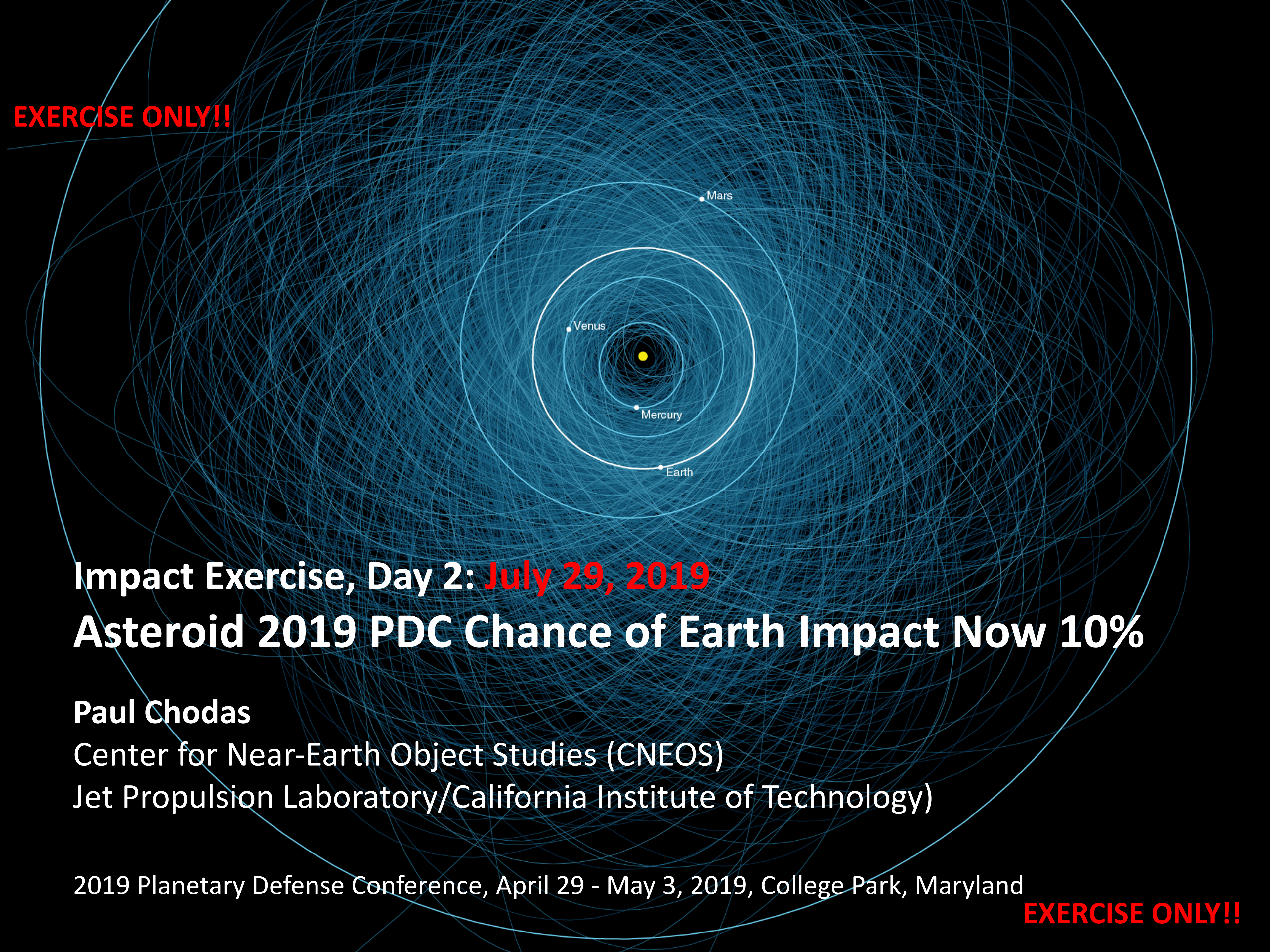
EXERCISE ONLY!!



Impact Exercise, Day 2: July 29, 2019

Asteroid 2019 PDC Chance of Earth Impact Now 10%

Paul Chodas
Center for Near-Earth Object Studies (CNEOS)
Jet Propulsion Laboratory/California Institute of Technology)

2019 Planetary Defense Conference, April 29 - May 3, 2019, College Park, Maryland

EXERCISE ONLY!!

EXERCISE

Chance of Impact in 2027 Now 10%

Jet Propulsion Laboratory
California Institute of Technology

- The impact probability for asteroid 2019 PDC has now grown to 10%
  - Three months of continuous tracking have improved the orbit accuracy, but the new observations did not eliminate the possibility of impact
- NEOWISE observed the asteroid in late April; these data constrained the size estimate for 2019 PDC to 140 to 260 meters (equivalent spherical)
  - If the asteroid impacts, the energy released would be ~100 to ~800 megatons
- If the asteroid happens to be on a collision course, we are net yet able to predict where it might impact, it could be anywhere on the risk corridor
- 2019 PDC will continue to be observable from ground-based telescopes for another 6 months, but then will become too faint to be detected
- If the asteroid is headed for impact, we won't be certain until late 2020
- The Space Missions Planning Advisory Group (SMPAG) has recommended that space agencies begin work on mitigation efforts
- For more info: **https://cneos.jpl.nasa.gov/pd/cs/pdc19/day2.html**

EXERCISE ONLY!!

EXERCISE

Update on Physical Properties of 2019 PDC

- Size estimate, based on NEOWISE observations: 185 ± 45 meters
  - Albedo in the range of roughly 5% to 18%
- Spectral Class still indeterminate, as is the likely density
- 2019 PDC showed a distinct light curve, with an amplitude of over 0.5 magnitudes and period of roughly 12 hours
- Further refinements of the physical properties of 2019 PDC will be difficult, as the asteroid is receding from the Earth and becoming fainter

PDC19 Impact Exercise, Day 2: Probabilistic Asteroid Impact Risk Assessment

Lorien Wheeler

Donovan Mathias, Clemens Rumpf, Jessie Dotson, Michael Aftosmis,

Barbara Jennings **(SNL)**
Bill Fogleman **(GRIT)**

NASA Ames Research Center

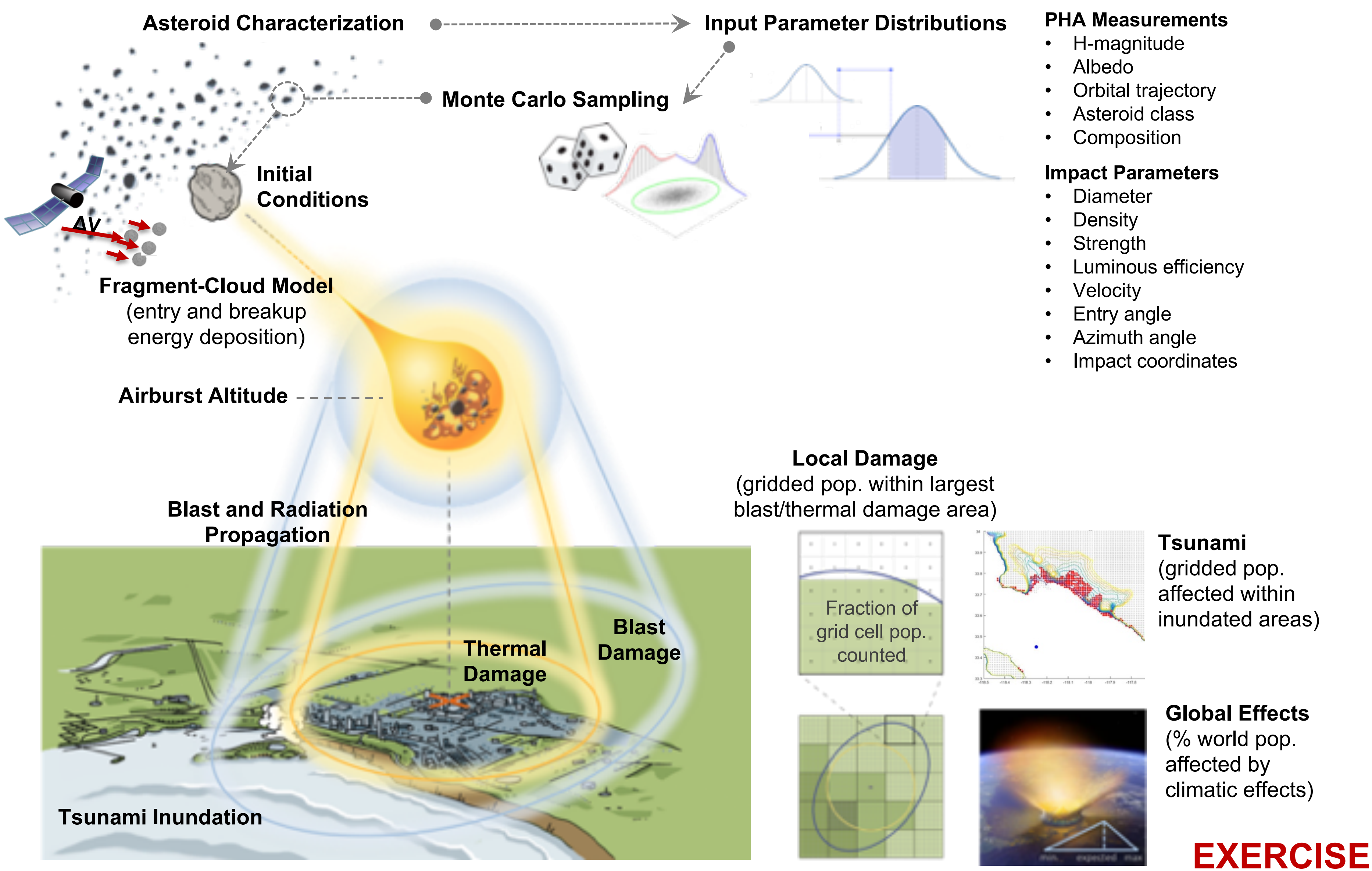
Asteroid Threat Assessment Project

IAA Planetary Defense Conference

April 29 – May 3, 2019

College Park, MD

Probabilistic Asteroid Impact Risk (PAIR)



EXERCISE

Local Ground Damage

- Local ground damage sources:
  - Blast overpressure
  - Thermal radiation
- Ground damage is 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

Damage Level	Population fraction	Blast Threshold (psi)	Thermal 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	cotton/denim clothing ignites
Unsurvivable	100%	10 psi – complete devastation	sand explodes, roll roofing ignites

Ames Research Center

Impact Risk Summary

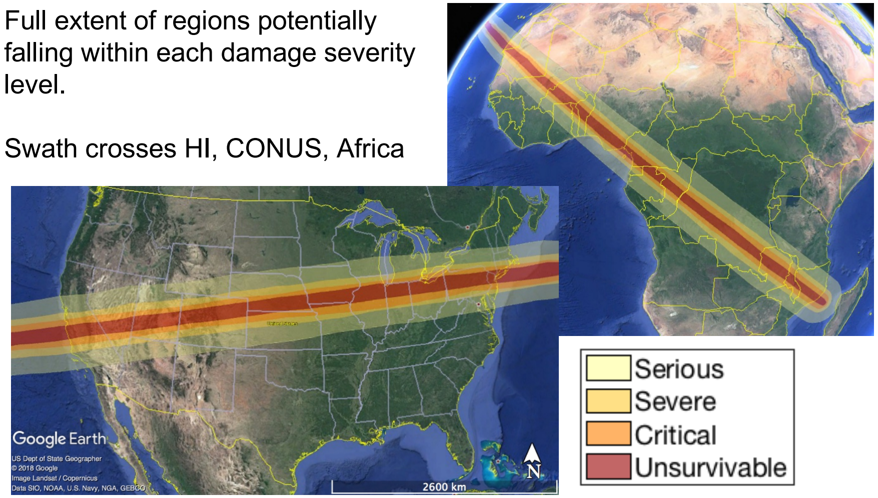
Characterization Summary & Updates

- Assessment date: 29 July 2019
- Potential impact date: 29 April 2027 (7.75 years)
- Earth impact probability: 10%
- Obtained albedo and size refinements from NEOWISE observation
- Diameter (m): 185 ± 45 (1-σ), range 114–492
- Energy (Mt): mean 340, full range 46–5800,
- Type: Unknown. Type probabilities based on albedo, but all types remain possible.

