Near-Earth Asteroid Deflection Strategies

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Basics of NEA Deflection

- **The impact of a near-Earth asteroid (NEA) is a natural hazard that can be prevented or mitigated given sufficient warning time and capable systems and technologies.**
- **Change the impacting NEA's orbit so it intersects the Earth's orbit earlier or later than normal.**
  - Make sure that the object is not in the "wrong place at the wrong time!"
  - Apply a change in velocity (ΔV) in the proper direction (typically along or against the impactor's direction of motion).

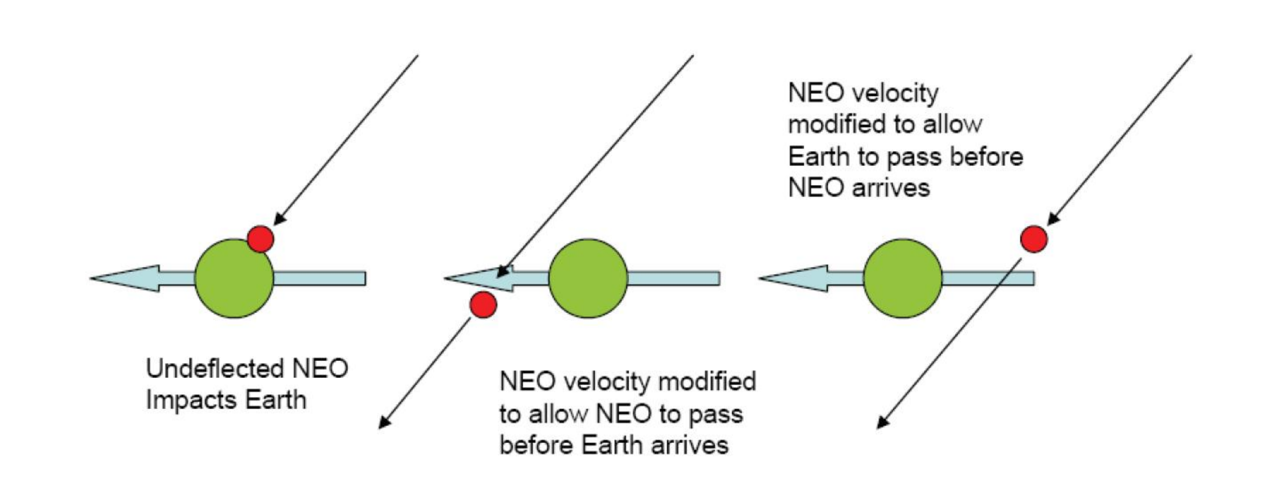


Image Credit: NASA

Early Response Requires Less ΔV

- Early detection and precise orbit determination are the keys to reducing the amount of ΔV required to alter the impactor's orbit.

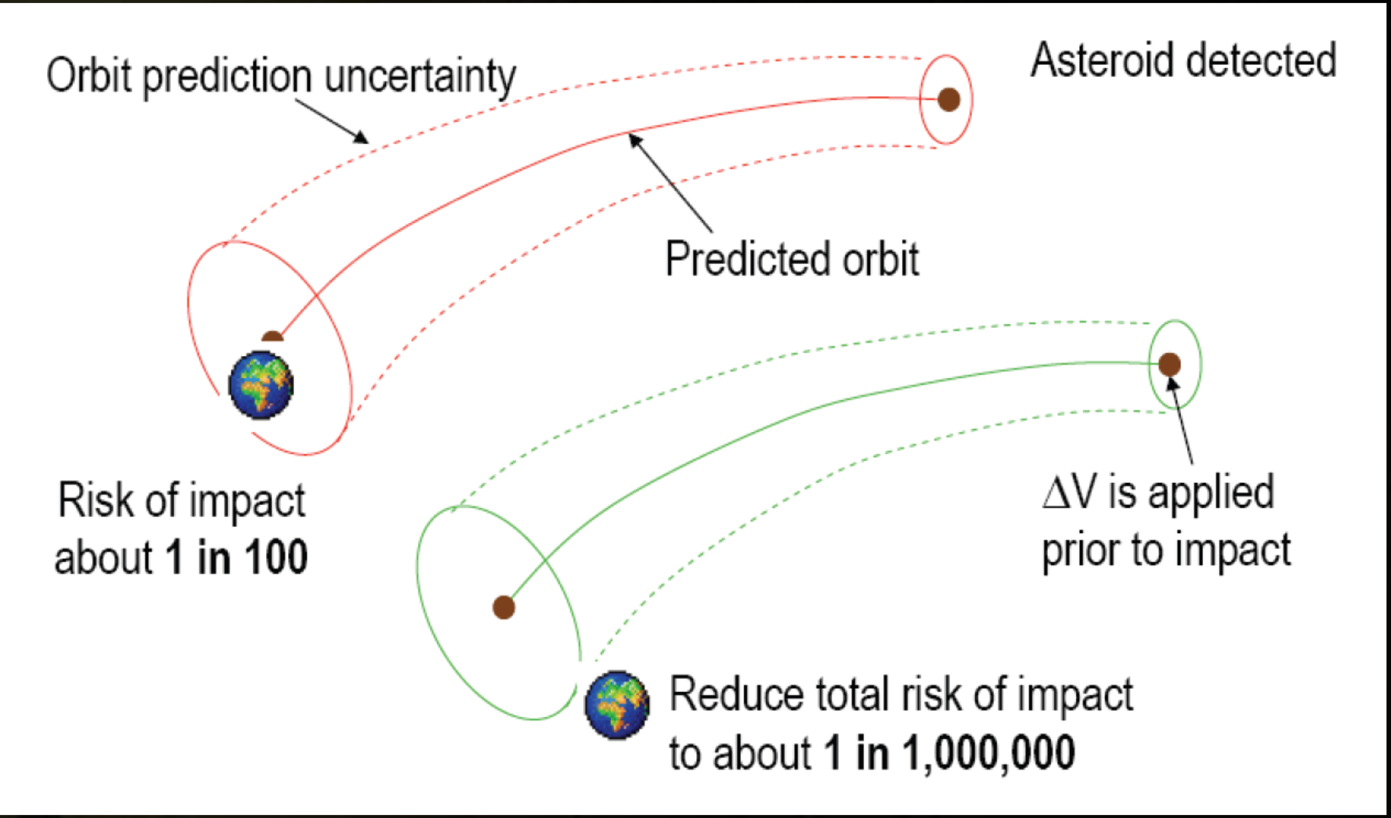


Image Credit: NASA

NEAs and NEOs – What's the Difference?

