Airburst & Blast Damage Modeling Sensitivities for Asteroid Impact Risk Assessment

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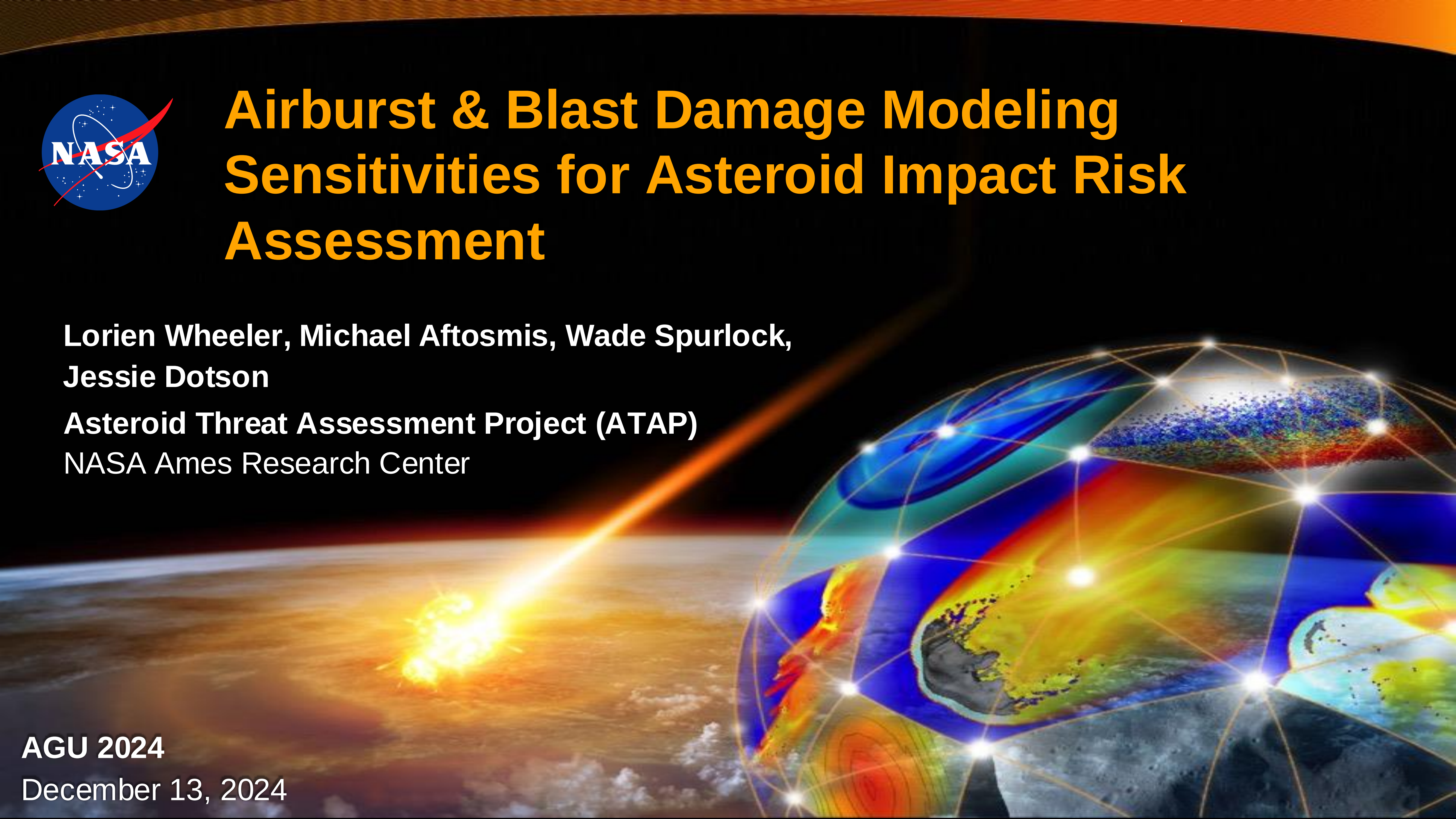

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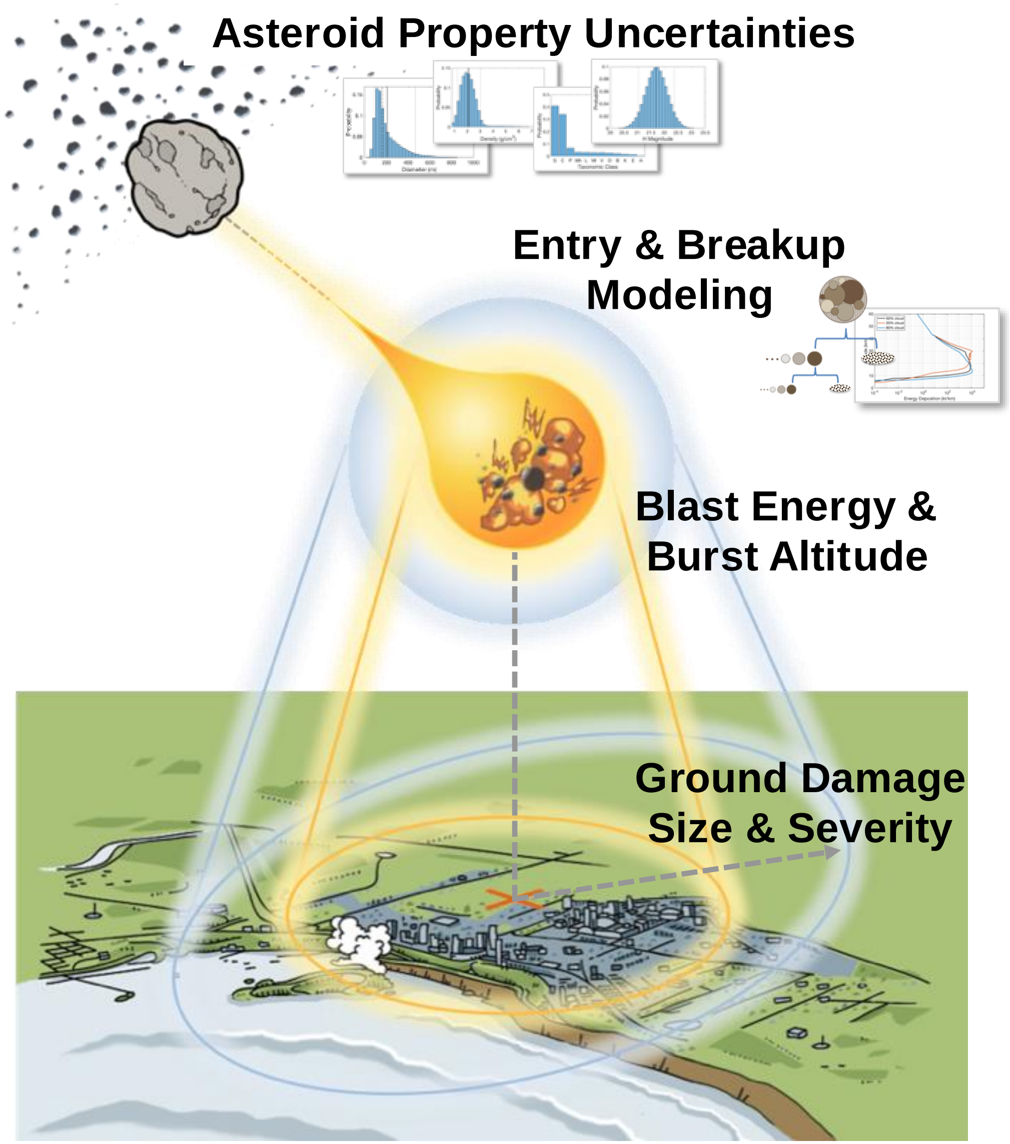
Airburst & Blast Damage Risk Modeling Study



Asteroid Property Uncertainties

Entry & Breakup Modeling

Blast Energy & Burst Altitude

Ground Damage Size & Severity

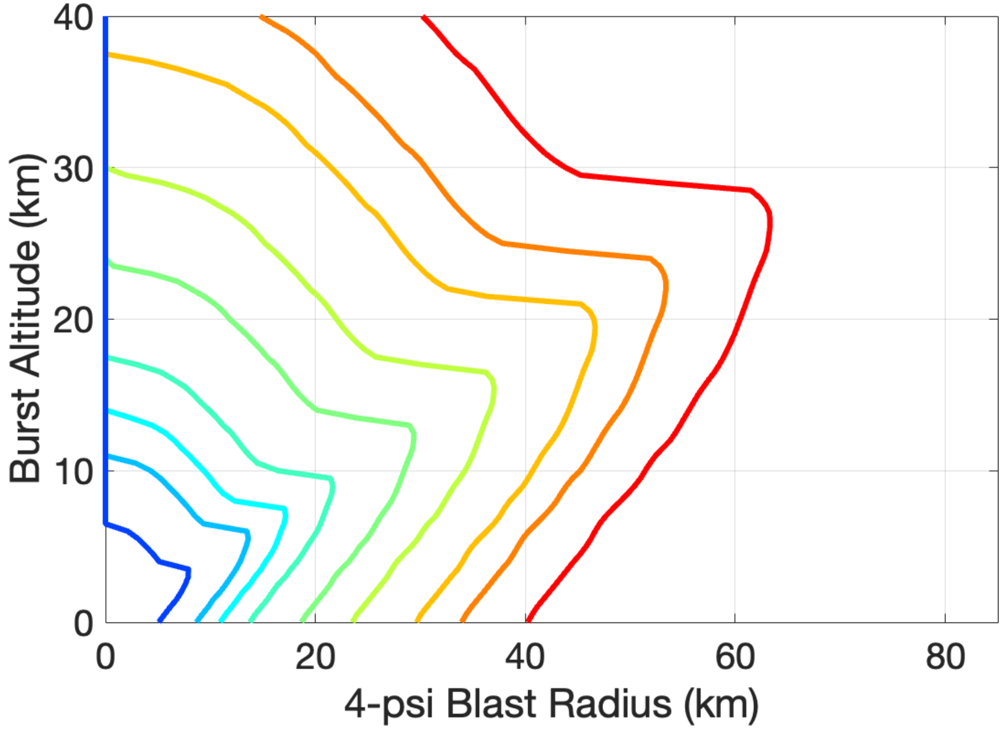
Using the Probabilistic Asteroid Impact Risk (PAIR) model to investigate airburst and blast damage trends across a wide range of asteroid sizes and properties…

- What key blast physics and blast modeling factors are at play?
- What burst altitude ranges are likely for different asteroid sizes?
- How do different blast energy and altitude combinations affect potential ground damage trends?
- What airburst regimes pose the greatest damage risks given the uncertainties in an impact scenario?

