HYPOTHETICAL EXERCISE

# Planetary Defense Mission Options Analysis for the 2023 PDC Hypothetical Impact Exercise Scenario


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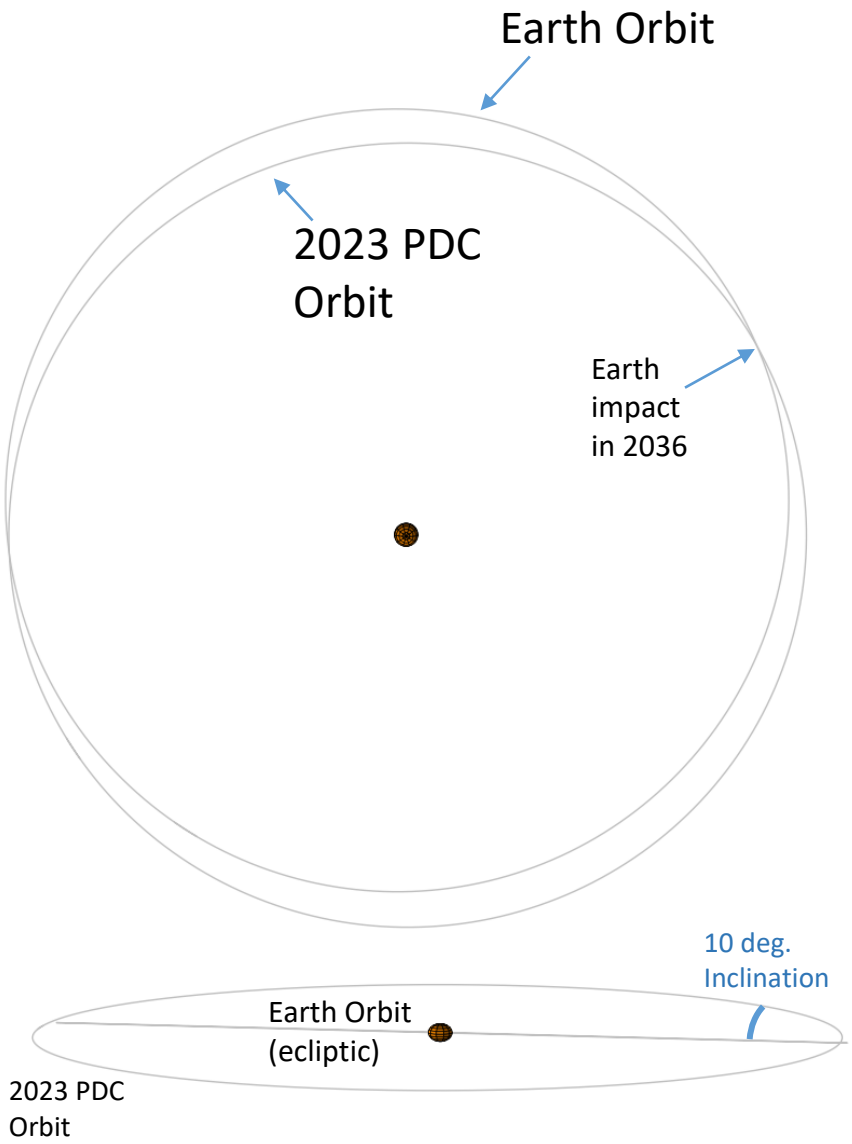
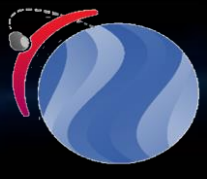
# 2023 PDC Hypothetical Asteroid Impact Scenario Overview

- **Key dates:**
  - 10 January, 2023: Discovery
  - 3 April, 2023: Earth impact probability reaches ~1%
    - **Start of space mission option assessments**
  - 1 July 2023: Earth impact probability projected to reach ~10%, **if** asteroid is indeed on an Earth-impacting trajectory
    - **Authority to Proceed (ATP) for space mission development**
  - 1 November 2023: Earth impact probability projected to reach ~100%, **if** asteroid is indeed on an Earth-impacting trajectory
  - 22 October 2036: Earth impact (**if** asteroid is indeed on an Earth-impacting trajectory)
- The 2023 PDC asteroid is in an Earth-like orbit, but with relatively high inclination → rendezvous missions require high ΔV
  - Orbit semi-major axis: ~0.99 au
  - Orbit eccentricity: ~0.009
  - Orbit inclination: 10.2 deg



# Deflection Options Assessment



- **Kinetic Impactor**:
  - Launch: June 11, 2028 (~5 years after ATP, ~8.4 years before Earth impact)
  - Kinetic impact: July 6, 2030 (~6.3 years before Earth impact)
    - Asteroid impact speed: ~11.33 km/s (DART's impact speed was ~6.14 km/s)
  - A minimum of 5 Falcon Heavy launches would be required to deflect the 10th percentile realization of the asteroid
  - For the 90th percentile asteroid, an unrealistic 276 launches would be required
  - **If the asteroid is near or above the mean size / mass, an impractical number of heavy-lift launches would be required for robust deflection**

