Impact Risk Assessment Briefing:

2023 PDC Hypothetical Asteroid Impact Exercise

Epoch 1 – Initial Threat Discovery

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Asteroid Threat Assessment Project (ATAP)

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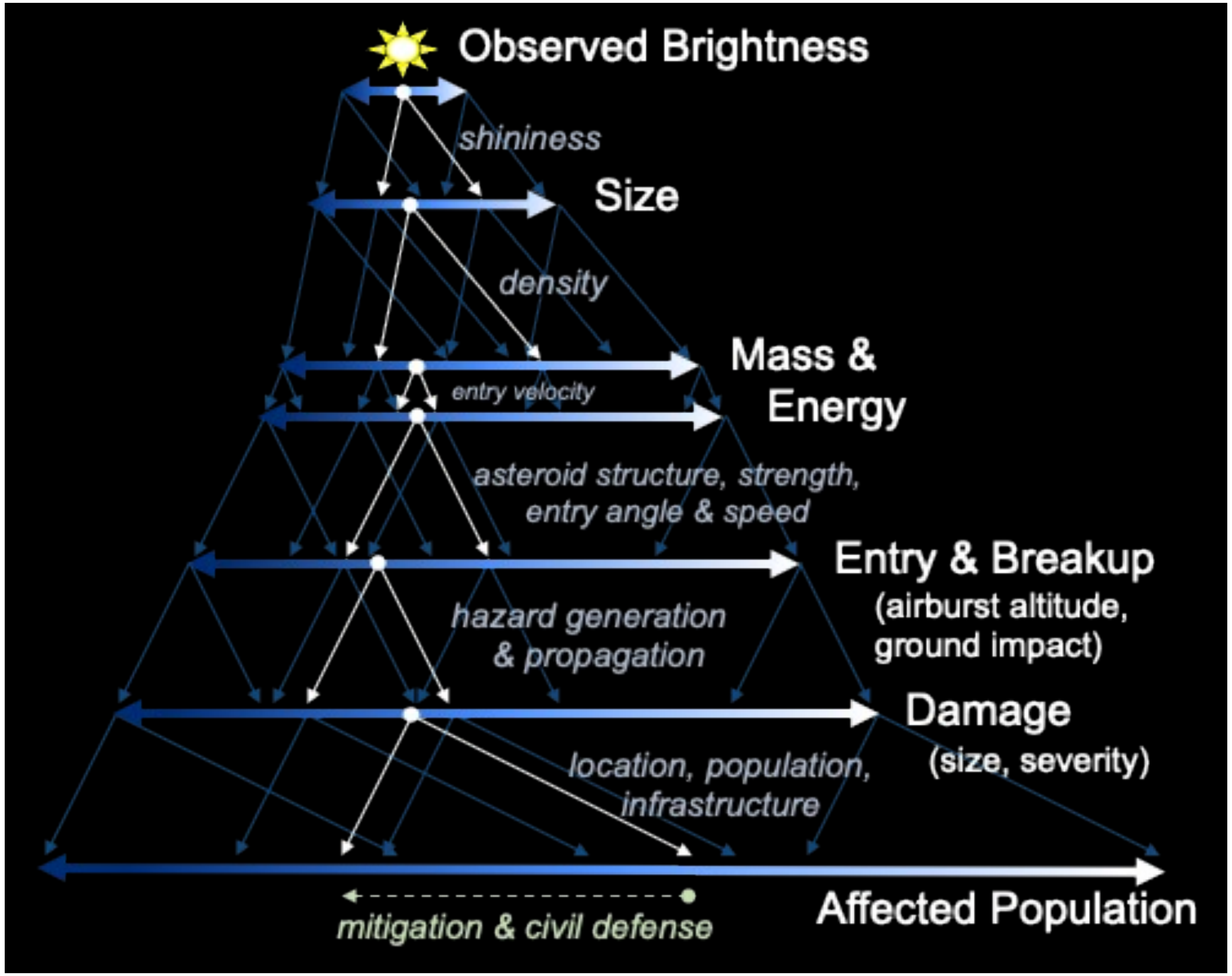
Asteroid Property & Damage Uncertainties

- 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)

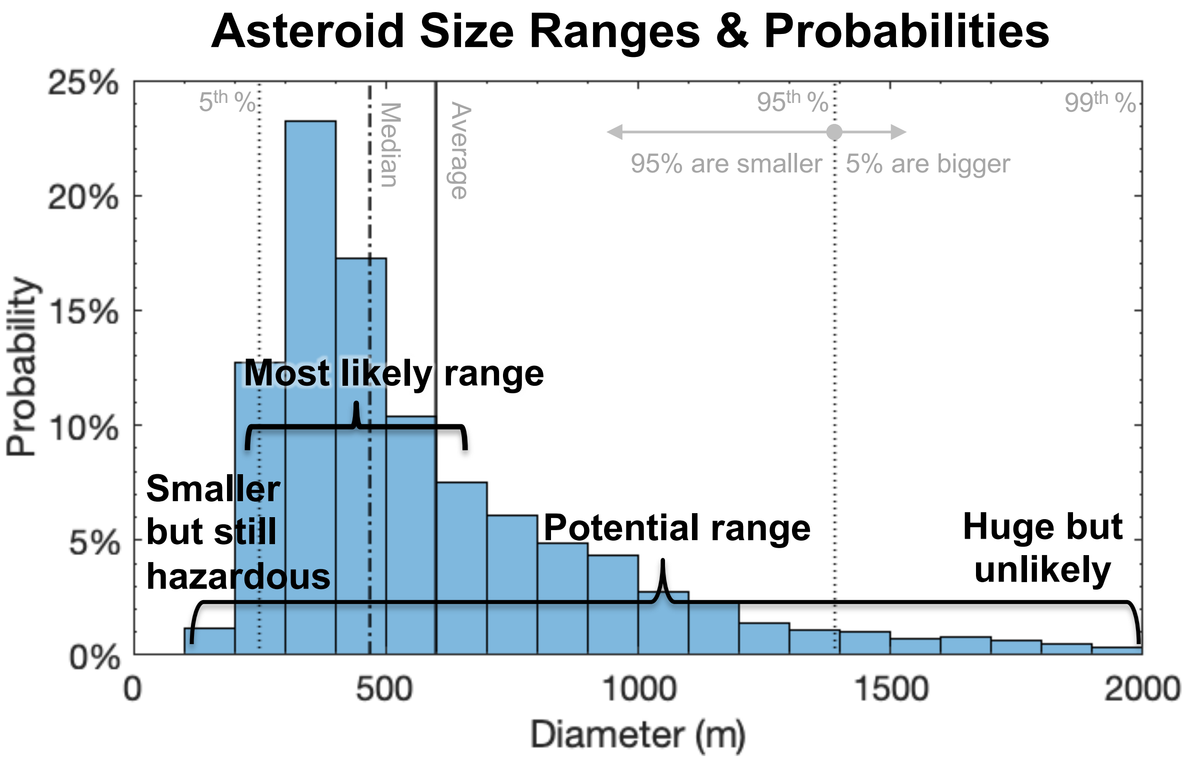
Cascade of uncertainty ranges from asteroid observation to damage potential



HYPOTHETICAL EXERCISE

Asteroid Size & Properties

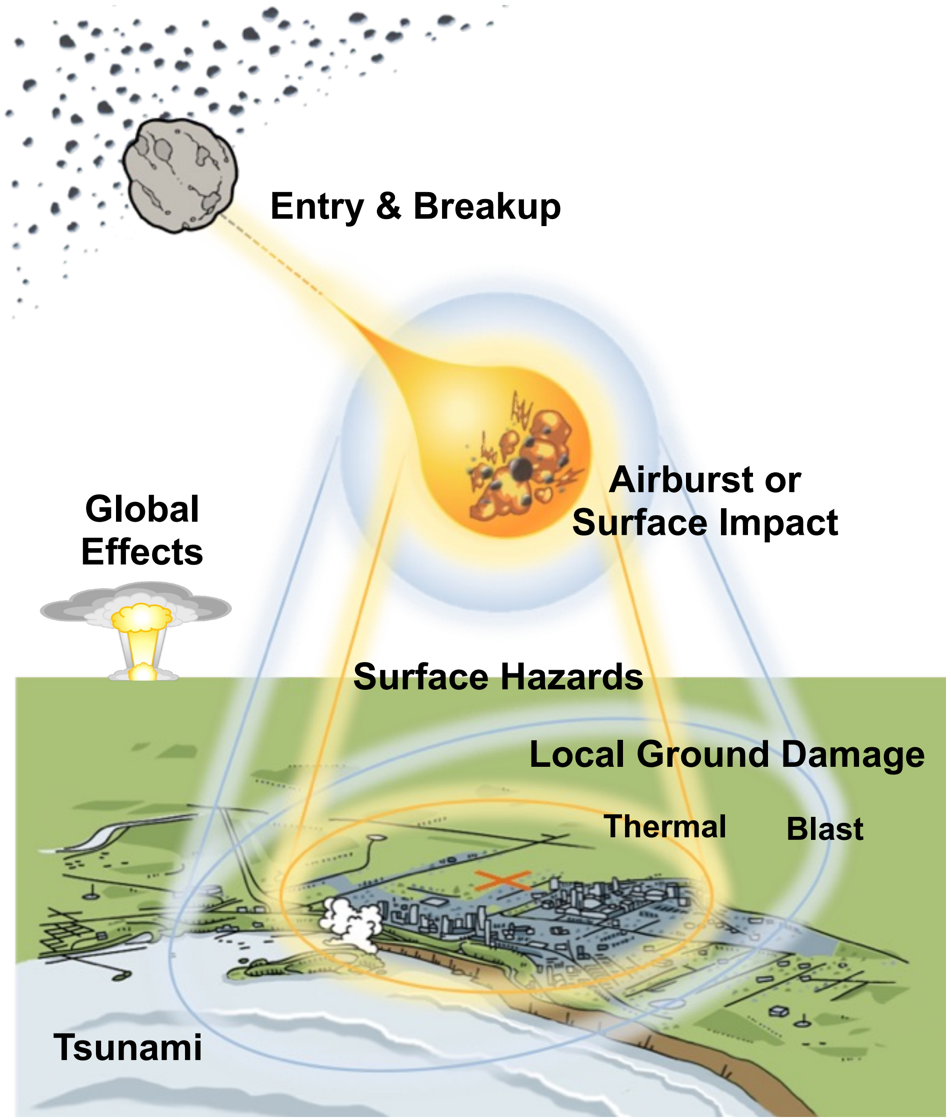
- Remote observation data available:
  - Only estimated brightness (H~19.4)
  - Asteroid type and properties are unknown
- **Asteroid size range is hazardously large and highly uncertain**
  - Size and density uncertainties lead to huge ranges in mass, energy, and potential damage
  - Smallest sizes are hazardous, and could produce large blast damage
  - Upper kilometer-scale size range is less likely but catastrophic
- **Rapid reconnaissance missions are needed** to better determine asteroid size, damage, and mitigation requirements.



