

2021 PDC Hypothetical Impact Exercise: Probabilistic Asteroid Impact Risk

Lorien Wheeler

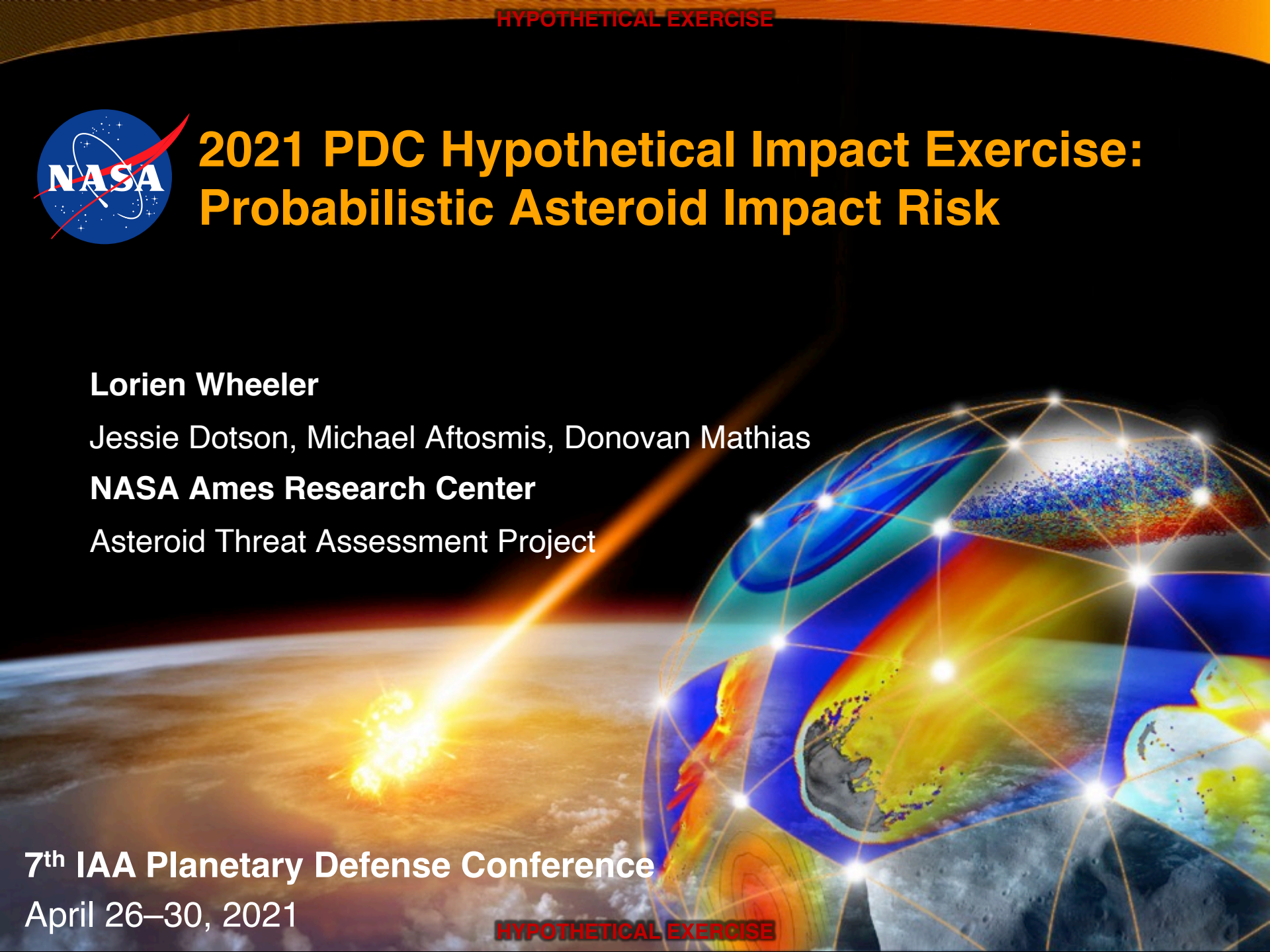
Jessie Dotson, Michael Aftosmis, Donovan Mathias

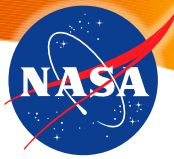
NASA Ames Research Center

Asteroid Threat Assessment Project

7th IAA Planetary Defense Conference

April 26–30, 2021

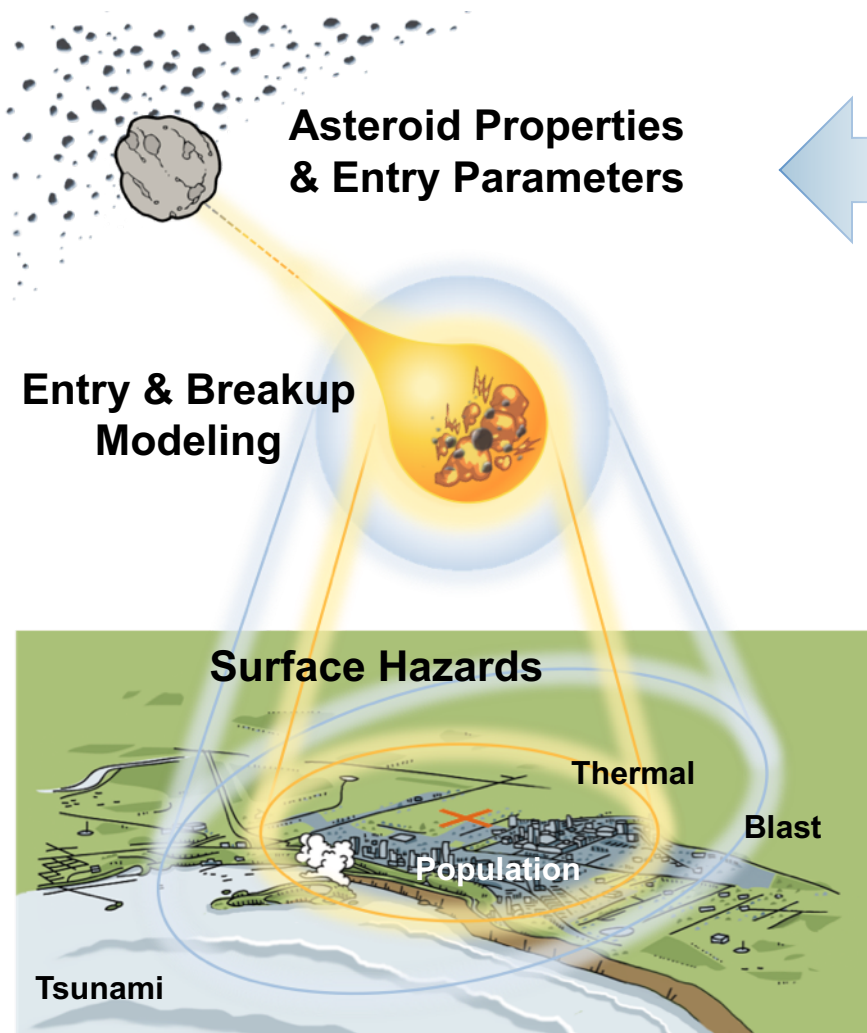




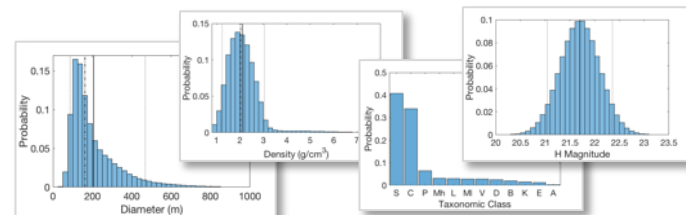
SCENARIO DAY 1 INJECT

Impact Scenario Threat Assessment

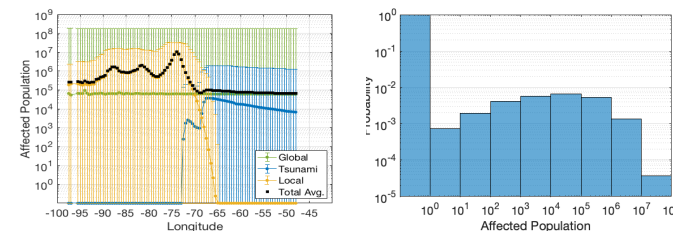
Probabilistic Asteroid Impact Risk (PAIR) Model



Asteroid Property Distributions



Probabilistic damage and risk results

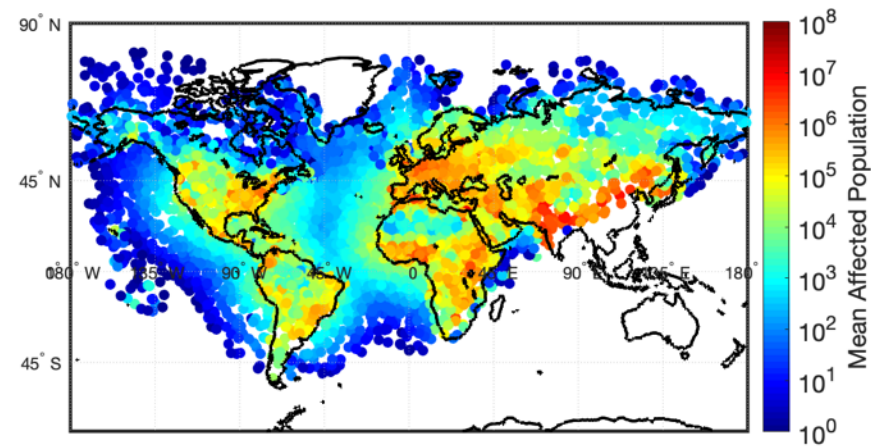


Impact Risk Summary

Characterization Summary & Updates

- Assessment date: 20 April 2021 (initial discovery)
- Potential impact date: 20 October 2021 (6 mo.)
- Earth impact probability: 5%
- Diameter: mean ~150 m, range ~35–700 m
- Energy: mean 256 Mt, range ~1 Mt – 13 Gt
- Properties: unknown type of physical properties

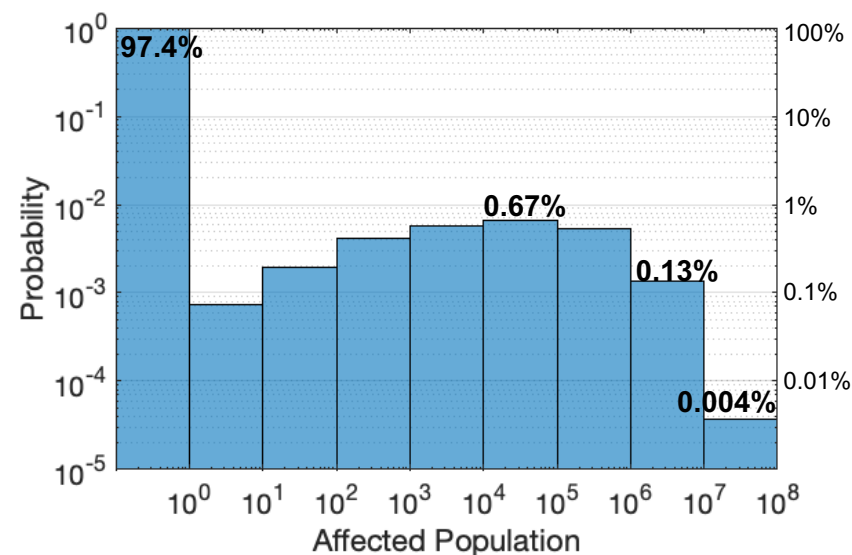
Risk Regions



Hazard Summary

- Affected Population: 0–86M, 6k average (117k average among impacting cases)
- Primary hazard is airburst/impact causing blast overpressure, from minor structural damage to potentially unsurvivable levels
- Damage radii: 0–500 km, ~90 km average
- Risk of tsunami is low, but large impacts near coast could cause significant inundation
- No population damage is most likely: 97% total chance (~50% chance among impacting cases)

Affected Population Risks

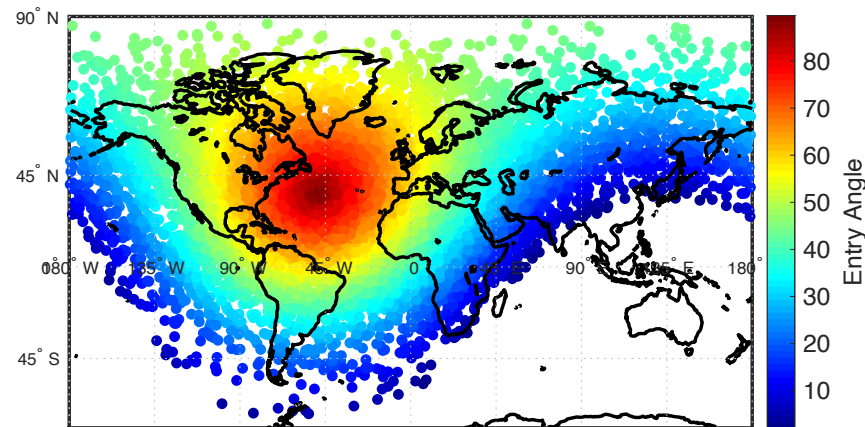


Entry Parameters & Locations

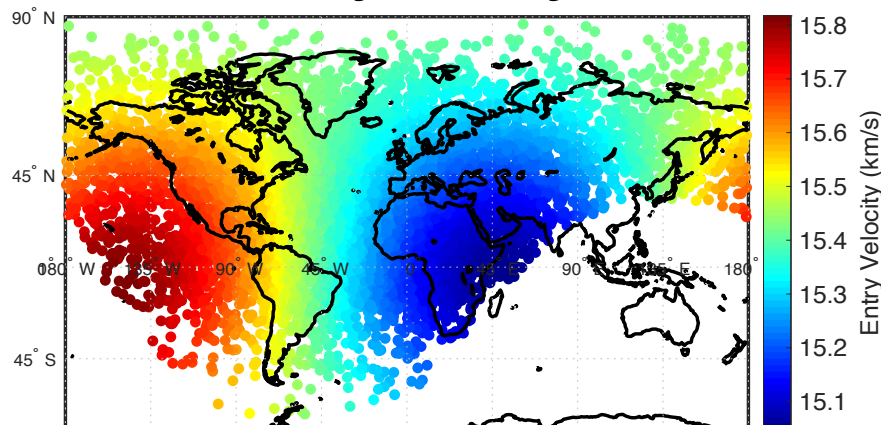
5% chance of Earth impact with potential impact regions spanning most of the globe, centered around mid-Atlantic

