HYPOTHETICAL EXERCISE

Probabilistic Asteroid Impact Risk Assessment:
2023 PDC Hypothetical Impact Exercise Epoch 2

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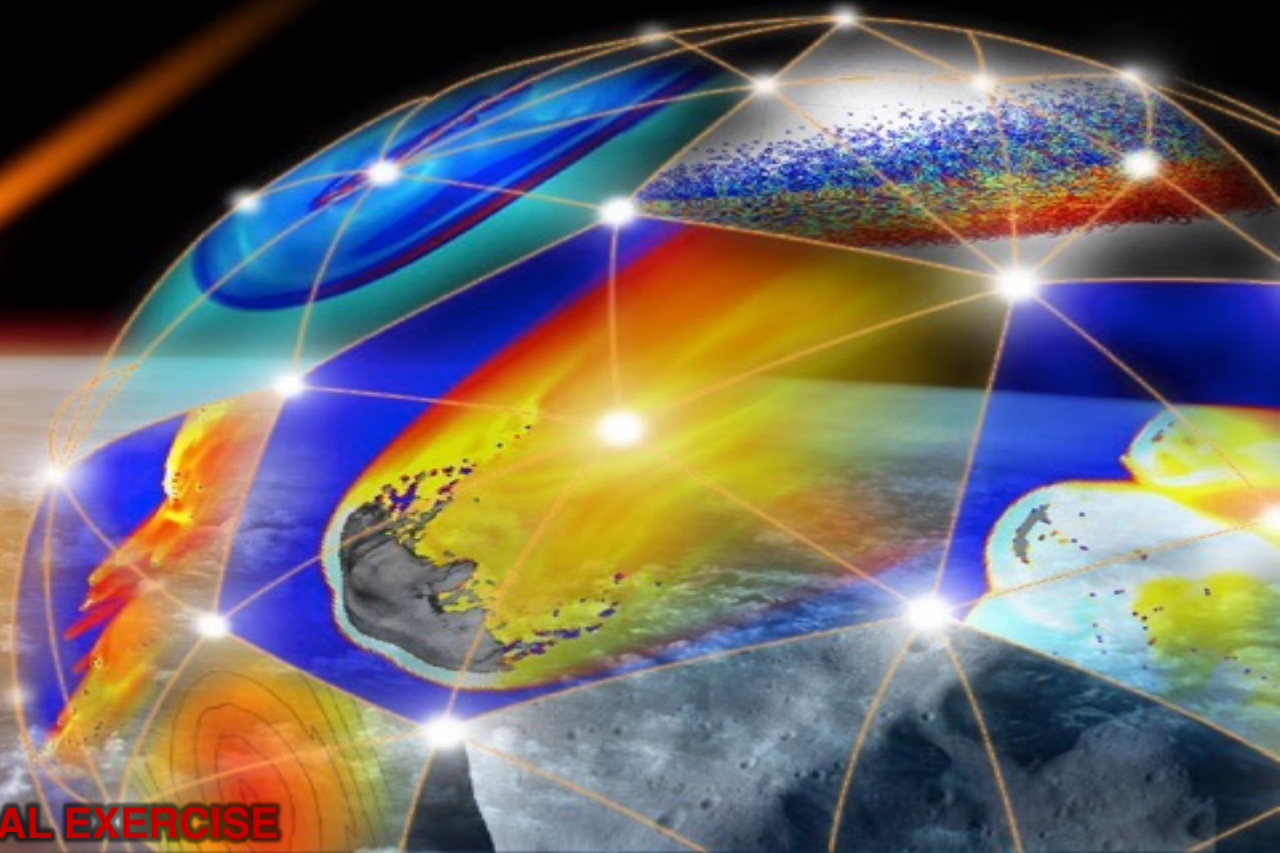


8th IAA Planetary Defense Conference
April 2023

HYPOTHETICAL EXERCISE

Contents

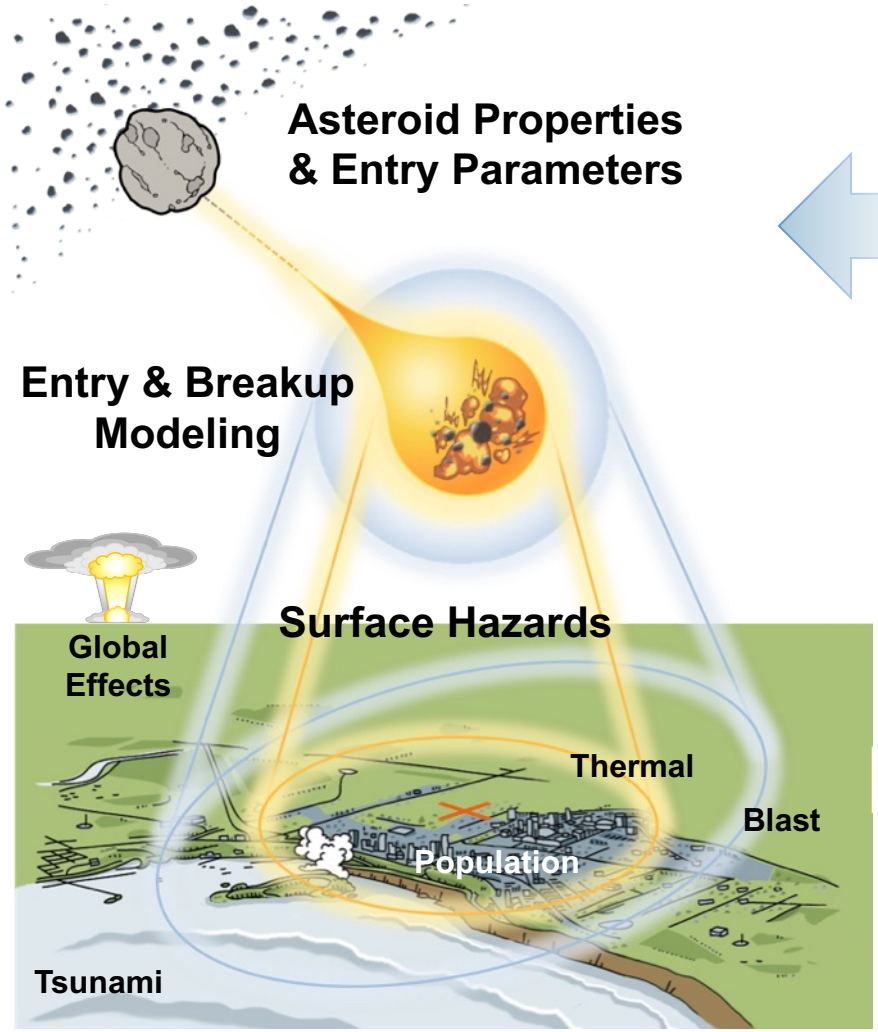
This presentation summarizes impact risk assessment results for Epoch 2 of the 2023 PDC hypothetical asteroid impact scenario. Epoch 2 represents the assessment phase before launch of the first reconnaissance mission, around 7 months after initial discovery, when the asteroid orbit is confirmed to impact Earth somewhere over Africa, and asteroid property estimates include minor typing and albedo refinements from remote ground observations.

Introductory information on the asteroid threat assessment processes and details on the risk modeling, impact hazards, affected population estimates, and damage risk maps used in this assessment can be found in the Introduction to Impact Risk Assessment presentation on the CNEOS impact scenario website.

