Impact Risk Assessment:

PDC25 Hypothetical Asteroid Impact Exercise

Epoch 2 – Flyby Reconnaissance Mission Data

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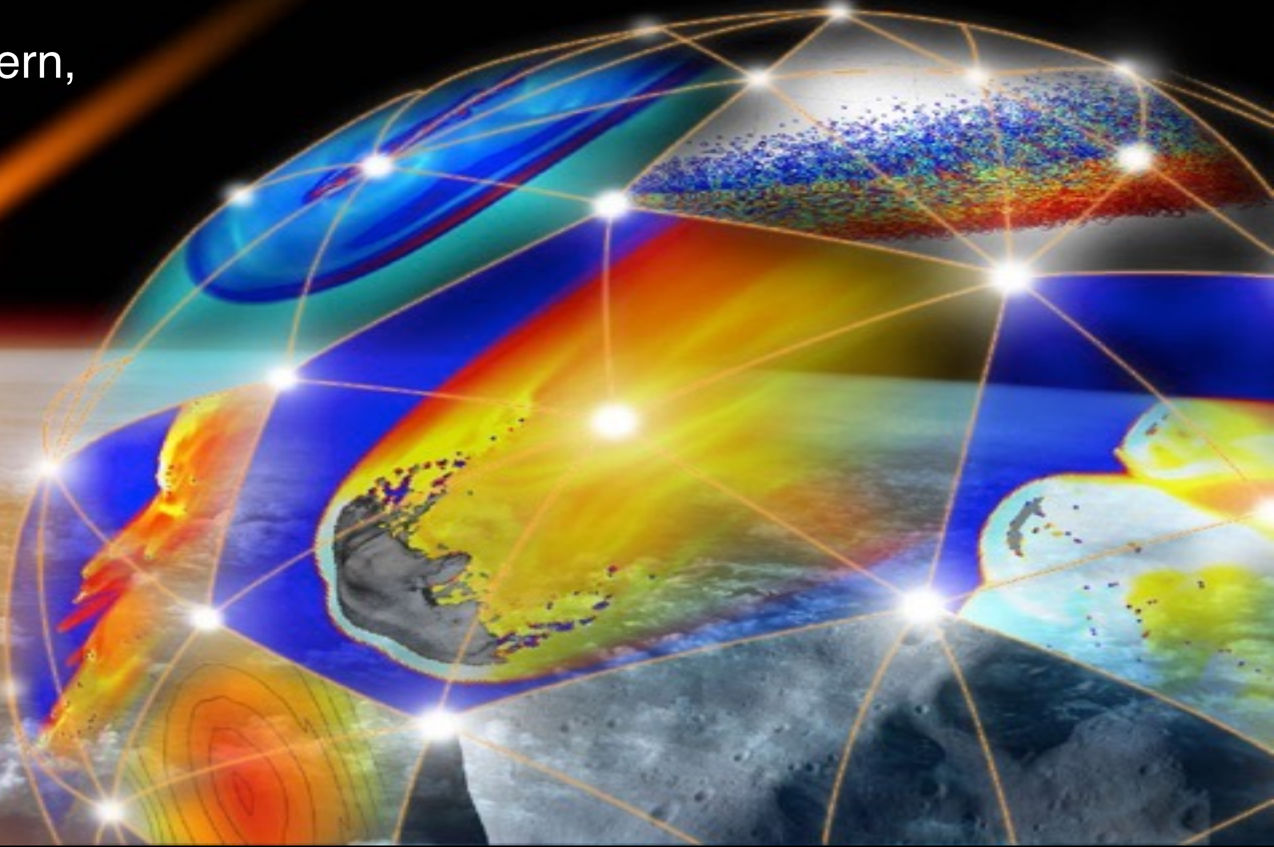
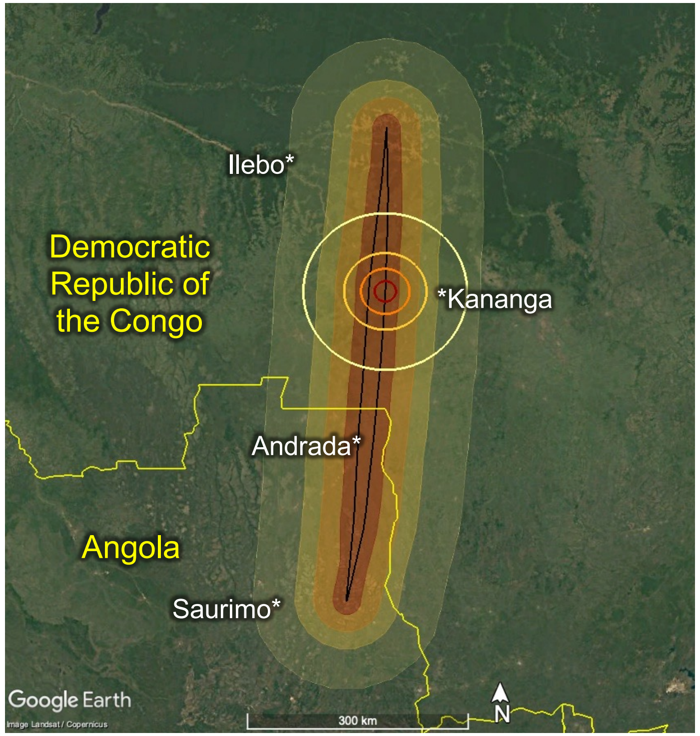


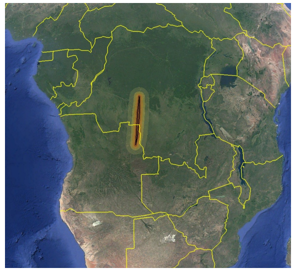
9th IAA Planetary Defense Conference
May 2025

Impact Hazard Summary

Epoch 2 assessment date: 28 April 2028

100% chance of Earth impact in 13 years by a **~150 m** asteroid with ~**45–160 Mt** of impact energy. Impact would cause extensive blast damage across a large region in Angola and/or DRC.





Serious	
Severe	
Critical	
Unsurvivable	
Damage Centers	

Risk region swath map: Regions potentially at risk, given range of damage locations and sizes (shaded areas). A median-sized damage area is shown at sample high-population location (rings).

- 100% chance of damage to populated regions among possible impact locations
- Primary hazard is a large, destructive blast wave from a high-energy, low-altitude airburst
- Damage severities could reach unsurvivable levels near airburst, extending to large areas of structural damage, fires, or shattered windows
- Serious damage would likely extend out ~100–120 km (~60–75 mi) or possibly further

Damage would most likely affect **many hundreds-of-thousands of people**, with a potential range between tens-of-thousands to over a million depending on location and damage areas.

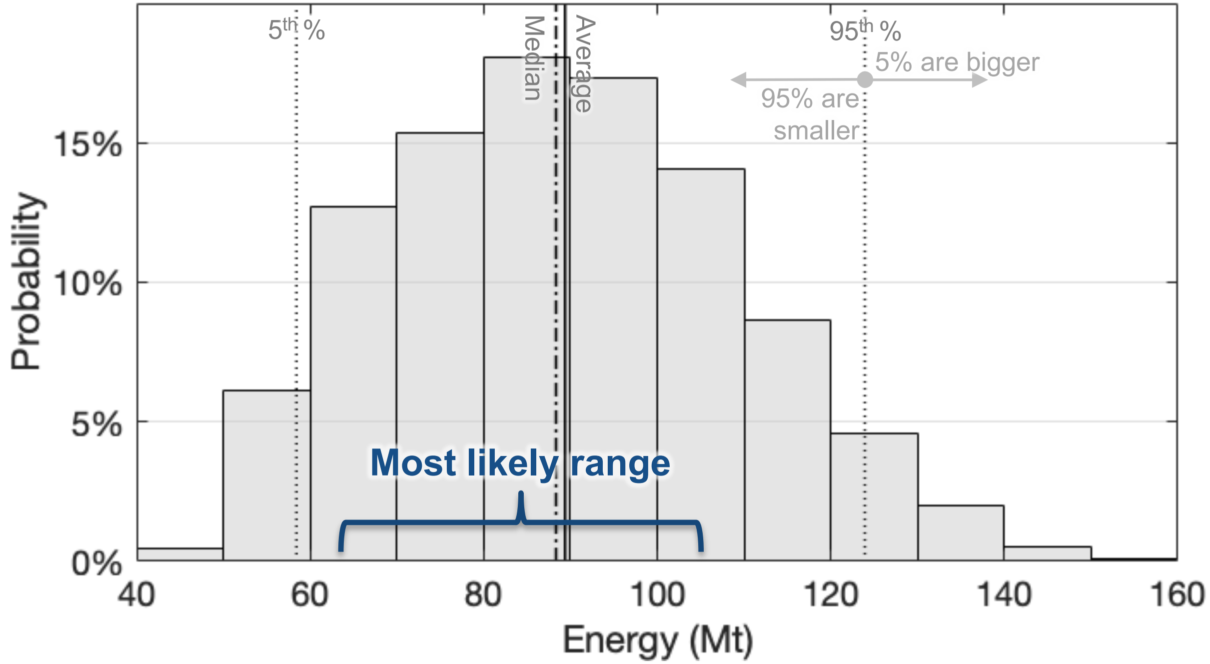
Asteroid Size & Properties

Flyby mission obtained direct measurement of physical size, but composition, mass, and impact energy are still moderately uncertain