**Required ΔV for deflection** for the worst-case (mid-chord) impact location in Mid 2030 is ~**25 mm/s**

- **Standoff Nuclear Detonation Deflection**:
  - Launch: October 2027 (~4.5 years after ATP)
  - Deflection date: August 2030 (optimal deflection date with at least 7 years from ATP)

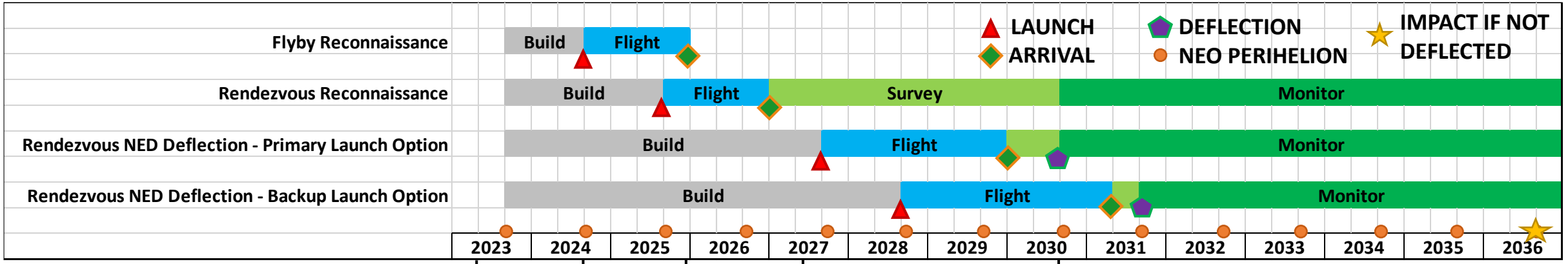
Nuclear explosive device (NED) payload required is asteroid mass dependent:

| Mass realization of asteroid | Asteroid diameter | Asteroid density | Required NED yield | Required NED payload mass |
|---|---|---|---|---|
| 10th percentile | 295 m | 1.8 g/cm$^3$ | 0.107 MT | 60 kg |
| 90th percentile | 1119 m | 1.8 g/cm$^3$ | a) 3 x 2.3 MT NEDs<br>b) 6 x 0.72 MT NEDs | a) 3714 kg<br>b) 2404 kg |

  - A rendezvous mission, launching on a single Falcon Heavy Expendable & using an 8 kW NEXT-C propulsion system, can deliver up to 6067 kg
  - **A single launch can deliver more than enough NED yield to deflect the 90th percentile realization of the asteroid**

**Kinetic impactor deflection of this asteroid is impractical, while nuclear deflection is practical**

# Timeline for Selected Exemplar Space Mission Options




**3 Apr 2023: Earth Impact Probability ~1%**
→ Start of mission options assessments

**23 Oct 2024: Flyby Recon Mission Launch Opportunity**

**1 Dec 2025: Flyby Recon Mission encounters asteroid at ~1.7 km/s**
- Flyby recon provides substantial reduction in asteroid orbit / Earth impact location uncertainties, & partial reduction of asteroid physical properties uncertainties

**1 June 2027: Rendezvous Recon Mission completes 7-month survey of asteroid**
- Rendezvous recon provides substantial reduction in the asteroid's orbital & physical properties uncertainties
- Rendezvous spacecraft could remain with asteroid to provide ongoing situational awareness during & after subsequent deflection attempts

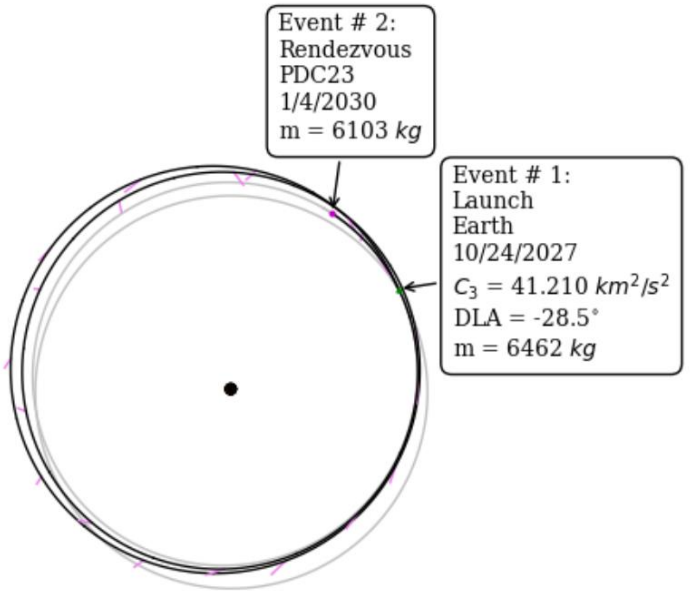
**Aug. – Sept. 2030: Deflection of Asteroid**
- Rendezvous Deflection Mission could launch in October 2027 & arrive at the asteroid in January 2030, ~7 months prior to beginning a series of NED detonations during the asteroid's late August 2030 perihelion passage

