

Impact Threat Exercise at the 2017 Planetary Defense Conference

Paul Chodas (Jet Propulsion Laboratory/California Institute of Technology)

Small Bodies Assessment Group 17th Meeting,
Goddard Space Flight Center, June 12-14, 2017

EXERCISE ONLY!!



Asteroid Impact Exercises



- Hypothetical scenario with an asteroid on a collision course with Earth, using realistic orbital dynamics
- Simulate what we would know when, what the decision-making processes would have to be, and how the threat could be mitigated
- Presented in a series of time steps (“injects”), with mock press releases at each step
- Exercises conducted with FEMA in 2013, 2014 and 2016
- More elaborate exercises conducted at Planetary Defense Conferences (PDCs) in 2013, 2015 and 2017
- Details for PDC17 online: <https://cneos.jpl.nasa.gov/pd/cs/pdc17/>
 - Trajectories available on HORIZONS: “2017 PDC” and “2017 PDCa”
- Collaborators included Brent Barbee (GSFC), Stas Petropoulos (JPL), Mark Boslough (Sandia), Barbara Jennings, Lorien Wheeler (ARC), Donovan Matthias (Ames)



NEO Deflection

- Technologically feasible, given sufficient warning (years to decades)
- Deflect the object by slightly changing its velocity, typically by $\Delta V = \sim 1\text{-}2 \text{ cm/s}$
 - The earlier the ΔV is applied, the smaller the required change
- Warning time is a key: “Find them early”
- Achievable ΔV depends inversely on object mass, which is initially highly uncertain, an order of magnitude or more
- A pre-cursor “characterization” mission is highly recommended to measure physical properties like size, mass, density and strength
- For PDC17, two deflection techniques were considered: Kinetic Impactor (KI) and standoff nuclear; slow-push techniques not used
- CNEOS hosted an Asteroid Deflection Workshop at Caltech in Feb.
- Solar electric propulsion (SEP) was clearly an enabling technology



1. Setup: Asteroid “2017 PDC”

- Discovery on March 6, 2017; visual magnitude ~ 21 .
- Simulated observations: typical cadence (initially), typical data noise
- JPL’s Sentry and ESA’s CLOMON detect chance of impact in 2027
- Typical nightly follow-up leads to slowly rising impact probability:
 - 1-in-10,000 after 2 weeks; 1-in-1000 after 4 weeks
- Magnitude peaks at 20.4 on April 6; close approach 0.13 au on April 27
- Asteroid size is poorly constrained: $H = 21.9 \Rightarrow \sim 100$ to ~ 300 meters
- On Day 1 of the PDC (May 15), impact probability is at 1%
- Attendees participated in decision making: “Build-Your Own Adventure”

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Hypothetical Threat Exercise Organization

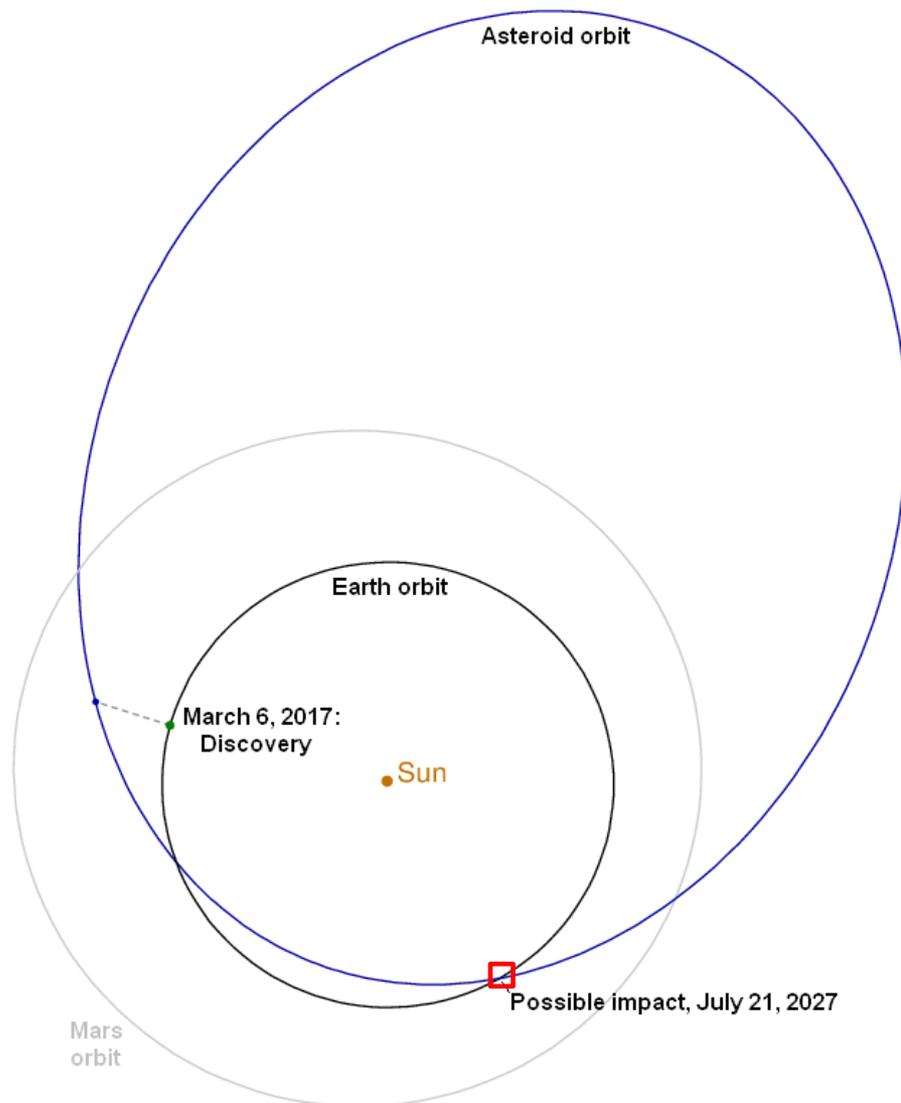


Seven focus groups were established to examine, discuss, and provide recommendations to Group 8

- **Group 1: International Asteroid Warning Group (IAWN)** —What is known about the threatening object? What's its size, mass, shape, etc.?
- **Group 2: Impact Effects**—What would happen were the object to enter Earth's atmosphere and impact? How big would the area affected be?
- **Group 3: Deflection and Disruption**—What techniques are available and suitable to deflect or disrupt the threatening object away from Earth or move it to a different impact location should either be necessary?
- **Group 4: Space Mission Planning Advisory Group (SMPAG)** —What would a mission or campaign to send one or more deflection/disruption payloads to the threatening object look like (e.g., how long would it take to build, launch, and get the payload to the object)?
- **Group 5: Decision to Act**—What considerations will affect the decision to do something (e.g., is the risk level high enough to take action)?
- **Group 6: Communication to and from the Public**—What is the public saying about the risk and actions that might be taken?
- **Group 7: Disaster Planning and Management**—What preparations should be made to prepare for an impact?
- **Group 8: World Leaders**—Make decisions on actions to be taken