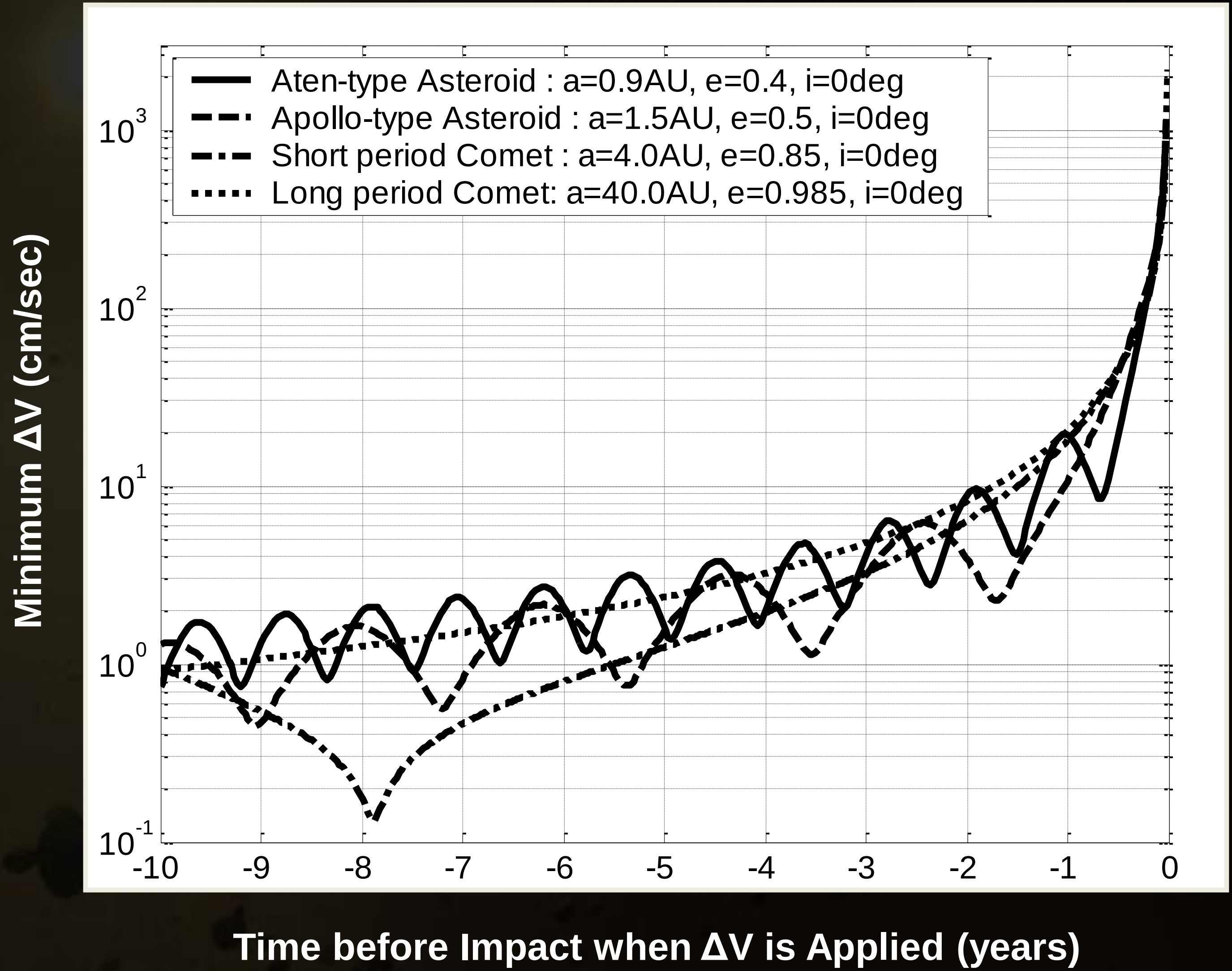
- **Near-Earth objects (NEOs) include asteroids and comets that have been gravitationally nudged to come near the Earth and possibly collide with it.**
- **The threat can be divided into four categories**

1. Well-defined Orbits
   - Detected and tracked near-Earth asteroids (NEAs)
   - Warning time = Decades
2. Uncertain Orbits
   - Newly discovered NEAs and Short-Period Comets (SPCs)
   - Warning time = Years
3. Immediate Threats
   - Long-Period Comets (LPCs) and Small NEAs
   - Warning time = Months
4. No Warning
   - Unknown NEAs, SPCs and LPCs
   - Warning time = Days

- SPCs have orbital periods <200 years and originate from the Edgeworth–Kuiper belt
- LPCs have orbital periods >200 years and originate from the Oort cloud

Early Response Requires Less ΔV

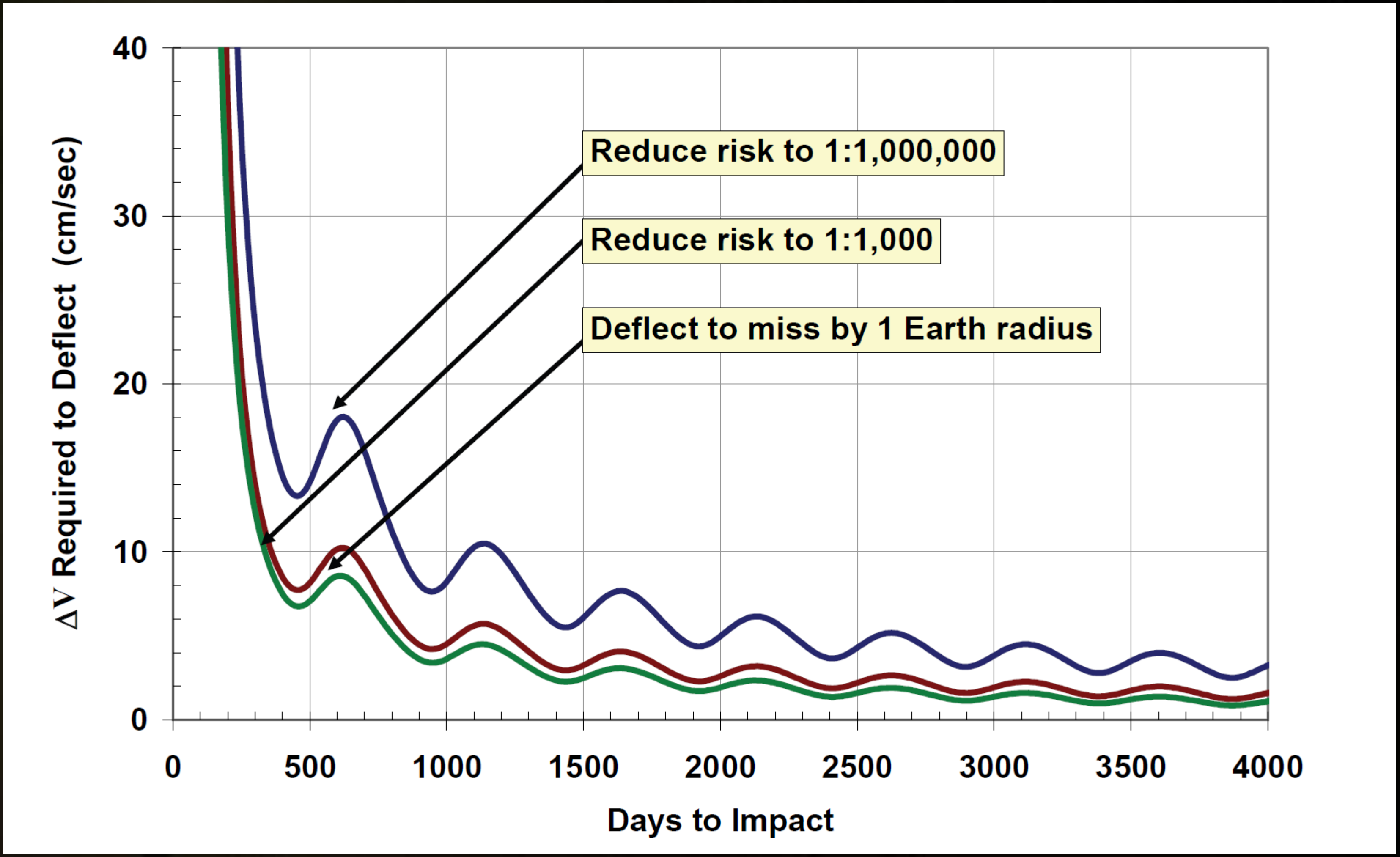
Estimated Minimum ΔV Required to Deflect Example Impactors by 1 Earth Radius (Pre-Perihelion Impact)