	Diameter	Impact Energy
Median	470 m (1540 ft)	230 Mt
Average	600 m (1950 ft)	11,600 Mt
Most likely	220–660 m (720–2160 ft)	54–5,500 Mt
Range	150–2000 m (490–6560 ft)	54–160,000 Mt

[Property inference model: J. Dotson PDC 2023]

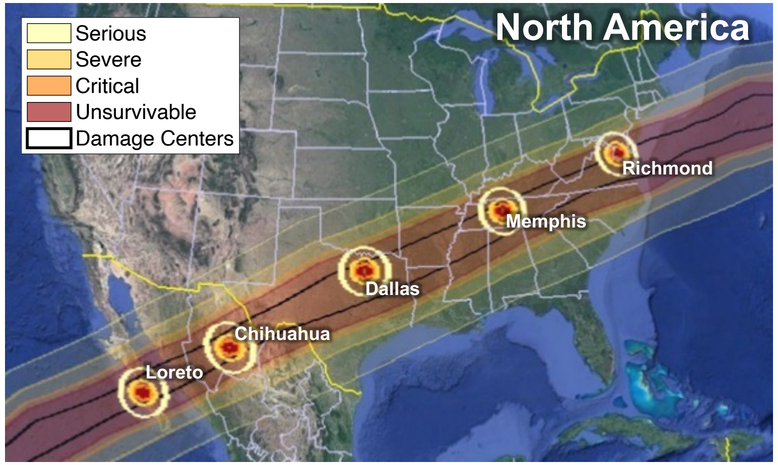
Asteroid Impact Hazards

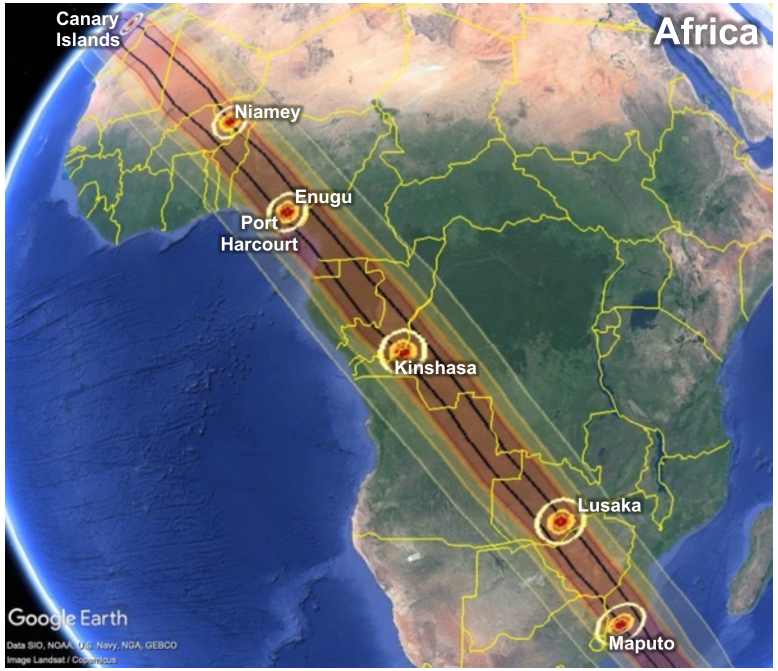


- **Asteroids can cause damage by breaking up and bursting in the atmosphere or impacting the surface**
- **Primary impact hazards are:**
  - **Local ground damage:** Airbursts and surface impacts can produce explosive blast waves and thermal fireballs
  - **Tsunami:** Ocean impacts could cause significant 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 large asteroid size ranges in this scenario could potentially cause any of these hazards**

HYPOTHETICAL EXERCISE

Local Ground Damage





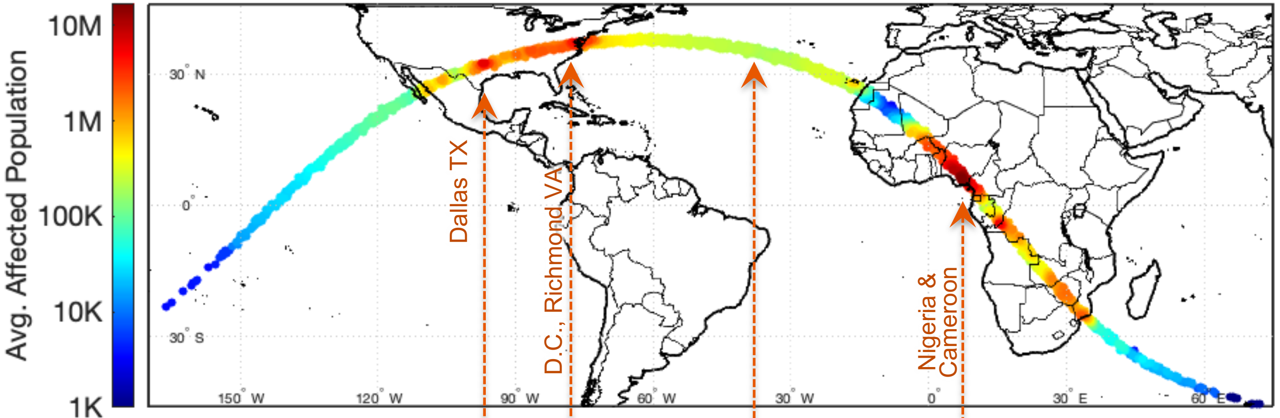
Damage risk swath: Extent of regions *potentially* at risk to ground damage, given ranges of potential impact locations and damage sizes (out to 95th%). Rings show median-sized (50th%) damage footprints at sample locations.

- Primary hazard for this asteroid size range is a large ground impact or low airburst causing a highly destructive blast wave and fireball
- Damage Sizes & Severities:
  - Damage severities reach unsurvivable levels, extending to large areas of structural damage, fires, and shattered windows
  - Most likely serious damage range is ~100–200 km (60–120 mi) in radius (median 160 km, 100 mi)
  - Largest outer damage areas could extend out over 600 km (370 miles) or more in radius

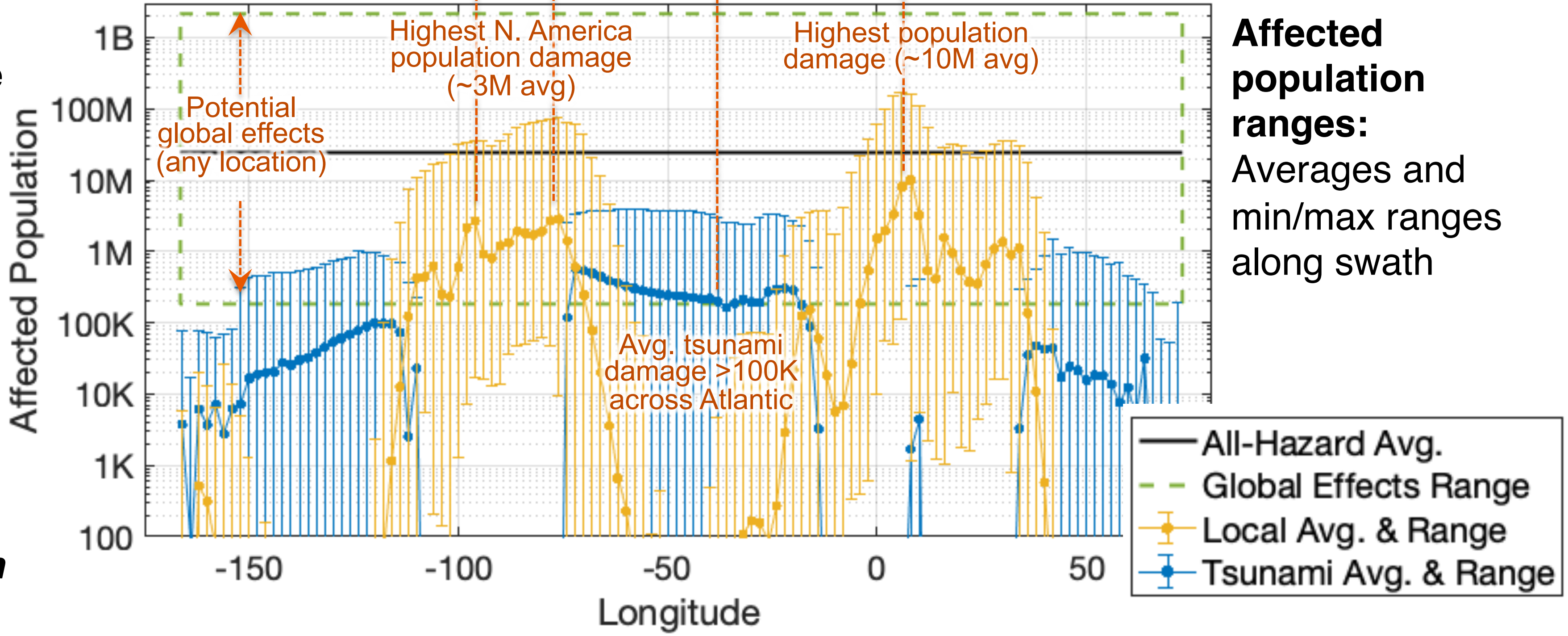
	Damage Level Description
Serious	Windows shatter, some structure damage
Severe	Widespread structure damage, or 3rd degree burns
Critical	Residential structures collapse, or clothing ignites
Unsurvivable	Devastation, structures flattened or burned