Orbit of Asteroid 2017 PDC



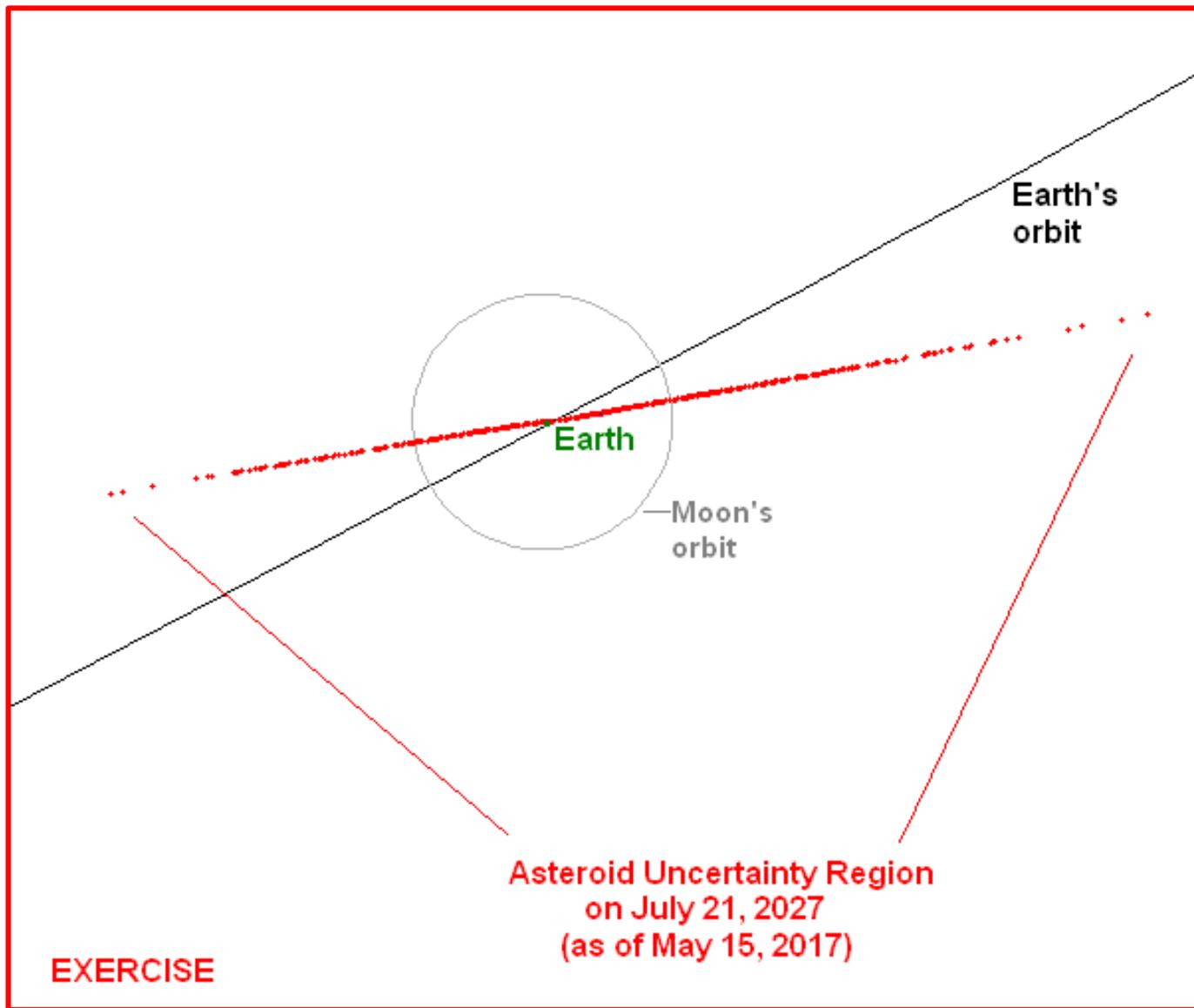
Perihelion: 0.9 au
Aphelion: 3.6 au
Orbit period: 3.35 yr
Inclination: 6.3 deg

H = 21.85
Size: ~100 – ~300 m

Possible impact
occurs 3.2 orbits
after discovery, on
July 21, 2027



2017 PDC Position Uncertainty on July 21, 2027



Uncertainty region on July 21, 2027, using data up to May 15, 2017

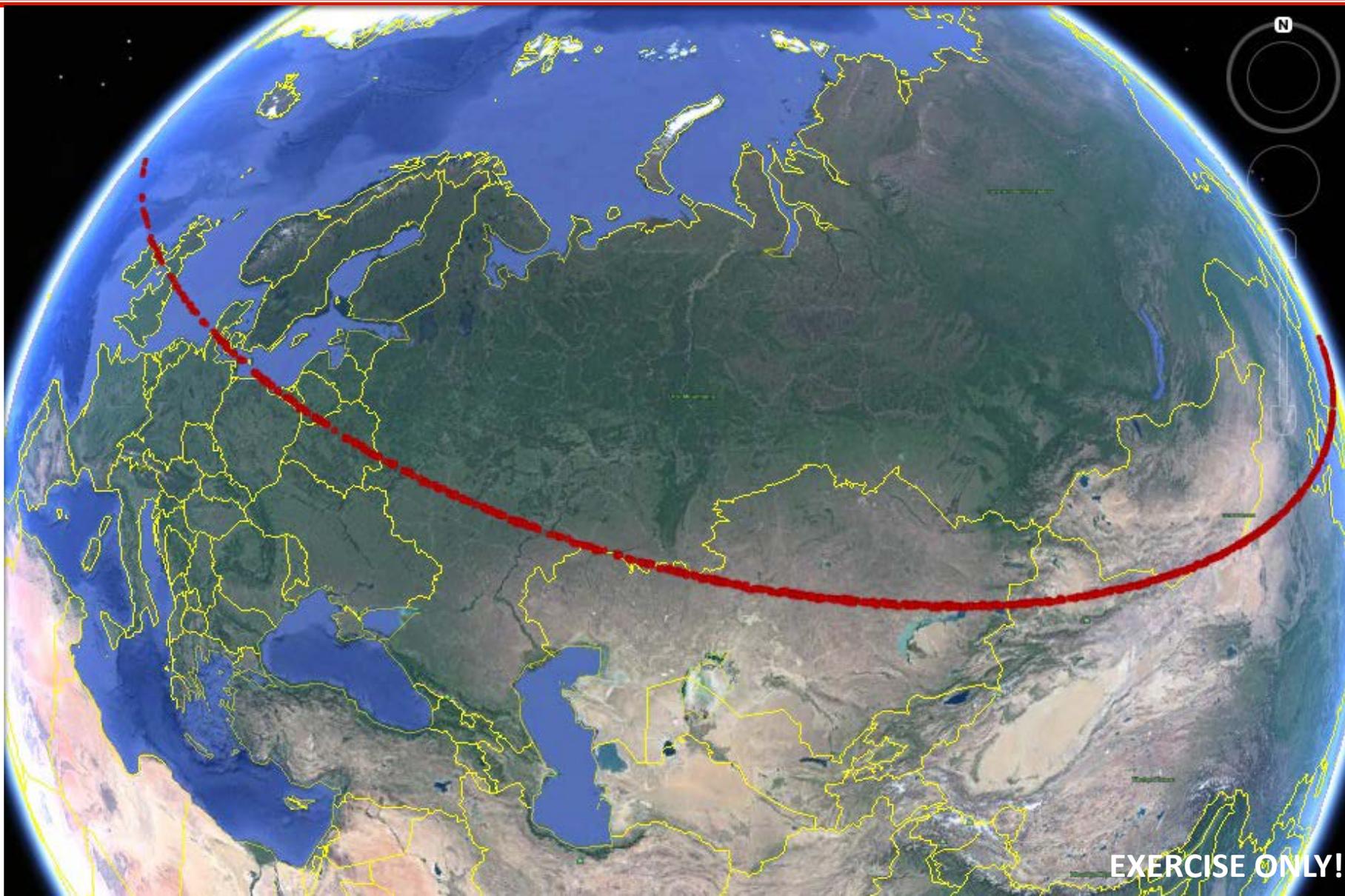
Uncertainty region will shrink as more observations are added

Asteroid Uncertainty Region on July 21, 2027 (as of May 15, 2017)

