# Planetary Defense Conference 2021
# Asteroid Impact Exercise

**Lorien Wheeler**
**NASA Ames Research Center**
Asteroid Threat Assessment Project (ATAP)

Jessie Dotson (NASA Ames, ATAP)

Paul Chodas (CNEOS, JPL, CalTech)

Brent Barbee (NASA Goddard)

**25th Meeting of the Small Bodies Assessment Group**
June 7, 2021

HYPOTHETICAL EXERCISE

# 2021 PDC Impact Exercise Team

- Scenario development and assessment:
  - Orbital modeling: Paul Chodas (NASA JPL, CNEOS)
  - Mission design: Brent Barbee (NASA Goddard)
  - Asteroid characterization: Jessie Dotson (NASA Ames)
  - Risk assessment: Lorien Wheeler (NASA Ames)
- Organizers & panel chairs:
  - Nahum Melamed (Aerospace Corp.)
  - Bill Ailor (Aerospace Corp.)
  - Lindley Johnson (NASA PDCO)
  - Kelly Fast (NASA PDCO, IAWN)
  - Gerhard Drolshagen (SMPAG, Univ. Oldenburg)
  - Detlef Koschny (ESA Planetary Defense Office)
  - L.A. Lewis (FEMA, DHS)
  - Alissa Haddaji (Harvard Law School)
  - Linda Billings (NASA PDCO)
  - Mark Boslough (LANL)
  - Romana Koffler (UNOOSA)
  - Alex Karl (IAF TC on NEOs)
- Groups:
  - NASA Planetary Defense Coordination Office (PDCO)
  - NASA JPL Center for Near-Earth Object Studies (CNEOS)
  - NASA Ames Research Center, Asteroid Threat Assessment Project (ATAP)
  - NASA Goddard Space Flight Center
  - ESA Planetary Defense Office
  - International Asteroid Warning Network (IAWN)
  - Space Mission Planning Advisory Group (SMPAG)
  - UN Office of Outer Space Affairs (UNOOSA)
  - Aerospace Corp.

# Hypothetical Asteroid Impact Exercises

Hypothetical impact exercises role-play through the discovery, assessment, and response options for a realistic invented asteroid threat scenario

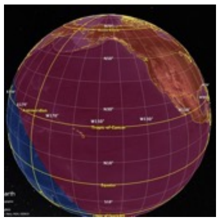
- PDC Exercise Approach
  - Scenario specifications (orbit, properties, available observations) are planned in advance by the exercise team
  - Assessments are performed to demonstrate the observational refinement, potential impact risks, mitigation mission options, and other response factors
  - Evolving scenario information and assessments are presented to conference attendees in several ‘injects’ over several days of the conference
  - Panels representing decision makers and response agencies discuss and react
  - Initial scenario information is made available to public/attendees on the CNEOS exercise website for additional independent studies
- Purpose
  - Test and improve our assessment tools, processes, and response preparedness
  - Identify key gaps or advancement needs
  - Raise awareness of potential asteroid threat and need for Planetary Defense
  - Provide opportunity for international PD community to collaborate on a common scenario, and share current knowledge, tools, and capabilities

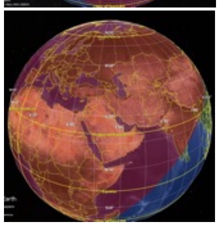
# 2021 PDC Scenario Overview

## (Paul Chodas, CNEOS/JPL)

Scenario was designed as a short-warning, mid-sized impactor case to emphasize needs for discovery assets, rapid-response mitigation capabilities, and disaster response planning

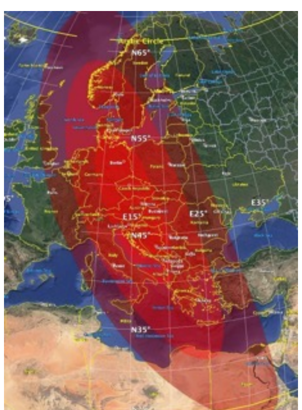
### Day 1: Initial discovery & risk assessment





- Scenario date: 26 April 2021, ~6 mo. before potential impact
- 5% Earth impact probability
- Potential impact region spanning 2/3 of the globe
- Nothing known about object except for H-magnitude estimate of 22.4 ± 0.3 (1σ)

### Day 2: Mission options for confirmed impact



- Scenario date: 2 May 2021, ~6 mo. before impact
- Precovery of object in archival images refines orbit and confirms impact region crossing central Europe to N. Africa
- Mitigation and recon mission options are assessed but cannot be launched in time

### Day 3: Impending impact risk assessment


- Scenario date: 30 June 2021, <4 mo. before impact
- 100% impact probability somewhere over central Europe
- NEOWISE marginal detection reduces largest sizes range
- No mitigation possible, disaster response planning needed

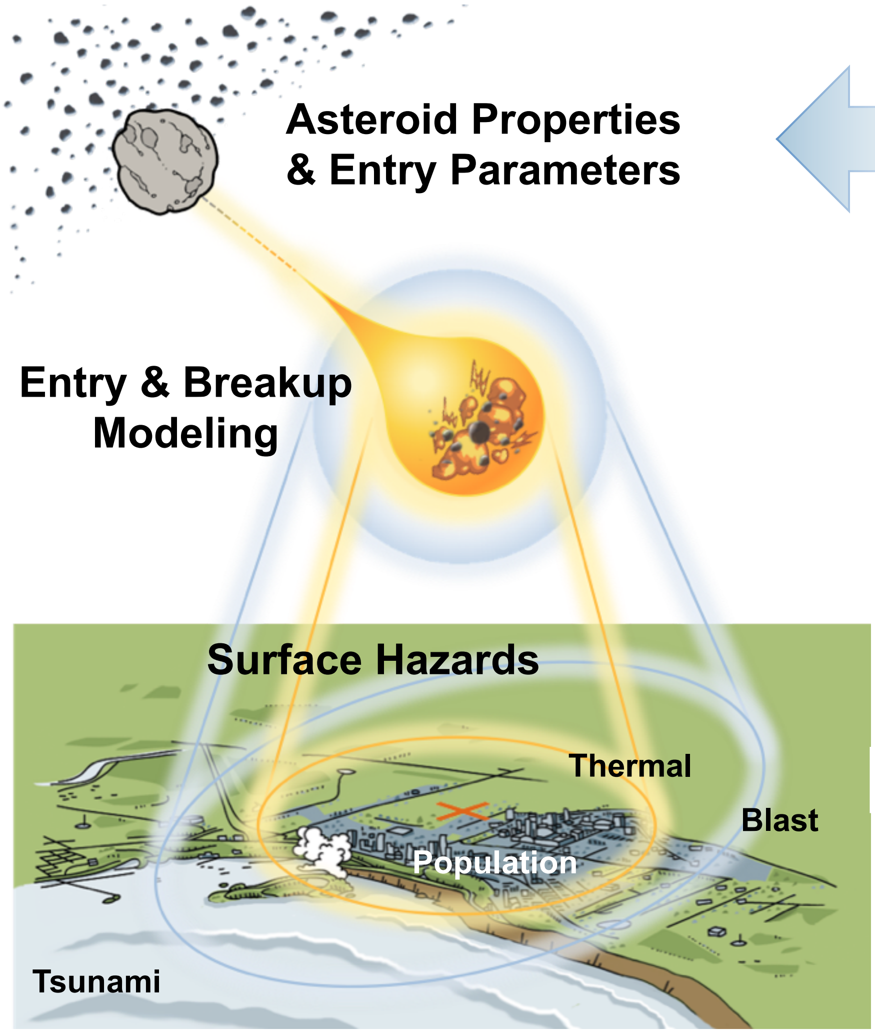
### Day 4: Final impact damage region update


- Scenario date: 14 Oct 2021, 6 days before impact
- Goldstone radar refines diameter to 105 ± 11 m
- Impact location well-resolved to region near border of Czech Republic, Germany, Austria
- Other properties still unknown

Ames Research Center

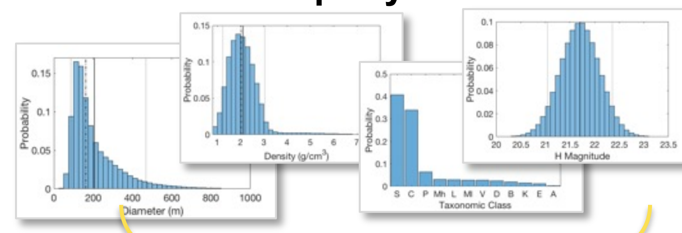
# Asteroid Impact Threat Assessment

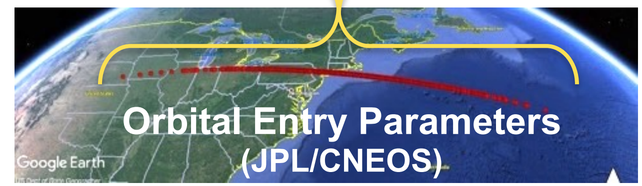
## Probabilistic Asteroid Impact Risk (PAIR) Model



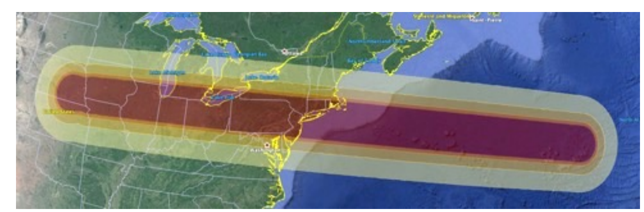

## Impact Threat Scenario

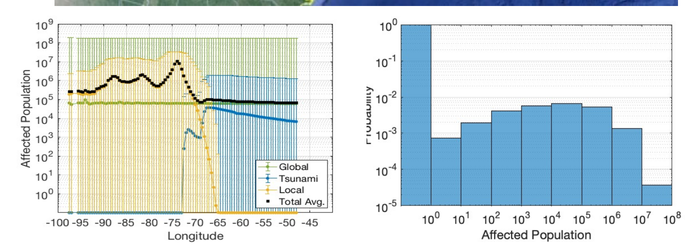
### Asteroid Property Distributions




### Probabilistic Risk and Damage





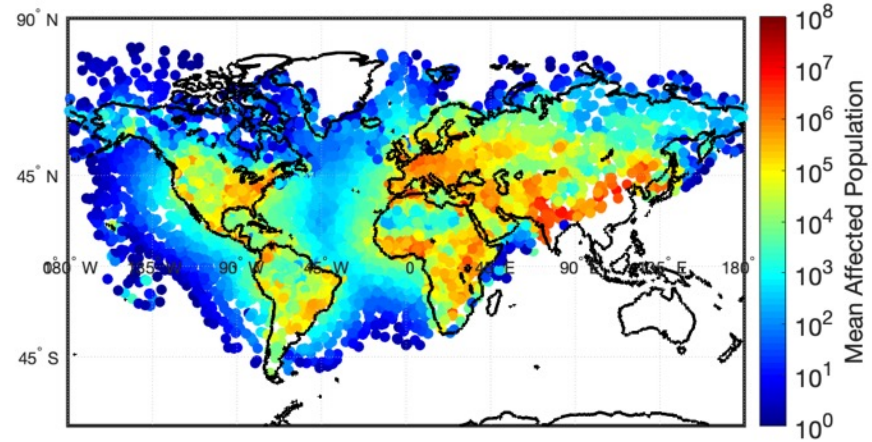
Ames Research Center

# Day 1 Impact Risk Summary

## Characterization Summary & Updates

- Assessment date: 26 April 2021 (initial discovery)
- Potential impact date: 20 October 2021 (6 mo.)
- Earth impact probability: 5%
- H magnitude: 22.4 ± 0.3 (1$\sigma$), unknown albedo
- Diameter: 35–700 m, ~150 m average
- Energy: 1 Mt – 13 Gt, 256 Mt average
- Properties: unknown type or physical properties

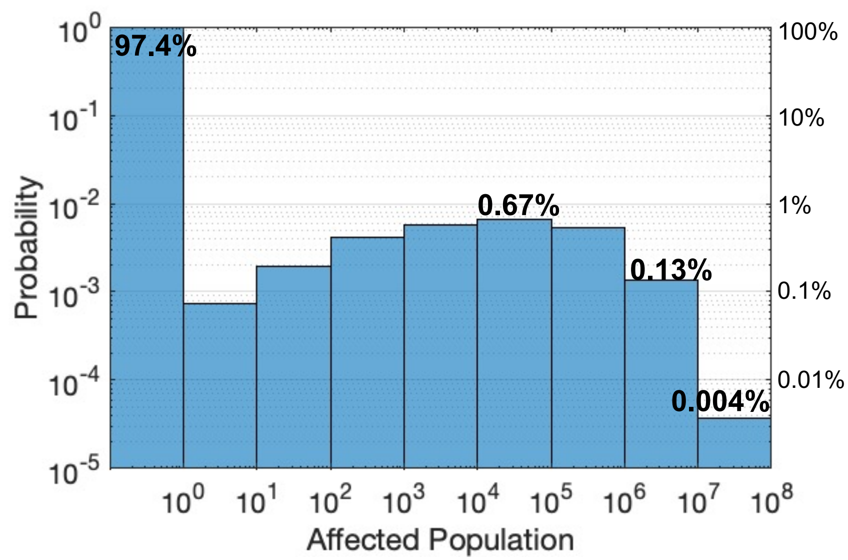
## Affected Population Damage Map




## Hazard Summary

- Potential damage sizes, severities, and locations remain very uncertain
- Primary hazard: airburst/impact causing blast overpressure, from minor structural damage to potentially unsurvivable levels
- Damage radii: 0–470 km, ~90 km average
- Affected Population: 0–86M, 6k average
- 97% chance of no damage, with small chances of affecting thousands to millions of people

## Affected Population Risks

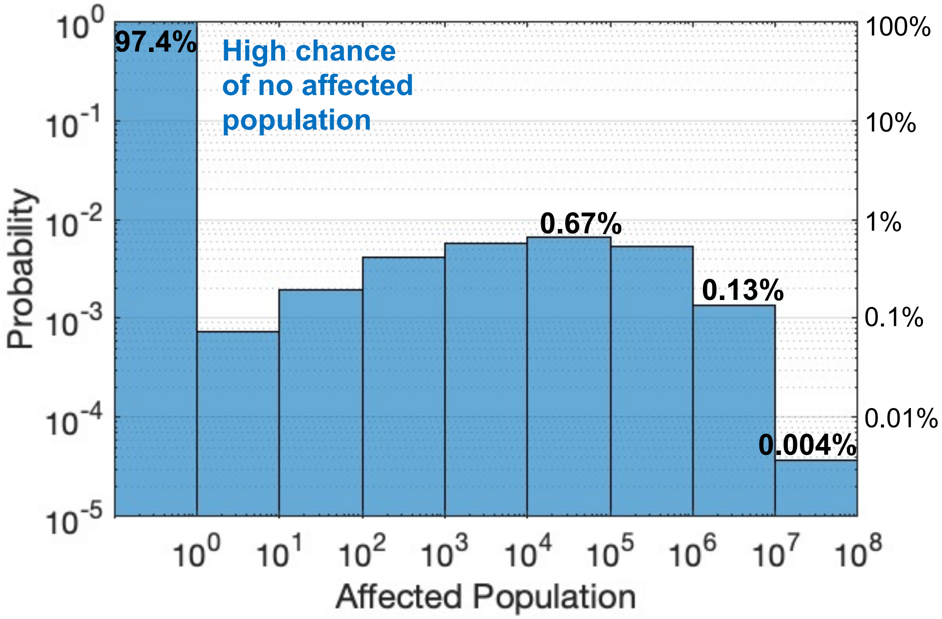




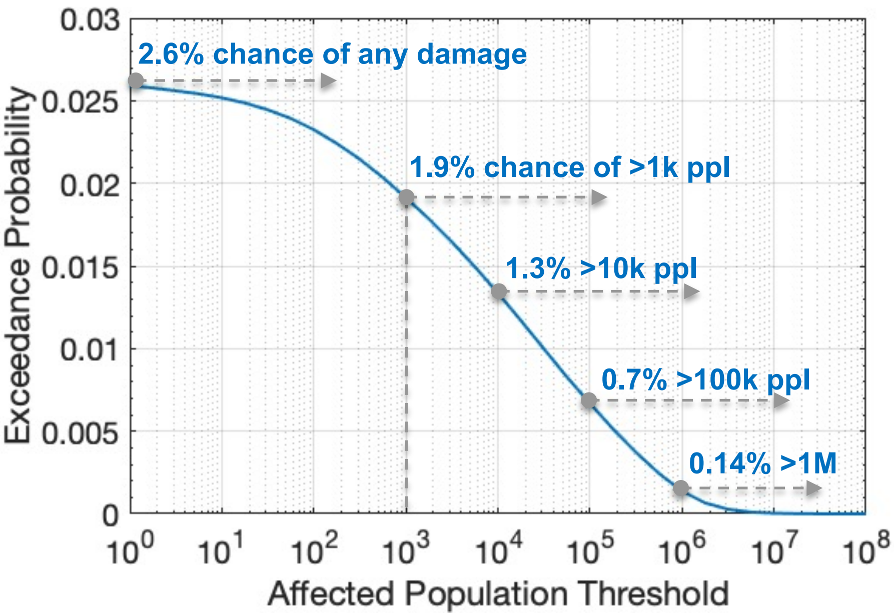
HYPOTHETICAL EXERCISE

# Day 1 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)
- Only 0.14% total chance of affecting over 1M people, 0.004% chance of >10M people

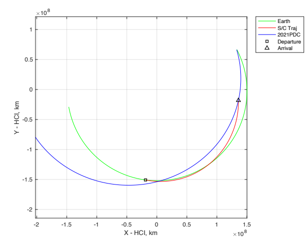

HYPOTHETICAL EXERCISE

# Day 2 Mission Options Assessment
## (Brent Barbee, NASA Goddard)

- Rapid launch capabilities are not yet available:
  - If confronted with the 2021 PDC hypothetical scenario in real life, we would not be able to launch any space craft on such short notice
- Considered mission options if immediate launch were hypothetically available
  - Deflection is not practical in this scenario because it would require too much dv too far in advance
  - Looked at both recon and disruption missions aiming to deliver maximum possible NED size, given large uncertainties in asteroid size
  - Used launch performance models to calculate potential rendezvous and flyby missions, launching at least 12 days after discovery and arriving at asteroid at least 1 month before impact

