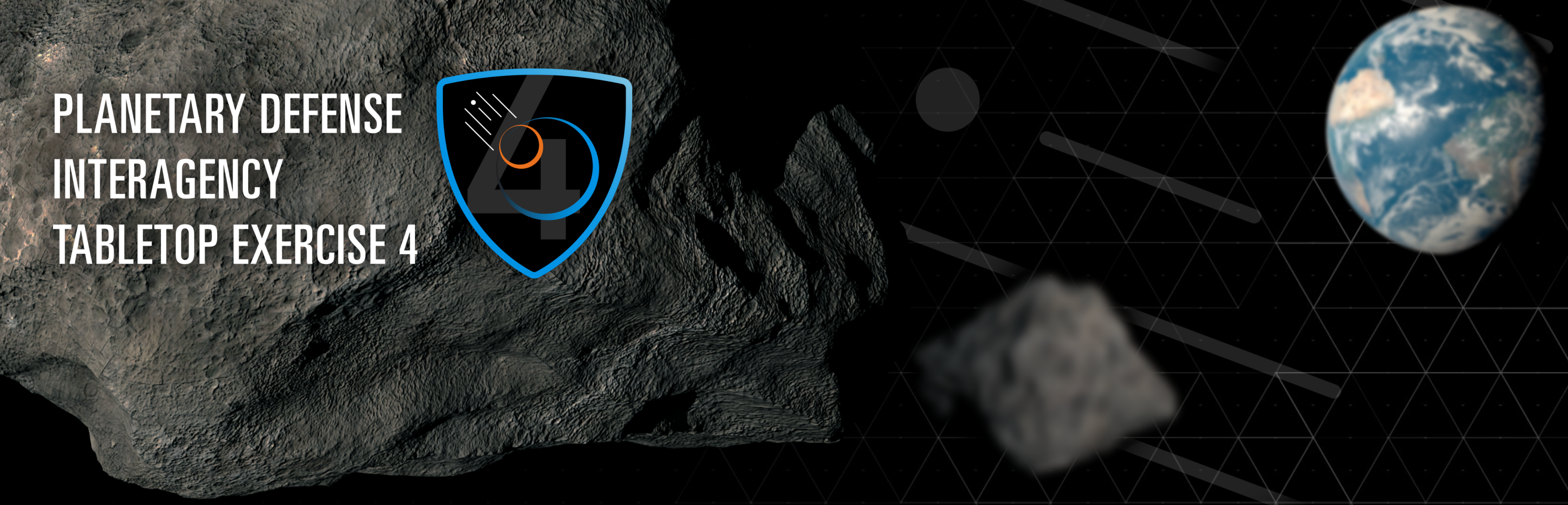
PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4



Day 1

NASA

PLANETARY DEFENSE COORDINATION OFFICE

U.S. DEPARTMENT OF HOMELAND SECURITY

FEMA

EMERGENCY MANAGEMENT NORTH CAROLINA

WINSTON-SALEM FORSYTH COUNTY NC EMERGENCY MANAGEMENT

cneos

Ames Research Center

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

Day 1 Introduction

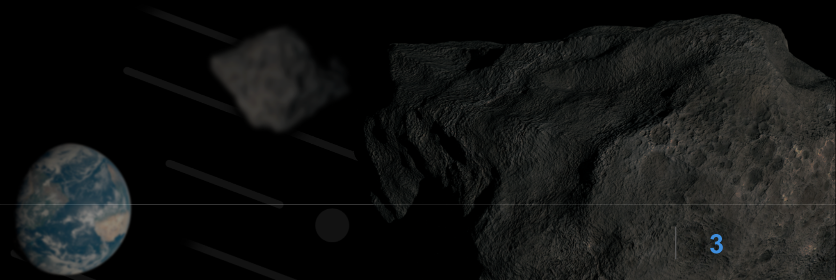
Welcomes, Objectives, What to Expect

Dipak Srinivasan
TTX Project Manager
Johns Hopkins Applied Physics Laboratory
dipak.srinivasan@jhuapl.edu

NASA
PLANETARY DEFENSE COORDINATION OFFICE
U.S. DEPARTMENT OF HOMELAND SECURITY
FEMA
EMERGENCY MANAGEMENT NORTH CAROLINA
WINSTON-SALEM FORSYTH COUNTY NC EMERGENCY MANAGEMENT
cneos
Ames Research Center
JOHNS HOPKINS APPLIED PHYSICS LABORATORY

Agenda

- Welcome
- Few words from our sponsor
  - Lindley Johnson, NASA Planetary Defense Coordination Officer
- Few words from our TTX Director
  - L.A. Lewis, NASA PDCO FEMA Detailee
- Why we are here
- Objectives
- What to expect



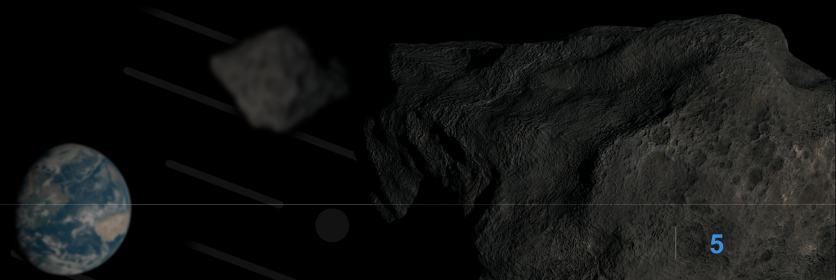
Why We Are Here

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

- What would we do if we knew a sizable asteroid was headed our way?
- Do we understand everyone’s roles in this scenario?
- After we’re done, what can do well ahead of time to be better prepared for this?

Objectives

1. *Increase the understanding* by personnel and U.S. government institutions of near-Earth object (NEO) threats and their roles in mitigating that threat
    - Opportunity to understand what the role of USSPACECOM is
2. *Test methods of communicating* information both to and among decision-makers
3. *Exercise post-impact protocols*, including involvement of local government

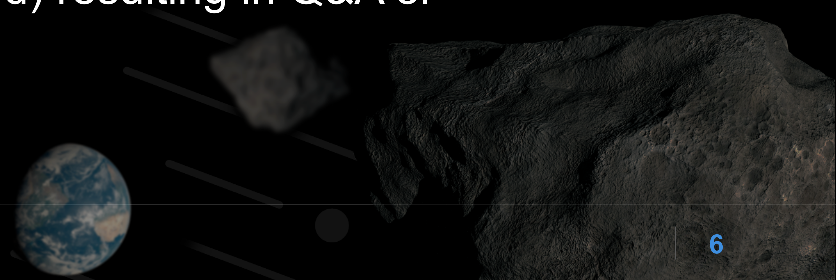


Structure of the TTX

- Set of “Planetary Defense 101” short briefs
- TTX broken into five “modules,” numbered 0–4
  - Each module represents a different segment of time between discovery of the asteroid through post-impact protocols

Module	Description
0	Quick briefing of the read-ahead materials
1	6 months before impact
2	2 months before impact
3	6 days before impact
4	Post-impact response and recovery

- Module structure
  - Series of injects (either new information presented or questions posed) resulting in Q&A or discussion
  - Hot wash with Participant Feedback Forms (PFFs)

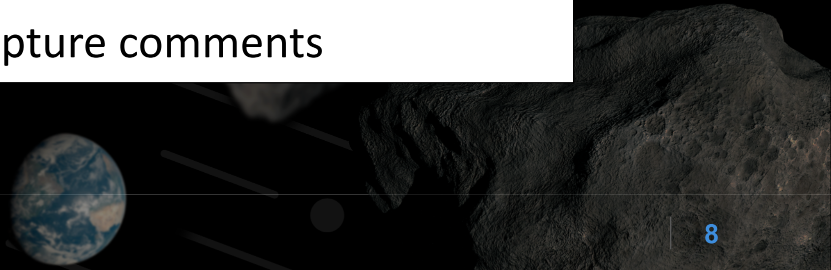


Agenda for Day 1

Day 1	Start (EST)	Stop (EST)	Duration	Activity
23-Feb	12:30	13:00	0:30	Arrival and Check-in *for any in-person people*
	13:00	13:20	0:20	Welcome, Objectives, What to Expect
	13:20	13:35	0:15	Technical logistics
	13:35	13:55	0:20	Introduction to Planetary Defense 101
	13:55	14:10	0:15	Why Planetary Defense 101
	14:10	14:30	0:20	Asteroid Detection and Tracking 101
	14:30	14:45	0:15	Break
	14:45	15:00	0:15	Asteroid Damage Modeling 101
	15:00	15:15	0:15	Space Mitigation Strategies 101
	15:15	15:30	0:15	***Module 0***: Background, Initial Detection
	15:30	15:40	0:10	Pre-exercise Participant Feedback
	15:40	16:30	0:50	***Module 1a***: Early Mitigation Options
	16:30	16:45	0:15	Debrief Day 1

Agenda for Day 2

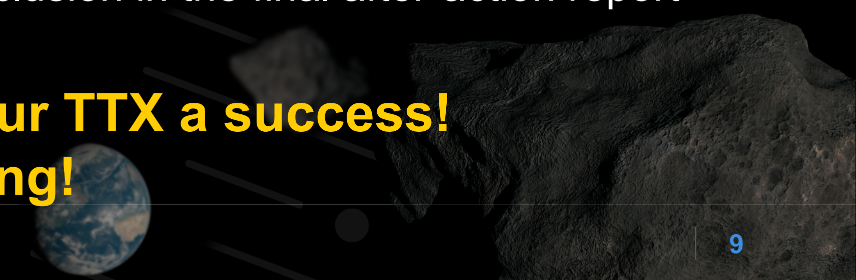
Day 2	Start (EST)	Stop (EST)	Duration	Activity
24-Feb	7:00	8:00	1:00	Arrival and Check-in (continental breakfast served)
	8:00	8:30	0:30	Welcome, Objectives, What to Expect
	8:30	9:30	1:00	***Module 1b***: Continue Early Mitigation Options
	9:30	9:45	0:15	Break
	9:45	11:35	1:50	***Module 2***: Early Preparedness
	11:35	12:35	1:00	Lunch
	12:35	14:25	1:50	***Module 3***: Final Preparedness and Readiness
	14:25	14:40	0:15	Break
	14:40	16:30	1:50	***Module 4***: Response and Transition to Recovery
	16:30	17:00	0:30	Debrief, capture comments



Online Protocols

- For Zoom participants
  - Keep mics muted when not in active conversation
  - Please rename your Zoom to include your Name and Organization, e.g., Dipak Srinivasan/APL
  - Smile! When speaking, or otherwise, we encourage you to keep your cameras on as much as possible
  - For chats:
    - Use Zoom Chat for only discussing administrative/logistic concerns
    - Use MeetingSphere Chat for any exercise-specific discussions
  - Feel free to use the TTX4 Zoom background provided to you
- For all participants – MeetingSphere Chat
  - MeetingSphere will be running a parallel set of static slides as the main Zoom PowerPoint
  - Each MeetingSphere slide will have its own chat thread, enabling focused topic-based conversation even if time constraints force the exercise to move on
  - Participants can either continue chats in the “main” chat room or scroll back to the prior slide(s)
  - There is also a “Parking Lot” discussion board to capture ideas or conversation threads that we had to abandon for time purposes, both for potential follow-up and to ensure inclusion in the final after-action report

Your discussions are the data we seek to help make our TTX a success!
Please keep those good thoughts flowing!



PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

NASA
PLANETARY DEFENSE COORDINATION OFFICE
U.S. DEPARTMENT OF HOMELAND SECURITY
FEMA
JOHNS HOPKINS APPLIED PHYSICS LABORATORY
cneos
Ames Research Center
NORTH CAROLINA EMERGENCY MANAGEMENT
WINSTON-SALEM FORSYTH COUNTY NC EMERGENCY MANAGEMENT

PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

Zoom & MeetingSphere “How to” and Login

Online Protocols

Aaron Chrietzberg
Aaron.Chrietzberg@jhuapl.edu
(240) 228-9405

Login Information

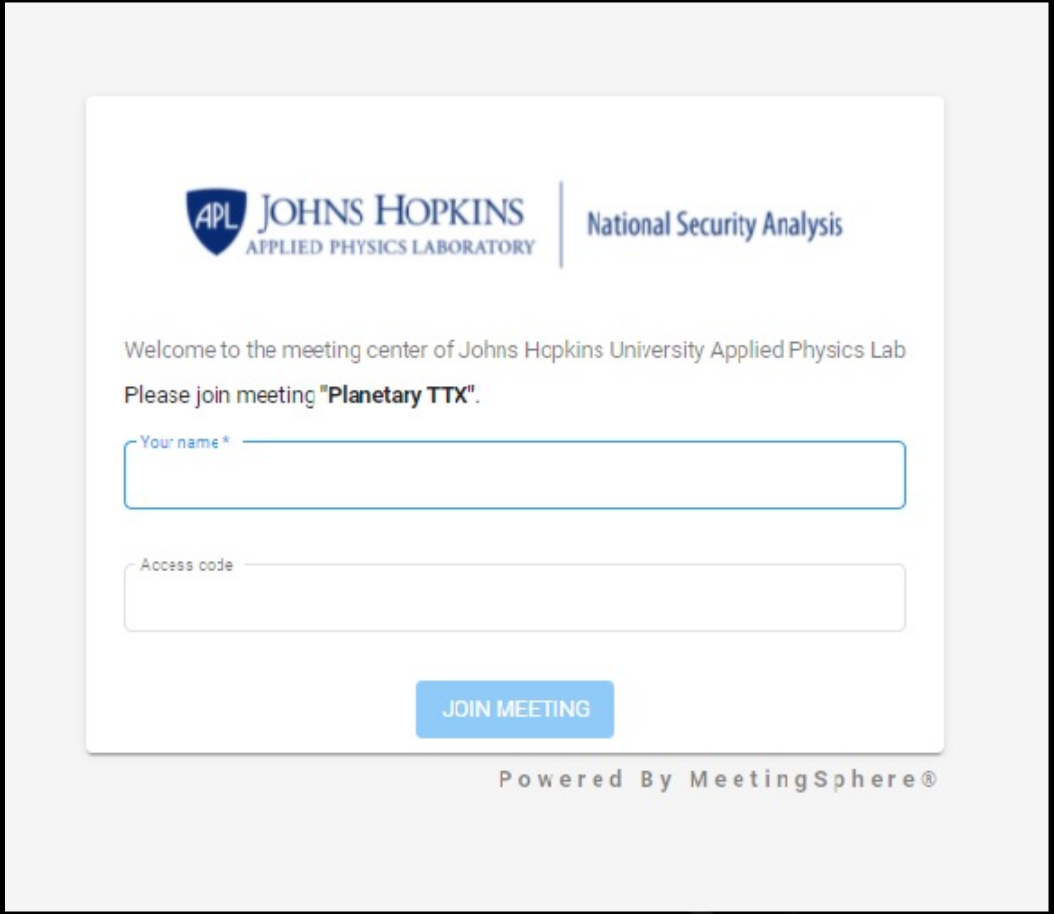
https://msphere.jhuapl.edu/planetary

Please provide your full name:

- **Name, Title, Organization**

Access Code: 9999

*Users are encouraged to login ahead of the event to test and become familiar with the tool.



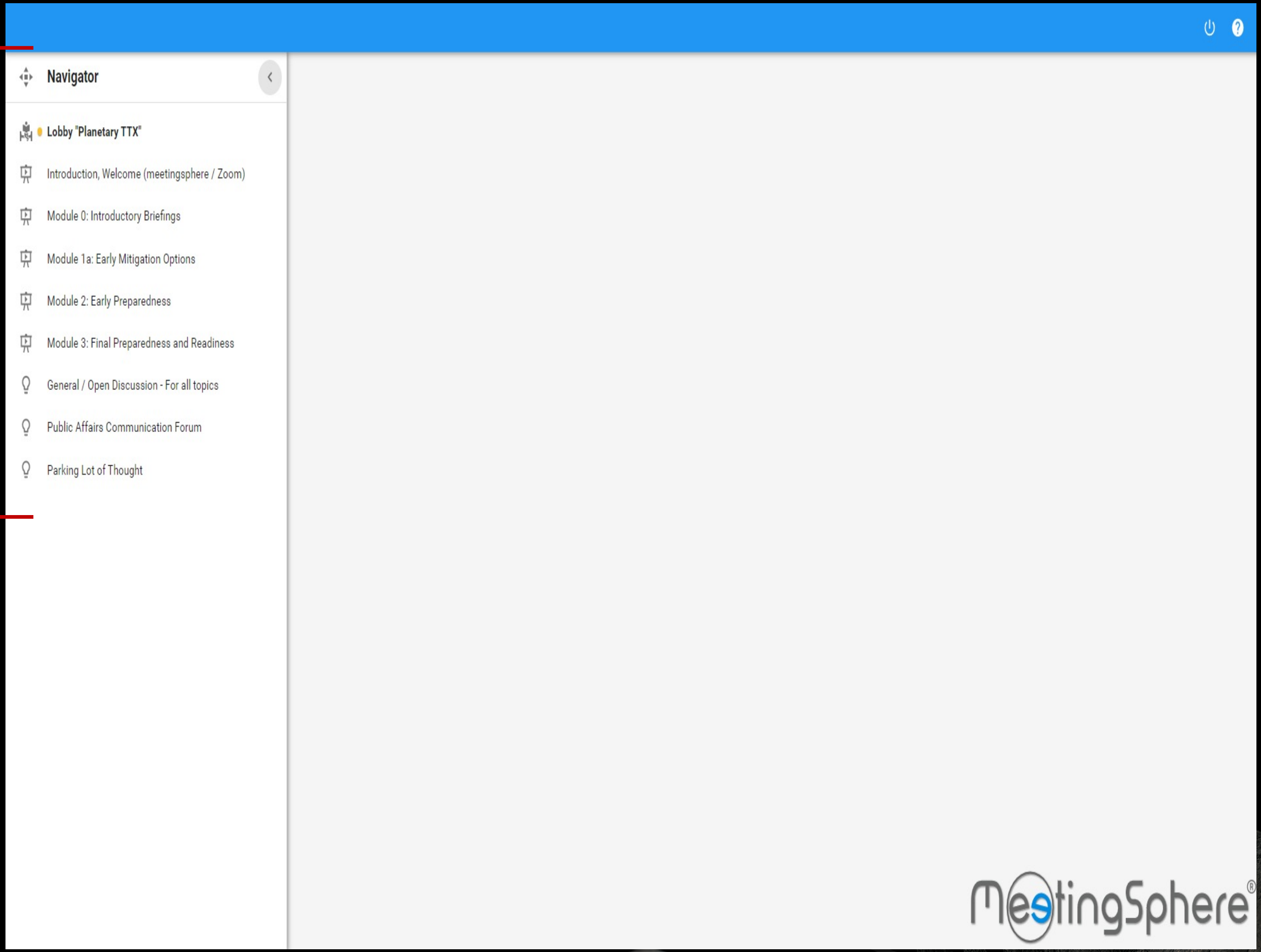
Welcome to the meeting center of Johns Hopkins University Applied Physics Lab

Please join meeting **"Planetary TTX"**.

All electronic and chat box comments, which may contain identifiable information and remain attributable to the submitter, will be used only for the purposes of this TTX and to inform, in the aggregate, research efforts and post-event evaluation reports.

Navigation Panel

- The agenda for the TTX will be displayed on the left-hand side upon logging into the tool.
- Please click on the agenda item of your choice for more information.
- Please note that, due to your specific role, you may be PULLED into new agenda items.
- Please also be advised that we may mute your mic to focus participation on specific decision-makers as relevant to the scenario event.



Navigator

Lobby "Planetary TTX"

Introduction, Welcome (meetingsphere / Zoom)

Module 0: Introductory Briefings

Module 1a: Early Mitigation Options

Module 2: Early Preparedness

Module 3: Final Preparedness and Readiness

General / Open Discussion - For all topics

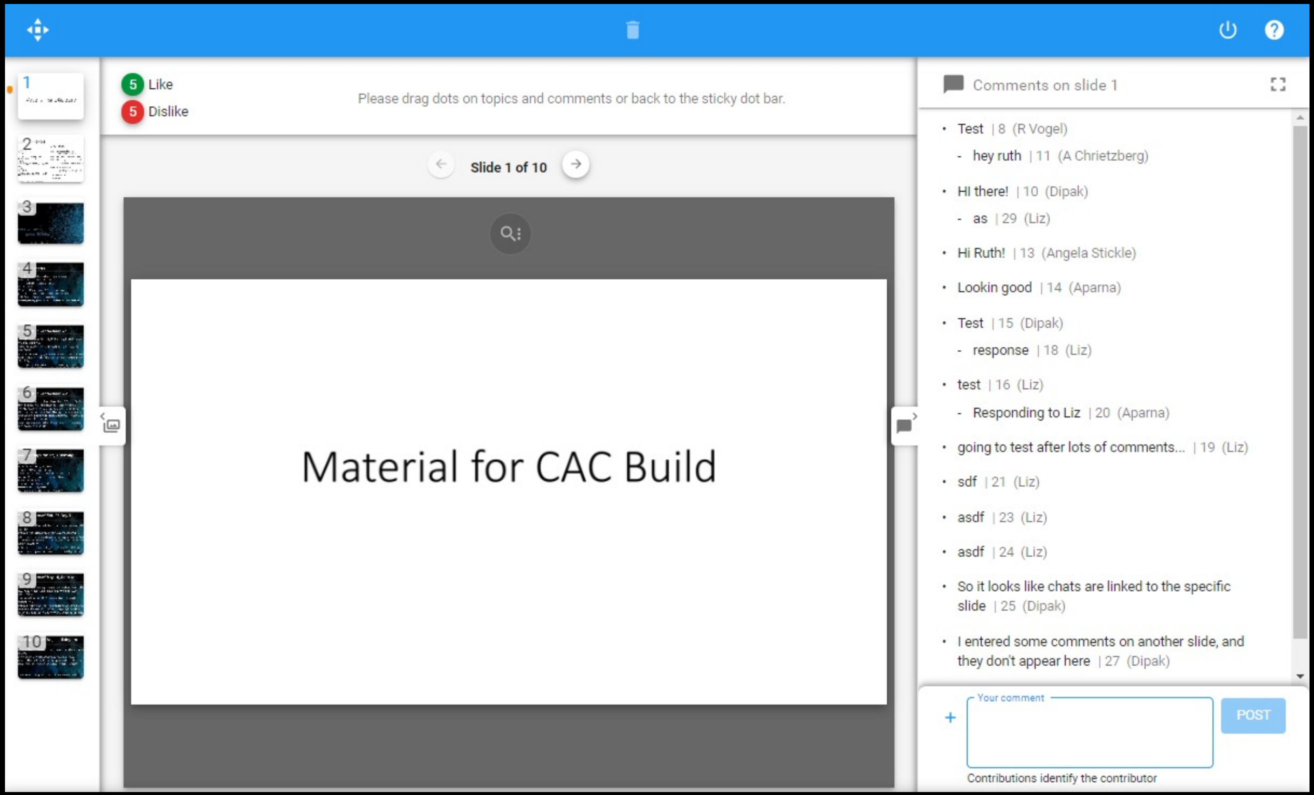
Public Affairs Communication Forum

Parking Lot of Thought

Presentation Mode

To advance or review slides, click the forward and backward arrows.

Slide Deck



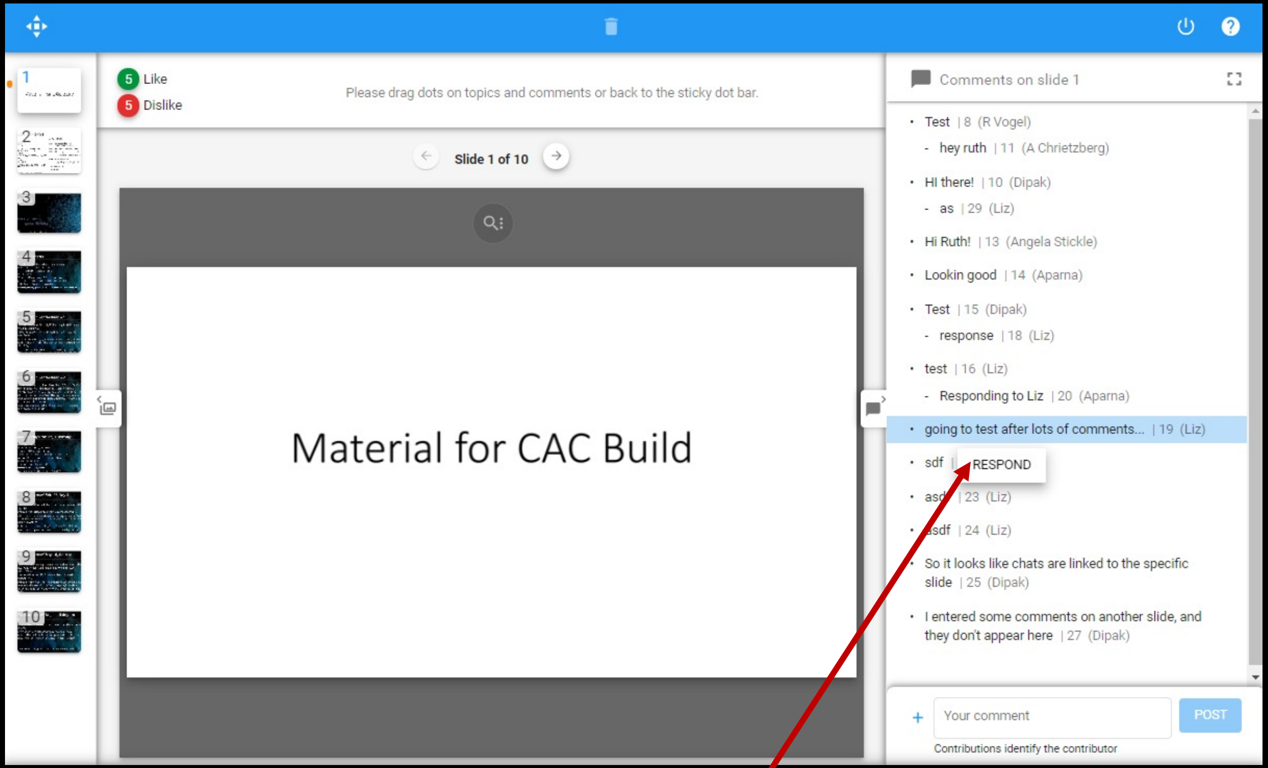
- Test | 8 (R Vogel)
  - hey ruth | 11 (A Chrietzberg)
- HI there! | 10 (Dipak)
  - as | 29 (Liz)
- Hi Ruth! | 13 (Angela Stickle)
- Lookin good | 14 (Aparna)
- Test | 15 (Dipak)
  - response | 18 (Liz)
- test | 16 (Liz)
  - Responding to Liz | 20 (Aparna)
- going to test after lots of comments... | 19 (Liz)
- sdf | 21 (Liz)
- asdf | 23 (Liz)
- asdf | 24 (Liz)
- So it looks like chats are linked to the specific slide | 25 (Dipak)
- I entered some comments on another slide, and they don't appear here | 27 (Dipak)

Please use the Chat box on the right-hand side to offer/submit comments. Each slide will retain/track its own associated comments.

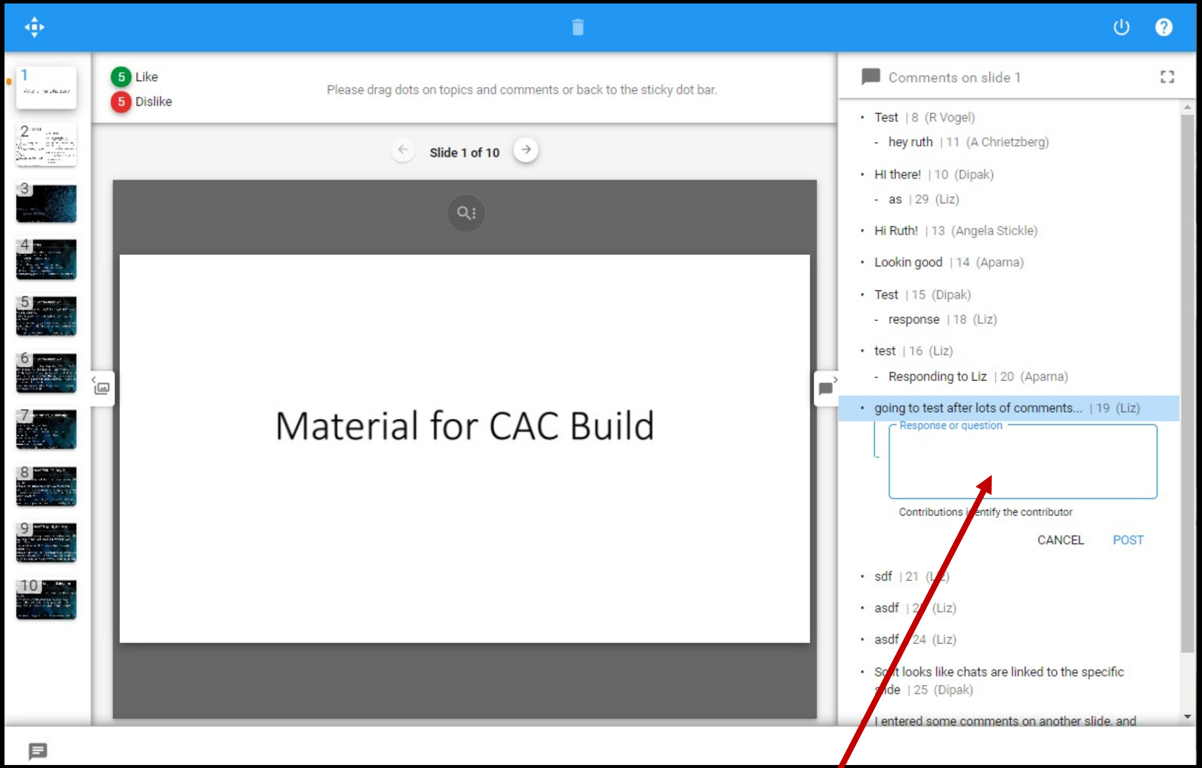
To post: Please enter your comment in the box on the bottom right and press enter or click the “Post” button.

Replying to a Comment

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4



- Test | 8 (R Vogel)
  - hey ruth | 11 (A Chrietzberg)
- HI there! | 10 (Dipak)
  - as | 29 (Liz)
- Hi Ruth! | 13 (Angela Stickle)
- Lookin good | 14 (Aparna)
- Test | 15 (Dipak)
  - response | 18 (Liz)
- test | 16 (Liz)
  - Responding to Liz | 20 (Aparna)
- going to test after lots of comments... | 19 (Liz)
- sdf | RESPOND
- asd | 23 (Liz)
- sdf | 24 (Liz)
- So it looks like chats are linked to the specific slide | 25 (Dipak)
- I entered some comments on another slide, and they don't appear here | 27 (Dipak)



- Test | 8 (R Vogel)
  - hey ruth | 11 (A Chrietzberg)
- HI there! | 10 (Dipak)
  - as | 29 (Liz)
- Hi Ruth! | 13 (Angela Stickle)
- Lookin good | 14 (Aparna)
- Test | 15 (Dipak)
  - response | 18 (Liz)
- test | 16 (Liz)
  - Responding to Liz | 20 (Aparna)
- going to test after lots of comments... | 19 (Liz)

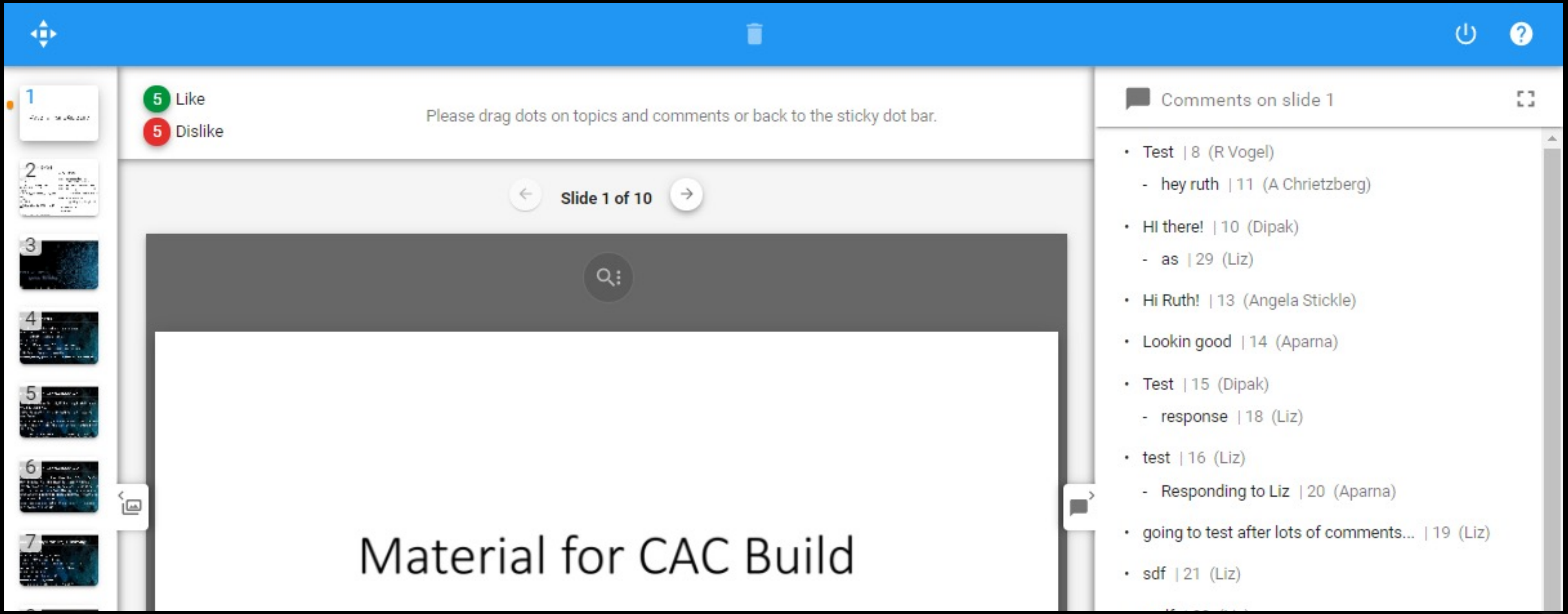
- sdf | 21 (L
- asdf | 2 (Liz)
- asdf 24 (Liz)
- So it looks like chats are linked to the specific ide | 25 (Dipak)
- I entered some comments on another slide, and

To Reply to a comment:
1) Select the initial comment.
2) Once the "Respond" button appears, click it.

