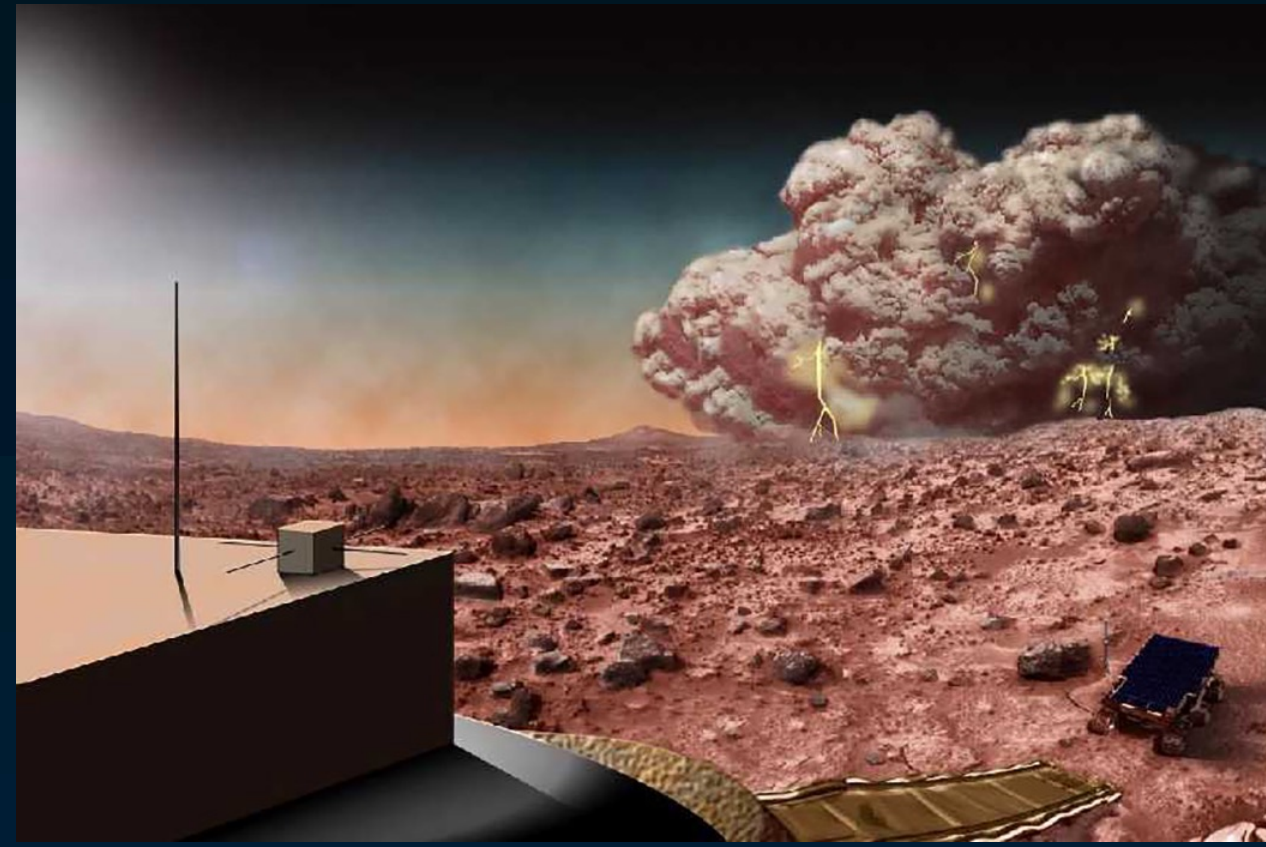


Introduction

- **Particulates** in planetary atmosphere **pose significant risk** to spacecraft health during hypersonic entry.
- Recent work indicates **TPS erosion due to particle impacts** comparable to thermochemical ablation [1].
- Limited characterization of **indirect effects of particulates** on hypersonic environment:
 - **Change in radiative energy transfer**
 - **Altered wall roughness due to pitting**
 - **Induce flow transition**
- Vagrant weather + long mission travel times require **multi-physics analysis to deliver robust designs**.