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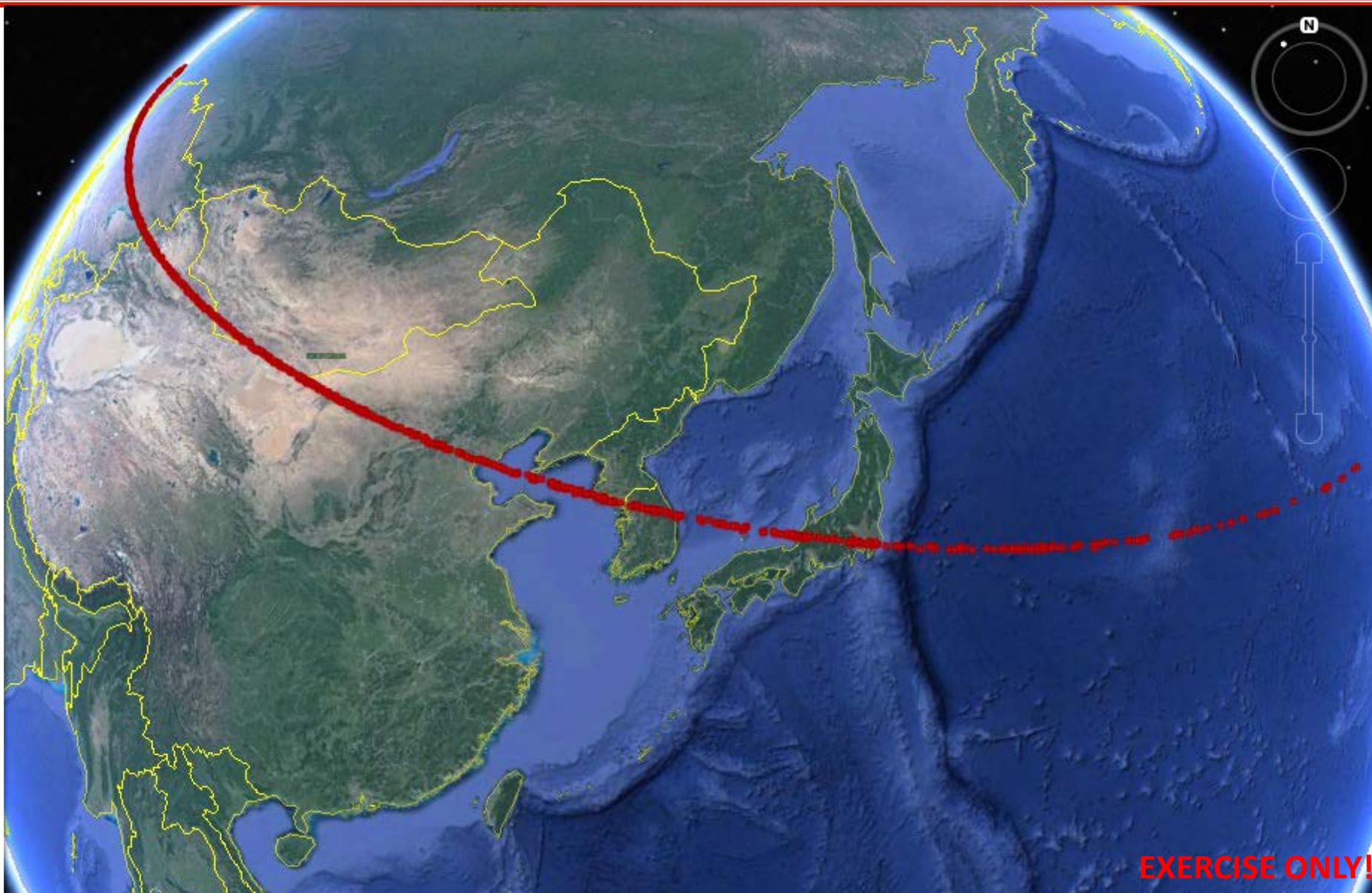
2017 PDC Risk Corridor - West



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2017 PDC Risk Corridor - East



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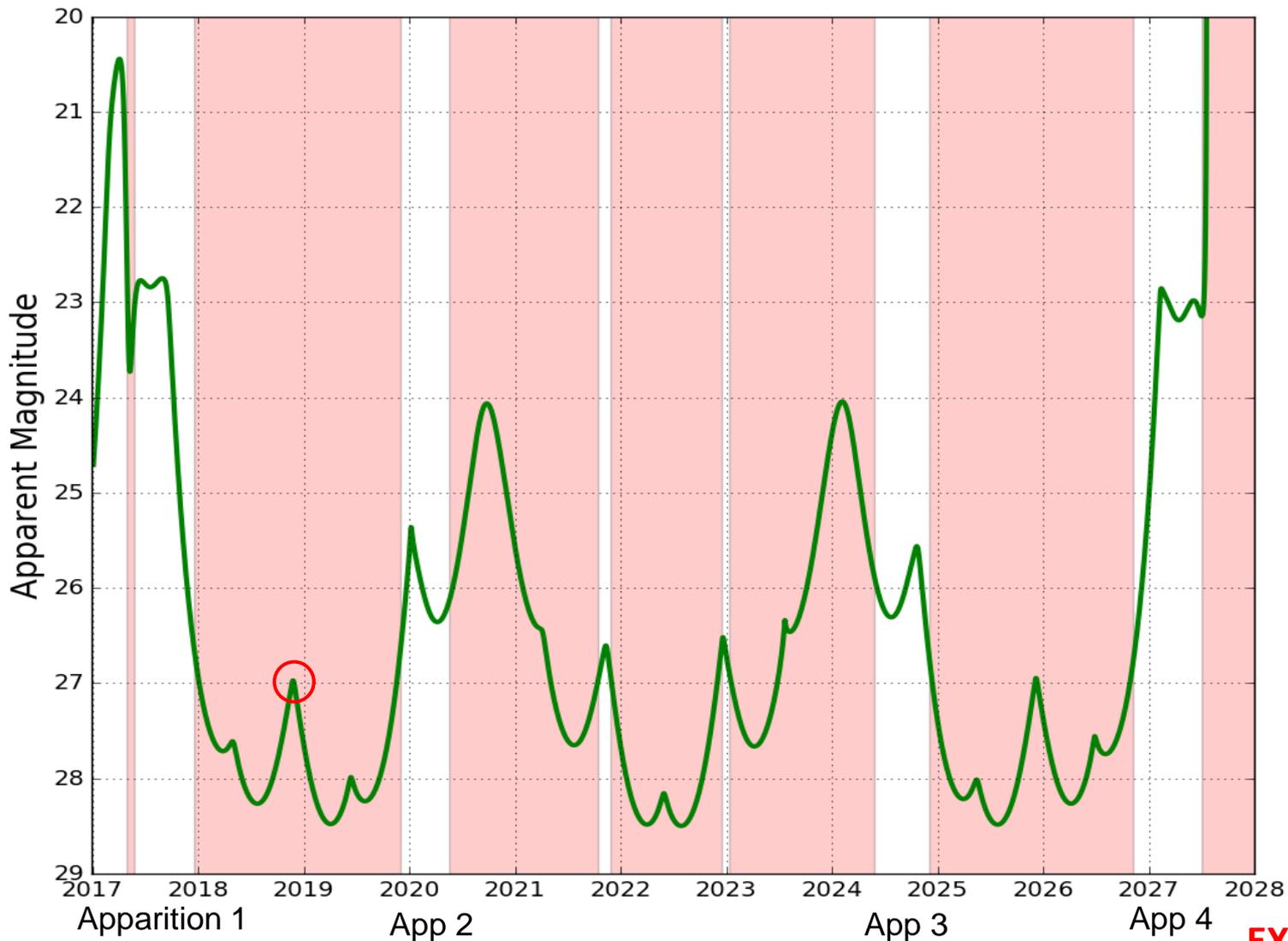


When Is 2017 PDC Visible from Earth?



Not visible during shaded times (AppMag > 26.8 or solar elongation < 45 deg)

Telescope Category:



1 m

2 m

4 m

8 m

HST

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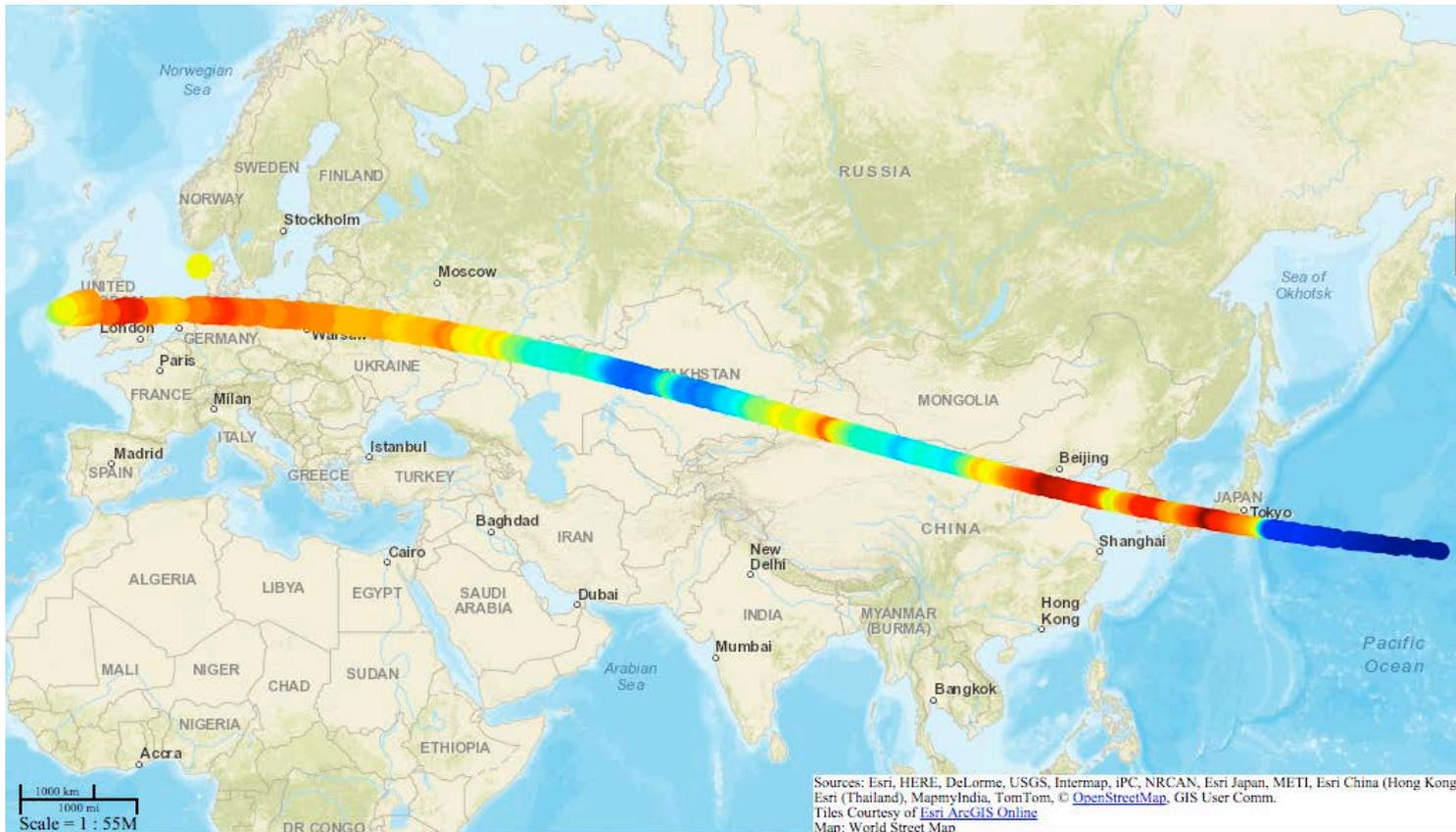
2017 PDC: Impact Probability vs. Time