3) This will open a text field where you can type your response.
4) To post your comment, click "Post."

Returning to the Navigation Panel / Agenda:

- To return to the Navigation panel / agenda, select the “compass” icon on the top left.
- Do not select the back arrow in the browser!



Please drag dots on topics and comments or back to the sticky dot bar.

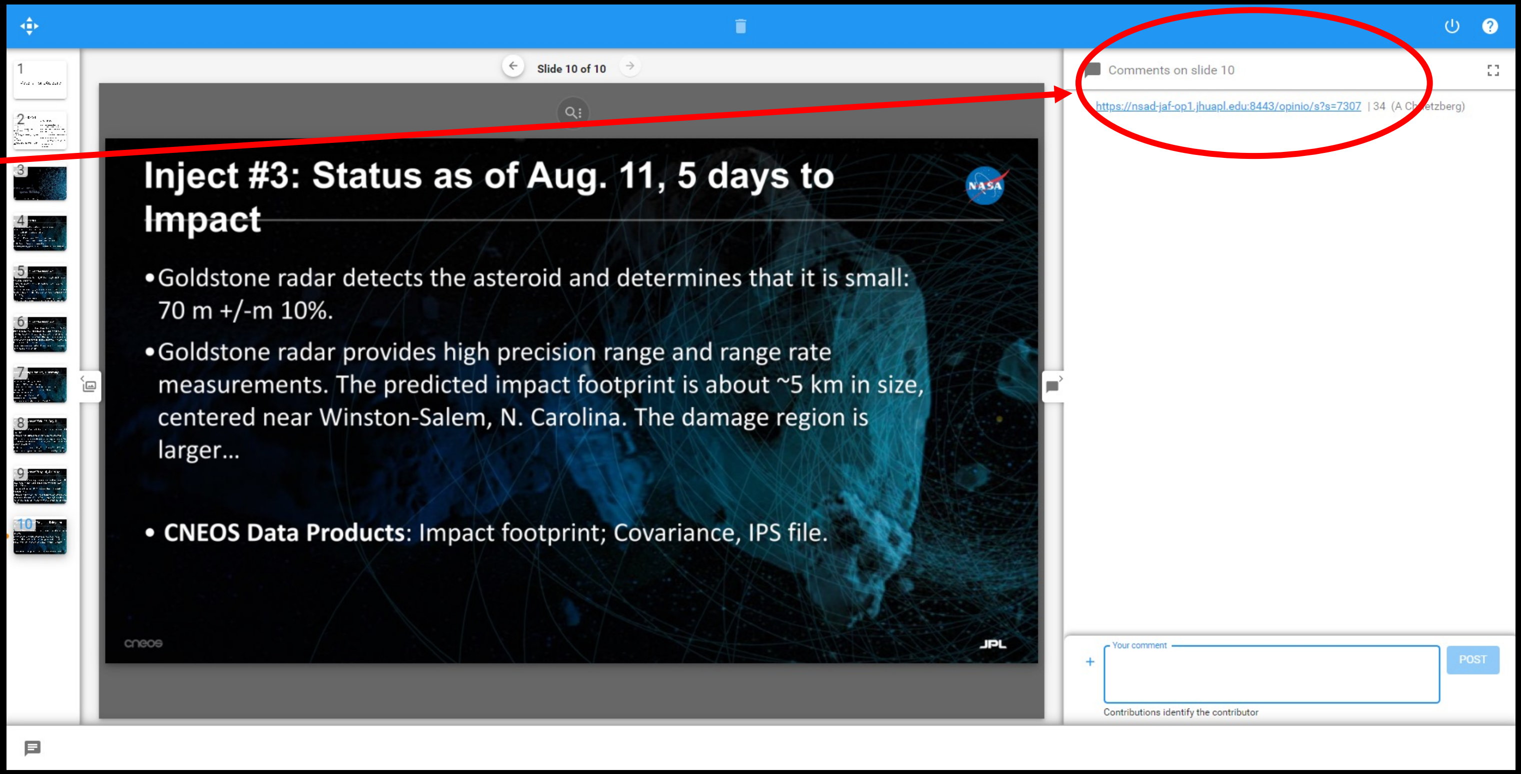
- Test | 8 (R Vogel)
  - hey ruth | 11 (A Chrietzberg)
- HI there! | 10 (Dipak)
  - as | 29 (Liz)
- Hi Ruth! | 13 (Angela Stickle)
- Lookin good | 14 (Aparna)
- Test | 15 (Dipak)
  - response | 18 (Liz)
- test | 16 (Liz)
  - Responding to Liz | 20 (Aparna)
- going to test after lots of comments... | 19 (Liz)
- sdf | 21 (Liz)

Material for CAC Build

To Fill-Out the Surveys:

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

- At the end of each module, a link to a survey will be posted in the comments section of the chat.
- To access the survey, simply click on the URL link and the survey will open in your browser window.
- The surveys will also be posted on the primary navigation page for your ease.



Inject #3: Status as of Aug. 11, 5 days to Impact

- Goldstone radar detects the asteroid and determines that it is small: 70 m +/-m 10%.
- Goldstone radar provides high precision range and range rate measurements. The predicted impact footprint is about ~5 km in size, centered near Winston-Salem, N. Carolina. The damage region is larger…
- **CNEOS Data Products**: Impact footprint; Covariance, IPS file.

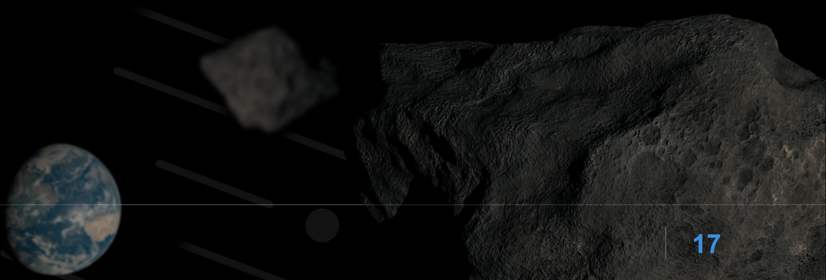
Comments on slide 10

https://nsad-jaf-op1.jhuapl.edu:8443/opinio/s?s=7307 | 34 (A Ch etzberg)

Your comment

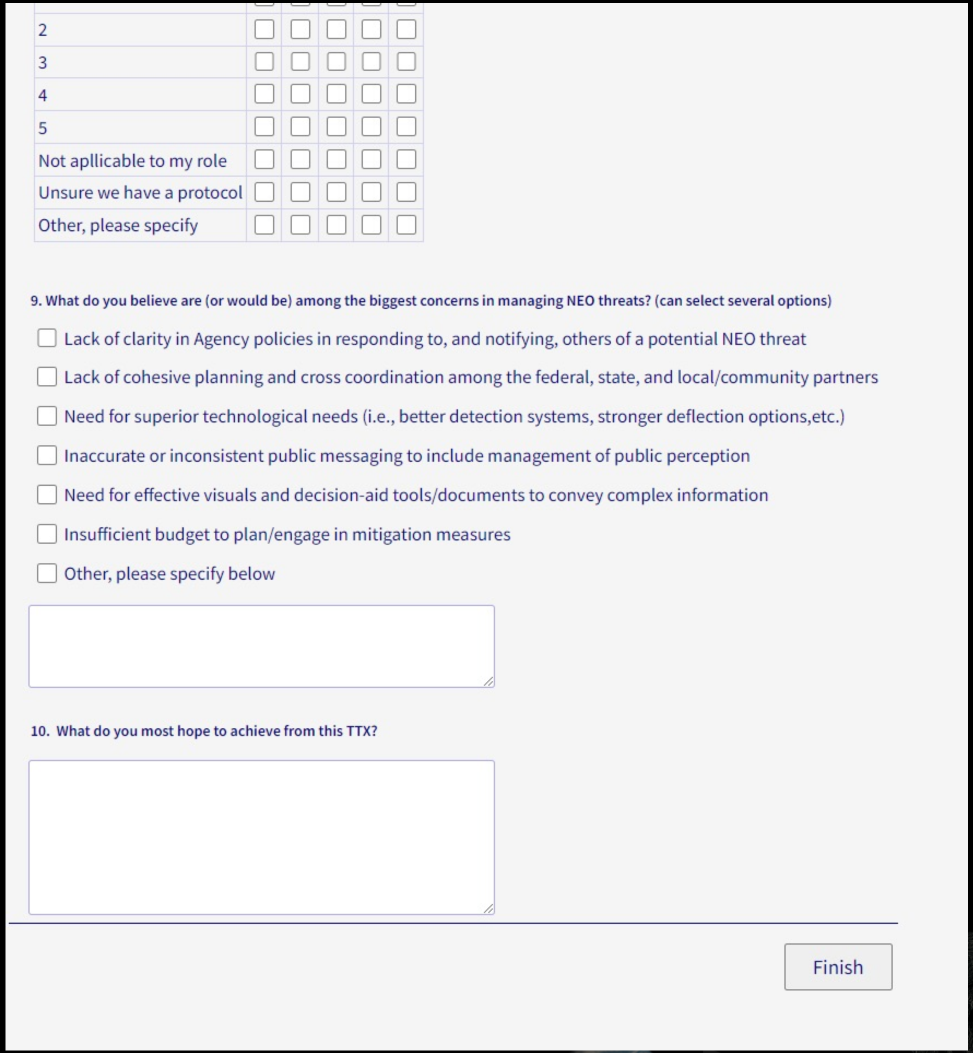
POST

Contributions identify the contributor



To Select the Survey(s):

- Upon completion of the survey, don’t forget to select the “Finish” button!
- **The surveys represent a critical data collection tool – we welcome and appreciate your thoughtful feedback to help gauge whether key objectives were met to best inform our senior U.S. military and civilian leaders in defending against, and addressing, an asteroid threat to our homeland.**



2	☐	☐	☐	☐	☐
3	☐	☐	☐	☐	☐
4	☐	☐	☐	☐	☐
5	☐	☐	☐	☐	☐
Not apllicable to my role	☐	☐	☐	☐	☐
Unsure we have a protocol	☐	☐	☐	☐	☐
Other, please specify	☐	☐	☐	☐	☐

9. What do you believe are (or would be) among the biggest concerns in managing NEO threats? (can select several options)

☐ Lack of clarity in Agency policies in responding to, and notifying, others of a potential NEO threat

☐ Lack of cohesive planning and cross coordination among the federal, state, and local/community partners

☐ Need for superior technological needs (i.e., better detection systems, stronger deflection options,etc.)

☐ Inaccurate or inconsistent public messaging to include management of public perception

☐ Need for effective visuals and decision-aid tools/documents to convey complex information

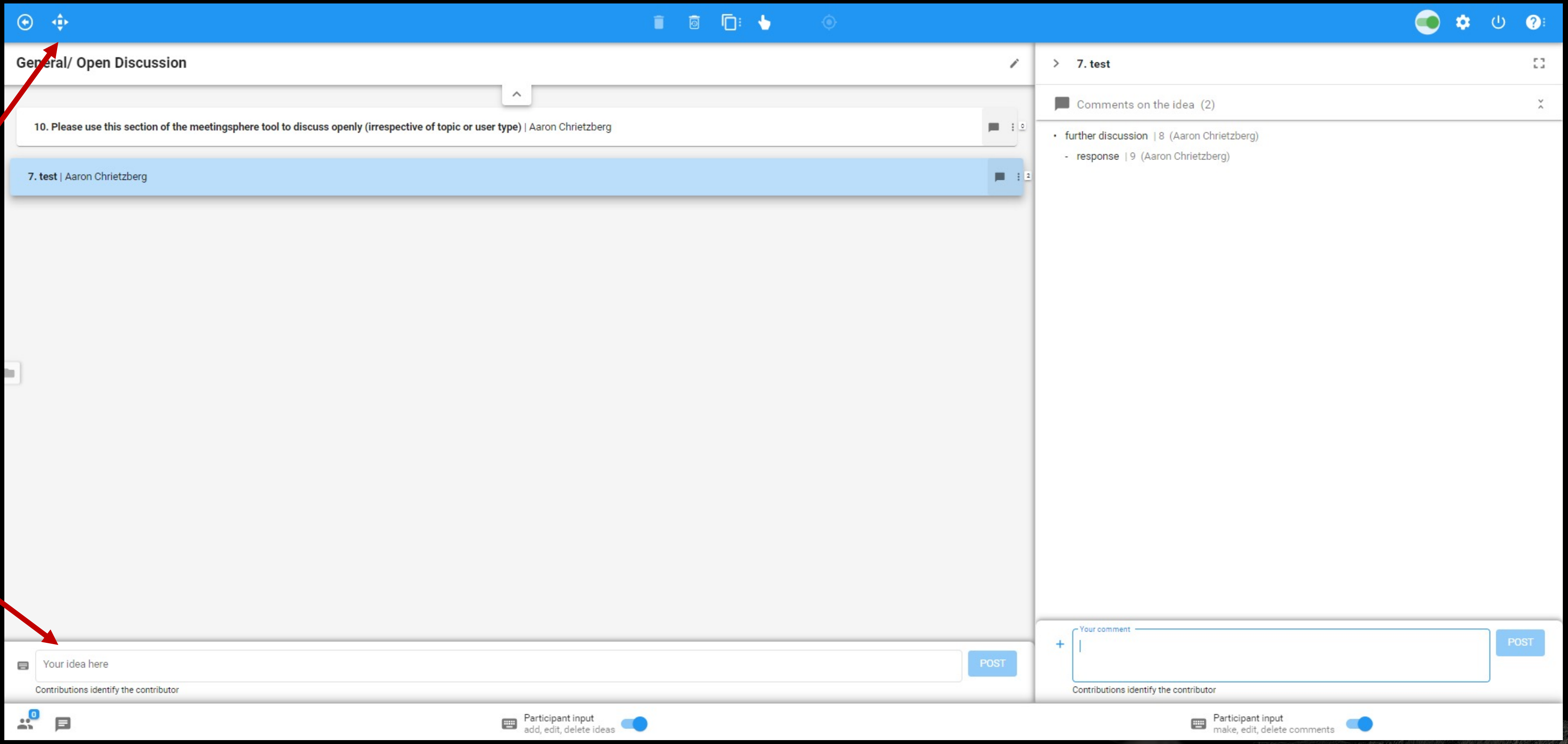
☐ Insufficient budget to plan/engage in mitigation measures

☐ Other, please specify below

10. What do you most hope to achieve from this TTX?

Open Discussion Chat

- To provide for general discussion beyond presentations: An “Open Discussion Chat” has been added to the agenda.
- To access this agenda: Return to the navigation compass on the top left of the screen.
- To enter an initial comment: Type your idea in the comment section below – and press “Post.”


General/ Open Discussion

10. Please use this section of the meetingsphere tool to discuss openly (irrespective of topic or user type) | Aaron Chrietzberg

7. test | Aaron Chrietzberg

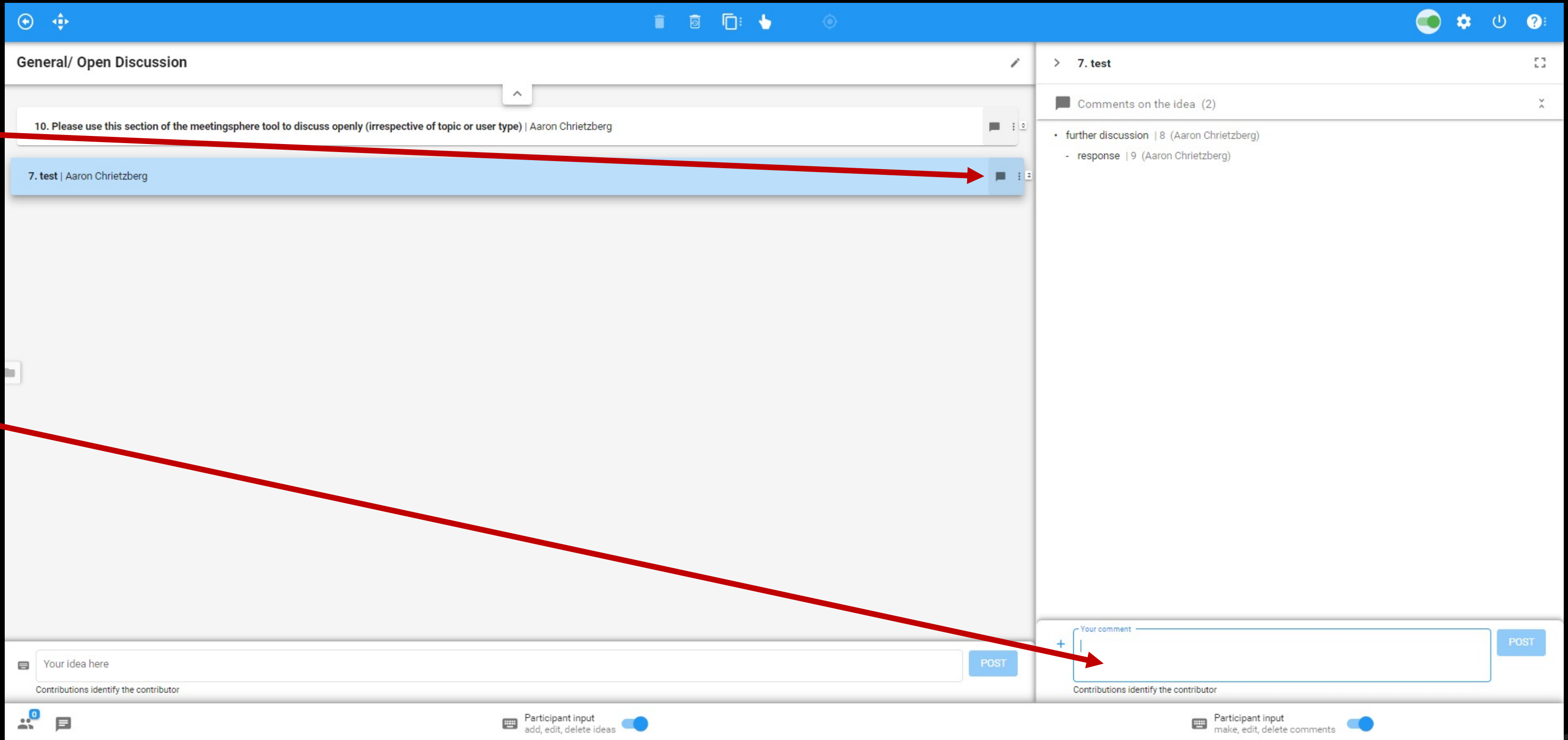
7. test

Comments on the idea (2)

- further discussion | 8 (Aaron Chrietzberg)
  - response | 9 (Aaron Chrietzberg)

Open Discussion Chat (continued):

- To reply to a comment – or discuss further – click on the folder to the right of the initial comment.
- To reply, enter your comments in the comment section provided at the bottom right.
- If you wish to respond to a specific comment, on the right you can click on the initial comment before replying at the bottom right.



General/ Open Discussion

10. Please use this section of the meetingsphere tool to discuss openly (irrespective of topic or user type) | Aaron Chrietzberg

7. test | Aaron Chrietzberg

7. test

Comments on the idea (2)

- further discussion | 8 (Aaron Chrietzberg)
  - response | 9 (Aaron Chrietzberg)

PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

NASA

PLANETARY DEFENSE COORDINATION OFFICE

FEMA

APL
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

cneos

Ames Research Center

EMERGENCY MANAGEMENT
NORTH CAROLINA

WINSTON-SALEM FORSYTH COUNTY NC
EMERGENCY MANAGEMENT
Est. 1951

NASA’s Planetary Defense Program

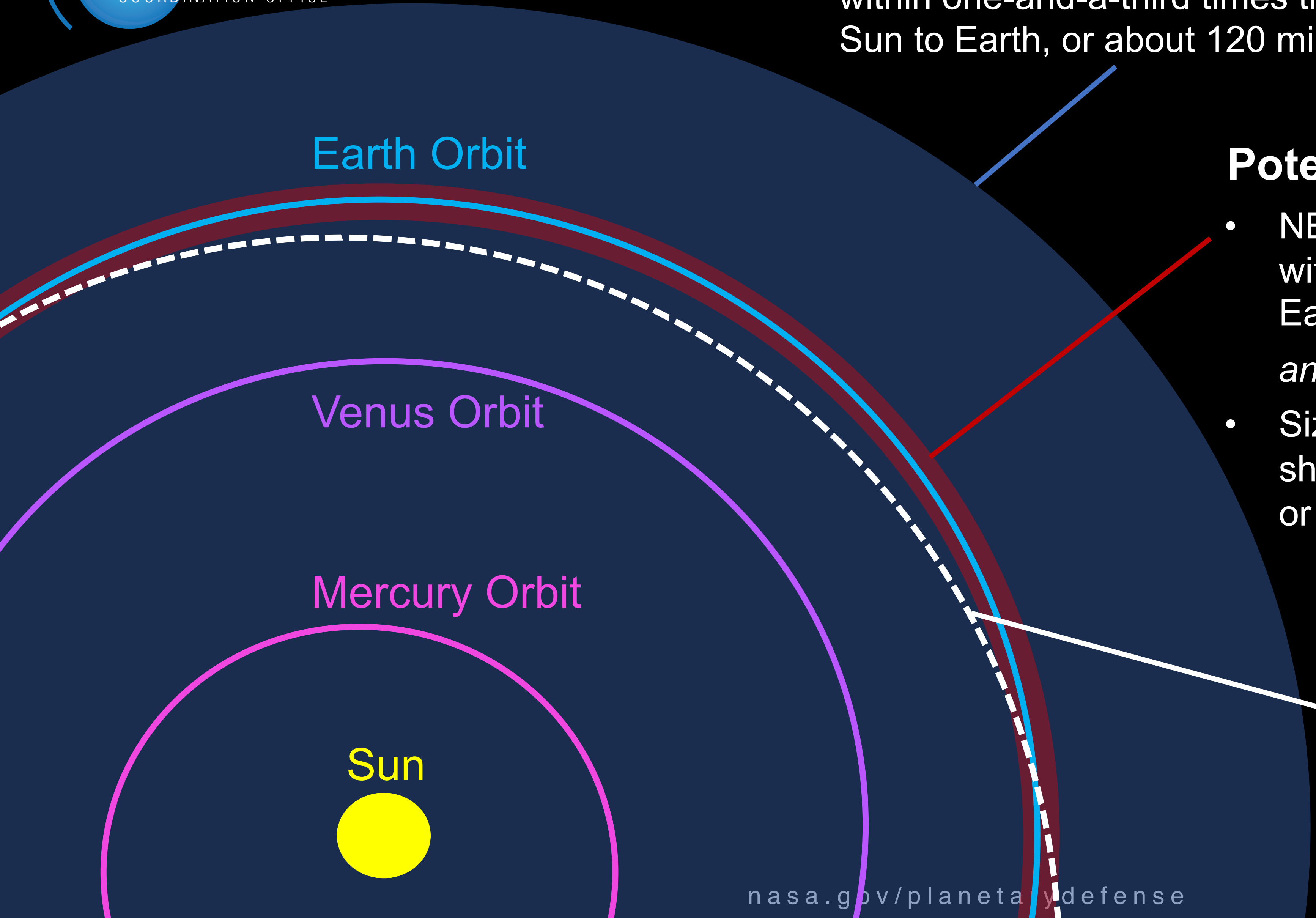
Lindley Johnson
NASA’s Planetary Defense Officer

Kelly Fast
Near-Earth Object Observations Program Manager

Planetary Defense Coordination Office
Planetary Science Division
NASA Headquarters
Washington, DC

23 February 2022

PLANETARY DEFENSE
COORDINATION OFFICE



Near-Earth Objects (NEOs)

Asteroids and comets with orbits that bring them within one-and-a-third times the distance from the Sun to Earth, or about 120 million miles (blue zone)

Potentially Hazardous Objects

- NEOs with orbits that bring them within about 5 million miles of Earth's orbit (red zone)

and

- Size that could do regional damage should they impact Earth (~500 feet or ~140 meters in size and larger)

Orbit of Bennu

- Potentially hazardous asteroid
- Object of NASA's OSIRIS-REx mission

Planetary Defense Coordination Office

The Planetary Defense Coordination Office (PDCO) was established in January 2016 at NASA HQ to manage planetary defense–related activities across NASA as well as coordinate with both U.S. interagency and international efforts to study and plan a response to the asteroid impact hazard.

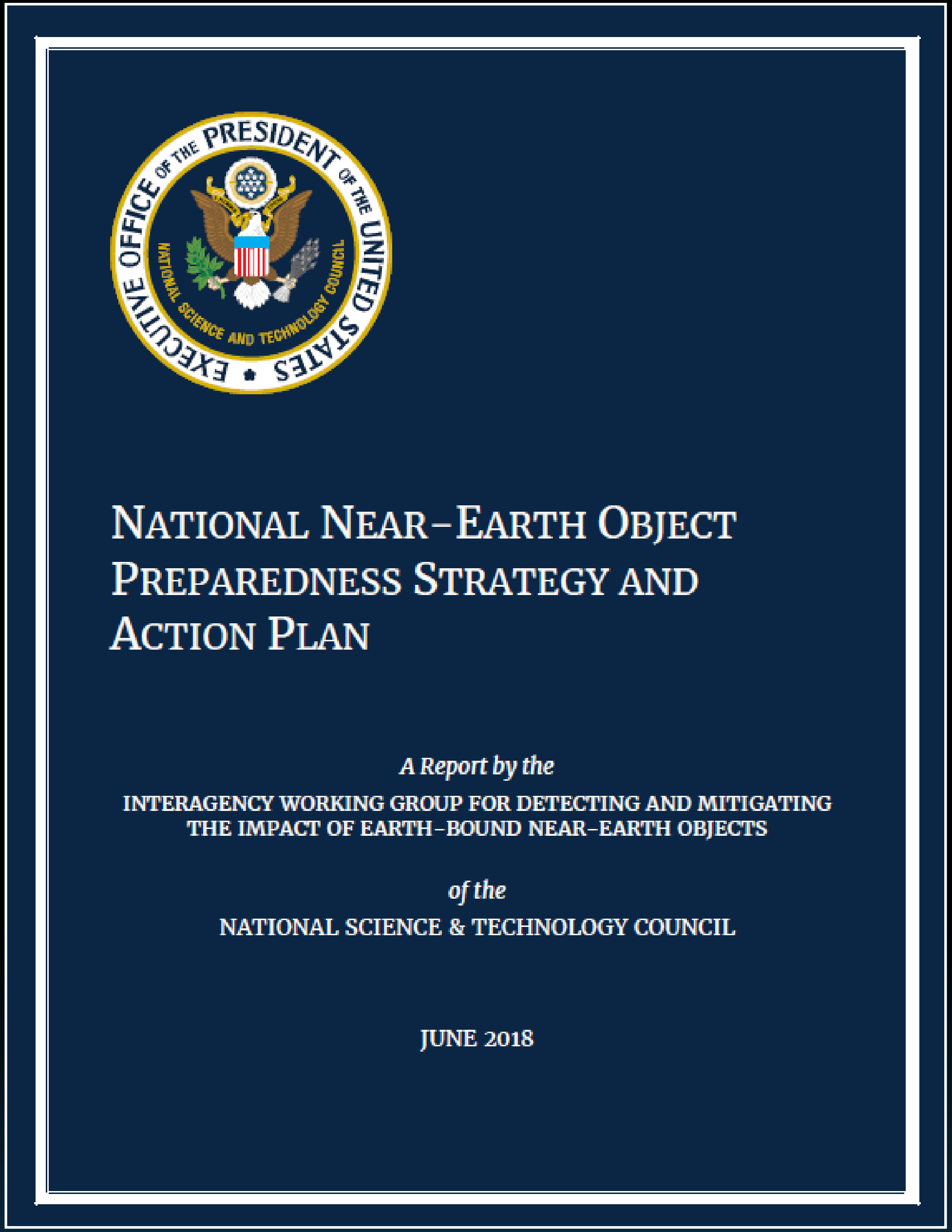
Mission Statement

Lead national and international efforts to:

- Detect any potential for significant impact of Earth by natural objects
- Appraise the range of potential effects by any possible impact
- Develop strategies to mitigate impact effects on human welfare

White House Guidance released on 20 June 2018

https://www.nasa.gov/sites/default/files/atoms/files/ostp-neo-strategy-action-plan-jun18.pdf



NATIONAL NEAR–EARTH OBJECT PREPAREDNESS STRATEGY AND ACTION PLAN

A Report by the

INTERAGENCY WORKING GROUP FOR DETECTING AND MITIGATING THE IMPACT OF EARTH–BOUND NEAR–EARTH OBJECTS

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

JUNE 2018

PLANETARY DEFENSE
COORDINATION OFFICE

National Near-Earth Object Preparedness Strategy and Action Plan

Goals in the 10-year Action Plan:

- Enhance NEO detection, characterization, and tracking capabilities
- Improve modeling, predictions, and information integration
- Develop technologies for NEO deflection and disruption
- Increase international cooperation on NEO preparation
- Establish NEO impact emergency procedures and action protocols

PLANETARY DEFENSE

ASSESS

[CENTER FOR NEAR EARTH OBJECT STUDIES]

SEARCH, DETECT & TRACK

[SPACE-BASED & GROUND-BASED OBSERVATIONS, IAWN]

MITIGATE

[DART, FEMA EXERCISES]

CHARACTERIZE

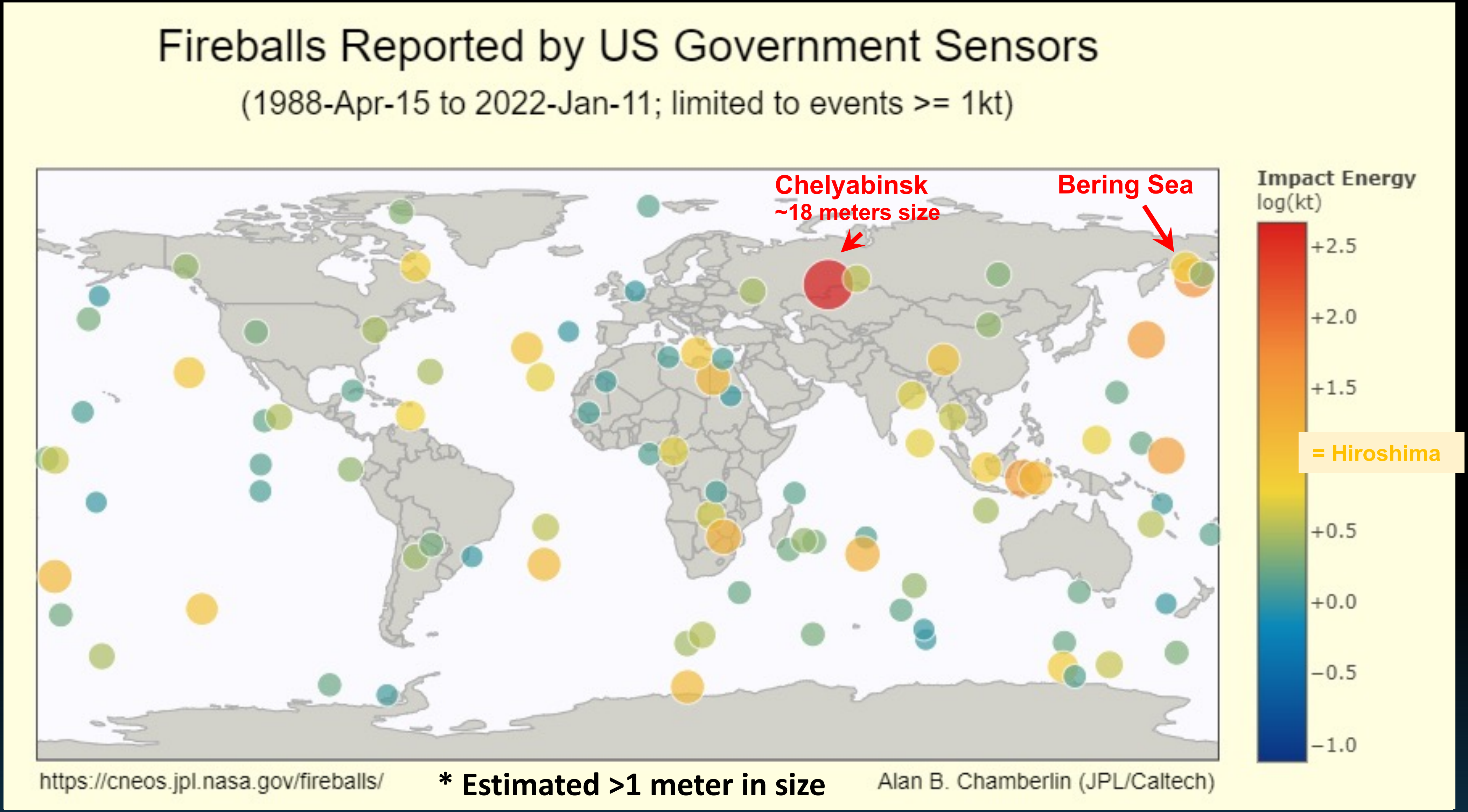
[NEOWISE, GOLDSTONE, IRTF]

PLAN & COORDINATE

[SMPAG, PIERWG, NITEP IWG]

PLANETARY DEFENSE
COORDINATION OFFICE

Small Asteroid* Impacts – 886 Reported



Fireballs Reported by US Government Sensors

(1988-Apr-15 to 2022-Jan-11; limited to events >= 1kt)

Chelyabinsk
~18 meters size

Bering Sea

https://cneos.jpl.nasa.gov/fireballs/

*** Estimated >1 meter in size**

Alan B. Chamberlin (JPL/Caltech)

PLANETARY DEFENSE
COORDINATION OFFICE

Asteroid Impact Relative Energy

Diameter of Impacting Asteroid	Type of Event	Approximate Impact Energy (MT)	Average Time Between Impacts (Years)
5 m (16 ft)	Bolide	0.01	1
10 m (33 ft)	Superbolide	0.1	10
25 m (80 ft)	Major Airburst	1	100
50 m (160 ft)	Local Scale Devastation	10	1000
140 m (460 ft)	Regional Scale Devastation	300	20,000
300 m (1000 ft)	Continent Scale Devastation	2,000	70,000
600 m (2000 ft)	Below Global Catastrophe Threshold	20,000	200,000
1 km (3300 ft)	Possible Global Catastrophe	100,000	700,000
5 km (3 mi)	Above Global Catastrophe Threshold	10,000,000	30 million
10 km (6 mi)	Mass Extinction	100,000,000	100 million

Protected by atmosphere

Still vulnerable

Working on it!