- Entry parameters vary across the globe, but are well-known for given impact points
- **Entry Angle:**
 - Vertical (90°) entries near mid-Atlantic
 - Shallow/skimming entries near edges
- **Entry Velocity:**
 - 15-16 km/s
 - Little variation across points
- Velocity determines impactor energy and entry angle affects burst altitude ranges for damage models

Entry Angle (from horizontal)



Entry Velocity

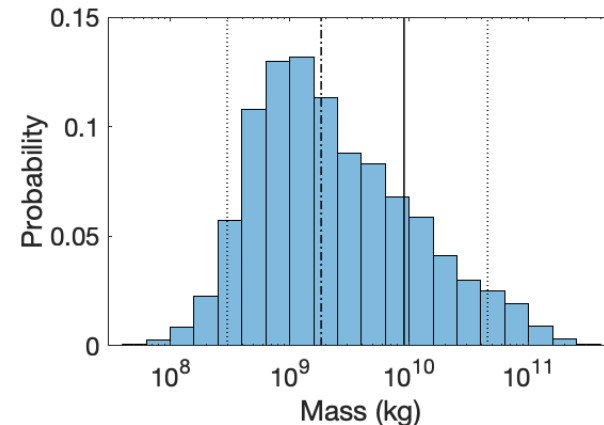
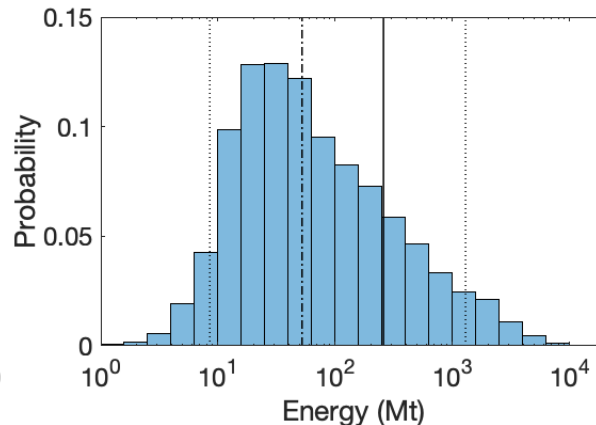
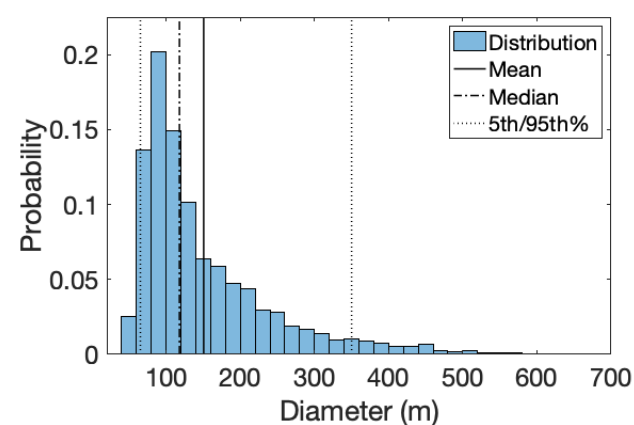


Asteroid Properties

- Asteroid sizes and properties are highly uncertain**, ranging from small objects that would pose little threat to objects hundreds of meters across with gigatons of impact energy
- Maximum sizes are very large, but also very unlikely**
- Averages are ~150 m, 250 Mt
- Likelier size ranges are smaller
- Type and properties are unknown, ranging from more common stony types to rare iron types

Asteroid Size Ranges

	Diameter (m)	Energy (Mt)	Mass (kg)
Full range	35–700	1–13,000	4.4e7–4.4e11
Average	150	250	9.1e9
Median	118	52	1.8e9
Most likely	~80–120	~20–50	~1e9
5th–95th %	65–350	~8–1280	3e8–4.5e10



[Property inference model: J. Dotson PDC 2021]

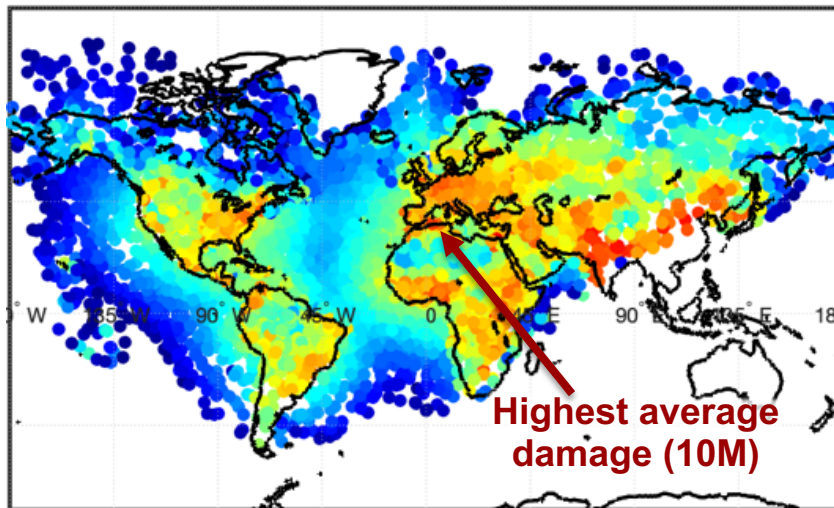
Affected Population Ranges Across Globe

(among 5% Earth-impacting cases)

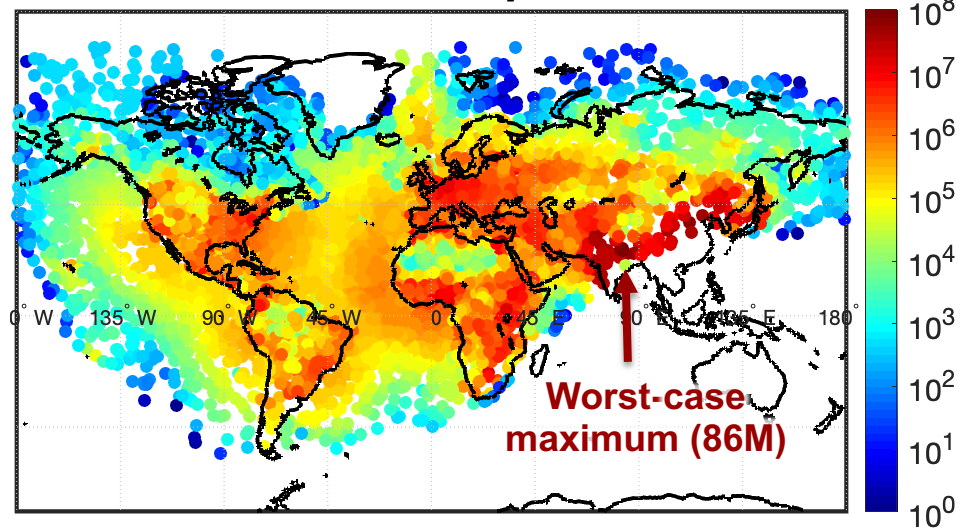
Affected population ranges from 0 to tens of millions across the globe, depending on population density and damage ranges

- Average affected population range: 0–10M across entry points (117k overall avg)
- Max affected population range: 0–86M across entry points (1M avg. max among all points)
- Worst case maximum is at very edge of potential impact zone (unlikely skimming entry)

Average Affected Population



Max Affected Population

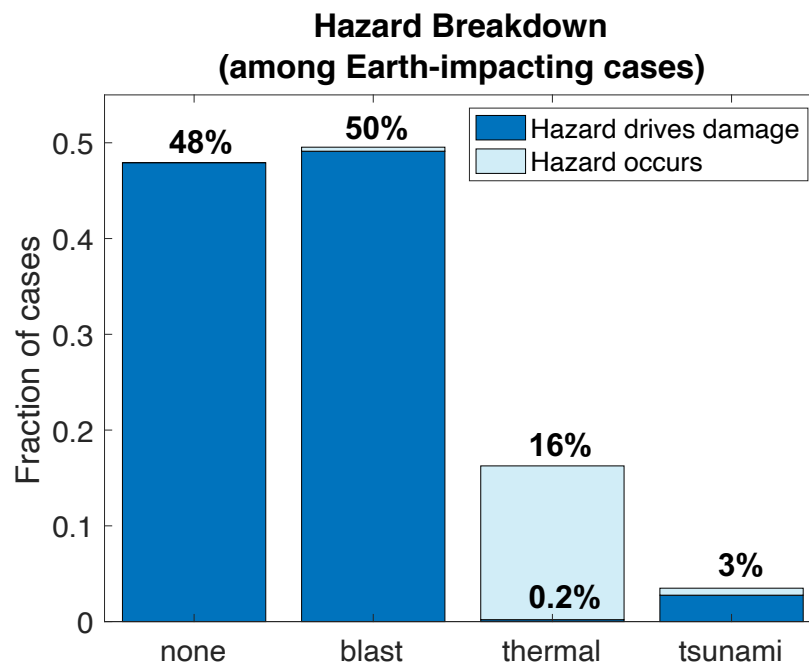


Maps of average and maximum affected population for each sampled impact entry point, given the potential range in asteroid properties and resulting damage
(ocean points represent tsunami damage to surrounding coastal regions)

Hazard Sources

(relative hazard risks among 5% Earth-impacting cases)

