Human Exploration of Near-Earth Objects Accessibility Study

ESMD AA Briefing

Washington, D.C.

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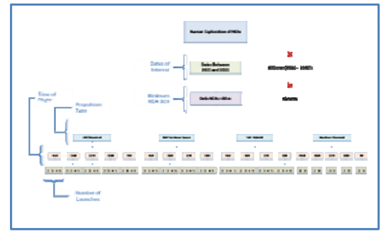
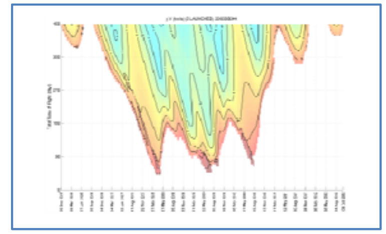
Presentation Outline

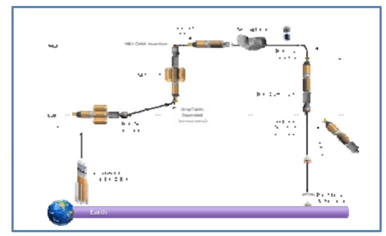
- **NEA Accessibility Key Considerations**



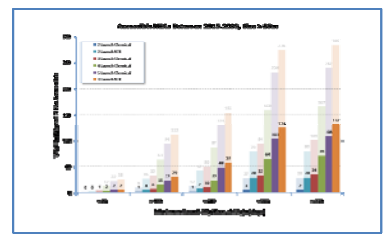
- **Trajectory Generation Methodology**



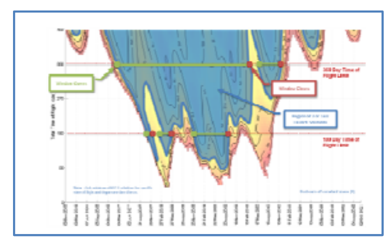
- **Human Exploration of NEAs Architecture Formulation and Mass Modeling Approach**



- **NEA Accessibility Sensitivity Results**

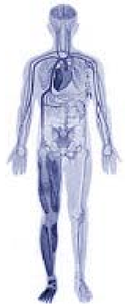


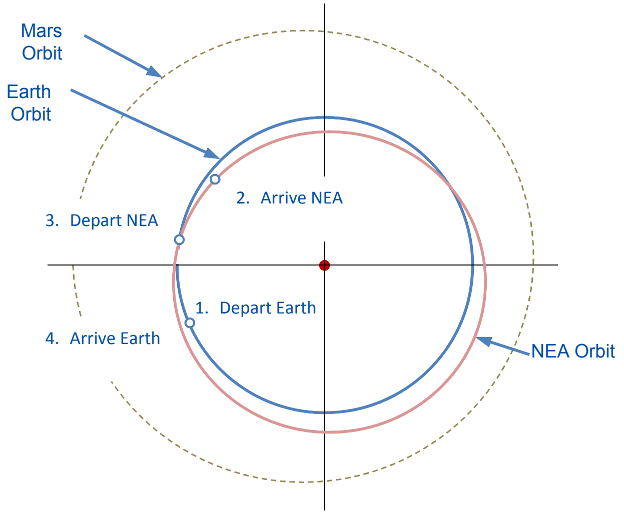
- **Injection Window and Opportunity Characteristics**



Key Questions to be Addressed

- How short can the trip times be reduced in order to reduce crew exposure to the deep-space radiation and micro-gravity environment?
- Are there options to conduct easy, early missions?
- What is the affect of infusion of advanced propulsion technologies on target availability
- When do the departure opportunities open up, how frequent and how long are they?
- How many launches are required to conduct a round trip human mission to a NEA?
- And, based on the above, how many Near-Earth Asteroids are available





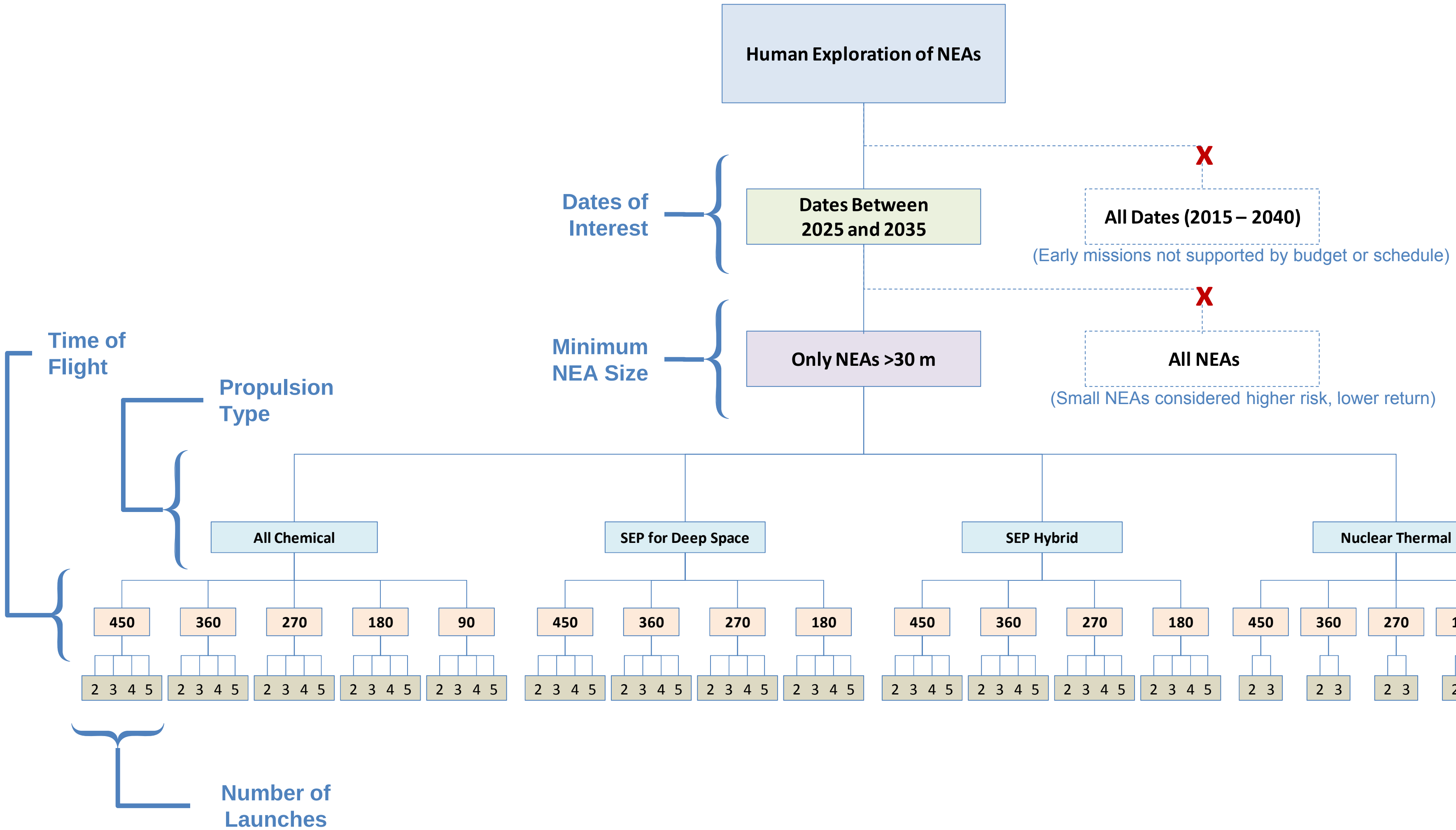
Human Exploration of Near Earth Asteroids

Key Mission Design Criteria

Human Exploration of NEAs

Mission Date		All Dates 2015 - 2040	Selected Dates 2025 - 2035		
NEA Size		Any Size	Size ≥ 30 m		
Propulsion Type	Chemical	Nuclear Thermal	Solar/Chemical Hybrid	All SEP	
Time of Flight	Time ≤ 90 Days	Time ≤ 180 Days	Time ≤ 270 Days	Time ≤ 360 Days	Time ≤ 450 Days
Number of Launches	2 or less	3 or less	4 or less	5 or less	

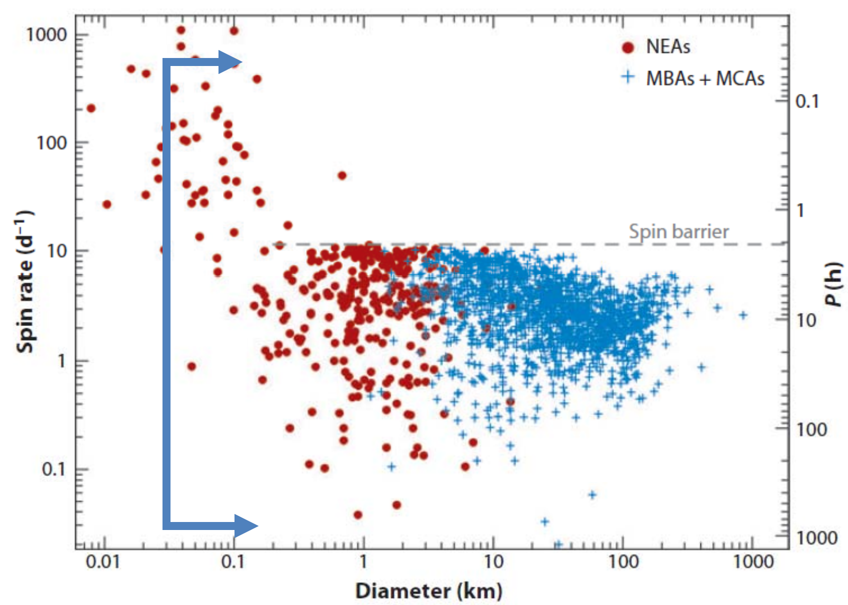
Human Exploration of Near Earth Asteroids
Key Mission Design Criteria



Spin Rates and Surface/Internal Structure vs. Diameter

- **Asteroid spin rate and surface/internal structure are significant factors in target qualification**
- **Small asteroids (~50-100 m or smaller) have a tendency to be fast rotators and are more likely to be monolithic with less surface regolith**
- **Large asteroids (~100 m or larger) tend to rotate more slowly and have a high probability of being rubble piles comprised of a variety of particle sizes**
- **Spin barrier (P_{rot} ~2.2 h), also known as the rubble pile limit, is the fastest a sphere of density ~2 g/cm^3 can rotate without throwing material off its equator**
- **All large NEAs *could* be rubble piles, and recent studies indicate small NEAs can also be rubble piles**

Near-Earth Asteroids (NEAs) are the red dots (●) in the figure below



Asteroid rotation rate ω_{rot} *(rotations per day, left axis) and rotation period* P_{rot} *(h per rotation, right axis)* plotted versus asteroid diameter *D (km), obtained by brightness (absolute magnitude) and brightness* variation (periodicity) studies of hundreds of asteroids. The "spin barrier" at P_{rot} ** 2.2 h appears to be an* abrupt threshold transgressed by only one known asteroid larger than ~300 m diameter. Near-Earth asteroids (NEAs) are shown as circles; main-belt asteroids (MBAs) and Mars-crossing asteroids (MCAs) are shown as small crosses. Figure courtesy of Petr Pravec. Ref. Asphaug, 2009.