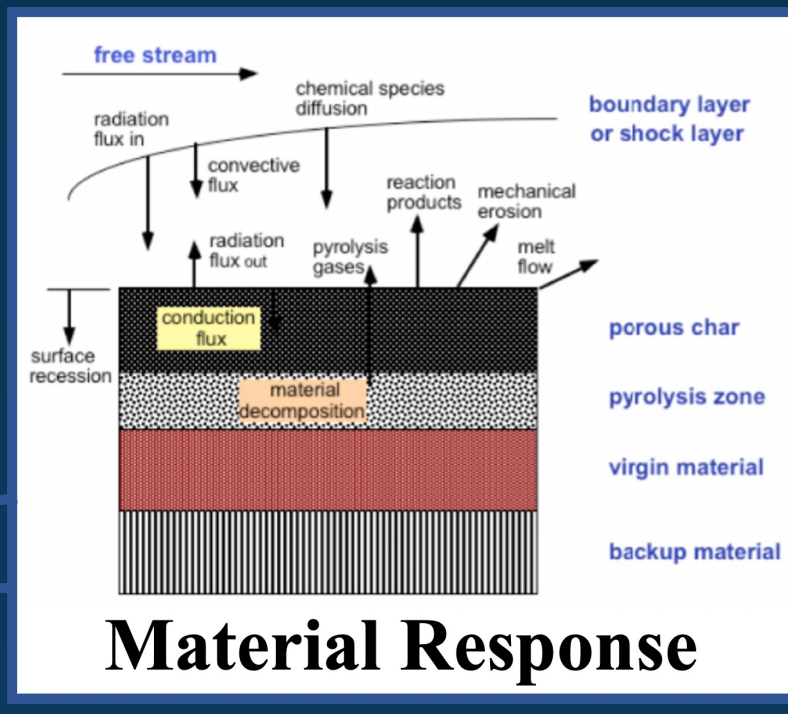
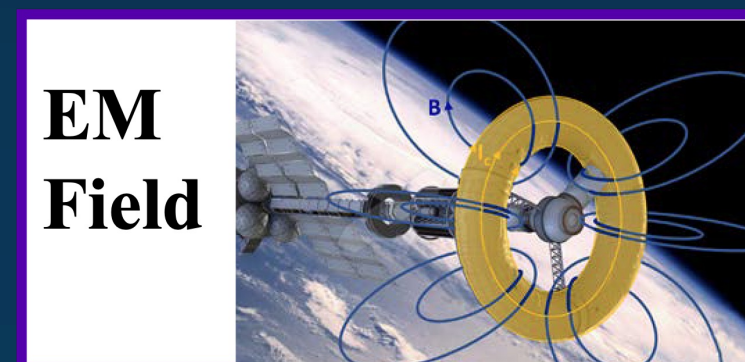
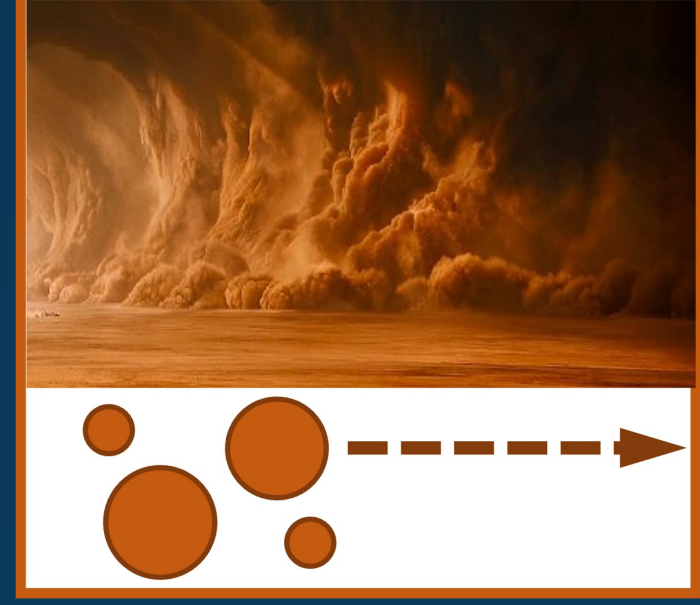