**Ballistic**

*Chemical propulsion*

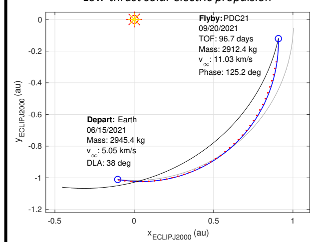



Ballistic analysis by NASA/GSFC: Brent Barbee

| | |
|---|---|
| Departure Date | 2021-06-14 |
| TOF (days) | 98.0 |
| Arrival Date | 2021-09-20 |
| Mass Delivered to NEO (kg) | 2787.1 |
| Phase angle @ Intercept | 125.9° |
| SC/NEO Rel. Spd. @ Intercept (km/s) | 10.73 |
| Departure C3 (km²/s²) | 27.764 |
| Declination of Launch Asymp., DLA | 39.79° |

**NEXT-C Propulsion (similar to DART)**

*Low-thrust solar electric propulsion*

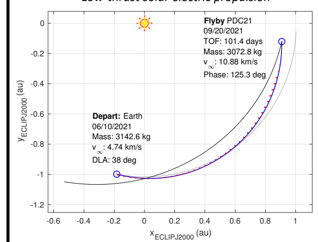



Low-thrust analysis by CNEOS/JPL/CalTech: Javier Roa

| | |
|---|---|
| Departure Date | 2021-06-15 |
| TOF (days) | 96.7 |
| Arrival Date | 2021-09-20 |
| Mass Delivered to NEO (kg) | 2912.4 kg |
| Phase angle @ Intercept | 125.2° |
| SC/NEO Rel. Spd. @ Intercept (km/s) | 11.03 |
| Departure C3 (km²/s²) | 25.503 |
| Declination of Launch Asymp., DLA | 38.00° |

**XIPS25 Propulsion**

*Low-thrust solar electric propulsion*




Low-thrust analysis by CNEOS/JPL/CalTech: Javier Roa

| | |
|---|---|
| Departure Date | 2021-06-10 |
| TOF (days) | 101.4 |
| Arrival Date | 2021-09-20 |
| Mass Delivered to NEO (kg) | 3072.8 |
| Phase angle @ Intercept | 125.3° |
| SC/NEO Rel. Spd. @ Intercept (km/s) | 10.88 |
| Departure C3 (km²/s²) | 22.468 |
| Declination of Launch Asymp., DLA | 38.00° |

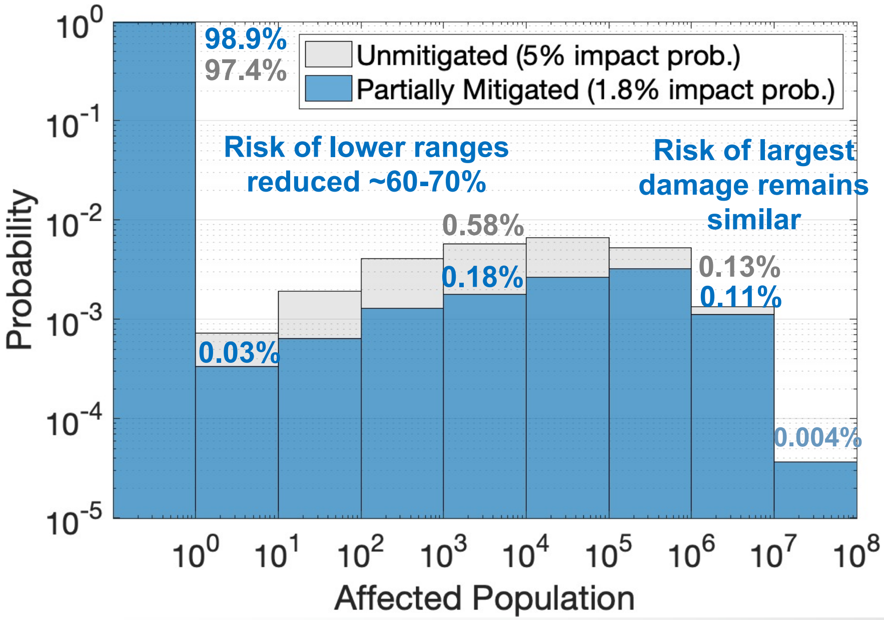
# Day 2 Hypothetical Risk Mitigation

**How much could a hypothetical NED mission reduce risk of impact damage?**

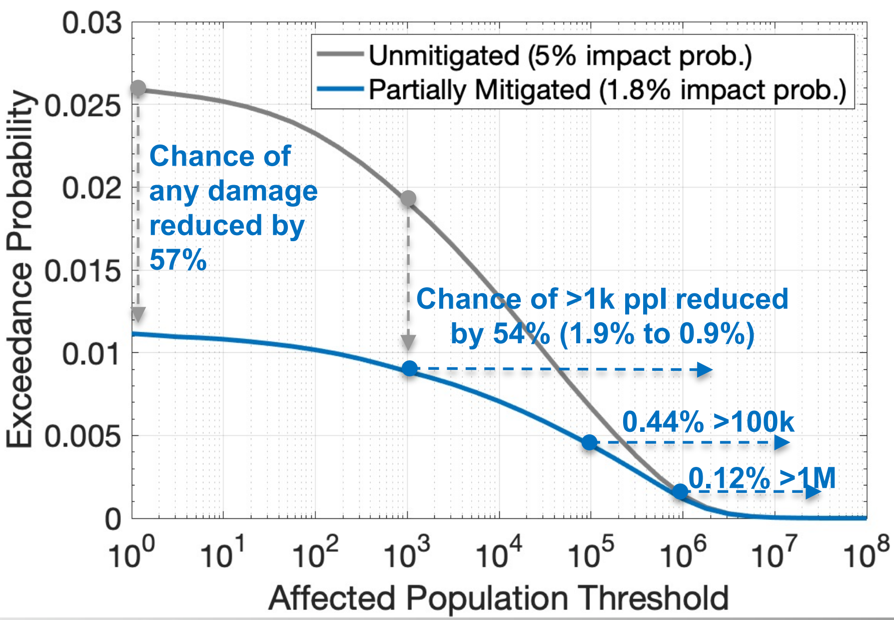
Assuming successful mitigation of all objects under mass/density disruption criteria:

- ~64% of cases successfully mitigated, reducing impact probability from 5% to ~1.8%
- Average affected population reduced by ~20%, from ~5,900 to ~ 4,700
- Chance of damage affecting any population reduced by 57% (from 2.6% to 1.1%).
- Chance of affecting lower population ranges reduced by ~60-70%
- Risk of largest population ranges (>1M or >10M) remains low but similar due to unmitigated largest objects

**Population risk histogram:** Probabilities of affecting the number of people within each range




**Population exceedance risk:** Probability of affecting *at least* the given number of people *or more*





HYPOTHETICAL EXERCISE

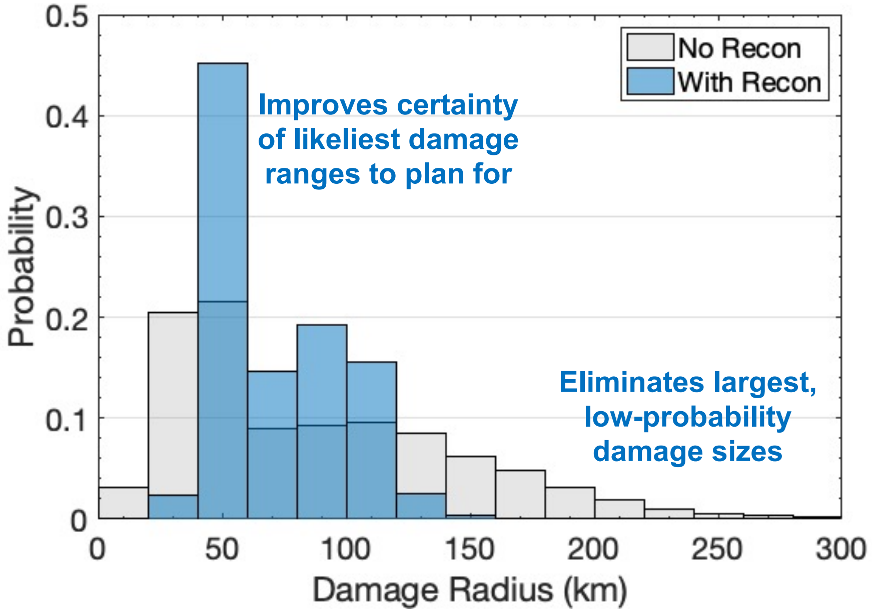
# Day 2 Recon Mission Benefits for Disaster Planning

**How much could a hypothetical recon mission refine damage area estimates?**

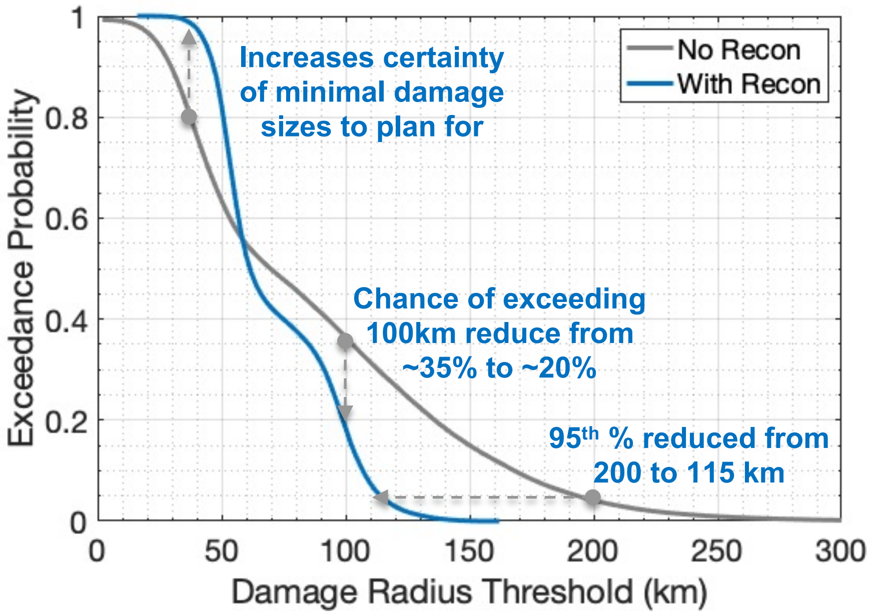
Assuming recon could determine diameter to within 10% for a median-sized 118 m object:

- Asteroid diameter range reduced to 118±12 m (~106–130 m vs 30–700 m without recon)
- Substantially narrows range of potential damage areas for disaster response and improves confidence in likeliest damage areas to plan for
- Reduces maximum potential radius from ~470 km to ~160 km

**Damage radius risk histogram:** Probabilities of damage radii within each range




**Damage radius exceedance risk:** Probability of damage radii being *at least* the given size *or larger*





HYPOTHETICAL EXERCISE

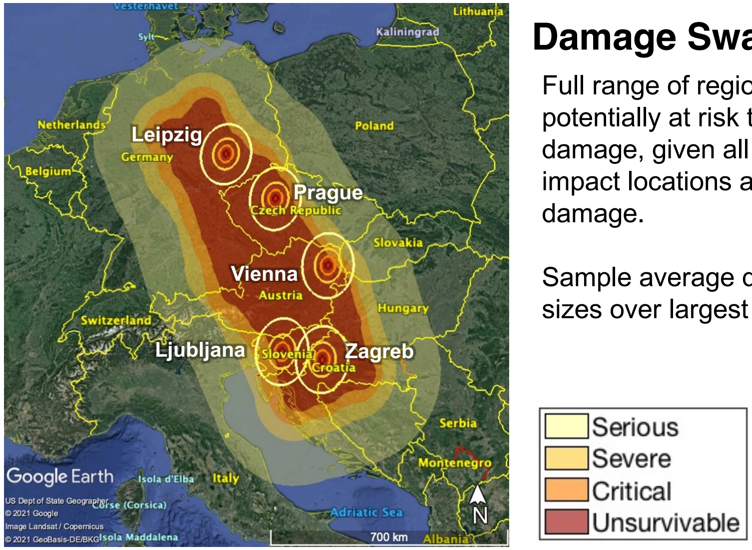
# Day 2 Mission Options Findings
## (Brent Barbee, NASA Goddard)

- Current Capabilities & Challenges
  - Current real-world infrastructure for spacecraft development and launch would not enable us to deploy either reconnaissance or mitigation spacecraft in such a short warning scenario if this were a real situation.
  - Deflection would not be practical due to the short warning time
  - Robust disruption using an NED would be the only viable in-space mitigation option
  - Short warning mission options require high-speed flybys at poor solar phase angles, which can pose significant guidance and navigation challenges
  - It is difficult to define mitigation mission requirements or assess mitigation effectiveness given large uncertainties in asteroid size and properties
- Early NEO detection and rapid response spacecraft launch are both key capabilities for effective planetary defense preparedness
  - Deploying a nuclear disruption mission could significantly reduce the risk of impact damage, despite substantial uncertainties in the asteroid's properties
  - Deploying a flyby reconnaissance spacecraft would significantly reduce the uncertainties faced by disaster response planners
  - Enhanced NEO detection systems are affordable, technologically ready, and under development (NASA's NEO Surveyor space-based telescope mission)

# Day 3 Impact 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




## Damage Swath

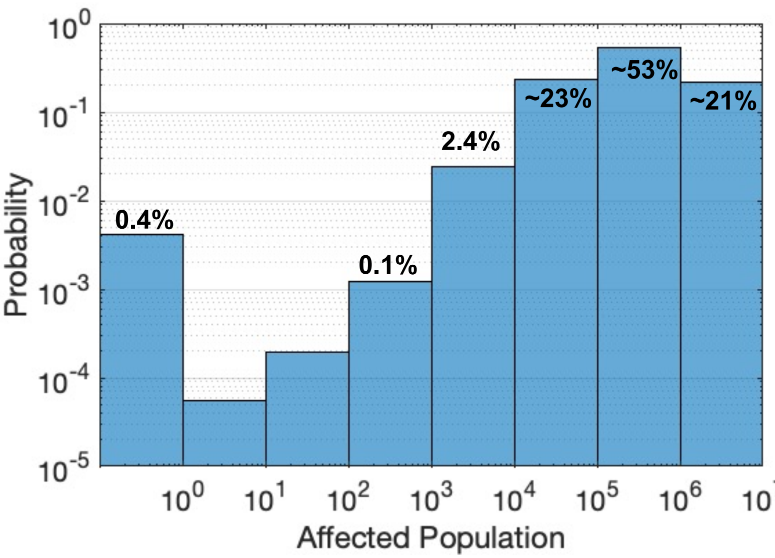
Full range of regions potentially at risk to ground damage, given all potential impact locations and largest damage.