Potential Damage Zone Map

Full extent of regions potentially falling within each damage severity level.

Swath crosses HI, CONUS, Africa

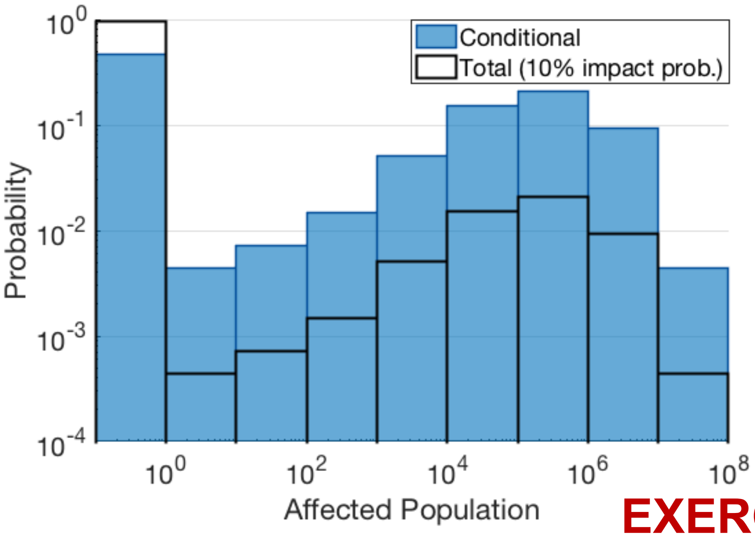


Hazard Summary

- Affected population: mean 375k, range 0–19M
- Airburst causing blast overpressure is primary hazard.
- Small risk of tsunami if impact is very large or near coast.

Damage Levels	Mean Radius	Radius Range
Serious	137 km	46 – 419 km
Severe	72 km	14 – 207 km
Critical	43 km	0 – 137 km
Unsurvivable	19 km	0 – 56 km

Affected Population Probabilities

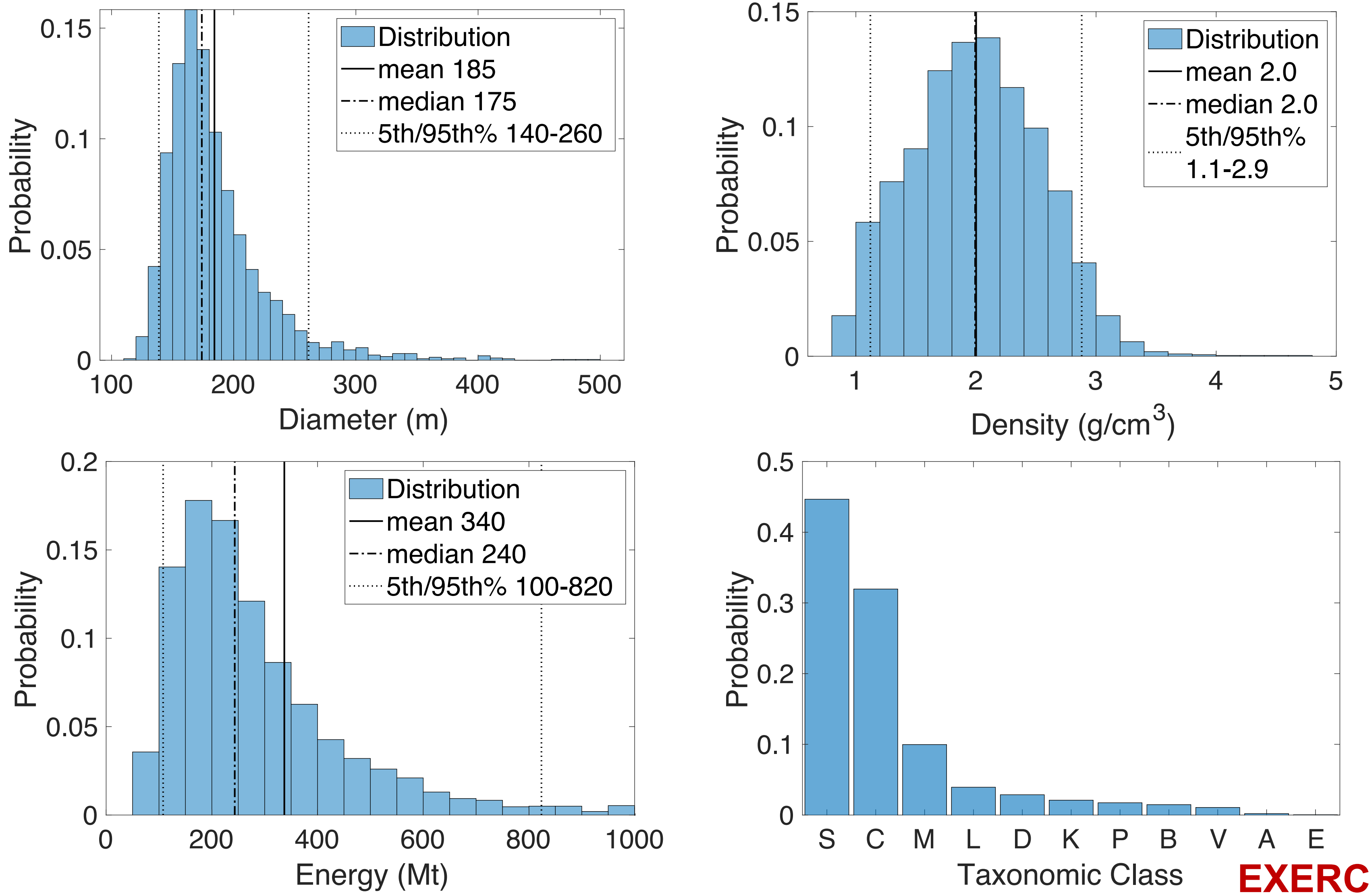


EXERCISE

EXERCISE

Asteroid Properties

- J. Dotson, Bayesian Inference of Physical Properties for Impact Scenarios (IAA-PDC-19-02-P12)



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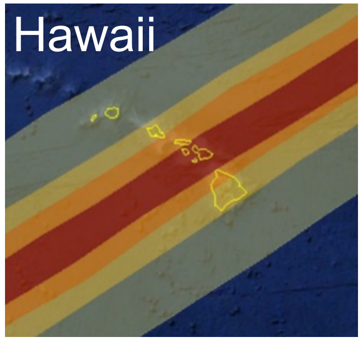
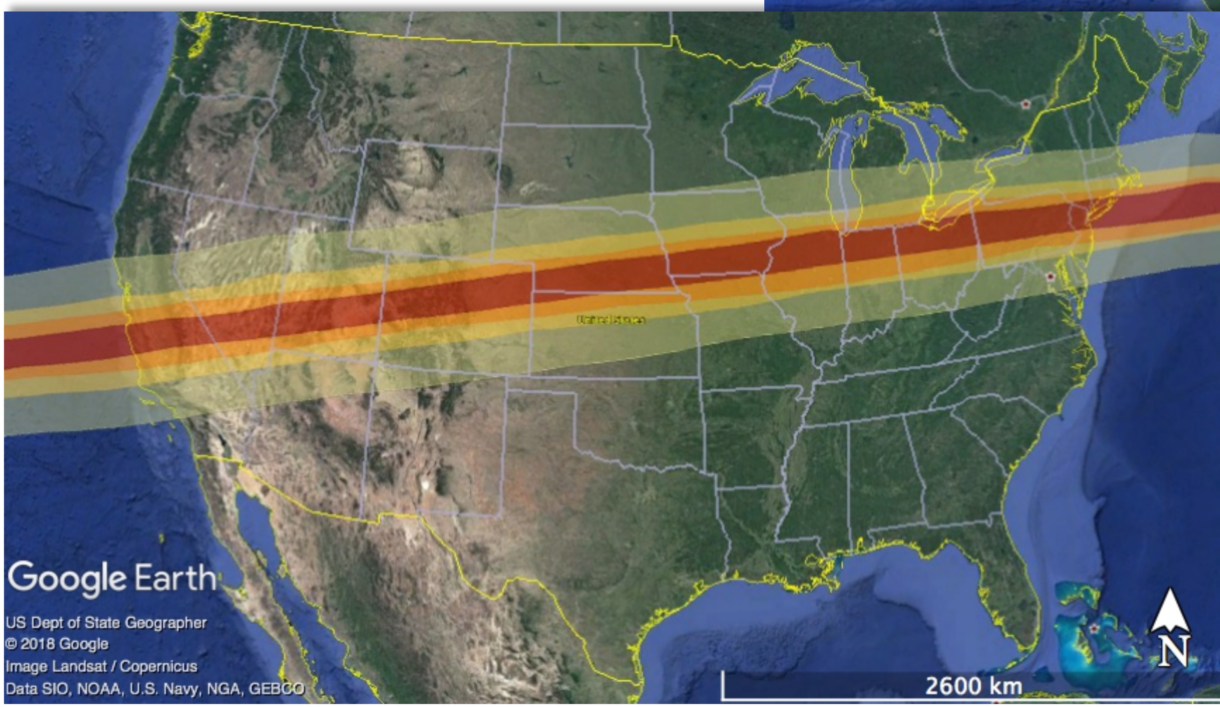
Potential Damage Swath