Martian Dust Storm

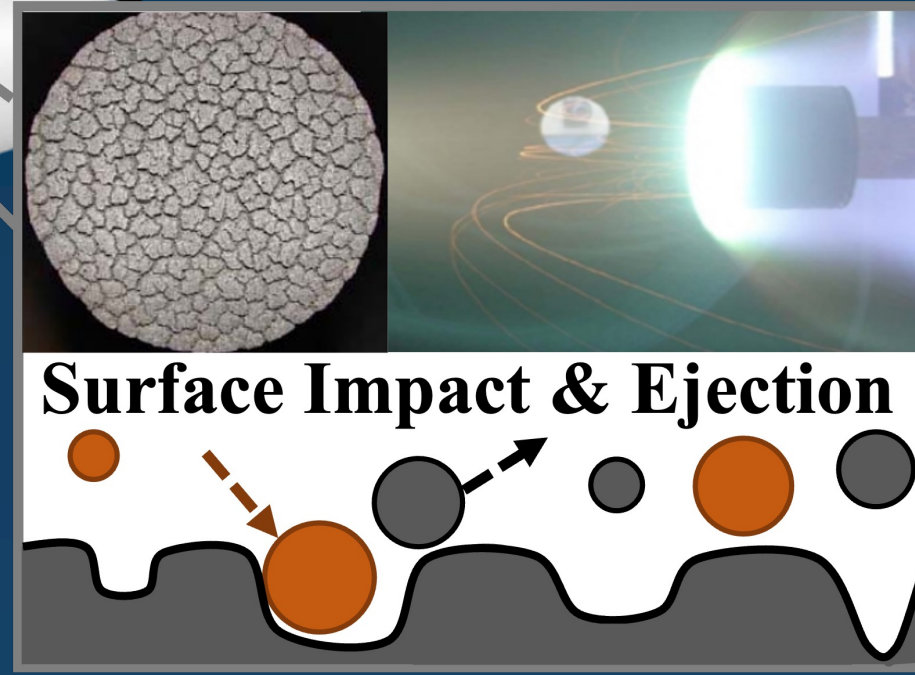
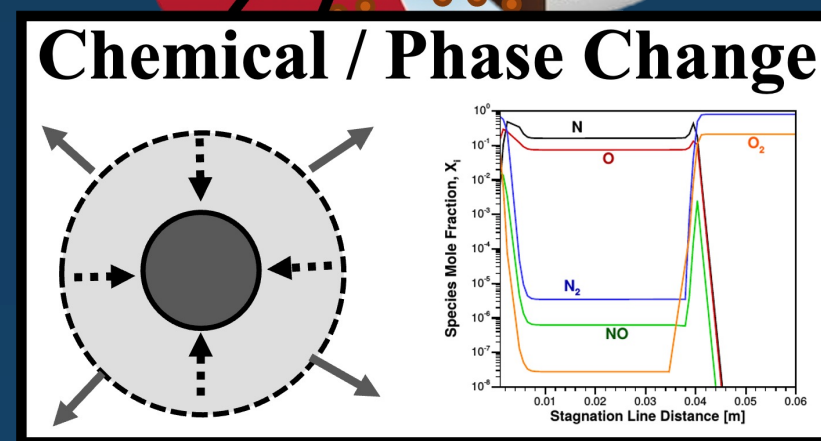
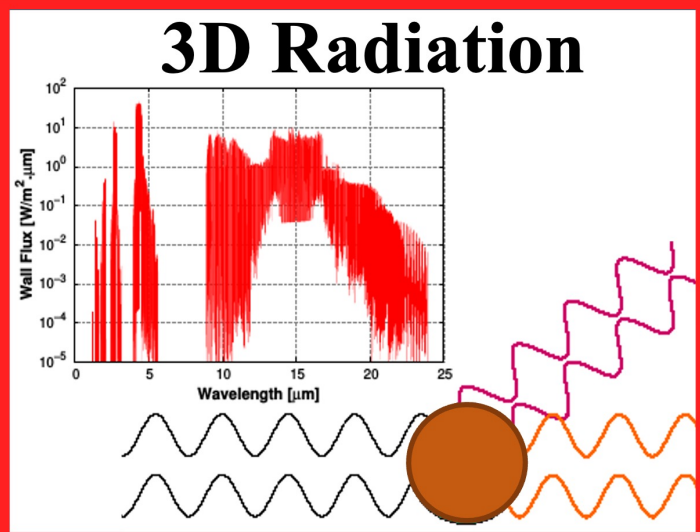
Objective

“Perform integrated high-fidelity modeling of radiative heat transfer (NERO) and particulate flow dynamics (DUST) in order to 1) assess impact of this interplay on spacecraft environment, 2) demonstrate multi-physics capabilities under development at NASA/ESM.”