Sample average damage sizes over largest cities

## 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

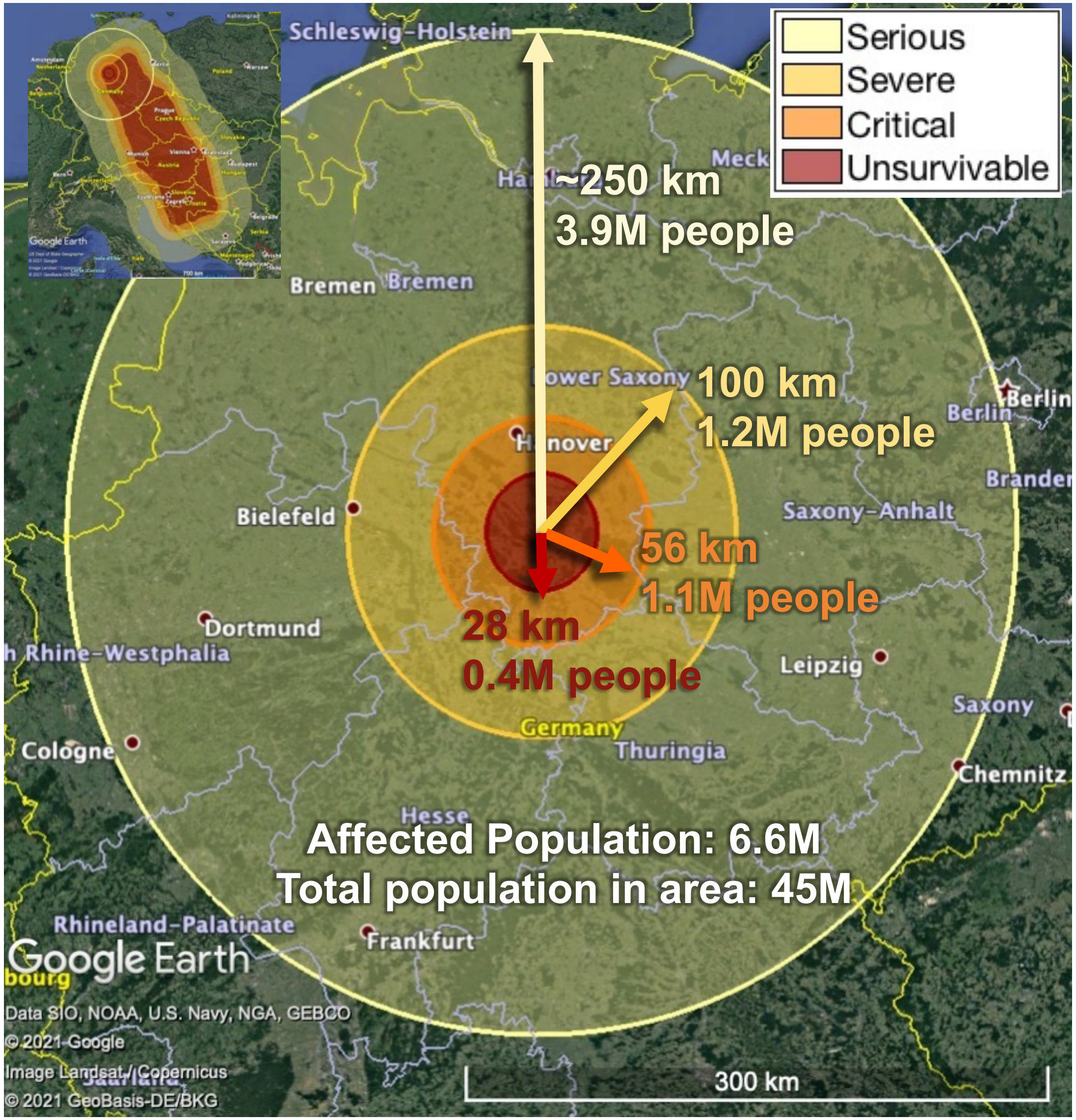
## Affected Population Risk





HYPOTHETICAL EXERCISE

# Day 3 Max Affected Population Case
## (maximum affected population among all modeled cases)

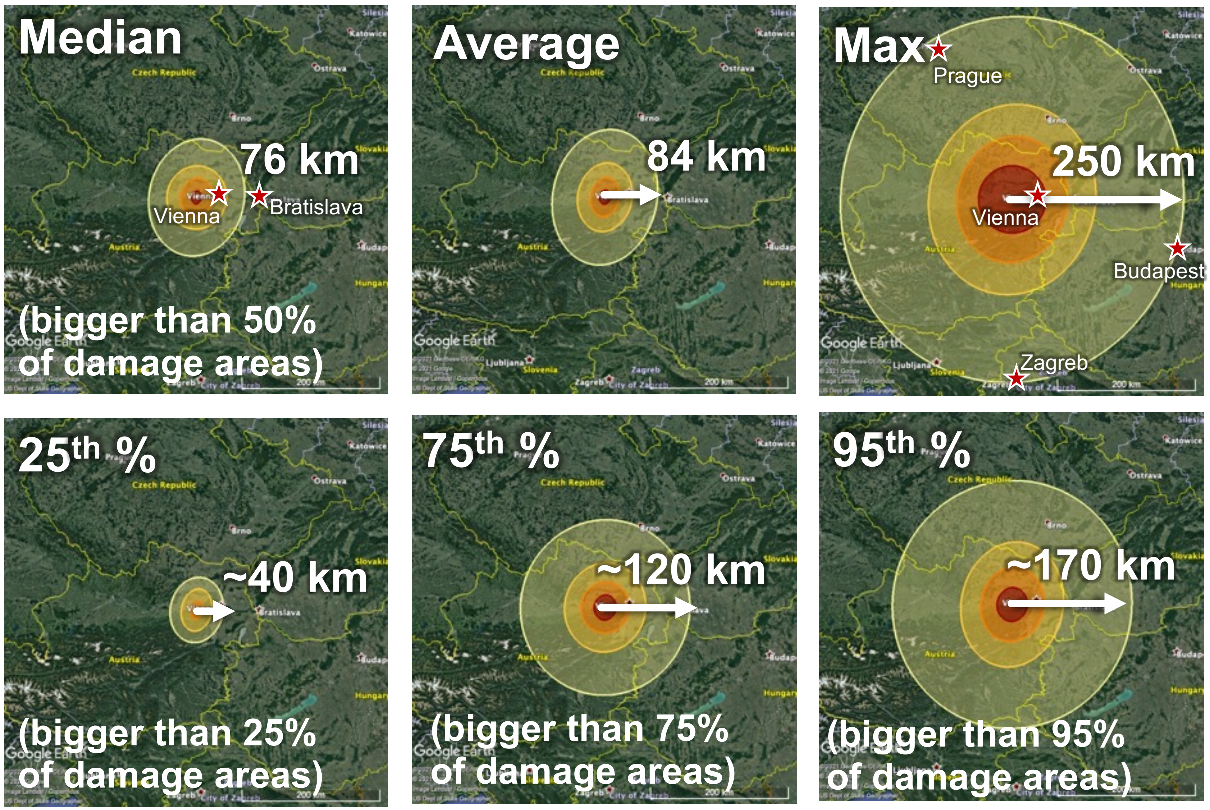



**Affected population is driven by larger, less-severe damage levels**

- 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

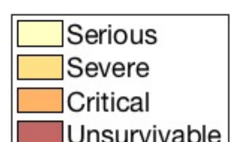
# Day 3 Sample Damage Footprint Sizes
## (over same sample region near Vienna)

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

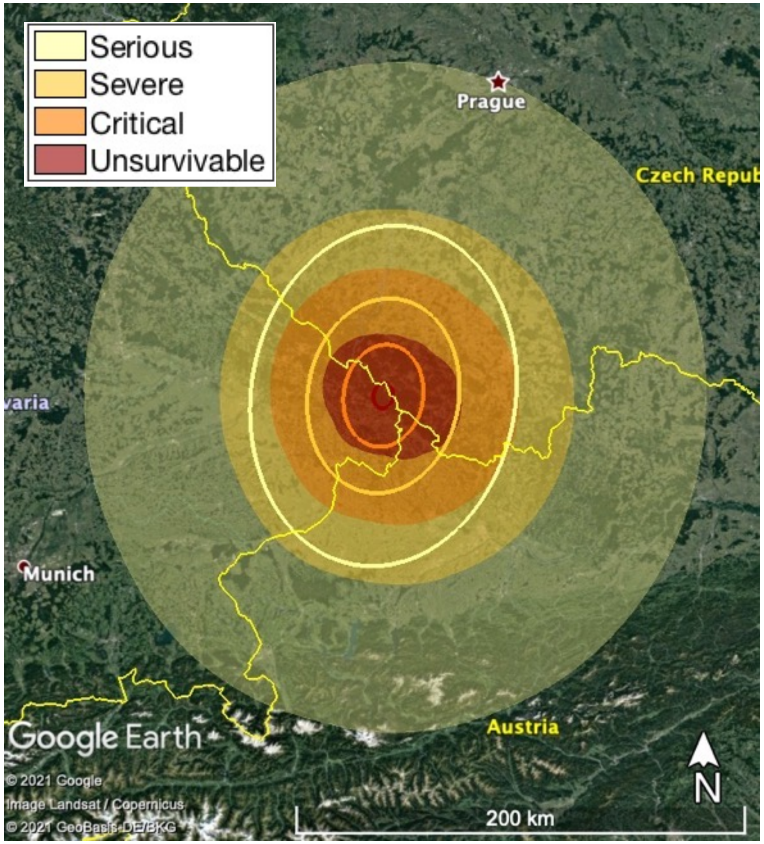



- Worst-case areas can be too large to evacuate, and are very unlikely
- Probabilities of different damage ranges and severities can be used to prioritize effective response
- Radius percentile indicates the chance that the damage will be smaller than that size

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



# Day 4 Final Risk Region Update
## (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, including worst-case objects and all sampled impact locations. Estimated average footprint sizes are shown as overlaid rings.

Concluded scenario with brief update on final estimate of damage risk region, given final impact trajectory and radar size refinements six days before impact.

**Asteroid properties**

- Diameter: 67-140 m, mean 105 m
- Energy: 9-156 Mt, mean 40 Mt
- Entry: ~ 15.2 km/s, 53˚
- Other asteroid properties remain unknown

**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

# Exercise Takeaways

- Observation and Detection
  - Precoveries of objects in archival images could play an important role in assessing impact probability and location
  - Early NEO detection capabilities are critical to detecting objects earlier orbits to provide longer warning time
  - Object size and properties can remain highly uncertain even days before impact
- Risk Assessment
  - Damage probabilities must be be evaluated across broad range of uncertain asteroid properties and impact locations
  - Affected population risk were driven more by larger lower-severity damage levels than by smaller higher-severity damage levels
  - Worst-case damage can be very large but also unlikely, and can arise from unexpected cases
  - Probabilistic risks enable response decisions to consider both the severity and likelihood of potential impact consequences
- Mission Options
  - Short-warning scenarios would necessitate nuclear disruption due to time constraint and large asteroid size uncertainties
  - Rapid-response launch capabilities do not currently exist to enable any mitigation or reconnaissance missions with this little warning
  - If rapid launch were possible, NED disruption could mitigate risk from a substantial fraction of the size range, and recon missions could greatly reduce damage uncertainties
- Disaster Response & Communication
  - Scenario provided valuable awareness and interchange with disaster response groups
  - Highlighted need to develop civil emergency response plans to shelter or evacuate large regions within short timeframe
  - Need to establish clear damage risk metrics tied to actionable disaster response criteria
  - Raised key issues in communicating uncertain risks to media and public

# REFERENCES


HYPOTHETICAL EXERCISE

# Additional PDC Exercise Information References

- CNEOS 2021 PDC impact exercise website:
  - https://cneos.jpl.nasa.gov/pd/cs/pdc21/
- PDC 2021 conference website:
  - https://iaaspace.org/event/7th-iaa-planetary-defense-conference-2021/
- UNOOSA webcast of conference and exercise presentations:
  - https://www.youtube.com/playlist?list=PLaOqa4cng0GF56U0oJMKEjKfLXFBhuxBk
- NASA HQ Web Feature:
  - https://www.nasa.gov/feature/nasa-to-participate-in-tabletop-exercise-simulating-asteroid-impact
- Media articles:
  - Space.com: https://www.space.com/planetary-defense-asteroid-impact-scenario-exercise-2021
  - Gizmodo.com: https://gizmodo.com/an-asteroid-impact-simulation-is-currently-underway-and-1846783079 and https://gizmodo.com/the-asteroid-impact-simulation-has-ended-in-disaster-1846800347
  - IFLScience.com: https://www.iflscience.com/space/large-chunk-of-europe-annihilated-in-nasas-latest-asteroid-impact-simulation-exercise/
  - Vice.com: https://www.vice.com/en/article/5dbbz8/scientists-tried-and-failed-to-stop-a-hypothetical-deadly-asteroid-in-an-exercise
  - Many others…

Ames Research Center

# Related PDC 2021 Presentations

NASA

## 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)

# Asteroid Threat Assessment 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

# BACKUP

# DAY 1 RISK ASSESSMENT

Ames Research Center

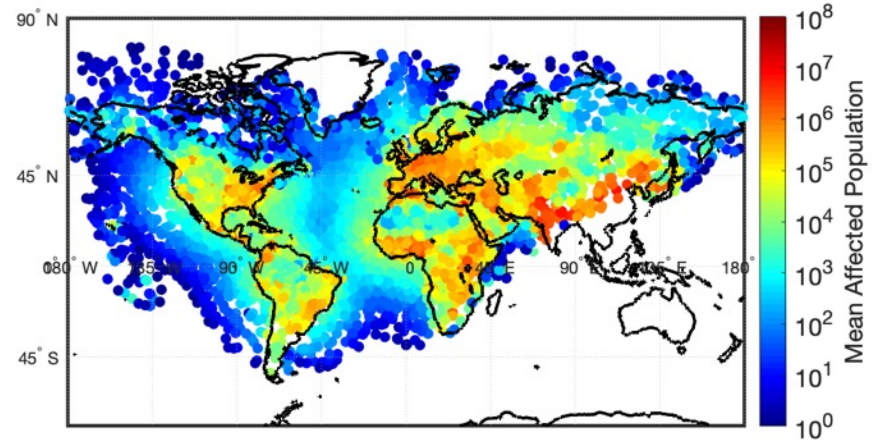
# Impact Risk Summary

NASA

## Characterization Summary & Updates

- Assessment date: 26 April 2021 (initial discovery)
- Potential impact date: 20 October 2021 (6 mo.)
- Earth impact probability: 5%
- Diameter: 35–700 m, ~150 m average
- Energy: 1 Mt – 13 Gt, 256 Mt average
- Properties: unknown type or physical properties

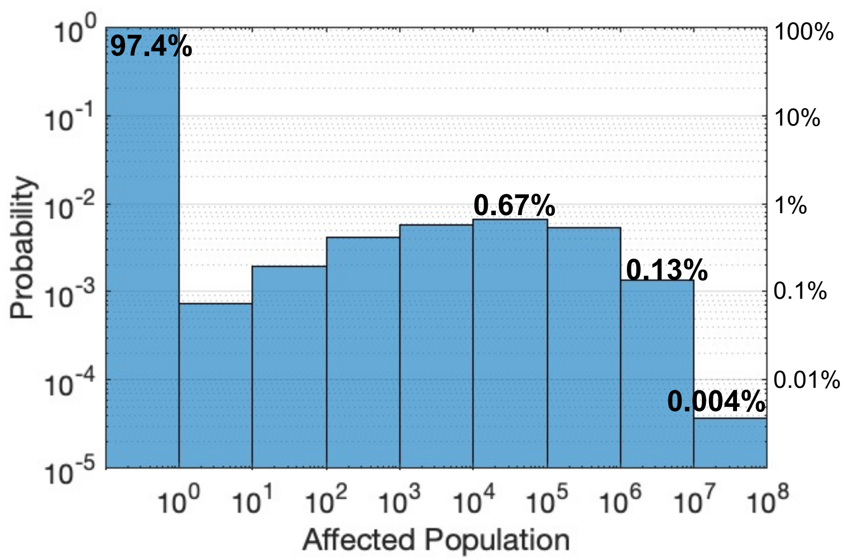
## Impact Damage Map




## Hazard Summary

- Potential damage sizes, severities, and locations remain very uncertain
- Primary hazard: airburst/impact causing blast overpressure, from minor structural damage to potentially unsurvivable levels
- Damage radii: 0–470 km, ~90 km average
- Affected Population: 0–86M, 6k average
- 97% chance of no damage, with small chances of affecting thousands to millions of people

## Affected Population Risks





HYPOTHETICAL EXERCISE

Ames Research Center

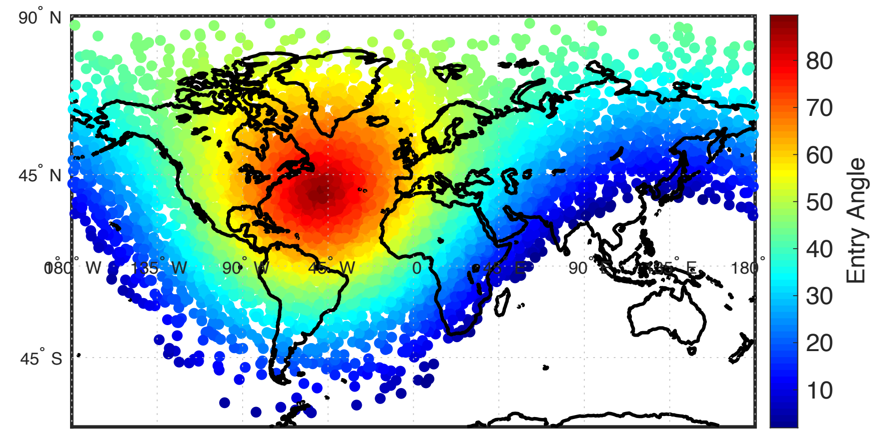
NASA

# Entry Parameters & Locations

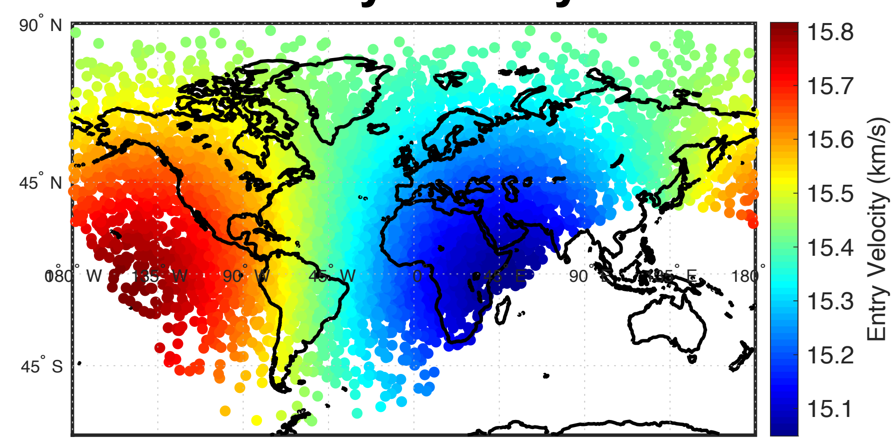
5% chance of Earth impact with potential impact regions spanning most of the globe, centered around mid-Atlantic

- 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**




[Impact entry data: P. Chodas, CNEOS/JPL]
https://cneos.jpl.nasa.gov/pd/cs/pdc21/


HYPOTHETICAL EXERCISE

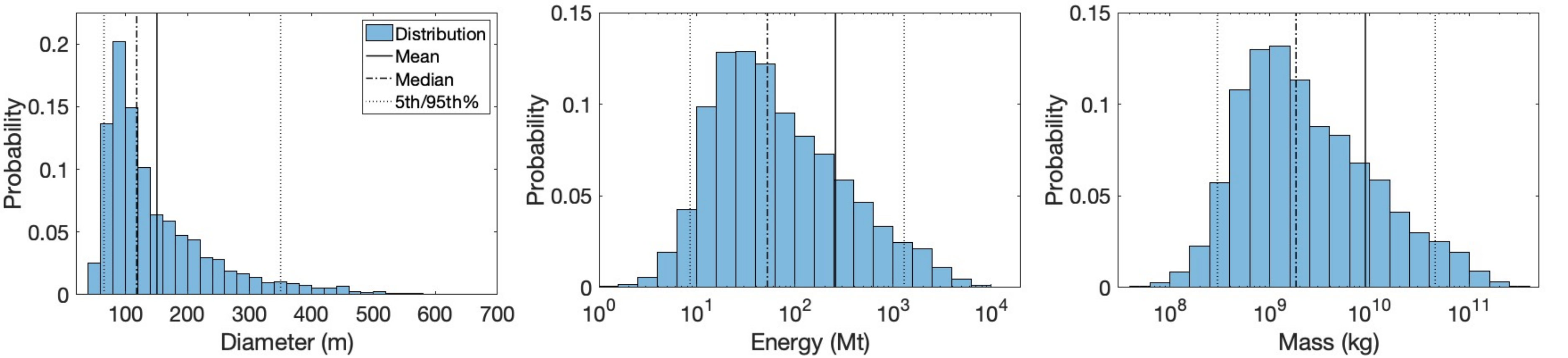
Ames Research Center

# 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 | ~65–125 | ~20–50 | ~1e9 |
| 5th–95th % | 65–350 | ~8–1280 | 3e8–4.5e10 |




[Property inference model: J. Dotson PDC 2021]