Spin Rates and Surface/Internal Structure vs. Diameter

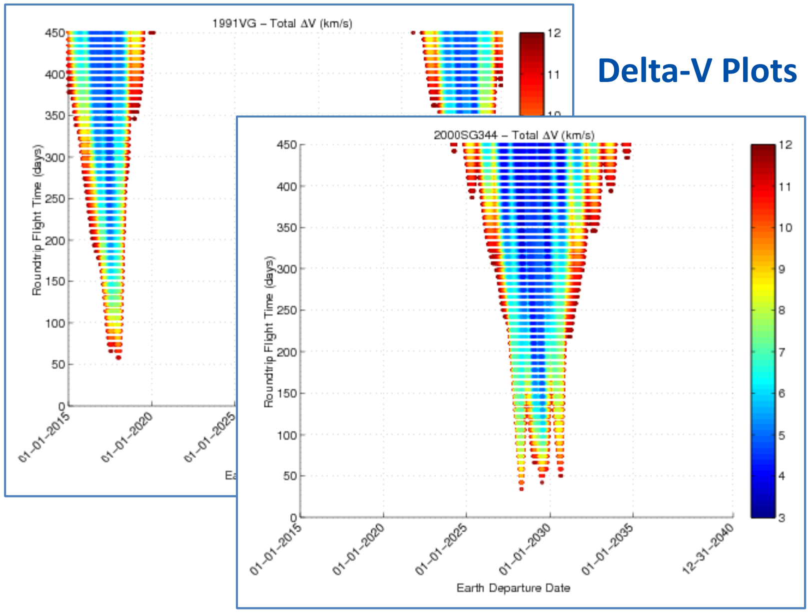
- **Surface exploration may require maintaining a fixed relative position with the NEA. A slow NEA spin rate and the ability to anchor to the NEA are desirable.**
- **Attaching to a micro-gravity bound rubble pile may pose significant operational complexity**
- **Larger NEAs are desired to maximize the diversity of surface terrains/compositions for scientific study, but smaller NEAs also offer significant science return.**
- **Finding a NEA that is "just right" (i.e., larger, substantially monolithic, and with a slow spin) could be enabling for human exploration**
- **NEA size estimates are based on observed visual brightness (absolute magnitude, Hmag), which can lead to uncertainties of up to a factor of ~5**

- **NEAs with an *estimated* diameter of 30 m or larger were used as the lower threshold for this assessment**

TRAJECTORY GENERATION METHODOLOGY

Ballistic Trajectory Generation Approach

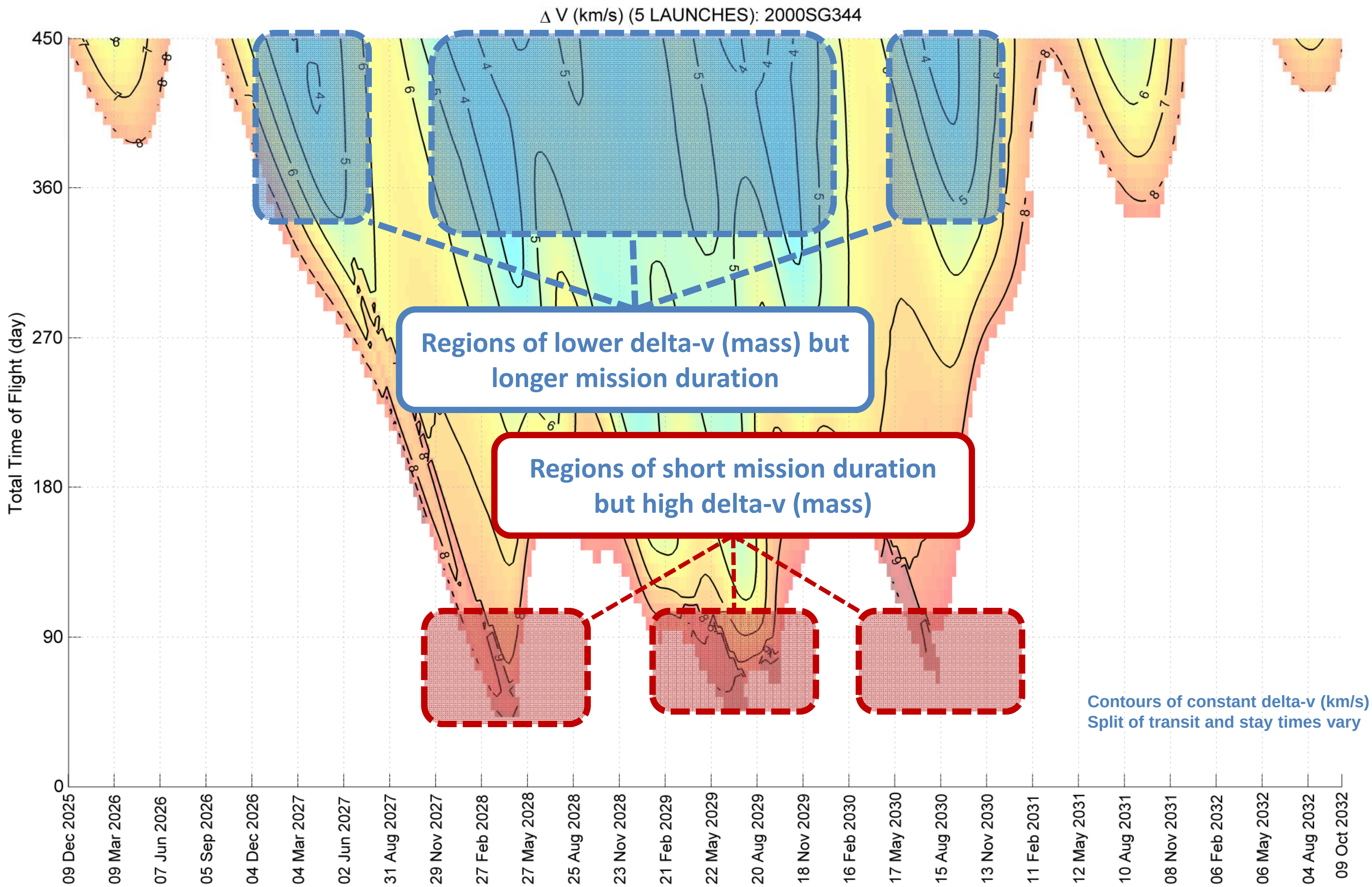
- **Used all NEAs officially designated by the Minor Planet Center (MPC) as of 2/3/2011, contained in the JPL NEA database with ephemerides generated on JPL HORIZONS**
- **Opened up the search parameters to explore the problem and look for new possible targets**
  - Departure epochs: 2015-2040
  - Earth Departure $C_3 \leq 60$ km/s
  - Total Velocity Change: $\Delta V_{Total} \leq 12$ km/s
  - Stay Time ≥ 8 days
  - Total Flight Time ≤ 450 days
  - Earth Entry Speed V_{EI} limit ≤ 12.0 km/s
- **Trajectories meeting above criteria**
  - 79,153,947 unique trajectories
  - 765 of the 7655 NEAs
  - But not all of these 765 would be considered “accessible” from a programmatic, mission planning, or technological perspective



Delta-V Plots

Example Sensitivity of High-Thrust Delta-v and Trip Time

Near Earth Asteroid 2000SG344



HUMAN EXPLORATION OF NEAS

Architecture Formulation

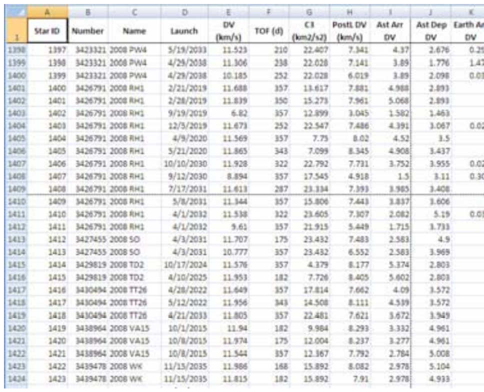
Mass Modeling Approach

Architecture Development Overview

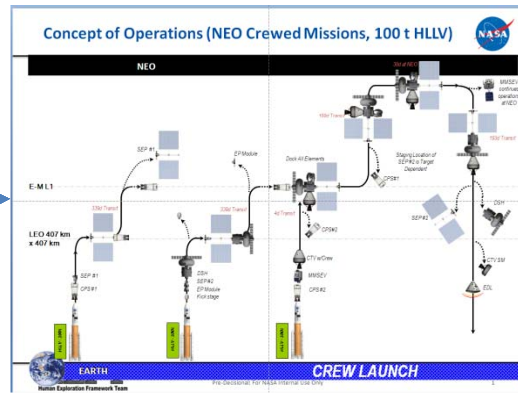
- **The trajectory scans by both the GSFC and JPL teams produced over 79 million potential trajectories to thousands targets**
- **Of those millions of trajectories, thousands may represent "good" candidate mission opportunities**
- **A streamlined process was established to translate the trajectories into key figures of merit to support stakeholder decision process**
- **Several different transportation approaches were considered, including**
  - All chemical propulsion
  - Nuclear Thermal Propulsion (NTP)
  - Electric Propulsion (Solar Electric) for the deep space portion of the mission
  - Hybrid Propulsion as characterized by chemical boost + Solar Electric (HEFT approach)
- **Methodology**
  1. Utilize mission concepts and payloads consistent with the Human Exploration Framework Team (HEFT) assessments
  2. Establish mission concept of operations
  3. Apply parametric propulsion system sizing
  4. Estimate initial mass in LEO and required number of heavy lift launches required for each trajectory

Architecture Mass Estimation Applied Methodology

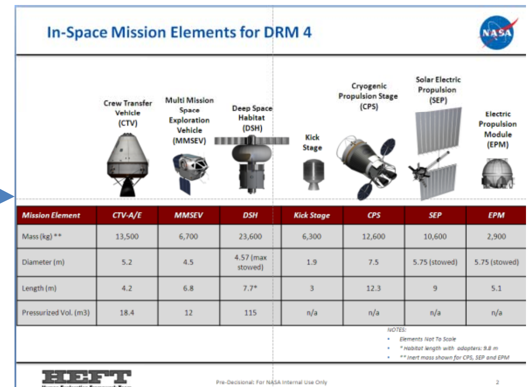
Trajectory Scans



Operational Concept



Mission Payload Definition



Propulsion System Parametric Sizing

$$R = e^{\frac{\Delta V}{g * I_{sp}}}$$

$$Mass_{prop} = Mass_{payload} * (R - 1) * \frac{(1 - f_{inert})}{1 - R * f_{inert}}$$