Affected Population Ranges Along Impact Swath

- **Impacts over land cause most population damage**
  - Average affected populations are ~10K–10M ppl across Africa and N. America
  - Largest impacts ~10M-100M ppl
  - Highest damage is around Nigeria (~10M people average)
- **Large ocean impacts could cause significant tsunami across Atlantic or near coasts**
  - Average affected populations ~10K–600K ppl
  - Largest impacts ~100K–4M
  - Atlantic impacts have greatest tsunami risk
- ***Global effects could affect millions to billions of people from any location***



Average affected population map: Average for each potential entry point (among all potential asteroid sizes and properties)



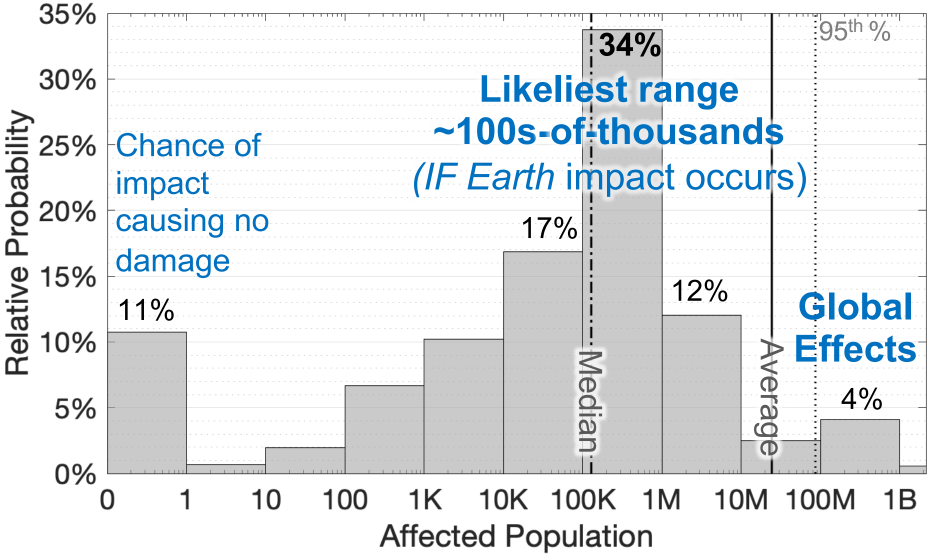
Affected population ranges: Averages and min/max ranges along swath

HYPOTHETICAL EXERCISE

Affected Population Risks

Likelihood of How Many People Damage Could Affect

Damage Probabilities among Earth-Impacting Cases (1% Impact Probability)



Impact Damage Probabilities:
Relative chance of damage affecting the number of people within each range, *if Earth impact occurs.*

Population Threshold	Probability (if Earth impact occurs)
>10K	70%
>100K	53%
>1M	19%
>10M	7%
>100M	5%
>1B	~0.6%

Impact Damage Exceedance Risks:
Chance of damage affecting ***at least*** the given number of people *or more, if Earth impact occurs.*

- **High chance of significant population damage if Earth impact occurs**
  - Damage very likely to affect hundreds of thousands of people or more
  - Smaller but significant chance of catastrophic damage affecting ~100M to ~2B people
- **Average population risk is ~24M among Earth-impacting cases** (driven by potential for global effects)
- ***High total average risk of ~240K people even when including the 1% chance of earth impact***

Impact Risk Summary

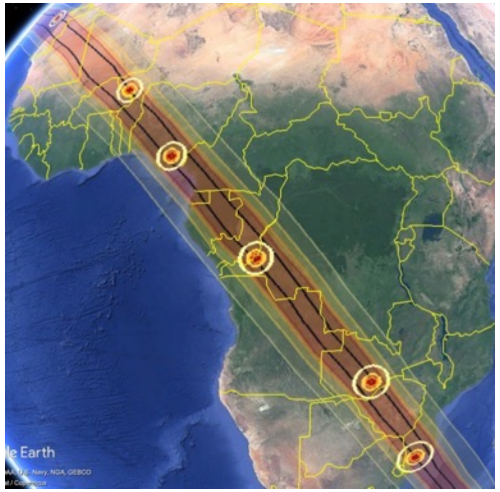
Assessment 1: Initial Discovery, 3 April 2023

Asteroid Characterization Summary

- Earth impact probability: ~1% chance of impact on 22 Oct. 2036
- Initial observations of object brightness (H magnitude ~19.4) indicate a very large, hazardous object, with large uncertainties in potential size and properties
- Diameter: 150–2000 m (490–6560 ft), most likely 220–660 m (720–2160 ft), median size 470 m (1540 ft)
- Impact Energy: 54–160,000 megatons (Mt), most likely 54–5,500 Mt, median 230 Mt

Risk Region Swath Map

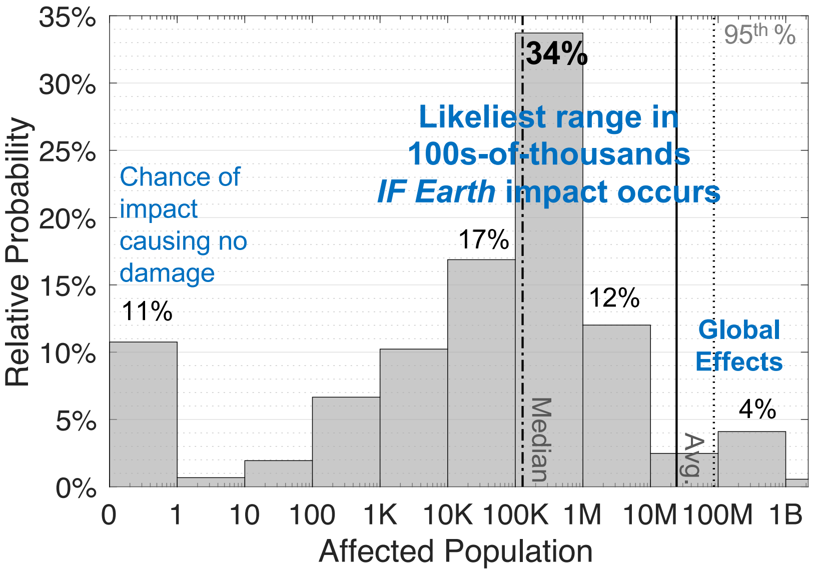
Regions potentially at risk, given range of damage locations and sizes. Median-sized damage areas are shown at sample locations.



Hazard Summary

- Large ranges of potential damage sizes, severities, and locations
- Asteroid is likely to miss Earth, but there is ~90% chance of potentially large population damage if impact occurs
- Impact would cause large blast & thermal damage reaching unsurvivable levels, with serious damage likely extending ~100–200 km (~60–120 mi) outward, and possibly out 600 km (370 mi) or more
- Large ocean impacts are likely to cause significant tsunami damage, especially across Atlantic regions or near coasts
- Largest possible sizes could cause catastrophic global-scale effects (6% chance)

Affected Population Risks



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

Range: 0–2B ppl

~24M avg. if Earth impact occurs

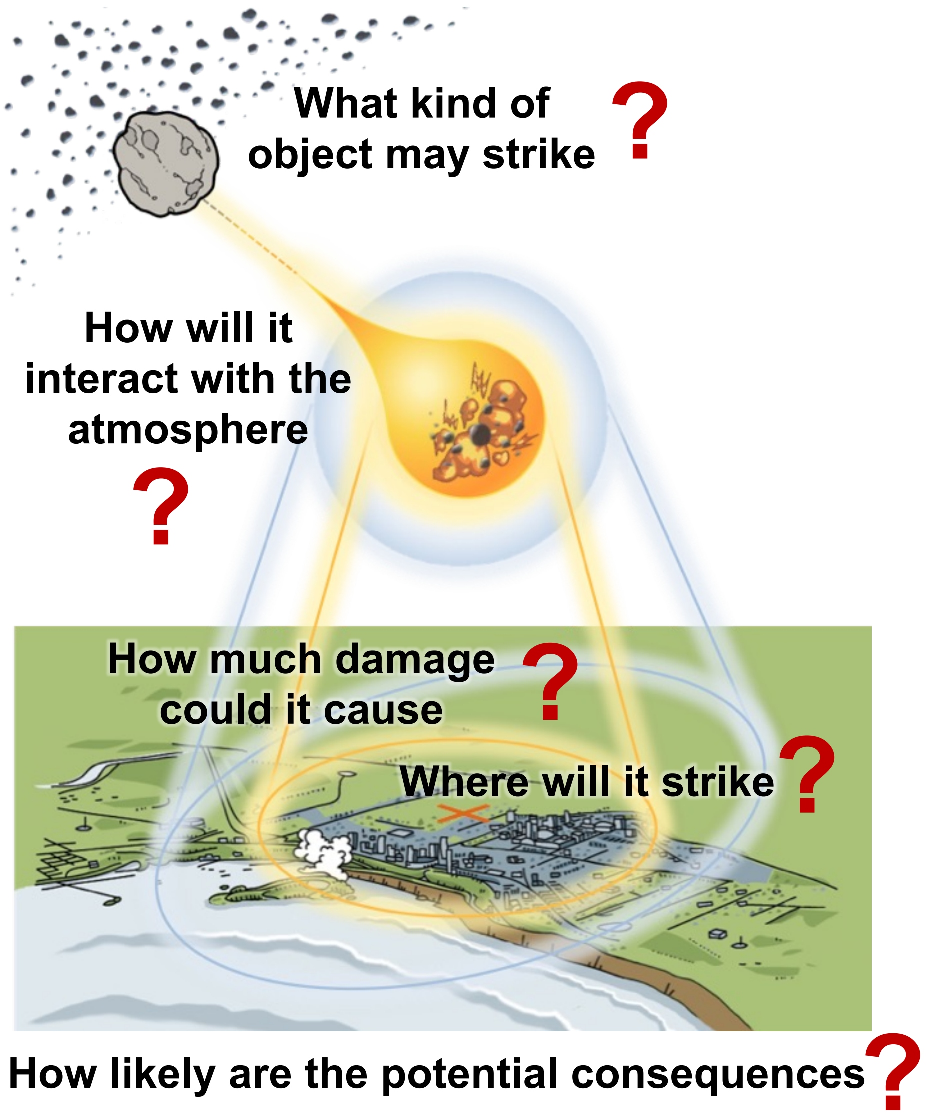
~240K total avg. risk (with ~1% Earth-impact probability)

