

# Asteroid Impact Risk Assessment: Weighing the Potential Damage

**Lorien Wheeler**

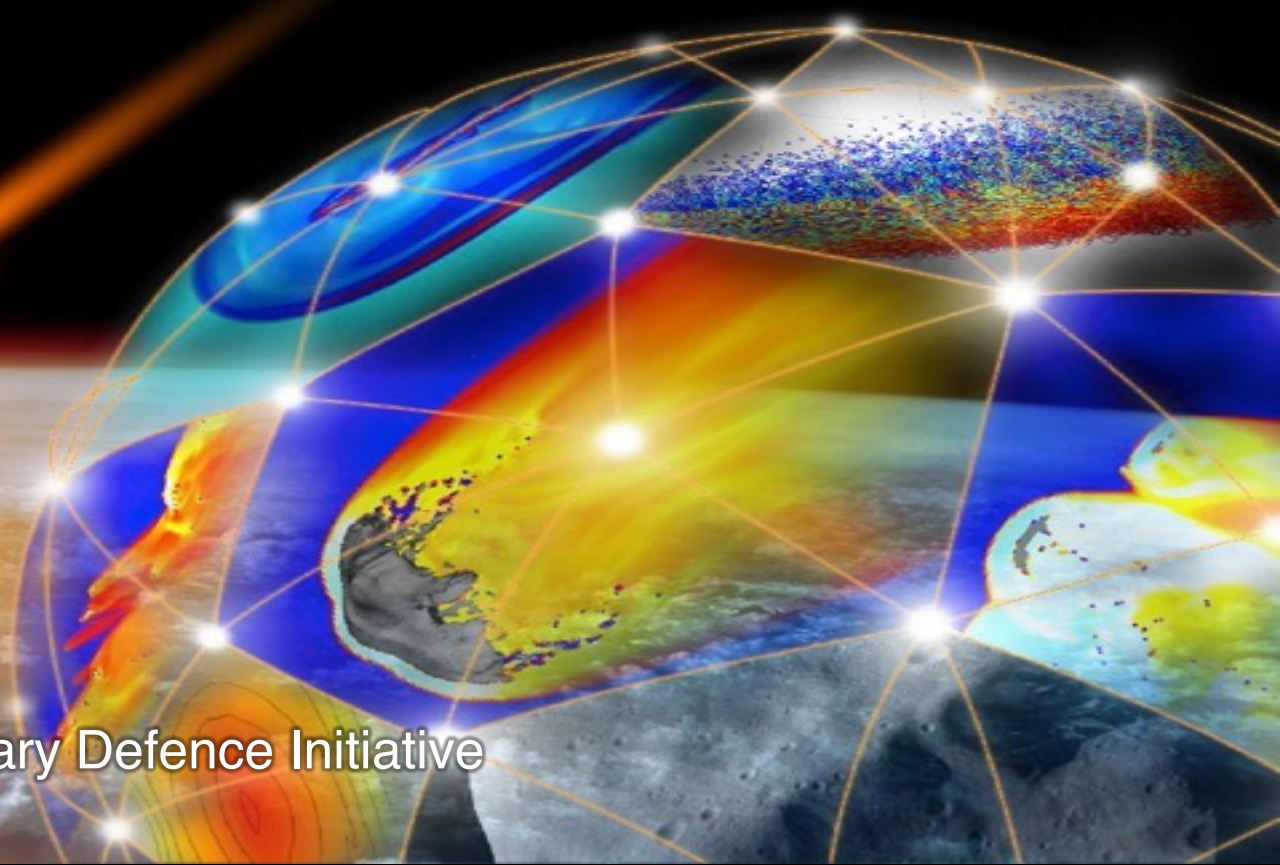
**Asteroid Threat Assessment Project (ATAP)**

NASA Ames Research Center

International Asteroid Day 2025

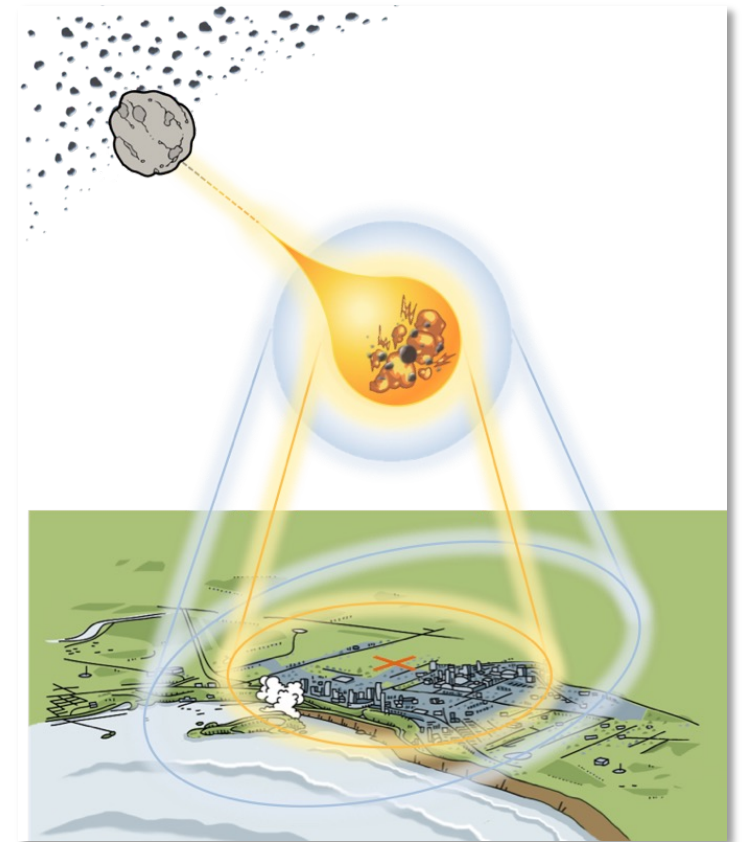
Afternoon with the Avengers: Our Real-World Planetary Defence Initiative

30 June 2025, Cranfield University, UK

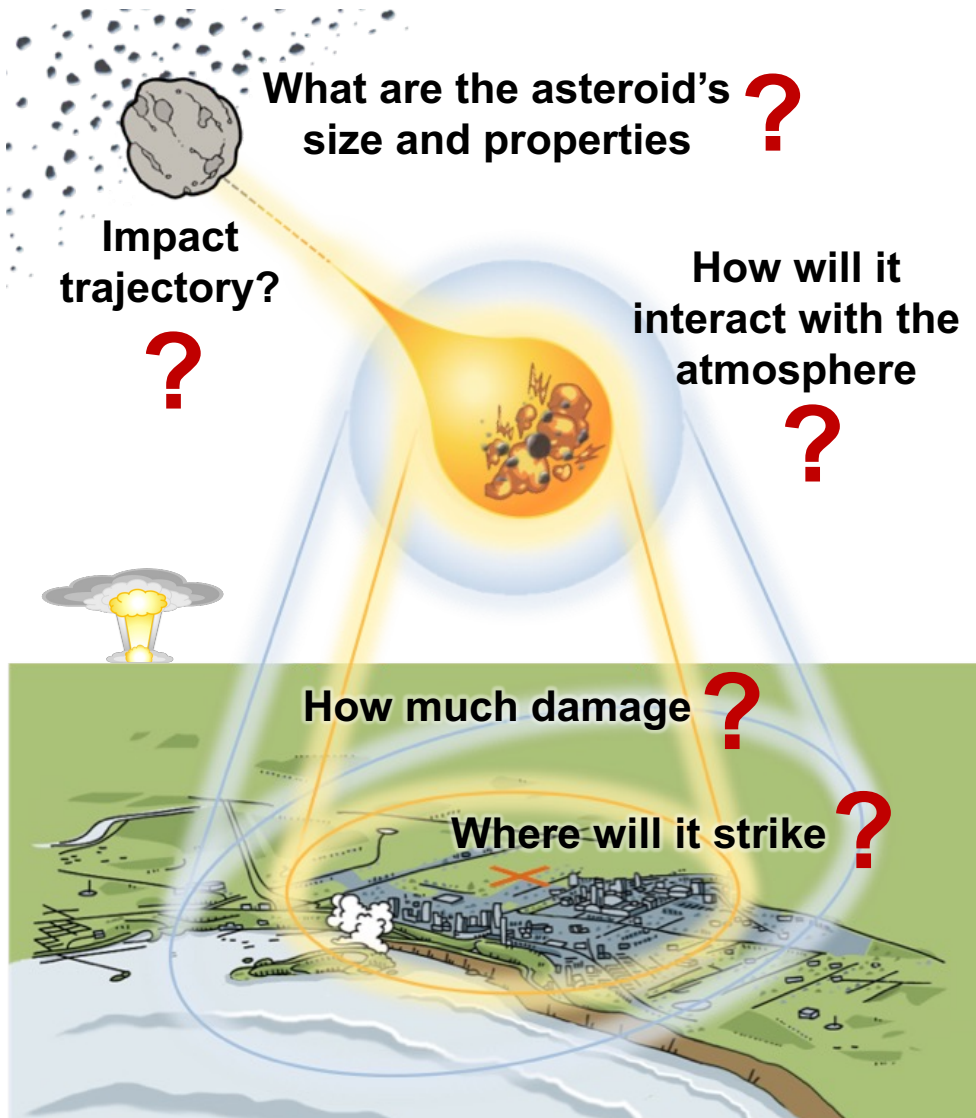


# Overview

- Asteroid impact risk assessment
- Impact hazards and damage effects
- Asteroid property & damage uncertainties
- Risk assessment modeling for specific impact scenarios
- Impact risk assessment result examples



# Asteroid Impact Risk Assessment

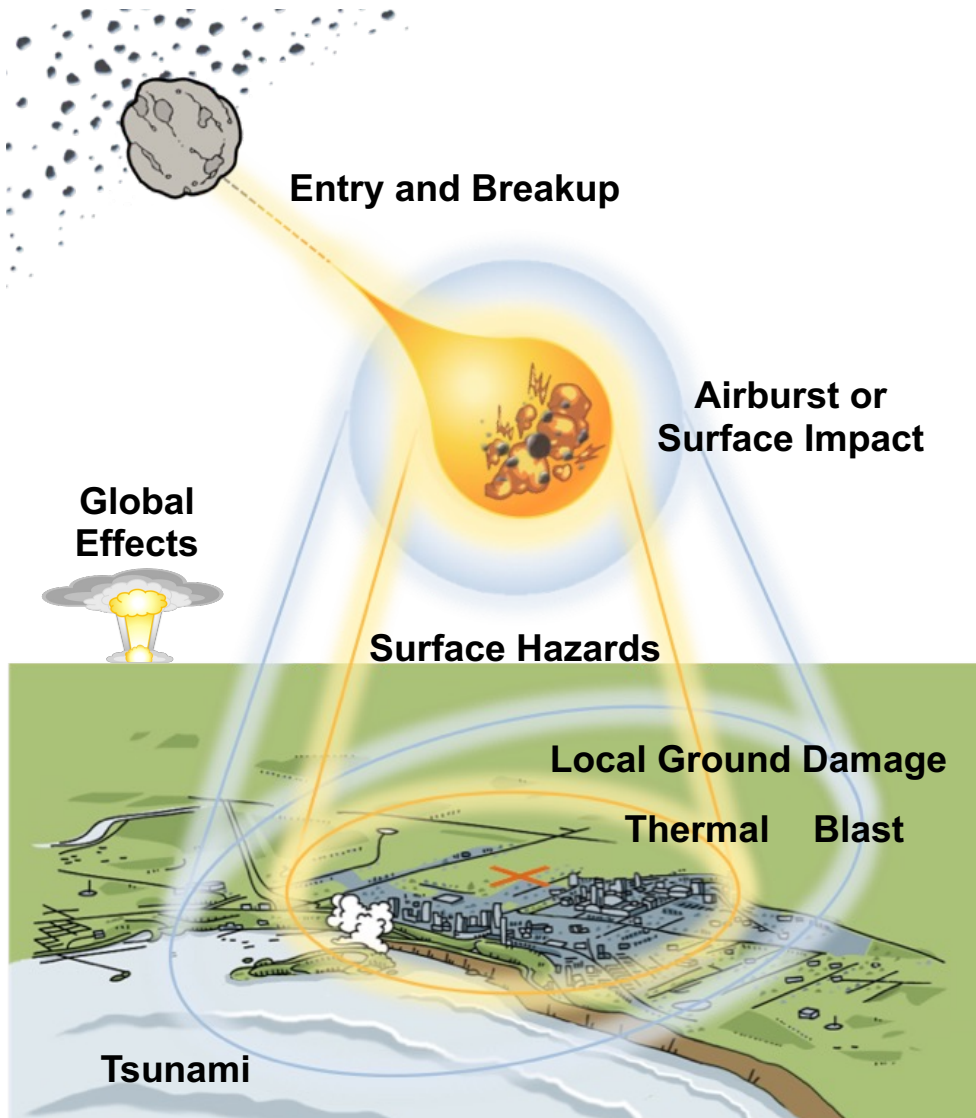


How *likely* are the potential consequences

Evaluating potential damage from asteroid impacts involves large uncertainties across all aspects of the problem

Risk assessment evaluates both the severity and likelihood of potential outcomes, given the level of uncertainty about all the contributing factors

# Asteroid Impact Hazards



- Asteroids can cause damage by exploding in the atmosphere or by impacting Earth's surface
- Potential hazards include destructive blast waves, thermal fireballs, tsunamis, or global climatic effects
- For most asteroid sizes, blast damage is the predominant hazard
- Damage depends on asteroid properties, atmospheric entry, impact location, and other factors