Contents:

Asteroid Impact Threat Assessment

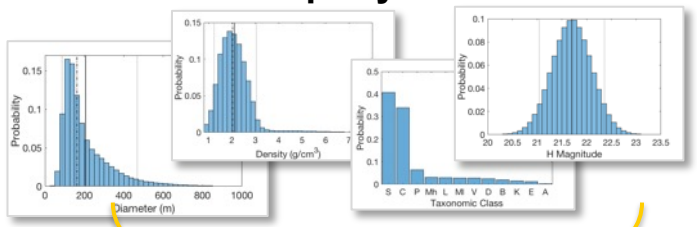
Probabilistic Asteroid Impact Risk (PAIR) Model



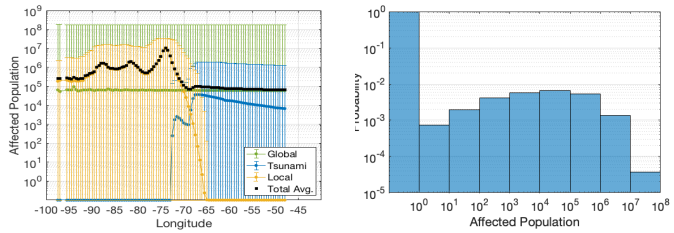
[PAIR model: Mathias et al., 2017; Stokes et al., 2017]

Impact Threat Scenario

Asteroid Property Distributions



Probabilistic Damage and Risk



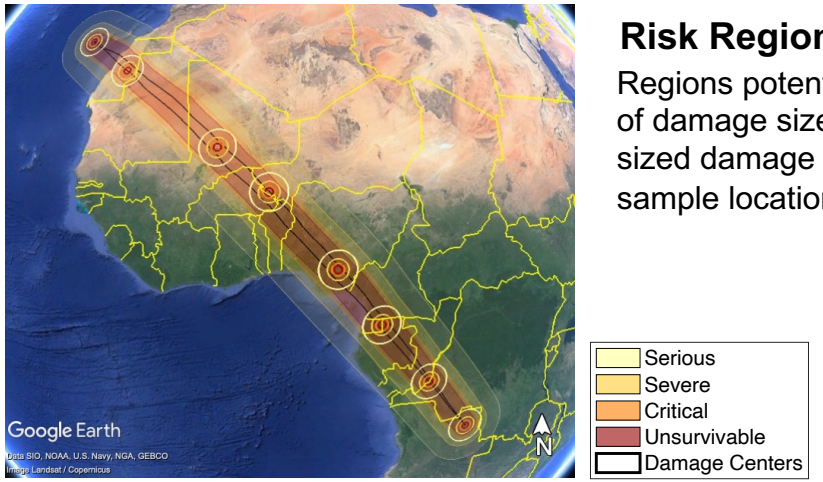
- Risk model uses fast-running physics-based models to assess millions of impact cases representing the range of possible asteroid properties and impact locations.
- Atmospheric entry, breakup, and resulting hazards (blast, thermal, tsunami, global effects) are modeled for each case.
- Probabilities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

Impact Risk Summary

Assessment 2: Remote Observations Before Mission Launch, 23 October 2024

Asteroid Characterization Summary

- Potential impact date: 22 Oct. 2036
- Earth impact probability: 100%
- Likeliest asteroid size range increased based on color data from ground observations refining estimates of asteroid type and albedo
- Diameter: 170–2100 m (550–6900 ft), most likely 300–880 m (970–2890 ft), median size 620 m (2020 ft)
- Asteroid Energy: 76–190,000 megatons (Mt), most likely 76–10,400 Mt, median 4,850 Mt



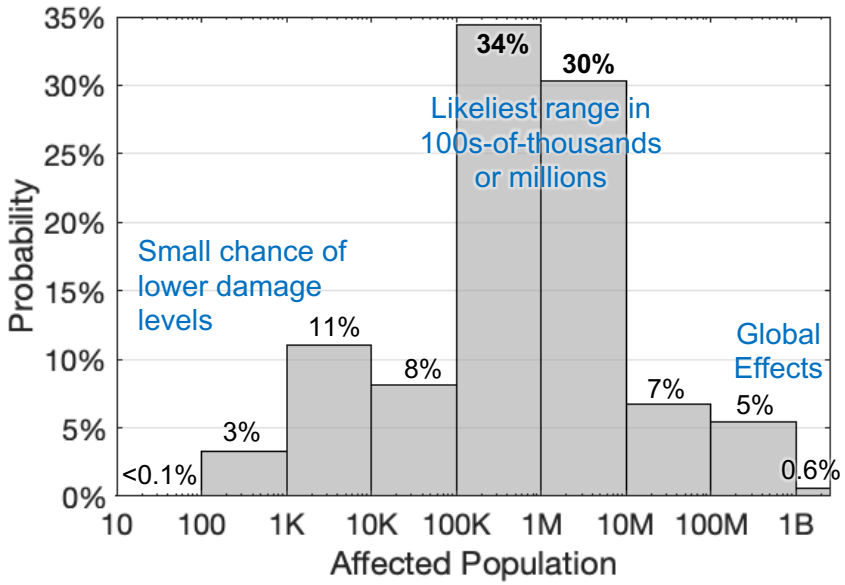
Risk Region Swath Map

Regions potentially at risk, given range of damage sizes and locations. Median-sized damage areas are shown at sample locations.

Hazard Summary

- Damage risk has increased substantially due to confirmed Earth impact likely over land, and higher likelihood of larger asteroid sizes
- Significant damage is likely for all potential impact sizes & locations
- Impact would cause large blast & thermal damage reaching unsurvivable levels, with serious damage likely extending ~100–240 km (~60–150 mi) outward, and possibly 600 km (400 mi) or more
- Tsunami could cause significant damage if large impactors were partially deflected into the ocean
- Largest impacts could cause catastrophic global effects (9% chance)
- Large uncertainties remain in potential damage extents & severities