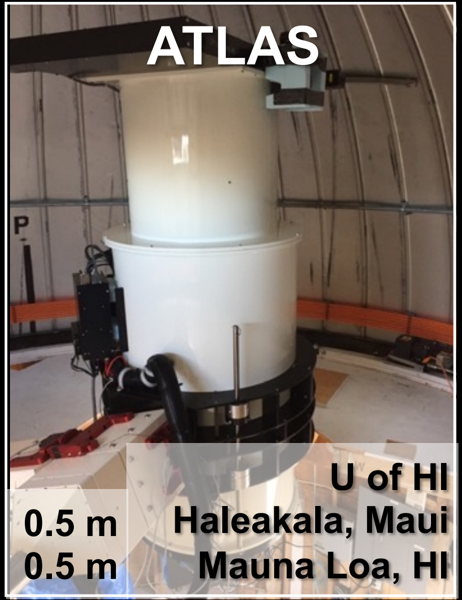
Found them all!

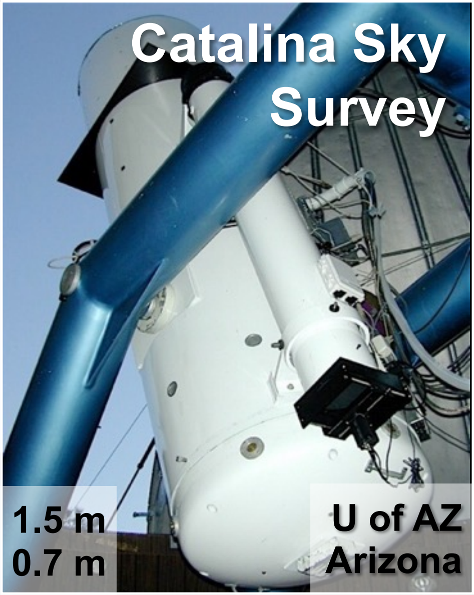
PLANETARY DEFENSE
COORDINATION OFFICE

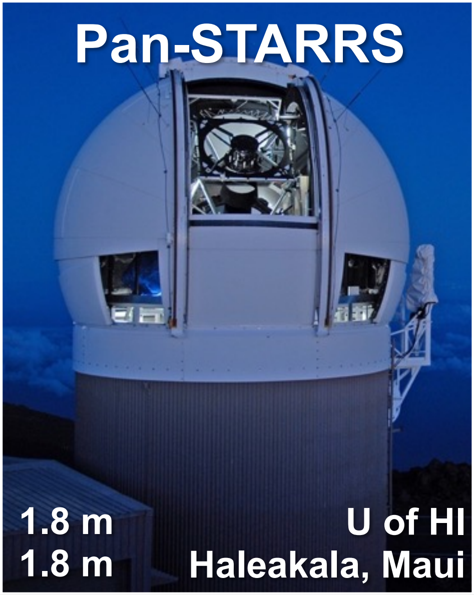
NASA’s NEO Search Program

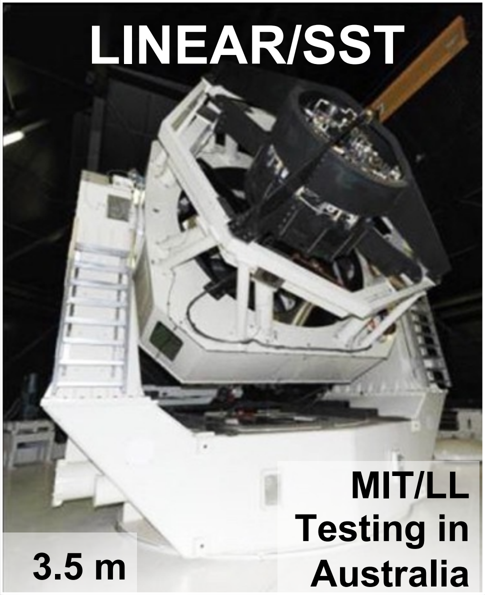
(Current Survey Systems)


NEOWISE
0.4 m
JPL
Sun-synchronous low Earth orbit


ATLAS
0.5 m U of HI
0.5 m Haleakala, Maui
Mauna Loa, HI


Catalina Sky Survey
1.5 m U of AZ
0.7 m Arizona

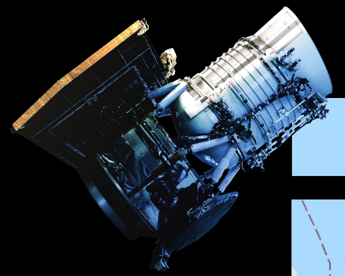

Pan-STARRS
1.8 m U of HI
1.8 m Haleakala, Maui


LINEAR/SST
3.5 m
MIT/LL
Testing in
Australia

ATLAS sites in Chile and South Africa were installed in 2021

Also processing of data for NEO detections from Caltech’s Zwicky Transient Facility

nasa.gov/planetarydefense



NEOWISE

NASA-Funded Near-Earth Object Survey (Discovery) Telescopes

ZTF (analysis)

Catalina Sky Survey

ATLAS HKO & MLO
Pan-STARRS 1 & 2

ATLAS CHL

ATLAS STH

LINEAR/SST (analysis)

Planetary Data System's Small Bodies Node

NEO position measurements from observatories --------▸

IAU The International Astronomical Union
Minor Planet Center
http://minorplanetcenter.net/

----▸
- Identification
- Designation
- Initial orbit computation

NASA Jet Propulsion Laboratory
California Institute of Technology
cneos Center for Near Earth Object Studies
https://cneos.jpl.nasa.gov/

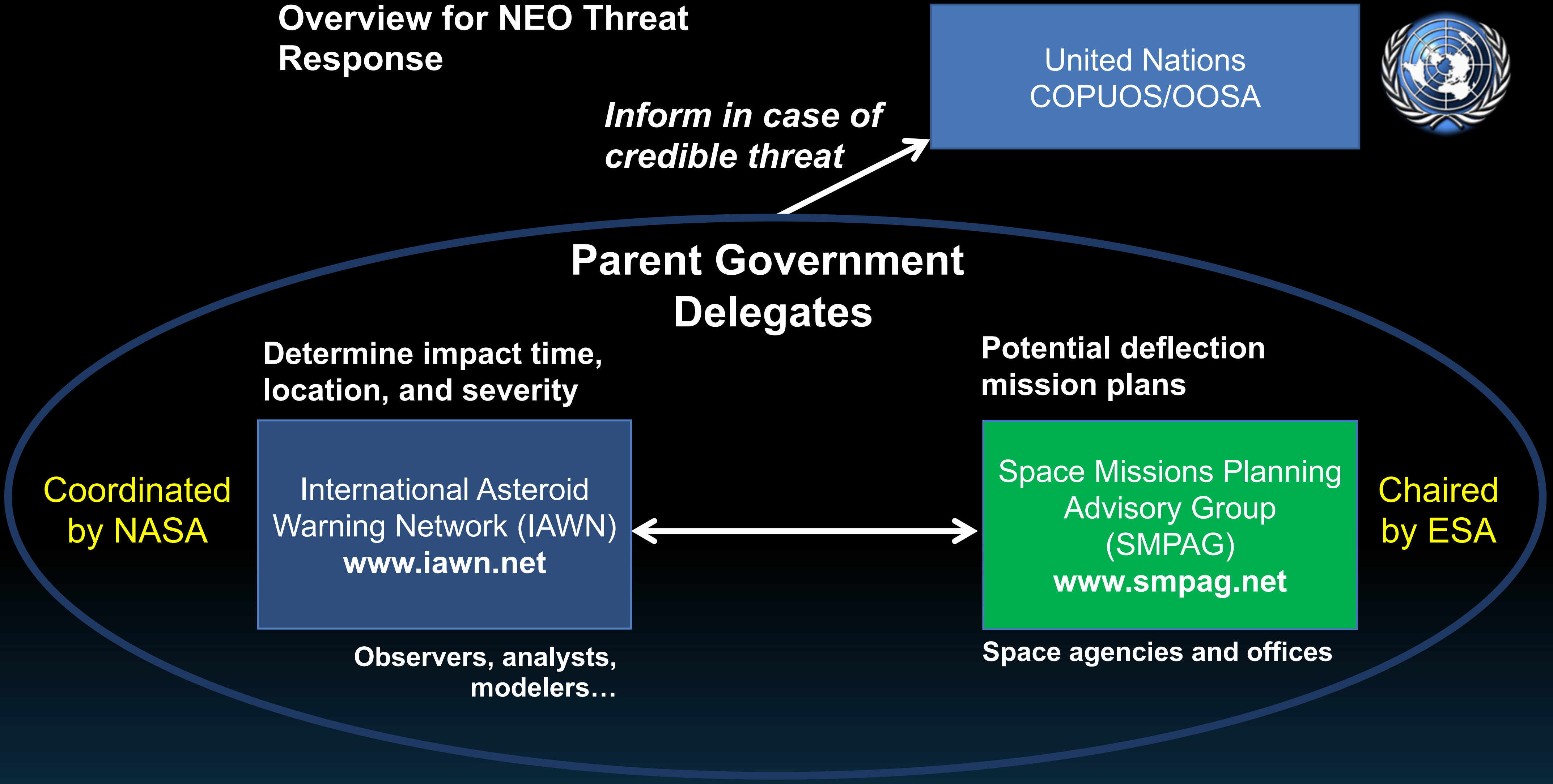
--------▸ High-precision NEO orbits
- Short term: new discoveries
- Long term: future orbits of hazardous asteroids

--------▸ Time, location, and geometry in the event of a predicted impact

https://cneos.jpl.nasa.gov/sentry/

United Nations Office for Outer Space Affairs (OOSA)
Committee on the Peaceful Uses of Outer Space (COPUOS)

Overview for NEO Threat Response



United Nations
COPUOS/OOSA

Inform in case of credible threat

Parent Government Delegates

Determine impact time, location, and severity

Coordinated by NASA

International Asteroid Warning Network (IAWN)
www.iawn.net

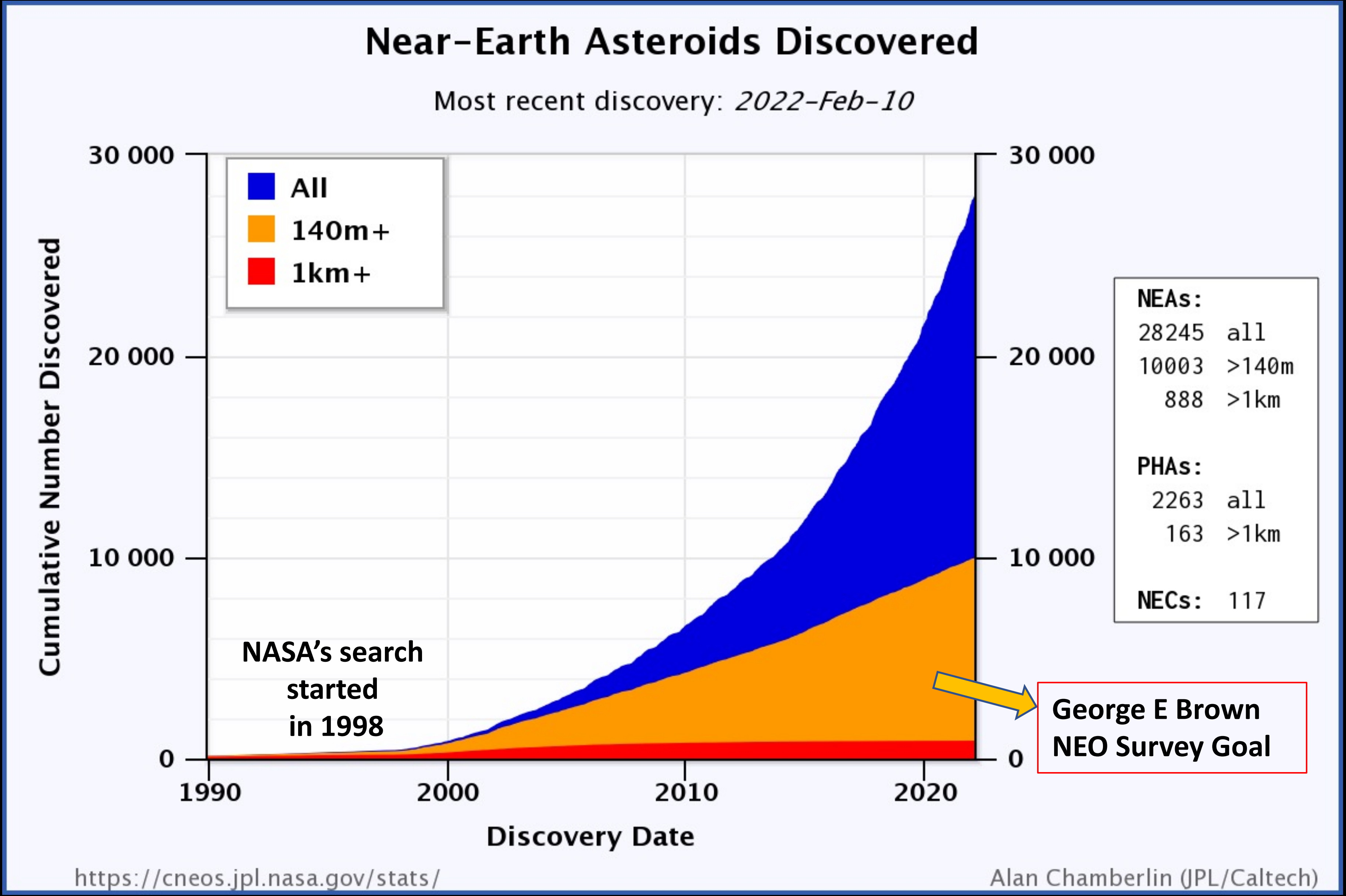
Observers, analysts, modelers…

Potential deflection mission plans

Space Missions Planning Advisory Group (SMPAG)
www.smpag.net

Chaired by ESA

Space agencies and offices



Near-Earth Asteroids Discovered

Most recent discovery: *2022-Feb-10*

NASA's search started in 1998

George E Brown NEO Survey Goal

https://cneos.jpl.nasa.gov/stats/

Alan Chamberlin (JPL/Caltech)

**Potentially Hazardous Asteroids come within 7.5 million kilometers of Earth orbit*

nasa.gov/planetarydefense

PLANETARY DEFENSE
COORDINATION OFFICE

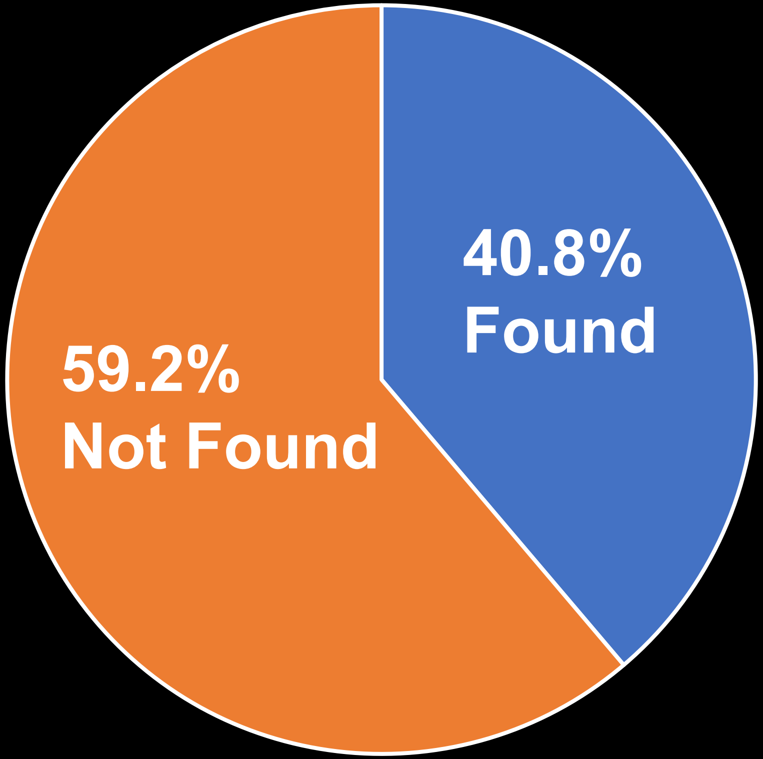
Progress: 140 Meters and Larger

Total population estimated to be ~25,000

George E. Brown NEO Survey Goal: (tasked in 2005)

Find at least 90% of NEOs 140 meters and larger within 15 years

NEO Survey Status as of 31 Dec 2021

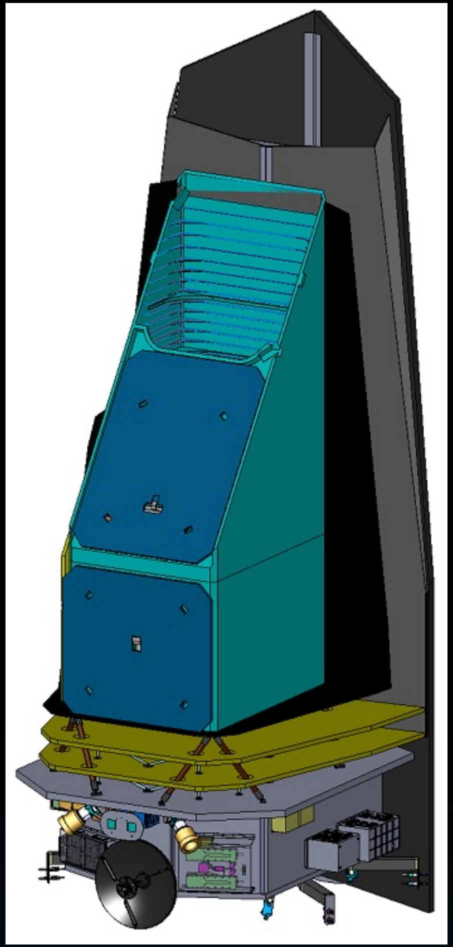


At the current assets' discovery rate, it will take more than 30 years to complete the survey. New capabilities in development will cut that time in half.

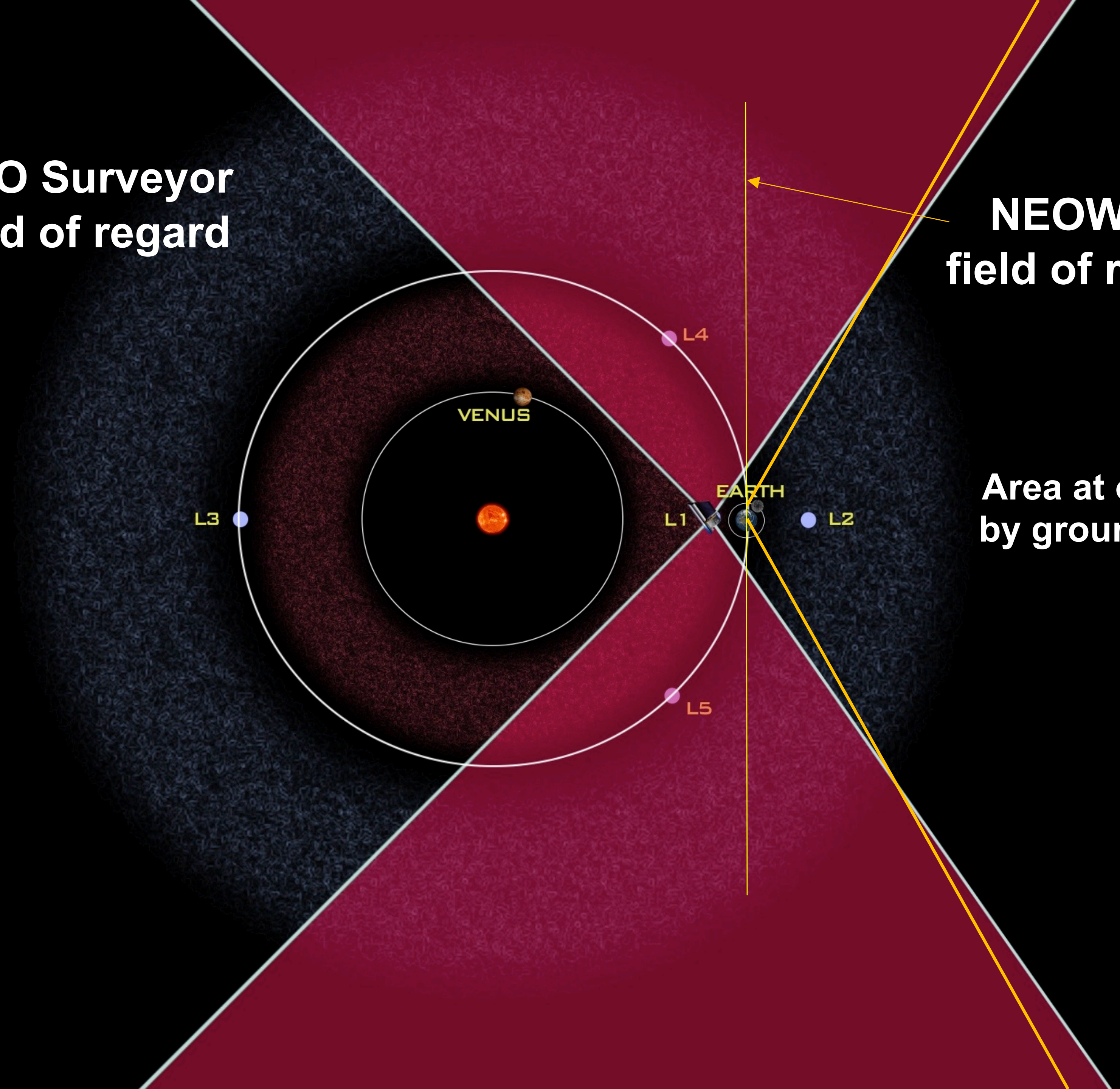
NEO Surveillance Mission

Objectives:

- Find 65% of undiscovered potentially hazardous asteroids (PHAs) >140 meters in 5 years (goal: >90% in 10 years)
- Estimate sizes directly from infrared signatures
- Compute cumulative chance of impact over next century for PHAs >50 meters and for comets
- Deliver new tracklet data daily to the Minor Planet Center
- On track for PDR and KDP-C "Confirmation" in fall 2022
- President's Budget Request for FY22, if enacted, would fully fund the Phase B project development
- Planned launch readiness date in early 2026



NEO Surveyor Space-Based IR Observatory



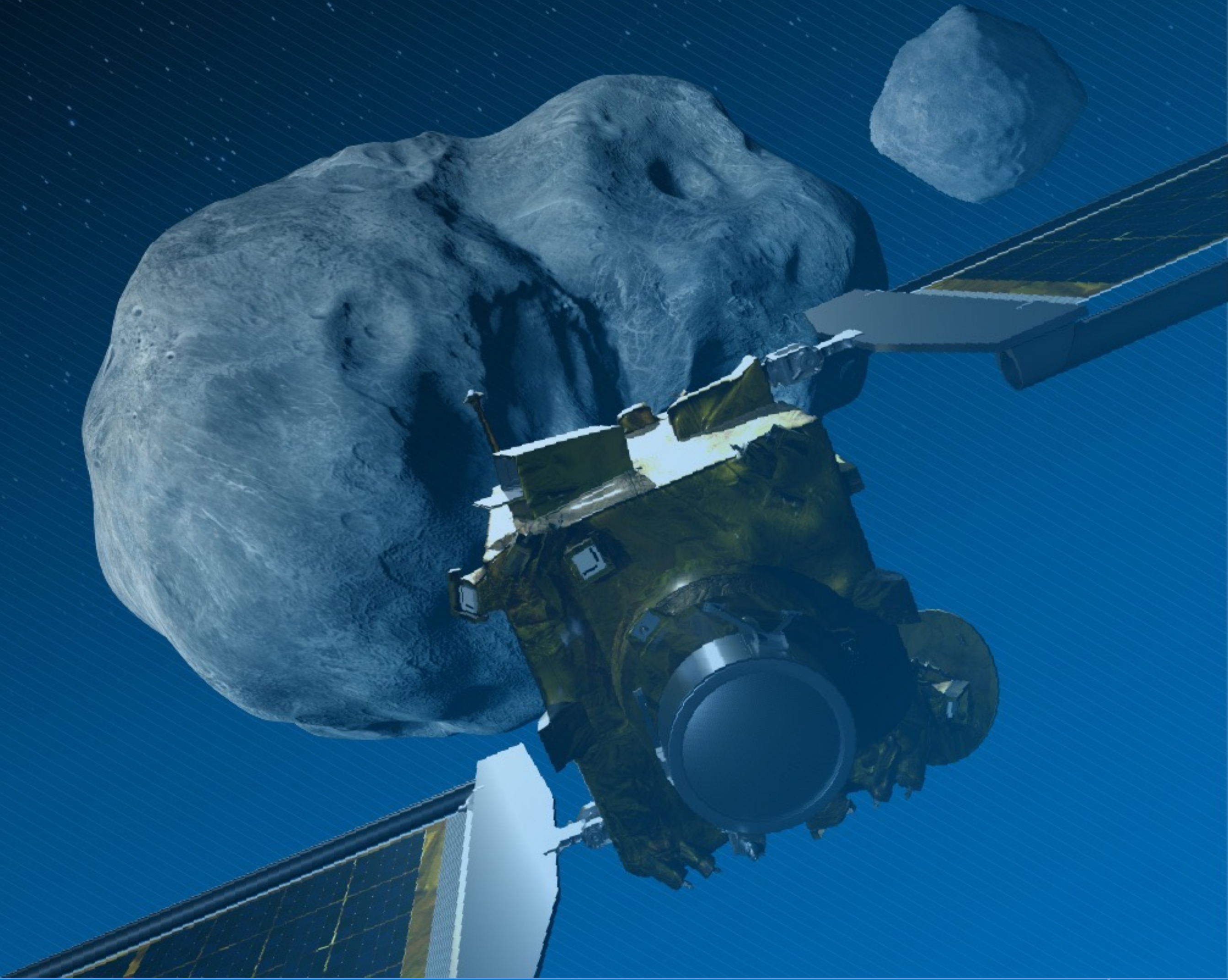
NEO Surveyor field of regard

NEOWISE field of regard

Area at opposition seen by ground-based assets

DART

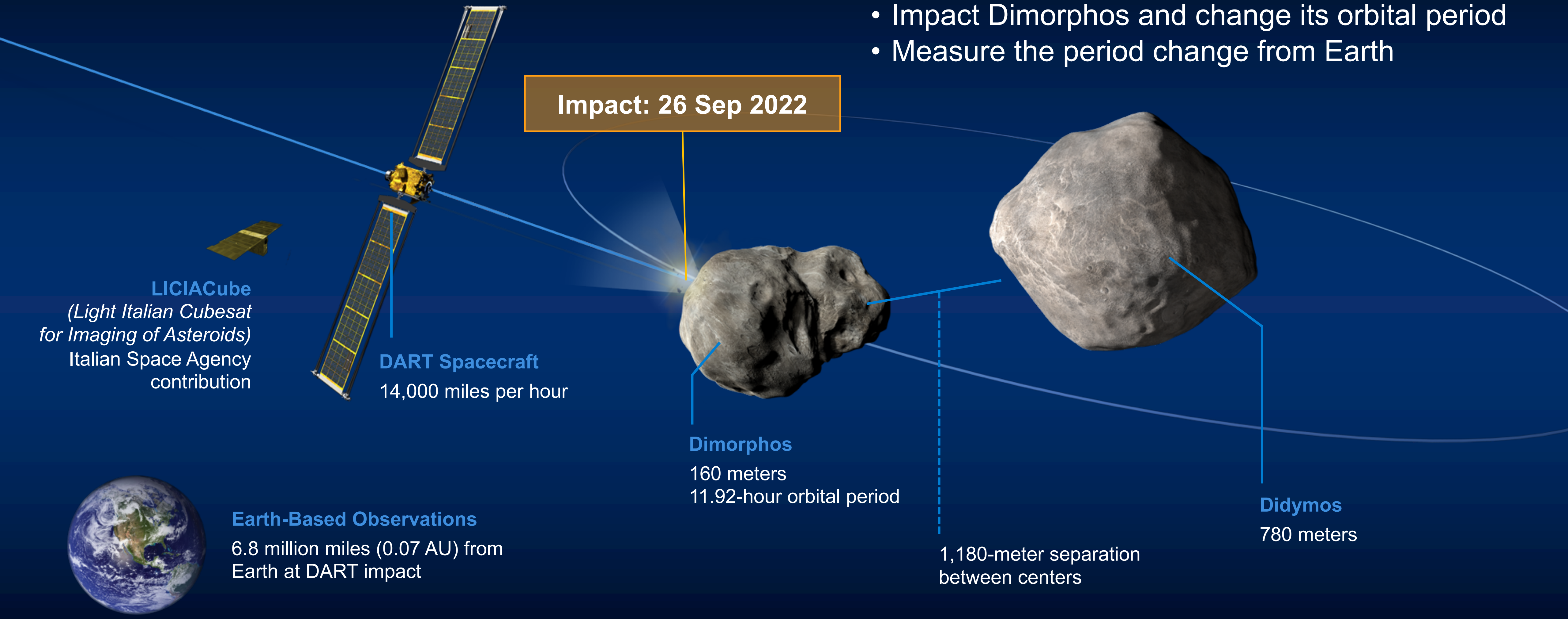
Double Asteroid Redirection Test



Launched on 24 Nov 2021 at 1:21 a.m. EST

SpaceX Falcon 9
Vandenberg Space Force Base, CA

- Target the binary asteroid Didymos system
- Impact Dimorphos and change its orbital period
- Measure the period change from Earth



Impact: 26 Sep 2022

LICIACube
(Light Italian Cubesat for Imaging of Asteroids)
Italian Space Agency contribution

DART Spacecraft
14,000 miles per hour

Dimorphos
160 meters
11.92-hour orbital period

1,180-meter separation between centers

Didymos
780 meters

Earth-Based Observations
6.8 million miles (0.07 AU) from Earth at DART impact

PLANETARY DEFENSE
COORDINATION OFFICE

NASA

nasa.gov/planetarydefense

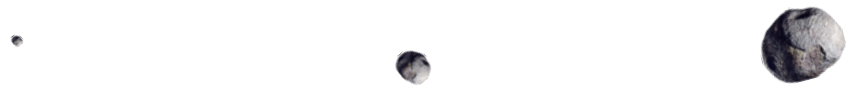
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

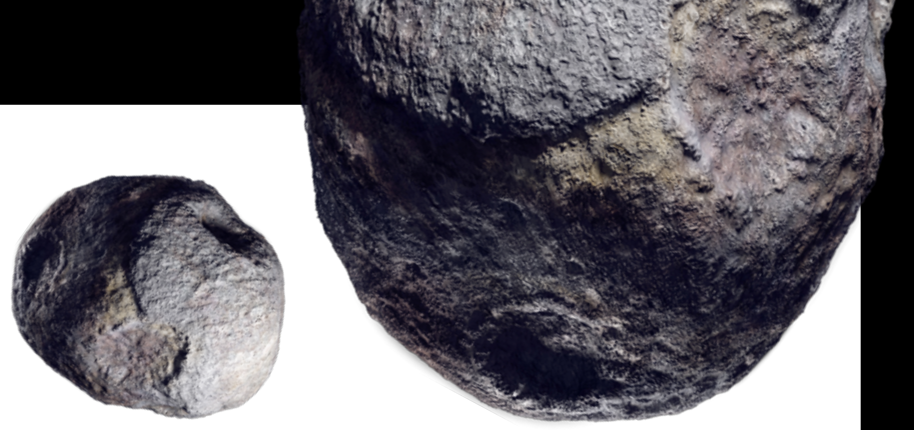
Asteroid Impacts

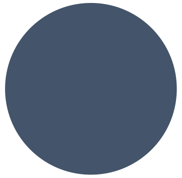
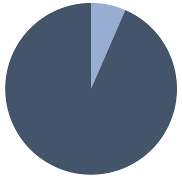
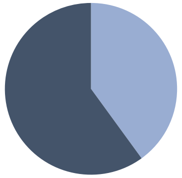
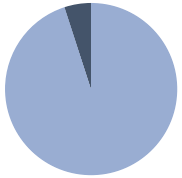
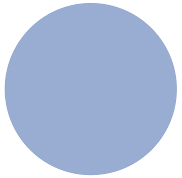
Consequences and Analogies

Andy Rivkin
Johns Hopkins Applied Physics Laboratory
andy.rivken@jhuapl.edu

The Hazard by the Numbers





How Big?	**10 meters**	**50 meters**	**140 meters**	**1000 meters**	**10,000 meters**
How Often?	~1 per **decade**	~1 per **1000 years**	~1 per **20,000 years**	~1 per **700,000 years**	~1 per **100 million years**
How Bad?	Very bright fireball, strong sonic boom could break windows if close to habitation	Local devastation, regional effects, may or may not leave an impact crater	Crater of 1–2 kilometers in diameter, deadly over metro areas/states, mass casualties	10-kilometer crater, global devastation, possible collapse of civilization	100-kilometer crater, global devastation, mass extinctions of terrestrial life
Approx. impact energy (megatons)	0.1	10	300	100,000	100,000,000
How Many?	**~45 million**	**~120,000**	**~25,000**	**~900**	**4**
% Discovered	**0.03%**	**7%**	**40%**	**95%**	**100%**
● Located ● Not located					

Small Celestial Debris Hits Earth Frequently, Mostly Burns Up

- 100 tons of material impacts the Earth every day (mostly dust)