- New data from flyby space mission:
  - Direct measurement of physical size (volume, shape)
  - Confirmed S taxonomy
- Estimated asteroid size and property ranges:
  - Asteroid size is most likely between ~148–153 m but could range from ~140–160 m (spherical equivalent)
  - Elongated shape around twice as long as wide
  - 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^3, potentially ~1.1–3.8 g/cm^3 with macroporosity between 0–60%

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

Asteroid Size Ranges & Probabilities

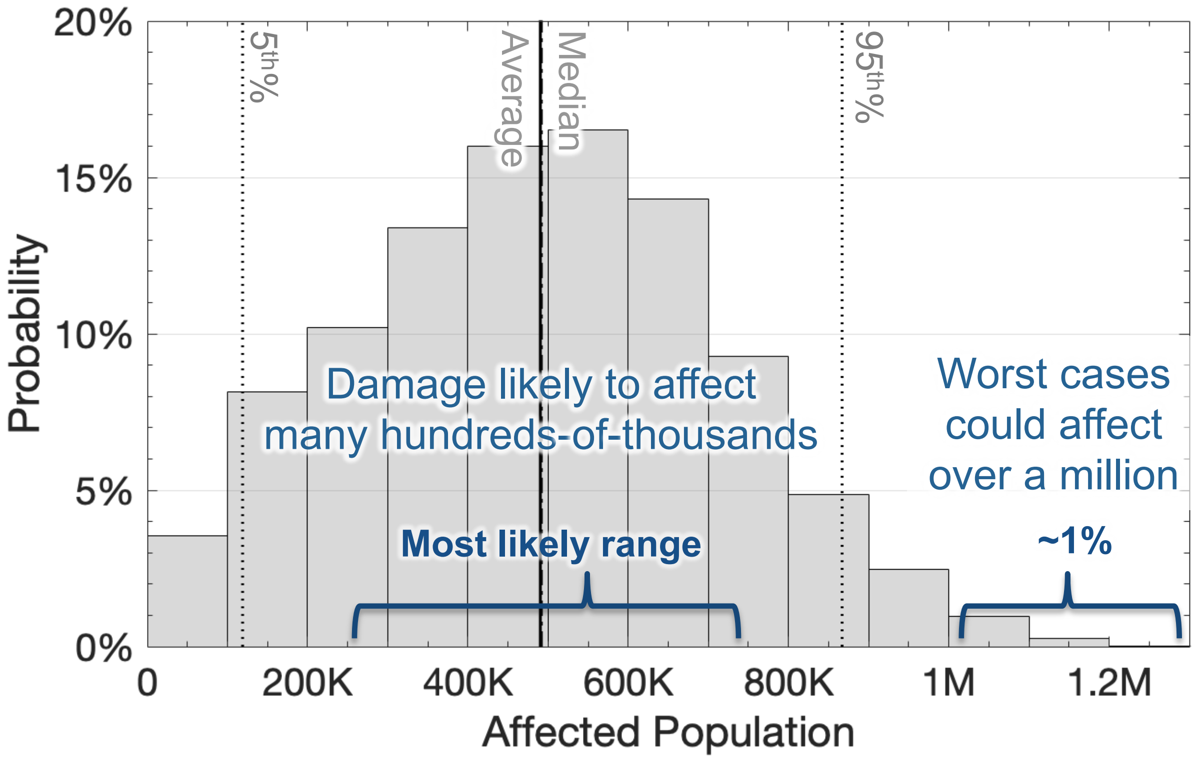


	Diameter (spherical)	Mass	Energy
Median	150 m (492 ft)	3.9e9 kg	88 Mt
Average	150 m (492 ft)	4.0e9 kg	89 Mt
Most likely	148–153 m (486–502 ft)	2.8e9–4.7e9 kg	63–105 Mt
5th–95th %ile	146–154 m (479–505 ft)	2.6e9–5.5e9 kg	58–124 Mt
Range Modeled	140–160 m (460–520 ft)	2.0e9–7.0e9 kg	45–160 Mt

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

Affected Population Risks

Damage probabilities among modeled impact sizes and locations



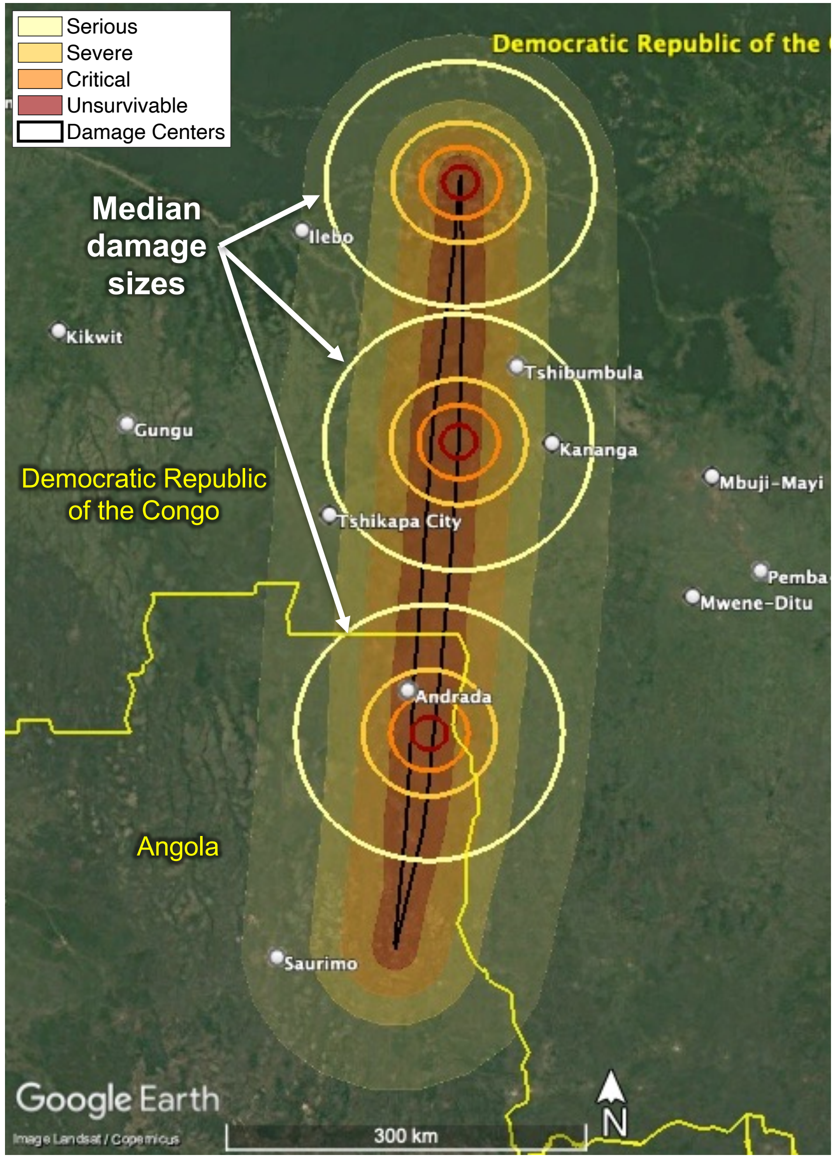
100% chance of damage to populated regions, most likely affecting ~260K–740K people, potentially over 1M people

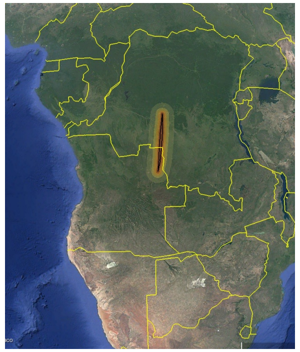
Affected population threshold	**Chance of damage *exceeding* threshold**
>30K	~100%
>100K	96%
>500K	48%
>800K	9%
>1M	1.3%

Affected population range: **~30 thousand to >1 million** people
~490 thousand people affected on average

[PAIR impact risk modeling: Wheeler et al., 2024]

Ground Damage Risk Swath





Areas ***potentially*** at risk to ground damage span a region 870 km long by 270 km wide, crossing parts of Angola and the Democratic Republic of the Congo

- This risk swath map show the extent of regions potentially at risk to local ground damage, including the range of possible damage sizes and locations
- Black border shows range of impact locations
- Shaded regions show potential damage extents (out to 95^{th} percentile of damage sizes)
- Rings show median-sized damage footprints at sample high-population locations

	Damage Level Description
Serious	Windows shatter, some structure damage
Severe	Widespread structure damage or third-degree burns
Critical	Residential structures collapse or clothing ignites
Unsurvivable	Devastation, structures flattened or burned