Affected Population Risks



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

Total avg. risk: 32M

Median: 712K

Likely 100s-of-thousands or millions

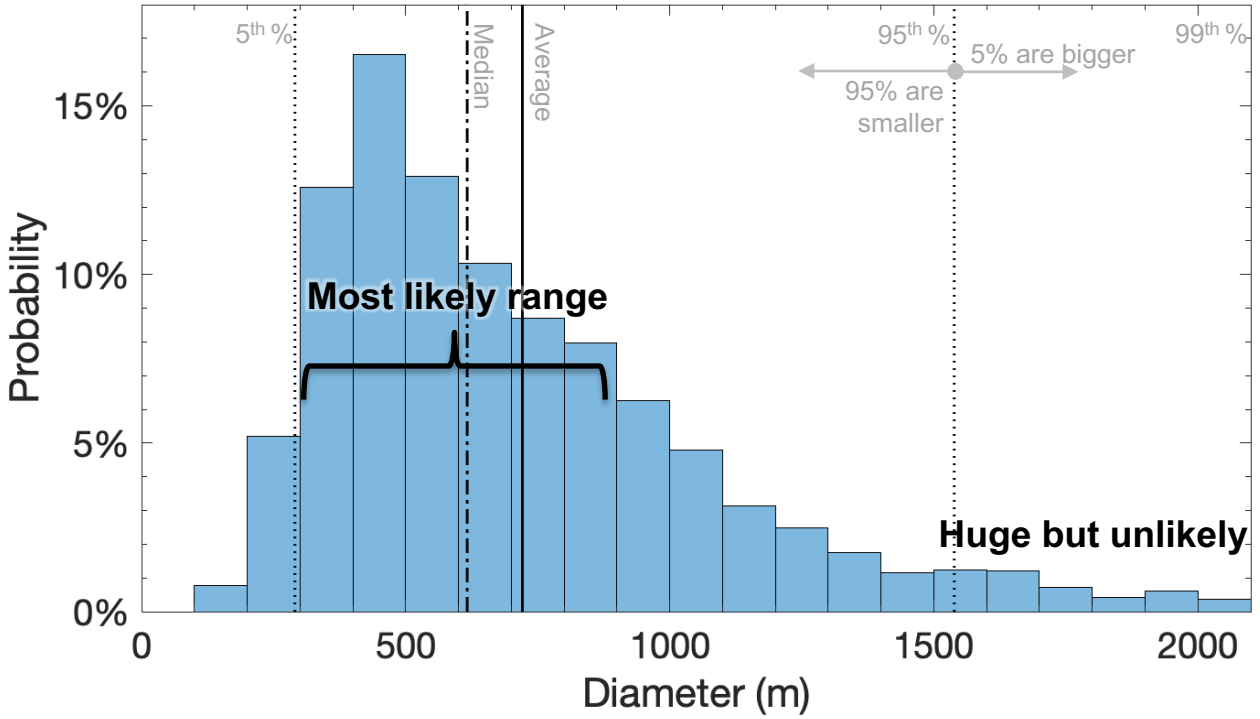
Possibly up to ~2B for global effects

HYPOTHETICAL EXERCISE

Asteroid Size & Properties

- Asteroid size estimates from remote ground observations since initial discovery:
  - Most likely size ranges are between 300–880 meters (~1000–3000 feet) in diameter
  - Largest sizes could be over 2 km (1.3 mi) in diameter
- Color data from ground observations have refined size and type estimates since initial discovery
  - Asteroid is likelier to be a C type (52% probability) and less relatively likely to be an S type (17%)
  - Type refinements suggest object is more likely to be darker (lower albedo) and therefore larger
  - Potential upper and lower size range remains similar to initial estimates, but likeliest sizes have increased
- Remaining size and property uncertainties result in very large ranges of mass, energy, and damage
  - Larger size estimates cause exponentially larger increases in mass and energy

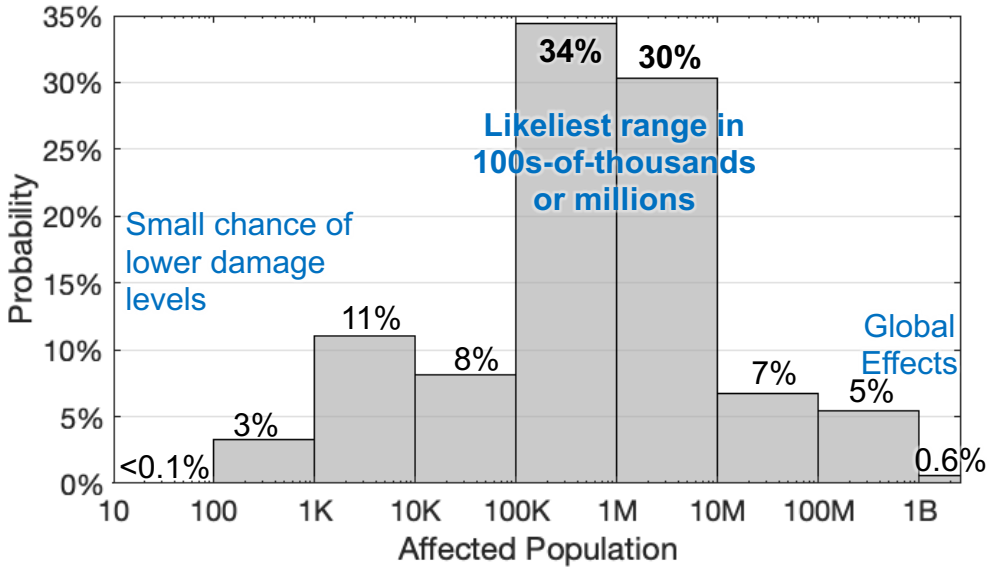
Asteroid Size Ranges & Probabilities



	Diameter	Mass	Energy
Median	620 m (2020 ft)	2.5e11 kg	4,850 Mt
Average	720 m (2370 ft)	8.5e11 kg	16,300 Mt
Most likely	300–880 m (970–2890 ft)	4.0e9–5.4e11 kg	76–10,400 Mt
Range	170–2100 m (550–6900 ft)	4.0e9–1.0e13 kg	76–190,000 Mt

[Property inference model: J. Dotson PDC 2021]

Affected Population Risks



Population Risk Histogram: Probabilities of affecting the number of people within each range

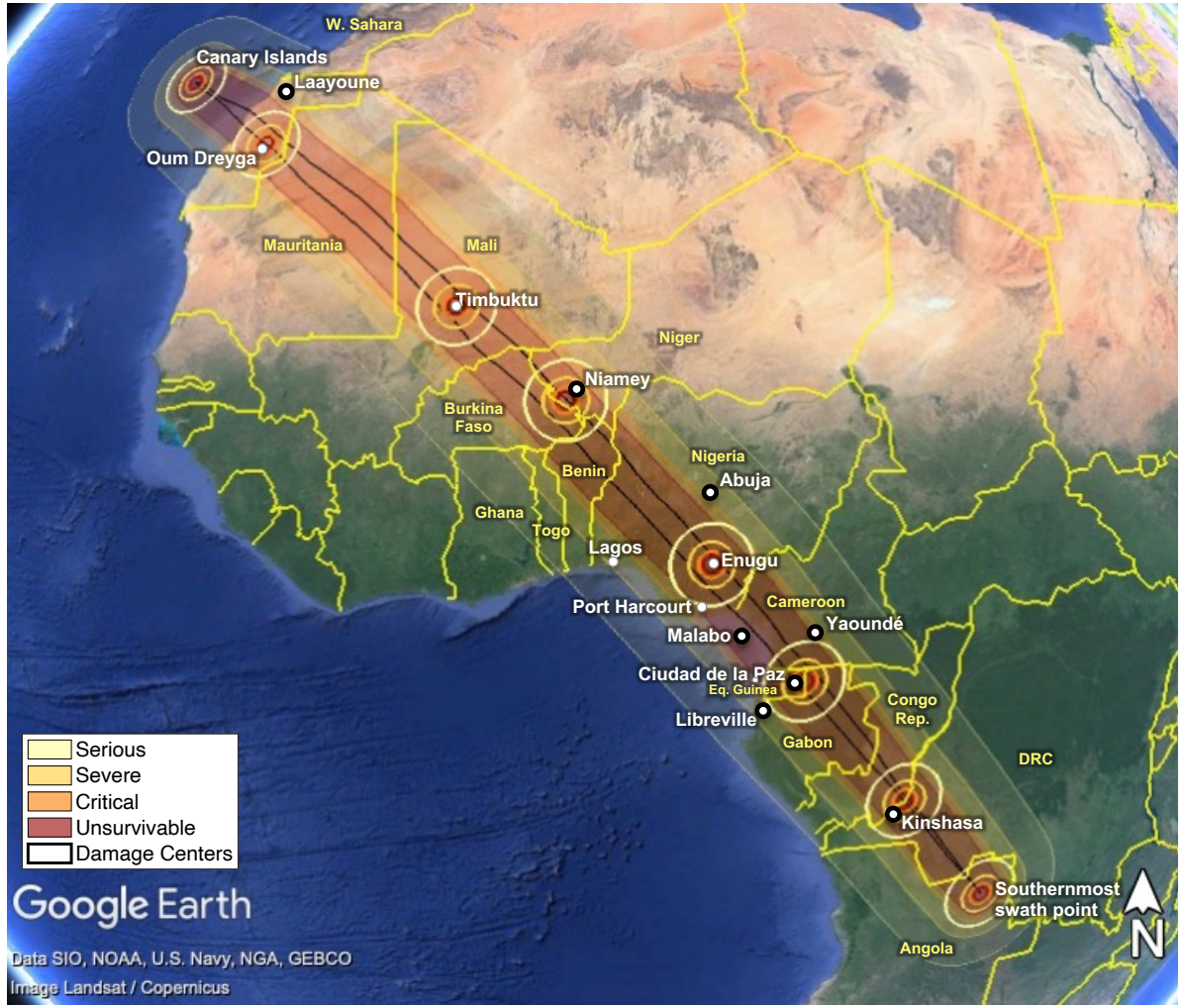
Affected Population Threshold	Probability of Damage Exceeding Threshold
Any	~100%
>1K	97%
>10K	86%
>100K	77%
>1M	43%
>10M	13%
>100M	6%
>1B	0.6%

