Sensitivity Study of Impact Risk Model Results to Thermal Radiation Damage Model for Large Objects

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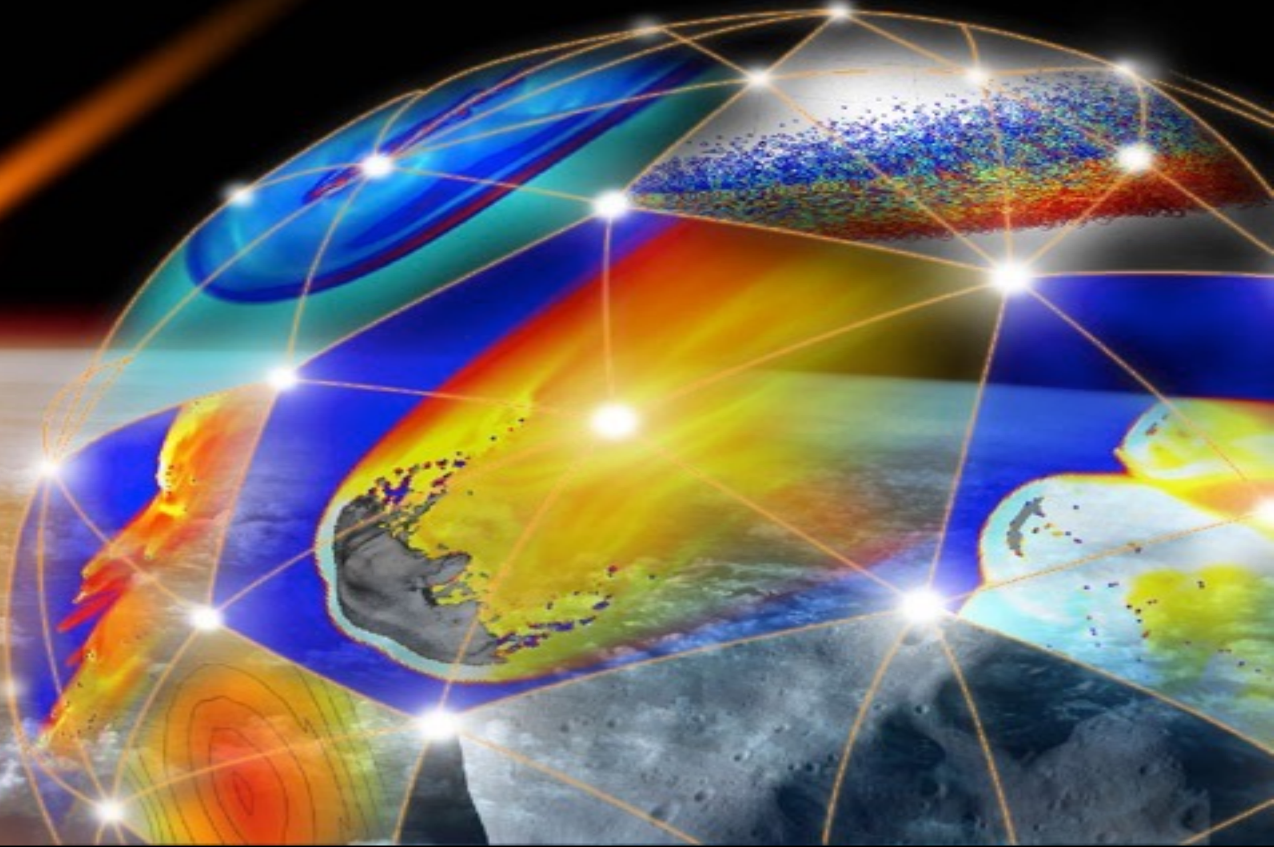