Source: NASA 2001-2002 Comet/Asteroid Protection System (CAPS) Study

Deflection ΔV vs. Miss Distance & Risk Reduction

Example NEA

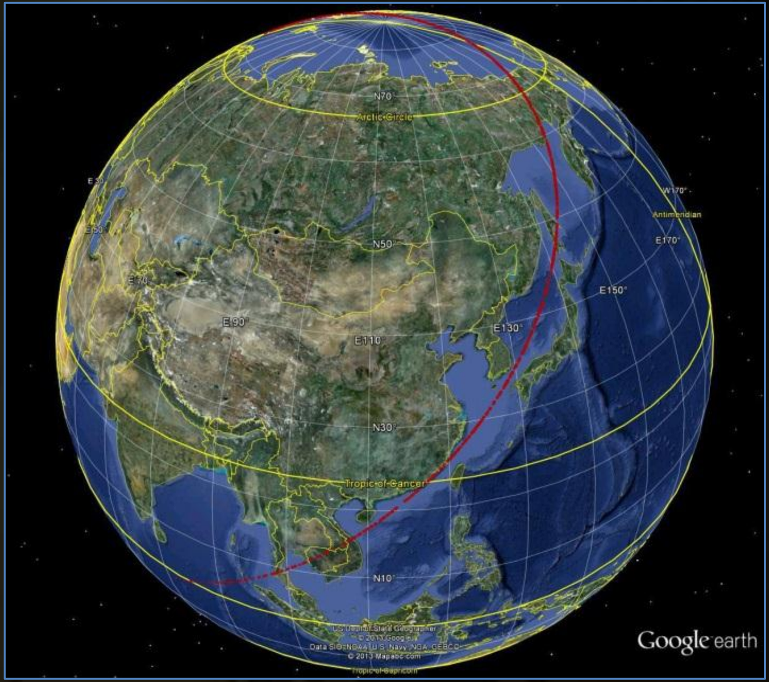


Source: NASA 2006 Near-Earth Object Survey and Deflection Study

Impact Uncertainty & Deflection Considerations

- Even when an impact with the Earth is confirmed, the exact impact point is uncertain.

Image Credit: NASA/JPL



- Red line represents the line of potential impact sites.
- This "risk corridor“ is altered during a deflection effort and moves across the Earth’s surface (geopolitical considerations).

NEA Characterization

- **NEAs have a wide range of orbits and physical characteristics.**
  - Threat characterization – precise orbit determination and risk analysis using available data to predict the probability of Earth impact. Provides prediction of impact date/time, along with impact velocity and estimated energy release.
  - Object characterization – other information needed for deflection/disruption/mitigation – size, mass, gravity field, composition, structure, spin state/rate, regolith/dust, surface charging, and possible companions, etc.
  - NEAs range from objects that are carbonaceous to stony to mostly metallic, with vastly different porosity and structural integrity.
- **Characterizing both is critical to successfully deflecting an impacting object.**
- **Earth-based radar is essential and robotic precursors are extremely valuable.**

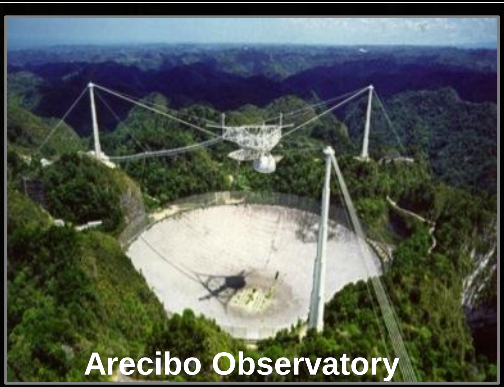


Image Credits: NASA

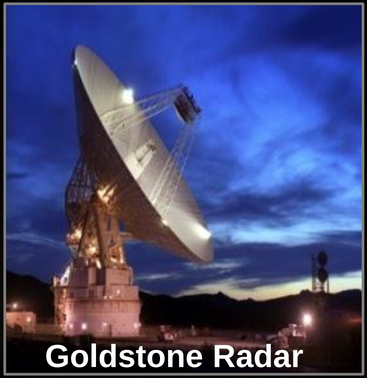
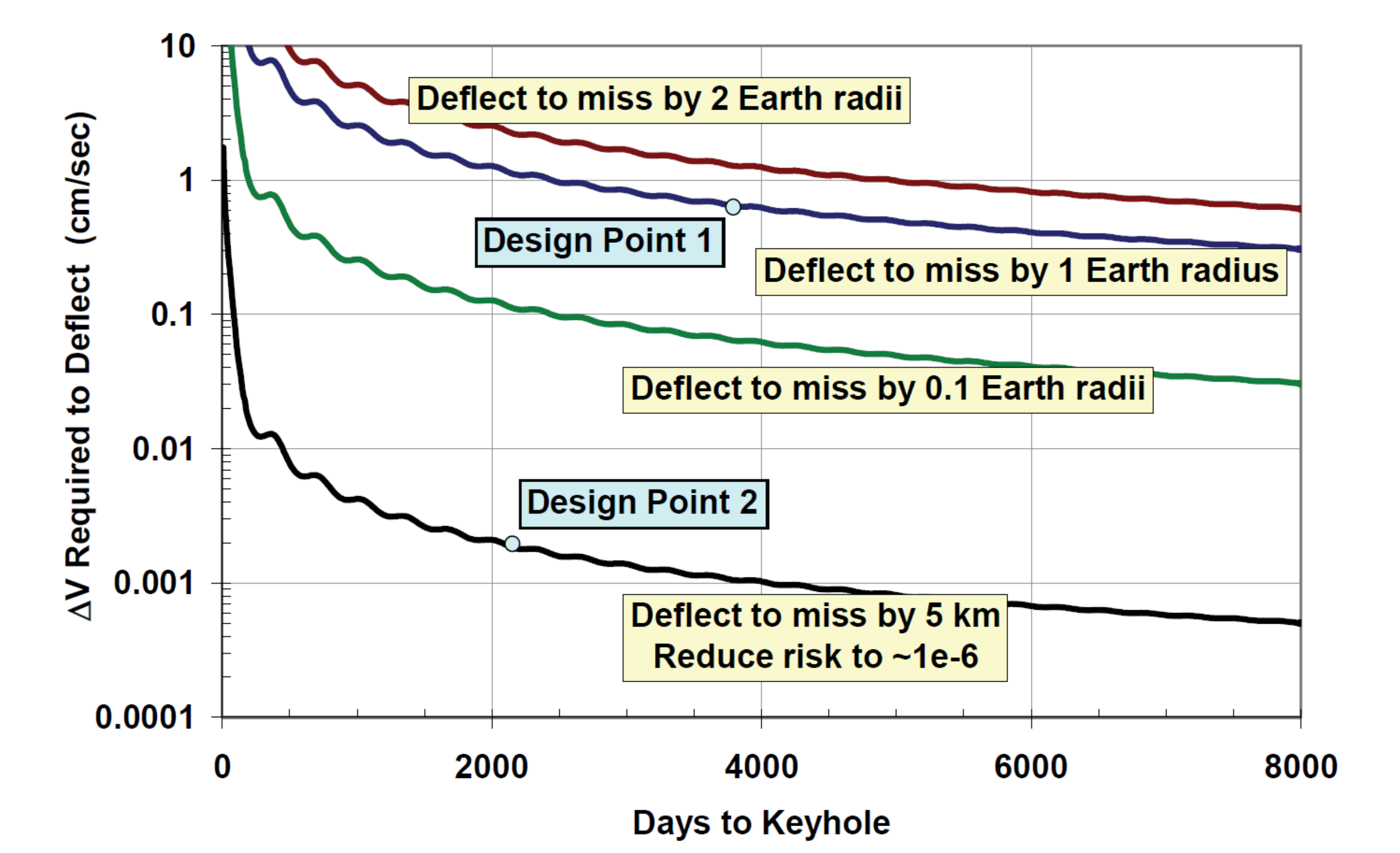


Image Credit: SpaceWorks Engineering, Inc.