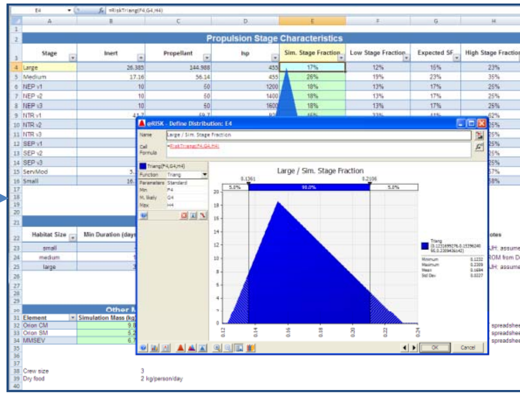
$$Mass_{inert} = Mass_{prop} * \frac{f_{inert}}{1 - f_{inert}}$$

$$Mass_{stage} = Mass_{prop} + Mass_{inert}$$

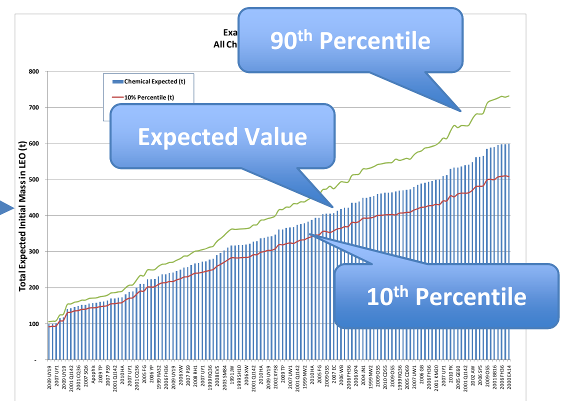
$$Mass_{phase} = Mass_{stage} + Mass_{payload}$$

Define Simulation Variables

To account for early conceptual designs



Simulation Results



Transportation and Exploration Systems Assumptions

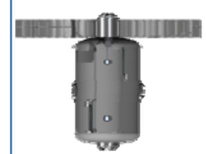
Space Exploration Vehicle

- Same assumptions as HEFT
- Primary purpose is for exploration of the NEA
- Supports crew of 2 for 14 days
- Nominal mass = 6.7 t

Multi Purpose Crew Vehicle

- Same assumptions as HEFT (CTVE-AE configuration)
- CM inert = 9.8 t
- SM inert = 5.2 t
- SM specific impulse = 328 s

Deep Space Habitat

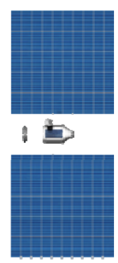


- Sizing consistent with HEFT
- Nominal mass ~ 21.2 t
- Consumables loaded based on mission duration

Chemical Propulsion Stage

- Sizing consistent with HEFT
- Parametric design with each stage optimized
- Zero-boiloff cryo management
- Stage fraction ~ 15%
- Specific impulse = 455 s

Solar Electric Propulsion



- Consistent with HEFT
- Spacecraft alpha ~60 kg/kw (jet), 35 kg/kw (spacecraft)
- Specific impulse = 1600 s
- Xe tank fraction = 15%
- Total power < 700 kWe

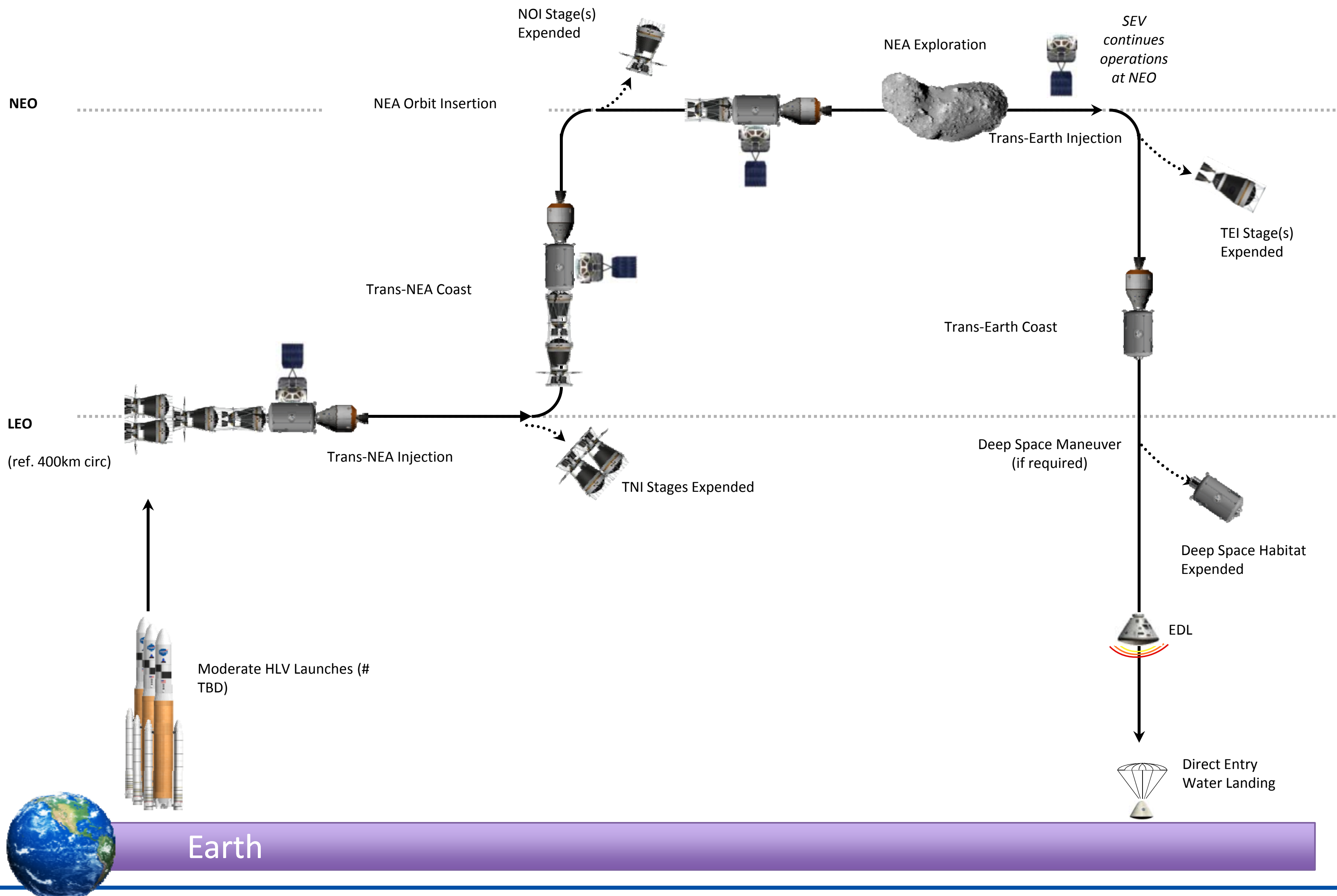
Nuclear Thermal Propulsion

- Consistent with Mars DRA 5
- NERVA-derived common core propulsion (20 t core)
- 3 x 111 kN engines
- Specific Impulse = 900 s
- All LH2 fuel with zero boil-off
- Drop tanks @ 27% tank fraction

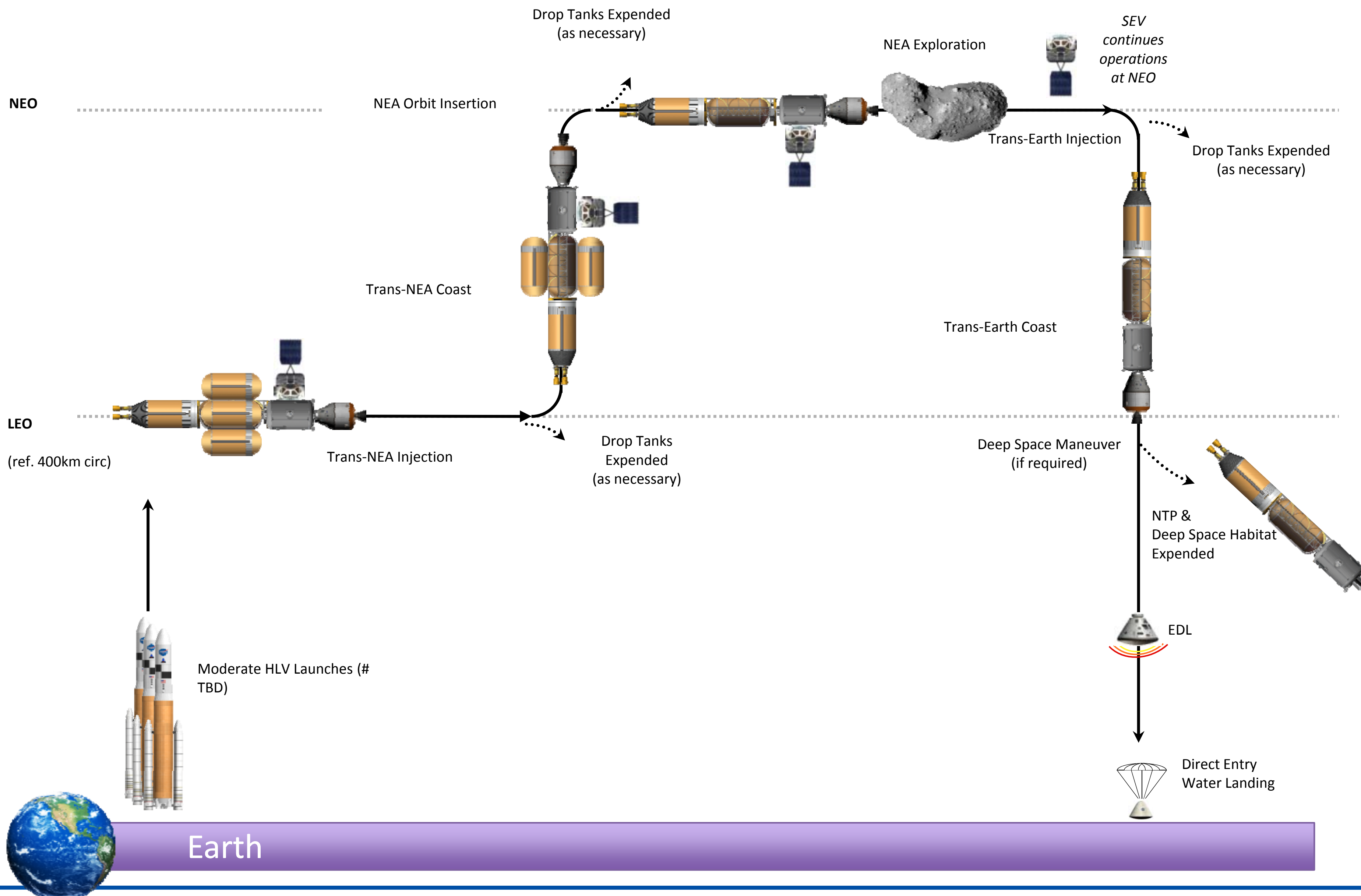
Space Launch System

- Consistent with HEFT
- No specific design assumed
- Gross Performance ~ 100 t
- Net Performance ~ 87.75 t (HEFT-2 assumption for knock downs for flight performance reserves and adapters)