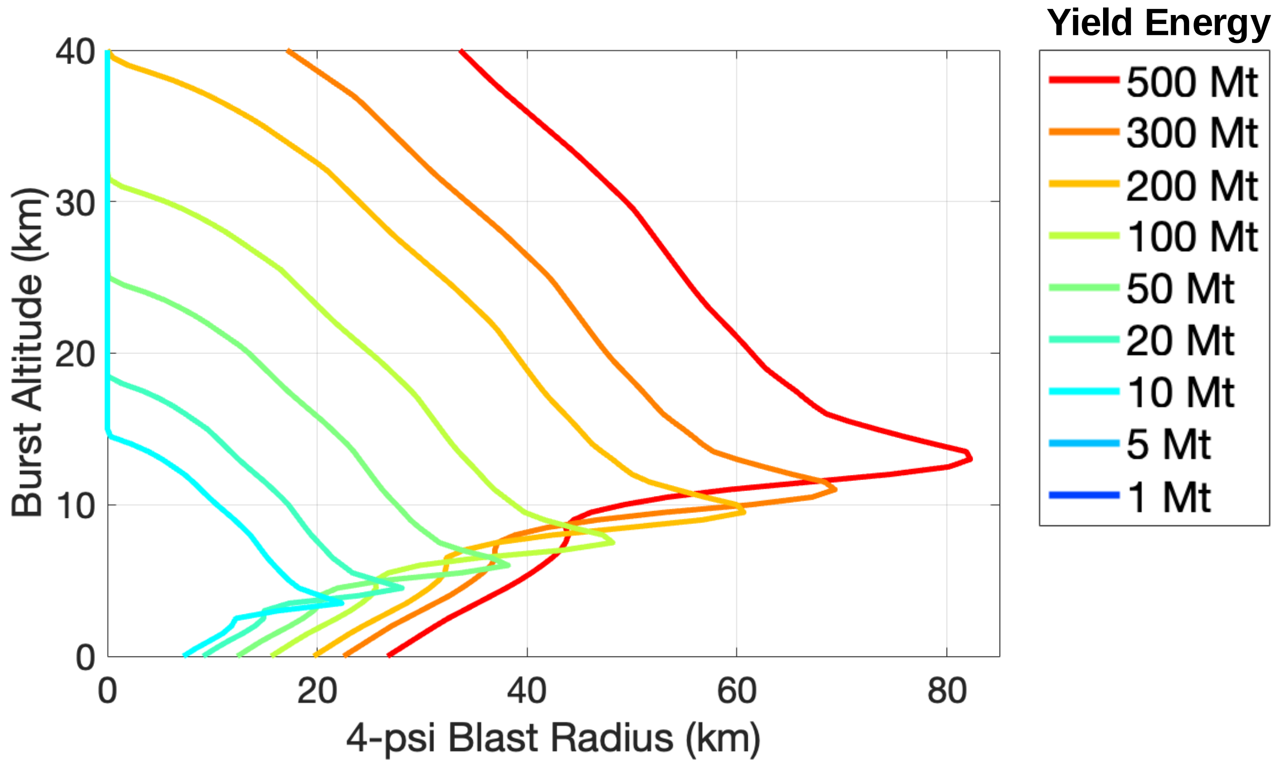
Height-of-Burst (HOB) Maps

HOB maps give ground damage radii as a function of energy (yield) and effective burst altitude.

Nuclear-based HOB maps
used for small yields (<5 Mt) but cannot scale accurately to large yields



CFD Simulation-based HOB maps
used for larger yields (>250 Mt) to account for atmospheric buoyancy effects

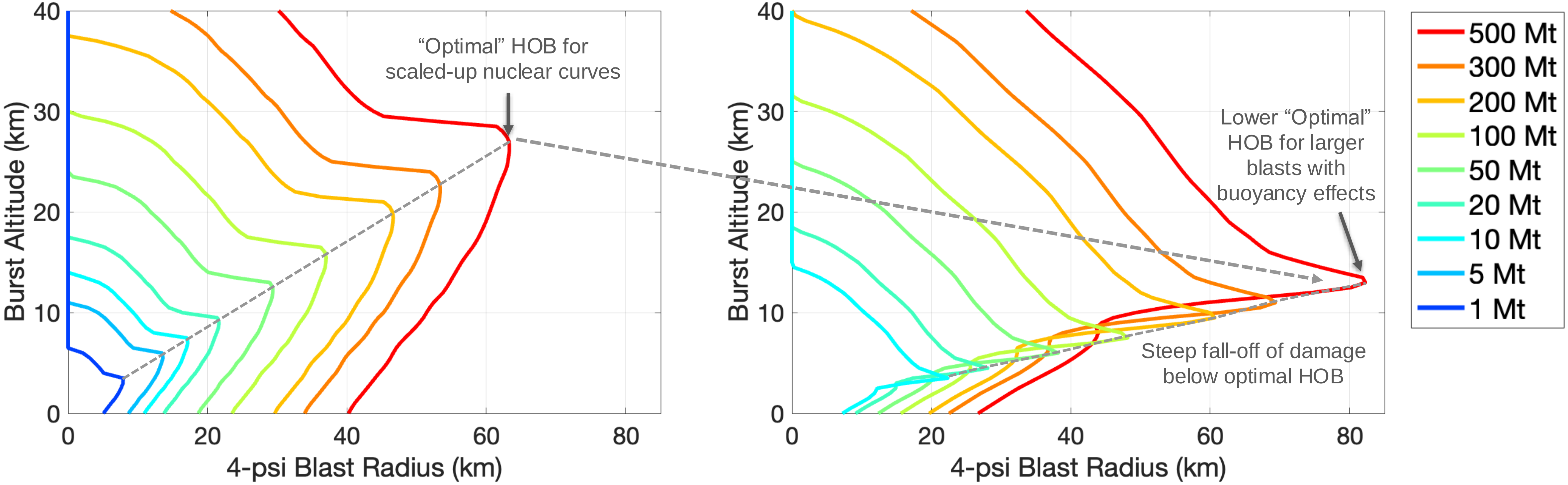


CFD HOB maps: Aftosmis et al., 2019, *Acta Asto*.

“Optimal” Burst Altitudes Cause Biggest Ground Damage

For a given yield energy, there is an “optimal” burst altitude that produces the largest ground radius for a given overpressure level

- Optimal HOB increases with yield energy (larger asteroids must burst higher to do maximal damage)
- Ground damage extent decreases for bursts below the optimal altitude
- Simulation-based HOB maps have lower optimal burst altitudes, larger maximal ground radii, and steeper fall-offs than the scaled-up nuclear curves



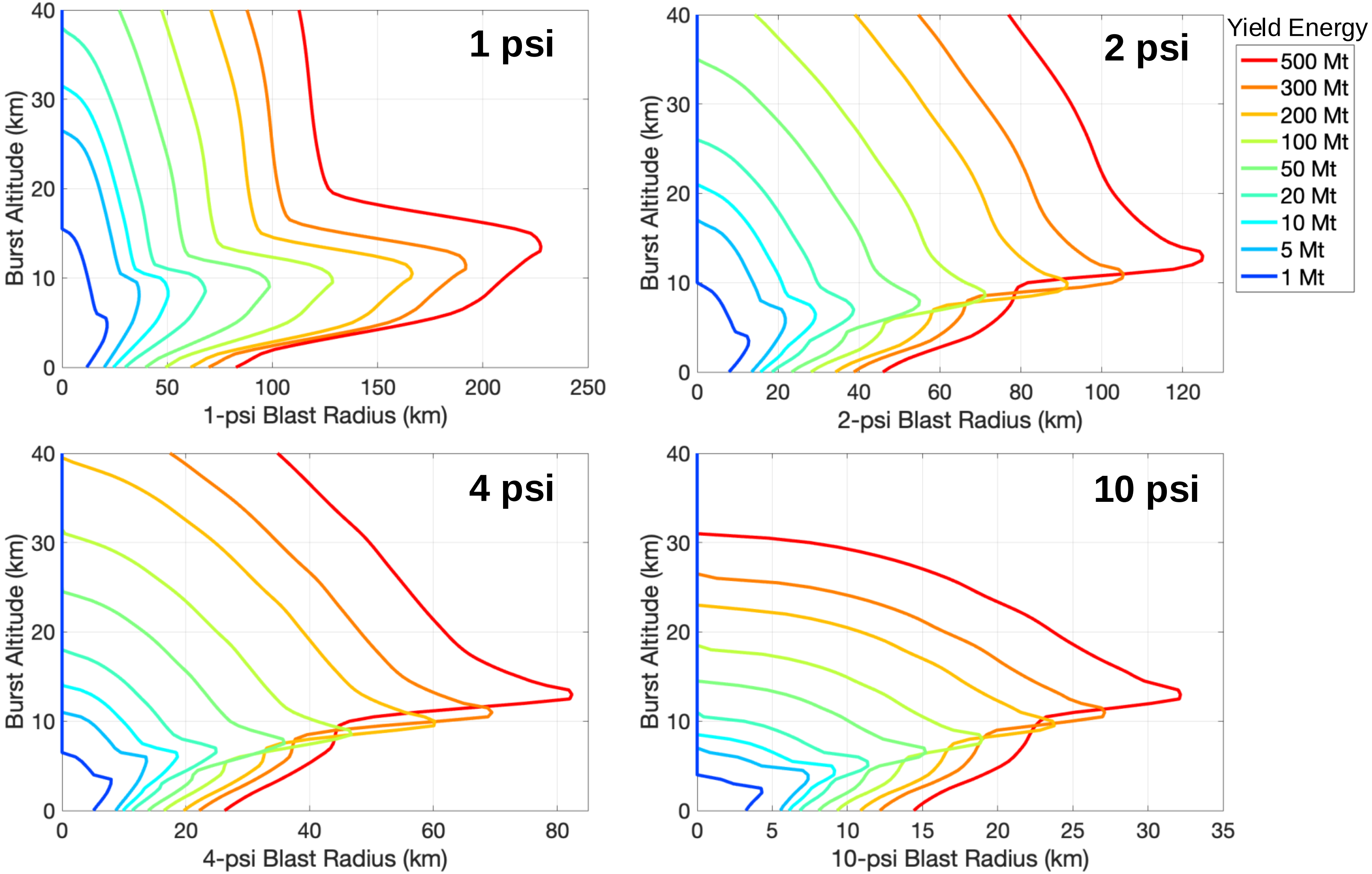
“Optimal” HOB for scaled-up nuclear curves

