2021 PDC Hypothetical Impact Exercise: Probabilistic Asteroid Impact Risk

Scenario Day 3

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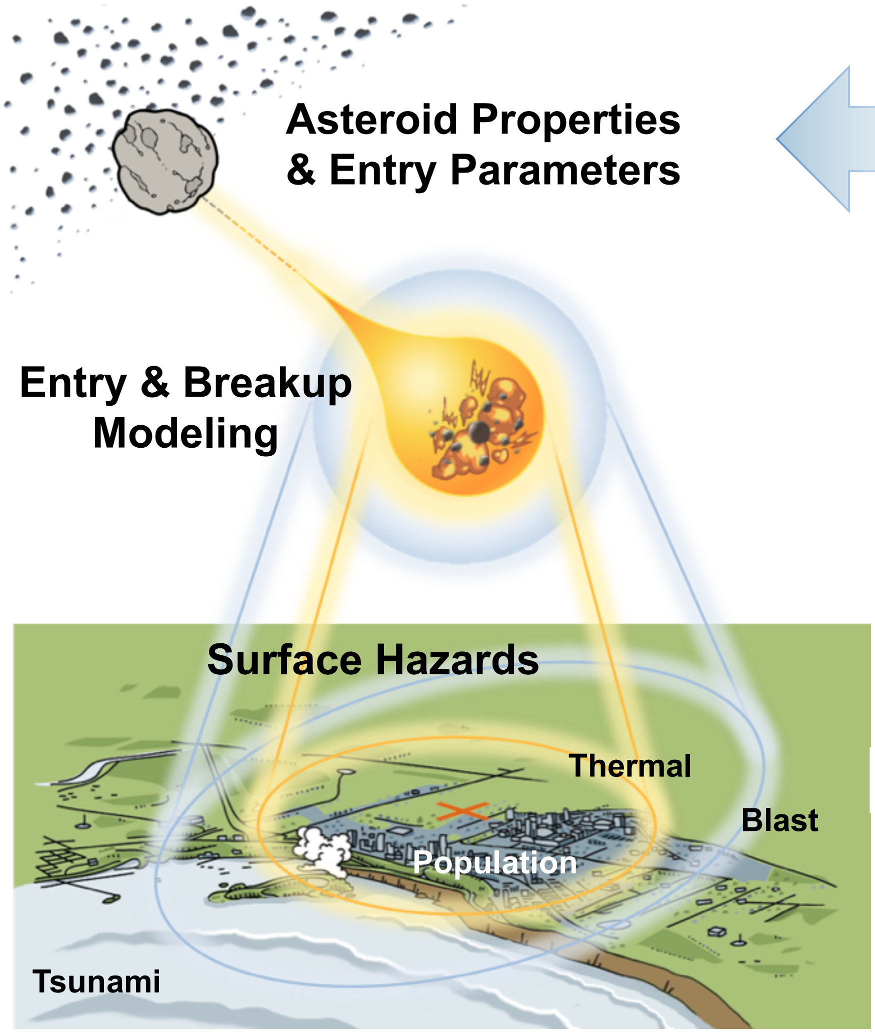
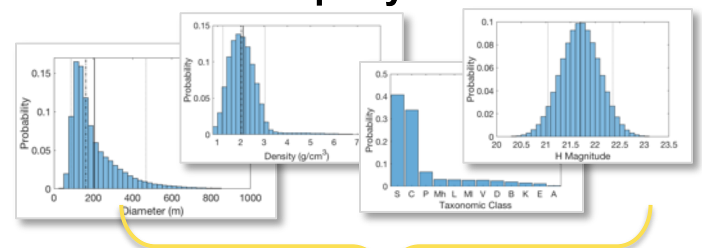
Asteroid Impact Threat Assessment

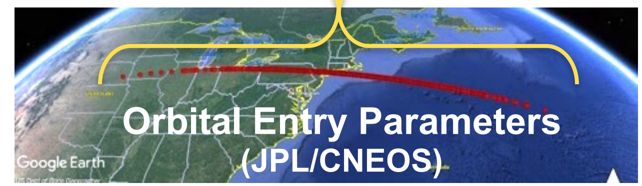
Probabilistic Asteroid Impact Risk (PAIR) Model



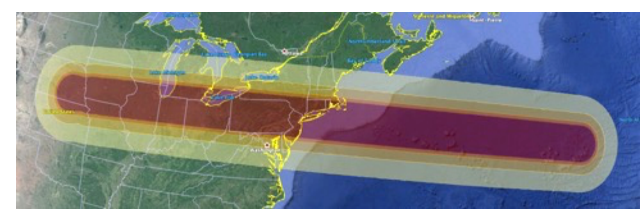
Impact Threat Scenario

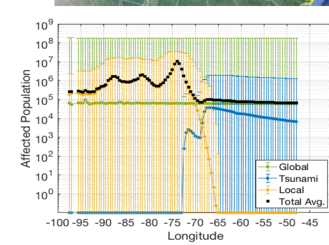
Asteroid Property Distributions

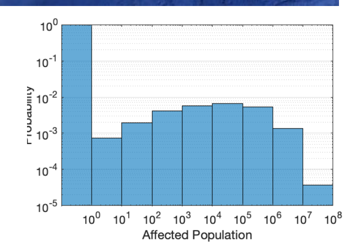




Probabilistic Risk and Damage







Ames Research Center

Impact Risk Summary

NASA

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

Damage Swath

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

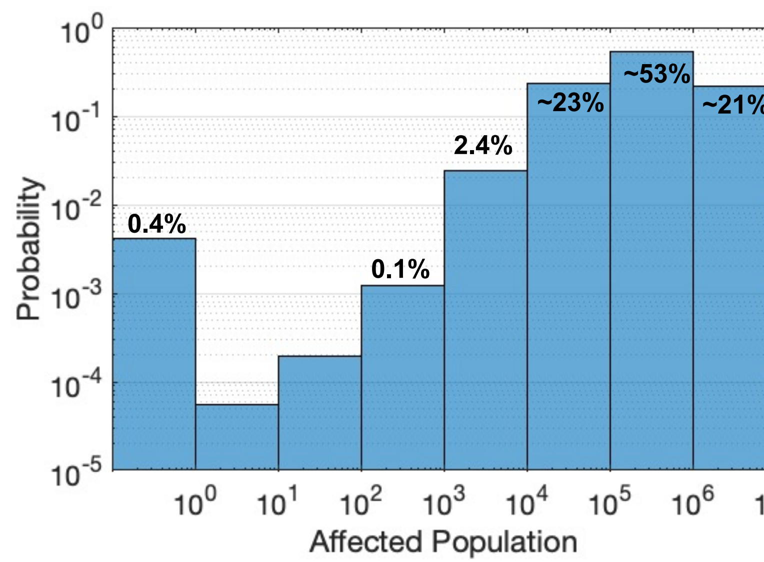
Sample average damage sizes over largest cities