- Serious
- Severe
- Critical
- Unsurvivable

EXERCISE

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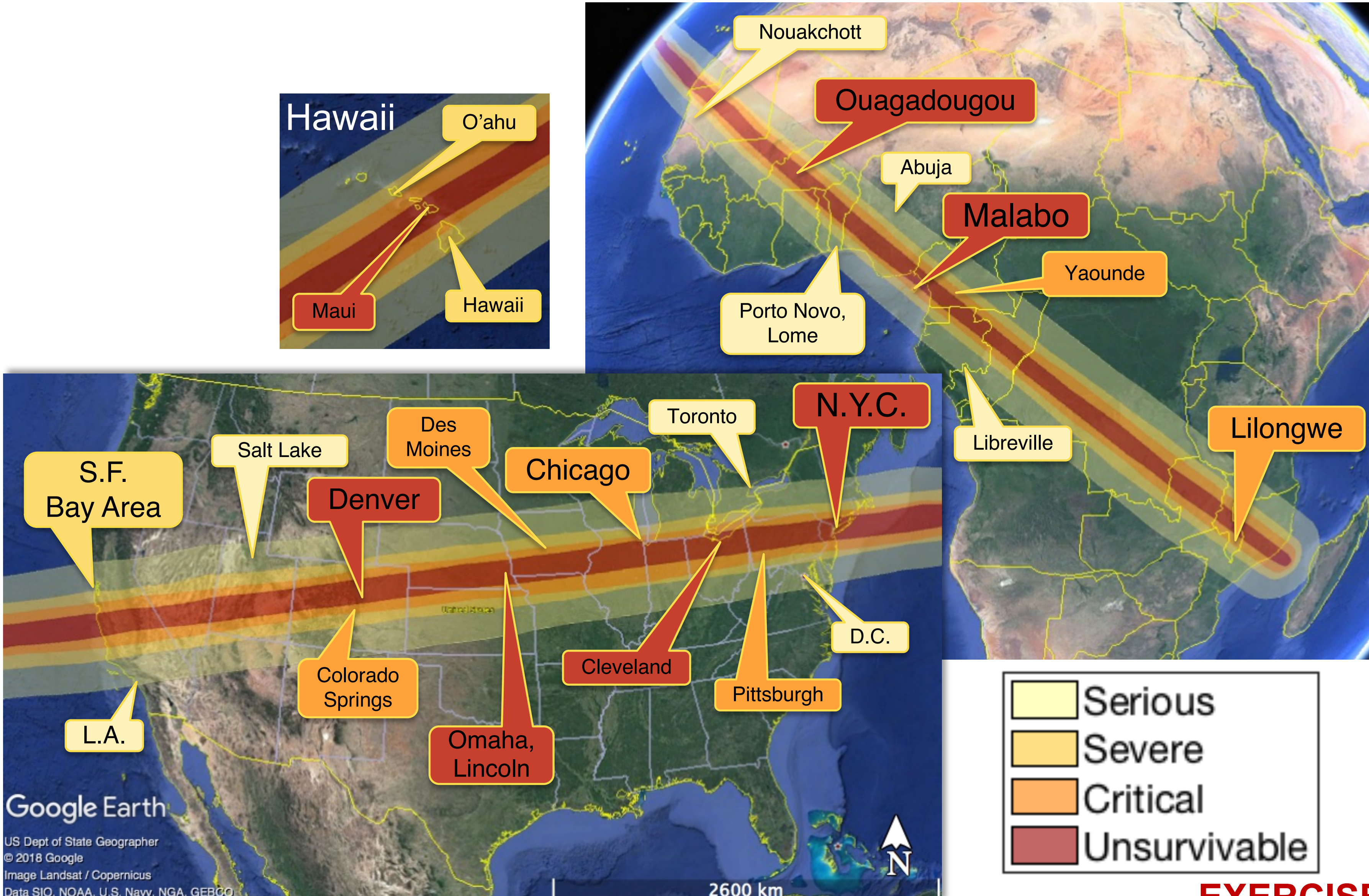
Potential Damage Swath



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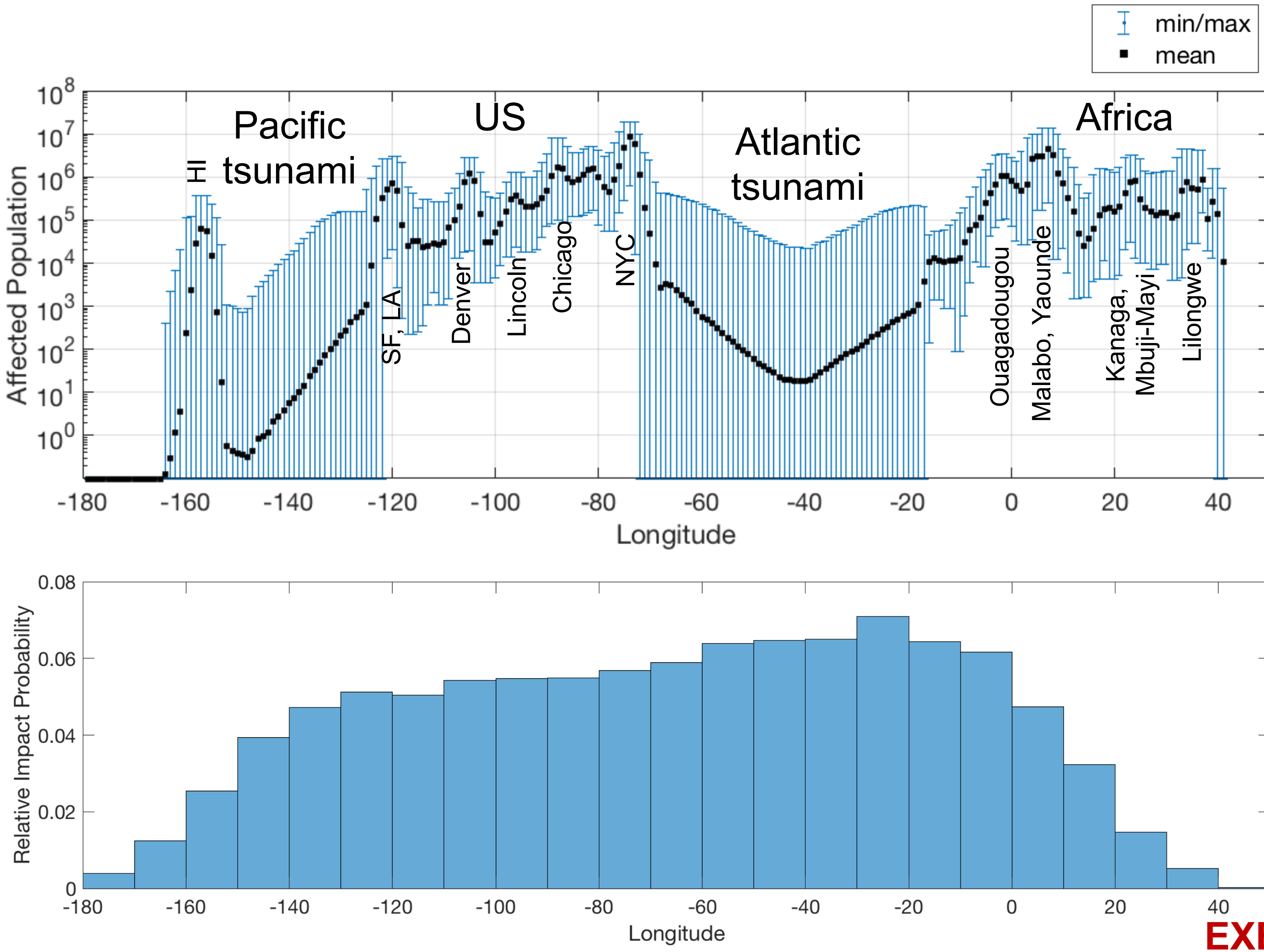
Population Risk along the Swath



EXERCISE

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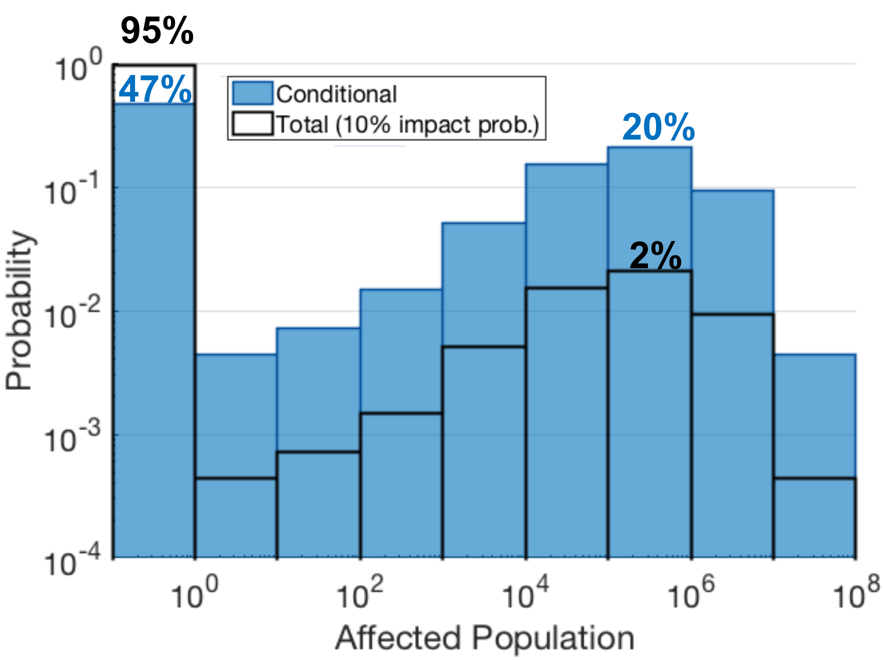
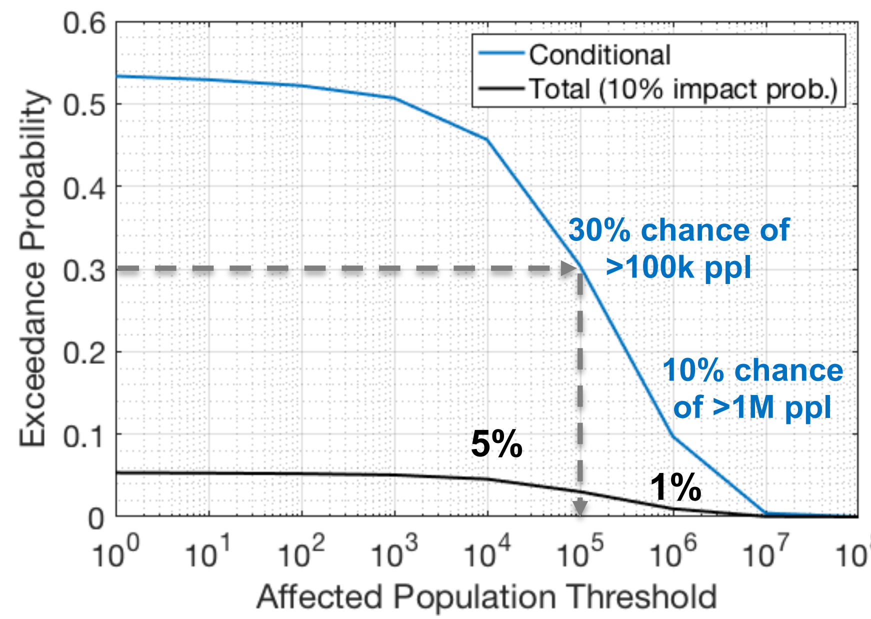
Affected Population Probabilities