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Introduction

- NASA's Probabilistic Asteroid Impact Risk (PAIR) model is used to assess potential damage from multiple hazards – **local ground damage (blast and thermal)**, tsunamis, global effects
- Blast is typically the leading local ground damage hazard, although thermal radiation can produce substantial damage particularly for larger objects and at greater severity levels
- Uncertainties exist in asteroid properties and other parameters used in thermal radiation models and as thermal damage becomes more important we need to **determine which modeling sensitivities affect leading hazard determination** (defines zone at risk to given level of damage)

Sensitivity Study:

1. Determine which parameters within thermal model have most significant influence on overall results
2. Investigate sensitivities in other thermal models and compare results
3. Evaluate sensitivities in context of the PDC 2023 scenario
4. Highlight where additional model refinement may be beneficial

Sensitivity Study Setup

Three thermal models considered

1. **Collins model – Current model implemented in PAIR (Collins et al. 2005)**
2. Institute of Geospheres Dynamics, Russian Academy of Sciences (IDG RAS) model (Popova et al. 2021)
3. NASA's Asteroid Threat Assessment Project (ATAP) model (Johnston and Stern 2019)

- Each asteroid property or parameter is **varied one at a time** across a range of values based on PDC 2023 Epoch 1 information
- 4 damage severity levels are considered: **Serious**, Severe, Critical, **Unsurvivable**

Baseline Case

	Collins et al.	IDG RAS	NASA ATAP
Energy (Gt)	10.29	10.29	-
Diameter (m)	800	800	800
Velocity (km/s)	12.673	12.673	12.673
Density (kg/m3)	2000	2000	2000
Luminous Efficiency	0.003	-	-
Source Height (km)	-	38	-
Entry Angle (deg)	-	-	54.34
Strength (MPa)	-	-	2

Current PAIR Thermal Model – Collins et al.

- Collins model is based on **energy-scaled nuclear data** from Glasstone and Dolan and predicts the thermal radiation damage radius caused by a **spherically expanding fireball** generated from a ground impact

- Calculates the thermal exposure ϕ (heating per area) at a distance r from the impact location

$$\phi = \frac{\eta E}{2\pi r^2} = \frac{energy\ emitted\ as\ thermal\ radiation}{area\ over\ which\ energy\ is\ spread}$$

- Includes an energy scaling law to determine thermal exposure ϕ_i required to ignite a material, accounts for impact-energy dependence

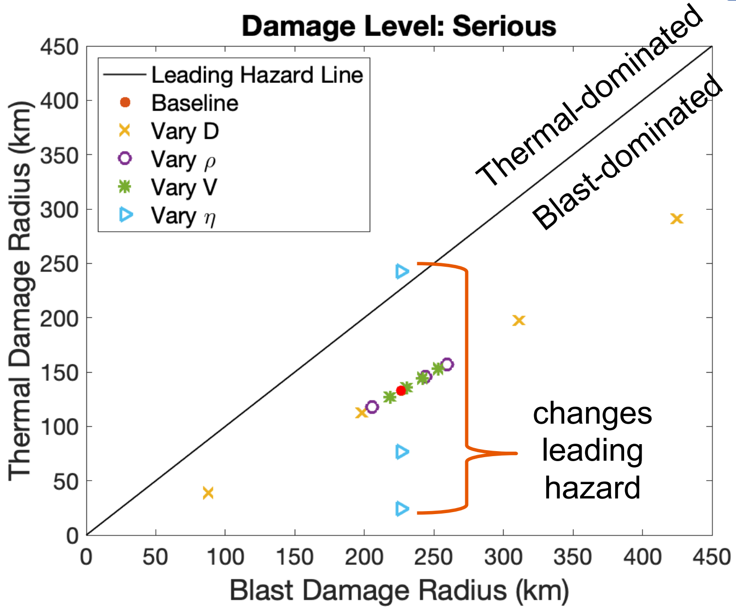
$$\phi_i = \phi_i(1\ Mt)E_{Mt}^{\frac{1}{6}}$$