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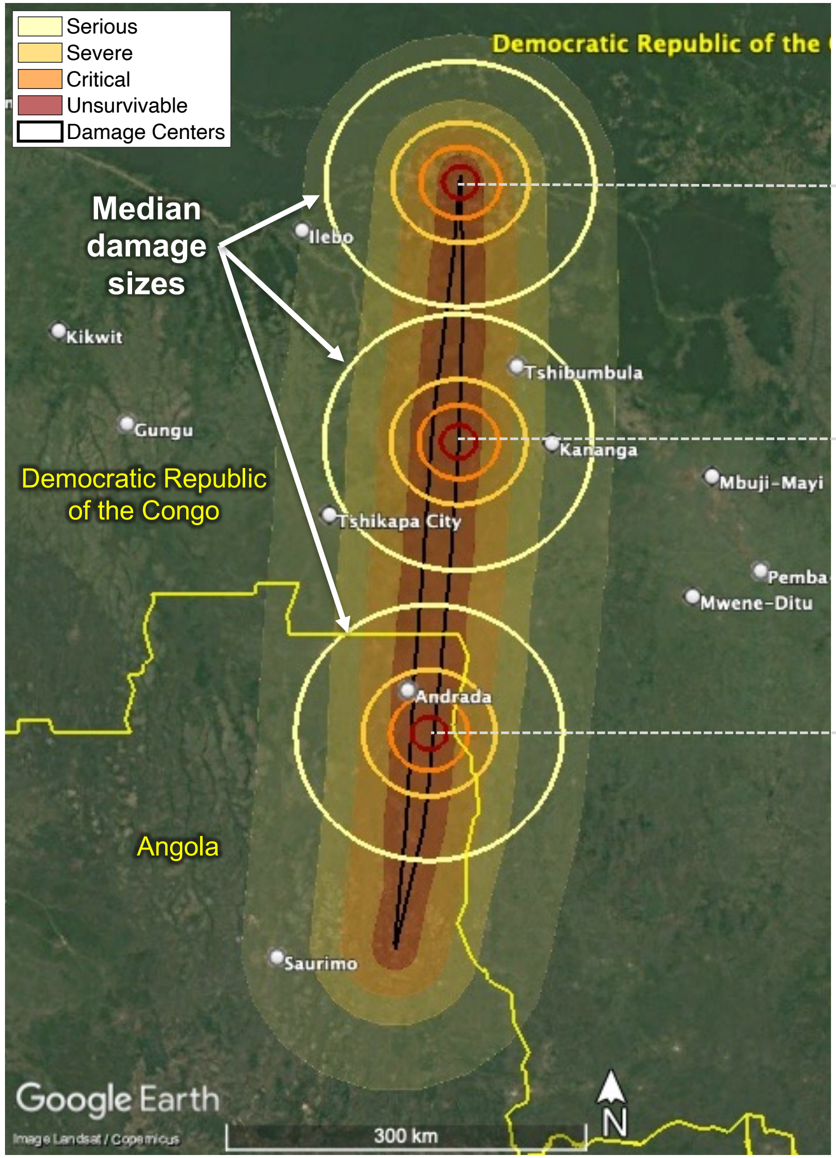
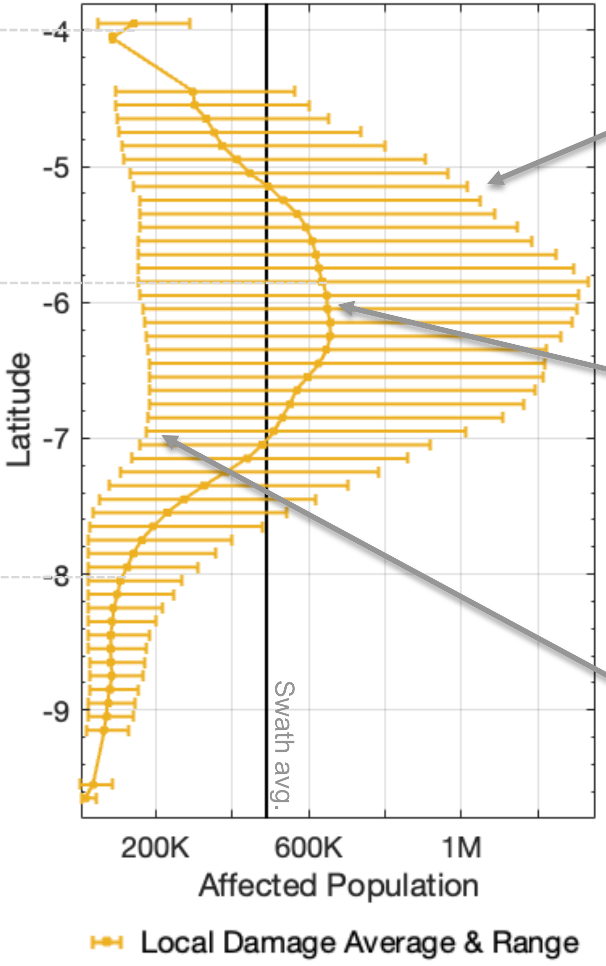
Affected Population Ranges by Location



Affected population ranges for potential damage sizes along impact locations



Large damage could affect hundreds-of-thousands to over 1 million people

Average damage could affect tens-of-thousands to ~700 thousand people

Smaller damage could affect several thousands to ~200 thousand people

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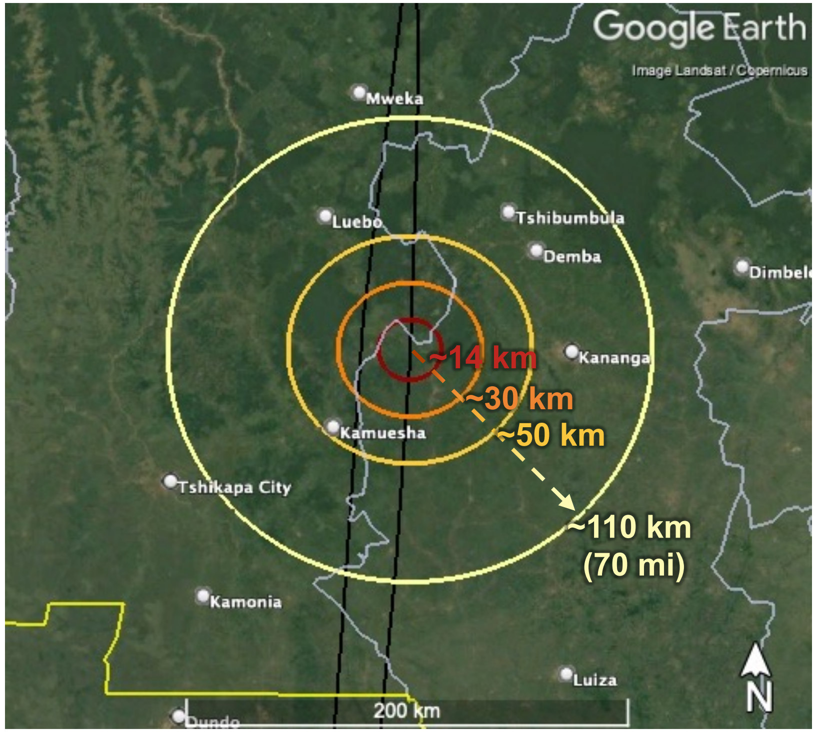
Potential Damage over Highest-Population Area

Example ground damage size ranges

Median (50^{th}%) Damage



Damage areas would most likely extend ~100–110 km (~60-75 miles) in radius

Large (95^{th}%) Damage

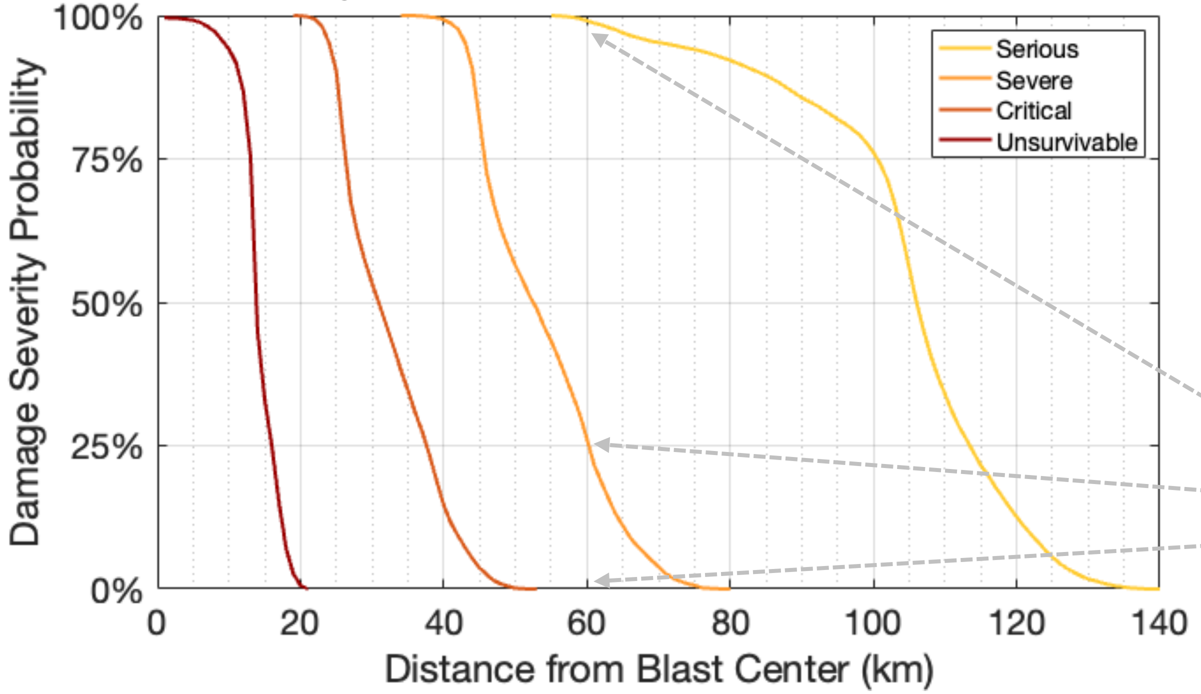
Largest damage areas could extend out over ~130 km (~80 miles) or more in radius

- Damage severities could reach **unsurvivable** levels near airburst, extending to larger areas of **structural damage, fires, and shattered windows**
- Damage is likely to span multiple cities and provinces

Legend:
- Serious
- Severe
- Critical
- Unsurvivable
- Damage Centers

Damage Severity Risks by Distance

Likelihood of damage reaching given severity levels as a function of distance



How far away from the blast would people need to evacuate to reduce damage risks below given probabilities?