Primary Deflection vs. Keyhole Deflection

- **A primary deflection is the application of ΔV to the NEA to alter it's orbit sufficiently that it does not result in an impact with the Earth.**
- **A keyhole deflection takes advantage of the knowledge that the NEA will pass through a small region of near-Earth space which will result in a collision with the Earth on a subsequent encounter.**
  - A resonant return is created by the gravitational interaction of the object during a preceding Earth encounter.
  - Avoiding a keyhole requires much less ΔV than does a primary deflection.
  - Applies to a small percentage of impactors (likely less than 10%).

Example of ΔV Required for Keyhole Deflection



- **Example for Apophis (2004 MN4) deflection effort before possible 2029 keyhole encounter.**
  - **Design Point 1** – action 10 years prior to keyhole and unrefined orbit knowledge.
  - **Design Point 2** – action 6 years prior to keyhole and refined orbit knowledge from additional observations.

Source: NASA 2006 Near-Earth Object Survey and Deflection Study

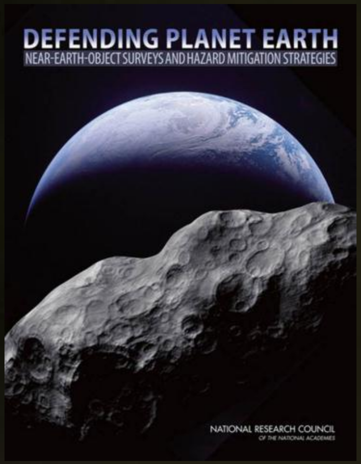
Rapid "Impulsive" Techniques for NEA Deflection

- **Application produces immediate result**
- **Effectiveness is dependent on the NEA properties (highly uncertain and variable)**
- **Large, concentrated forces have the potential for NEA fragmentation/disruption**
- **Examples:**
  - Kinetic Impactor
  - Conventional Explosives (surface or sub-surface)
  - Nuclear Detonation (stand-off, surface, sub-surface) with potential delivery system using an very-high-velocity impactor

Slow "Push/Pull" Techniques for NEA Deflection

- **Long duration (months to many years depending on NEA size) and small forces applied**
- **Efficient use of resources (propellant, power, in situ materials)**
- **Four basic categories:**
  - Enhance natural effects
  - Apply contact force
  - Apply gravitational force
  - Ablation/expulsion of surface material
- **Examples:**
  - Albedo/Thermal Response Modification (Yarkovsky effect) - likely centuries required for a 200 m NEA
  - Direct Push ("Space Tug")
  - Mass Driver
  - Gravity Tractor (GT) and Enhanced Gravity Tractor (EGT)
  - Ion Beam Deflection (IBD)
  - Surface Ablation (laser and solar)

Planetary Defense Strategies



2010 National Research Council Committee

"Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies"

- **Finding:** **No single approach to mitigation is appropriate and adequate** for completely preventing the effects of the full range of potential impactors, although civil defense is an appropriate component of mitigation in all cases. **With adequate warning, a suite of four types of mitigation is adequate to mitigate the threat from nearly all NEOs except the most energetic ones.**

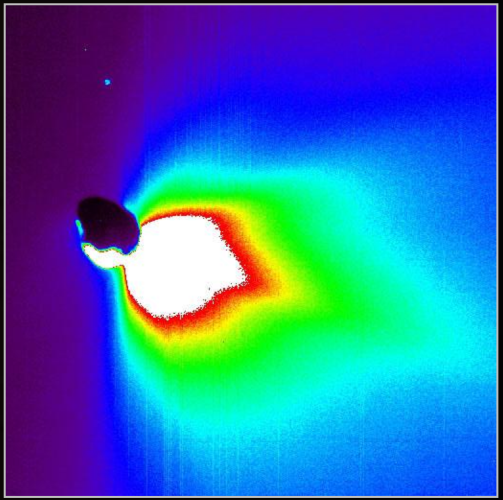
TABLE 5.1 Summary of Primary Strategies for Mitigating the Effects of Potential Impacting Near-Earth Objects

Strategy	Range of Primary Applicability
Civil defense (e.g., warning, shelter, and evacuation)	Smallest and largest threats. Threat of any size with very short warning time.
Slow push (e.g., "gravity tractor" with a rendezvous spacecraft)	A fraction (<10%) of medium-size threats. Usually requires decades of warning time.
Kinetic impact (e.g., interception by a massive spacecraft)	Most medium-size threats. Requires years to decades of warning time.
Nuclear detonation (e.g., close-proximity nuclear explosion)	Large threats and short-warning medium-size threats. Requires years to decades of warning time.

Kinetic Impactor

- Very-high-velocity (typically >5 km/s) collision with the NEA using the spacecraft or a deployed impactor.
- Relatively simple technique within current capabilities with reasonable hardware and control development. Likely the method of choice for <500 m impactors provided that sufficient warning time is available.
- Effectiveness depends on the NEA's structure (solid or rubble pile) which dictates the momentum exchange efficiency (β), which is a major uncertainty.
- Terminal targeting becomes more difficult as relative velocity increases.
- Demonstrated on a small scale by NASA's Deep Impact Mission on Comet Tempel 1 in 2005 (370 kg impactor at 10.2 km/s).

Image Credits: NASA/JPL-Caltech/UMD



Nuclear Detonation

- **Most mass efficient deflection technique.**
  - Standoff
  - Surface
  - Subsurface
- **Currently, the only viable option for large NEAs (>500 m diameter) with short warning times (months to years).**
- **As with kinetic impactor, the NEA's structure will dictate the effectiveness of the technique – a dissipative, low-density surface will result in less ejecta and lower ΔV imparted.**
- **The Hypervelocity Asteroid Intercept Vehicle (HAIV) concept, shown here, can be employed to deliver a sub-surface detonation.**

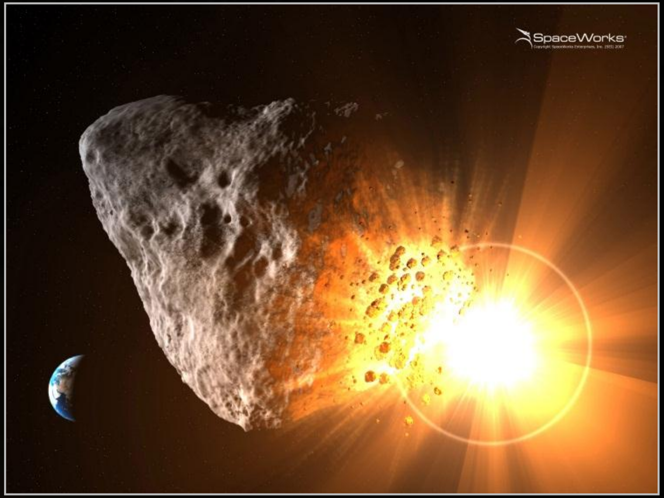


Image Credit: SpaceWorks Engineering, Inc..