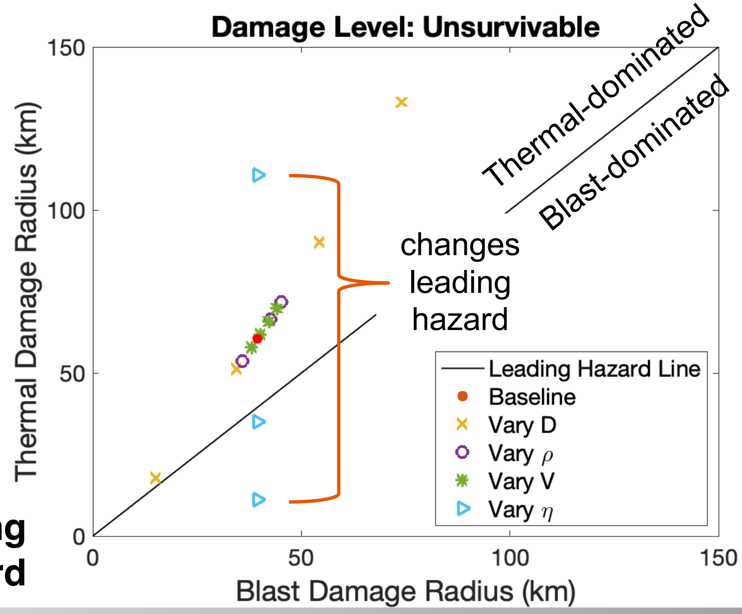
$$\boxed{r = \sqrt{\frac{\eta E}{2\pi \phi_i}} = \begin{matrix} radius\ over\ which\ ignition \\ of\ a\ given\ material\ occurs \end{matrix}}$$

- Uses luminous efficiency parameter η to represent how much energy contributes to thermal damage, uncertain parameter (1e-4 to 1e-2, nominal 0.003)

Sensitivity Analysis

- Properties and parameters considered
  - Diameter, velocity, density → energy
  - Luminous efficiency
- Results are shown for the **Serious** and **Unsurvivable** damage severity levels
- Variations in diameter, velocity, density, and therefore **energy**, produce similar trends in blast and thermal results – No significant influence on leading hazard determination by uncertainties in these parameters for this regime
- Variations in **luminous efficiency** have a significant effect on thermal model results – **Uncertainty in this parameter can lead to changes in the leading hazard**