**Notes:**
- Dates dictated by orbital mechanics & spacecraft / launch vehicle capability
- ~1.5 years to develop Flyby Recon Mission -- Unprecedentedly short development time for interplanetary mission, but mission is ~simple & would have high priority
- ~2.5 years to develop Rendezvous Recon Mission -- Less stressful than shorter Flyby Recon Mission development time
- ~4.5 years to develop Rendezvous NED Deflection Mission -- Similar to traditional interplanetary mission timeline, but all 3 missions being developed in parallel
- ~22 months between Flyby Recon asteroid encounter & launch of Rendezvous NED Deflection Mission to use Flyby Recon Mission data & refine Rendezvous NED Deflection Mission design before launch
- ~4 months between completion of Rendezvous Recon survey & launch of Rendezvous NED Deflection Mission to use Rendezvous Recon Mission data about asteroid & make final refinements to the Rendezvous Deflection Mission design before launch

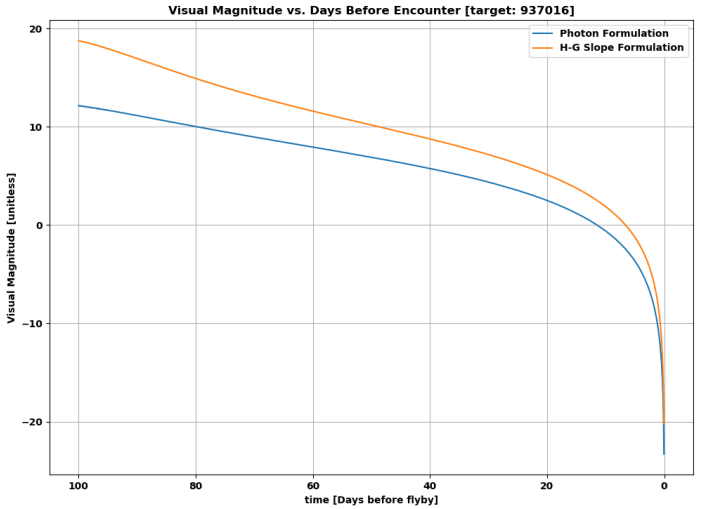
# NED Deflection Mission Design

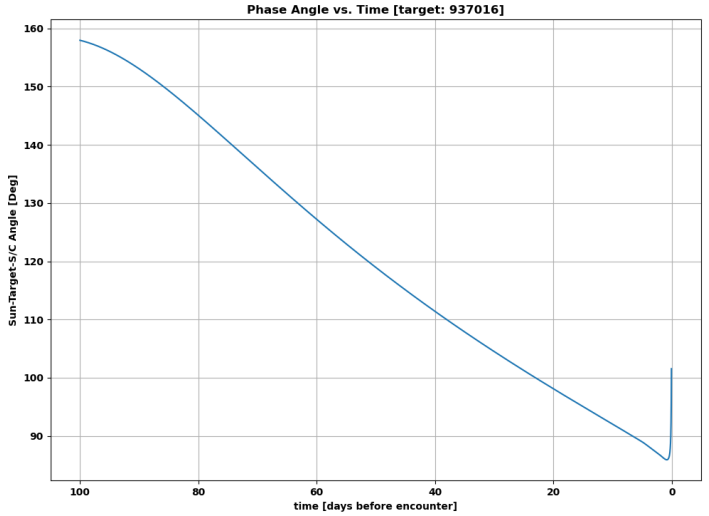
## Primary Rendezvous Deflection Option

**Launch vehicle:** Falcon Heavy Expendable
**Launch date:** 10/24/2027
**Rendezvous date:** 1/4/2030
**Propulsion type**: solar electric propulsion (SEP)
**End of life solar array power at 1 AU**: 8 kW
**Electric propulsion (EP) thrusters**: 1 active NEXT-C thruster
**EP propellant mass:** 394 kg (includes 10% margin)
**Delivered mass:** 6067 kg (margined prop not included)




SEP is enabling for delivering the required rendezvous deflection payload without resorting to a SLS launch




### Estimated Detection Using DRACO With A 12 ms Exposure Time

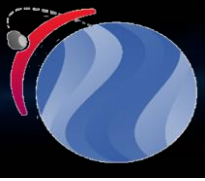
| Case | Target size [m]/albedo | H magnitude | Detection distance [km] | Time before intercept [days] |
|---|---|---|---|---|
| Rendezvous Deflection (a) | 220/0.48 | 19.7 | 8.2e5 | 85. |
| Rendezvous Deflection (b) | 660/0.093 | 19.1 | 9.5e5 | 90.3 |
| Rendezvous Recon, Chemical Propulsion (a) | 220/0.48 | 19.7 | 18.e5 | 14.7 |
| Rendezvous Recon, Chemical Propulsion (b) | 660/0.093 | 19.1 | 22.e5 | 18.2 |
| Rendezvous Recon, SEP (a) | 220/0.48 | 19.7 | 10.8e5 | 43.9 |
| Rendezvous Recon, SEP (b) | 660/0.093 | 19.1 | 12.7e5 | 47.4 |