Lagrangian Dust



Material Response

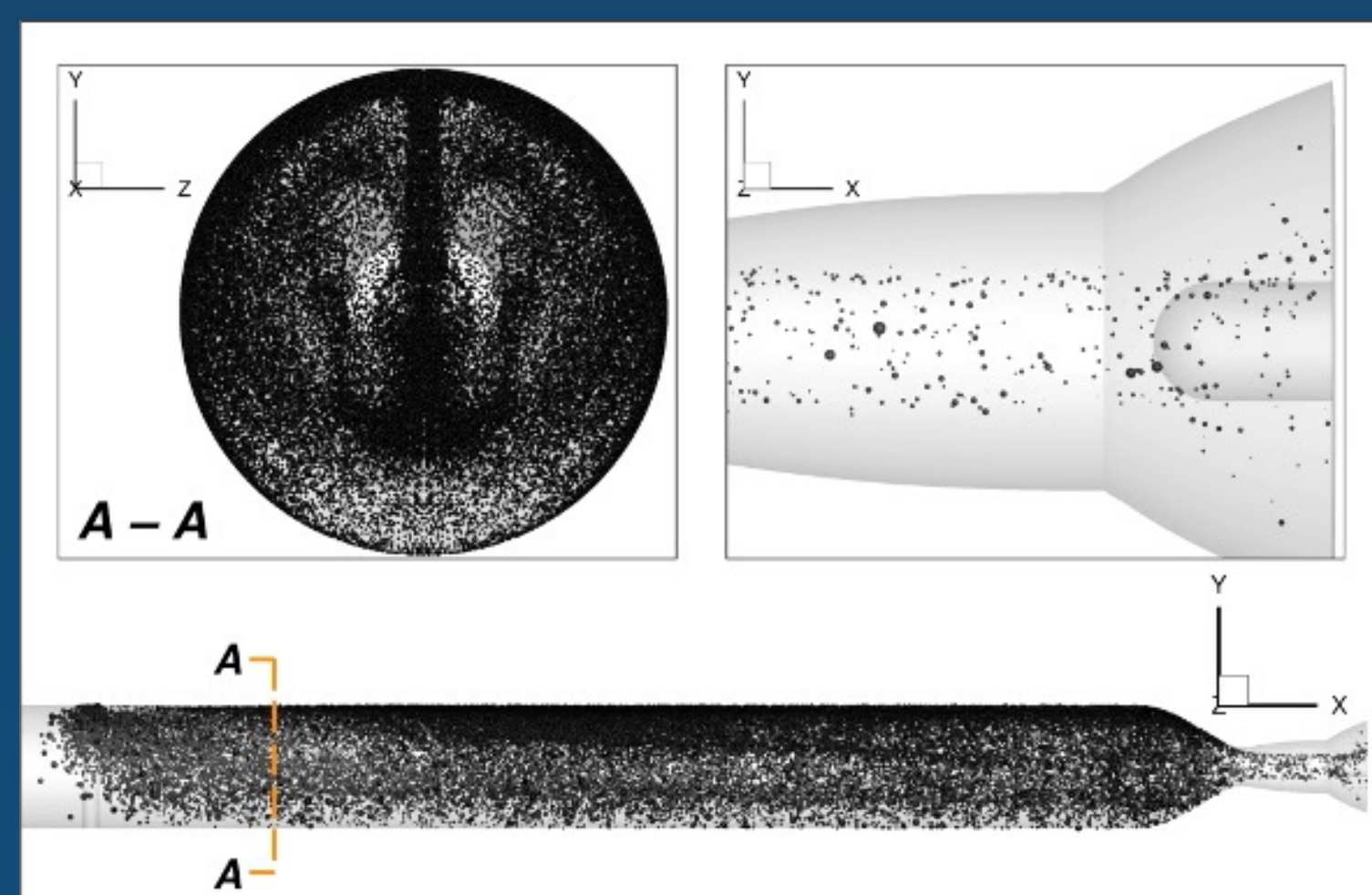


Surface Impact & Ejection

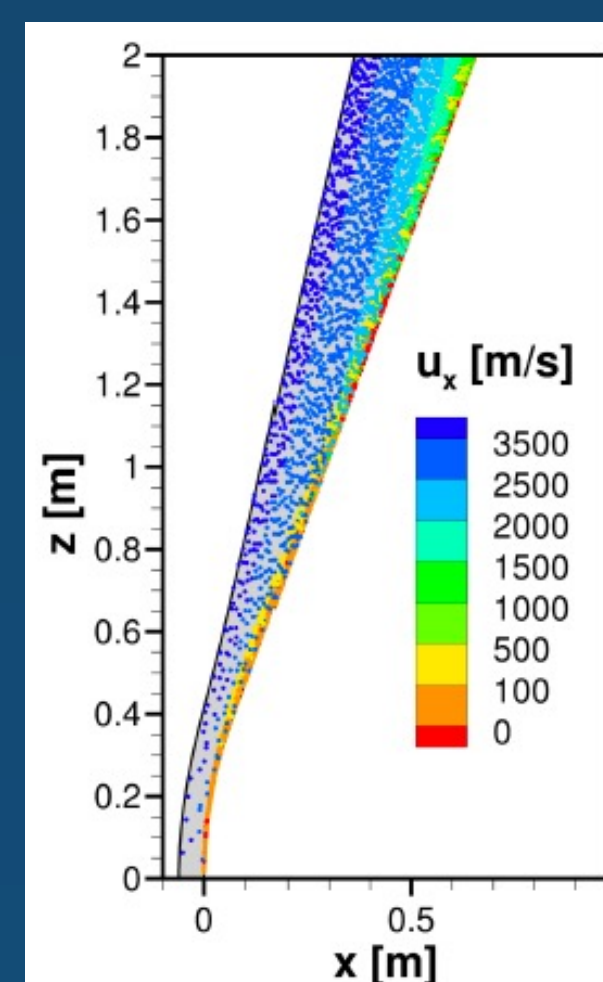
Multi-Physics Simulation Suite for Hypersonic Flows at NASA/ESM

DUST: Dust Simulation and Tracking

DUST [2] is a massively parallel, **variable-fidelity**, Lagrangian particle solver that links with **US3D** [3] – an unstructured, finite-volume hypersonic flow code.