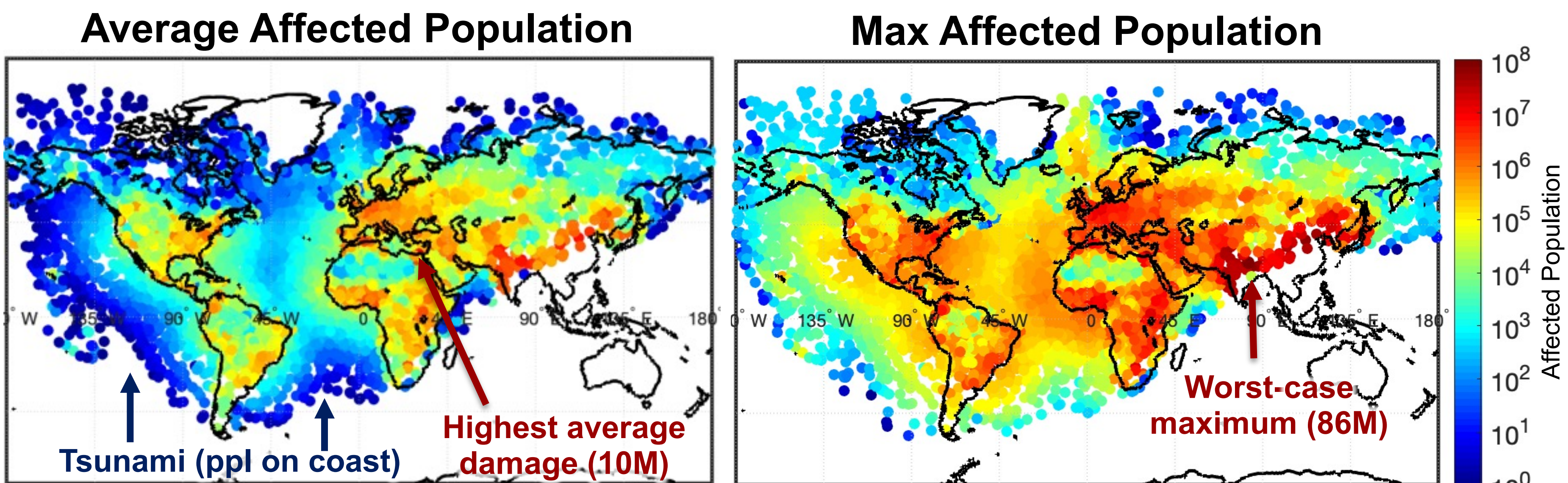
Ames Research Center

# 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)



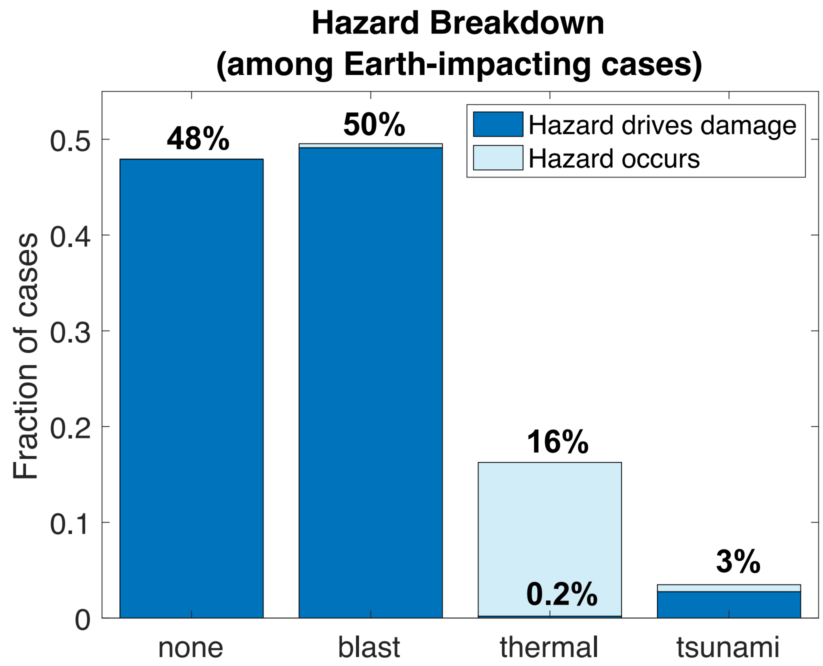

**Maps of average and maximum affected population for each sampled impact entry point, given the potential range in asteroid properties and resulting damage**

(ocean points represent tsunami damage to surrounding coastal regions)

# Hazard Sources

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

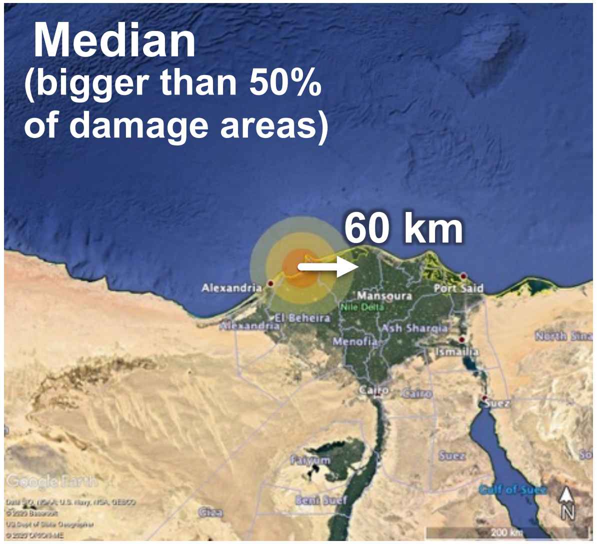
- Blast damage is the predominant hazard source in ~50% of impact cases
- Thermal damage also occurs in ~16% of cases, but is smaller and less severe than blast damage in nearly all cases
- Risk of tsunami is low, occurring in ~3% of impact cases, but the largest impacts could cause significant inundation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

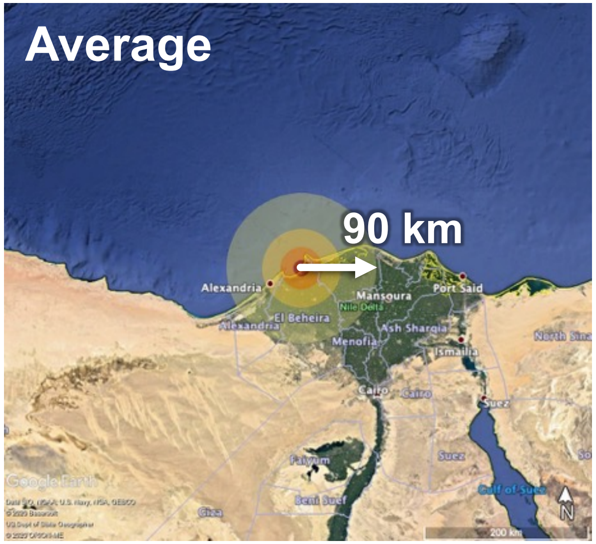


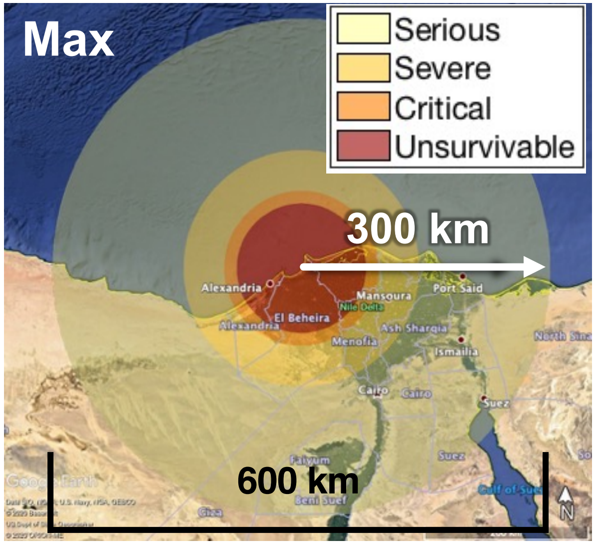

| Hazard Source | % Cases Hazard Occurs | % Cases Hazard Drives Damage | Average Affected Population | Affected Population Range |
|---|---|---|---|---|
| **Blast** | 50% | 49% | 117,000 | 0–86M |
| **Thermal** | 16% | 0.2% | 8,000 | 0–48M |
| **Tsunami** | 3.5% | 2.8% | 940 | 0–1.8M |
| **No Damage** | 48% | 48% | 0 | 0 |

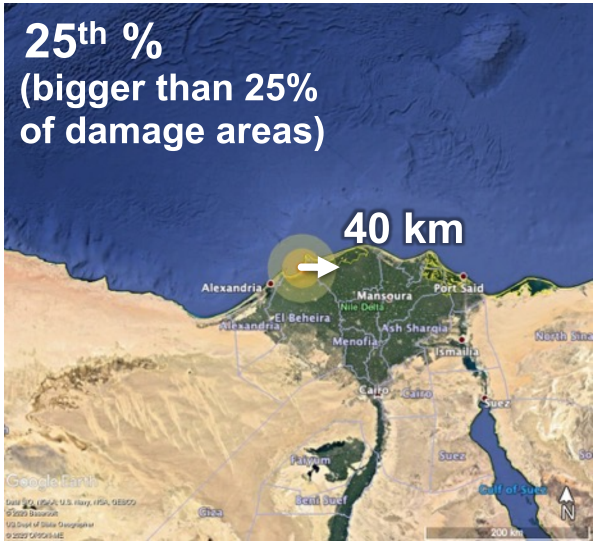
# Sample Blast Damage Sizes

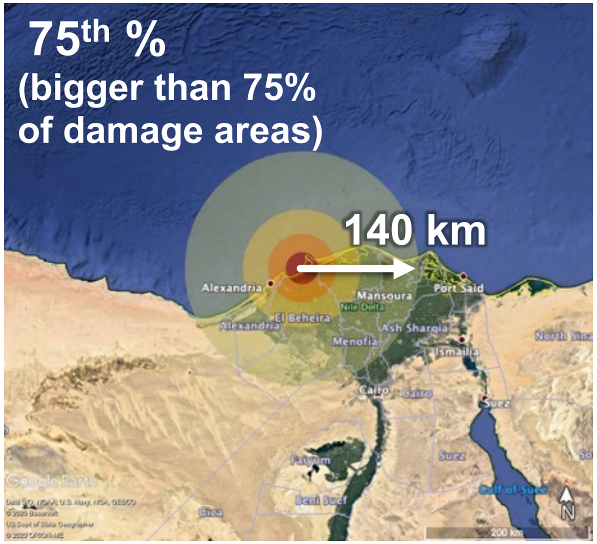
## (regional sizes for an entry point near Alexandria, Egypt)

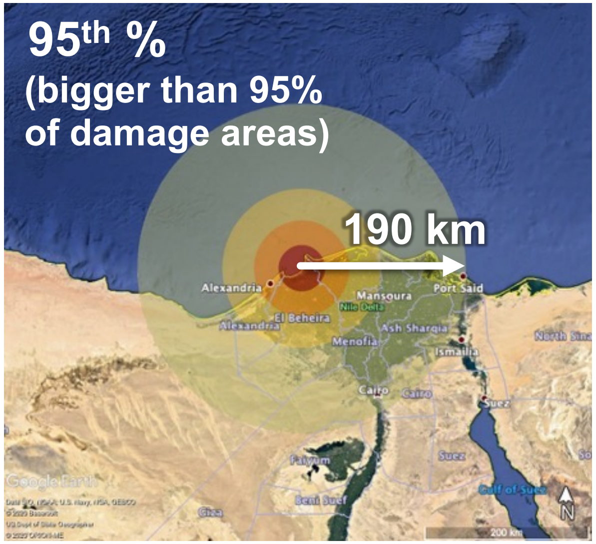


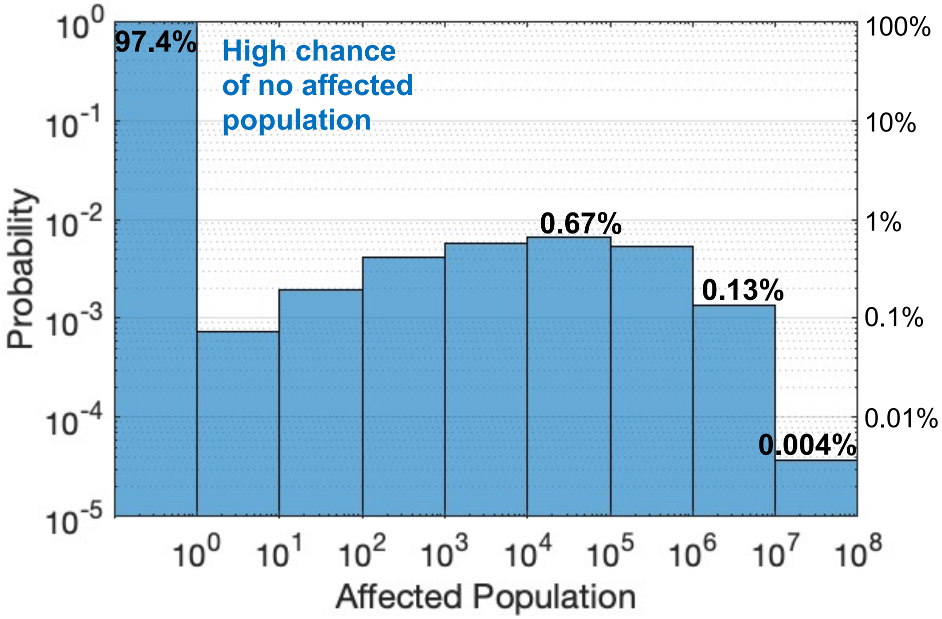



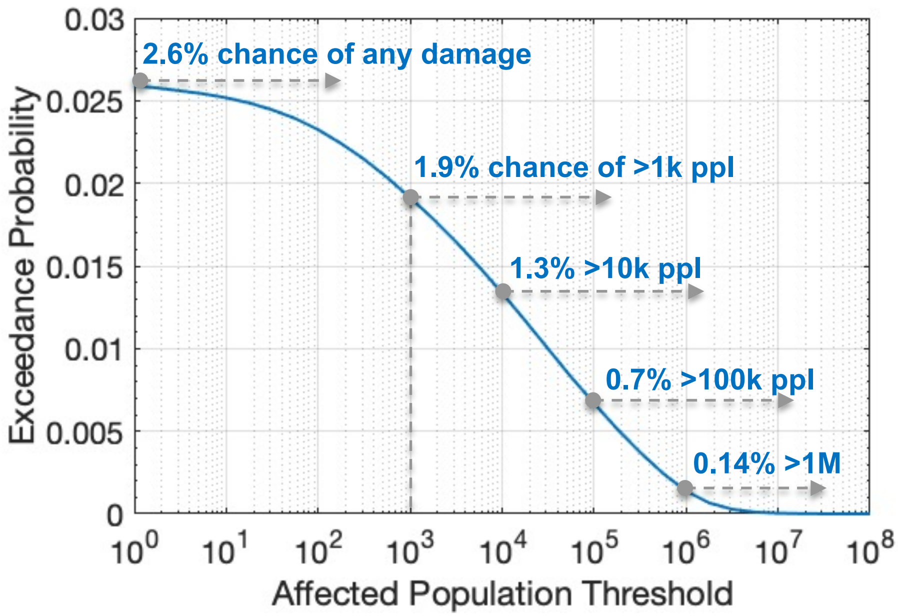



# Total Affected Population Risks
## (Total Risk with 5% Earth Impact Probability)

**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)
- 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 6,000 people
  - 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 | ~65–125 | ~20–50 | ~20–60 | 0 | 0 |
| $5^{th}$–$95^{th}$ % | 65–350 | 8–1280 | 25–190 | 0–550k | 0–0 |

# Risk Assessment Next Steps

- Continuing Threat Assessment:
  - Updated risk assessments will be performed as additional information is gained about the object and potential impact
  - More detailed risk analysis and damage simulations can be performed for critical hazards as impact location and object size are refined
- Risk Information for Decisions and Response Support:
  - Probabilistic risks enable response decisions to consider both the severity and relative likelihood of potential 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 probabilities can support preliminary disaster response planning to prepare for potentially large damage within short warning time

# DAY 2 MISSION OPTIONS ASSESSMENT (BRENT BARBEE, NASA GODDARD)

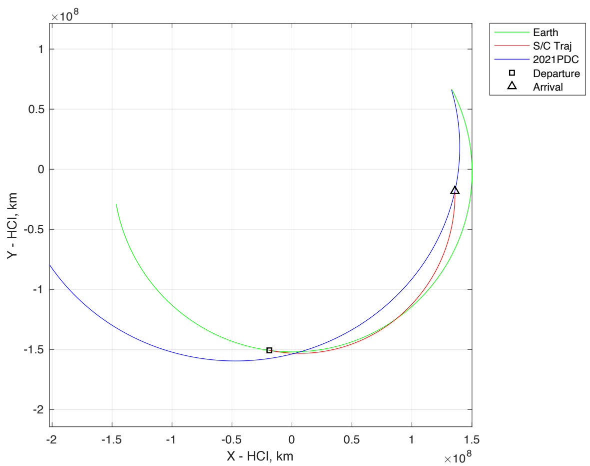
# Day 2 Mission Options Assessment
## (Brent Barbee, NASA Goddard)

- Rapid launch capabilities are not yet available
- Early NEO detection and rapid response spacecraft launch are both key capabilities for effective planetary defense preparedness
- Enhanced NEO detection systems are affordable, technologically ready, and under development – they are our next priority
  - NASA's NEO Surveyor  space-based telescope mission
- Deflection is not practical in this scenario because it would require too much dv imparted to the asteroid and too far in advance of Earth encounter
- If confronted with the 2021 PDC hypothetical scenario in real life, we would not be able to launch any space craft on such short notice
- Considered mission options if immediate launch were hypothetically available
  - Launch performance model, with optimistic launch no earlier than 12 days after discovery, and asteroid rendezvous no later than 1 month before impact
  - Calculated missions for rendezvous and flyby, both ballistic and low-thrust SEP
  - Looked at both recon and disruption missions aiming to deliver maximum possible NED size, given large uncertainties in asteroid size

# Maximum Flyby Spacecraft Mass
# (Brent Barbee, NASA Goddard)

## Ballistic

*Chemical propulsion*

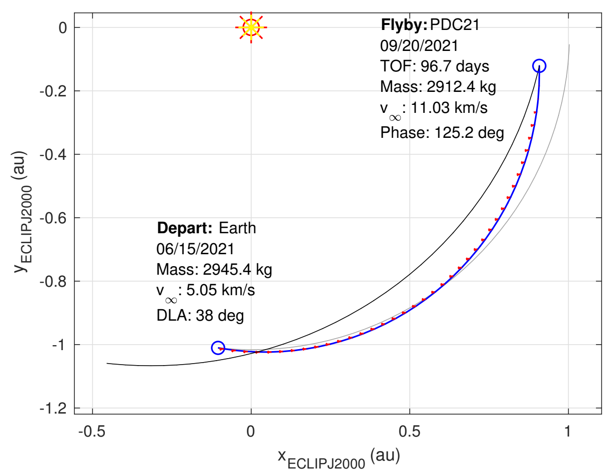



Ballistic analysis by NASA/GSFC:
Brent Barbee

| | |
|---|---|
| Departure Date | 2021-06-14 |
| TOF (days) | 98.0 |
| Arrival Date | 2021-09-20 |
| Mass Delivered to NEO (kg) | 2787.1 |
| Phase angle @ Intercept | 125.9° |
| SC/NEO Rel. Spd. @ Intercept (km/s) | 10.73 |
| Departure C3 ($km^2/s^2$) | 27.764 |
| Declination of Launch Asymp., DLA | 39.79° |