- Serious
- Severe
- Critical
- Unsurvivable

Hazard Summary

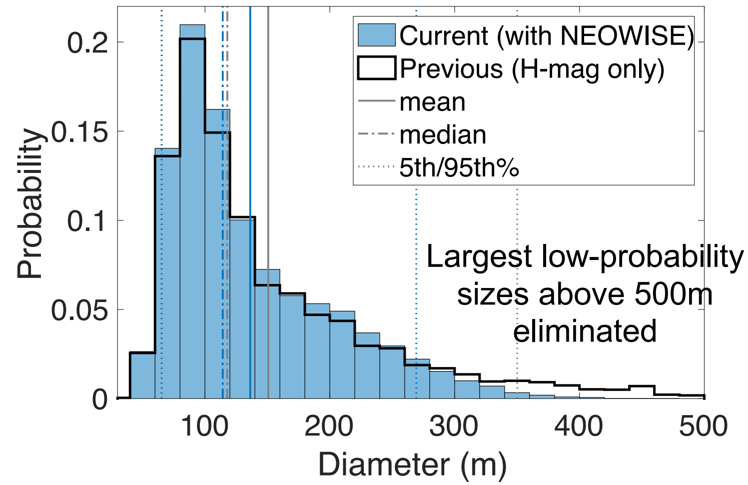
- Affected Population: 0–6.6M, average 580k, most likely several hundreds of thousands
- Primary hazard is airburst or impact causing blast overpressure and possibly thermal damage
- Damage radii: 0–250 km, average ~80 km
- Damage levels: minor structural damage and burns to potentially unsurvivable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

Affected Population Risk

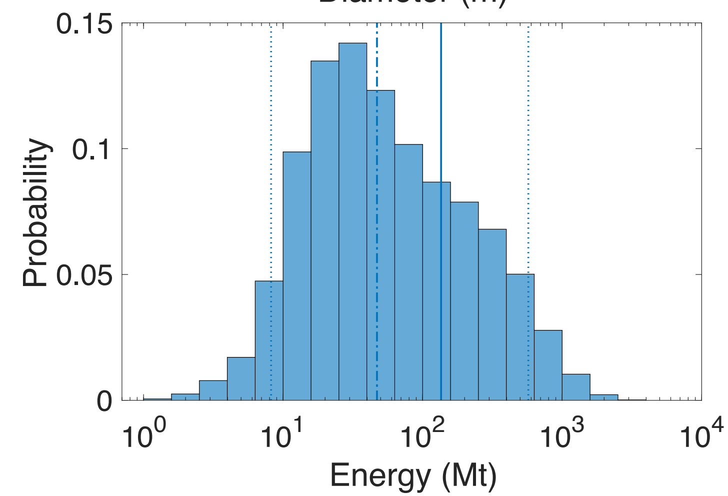


Asteroid Properties & Entry

- **Entry parameters are well known :** 15.2–15.3 km/s, 50–55° entry angle
- **Asteroid sizes and properties remain highly uncertain:** Observational data reduced max sizes, but range is still large and likely sizes remain similar.
  - Diameter constraint from NEOWISE weak detection 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
  - Maximum sizes are very large, but also unlikely



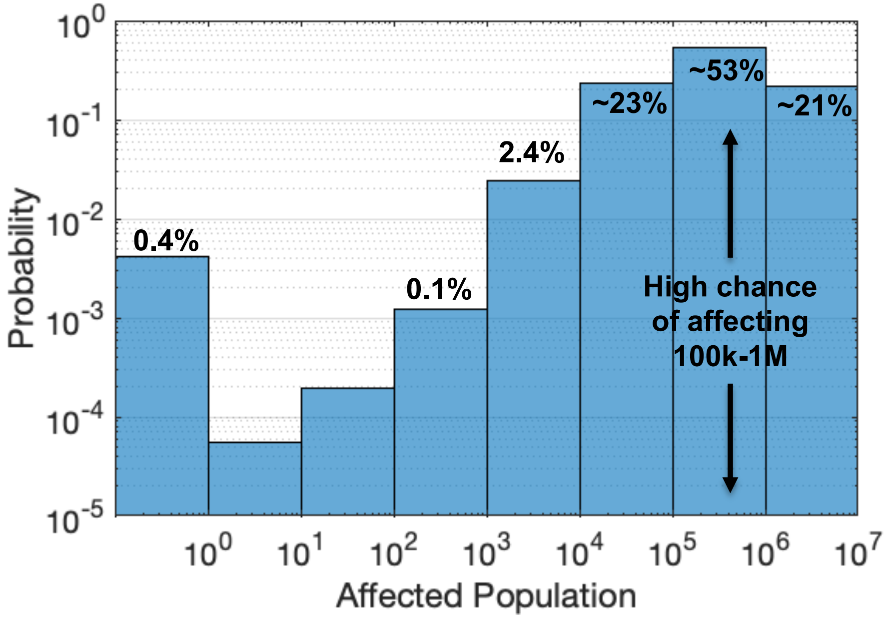
	Diameter (m)	Energy (Mt)
Full range	~35–500	~1–3700
Average	136	136
Median	114	47
Most likely	~65–120	~20–50
5th–95th %	65–270	~8–570



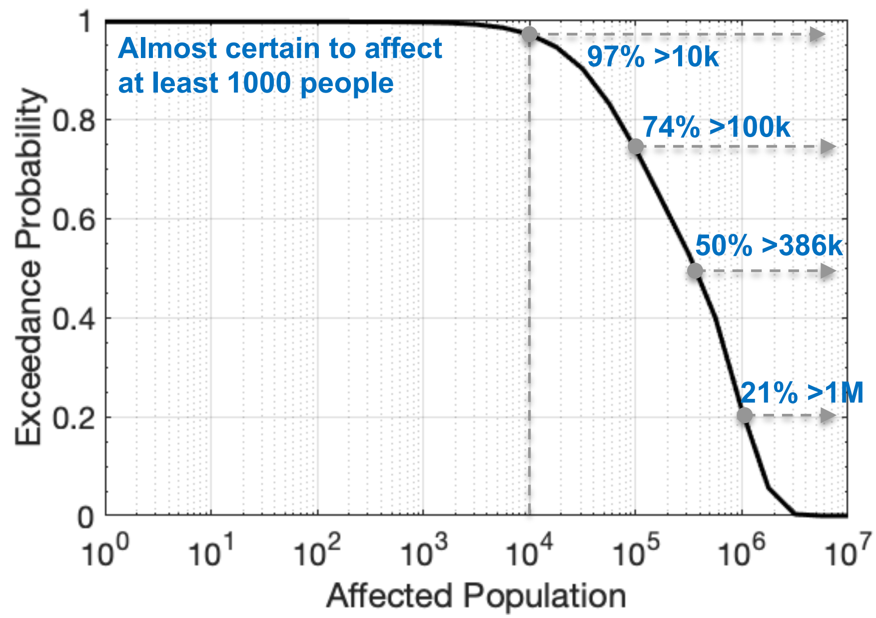
[Property inference model: J. Dotson PDC 2021] [NEOWISE: J. Masiero PDC 2021]