Population risk histogram: probabilities of different population ranges being affected

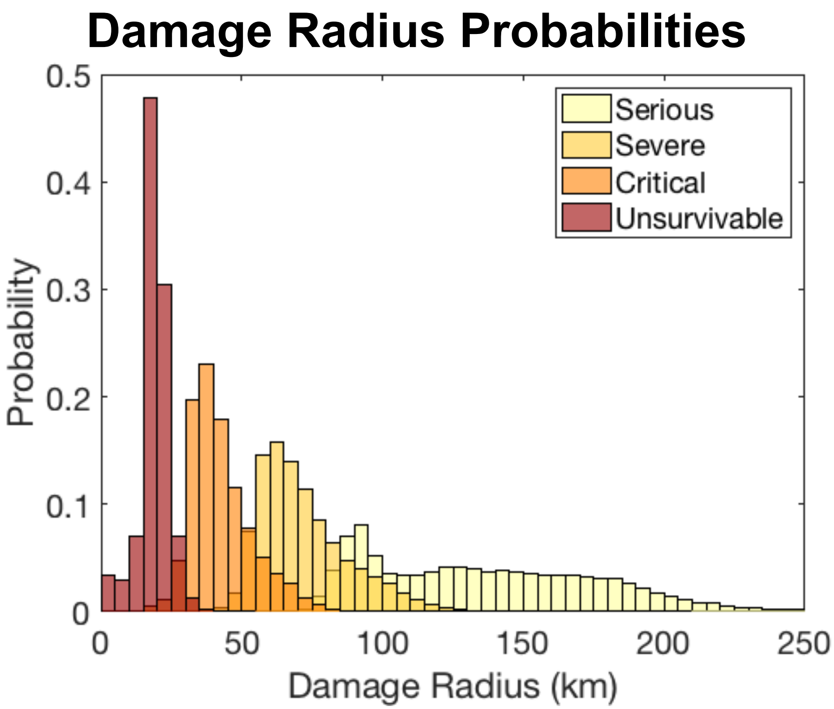
Damage exceedance probabilities: Likelihood of a certain number of people or more being affected

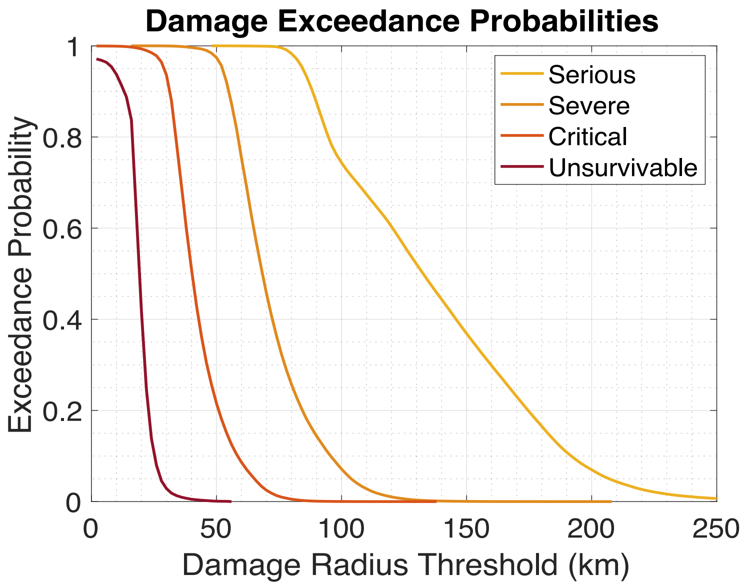




- **Probability of Earth strike: 10%**
- **Total probabilities:** account for chance that asteroid misses Earth (90%)
- **Conditional probabilities:** probabilities *if* an Earth strike occurs

Hazard & Damage Probabilities





Damage Levels	Mean Radius (km)	Radius Range (km)
Serious	137	46 – 419
Severe	72	14 – 207
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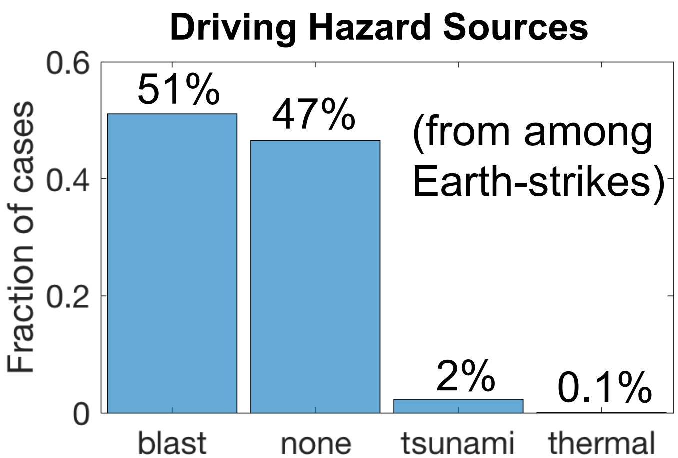
Unsurvivable	19	0 – 56

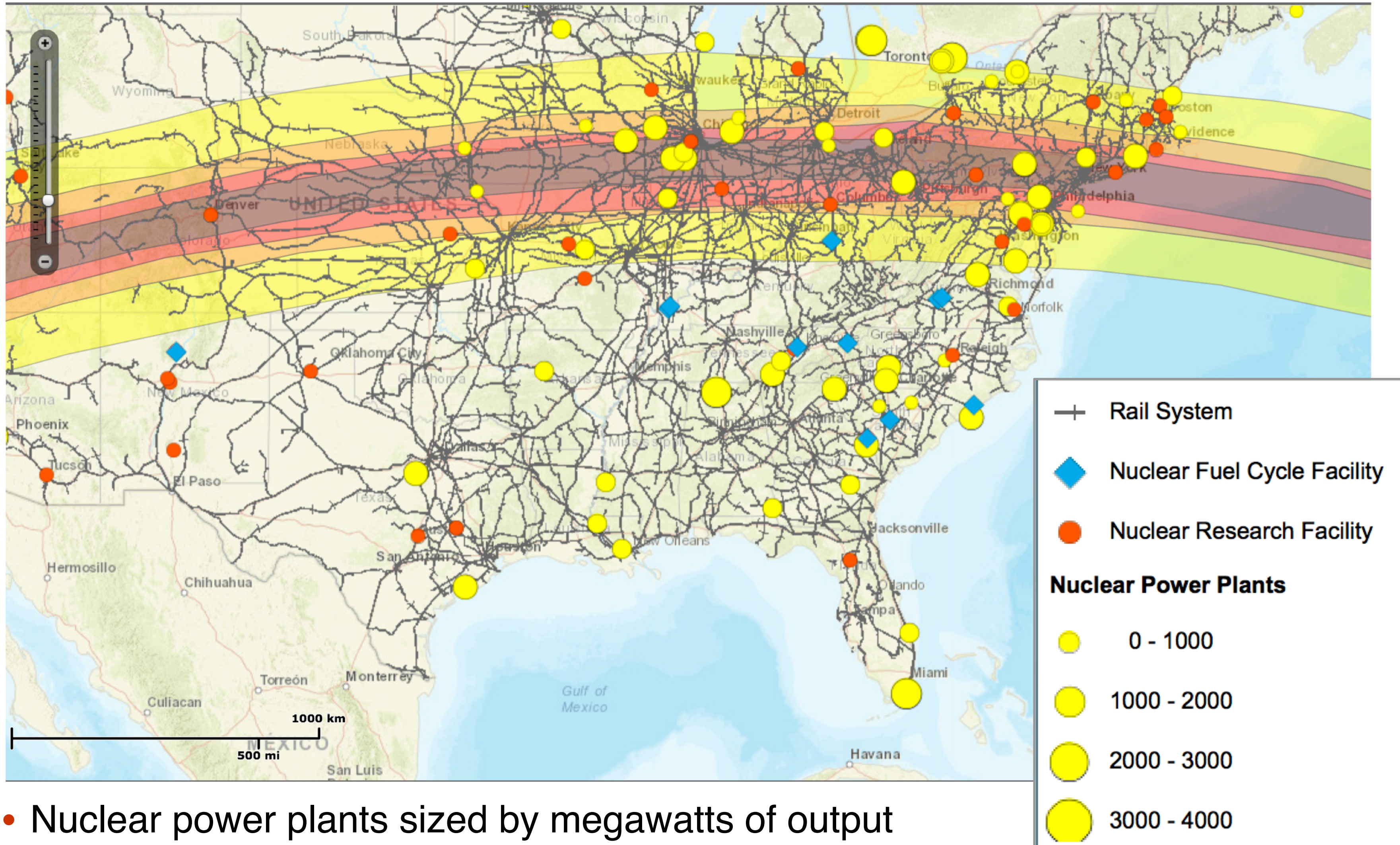


EXERCISE

EXERCISE

US Infrastructure at Risk

Barbara Jennings (Sandia National Laboratory), Bill Fogleman (GRIT)



- Nuclear power plants sized by megawatts of output
- 1 MW powers 750-1000 homes

EXERCISE

EXERCISE

Ames Research Center

US Metropolitan Areas at Risk

Barbara Jennings (Sandia National Laboratory), Bill Fogleman (GRIT)