## NEXT-C Propulsion (similar to DART)

*Low-thrust solar electric propulsion*

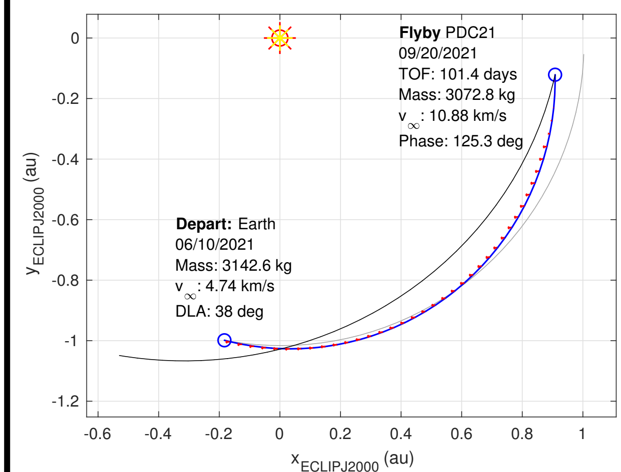



Low-thrust analysis by CNEOS/JPL/CalTech:
Javier Roa

| | |
|---|---|
| Departure Date | 2021-06-15 |
| TOF (days) | 96.7 |
| Arrival Date | 2021-09-20 |
| Mass Delivered to NEO (kg) | 2912.4 kg |
| Phase angle @ Intercept | 125.2° |
| SC/NEO Rel. Spd. @ Intercept (km/s) | 11.03 |
| Departure C3 ($km^2/s^2$) | 25.503 |
| Declination of Launch Asymp., DLA | 38.00° |

## XIPS25 Propulsion

*Low-thrust solar electric propulsion*




Low-thrust analysis by CNEOS/JPL/CalTech:
Javier Roa

| | |
|---|---|
| Departure Date | 2021-06-10 |
| TOF (days) | 101.4 |
| Arrival Date | 2021-09-20 |
| Mass Delivered to NEO (kg) | 3072.8 |
| Phase angle @ Intercept | 125.3° |
| SC/NEO Rel. Spd. @ Intercept (km/s) | 10.88 |
| Departure C3 ($km^2/s^2$) | 22.468 |
| Declination of Launch Asymp., DLA | 38.00° |

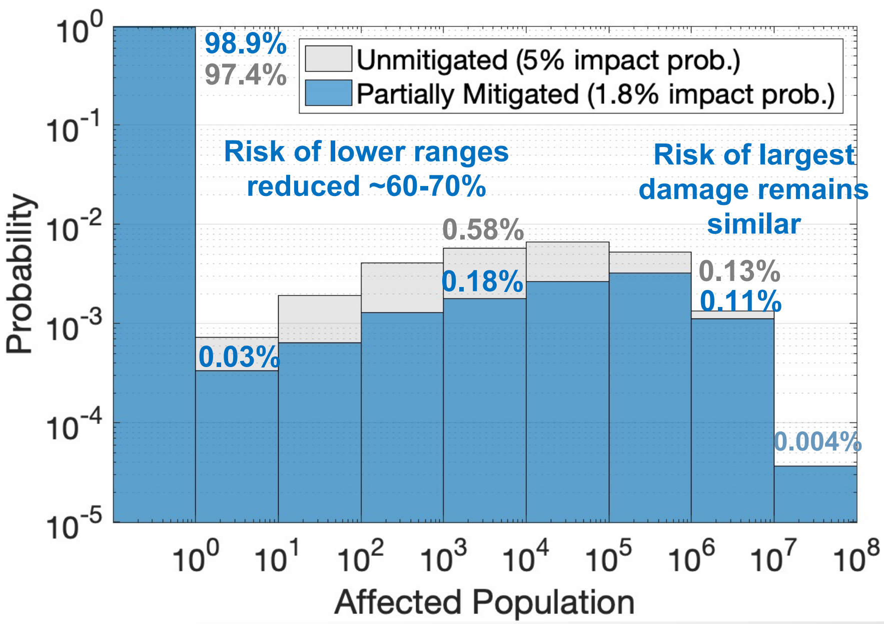
# Hypothetical Risk Mitigation

**How much could a hypothetical NED mission reduce risk of impact damage?**

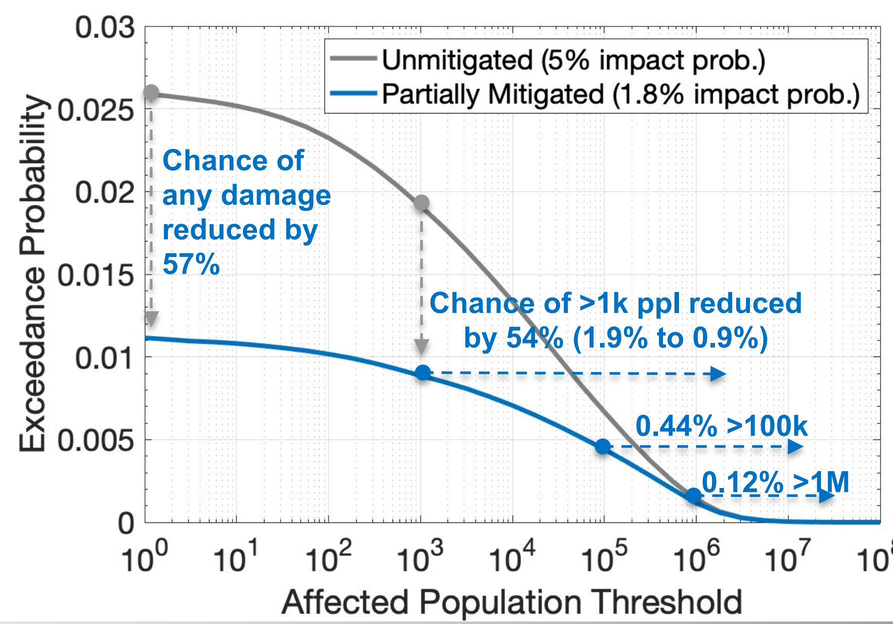
Assuming successful mitigation of all objects under mass/density disruption criteria:

- ~64% of cases successfully mitigated, reducing impact probability from 5% to ~1.8%
- Average affected population reduced by ~20%, from ~5,900 to ~ 4,700
- Chance of damage affecting any population reduced by 57% (from 2.6% to 1.1%).
- Chance of affecting lower population ranges reduced by ~60-70%
- Risk of largest population ranges (>1M or >10M) remains low but similar due to unmitigated largest objects

**Population risk histogram:** Probabilities of affecting the number of people within each range




**Population exceedance risk:** Probability of affecting *at least* the given number of people *or more*



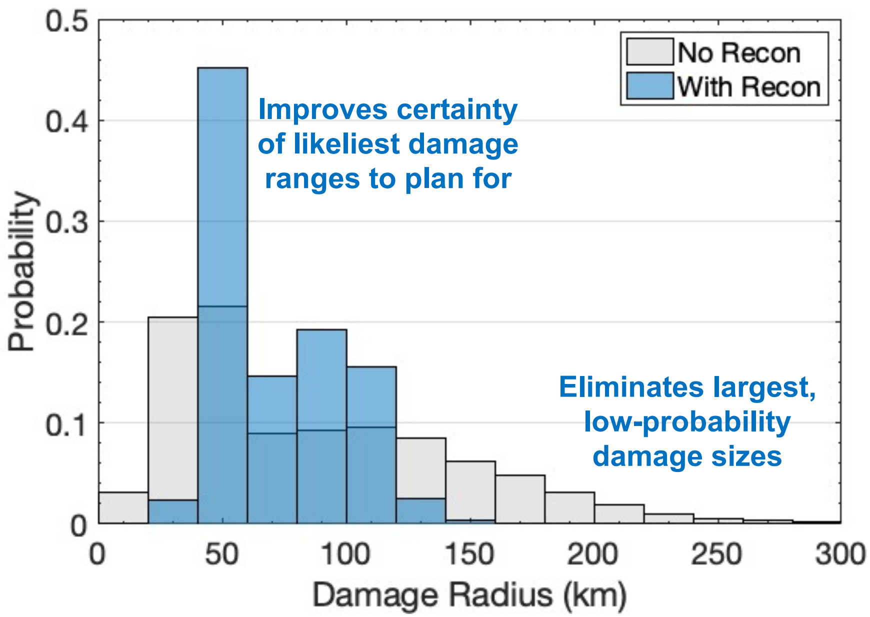
# Recon Mission Benefits for Disaster Planning

**How much could a hypothetical recon mission refine damage area estimates?**

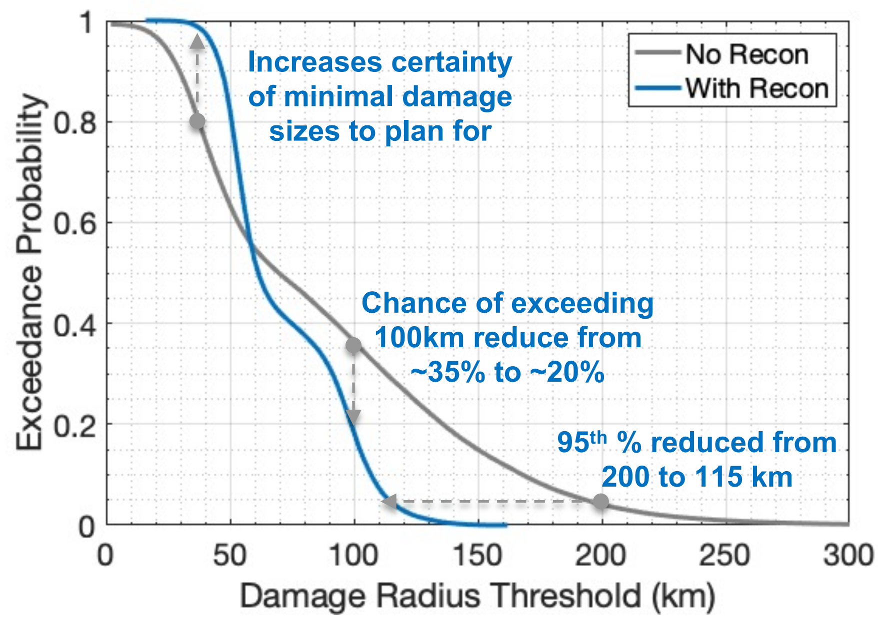
Assuming recon could determine diameter to within 10% for a median-sized 118 m object:

- Asteroid diameter range reduced to 118±12 m (~106–130 m vs 30–700 m without recon)
- Substantially narrows range of potential damage areas for disaster response and improves confidence in likeliest damage areas to plan for
- Reduces maximum potential radius from ~470 km to ~160 km

**Damage radius risk histogram:** Probabilities of damage radii within each range




**Damage radius exceedance risk:** Probability of damage radii being *at least* the given size *or larger*



# Day 2 Summary of Mission Options Findings and Recommendations

## (Brent Barbee, NASA Goddard)

- It is difficult to define mitigation mission requirements or assess the likelihood of mitigation mission success (due to 2021 PDC's uncertain properties)
- Current real-world infrastructure for spacecraft development and launch would not enable us to deploy either reconnaissance or mitigation spacecraft in such a short warning scenario if this were a real situation.
- Deflection would not be practical due to the short warning time
- Robust disruption of the asteroid would be the only practically viable in-space mitigation
- These short warning mission options require high-speed flybys at poor solar phase angles, which can pose significant guidance and navigation challenges
- Deploying a nuclear disruption mission could significantly reduce the risk of impact damage, despite substantial uncertainties in the asteroid's properties
- Deploying a flyby reconnaissance spacecraft (if a disruption mission is foregone) would significantly reduce the uncertainties faced by disaster response planners

# DAY 3 RISK ASSESSMENT

# Impact 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


## Damage Swath

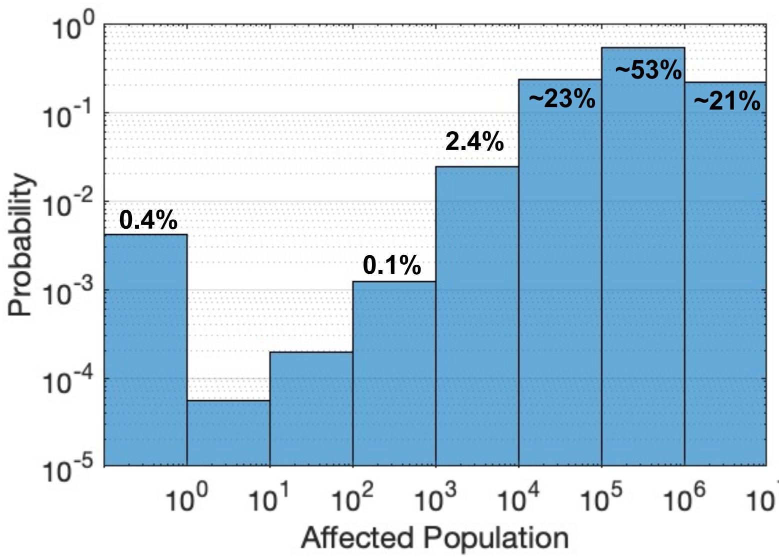
Full range of regions potentially at risk to ground damage, given all potential impact locations and largest damage.

Sample average damage sizes over largest cities

## 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

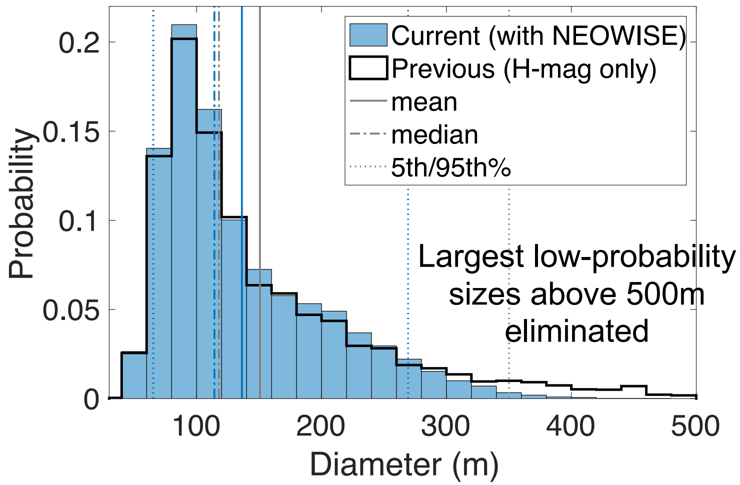
## Affected Population Risk



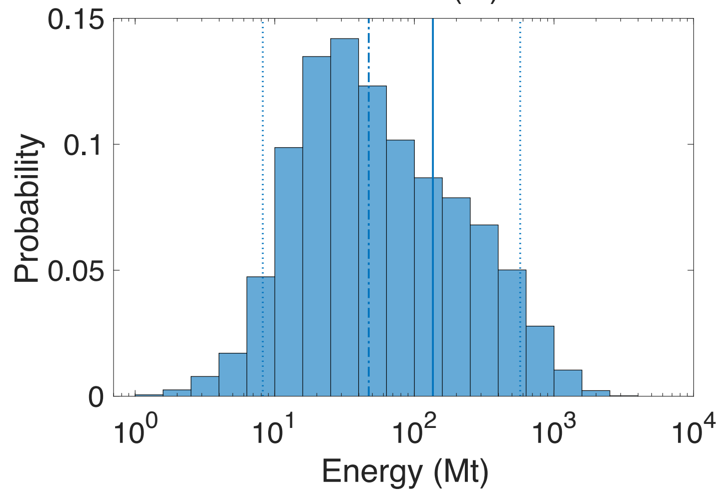
Ames Research Center

# 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



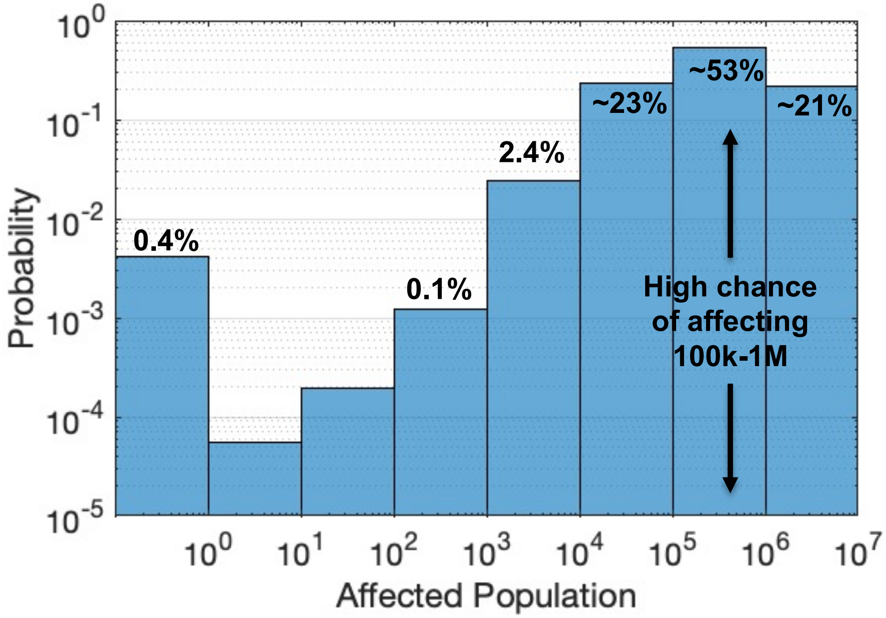

| | Diameter (m) | Energy (Mt) |
|---|---|---|
| Full range | ~35–500 | ~1–3700 |
| Average | 136 | 136 |
| Median | 114 | 47 |
| Most likely | ~65–120 | ~20–50 |
| 5th–95th % | 65–270 | ~8–570 |



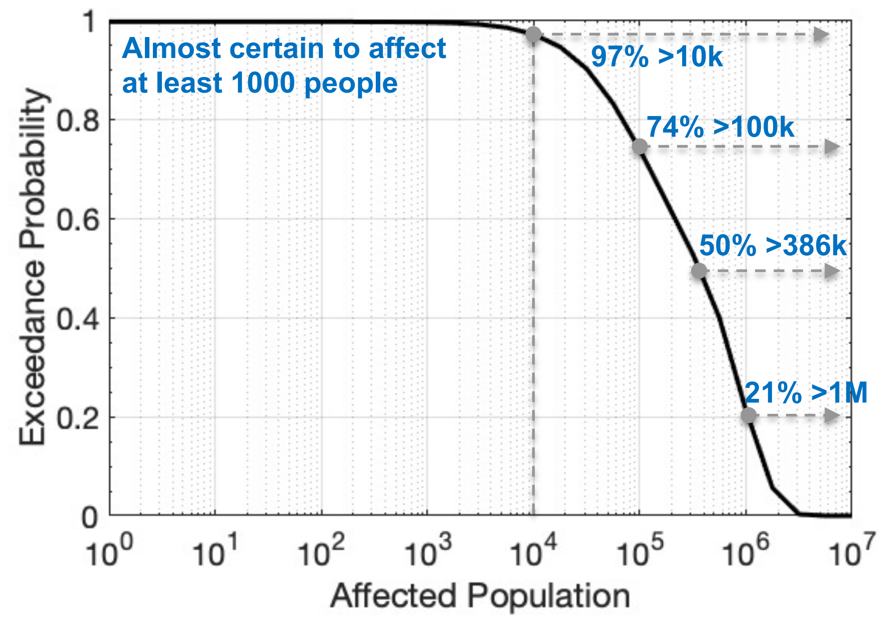

[Property inference model: J. Dotson PDC 2021] [NEOWISE: J. Masiero PDC 2021]