# Asteroid Size & Property Uncertainty

What we would like to know about the object

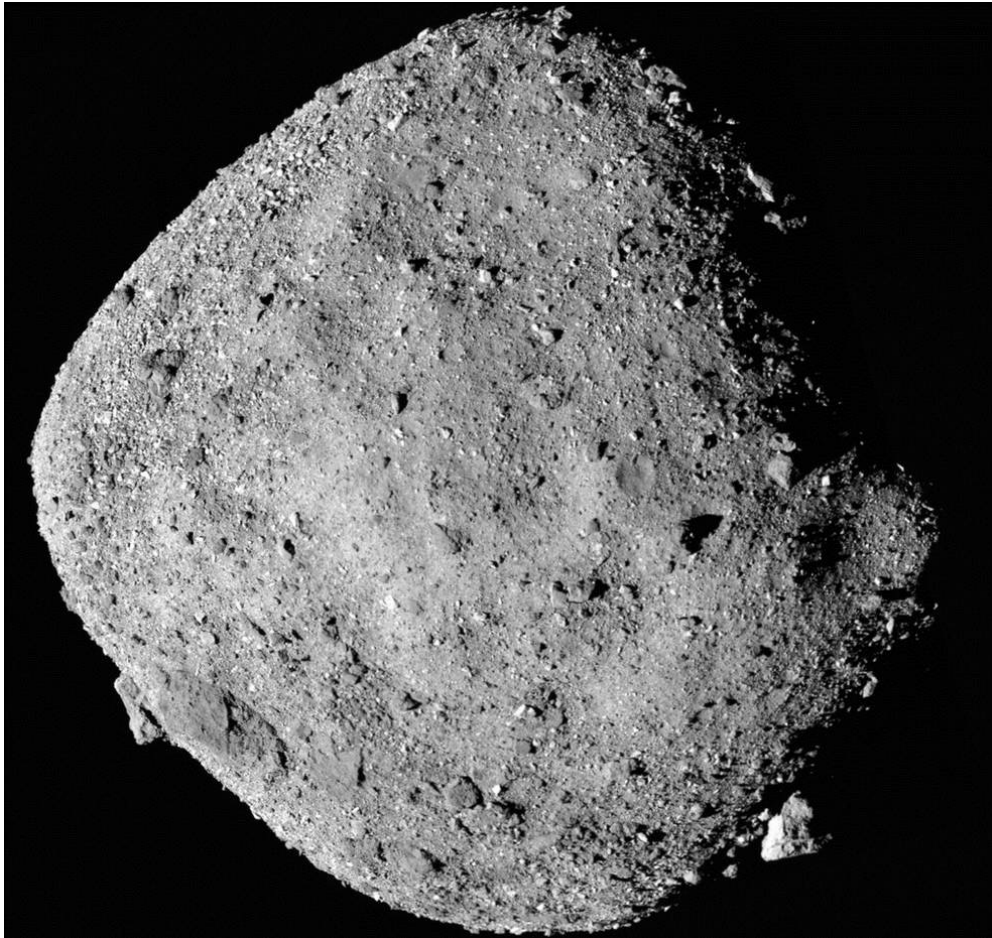


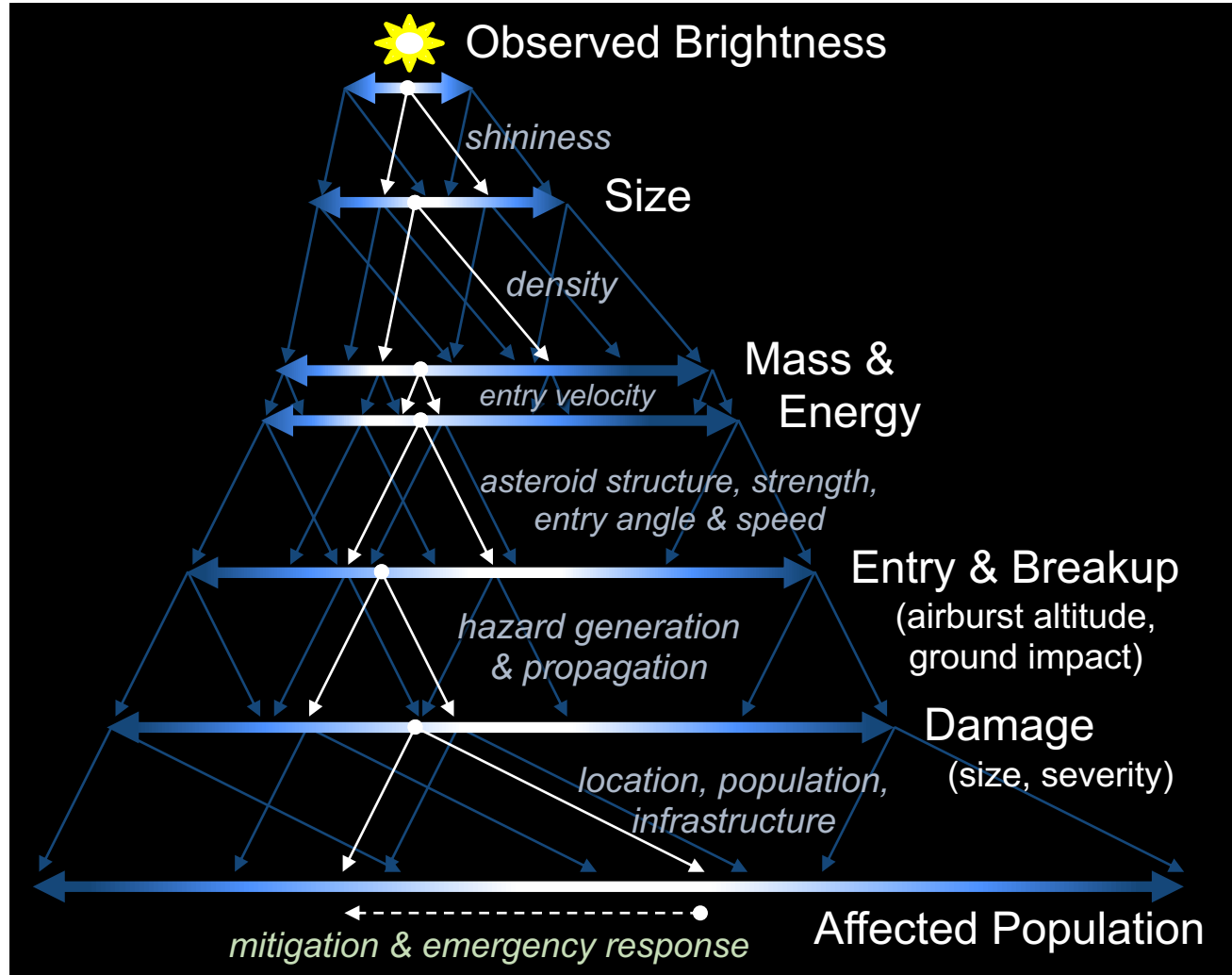
Image of asteroid Bennu from OSIRIS-Rex mission (Image credit: NASA)

What we actually know initially



Telescope observation of asteroid Apophis.  
(Credit: Nic Erasmus, SAAO's Lesedi Telescope, IAWN Apophis 2021 Observing Campaign,  
[https://iawn.net/obscamp/Apophis/apophis\\_gallery.shtml](https://iawn.net/obscamp/Apophis/apophis_gallery.shtml))

# Asteroid Property and Damage Uncertainties

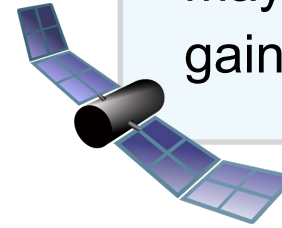
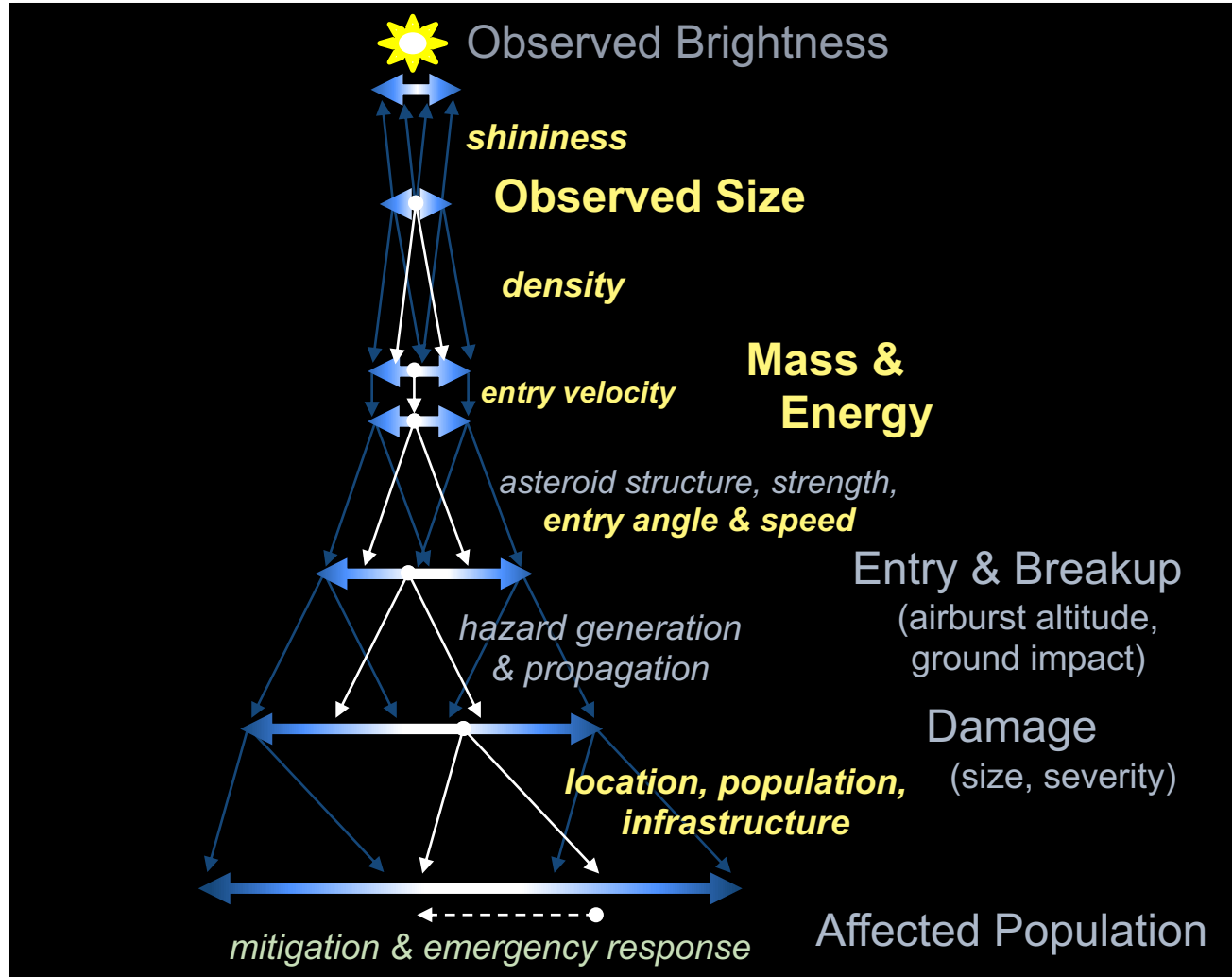


Uncertainties in asteroid properties, impact location, and damage models...

...cascade into huge uncertainties in potential damage.

\* Conceptual diagram only – Not to scale

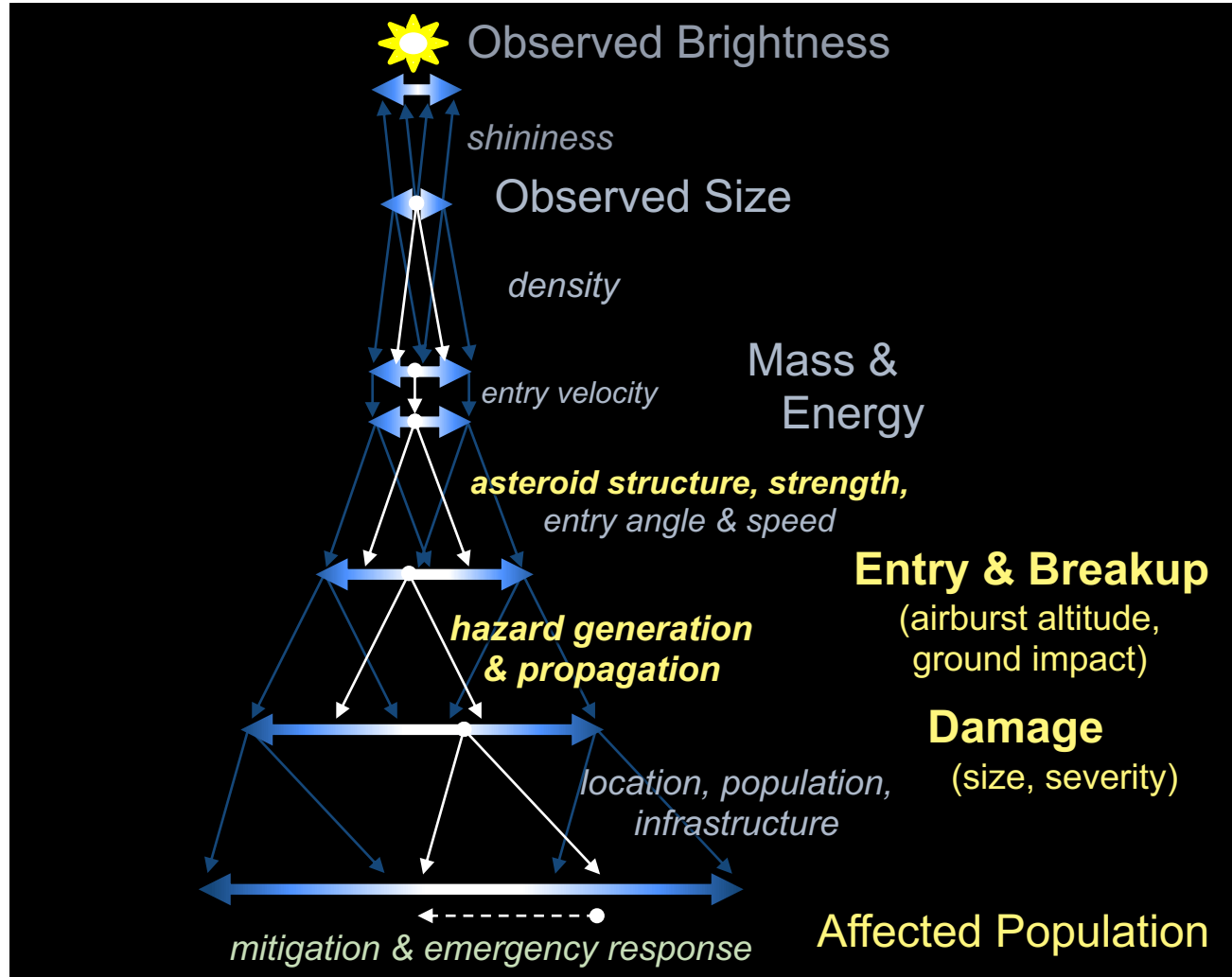
# Asteroid Property and Damage Uncertainties



Some key uncertainties may shrink or shift as we gain data.