# Appendix

# Kinetic Impactor Deflection Performance Summary

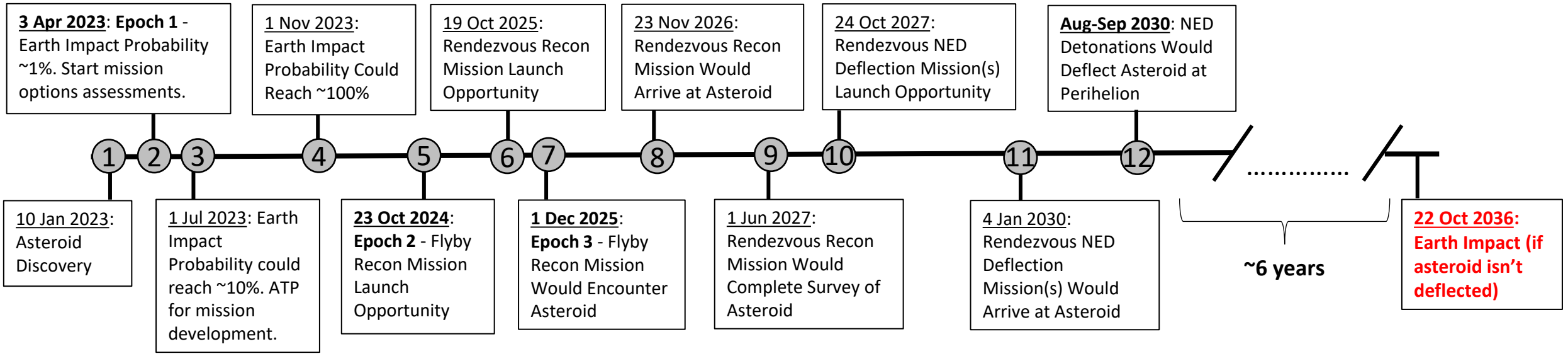
- Results shown here are for the most performant ballistic kinetic impactor trajectory solution, identified via grid search (see appendix).
- Launch: June 11, 2028
  - ~5 years after ATP, ~8.4 years before Earth impact
- Kinetic impact: July 6, 2030
  - ~6.3 years before Earth impact
  - Asteroid impact speed: ~11.33 km/s (DART's impact speed was ~6.14 km/s)
  - Required deflection ΔV to move mid-chord impact point off Earth: 25 mm/s
- Deflection performance for 1 Falcon Heavy Expendable launch:
  - Kinetic impactor spacecraft mass: 6918 kg (DART's mass was 580 kg at impact)
  - Assume momentum enhancement factor β = 3.6 (mean estimate from DART mission results)
  - For the 10$^{th}$ percentile (by mass) realization of the asteroid (295 m diameter, 1.8 g/cm$^3$ density):
    - ΔV = 11.6 mm/s, actual Earth impact point would need to be within 0.44 Earth radii (2806 km) of westward limb
  - For the 90$^{th}$ percentile (by mass) realization of the asteroid (1119 m diameter, 1.8 g/cm$^3$ density):
    - ΔV = 0.21 mm/s, actual Earth impact point would need to be within 0.006 Earth radii (38 km) of westward limb
- A minimum of 5 Falcon Heavy launches would be required to deflect the 10$^{th}$ percentile realization of the asteroid, before including redundancy/margin.
- For the 90$^{th}$ percentile asteroid, an unrealistic 276 launches would be required, before including redundancy/margin.
- If the momentum enhancement factor were to turn out to be more or less than 3.6, proportionately more or less launches would be required for any of the above cases.
- **If the asteroid turns out to be near or above the mean size / mass, a impractically large number of heavy lift launches would be required for robust kinetic impactor deflection performance, including appropriate margins.**

# Standoff Nuclear Detonation Deflection Performance Summary



- Assuming 4.5 years to ready a nuclear deflection rendezvous mission for launch in October 2027, the ideal time frame for deflecting the asteroid is August 2030.
- The required ΔV for deflection is 24.4 mm/s, for the worst-case (mid-chord) impact location.
- To deflect the 10$^{th}$ percentile (by mass) realization of the asteroid (295 m diameter, 1.8 g/cm$^3$ density):
  - Required nuclear explosive device (NED) yield is 0.107 MT, with a payload mass of 60 kg.
- To deflect the 90$^{th}$ percentile (by mass) realization of the asteroid (1119 m diameter, 1.8 g/cm$^3$ density):
  - Multiple NEDs are needed, with total payload mass dependent on configuration.
  - 3 x 2.3 MT NEDs, with a total payload mass of 3714 kg
  - 6 x 0.722 MT NEDs, with a total payload mass of 2404 kg
- The rendezvous mission, launching on a single Falcon Heavy Expendable and using an 8 kW NEXT-C propulsion system, can deliver up to 6067 kg to rendezvous with the asteroid.
- **A single launch can deliver more than enough NED yield to deflect the 90$^{th}$ percentile realization of the asteroid.**
  - Two or more nuclear deflection spacecraft could be launched to provide redundancy.
- **Kinetic impactor deflection of this asteroid is impractical, while nuclear deflection is practical.**

