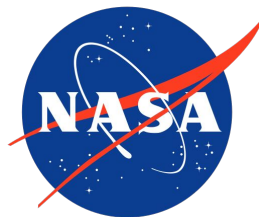


## HYPOTHETICAL EXERCISE

# NASA Analysis of Space Mission Options for the 2025 Planetary Defense Conference Hypothetical Asteroid Impact Threat Scenario

IAA-PDC-25-01-87



May 6, 2025

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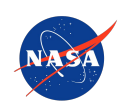
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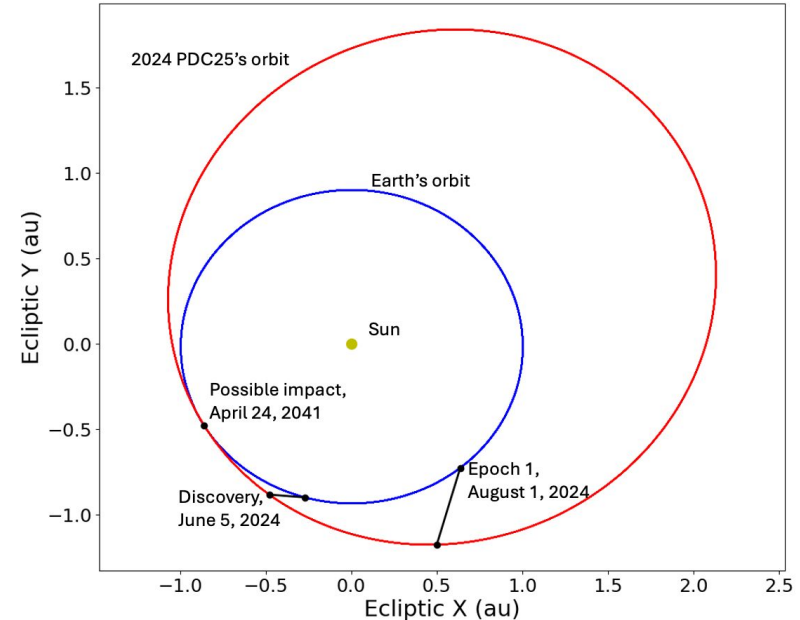
HYPOTHETICAL EXERCISE



## HYPOTHETICAL EXERCISE

# Scenario Overview: Epochs 1 and 2

- **Simulated asteroid 2024 PDC25 is discovered on June 5, 2024, with possible Earth impact on April 24, 2041**
  - $H = 21.9$ ,  $SMA = 1.7$  au,  $ECC = 0.4$ ,  $INC = 11^\circ$
- **Epoch 1: August 1, 2024**
  - Earth impact probability (IP) = 1.6%
  - Analysis of space mission options begins.
- **ATP for development of space missions is assumed in October 2024, when IP rises above 10%.**
  - Flyby reconnaissance mission begins development for launch.
  - Rendezvous reconnaissance mission and Kinetic Impactor (KI), Ion Beam Deflection (IBD), and Nuclear Explosive Device (NED) deflection missions all begin Phase A/B work.
- **Earth IP reaches 100% in September 2025.**
- **Epoch 2: April 28, 2028**
  - Flyby reconnaissance spacecraft encounters asteroid on April 12, 2028
  - Data from reconnaissance mission is processed, and both estimates of asteroid physical properties and analyses of KI/IBD/NED mission options are updated by April 28, 2028.