# 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



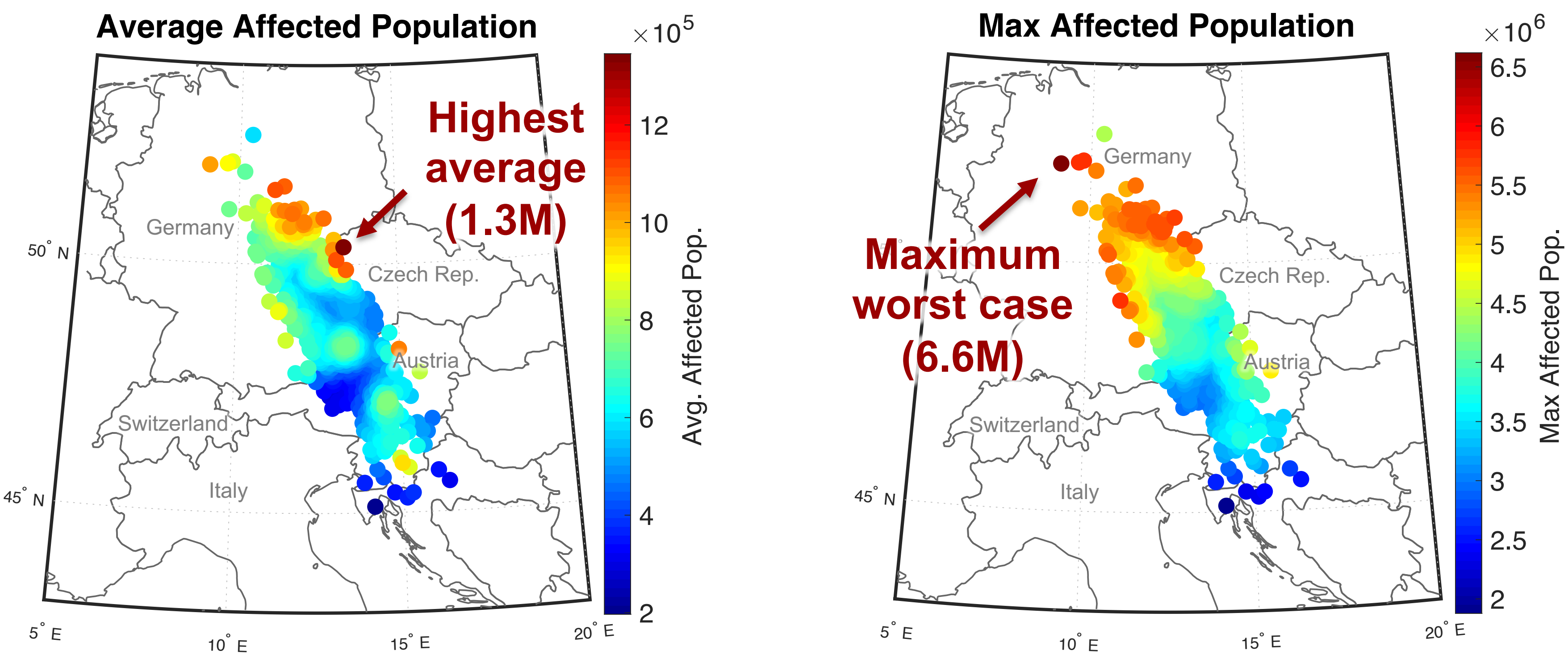

- **Damage is likely to affect several hundred thousand to a million people**
- Average of ~580k people affected
- Maximum worst case: 6.6 million people (among modeled cases)
- 97% chance of affecting at least 10k people, 74% chance of >100k, 21% chance of >1M
- <1% chance of affecting fewer than 1k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

Ames Research Center

# 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)

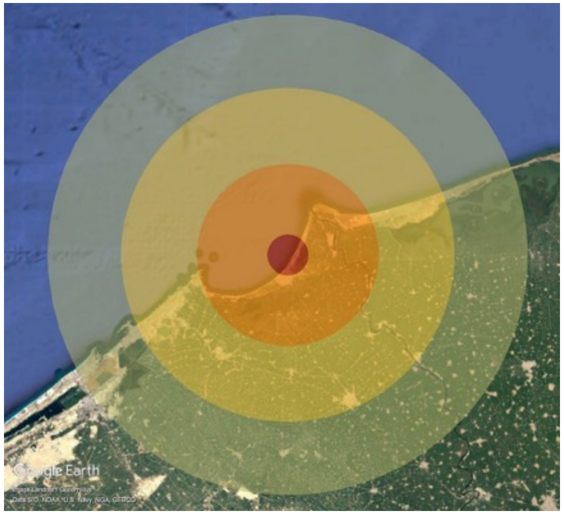



**Maps of average and maximum affected population for each sampled impact entry point, given the potential range in asteroid properties and resulting damage**

Ames Research Center

# Ground Damage Severity Levels

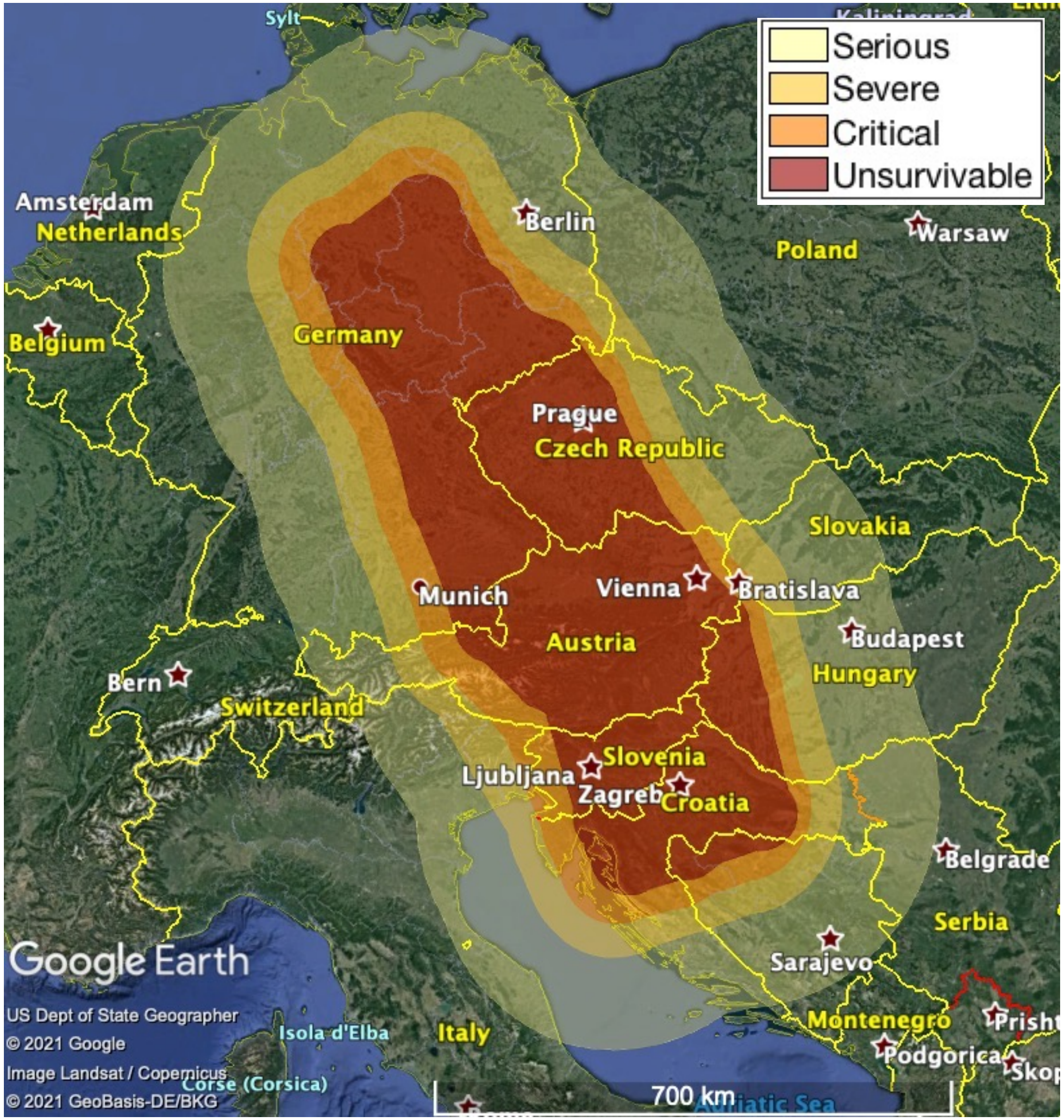
- Blast and thermal damage are assessed at four severity levels, with each level affecting different fractions of the population within that region
- For each damage level, the larger of the equivalent blast or thermal radius is used to determine the area and affected population for that level.
- Blast 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 | $2^{nd}$ 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

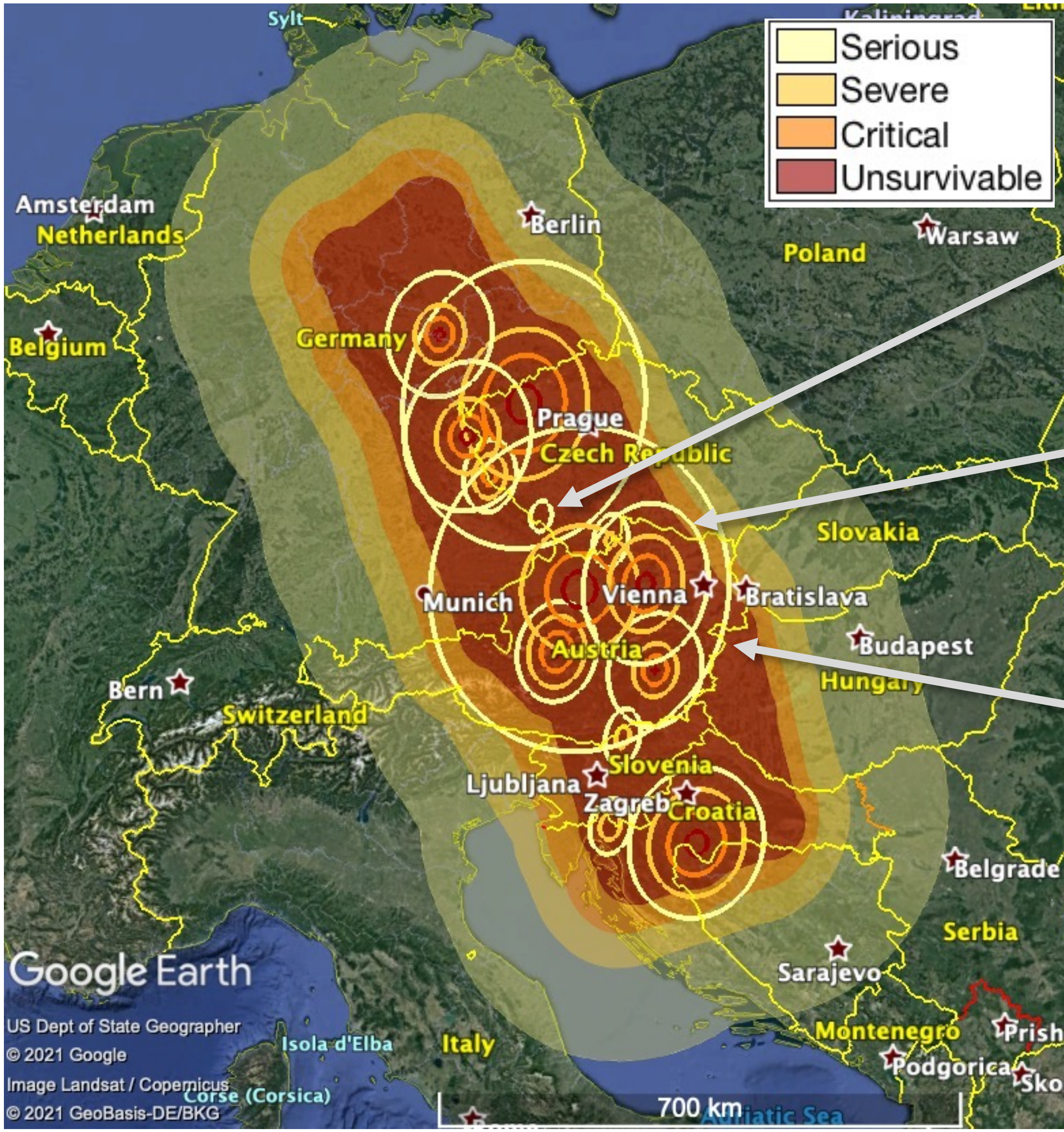
**Extent of swath region:**

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


HYPOTHETICAL EXERCISE

# Damage Risk Swath

## (sample damage footprint variations)



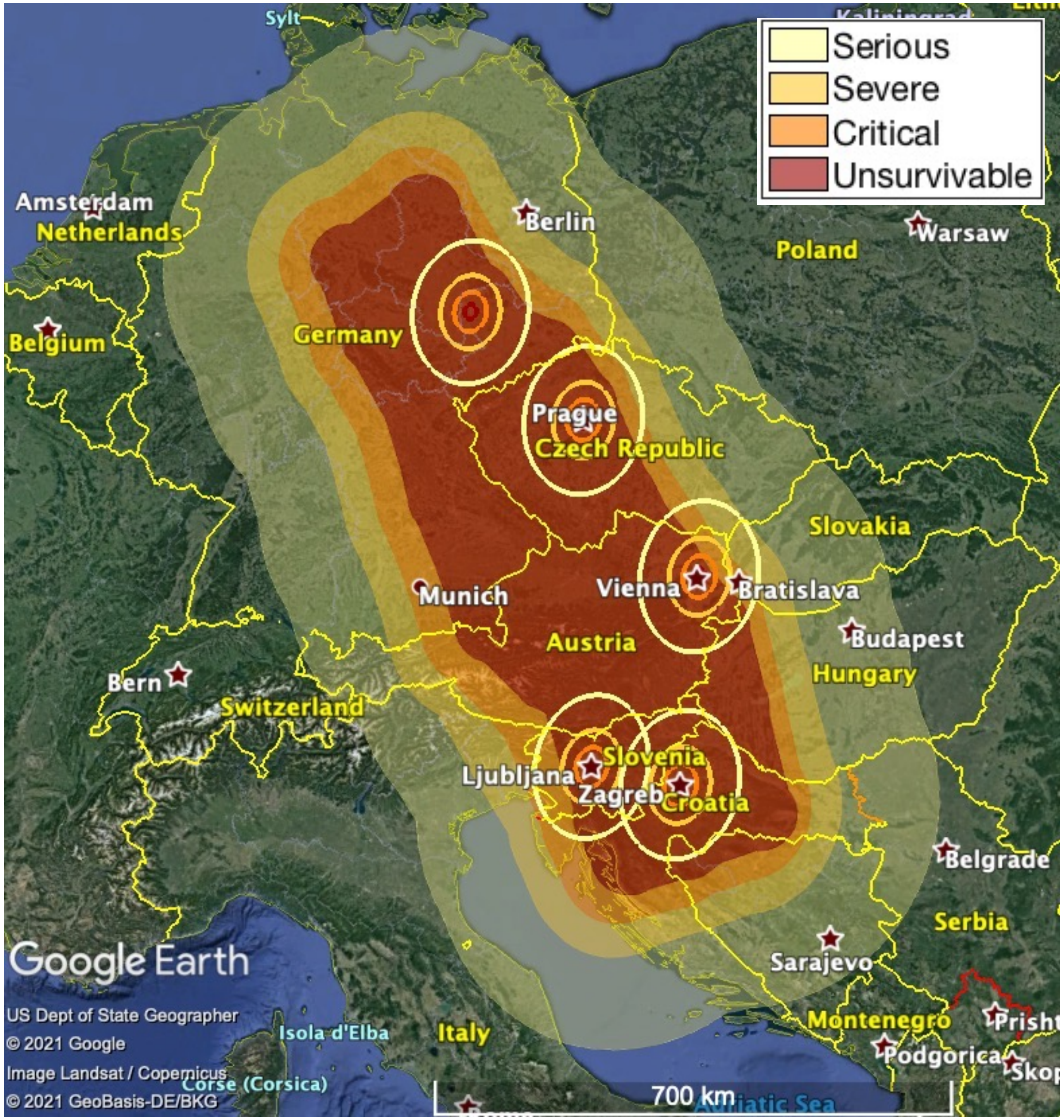

**Actual potential damage areas and locations vary widely, including:**

- 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


HYPOTHETICAL EXERCISE

# Damage Risk Swath

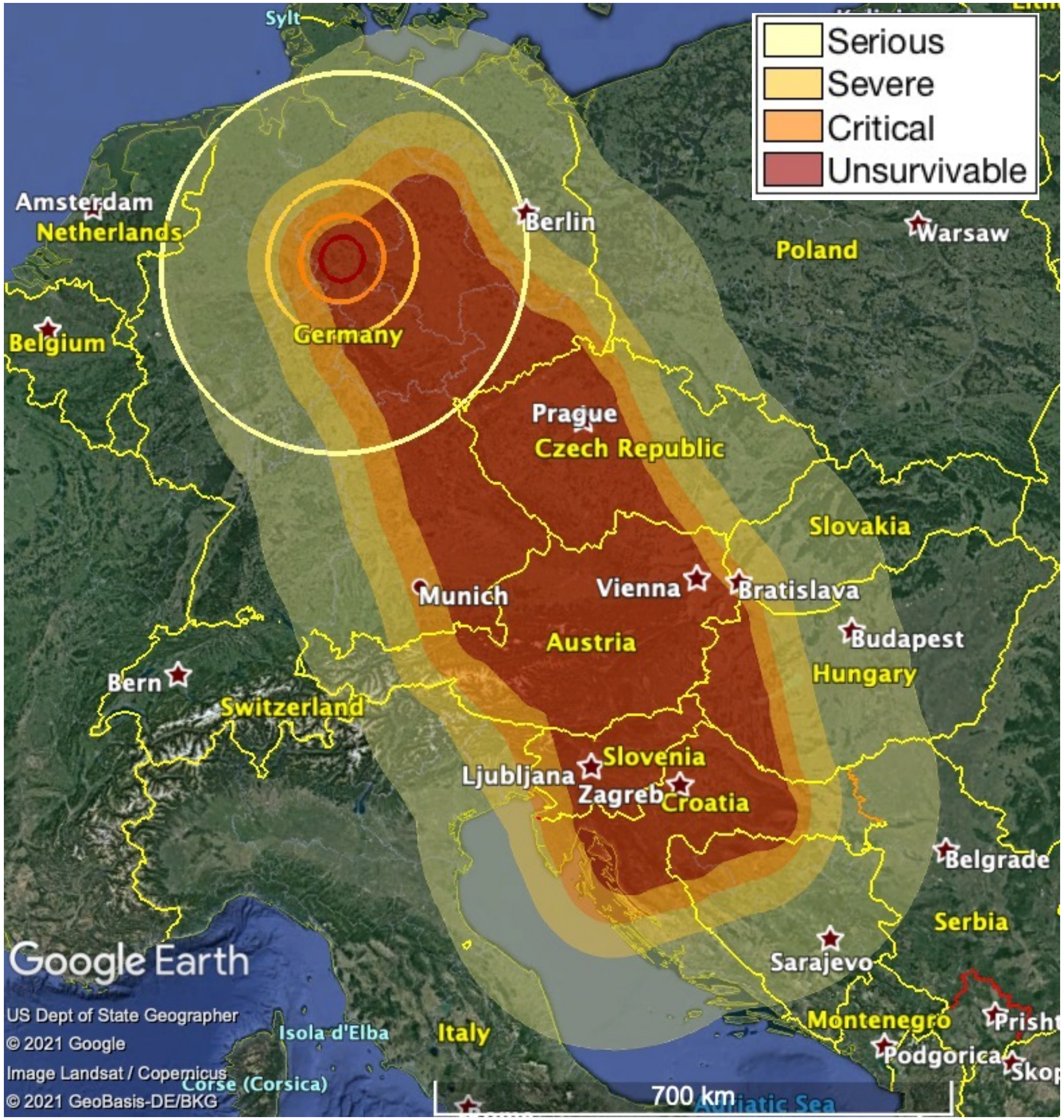
## (average damage footprint at large cities)