# Timeline of Key Events

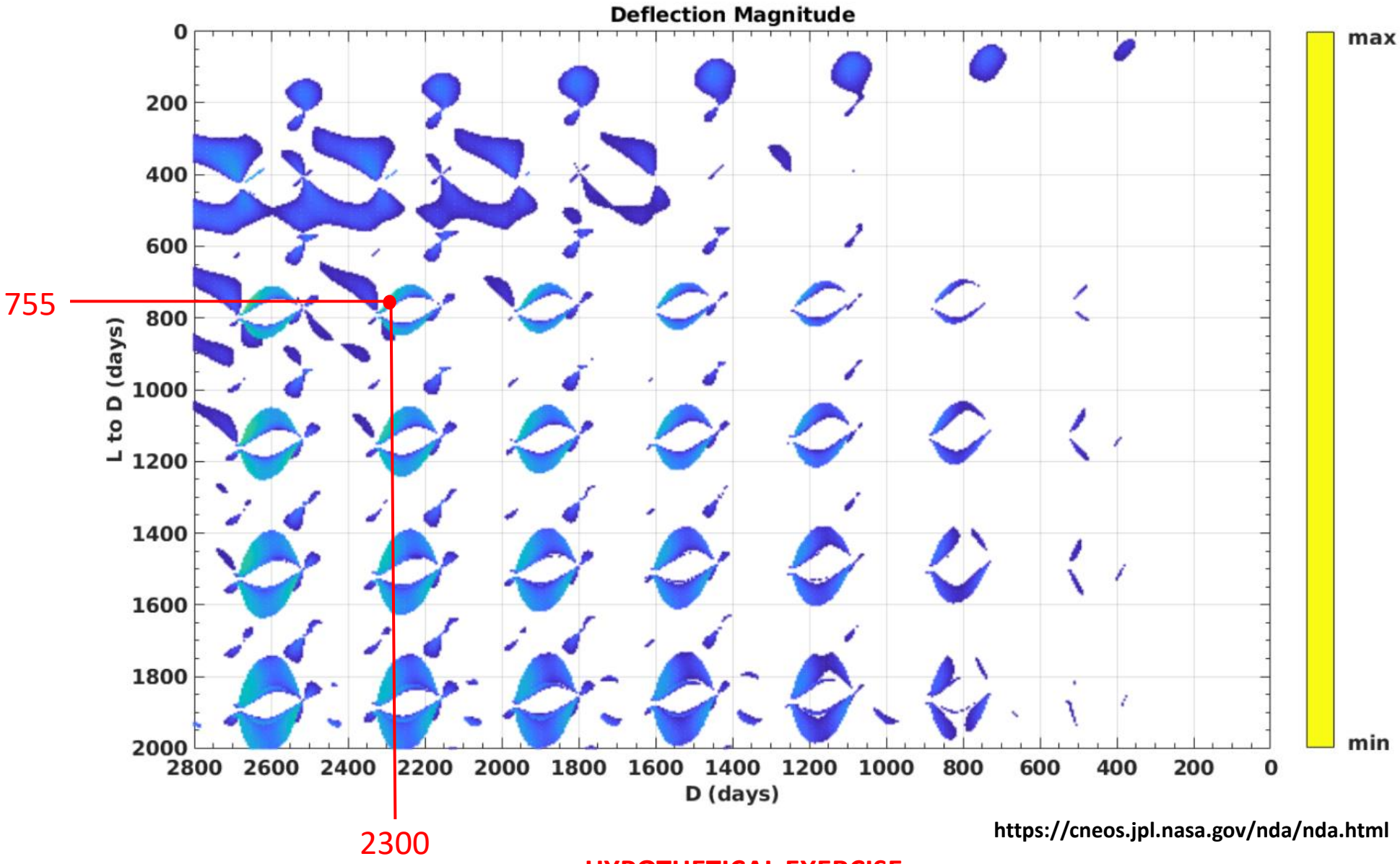



- **Notes:**
  - ~1.5 years is available to develop the Flyby Recon Mission. This is an unprecedentedly short development time for an interplanetary mission, but this is a very simple mission and it would likely have the highest of priorities.
  - ~2.5 years are available to develop the Rendezvous Recon Mission. That is less stressful than the shorter Flyby Recon Mission development time.
  - ~4.5 years are available to develop the Rendezvous NED Deflection Mission. This is similar to the traditional ~5 year development time for interplanetary missions, but it must be kept in mind that all three missions---Flyby Recon, Rendezvous Recon, and Rendezvous NED Deflection---are all being developed in parallel.
  - ~22 months are available between the Flyby Recon asteroid encounter and launch of the Rendezvous NED Deflection Mission to use the Flyby Recon Mission data about the asteroid to refine the Rendezvous NED Deflection Mission design before it launches.
  - ~4 months are available between the completion of the Rendezvous Recon asteroid survey and launch of the Rendezvous NED Deflection Mission to use the Rendezvous Recon Mission data about the asteroid to make final refinements to the Rendezvous Deflection Mission design before it launches.

# 2023 PDC Hypothetical Asteroid Impact Scenario Epochs

- **Epoch 1:**
  - 3 April 2023