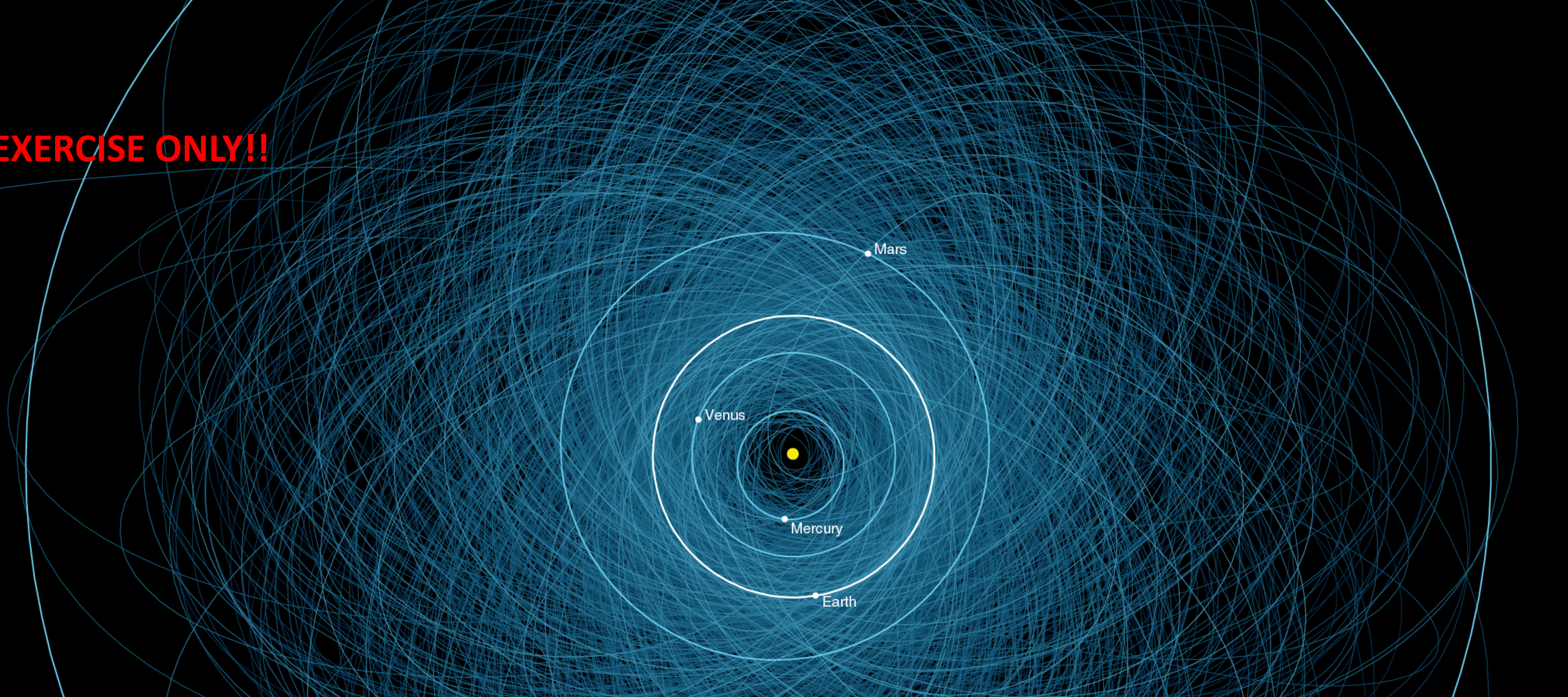
Rank	US Metropolitan Area	Forecasted Gross Metropolitan Product of US in 2019 (Billions)*	Population**	Other
1	New York-Newark-Jersey City, NJ-PA	$1,876.6	23,876,155	9th Largest Megacity and largest Metropolitan Area by land mass in the world
2	Long Beach-Anaheim, CA	$1,152.4	18,788,800	18th Largest Megacity in the world. 30th Largest Metropolitan area
3	Chicago, Naperville-Elgin, IL-IN-WI	$737.3	9,901,711	
5	Washington-Arlington-Alexandria, DC-VA-MD-WV	$585.9	9,764,315	Northeast megalopolis population 50M. Washington, DC 46th largest Megacity
6	San Francisco-Oakland-Hayward, CA	$563.3	4,727,357	Northwest megalopolis; 97th largest megacity in world.

* GMP "Forecasted Gross Metropolitan Product (GMP) of the United States in 2019, by metropolitan area (in billion current U.S. dollars) Statista The Statistics Portal, April 16, 2019

**Population "Annual Estimates of the residential Population, April 1, 2010-July 1, 2017 – Metropolitan Statistical Area; U.S. Census Bureau . March 27, 2018

EXERCISE

EXERCISE ONLY!!



Impact Exercise, Day 2: July 29, 2019

Asteroid 2019 PDC Chance of Earth Impact Now 10%

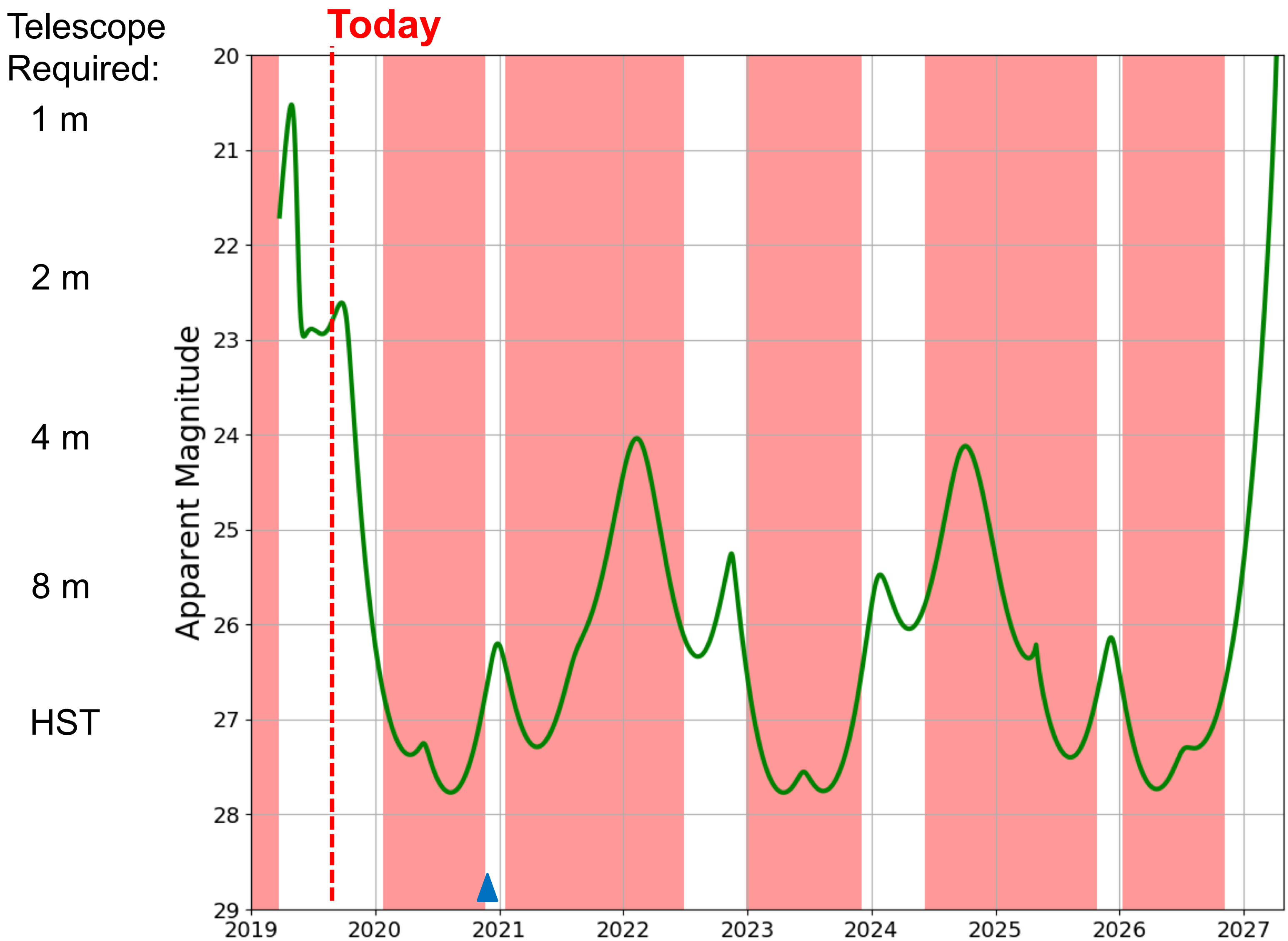
Paul Chodas
Center for Near-Earth Object Studies (CNEOS)
Jet Propulsion Laboratory/California Institute of Technology)

2019 Planetary Defense Conference, April 29 - May 3, 2019, College Park, Maryland

EXERCISE ONLY!!

2019 PDC Observability Windows

EXERCISE



Asteroid is not observable during the shaded periods, when:
Vmag < 26.5
or
Solar Elongation is > 50 deg

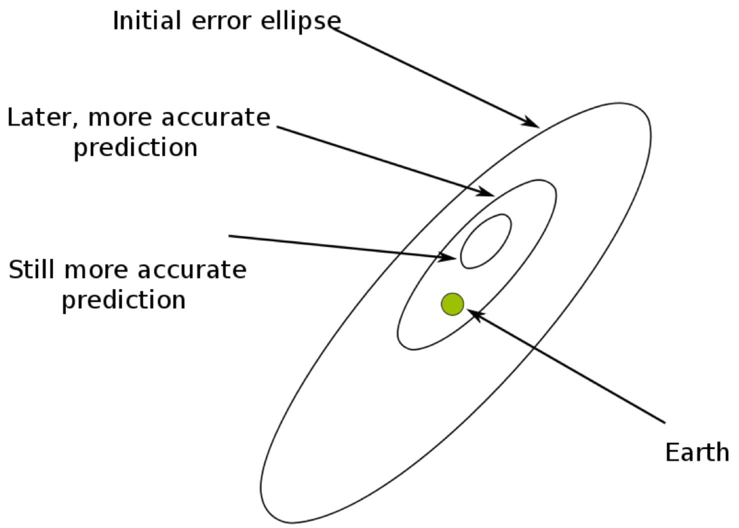
EXERCISE ONLY!!

Will Impact Probability Increase or Decrease?

Jet Propulsion Laboratory
California Institute of Technology

EXERCISE

- As 2019 PDC is observed, its orbit becomes more accurate, predictions for 2027 improve, and the uncertainty region shrinks
  - If the region shrinks away from the Earth, impact probability goes down
  - If the region shrinks and Earth remains inside, impact probability will grow