Lower “Optimal” HOB for larger blasts with buoyancy effects

Steep fall-off of damage below optimal HOB

PAIR Simulation-Enhanced HOB Maps

PAIR HOB maps for four blast overpressure levels

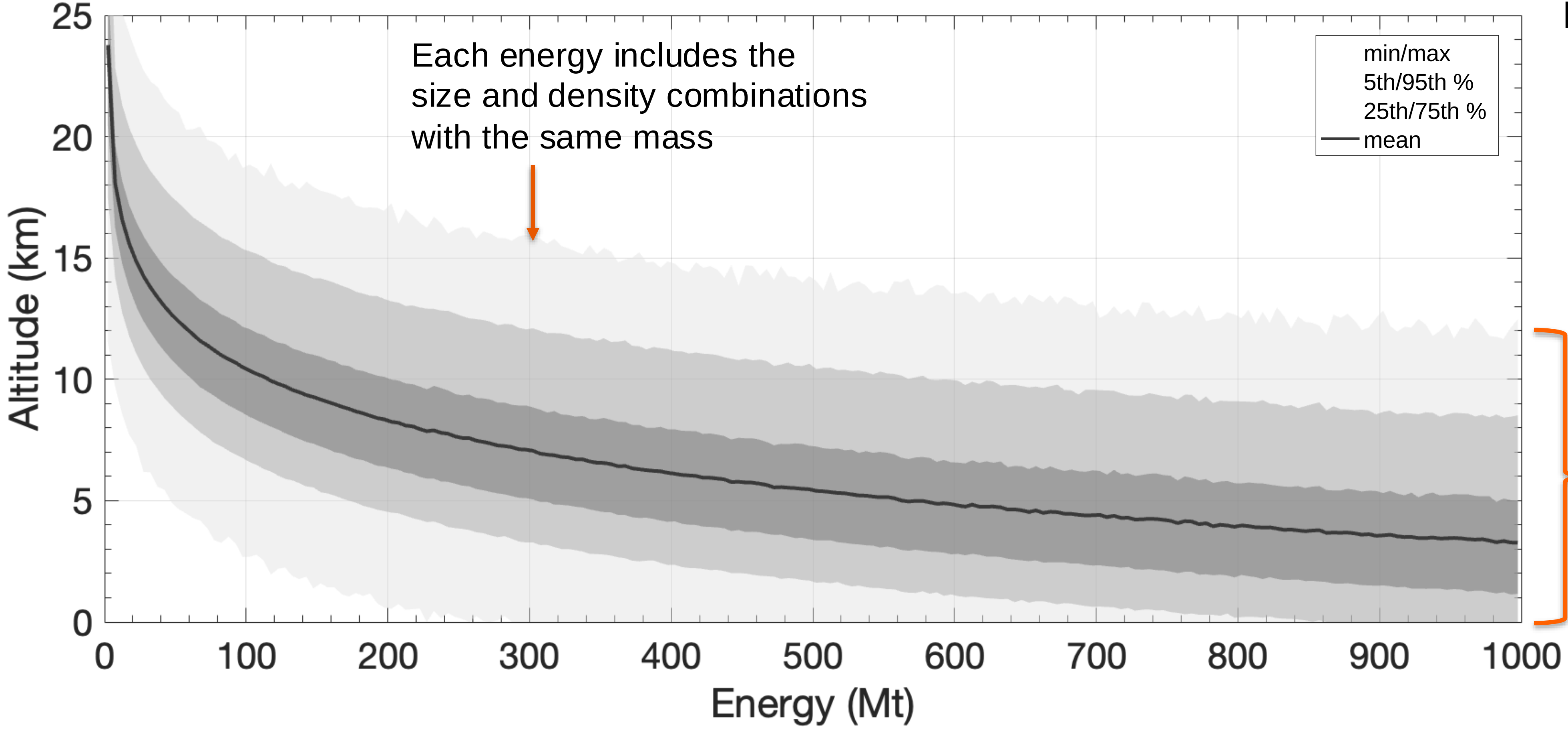


- PAIR uses nuclear curves for E < 5 Mt, simulation curves for E > 250 Mt, and interpolates between them for intermediate energies
- PAIR models blast overpressure at four damage levels ranging from 1 psi (window breakage) to 10 psi (devastation)
- HOB trends differ between blast overpressure levels, with different optimal altitudes and rates of change

Burst Altitude Ranges by Asteroid Energy

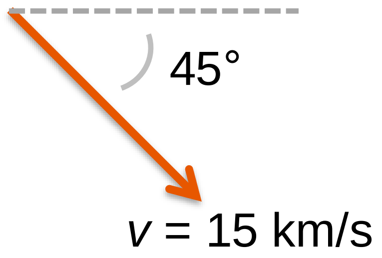
(for a nominal fixed entry at 15 km/s, 45°)

Energy and burst altitude are the two main factors determining blast damage



Each energy includes the size and density combinations with the same mass

Fixed nominal entry:

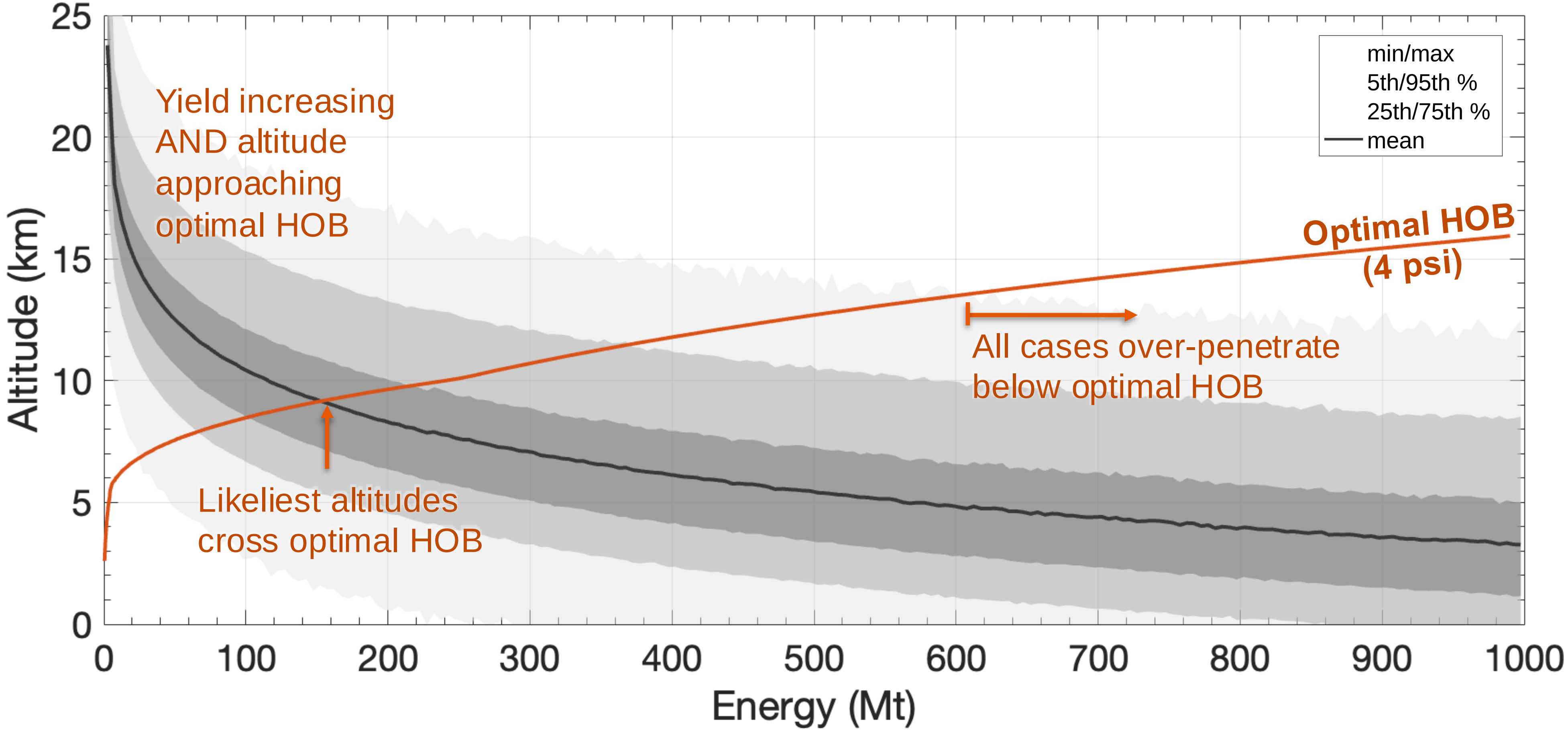


Altitude variations due to distributions of asteroid properties

- Density,
- Strength
- Entry & breakup modeling parameters

Burst Altitude Overlap with Optimal HOB

(PAIR simulation-enhanced HOB for 4 psi overpressure)