Example: at 60 km away there would be

- ~99% chance of damage reaching at least serious levels
- ~25% chance of damage reaching at least severe levels
- no critical or higher damage levels expected

Distances at which damage risks fall below various levels

Damage Level	Description	50% risk	25% risk	10% risk	1% risk	<0.02% risk
Serious	Windows shatter, some structure damage	106 km	114 km	122 km	132 km	139 km
Severe	Widespread structure damage or third-degree burns	52 km	60 km	66 km	74 km	79 km
Critical	Residential structures collapse or clothing ignites	31 km	38 km	42 km	48 km	52 km
Unsurvivable	Devastation, structures flattened or burned	14 km	16 km	18 km	20 km	21 km

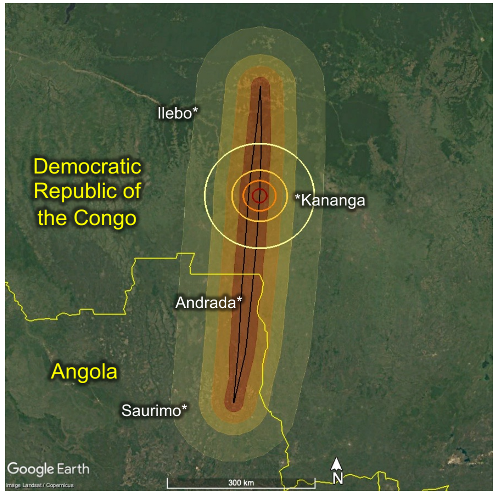
HYPOTHETICAL EXERCISE

Impact Risk Summary

Assessment 2 — Flyby Space Mission Data — 28 April 2028

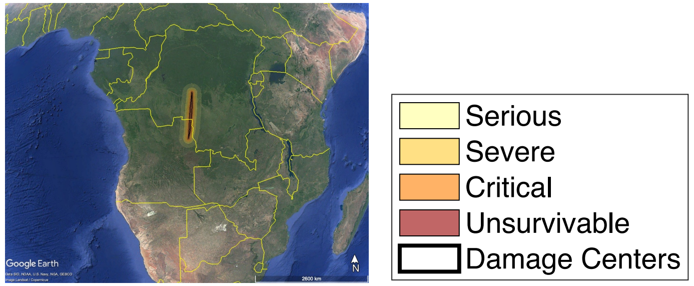
Asteroid Characterization Summary

- 100% chance of Earth impact on 24 April 2041 (~13 years)
- Available observation data: Flyby space mission obtained direct estimate of physical size (volume, shape) and confirmed S taxonomy
- Diameter (spherical equivalent): 140–160 m (460–520 ft), most likely 148–153 m (486–502 ft), median size 150 m (492 ft)
- Impact Energy: 45–160 Mt, most likely 60–105 Mt, median 88 Mt
- Properties: S type bulk density ranges, unknown structure, with an elongated shape around twice as long as it is wide



Risk Region Swath Map

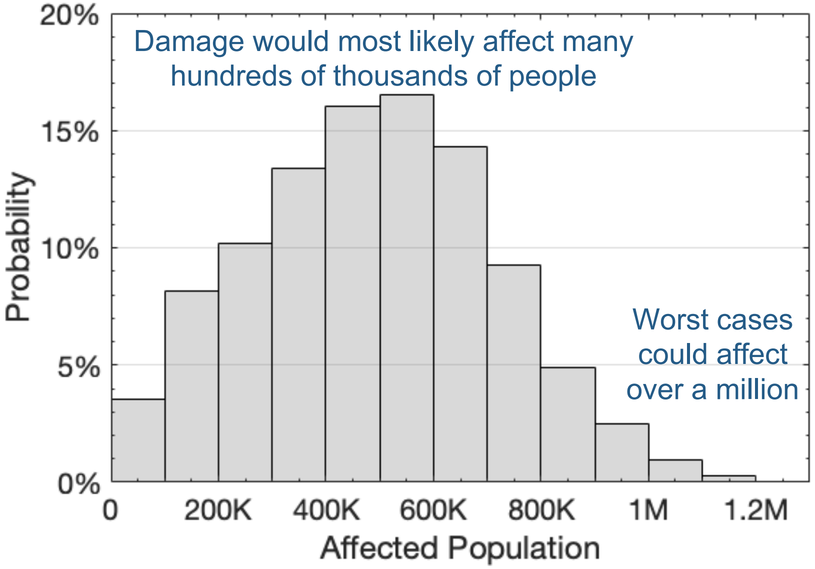
Regions potentially at risk, given range of damage locations and sizes (shaded areas). A median-sized damage area is shown at sample high-population location (rings).



Hazard Summary

- The asteroid is expected to cause extensive regional damage across Angola and/or the Democratic Republic of the Congo
- Primary hazard is a high-energy, low-altitude airburst and fireball causing destructive blast waves over large areas
- Blast damage would likely reach unsurvivable levels near airburst, with serious damage likely extending ~100–120 km (~60–75 mi) in radius, and possibly out over 130 km (80 mi) or more
- Thermal damage from larger fireballs could extend out ~0–14 km (9 mi) or possibly as far as ~40 km (25 mi) in radius, but is expected to be smaller and less severe than the blast damage

Affected Population Risks



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

Most likely: 260K–740K

Range: ~30K–1M

Average: ~490K

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PDC25 EPOCH 2 BACKUP DETAILS

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Local Blast & Thermal Damage Area Sizes

- Primary hazard is a high-energy, low-altitude airburst and fireball causing destructive blast waves and potential thermal damage
  - Significant blast damage is almost certain to occur, ranging from unsurvivable levels to shattered windows and structure damage over large areas
  - Thermal damage could also occur along with the blast damage but is almost always much smaller and less severe.
- Asteroid size measurements have refined estimated damage ranges, but uncertainty remains in asteroid energy, entry/breakup behavior, and airburst altitudes
  - Most likely outer damage radius range is ~100–120 km (~60–75 mi)
  - Largest outer damage areas could extend out ~130 km (~80 miles) or more in radius

Potential Blast Damage Severities and Sizes

Damage Level	Potential Blast Effects	Chance of Occurring	Damage Radius Ranges (km)		
			Median	Most Likely	Largest
Serious	Shattered windows, some structure damage	100%	110	100–120	130
Severe	Widespread structure damage	100%	50	45–60	80
Critical	Most residential structures collapse	100%	30	25–25	50
Unsurvivable	Complete devastation	99.6%	14	12–17	10

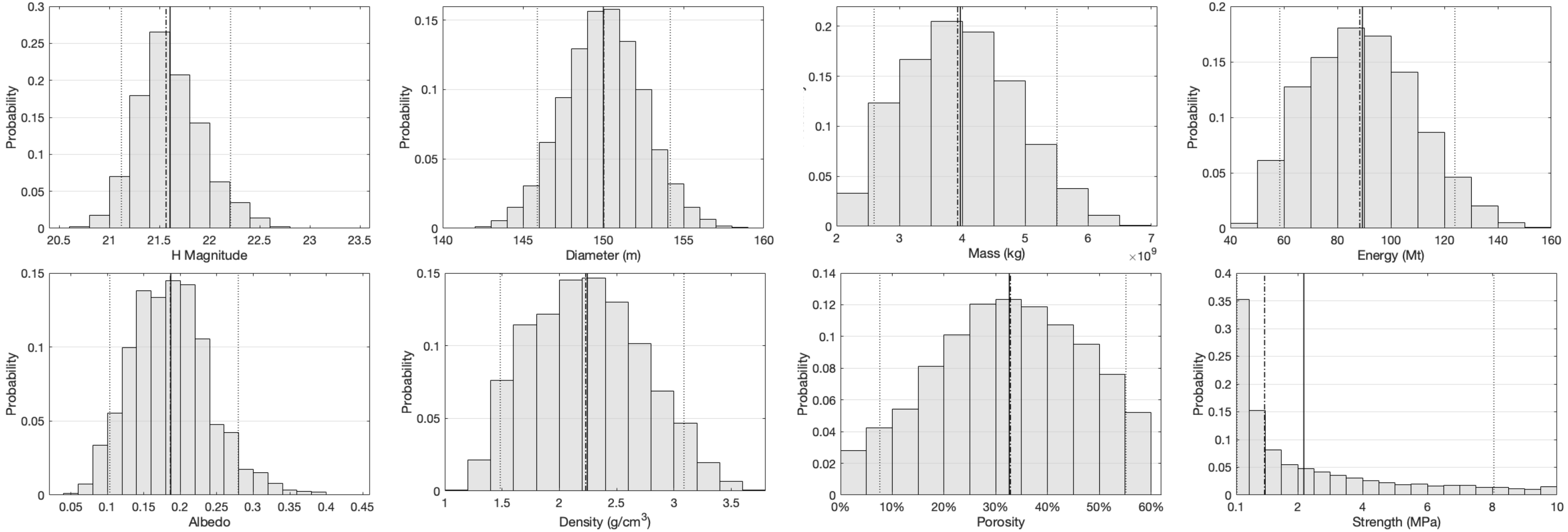
Potential Thermal Damage Severities and Sizes