\* Conceptual diagram only – Not to scale

# Asteroid Property and Damage Uncertainties

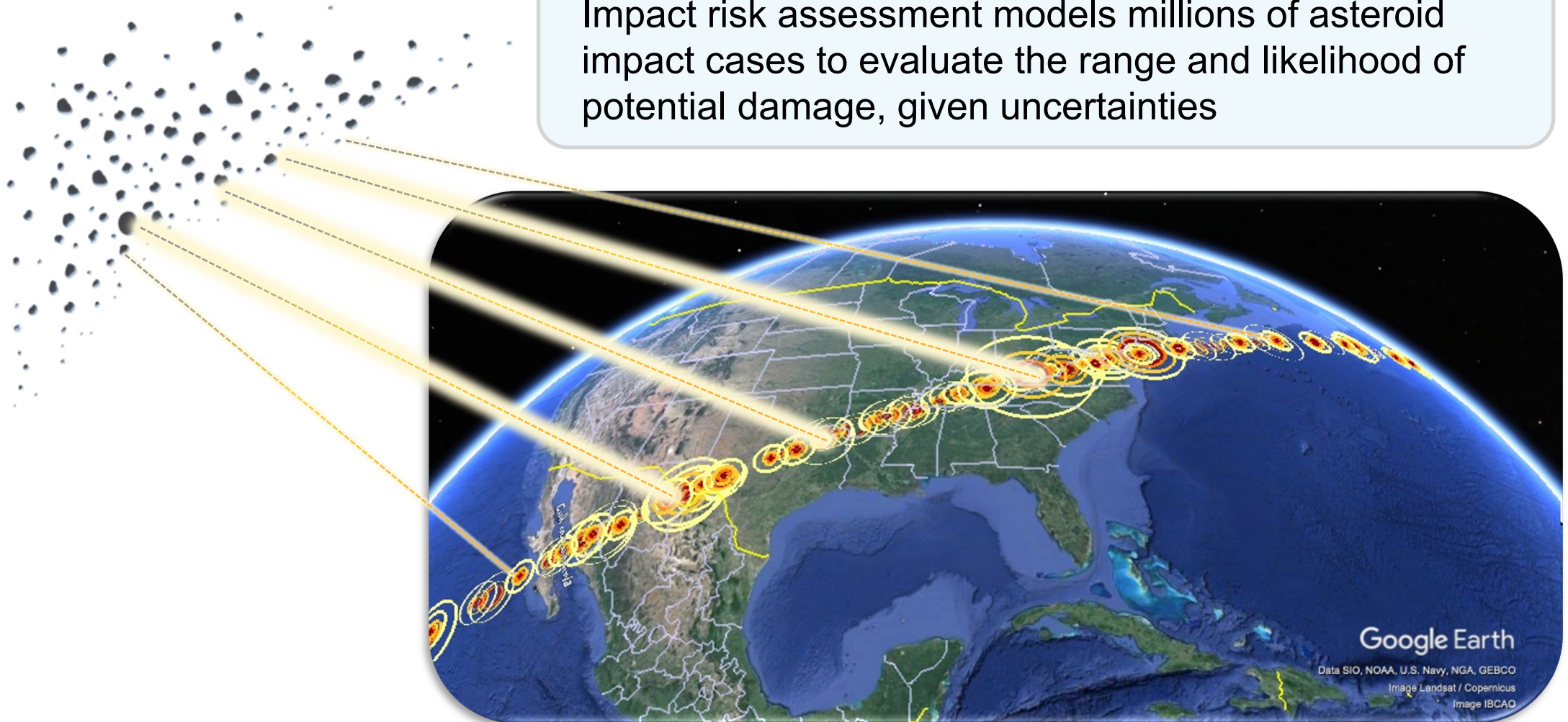


Some factors will remain uncertain through impact.

\* Conceptual diagram only – Not to scale

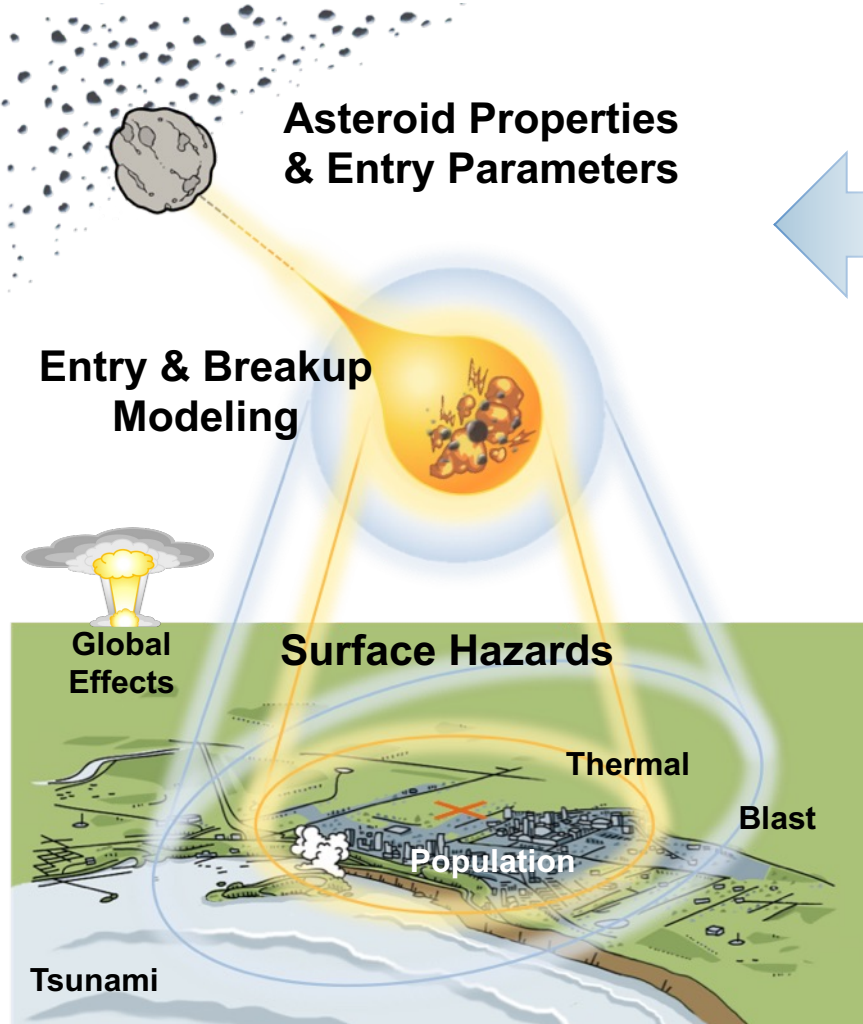
# Asteroid Impact Risk Assessment

Impact risk assessment models millions of asteroid impact cases to evaluate the range and likelihood of potential damage, given uncertainties



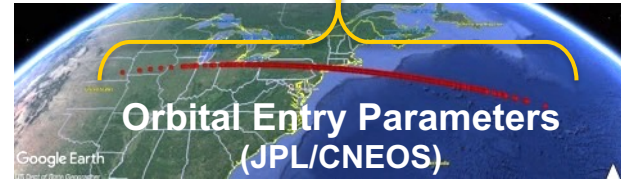
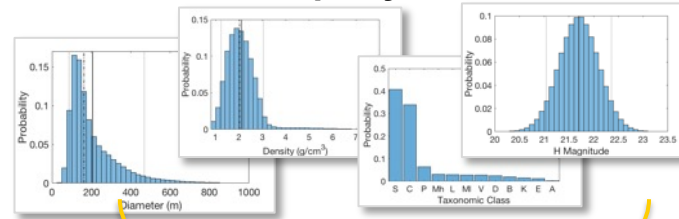
# Risk Assessment for Asteroid Impact Threats

## Probabilistic Asteroid Impact Risk (PAIR) Model

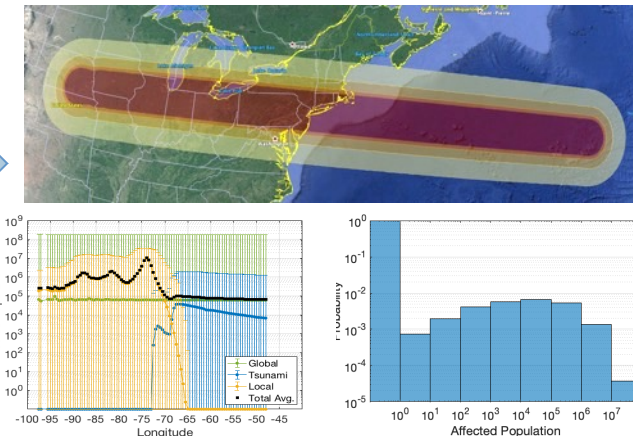


## Impact Threat Scenario

### Asteroid Property Distributions



### Damage and Risk Probabilities



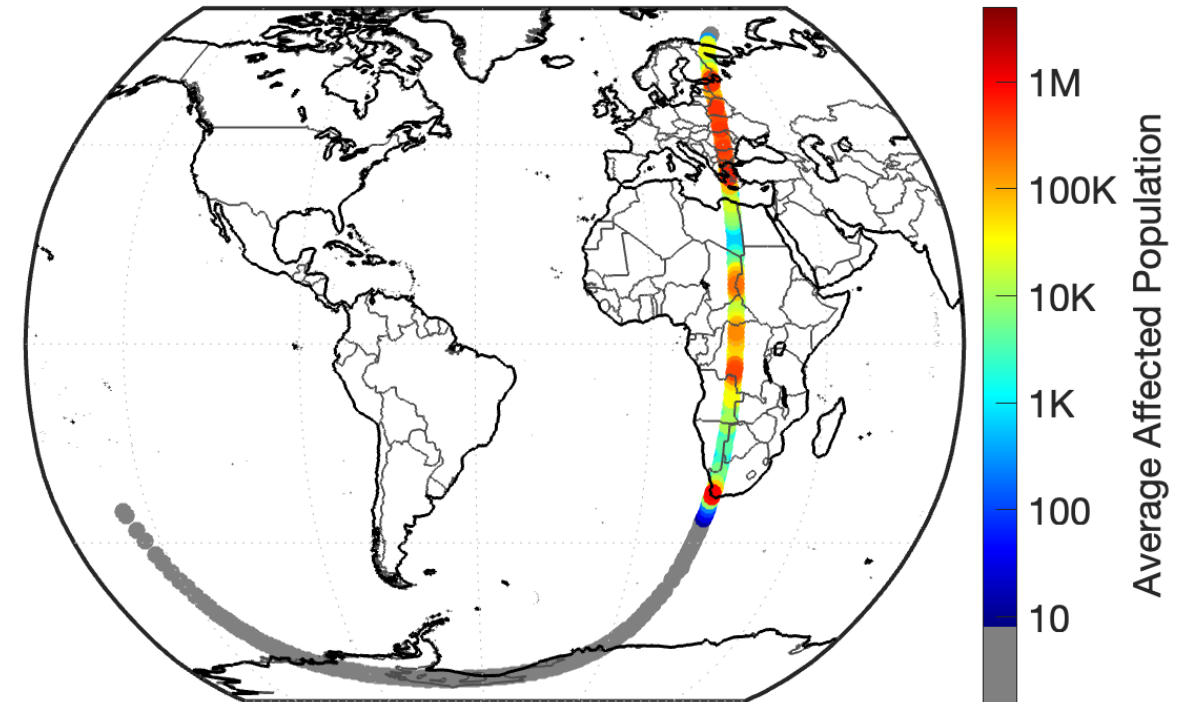
- PAIR risk model uses fast physics-based models to assess millions of impact cases representing the range of possible asteroid properties and impact locations.
- Atmospheric entry, breakup, and resulting hazards are modeled for each case.
- Probabilities of the resulting damage sizes, severities, and affected populations are computed.
- Regions at-risk are mapped.

# Hypothetical Impact Exercise Example

Hypothetical impact exercises use fictitious but realistic asteroid threat scenarios to test and develop planetary defense capabilities and response processes.