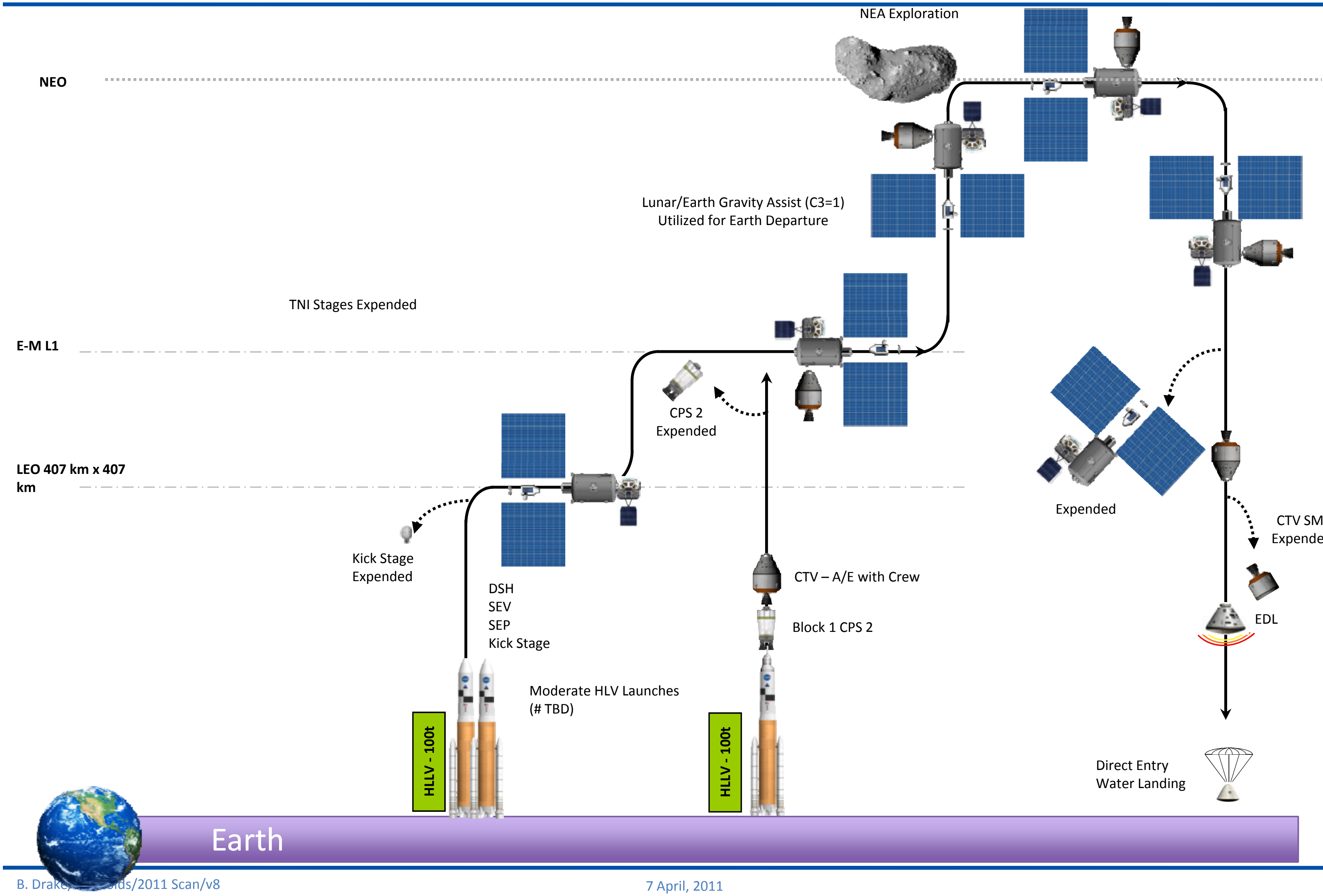
All Chemical NEA Mission Profile



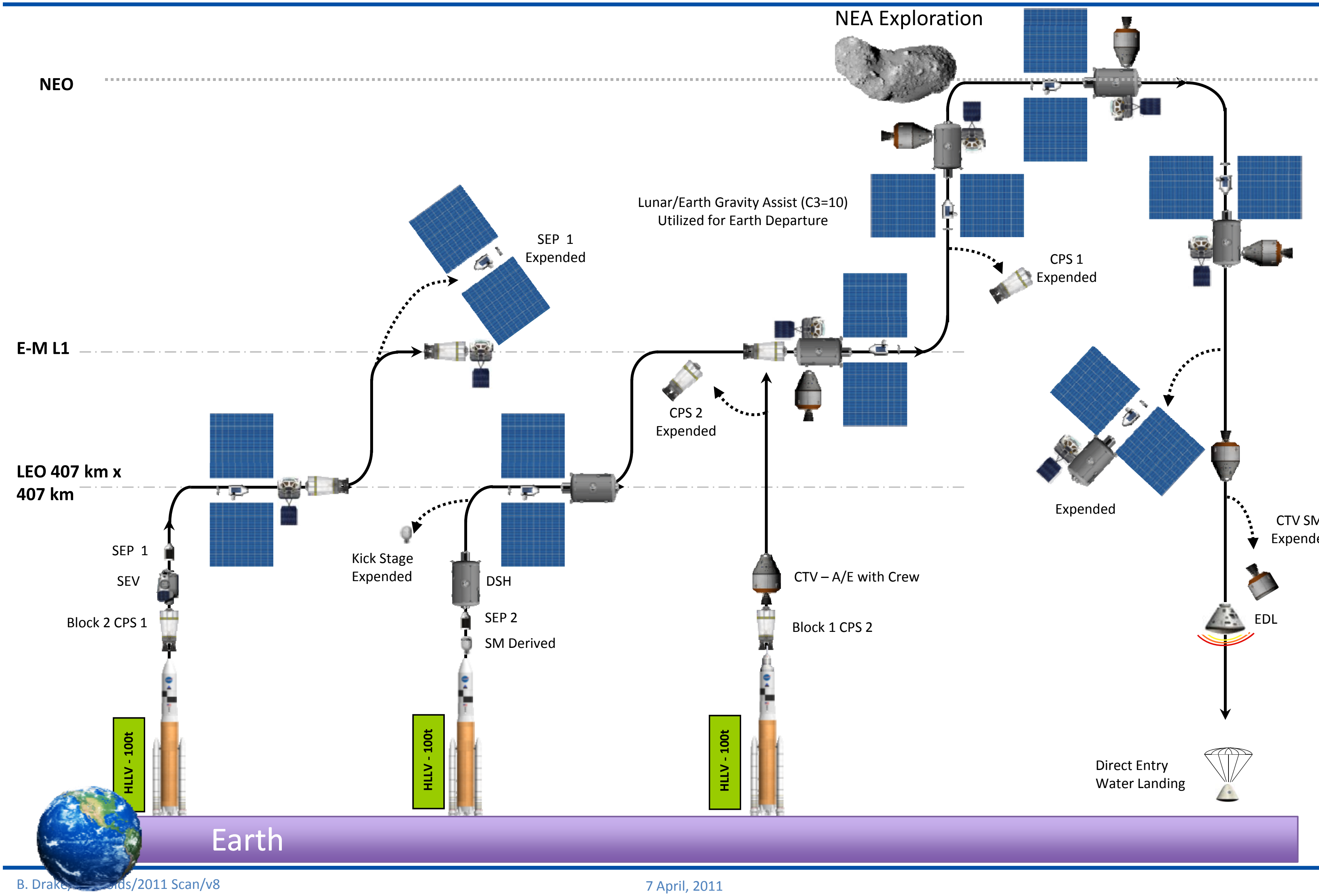
All Nuclear Thermal Propulsion NEA Mission Profile



SEP Only for Deep Space Mission Profile



SEP/Chemical Hybrid NEA Mission Profile

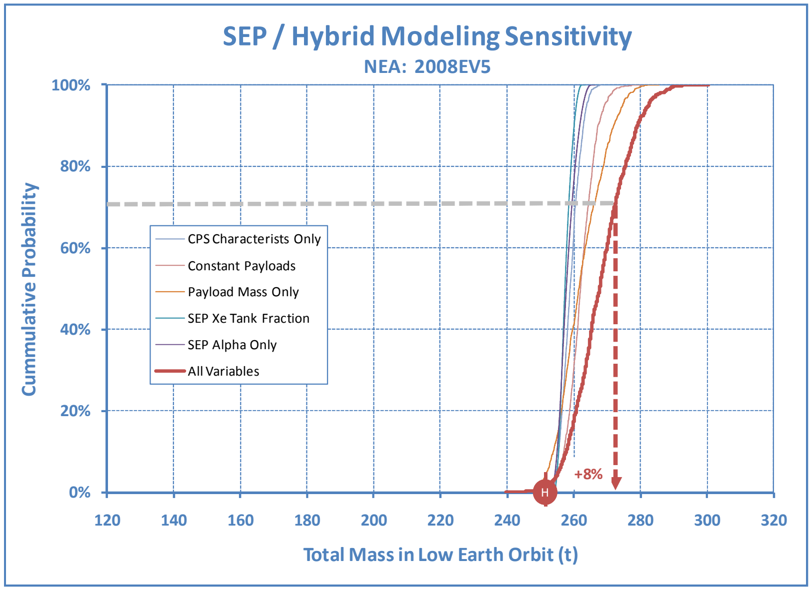


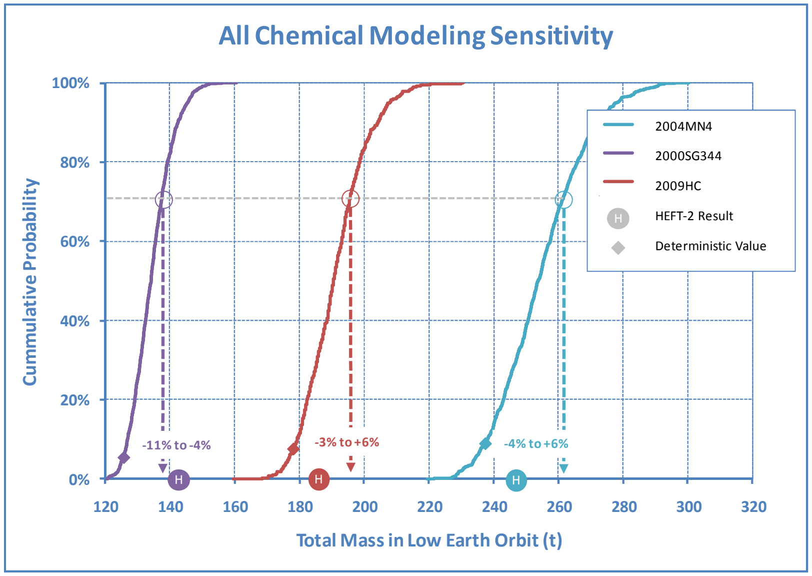
Disclaimers and other Cautions

- **Due to time limitations and the sheer magnitude of number of simulations to be run, parametric mass sizing was utilized**
- **Although the parametric results have been validated with results from more detailed assessments, the results contained herein should be used for comparative assessments only**
  - That is, understanding the relative trends of one approach versus another are appropriate.
  - Caution should be observed when making definitive statements, such as the absolute number of available targets.
  - Additional detailed assessments are required in order to make definitive statements. These assessments should focus on the more promising targets and include **mission design, system design, and operational design such as launch packaging and volume**.