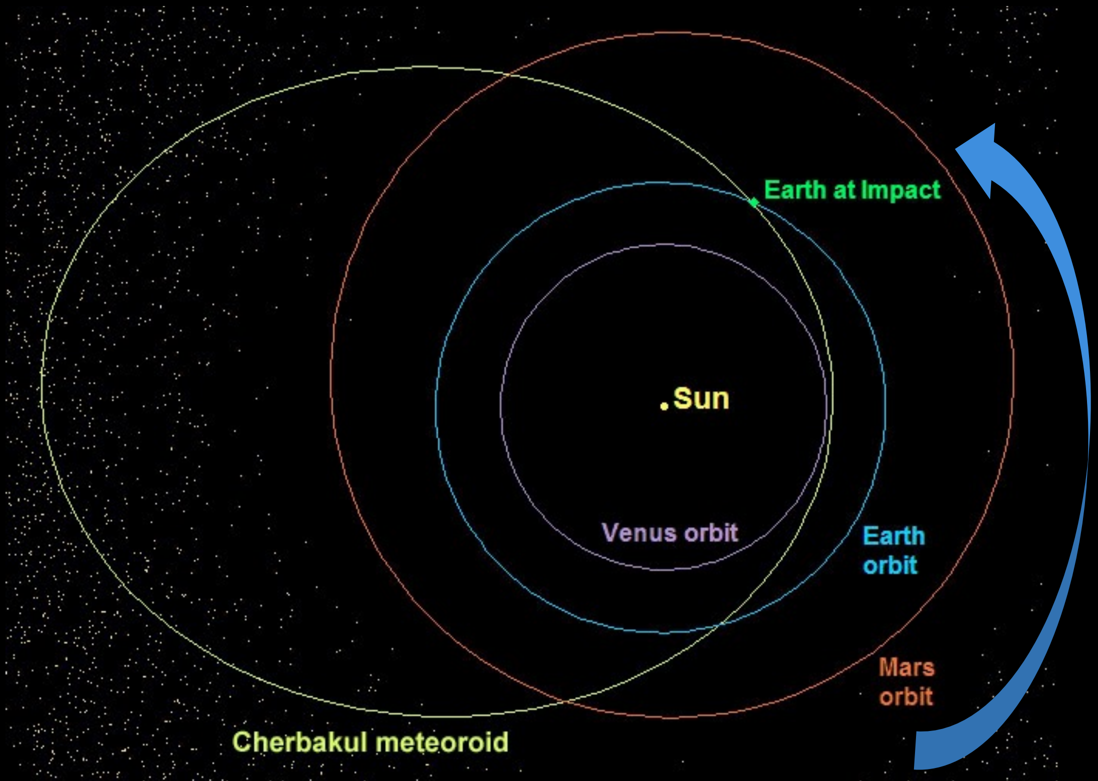
Peekskill Impact, October 1992

- Asteroid of roughly 1–2 m in diameter impacted Earth on 9 October 1992
- Airburst over eastern United States
- Largest recovered piece was 30 cm in diameter, struck car in New York City suburb of Peekskill


000km/h
2013/02/15 09:20:26
RT

Chelyabinsk Impactor's Orbit

- Originated in main asteroid belt
- Approached Earth from sunward direction
- Roughly 20–25 m in diameter



- Objects move counterclockwise around the Sun in this view

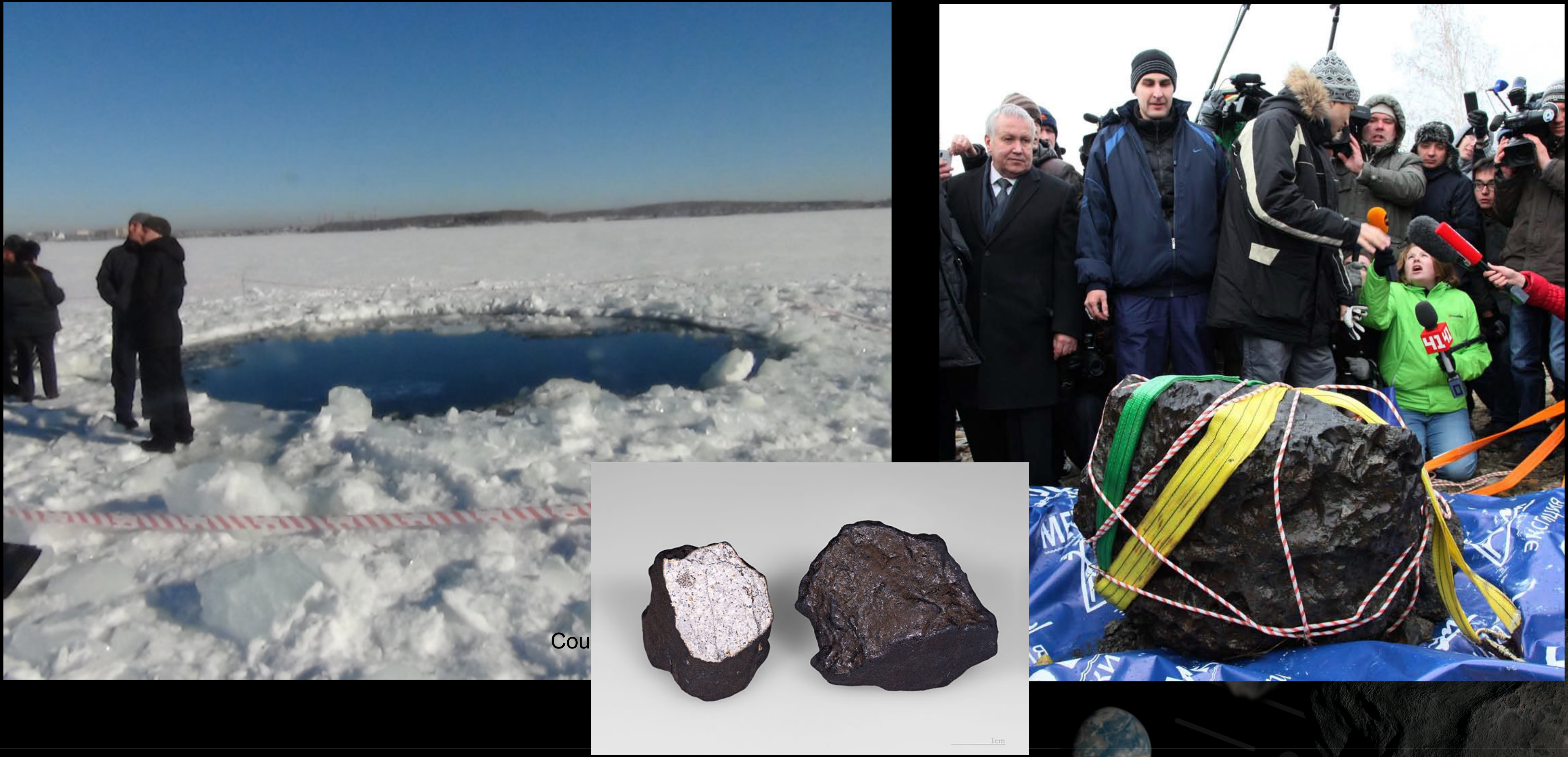
A Sense of Scale

Chelyabinsk impactor estimated to be about half the size of an Olympic-size pool (in two dimensions)

2016 U.S. Olympic trials
in Omaha, Nebraska


RT

Main Chelyabinsk Meteorite Landed in a Frozen Russian Lake



Meteor Crater (50,000 Years Ago)

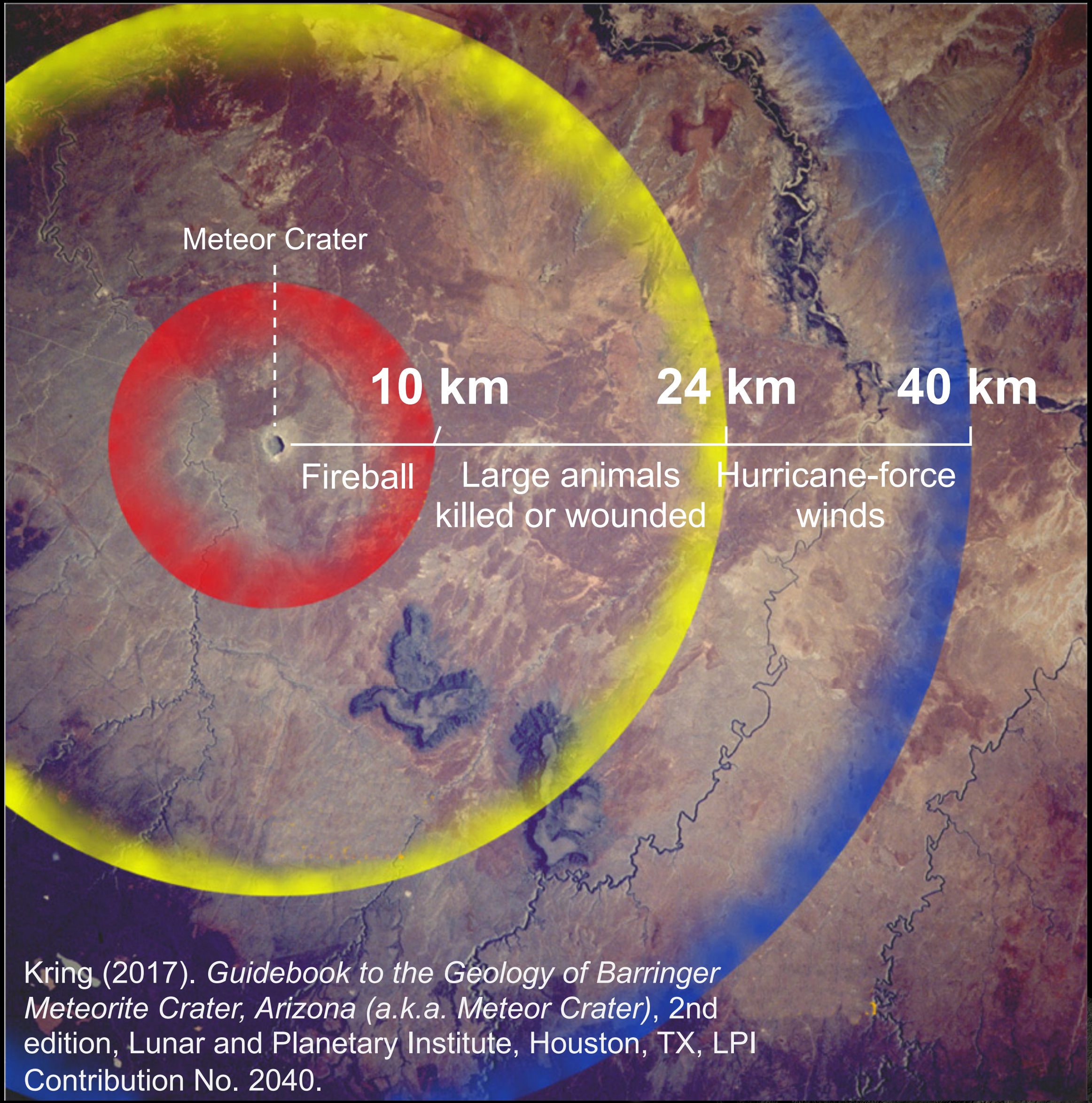
40- to 50-m metallic asteroid, 1-km crater,
every 10 thousand years or so

Many of the early geological studies focused on finding the big iron body they thought would be there…

…but the nature of these supersonic impacts destroys and disperses the impactor.

Barringer (“Meteor”) Crater

USGS/D. Roddy

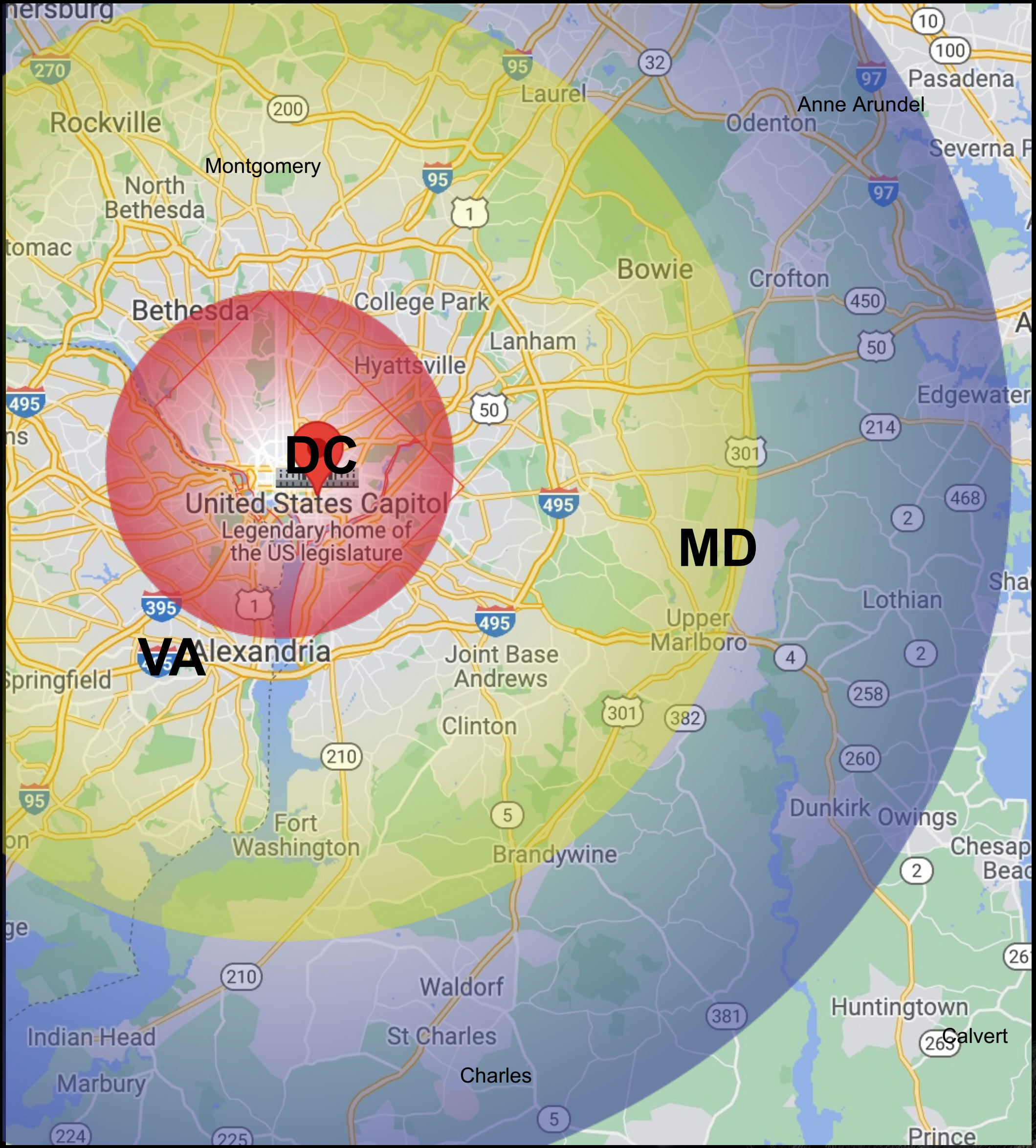


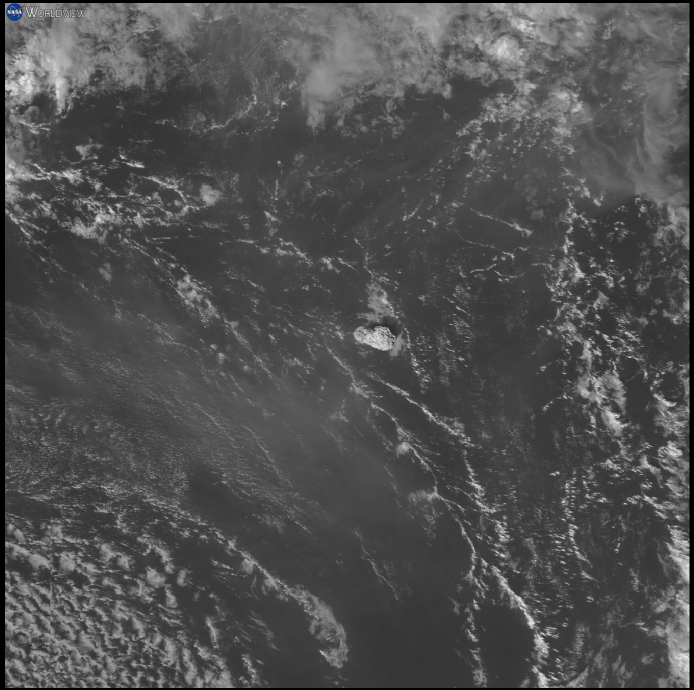
Kring (2017). *Guidebook to the Geology of Barringer Meteorite Crater, Arizona (a.k.a. Meteor Crater)*, 2nd edition, Lunar and Planetary Institute, Houston, TX, LPI Contribution No. 2040.

Barringer (“Meteor”) Crater

What if?

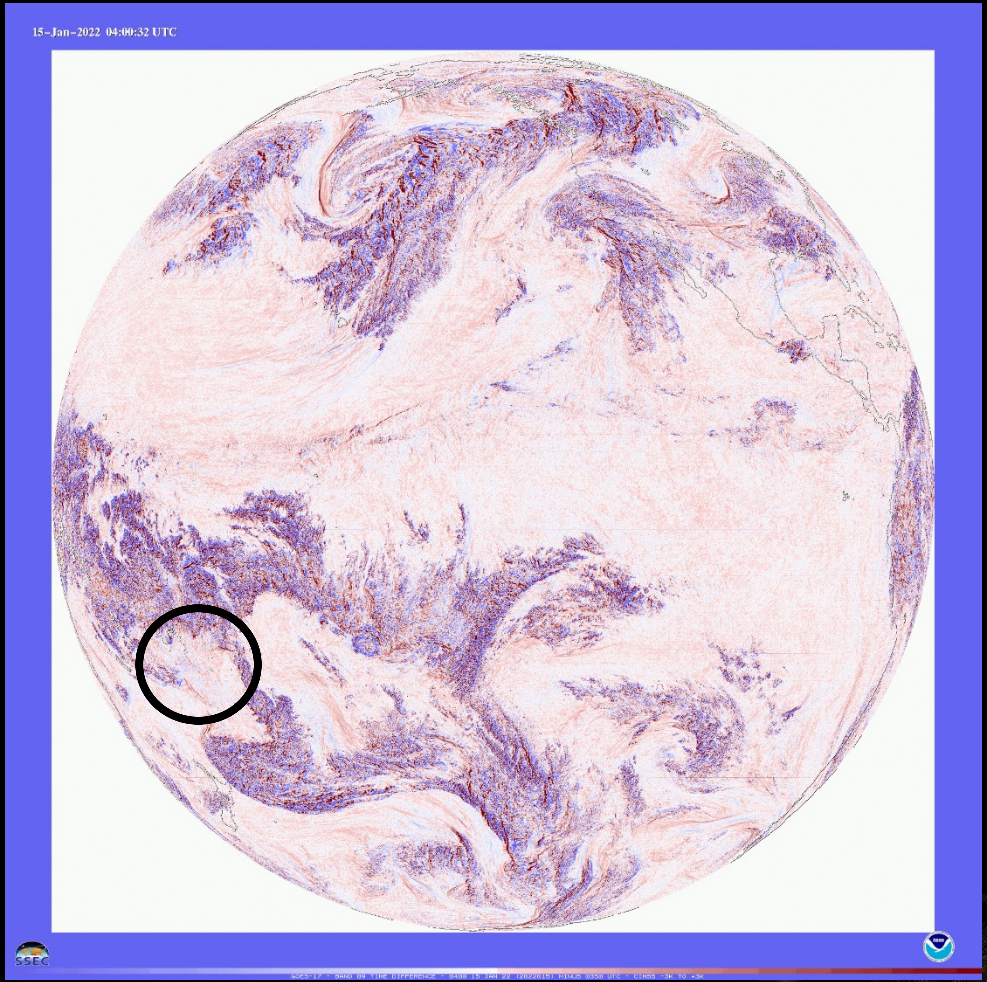
Photograph by Mario Roberto Durán Ortiz, 2014 (Creative Commons CC-BY-SA 4.0)





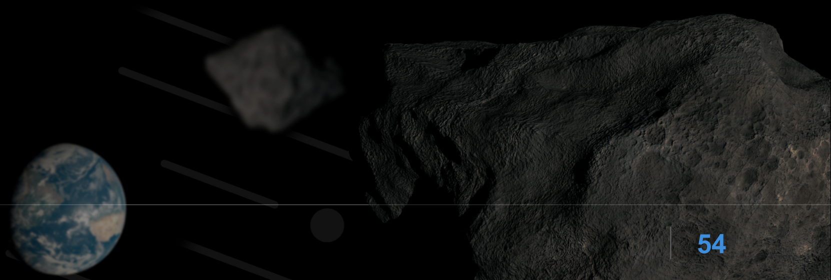
Tonga volcanic eruption on 15 January 2022:

- Estimated energy of 4–20 MT of TNT
- Equivalent to impact of typical 50- to 75-m asteroid at typical speeds



What do we need to know, and how do we learn it?

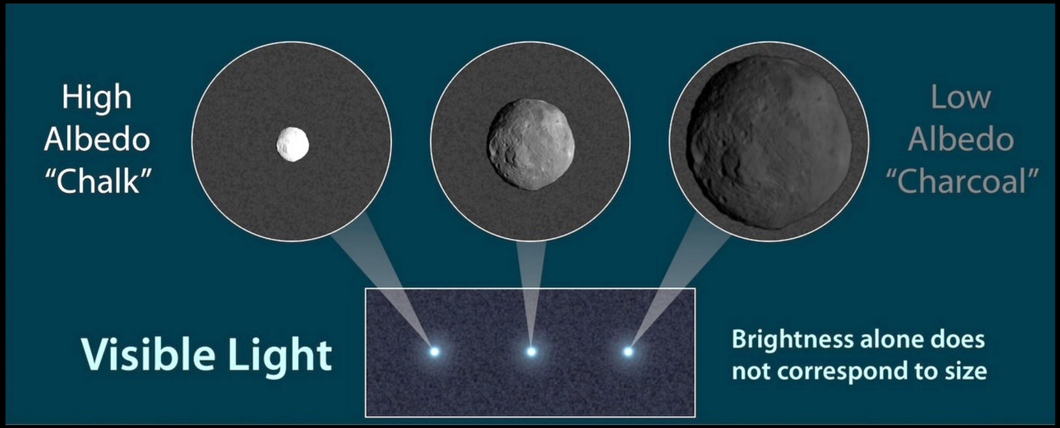
- Impact energy!
  - Speed
  - Mass
- Mass hard to remotely measure
  - Size
  - Density
- Size can be measured/estimated remotely
  - Measure reflected brightness, estimate reflectivity
  - Measure emitted heat, directly get size
- Can sometimes remotely measure composition
  - When available, allows density estimate, reflectivity estimate



Seizing Sizes

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

- Usually, we observe brightness, not size.
- Big dark things can be as bright as small high-albedo ("shiny") things.
- One of the snowballs on the right would be as bright as one of the bricks of charcoal if all we could measure was the amount of light from each.
- Until/unless a more diagnostic measurement can be made for a particular object, we must estimate its size from its brightness.



Bottom-Line Takeaways

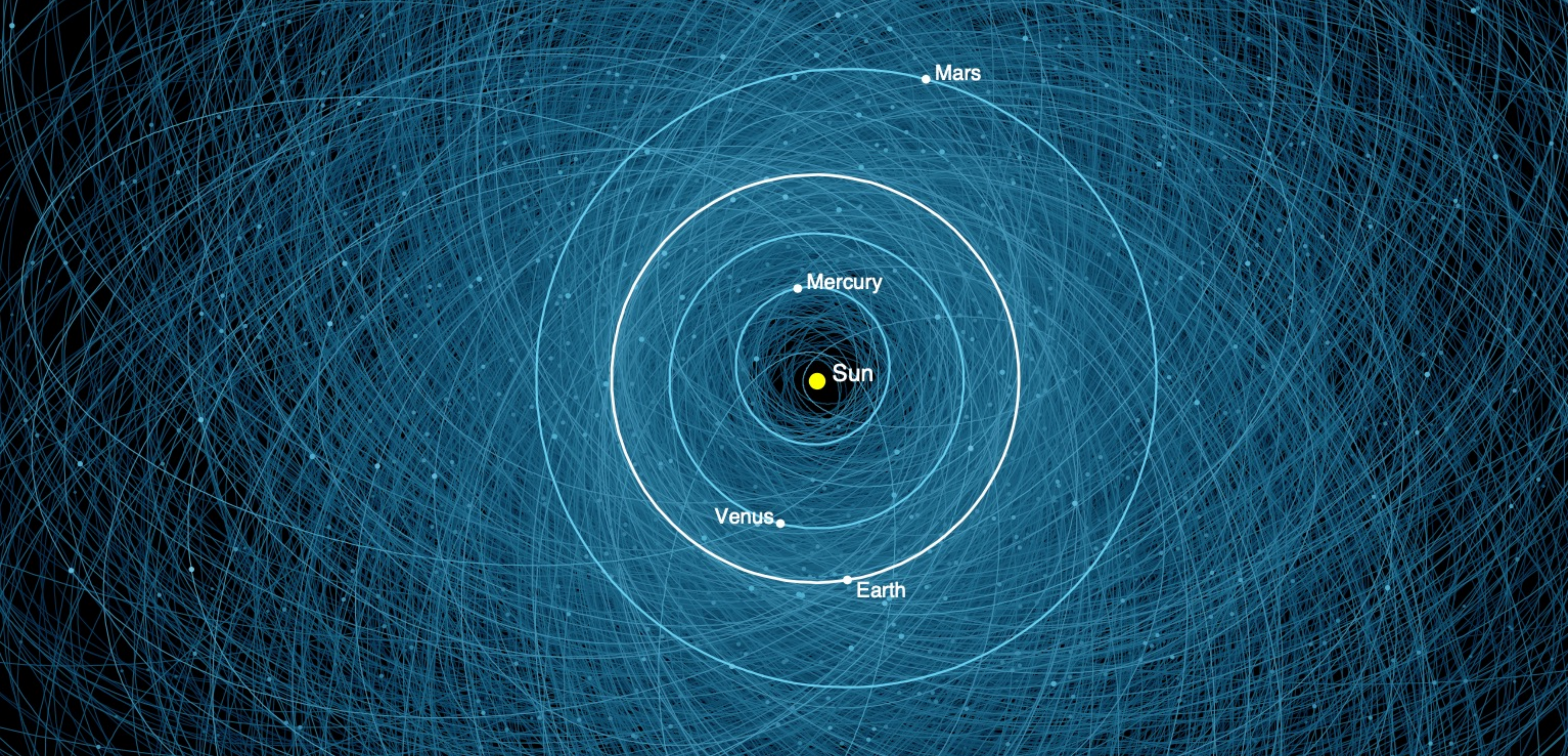
- Impacts happen all the time.
- Larger impacts happen less frequently, but with increased consequences.
- Impacts of 50-m objects can devastate a region.
- Properties that we want to know must often be estimated rather than directly measured.

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Introduction to CNEOS, Predicting Impacts, and 2022 TTX

How asteroids are discovered, orbits computed and the chances of impact assessed

Paul Chodas, Davide Farnocchia & Ryan Park
Center for NEO Studies (CNEOS)
Jet Propulsion Laboratory, California Institute of Technology



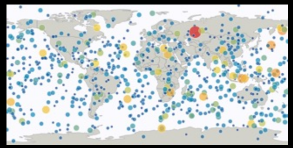
Orbits of Potentially Hazardous Asteroids (PHAs)

Center for
Near Earth Object
Studies

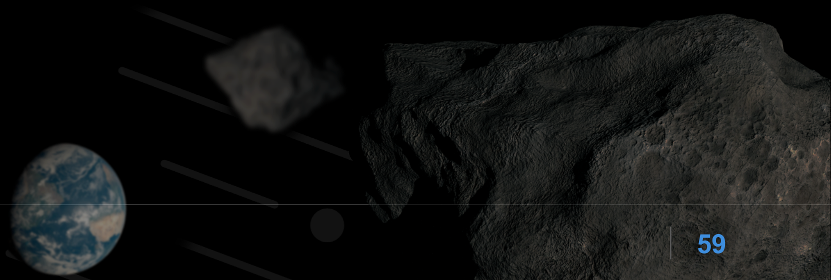
NASA's center for computing NEO orbits and assessing their chances of Earth impact

- Compute Orbits
- Predict Close Approaches
- Predict Sky Positions (Future & Past)
- Assess Chances of Impact (Sentry)
- Extensive Website (https://cneos.jpl.nasa.gov)

- Fireball Reports



- Searchable Small-Body Database
- Predict Accurate Impact Times and Locations (e.g. Shoemaker-Levy 9 in 1993 and 2008 TC3 in 2008)
- Design Hypothetical Impact Scenarios



Jet Propulsion Laboratory
California Institute of Technology

cneos Center for Near Earth Object Studies

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

CNEOS is NASA's center for computing asteroid and comet orbits and their odds of Earth impact.

Fireballs

Sentry

Quick Links

- NEO Basics
- NEO DB Query
- Sentry (impact risk)
- Accessible NEAs
- Close Approach Tutorial
- NASA PDCO
- Asteroid Watch on Twitter
- Horizons
- Solar System Dynamics

Next NEO Close Approach within 10 Lunar Distances (LD)

Object:	2022 BF
Date:	2022-Jan-26 01:50 ± 00:06 (hh:mm)
Dist:	1.27 LD (min: 1.27 LD)
H:	27.1

See our Close Approach Tables for more

Top News Stories

[full story]

NASA’s Next-Generation Asteroid Impact Monitoring System Goes Online

2021-12-06

To date, nearly 28,000 near-Earth asteroids (NEAs) have been found by survey telescopes that continually scan the night sky, adding new discoveries at a rate of about 3,000 per year. But as larger and more advanced survey telescopes turbocharge the search over the next few years, a rapid uptick in discoveries is expected. In anticipation of this increase, NASA astronomers have developed a next-generation impact monitoring algorithm called Sentry-II to better evaluate NEA impact probabilities.

International Observation Campaign Will Assess Asteroid Timing Accuracies

2021-10-07

The International Asteroid Warning Network (IAWN) will conduct an observational campaign in November with the goal of assessing the accuracy of the observation times reported by asteroid observers.