- Mitigation decisions will be based on impact probability
- Times when 2017 PDC will be observable can be predicted:
 $V_{\text{mag}} < 26.7$ and solar elongation > 45 deg \Rightarrow 4 apparitions
- Assuming 1) asteroid is on an impact trajectory and 2) an achievable observation schedule, we can predict the fastest possible rise of impact probability *Pip*
- *Pip* no higher than 10% in July 2017, and no higher than 26% by the end of the first apparition (December 2017)
- Day 1 recommendation: a special observing campaign to observe asteroid at $V_{\text{mag}} = \sim 27$ in Nov. 2018, perhaps using HST or VLT
 - Without these observations, impact probability would remain frozen at 26% until the second apparition begins in Nov. 2019
- Additional recommendation: Begin developing missions

Risk Assessment: Blast Damage



Risk Assessment: Affected Population



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CNEOS NEO Deflection App (NDA)

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



Delta-V Mode | **Intercept Mode**

Time of Deflection (D): 1096 days

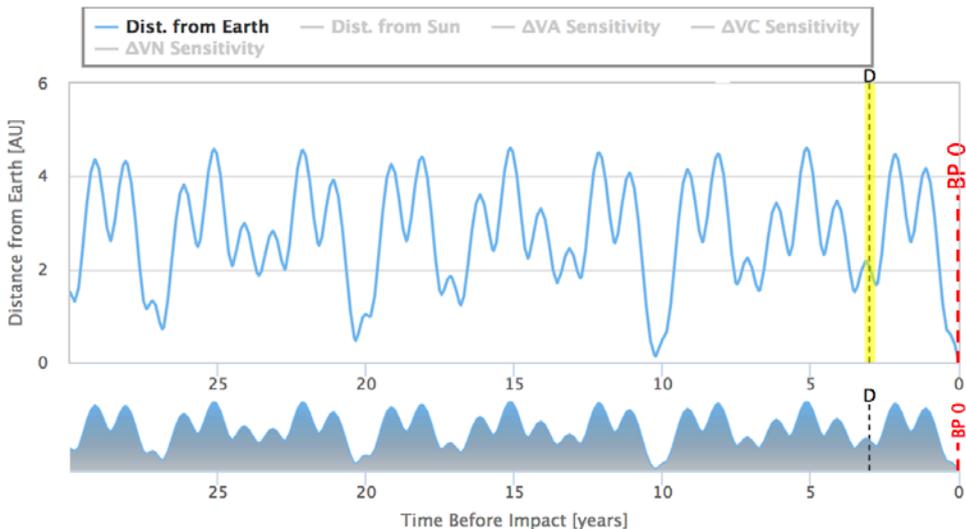
ΔVA : 0.000 mm/s
 ΔVC : 0.000 mm/s
 ΔVN : 0.000 mm/s

Simulated Near Earth Object (NEO)
 PDC17a a=2.24 i=6 e=0.61 View Orbital Parameters

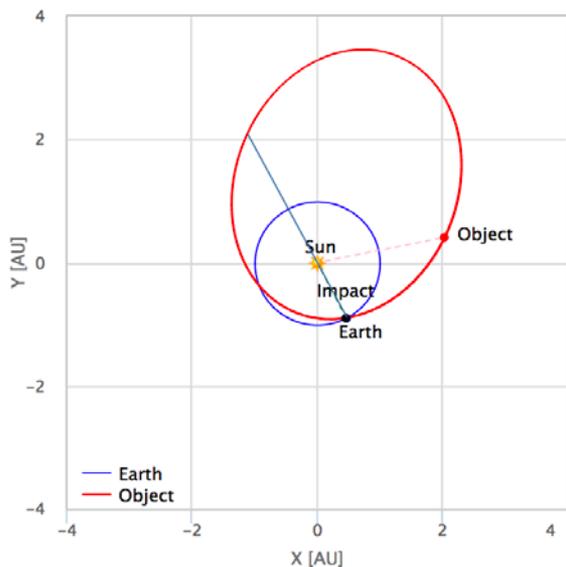
Diameter: 0.14 km
 Density: 1.25 g/cm^3
 Beta: 0.0001
 Mass: kg

Object parameters are only applicable in Intercept Mode

Reset | Slider Δ 's | Advanced Mode | Tips



Orbit and Positions at Deflection



Orbit Changes

ΔVA : 0.000 mm/s
 ΔVC : 0.000 mm/s
 ΔVN : 0.000 mm/s
 Total ΔV : 0.000 mm/s
 Period at D: 1225.064 d
 Δ Period: 0.0000 s

B-Plane Values

ζ (zeta): 0.737 R_e
 ξ (xi): -0.880 R_e
 B magnitude: 1.148 R_e
 Capture Rad.: 1.310 R_e
 Perigee Dist.: 0.845 R_e