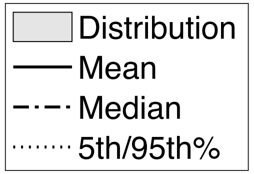
Damage Level	Potential Thermal Effects	Chance of Occurring	Damage Radius Ranges (km)		
			Median	Most Likely	Largest
Serious	2nd degree burns	69%	8	0–14	40
Severe	3rd degree burns	59%	4	0–10	30
Critical	Clothing ignition	43%	0	0–5	20
Unsurvivable	Structure ignition	35%	0	0–3	18

Asteroid Property Details

Statistical percentiles and highest-probability interval ranges for asteroid property distribution samples modeled*

	Mean	5th%	25th%	Median (50th%)	75th%	95th%	Most Likely Range (68%)	Full Range Modeled
Diameter (m)	150	146	148	150	152	154	148 – 153	141 – 159
Mass (kg)	3.97E+09	2.60E+09	3.30E+09	3.92E+09	4.59E+09	5.51E+09	2.81E+09 – 4.67E+09	2.01E+09 – 7.03E+09
Energy (Mt)	89	58	74	88	103	124	63 – 105	45 – 158
H Magnitude	21.61	21.12	21.38	21.57	21.81	22.21	21.27 – 21.88	20.60 – 23.51
Albedo	0.19	0.10	0.15	0.19	0.22	0.28	0.13 – 0.23	0.03 – 0.45
Density (kg/m³)	2244	1484	1862	2229	2590	3088	1613 – 2646	1128 – 3705
Porosity (%)	33%	8%	22%	33%	44%	55%	19 – 50%	0 – 60%
Strength (MPa)	2.14	0.12	0.31	1.01	3.10	7.92	0.10 – 2.25	0.10 – 10





* Property stats are each computed *independently*. Multiple values from a given percentile cannot necessarily be combined to represent a single physically-plausible asteroid.

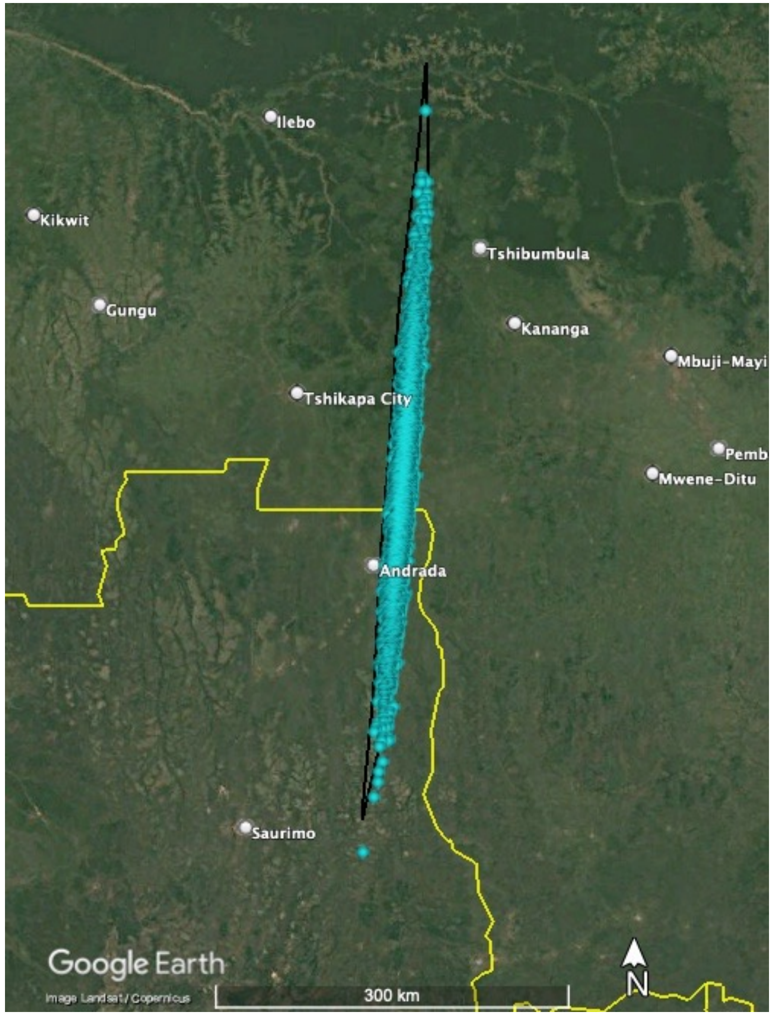
[Property model: J. Dotson et al., 2024]

HYPOTHETICAL EXERCISE

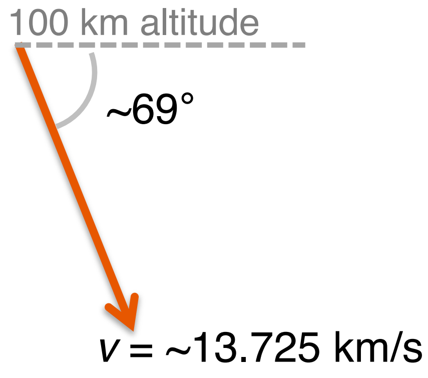
Entry Parameters & Locations

- **Chance of Earth impact: 100%**
- **Impact Locations:**
  - Potential entry points span a narrow region roughly 470 km long over Angola and the Democratic Republic of the Congo.
  - Entry parameters vary only slightly among the entry points, and are well-known for given points
- **Entry Velocity:**
  - ~13.725 km/s (13.723–13.728 km/s)
  - Little variation across points
- **Entry Angle:**
  - Entry angle is moderately steep at around ~69° (~67°–71°) from horizontal
- **Entry Direction (Heading):**
  - Entry flight directions are nearly directly northward

Modeled Entry Points & Airburst Region



Entry Trajectory



The 5000 sampled entry points modeled in the risk assessment are shown as cyan dots. Entry points are at 100 km altitude. The black outline bounds locations of the airbursts along the northward entry trajectories.

[Impact entry data: D. Farnocchia, CNEOS/JPL, https://cneos.jpl.nasa.gov/pd/cs/pdc25/]

Additional Resources

- Additional scenario information, results, and tools will be available on the CNEOS exercise website: https://cneos.jpl.nasa.gov/pd/cs/pdc25/
  - **Interactive impact risk dashboard:** Additional PAIR impact risk results for this exercise scenario can be explored in an interactive web dashboard tool, which includes additional hazard summaries, plots and data tables on damage sizes and severities, and zoomable maps of the damage risk swath and sample damage footprint examples.
  - **Google Earth damage risk maps:** A Google Earth KML file of the damage risk swath and sample damage footprint sizes for this exercise scenario will be available for download.
  - **Introduction to Asteroid Impact Risk Assessment presentation**: Introductory information on asteroid threat assessment and details on the risk modeling, impact hazards, affected population estimates, and damage risk maps.
  - **Asteroid physical property characterization**: Further details on physical characterization of asteroid 2024 PDC25 after the Epoch 2 flyby reconnaissance mission.
  - **Orbital details:** JPL/CNEOS orbit information, data, and tools.
- ATAP impact risk modeling references:
  - Details on the **Probabilistic Asteroid Impact Risk (PAIR)** model and impact threat assessment process used to produce these results are published in: Wheeler et al., 2024 [doi:10.1016/j.actaastro.2023.12.049]
  - Details on the **Asteroid Property Inference Network (APIN)** model used to generate the asteroid property cases for this assessment are published in: Dotson et al., 2024 [doi:10.1016/j.actaastro.2024.04.020]
  - See reference slide for additional ATAP PAIR, hazard modeling, and entry modeling journal papers.