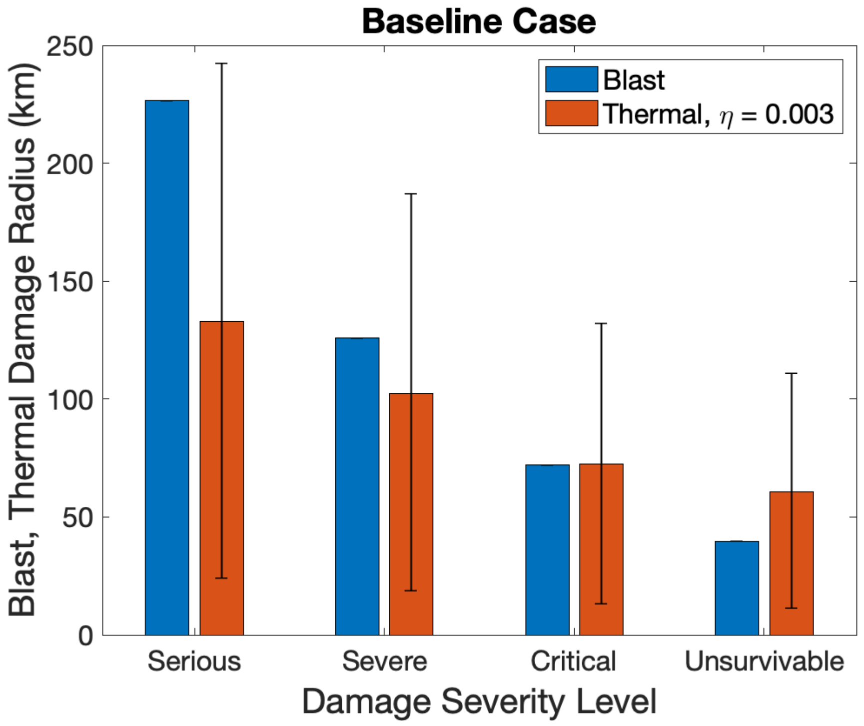


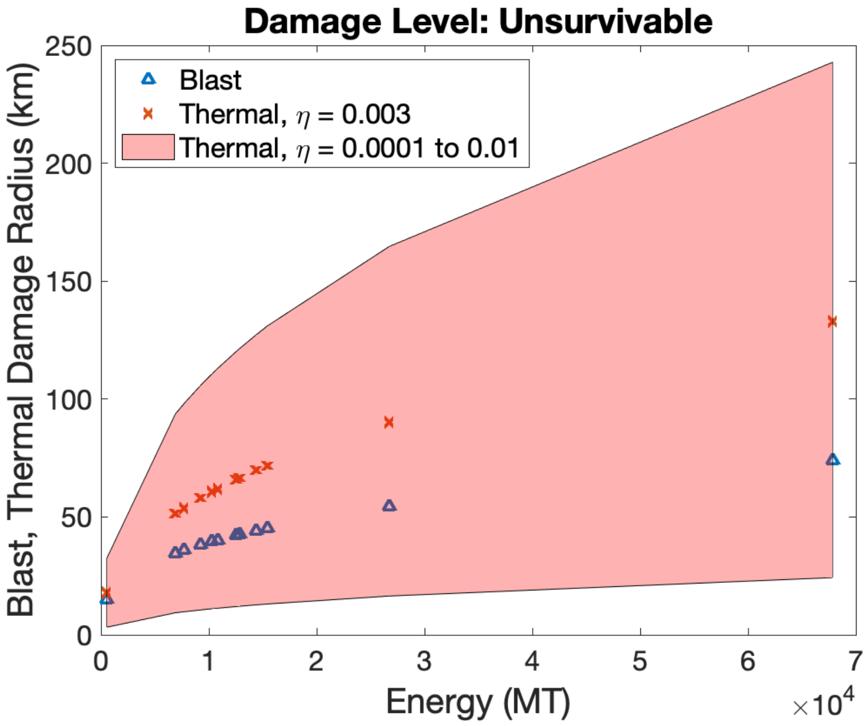


Points below the diagonal line indicate blast is the leading hazard and points above indicate thermal is the leading hazard

Luminous Efficiency

- Potential **thermal** damage spread is shown as error bars given accepted luminous efficiency value range
- Higher luminous efficiency values needed to overcome **blast** at lower severity levels
- Shaded region highlights range of potential thermal damage given accepted luminous efficiency range
- **Blast** or **thermal** could be the leading hazard depending on the luminous efficiency value chosen





Consistent luminous efficiency sensitivity observed across damage severity levels and object sizes

Additional Models – IDG RAS, NASA ATAP

- Two additional thermal radiation damage models are considered for comparison
- These models are not dependent on the uncertain luminous efficiency parameter found in the Collins model

Model 1: IDG RAS

- Developed by the Institute of Geospheres Dynamics, Russian Academy of Sciences
- Scaling relation calculates thermal exposure on the ground based on a series of entry and impact simulations
- Crater forming equations used for all cases ($D \geq 300$ m)