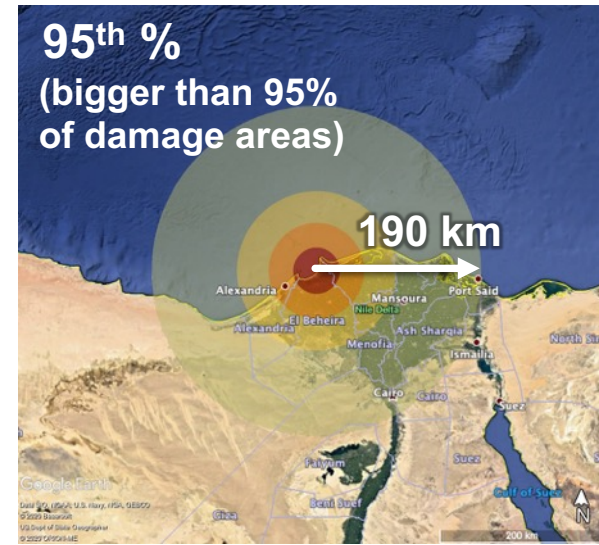
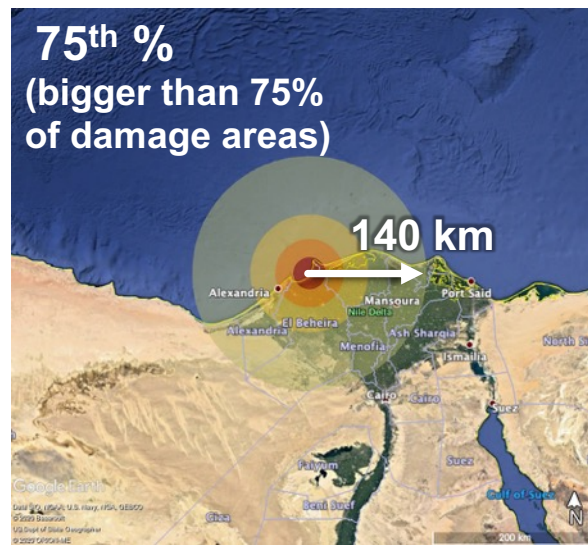
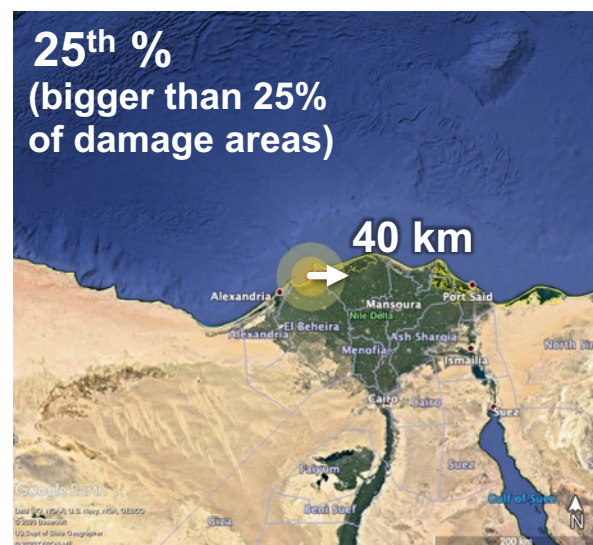
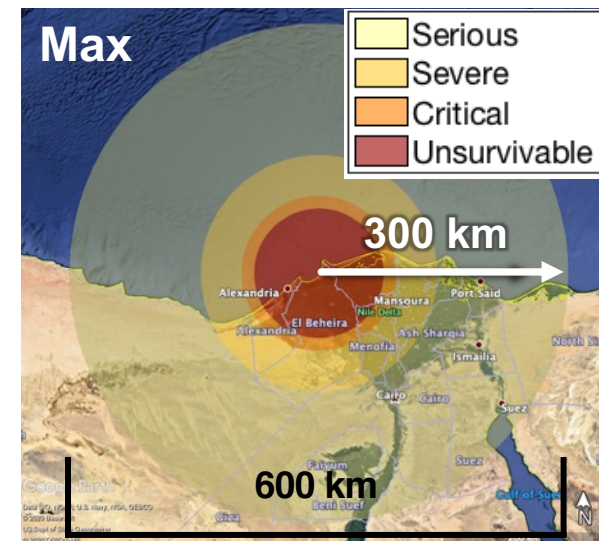
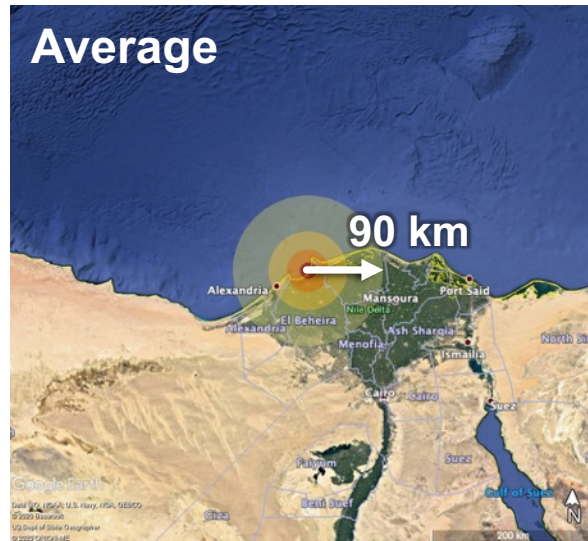
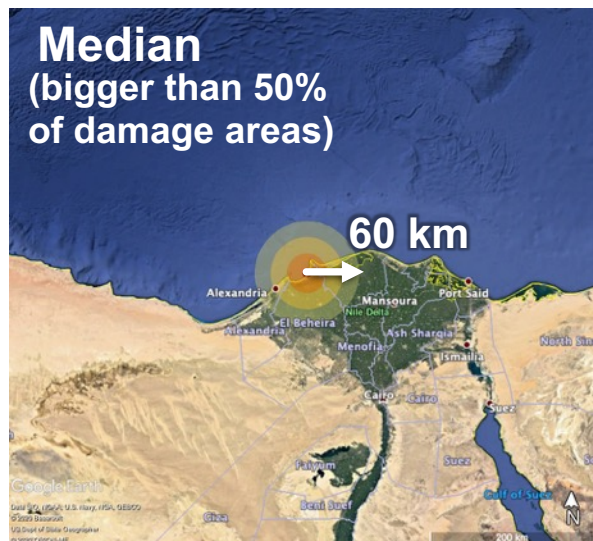
- Blast damage is the predominant hazard source in ~50% of impact cases
- Thermal damage also occurs in ~16% of cases, but is smaller and less severe than blast damage in nearly all cases
- Risk of tsunami is low, occurring in ~3% of impact cases, but the largest impacts could cause significant inundation
- No global effects are expected, but potential for regional environmental effects from larger impacts is unknown
- No damage occurs in 48% of cases



Hazard Source	% Cases Hazard Occurs	% Cases Hazard Drives Damage	Average Affected Population	Affected Population Range
Blast	50%	49%	117k	0–86M
Thermal	16%	0.2%	8k	0–48M
Tsunami	3.5%	2.8%	940	0–1.8M
No Damage	48%	48%	0	0

Sample Blast Damage Sizes

(regional sizes for an entry point near Alexandria, Egypt)

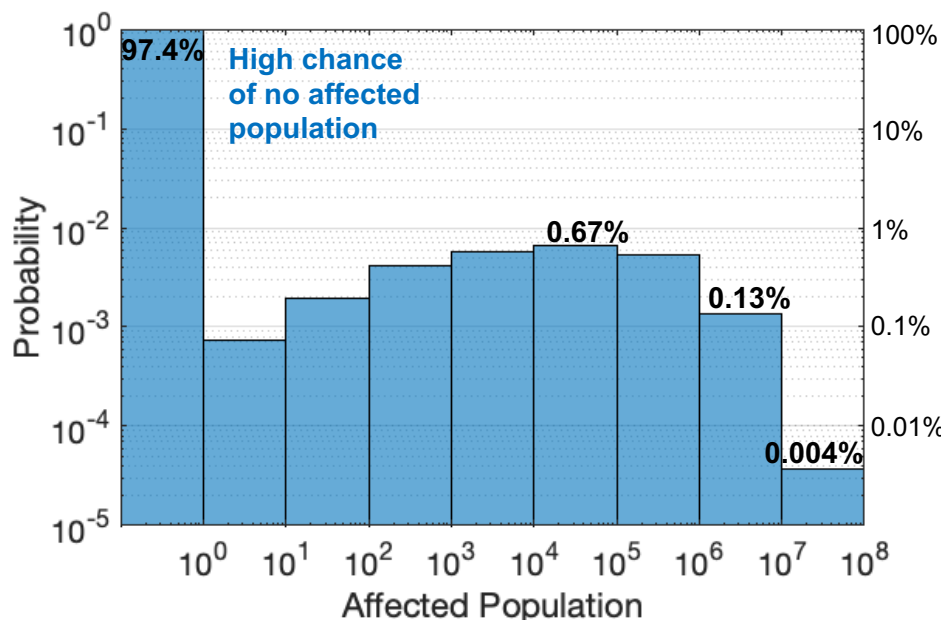


Total Affected Population Risks

(Total Risk with 5% Earth Impact Probability)

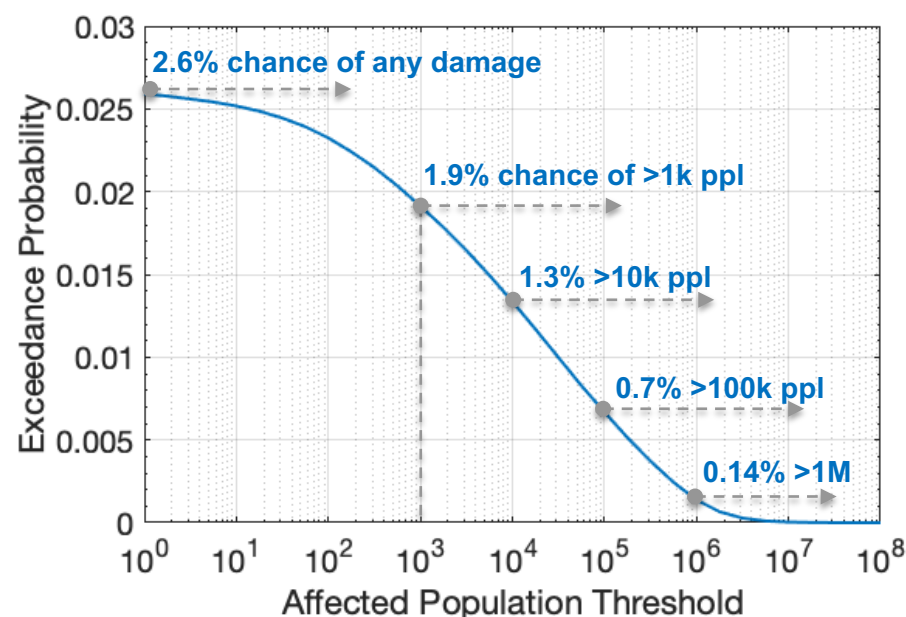
Population risk histogram:

Probabilities of affecting the number of people within each range



Population exceedance risk:

Probability of *at least* the number of people *or more* being affected



- **Average affected population:** ~6k total (with 5% impact probability), ~117k among Earth-impacting cases (~50% of which cause some population damage)
- **No damage most likely:** >97% chance of no people affected (with 5% impact probability)
- **Maximum affected population:** 86 million people (but very unlikely)
- But only 0.14% total chance of affecting over 1M people, 0.004% chance of >10M people

Impact Risk Summary

- Object size, potential impact location, and resulting damage all remain highly uncertain
 - Earth impact probability is still low (5%)
 - Maximum impactor sizes and damage consequences are very large, but also very unlikely
- Affected Population Risks:
 - Range 0–86M people, average total population risk of 6k
 - No population damage is most likely (97% total chance, 48% chance among impacting cases).
 - ~2% chance of affecting >1000 people, 1.3% chance of >10,000 people, 0.14% of >1 million people
- Hazard Summary:
 - Blast damage is the predominant hazard source, with potential ground damage radii up to several hundred kilometers
 - Thermal and tsunami damage are also possible, but less likely and less severe
 - No large-scale global effects expected, but potential for regional environmental or economic effects remains unknown.

	Asteroid Diameter (m)	Impact Energy (Mt)	Damage Radius (km) (given impact)	Affected Population (given impact)	Affected Population (5% impact)
Full range	~35–700	~1–13,000	0–470	0–86M	0–86M
Average	150	250	90	117k	6k
Most likely	~80–120	~20–50	~20–60	0	0
5 th –95 th %	65–350	8–1280	25–190	0–550k	0–0

Threat Assessment for Response Decisions

- Continuing Threat Assessment:
 - Updated risk assessments will be performed as additional information is gained about the object and potential impact
 - More detailed risk modeling and damage simulations can be performed for critical blast, thermal, or tsunami hazards as impact location is refined
- Risk-Informed Decisions and Response Support:
 - Probabilistic risk assessments enable response decisions to consider both the severity and relative likelihood of the range of impact consequences, given large uncertainties
 - Asteroid property distributions will be provided to mission designers to inform mitigation capability requirements
 - Risk assessments can be performed to evaluate the benefit of proposed mitigation or reconnaissance mission options
 - Damage area size and severity probabilities can support preliminary disaster response planning to prepare for potentially large damage within short warning time

SCENARIO DAY 3 INJECT

Risk Summary

Characterization Summary & Updates

- Assessment date: 30 June 2021
- Potential impact date: 20 October 2021 (<4 mo.)
- Earth impact probability: 100%
- Diameter: mean 136 m, range ~35–500 m
- Energy: mean 136 Mt, range 0.7–3700 Mt
- Entry: 15.2–15.3 km/s, 50–55° entry angle
- Properties: unknown type or physical properties

Hazard Summary

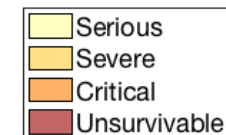
- Affected Population: 0–6.6M, average 580k, most likely several hundreds of thousands
- Primary hazard is airburst or impact causing blast overpressure and possibly thermal damage
- Damage radii: 0–250 km, average ~80 km
- Damage levels: minor structural damage and burns to potentially unsurvivable levels



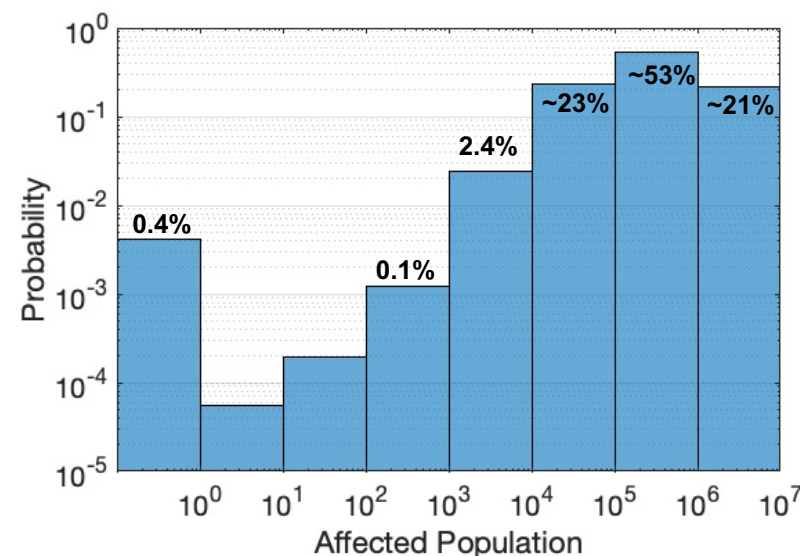
Damage Swath

Full range of regions potentially at risk to ground damage, given all potential impact locations and largest damage.