HYPOTHETICAL EXERCISE

BACKUP

Risk Modeling Details and Reference Info

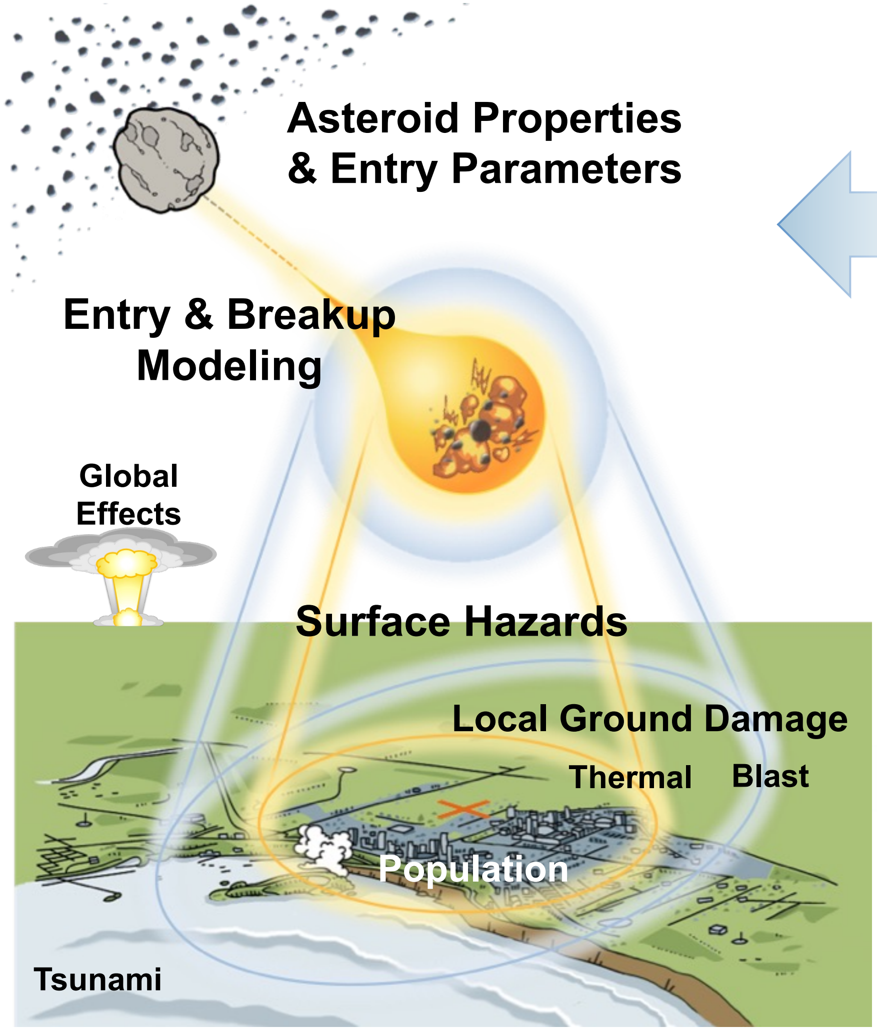
What is Asteroid Impact Risk Assessment?



- 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 Risk Assessment

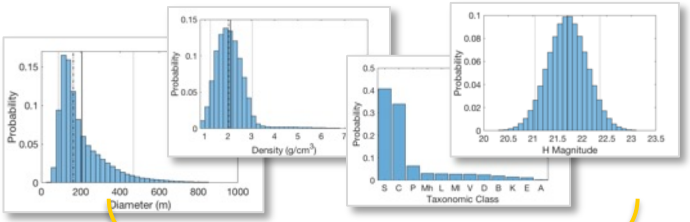
Probabilistic Asteroid Impact Risk (PAIR) Model

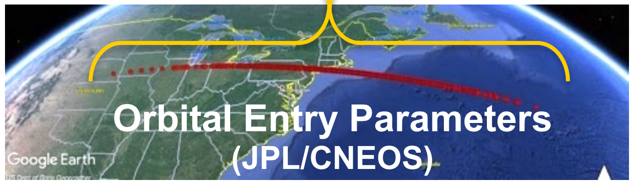


[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

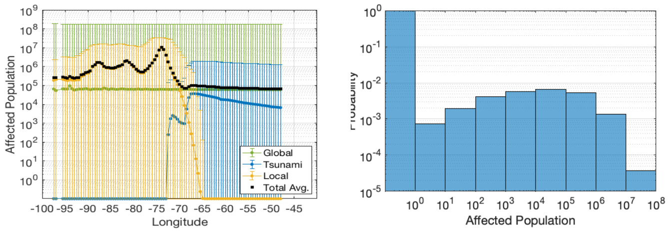
Impact Threat Scenario

Asteroid Property Distributions





Probabilistic Damage and Risk



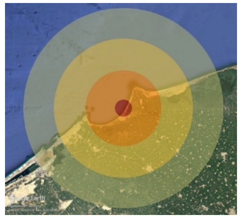
- Risk assessment models damage for millions of impact cases representing the range of possible asteroid properties and impact locations.
- Impact hazards assessed: local blast & thermal ground damage, tsunami, global effects
- Results give probabilities of damage sizes, severities, and affected populations.
- Regions potentially at risk to local damage are mapped.

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

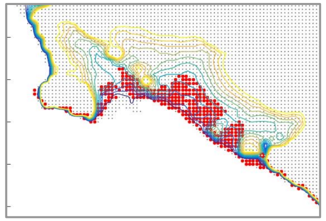
[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

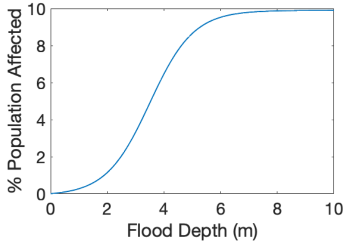
Local Blast & Thermal Affected Population



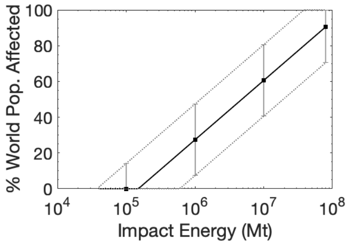
Severity	% Pop. Affected
Serious	10%
Severe	30%
Critical	60%
Unsurvivable	100%

Tsunami Affected Population



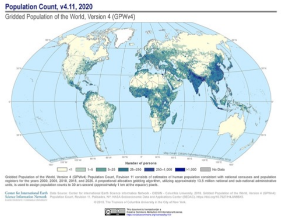


Global Effects Affected Populations

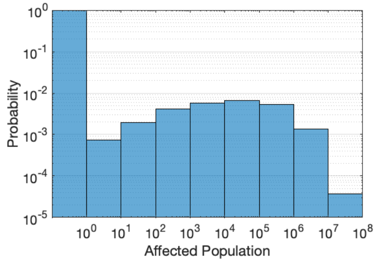


Impact Energy (MT)	% Population Affected		
	Min	Nominal	Max
4.E+04	0	0	0
8.E+04	0	0	10
2.E+05	0	0	20
3.E+05	0	10	30
6.E+05	0	20	40
1.E+06	10	30	50
2.E+06	20	40	60
5.E+06	30	50	70
1.E+07	40	60	80
2.E+07	50	70	90
4.E+07	60	80	100
8.E+07	70	90	100