Model 2: NASA ATAP

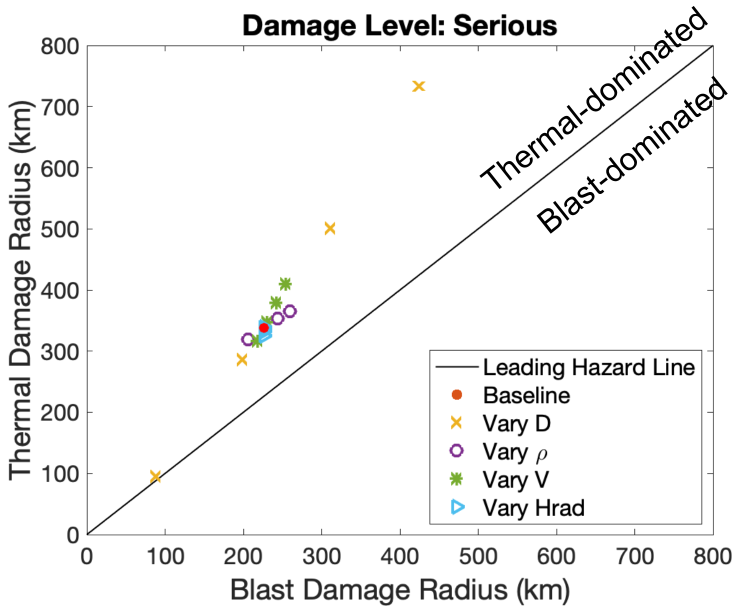
- Developed by Johnston and Stern of NASA's Asteroid Threat Assessment Project
- Correlation for ground radiative flux based on detailed flow field and radiation simulations
- Computes thermal exposure on the ground from the shock-layer and wake of an asteroid entry by integrating ground radiative flux through a trajectory
- Originally developed for smaller objects, expanded for larger objects

All three models have different approaches

Sensitivity Analysis

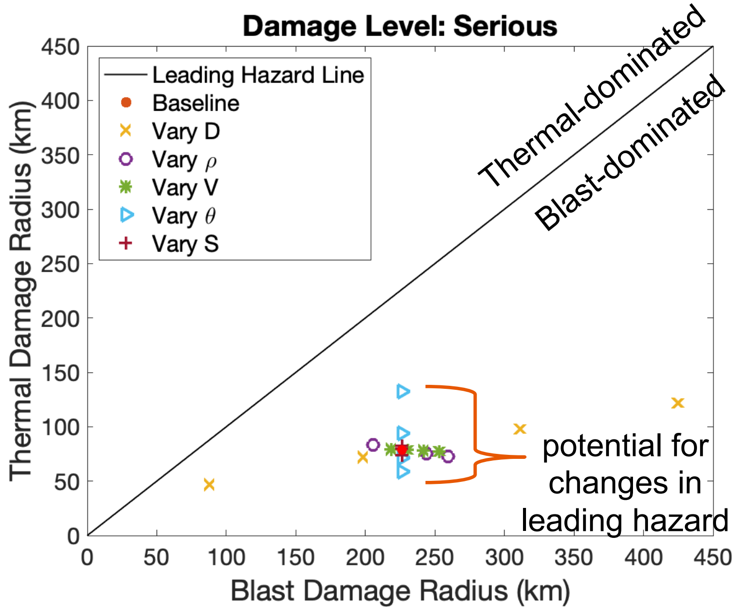
IDG RAS

- Properties and parameters considered
  - Diameter, velocity, density → energy
  - Radiation source height
- Results consistently show this model exceeds blast damage across all severity levels
- No significant influence on leading hazard determination by uncertainties in these parameters