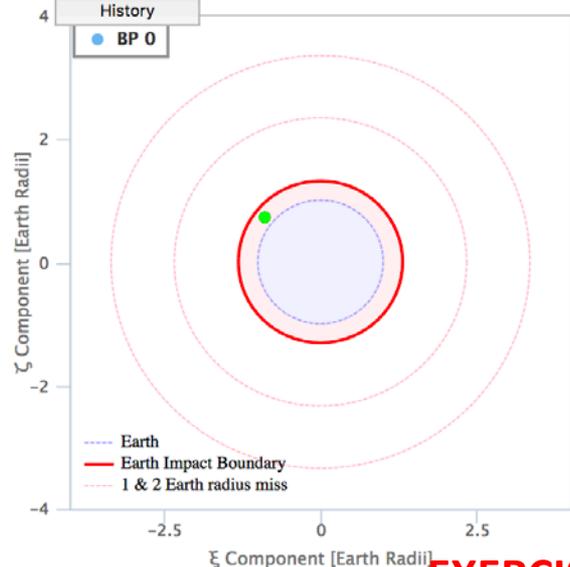
IMPACT

V_{∞} : 13.212 km/s

* R_e = Earth Radii

Save Current Session
 Restore Session
 Deflection Map

B-Plane

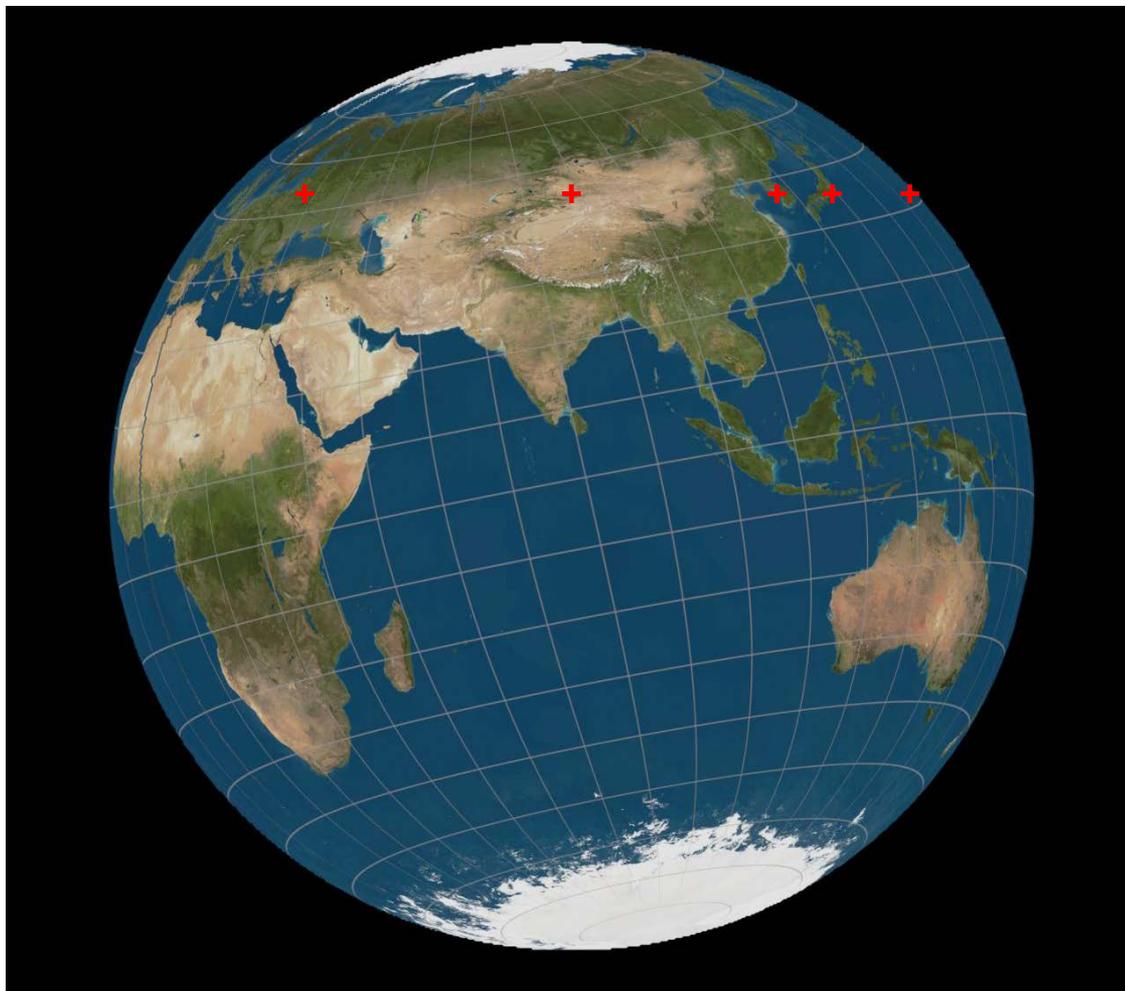


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Required vs. Achievable Deflection

26,600 km ←
2940 km ←
D= 250m: 0.46 cm/s
D= 120m: 4.14 cm/s



Eastwards deflection
on 2024-Jan-23,
Atlas V launch,
 $\rho = 1.5 \text{ g/cc}$, $\beta=1$

←
Easier direction
for Kinetic
Impactors

BUT, to avoid
disruption,
 $\Delta v < 0.1 v_{\text{esc}}$

=> For D = 120m:
 $\Delta v_{\text{max}} = 0.55 \text{ cm/s}$



Uncertainties in Deflection Campaign Design



- Low impact probability early on hampers decision to build missions
- Even when impact is nearly certain, required deflection is still uncertain
- With only ground-based measurements, mass M of the asteroid is uncertain by an order of magnitude
 - deflection achievable from a single KI mission is uncertain by an order of magnitude
- Momentum enhancement factor β also very uncertain
- Even with in-situ characterization, achievable deflection for any given mission design would still be uncertain by a factor of several
- Even with in-situ characterization, the **number** of KI missions required to move the trajectory off the Earth is uncertain by a factor of several

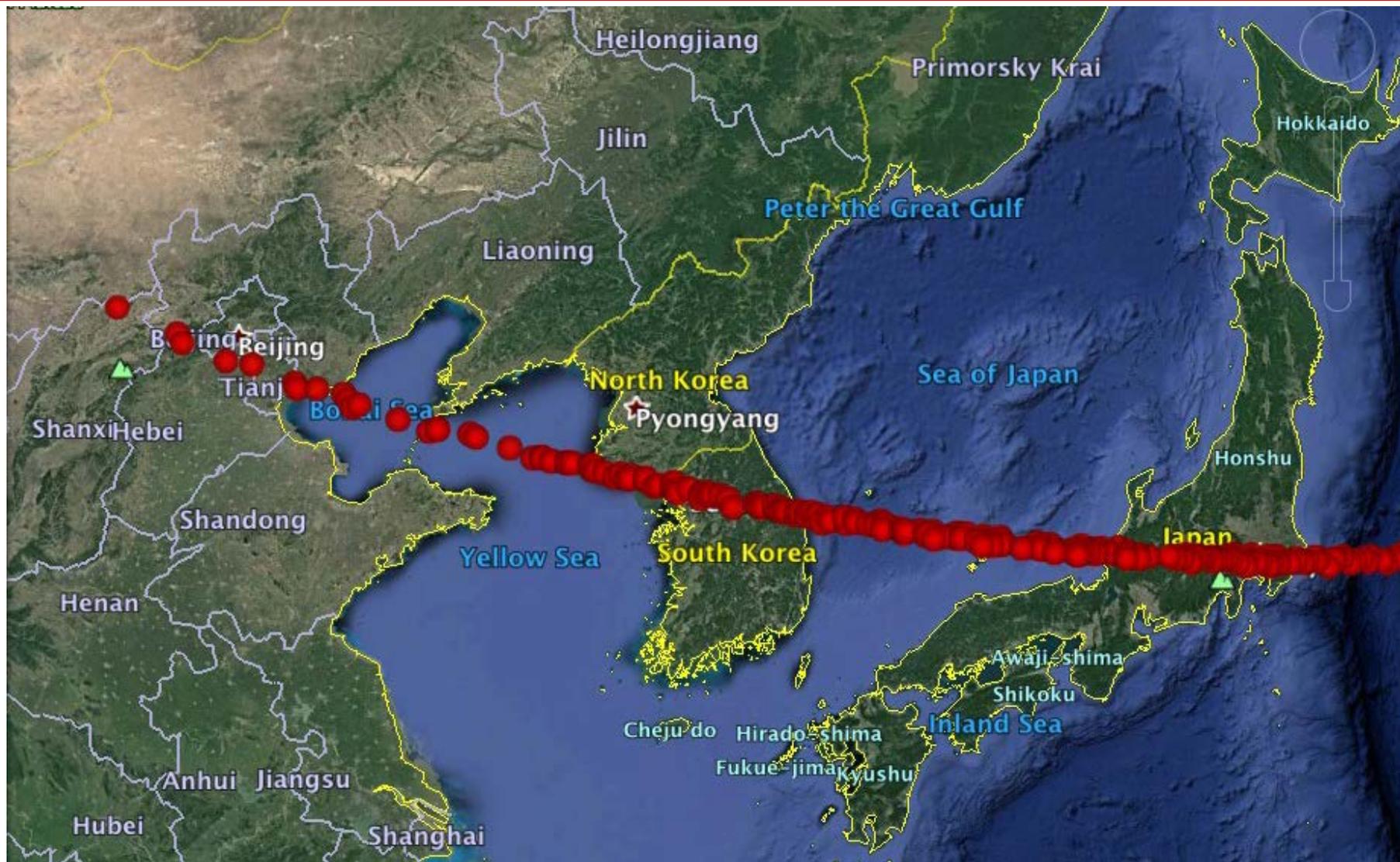


2. Nov. 30, 2018: Chance of Impact Now 96%

- Special observations taken at $V_{\text{mag}} = \sim 27$; they extend the data arc and dramatically improve the orbit estimate
 - HST and Subaru 8-meter
- 2017 PDC is on a course that almost certainly will impact Earth on July 21, 2027, less than 9 years from now
- Asteroid had been unobservable for 11 months, during which time the impact probability was 26%; for the next 11 months, the asteroid will again be unobservable
- Updated size estimate based on NEOWISE: 200 - 280 meters
 - Albedo of roughly 4% to 8%
- Possible impact locations now confined to a footprint stretching from China, across North and South Korea, Japan, and into the Pacific