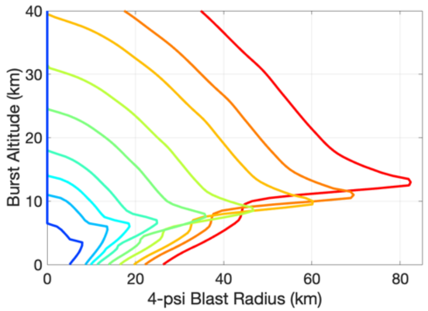


Yield increasing AND altitude approaching optimal HOB

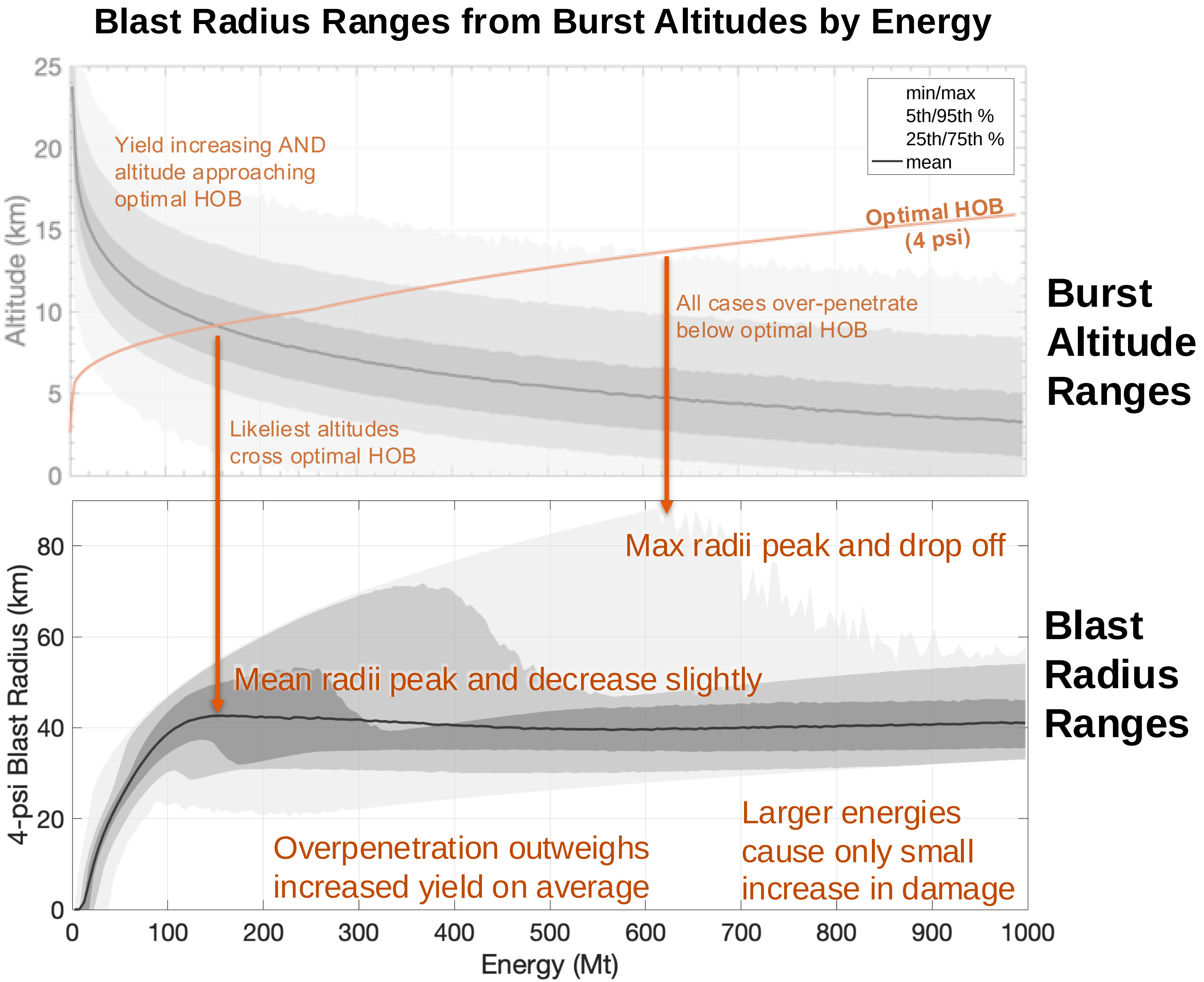
Likeliest altitudes cross optimal HOB

All cases over-penetrate below optimal HOB

PAIR simulation-enhanced HOB for 4 psi overpressure



Optimal HOB Drives Blast Damage Trends



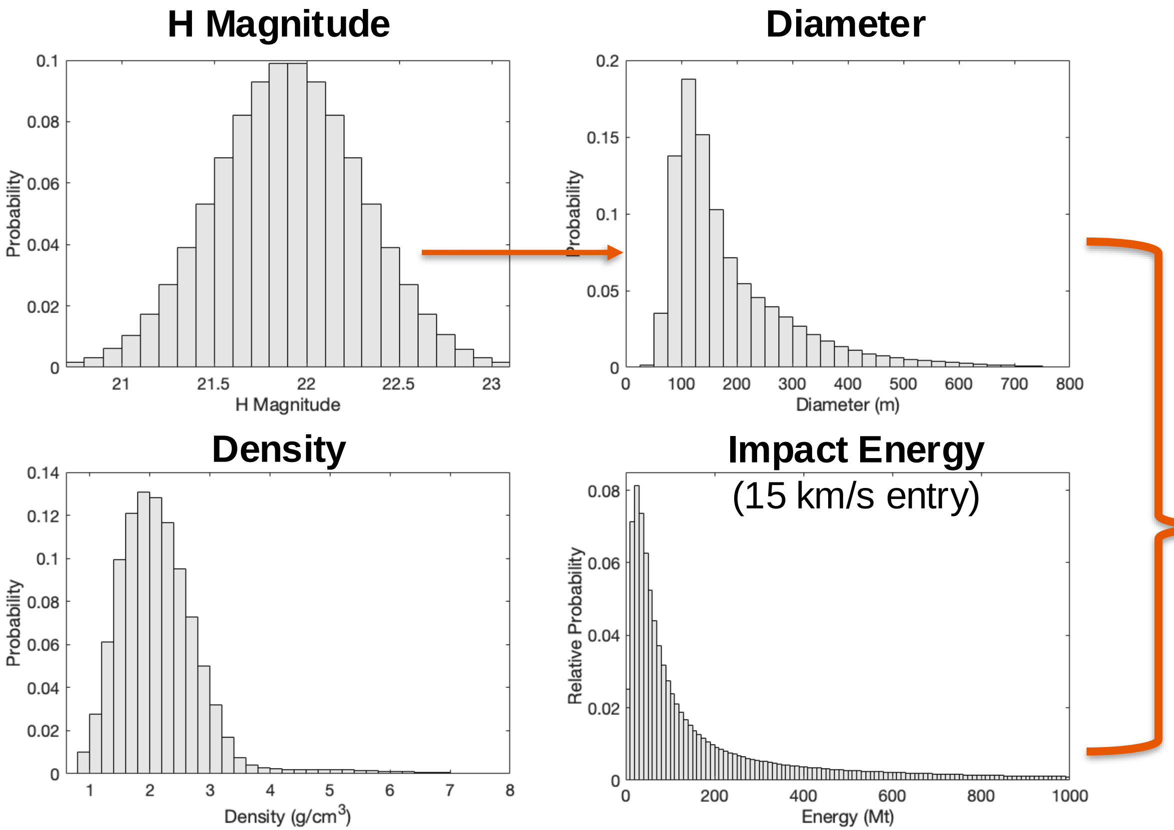
- Damage radius increases rapidly over smaller size ranges where both yield is increasing and burst altitude is approaching optimal HOB
- Mean damage radius peaks where mean burst altitude crosses optimal HOB
- Max radii peak and drop off significantly beyond energies at which all cases over-penetrate below optimal HOB
- Blast radii become less sensitive to increases in energy once most cases over-penetrate or impact ground

Total Damage Risk for an Impact Threat Scenario

H 21.9 object (15 km/s, 45° entry)

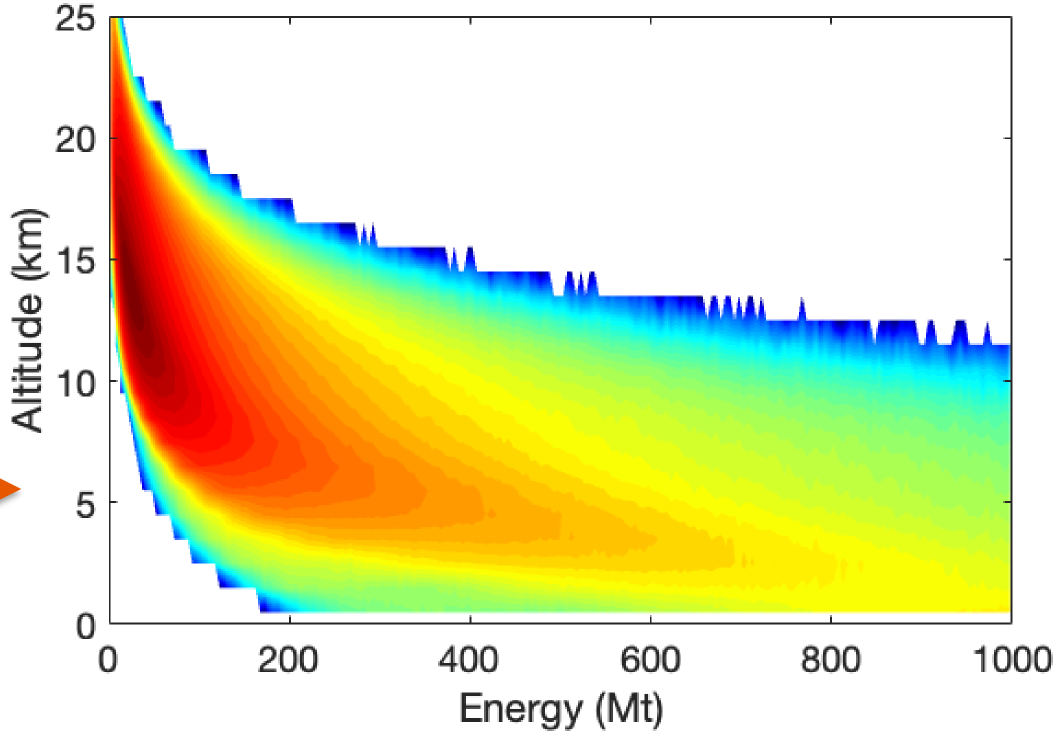
Blast damage risk for an impact threat scenario depends on the relative probabilities of the asteroid's potential size, properties, and resulting airburst behavior.

Property distributions for an H 21.9 asteroid case (no knowledge of type or properties)



Relative Probability of Asteroid Energy and Burst Altitude Occurrence

(15 km/s, 45° entry)

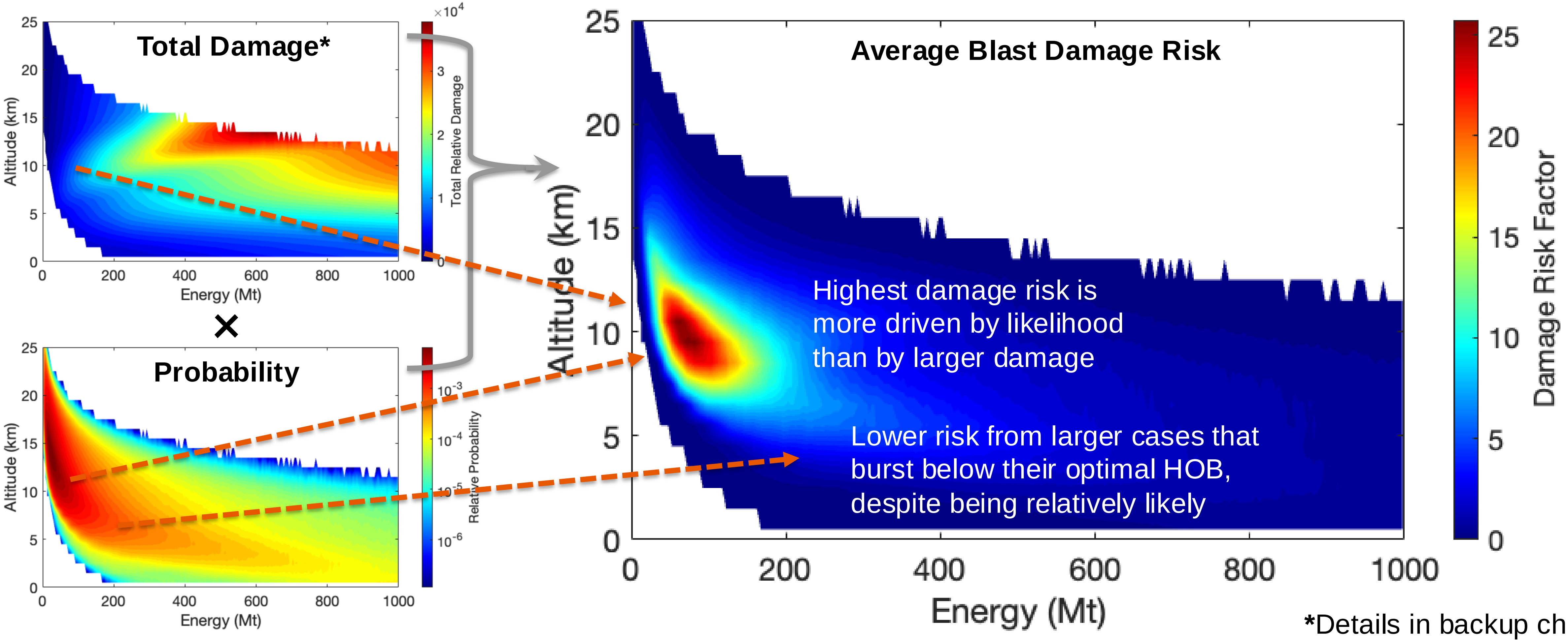


Property characterization: Dotson et al., 2024, *Acta Asto*.

Total Damage Risk for an Impact Threat Scenario

Asteroid size and property probabilities for an H 21.9 object (15 km/s, 45° entry)

Blast damage ***risk*** depends both on the total damage and the probability. Here we compare the average risk from blasts of each energy and altitude, accounting for their relative probability.



Highest damage risk is more driven by likelihood than by larger damage

Lower risk from larger cases that burst below their optimal HOB, despite being relatively likely