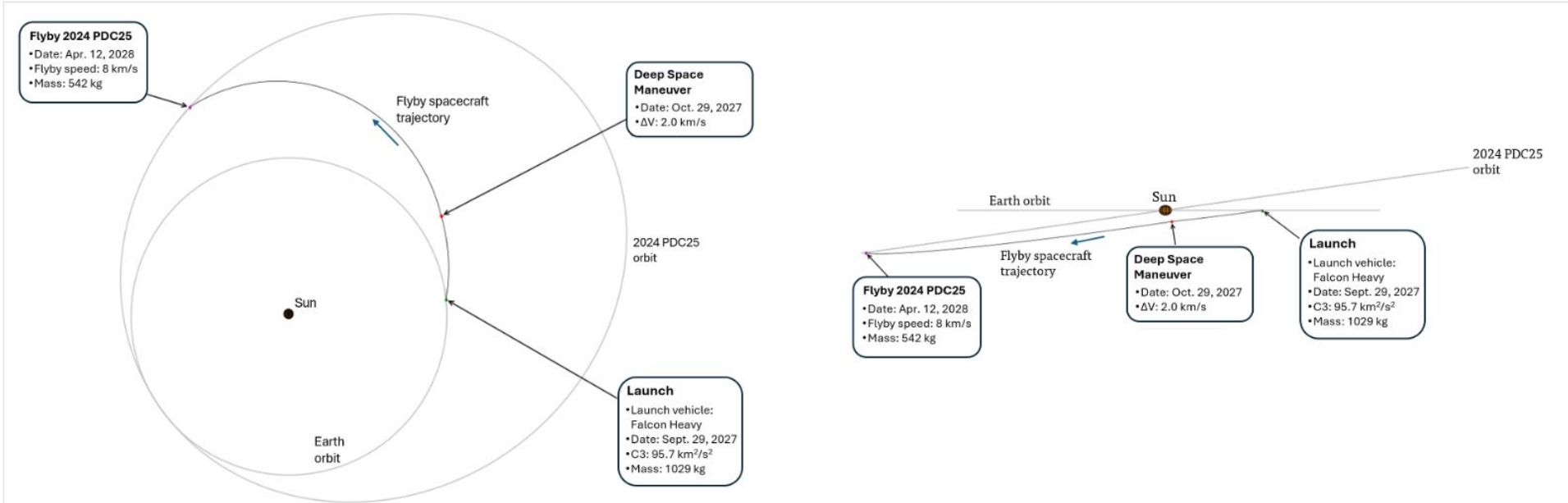


HYPOTHETICAL EXERCISE



## HYPOTHETICAL EXERCISE

# Fast Flyby Recon Mission Encounters 2024 PDC25 in April 2028



Fast flyby reconnaissance spacecraft trajectory from Earth to 2024 PDC25, as seen in an ecliptic plane view (left) and as seen looking at the ecliptic plane edge-on (right). The spacecraft reaches the asteroid six and a half months after launch, flying past it at distance of 100 km and a relative speed of 8 km/s.

<https://cneos.jpl.nasa.gov/pd/cs/pdc25/epoch2.html>

## HYPOTHETICAL EXERCISE



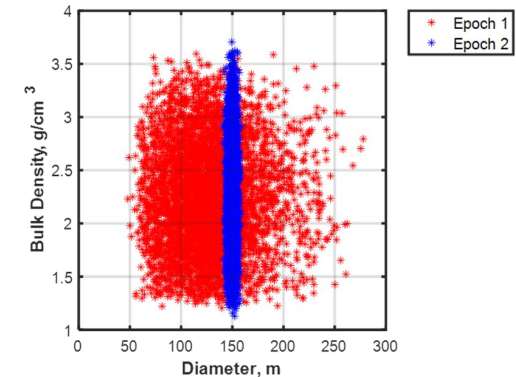
# HYPOTHETICAL EXERCISE

## Asteroid Physical Properties

In this analysis, we will concentrate on three potential realizations of the asteroid: **Low Mass**, **50th %tile Mass**, and **High Mass**.

Physical Property	Lowest Mass	Low Mass	5th Percentile	25th Percentile	50th Percentile	75th Percentile	95th Percentile	High Mass	Highest Mass
Diameter (m)	147	152	149	149	150	151	152	154	155
Bulk Density (g/cm <sup>3</sup> )	1.211	1.128	1.514	1.902	2.207	2.54	2.968	3.372	3.598
Porosity	0.595	0.596	0.57	0.402	0.313	0.244	0.093	0.062	0.039
Mass (billion kg)	2.00	2.09	2.60	3.31	3.93	4.59	5.49	6.41	7.03
Surface Escape Velocity (cm/s)	6.05	6.04	6.85	7.68	8.33	9.00	9.79	10.57	10.99
Absolute Magnitude	21.42	21.98	22.16	21.24	21.6	21.59	21.58	21.86	22.28
Albedo	0.221	0.123	0.109	0.253	0.179	0.179	0.178	0.135	0.09
Taxonomic Type	S	S	S	S	S	S	S	S	S
Best-fit Ellipsoid Axis 2a (m)	115	122	123	120	119	119	121	112	126
Best-fit Ellipsoid Axis 2b (m)	118	122	116	115	117	120	124	125	126
Best-fit Ellipsoid Axis 2c (m)	235	237	230	241	244	242	236	259	234