Asteroid Impacts Can Be Predicted Extremely Accurately

Tiny asteroid 2008 TC3 discovered 19 hours before impact in Oct. 2008

As tracking data came in, impact probability went to 100% within 1 hour

11 hours before impact we predicted the asteroid would hit in N. Sudan

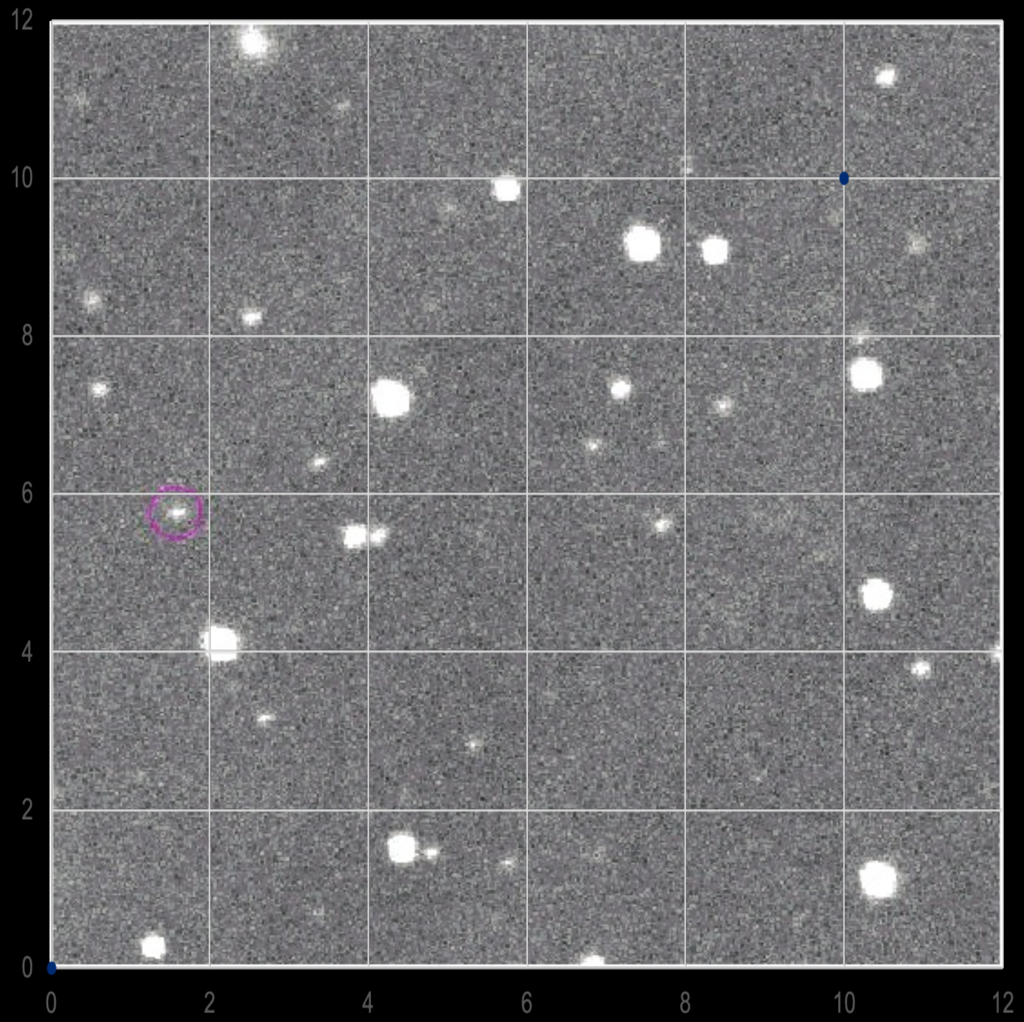
A month or so later a search party found meteorites within 1 km of our predicted path

Predicted path

Meteorites found within 1 km of predicted path

Meteorite on the desert floor

How Asteroids Are Discovered



Discovery images for 2008 TC3 from Catalina Sky Survey

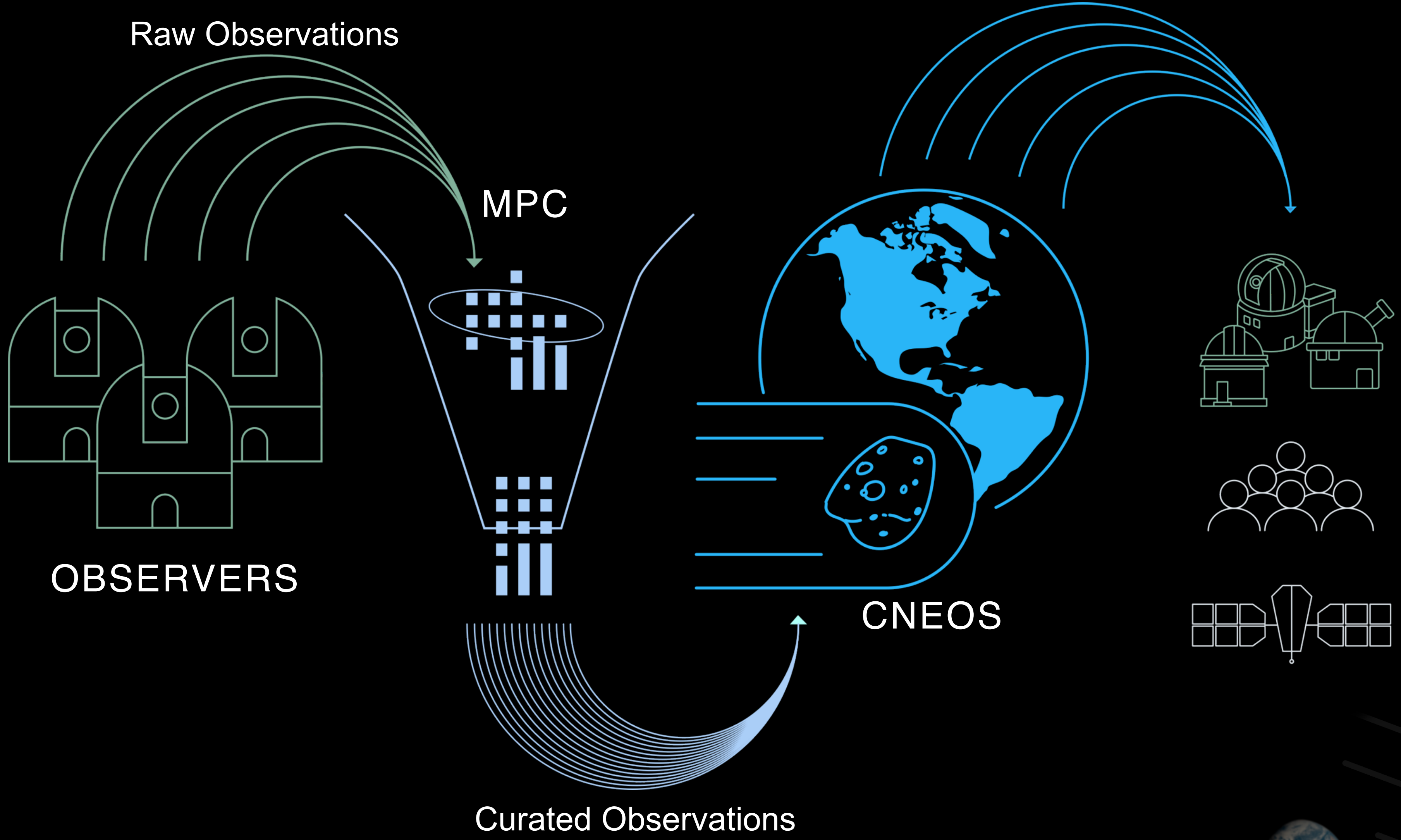
Ground-based optical telescopes with wide-field cameras take hundreds of images of the sky every night

Typically, 4 images of each patch of sky are taken over the course of about 1 hour

An asteroid looks like a star, but it moves against the star background from one image to the next

The celestial latitude / longitude coordinates of the asteroid in each image are measured and reported along with the exact time of the image

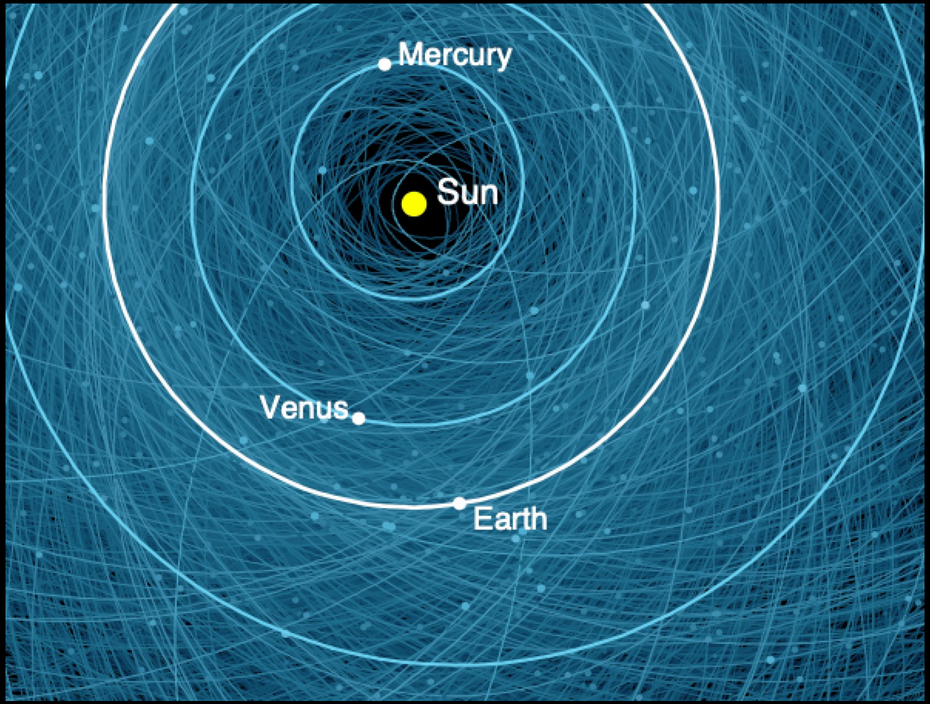
NEO Observations to Impact Predictions



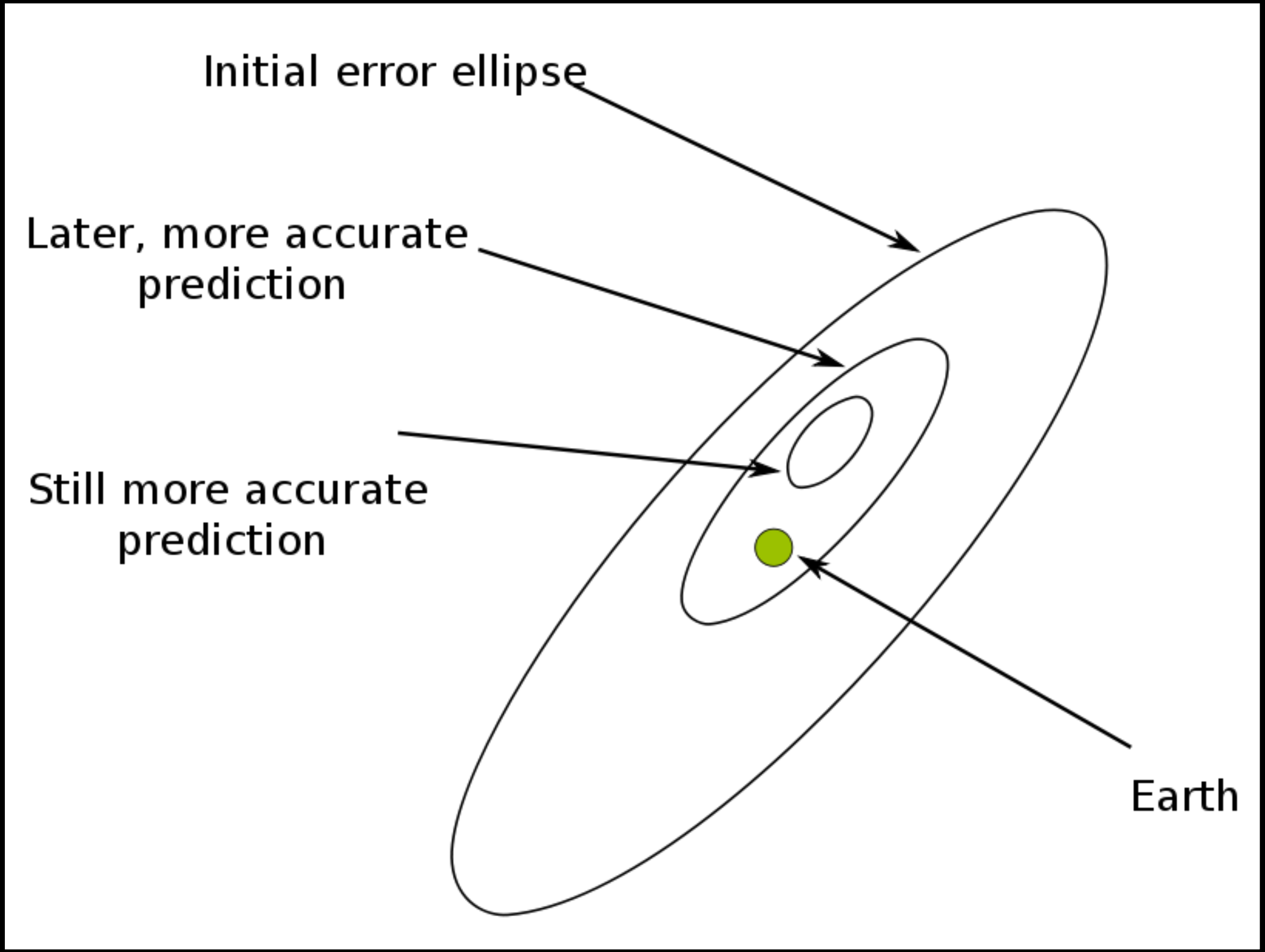
- Orbits
- Sky Position Predictions
- Close Approaches
- Potential Impacts
- Impact Time & Location

How an Asteroid’s Orbit Is Computed

- Tracking data are celestial sky coordinates: they don’t tell us how far away an asteroid is, or how fast it’s moving
- To determine an asteroid’s orbit we try various possible orbits until we find the one that most closely predicts all the observations
- For a given orbit, we can compute the asteroid’s future positions accurately
- No orbit fits all the observations exactly; the differences are due to small measurement errors in the observations
- We calculate the orbit uncertainty based on the uncertainties in the observations
- When we predict an asteroid’s future position, we also compute the uncertainty in that position, which we call the “uncertainty region”
- The longer we track an asteroid the better we know its orbit, and the more accurately we can predict its future position

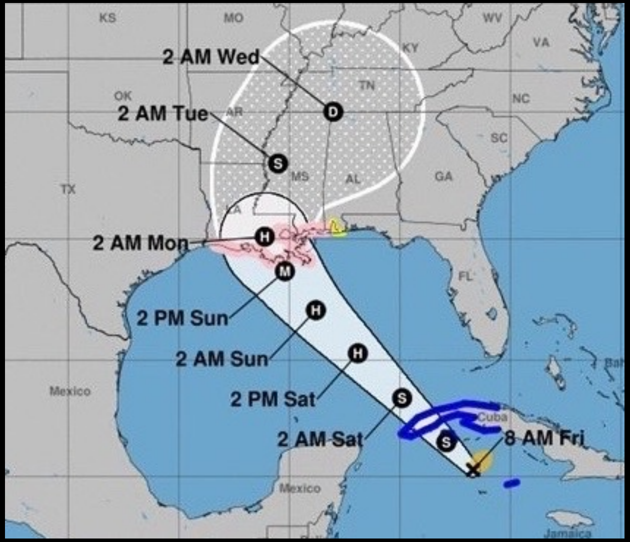


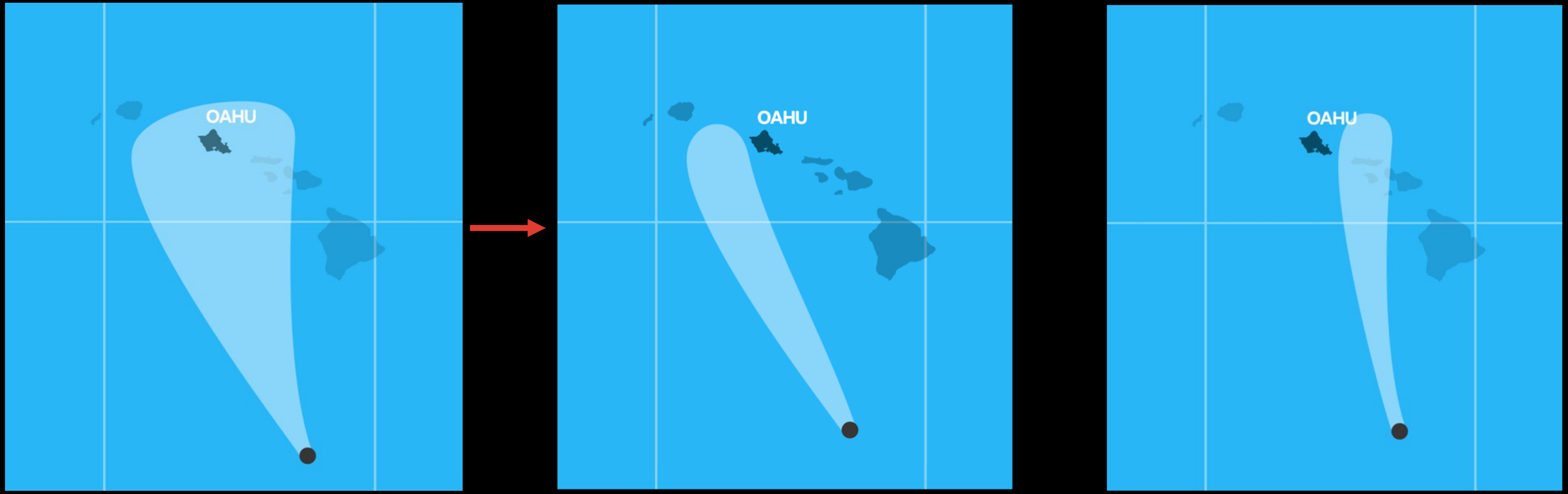
Computing Impact Probability



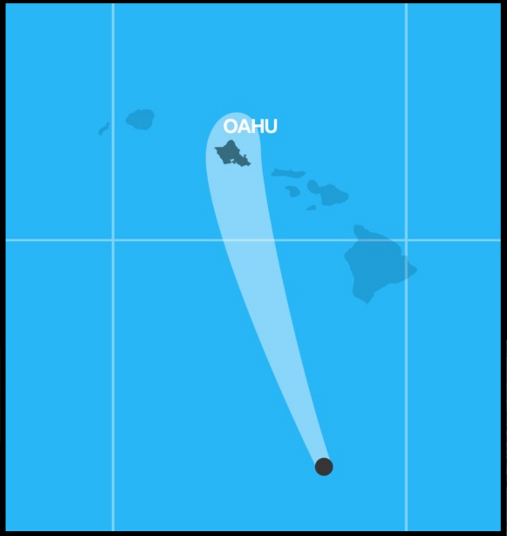
- An asteroid's uncertainty region is 3D, but we project it into a "target plane" to get an uncertainty ellipse
- If the ellipse intersects the Earth, an impact is possible; the fraction of overlap indicates the probability
- As the asteroid is tracked, its orbit gets more accurate and the ellipses will shrink
- If the ellipses shrink away from Earth the probability will go down; otherwise the probability will go up

Similarity with Predicting a Hurricane Trajectory



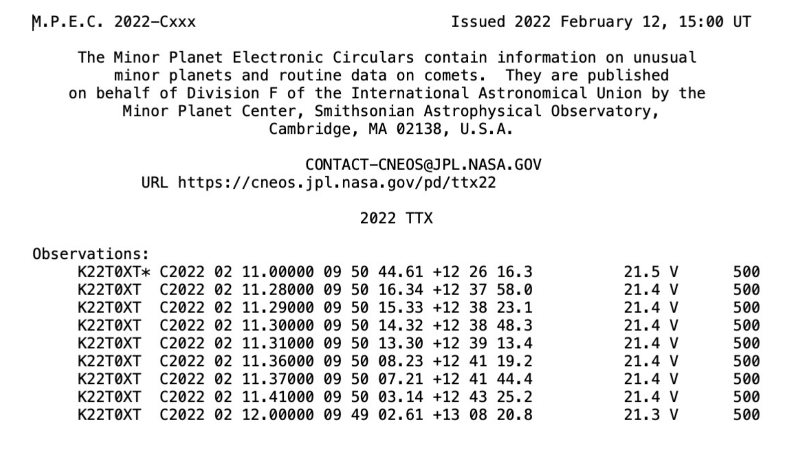


- A hurricane prediction also has a cone of uncertainty
- As time passes, the hurricane moves and the cone narrows
- Whereas a specific location like Oahu might be at risk one day, it may not be the next day, if the narrower cone misses: impact ruled out
- Or, if the narrower cone still includes Oahu, the impact probability goes up
- Predicting an asteroid impact is somewhat similar, only it’s in 3D



Introduction to the 2022 TTX Scenario

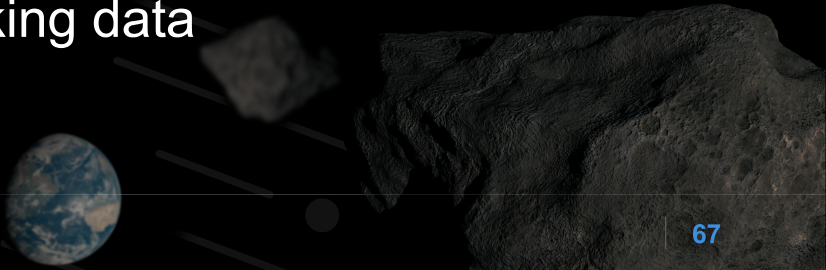
- New asteroid is discovered on **11 February 2022**
- MPC assigns the designation: **2022 TTX**
- CNEOS computes the orbit and detects a small chance of impact for 16 August 2022, six months away
- Continued tracking over the next five nights leads to increasingly accurate orbits
- The Impact probability keeps rising each day, and has now reached 5%



```
M.P.E.C. 2022-Cxxx                             Issued 2022 February 12, 15:00 UT

     The Minor Planet Electronic Circulars contain information on unusual
         minor planets and routine data on comets.  They are published
    on behalf of Division F of the International Astronomical Union by the
          Minor Planet Center, Smithsonian Astrophysical Observatory,
                          Cambridge, MA 02138, U.S.A.

                              CONTACT-CNEOS@JPL.NASA.GOV
            URL https://cneos.jpl.nasa.gov/pd/ttx22

                                   2022 TTX

Observations:
     K22T0XT* C2022 02 11.00000 09 50 44.61 +12 26 16.3          21.5 V      500
     K22T0XT  C2022 02 11.28000 09 50 16.34 +12 37 58.0          21.4 V      500
     K22T0XT  C2022 02 11.29000 09 50 15.33 +12 38 23.1          21.4 V      500
     K22T0XT  C2022 02 11.30000 09 50 14.32 +12 38 48.3          21.4 V      500
     K22T0XT  C2022 02 11.31000 09 50 13.30 +12 39 13.4          21.4 V      500
     K22T0XT  C2022 02 11.36000 09 50 08.23 +12 41 19.2          21.4 V      500
     K22T0XT  C2022 02 11.37000 09 50 07.21 +12 41 44.4          21.4 V      500
     K22T0XT  C2022 02 11.41000 09 50 03.14 +12 43 25.2          21.4 V      500
     K22T0XT  C2022 02 12.00000 09 49 02.61 +13 08 20.8          21.3 V      500
```

Simulated discovery announcement from MPC

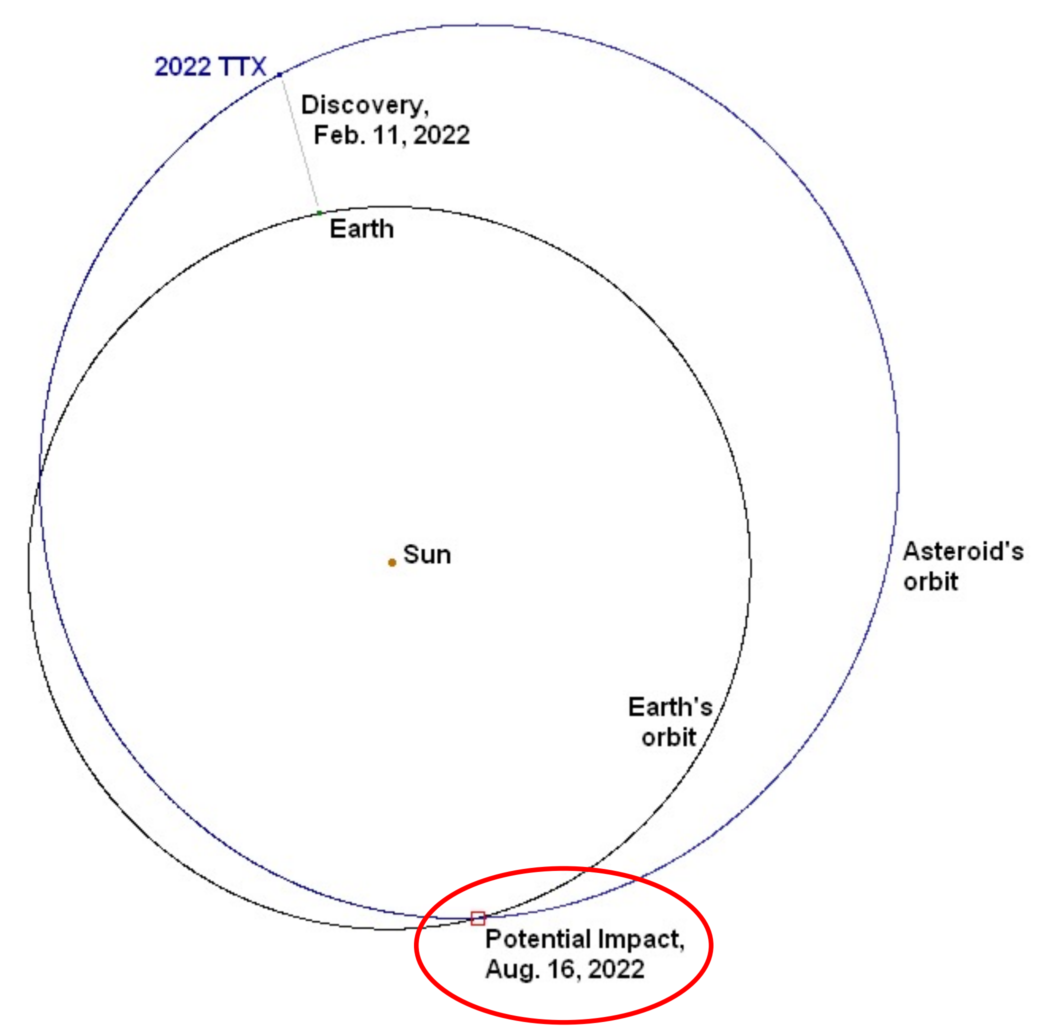
- Asteroid size is highly uncertain: brightness measurement indicate the size range is 40–440 m (130–1440 ft)
  - Orbital calculations do not depend on the size of the object, whereas impact effects predictions do
- Image archives are being searched for more prediscovery tracking data



EXERCISE EXERCISE EXERCISE

The Orbit of 2022 TTX

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4



The asteroid orbit is mostly outside of Earth’s orbit

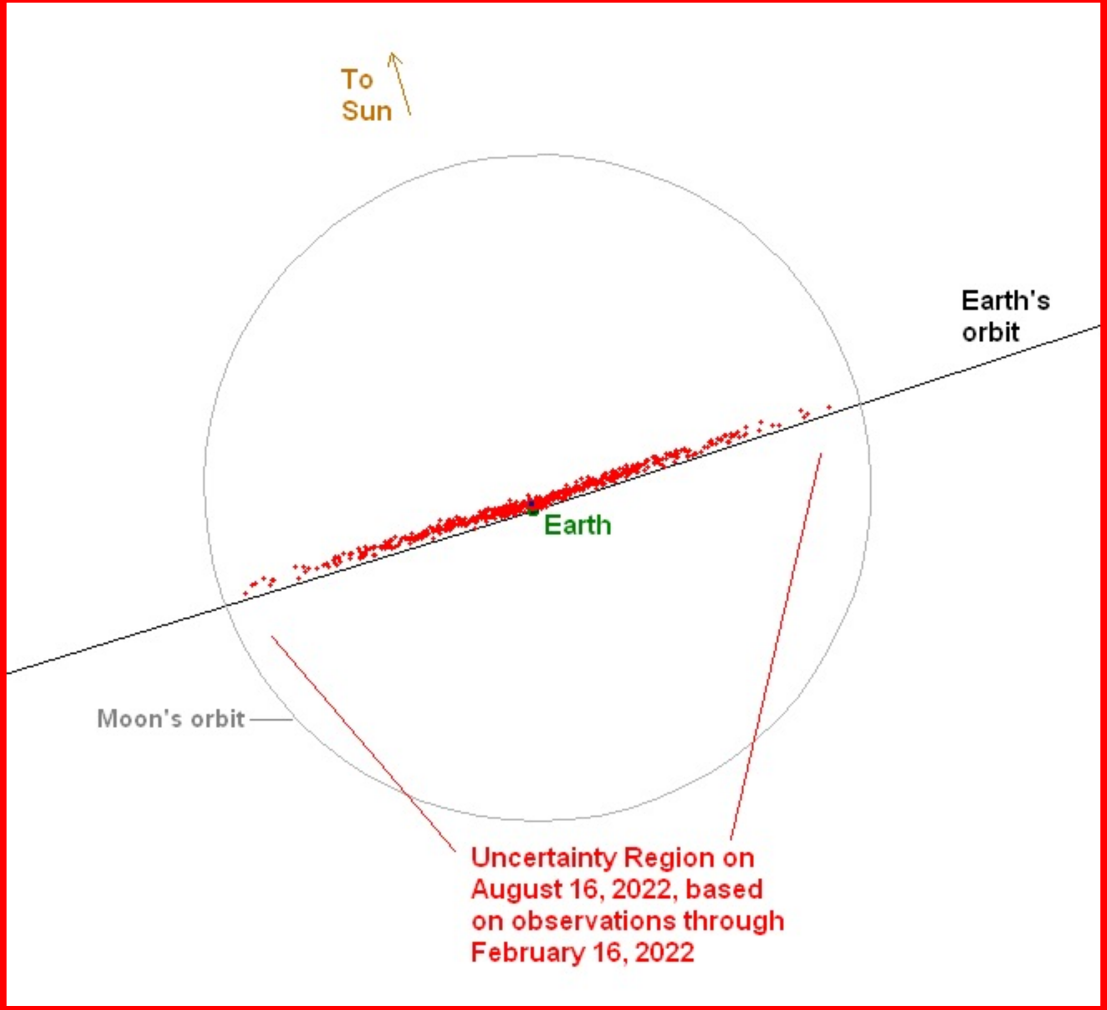
The relative positions at discovery are noted

The point where the two orbits intersect is indicated by the tiny red box

The orbits don’t intersect at the other crossing point because the asteroid orbit is tilted

EXERCISE EXERCISE EXERCISE

Uncertainty in Predicted Position on Aug. 16

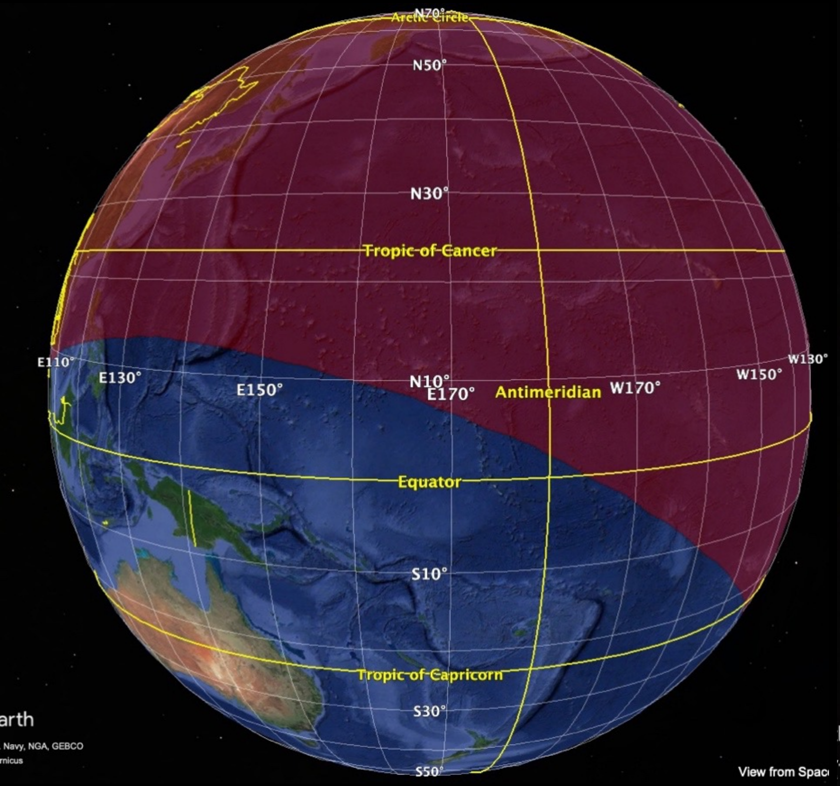


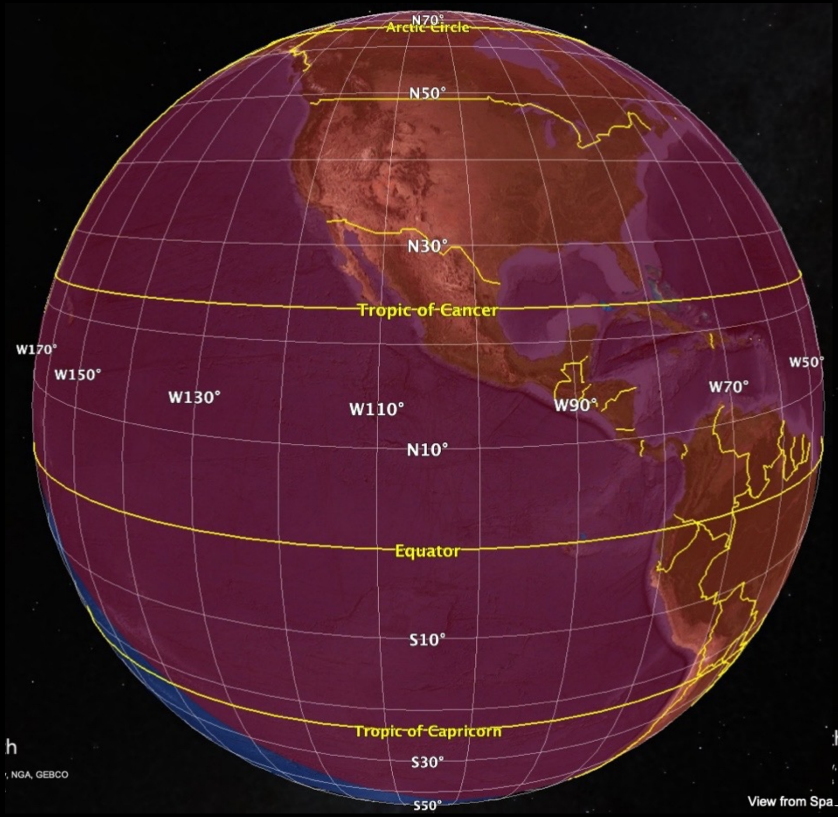
Uncertainty Region on August 16, 2022, based on observations through February 16, 2022

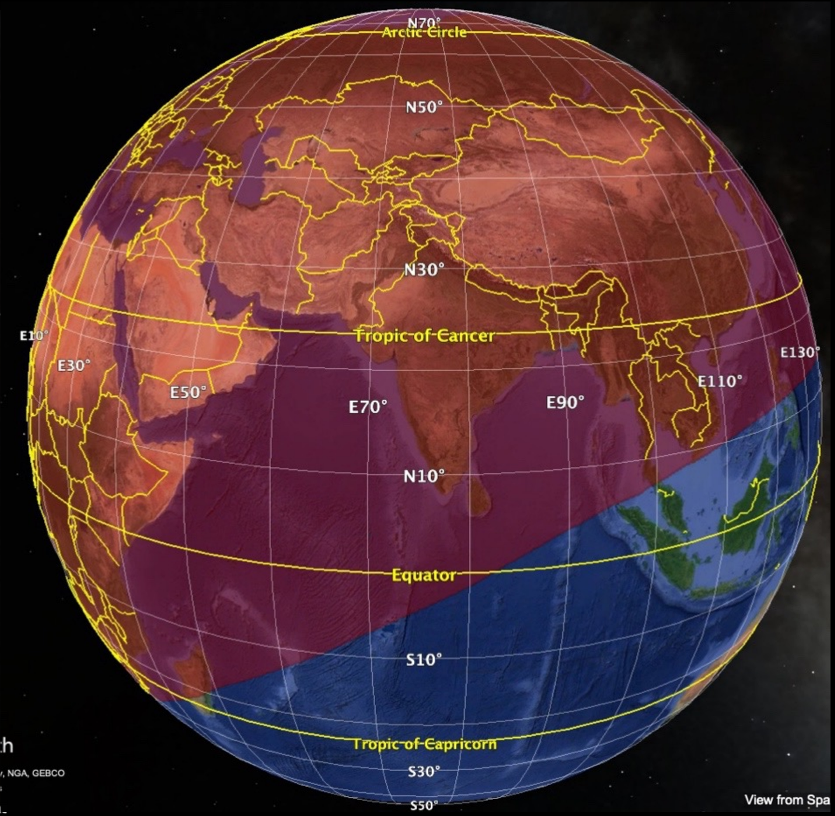
- The **red dots** envelope a region of space where the asteroid will be when it encounters Earth on 16 August 2022
- The orbit is not yet accurate enough to indicate where the asteroid will be within this region
- 5% of the region intersects Earth
- As more observations are made, the uncertainty region will shrink

Module 0: Predicted Impact Region

The region covers 2/3 of the Earth surface, here shaded here in red/purple:



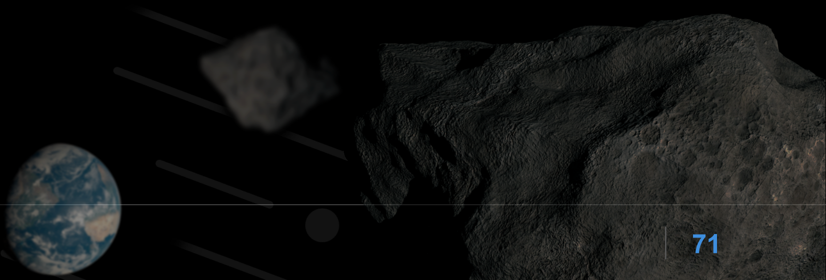




The region covers more than a hemisphere because Earth's gravity causes near-miss trajectories to bend inwards and impact