  - Earth impact probability reaches ~1%
- **Epoch 2:**
  - 23 October 2024
  - Opportunity to launch Flyby Recon Mission
- **Epoch 3:**
  - 1 December 2025
  - Flyby Recon Mission would encounter the asteroid with a flyby speed of ~1.7 km/s
  - Flyby recon would provide substantial reduction in asteroid orbit / Earth impact location uncertainties, and partial reduction of asteroid physical properties uncertainties
- **Epoch 4:**
  - 1 June 2027
  - Rendezvous Recon Mission would complete its survey of the asteroid
    - The Rendezvous Recon Mission could launch on 19 October 2025, arrive at the asteroid 23 November 2026, and spend ~7 months surveying the asteroid
  - Rendezvous recon would provide substantial reduction in the asteroid's orbital and physical properties uncertainties
  - The rendezvous spacecraft could remain with the asteroid to provide ongoing situational awareness during and after subsequent deflection attempts, e.g., in 2030
- **Deflection of the asteroid could occur during August-September 2030**
  - A Rendezvous Deflection Mission could launch in October 2027 and arrive at the asteroid in January 2030, ~7 months to prior to beginning a series of Nuclear Explosive Device detonations near the asteroid during the time frame surrounding the asteroid's late August 2030 perihelion passage

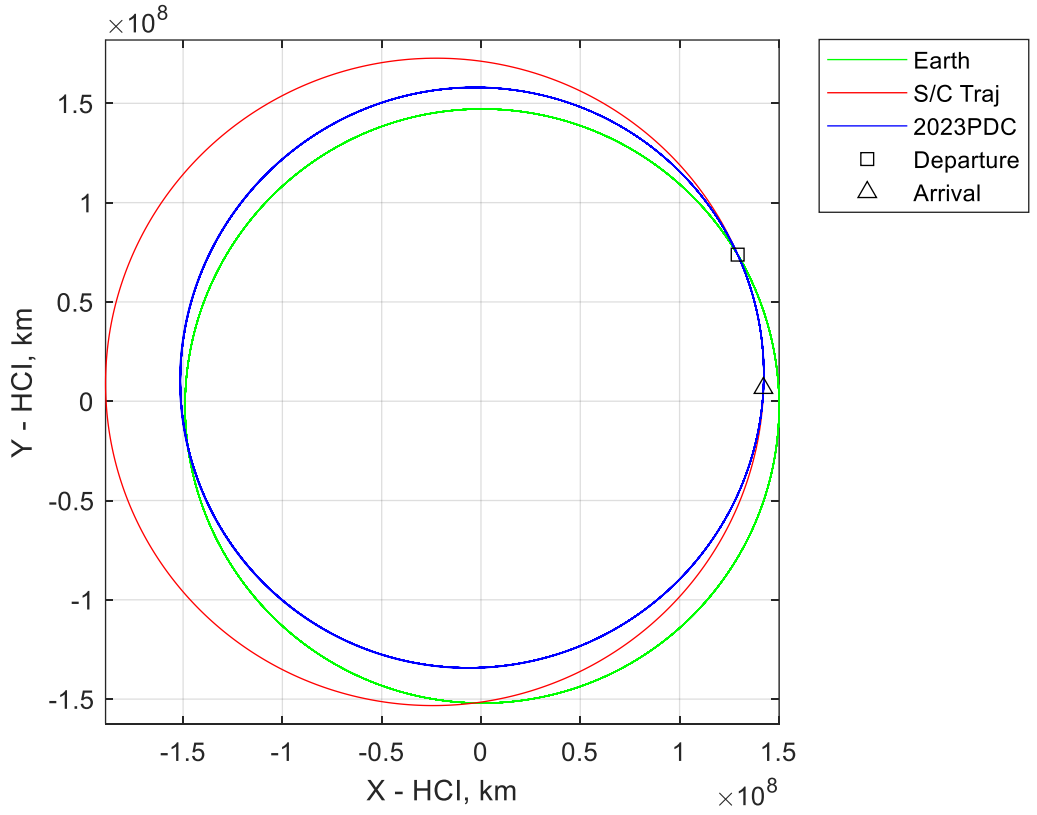
# Optimal Ballistic Kinetic Impactor Trajectory