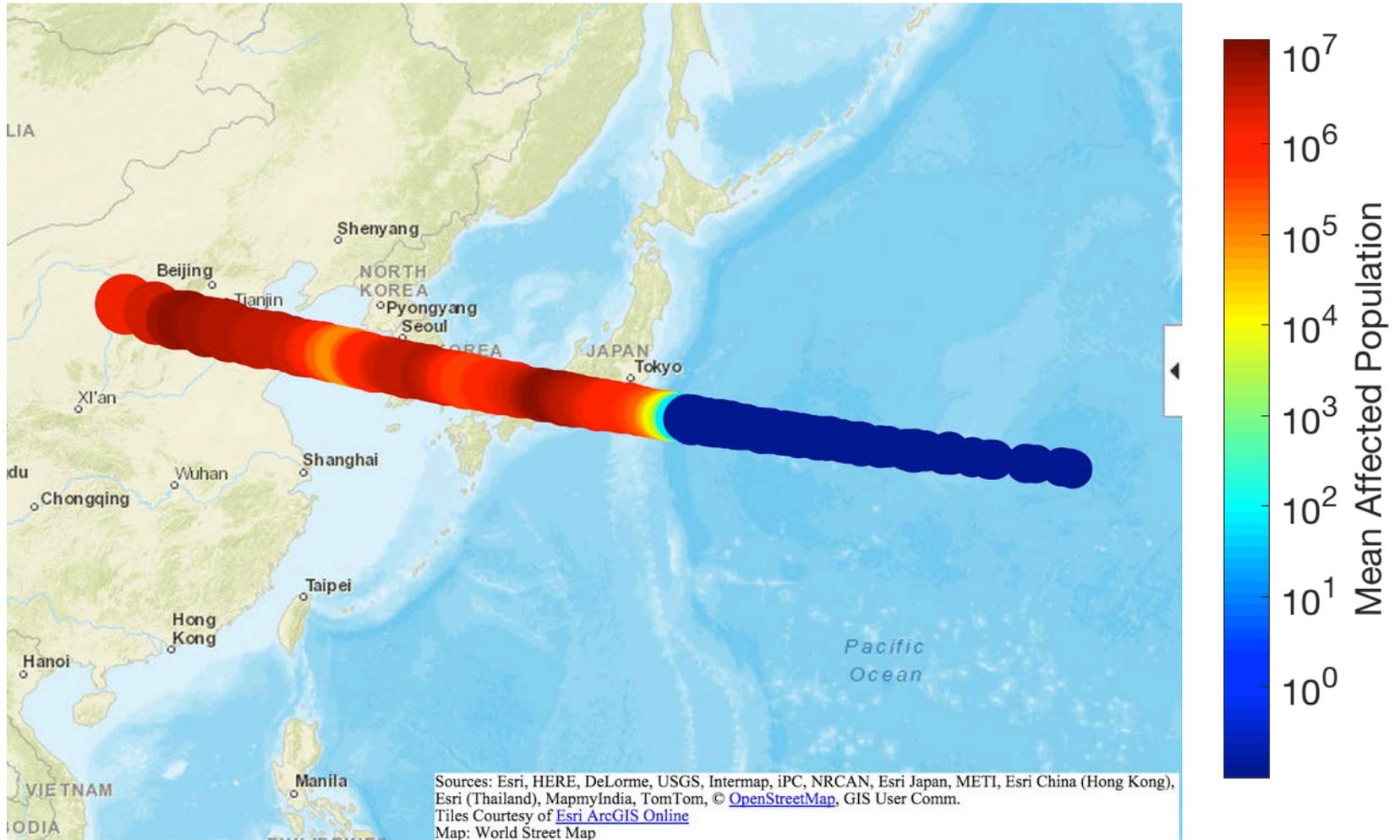


Possible Impact Locations for 2017 PDC



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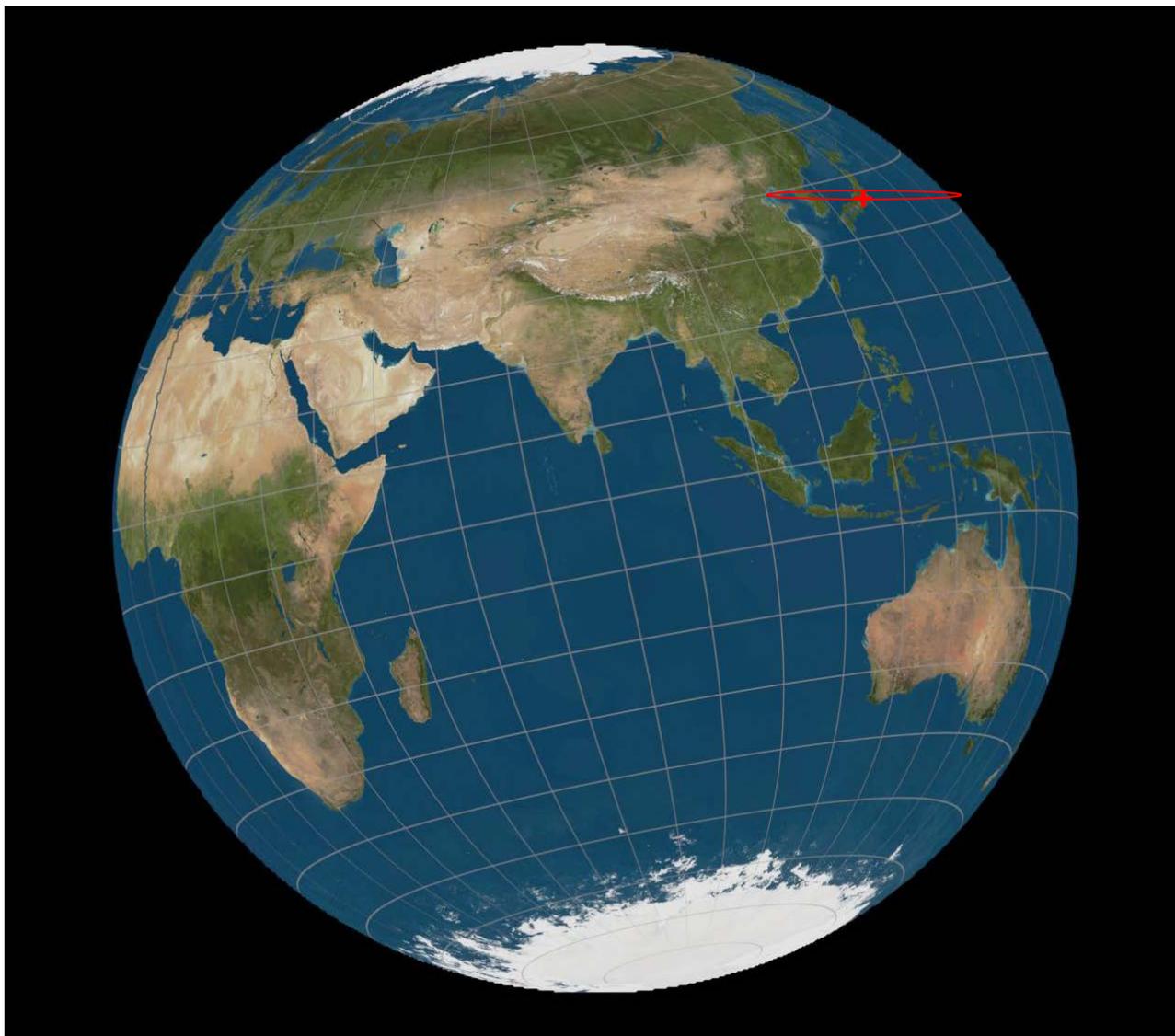
Risk Assessment: Affected Population



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Impact Footprint in the B-Plane



←
West: Easier
direction for
Kinetic Impactors,
but more Δv
required

→
East: More difficult
direction for
Kinetic Impactors,
but less Δv
required

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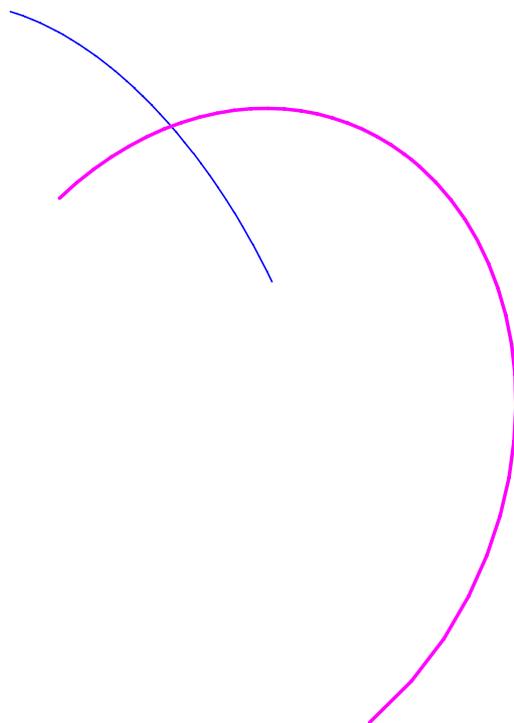