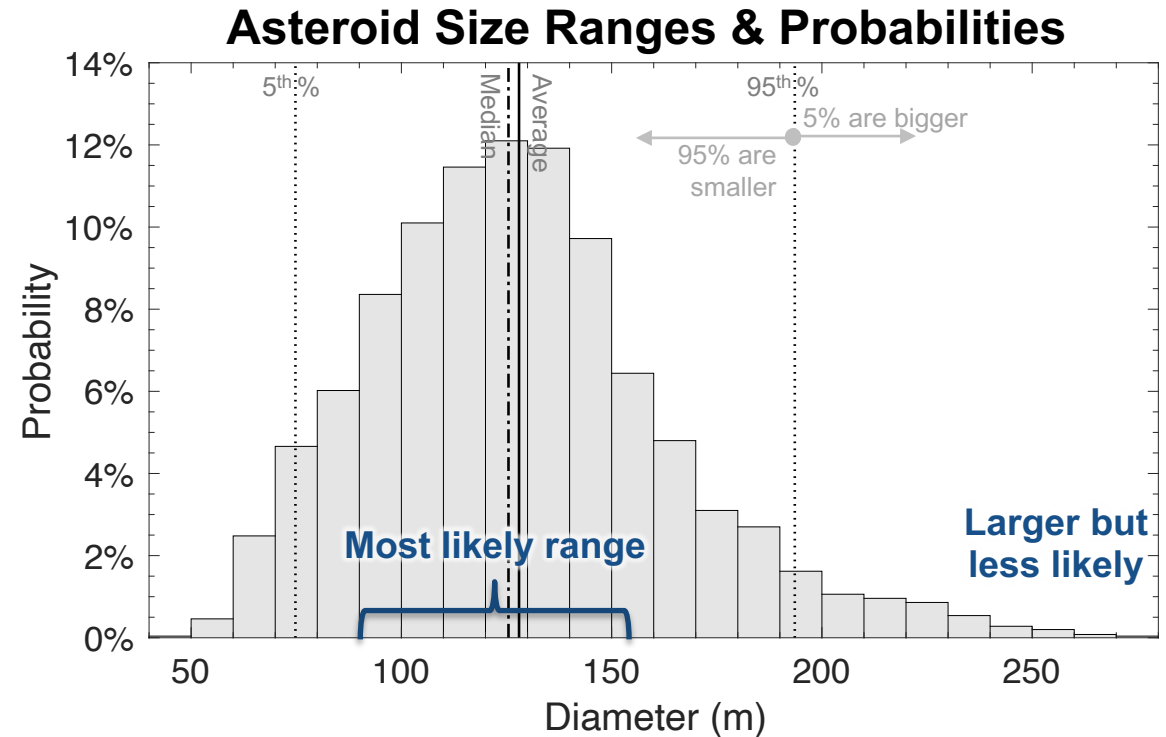
- 2025 Planetary Defense Conference (PDC25) impact exercise scenario:
  - ~1.6% chance of Earth impact somewhere along a globe-spanning corridor
  - Asteroid 50–280 m across with 3–720 Mt of impact energy.
  - Large ranges of potential damage sizes, severities, and locations are possible.
- Exercise details available at <https://cneos.jpl.nasa.gov/pd/cs/>

Average affected population along potential impact regions



# Asteroid and Impact Properties

	Asteroid Diameter	Impact Energy (megatons TNT)
<b>Median</b>	125 m (412 ft)	50 Mt
<b>Most Likely</b>	90–160 m (300–520 ft)	5–70 Mt
<b>Range</b>	50–280 m (160–920 ft)	3–720 Mt



**Asteroid size, type, and properties are uncertain, resulting in very large ranges of potential mass, impact energy, and damage.**



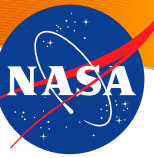
# Ground Damage Risk Swath



Damage Level	Description
Serious	Windows shatter, some structure damage
Severe	Widespread structure damage
Critical	Residential structures collapse
Unsurvivable	Devastation, structures flattened or burned

**Damage risk swath shows extent of regions potentially at risk to ground damage, given ranges of potential damage locations and sizes**

- Black border shows range of potential airburst/impact locations
- Shaded regions show potential extent of local ground damage
- Rings show median-sized damage footprints at sample high-population locations

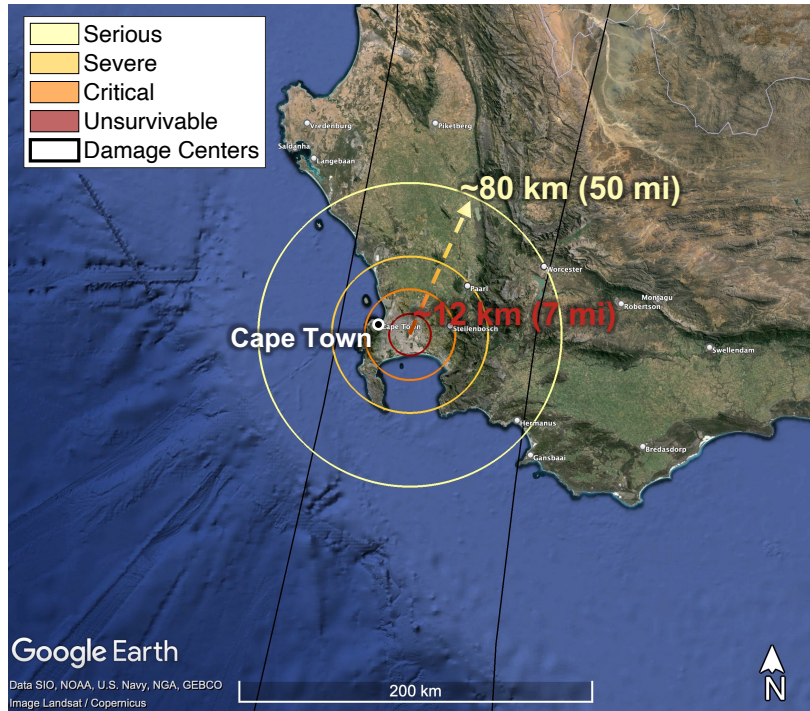


# Potential Ground Damage Sizes & Severities

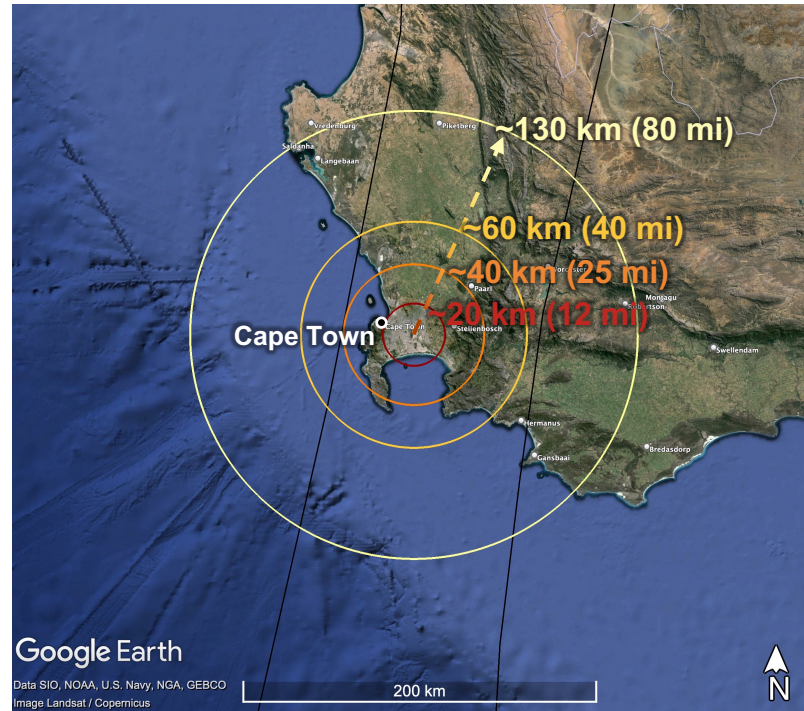
Likely damage sizes could span multiple metropolitan areas or counties

Large damage sizes could span multiple regions or states

Damage severities could reach **unsurvivable** levels near airburst, extending to larger areas of **structural damage, fires, and shattered windows**



Median (50<sup>th</sup>%) Damage



Large (95<sup>th</sup>%) Damage

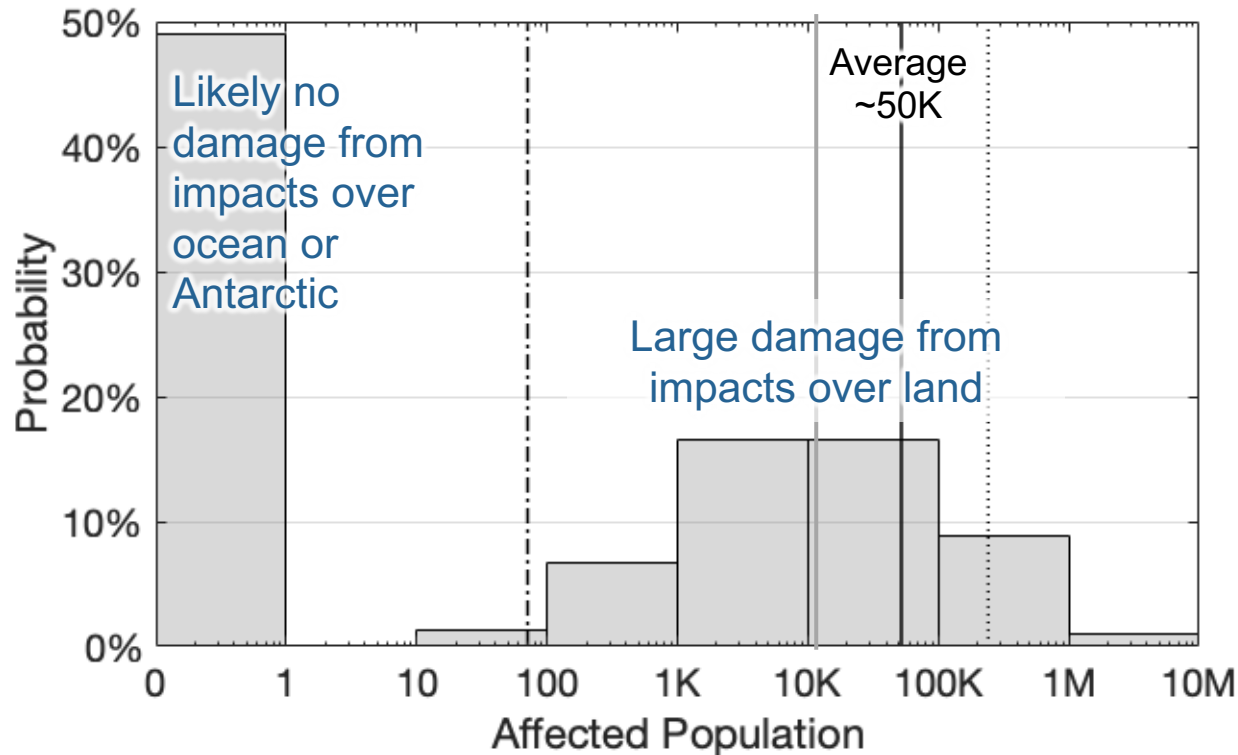
### Damage Level Description

Serious	Windows shatter, some structure damage
Severe	Widespread structure damage
Critical	Residential structures collapse
Unsurvivable	Devastation, structures flattened or burned



# Affected Population Risks

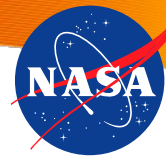
Damage probabilities among Earth-Impacting cases



Likelihood of the impact affecting at least this many people or more

Affected population threshold	Chance of damage exceeding threshold
Any	51%
>1K	43%
>10K	26%
>100K	10%
>1M	1%

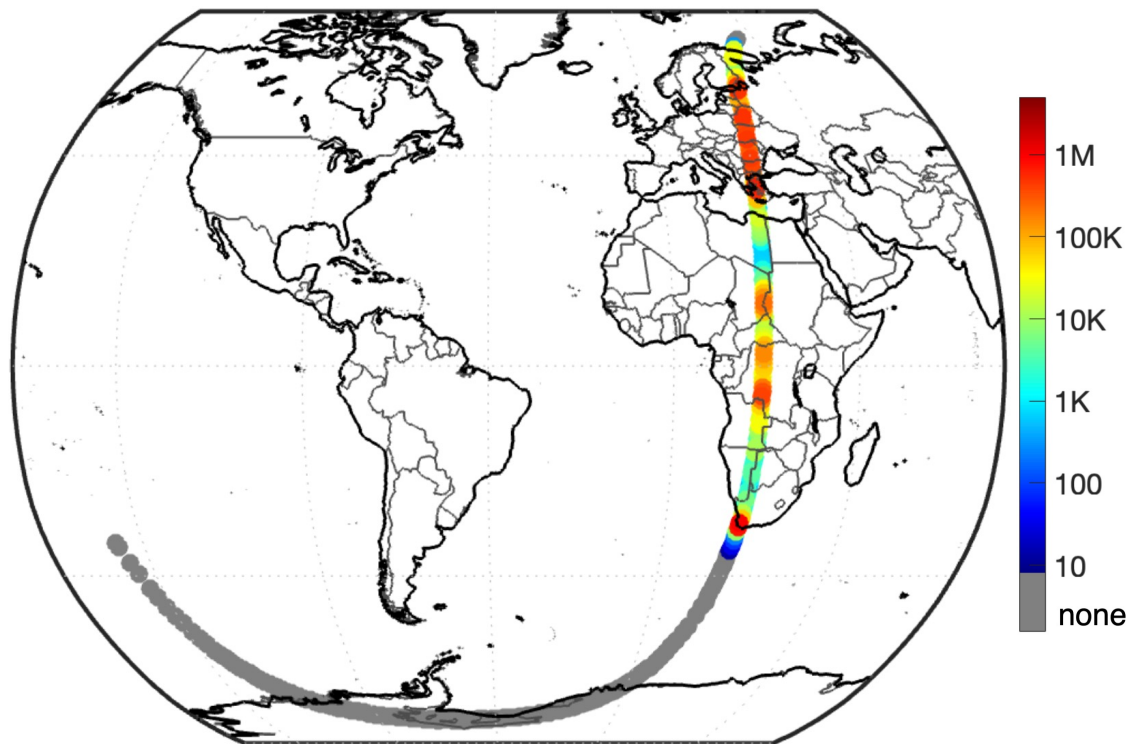
Either no damage or very large damage are both relatively likely...  
 Poses challenging uncertainty for decision-makers weighing cost/benefit of response actions