Parametric Results Comparison to Detailed Designs

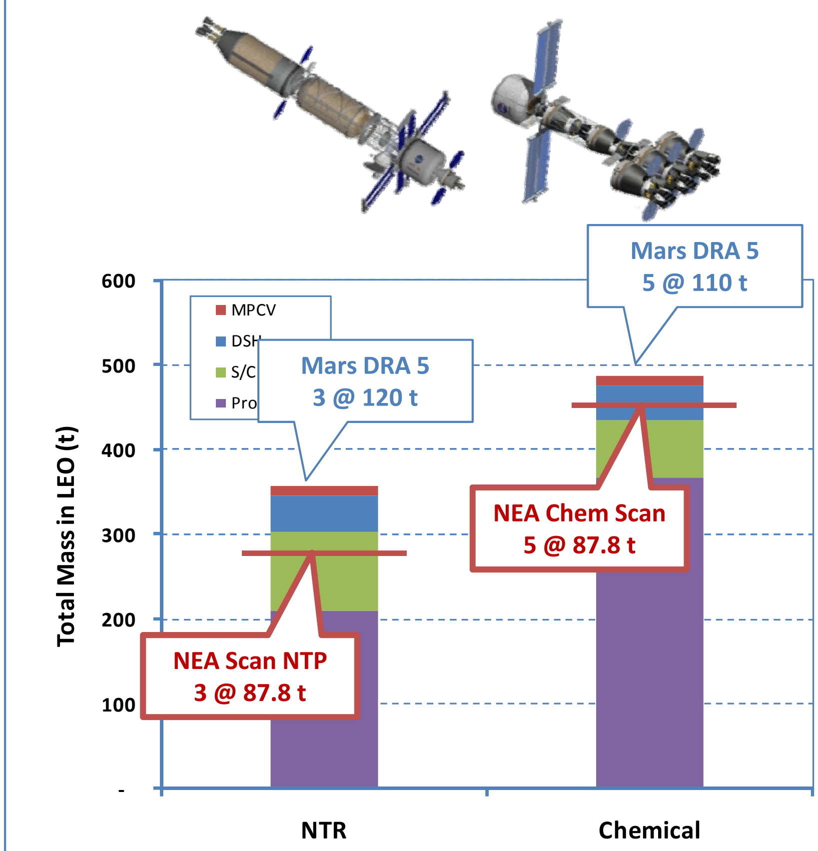
- **HEFT-2 detailed design assessments compared to parametric modeling approach**
- **Monte Carlo simulation conducted to assess sensitivity of parametric models to key model variables including:**
  - SEP spacecraft efficiency (alpha)
  - Xe tank fraction
  - DSH Mass
  - SEV Mass
  - CPS stage fraction and inert mass
- **Monte Carlo simulation results indicate parametric mass model compares favorably**
  - Deterministic expected mass within 10% of HEFT-2 results
  - 70th percentile simulation result within 8% of HEFT-2 results
  - Deterministic mass used for this analysis





Setting the Mission Architecture Mass Bounds

- All NEA missions require a minimum of 2 heavy lift launches (SLS-class)
- Human NEA missions can represent a "dry run" of the inter-planetary crew transfer portion of a human Mars mission
- For this assessment, NEA mission mass constraints limited to those to just shy of the crew portion of Mars DRA 5.0*
  - NTP 3 Launches
  - Chemical 5 Launches
  - SEP 4 Launches

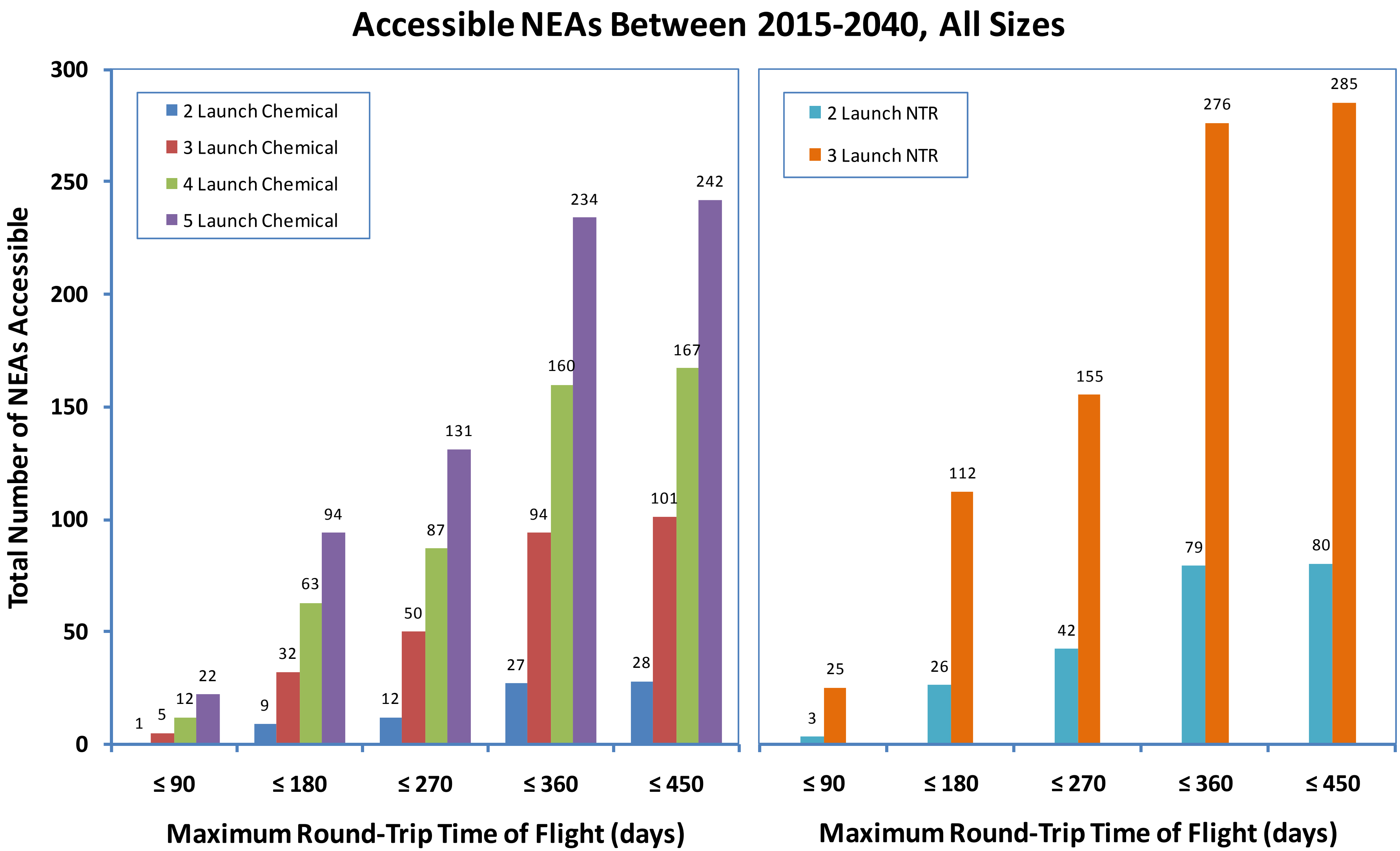


* Note: If short stay (opposition class orbital missions are desired for Mars orbital or surface missions, the total number of required launches will increase significantly.