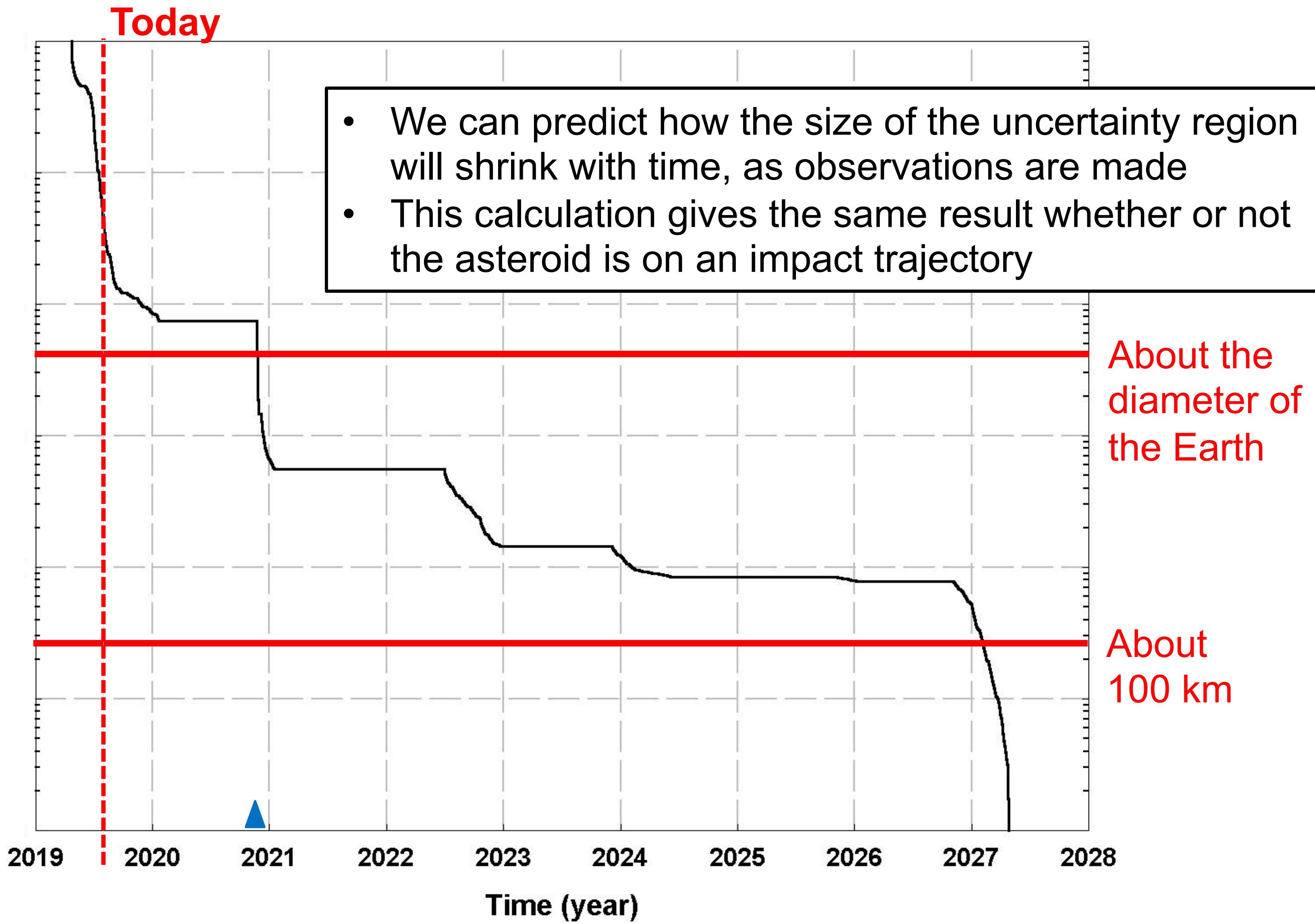


- Since we can predict the times when future observations will be possible, and we can predict how much the uncertainty region will shrink
- If the asteroid really is on a collision course, we can predict how high the impact probability *might* get:
  - 70% by January 2020, when observations will cease for ~10 months
  - 100% in late November 2020

EXERCISE ONLY!!

2019 PDC: Size of the Uncertainty Region

EXERCISE



- We can predict how the size of the uncertainty region will shrink with time, as observations are made
- This calculation gives the same result whether or not the asteroid is on an impact trajectory

EXERCISE ONLY!!

EXERCISE

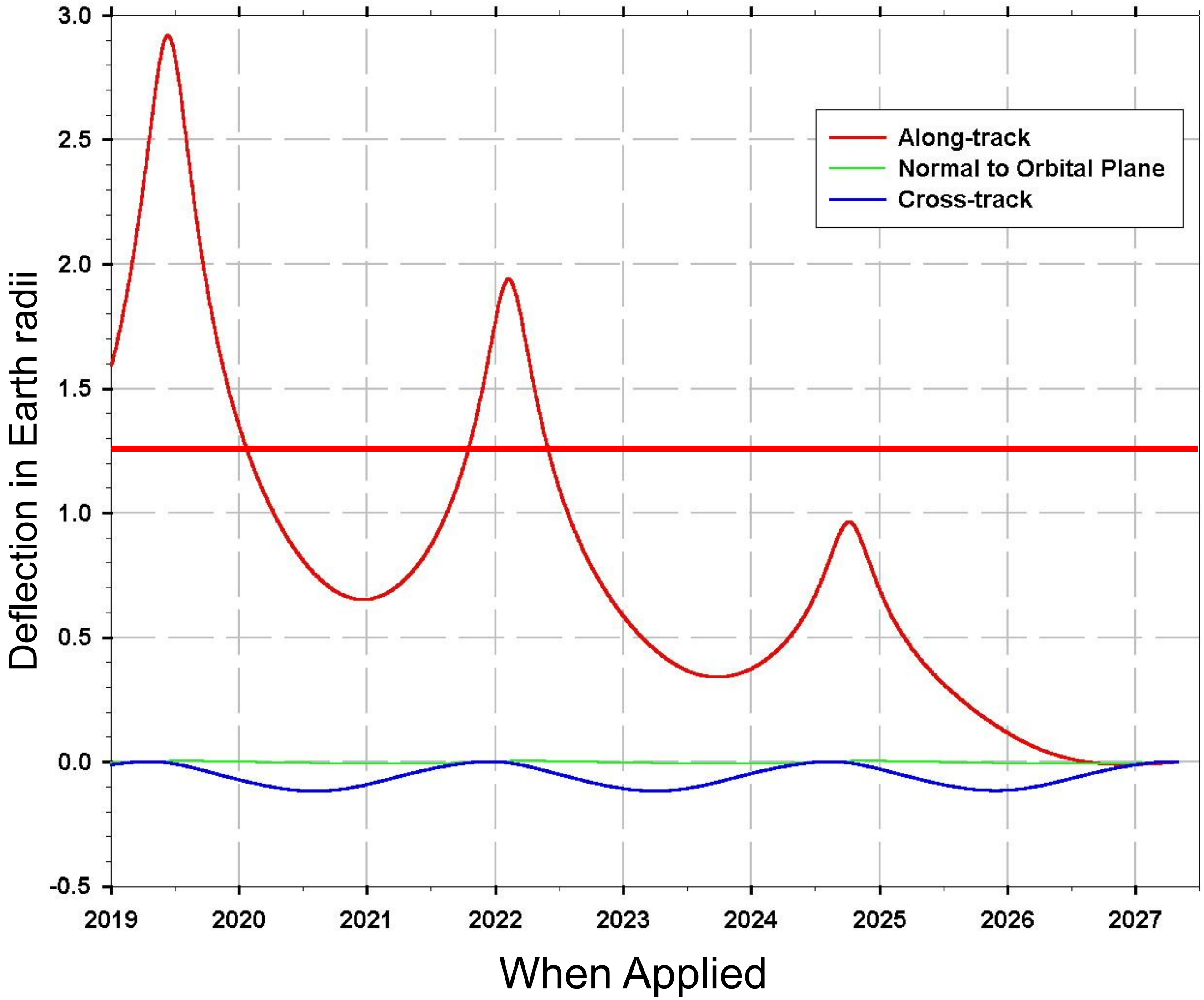
Deflecting Asteroid 2019 PDC

- Change the trajectory by imparting a small velocity change ("delta-V")
- Velocity change doesn't need to be large if applied years before the potential impact (a few cm/s or several hundredths of a mile-per-hour)
- SMPAG advises consideration of two methods for deflection:
- **Kinetic Impactor (KI)**: Collide a large spacecraft into the asteroid at high velocity (10 to 20 km/s); spacecraft momentum is transferred to asteroid
- **"Standoff" Nuclear Detonation**: Explode a nuclear device near the asteroid, the surface vaporizes (ablates) and the asteroid recoils
- If asteroid 2019 PDC is to be deflected, the schedule is tight:
  - Missions must be developed and built quickly, in less than 2 to 3 years
  - Favorable launch times are fixed and only occur once every year or two
  - Once launched, spacecraft take roughly 1 to 2 years to reach this asteroid
  - Asteroid must be deflected at least 2 to 3 years before the potential impact

EXERCISE

2019 PDC Deflection for 1 cm/s Delta-V

Jet Propulsion Laboratory
California Institute of Technology



Most effective direction is Along-Track, and the earlier the better

Capture Disk radius: 1.24 times real Earth radius because of gravitational focusing

EXERCISE ONLY!!

EXERCISE

How Deflection Affects the Trajectory

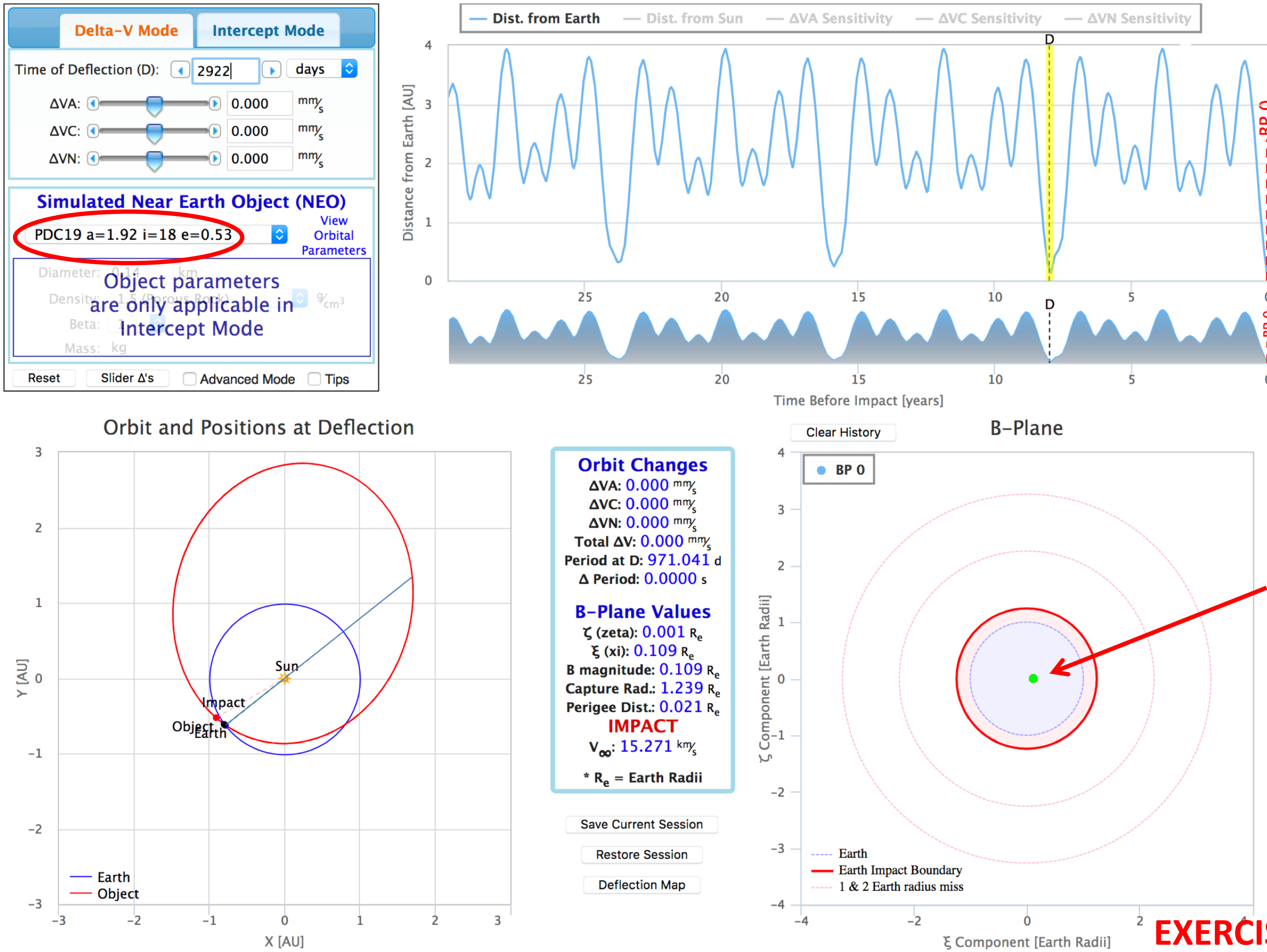
Jet Propulsion Laboratory
California Institute of Technology