**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)



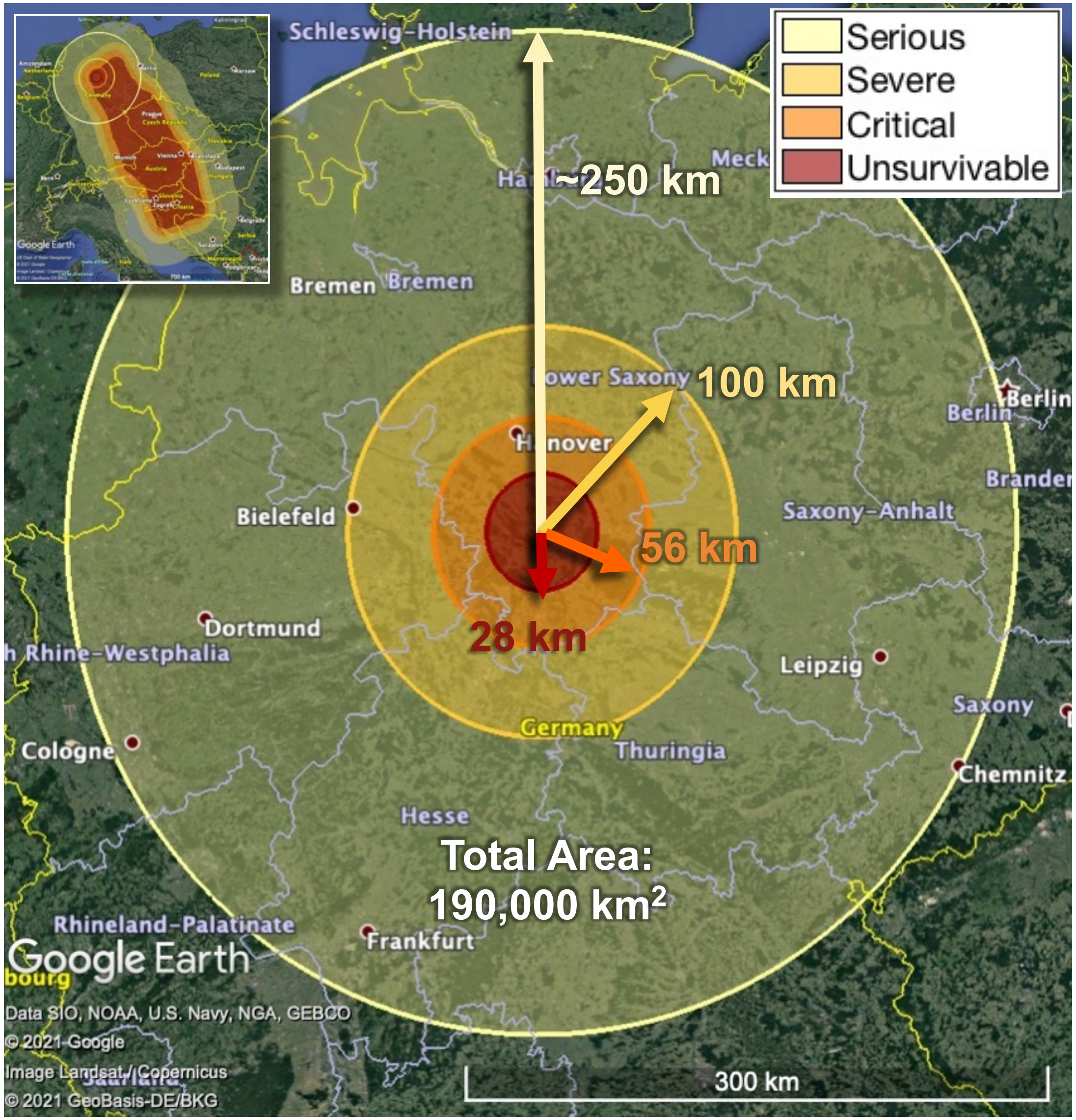

**Worst case affecting greatest number of people**

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

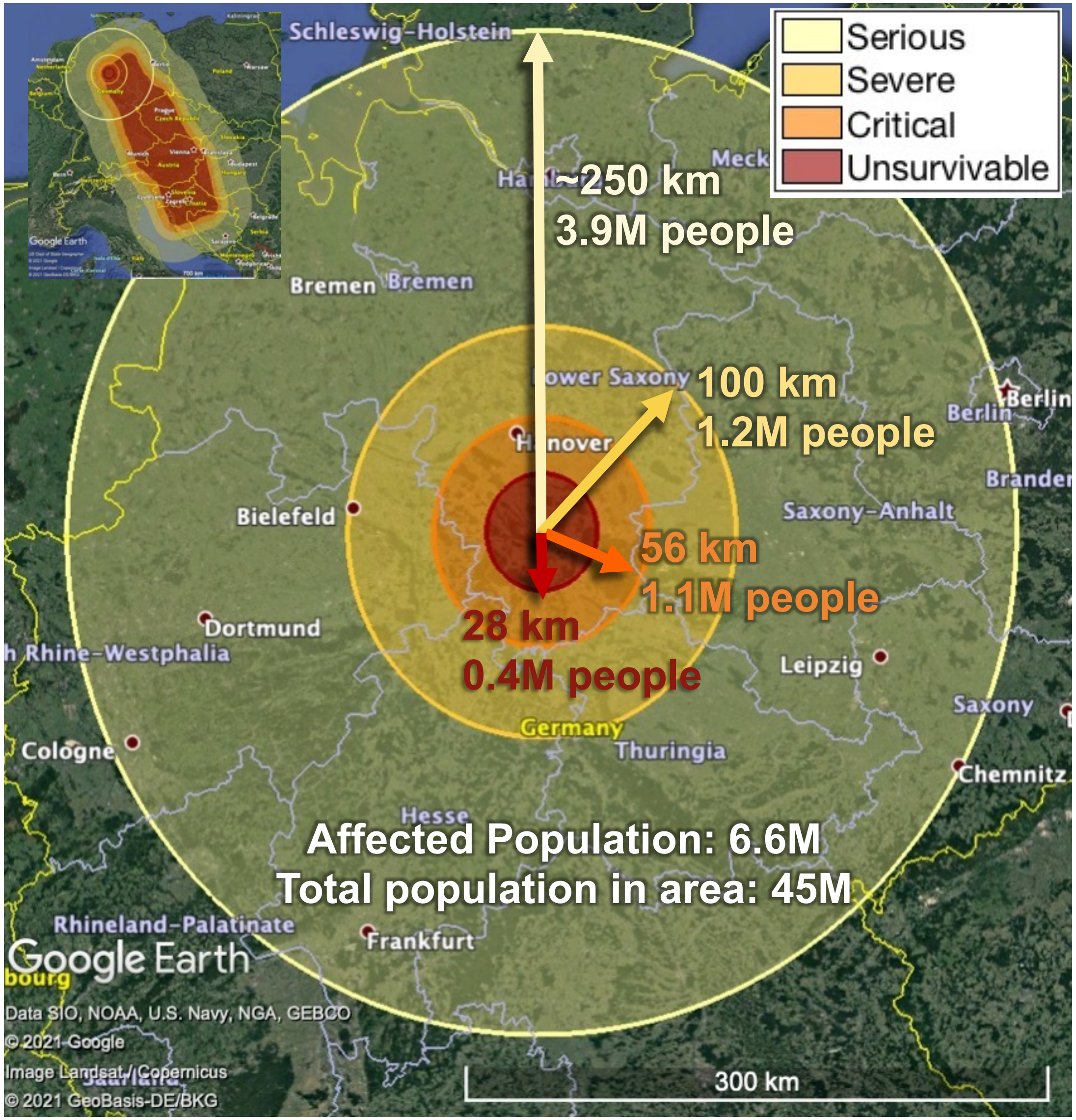
# Maximum Affected Population Case
## (maximum affected population among all modeled cases)




**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)



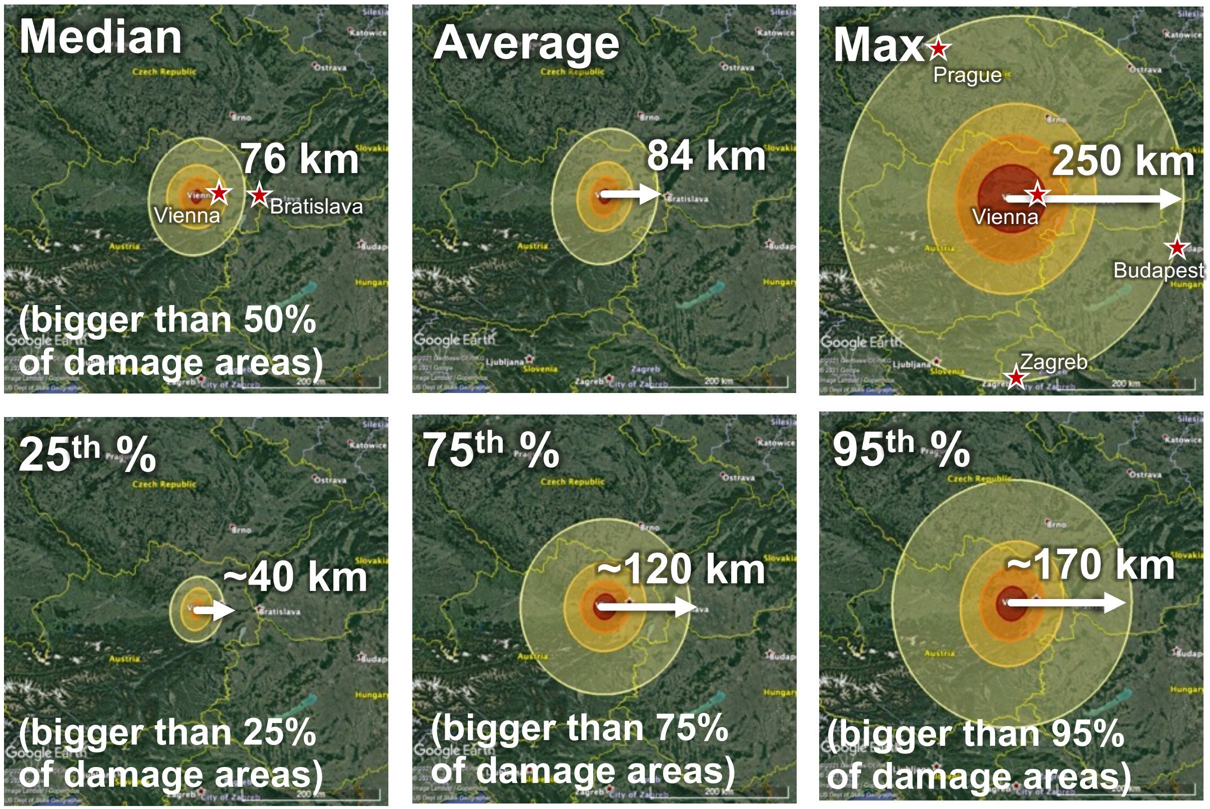

**Affected population is driven by larger, less-severe damage levels**

- 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



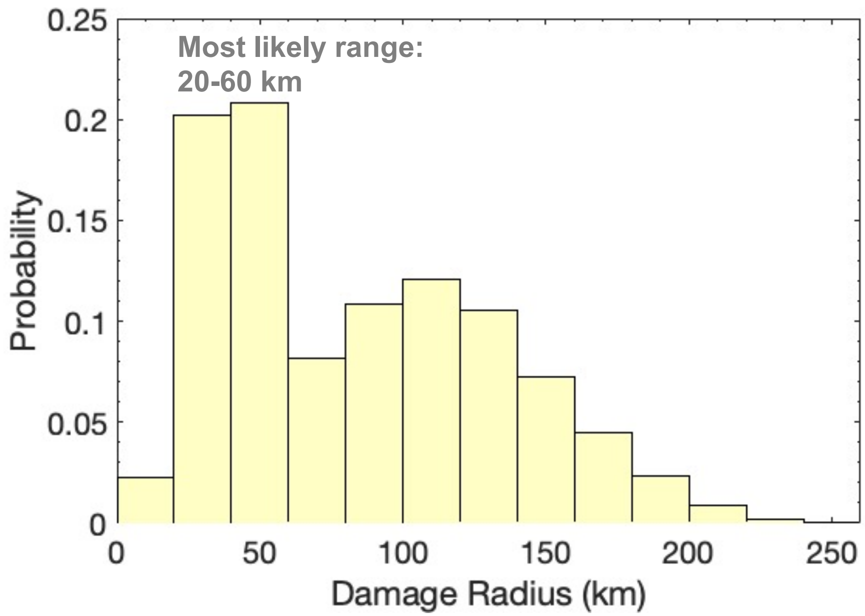

- Worst-case areas can be too large to evacuate, and are very unlikely
- Probabilities of different damage ranges and severities can be used to prioritize effective response
- Radius percentile indicates the chance that the damage will be smaller than that size

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

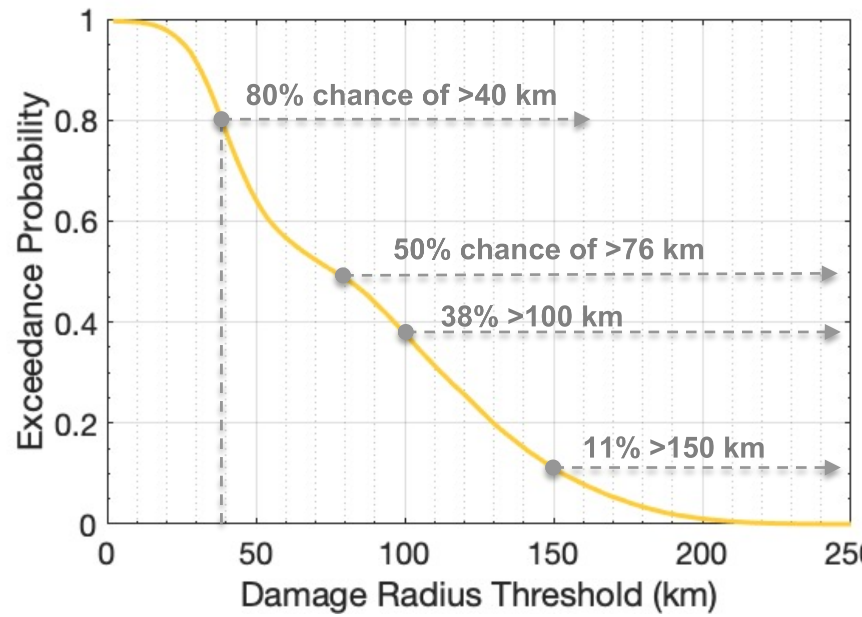
Serious
Severe
Critical
Unsurvivable

# 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*

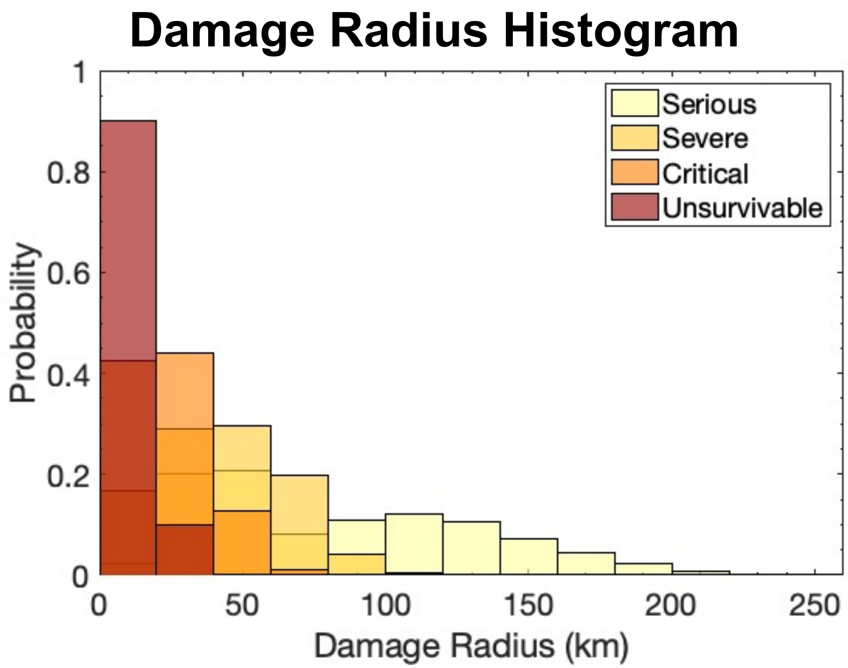


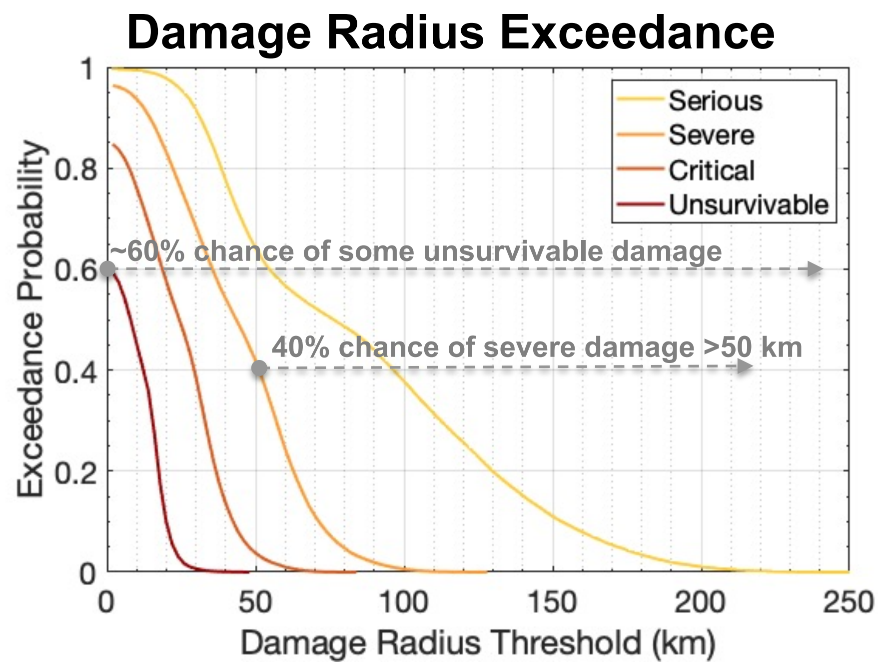

### Serious Damage Radius Stats (km)

| 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)