Population Exceedance Risks: Probabilities of damage affecting ***at least*** the given number of people *or more*

[PAIR affected population details: Stokes et al., 2017]

- **Population risk has increased substantially due to confirmed Earth impact (likely over land), and increased asteroid size estimates**
  - Large ranges remain in potential damage sizes, severities, and populations across impact locations
  - Damage is likely to affect 100s-of-thousands to several millions of people
  - Smaller but notable chance of much larger ranges, potentially up to ~2B people, for worst global effects
  - Low chance of affecting under 1K people
- **Affected population risk:**
  - Total average risk: 32M people
  - Median affected population: 712K people
- **Probabilities of large population damage:**
  - 77% chance of affecting **over 100K** people
  - 43% chance of affecting **over 1M** people
  - 13% chance of affecting **over 10M** people
  - 6% of affecting **over 100M** people
  - 0.6% chance of affecting **over 1B** people

Damage Risk Swath



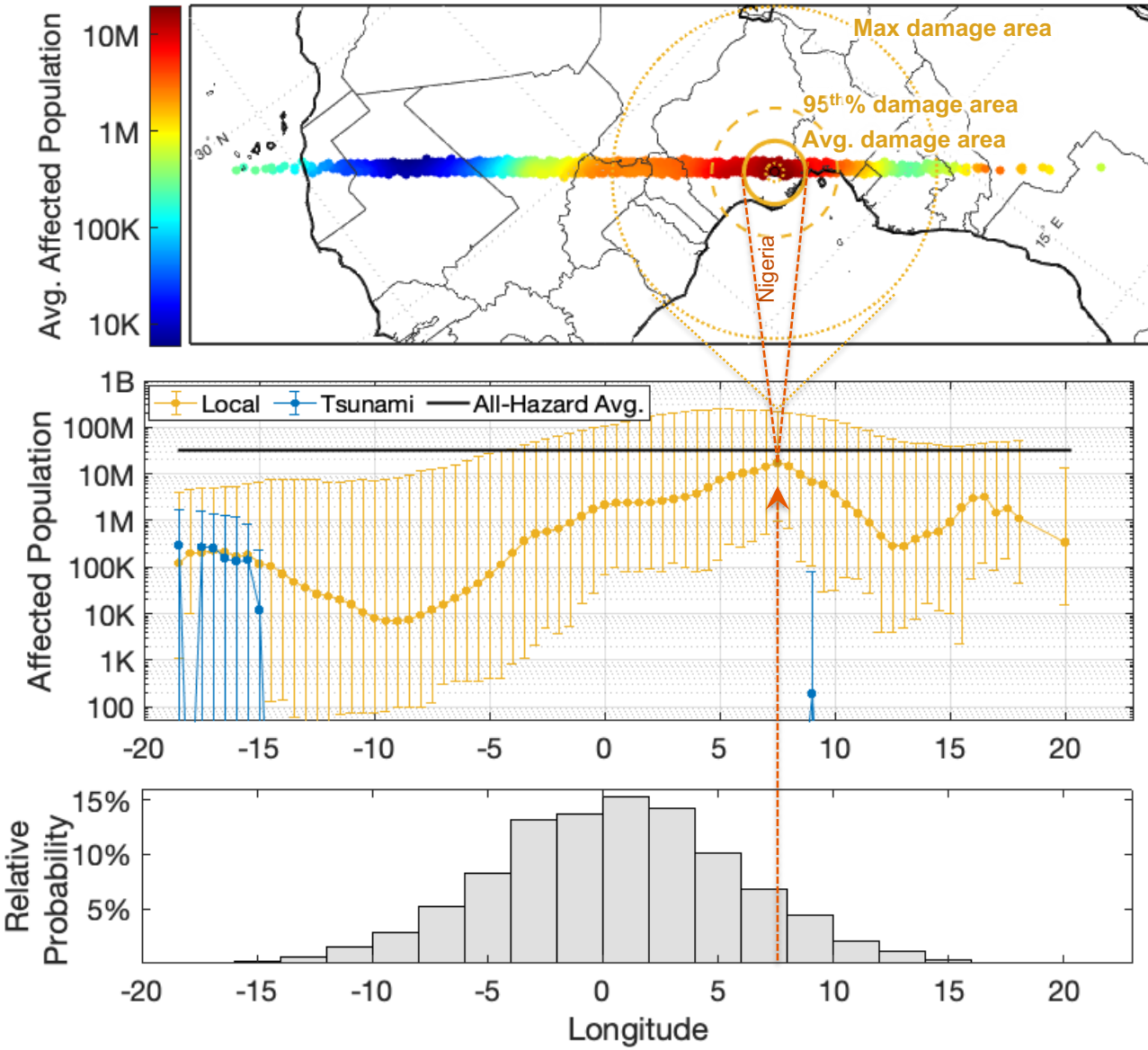
Damage risk swath: Shows extent of regions *potentially* at risk to *local ground damage**, given ranges of potential damage sizes and locations

- Damage risk swath:
  - Black outline shows globe-spanning range of potential impact locations modeled (damage-center locations)
  - Shaded areas show potential extent of *local ground damage**, given range of impact sizes and locations, colored by damage severity level
  - Rings show median-sized damage footprints at sample locations
- Extent of current risk region:
  - Spans Western and Central Africa, from the Canary Islands to Angola
  - Impact corridor is ~100-150 km (~60-90 mi) wide
  - Swath damage regions extend ~1000 km (600 mi) across
  - Extent of potential impact locations will shrink as observations refine the orbital data
  - Extent of damage range could also shrink if missions or observations can further constrain asteroid size or type

* Swath extent shown covers local ground damage sizes out to the 95th percentile (does not include regions potentially at at risk to tsunami or global effects)

Affected Population Ranges Along Swath

- Impacts over land cause most population damage
  - Average local affected population ranges are 6K-20M across Africa
  - Largest cases affect ~5M-200M
  - Smallest cases affect in the hundreds of people over the least populated desert regions, but affect at millions over the most populated
- Ocean impacts possible but unlikely at north-western edge of swath
  - Only small probability of ocean impacts at northwestern edge of swath
  - These cases could cause both blast and/or tsunami damage affecting similar population ranges
- Highest impact risk region is Nigeria & Cameroon with an average affected pop of ~20M