- **Low Mass** = The asteroid mass at the lower limit of the 99.7% HPDI (highest posterior density interval) for the distribution of potential asteroid mass.
- **High Mass** = The asteroid mass at the upper limit of the 99.7% HPDI for the distribution of potential asteroid mass.
- **Note:** The 99.7% HPDI (spanned from Low Mass to High Mass) represents the smallest interval that contains 99.7% of the potential mass values for the asteroid.



Asteroid diameter vs. bulk density distribution during **Epoch 1** (pre flyby recon) and **Epoch 2** (post flyby recon).

# HYPOTHETICAL EXERCISE

## Asteroid Deflection Distances

### Northward Deflection B-Plane Distance:

- 7,370 km (125 km asteroid perigee altitude)
- Includes  $3\sigma$  uncertainty in impact location
- ~33% of impact risk chord length in the B-plane

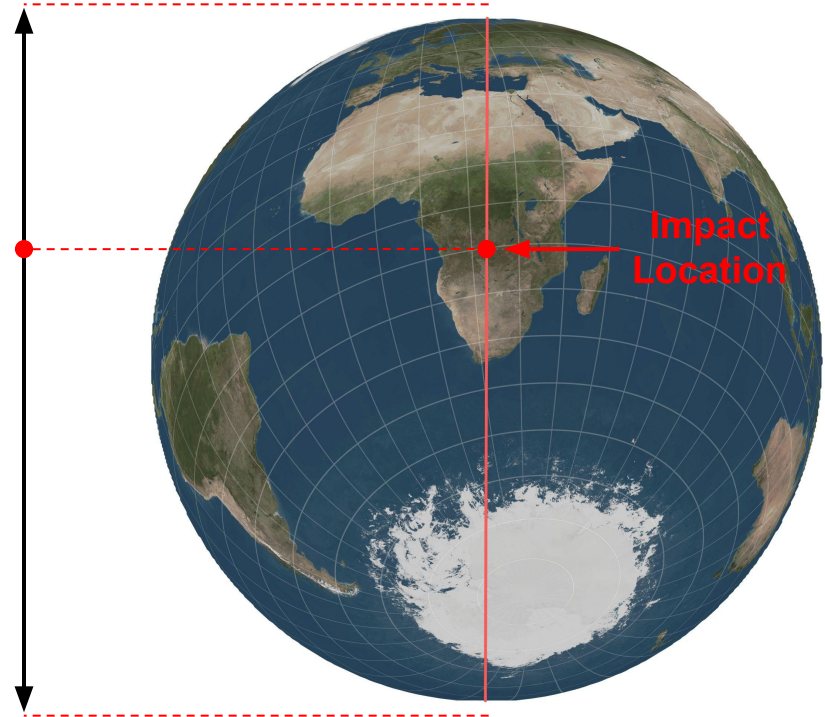
Nuclear Explosive Devices (NEDs) and Ion Beam Deflection (IBD) can deflect in this direction.

### Southward Deflection B-Plane Distance:

- 15,352 km (125 km asteroid perigee altitude)
- Includes  $3\sigma$  uncertainty in impact location
- ~70% of impact risk chord length in the B-plane

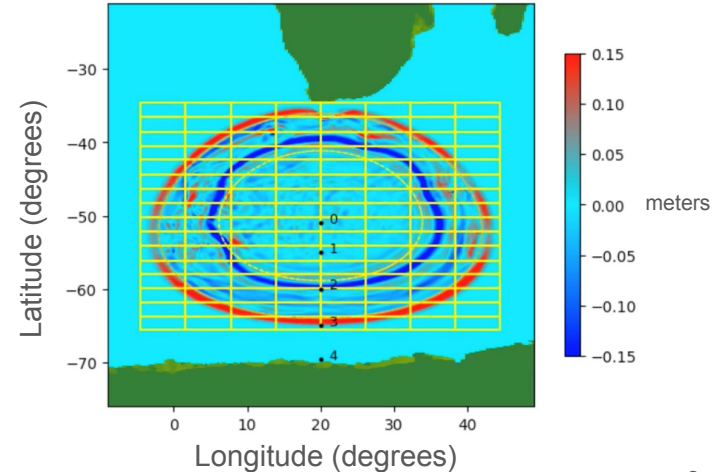
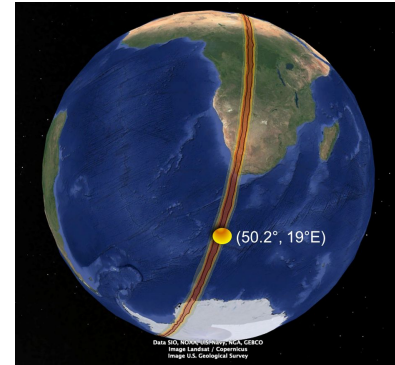
Kinetic impactors can only deflect in this direction.