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



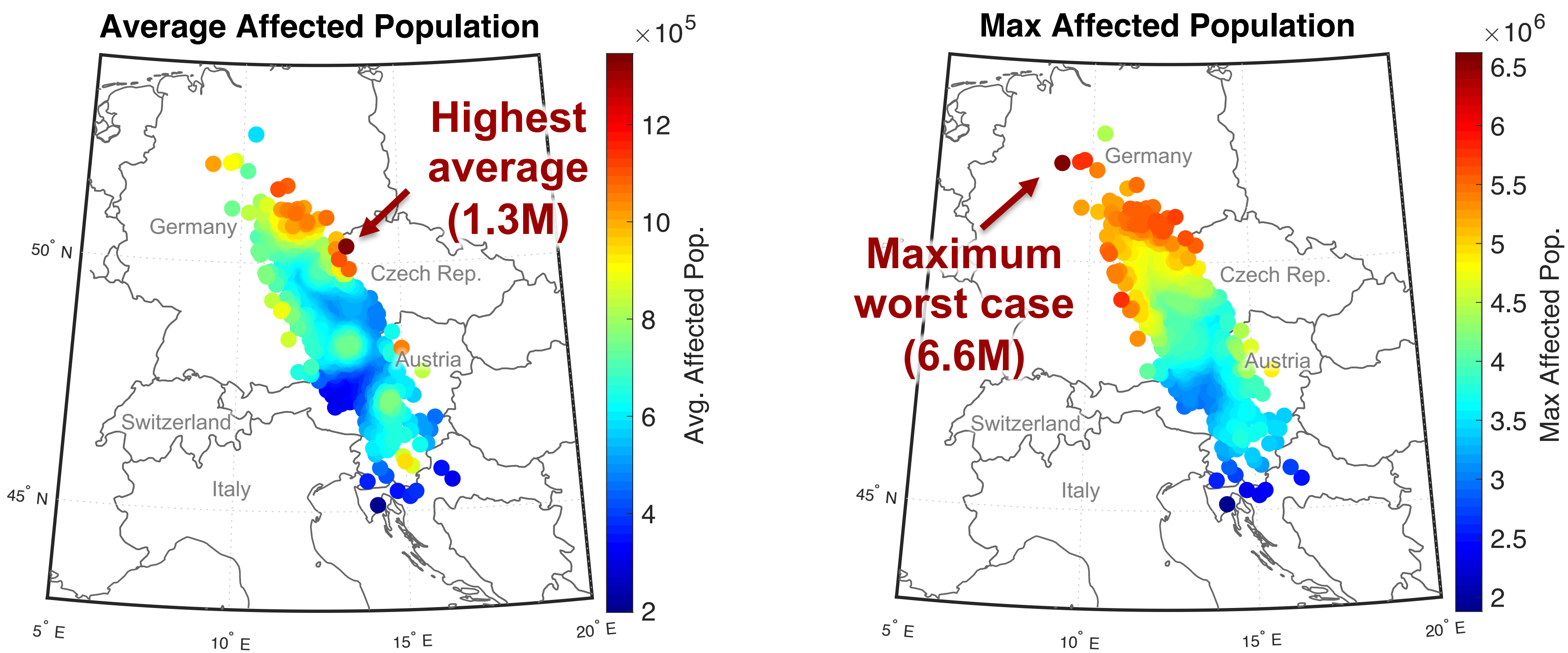
- **Damage is likely to affect several hundred thousand to a million people**
- Average of ~580k people affected
- Maximum worst case: 6.6 million people (among modeled cases)
- 97% chance of affecting at least 10k people, 74% chance of >100k, 21% chance of >1M
- <1% chance of affecting fewer than 1k people. 0.4% chance of no damage.

HYPOTHETICAL EXERCISE

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)

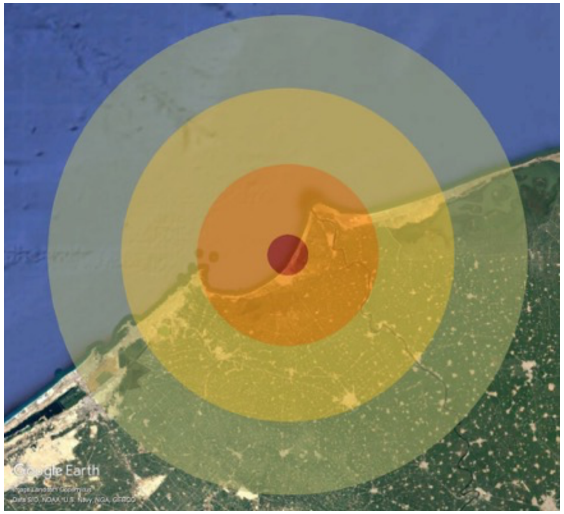


Maps of average and maximum affected population for each sampled impact entry point, given the potential range in asteroid properties and resulting damage

HYPOTHETICAL EXERCISE

Ground Damage Severity Levels

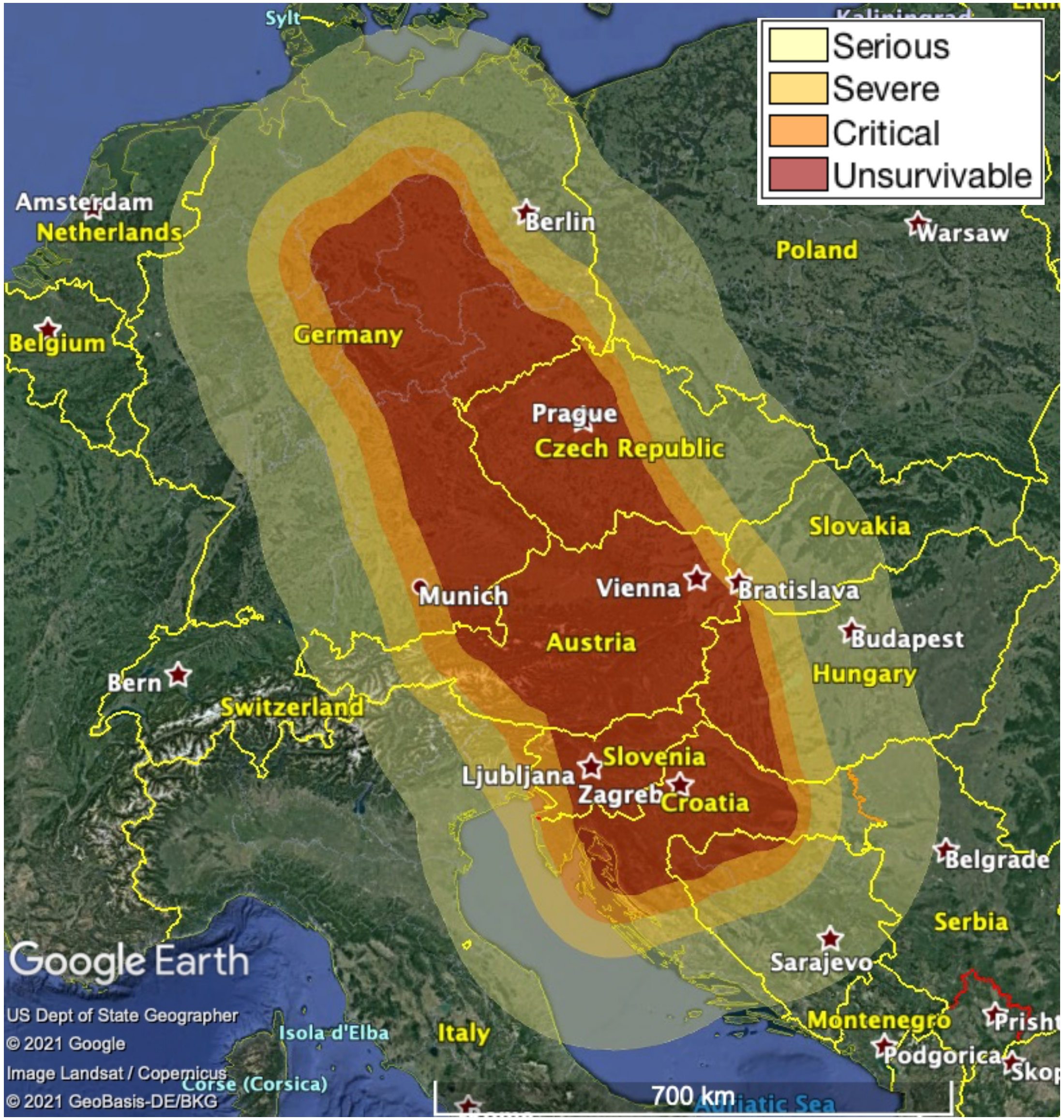
- Blast and thermal damage are assessed at four severity levels, with each level affecting different fractions of the population within that region
- For each damage level, the larger of the equivalent blast or thermal radius is used to determine the area and affected population for that level.
- Blast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