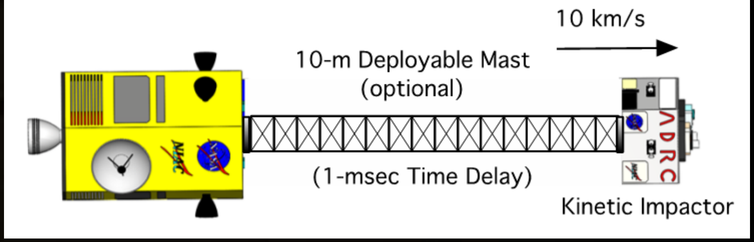
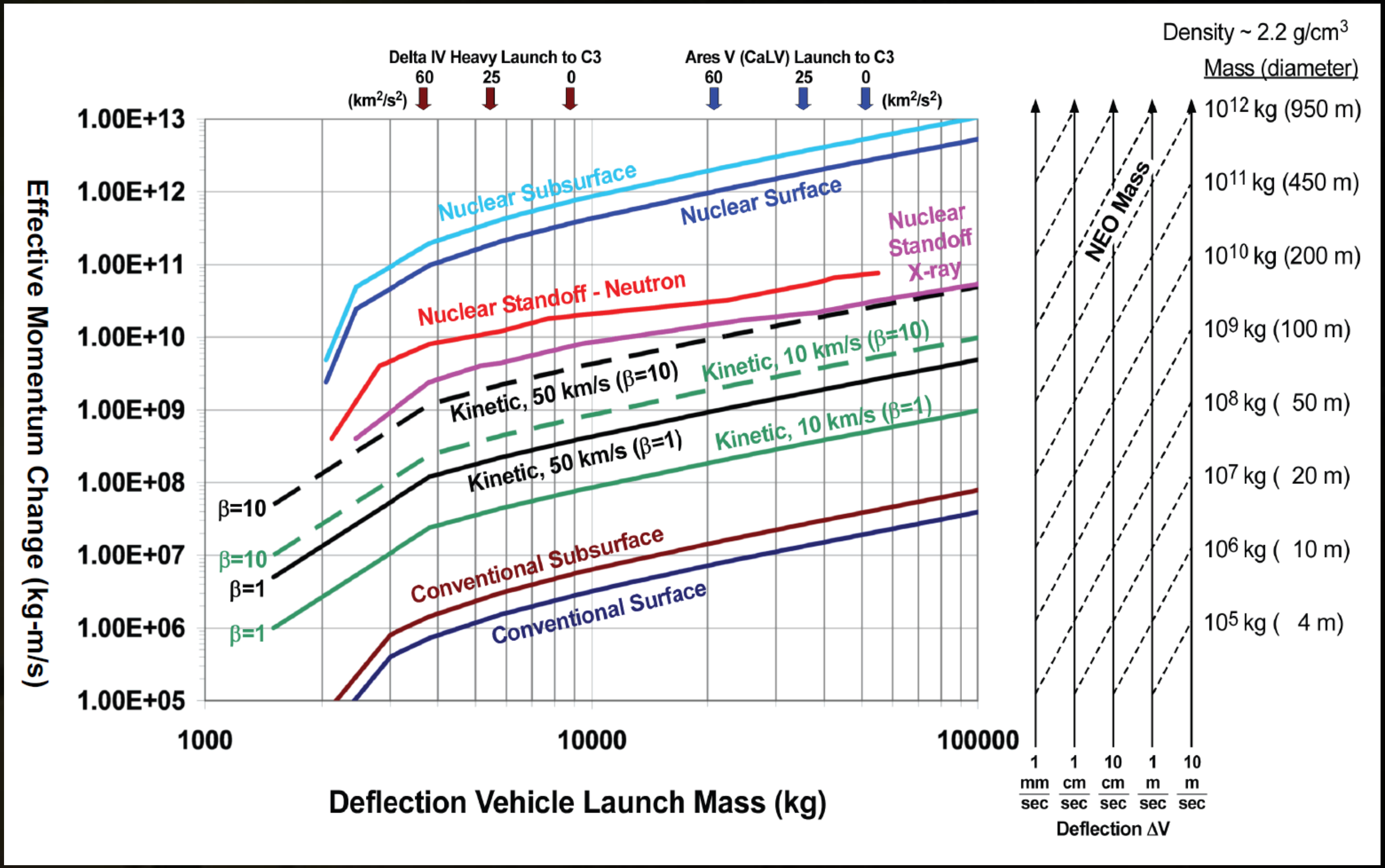


Image Credit: Asteroid Deflection Research Center

Effectiveness of Impulsive Systems



Source: NASA 2006 Near-Earth Object Survey and Deflection Study

Direct Contact – “Space Tug” and Mass Driver

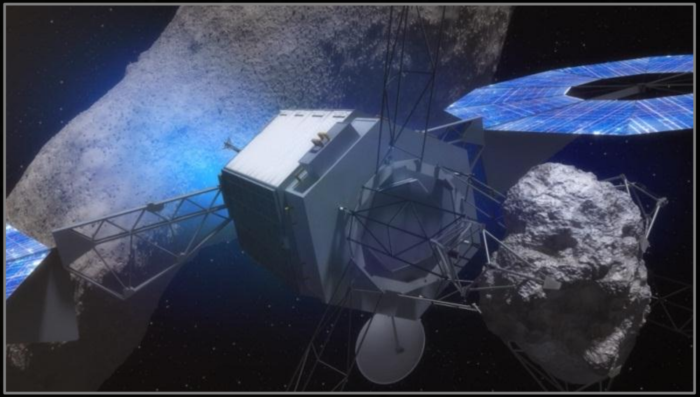
- Approach requires extended mechanical connection with the NEA.
- Can utilize high-specific impulse solar or nuclear electric propulsion (chemical propulsion is likely mass prohibitive).
- Rotation of the NEA can drastically reduce the technique’s effectiveness or requires a change in the rotation state of the NEA.
- Mass drivers harvest and eject material from the surface to impart momentum to the NEA.
- Current lack of understanding of small body surface and subsurface characteristics increase the risk of direct contact.

Image Credit: NASA/AMA, Inc.

Image Credit: SpaceWorks Engineering, Inc..

Gravity Tractor – Standard and Enhanced

- **Use of mutual gravitational attraction to “pull” the NEA and change its orbit while maintaining spacecraft separation utilizing high-specific impulse propulsion.**
- **Spacecraft Only.**
  - Extended operations at the NEA (years).
  - Requires long warning times.
- **Enhanced Gravity Tractor (EGT) using mass augmentation at the NEA.**
  - Total mass can be significantly enhanced to reduce time required for deflection (10X or more).
  - Requires interaction with the NEA’s surface to collect sufficient amount of material.
- **Halo orbit approach increases operational efficiency by keeping thruster plume away from the NEA, eliminates thrust loses and increases control authority by not canting thrusters, and allows multiple spacecraft to work cooperatively.**



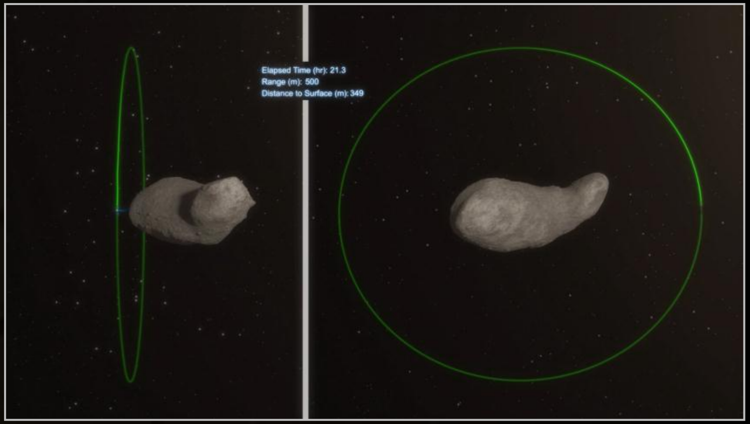
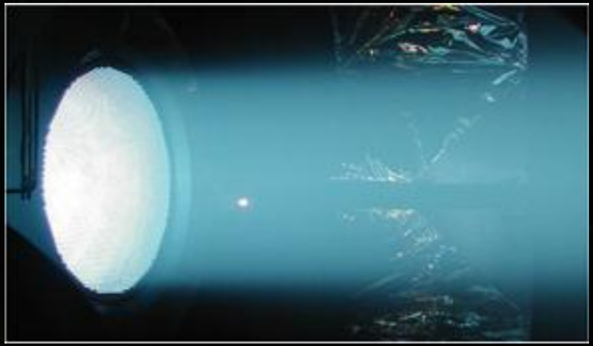


Image Credits: NASA/AMA, Inc.