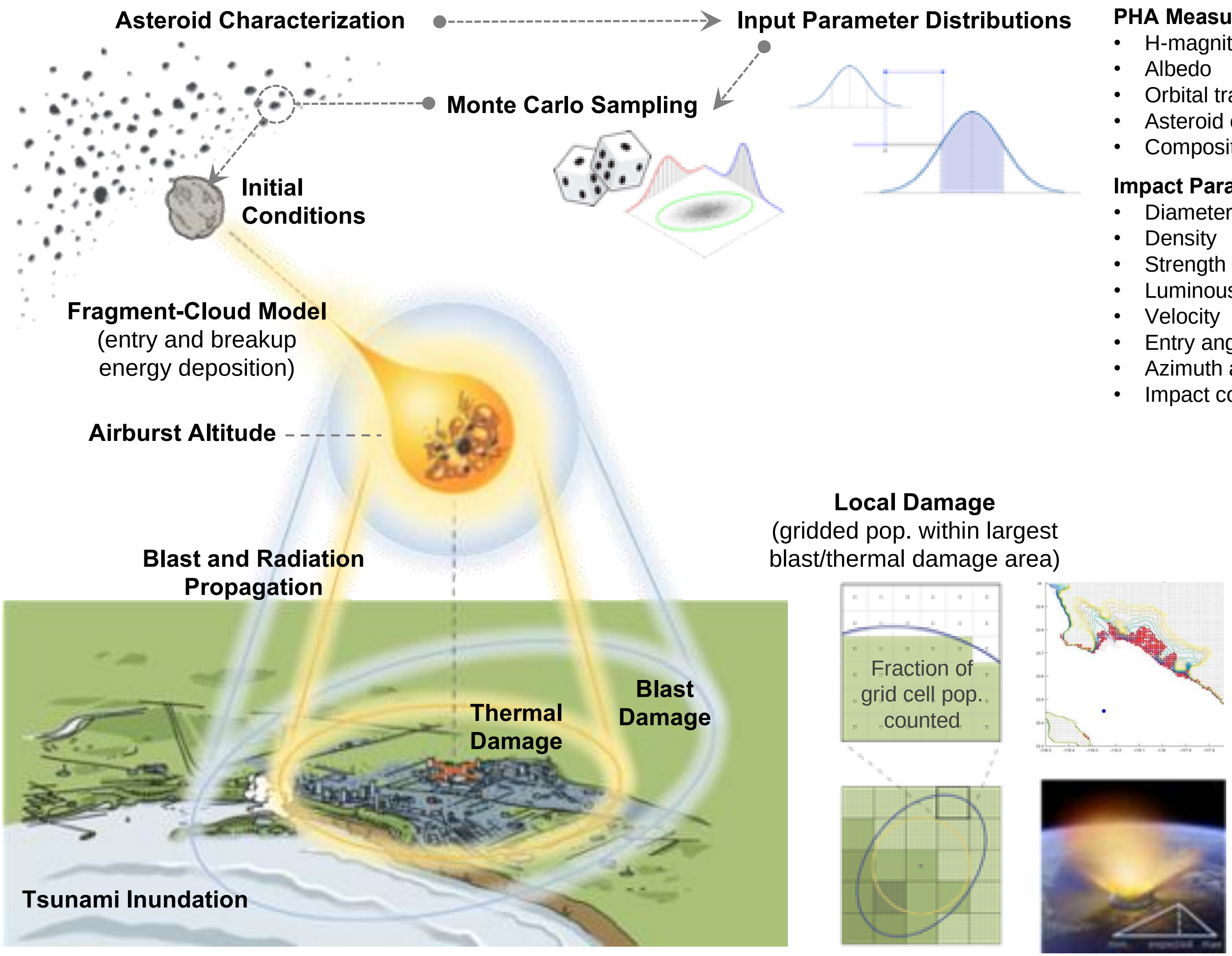
*Details in backup charts

Summary

- Blast damage trends in the current HOB modeling approach depend on the interplay between breakup altitude ranges and optimal burst heights for different energies and overpressure levels
- Small lower-energy impactors tend to burst above their low optimal HOB, while higher-energy impactors tend to over-penetrate below their higher optimal HOB, reducing their damage potential
- For large impactor sizes, the highest burst altitudes cause greater damage than larger, lower bursts or ground impacts, but are also less likely
- Blast damage radii can become much less sensitive to further increases in impactor energy once most cases over-penetrate below optimal HOB or impact ground
- Overall average blast risk levels are driven more by likeliness than by maximum damage potential

BACKUP

Probabilistic Asteroid Impact Risk (PAIR) Model



Asteroid Characterization

Input Parameter Distributions

Monte Carlo Sampling

Initial Conditions

Fragment-Cloud Model
(entry and breakup energy deposition)

Airburst Altitude

Blast and Radiation Propagation

Thermal Damage

Blast Damage

Tsunami Inundation

PHA Measurements

- H-magnitude
- Albedo
- Orbital trajectory
- Asteroid class
- Composition

Impact Parameters

- Diameter
- Density
- Strength
- Luminous efficiency
- Velocity
- Entry angle
- Azimuth angle
- Impact coordinates

Local Damage
(gridded pop. within largest blast/thermal damage area)

Fraction of grid cell pop. counted

Tsunami
(gridded pop. affected within inundated areas)

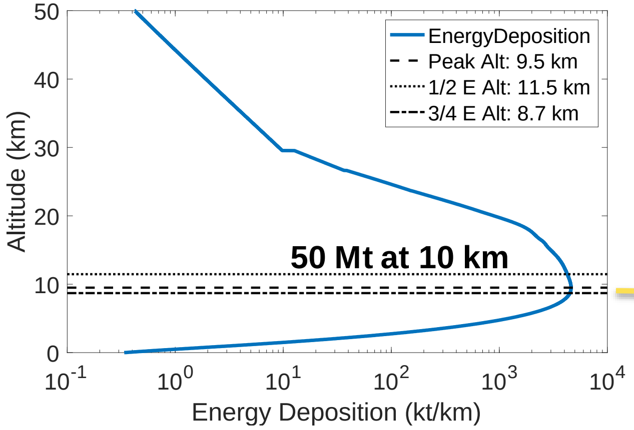
Global Effects
(% world pop. affected by climatic effects)

- PAIR uses fast-running engineering models of asteroid entry and damage to assess impact risk for millions of sampled asteroid impact cases with uncertain properties (Mathias et al., 2017)
- Asteroid properties are sampled using inference model based on current knowledge of general asteroid populations and any specific observational data for a given impact scenario (J. Dotson, PDC 2021)
- Entry parameters and locations are determined from orbital propagation models (P. Chodas, CNEOS/JPL)
- Modeling parameters are sampled over uncertainty ranges to represent model uncertainties or variability of entry/damage outcomes

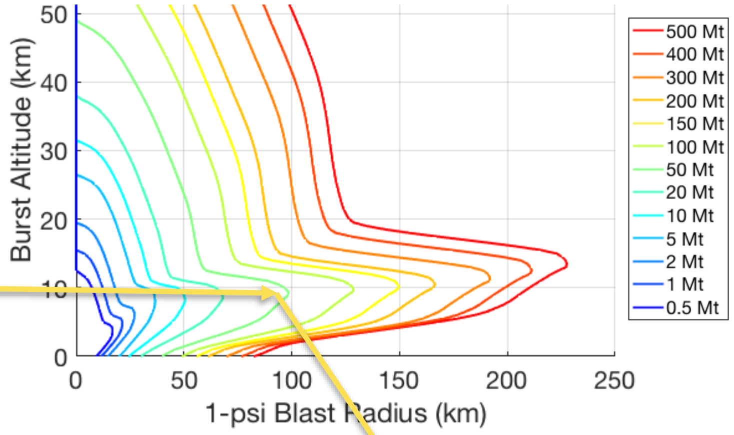
PAIR Blast Damage Modeling Overview

PAIR evaluates blast damage at four severity levels, and each level affects different fractions of the population within that region

Atmospheric Energy Deposition



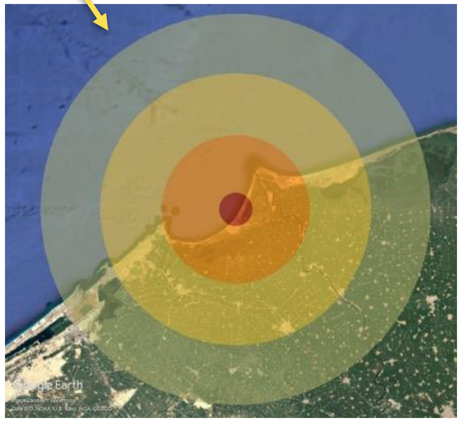
Height-of-Burst (HOB) Map



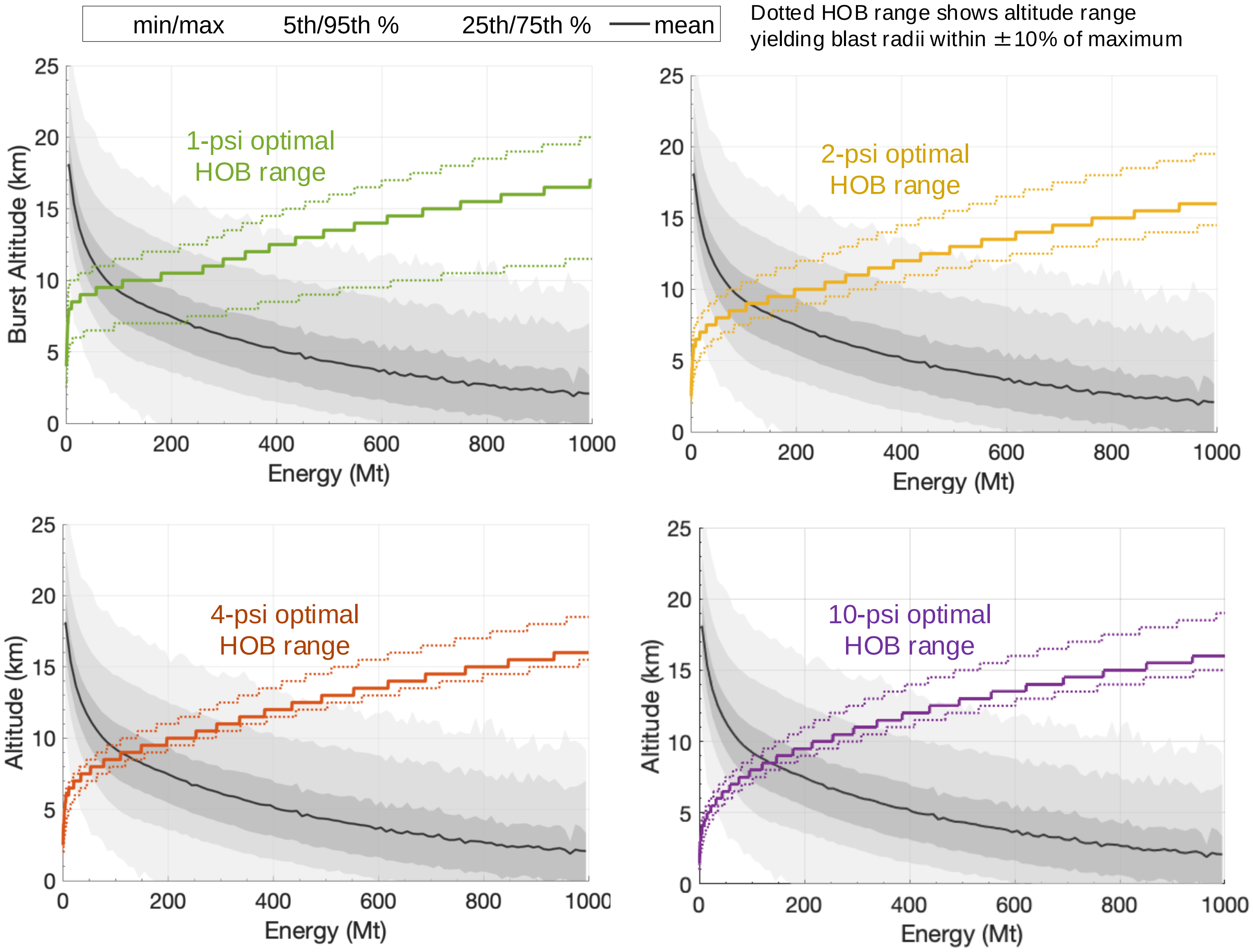
- Fragment-Cloud Model (FCM) is used to model atmospheric entry and breakup of each probabilistic impact case
- Entry/breakup depend on sampled size, density, strength, entry velocity and angle, and breakup modeling parameters
- Effective burst altitudes or ground impact are determined from FCM energy deposition peak or energy fraction (peak used here)
- Height-of-burst (HOB) maps are used to estimate blast footprint sizes based on impactor energy and effective burst altitude

PAIR Blast Damage Severity Levels (Stokes et al., 2017)

Damage Level	Overpressure Threshold	Population Fraction	Damage Severity
Serious	1 psi	10%	Window breakage, some structure damage
Severe	2 psi	30%	Widespread structural damage
Critical	4 psi	60%	Most residential structures collapse
Unsurvivable	10 psi	100%	Complete devastation