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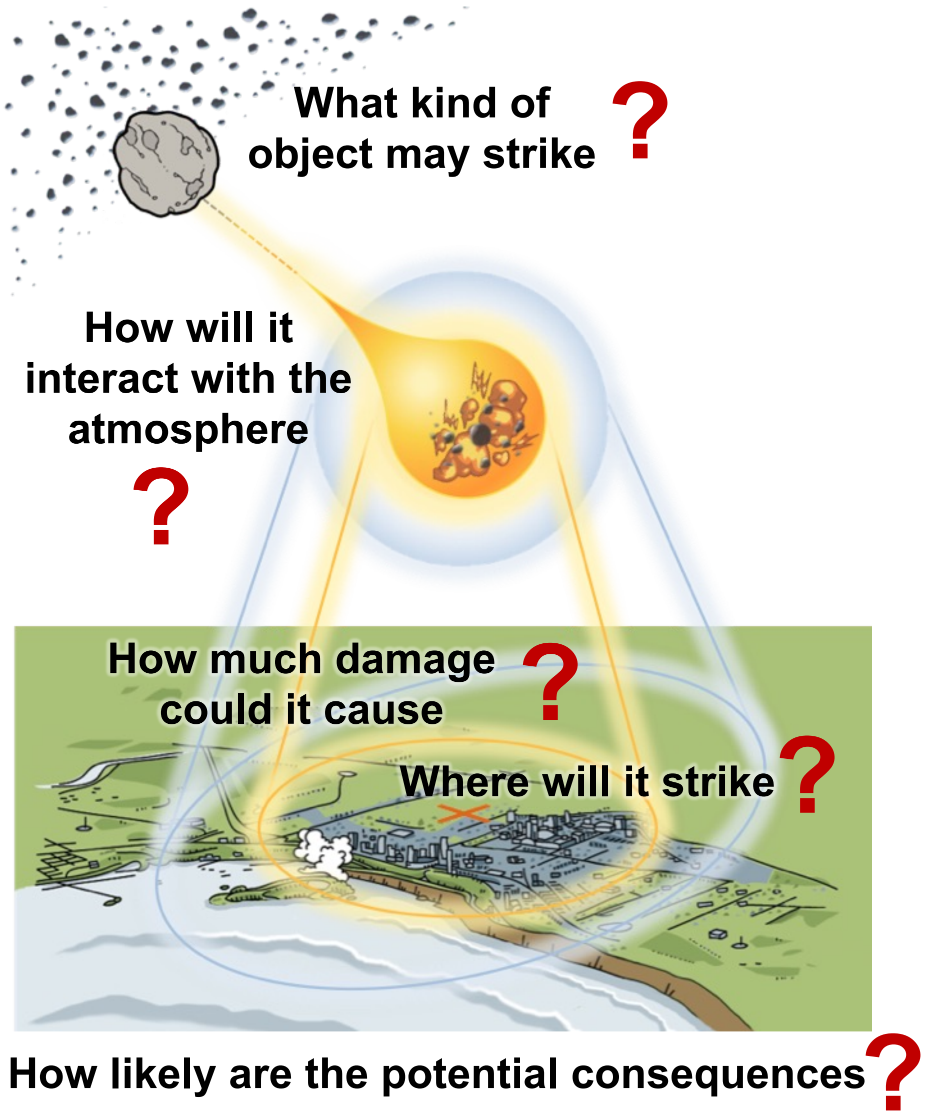
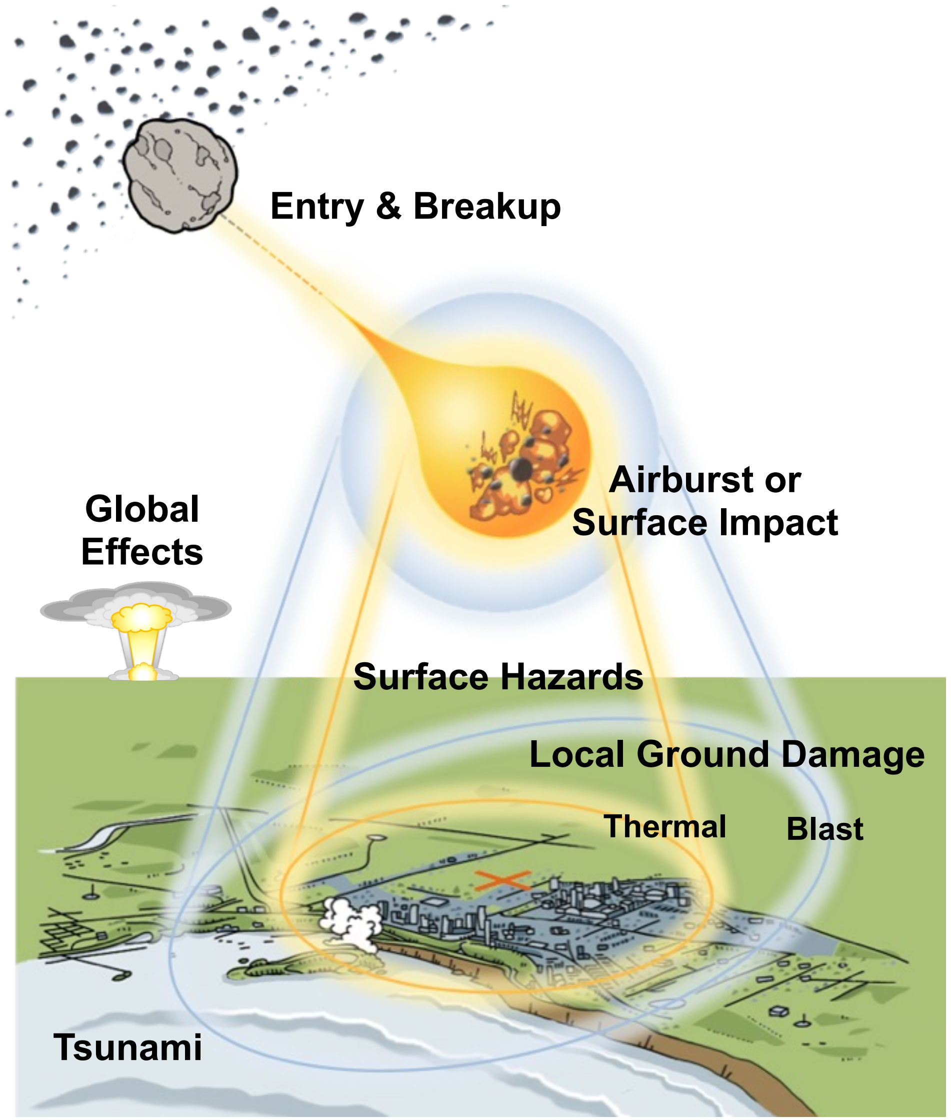
PROBABILISTIC ASTEROID IMPACT RISK MODELING DETAILS & REFERENCES

What is Asteroid Impact Risk Assessment?



- Risk assessment evaluates both the severity and likelihood of potential outcomes, given the uncertainties about 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)
  - Initial 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)

Asteroid Impact Hazards

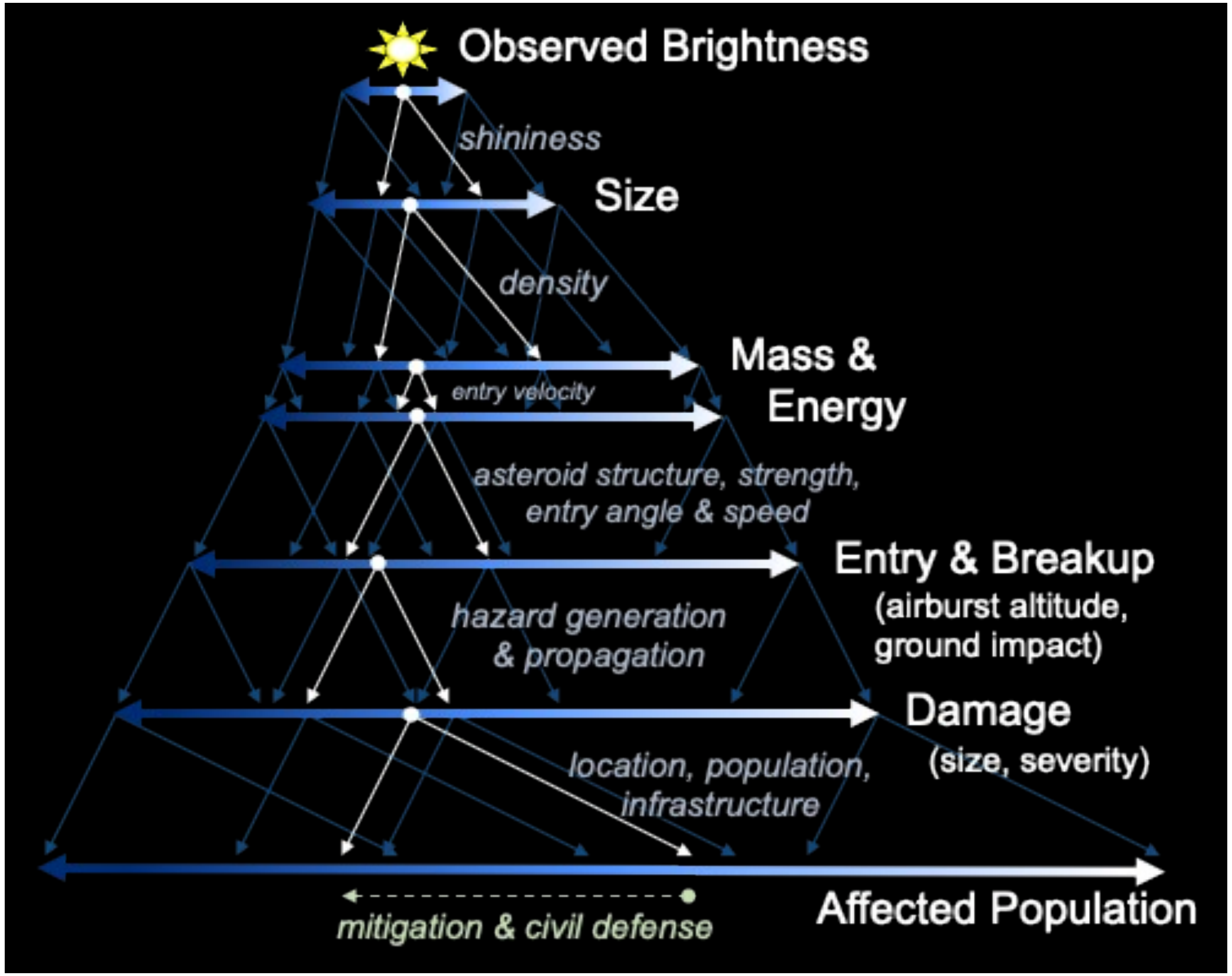


- **Asteroids can cause damage by breaking up and bursting in the atmosphere or impacting the surface**
- **Primary impact hazards are:**
  - **Local ground damage:** Airbursts and surface impacts can produce explosive blast waves and thermal fireballs
  - **Tsunami:** Ocean impacts could cause significant tsunami inundation if impact is very large or near to a populated coast
  - **Global effects:** Large-scale impacts could produce enough atmospheric ejecta to cause global climatic effects
- **The asteroid sizes in this scenario are most likely to cause blast damage from a high-energy, low-altitude airburst.**