Sample average damage sizes over largest cities



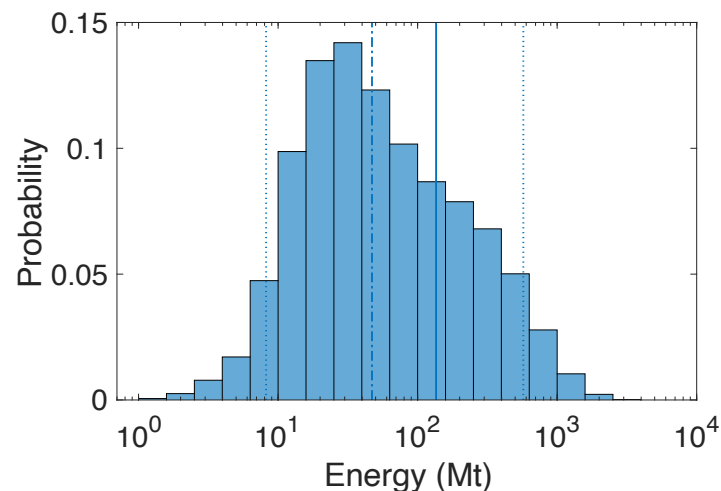
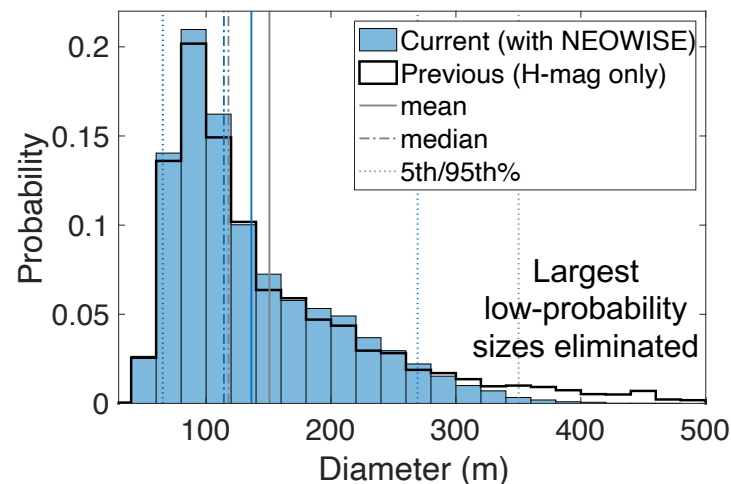
Affected Population Risk



Asteroid Properties

- Asteroid sizes and properties remain highly uncertain:** from small objects that would pose little threat to objects hundreds of meters across with several gigatons of energy
 - Maximum sizes are very large, but also unlikely
 - Diameter constraint from NEOWISE eliminated largest, low-probability sizes
 - Reduced maximums from ~700m to ~500m
 - Main size distribution remains similar
 - Type and properties are unknown, ranging from more common stony types to rare iron-types

	Diameter (m)	Energy (Mt)
Full range	~35–500	~1–3700
Average	136	136
Median	114	47
Most likely	~80–120	~20–50
5 th –95 th %	65–270	~8–570



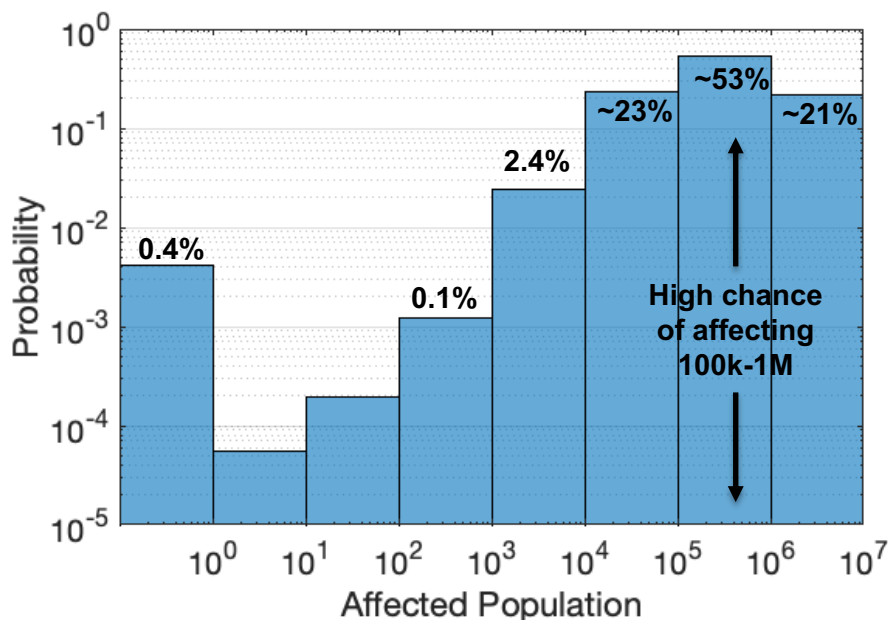
[Property inference model: J. Dotson PDC 2021] [NEOWISE: J. Masiero PDC 2021]

Affected Population Risks

(Total Risk with 100% Earth Impact Probability)

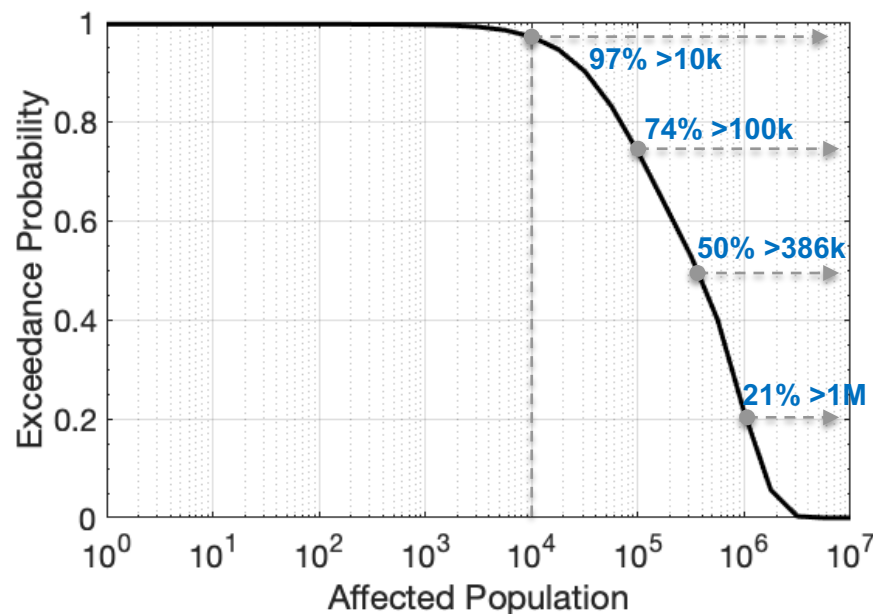
Population risk histogram:

Probabilities of affecting the number of people within each range



Population exceedance risk:

Probability of *at least* the number of people *or more* being affected

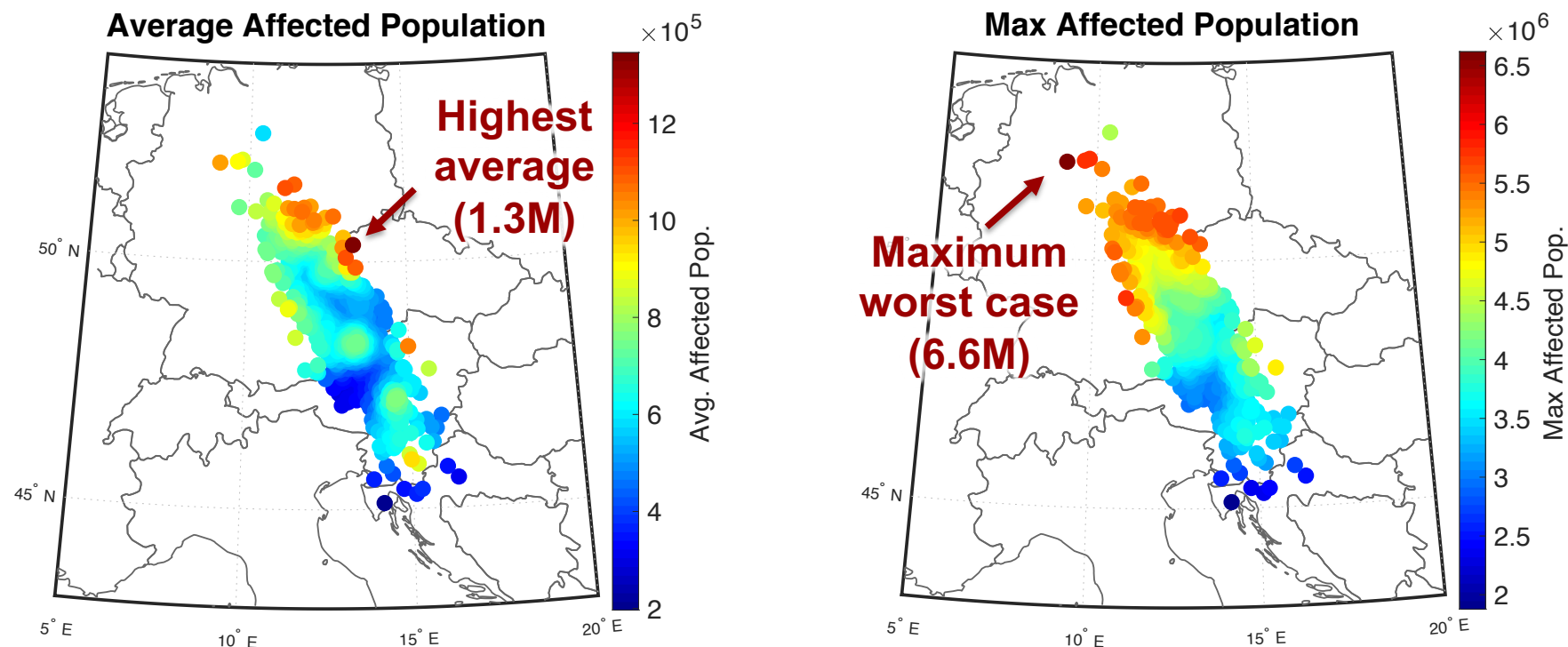


- **Damage is likely to affect several hundred thousand to a million people**
- Average of ~580k people affected
- Maximum worst case: 6.6 million people (among modeled cases)
- 97% chance of affecting at least 10k people, 74% chance of >100k, 21% chance of >1M
- <1% chance of affecting fewer than 1k people. <0.5% chance of no damage.

Affected Populations Across Swath

Affected population ranges vary significantly across swath, depending on local population densities

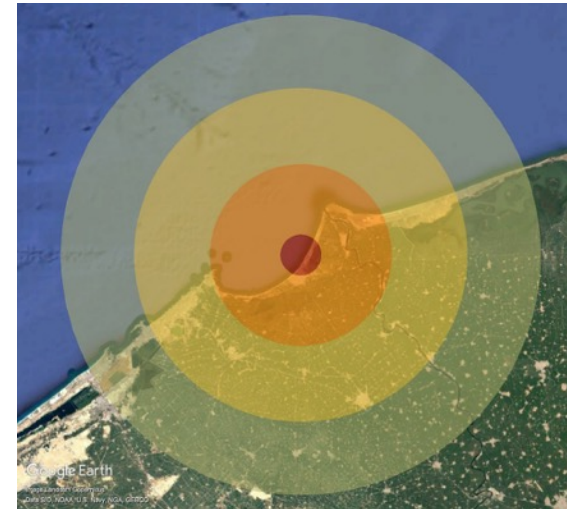
- Average affected population range: ~200k–1.3M across entry points (~580k overall avg)
- Max affected population range: 2M–6.6M across entry points (4M avg max among all points)



Maps of average and maximum affected population for each sampled impact entry point, given the potential range in asteroid properties and resulting damage

Ground Damage Severity Levels

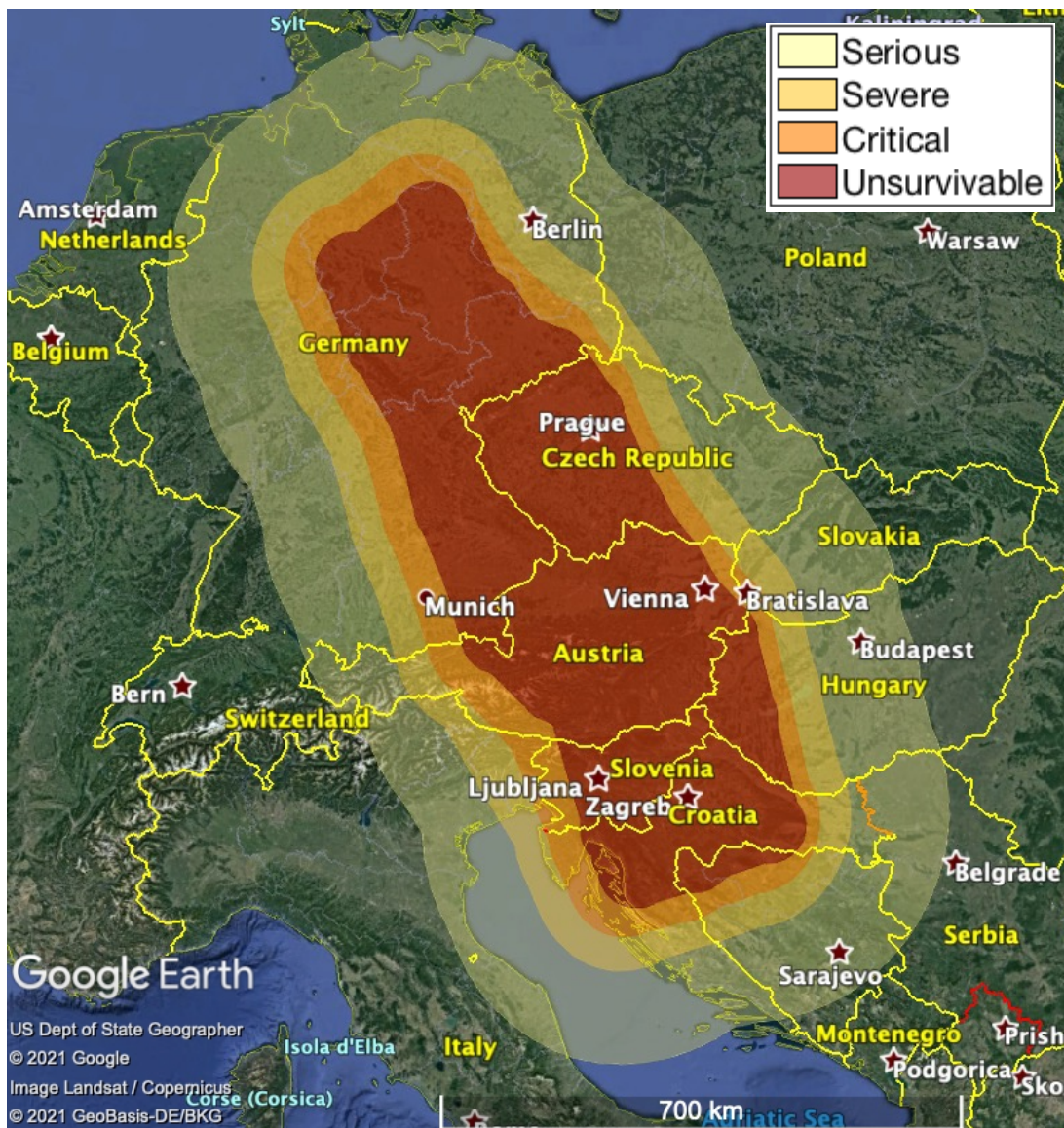
- Blast and thermal damage are assessed at four severity levels, with each level affecting different fractions of the population within that region
- For each damage level, the larger of the blast or thermal radius is used to determine the area and affected population for that level.
- Blast is the predominant hazard for most cases in this scenario