NEA Accessibility Sensitivity Results

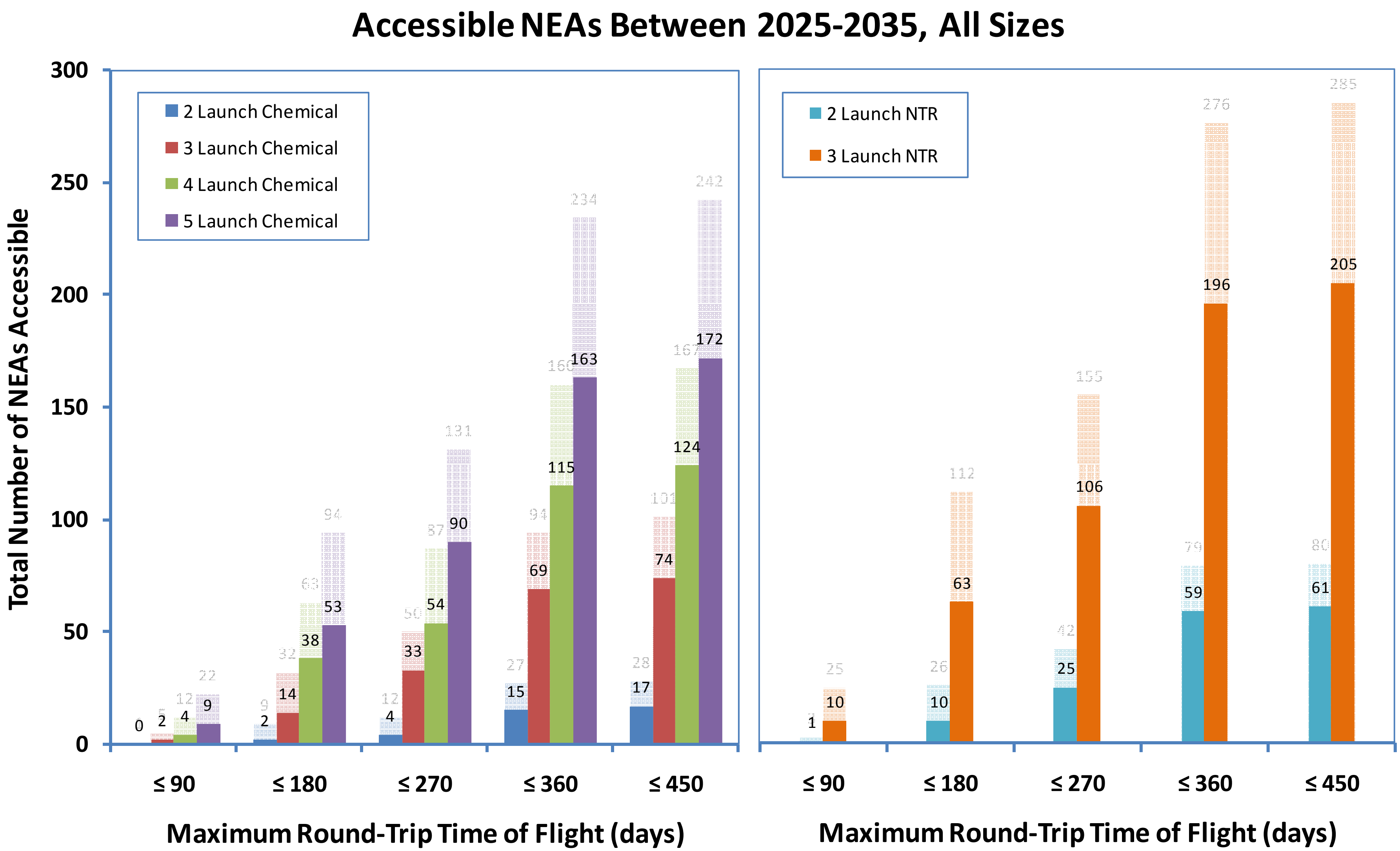
High Thrust Ballistic Trajectories

All Dates, All Sizes

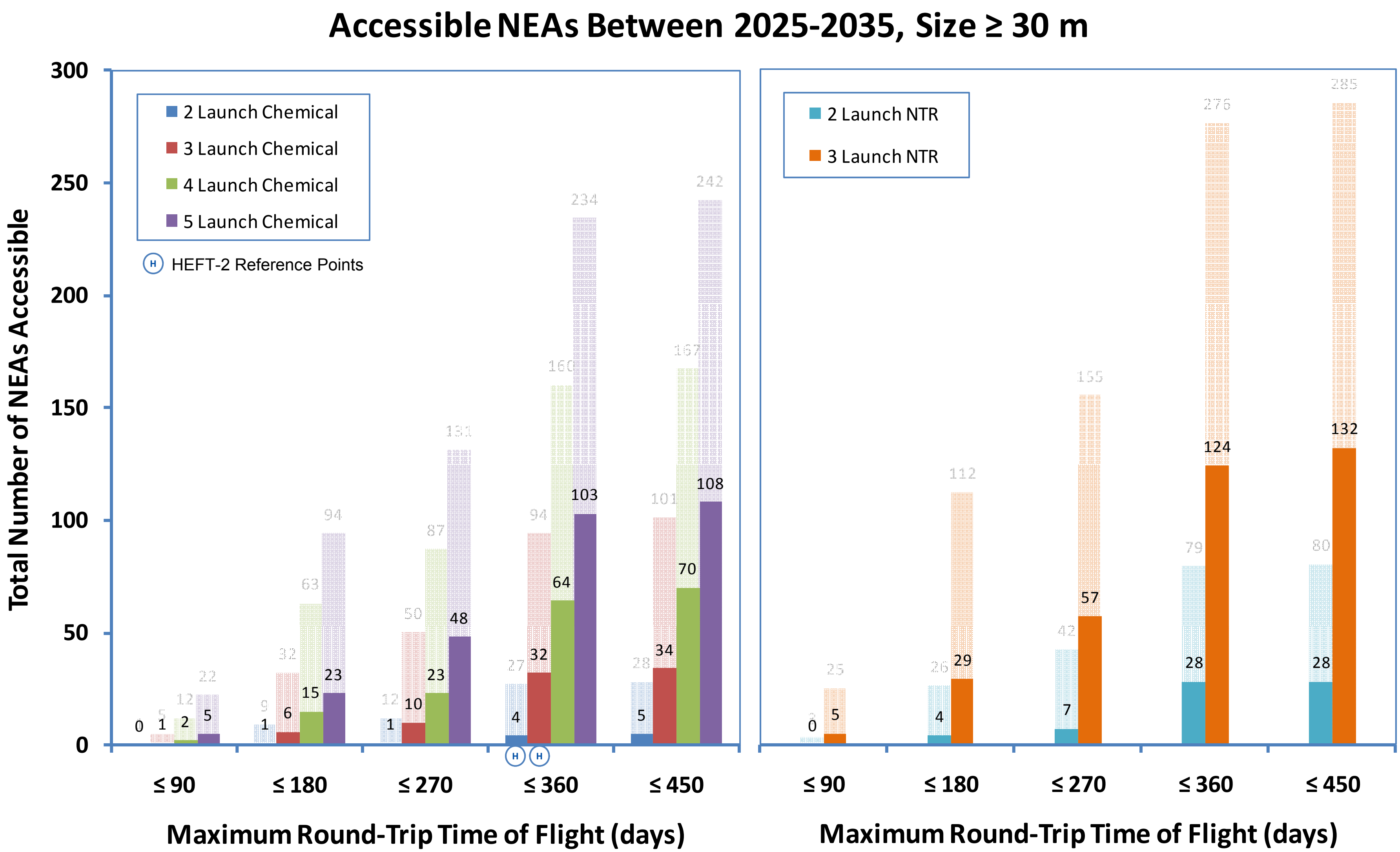


High Thrust Ballistic Trajectories

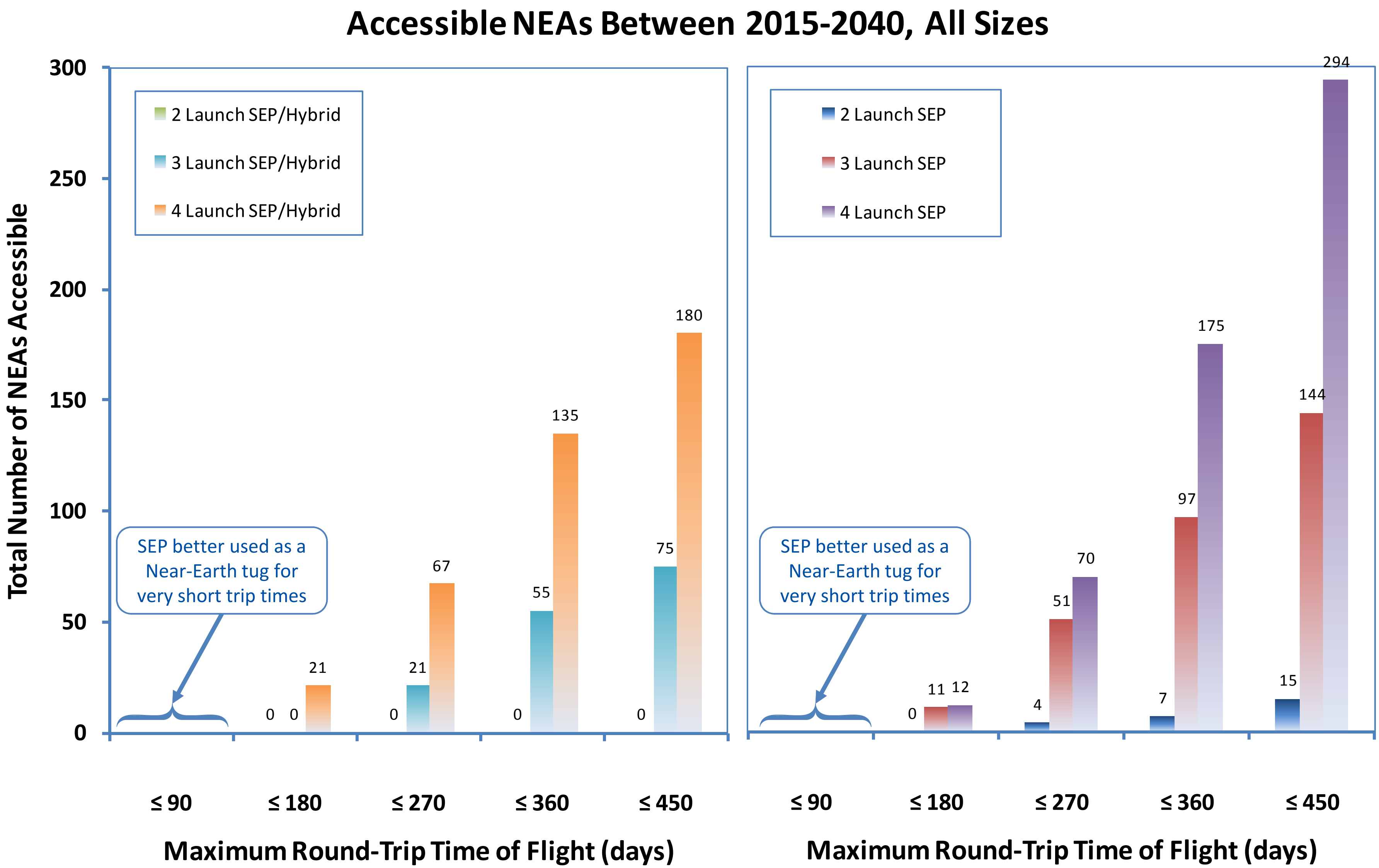
Selected Period of Interest Between 2025 and 2035, All Sizes



High Thrust Ballistic Trajectories
Dates Between 2025-2035 and Size Greater than 30 m