Average affected population: Average for each potential entry point, given range of potential asteroid sizes and properties

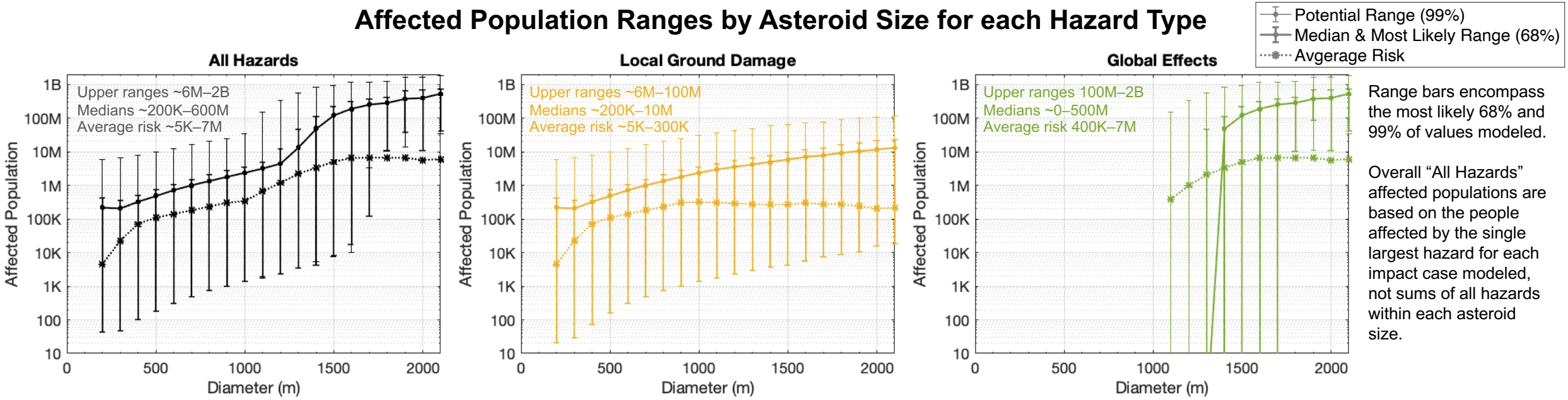
Affected population ranges: Averages and min/max ranges along swath (within 1/2° longitude increments)

Relative impact probability among potential swath regions, given an Earth-impact

Hazard Damage Ranges By Asteroid Size

- Large ranges of population damage remain both across potential asteroid sizes and among each asteroid size range (due to different impact locations and other unknown asteroid properties that affect impact energy and hazard factors).
- **Significant population damage is likely across all potential asteroid sizes.** Largest possible asteroid sizes would cause extreme population damage across all hazards, but are also relatively less likely compared to smaller asteroid sizes.
- The ***average risk*** for each size range (plotted as asterisks) scales the *average affected population* of each asteroid size by the *relative likelihood* of that size range.
- **Local ground damage** ranges are significant across all potential asteroid sizes.
- **Global effects** pose the largest average risk levels, even given low-probability of kilometer-scale asteroid sizes
- **Greatest total average risk levels** are from ~1600 m objects, and greatest local damage risk levels are from ~1000 m objects.

Affected Population Ranges by Asteroid Size for each Hazard Type



Range bars encompass the most likely 68% and 99% of values modeled.

Overall "All Hazards" affected populations are based on the people affected by the single largest hazard for each impact case modeled, not sums of all hazards within each asteroid size.

Summary

- **Risk assessment indicates significant potential damage sizes, severities, and risk probability levels across all potential asteroid size ranges and impact locations**
  - Total risk levels are very high and have increased significantly since initial discovery
  - Extreme global effects risks posed by largest potential impact sizes drive risk levels despite their lower probability
  - Local damage areas from even the smaller and moderate range of impact sizes would require large-scale evacuation, civil defense, and infrastructure protection measures over very large areas.
  - Ocean impacts are now unlikely, but could cause significant inundation along with local blast damage if one occurred.
- **Recommendations:**
  - Reconnaissance missions and additional observations are needed as soon as possible to refine size range and prepare mitigation measures to deflect or disrupt potentially large objects
  - Additional modeling & simulation studies of large-scale impact effects are recommended to better assess potential damage levels and determine appropriate response measures, given current model uncertainties in these regimes

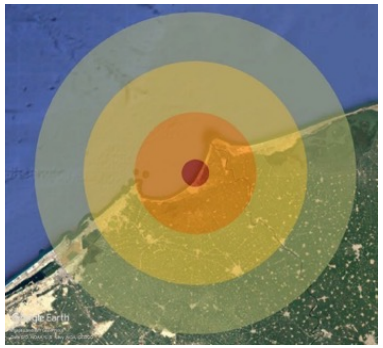
	Chance of Hazards Causing Damage	**Affected Population Ranges**				
		Average	Median	95th%	99th%	Largest worst-case modeled
Overall Affected Population	100%	32M	712K	161M	822M	2.6B
Global Effects	9%	30M	0	161M	822M	2.6B
Local Blast/Thermal	100%	3M	660K	14M	39M	242M
Tsunami (all land/water)	0.2%	300	0	0	0	1.7M
Tsunami (water cases only)	84%	132K	38K	585K	1M	1.7M

HAZARD DAMAGE & RISK DETAILS:

Local Blast & Thermal Damage
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 likely asteroid sizes and outer damage levels
  - Blast tends to be larger and more severe than the potential thermal damage in most cases, and usually define the larger outer serious and severe risk regions for emergency response planning
  - Critical and unsurvivable thermal damage areas can be larger than equivalent blast levels for the larger impact sizes



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

Local Blast & Thermal Damage Area Sizes

- Most likely local hazard is a large ground impact causing a highly destructive blast wave and thermal fireball from the entry and impact
  - Significant blast damage is certain to occur, ranging from unsurvivable levels to shattered windows and structure damage over large areas
  - Significant thermal damage is also nearly certain to occur and reach unsurvivable levels (>99% chance)
  - Thermal damage tends to be smaller than the corresponding blast regions, but largest impactors may cause larger thermal damage areas
- Uncertain asteroid size and properties result in a large range of possible damage sizes
  - Most likely outer damage radius range is ~100–240 km (60–150 mi)
  - Largest outer damage areas could extend out over 600 km (~400 miles) or more in radius

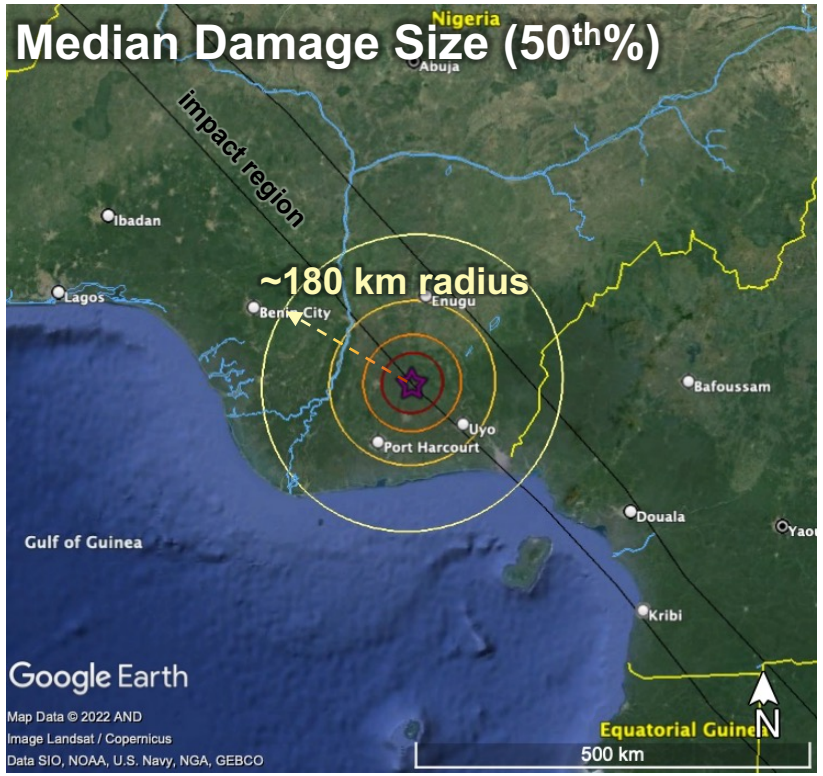
Potential Blast Damage Severities and Sizes