Damage Level	Population fraction	Blast Overpressure Threshold (psi)	Thermal Exposure Threshold
Serious	10%	1 psi – window breakage and some structural damage	2nd degree burns
Severe	30%	2 psi – doors and windows blown out, widespread structural damage	3rd 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)



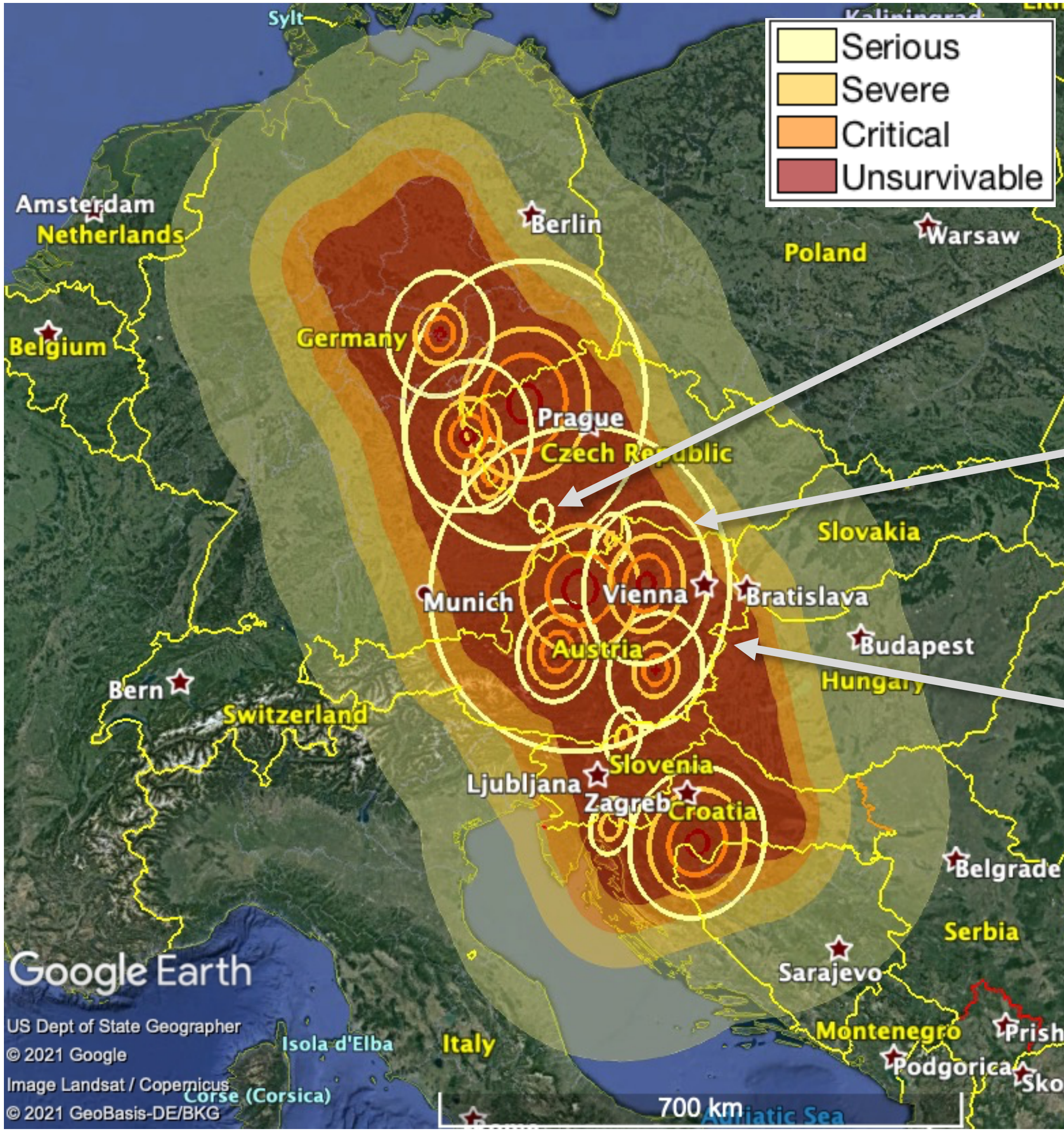
Damage risk swath:

- **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)