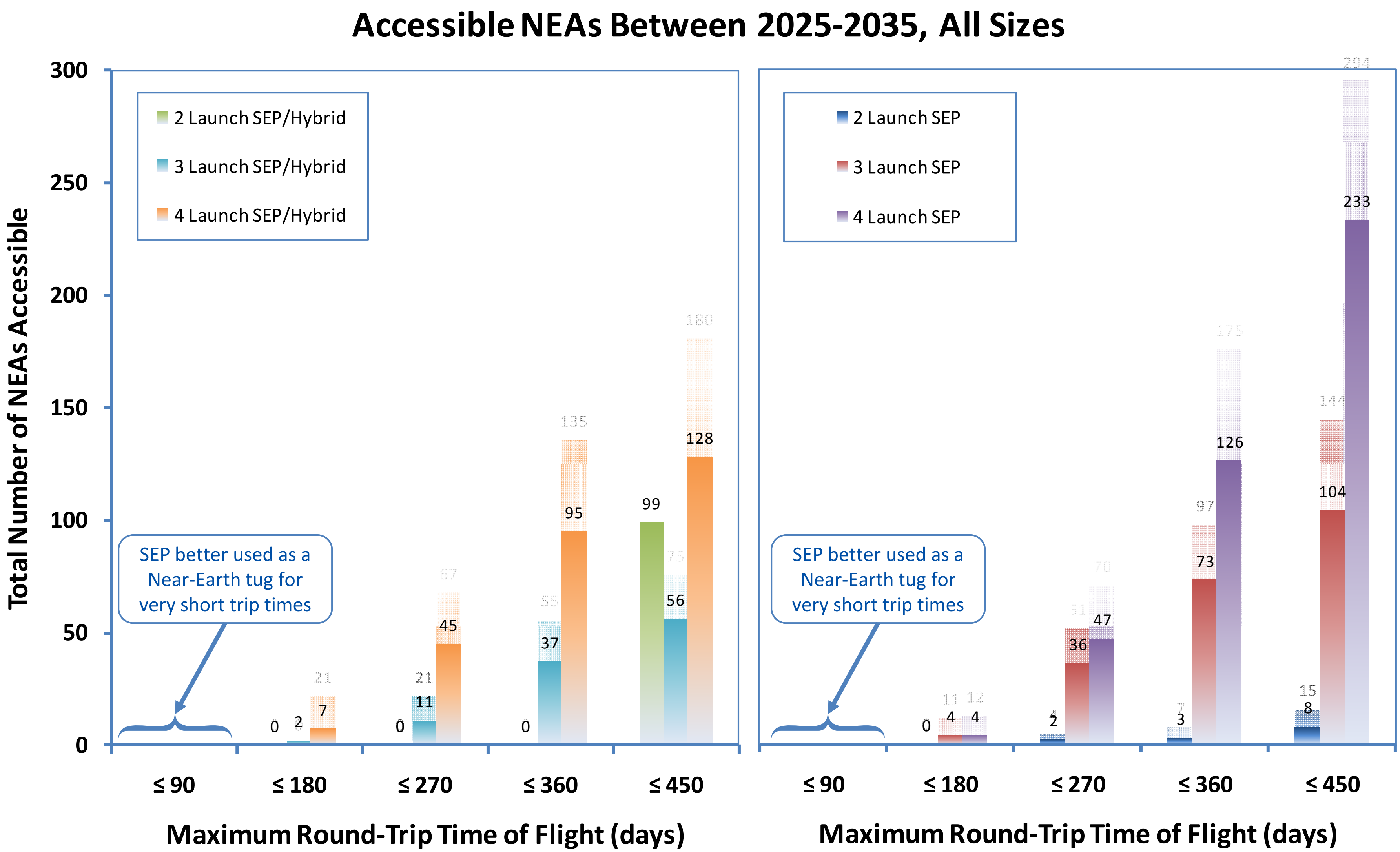


Low Thrust Trajectories
All Dates, All Sizes



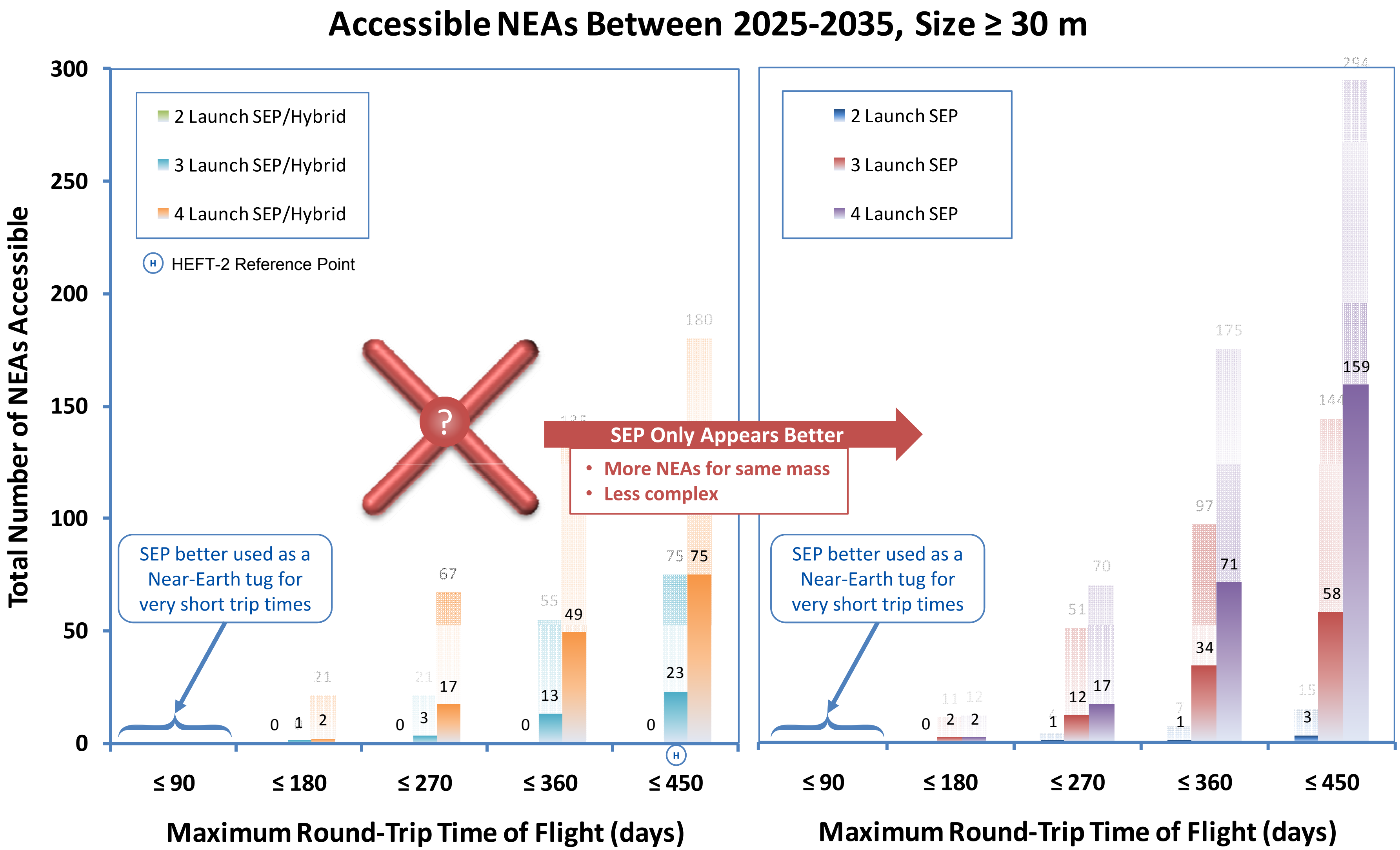
Low Thrust Trajectories

Selected Period of Interest Between 2025 and 2035, All Sizes



Low Thrust Trajectories

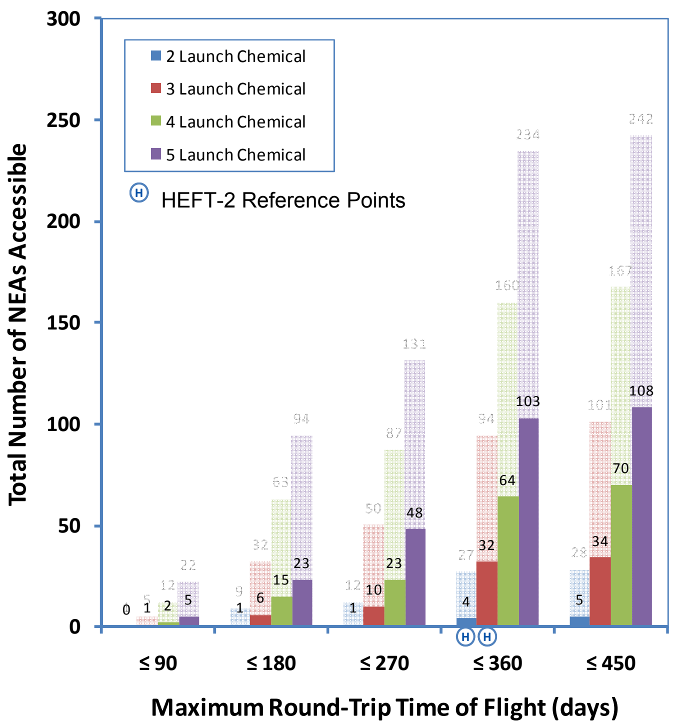
Dates Between 2025-2035 and Size Greater than 30 m



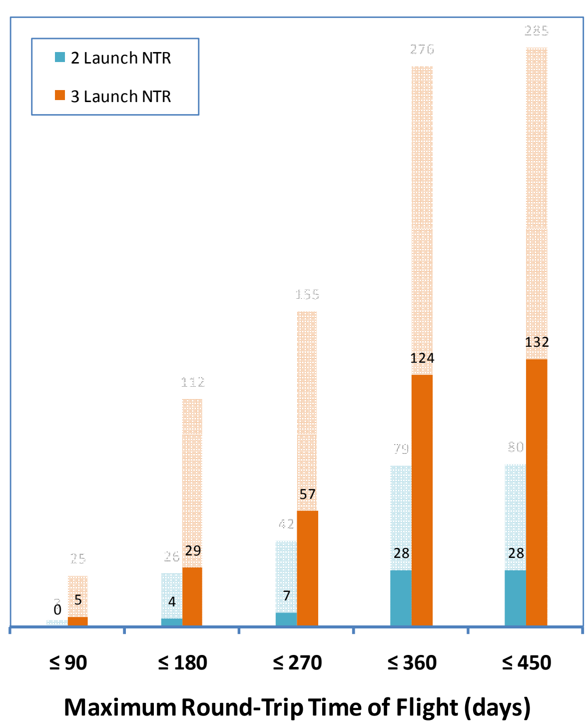
Summary Comparison of Propulsion Choice

Dates Between 2025-2035 and Size Greater than 30 m

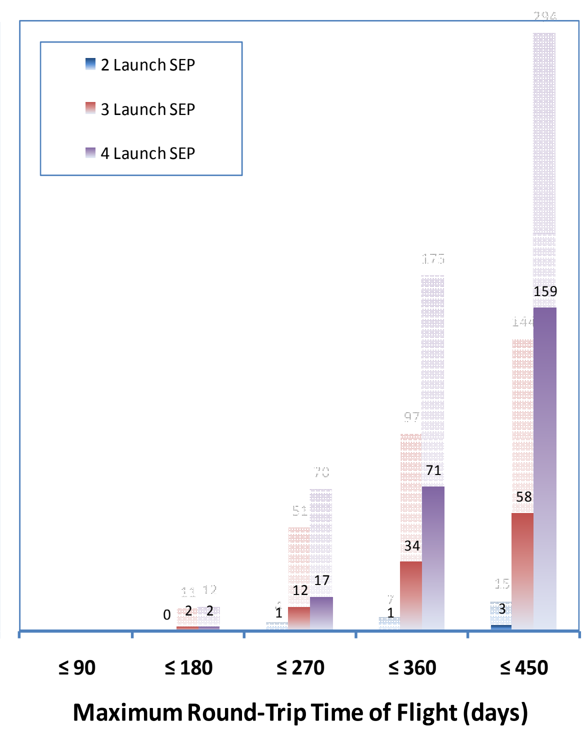
All Chemical Propulsion



All Nuclear Thermal Propulsion



All Solar Electric Propulsion



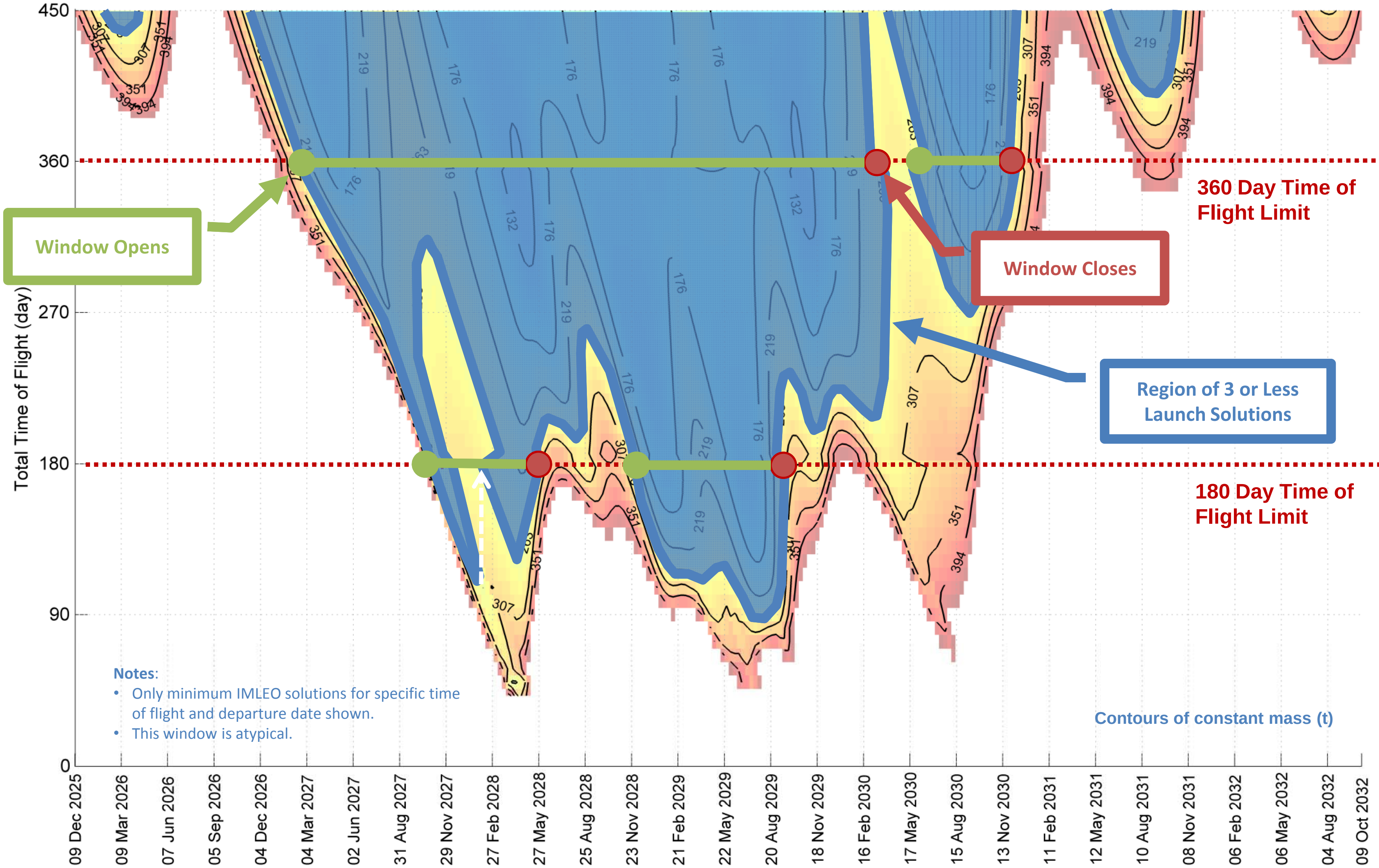
INJECTION WINDOW AND OPPORTUNITY CHARACTERISTICS