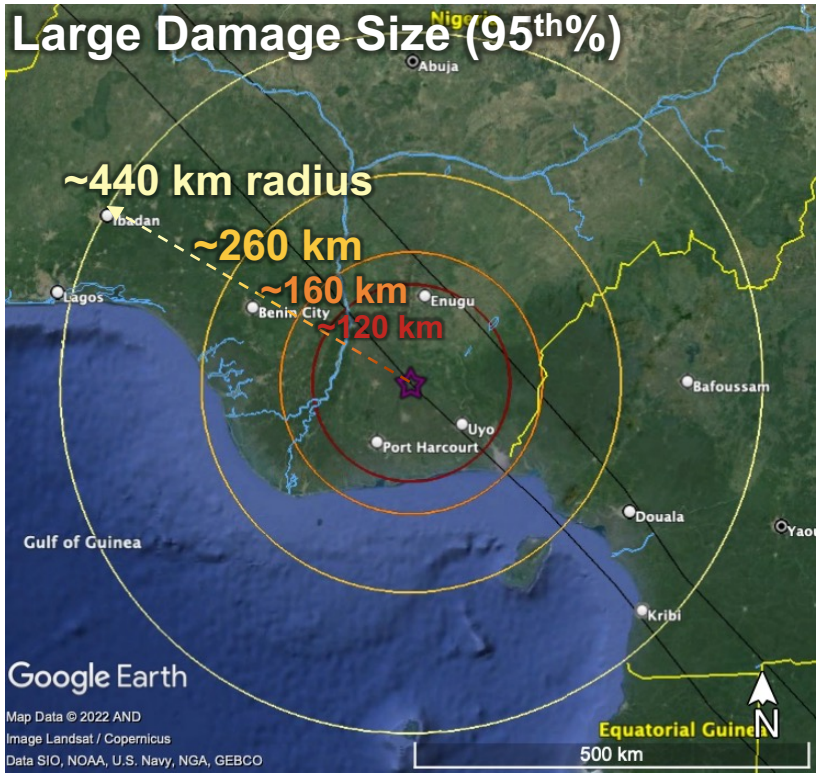
Damage Level	Potential Blast Effects	Chance of Occurring	Damage Radius Ranges (km)		
			Median	Most Likely	Range
Serious	Shattered windows, some structure damage	100%	181	100–240	70–600
Severe	Widespread structure damage	100%	99	50–130	40–330
Critical	Most residential structures collapse	100%	56	30–70	20–190
Unsurvivable	Complete devastation	100%	31	15–40	10–110

Potential Thermal Damage Severities and Sizes

Damage Level	Potential Thermal Effects	Chance of Occurring	Damage Radius Ranges (km)		
			Median	Most Likely	Range
Serious	2nd degree burns	~100%	59	8–90	0–490
Severe	3rd degree burns	~99%	46	6–70	0–380
Critical	Clothing ignition	~99%	32	5–50	0–270
Unsurvivable	Structure ignition	~99%	27	4–40	0–220

Sample Ground Damage Sizes over Nigeria
(highest median population damage location along swath)





- Rings show sample damage footprint sizes at a single sample location
- Black border shows range of potential impact locations (damage center points) along swath
- Percentiles give the chance that the damage region could be up to the given size or smaller

Local Ground Damage Radius Sizes (km / mi)

Damage Level	Mean	25th %	**50th %**	75th %	**95th %**
Serious	210 km (130 mi)	140 km (85 mi)	**180** km (110 mi)	260 km (160 mi)	**440** km (270 mi)
Severe	120 km (75 mi)	80 km (45 mi)	**100** km (60 mi)	150 km (90 mi)	**260** km (160 mi)
Critical	70 km (45 mi)	40 km (25 mi)	**60** km (35 mi)	90 km (55 mi)	**160** km (100 mi)
Unsurvivable	50 km (30 mi)	30 km (15 mi)	**40** km (25 mi)	60 km (35 mi)	**120** km (75 mi)

	Damage Level Description
	Windows shatter, minor structure damage
	Widespread structure damage, or 3rd degree burns
	Residential structures collapse, or clothing ignites
	Devastation, structures flattened or burned

Global Effects (GE)

- The largest potential impacts could produce enough ejecta to cause global climatic effects, potentially affecting substantial fractions of world population
  - 9% chance of global effects from large asteroids with impact energies between 40–190 gigatons (diameters over ~1 km or 3,300 feet, depending on density and entry velocity)
  - Affected population estimates are in the tens-of-millions to hundreds-of-millions, with worst-case estimates affecting over 2 billion people (>25-30% of world population)
  - Total average GE affected population ~30M people (among all potential impactor sizes, including sub-global sizes)
- Global effects risk has increased since initial discovery due to slightly higher likelihood of larger asteroid sizes
  - Chance of global effects occurring has increased from 6% to 9% since initial discovery
  - Average GE affected population has increased from ~24M to ~30M since initial discovery
- Global effects drive greatest average population risk levels despite low probability
  - Although these large sizes are still relatively unlikely, the potential consequences are extreme and pose a high level of risk
- Large uncertainties remain in what asteroid sizes may start to cause onset of these effects, amounts of ejecta, and severity or specifics of resulting climate effects.

[PAIR global effects model details: Stokes et al., 2017]

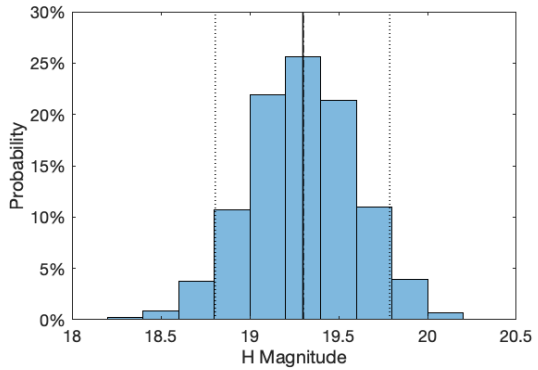
ASTEROID PROPERTY & ENTRY DETAILS:

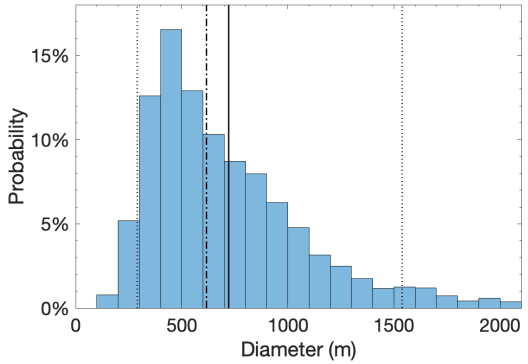
Asteroid Property Distributions
Atmospheric Entry Parameters