SEDAC Gridded Population Data

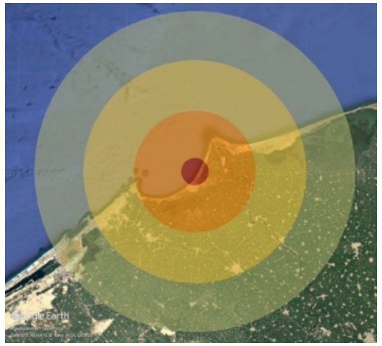


Population Risks



Local Blast & Thermal Ground Damage

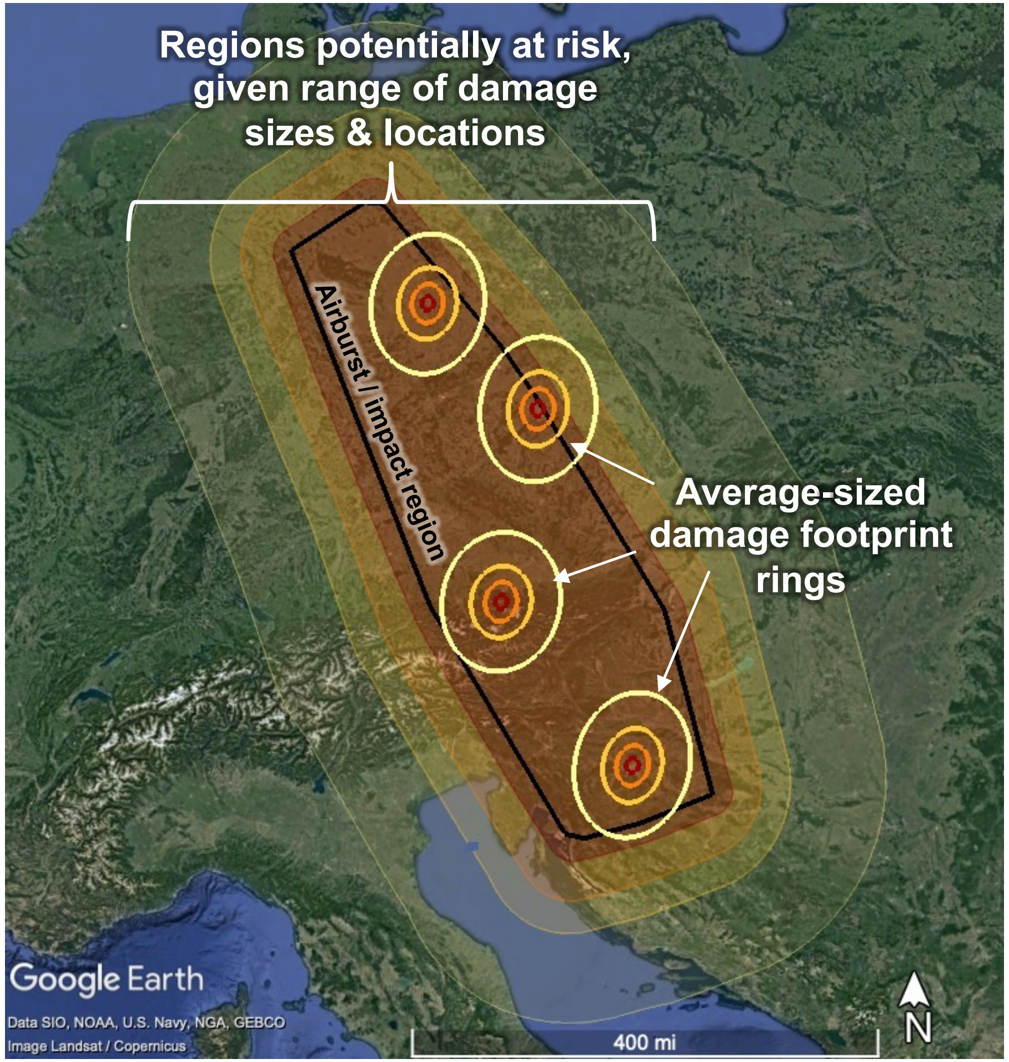
- Large impacts or airburst can generate destructive blast waves and thermal heat that can cause various levels of injury, fatalities, structural damage, and/or fires extending far around the impact location.
- Risk model assesses blast and thermal ground damage *independently* at four equivalent severity 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 sub-global-scale asteroid sizes
  - 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

HYPOTHETICAL EXERCISE

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

* Swath extents shown for the 2023 PDC 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.

BACKUP

Additional Epoch 1 Risk Assessment Summaries & Details

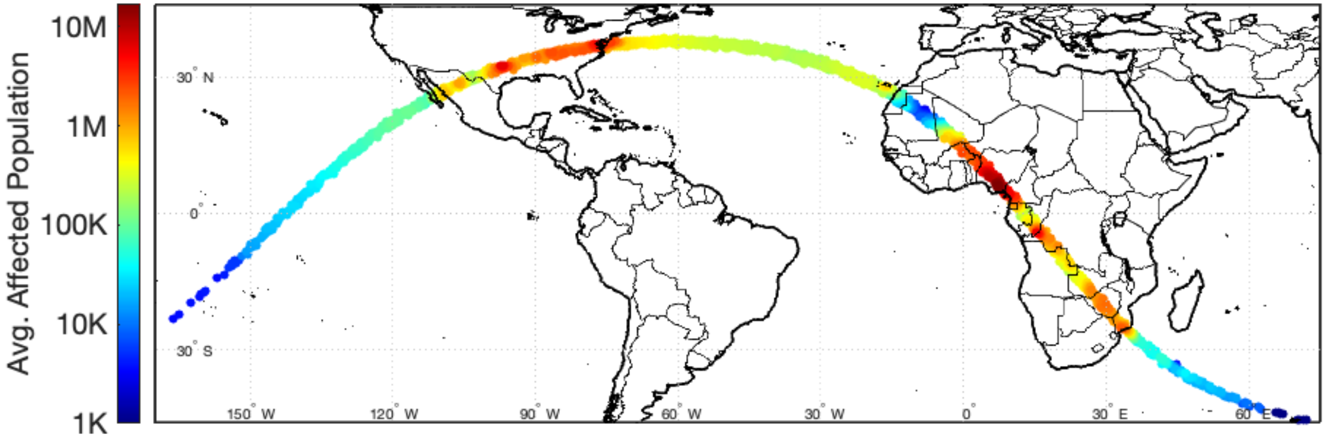
HYPOTHETICAL EXERCISE

Ames Research Center

Impact Damage & Risk Summary

- 1% chance of Earth impact by a large asteroid ~150–2000 m in diameter, with potential impact locations across a globe-spanning corridor
- **Risk assessment indicates significant damage is likely across all potential asteroid sizes and impact locations**

Avg. Affected Population along Potential Impact Locations

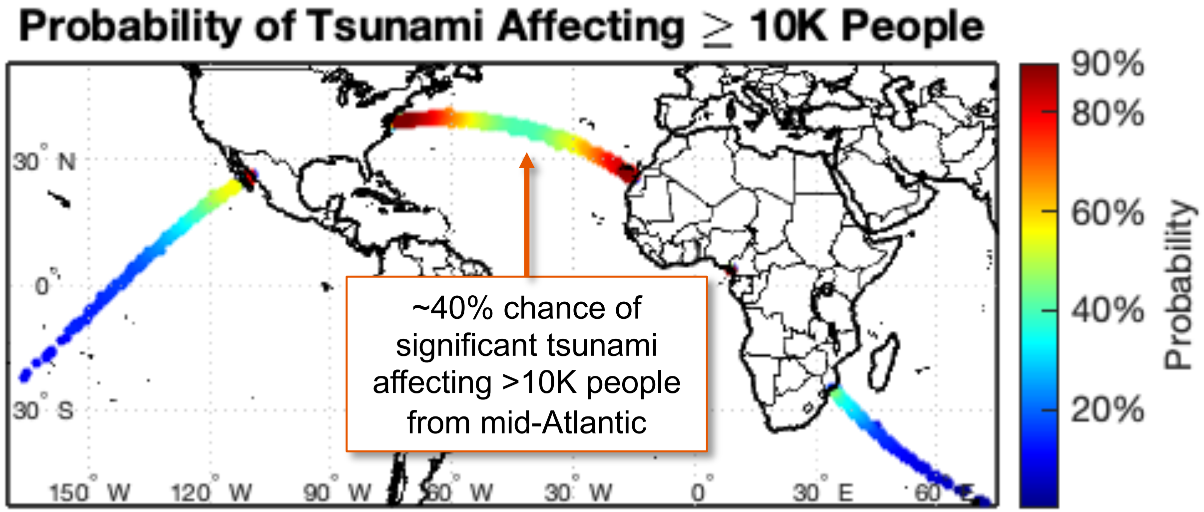


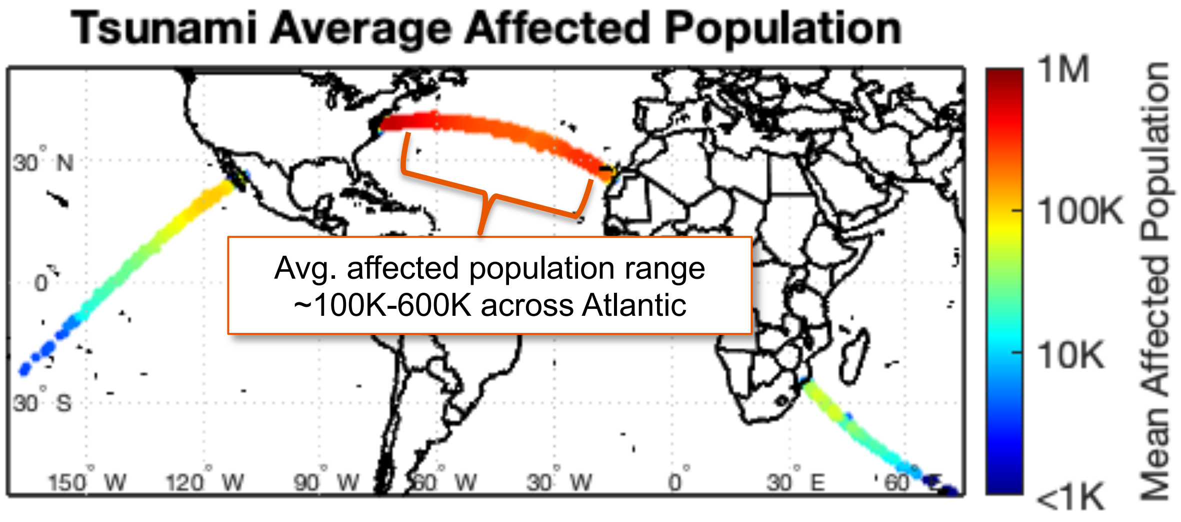
- **Population Risk:** Damage is most likely to affect hundreds-of-thousands of people, with a potential range from 0 to ~1B and an average of 24M among Earth-impacting cases
- **Local Ground Damage:** Impacts from all potential sizes would cause large blast and thermal damage reaching unsurvivable levels, with serious damage likely extending hundreds of kilometers outward
- **Tsunami:** Larger ocean impacts could also cause significant tsunami, with potentially large damage likely across Atlantic regions or near coasts
- **Global Effects:** Global effects from largest impacts could affect substantial fractions of the world population (hundreds of millions up to 2 billion), and drive high overall risk levels despite their lower (6%) probability

High risk and large uncertainties demonstrate a need for reconnaissance missions to better determine the size of the asteroid, its potential damage, and appropriate mitigation responses.