NEDs and IBD can also deflect in this direction.



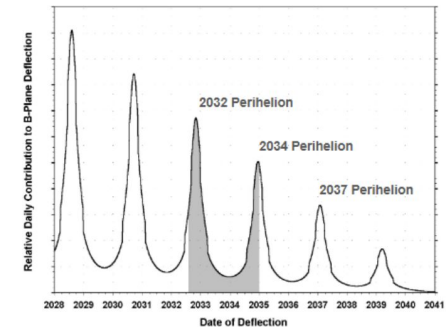
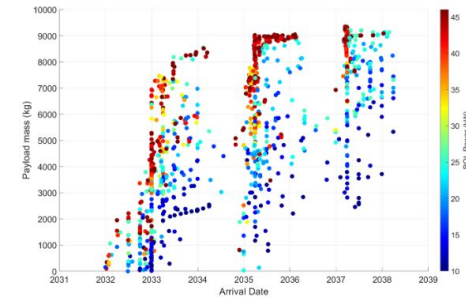
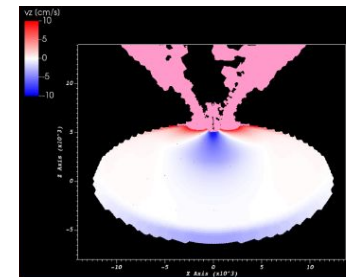
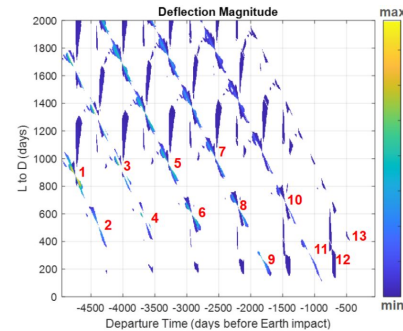
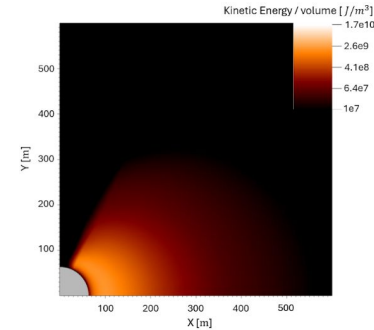
## Southward Partial Deflection

- The NASA/ARC Asteroid Threat Assessment Project (ATAP) provided a preliminary analysis of a southward partial deflection into the ocean.
- The partial deflection zone is  $-38.6^\circ$  to  $-50.2^\circ$  latitude along the risk corridor, which translates to a B-plane deflection distance requirement that is 23–28% of the impact risk chord length, including the  $3\sigma$  impact location uncertainty.
- **Although due diligence was exercised in this analysis, important uncertainties remain, e.g., regarding potential impact/tsunami effects on Antarctic ice and associated subsequent potential negative effects, both local and global. The fact of these uncertainties should be taken into account when considering the partial deflection option.**



## Analysis Methodologies

- **Multi-physics, mesh-based. hydrodynamics simulations (KI, NED).**
- **Genetic algorithm optimization** (low thrust, solar electric propulsion rendezvous for reconnaissance, IBD, NED).
- **Grid optimization** (ballistic single/multiple KI).
- **IBD simulations** to optimize deflection performance.
- *The heuristic for avoiding unwanted asteroid fragmentation of  $\Delta V \leq 10\% V_{\text{escape}}$  strongly drives the need for multiple KIs and multiple NED detonations.*