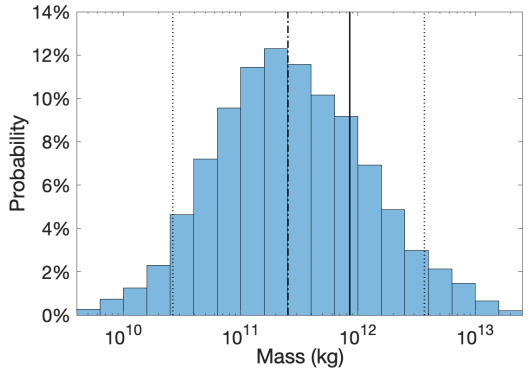
Asteroid Property Details

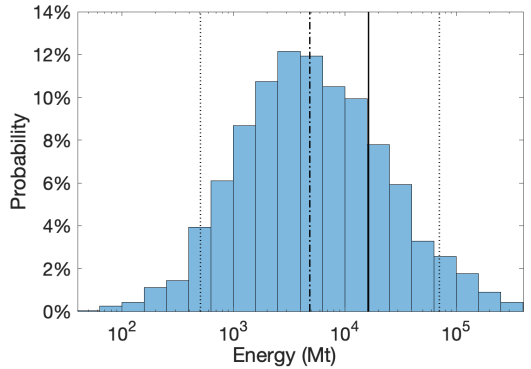
Statistical percentiles and highest-probability interval ranges for asteroid property distribution samples modeled*

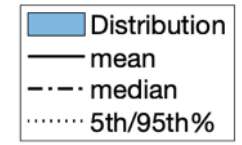
	Mean	5th%	25th%	Median (50th%)	75th%	95th%	Most Likely Range (68%)	Potential Range (99%)
Diameter (m)	721	290	434	617	901	1539	294 – 880	167 – 2107
Mass (kg)	8.5E+11	2.6E+10	9.6E+10	2.5E+11	7.5E+11	3.7E+12	4.0E+09 – 5.4E+11	4.0E+09 – 1.0E+13
Energy (Mt)	1.6E+04	5.1E+02	1.8E+03	4.9E+03	1.4E+04	7.1E+04	7.6E+01 – 1.0E+04	7.6E+01 – 1.9E+05
H Magnitude	19.3	18.8	19.1	19.3	19.5	19.8	19.0 – 19.6	18.6 – 20.1
Albedo	0.13	0.02	0.04	0.09	0.17	0.38	0.01 – 0.15	0.01 – 0.73
Density (g/cm^3)	2.2	1.2	1.6	2.0	2.5	3.7	1.3 – 2.6	0.840 – 6.0
Porosity (%)	32%	8%	22%	33%	43%	55%	16% – 47%	2.5% – 60%
Strength (MPa)	2.2	0.1	0.3	1.1	3.2	7.9	0.1 – 2.4	0.1 – 9.6

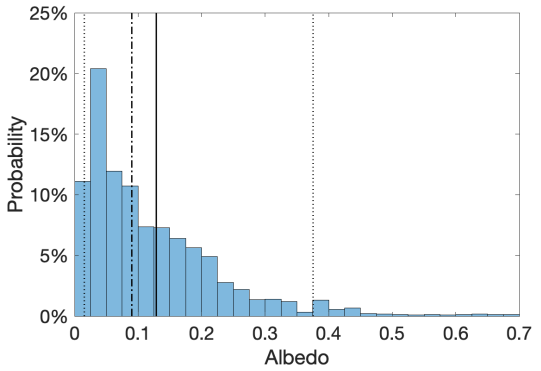


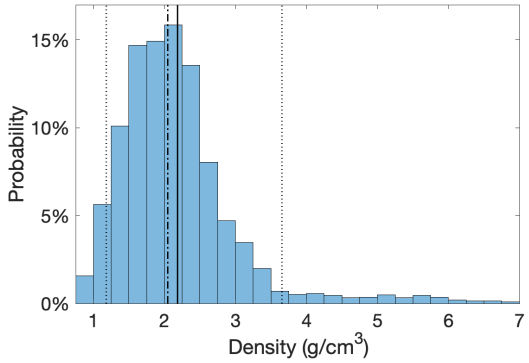


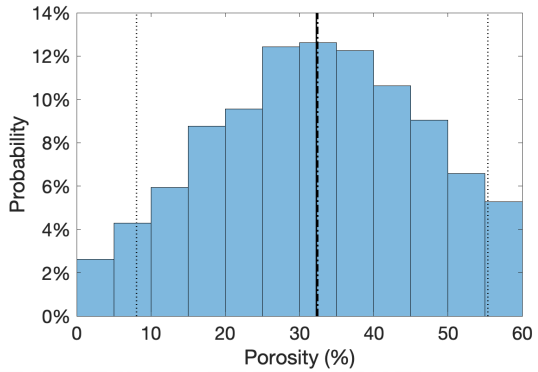


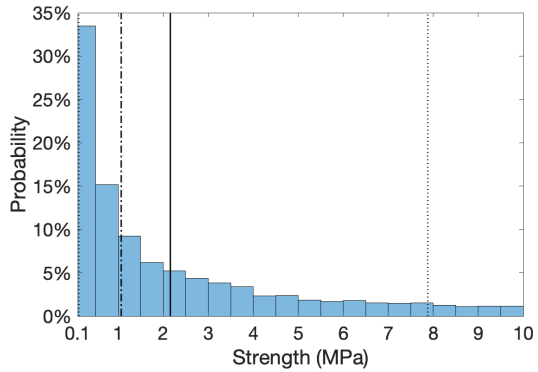












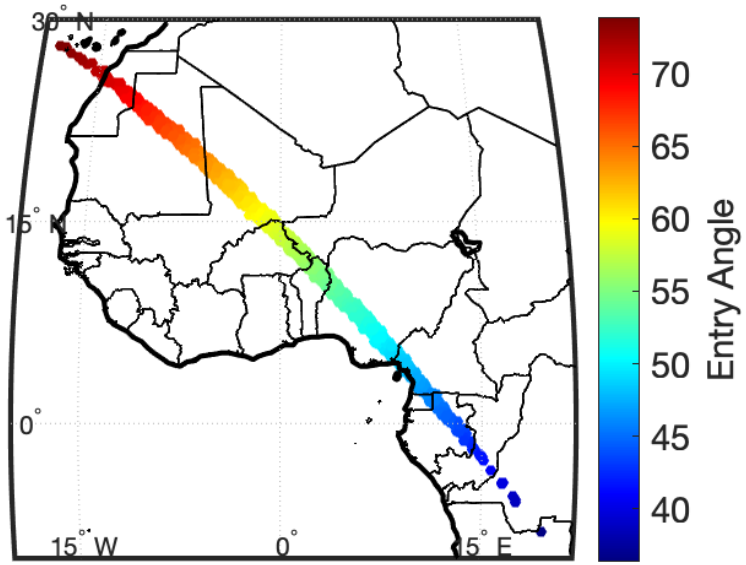
* Property stats are each computed *independently*. Multiple values from a given percentile cannot necessarily be combined to represent a single physically-plausible asteroid.