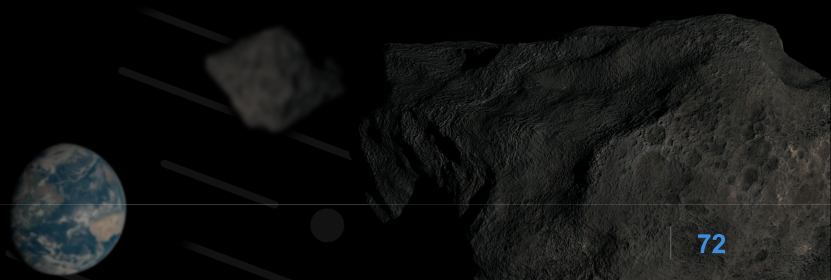
Plans for More Observations of 2022 TTX

- The asteroid is distant (37 million miles away), and it won’t get much closer for several more months
- It is too distant to be detected by radar; it won’t be within radar range until August
- The asteroid is faint but can be tracked optically, using large telescopes, for most of the six months up to impact; it will be observable on most nights through August
- Continued tracking of this asteroid is essential for obtaining the most accurate possible orbit and impact assessment
- Sky-image archives are being searched for possible prediscovery observations within the region of sky the asteroid may have traversed seven years ago, when it made a distant flyby of Earth



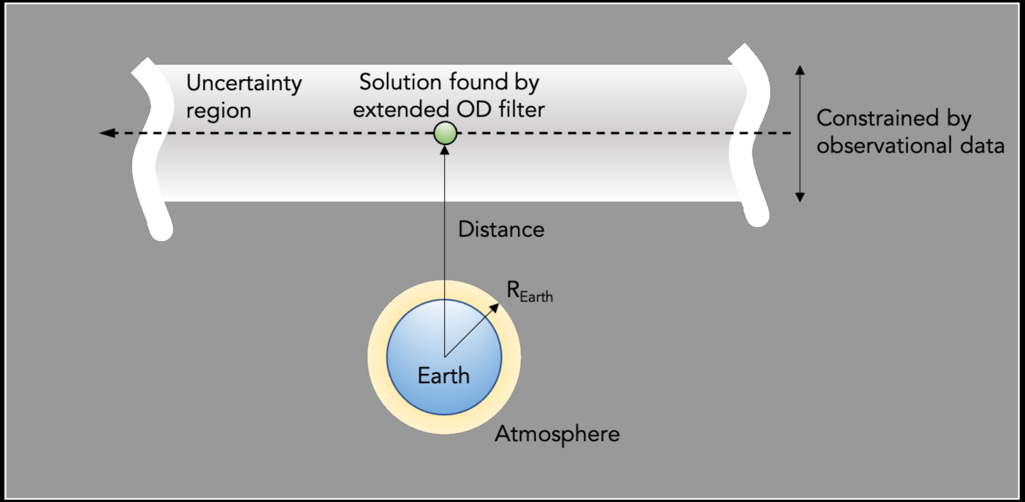
Backups

- Sentry



Sentry: Long-Term Impact Predictions

- Sentry is an impact monitoring system that checks all possible trajectories for an asteroid, looking for those trajectories that might impact Earth over the next 100 years
- For each potential impacting trajectory, Sentry reports the impact probability and assesses the risk
- The Sentry Risk Table is continually updated on the CNEOS website
- Currently there are 1378 asteroids on the table
- Almost all of the potential impacts have either extremely low probabilities (less than 1 in a million), or are tiny asteroids that would likely disintegrate in the atmosphere if they should be headed for Earth



PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

NASA

PLANETARY DEFENSE COORDINATION OFFICE

FEMA

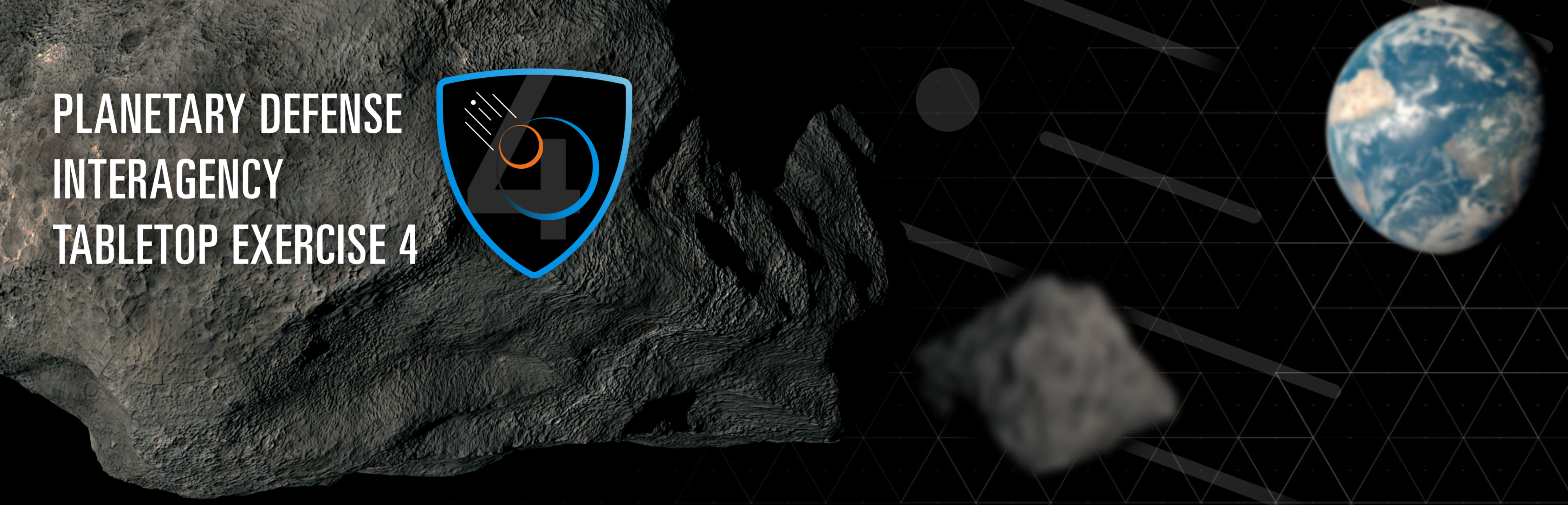
JOHNS HOPKINS APPLIED PHYSICS LABORATORY

cneos

Ames Research Center

EMERGENCY MANAGEMENT NORTH CAROLINA

WINSTON-SALEM FORSYTH COUNTY NC EMERGENCY MANAGEMENT



PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

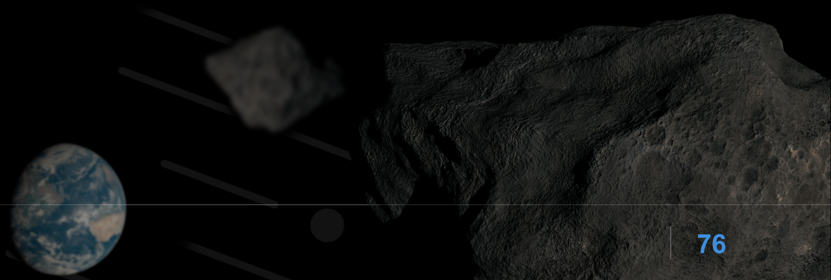
Asteroid Threat Assessment

Assessing Asteroid Impact Damage and Risks

Lorien Wheeler
Jessie Dotson, Michael Aftosmis, Eric Stern, Donovan Mathias
Asteroid Threat Assessment Project (ATAP)
NASA Ames Research Center

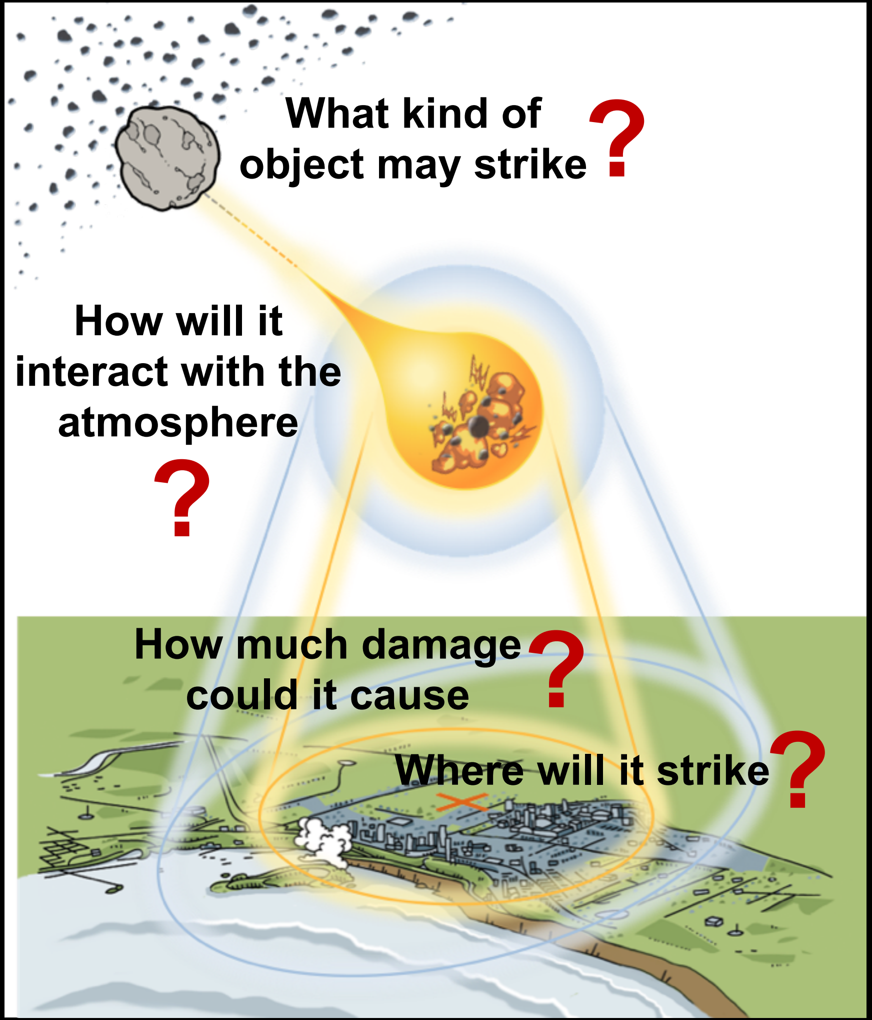
Outline

- What is asteroid impact risk assessment?
- Asteroid properties and uncertainties
- Impact hazards and damage effects
- Risk assessment modeling for specific impact scenarios
- Impact risk assessment result examples



What Is Asteroid Impact Risk Assessment?

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4



How likely are the potential consequences?

- Risk assessment evaluates both the range and likelihood of potential outcomes, given the level of uncertainty or knowledge of the factors
- Evaluating asteroid impact risks involves large uncertainties across all aspects of the problem:
    - Impact probability, potential impact locations, entry trajectories (speed, entry angle)
    - Initial asteroid sizes and properties (density, strength, structure, composition, shape, etc.)
    - Atmospheric entry, breakup, airburst or impact behavior
    - Severity and range of resulting hazards
    - Population and infrastructure within damage regions
- Some uncertainties shrink as we gain knowledge over time (impact locations, asteroid size), while some remain unknown (specific asteroid properties, entry/breakup behavior, damage uncertainties)

Asteroid Size and Property Uncertainty

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

What we would like to know about the object...

Image of asteroid Bennu from OSIRIS-REx mission (Image credit: NASA)

What we actually know…

Telescope observation of asteroid Apophis (Credit: Nic Erasmus, South African Astronomical Observatory's Lesedi Telescope, IAWN Apophis 2021 Observing Campaign, https://iawn.net/obscamp/Apophis/apophis_gallery.shtml)

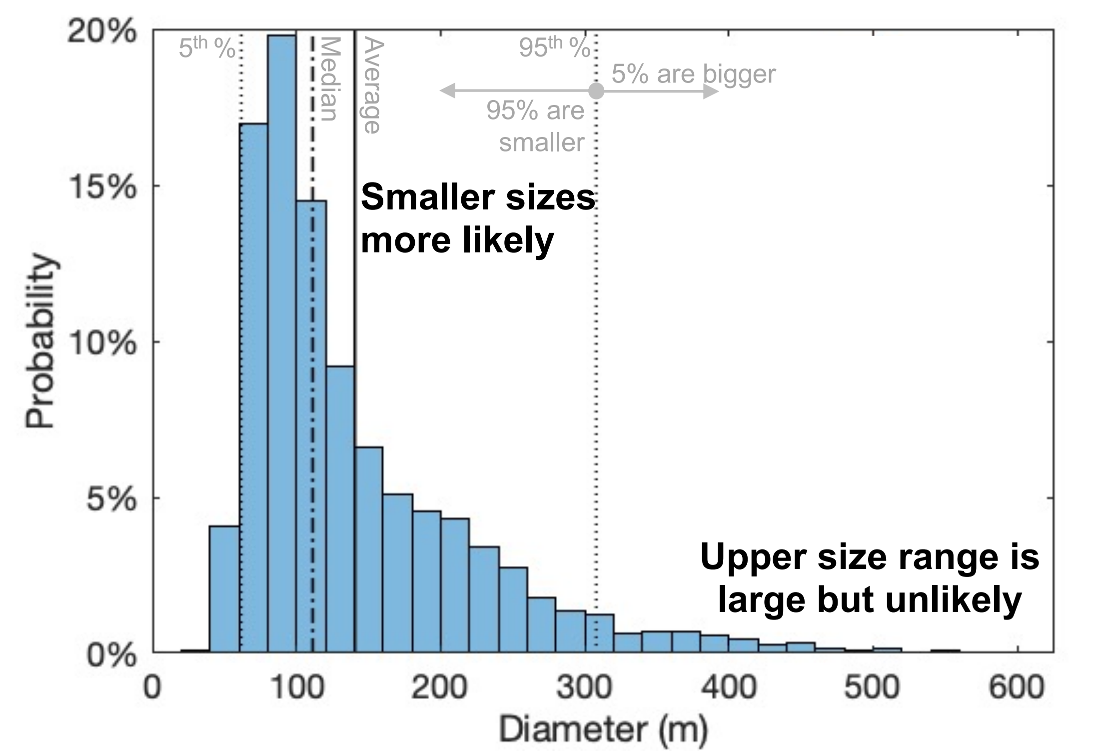
Asteroid Size and Properties

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Asteroid sizes and physical properties are highly uncertain.

- Upper size range is large but relatively unlikely
- Smaller size ranges are more likely
- Asteroid properties (density, composition structure, strength) are usually unknown, ranging from more common stony types and rubble piles to rarer high-density iron types
- Size and density uncertainties together result in very large ranges of potential mass and impact energy

Asteroid Diameter Distribution

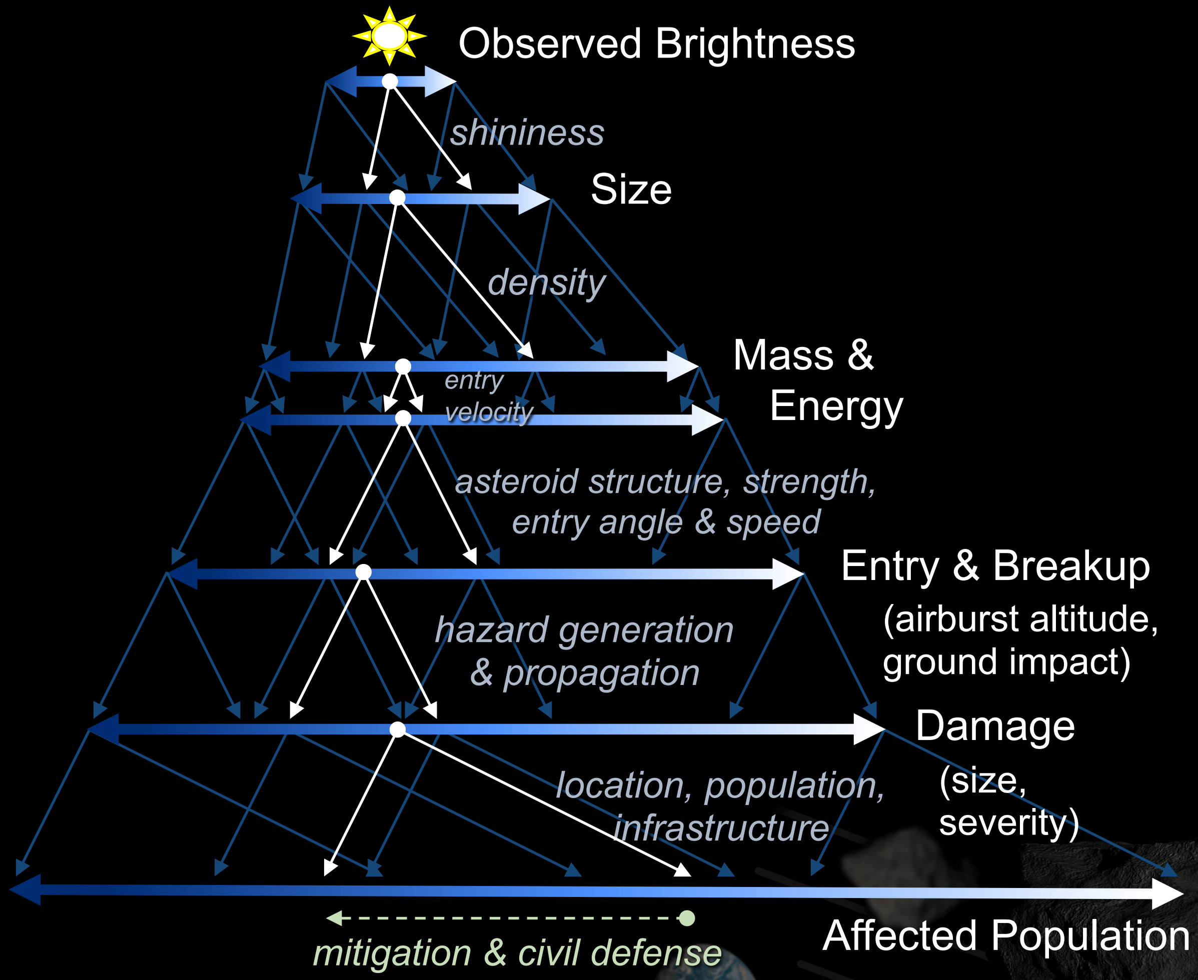


Asteroid Property and Damage Uncertainties

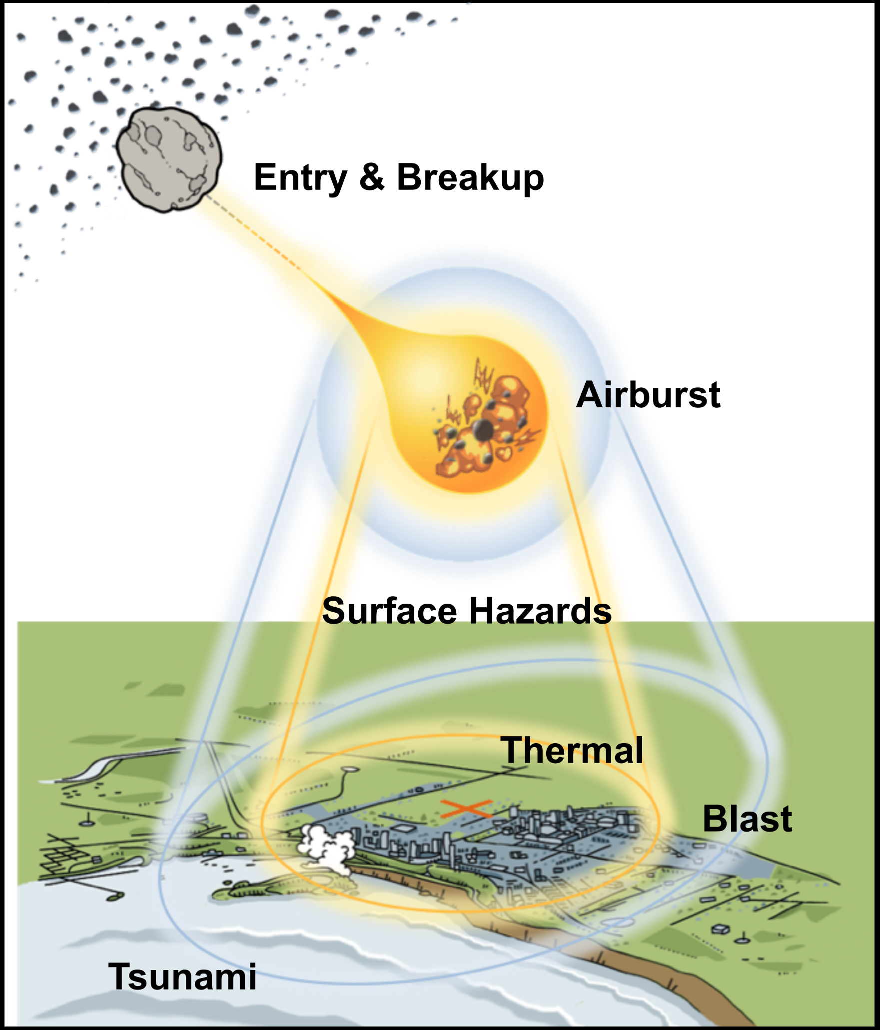
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

- Size and density uncertainties together result in very large ranges of potential mass and impact energy
- Unknown composition/structural properties affect range of mass, strength, and atmospheric entry/breakup
- These properties determine how much energy the asteroid can deliver to the various hazards and how much damage they could do
- Asteroid impact energy:
  - Initial kinetic energy of the asteroid (asteroid mass, entry velocity)
  - Usually given in units of megatons (Mt) of TNT equivalent

Cascade of uncertainty ranges from asteroid observation to damage potential

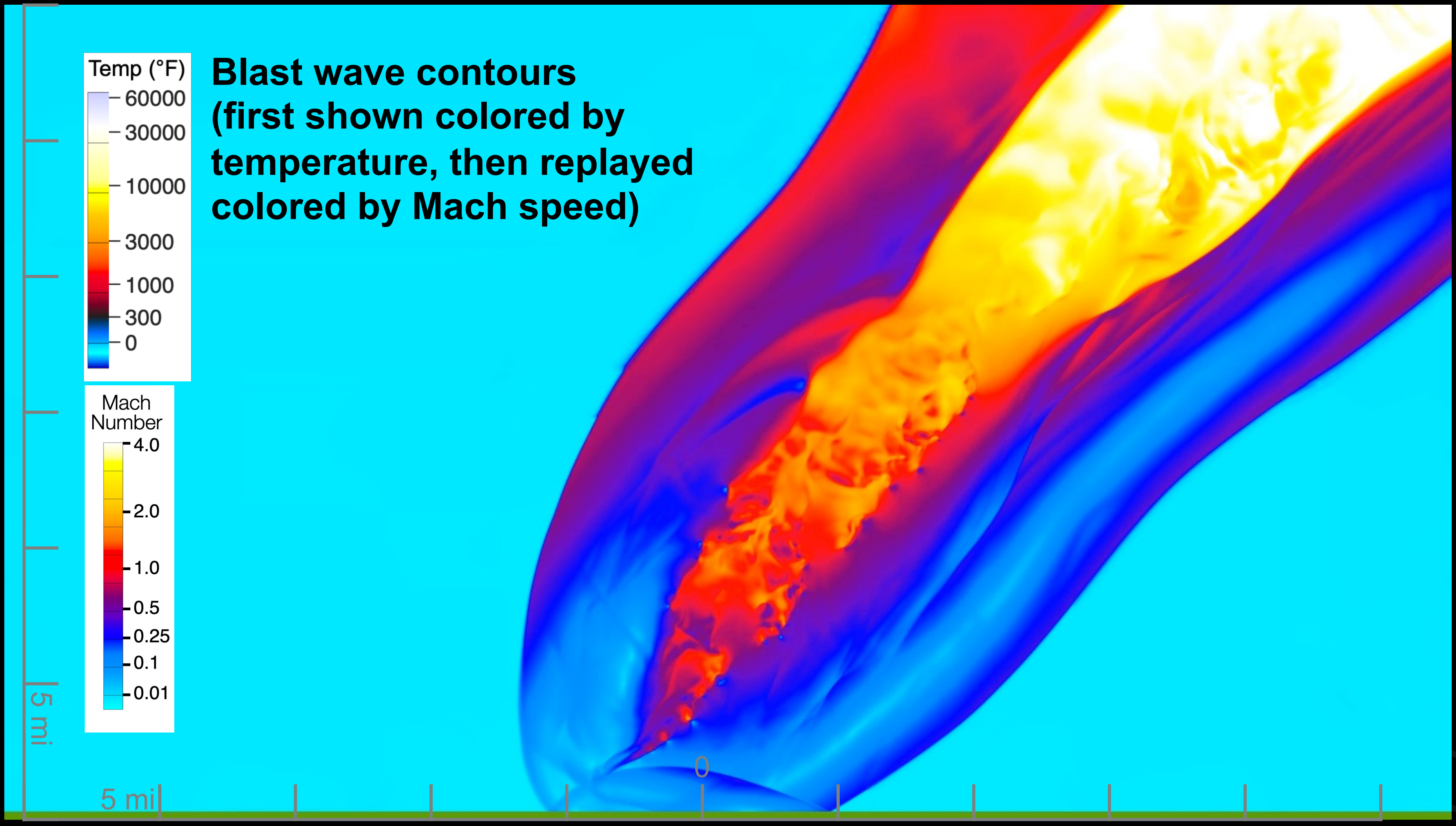


Asteroid Hazards



- Asteroids can cause damage either by breaking up and bursting in the atmosphere or by impacting the surface
  - "Asteroid impact" generally refers to an asteroid hitting Earth, including airbursts (not just ground-cratering events)
- Blast damage:
  - Airbursts and surface impacts can produce explosive blast waves, which can cause damage ranging from shattered windows to flattened structures.
- Thermal damage:
  - Thermal heating from airburst/impact fireballs can cause damage ranging from mild skin burns to lethal infernos and structure fires
- Tsunami damage:
  - Ocean impacts could cause significant inundation if impact is very large and or near a populated coast
- For the asteroid sizes in this exercise scenario, blast damage from an airburst is the predominant hazard

Airburst Blast Simulation (movie)



Blast wave contours (first shown colored by temperature, then replayed colored by Mach speed)

Cart3D Computational Fluid Dynamics Simulation (Credit: Michael Aftosmis, Asteroid Threat Assessment Project, NASA Ames)

Simulation of blast from a 120-m, 50-Mt asteroid airburst

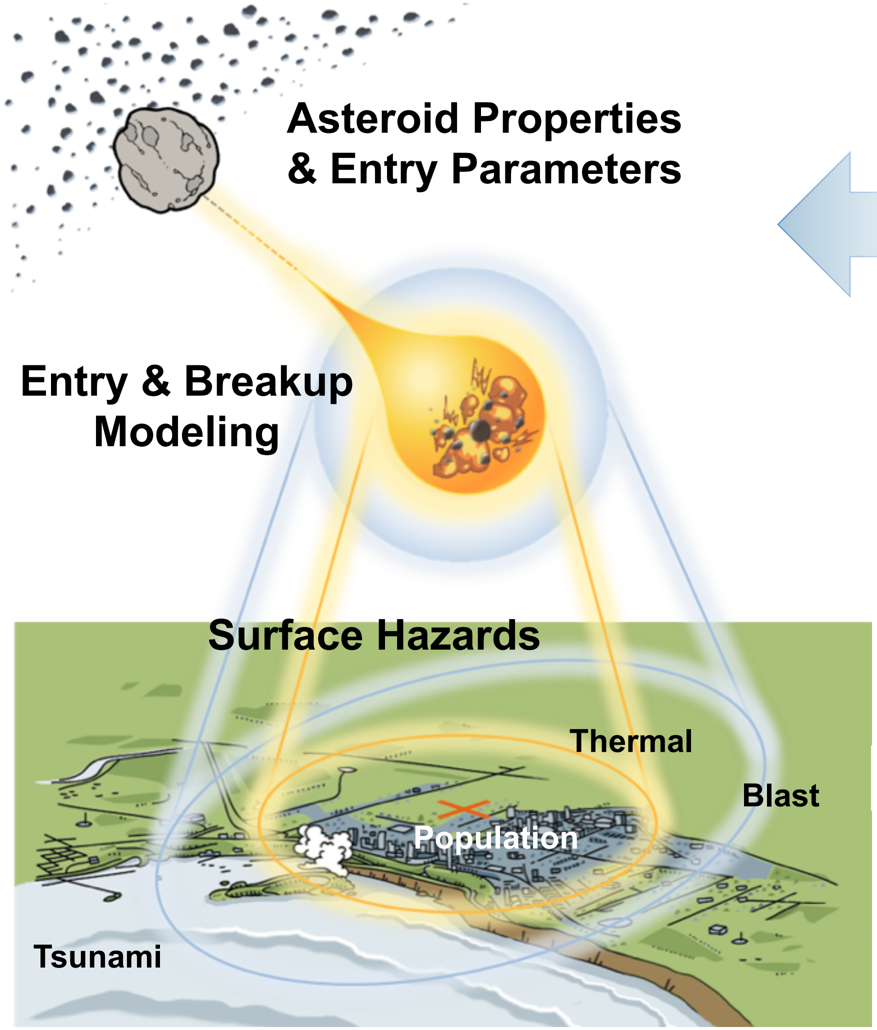
- Entry: Shockwaves emanate from the entry path as the asteroid enters at high speeds
- Airburst: Asteroid disrupts catastrophically under high aerodynamic pressures, producing an explosion-like blast
- Ground damage: Shock front reflects off the ground and sends a powerful blast wave outward across the ground

Risk Assessment for Impact Scenarios

Risk Modeling Process and Result Examples

Asteroid Impact Threat Assessment

Probabilistic Asteroid Impact Risk (PAIR) Model



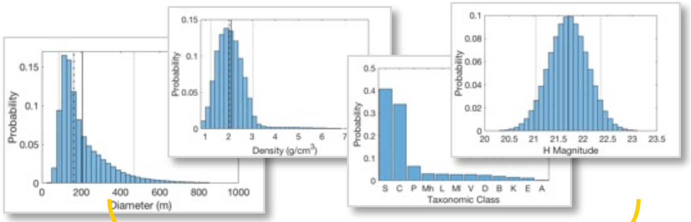
Asteroid Properties & Entry Parameters

Entry & Breakup Modeling

Surface Hazards

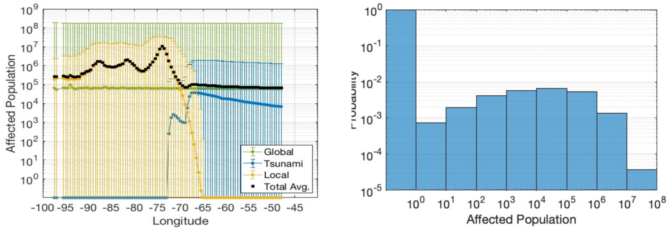
Impact Threat Scenario

Asteroid Property Distributions



Orbital Entry Parameters
(JPL/CNEOS)

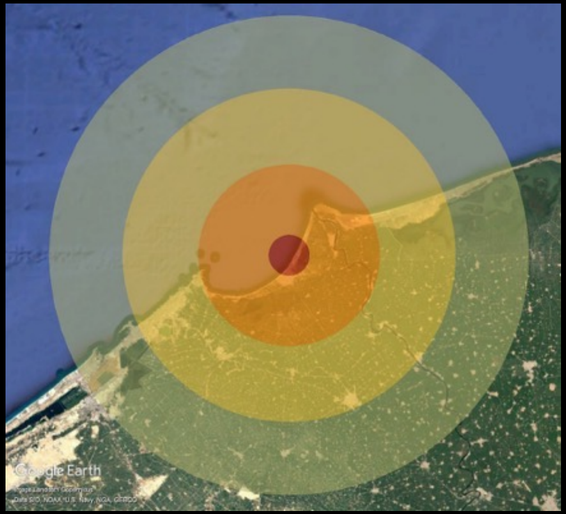
Probabilistic Damage and Risk



Local Ground Damage Severity Levels

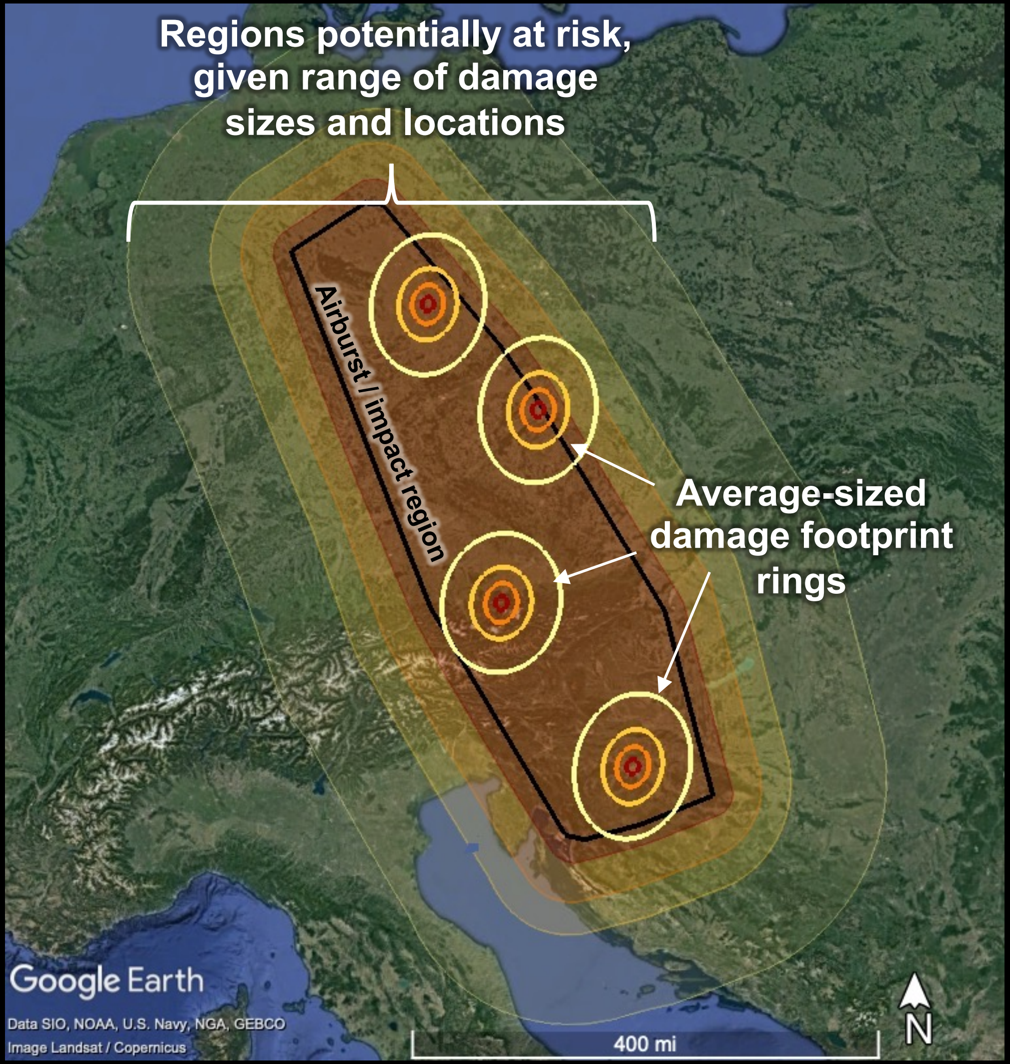
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

