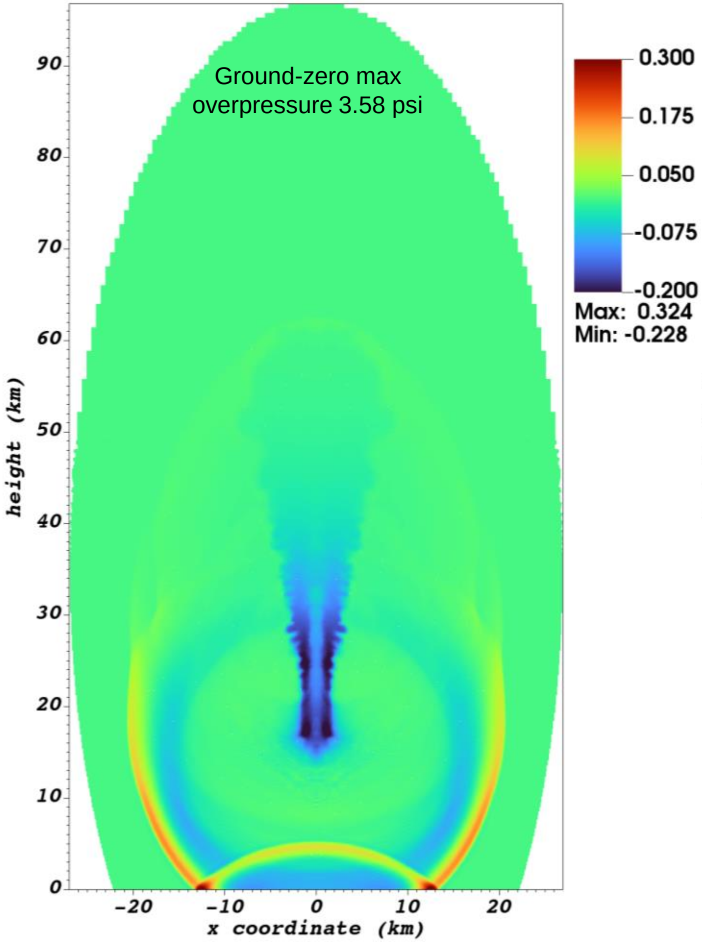
Popova 2013 fit their fragmentation-based semi-analytic model (Popova 2011) to the observed light curve. Red and blue represent two realization of the model.