Space Missions to 2017 PDC

- Once impact probability passes 1%, the Space Missions Planning Advisory Group (SMPAG) would become active in advising for and coordinating an international program of space missions to 2017 PDC
- The various space agencies may not devote serious resources to these missions until the impact probability gets higher, perhaps ~10% (July 2017)
- Assume a minimum development time of 2 years
- Several types of space missions were considered:
 - Early **fast flyby** characterization: launch in Oct. 2019, flyby May 2020 ✓
 - **Rendezvous** characterization and observer spacecraft: launch in June 2020, arrival in May 2023 (2 spacecraft?) ✓
 - Kinetic Impactor Eastwards (**KI-E**): launch in March 2020, deflection Feb. 2024 (6-8 spacecraft?) ✓
 - Kinetic Impactor Westwards (**KI-W**): launch in July 2023, deflection Feb. 2024 (6-8 spacecraft?)
- Recommendation: Aggressive development of the indicated missions



Trajectory for KI-Eastwards Mission



Launch: Mar. 28, 2020

Deflect: Feb. 24, 2024

This trajectory boosts the velocity of the asteroid, thereby moving the asteroid's impact point eastwards

This trajectory is difficult to attain, requires a long flight time, and arrives at the asteroid at a relatively low velocity: 8 km/s

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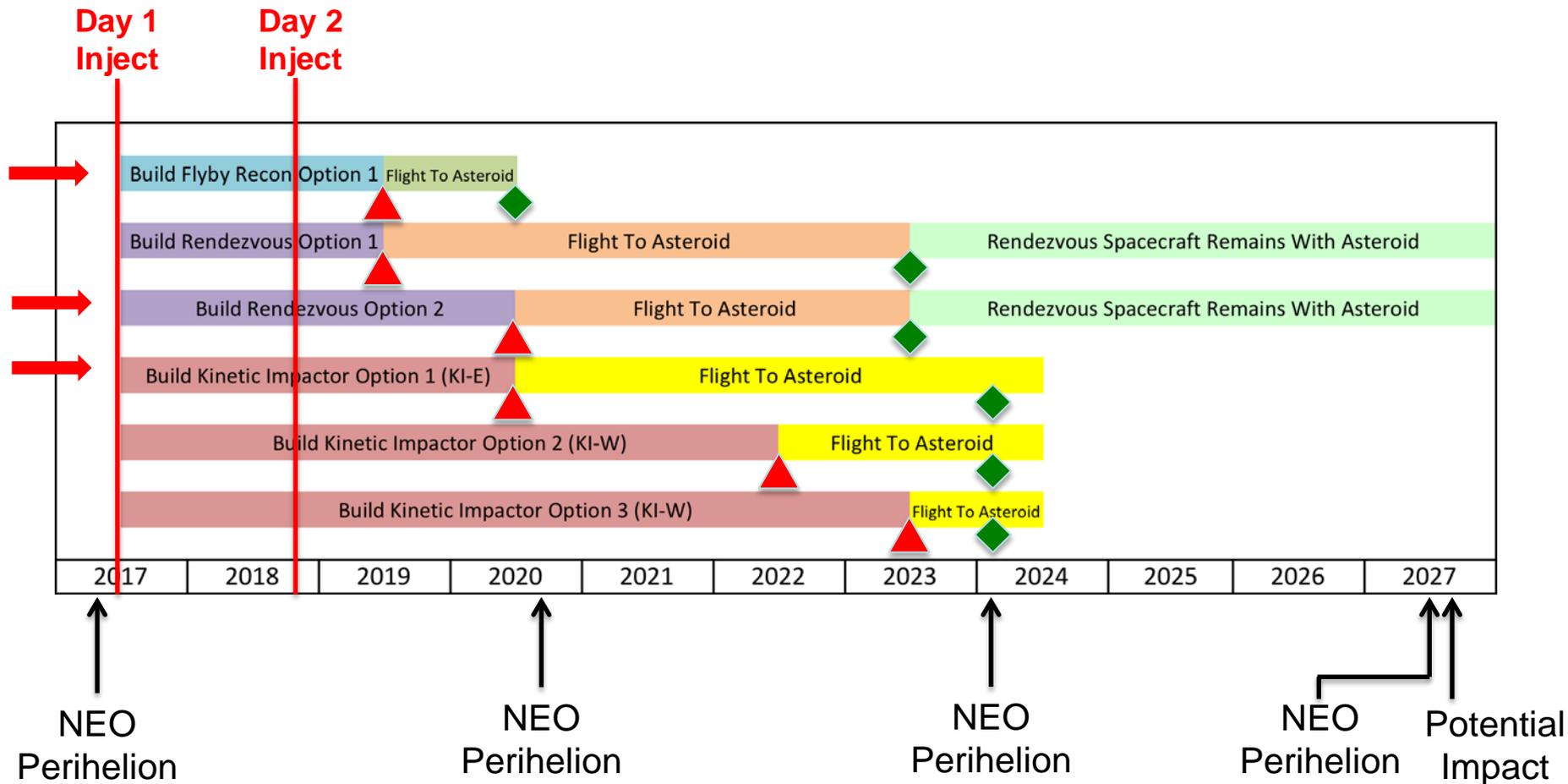


2017 PDC: Summary of Inject Dates



▲ LAUNCH

◆ ARRIVAL

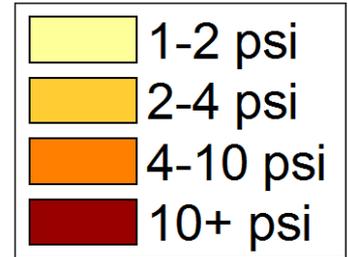
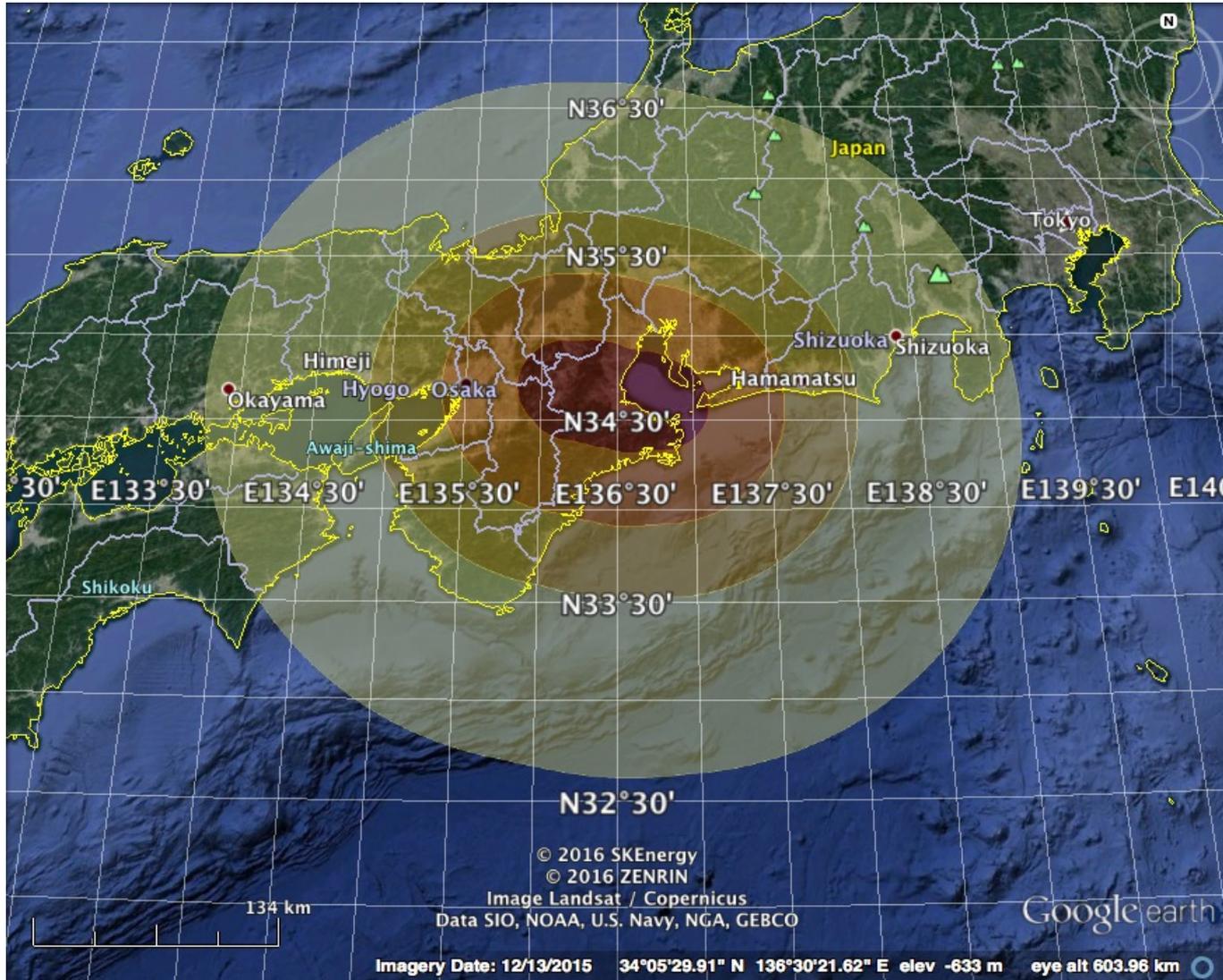