- Blast and thermal damage are assessed independently at four severity levels
  - For each damage level, the **larger** of the associated blast or thermal damage is used to determine the area and affected population for that level
  - Damage regions indicate ***either*** blast or thermal effects could exceed the given severity, ***not*** the occurrence of both effects within the entire region
- **Blast** is the predominant hazard for most asteroid sizes
  - Blast tends to be larger and more severe than the potential thermal damage in most cases
  - Blast areas usually define the larger risk regions for emergency response planning



Damage Level	Potential Blast Damage Effects	Potential Thermal Damage Effects
Serious	**Shattered windows, some structural damage**	Second-degree burns
Severe	**Widespread structural damage, doors and windows blown out**	Third-degree burns
Critical	**Most residential structures collapse**	Clothing ignition
Unsurvivable	**Complete devastation**	Structure ignition, incineration

Risk Region Swath Maps



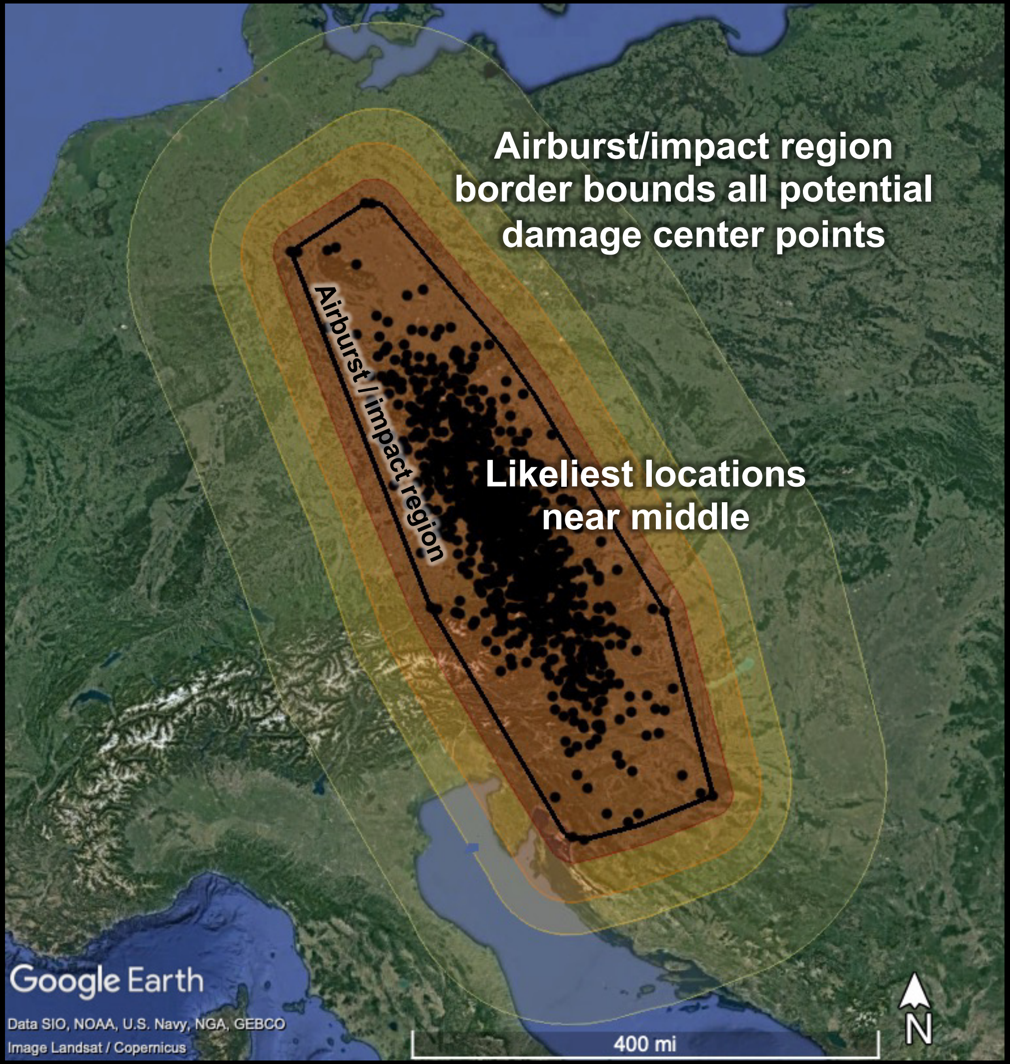
Example from 2021 Planetary Defense Conference Exercise

Risk swaths show range of regions ***potentially*** at risk, including range of possible damage sizes and locations

- Black outline shows range of potential impact points (damage-center locations)
- Shaded areas show potential at-risk regions given range of damage sizes and locations
- Rings show an average-sized damage footprint at sample locations

Damage Level	Description
Serious	Window breakage, some minor structural damage
Severe	Widespread structure damage, doors/windows blown out
Critical	Most residential structures collapse
Unsurvivable	Complete devastation

Risk Region Swath Maps



Risk swaths show range of regions ***potentially*** at risk, including:

- Range of potential impact damage locations (from orbit and entry)
  - Orbital uncertainty gives spread of entry locations
  - Damage location depends on airburst/impact point along entry trajectory
  - Airburst/impact border bounds all potential damage center-points, with likelier regions toward the middle

Risk Region Swath Maps

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Risk swaths show range of regions ***potentially*** at risk, including:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges + unknown entry, airburst, or impact factors

Risk Region Swath Maps

Risk swaths show range of regions ***potentially*** at risk, including:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges + unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels

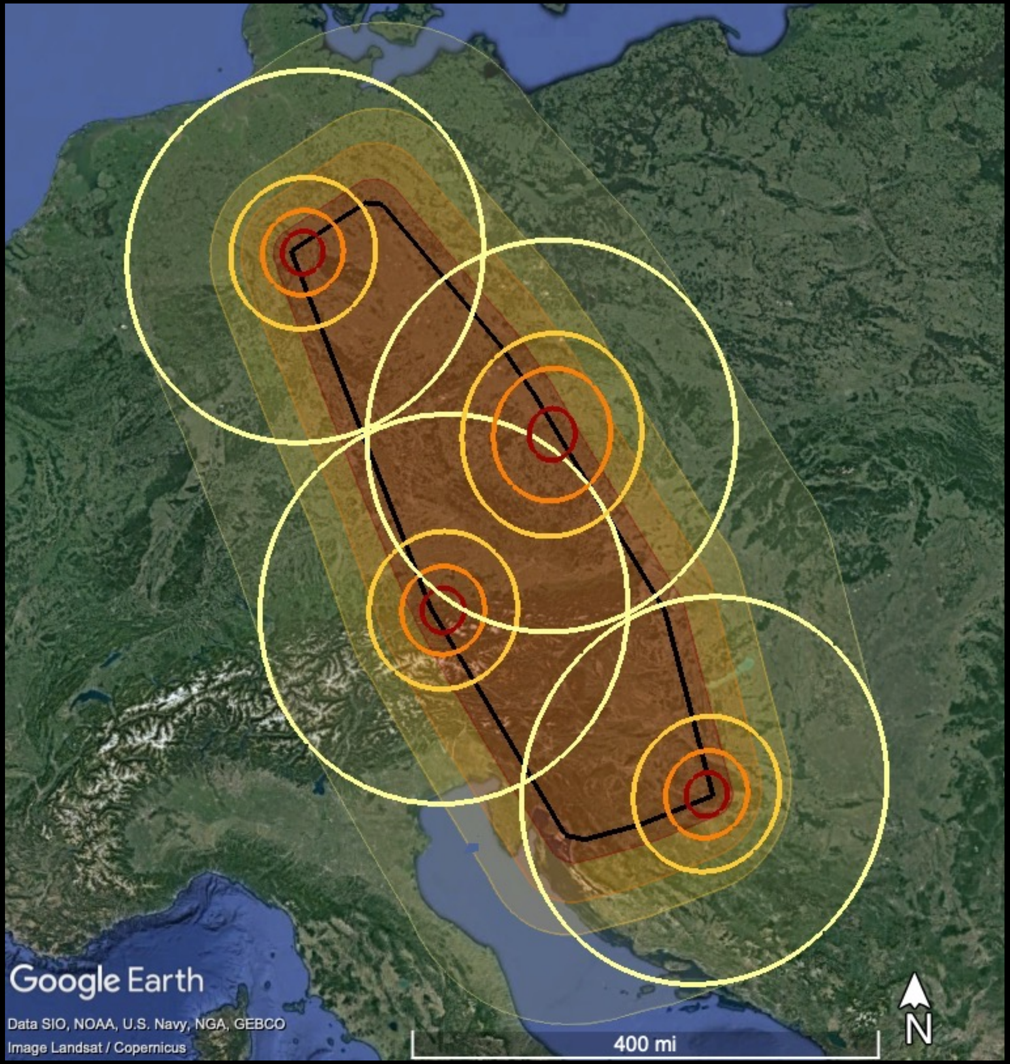
Risk Region Swath Maps

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Risk swaths show range of regions ***potentially*** at risk, including:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges + unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)

Risk Region Swath Maps



Risk swaths show range of regions ***potentially*** at risk, including:

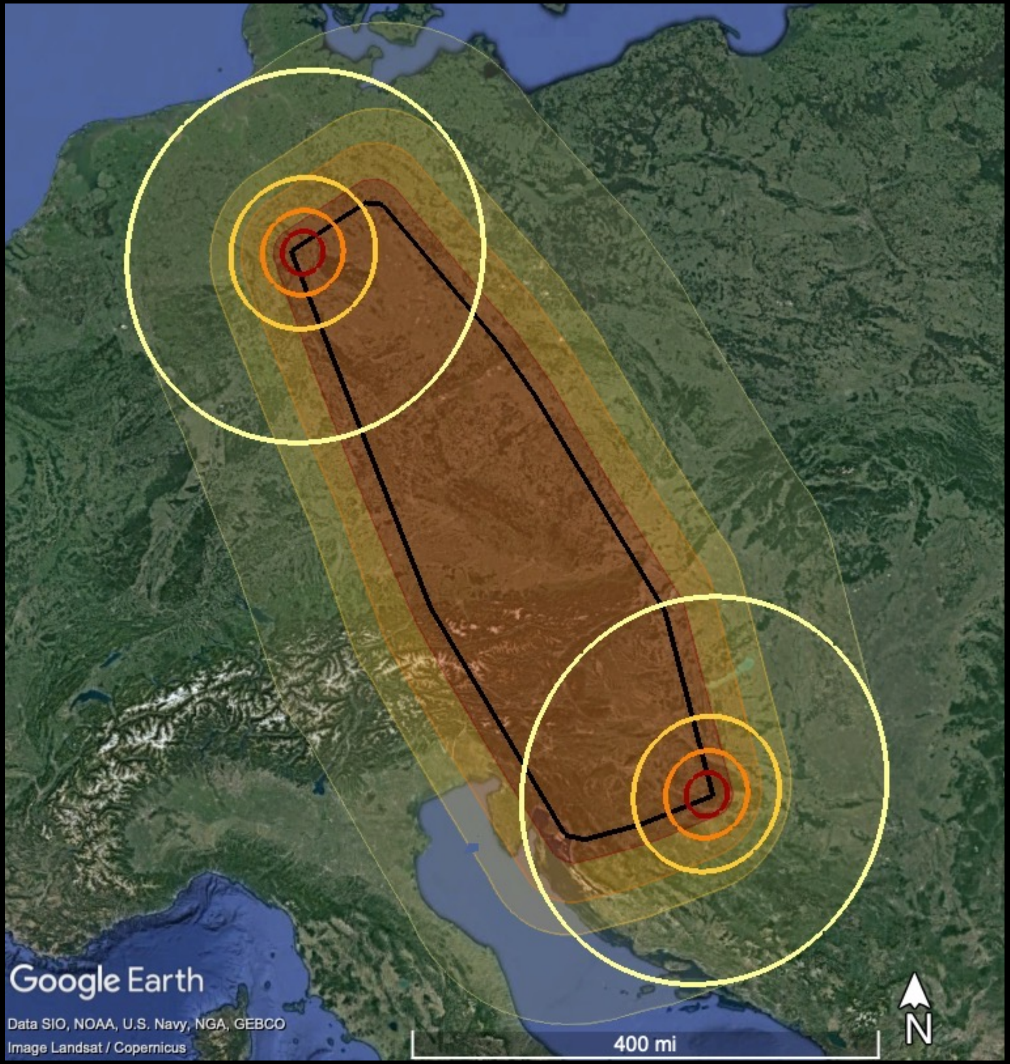
- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges + unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)
  - Very large but unlikely areas (from the largest, least-likely possible impact sizes)

Risk Region Swath Maps

Risk swaths show range of regions ***potentially*** at risk, including:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges + unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)
  - Very large but unlikely areas (from the largest, least-likely possible impact sizes)
  - And everything in between…

Risk Region Refinement Over Time



- Risk swath regions start out very large but will contract with additional observations during the asteroid’s approach.

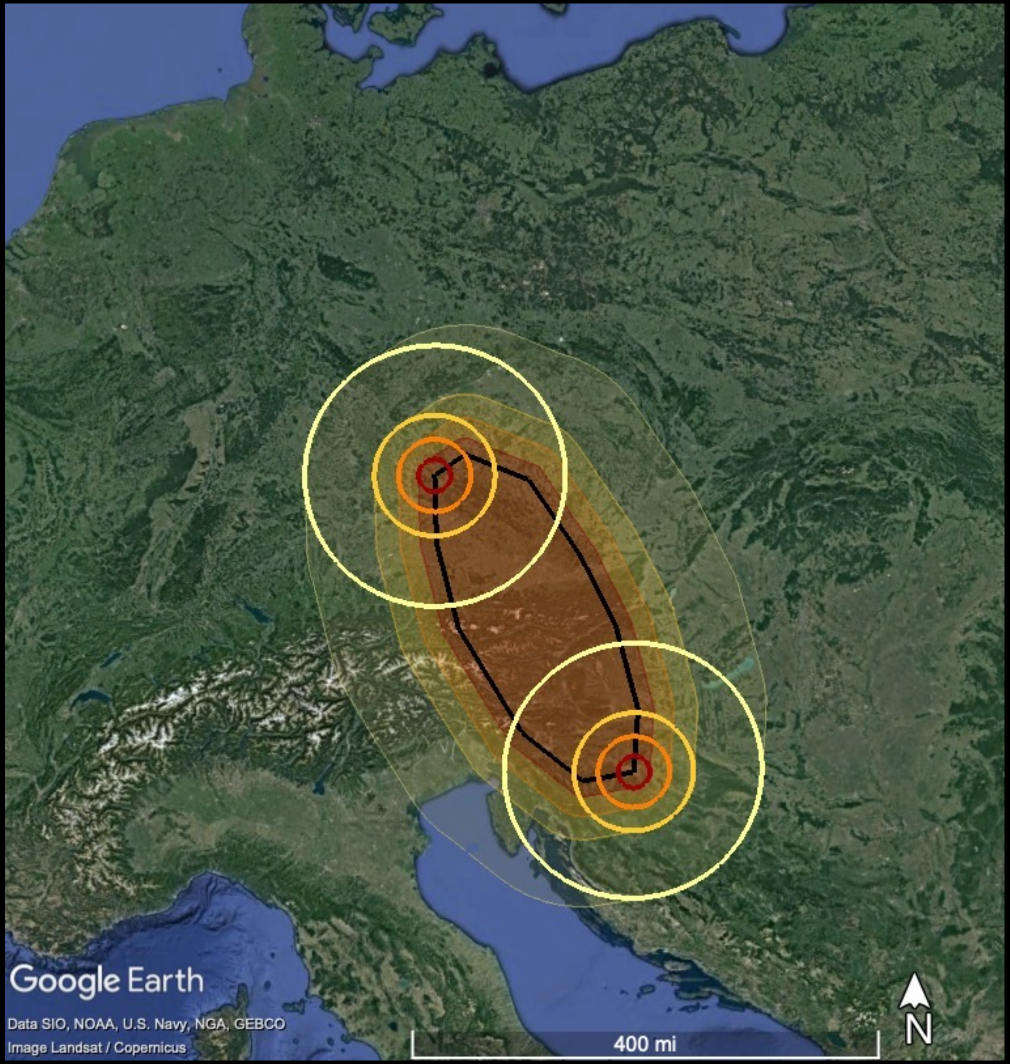
Risk Region Refinement Over Time

- Risk swath regions start out very large but will contract with additional observations during the asteroid’s approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer because of asteroid size/property uncertainties through much of the approach

EXERCISE EXERCISE EXERCISE

Risk Region Refinement Over Time

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4



- Risk swath regions start out very large but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer because of asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range

EXERCISE EXERCISE EXERCISE

Risk Region Refinement Over Time

- Risk swath regions start out very large but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer because of asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range
  - Impact region will continue to shrink

Risk Region Refinement Over Time

- Risk swath regions start out very large but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer because of asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range
  - Impact region will continue to shrink
  - In the final days before impact, the trajectory will be well known, location range will be small, and radar may be able to estimate asteroid size

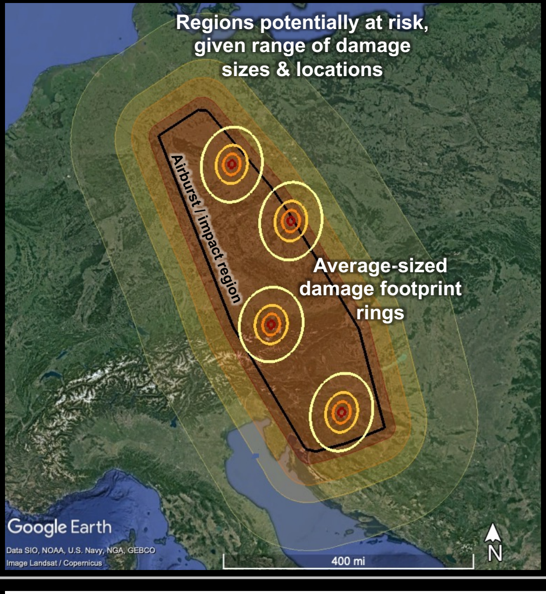
Risk Region Refinement Over Time

- Risk swath regions start out very large but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer because of asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range
  - Impact region will continue to shrink
  - In the final days before impact, the trajectory will be well known, location range will be small, and radar may be able to estimate asteroid size
  - Only after impact will we know how much damage actually occurs from the wide range of initial possibilities

Impact Risk Summary Dashboard

Asteroid Characterization Summary

- Earth-impact data to date (impact probability, potential impact date)
- Updates on any new observational data on the asteroid
- Estimated asteroid sizes, energies, or other properties



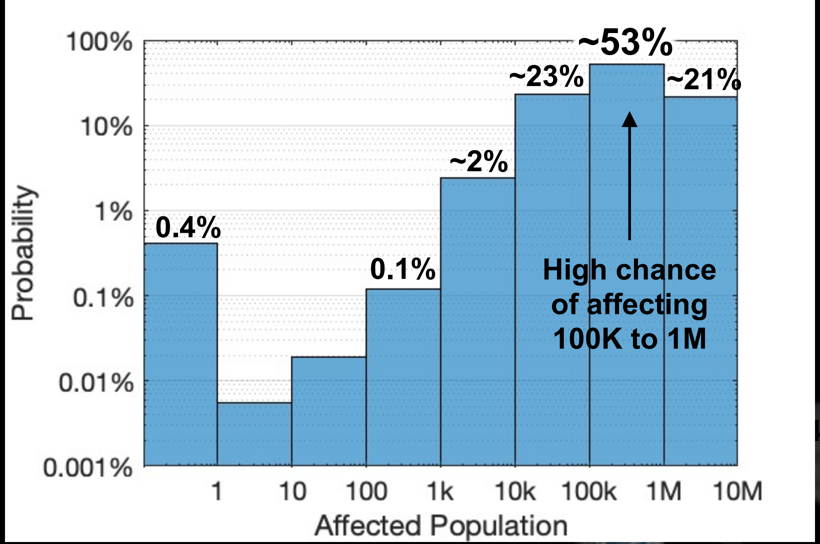
Risk Swath

Regions potentially at risk for ground damage, given ranges of potential impact locations damage sizes

Average-sized damage footprints are shown as rings over sample cities

Impact Hazard Summary

- Summary of potential impact hazards
- Ranges of damage sizes and severities
- How many people could be affected by the range of damage



Population Risk

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

PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

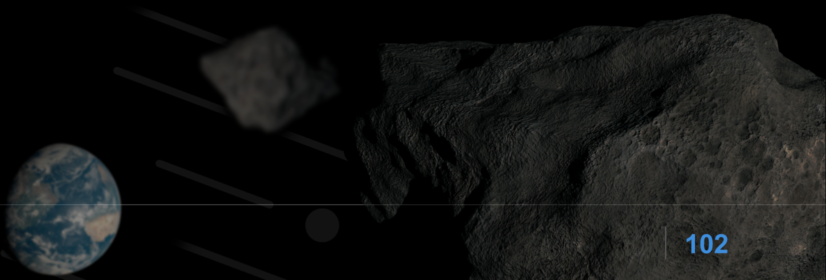
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Deep Space NEO Mitigation 101

Brent W. Barbee
Principal Investigator for Planetary Defense Research at NASA/GSFC
brent.w.barbee@nasa.gov

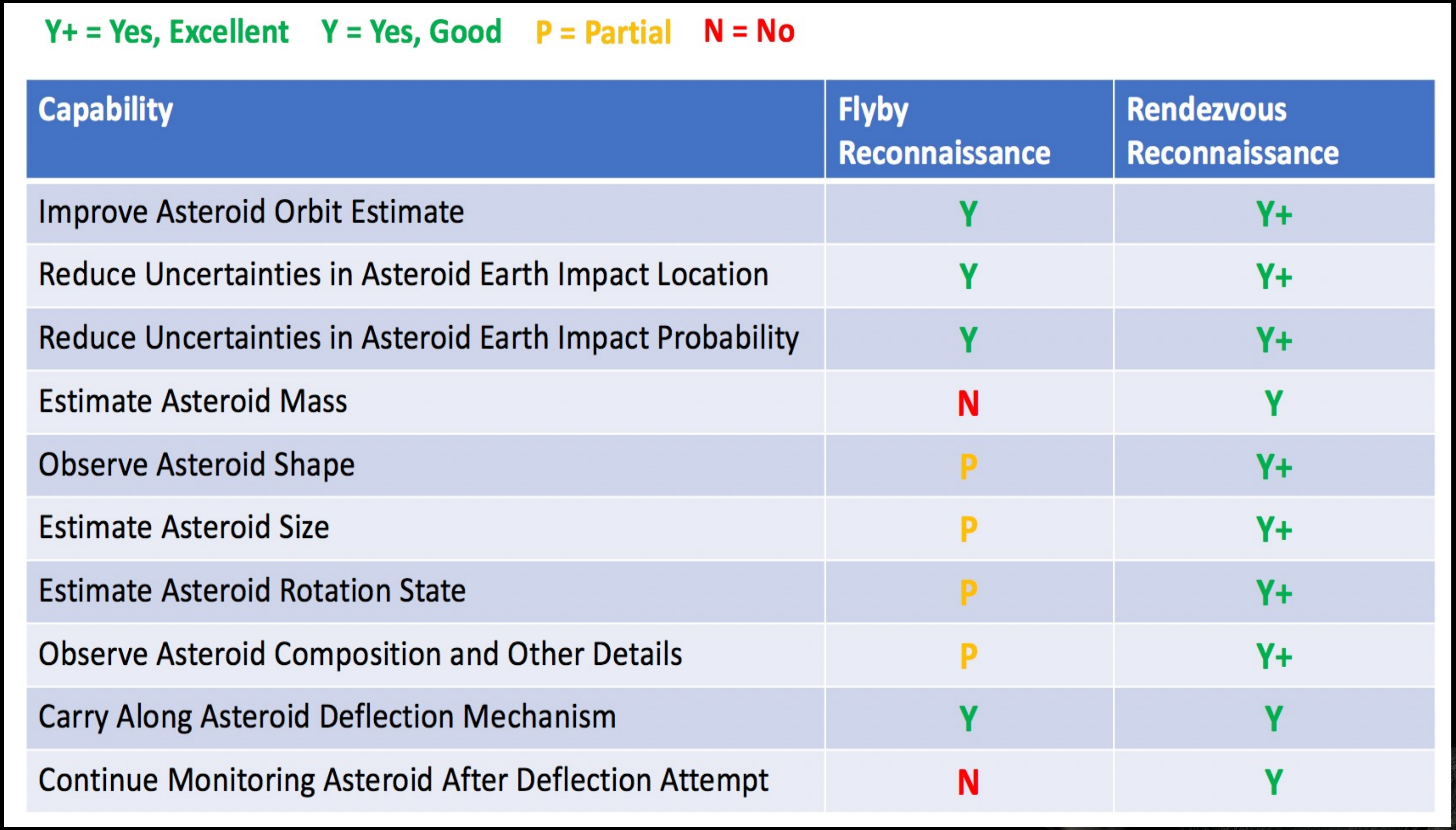
Planetary Defense Mission Types

- **Reconnaissance**
  - Spacecraft collects data about the asteroid/comet (orbit, physical properties such as size, mass, etc.) and ascertains whether the object is indeed on an Earth impact trajectory.
  - A reconnaissance mission could include systems for asteroid/comet deflection or disruption, as an alternative to launching additional deflection/disruption spacecraft later. For example, a reconnaissance mission might carry a nuclear explosive device (NED) in case it is needed.
- **Deflection**
  - Spacecraft changes the asteroid/comet's speed around the Sun in a way that prevents Earth impact.
  - Deflection generally requires longer warning times than disruption.
- **Disruption**
  - Spacecraft carries an NED to the asteroid/comet that is sufficient to robustly disrupt the object.
  - Robust disruption means breaking the asteroid/comet into many small and widely scattered fragments, such that the fragments do not pose a threat to Earth's surface or orbital assets.
  - Robust disruption is possible with a short warning time, provided adequate infrastructure for rapidly launching a mission is in place.



Reconnaissance Missions

- Reconnaissance ideally precedes deflection/disruption, when circumstances permit.
- A flyby mission is usually easier to execute than a rendezvous mission, but it provides less benefit.



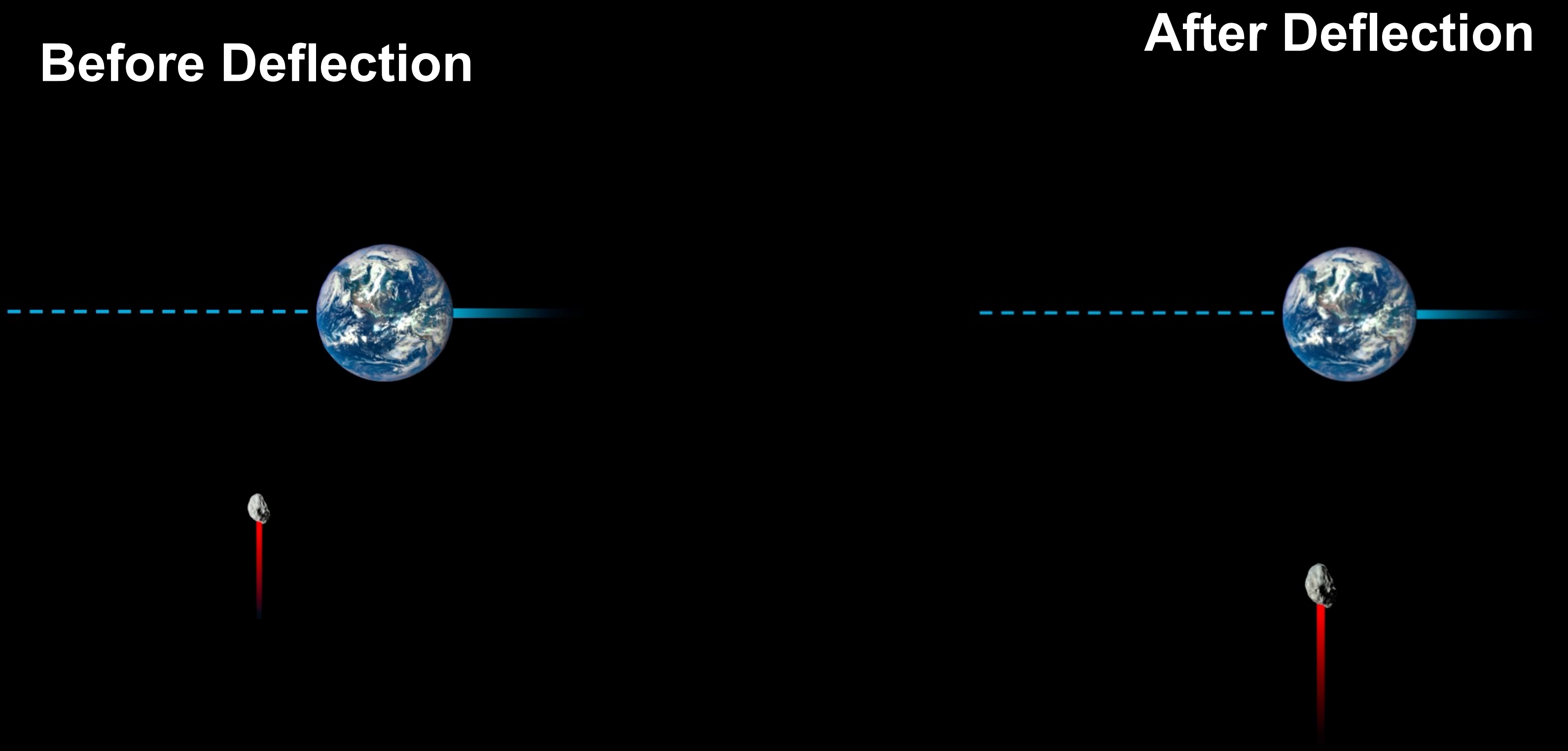
Y+ = Yes, Excellent   Y = Yes, Good   P = Partial   N = No

Capability	Flyby Reconnaissance	Rendezvous Reconnaissance
Improve Asteroid Orbit Estimate	Y	Y+
Reduce Uncertainties in Asteroid Earth Impact Location	Y	Y+
Reduce Uncertainties in Asteroid Earth Impact Probability	Y	Y+
Estimate Asteroid Mass	N	Y
Observe Asteroid Shape	P	Y+
Estimate Asteroid Size	P	Y+
Estimate Asteroid Rotation State	P	Y+
Observe Asteroid Composition and Other Details	P	Y+
Carry Along Asteroid Deflection Mechanism	Y	Y
Continue Monitoring Asteroid After Deflection Attempt	N	Y

Deflection: Avoiding Earth Impact

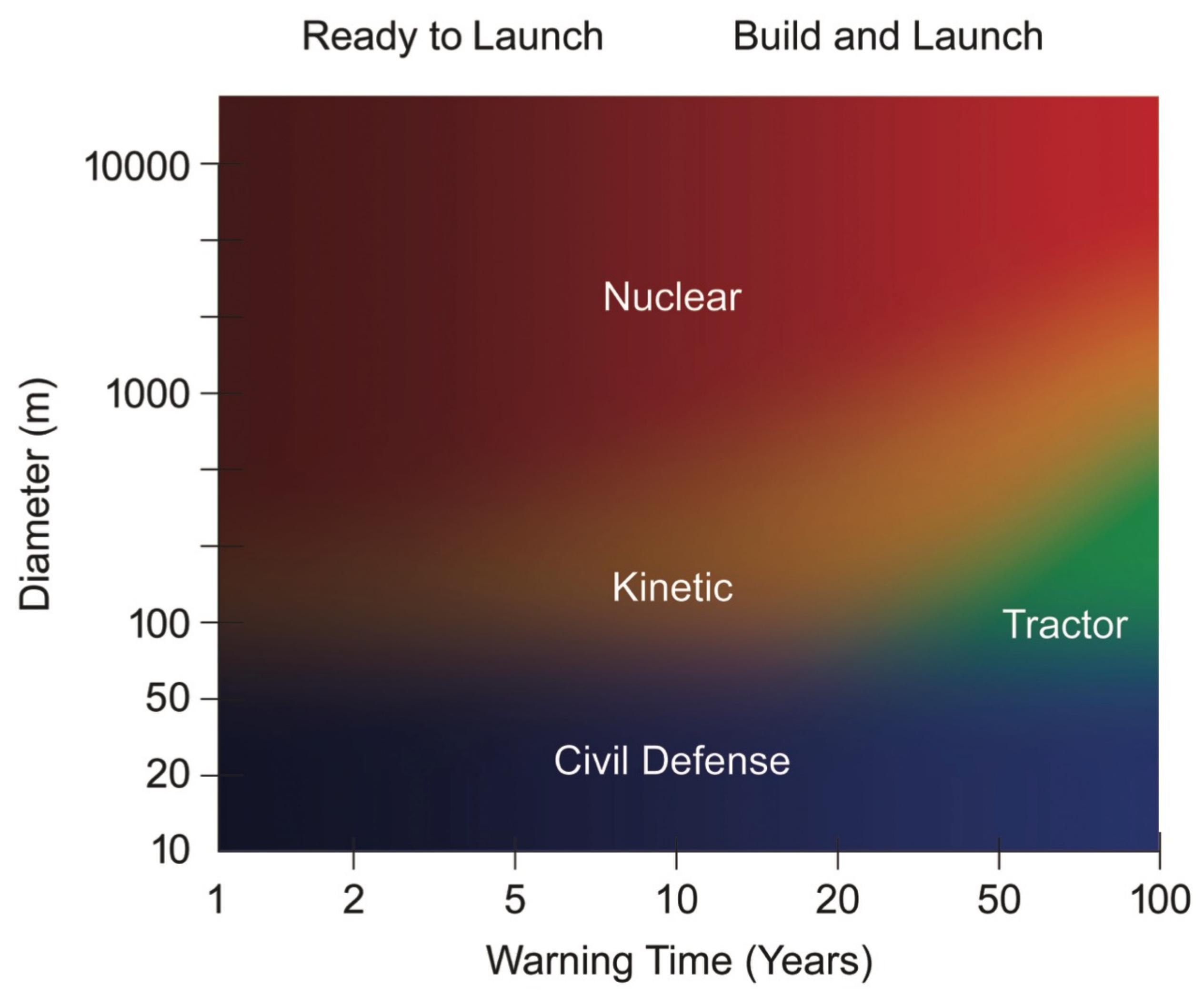
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Much like two vehicles approaching an intersection at the same time, collision will occur unless one of the vehicles slows down or speeds up. Thus, to avoid Earth impact, we deflect an asteroid or comet by changing its speed (slowing it down or speeding it up).