Increasing the Entry Angle Decreases the Burst Height

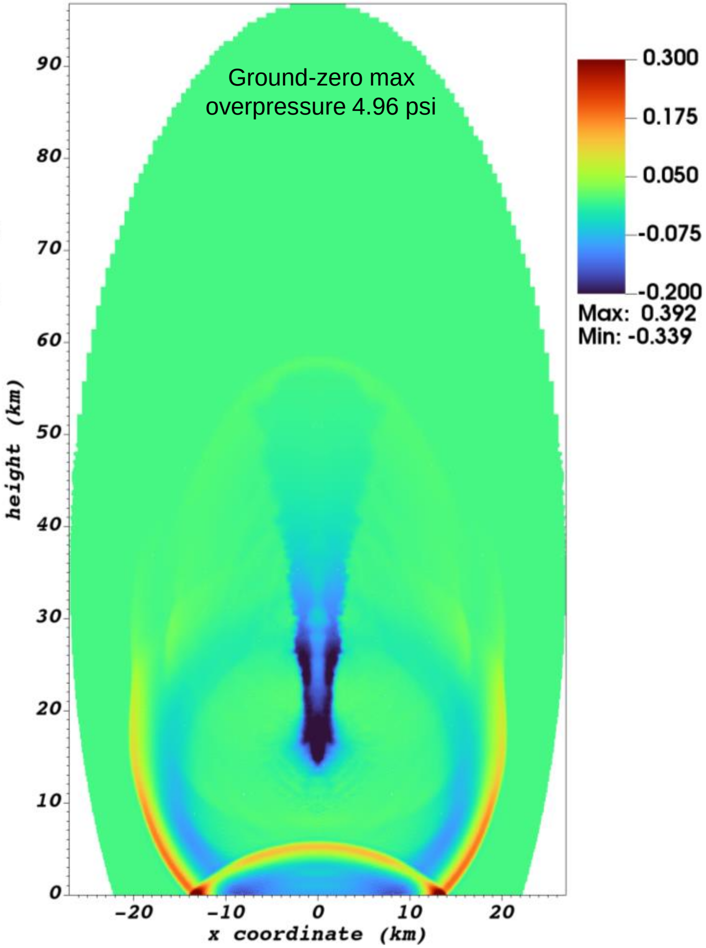


Deposition Technique Affects the Predicted Overpressure

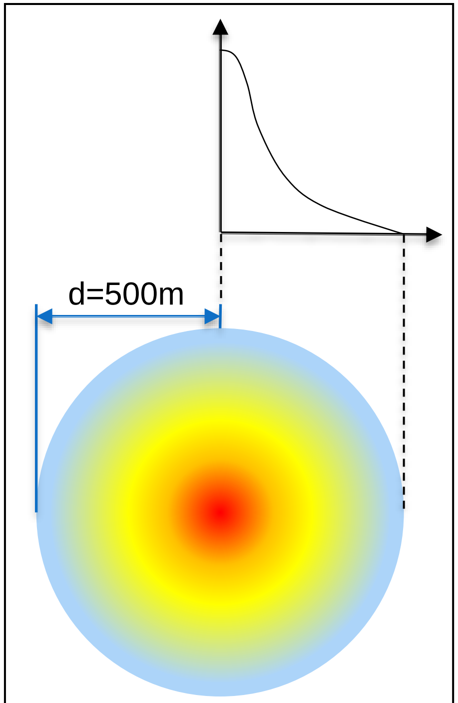
Energy



Energy & Momentum



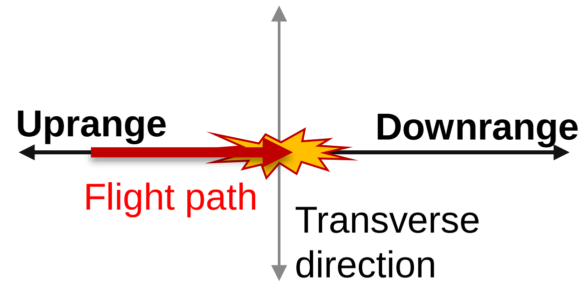
Deposition Geometry



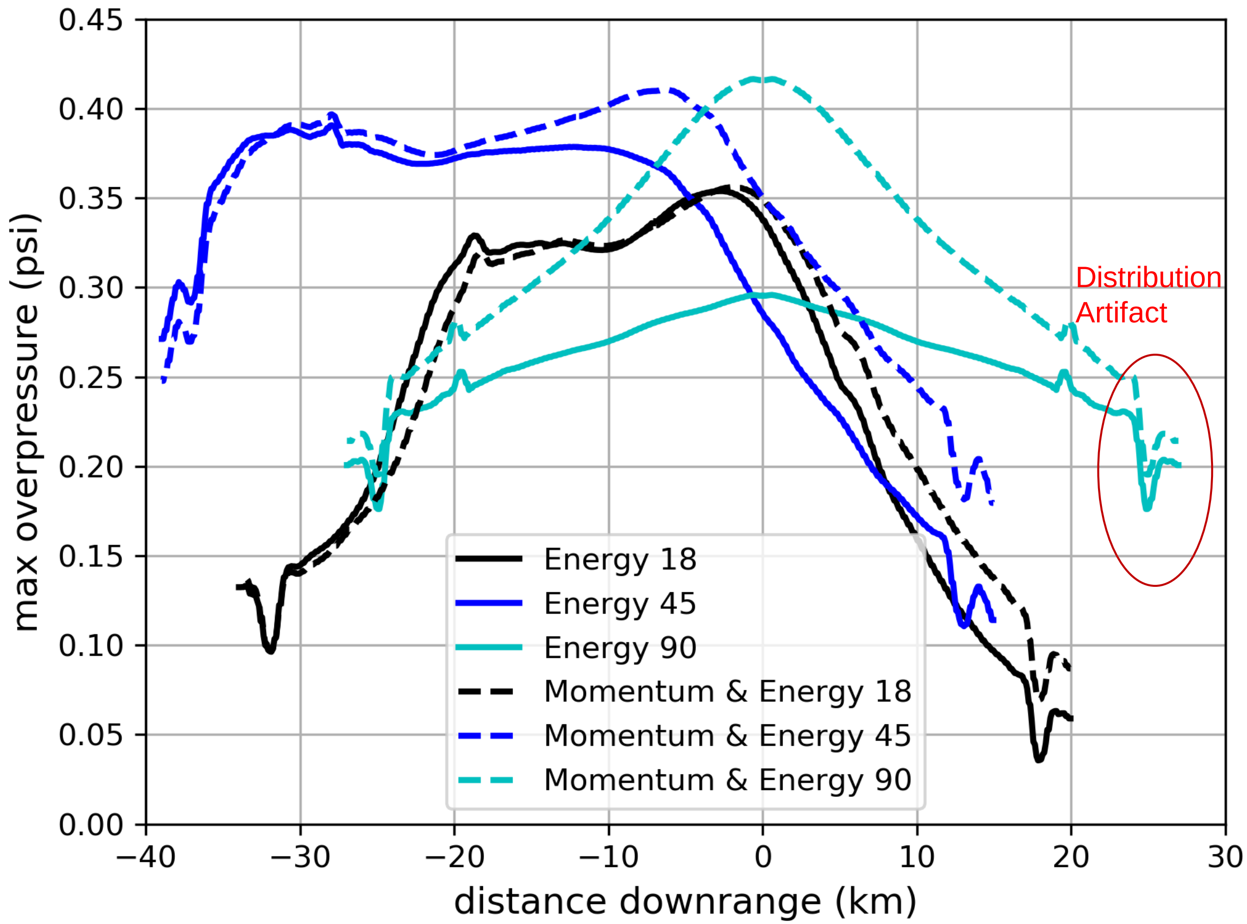
Depositing momentum in addition to energy increased peak overpressure by > 20% at 60s.*

* Total energy deposit is the same between the two approaches. **Energy** is 100% thermal energy. **Energy & Momentum** is a balance between kinetic and thermal energy set by conservation laws and the deposition geometry.

Steep Trajectories are More Sensitive to the Deposition Technique



- Steeper trajectories are more sensitive to the deposition technique.
- Peak overpressure varies by 40%.
- 45° entry yields a 30 km region with overpressures 15% above the peak for 18°.
- 90° entry directs much of the energy horizontally producing a flatter overpressure curve.



These effects simulations are under-resolved and meant to qualitatively compare entry angle and deposition technique effects on the ground signature.

Conclusions

- 3D Spheral simulation within 3 km of Borovicka's observation-derived altitude of peak energy deposit.
- Shallow entry angles result in higher bursts.
- A shallow entry and higher burst does not necessarily mean ground overpressures will be lower.
- Simulations of steep entries (~90°) are sensitive to the deposition technique whereas shallow entries (≤ 45°) are relatively insensitive.