Dusty Flows In DLR GBK Wind Tunnel



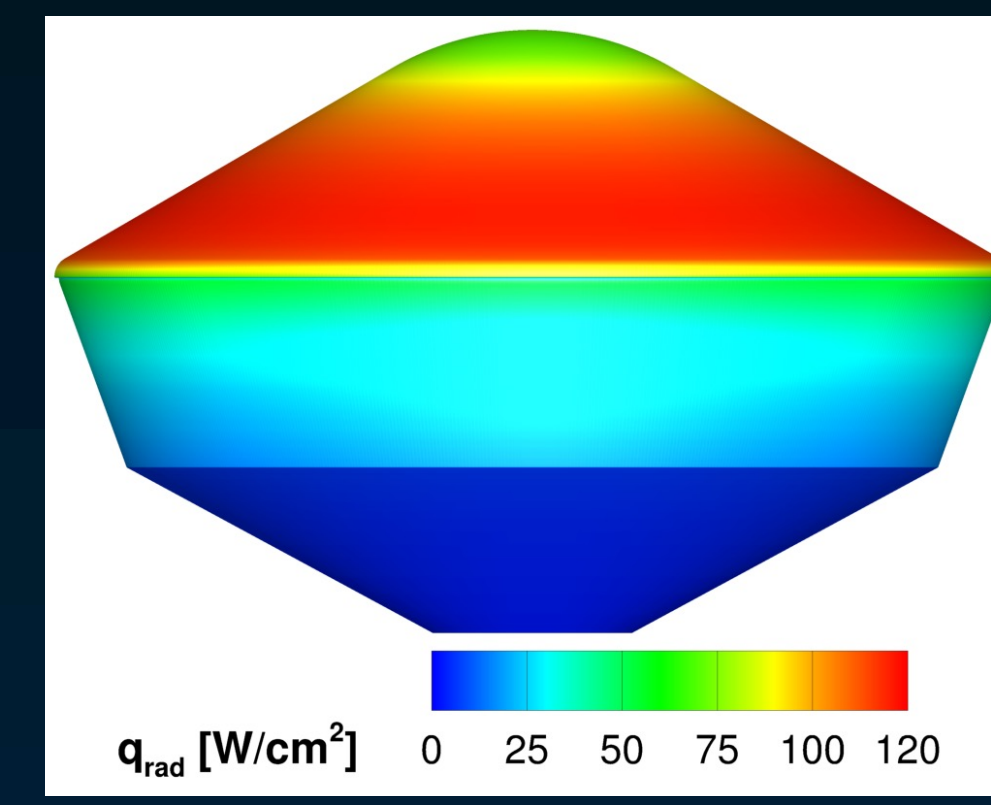
Particle Collisions Near Mars 2020

References

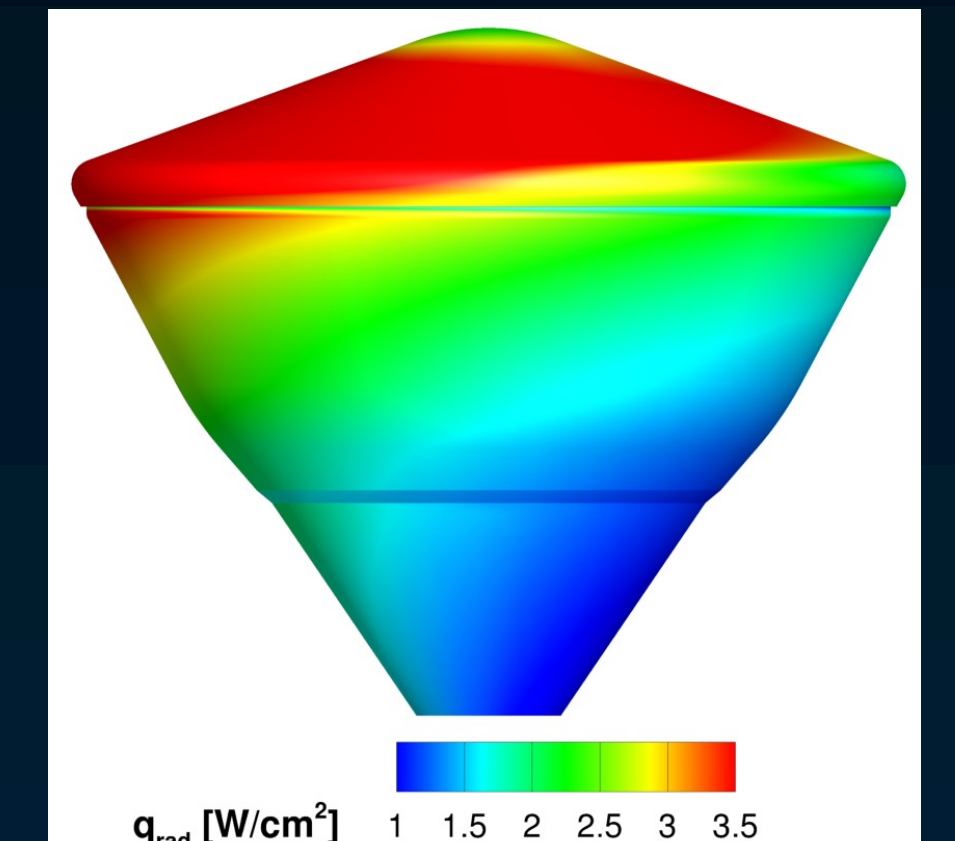
- [1] Palmer, G., Ching, E., Ihme, M., Alloys, D., and Gulhan, A., “Modeling Heatshield Erosion due to Dust Particle Impacts for Martian Entries,” *JSR* (2020).
- [2] Sahai, A. and Palmer, G., “Variable-fidelity Euler–Lagrange framework for simulating particle-laden high-speed flows,” *AIAA J* (2022).
- [3] Candler, G., Johnson, H., Nompelis, I., Subbareddy, P., Drayna, T., Gidzak, V., and Barnhardt, M., “Development of the US3D Code for Advanced Compressible and Reacting Flow Simulations,” *AIAA Paper* (2015).
- [4] Sahai, A. and Johnston, C.O., “On Computationally Efficient Radiative Transfer Calculations for Three-dimensional Entry Problems,” *AIAA Paper* (2023).
- [5] Lavvas, P., Yelle, R. V., and Griffith, C. A., “Titan’s vertical aerosol structure at the Huygens landing site: Constraints on particle size, density, charge, and refractive index,” *Icarus* (2010).

NERO: Non-Equilibrium Radiation

NERO [4] is a high-fidelity 3D radiation solver (linked to **US3D**) that delivers upto **1000x speed-up** using finite-volume discretization, mesh reordering, and novel reduced-order spectral models.