# HYPOTHETICAL EXERCISE

## Kinetic Impactor (KI) Performance Summary

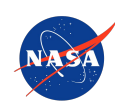
### Primary

Primary: Number of KI Spacecraft Required to Complete Deflection & Completion Date			
	$\beta$		
Asteroid Mass	2	5	8
Low Mass	6 Dec 2036	3 Nov 2032	
50th %tile	6 Dec 2036	4 Dec 2034	4 Dec 2034
High Mass	5 Dec 2036	5 Dec 2036	4 Dec 2034

### Backup

Backup: Number of KI Spacecraft Required to Complete Deflection & Completion Date			
	$\beta$		
Asteroid Mass	2	5	8
Low Mass	6 Feb 2037	5 Feb 2037	
50th %tile	5 Feb 2037	5 Feb 2037	4 Jan 2037
High Mass	5 Feb 2037	4 Jan 2037	4 Jan 2037

The more likely combinations of  $\beta$  and asteroid mass are highlighted in light green.



# HYPOTHETICAL EXERCISE

## Ion Beam Deflection (IBD) Performance Summary

### Purpose-Built 46 kW IBD Spacecraft: Number of IBD Spacecraft & Deflection Completion Dates

#### Northward

Option:	Ep1 OptA (22kW)	Early1 (46kW)	Early2 (46kW)	Primary (46kW)	Backup (46kW)
Launch	10/9/2029	4/25/2029 (5.5 mo. earlier)	6/2/2029 (4.2 mo. earlier)	10/3/2029	4/10/2030 (6.2 mo. later)
Arrival	7/9/2032	4/27/2032	6/4/2032	7/6/2032	10/1/2032
Asteroid Mass %ile:	Required Number of Launches: Completion Dates:				
Low	2 Dec 2034	1 Mar 2034	1 Jun 2034	1 Aug 2034	1 Dec 2034
50th	3 Mar 2035	1 Oct 2036	1 Nov 2036	2 Jun 2034	2 Dec 2034
High	4 Feb 2037	2 Feb 2035	2 Mar 2035	2 Apr 2035	2 Dec 2036

#### Southward

Option:	Ep1 OptA (22kW)	Early1 (46kW)	Early2 (46kW)	Primary (46kW)	Backup (46kW)
Launch	10/9/2029	4/25/2029 (5.5 mo. earlier)	6/2/2029 (4.2 mo. earlier)	10/3/2029	4/10/2030 (6.2 mo. later)
Arrival	7/9/2032	4/27/2032	6/4/2032	7/6/2032	10/1/2032
Asteroid Mass %ile:	Required Number of Launches: Completion Dates:				
Low	3 Dec 2036	1 Feb 2037	1 Mar 2037	2 Sep 2034	2 Jan 2035
50th	5 Feb 2037	2 Dec 2036	2 Jan 2037	3 Dec 2034	3 Jul 2035
High	8 Mar 2037	3 Mar 2037	3 Apr 2037	4 Jul 2035	4 Jan 2037

#### Southward Partial

Option:	Ep1 OptA (22kW)	Early1 (46kW)	Early2 (46kW)	Primary (46kW)	Backup (46kW)
Launch	10/9/2029	4/25/2029 (5.5 mo. earlier)	6/2/2029 (4.2 mo. earlier)	10/3/2029	4/10/2030 (6.2 mo. later)
Arrival	7/9/2032	4/27/2032	6/4/2032	7/6/2032	10/1/2032
Asteroid Mass %ile:	Required Number of Launches: Completion Dates:				
Low	1 Nov 2036	1 Jan 2033	1 Feb 2033	1 Mar 2033	1 Aug 2034
50th	2 Apr 2035	1 Nov 2034	1 Dec 2034	1 Dec 2034	1 Jun 2035
High	3 Dec 2036	1 Feb 2037	1 Mar 2037	2 Sep 2034	2 Jan 2035