NASA ATAP

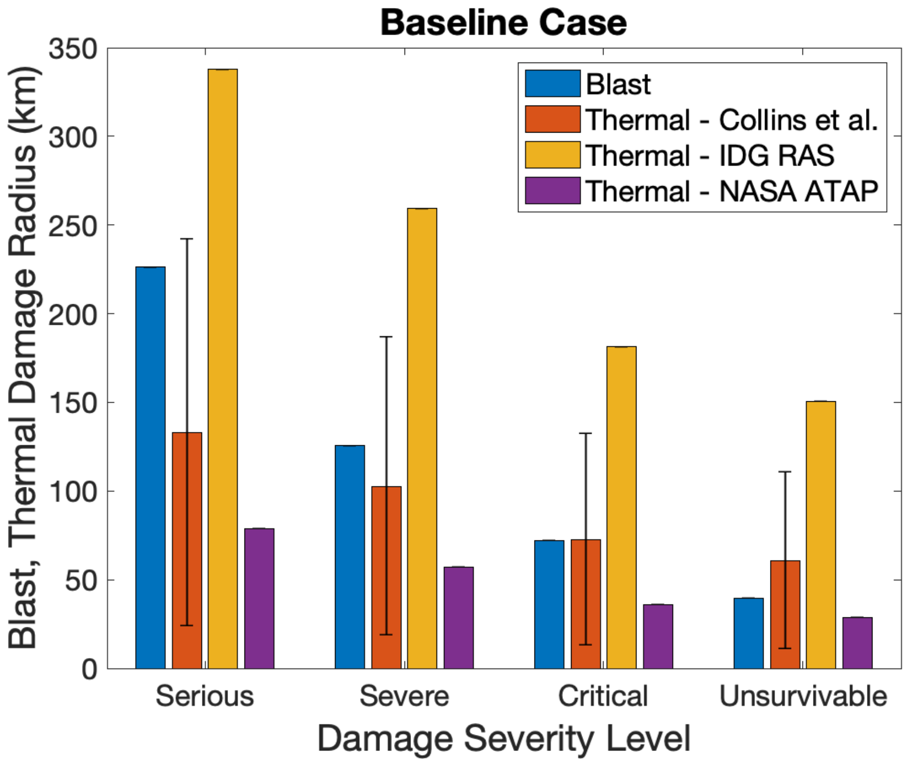
- Properties and parameters considered
  - Diameter, velocity, density → energy
  - Strength, entry angle
- Thermal results with this model are generally much lower than blast damage
- **Uncertainty in entry angle can have an effect on thermal model results at higher severity levels**



Model Comparison

Compare all three thermal models to **blast** for the nominal baseline case

- **Collins et al.** thermal model implemented in PAIR exceeds blast at higher severity levels for this case under nominal conditions
- **IDG RAS** thermal model is noticeably larger than blast at all severity levels for this case and exceeds the Collins et al. model range
- **NASA ATAP** thermal model is smaller than blast at all severity levels for this case and is within Collins et al. model range