[Property model: J. Dotson PDC 2021]

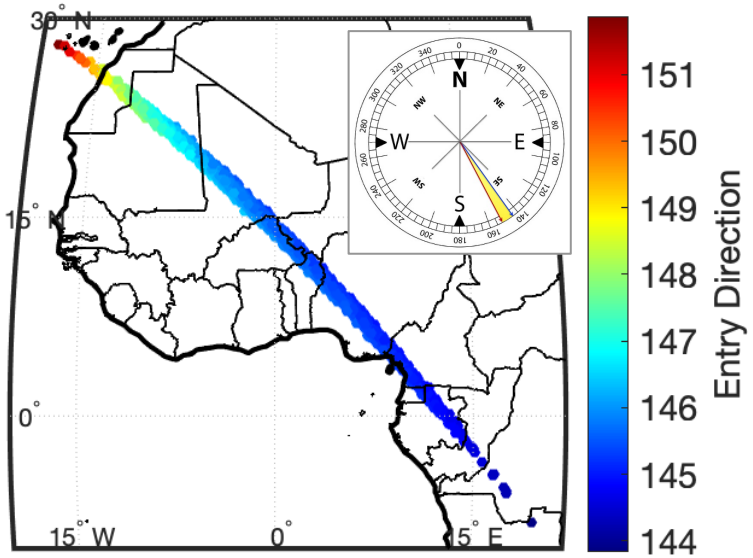
Entry Parameters & Locations

- Confirmed 100% chance of Earth impact somewhere along a corridor crossing Northwestern & Central Africa, from Canary Islands to northern Angola.
- Entry parameters vary across the potential corridor, but are well-known for given impact points
- **Entry Velocity:**
  - 12.67 km/s
  - Negligible variation across corridor
- **Entry Angle:**
  - ~36° – 74° across corridor
  - Steep entries (74°) at NW end
  - Shallow entries (36°) at SE end
- **Entry Direction (CW from N):**
  - Entry flight direction is between SE–SSE along corridor
  - ~SSE (152°) at NW end
  - ~SE (144°) at SE end

Entry Angle (deg. from horizontal)



Entry Direction (deg. clockwise from N)



[Impact entry data: P. Chodas, CNEOS/JPL, https://cneos.jpl.nasa.gov/pd/cs/pdc23/

REFERENCES

ATAP Impact Risk & Hazard Modeling Papers

Probabilistic Asteroid Impact Risk (PAIR) Model

- **Mathias et al., 2017.** A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009
- **Stokes et al., 2017.** Update to determine the feasibility of enhancing the search and characterization of NEOs. National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf
- **Wheeler & Mathias, 2018.** Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus, 327, 83–9. https://doi.org/10.1016/j.icarus.2018.12.017
- **Rumpf et al., 2020.** Deflection driven evolution of asteroid impact risk under large uncertainties. Acta Astronautica 176, 276–286. https://doi.org/10.1016/j.actaastro.2020.05.026
- **Reddy et al., 2022.** Apophis planetary defense campaign. Planetary Science Journal, 3:123 (16pp). https://doi.org/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 374, 114790. https://doi.org/10.1016/j.icarus.2021.114790
- **Reddy et al., 2019.** Near-Earth Asteroid 2012 TC4 Campaign: results from a global planetary defense exercise. Icarus 326, 133–150. https://doi.org/10.1016/j.icarus.2019.02.018
- **Population data:** SEDAC GPW v4.11 gridded population counts, year 2020 (UN-adjusted values). CIESIN, Columbia University, 2016. http://dx.doi.org/10.7927/H4SF2T42

Entry & Breakup Energy Deposition Modeling

- **Wheeler et al., 2018.** Atmospheric energy deposition modeling and inference for varied meteoroid structures. Icarus 315, 79–91. https://doi.org/10.1016/j.icarus.2018.06.014
- **Wheeler et al., 2017.** A fragment-cloud model for asteroid breakup and atmospheric energy deposition. Icarus 295, 149–169. https://doi.org/10.1016/j.icarus.2017.02.011
- **Register et al., 2020.** Interactions between asteroid fragments during atmospheric entry. Icarus 337, 113468. https://doi.org/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 156, 278-283. https://doi.org/10.1016/j.actaastro.2017.12.021
- **Robertson & Mathias, 2019.** Hydrocode simulations of asteroid airbursts and constraints for Tunguska. Icarus 327, 36–47. https://doi.org/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. https://doi.org/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 354, 114037. https://doi.org/10.1016/j.icarus.2020.114037
- **Johnston & Stern, 2018.** A model for thermal radiation from the Tunguska airburst. Icarus, 327, 48–59. https://doi.org/10.1016/j.icarus.2019.01.028
- **Johnston et al., 2018.** Radiative heating of large meteoroids during atmospheric entry. Icarus 309, 25–44. https://doi.org/10.1016/j.icarus.2018.02.026

Tsunami Simulations

- **Robertson & Gisler, 2019.** Near and far-field hazards of asteroid impacts in oceans. Acta Astronautica 156, 262–277. https://doi.org/10.1016/j.actaastro.2018.09.018
- **Berger & Goodman, 2018.** Airburst-generated tsunamis. Pure Appl. Geophys. 175 (4), 1525-1543. https://doi.org/10.1007/s00024-017-1745-1
- **Berger & LeVeque, 2018.** Modeling issues in asteroid-generated tsunamis. NASA Contractor Report NASA/CR-2018-219786. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180006617.pdf
- **Berger & LeVeque, 2022.** Towards Adaptive Simulations of Dispersive Tsunami Propagation from an Asteroid Impact. Proc. ICM, St. Petersburg, Russia, 2022 (submitted). https://doi.org/10.48550/arXiv.2110.01420

Related PDC 2023 Presentations

PDC 2023 presentation materials, webcast recordings, and impact exercise details available at:

- https://www.unoosa.org/oosa/en/ourwork/topics/neos/2023/IAAPDC/index.html
- https://atpi.eventsair.com/QuickEventWebsitePortal/23a01---8th-planetary-defense-conference/programme-website/Agenda
- https://cneos.jpl.nasa.gov/pd/cs/pdc23/

PDC 2023 Hypothetical Asteroid Impact Exercise Session (3 April 2023)

- **Wheeler** et al., "Impact Risk Assessment Briefing: 2023 PDC Hypothetical Asteroid Impact Exercise Epoch 1"
- **Chodas** et al., "The 2023 PDC Hypothetical Impact Scenario: Epoch 1 Summary"
- **Barbee** et al., "PDC 2023 Simulated Impact Threat Scenario SMPAG Mission Option Analysis"

Impact Effects (Session 7, 6 April 2023)

- **Wheeler** et al., "Asteroid Impact Risk Across Transitional Hazard Regimes"
- **Dotson** et al., "Consequences of Asteroid Characterization on the State of Knowledge about Inferred Physical Properties and Impact Risk"
- **Coates** et al., "Sensitivity Study of Impact Risk Model Results to Thermal Radiation Damage Model for Large Objects"
- **Chomette** et al., "Machine learning for the prediction of local asteroid damages"
- **Stern** et al., "Advances in Entry Modeling for Impact Risk Assessment"
- **Aftosmis** et al., "High-fidelity Blast Propagation Modeling for Hypothetical Asteroid 2023 PDC"
- **Titus** et al., "Asteroid Impacts and Cascading Hazards"

Disaster Management & Impact Response (Session 8, 6 April 2023)

- **Robertson** et al., "Evacuation and Shelter Plans for Asteroid Impacts"

Space Mission & Campaign Design Session (Session 6, 5 April 2023)

- **Barbee** et al., "Planetary Defense Mission Campaign Design for the 2023 PDC Hypothetical Asteroid Impact Scenario"