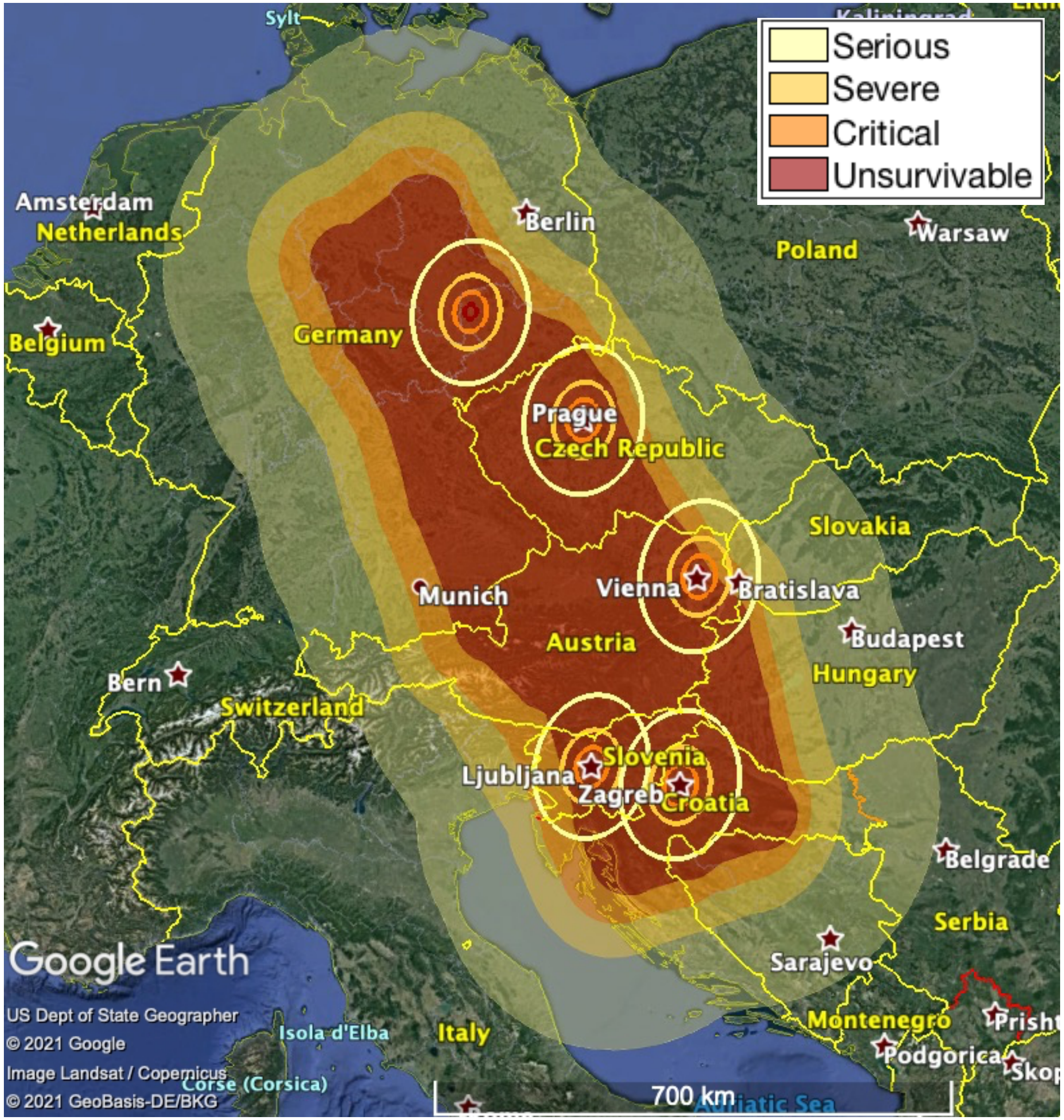


Actual potential damage areas and locations vary widely, including:

- 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)



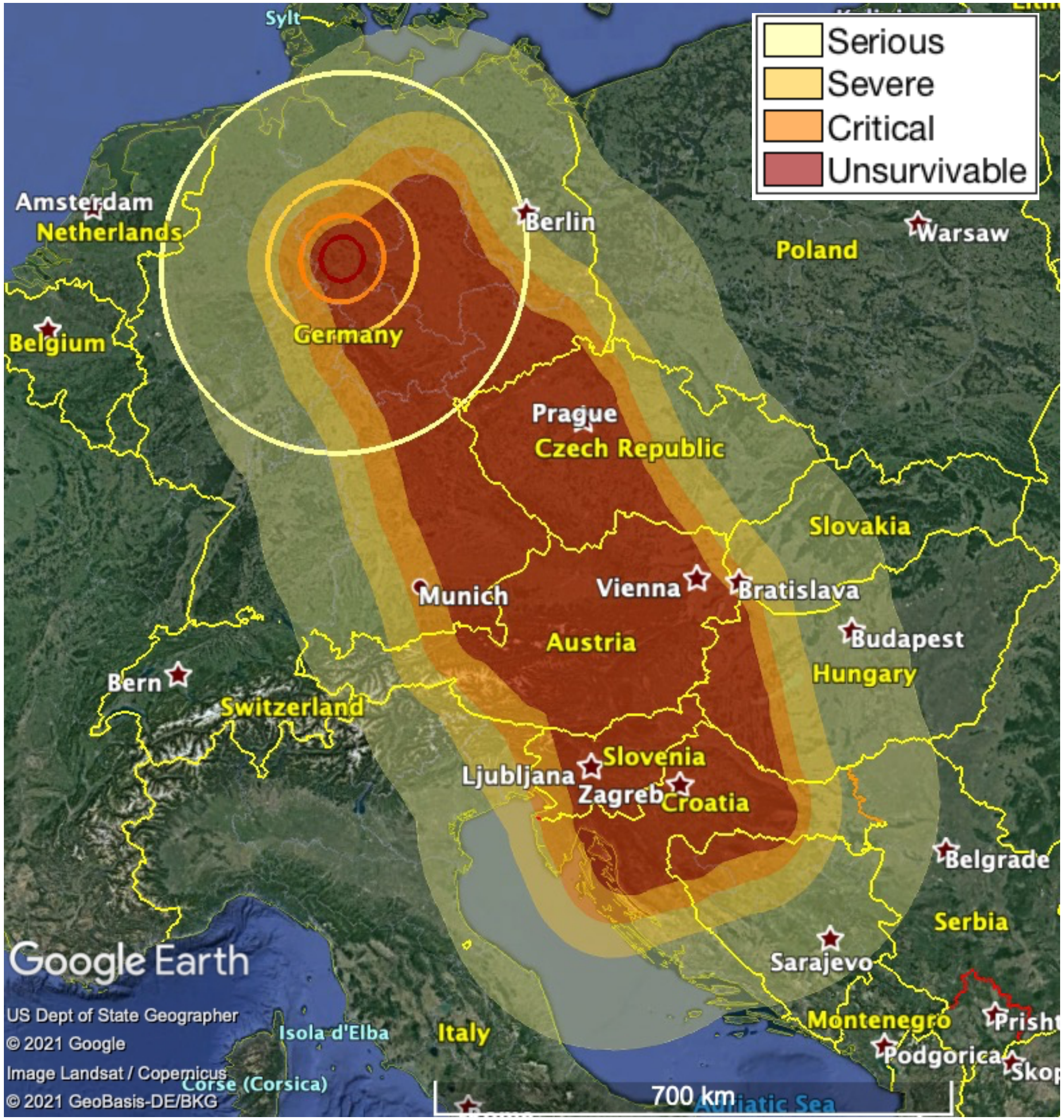
Sample average damage footprints over cities:

- 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

HYPOTHETICAL EXERCISE

Damage Risk Swath

(maximum affected population among all modeled cases)