Damage Level	Population fraction	Blast Threshold (psi)	Thermal Exposure Threshold
Serious	10%	1 psi – window breakage and some structural damage	2 nd degree burns
Severe	30%	2 psi – doors and windows blown out, widespread structural damage	3 rd degree burns
Critical	60%	4 psi – most residential structures collapse	clothing ignition
Unsurvivable	100%	10 psi – complete devastation	incineration

Damage Risk Swath

(full extent of regions potentially at risk)



Damage risk swath:

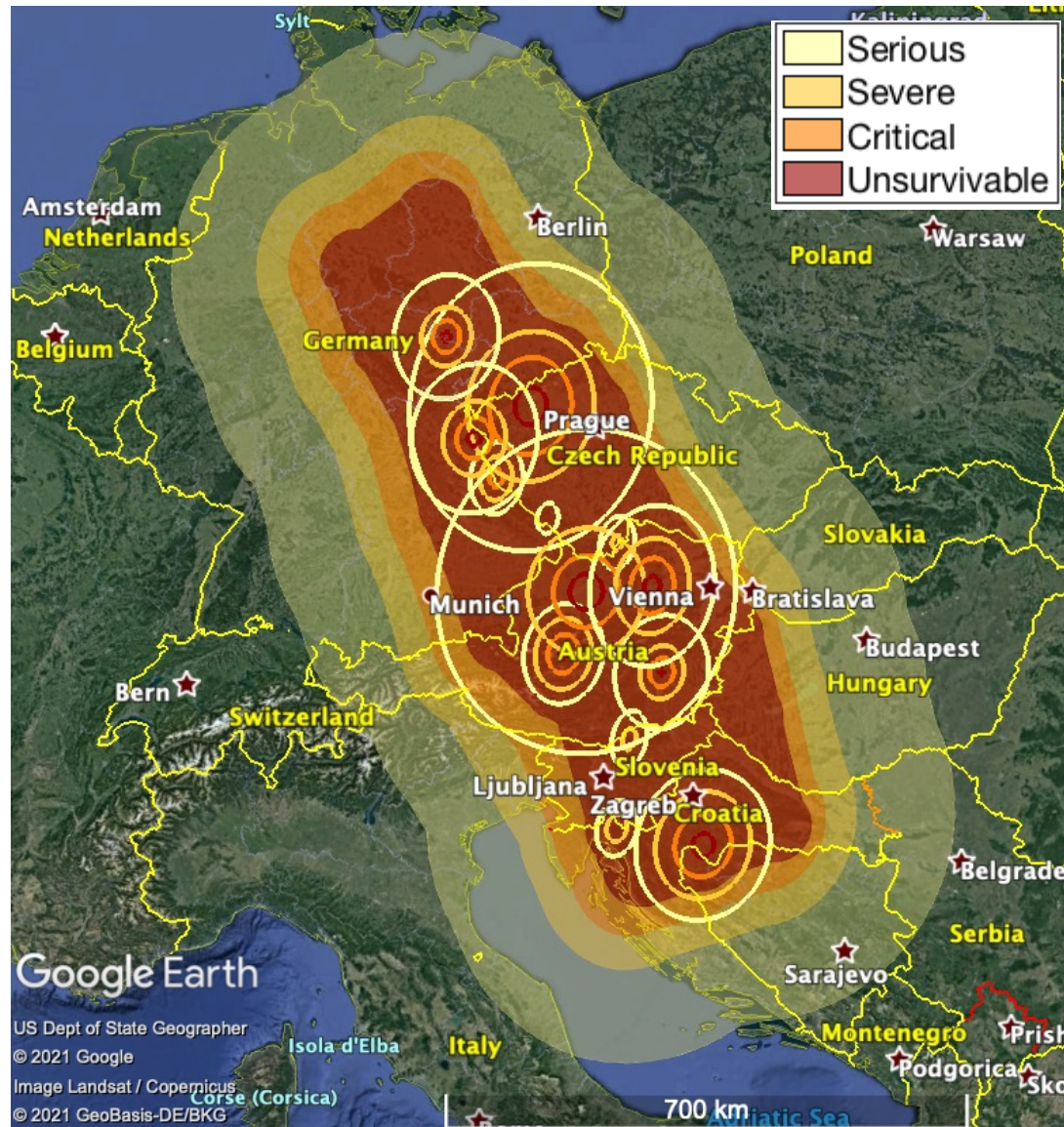
- Shows full range of regions potentially at risk to local ground damage from all modeled cases
- Includes unlikely worst-case objects and all sampled impact locations

Extent of swath region:

- ~1400 km long, ~700 km wide
- ~42–55° N Lat, 6–21° E Lon

Damage Risk Swath

(sample damage footprint variations)

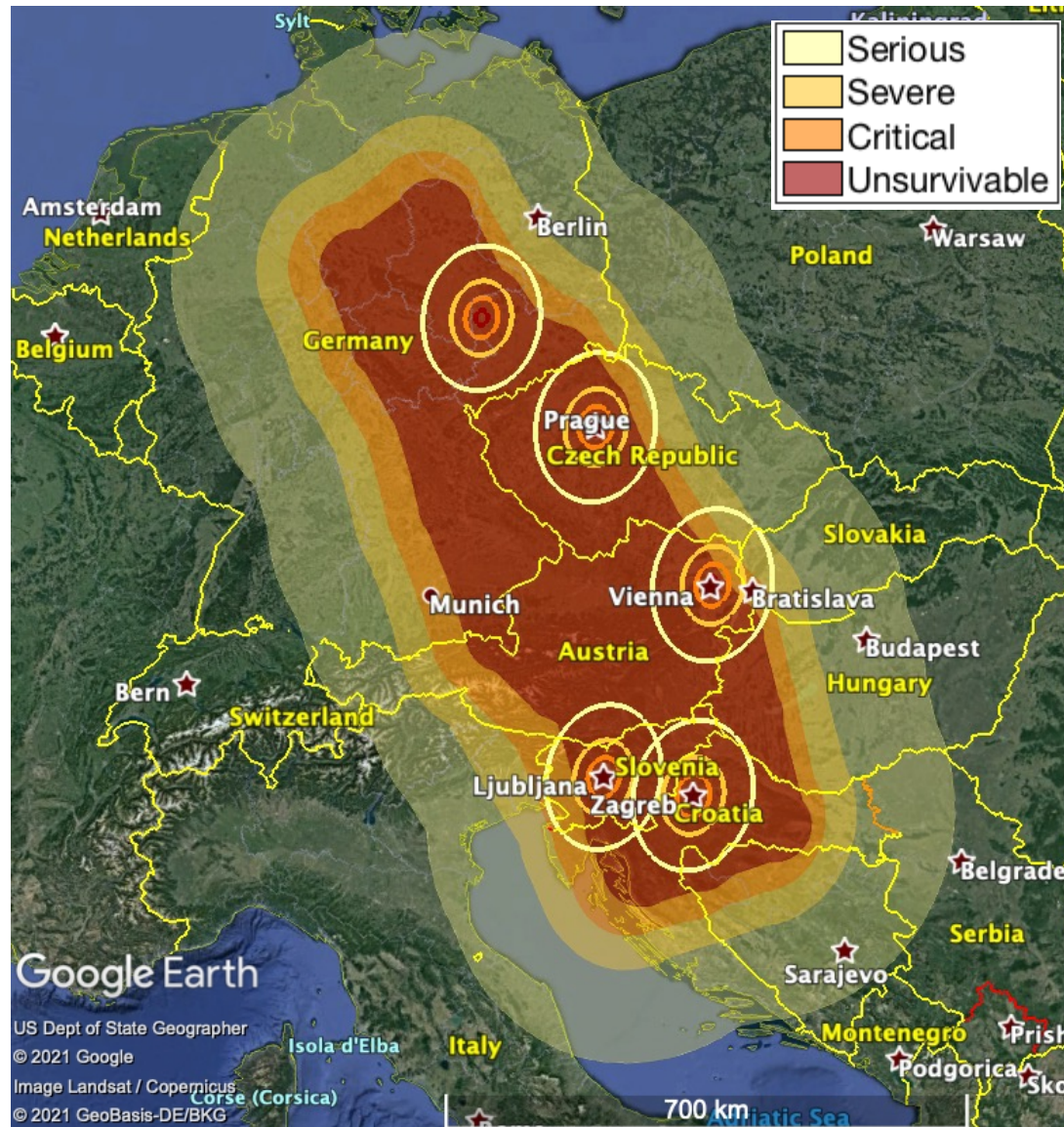


Actual potential damage areas and locations vary widely, including:

- Small areas with only lower damage severities, located over lower-population areas
- Larger regions with greater severity, typical of the average impactor size estimates
- Very large and unlikely worst-case ranges
- And everything in between

Damage Risk Swath

(average damage footprint at large cities)

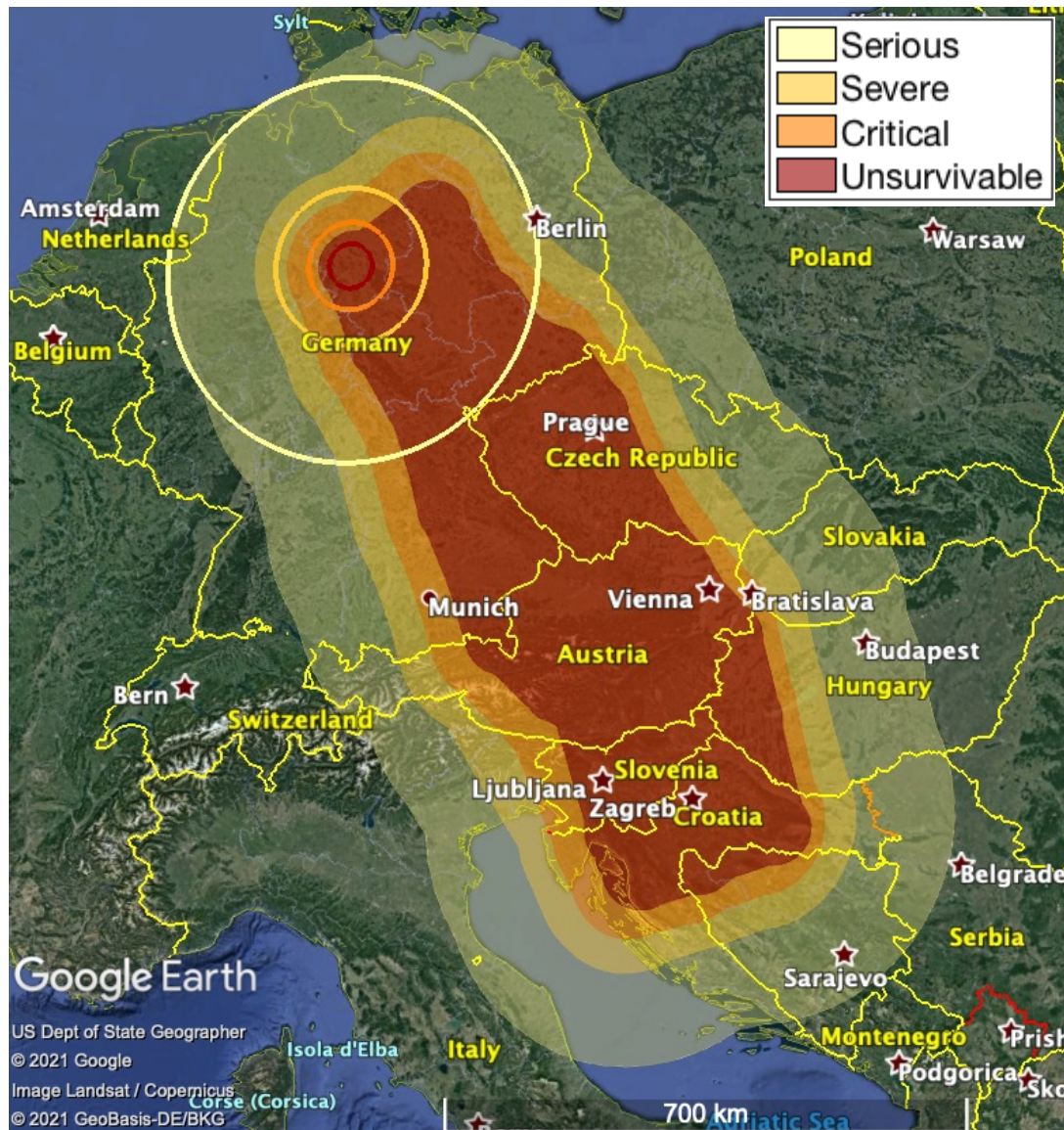


Sample average damage footprints over cities:

- Average blast radii:
 - Serious: ~80 km
 - Severe: ~40 km
 - Critical: ~20 km
 - Unsurvivable: ~10 km
- Range/likelihood of potential damage sizes is similar across swath locations
 - Entry parameters don't vary much over small region
 - Damage area variation driven by asteroid property and breakup/airburst uncertainties

Damage Risk Swath

(maximum affected population among all modeled cases)



Worst case affecting greatest number of people

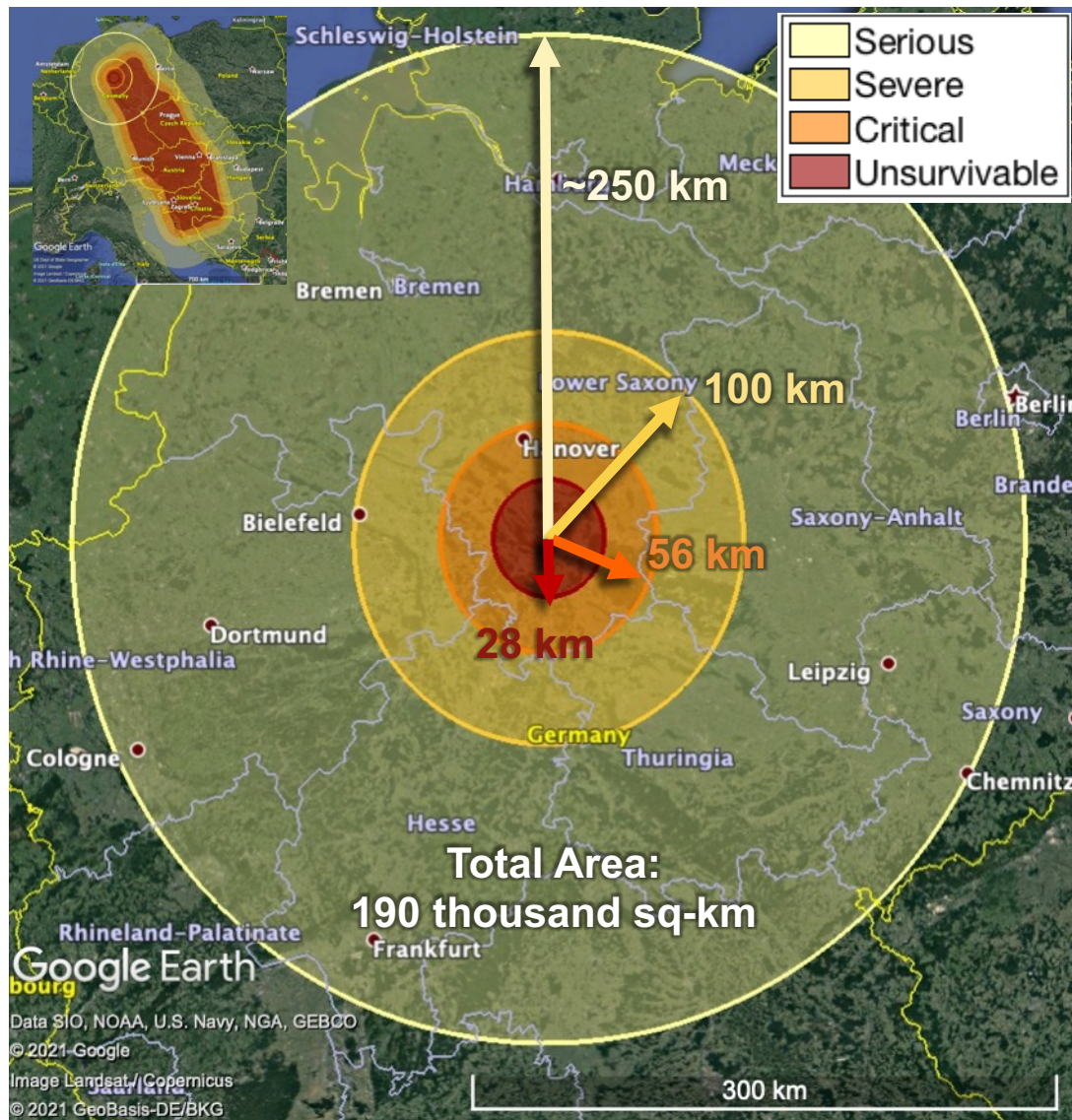
- Blast from 400m, 1.3 Gt asteroid extending over northern Germany
- Affected population: 6.6M
- Damage area: ~190,000 km²

Worst-case damage extremes are very unlikely

- Point at very edge of potential risk swath (least likely)
- Unlikely large asteroid size (<0.1% are over 400m, <1% are over 1 Gt)

Maximum Affected Population Case

(maximum affected population among all modeled cases)

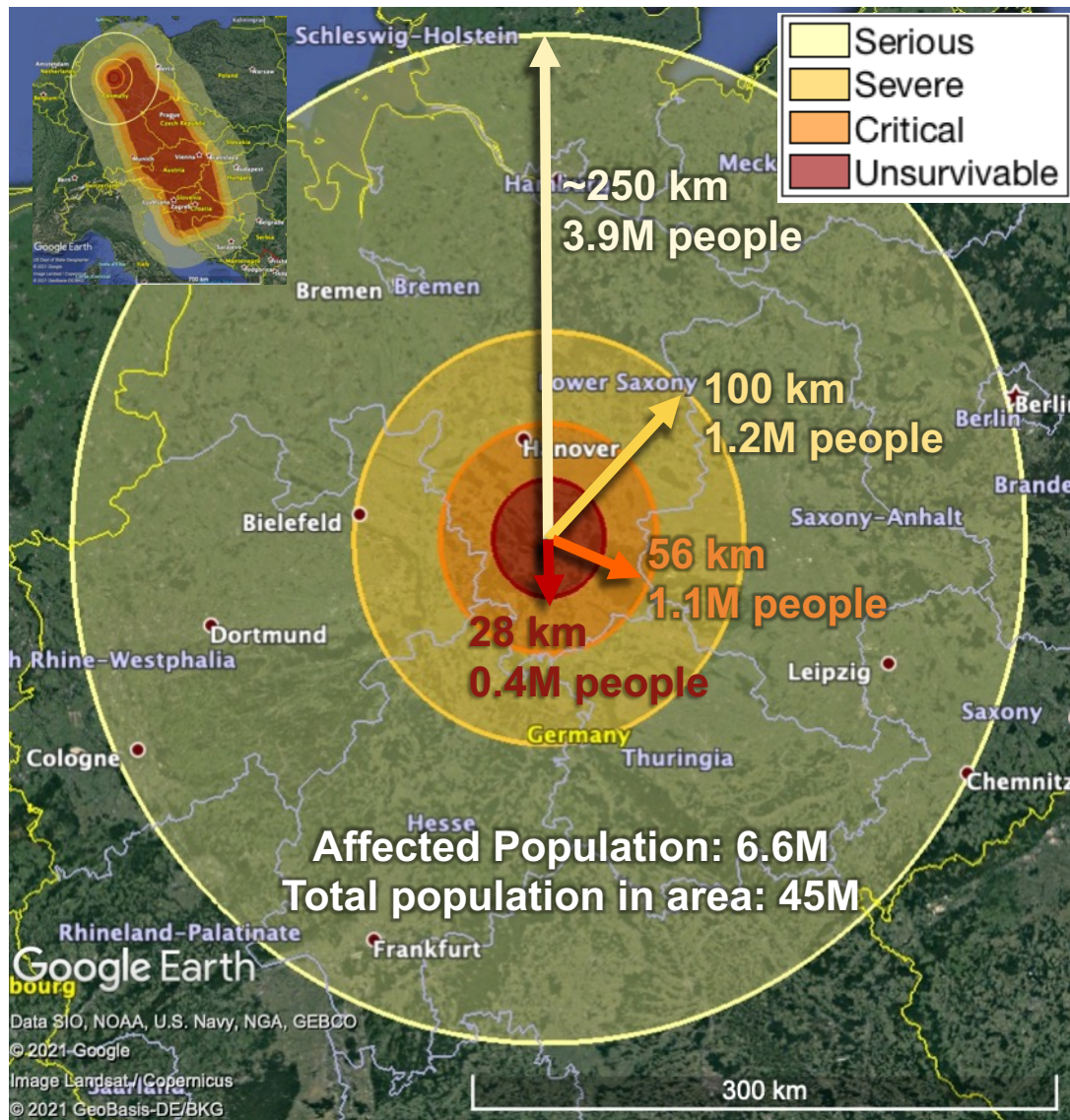


Damage region extent and severity levels

- Blast damage radii:
 - Serious (1 psi): 250km
 - Severe (2 psi): 100 km
 - Critical (4 psi): 56 km
 - Unsurvivable (10 psi): 28 km
- Thermal damage radii
 - Much smaller and fall within unsurvivable blast area
 - Serious (2nd deg. burns): 11 km
 - Severe (3rd deg. burns): 7 km
 - No more severe levels

Maximum Affected Population Case

(maximum affected population among all modeled cases)

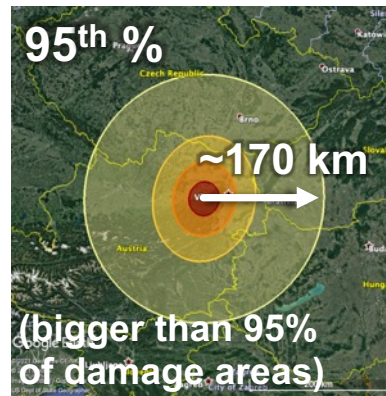
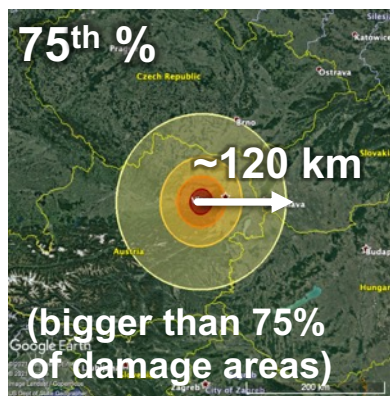
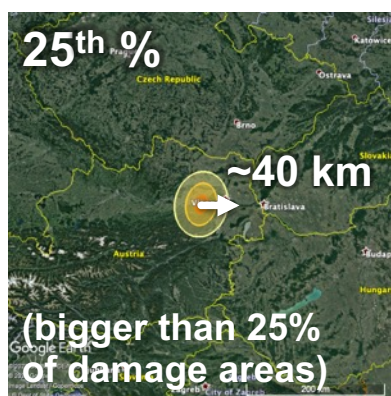
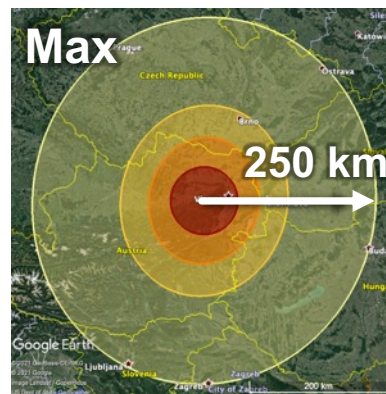
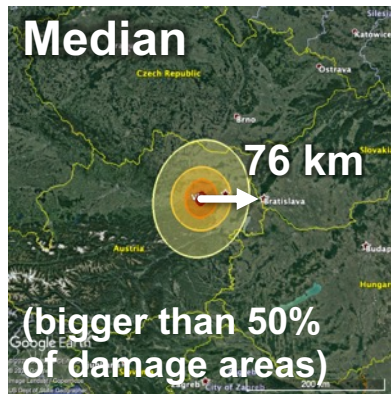


Affected population is driven by larger, less-severe damage levels

- Affected population: 6.6 million
 - Serious: 3.9M (10% of 39M)
 - Severe: ~1.2M (30% of 4M)
 - Critical: ~1.1M (60% of 1.9M)
 - Unsurvivable: ~0.4M (100%)
- Most severe damage level is **not** centered over highest-population city
- Outer damage levels span multiple cities and generally populated area

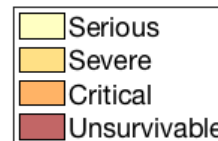
Sample Damage Footprint Sizes (over same sample region near Vienna)

Disaster response plans must consider both the likelihood and severity of the potential range of outcomes



- Worst-case areas can be too large to evacuate, and are very unlikely
- Probabilities of different damage ranges and severities can be used to prioritize effective response
- Radius percentile indicates the chance that the damage will be smaller than that size

Maps of probabilistic damage footprint sizes for emergency response and evacuation planning