Ion Beam Deflection

- Utilizes a beam of quasi-neutral plasma from an electric propulsion system to impinge upon the NEA's surface to create a force and/or a torque on the target.
- Uses second set of thrusters along with propellant to counter the thrust applied to the spacecraft by the ion beam directed at the NEA.
- Permits continuous thrust from a hovering spacecraft without need for physical attachment to the NEA.
- Efficiency depends on ion beam divergence angle and distance from spacecraft to the NEA



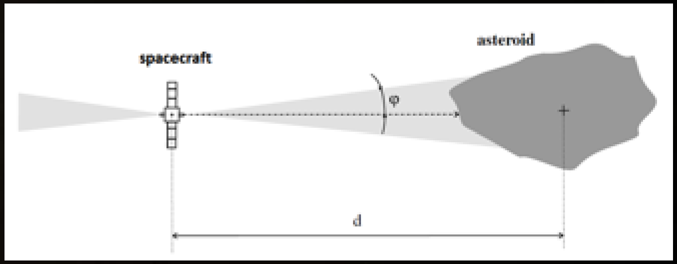
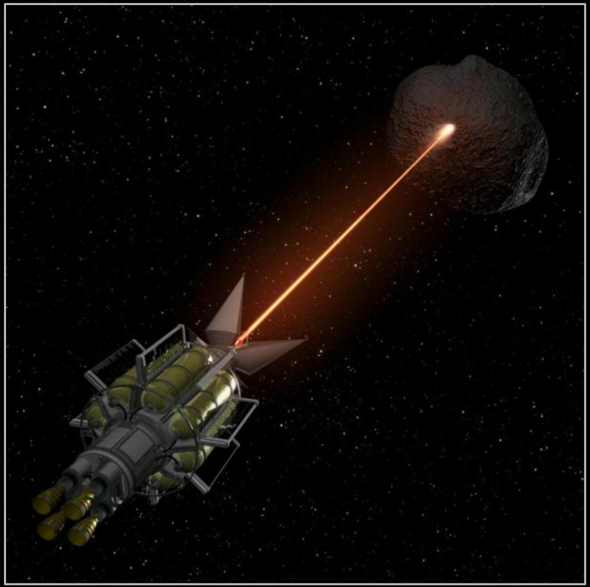


Image Credits: JPL-Caltech

Surface Ablation

- No contact with the NEA surface required.
- High temperature ablation of the surface to provide ΔV (uses the NEA's material).
- Only station keeping propellant needed for spacecraft.
- Effective on wide range of surface materials and insensitive to rotation rate.
- Controlled, low-acceleration and non-disruptive orbit modification.
- Laser ablation requires multi-megawatt to gigawatt-class electrical power systems along with advanced thermal management systems
- Solar ablation requires large concentrator mirrors or lenses. Secondary mirrors must accommodate high heating loads.
- Sufficiently accurate spacecraft pointing to maintain heat transfer on the surface



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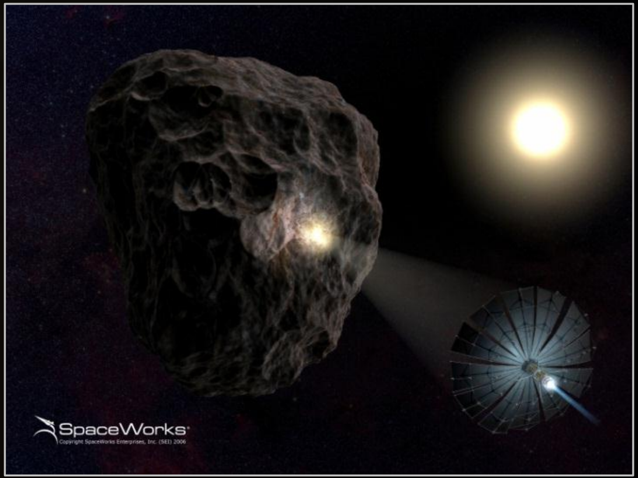
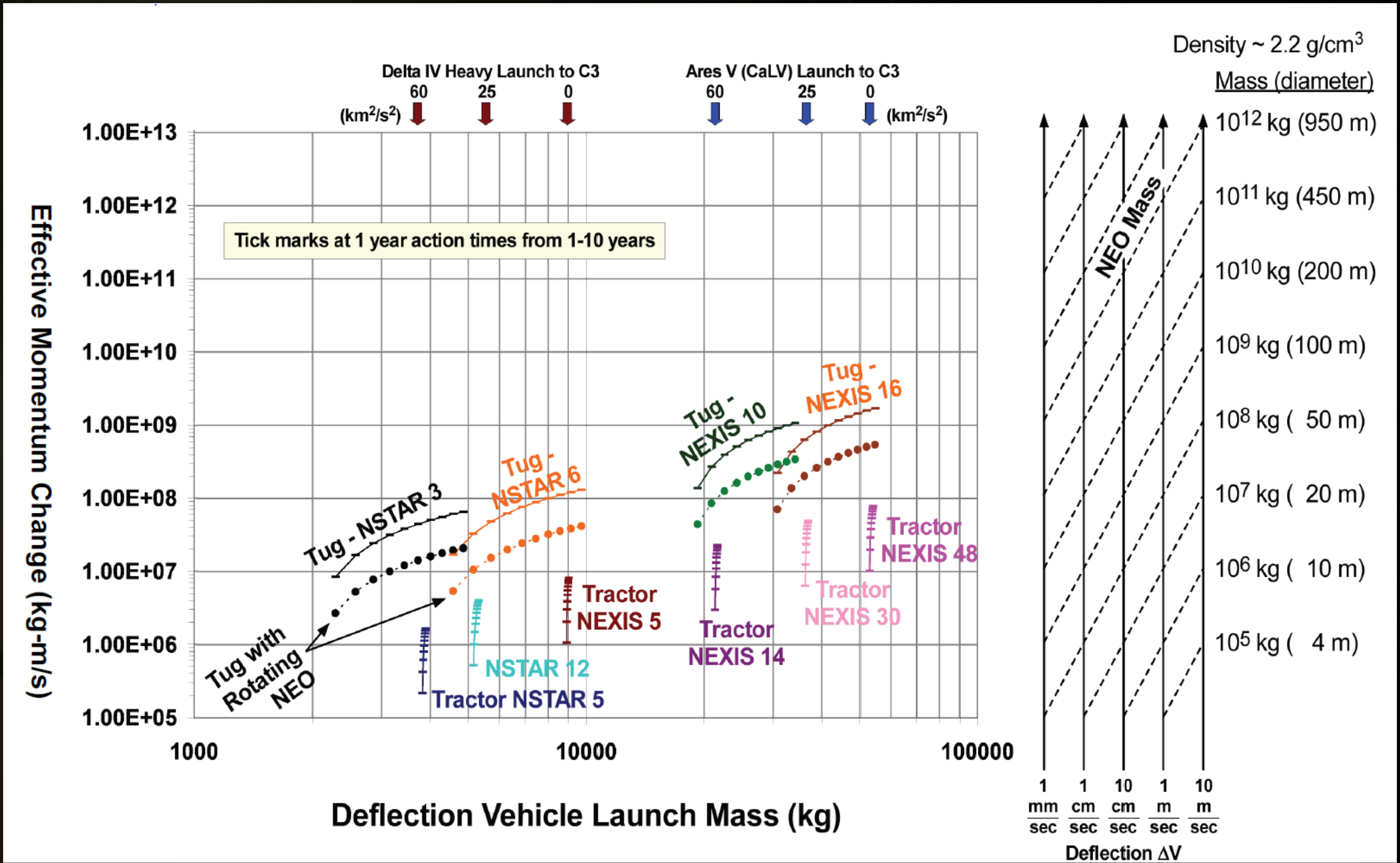


Image Credit: SpaceWorks Engineering, Inc..