# Damage estimates are refined as we gain more data

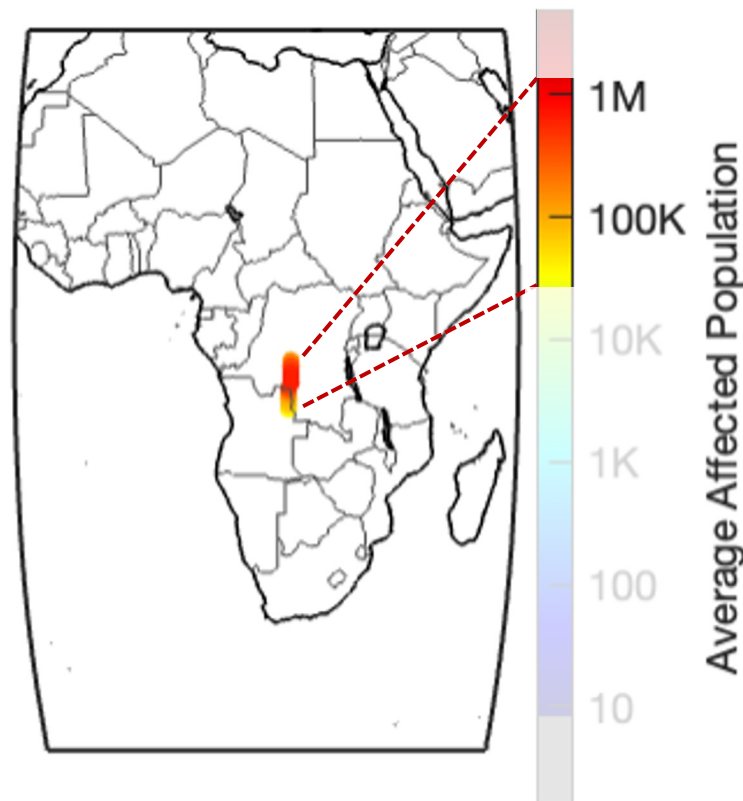
## Initial Discovery

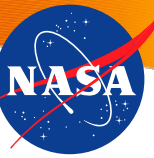
Small chance of impact with many large damage uncertainties.



## After Flyby Mission

Measured asteroid size and trajectory confirm large damage to populated regions.





# Response Decision & Communication Support

## International notifications & communication

**EXERCISE**

**INTERNATIONAL ASTEROID WARNING NETWORK (IAWN)**

**POTENTIAL ASTEROID IMPACT NOTIFICATION – HYPOTHETICAL SIMULATION**

Date: August 1, 2024

From: International Asteroid Warning Network (IAWN)  
 Point of Contact: IAWN Contributing Office for the IAWN Steering Committee (email)  
 To: Chief Space Mission Hearing Agency (email) (SMPAG)  
 United Nations Office of Outer Space Affairs  
 Title: Potential Impact of Near-Earth Asteroid 2024 PC25

**Impact Probability:** 1.0% as calculated by NASA, JPL, CNES and ESA NEOCC

**Impact Date:** 24 April 2041

**Impact Risk Consider:** Across Eastern Europe, the Mediterranean Sea, and Africa from the Bay of Benue to the Cape of Good Hope, across the South Atlantic to the Antarctic coast, and to the South Pacific.

**Asteroid Size:** Most likely in the range 90–160 m (300–520 ft) in diameter, but possibly in the range 50–200 metres (150–650 feet).

**Expected Damage Level if Impact Occurs:** Regional blast damage, likely extending up to 150 km from impact location, but possibly as far as 200 km. Energy released most likely to be in the range 5–70 Mt, but possibly in the range 3–750 Mt.

**When will there be new information?** The asteroid will be observable, and information will be updated, through mid-October 2025 and then again starting in August 2025.

**Technical Information:** <https://cneos.jpl.nasa.gov/cia/2024/>

**ADDITIONAL DETAILS:**

- Impact Probability:** There is a 1.0% probability that near-Earth asteroid 2024 PC25 will impact Earth on 24 April 2041 as independently calculated by the IAWN Center for Near-Earth Object Studies (CNEOS) and the USA Near-Earth Object Coordination Centre (NEOCC). While there is uncertainty in whether the asteroid will impact Earth, if an impact occurs, it will be on this date.
- Impact Risk Consider:** The impact risk comes for 2024 PC25, which is the region of Earth where a potential impact is possible, extends across Eastern Europe, the Mediterranean Sea, and Africa from the Bay of Benue to the Cape of Good Hope, across the South Atlantic to the Antarctic coast near the Antarctic Peninsula, and to the South Pacific (see Graphic 2 below).
- Discovery:** The near-Earth asteroid 2024 PC25 has been tracked since it was first observed on 5 June 2024 by the Catalina Sky Survey of the University of Arizona near Tucson, Arizona, during near-Earth asteroid survey operations for NASA. Continued observations indicated a non-zero impact probability that rose to 1% on 27 July 2024. This risk notification threshold by IAWN, NASA, CNES and ESA NEOCC coordinated closely with each other and with the Minor

**EXERCISE**

**HYPOTHETICAL EXERCISE**

**Impact Risk Dashboard**

**Assessment 1 – Initial Discovery & SMPAG Notification – 1 August 2024**

**Asteroid Characterization Summary**

- ~1.0% chance of Earth impact on 24 April 2041 (±17 years) from a Non-Bariol asteroid with uncertain size and properties
- Available observation data: Ground-based brightness estimates; ZWST astrophysical diameter and determined S taxonomy
- Diameter: 20–200 m (66–656 ft); most likely 90–160 m (300–520 ft); median size: 125 m (412 ft)
- Impact Energy: 5–70 Mt, most likely 5–70 Mt, median 50 Mt
- Properties: S type bulk density ranges, unknown structure

**Hazard Summary**

- Large ranges of potential damage sizes, severities, and locations
- Primary hazard is a high-energy, low-altitude airburst and thermal loading, including blast waves, over large areas
- Blast damage could likely reach considerable levels near impact, with vertical damage likely extending ~40–110 km (~130–70 mi) in radius, and possibly out over 200 km (125 mi) or more
- Likely damage sites could span multiple metropolitan areas or counties, with large damage sites could span regions or states
- Airbursts in this size range are unlikely to cause significant tsunamis, but largest cases could cause transoceanic damage if near coasts

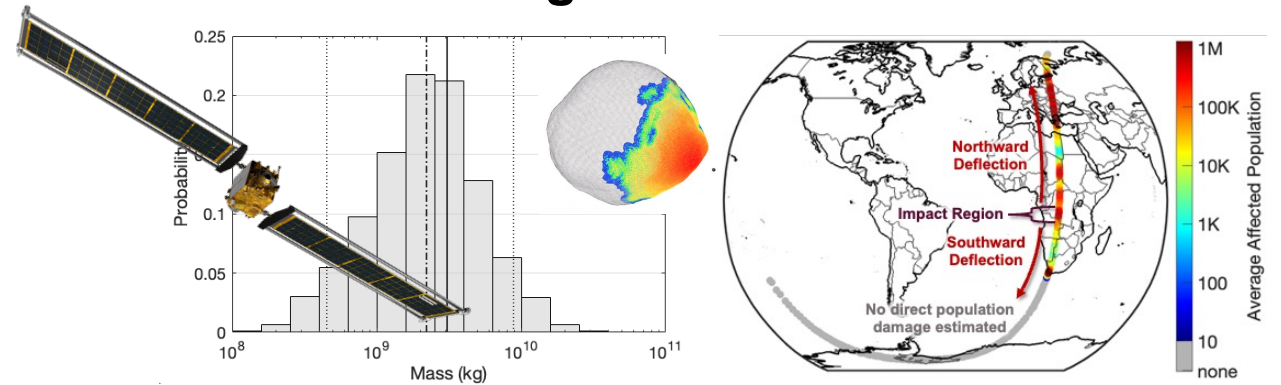
**Affected Population Risks (given Earth-impact)**

Probabilities of how many people could be affected by the potential damage

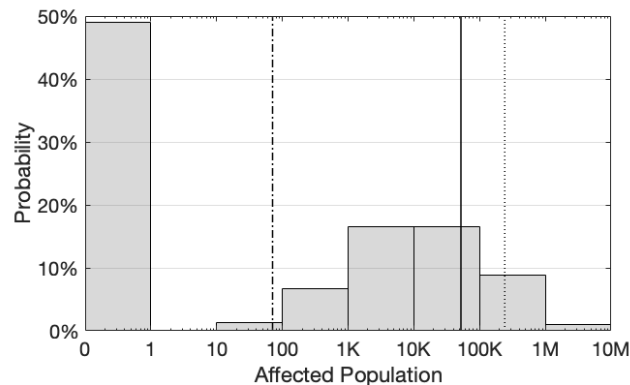
Range: 0–5M ppl  
 ~50% and ~10% of Earth impact occurs  
 ~500 total avg. risk (with 1.0% Earth-impact probability)

**EXERCISE**

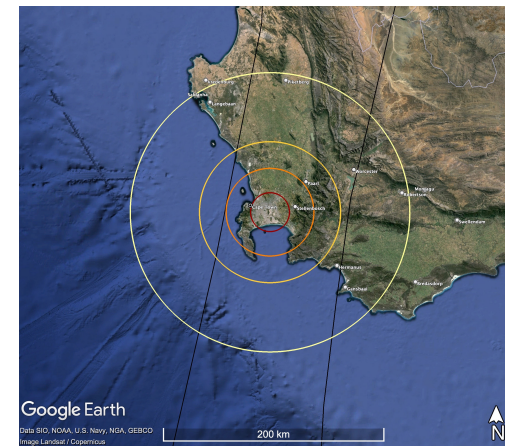
## Mitigation mission design based on asteroid size ranges and outcome risks

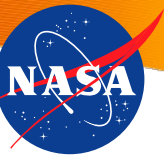


## Threat response decisions based on damage risks

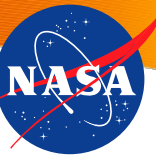


## Emergency response and disaster planning



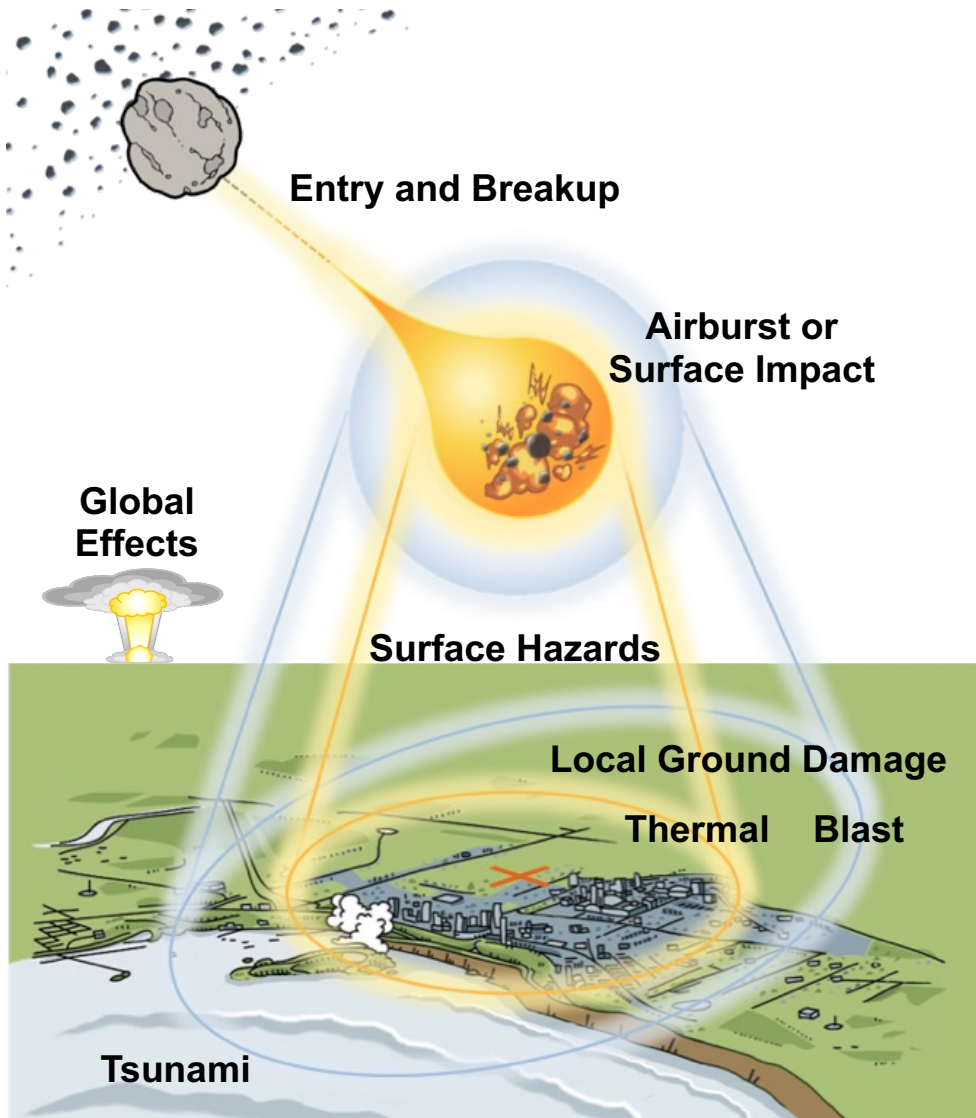


**THANK YOU**

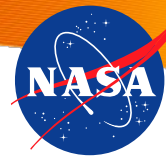


# BACKUP

# Asteroid Impact Hazards



- Asteroids can cause damage either by breaking up and bursting in the atmosphere or impacting the surface
- Local blast damage:
  - Airbursts or surface impacts produce explosive blast waves, that can cause damage ranging from shatter windows to flatten structures.
  - Primary hazard for most asteroid sizes.
- Local thermal damage:
  - Thermal heating from fireballs can cause damage ranging from mild to lethal skin burns, fires, to incineration.
  - Generally smaller and less severe than accompanying blast.
- Tsunami damage:
  - Large ocean impacts could cause significant inundation to surrounding coasts.
- Global effects:
  - Large-scale impacts could produce enough atmospheric ejecta to cause global climate effects or other cascading regional hazards.