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

# *Flyby Reconnaissance Mission Details*

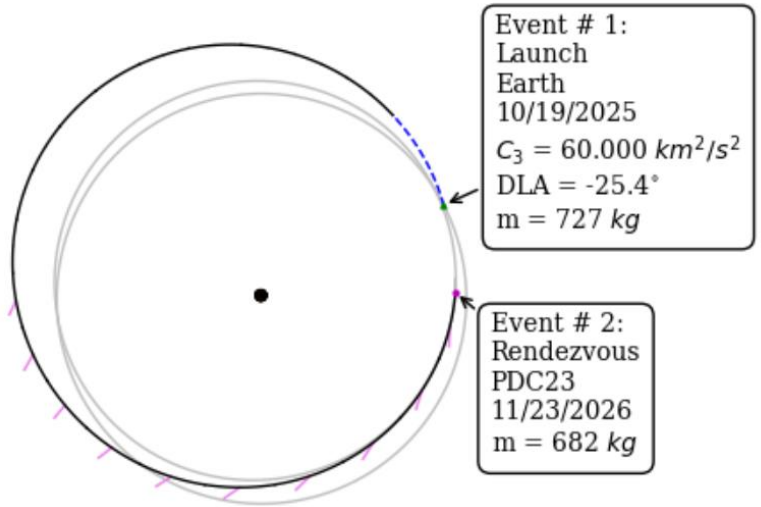
**Launch Vehicle:** Falcon Heavy (recovery or expendable)
**Launch:** 2024-10-23
**Arrival Date:** 2025-12-01 (404 day TOF)
**Departure C3:** 46.235 $km^2/s^2$
**Declination of Launch Asymptote (DLA):** -35.614 deg
**Asteroid flyby speed:** 1.738 km/s
**Approach phase angle:** 110.53 deg
**Spacecraft mass capability:** >500 kg



# Rendezvous Reconnaissance Mission Details

## Solar Electric Propulsion Option

**LV: Vulcan VC2***
**EOL power:** 5 kW
**EP thruster:** 1 NEXT-C
**Launch:** 10/19/2025
**Arrive:** 11/23/2026 (400-day TOF)
**EP prop mass:** 50 kg with 10% margin
**Delivered mass:** 682 kg (includes 4.5 kg of margined prop)

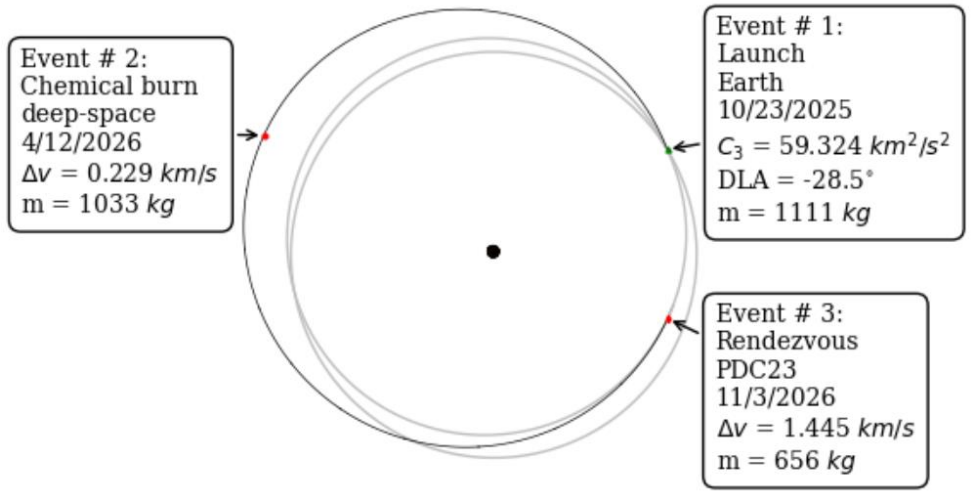



## Chemical Propulsion Option

(Storable hypergolic bipropellant, Isp=324 s)

**LV: Vulcan VC2***

**Thruster:** 324 s Isp storable hypergolic bipropellant
**Launch:** 10/23/2025
**Arrive:** 11/3/2026
**Prop mass:** 500 kg with 10% margin
**Delivered mass:** 656 kg (includes 50 kg of margined prop)




**Note: The Vulcan VC2 has not yet flown, but would be right-sized for these missions. The currently available Falcon Heavy launch vehicle is more than capable of flying these missions.*