- Deflection mostly moves an asteroid along its orbit path
- Even a few centimeters per second of velocity change can move an asteroid thousands of kilometers along the orbit path in just a few years
- Deflection moves the impact point only along the risk corridor, but if the deflection is large, it moves the trajectory entirely “off” the Earth
- For 2019 PDC, if the deflection increases the asteroid velocity, the impact point will move west; decreasing the velocity moves it east
- For Kinetic Impactors, it is generally much easier to decrease the asteroid’s velocity than to increase it: ”just get in the way of it”
- For 2019 PDC, Kinetic Impactors are more effective at moving the impact point eastwards than westwards
- Standoff nuclear deflection can deflect in either direction equally well

EXERCISE

CNEOS NEO Deflection App (NDA)

https://cneos.jpl.nasa.gov/nda/nda.html



Assumed Impact Location

EXERCISE ONLY!!

EXERCISE

Earth in the 2019 PDC B-Plane

Chord length across Earth disc: 15,800 km

West Is the Difficult direction for Kinetic Impactors

Uncertainty Region

East is the Easier direction for Kinetic Impactors

EXERCISE ONLY!!

EXERCISE

How Can We Commit to Deflection with All This Uncertainty?

- Should we start developing space missions before impact is certain?
  - Should we start when the probability is only 10%?
  - Even if the asteroid is on a collision course, we won't be certain for 16 months
  - Can we wait 16 months before doing anything, or will it then be too late?
- We can't yet predict how much deflection is required, or even which direction is better: the orbit accuracy is not yet good enough
- We don't know the asteroid's physical properties (size and mass) well enough to predict how much delta-v any given mission can achieve
  - How many deflection missions would be required: 1? 5? 10?
- We don't know how the asteroid will respond to a deflection: Will it disrupt? Will ejecta from the spacecraft impact enhance the deflection?
- A reconnaissance mission could reduce some of these uncertainties, but is there enough time for it?

EXERCISE

Recon Missions Reduce Uncertainty

- Recon missions would provide extremely accurate orbit measurements:
  - Enables a precise prediction of the impact location
  - The we would know how much deflection is needed, and the better direction
- Recon missions provide improved estimates of asteroid size and mass
  - Mass is a key parameter in any deflection attempt and may help in deciding which method to use
  - A rendezvous recon mission would determine the mass very accurately
  - A flyby mission would not determine the mass directly, but could do so indirectly, through the size, shape and density estimates
- A more accurate mass estimate also enables more accurate predictions of impact energy and impact effects
- A rendezvous recon mission could also remain on station to observe the deflection, measure the achieved velocity change, and provide data to compute the post-deflection trajectory

EXERCISE

2019 PDC Mitigation Mission Options

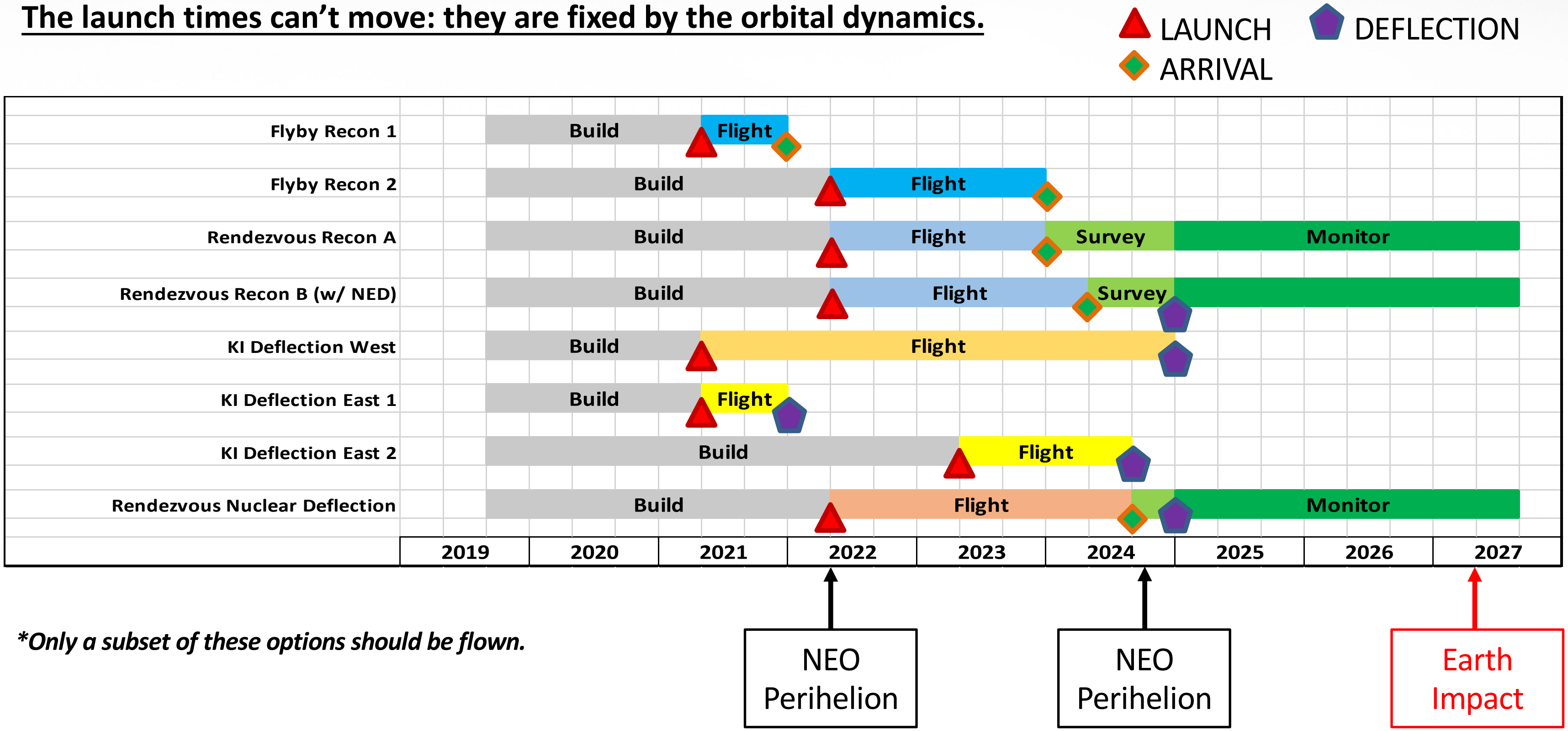
Conference Day 2

Brent Barbee (NASA/GSFC)
Paul Chodas (CNEOS/JPL/Caltech)
Joshua Lyzhoft (NASA/GSFC)
Anastassios E. Petropoulos (CNEOS/ JPL/Caltech)
Javier Roa (CNEOS/ JPL/Caltech)
Bruno Sarli (NASA/GSFC)

EXERCISE

Timeline of Mission Options

The launch times can't move: they are fixed by the orbital dynamics.



**Only a subset of these options should be flown.*

Mission Trajectory Options

- Reconnaissance (Recon) options:
  - Flyby (high-speed intercept)
  - Rendezvous (matching NEO position & velocity)
- Deflection options:
  - Kinetic impactor (high-speed intercept)
  - Standoff nuclear detonation (rendezvous-— matching NEO position & velocity)
    - Can also be performed via high-speed intercept if necessary, but rendezvous is preferable when possible

Kinetic Impactor (KI) and Nuclear Deflection DV Requirements

- Kinetic impactor deflection:
  - Deflection date: 2024-08-30
    - Driven by the mission trajectory design, which will be discussed in a subsequent section
  - Required Deflection DV: 5.9 cm/s
    - Must be capable of deflecting all the way across Earth's disk, in case true impact location turns out to be worst-case (near the westward limb)
- Standoff nuclear detonation:
  - Deflection date: 2024-10-21
    - Deflection performed after rendezvous, rather than via flyby, and so this deflection date was selected to minimize the required DV for deflection.
      - Detonating during a high-speed intercept is possible, but detonating after a rendezvous is preferred.
    - The rendezvous spacecraft carrying the nuclear devices would arrive at least several months before the deflection date, providing time to survey the asteroid first.
  - Required Deflection DV: 1.32 cm/s
    - Only needs to be able to deflect across half of the Earth's disk, because the nuclear deflection can be performed eastwards or westwards

Asteroid Deflection vs. Disruption

- Deflecting the asteroid as a whole is desirable when the scenario permits
- If the DV applied to the asteroid is ~10% or more of the asteroid's surface escape velocity, there is a risk of accidental weak disruption of the asteroid
  - That could leave significant portions of the original asteroid on an Earth-impact trajectory
- Deliberate and robust disruption of the asteroid may be possible as an alternative to deflection, but requires DV applied to the asteroid on the order of at least 10 times the asteroid's escape velocity