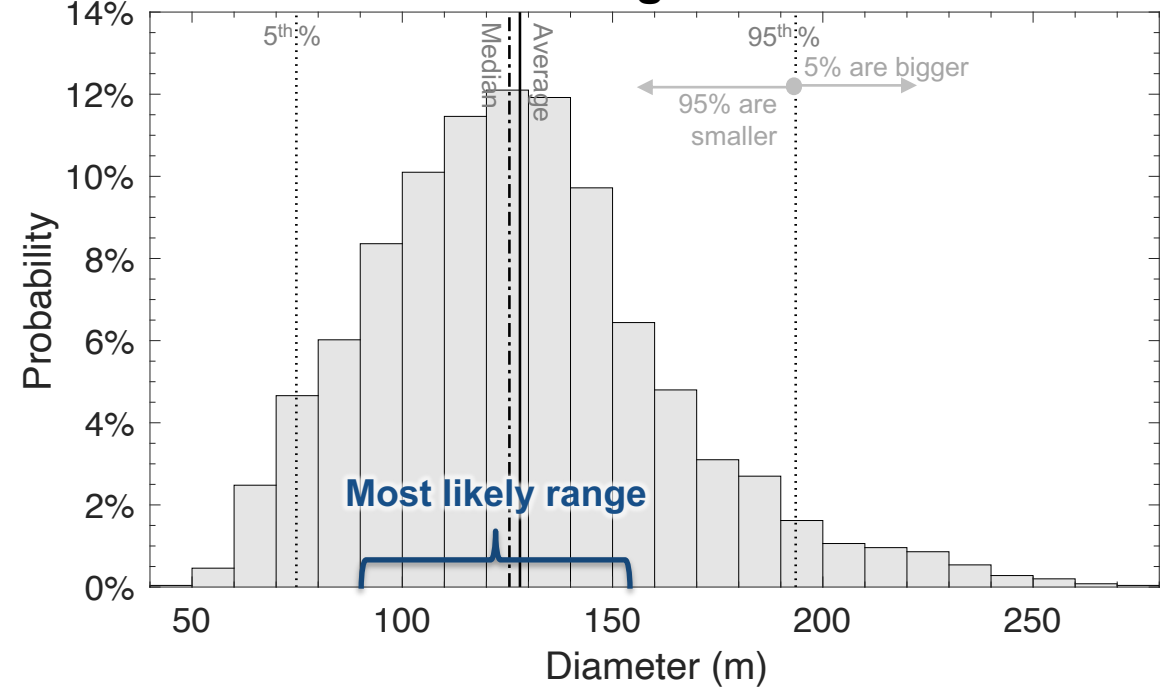


# Asteroid Size & Properties

**Asteroid size range is hazardous but uncertain.**  
 Size and property uncertainties result in large ranges of potential mass, energy, and damage.

- Available observation data to-date:
  - Initial ground-based observations estimated sizes based on brightness (H magnitude)
  - JWST observation refined diameter estimates and identified type S spectral class
- Estimated asteroid size and property ranges:
  - Asteroid diameter is most likely between ~90–160 m but could range from ~50–280 m
  - Stony type composition, but unknown structure, strength, and breakup properties ranging from weak rubble pile to stronger monolithic bodies
  - Bulk densities most likely ~1.6–2.7 g/cm<sup>3</sup>, potentially ~1.1–3.8 g/cm<sup>3</sup> with macroporosity between 0–60%

**Asteroid Size Ranges & Probabilities**



	Diameter	Mass	Energy
<b>Median</b>	125 m (412 ft)	2.2e9 kg	50 Mt
<b>Average</b>	128 m (420 ft)	3.1e9 kg	70 Mt
<b>Most likely</b>	90–160 m (300–520 ft)	2.4e8–3.3e9 kg	5–70 Mt
<b>5<sup>th</sup>–95<sup>th</sup> %</b>	70–190 m (230–630 ft)	4.5e8–8.8e9 kg	10–200 Mt
<b>Range Modeled</b>	50–280 m (160–920 ft)	1.2e8–3.1e10 kg	3–720 Mt

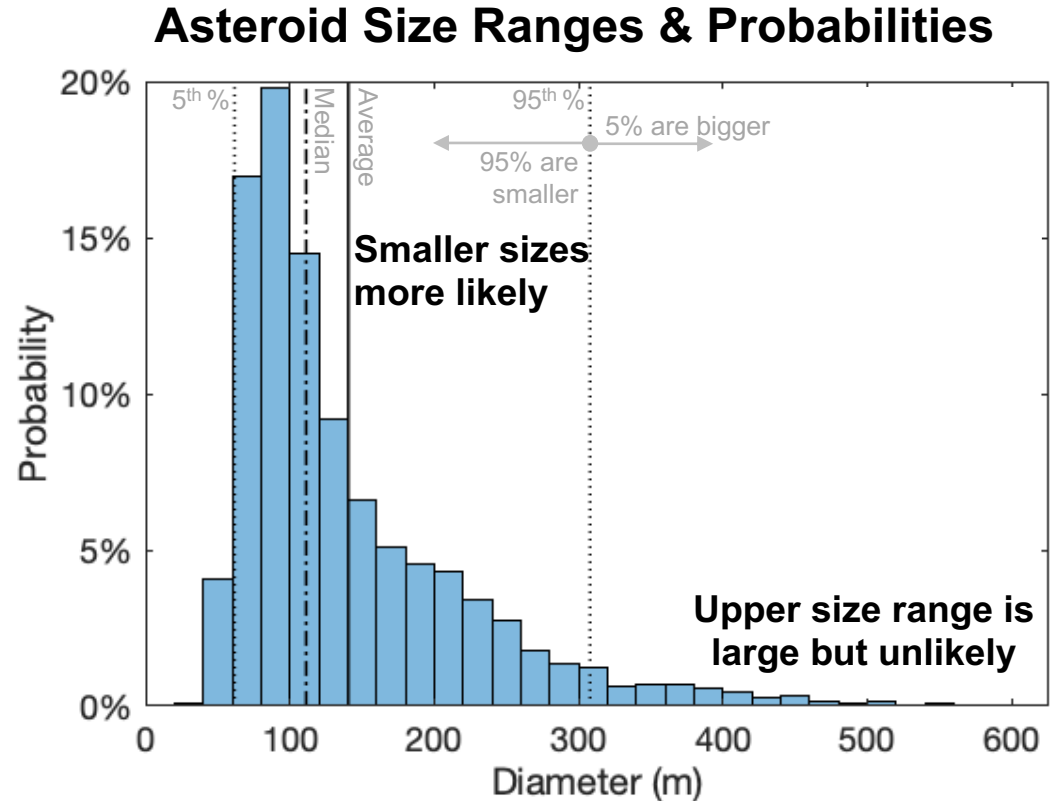
\* Property stats are computed *independently* and **cannot be combined** to represent a single asteroid.

[Property inference model: J. Dotson et al., 2024]

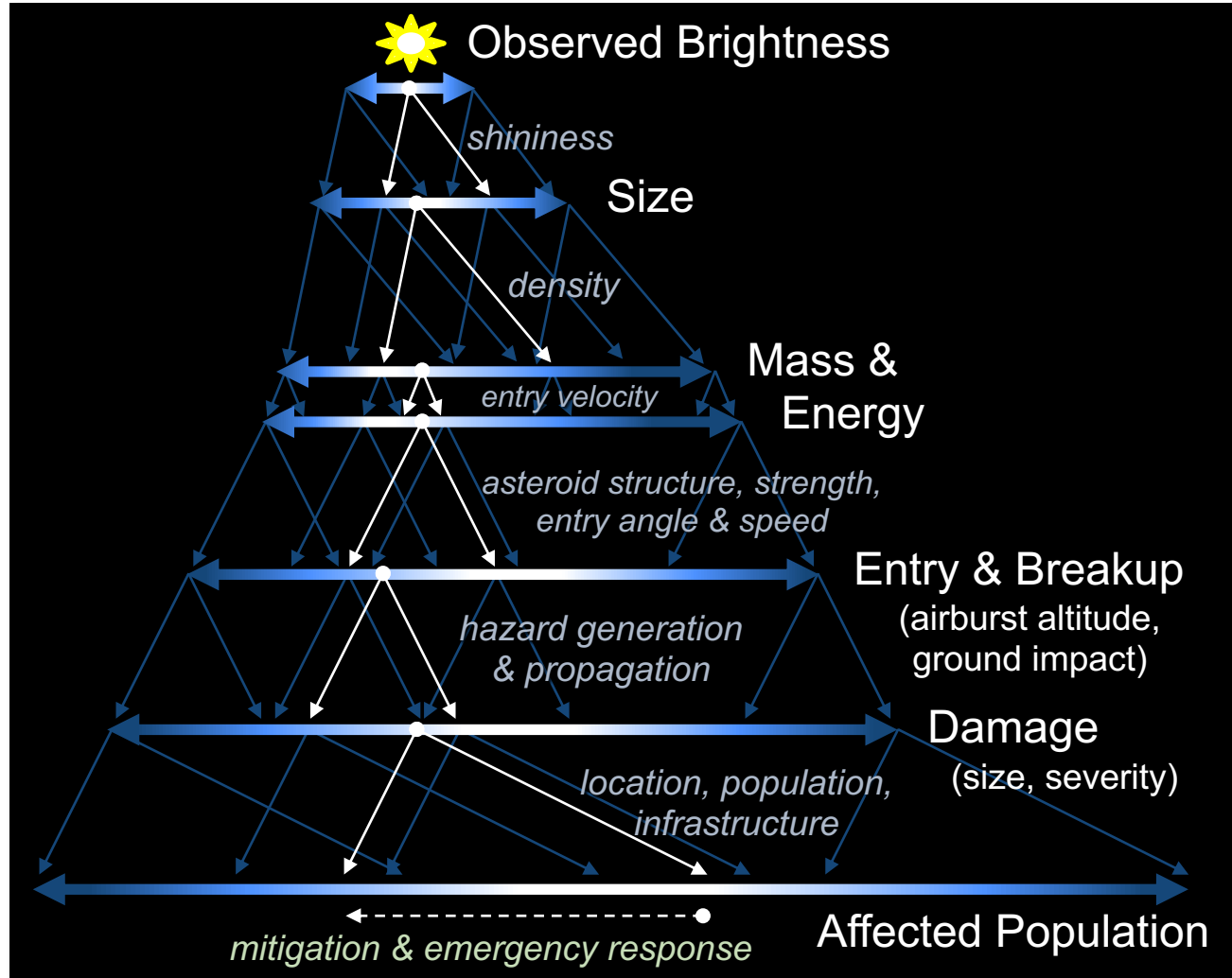
# Asteroid Size & Property Uncertainty

## Asteroid sizes and physical properties from remote observations are highly uncertain

- Upper size range can be large but relatively unlikely
- Smaller size ranges are generally more likely
- Asteroid properties (density, composition structure, strength) are often unknown, ranging from more common stony types and rubble piles to rarer high-density iron types
- Size and density uncertainties together result in very large ranges of potential mass and impact energy



# Asteroid Property and Damage Uncertainties

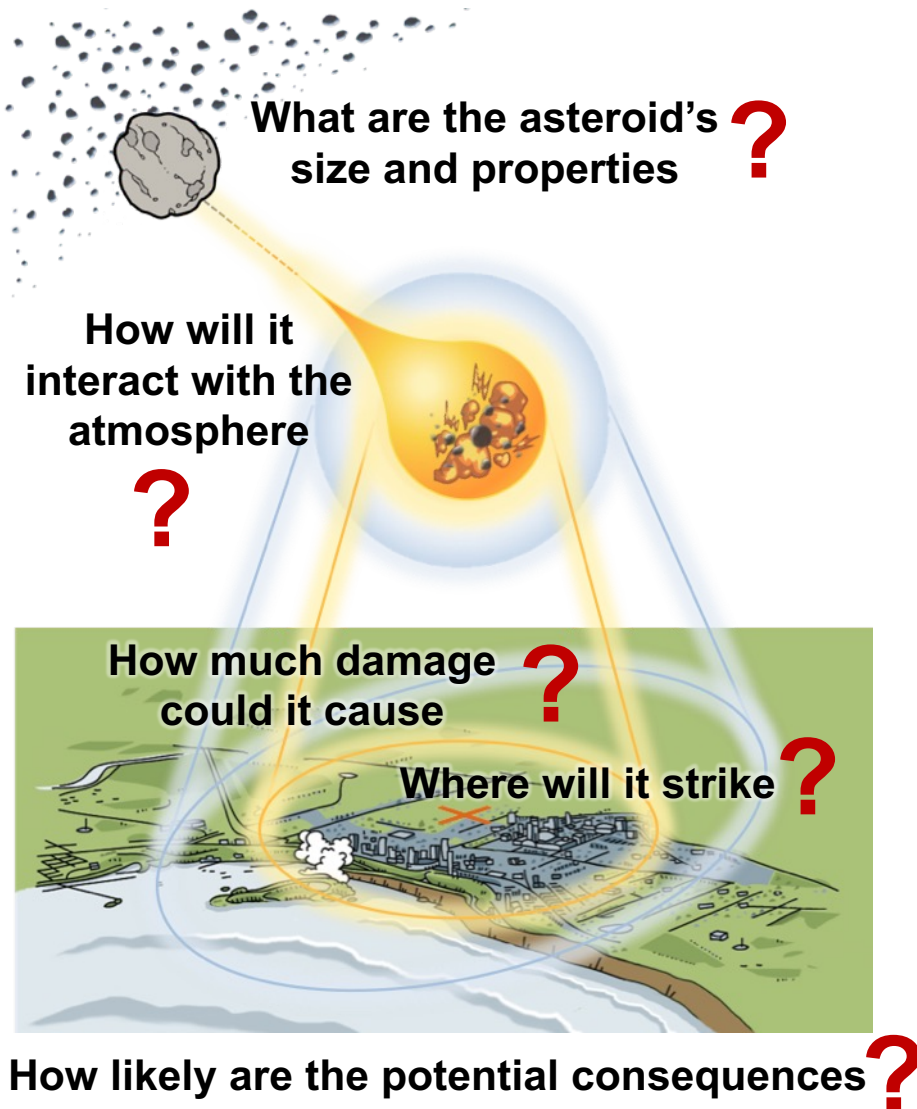


Uncertainties in asteroid properties, orbital trajectory, and damage models cascade into huge uncertainties in potential damage.