CN Radiation for Dragonfly

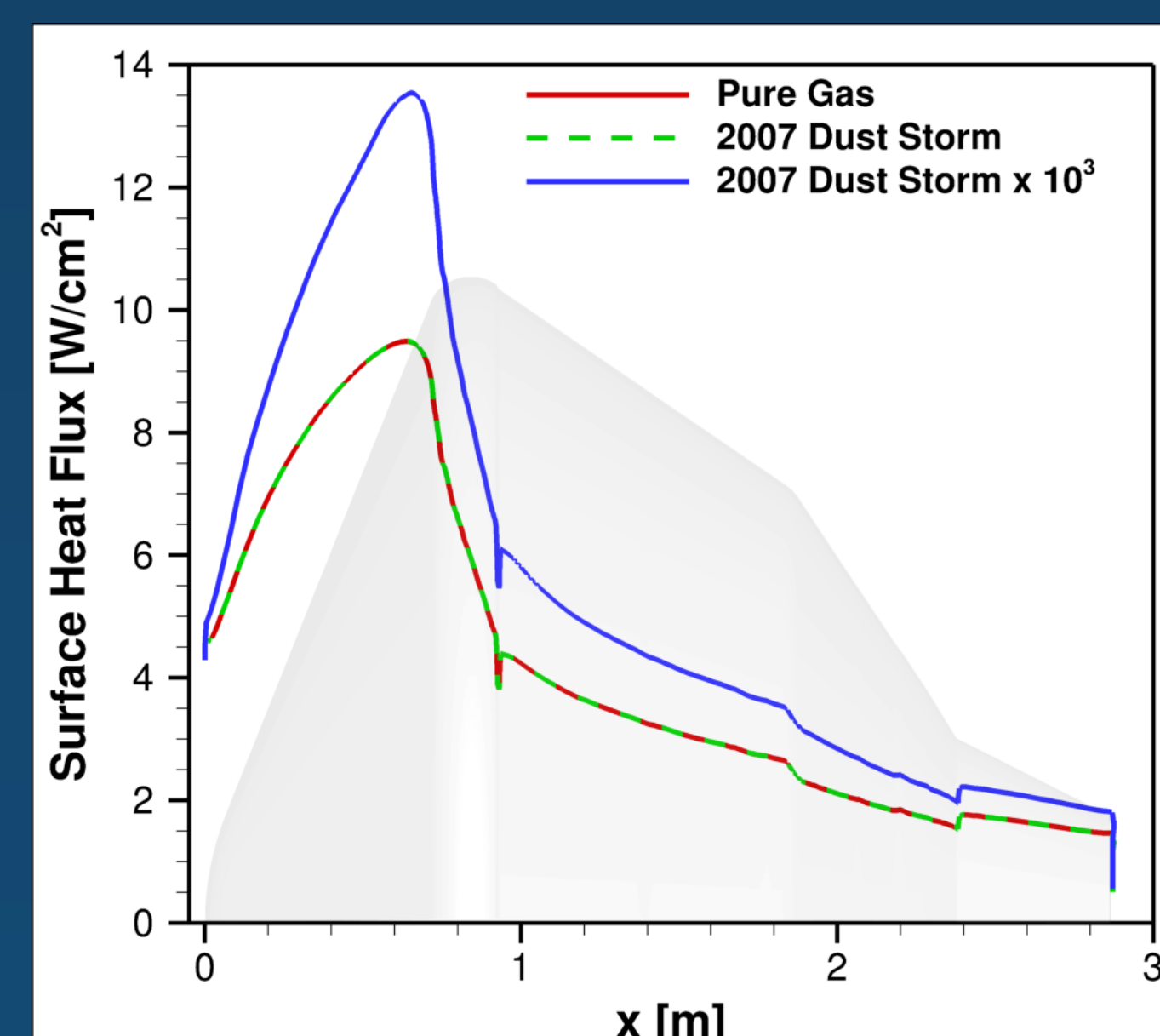


CO₂ + CO IR Radiation for Sample Return Lander

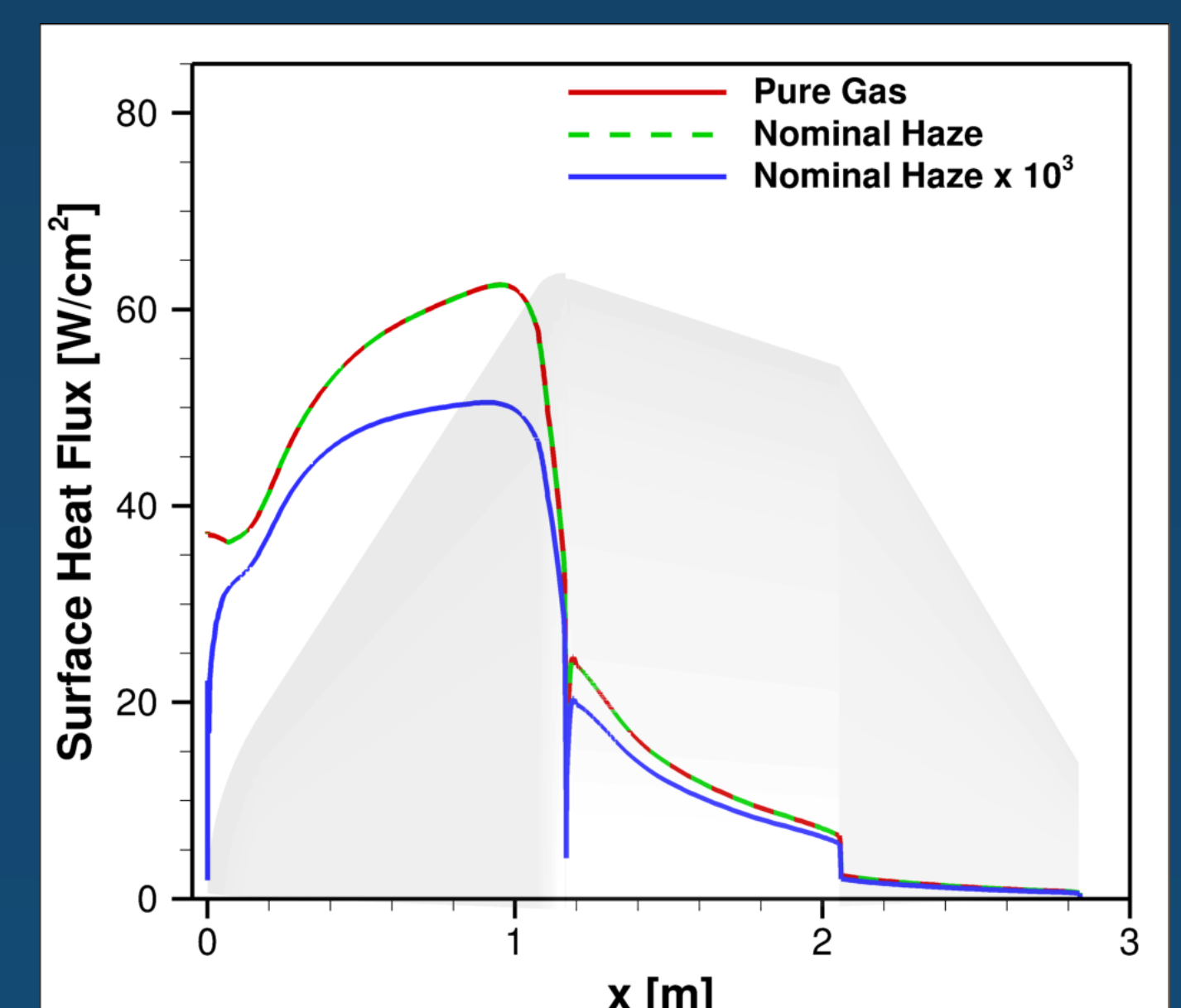
Methodology

- **NERO, DUST, US3D** exchange information through **General-purpose Library for Unstructured Environment (GLUE)**.
- Typical simulation proceeds as follows:
 - 1) Converged pure-gas flowfield solution is obtained using US3D at peak radiative heating conditions.
 - 2) DUST computes particle dynamics and cell-wise, time-averaged statistics.
 - 3) NERO accesses data from flow and particle fields to determine radiation.
- Particle extinction efficiency constant, grey body emission.
- Two scenarios considered:
 - **Mars 2020 entry** during dust storm
 - a. Johnston 10-species mixture; CO₂ + CO radiation
 - b. Polydisperse dust, Avg. $D_{\infty} = 6 \mu\text{m}$, $n_{\infty} = 9 \times 10^5 \text{ \#}/\text{m}^3$ (2007 Dust Storm [1])
 - **Dragonfly entry** through organic haze
 - a. Gokcen 21-species mixture; CN + C₂ radiation
 - b. Monodisperse haze, $D_{\infty} = 1.6 \mu\text{m}$, $n_{\infty} = 10^6 \text{ \#}/\text{m}^3$ (Titan Atmospheric Haze Model [5]). No emission from haze.

Outcome



Mars 2020 Surface Radiative Heat Flux



Dragonfly Surface Radiative Heat Flux

- Particle number density/size **not large enough to appreciably alter surface radiative heat flux**.
- Competing processes – additional emission, blocking of gas-phase radiation – cancel each other out.
- Increased number density can induce significant changes; E.g., particles trapped in vehicular features like recesses.
- Paves way for diverse **future applications**:
 - Particle deposition on sensor windows
 - Radiation measurements during spallation
 - Any combination of discrete physics – interaction between electromagnetic field, dust, and radiation.