## 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).

Ames Research Center

# 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 |

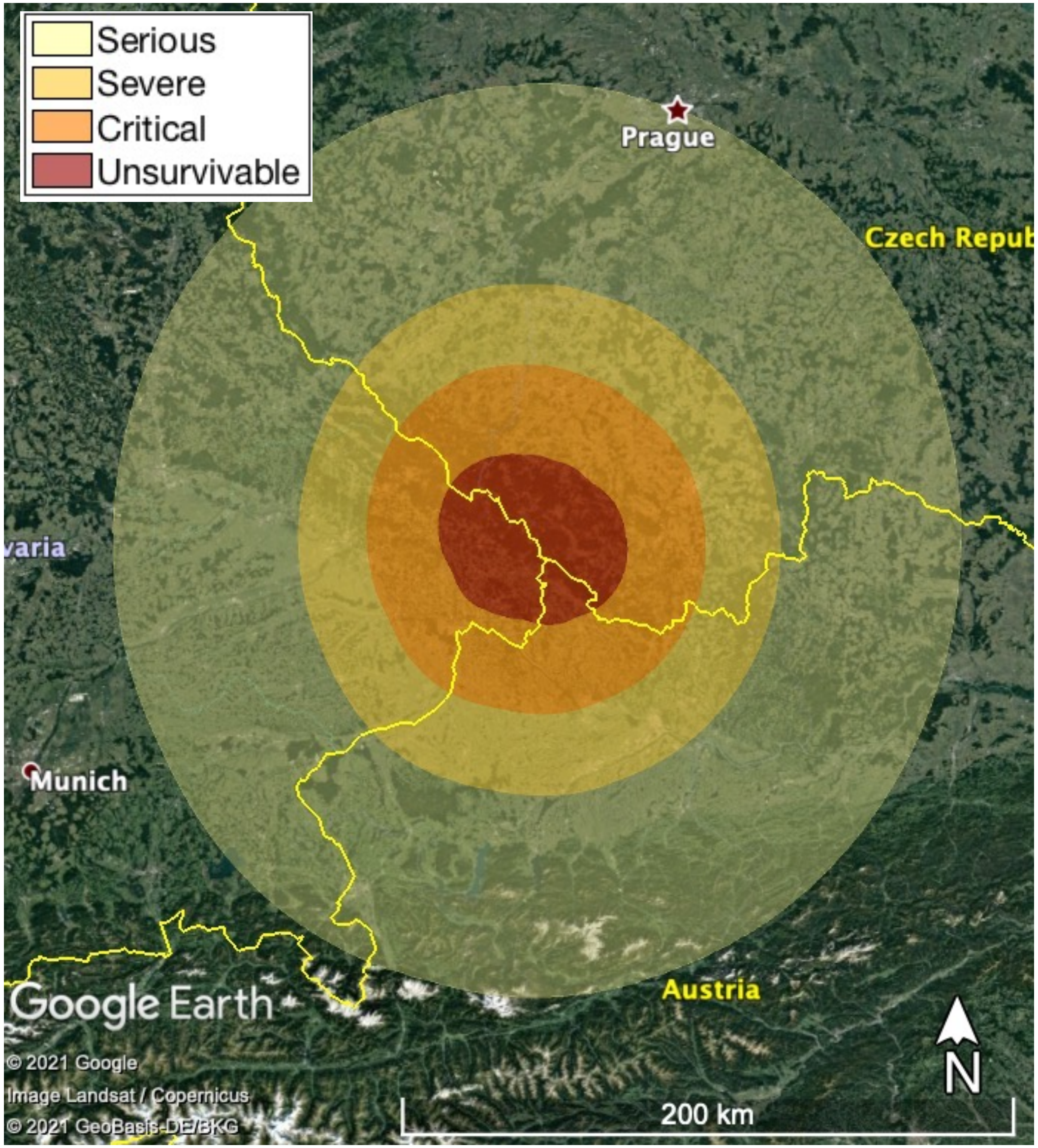
# Risk-Informed Disaster Response Support

- 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

# DAY 4 DAMAGE RISK REGION ASSESSMENT

# Final Damage Risk Swath

## (full extent of regions potentially at risk)



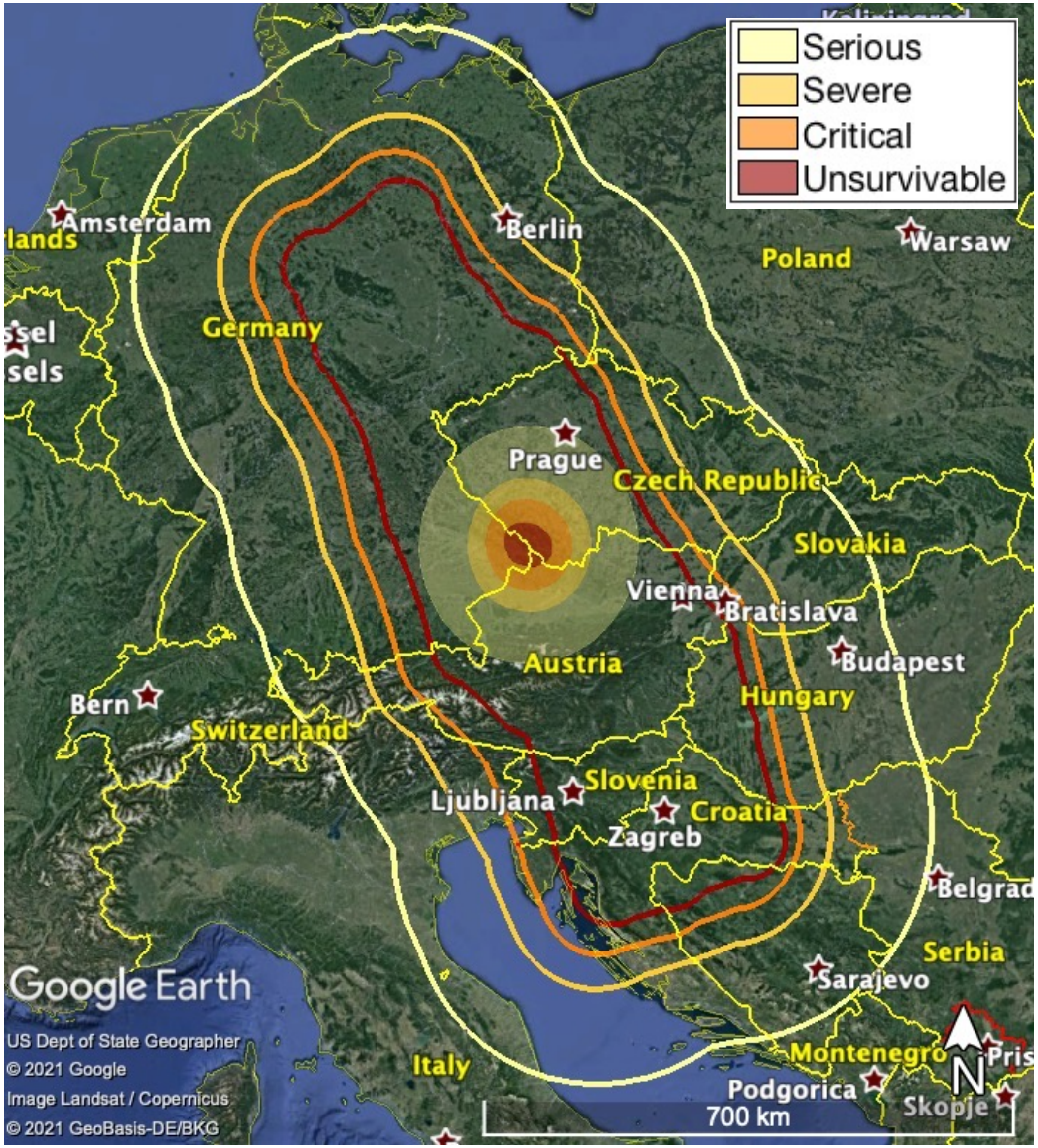

**Damage risk swath:**

- 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)



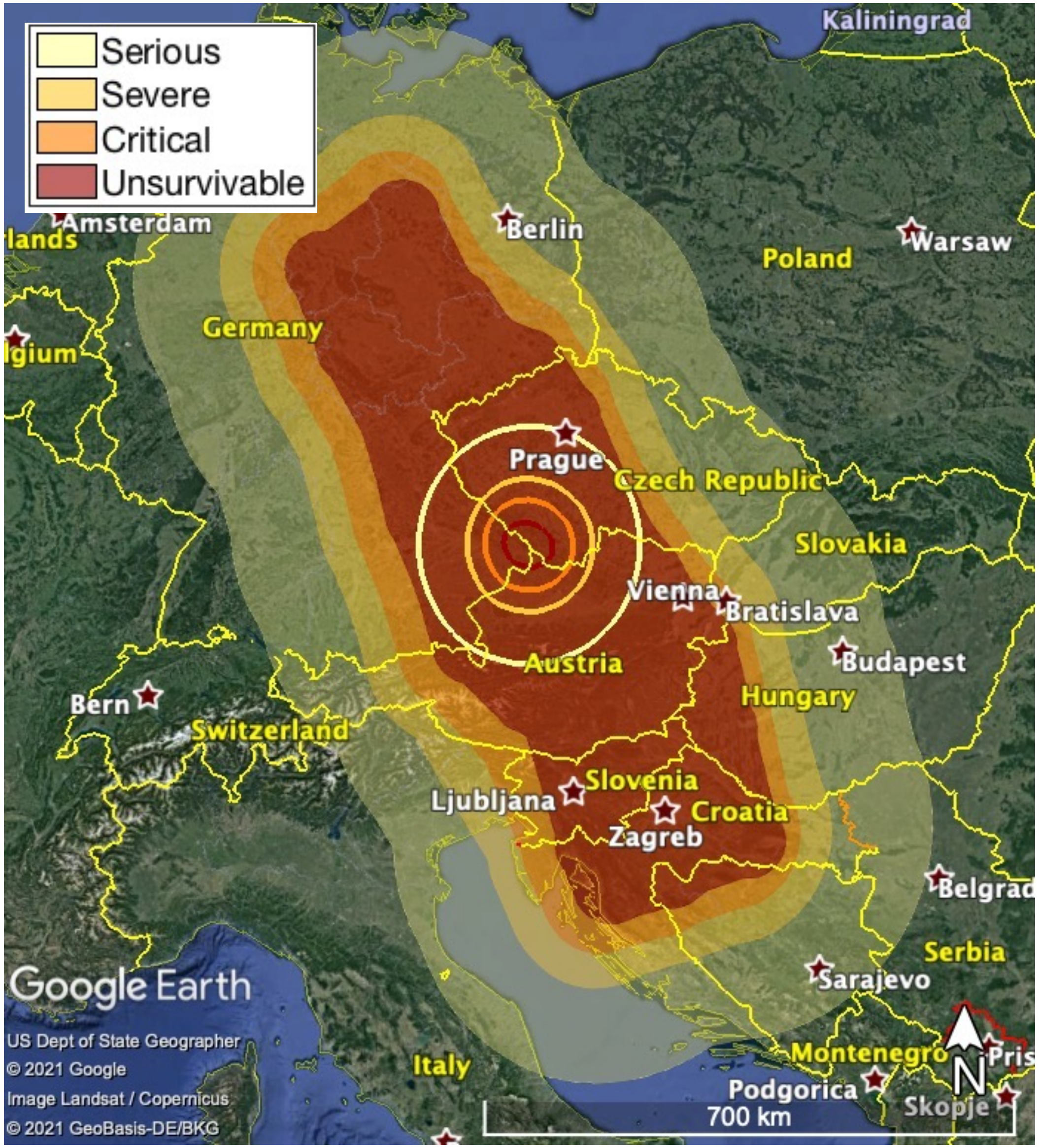

**Damage risk swath:**

- 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:**

- 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

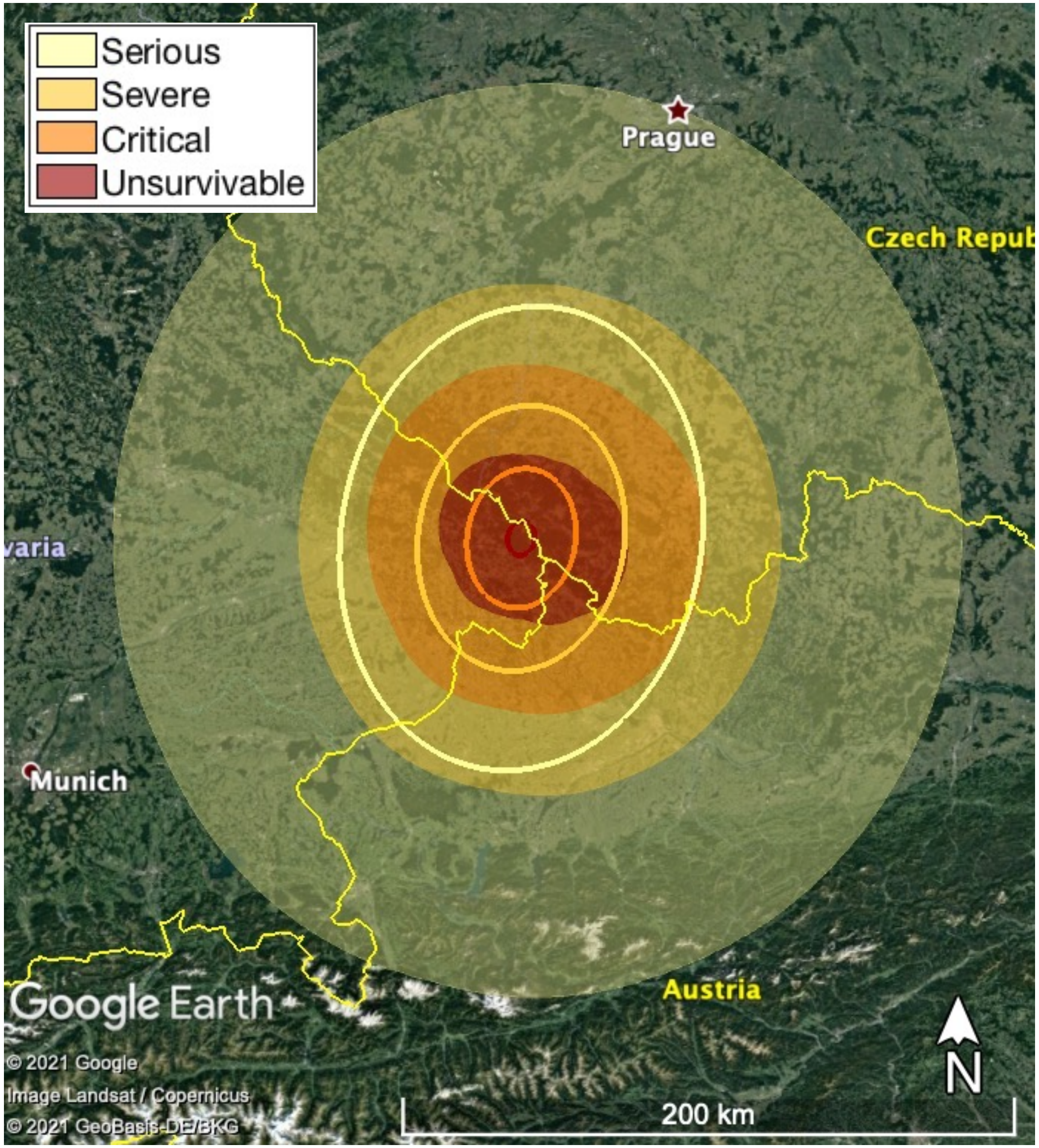
**Extent of swath region:**

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


HYPOTHETICAL EXERCISE

# 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:**

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

**Damage Radius Estimates:**

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


HYPOTHETICAL EXERCISE

# Final Scenario Takeaways

## (Paul Chodas, CNEOS, JPL)

- A short-warning scenario poses extreme challenges for in-space mitigation
- Had a more sensitive asteroid survey such as NEOSM or Rubin Observatory (LSST) been in place in 2014, it would almost certainly have detected the scenario object, and the 7-year warning of potential impact would have opened up a host of different possible outcomes. In particular, space missions would have been feasible for reconnaissance or simple kinetic-impactor deflection
- Precoveries could play a major role in assessing the impact probability of a threatening object, and in helping to constrain the impact location
- The large end of the estimated size range becomes the dominant factor in a scenario: capabilities that can put an upper bound on the size would be invaluable (space-based IR, planetary radar and recon missions)