Effectiveness of Example Slow Push/Pull Systems



Source: NASA 2006 Near-Earth Object Survey and Deflection Study

Comparison of Deflection Strategies – Readiness and Effectiveness

"Impulsive" Concepts	Readiness	Effectiveness
Conventional Explosive - Contact	High	Medium
Conventional Explosive - Subsurface	Medium	Medium
Kinetic Impact	High	High
Nuclear Surface Contact	High	Very High
Nuclear Standoff	High	Very High
Nuclear Subsurface	Medium	Medium
Nuclear Surface Delayed	Medium	High

"Slow Push" Concepts	Readiness	Effectiveness
Enhanced Yarkovsky	Low	Low
Focused Solar	Low	Medium
Gravity Tractor	Medium	Medium
Mass Driver	Low	Medium
Pulsed Laser	Low	Medium
Space Tug	Low	Medium

Source: NASA 2006 Near-Earth Object Survey and Deflection Study

Characterization Required for Impulsive Approaches

	Mass	Spin	Density	Material Properties	Size & Shape	Surface Properties
Conventional Expl. Surface - Contact	Yes	No	Helpful	Helpful	Helpful	Helpful
Conventional Expl. Subsurface	Yes	No	Helpful	Helpful	No	No
Kinetic Impactor	Yes	No	Helpful	Helpful	Helpful	No
Nuclear (Contact)	Yes	No	Helpful	Helpful	Helpful	No
Nuclear (Standoff)	Yes	No	No	No	No	No
Nuclear Explosive (Sub-Surface)	Yes	No	Helpful	Helpful	No	No
Nuclear Explosive (Surface Delayed)	Yes	Yes	Helpful	Helpful	No	Helpful

Source: NASA 2006 Near-Earth Object Survey and Deflection Study

Characterization Required for Slow Push/Pull Approaches

	Mass	Spin	Density	Material Properties	Size & Shape	Surface Properties
Yarkovsky	Yes	Yes	No	No	Yes	Yes
Focused Solar	Yes	Helpful	No	No	No	Yes
Gravity Tractor	Yes	Yes	No	No	Yes	No
Mass Driver	Yes	Yes	Yes	Yes	Helpful	Helpful
Pulsed Laser	Yes	Helpful	No	No	No	Yes
Space Tug	Yes	Yes	No	No	Yes	Yes

Source: NASA 2006 Near-Earth Object Survey and Deflection Study

Reaching the Target… in Time!

- **Get to the impacting NEA before it gets to us!**
  - Detection, tracking and characterization are critical first steps.
  - Only provides civil defense mitigation if we can't do anything to stop an impact.
- **Critical capability is to be able to deliver the deflection payload to the impacting object.**
  - Sufficiently capable launch vehicles – heavy-lift launch vehicles are extremely valuable as long as they are reliable.
  - Efficient and reliable in-space systems (propulsion, guidance, control, etc.)
  - Systems must be capable of delivering the required mass in sufficient time (low-thrust vs. high-thrust propulsion).
- **Telescopes and rockets may be the two most important inventions in human history!**

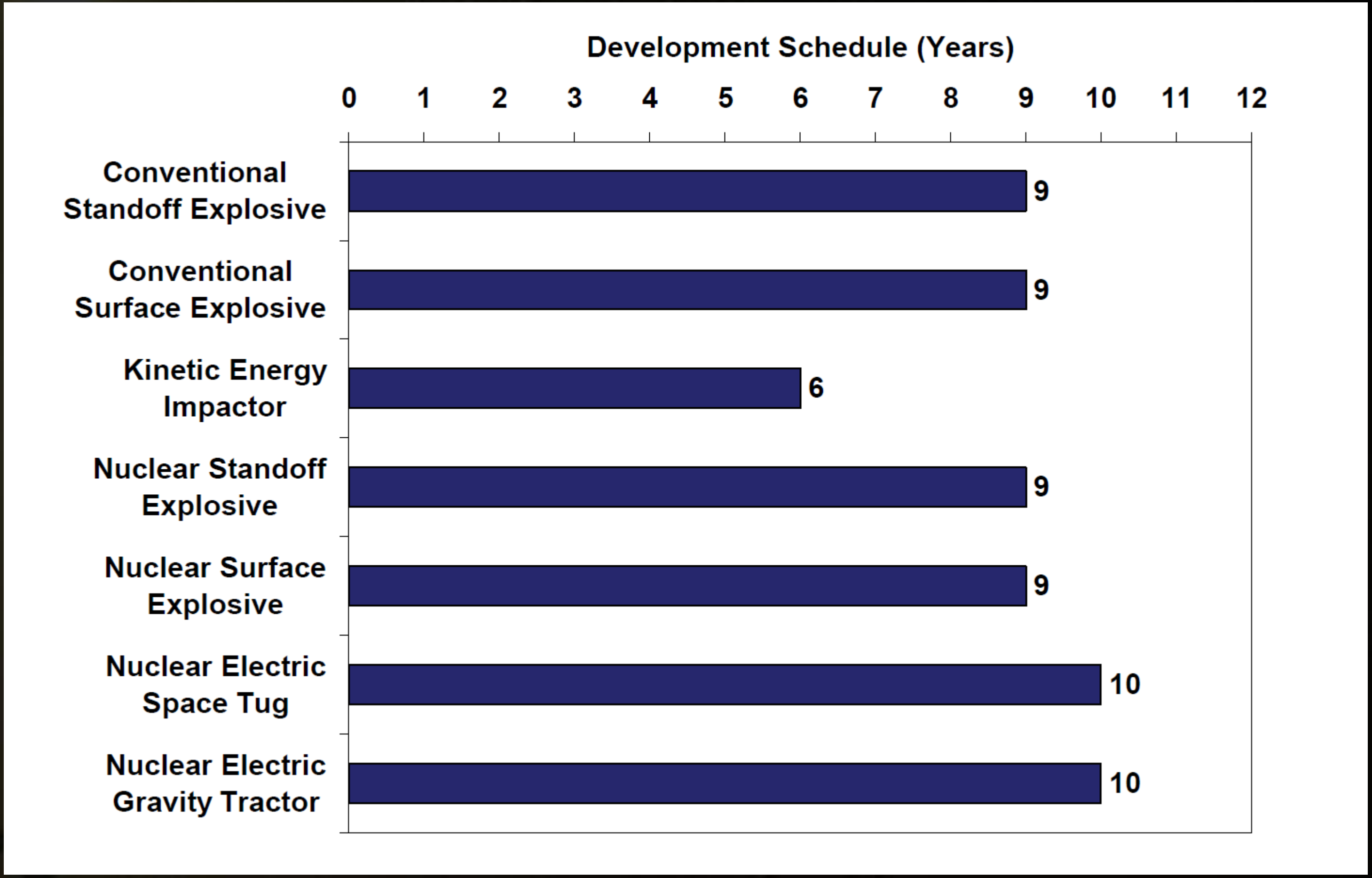
2010 NRC Committee Recommendation

2010 National Research Council Committee
"Defending Planet Earth:
Near-Earth Object Surveys and Hazard Mitigation Strategies"

– **Recommendation:** If Congress chooses to fund mitigation research at an appropriately high level, the first priority for a space mission in the mitigation area is an experimental test of a kinetic impactor along with a characterization, monitoring, and verification system, such as the Don Quijote mission that was previously considered, but not funded, by the European Space Agency. This mission would produce the most significant advances in understanding and provide an ideal chance for international collaboration in a realistic mitigation scenario.