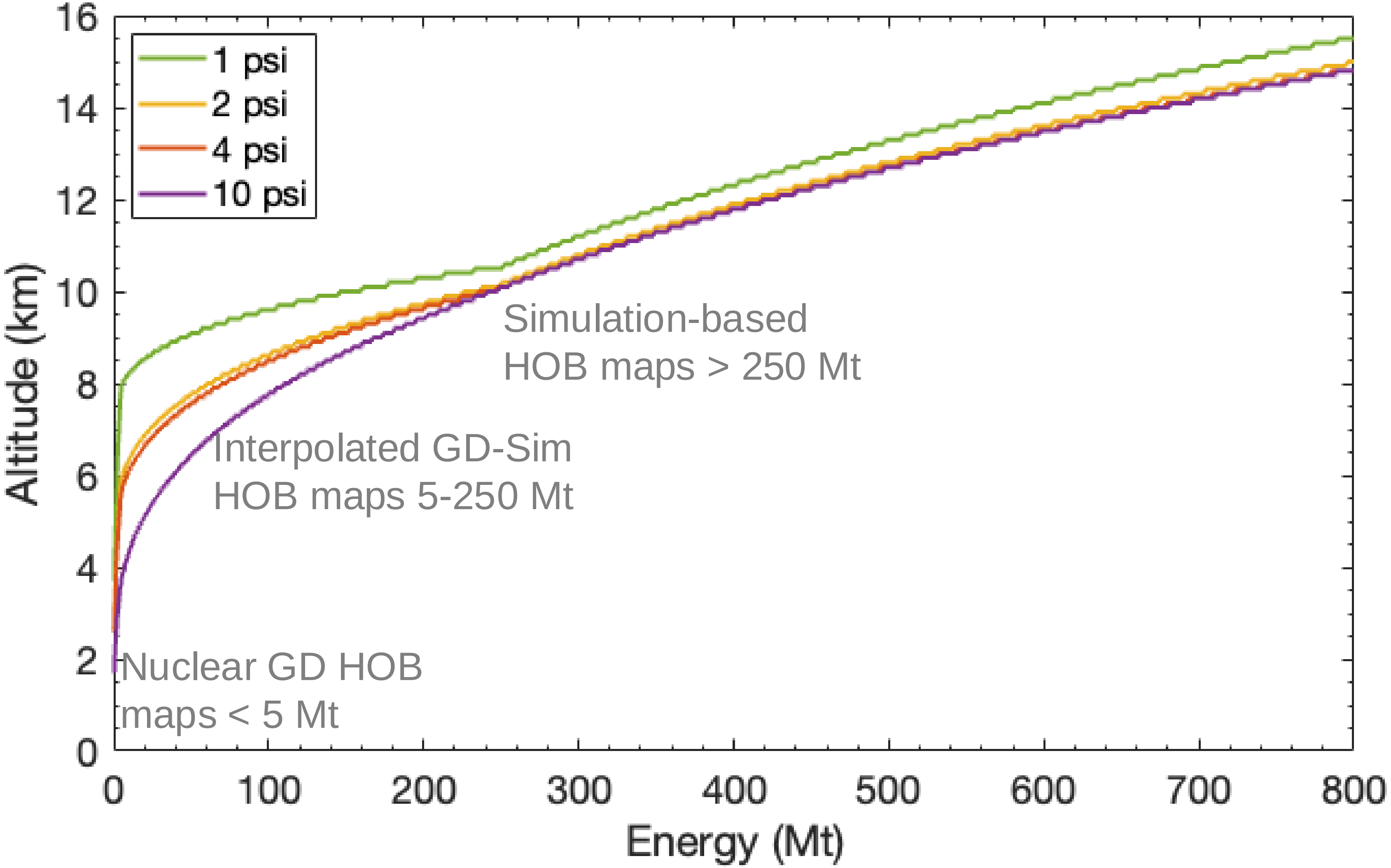
Burst Altitudes vs Optimal HOB



Dotted HOB range shows altitude range yielding blast radii within ±10% of maximum

- Blast damage is driven by two competing factors:
  - Increases in blast yield
  - Distance from optimal HOB
- Smaller/lower-energy objects tend to burst above their optimal HOB, making lower bursts worse
- Larger/higher-energy objects tend to over-penetrate below their optimal HOB, making higher bursts worse
- Airburst sensitivities and trends depend on crossover between the likely burst altitudes and the “optimal” HOB as larger objects penetrate lower in atmosphere

Optimal HOB by energy from PAIR blast model



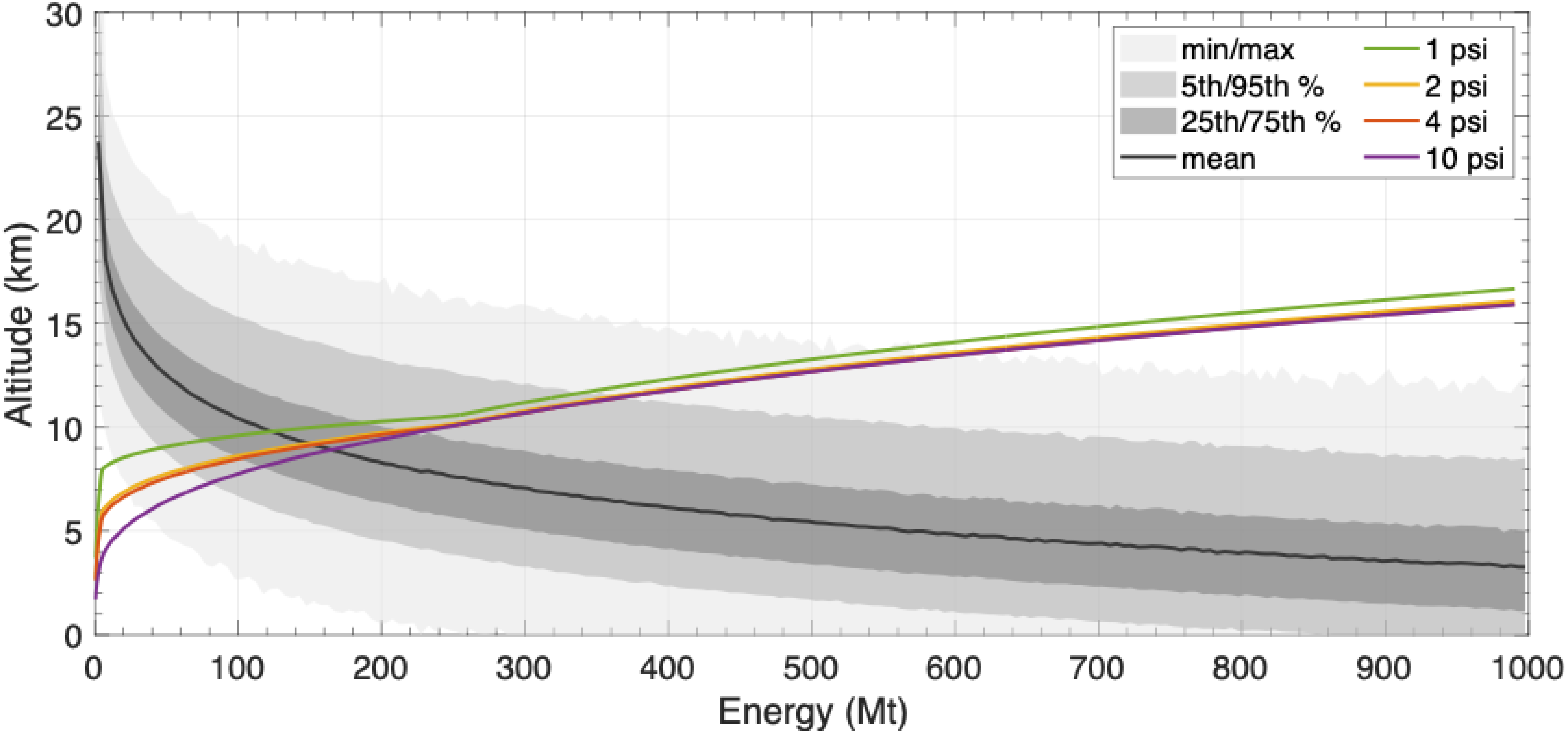
Simulation-based HOB maps > 250 Mt

Interpolated GD-Sim HOB maps 5-250 Mt

Nuclear GD HOB maps < 5 Mt

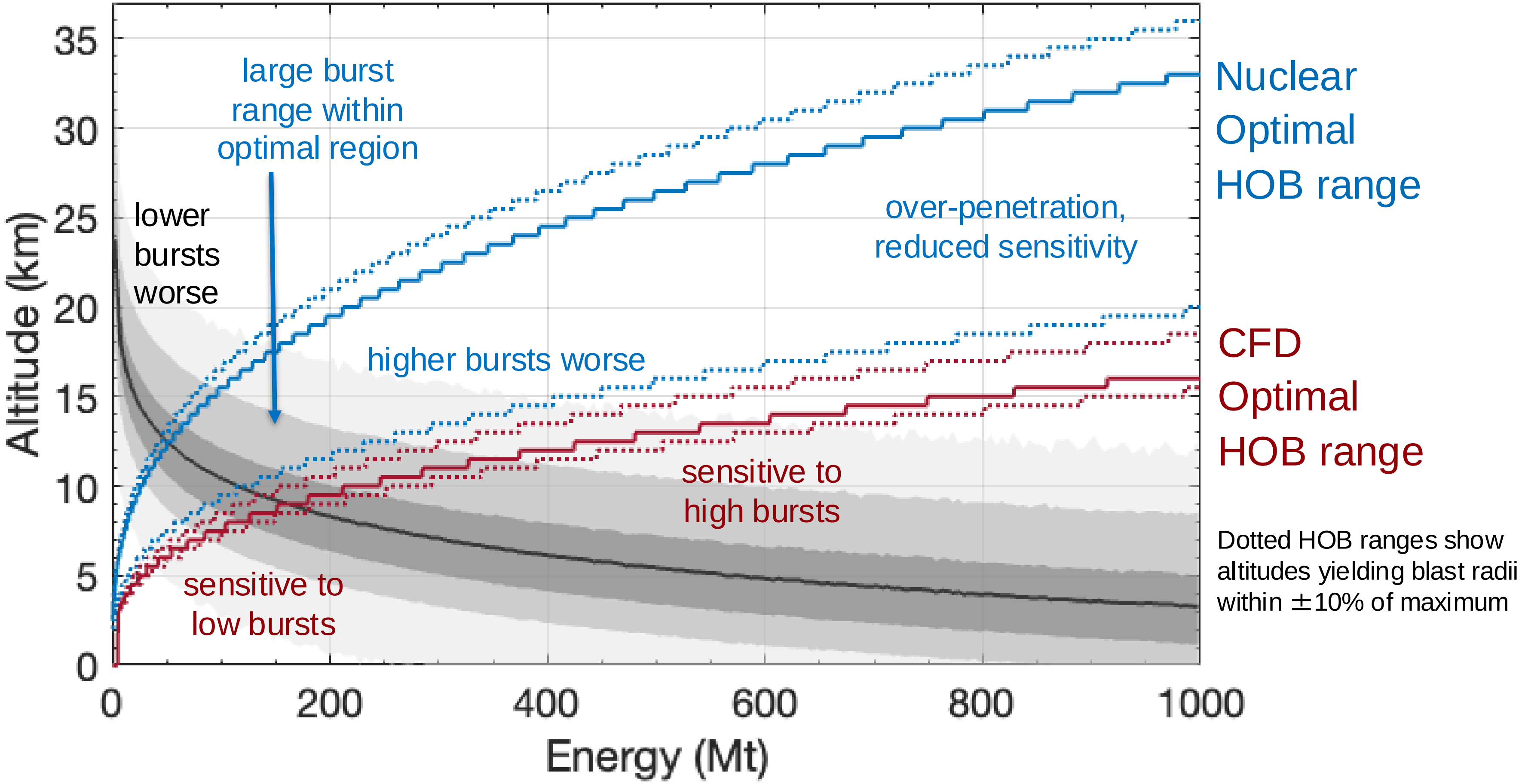
- Airburst altitude causing largest ground damage radius for each blast damage level
- Lower energies have larger spread in optimal altitudes for the different overpressure severities
- Larger energies have less spread.