Asteroid Property & Damage Uncertainties

- Evaluating the potential damage & risk from an asteroid threat involves many large uncertainties
  - Asteroid size and property uncertainties from limited observational data
  - Potential impact location, velocity, and entry angle from orbital uncertainties
  - Uncertainties in entry and damage modeling for large impact events
- Each factor contributes additional uncertainty, leading to very large ranges of potential impact energy and resulting damage estimates
- Some uncertainties will shrink as we gain data (impact locations, asteroid size), while some factors may remain unknown (damage modeling uncertainties)

Cascade of uncertainty ranges from asteroid observation to damage potential



HYPOTHETICAL EXERCISE

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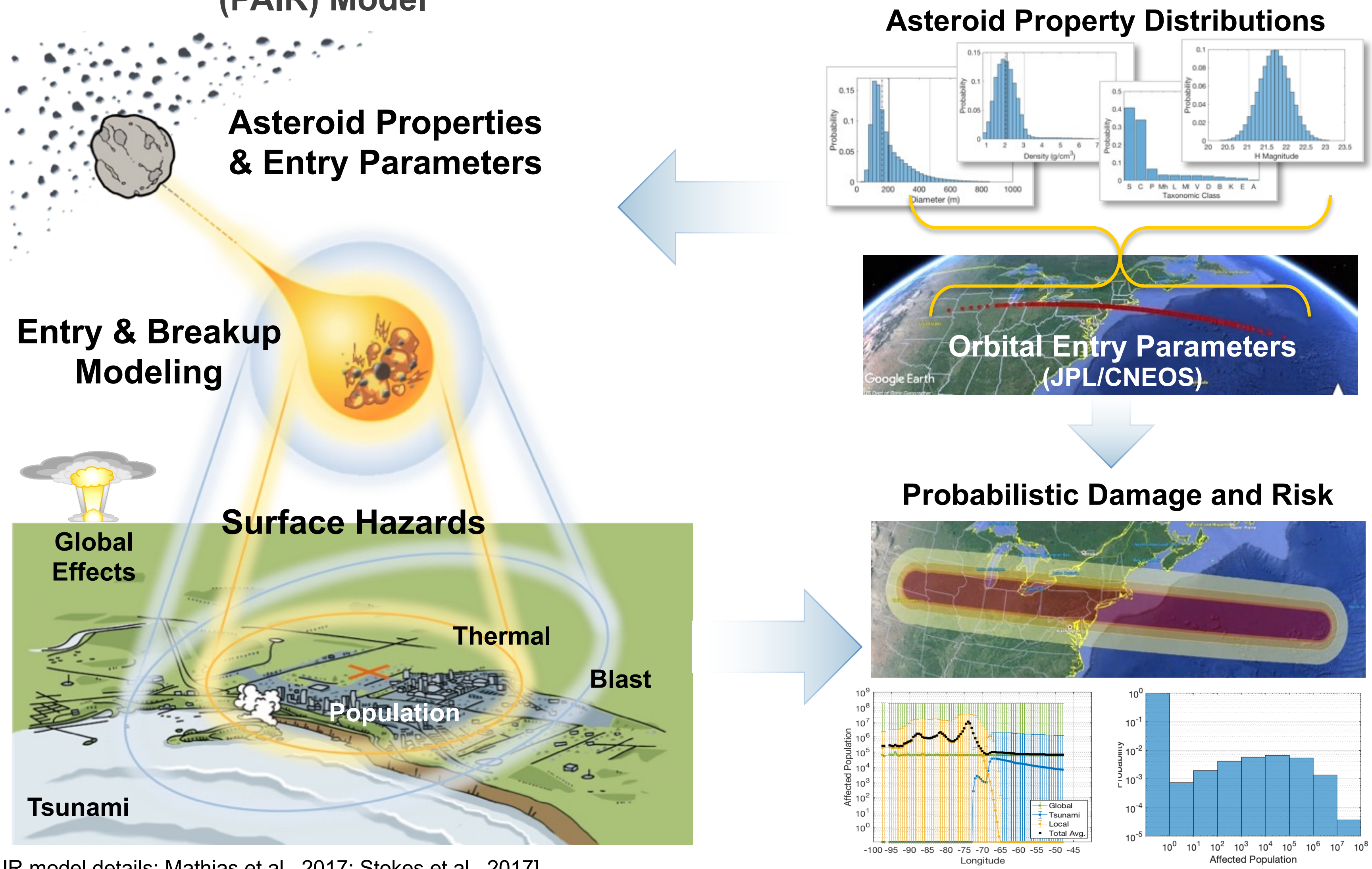
Asteroid Impact Threat Assessment

Probabilistic Asteroid Impact Risk (PAIR) Model

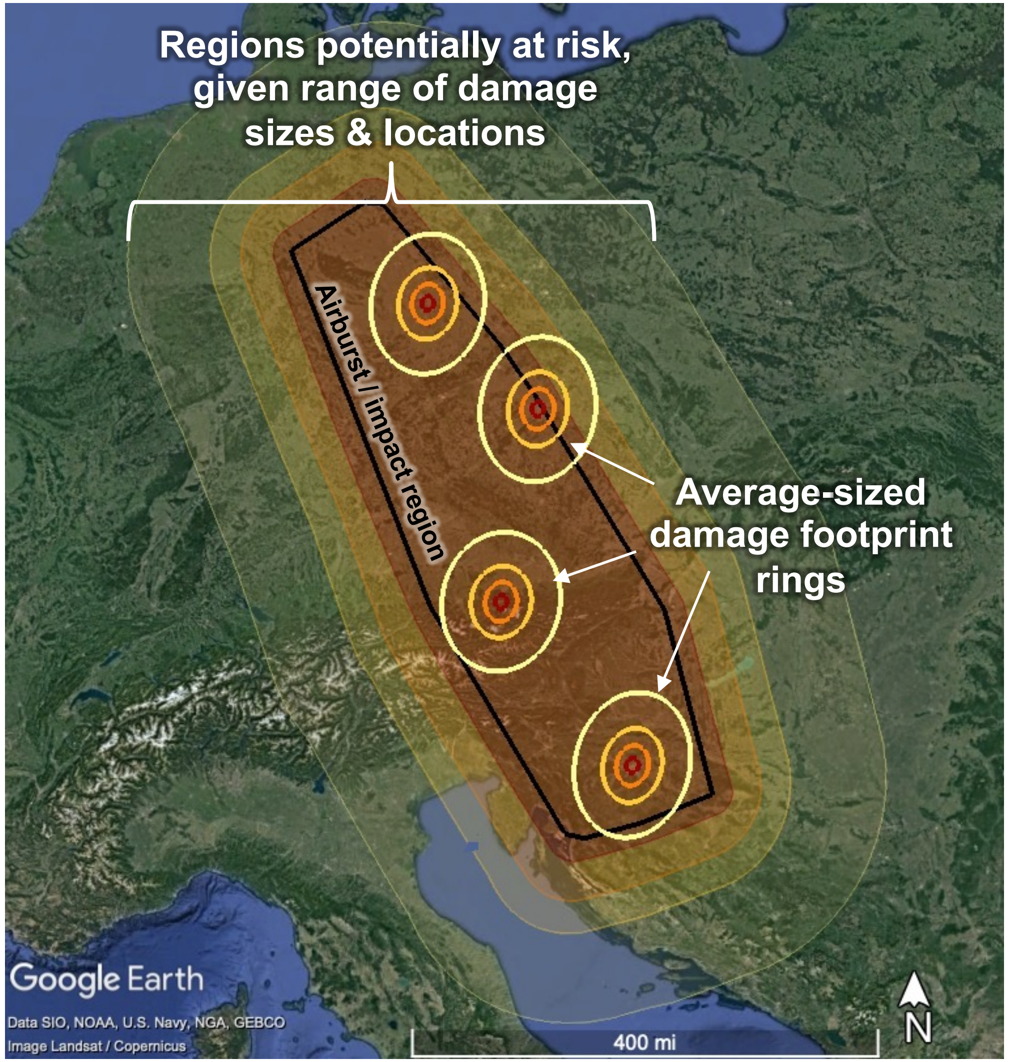
Impact Threat Scenario



- Risk model uses fast-running 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 (blast, thermal, tsunami, global effects) are modeled for each case.
- Probabilities of the resulting damage sizes, severities, and affected populations are computed.
- Regions at-risk to local damage are mapped.

[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

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

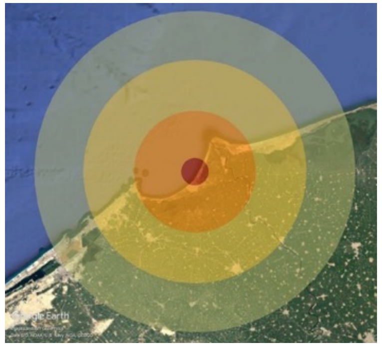
- Black outline shows range of potential impact points (damage-center locations)
- Shaded areas show potential at-risk regions given range of damage sizes and locations
- Rings show median-sized damage footprints at sample locations

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

* Swath extents shown for the 2024 PDC25 results cover local ground damage sizes out to the 95th percentile. Local damage maps do not include regions potentially at at risk to tsunami or global effects.