Worst case affecting greatest number of people

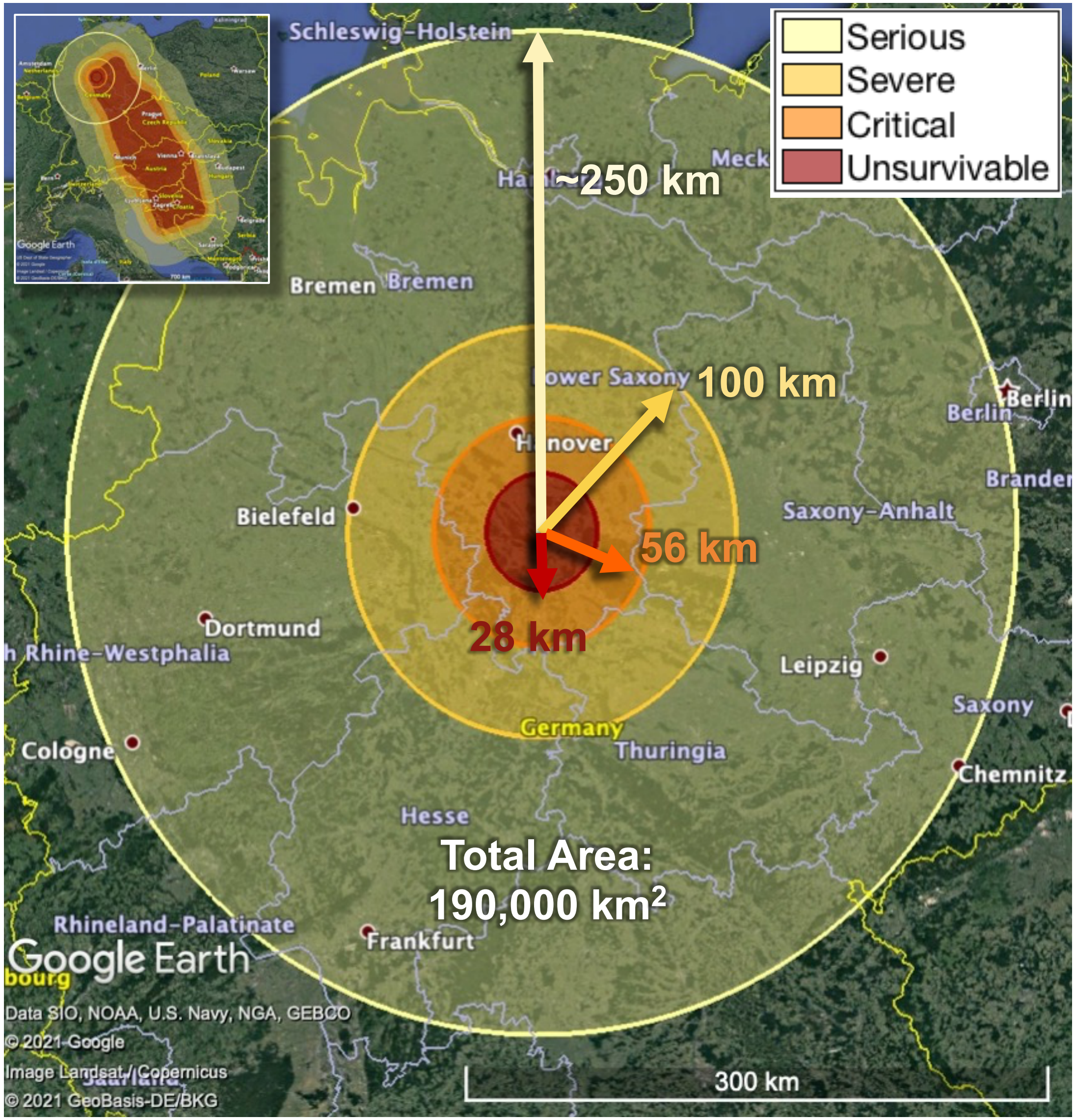
- Blast from 400m, 1.3 Gt asteroid extending over northern Germany
- Affected population: 6.6M
- Damage area: ~190,000 km^2

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)

HYPOTHETICAL EXERCISE

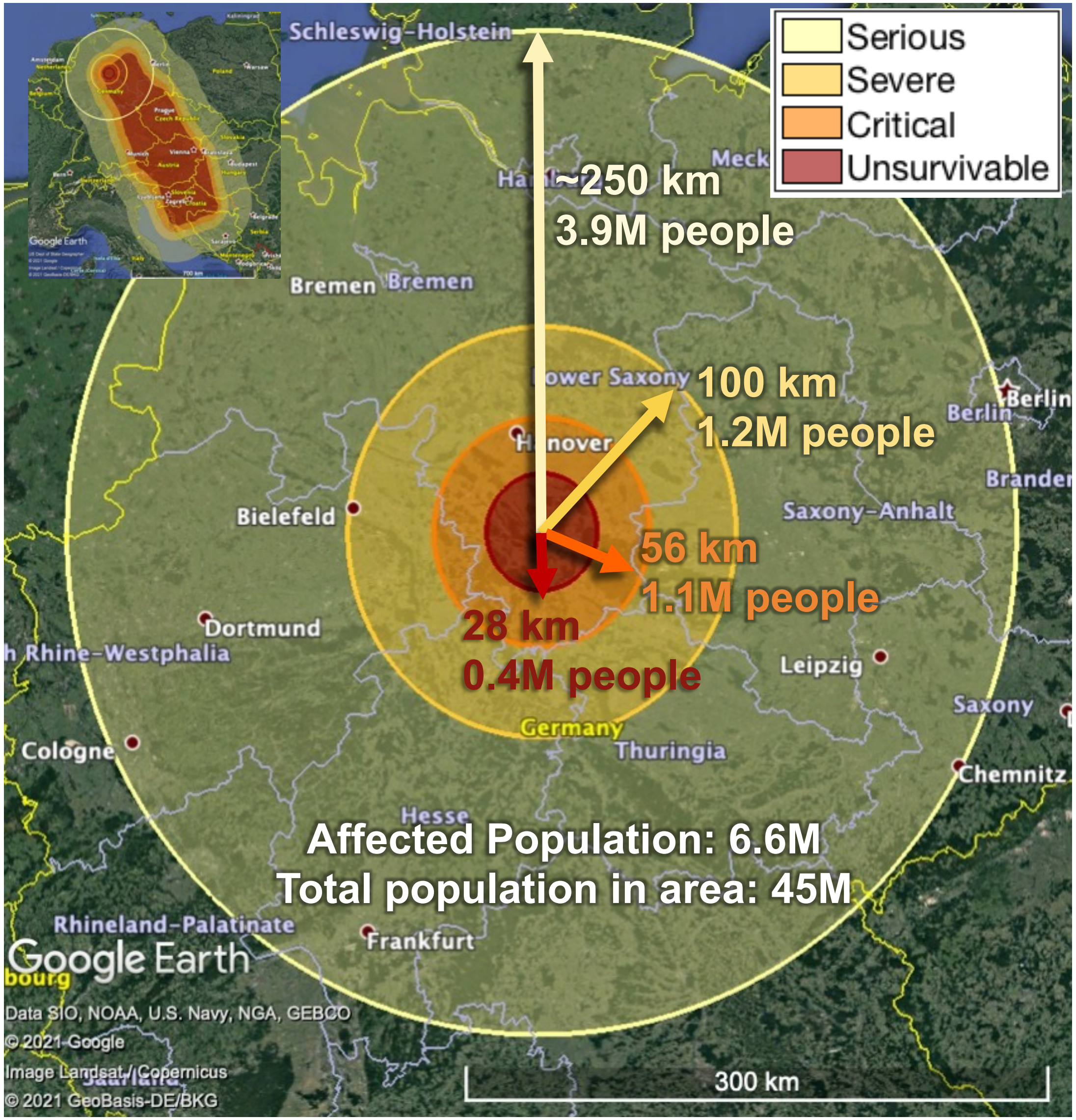
Maximum Affected Population Case
(maximum affected population among all modeled cases)