Tsunami Damage & Risk

- 48% of potential impact regions are over ocean
- Tsunami damage occurs in ~74% of ocean cases (36% chance among all impact cases)
- High chance of large tsunami from impacts across all Atlantic regions or near coasts of Mexico
  - Impacts near US East coast or West African coast pose greatest tsunami risks
  - Significant tsunami are less likely for S. Pacific or Indian Ocean regions further than ~1000 km offshore
- Tsunami population risks (among ocean impacts):
  - Average affected population ranges are 10K–620K across most ocean points (200K avg. over all)
  - 50% chance of large tsunami affecting >10K people (40–90% chance across all Atlantic points)
  - Largest tsunami could affect up to millions of people
- *Large uncertainties remain in potential severity and range of asteroid-generated tsunamis*

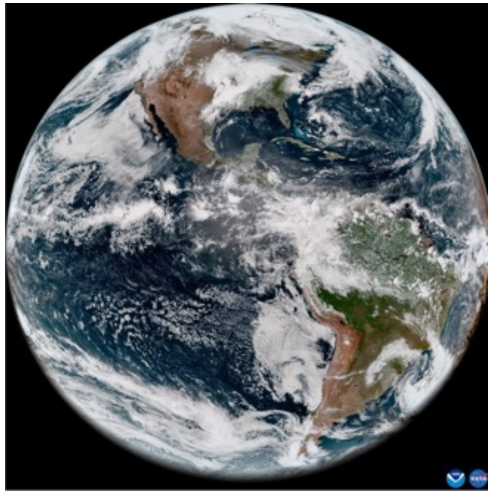




[PAIR tsunami model details: Stokes et al., 2017]

Global Effects (GE)

- **The largest impact sizes could cause global climatic effects endangering substantial fractions of world population**
  - **6% chance of global effects** from largest asteroid sizes (impact energies over 40 gigatons, diameters over ~1 km or 3,300 feet)
  - Affected population estimates for these sizes are **likely in the tens-of-millions** to **hundreds-of-millions**, with an **average of ~370 million** and worst-case estimates affecting around **1–2 billion people**
- **Global effects drive greatest average population risk levels despite lower probability**
  - **Average population *risk* from global effects is ~24M people** (among all potential impactor sizes, including likelihood of sub-global sizes with no GE)
  - Although largest sizes are less likely, the potential consequences are extreme and therefore pose a high level of risk
- **Large uncertainties remain** in what asteroid sizes may start to cause onset of climate effects, the severity or range of possible effects, and potential for other intermediate cascading regional environmental effects.



6% chance of GE occurring
Avg Population Risk: 24M

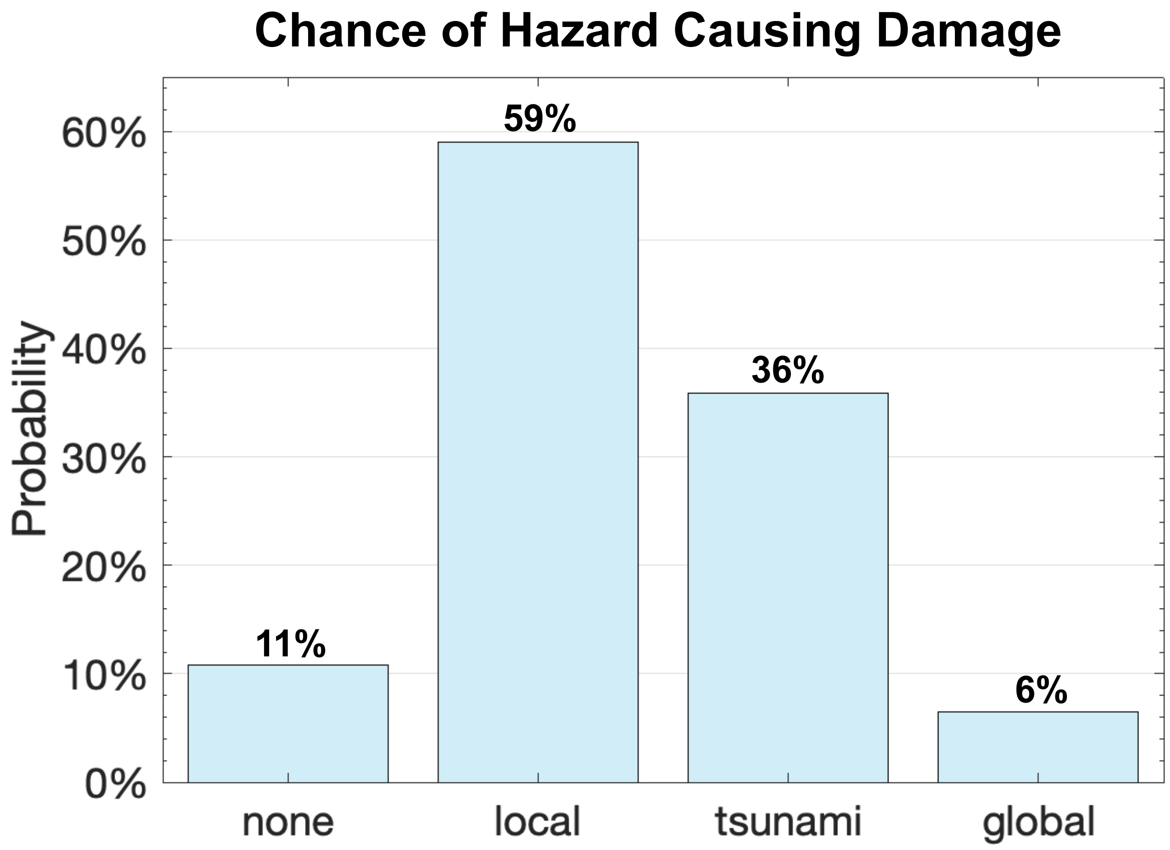
Affected Population Ranges (among 6% GE-causing cases)	
Range	~200K–2B
Most likely	85M–900M
Average	370M
Median	240M

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

Hazard Summary

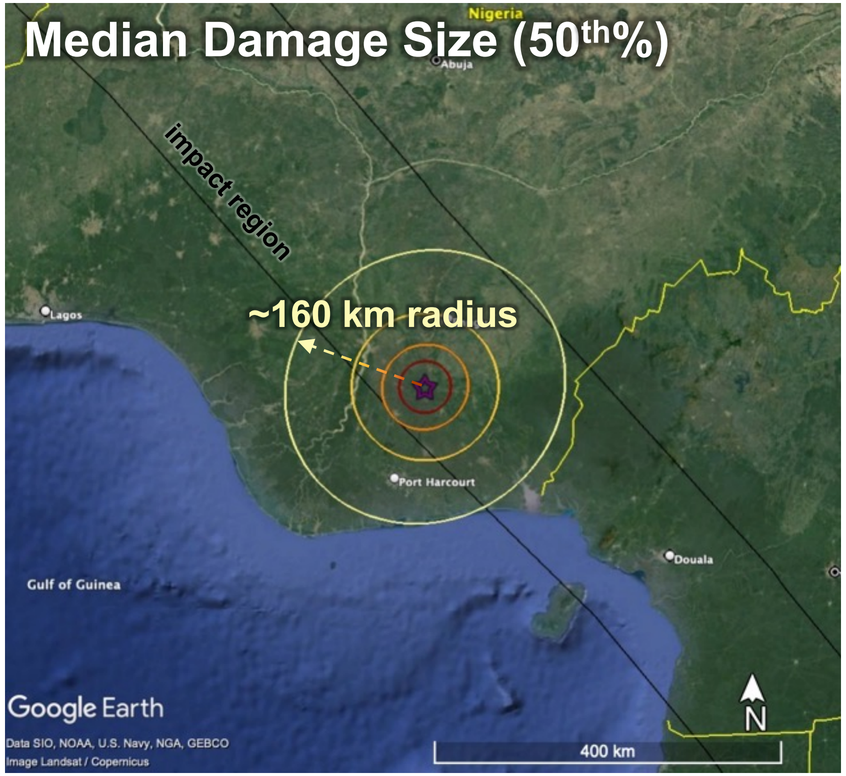
Hazard Likelihoods among ~1% of Earth-impacting Cases