Typical System Development Time

- Up to a decade could be required to develop a planetary defense system, which may be too long!



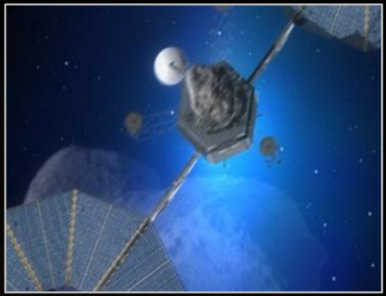
Source: NASA 2006 Near-Earth Object Survey and Deflection Study

The Deflection "Toolbox"

- **One approach doesn't work for every situation.**
- **Multiple approaches can provide a comprehensive, robust deflection capability.**
- **Multiple spacecraft and/or techniques**
  - For example, kinetic impact for primary deflection and GT or IBD for "clean-up" trim maneuvers.
- **Demonstrating and evaluating multiple approaches is needed to understand their effectiveness.**
  - Same target for a comparison of techniques.
  - As many different targets as possible.
- **The "latency time" (the time between the decision to act and the initiation of the deflection effort) can be reduced drastically by demonstrating techniques well before the discovery an impacting NEA.**

Examples of Technologies for Space Exploration and Planetary Defense

- **High-thrust/low-thrust, high-specific impulse propulsion systems (solar electric, plasma, nuclear, etc.) for delivering deflection or disruption systems to impactors and payloads for exploration missions.**
- **High-power electrical power systems (kW to GW) – propulsion, laser applications (ablation and power beaming), drilling and mining.**
- **Advanced thermal management systems to reject large amounts of waste heat.**
- **Advanced autonomous rendezvous and station-keeping capability for engaging a target at close range or contacting its surface.**
- **Low-gravity surface interaction systems and techniques – deliver planetary defense, resource extraction, or exploration payloads.**



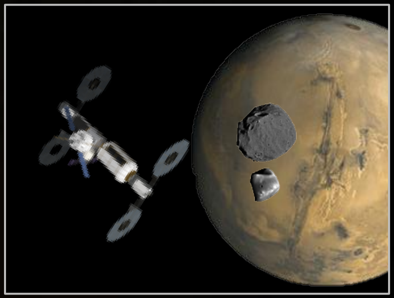
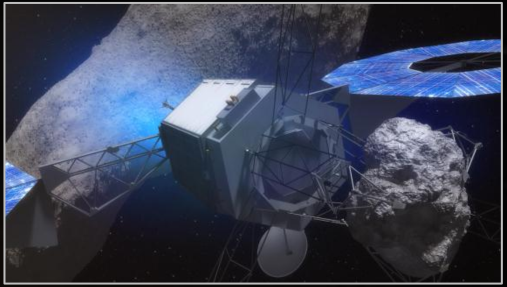


Image Credits: NASA

Resource Utilization and Planetary Defense

- **Asteroids and comets represent a valuable resource for space development, as well as an inevitable threat.**
- **No dedicated planetary defense system exists and funding one is unlikely due to the infrequency of impacts.**
- **Developing the technologies, systems, and operational approaches for utilization also helps us to be prepared to divert a future impactor.**
  - Slow push/pull techniques – EGT, IBD, laser ablation, etc.
  - Use spacecraft with augmented mass as a kinetic impactor.
- **Integrated solution**
  - Efficiently move large amounts of useful asteroidal material to permit processing technique demonstrations (departure vs. destination) to leverage the economic potential of NEAs .
  - Provides the foundation for “on call” planetary defense
  - No development and launch, along with personnel that are trained and proficient in operating the systems, can solve the “Impact Dilemma” (bulldozers for snowplows analogy).

Image Credit: Planetary Resources



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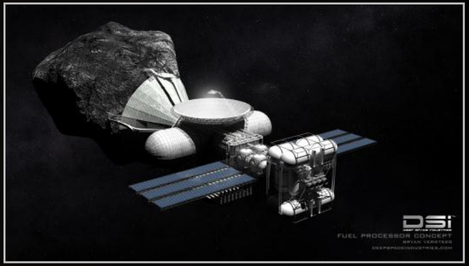

Image Credit: Deep Space Industries

Thank you for your time and attention.

Questions?

Backup – 2010 National Research Council Committee Mitigation Findings (1 of 2)

- **Finding #1:** No single approach to mitigation is appropriate and adequate for completely preventing the effects of the full range of potential impactors, although civil defense is an appropriate component of mitigation in all cases. With adequate warning, a suite of four types of mitigation is adequate to mitigate the threat from nearly all NEOs except the most energetic ones.
- **Finding #2:** Civil defense (evacuation, sheltering in place, providing emergency infrastructure) is a cost-effective mitigation measure for saving lives from the smallest NEO impact events and is a necessary part of mitigation efforts for larger events. If an NEO was predicted to impact on a specific, inhabited location, there would likely be strong pressure for implementing more than the most cost-effective method for saving lives.
- **Finding #3:** Slow-push-pull techniques are the most accurately controllable and are adequate for changing the orbits of small NEOs (tens of meters to roughly 100 meters in diameter) with decades of advance warning and for somewhat larger NEOs (hundreds of meters in diameter) in those few cases in which the NEO would pass through a keyhole that would put it onto an impact trajectory. Of the slow-push-pull techniques, the gravity tractor appears to be the most independent of variations in the properties of the NEO and by far the closest to technological readiness.
- **Finding #4:** Kinetic impactors are adequate to prevent impacts on Earth by moderate-sized NEOs (many hundreds of meters to 1 kilometer in diameter) with decades of advance warning. The concept has been demonstrated in space, but the result is sensitive to the properties of the NEO and requires further study.

Backup – 2010 National Research Council Committee Mitigation Findings (2 of 2)

- **Finding #5:** Other than a large flotilla (100 or more) of massive spacecraft being sent as impactors, nuclear explosions are the only current, practical means for changing the orbit of large NEOs (diameter greater than about 1 kilometer). Nuclear explosions also remain as a backup strategy for somewhat smaller objects if other methods have failed. They may be the only method for dealing with smaller objects when warning time is short, but additional research is necessary for such cases.
- **Finding #6:** For a wide range of impact scenarios, launch capability exists to deliver an appropriate payload to mitigate the effects of a NEO impact. For some scenarios, particularly short-warning scenarios, the capability is inadequate. The development of foreseen heavy-lift launch vehicles, such as the Ares cargo vehicle, should enable the use of a variety of methods for NEOs up to two times larger than is possible with current launch vehicles.
- **Finding #7:** The mitigation of the threat from NEOs would benefit dramatically from their in situ characterization prior to mitigation if there is time.
- **Finding #8:** Changing the orbit of an NEO given the current level of understanding is sufficiently uncertain that, in most cases, it requires an accompanying verification. This is easy to implement with many slow-push techniques, but it would require considerable additional effort for other techniques.