Kinetic Impactor (KI) and Nuclear Deflection DV Requirements

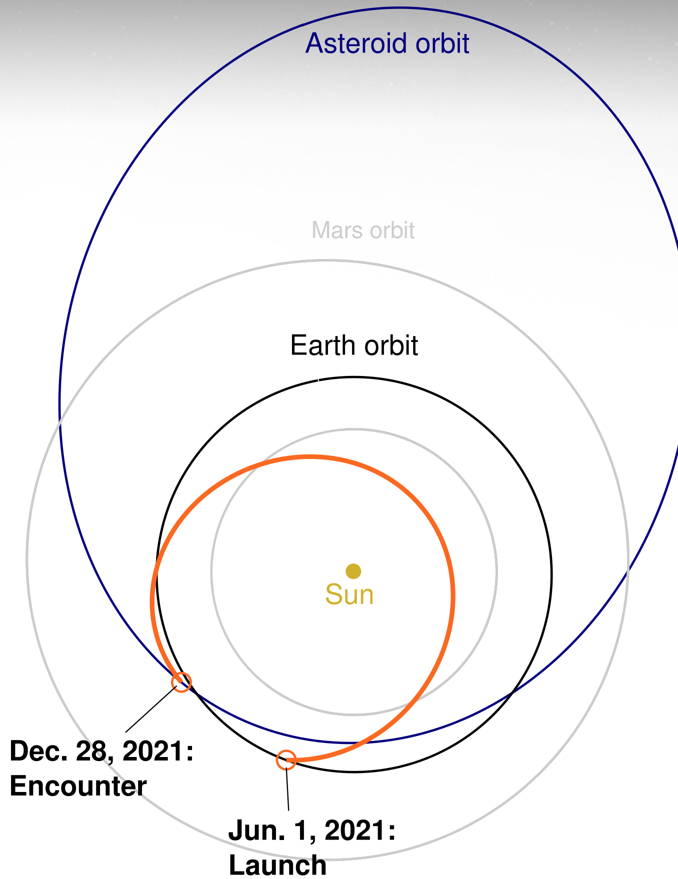
- The **5.9 cm/s DV** required for a worst-case KI eastward deflection is 40—140% of the asteroid's escape velocity (high risk of accidental asteroid disruption)
  - The range of possible asteroid sizes and densities, and the possibility of beta (B) >1, result in a range of launch vehicle requirements (Falcon Heavy (FH) and/or SLS)
    - B = 1.0: [1 to 10 FH], or [1 SLS Block 1] + [0 to 8 FHs]
    - B = 1.5: [1 to 7 FH], or [1 SLS Block 1] + [0 to 5 FHs]
    - B = 2.0: [1 to 5 FH], or [1 SLS Block 1] + [0 to 3 FHs]
- The **1.32 cm/s DV** required for a nuclear deflection is 9—31% of the asteroid's escape velocity (low risk of accidental asteroid disruption)
  - The nuclear deflection requires 1 FH launch of a ~1300 kg spacecraft, regardless of the asteroid's size
    - The standoff detonation distance is adjusted as needed for the asteroid mass (depending on asteroid mass, standoff distance varies between 119 and 472 m for a 100 KT nuclear device)

Uncertainties in Asteroid Response

- The response of the asteroid to an applied DV is difficult to predict precisely
  - Asteroid material ejected from the asteroid's surface by a kinetic impactor may increase the DV on the asteroid (i.e., "beta" factor greater than 1), which could enhance the deflection
  - Variations in asteroid surface topography, ejecta pattern, mass/porosity, etc., may result in the net DV vector not being entirely in the expected direction
- The deflection results presented previously did not include such uncertainties, nor did they account for reliability issues (i.e., some spacecraft failures are possible, particularly if construction is rushed due to the emergency situation)
- Deployment of additional deflection spacecraft to provide margin against under-performance should be considered

Flyby Recon 1 - Details

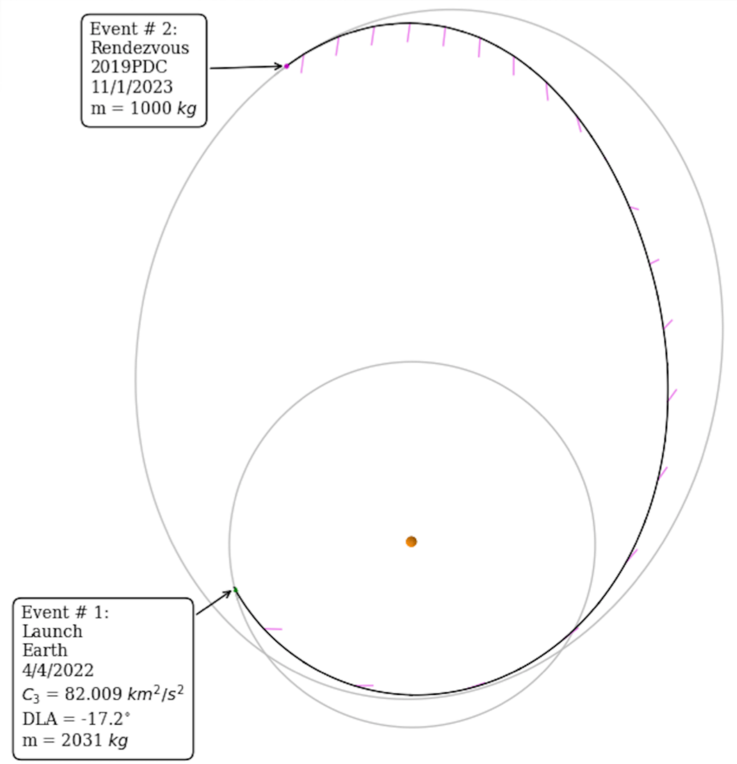
- Solar electric propulsion low-thrust
  - NEXT (HiThrust) – 90% duty cycle
  - 6 kW @ 1 au
- Build time: 1.9 years
- Launch: 2021-06-01
- Asteroid flyby: 2021-12-28
- Relative speed at flyby: 13 km/s
- Spacecraft mass: 500 kg
- Closest approach to Sun: 0.42 au



Credit: CNEOS/JPL/Caltech

Rendezvous Recon A - Details

- Solar electric propulsion low-thrust
  - 2 x BPT-4000 (XR5) – 90% duty cycle
  - 11 kW @ 1 au
- Build time: 2.6 years
- Launch: 2022-04-04
- Asteroid arrival: 2023-11-01
- Spacecraft mass: 1000 kg

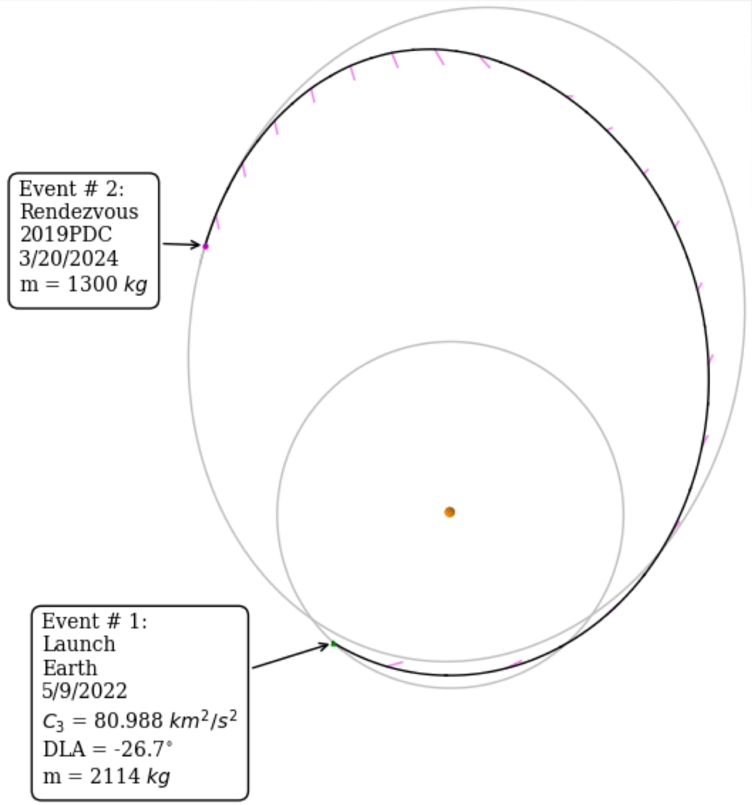


Credit: NASA/GSFC

EXERCISE

Rendezvous Recon B (w/NED) - Details

- Solar electric propulsion low-thrust
  - 2 x BPT-4000 (XR5) – 90% duty cycle
  - 11 kW @ 1 au
- Build time: 2.7 years
- Launch: 2022-05-09
- Asteroid arrival: 2024-03-20
- Spacecraft mass: 1300 kg
  - Includes up to three 100 KT NED free-flyer packages that could be used for deflection after ~7 month survey of asteroid
  - Spacecraft is moved to safe location to observe nuclear detonation(s)
- Deflection: 2024-10-21



Credit: NASA/GSFC

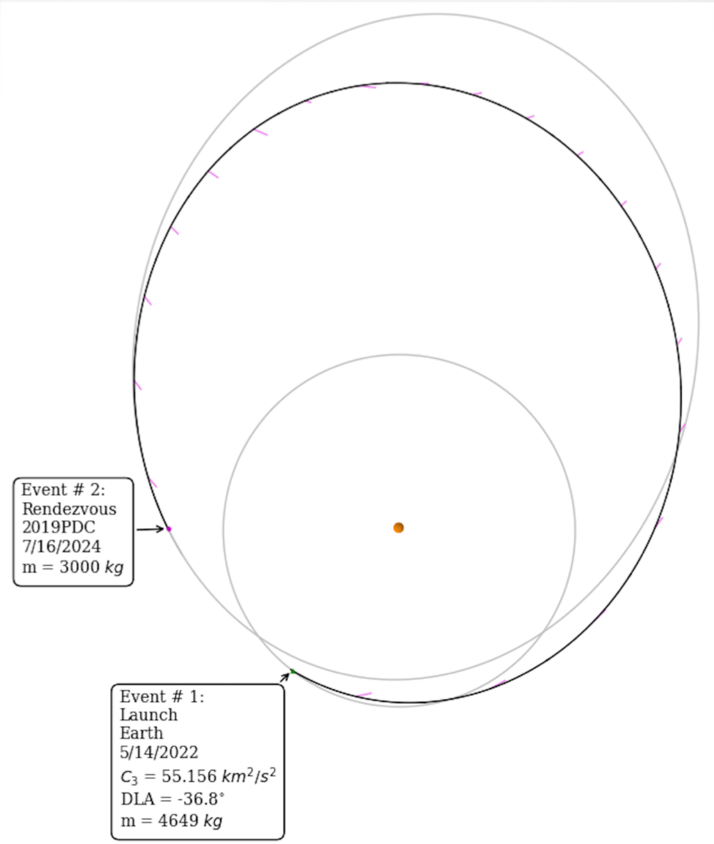
KI Deflection East 2 - Details

- Solar electric propulsion low-thrust
  - NEXT (HiThrust) – 90% duty cycle
  - 6 kW @ 1 au
- Build time: 3.7 years
- Launch: 2023-05-24
- Spacecraft mass: up to 13214 kg
  - Multiple KI spacecraft of less mass may be launched to avoid exceeding the ~10% V_escape threshold for any individual DV applied to the asteroid.

Credit: CNEOS/JPL/Caltech

Rendezvous Nuclear Deflection - Details

- Solar electric propulsion low-thrust
  - 2 x BPT-4000 (XR5) – 90% duty cycle
  - 11 kW @ 1 au
- Build time: 2.7 years
- Launch: 2022-05-14
- Asteroid arrival: 2024-07-16
  - ~3 months to study asteroid before deflection
- Spacecraft mass: 3000 kg
  - Includes either one 1 MT NED free-flyer package, or ten 100 KT packages, that could be used for deflection after a ~3 month survey of asteroid
  - Spacecraft is moved to safe location to observe nuclear detonation(s)
- Deflection: 2024-10-21



Credit: NASA/GSFC