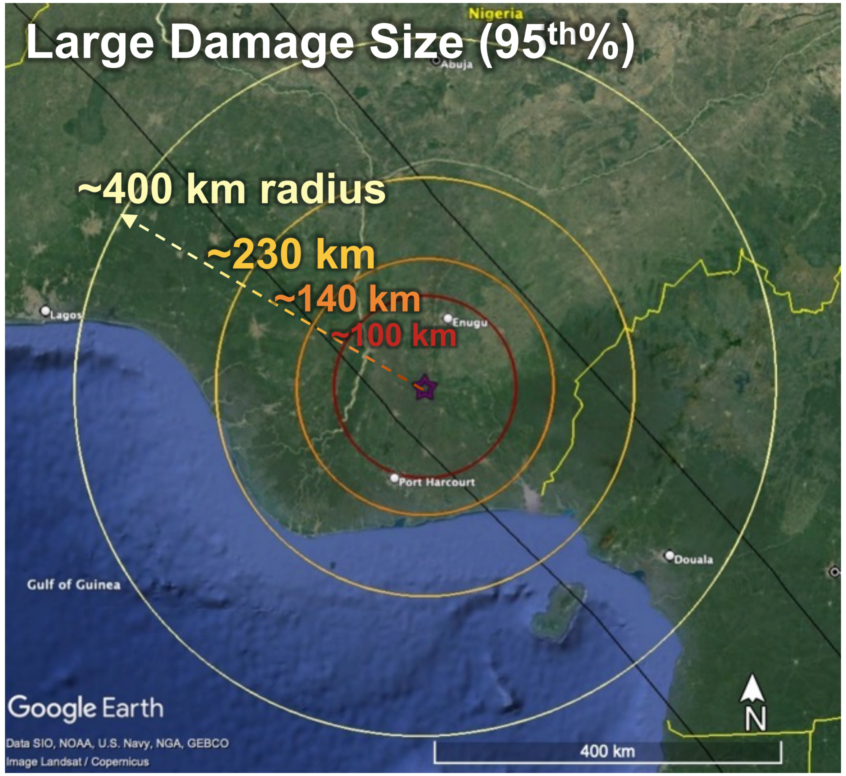
- 52% chance of impact over land, 48% water
- All impacts over land cause large local blast and thermal ground damage affecting populated areas (~60% of all impact cases)
- Tsunami damage occurs in ~74% of ocean cases (36% of all cases)
- Largest impactors could cause catastrophic global-scale effects in ~6% of cases
- Potential for regional environmental effects from larger sub-global impacts is unknown
- No damage occurs in ~11% of Earth-impact cases (smallest sizes over ocean)



* A single impact event can cause multiples hazards (e.g., blast + thermal, tsunami + local near-shore, or global + local or tsunami). Sum of all hazard occurrence probabilities may exceed 100%.

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





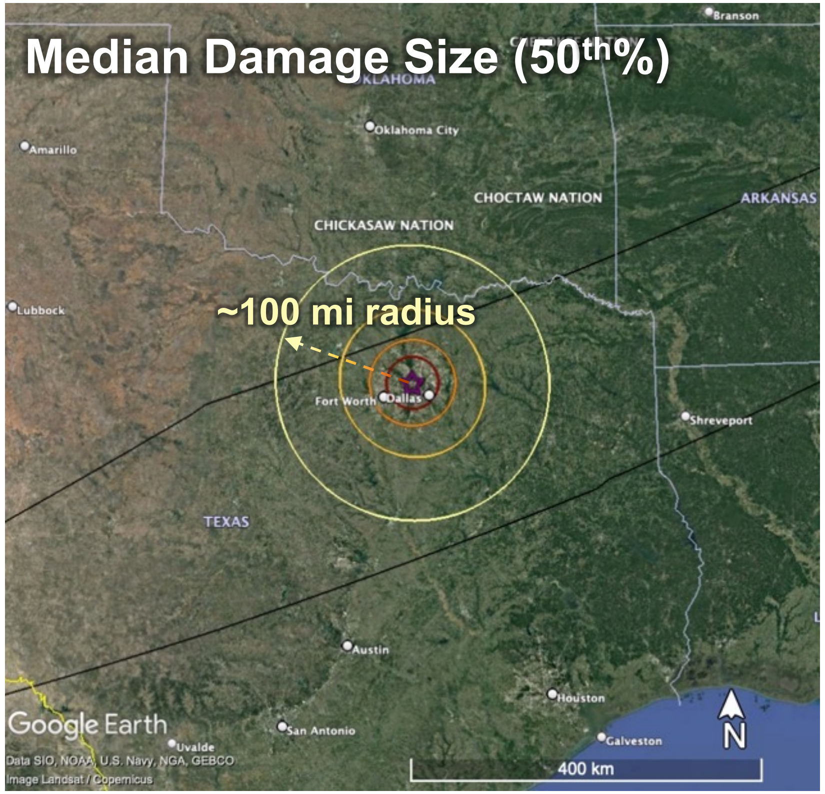
- Rings show sample damage footprint sizes at a single sample location
- Black border shows range of potential impact locations (damage center points) along swath
- Percentiles give the chance that the damage region could be up to the given size or smaller

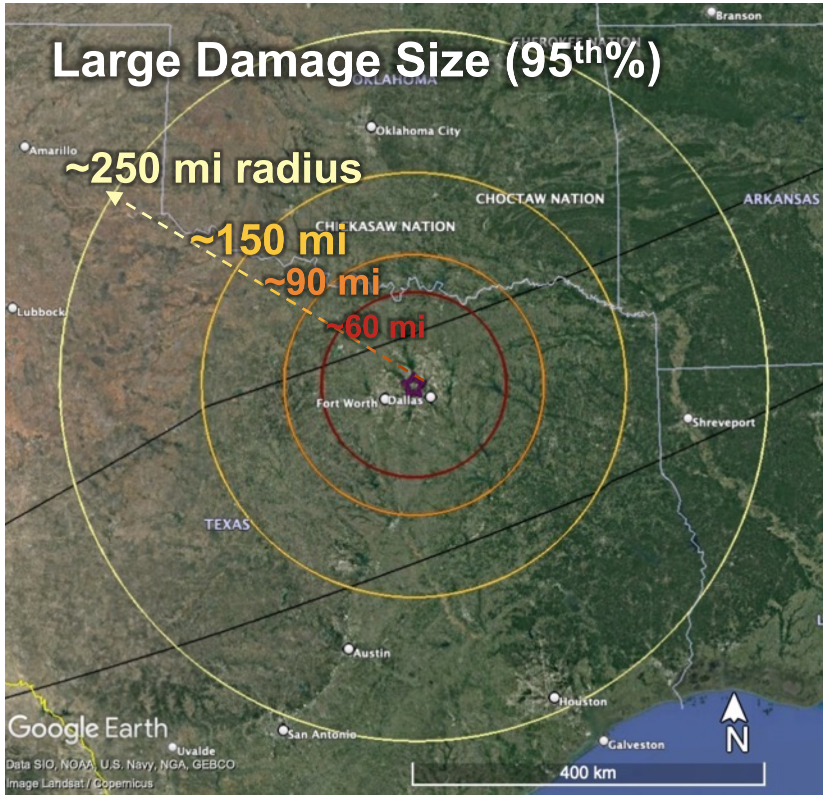
Local Ground Damage Radius Sizes (km / mi)

Damage Level	Mean	25th %	**50th %**	75th %	**95th %**
Serious	190 km (120 mi)	120 km (75 mi)	**160** km (100 mi)	220 km (140 mi)	**400** km (250 mi)
Severe	110 km (70 mi)	70 km (45 mi)	**90** km (55 mi)	120 km (75 mi)	**230** km (150 mi)
Critical	65 km (40 mi)	40 km (25 mi)	**50** km (30 mi)	75 km (45 mi)	**140** km (90 mi)
Unsurvivable	40 km (25 mi)	20 km (15 mi)	**30** km (20 mi)	50 km (30 mi)	**100** km (60 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

Sample Ground Damage Sizes over Dallas TX
(highest US population damage location)





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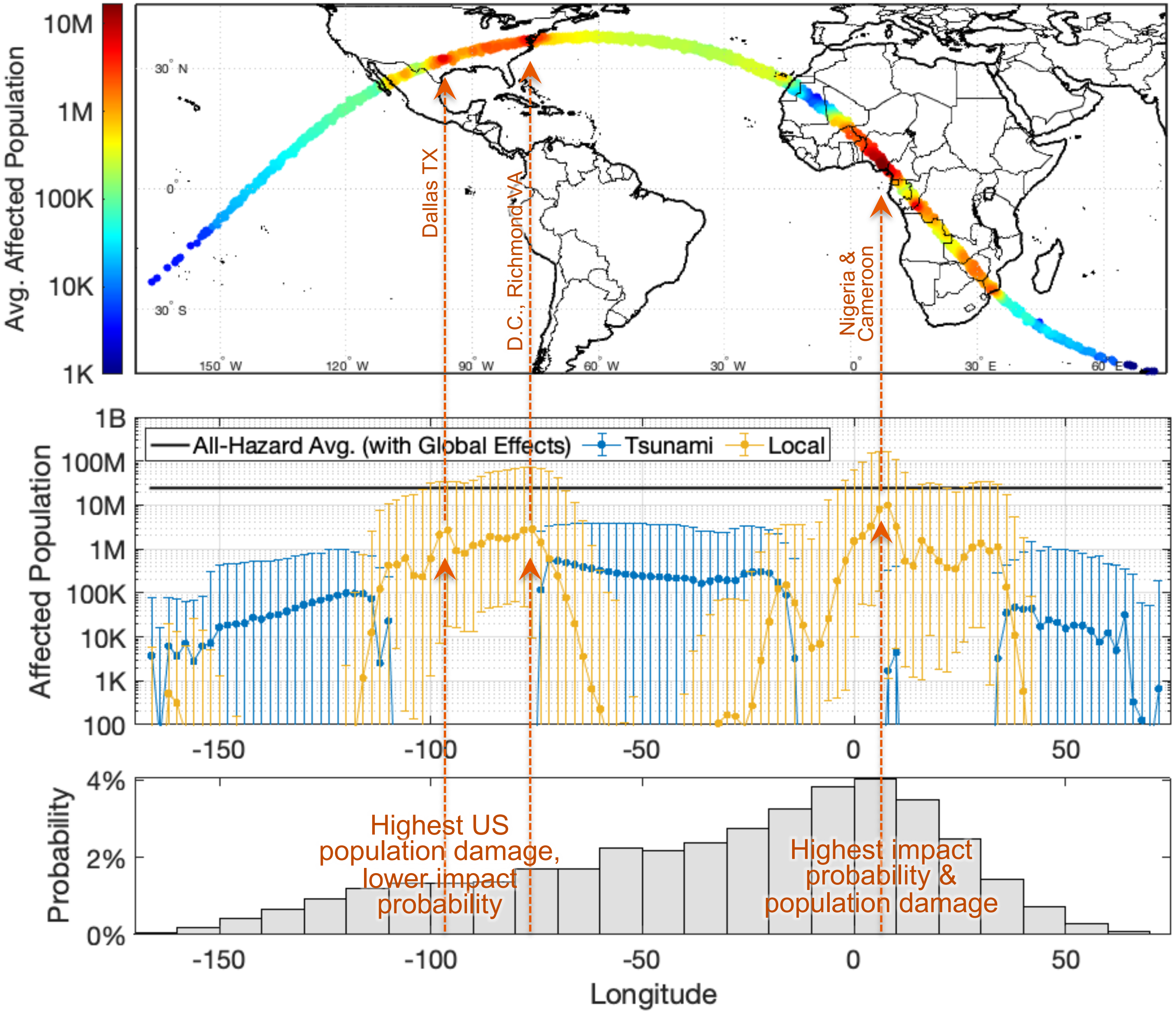
	Windows shatter, minor structure damage
	Widespread structure damage, or 3rd degree burns
	Residential structures collapse, or clothing ignites
	Devastation, structures flattened or burned