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)



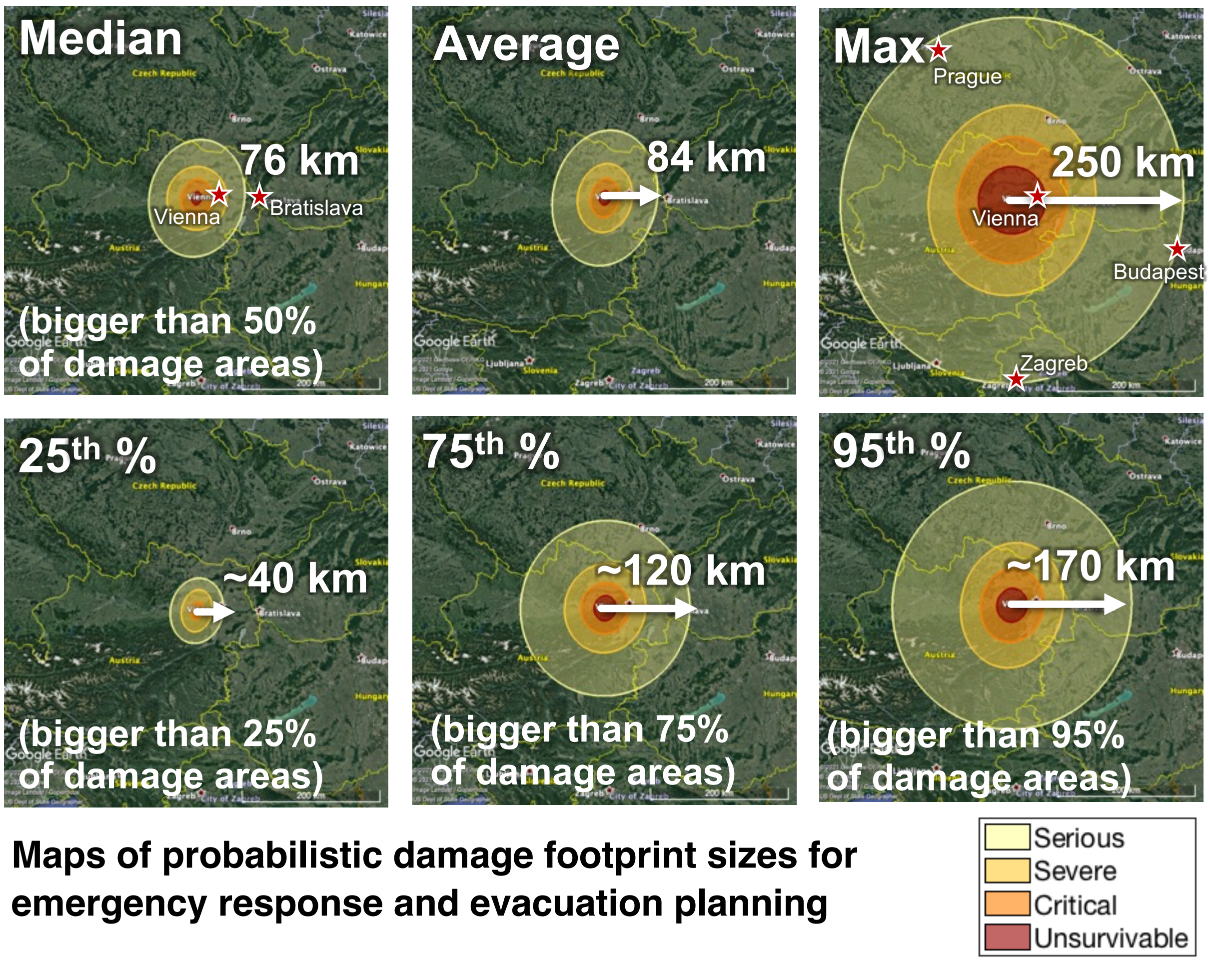
Affected population is driven by larger, less-severe damage levels

- 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

HYPOTHETICAL EXERCISE

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

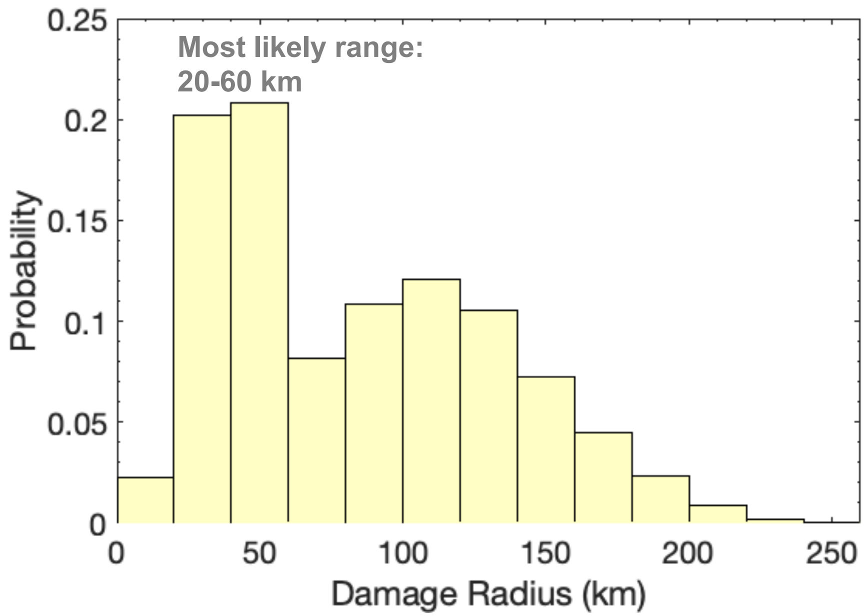


Maps of probabilistic damage footprint sizes for emergency response and evacuation planning

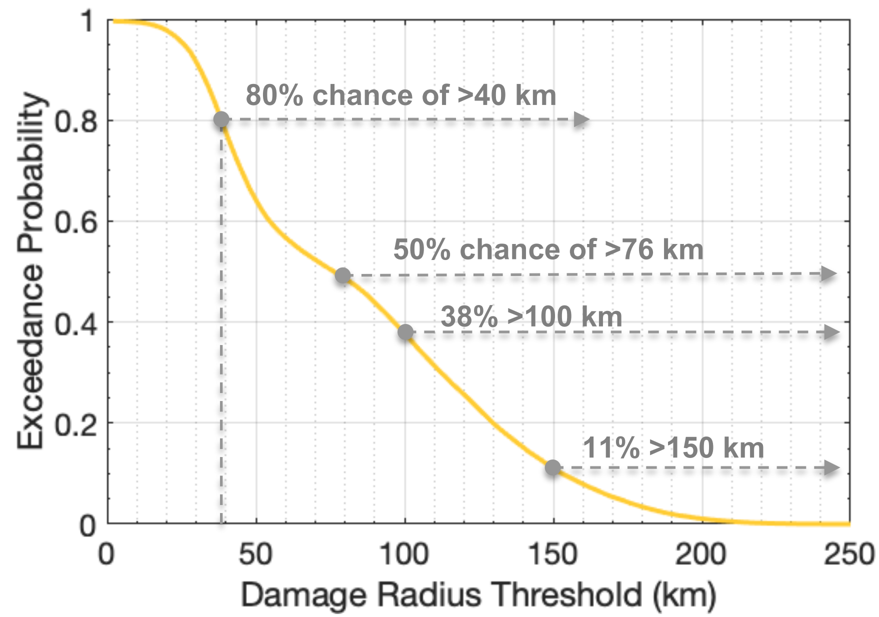
- Worst-case areas can be too large to evacuate, and are very unlikely
- Probabilities of different damage ranges and severities can be used to prioritize effective response
- Radius percentile indicates the chance that the damage will be smaller than that size