Burst Altitudes vs Optimal HOBs



Nuclear vs. CFD Optimal Burst Altitudes (4 psi)

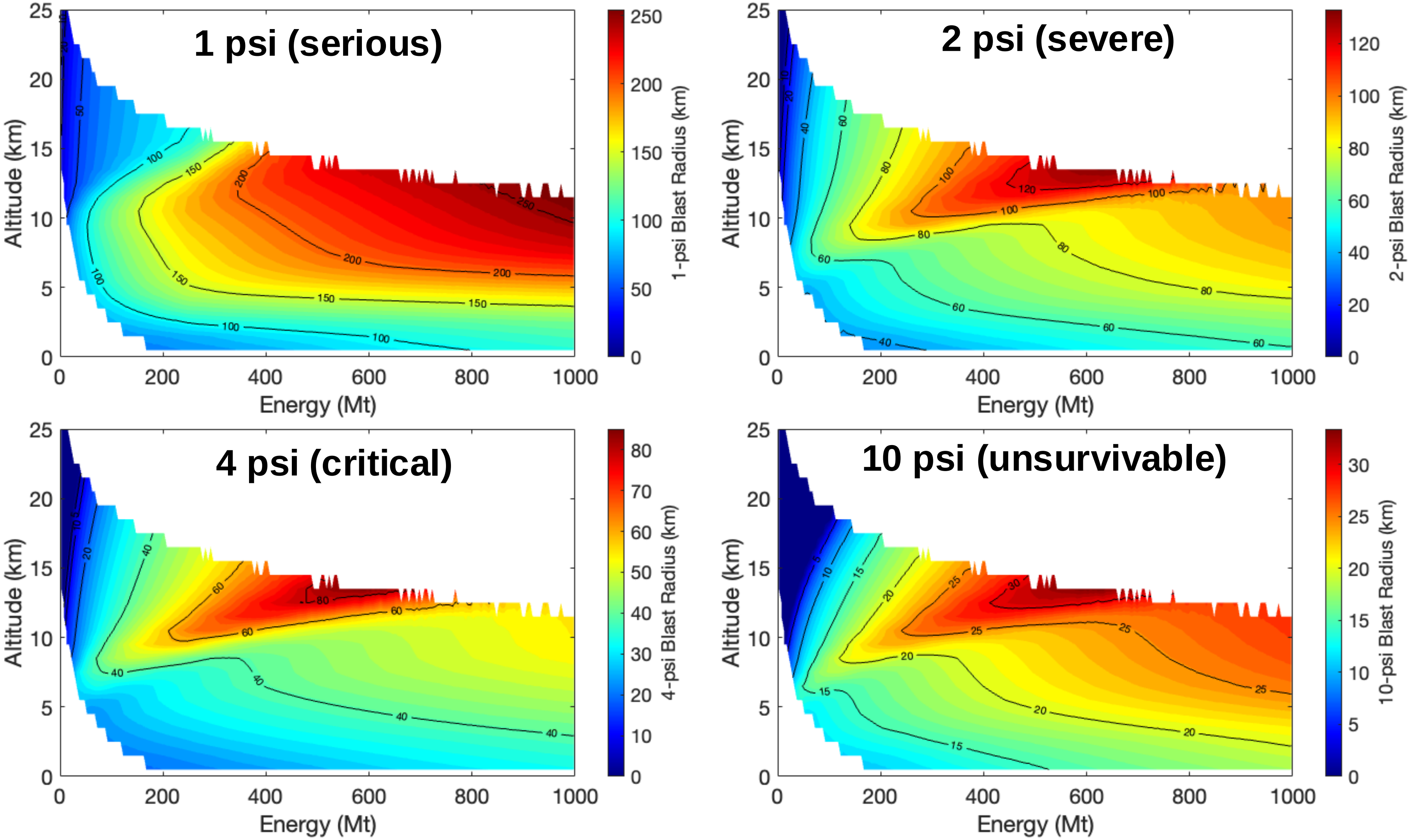
Sensitivity to strength and breakup factors depends upon how the resulting burst altitudes coincide with optimal burst altitude for different yield energies.



Dotted HOB ranges show altitudes yielding blast radii within ±10% of maximum

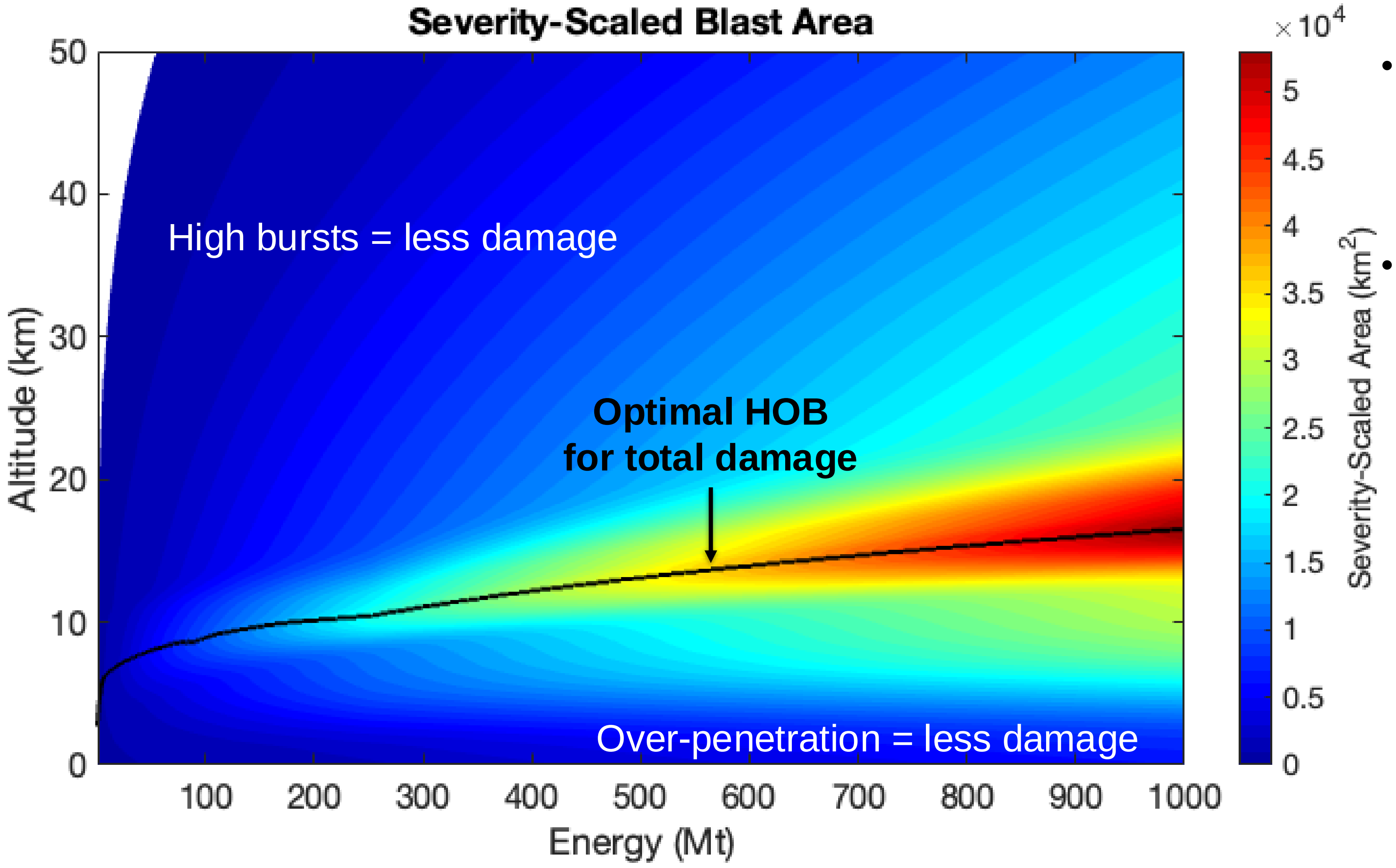
- Sensitive regions differ between nuclear HOB maps and CFD-based HOB maps for larger yields.
- Nuclear curves have higher, broader optimal altitude ranges
- Simulation-based curves have lower, narrower optimal range

Blast Radii vs Burst Altitude & Energy



- Damage trends differ among blast levels due to different forms of their HOB curves
- Largest 1-psi damage radii are produced by a broader range of larger energies at their highest possible burst altitudes
- Largest 2, 4, and 10 psi damage radii occur for energies ~400-600 Mt bursting near their highest altitudes, and are smaller for larger energies

Total Blast Damage by Energy & Altitude



- Severity-scaled damage area indicates the total damage from all blast levels, scaled by their relative severity and area
- Sum of each blast level area scaled by relative severity:
  - 10% 1 psi (serious) area
  - 30% 2 psi (severe) area
  - 60% 4 psi (critical) area
  - 100% 10 psi (unsurvivable) area

$$A_s = 0.1(A_{1psi}) + 0.3(A_{2psi}) \\ +0.6(A_{4psi}) + 1(A_{10psi})$$

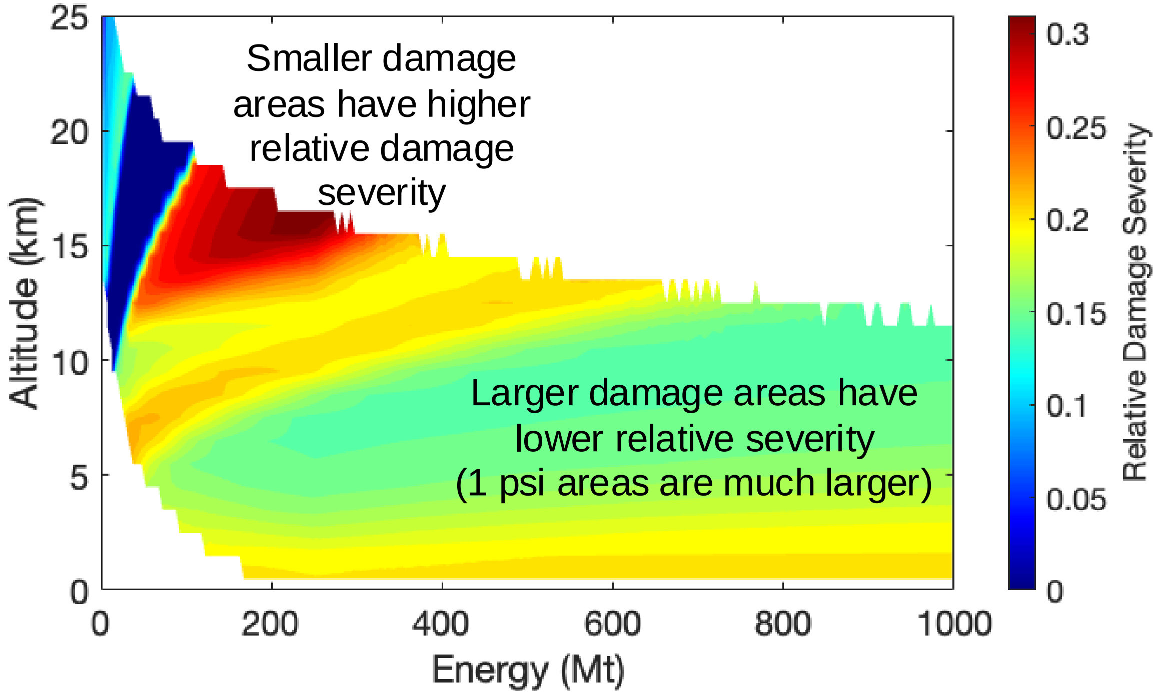
HYPOTHETICAL EXERCISE

Combined Total Blast Damage & Severities

Total blast damage depends on the combined relative sizes and severities of all blast overpressure levels within the damage regions. Here we compare the average severity levels and total effective ground damage.