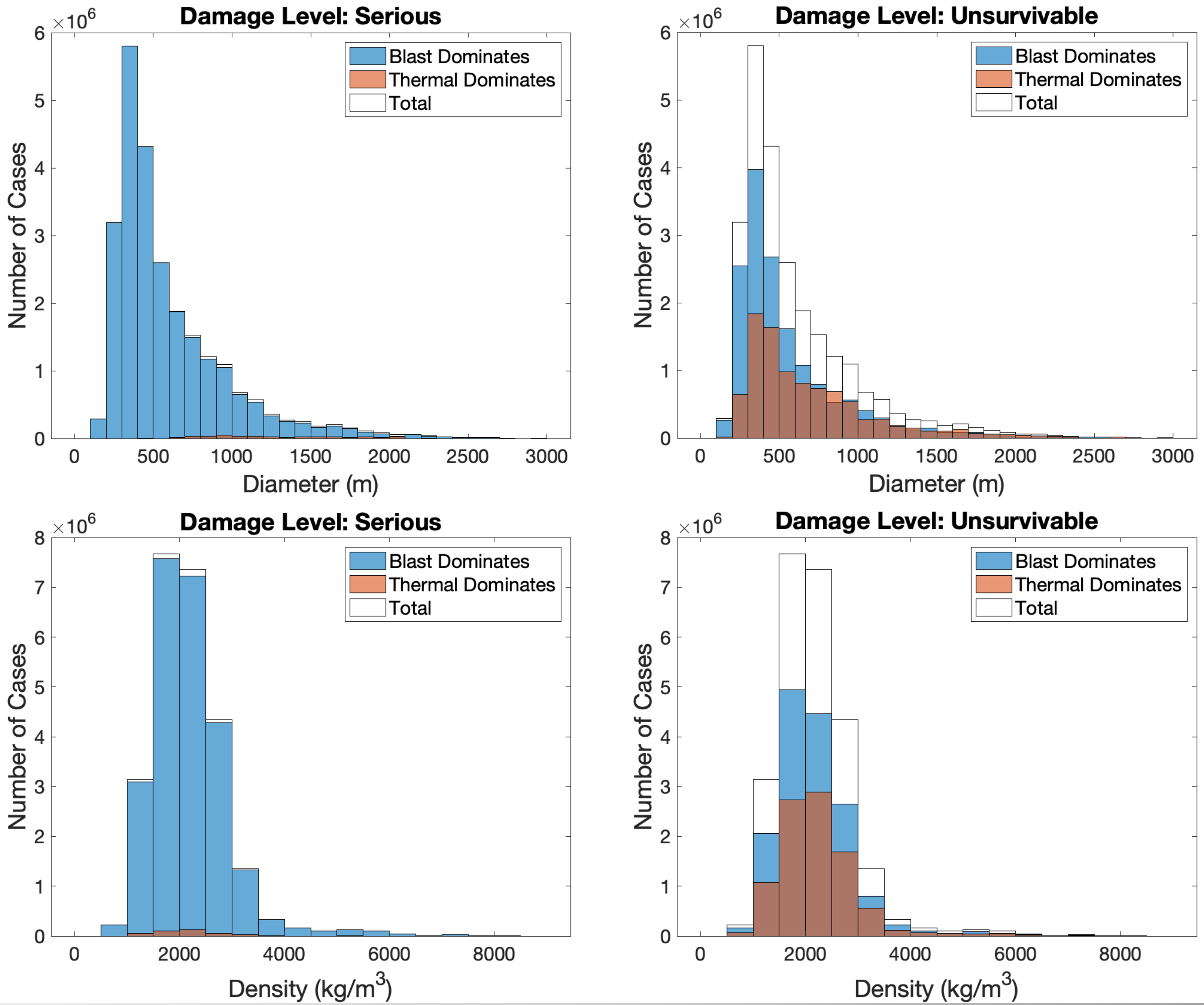
The leading hazard is sensitive to the thermal model used

PDC 2023 Scenario

- 25 million Epoch 1 cases considered
- Categorized by **diameter** and **density** → energy (velocity is well known in this scenario) at the **serious** and **unsurvivable** damage levels

- **Thermal much more of a factor at higher severity levels**
  - Start seeing thermal dominate in some cases above 150 Mt, and **thermal** and **blast** are about equally as likely by 700m at the unsurvivable level

- Distribution shapes are similar between **blast** and **thermal** – while energy is an important parameter in the amount of damage, leading hazard determination is not very sensitive to it