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*



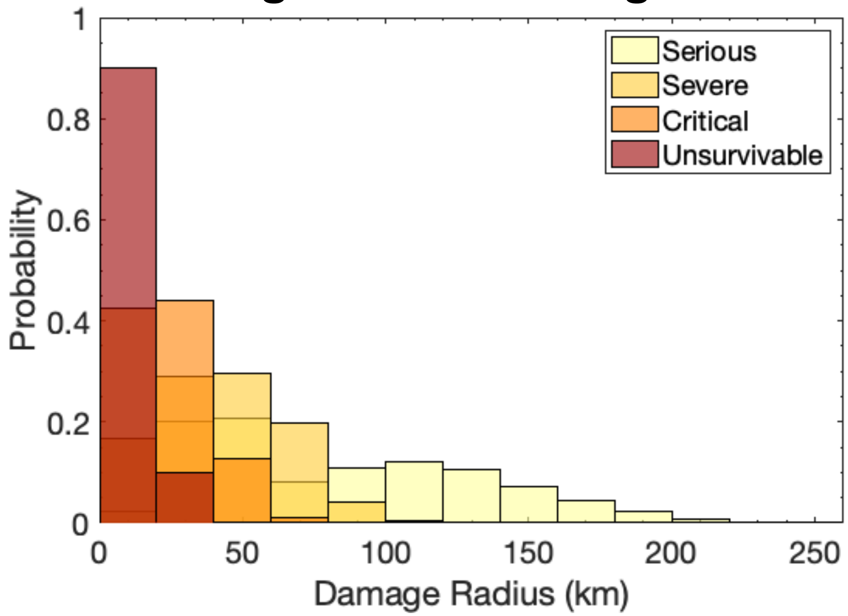
Serious Damage Radius Stats (km)

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

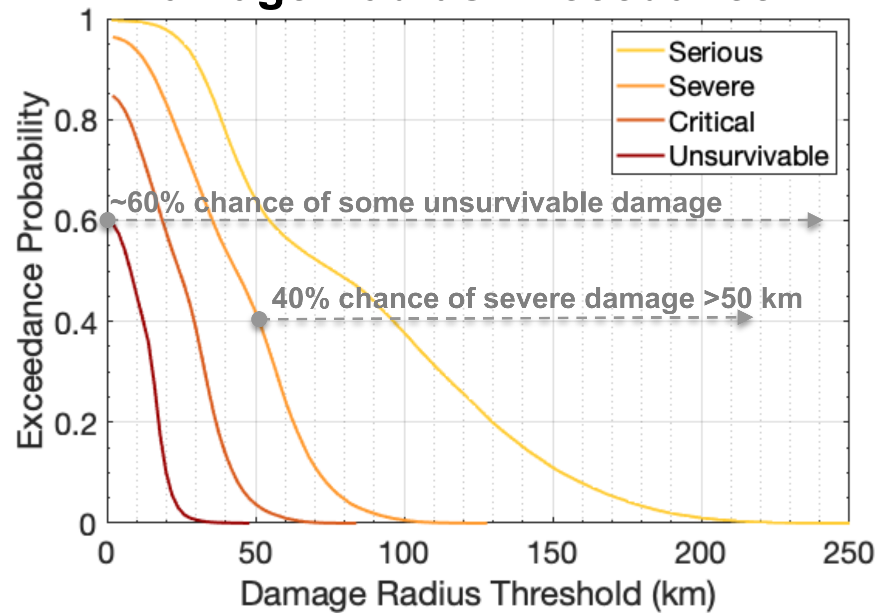
*Percentiles give the probability of the outcome being smaller than the given value (e.g., a 75^{th}% damage radius of 100 km means a 75% chance of being smaller than 100 km and a 25% chance of exceeding 100 km).

Damage Radius Probabilities
(all severity levels)

Damage Radius Histogram



Damage Radius Exceedance



Local Ground Damage Radius Stats (km)

Damage Level	Mean	Min	Max	5th %	25th %	Median	75th %	95th %
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	~35–500	~1–3700	0–250	0–6.6M
Average	136	136	84	580k
Most likely	~65–120	~20–50	20–60	100k–1M
5^{th}–95^{th} %	65–270	~8–570	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

REFERENCES

Related PDC 2021 Presentations

Asteroid Property Inference

- **Dotson** et al., "Bayesian Inference of Asteroid Physical Properties: Application to Impact Scenarios" (Impact Effects Session 9b)
- **Kelley** et al., "IAWN Planetary Defense Exercise: Apophis Observing Campaign 2020-2021" (Apophis Session 13)

Impact Effects – Hazard Modeling & Simulation

- **Aftosmis** et al., "High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2021 PDC," (Impact Effects e-lighting)
- **Wheeler** et al., "Probabilistic Blast Damage Modeling Uncertainties and Sensitivities" (Impact Effects e-lighting)
- **Mathias** et al., "Interaction of Meteoroid Fragments During Atmospheric Entry" (Impact Effects e-lighting)
- **Coates** et al., "Comparison of Thermal Radiation Damage Models and Parameters for Impact Risk Assessment" (Impact Effects e-lighting)
- **Berger** and LeVeque, "Towards Adaptive Simulation of Dispersive Tsunami Propagation from an Asteroid Impact" (Impact Effects Session 9b)
- **Titus** et al., "Asteroid Impacts – Downwind and Downstream Effects" (Impact Effects Session 9b)
- **Boslough**, "Airburst Consequence Modeling Using Artificial Ablation" (Impact Effects e-lighting)

Mitigation & Mission Design

- **Barbee** et al., "Risk-Informed Spacecraft Mission Design for the 2021 PDC Hypothetical Asteroid Impact Scenario" (Mission & Campaign Design Session 8b)

References

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
- Wheeler & Mathias, 2018. Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus, 327, 83–9. https://doi.org/10.1016/j.icarus.2018.12.017
- 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
- Rumpf et al., 2020. Deflection Driven Evolution of Asteroid Impact Risk Under Large Uncertainties. Acta Astonautica 176, 276¬–286. https://doi.org/10.1016/j.actaastro.2020.05.026
- Reddy et al., 2019. Near-Earth Asteroid 2012 TC4 Campaign: Results from Global Planetary Defense Exercise. Icarus 326, 133–150. https://doi.org/10.1016/j.icarus.2019.02.018

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 Simulations and Modeling

- 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

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

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

HYPOTHETICAL EXERCISE