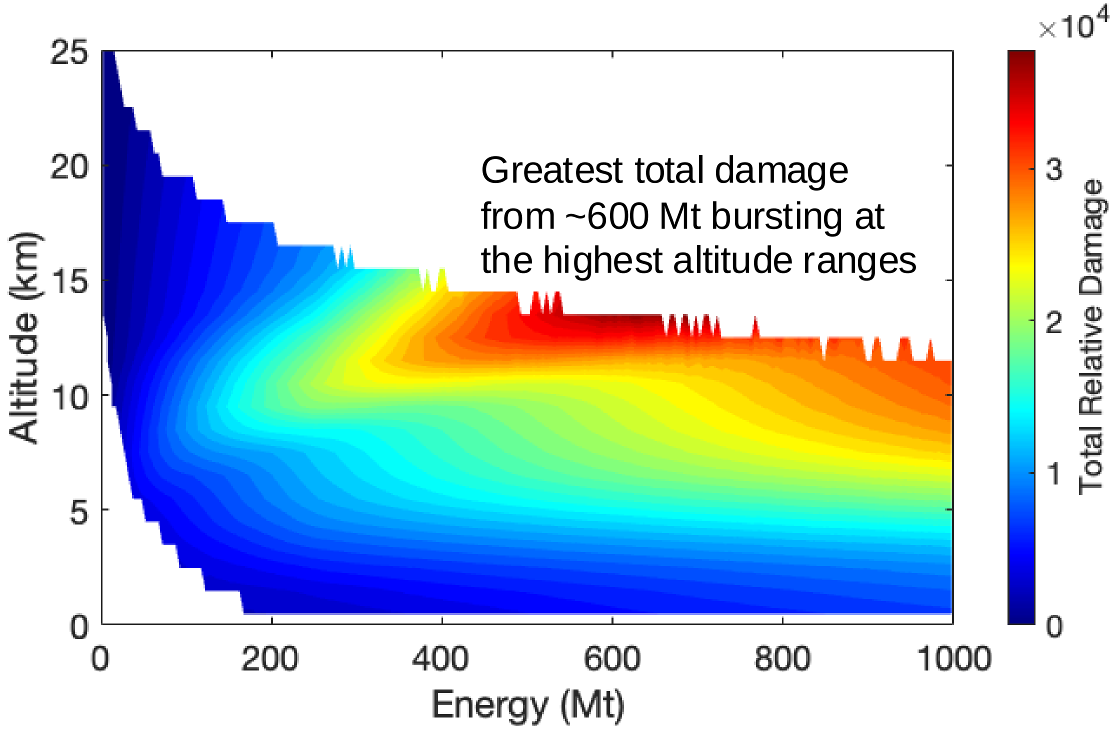
Average damage severity

Represents the area-weighted average severity of the four modeled overpressure levels within the total area



Effective severity-scaled damage areas

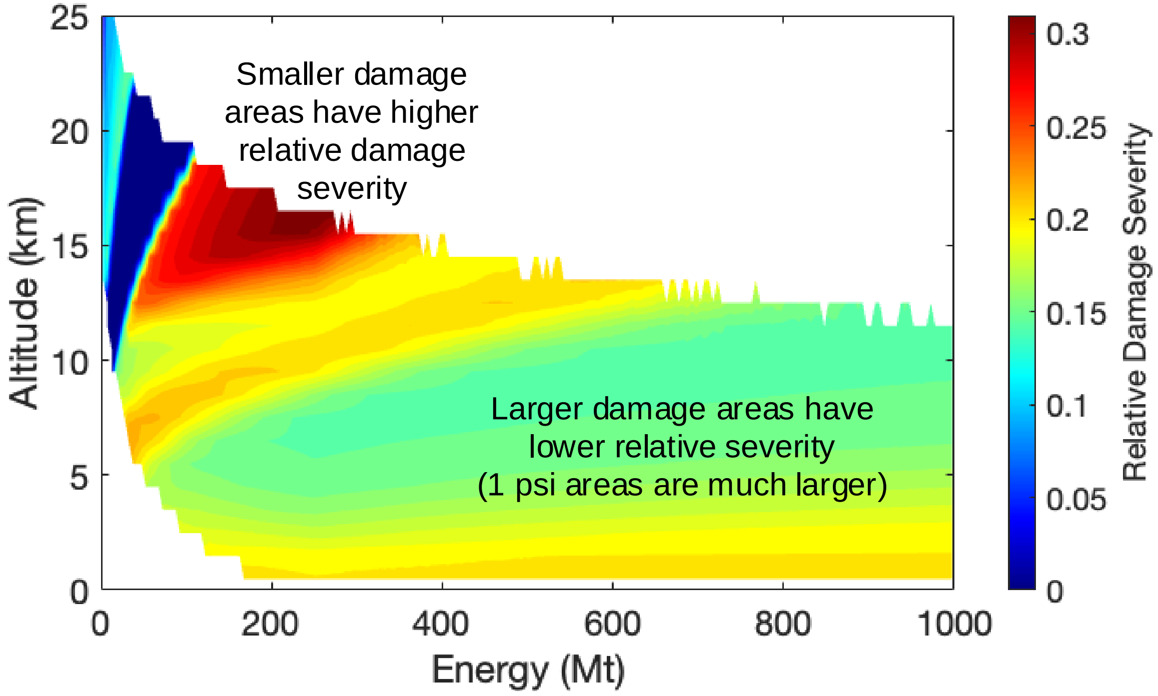
Represents total damage as the damage area scaled by the relative severity from all blast levels



Combined Total Blast Damage & Severities

Total blast damage depends on the combined relative sizes and severities of all blast overpressure levels within the damage regions. Here we compare the average severity levels and total effective ground damage.

Average damage severity as a function of burst energy and altitude

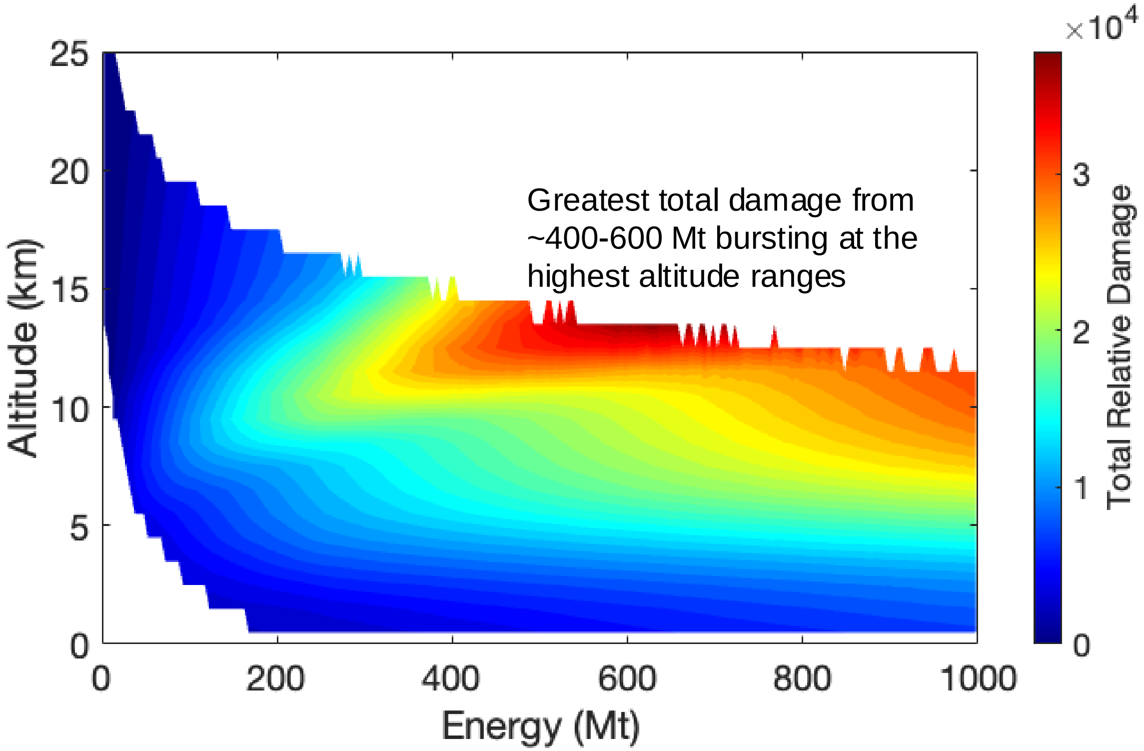


- Damage severity levels:
  - 10% damage in 1-psi area, 30% damage in 2-psi area, 60% damage in 4-psi area, 100% damage in 10-psi area
- Average damage severity factor:
  - Represents the area-weighted average severity of the four modeled overpressure levels within the total area
  - Does not reflect total footprint size, just average severity
- Damage severity trends
  - On average, highest damage severities are caused by ~200-Mt bursts at their highest altitude range ~15 km
  - For larger/lower blasts, lower-psi damage areas grow more than higher-psi areas, leading to lower average severities

Combined Total Blast Damage & Severities

Total blast damage depends on the combined relative sizes and severities of all blast overpressure levels within the damage regions. Here we compare the average severity levels and total effective ground damage.

Average effective damage areas as a function of burst energy and altitude



- Damage severity levels:
  - 10% damage in 1-psi area, 30% damage in 2-psi area, 60% damage in 4-psi area, 100% damage in 10-psi area
- Effective damage area:
  - Represents each case’s aggregate total amount of ground damage from all fractional damage levels
  - Equivalent 100% damage area (sum of each damage level area scaled by its relative damage fraction)
  - Given a uniform population density, then this would be the area that would contain the total affected population
- Effective damage area trends:
  - On average, mid-range energies can cause greater total damage than larger ground impacts if they breakup high
  - However, these maximal burst altitudes are also unlikely for large asteroids in that energy range

Abstract

Blast overpressure from a high-energy airburst or surface impact is the primary source of damage from potentially hazardous asteroid strikes. There are many sources of uncertainty in evaluating these potential damage risks, both in the approaches used to model the entry, breakup, and airburst behaviors of diverse asteroid properties, and in the blast modeling approaches used to estimate the ground damage from these very large-scale, high-energy events.

In this study, we use NASA’s Probabilistic Asteroid Impact Risk (PAIR) model to investigate trends and sensitivities in asteroid airburst altitudes and the resulting blast damage estimates across a range of asteroid sizes. In particular, we show how uncertainties in asteroid breakup behavior and effective airburst altitudes combine with height-of-burst (HOB) blast damage models to produce key sensitivities and trends in the amount of damage expected from different asteroid sizes and airburst altitudes.

We show airburst altitude ranges and probabilities stemming from asteroid entry and breakup modeling uncertainties, compare differences between traditional nuclear-based HOB blast models and simulation-based HOB models for larger asteroid energies, and show how the resulting interplay between likely burst altitudes and optimal burst heights affects blast damage trends across different asteroid sizes. Finally, we combine the relative likelihoods of asteroid sizes, airburst altitudes, and resulting blast damage severity to evaluate what airburst regimes pose the highest overall level of risk (when considering both the relative likelihood and scale of potential damage) for a mid-sized asteroid threat scenario. Results show what asteroid size regimes are most sensitive to airburst and blast modeling uncertainties, provide insight into nonintuitive trends in the size and severity of blast damage expected from different airburst events, and highlight where additional blast modeling studies or refinements may help improve future impact risk estimates.

PLAIN LANGUAGE SUMMARY:

This study uses a probabilistic asteroid impact risk model to assess the potential airburst altitudes and blast damage from millions of asteroid impact cases with varied sizes and properties. Results are used to investigate sensitivities and trends in the blast damage arising from uncertainties in airburst altitude modeling and blast modeling across a range of asteroid sizes.

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Probabilistic Asteroid Impact Risk (PAIR) Model

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Asteroid Property Characterization

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CFD Blast Simulations and HOB Model

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