### Repurposed PPE 60 kW IBD Spacecraft: Number of IBD Spacecraft & Deflection Completion Dates

#### Northward

Option:	Early1	Early2	Primary	Backup
Launch	4/14/2029 (5.4 mo. earlier)	6/2/2029 (4 mo. earlier)	10/2/2029	4/3/2030 (6.2 mo. later)
Arrival	3/16/2032	5/4/2032	7/26/2032	10/31/2032
Asteroid Mass %ile:	Required Number of Launches: Completion Dates:			
Low	1 Jan 2033	1 Jan 2033	1 May 2033	1 Nov 2034
50th	1 Jan 2035	2 Jan 2033	2 Apr 2033	2 Oct 2034
High	2 Jul 2034	2 Oct 2034	3 Jun 2033	3 Nov 2034

#### Southward

Option:	Early1	Early2	Primary	Backup
Launch	4/14/2029 (5.4 mo. earlier)	6/2/2029 (4 mo. earlier)	10/2/2029	4/3/2030 (6.2 mo. later)
Arrival	3/16/2032	5/4/2032	7/26/2032	10/31/2032
Asteroid Mass %ile:	Required Number of Launches: Completion Dates:			
Low	2 Jan 2033	2 Feb 2033	2 Jul 2033	2 Nov 2034
50th	2 Mar 2035	3 Oct 2033	3 Dec 2034	3 Feb 2035
High	4 Aug 2034	4 Nov 2034	5 Nov 2034	5 Jan 2035

#### Southward Partial

Option:	Early1	Early2	Primary	Backup
Launch	4/14/2029 (5.4 mo. earlier)	6/2/2029 (4 mo. earlier)	10/2/2029	4/3/2030 (6.2 mo. later)
Arrival	3/16/2032	5/4/2032	7/26/2032	10/31/2032
Asteroid Mass %ile:	Required Number of Launches: Completion Dates:			
Low	1 Nov 2032	1 Nov 2032	1 Dec 2032	1 May 2034
50th	1 Jun 2033	1 Sep 2033	1 Dec 2034	1 Jan 2035
High	2 Jan 2033	2 Feb 2033	2 Jul 2033	2 Nov 2034

# HYPOTHETICAL EXERCISE



## HYPOTHETICAL EXERCISE

# Nuclear Explosive Device (NED) Performance Summary

Number of NED Spacecraft Required to Complete Deflection & Completion Date				
	Launch Opportunity (Launch Year)			
Asteroid Mass	Early (2029)	Primary (2031)	Backup (2033)	Last-Ditch (2035)
Low Mass	1 Sep 2032	1 Dec 2034	1 Mar 2037	1 May 2039
50th %tile	1 Sep 2032	1 Dec 2034	1 Jan 2037	1 Mar 2039
High Mass	1 Sep 2032	1 Oct 2034	1 Jan 2037	1 Mar 2039