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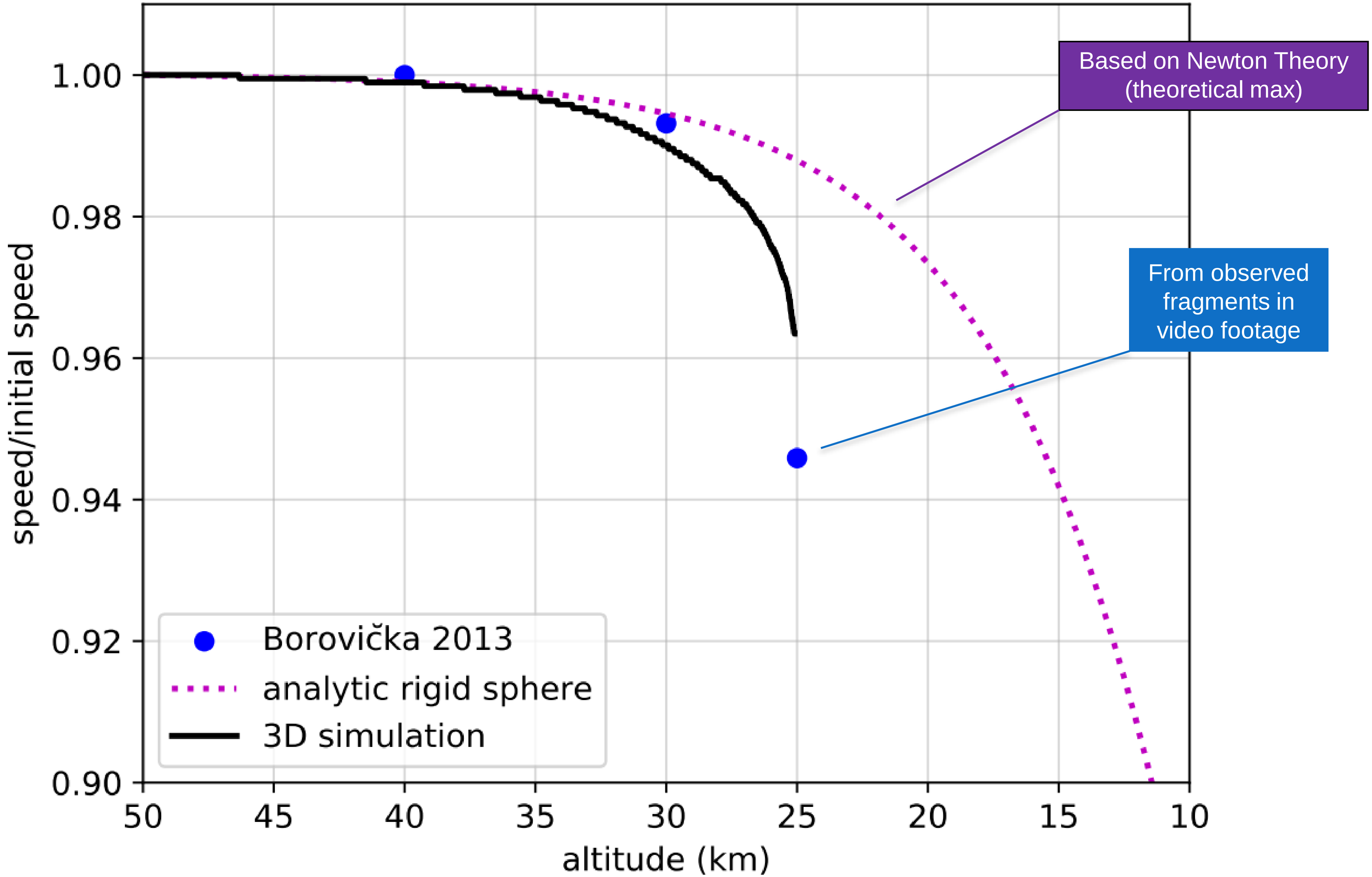
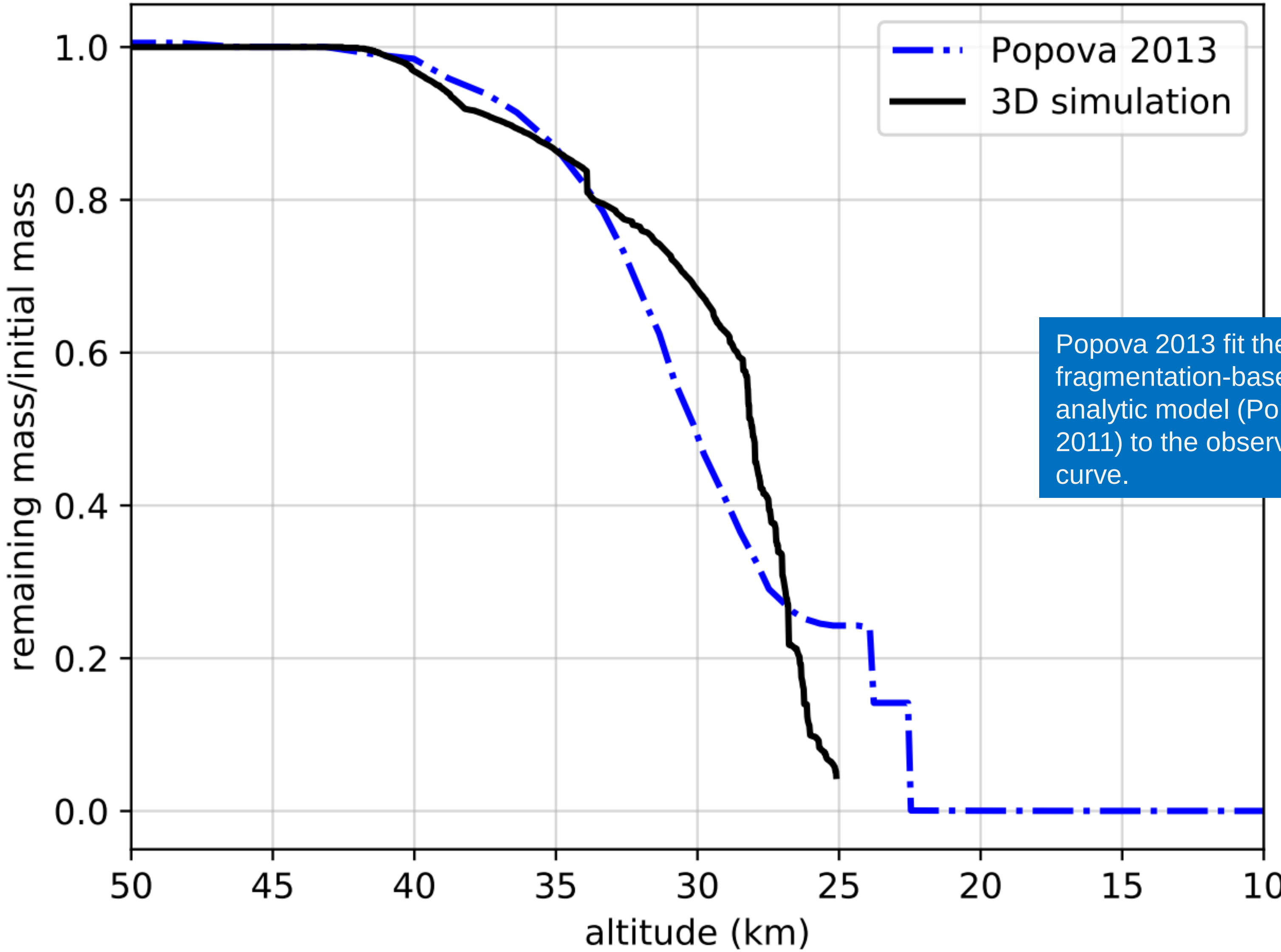
Velocity from 3D Chelyabinsk Entry Simulation Compared to Observation



Ablation from 3D Chelyabinsk Entry Simulation Compared to Popova



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