Deflection Technique Regimes of Applicability

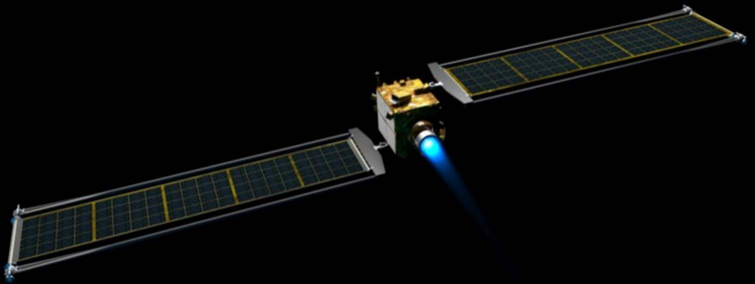
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

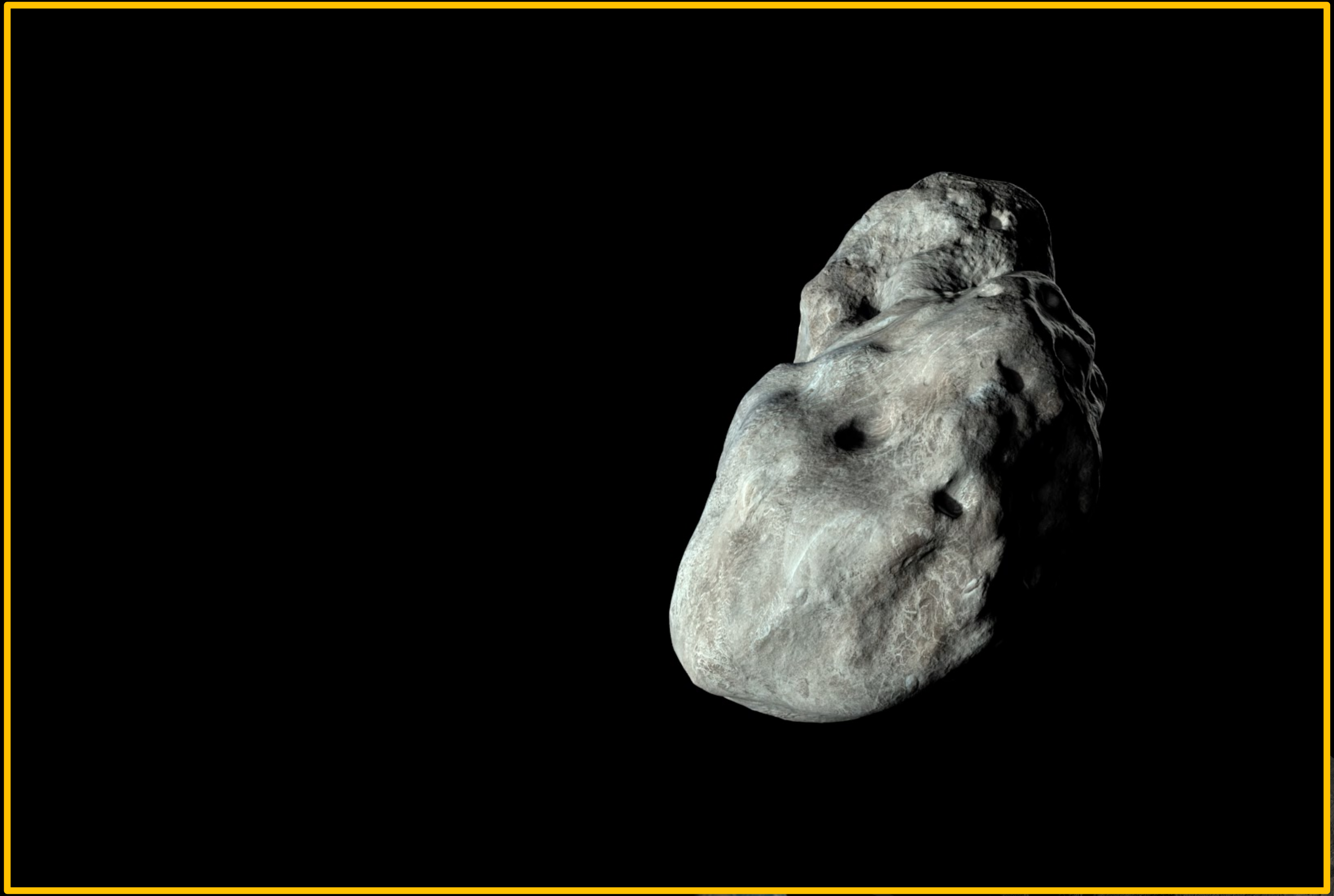


National Research Council (2010). *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*. Washington, DC: The National Academies Press, https://doi.org/10.17226/12842.

Deflection Technique: Kinetic Impactor

- **A spacecraft intercepts and rams into the asteroid/comet at high speed, creating ejecta that provides an additional push.**
- **DART is an example of a kinetic impactor.**

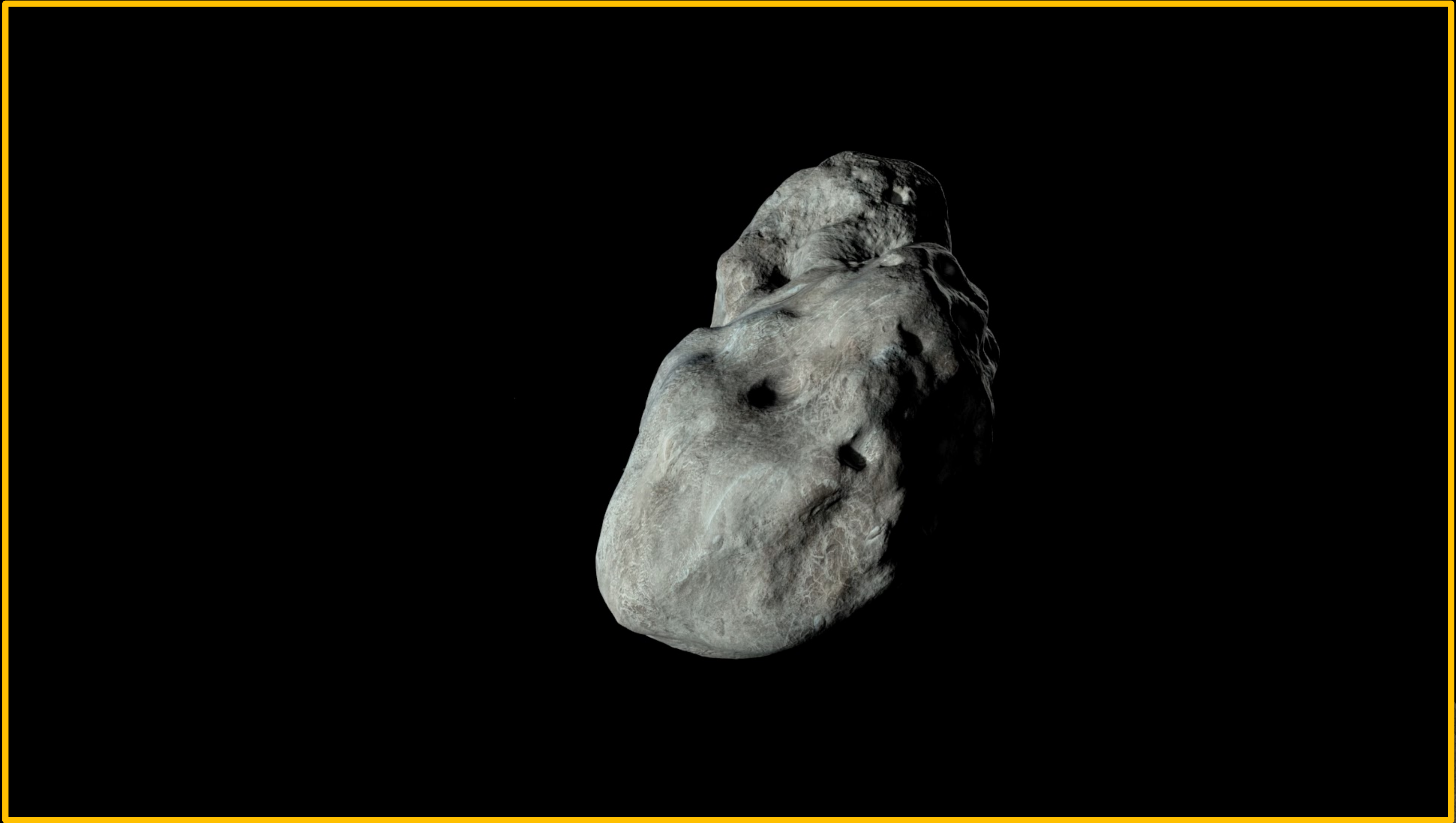




- **Key enabling technologies:**
    - High-performance guidance and control systems
    - Heavy-lift launch
    - Multiple launches

Deflection Technique: Standoff Nuclear Detonation

- **An NED is detonated near an asteroid/comet to vaporize surface material and cause the object to recoil, thus deflecting its path.**
- **Key enabling technologies:**
  - High-performance guidance and control systems
  - NED/spacecraft interfaces
  - Heavy-lift launch



Disruption Technique: Standoff Nuclear Detonation

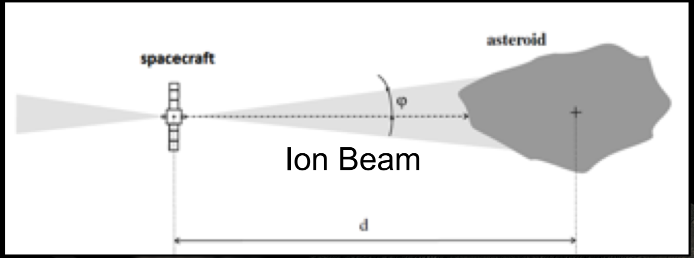
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

- **The NED yield and detonation distance are chosen to create a strong shock that breaks the object up into small and widely scattered fragments.**
- **Key enabling technologies:**
  - High-performance guidance and control systems
  - NED/spacecraft interfaces
  - Heavy-lift launch

Other Deflection Techniques

- **Gravity Tractor**
  - A rendezvoused spacecraft station-keeps near the asteroid/comet so that the spacecraft’s gravity gradually nudges the object over time.
    - *Key enabling technologies: high-efficiency solar electric propulsion systems, heavy-lift launch, multiple launches*
- **Enhanced Gravity Tractor**
  - A rendezvoused spacecraft collects a substantial mass from the asteroid/comet (e.g., a boulder) to increase the spacecraft’s gravity before it begins station-keeping as a gravity tractor. This allows the spacecraft to deflect the asteroid more quickly than it would otherwise, but it requires more propellant and is still a gradual process.
    - *Key enabling technologies: high-efficiency solar electric propulsion systems, heavy-lift launch, multiple launches, advanced robotics*
- **Ion Beam Deflection**
  - A rendezvoused spacecraft station-keeps near the asteroid/comet and aims its ion thruster exhaust at the object to gradually nudge it over time.
    - *Key enabling technologies: high-efficiency solar electric propulsion systems, heavy-lift launch, multiple launches*

Gravity Tractor



Ion Beam

Rendezvous vs. Intercept/Flyby

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

- **Rendezvous:** The spacecraft expends propellant to stop at the asteroid/comet and remain there.
- **Flyby/Intercept:** The spacecraft approaches the asteroid/comet at high relative speed and passes by it rapidly or hits it.
- Some kinds of missions require rendezvous, while some require intercept.
- Some kinds of missions can be either rendezvous or intercept.
- Intercept mission opportunities are often available earlier in the scenario timeline (and more frequently) than rendezvous mission opportunities (if any).
- Rendezvous is generally preferred when possible (except for kinetic impactors, of course).

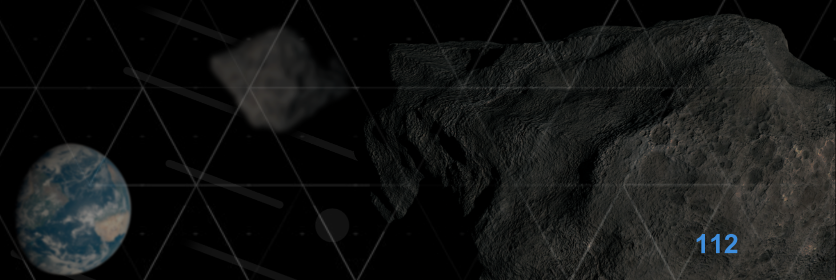
Mission Type	Rendezvous	Flyby/Intercept	Rapid Response (less than 5 years of warning)
Reconnaissance	✓	✓	✓
Kinetic Impactor Deflection		✓	?
NED Deflection	✓	✓	✓
NED Disruption	✓	✓	✓
Gravity Tractor/Ion Beam	✓		

Launch Considerations

- Launch vehicle availability will likely be a challenge during rapid response scenarios (e.g., <1 year of warning).
- Multiple launches may be required to deliver sufficient mass for deflection or disruption.
- Additional launches may be desired for redundancy.
- Additional interfaces and protocols would be needed if launching an NED.

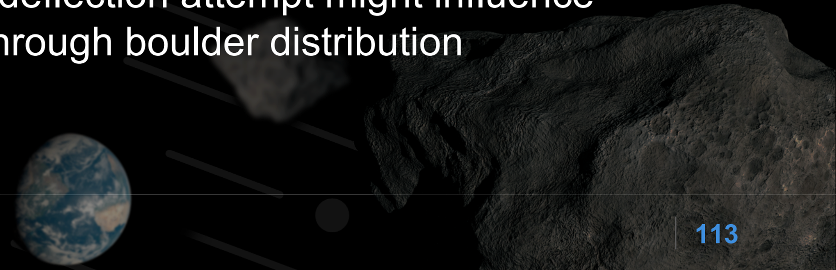
DART Launch
November 24, 2021
Image credit: NASA HQ

Appendix



Reconnaissance Data Priorities

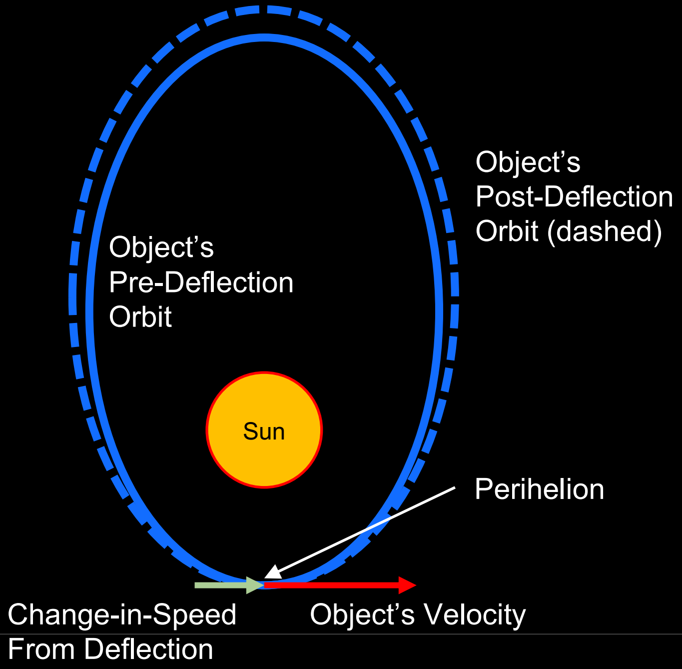
- Notionally prioritized asteroid characteristics to measure for planetary defense purposes (in decreasing order of priority):
  - Orbit
    - Precise orbit of near-Earth object (NEO)
    - Impact location
  - Physical Properties
    - Mass: Most important to know for a deflection/disruption attempt
    - Binarity: Special considerations are required for deflecting/disrupting binary NEOs
    - Shape: With mass, we can then solve for bulk density
    - Strength: Influences NEO response to deflection/disruption attempt, cratering during kinetic impactor (KI) deflection, etc.
    - Internal structure including porosity: Influences NEO response to deflection/disruption attempt, cratering during KI deflection, etc.
    - Mineral composition: Particularly the iron fraction in the first few millimeters to centimeters of the NEO’s surface (influences deflection/disruption method)
    - Detailed surface topology: Relevant for predicting how the ejecta from a deflection attempt might influence the achieved deflection; may inform understanding of internal structure through boulder distribution analyses, regolith presence, etc.

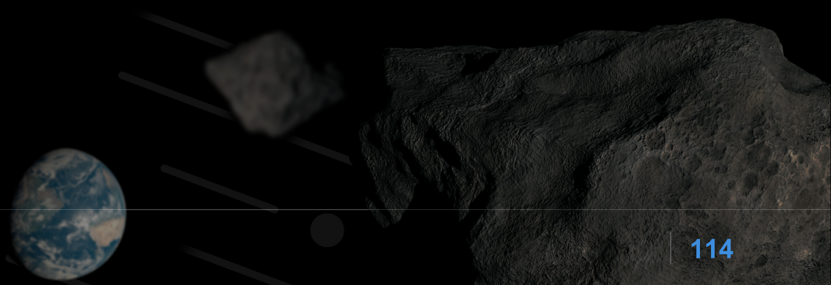


Deflection: Orbital Physics

PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

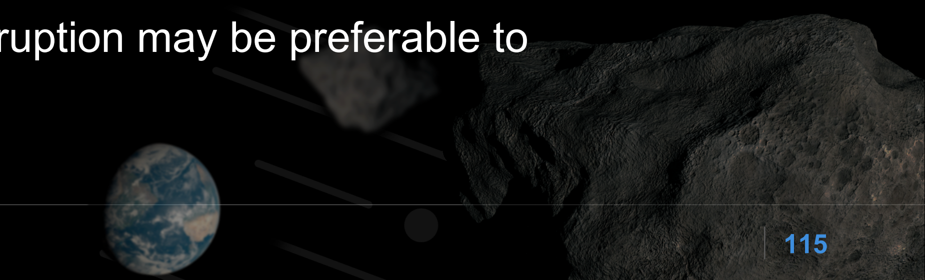
- Deflection performance is usually maximized by applying the change-in-speed in the same direction as the asteroid/comet's velocity, and when the asteroid/comet is closest to the Sun (that location on the object's orbit is referred to as perihelion).
  - However, during the object's final orbit before Earth impact, the best-performing deflection direction becomes more radial (i.e., oriented at least partially along the line between the Sun and the object).
- Deflecting objects on more Earth-like orbits (i.e., more circular orbits) is harder, all else being equal.





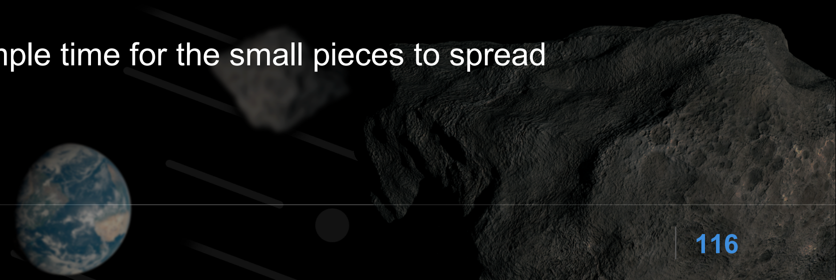
Deflection Considerations

- Deflection techniques are either impulsive or gradual.
  - Impulsive means a quick change in the speed of the asteroid or comet.
  - Gradual means a gentle push is applied to the asteroid or comet over a long period of time.
- Examples of impulsive deflection techniques:
  - Kinetic impactor
  - Standoff NED detonation
- Examples of gradual deflection techniques:
  - Gravity tractor or enhanced gravity tractor
  - Ion beam deflection
- For impulsive deflections, care must be taken to not push the asteroid/comet so hard that it begins to break apart.
  - If the asteroid/comet were to be partially/weakly broken apart, some significant pieces might still impact Earth.
  - If such a partial/weak fragmentation seems possible, then robust disruption may be preferable to deflection.



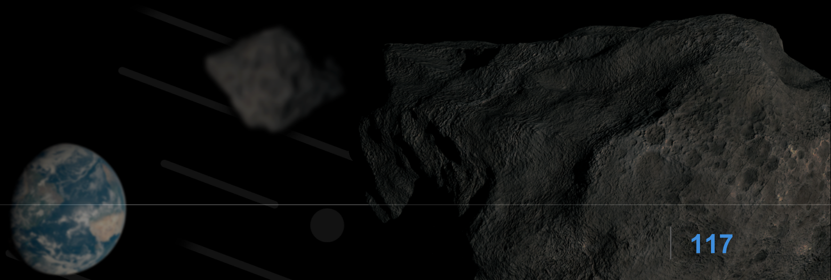
Deflection/Disruption Considerations

- Kinetic impactors have difficulty deflecting westward, while NEDs can deflect eastward or westward equally easily.
- The impulse imparted to an asteroid or comet by an NED can be tuned on the fly by selecting the distance from the object at which the NED is detonated.
- The amount of change-in-speed that an asteroid or comet can tolerate before beginning to break apart isn’t well characterized and will vary from object to object. For now, we use the heuristic that if the required change-in-speed for deflection is 10% or more of the object’s surface escape velocity, then there is a risk of accidentally breaking the object apart and we should consider designing a robust disruption mission rather than a deflection mission.
- Robust disruption definition: The NEO is purposely and forcefully blasted into many small and widely scattered fragments.
  - The largest remaining fragment is small enough that it would be harmlessly destroyed at high altitude in the Earth’s atmosphere (e.g., <10 m).
  - However, the fragments are all so widely scattered that it is very unlikely any fragments would encounter the Earth in the future anyhow.
- Heuristic requirements for robust disruption:
  - A change-in-speed is imparted to the asteroid or comet via standoff NED detonation that is at least 10 times the object’s surface escape velocity.
  - This is carried out at least 1 month before the object’s original Earth encounter date, to provide ample time for the small pieces to spread so far apart that they would not pose a threat to the Earth–Moon system.



Other Challenges

- High-speed intercept is challenging for kinetic impactors and the high-speed intercept version of standoff NED detonation:
  - Guidance, navigation, and control challenges for visible sensors versus infrared sensors at high solar phase angles
  - Proximity radar challenges for proper NED detonation distance sensing during high-speed approach
- We may be confronted with the need to deflect or disrupt a binary asteroid, which is an asteroid with its own moon, like the target of the DART mission, Didymos.
  - We believe ~1/6 of the near-Earth asteroids 200 m in size or larger are binary asteroids.
  - Contact binaries may comprise another ~1/6 of the population. These are asteroids formed of two smaller objects pressed against each other, like the asteroid Itokawa.



PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

NASA

PLANETARY DEFENSE COORDINATION OFFICE

FEMA

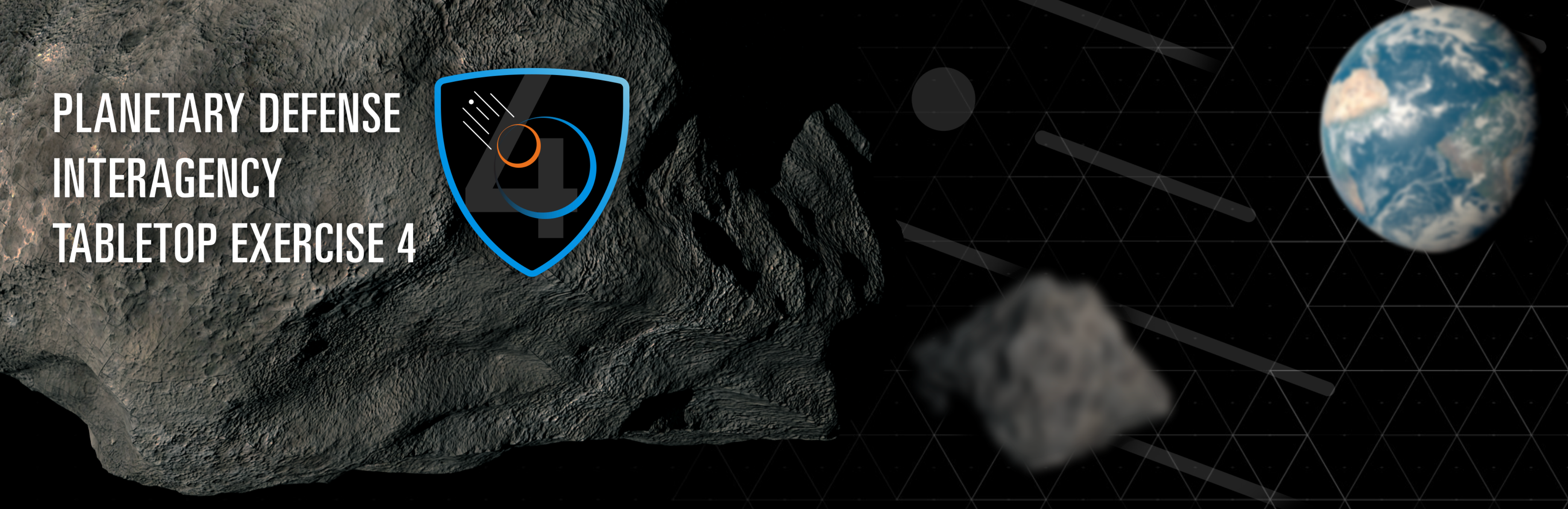
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

cneos

Ames Research Center

EMERGENCY MANAGEMENT
NORTH CAROLINA

WINSTON-SALEM
EMERGENCY MANAGEMENT
FORSYTH COUNTY NC



PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Module 0: TTX Scenario Description

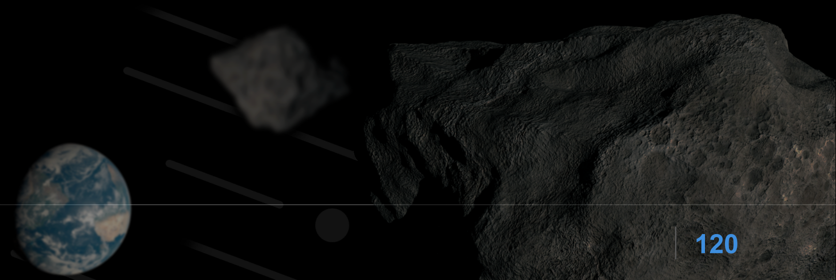
Read-Ahead Summary

Dipak Srinivasan
TTX Project Manager
Johns Hopkins Applied Physics Laboratory
dipak.srinivasan@jhuapl.edu

Terik Daly, Justin Atchison (APL)
Paul Chodas (JPL CNEOS)

Agenda

- Scenario briefing
- Hot wash and participant feedback

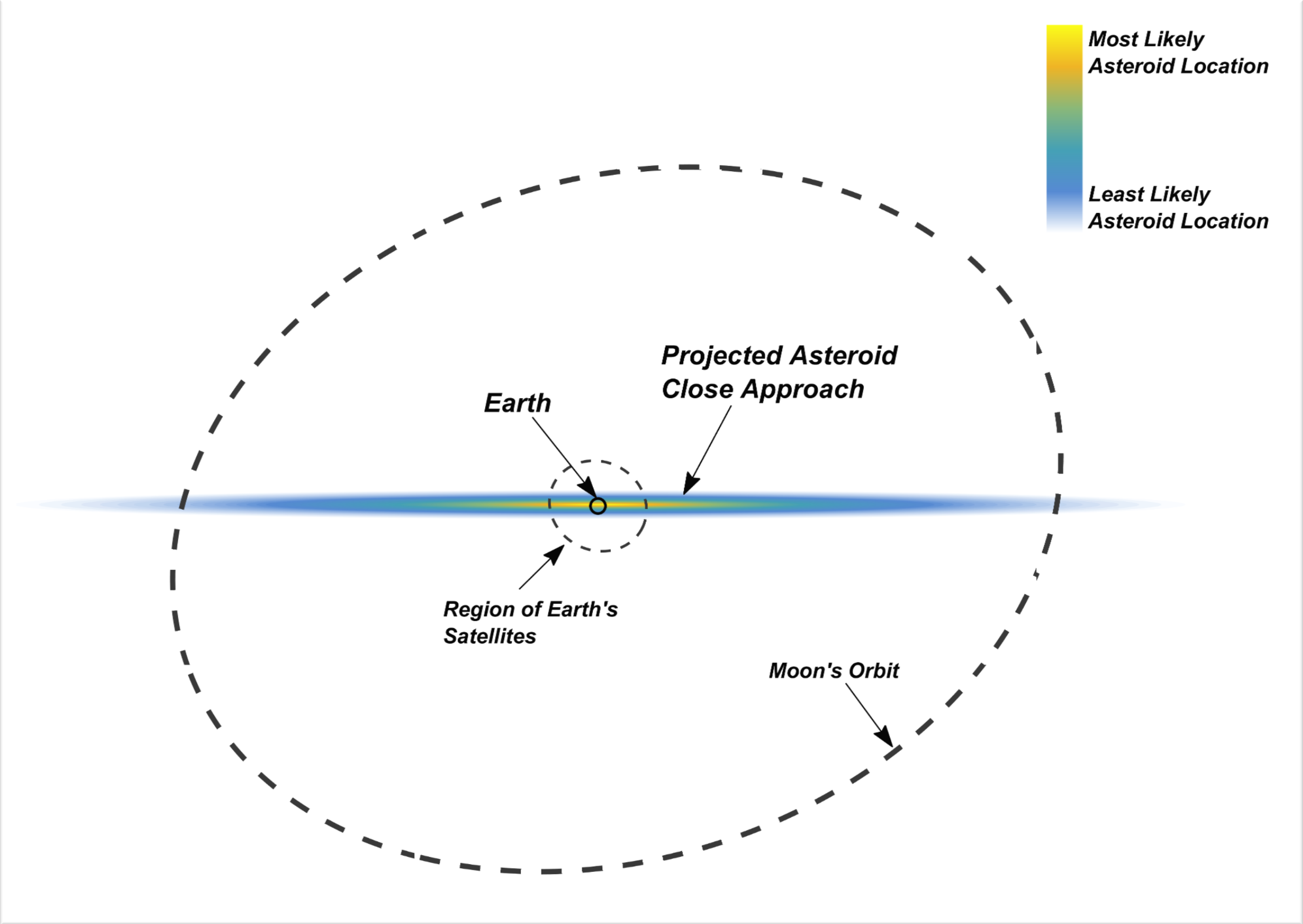


The Information We Have as of 16 Feb 2022

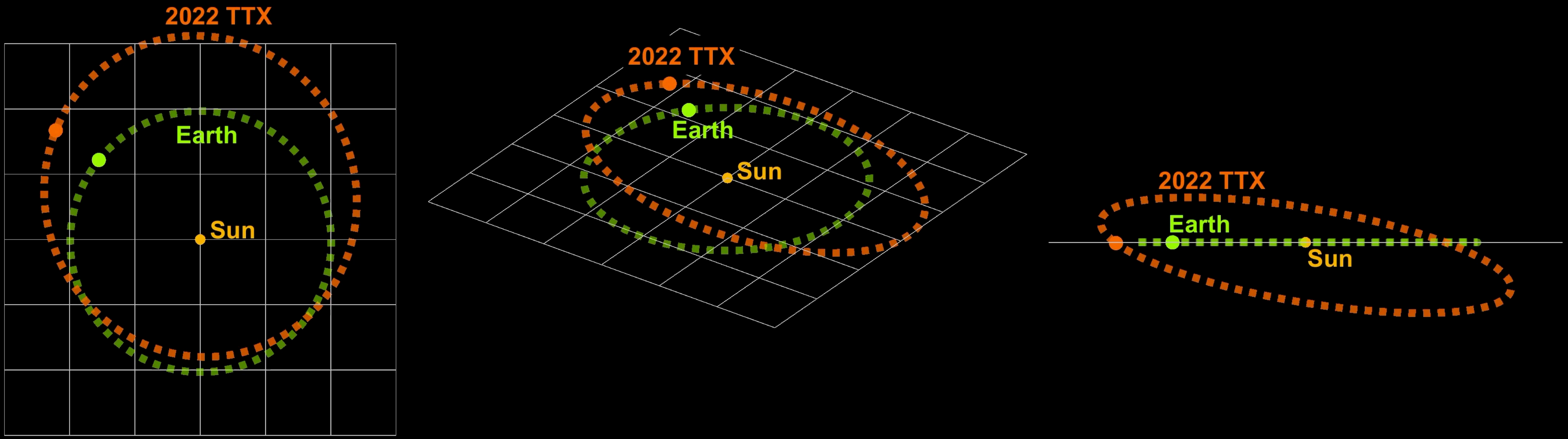
PLANETARY DEFENSE
INTERAGENCY
TABLETOP EXERCISE 4

Bottom line: We just discovered an asteroid, called *2022 TTX*, that has a 5% chance of hitting the Earth on 16 August 2022.

Feb 11	• Initial discovery of *2022 TTX*
Feb 12	• Tracking data from CNEOS gives us an impact probability of 0.04% on 16 Aug 2022
Feb 13	• Archival tracking data provide more information
Feb 16	• Additional data raise probability of impact to 5% • Asteroid size estimated to be between 40 and 440 m



Going Forward Through the Modules



11 Feb 2022

The TTX team's job:

- As time goes on, we will present new information as [simulated] additional tracking data provide refined estimates on the probability and potential location of impact.
- We will prompt discussions and decisions or recommendations that must be made.

Your job:

- As we move through the modules, you will be presented with more actionable information.
- Your discussions, recommended actions, and feedback responses are what we, the exercise team, want to capture.

PLANETARY DEFENSE INTERAGENCY TABLETOP EXERCISE 4

NASA

PLANETARY DEFENSE COORDINATION OFFICE

HIC SERVARE DIEM

U.S. DEPARTMENT OF HOMELAND SECURITY

FEMA

APL

JOHNS HOPKINS

APPLIED PHYSICS LABORATORY

cneos

Ames Research Center

EMERGENCY MANAGEMENT

N★C

NORTH CAROLINA

WINSTON-SALEM

Mitigation Preparedness

EMERGENCY MANAGEMENT

Recovery Response

FORSYTH COUNTY NC

★ Est. 1951 ★