HYPOTHETICAL EXERCISE



## HYPOTHETICAL EXERCISE

# KI, IBD, and NED Performance Comparison

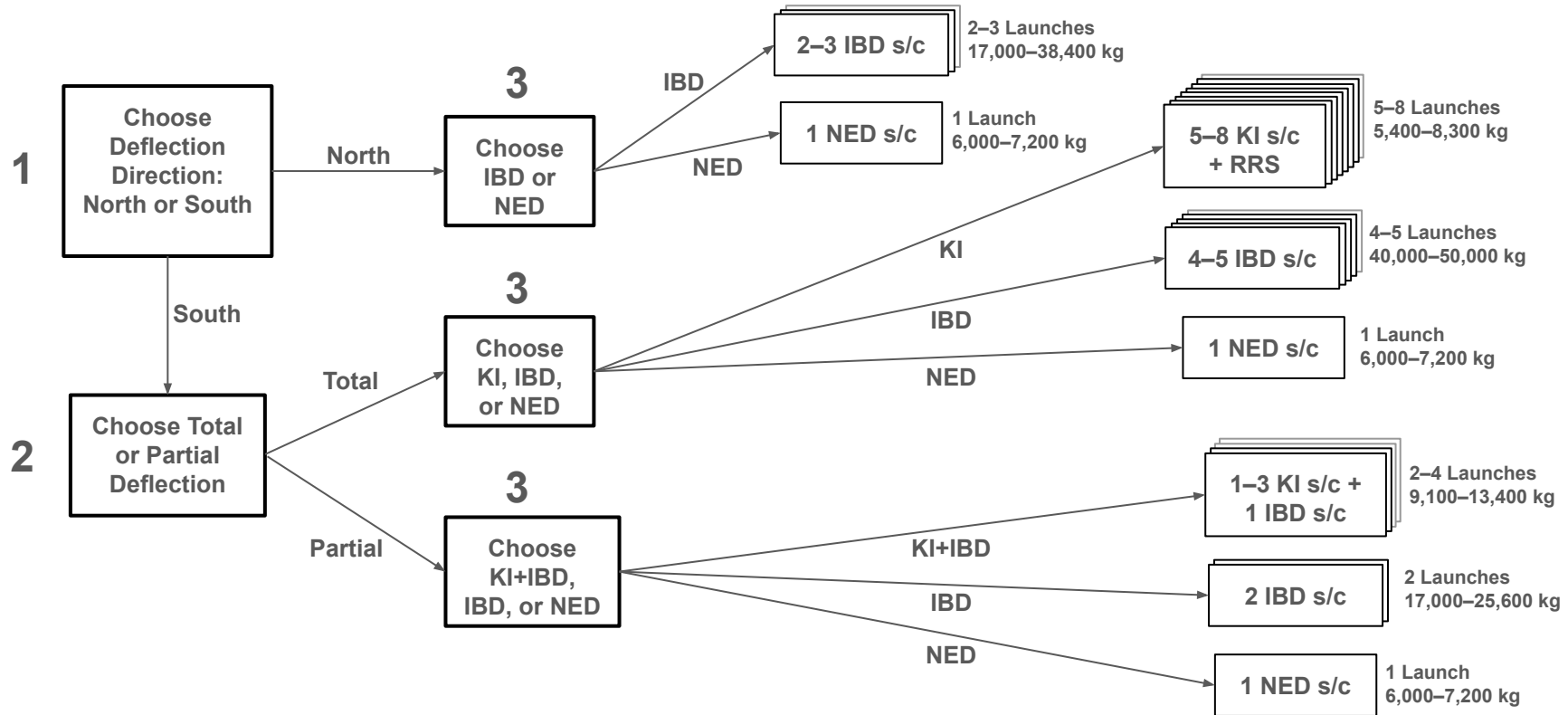
Deflection Mission Type	Northward Total Deflection		Southward Total Deflection		Southward Partial Deflection	
	Number of Spacecraft / Launches	Total Spacecraft Mass (kg)	Number of Spacecraft / Launches	Total Spacecraft Mass (kg)	Number of Spacecraft / Launches	Total Spacecraft Mass (kg)
<b>KI + RRS</b>	N/A	N/A	5-8	5,400-8,300	3	4,500
<b>IBD</b>	2-3	17,000-38,400	4-5	40,000-50,000	2	17,000-25,600
<b>NED</b>	1	6,000-7,200	1	6,000-7,200	1	6,000-7,200

- KI requires more spacecraft than NED does (4-7 vs. 1) due to the need to avoid accidental asteroid fragmentation, and to handle uncertainties in asteroid mass and  $\beta$ . Unlike NED and IBD, KI cannot deflect northward, only southward. *\*KI isn't precise enough for partial deflection on its own.*
  - Note that the KI missions require the support of the SEP Rendezvous Reconnaissance Spacecraft (RRS) mission currently under development for launch in Dec 2029 (arrives at the asteroid in Dec 2031, prior to when the 1st KI would strike the asteroid).
- IBD requires significantly more total spacecraft mass than NED or KI (and significantly more mass than previous interplanetary missions). The number of IBD spacecraft required for a southward total deflection is comparable to KI (e.g., 4-5 vs. 5-8).
- Deploying a combination of KI and IBD may also be considered, to provide some redundancy. Separate RRS not needed here—IBD spacecraft acts as RRS.
  - A KI + IBD partial deflection would require 1-3 KIs + 1 IBD spacecraft. IBD could provide clean-up capability for targeting the partial deflection zone precisely.
  - A KI + IBD total deflection could involve various combinations of KI and IBD spacecraft, bounded by the numbers in the table above.
- 1 NED-carrier spacecraft, carrying 9-12 free-flyer NEDs (100 kt each), can achieve total deflection northward or southward, or partial deflection southward; total spacecraft mass is in family with interplanetary mission flight heritage.



# HYPOTHETICAL EXERCISE

## Mission Options Summary Flowchart



HYPOTHETICAL EXERCISE