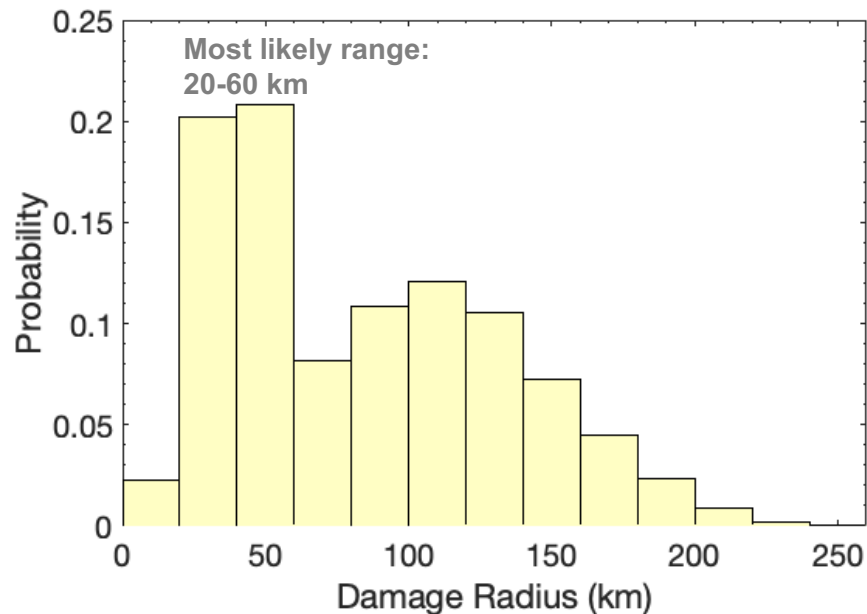


Damage Radius Probabilities

(outer serious damage level)

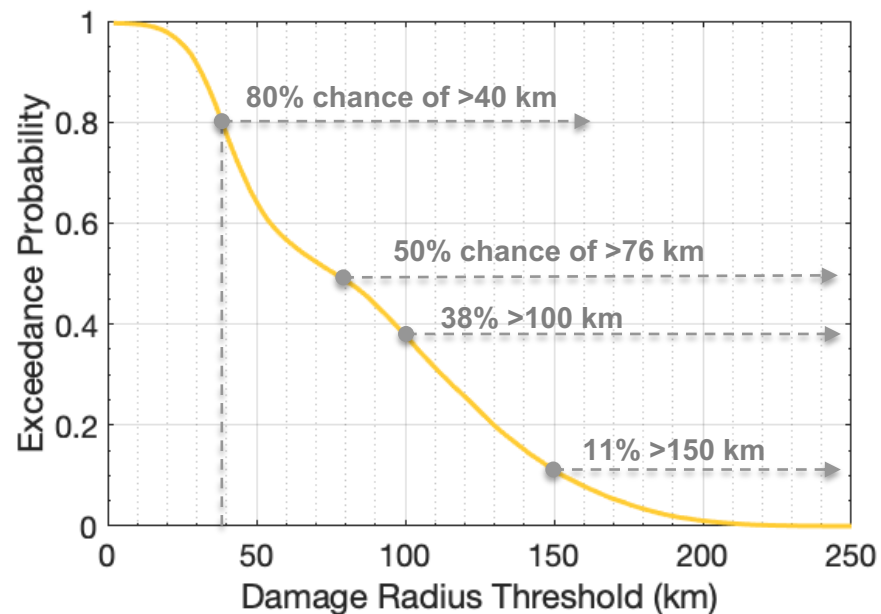
Damage Radius Histogram

Probabilities of damage radii within each range



Damage Radius Exceedance

Probability of *at least* the given damage radius or *larger*



Serious Damage Radius Stats (km)

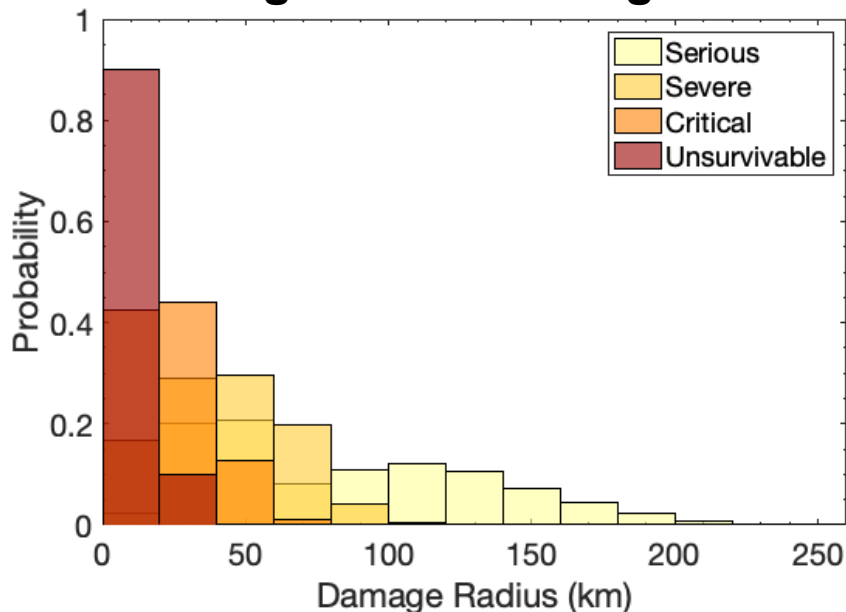
Damage Level	Mean	Min	Max	5 th %	25 th %	Median	75 th %	95 th %
Serious	84	0	255	26	42	76	121	172

*Percentiles give the probability of the outcome being smaller than the given value (e.g., a 75th damage radius of 100 km means a 75% chance of being smaller than 100 km and a 25% chance of exceeding 100 km).

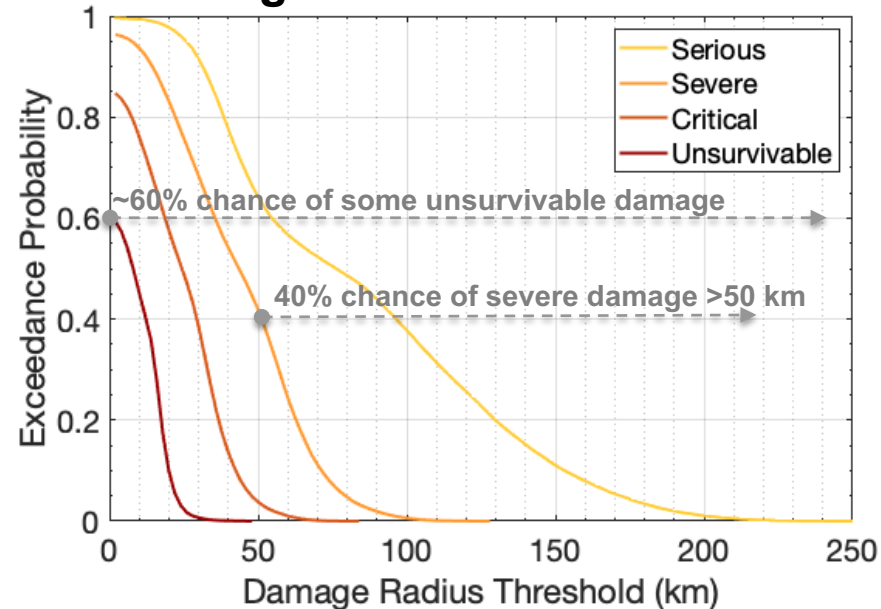
Damage Radius Probabilities

(all severity levels)

Damage Radius Histogram



Damage Radius Exceedance



Local Ground Damage Radius Stats (km)

Damage Level	Mean	Min	Max	5 th %	25 th %	Median	75 th %	95 th %
Serious	84	0	255	26	42	76	121	172
Severe	43	0	127	8	26	44	60	79
Critical	23	0	83	0	11	24	35	48
Unsurvivable	9	0	47	0	0	8	16	22

*Percentiles give the probability of the outcome being smaller than the given value (e.g., a 75th% damage radius of 100 km means a 75% chance of being smaller than 100 km and a 25% chance of exceeding 100 km).

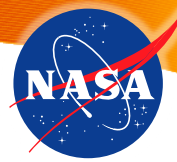
Impact Risk Summary

- Imminent impact over central Europe in ~ 4 months, with large range of potential damage
 - Object size and properties remain very uncertain, leading to large uncertainties in potential damage region size and severity
 - No in-space mitigation options are possible—civil emergency response is critical
- Large airburst or impact is likely to cause extensive blast damage over areas extending from tens to hundreds of kilometers in radius
 - Potential damage severities range from minor structural damage to unsurvivable building collapse and thermal exposure
 - Potential for subsequent regional environmental effects beyond damage area remains unknown
- Damage is likely to affect hundreds of thousands of people, potentially up to several million in rare worst-cases
 - Population risk is driven most by lower-severity damage levels that cover larger areas (rather than smaller, more severe damage levels)
 - Worst-case locations tend to span multiple urban areas rather than center directly over a single city.

	Asteroid Diameter (m)	Impact Energy (Mt)	Damage Radius (km)	Affected Population
Full range	$\sim 35\text{--}500$	$\sim 1\text{--}3700$	0–250	0–6.6M
Average	136	136	84	580k
Most likely	$\sim 80\text{--}120$	$\sim 20\text{--}50$	20–60	100k–1M
5 th –95 th %	65–270	$\sim 8\text{--}570$	26–172	16k–1.8M

Risk-Informed Disaster Response Support

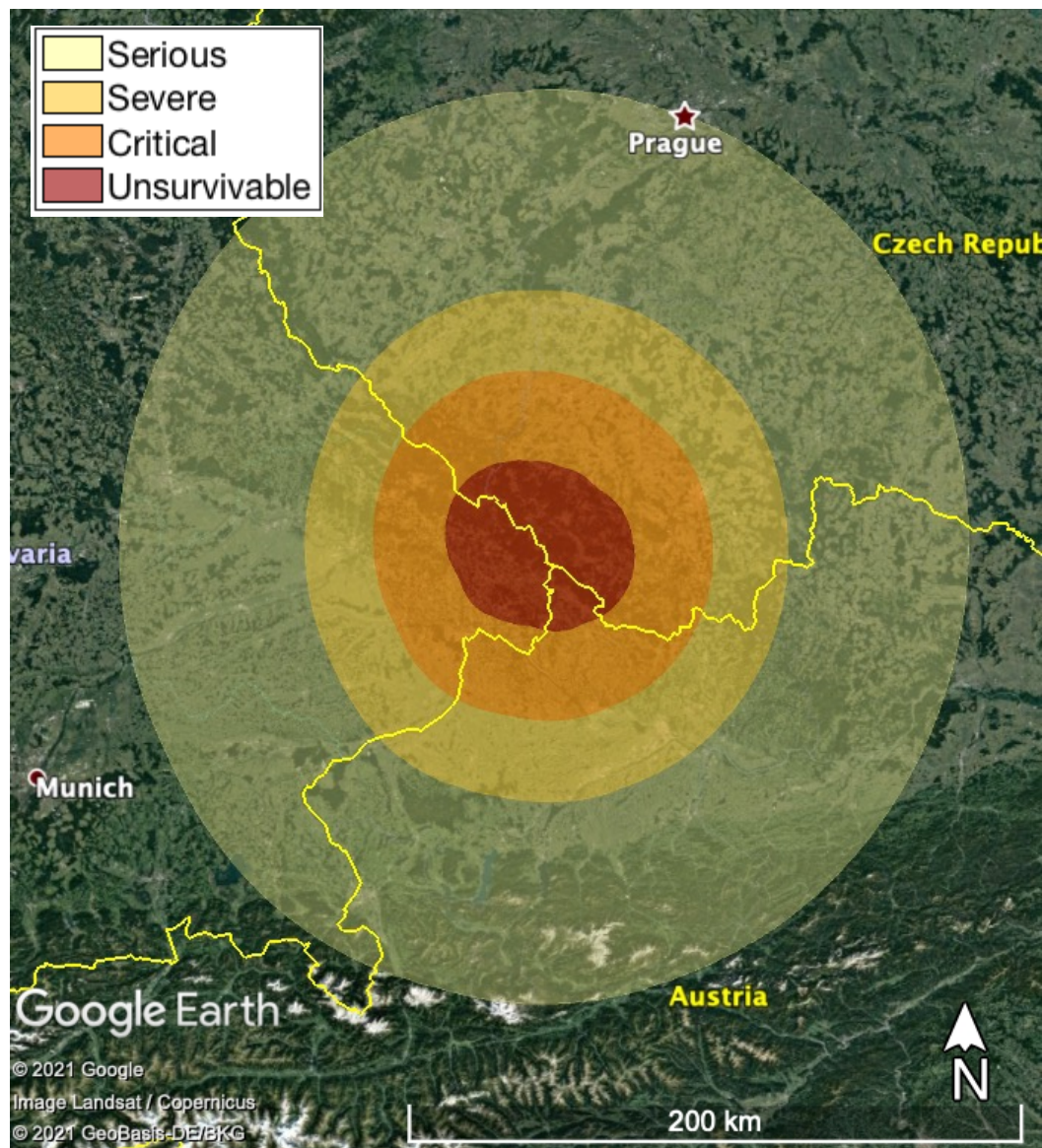
- Risk and damage assessments will continue with increasing fidelity as more information is gained about the incoming object
 - High-fidelity simulations can provide more accurate modeling of impact effects and resulting ground damage footprints for specific cases
 - Risk models can identify critical cases for simulations, given remaining unknowns
- Risk modeling will provide information on evolving damage ranges and probabilities to support emergency response planning
 - Damage region maps and ranges can be provided to local emergency response agencies for specific local infrastructure or evacuation planning
 - Probabilities of damage region sizes and severities can help inform most effective achievable civil response efforts, given large potential range of outcomes



DAY 4 SWATH

Final Damage Risk Swath

(full extent of regions potentially at risk)



Damage risk swath:

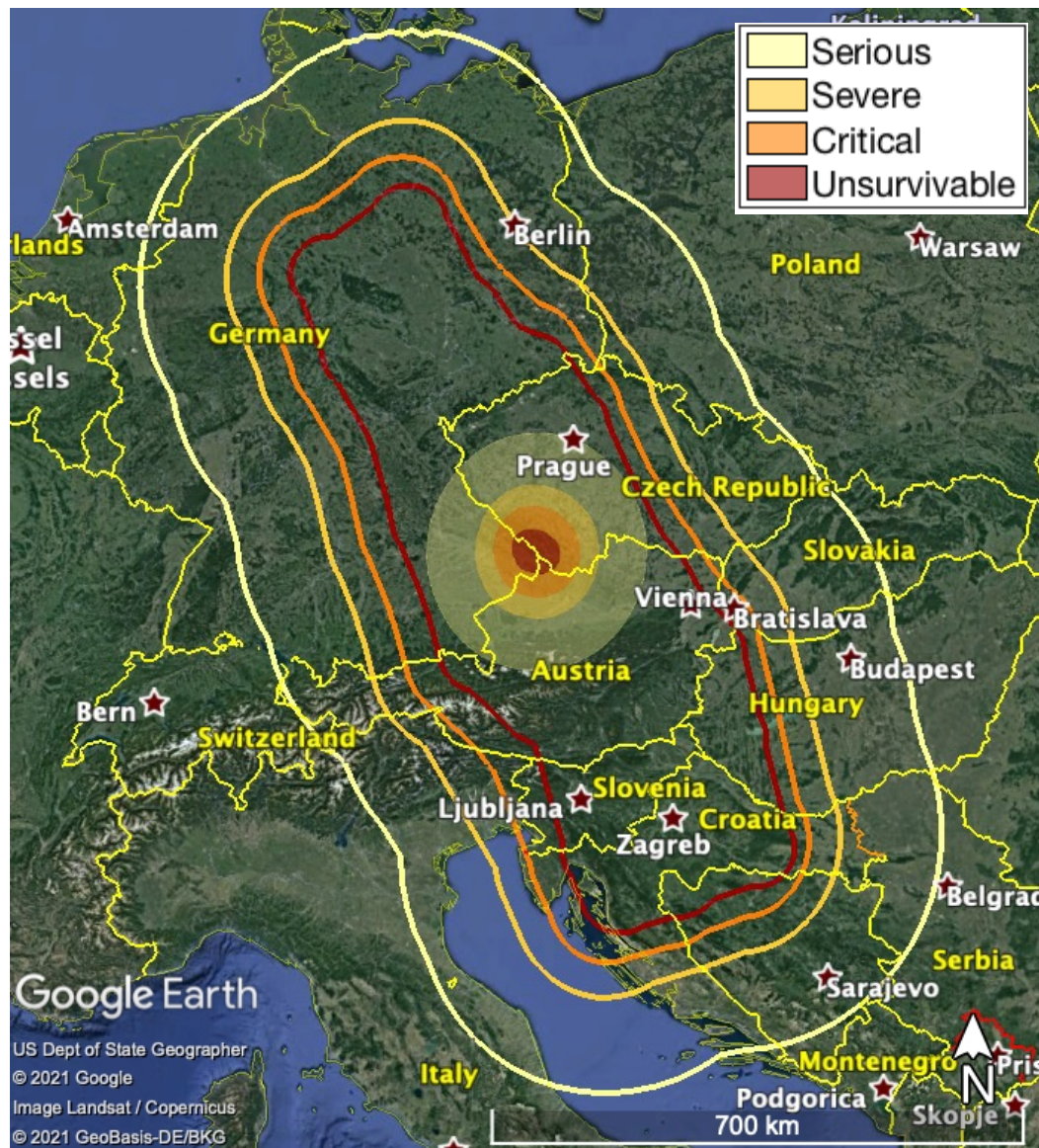
- Shows full range of regions potentially at risk to local ground damage from all modeled cases
- Includes unlikely worst-case objects and all sampled impact locations

Extent of swath region:

- ~300 km across (~150 km radius)
- Centered roughly around 48.83° N Lat, 13.73° E Lon

Final Damage Risk Swath

(full extent of regions potentially at risk)



Damage risk swath:

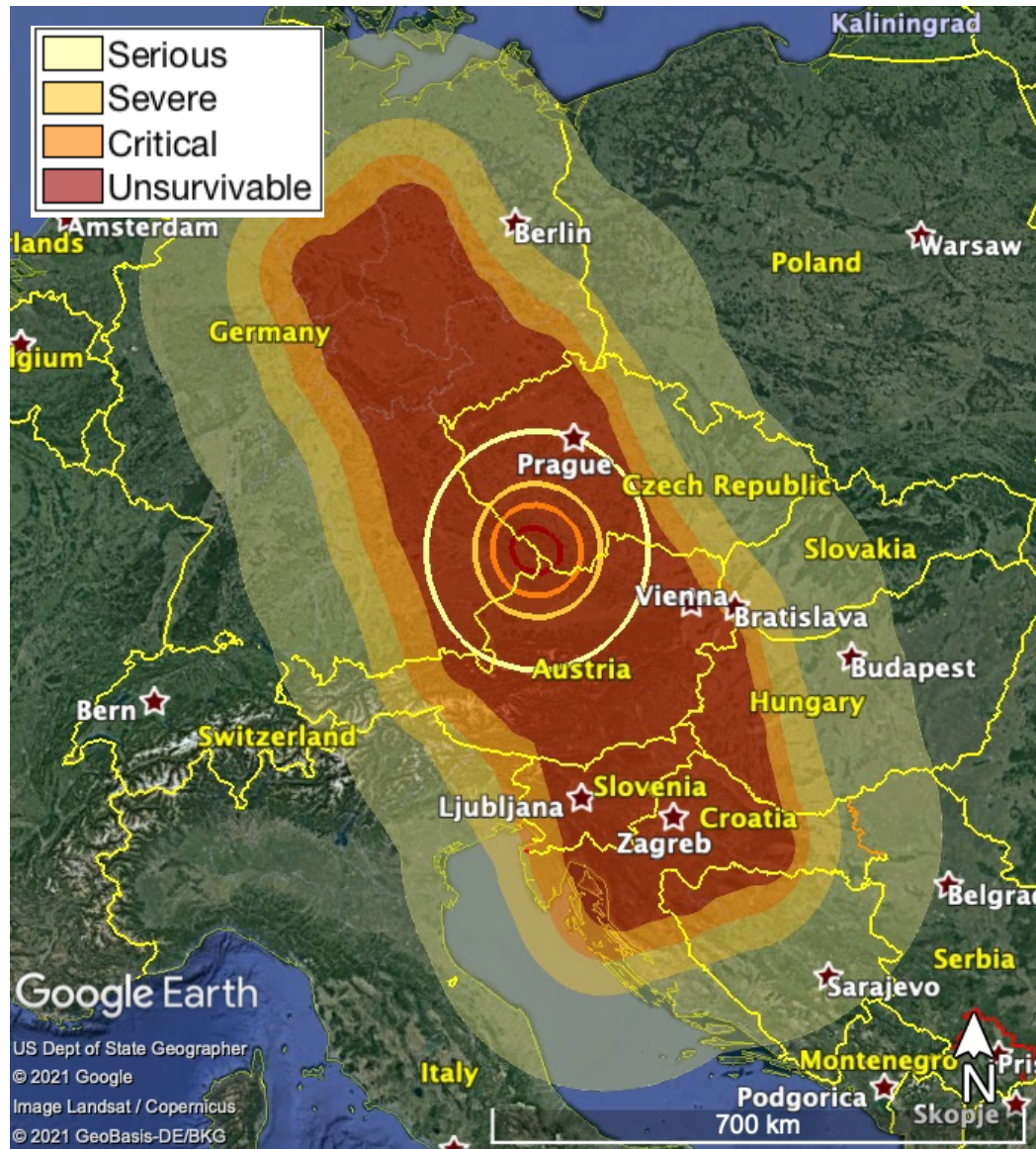
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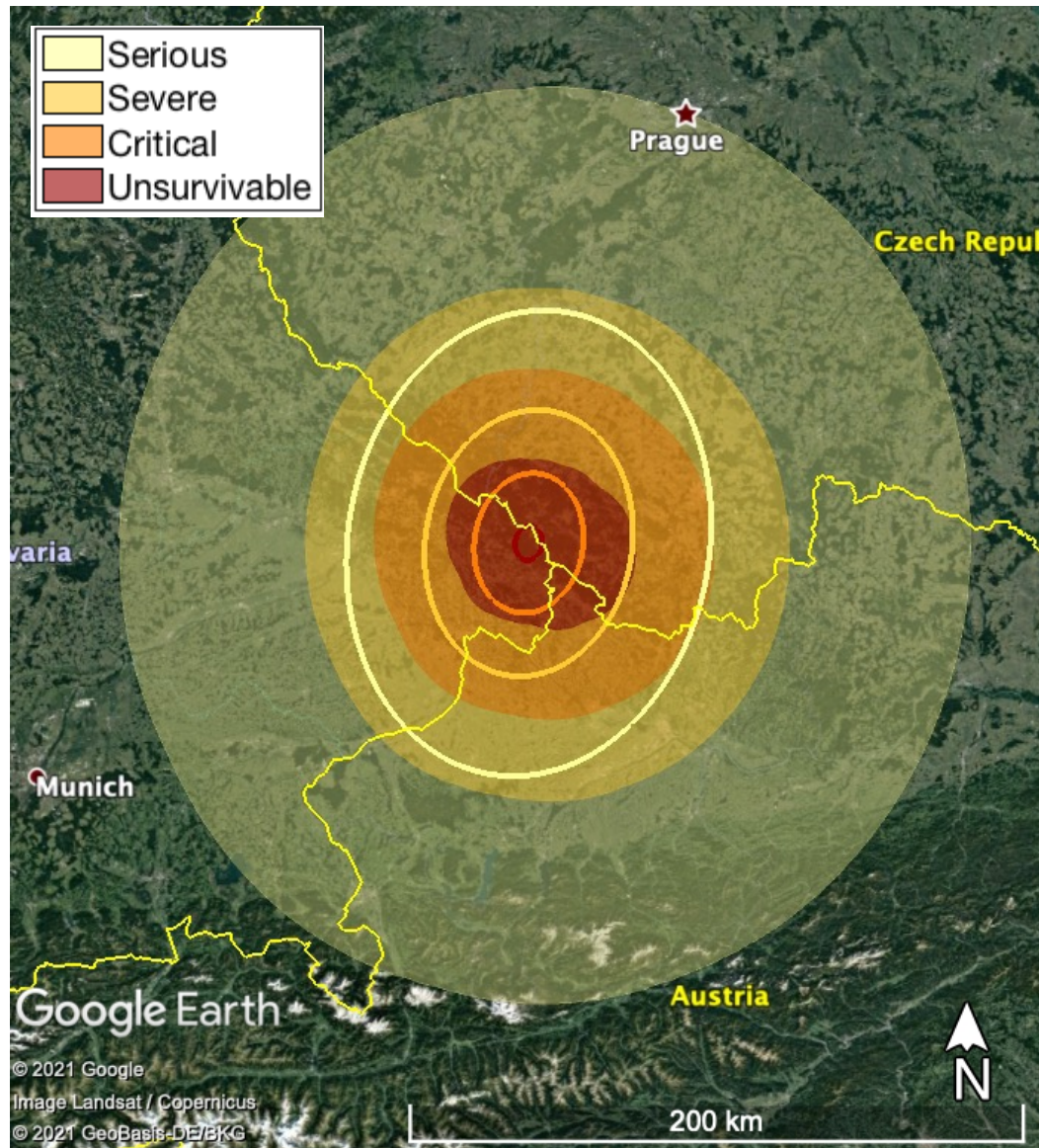
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- Shows full range of regions potentially at risk to local ground damage from all modeled cases
- Includes unlikely worst-case objects and all sampled impact locations

Extent of swath region:

- ~150 km radius
- Centered roughly around 48.83° N Lat, 13.73° E Lon

Damage Radius Estimates:

- Average: ~60-75 km
- Max: ~130 km

REFERENCE & BACKUP

Related PDC 2021 Presentations

- “Bayesian Inference of Asteroid Physical Properties: Application to Impact Scenarios,” J. Dotson et al.
- “High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2021 PDC,” M. Aftosmis et al.
- “Interaction of Meteoroid Fragments During Atmospheric Entry” D. Mathias et al.
- “Comparison of Thermal Radiation Damage Models and Parameters for Impact Risk Assessment,” A. Coates et al.
- “Airburst Consequence Modeling Using Artificial Ablation” M. Boslough
- “Tsunami with dispersion and mesh adaptation,” M.J. Berger and R.J. LeVeque
- “Asteroid Impacts – Downwind and Downstream Effects” T. Titus et al.
- “Risk-Informed Spacecraft Mission Design for the 2021 PDC Hypothetical Asteroid Impact Scenario” B. Barbee et al.
- “IAWN Planetary Defense Exercise: Apophis Observing Campaign 2020-2021” M. Kelley et al.

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- Mathias, D.L., Wheeler, L.F., Dotson J.L., 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>
- Wheeler, L.F., Mathias, D.L., 2018. Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus, 327, 83–9. <https://doi.org/10.1016/j.icarus.2018.12.017>
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https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf

Fragment-Cloud Model (FCM)

- Wheeler, L.F., Mathias, D.L., Stokan, E., Brown, P.G., 2018. Atmospheric energy deposition modeling and inference for varied meteoroid structures. Icarus 315, 79–91.
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CFD Blast Simulations and Modeling

- Aftosmis, M.J., Mathias, D.L., Tarano, A.M., 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>
- Aftosmis, M.J., et al., 2016. Numerical simulation of bolide entry with ground footprint prediction. 54th AIAA Aerospace Sciences Meeting SciTech Forum, (AIAA 2016-0998).
<https://doi.org/10.2514/6.2016-0998>