- Size and density uncertainties together result in very large ranges of potential mass and impact energy
- Unknown composition and structural properties affect range of mass, strength, and atmospheric entry/breakup
- These properties determine how much energy the asteroid can deliver to the various hazards and how much damage they could do

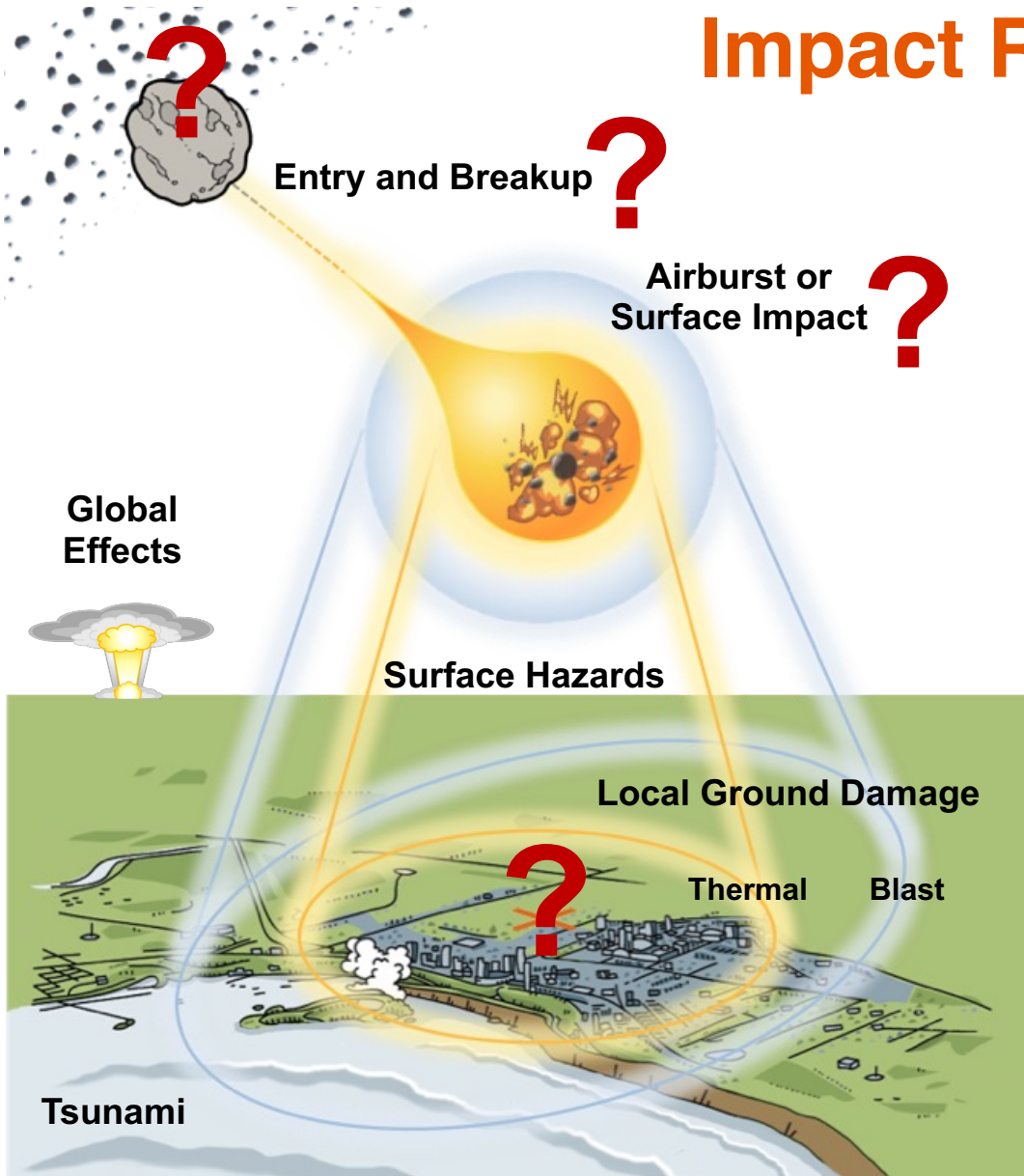
\* Conceptual diagram only – Not to scale

# What is Asteroid Impact Risk Assessment?



- Risk assessment evaluates both the severity and likelihood of potential outcomes, given the level of uncertainty about all the contributing factors
- Evaluating asteroid impact risks involves large uncertainties across all aspects of the problem:
  - Impact probability, potential impact locations, entry trajectories (speed, entry angle)
  - Asteroid sizes and properties (density, strength, structure, composition, shape, etc.)
  - Atmospheric entry, breakup, airburst or impact behavior
  - Severity and range of resulting hazards
  - Population and infrastructure within damage regions
- Some uncertainties shrink as we gain knowledge over time (impact locations, asteroid size), while some remain unknown (specific asteroid properties, entry/breakup behavior, damage uncertainties)

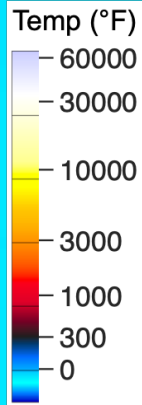
# Impact Risk Assessment



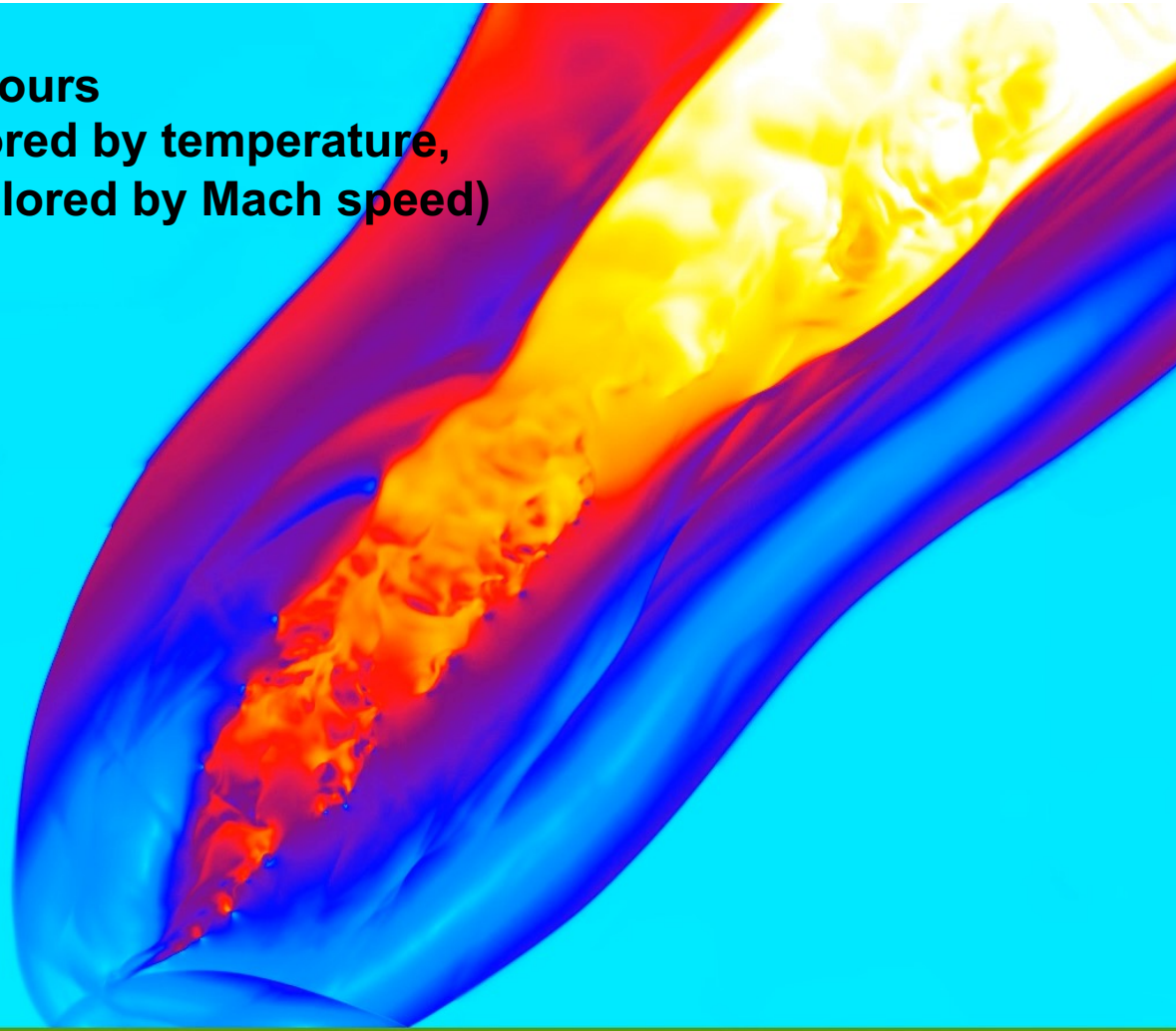
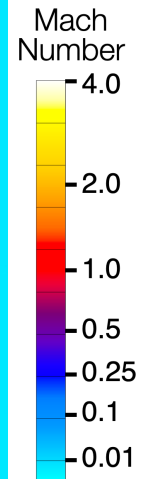
Risk assessment models millions of impact cases to evaluate the range and likelihood of potential damage.



# Airburst Blast Simulation (movie)



**Blast Wave Contours**  
(first shown colored by temperature,  
then replayed colored by Mach speed)



Blast from a 120-m, 50-Mt asteroid airburst

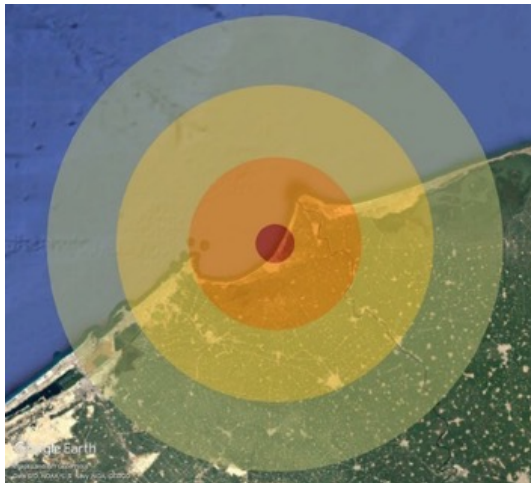
- Entry: Shockwaves emanate from the entry path as the asteroid enters at high speeds
- Airburst: Asteroid disrupts catastrophically under high aerodynamic pressures, producing an explosion-like blast
- Ground damage: Shock front reflects off the ground and sends a powerful blast wave outward across the ground

Cart3D Computational Fluid Dynamics (CFD) Simulation

Credit: Michael Aftosmis, NASA Ames. NASA High-End Computing, NASA Advanced Supercomputing Division.