3. May 15, 2020: Asteroid Is Binary; Impact Location Near Tokyo

- Fast flyby mission successfully encounters the asteroid
- 2017 PDC is binary: primary ~270 meters, secondary ~100 meters, loosely bound
- Size, mass and density now known much more accurately; mass to within ~20%
- Images yield accurate position measurements; impact projected to be near Tokyo on July 21, 2027, 7 years from now
- 6 KI-E spacecraft of various SEP designs launched in March 2020 to move the impact point eastwards (into the Pacific Ocean and then off the Earth)
- In the worst case ($\beta = 1$), at least five KI impactors must hit the target in order to avoid impact; otherwise there would be an impact in the Pacific Ocean
- Deflection of the primary also affects the secondary through the mutual gravitational attraction: its orbit will change in a largely unpredictable way; there is a chance that the secondary could escape the system

Blast Damage Zones



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Rendezvous/Observer Mission

- Two spacecraft readied for launch next month on a mission to rendezvous with 2017 PDC in May 2023, 3 years from now
- Decision makers still deliberating on whether or not to install deployable nuclear explosive devices (NEDs) on these spacecraft
- Spacecraft would be in place to either carry out a controlled nuclear deflection or observe the series of KI deflections; both would occur around perihelion (Feb. 2024)
- Recommendation: Launch both missions with the NEDs
- Data returned would be invaluable for assessing the results of the deflection, whether KI or nuclear, and establishing new trajectories for both components of the binary asteroid



4. June 2023: Rendezvous Mission Reaches Target; Use of Nuclear Device Being Considered

- Decision makers decided to include nuclear devices on both rendezvous observer spacecraft
- One rendezvous observer spacecraft has reached the asteroid and has been surveying and characterizing the binary asteroid for a month; the other mission failed enroute
- Asteroid still on a course headed for impact near Tokyo on July 21, 2027, now only 4 years away
- Asteroid 2017 PDC is binary, consisting of a primary body 270 meters in size and a secondary 90 meters in size
- Size, shape and volume of both bodies are now known very accurately (270m and 90m); secondary is only weakly bound
- 6 kinetic impactor spacecraft are still enroute for deflection in Jan. 2024
- Debate: Should the nuclear devices be used to deflect or not?



5. Feb. 2024: Deflection Successful

Outcome A:

- Decision makers decide to deploy the nuclear explosive device at a standoff distance of about 1 km from both the primary and secondary components
- Delta-v velocity change of at least 1 cm/s is sufficient to move it away from its Earth-impacting trajectory
- The secondary component was completely destroyed

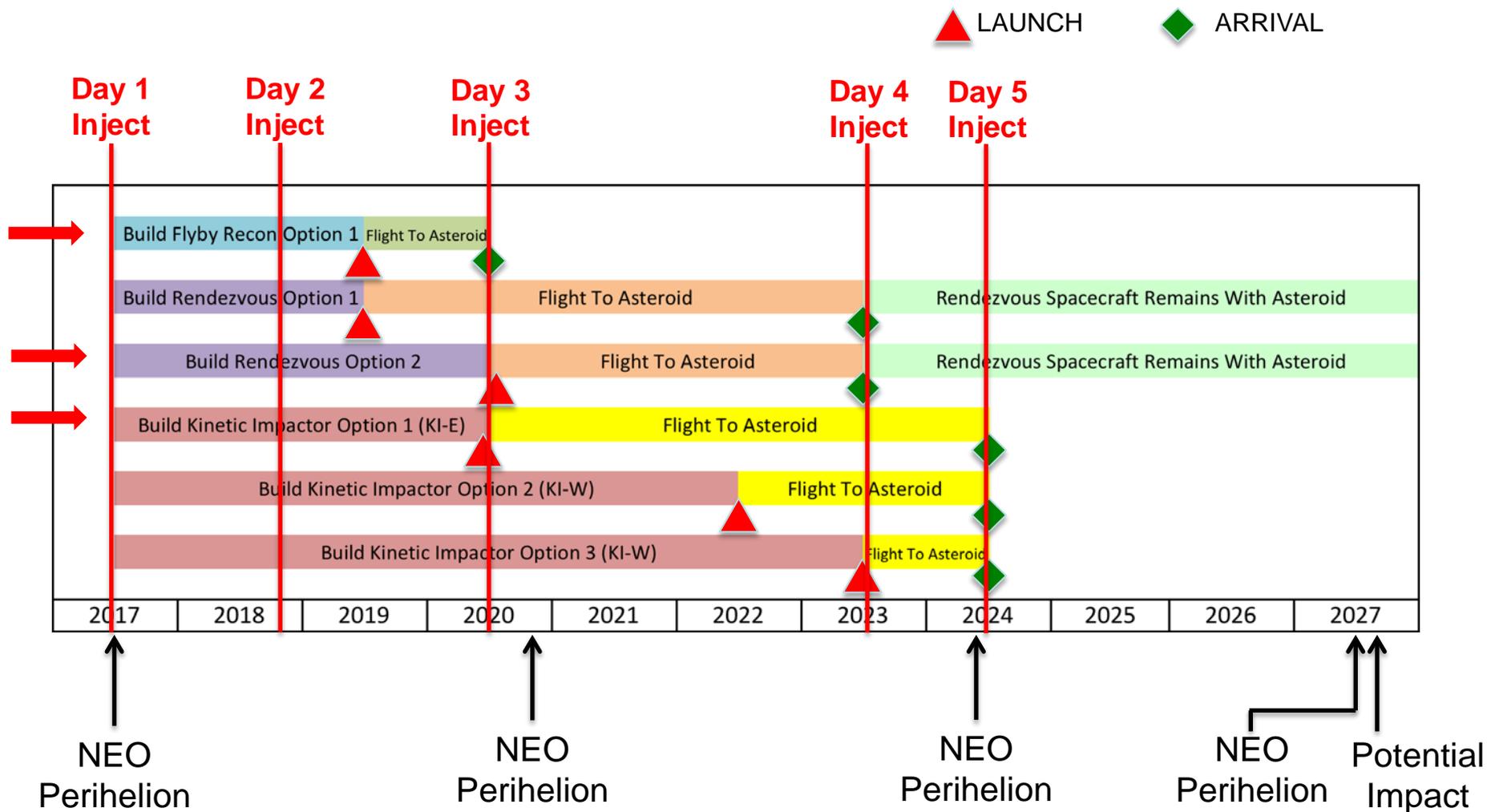
Outcome B:

- Decision makers decided to forgo use of the nuclear explosive device and rely on the series of kinetic impactors to deflect the asteroid
- Kinetic Impactor deflections spaced about 5 days apart; each removes ~ 0.08 cm/s from asteroid's velocity
- After the fourth KI deflection, both components of the asteroid receive enough delta-v to prevent impact

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2017 PDC: Summary of Inject Dates





2017 PDC: Some Key Takeaways

- A 10-year warning time is long enough to offer a wide range of space mission options
- Solar electric propulsion (SEP) widens the range of possible missions
- Take all possible measures to get ground-based observations as early as possible, even at very faint magnitudes
- An early fast response characterization mission is highly recommended and may be key to a successful deflection campaign
- Kinetic Impactor deflection capabilities are asymmetric, but both directions (east or west) are still possible
- A rendezvous/observer spacecraft is highly recommended and may be the best platform to carry out a nuclear deflection
- Use of nuclear explosive devices for asteroid deflection remains highly controversial