Local Blast & Thermal Damage Effects

- Large impacts and airburst can generate destructive blast waves and thermal heat radiation that can cause various levels of injury, fatalities, structural damage, and/or fires extending far around the impact location.
- Blast and thermal ground damage are assessed *independently* at four equivalent severity levels
  - The damage region for each severity level is determined from the *larger* of the equivalent blast *or* thermal damage area
  - Local ground damage regions indicate *either* blast or thermal effects could exceed the given severity threshold (*not* necessarily the occurrence of both effects within the entire region)
  - Local affected population estimates within each region are scaled by the relative severity of each damage level
- Blast is the predominant hazard for most airbursting and sub-global-scale asteroid sizes
  - Blast tends to be larger and more severe than the potential thermal damage in most cases, and usually defines the larger outer damage risk regions for emergency response planning
  - Depending on blast energy, airbursts can cause larger blast damage than ground impacts, while thermal damage decreases with airburst altitude



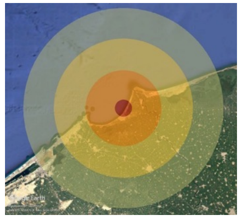
Damage Level	Relative Severity	Blast Damage Effects	Thermal Damage Effects
Serious	10%	Shattered windows, some structural damage	2nd degree burns
Severe	30%	Widespread structural damage	3rd degree burns
Critical	60%	Most residential structures collapse	Clothing ignites
Unsurvivable	100%	Complete devastation	Structures ignites, incineration

Affected Population Risks

- For each impact case modeled, PAIR computes the estimated number of people affected by each hazard type, based on the modeled damage location, area, severity, and local population
  - **Local blast & thermal ground damage:** affects 10–100% of local population depending on severity (additional details in following slides)
  - **Tsunami:** affects up to 10% of the local population depending on flood depth in each coastal area (based on tsunami wave height and ground elevation)
  - **Global effects:** affects estimated fractions of total world population, based on total impact energy and a randomly sampled severity factor
  - **Total affected population** estimates for each impact case are taken as the number of people affected by the largest hazard produced (not sums of multiple hazards)
- **Affected population risks:** population results for each impact case are aggregated to compute total population ***risks,*** reflecting the likelihoods of the possible effects for the overall impact scenario (i.e., probabilities of the impact affecting given ranges or thresholds of people)
- **Population data source:** SEDAC Gridded Population of the World (GPW) v4.11 gridded population counts, year 2020 UN-adjusted values

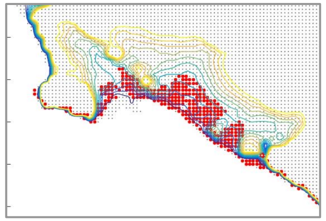
[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

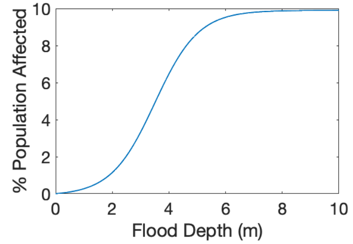
Local Blast & Thermal Affected Population



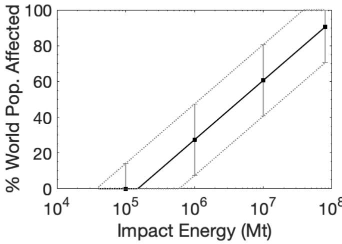
Severity	% Pop. Affected
Serious	10%
Severe	30%
Critical	60%
Unsurvivable	100%

Tsunami Affected Population



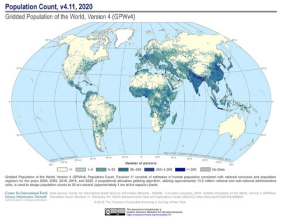


Global Effects Affected Populations

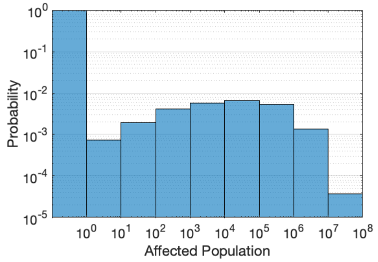


Impact Energy (MT)	% Population Affected		
	Min	Nominal	Max
4.E+04	0	0	0
8.E+04	0	0	10
2.E+05	0	0	20
3.E+05	0	10	30
6.E+05	0	20	40
1.E+06	10	30	50
2.E+06	20	40	60
5.E+06	30	50	70
1.E+07	40	60	80
2.E+07	50	70	90
4.E+07	60	80	100
8.E+07	70	90	100

SEDAC Gridded Population Data



Population Risks



HYPOTHETICAL EXERCISE

REFERENCES

HYPOTHETICAL EXERCISE

ATAP Impact Risk & Hazard Modeling Papers

Probabilistic Asteroid Impact Risk (PAIR) & Asteroid Characterization:

- **Wheeler et al., 2024.** Risk assessment for asteroid impact threat scenarios. Acta Astronautica. doi:10.1016/j.actaastro.2023.12.049
- **Dotson et al., 2024.** Consequences of asteroid characterization on the state of knowledge about inferred physical parameters and impact risk. Acta Astronautica. doi:10.1016/j.actaastro.2024.04.020
- **Coates et al., 2024.** Sensitivity study of impact risk model results to thermal radiation damage model for large objects. Acta Astronautica. doi:10.1016/j.actaastro.2024.02.022
- **Chomette et al., 2024.** Machine learning for the prediction of local asteroid damages. Acta Astronautica. doi:10.1016/j.actaastro.2024.01.049
- **Robertson et al., 2024.** Evacuation and shelter plans for asteroid impacts informed by hurricanes and nuclear explosions. Acta Astronautica. doi:10.1016/j.actaastro.2023.11.020
- **Mathias et al., 2017.** A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus. doi:10.1016/j.icarus.2017.02.009
- **Stokes et al., 2017.** Update to determine the feasibility of enhancing the search and characterization of NEOs. NASA. 2017_neo_sdt_final_e-version.pdf
- **Wheeler & Mathias, 2018.** Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus. doi:10.1016/j.icarus.2018.12.017
- **Rumpf et al., 2020.** Deflection driven evolution of asteroid impact risk under large uncertainties. Acta Astronautica. doi:10.1016/j.actaastro.2020.05.026
- **Reddy et al., 2024.** 2023 DZ2 Planetary Defense Campaign. Planet. Sci. J. doi:10.3847/PSJ/ad4a6d
- **Reddy et al., 2022.** Apophis planetary defense campaign. Planet. Sci. J. doi:10.3847/PSJ/ac66eb
- **Reddy et al., 2022.** Near-Earth Asteroid (66391) Moshup (1999 KW4) Observing Campaign: Results from a Global Planetary Defense Characterization Exercise. Icarus. doi:10.1016/j.icarus.2021.114790
- **Reddy et al., 2019.** Near-Earth Asteroid 2012 TC4 Campaign: results from a global planetary defense exercise. Icarus. doi:10.1016/j.icarus.2019.02.018
- **Geographic population data:** SEDAC GPW v4.11 gridded population counts, year 2020 (UN-adjusted values). CIESIN, Columbia University, 2016. doi:10.7927/H4SF2T42

Entry & Breakup Energy Deposition Modeling:

- **Wheeler et al., 2018.** Atmospheric energy deposition modeling and inference for varied meteoroid structures. doi:10.1016/j.icarus.2018.06.014
- **Wheeler et al., 2017.** A fragment-cloud model for asteroid breakup and atmospheric energy deposition. Icarus. doi:10.1016/j.icarus.2017.02.011
- **Register et al., 2020.** Interactions between asteroid fragments during atmospheric entry. Icarus. doi:10.1016/j.icarus.2019.113468

Blast Modeling and Simulation:

- **Aftosmis, et al., 2019.** Simulation-based height of burst map for asteroid airburst damage prediction. Acta Astronautica. doi:10.1016/j.actaastro.2017.12.021
- **Robertson & Mathias, 2019.** Hydrocode simulations of asteroid airbursts and constraints for Tunguska. Icarus. doi:10.1016/j.icarus.2018.10.017
- **Aftosmis, et al., 2016.** Numerical simulation of bolide entry with ground footprint prediction. 54th AIAA Aerospace Sciences Meeting. doi:10.2514/6.2016-0998

Thermal Radiation Modeling and Simulation:

- **Johnston et al., 2021.** Simulating the Benešov bolide flowfield and spectrum at altitudes of 47 and 57 km. Icarus. doi:10.1016/j.icarus.2020.114037
- **Johnston & Stern, 2018.** A model for thermal radiation from the Tunguska airburst. Icarus. doi:10.1016/j.icarus.2019.01.028
- **Johnston et al., 2018.** Radiative heating of large meteoroids during atmospheric entry. Icarus. doi:10.1016/j.icarus.2018.02.026

Tsunami Simulations:

- **Berger & LeVeque, 2022.** Towards adaptive simulations of dispersive tsunami propagation from an asteroid impact. Proc. ICM, 2022. doi:10.4171/icm2022/73
- **Robertson & Gisler, 2019.** Near and far-field hazards of asteroid impacts in oceans. Acta Astronautica. doi:10.1016/j.actaastro.2018.09.018
- **Berger & Goodman, 2018.** Airburst-generated tsunamis. Pure Appl. Geophys. doi:10.1007/s00024-017-1745-1