Population Damage Ranges Along Swath

- Impacts over land cause most population damage
  - Average affected population ranges are ~10K–10M across Africa and ~100K–3M across N. America
  - Maximums reach ~10M-100M
  - Highest damage & risk region is around Nigeria with an average affected pop of ~10M
- Significant tsunami are possible across all ocean regions if impact is very large
  - Average affected population ranges are ~10K–600K
  - Maximums reach ~100K–4M
  - Greatest tsunami risks are Atlantic impacts (especially near US East coast)



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 within 2° longitude increments along swath

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

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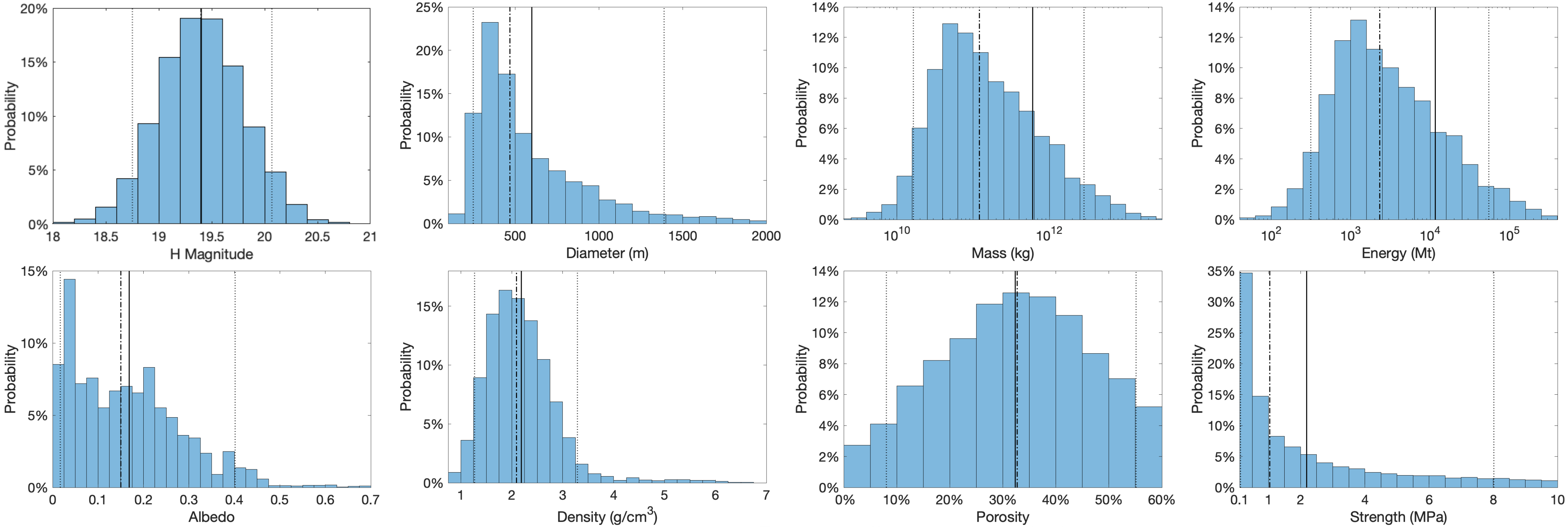
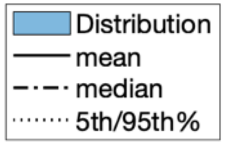
Asteroid Property Details

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)	600	250	347	469	738	1389	216 – 660	151 – 2000
Mass (kg)	6.0E+11	1.6E+10	4.7E+10	1.2E+11	4.2E+11	2.8E+12	2.8E+09 – 2.9E+11	2.8E+09 – 8.4E+12
Energy (Mt)	1.2E+04	3.1E+02	9.0E+02	2.3E+03	8.1E+03	5.5E+04	5.4E+01 – 5.5E+03	5.4E+01 – 1.6E+05
H Magnitude	19.40	18.75	19.13	19.40	19.67	20.07	19.02 – 19.82	18.34 – 20.4
Albedo	0.17	0.02	0.05	0.15	0.24	0.40	0.01 – 0.21	0.01 – 0.67
Density (g/cm³)	2.2	1.3	1.7	2.1	2.5	3.3	1.4 – 2.6	0.8 – 5.3
Porosity (%)	32%	8%	22%	33%	43%	55%	18% – 49%	1.8% – 60%
Strength (MPa)	2.2	0.1	0.3	1.0	3.2	8.0	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]

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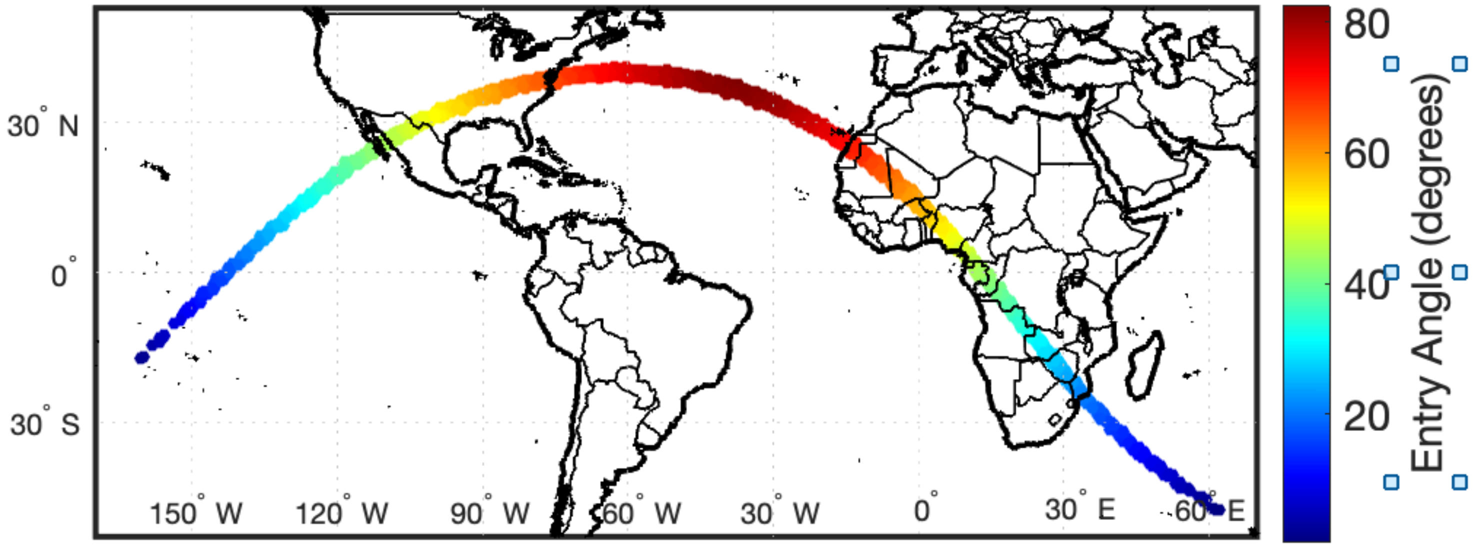
Entry Parameters & Locations

- Around 1% chance of Earth impact somewhere along a globe-spanning corridor from the South Pacific, across North America, Atlantic, Africa, and into the southern Indian Ocean.
- Entry parameters vary across the corridor, but are well-known for given impact points
- **Entry Velocity:**
  - 12.67–12.68 km/s
  - Little variation across swath
- **Entry Angle:**
  - Nearly-vertical entries (83°) in mid-Atlantic
  - Shallow skimming entries near edges
- **Entry Direction (CW from N):**
  - Entry direction rotates along swath
  - Southward over mid-Atlantic (90°)
  - SEbS at eastern edge (122°)
  - SW at western edge (225°)

Entry Angle (from horizontal)



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

HYPOTHETICAL EXERCISE

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HYPOTHETICAL EXERCISE

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