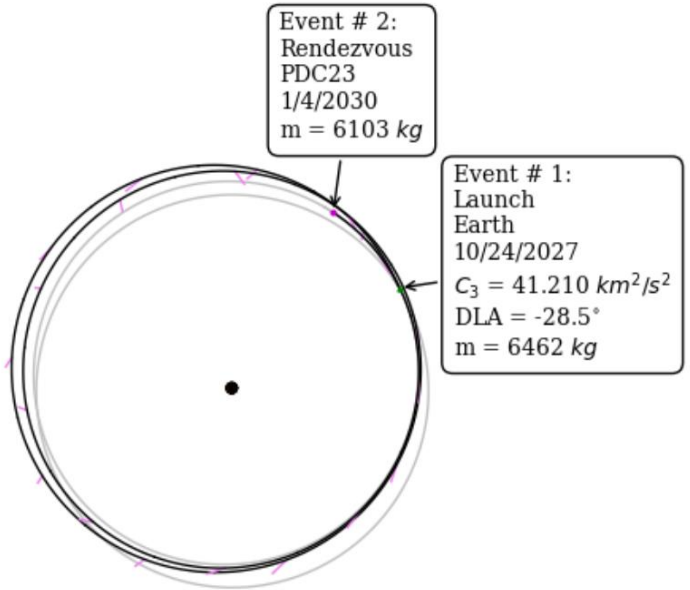
# NED Deflection Mission Details

- FHE and 8 kW SEP bus allows for >6000 kg delivered mass with only ~400 kg of EP prop within nominal deflection mission bounds
- Backup SEP option possible with 2028 launch & 2031 deflection opportunity, allowing longer duration between recon characterization & deflection mission launch

**Pysche s/c:**
4 SPT 140s
18 kW array
launch mass: 2600 kg
EP prop mass: ~1000 kg

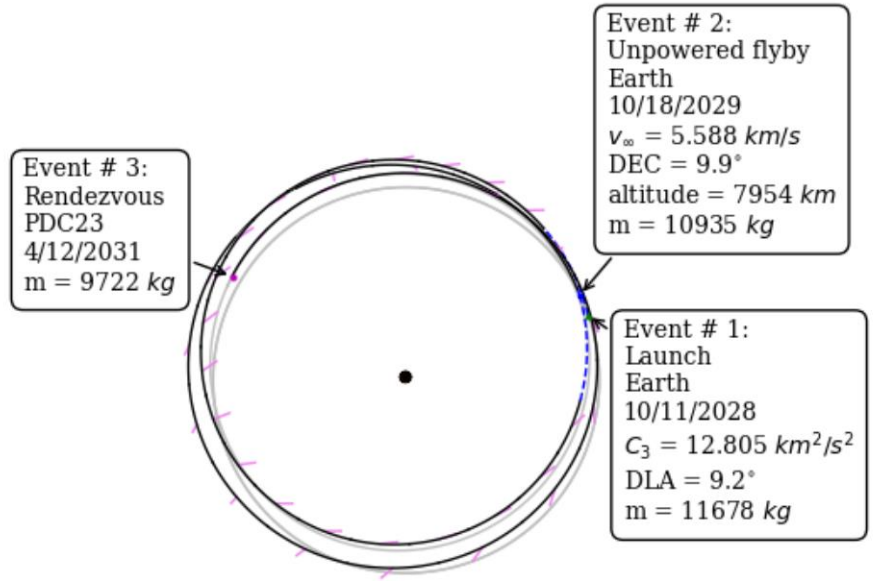
## Primary Launch Option

**LV:** Falcon Heavy Expendable
**Launch:** 10/24/2027
**Arrive:** 1/4/2030
**EOL power at 1 AU**: 8 kW
**Thrusters**: 1 active NEXT-C thruster
**Prop mass:** 394 kg (includes 10% margin)
**Delivered mass:** 6067 kg (margined prop not included)




## Backup Launch Option

**LV:** Falcon Heavy Expendable
**Launch:** 10/11/2028
**Arrive:** 4/1/2031
**EOL power at 1 AU**: 15 kW (can likely be lower)
**Thrusters**: 2 active BPT-4000 thrusters
**Prop mass:** 2153 kg (includes 10% margin)
**Delivered mass:** 9526 kg (margined prop not included)



# Space Mission Design Ground Rules & Assumptions

- **Solar electric propulsion (SEP) designs**
  - Duty cycle: 90%
  - Prop margin: 10%
  - Power margin: 10%
  - s/c bus power: 1 kW
  - 30 day forced coast after launch for s/c checkout
- **Chemical propulsion designs**
  - Bi-prop Isp: 324 s
  - Prop margin: 10% for statistical maneuvers & ACS tax
  - No mnvrs. until 30 days after launch for s/c check out
- **Planetary gravity assist flybys**
  - No restrictions on flyby body; up to 4 flybys evaluated w/ any combination of Earth, Venus, & Mars
  - No mnvrs. 30 days before flyby for missed thrust margin & dispersion corrections
  - No mnvrs. 2 days after flyby for navigation & mnvr. planning
- **Min solar radius**: 0.6 AU, max solar: 2.5 AU
- **Declination of launch asymptote**
  - +/- 28.5 deg for stock KSC LV performance curves