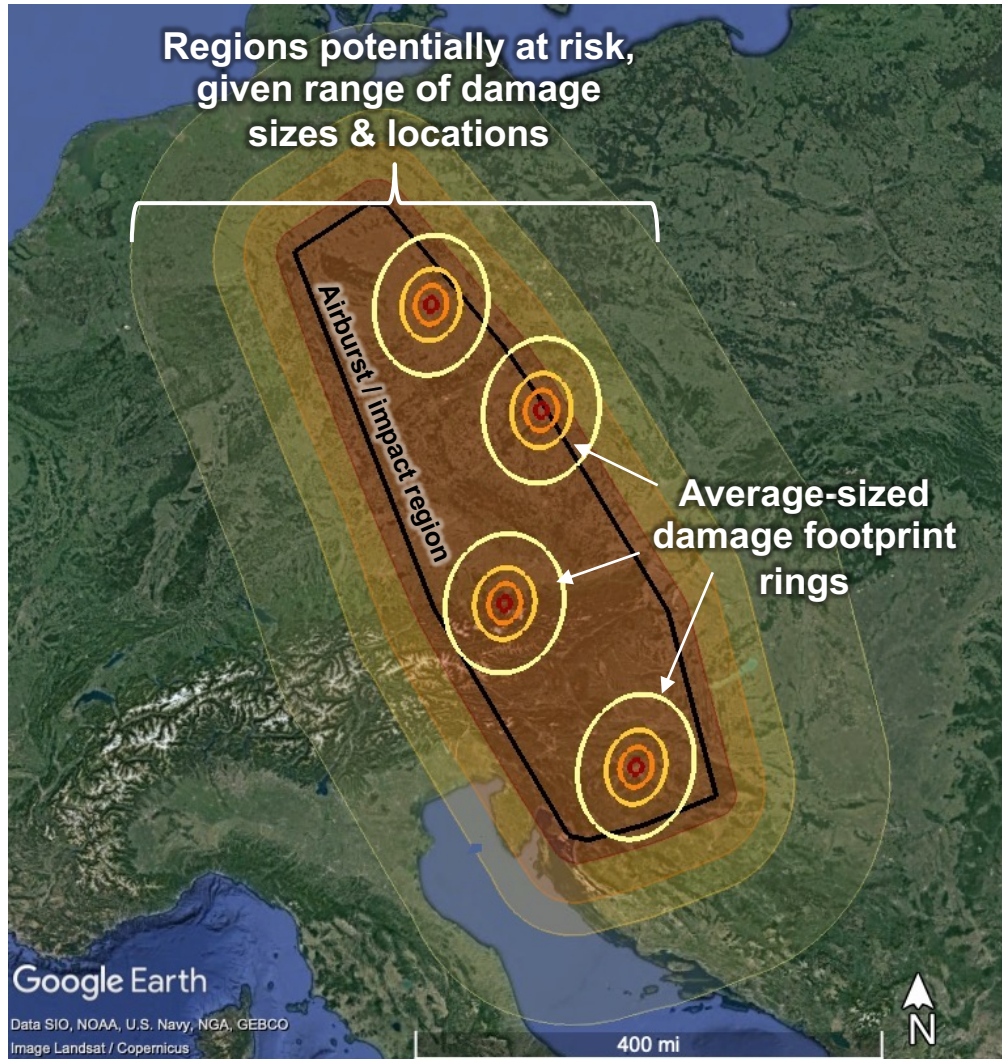
# Local Ground Damage Severity Levels

- Blast and thermal damage are assessed independently at four severity levels
  - For each damage level, the larger of the associated blast or thermal damage is used to determine the area and affected population for that level.
  - Damage regions indicate either blast or thermal effects could exceed the given severity, not the occurrence of both effects within the entire region
- Blast is the predominant hazard for most asteroid sizes
  - Blast tends to be larger and more severe than the potential thermal damage in most cases
  - Blast areas usually define the larger risk regions for emergency response planning



Damage Level	Potential Blast Damage Effects	Potential Thermal Damage Effects
<b>Serious</b>	<b>Shattered windows, some structural damage</b>	2 <sup>nd</sup> degree burns
<b>Severe</b>	<b>Widespread structural damage, doors and windows blown out</b>	3 <sup>rd</sup> degree burns
<b>Critical</b>	<b>Most residential structures collapse</b>	Clothing ignition
<b>Unsurvivable</b>	<b>Complete devastation</b>	Structure ignition, incineration

# Damage Risk Region Swath Maps



Example from 2021 Planetary Defense Conference Exercise

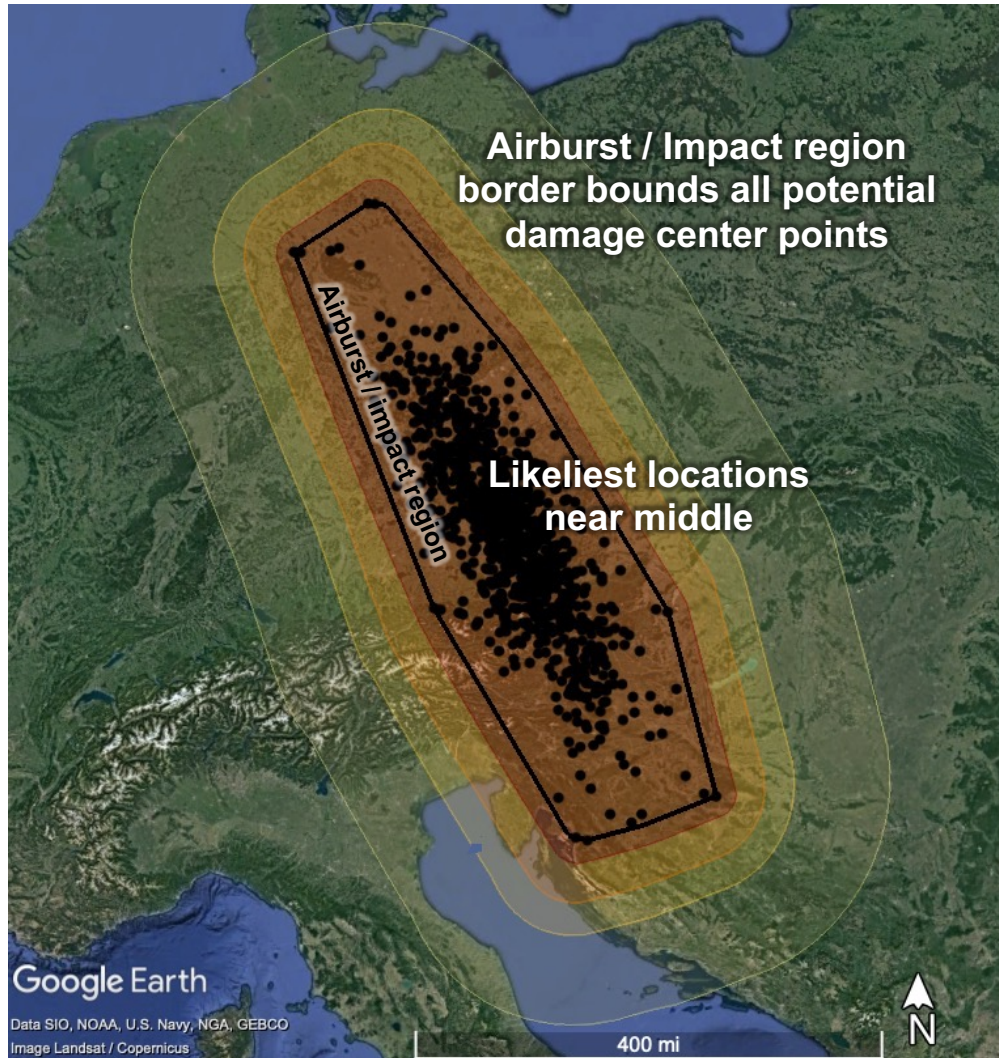
Risk swaths show range of regions **potentially** at risk to local ground damage, including range of possible damage sizes and locations

- Black outline shows range of potential impact points (damage-center locations)
- Shaded areas show potential at-risk regions given range of damage sizes and locations
- Rings show an average-sized damage footprint at sample locations

Damage Level	Description
Serious	Window breakage, some minor structure damage
Severe	Widespread structure damage, doors/windows blown out
Critical	Most residential structures collapse
Unsurvivable	Complete devastation

\* Main damage risk swath maps shown cover local ground damage sizes out to the 95<sup>th</sup> percentile. These local damage maps do not include regions potentially at risk to tsunami or global effects.

# Risk Region Swath Maps

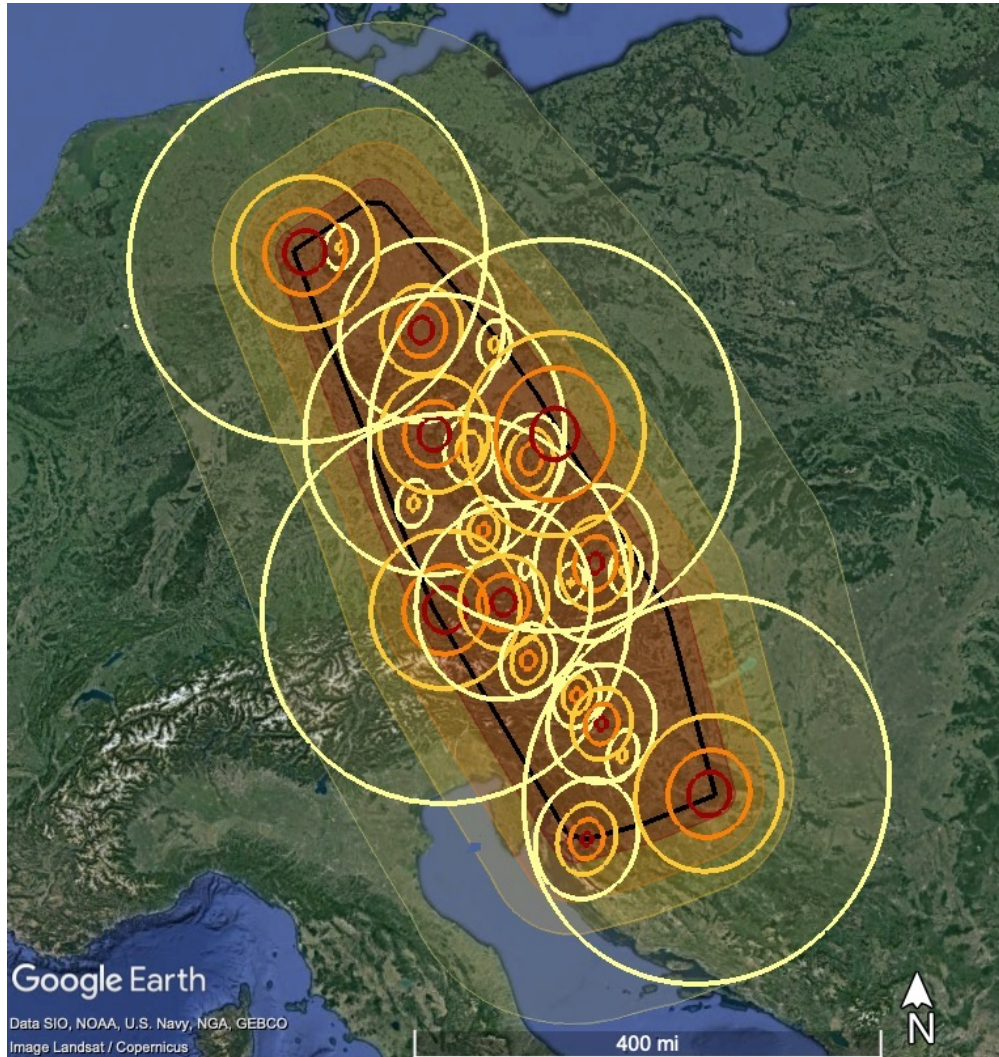


Example from 2021 Planetary Defense Conference Exercise

Range of regions *potentially* at risk includes:

- Range of potential impact damage locations (from orbit and entry)
  - Orbital uncertainty gives spread of entry locations
  - Damage location depends on airburst/impact point along entry trajectory
- Airburst / Impact border bounds all potential damage center-points, with likelier regions toward the middle

# Risk Region Swath Maps



Example from 2021 Planetary Defense Conference Exercise

Range of regions **potentially** at risk includes:

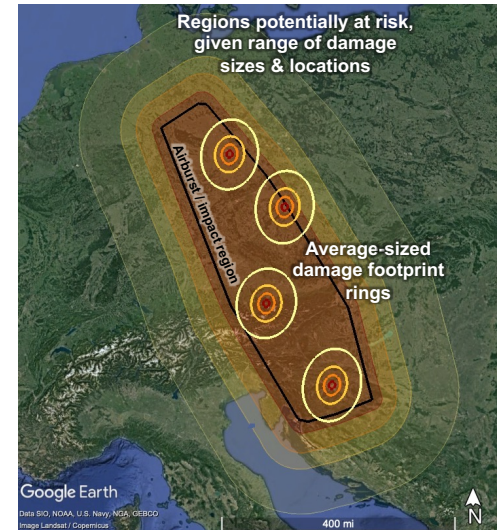
- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges  
+ Unknown entry, airburst, or impact factors



# Impact Risk Summary Dashboard

## Asteroid Characterization Summary

- Earth-impact data to-date (impact probability, potential impact date)
- Updates on any new observational data on the asteroid
- Estimated asteroid sizes, energies, or other properties



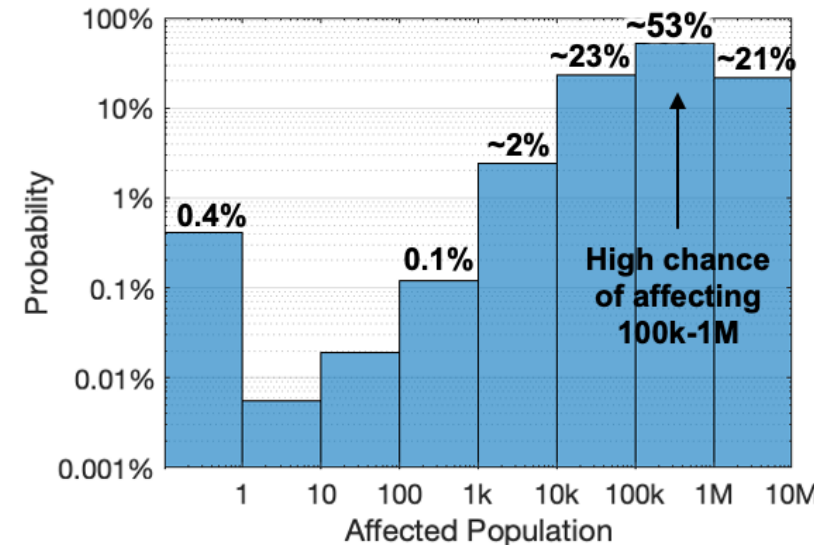
## Risk Swath

Regions potentially at risk to ground damage, given ranges of potential impact locations damage sizes.

Average-sized damage footprints are shown as rings over sample cities

## Hazard Summary

- Summary of potential impact hazards
- Ranges of damage sizes and severities
- How many people could be affected by the range of damage



## Population Risks

Probabilities of how many people could be affected by the potential damage.

Total risk probabilities reflect likelihoods of damage ranges across all potential asteroid sizes, properties, hazards, and impact locations modeled