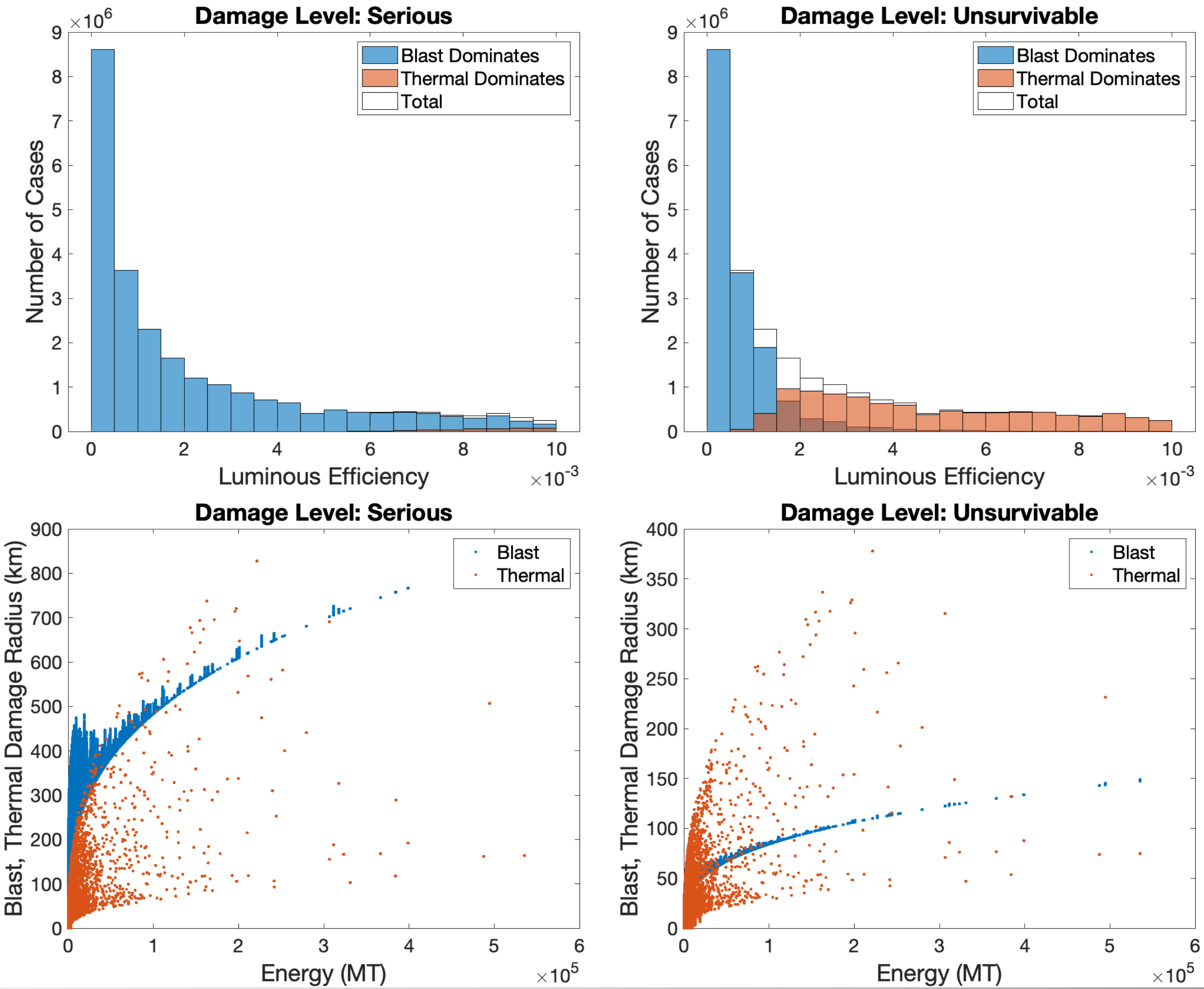


PDC 2023 Scenario

- 25 million Epoch 1 cases considered
- Categorized by **luminous efficiency** at the **serious** and **unsurvivable** damage levels

- **Thermal much more of a factor at higher severity levels**
- Distribution shapes are not similar (**blast**-dominated cases shifted left and **thermal**-dominated to the right) – **Overall leading hazard determination is sensitive to this parameter**

- Large spread in **thermal** damage highlights the influence of the luminous efficiency parameter



Conclusions

We have conducted a sensitivity study to determine which parameters and over what ranges cause the impact risk results generated by PAIR to be sensitive to thermal radiation damage. We determined the following conclusions and recommendations.

- The current thermal radiation damage model in PAIR is sensitive to the uncertain luminous efficiency parameter – **A better understanding of how to choose this parameter for a given case would improve the model**

- The three thermal models considered have different sensitivities and give significantly different results ranging from well below blast damage results to well above. The leading hazard determination is sensitive to the thermal radiation damage model – **Additional study to understand the differences would improve confidence in the models**

- **Thermal radiation damage plays an important role in impact risk results for this regime, particularly at higher damage severity levels**

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Thank you

QUESTIONS?