NEA Injection Window Assessments

- **Departure window characteristics determined for the high-thrust architectures**
  - All Chemical
  - All Nuclear Thermal Propulsion
- **Departure window characteristics for low-thrust trajectories require much more exhaustive assessments and were beyond the scope of this study**
- **Each of the 79M+ trajectories translated into estimated total mission mass for both the all chemical and all NTP architectures**
- **Data mined to extract when windows "open" and "close" for each accessible NEA**
- **An accessible NEA is one which satisfies selected criteria including total number of launches (total mass), round-trip time of flight, epoch (departure date), size, etc.**
- **For each accessible NEA, window characteristics determined including:**
  - Total number of windows within the specified criteria
  - Total number of days in all windows
  - Total number of trajectories in all windows

Anatomy of a NEA Injection Window

Example 3 Launch Solutions to NEA 2000SG344



Notes:
- Only minimum IMLEO solutions for specific time of flight and departure date shown.
- This window is atypical.

High Thrust Ballistic Trajectories

Dates Between 2025-2035 and Size Greater than 30 m

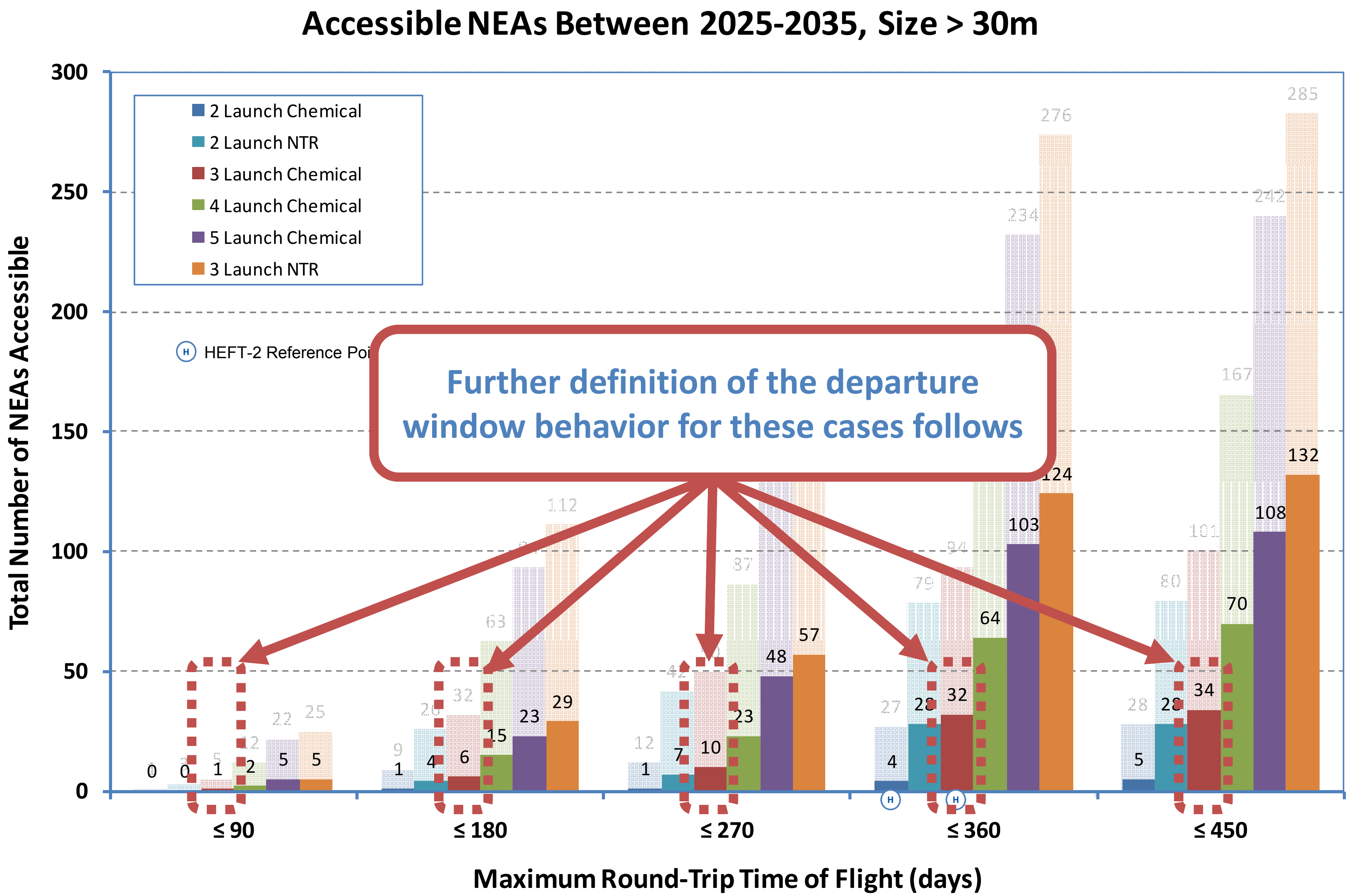


Table Nomenclature

Column	Descriptor
Case	Denotes the type of architecture case (chemical or NTR) and Earth entry speed limit
Time of Flight	Maximum total mission time of flight (days)
Number of Launches	Maximum number of launches (in increments of 87.75 t)
Number of Windows	Total number of injection windows within the specified criteria
Total Window Days	Total number of days in all windows within the specified criteria
Total Trajectories in Windows	Total number of trajectories in all windows. Provides an estimate of the how robust the target is in terms of available trajectories.
Hmag	Absolute visual magnitude (estimate of the NEAs intrinsic brightness)
Size Range	NEA size via measurement or estimated based on Hmag (m)
Rotation Period	Estimated rotation period (hours)
OCC	Orbit Condition Code which is a measure of how much anticipated uncertainty there is in the asteroid's orbit (longitudinal runoff) after 10 years (without more data)
Last Observed	Date of last observance
Next Observation	Anticipated date of next Earth-based observation based on visual magnitude limits of 24. Early observations could be achieved if larger/better assets are used.
Next Mission Opportunity	Opening window date for the next opportunity within the specified criteria

All Chemical

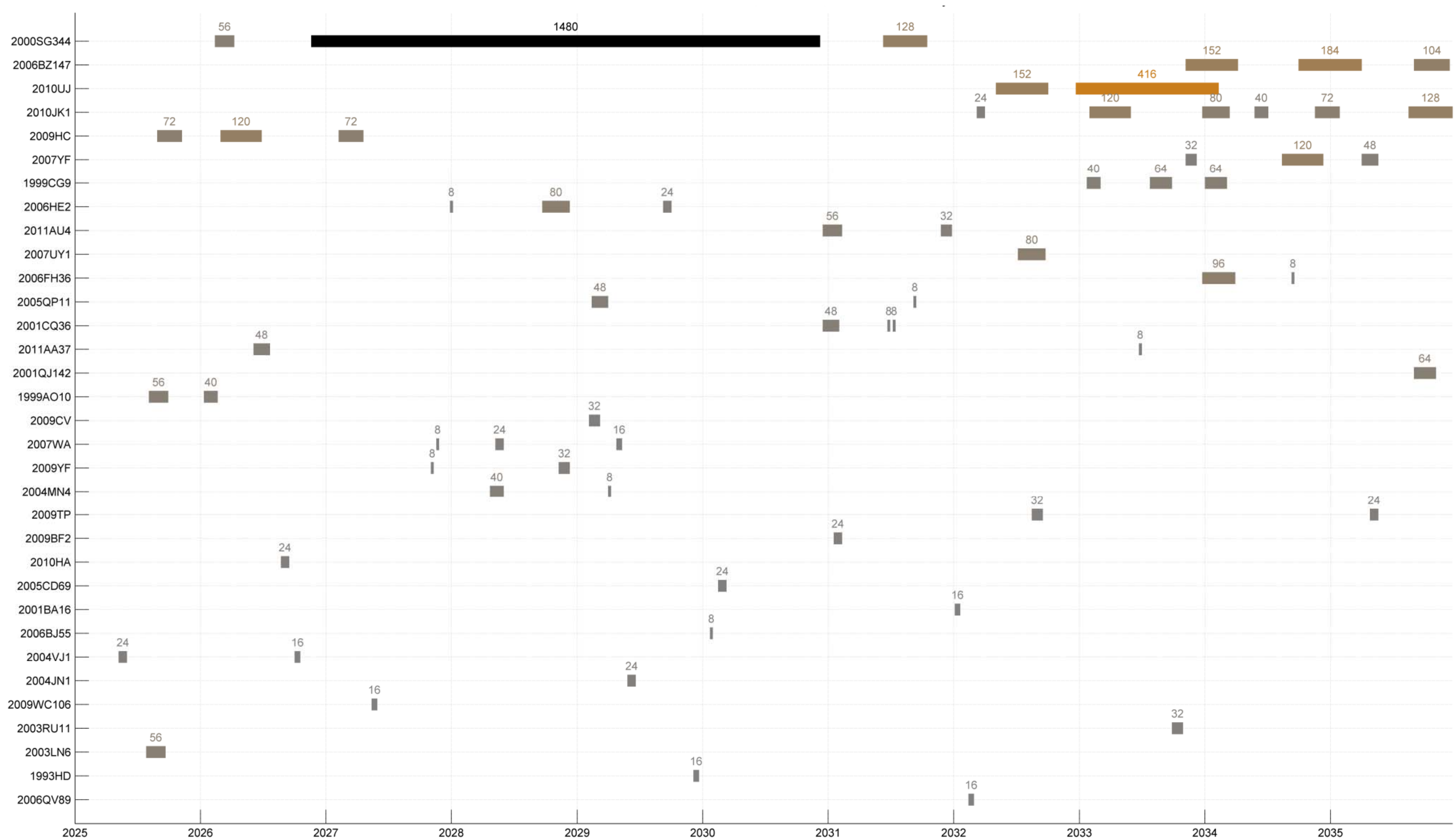
2025-2035, Size ≥ 30 m, Launches ≤ 3, Time ≤ 450 days

Case	Time of Flight < (days)	Number of Launches <	Asteroid Name	Number of Windows	Total Window Days	Total Trajectories in Windows	Hmag	Size Range (m)	Rotation Period (Hr)	OCC	Last Observed	Next Observation	Next Mission Opportunity
Chem-12.0	450	3	2000SG344	3	1664	1,158,676	24.79	21 - 66	-	3*	10/2000	5/2028	3/2026
Chem-12.0	450	3	2006BZ147	3	440	68,513	25.44	15 - 49	-	3	9/2007	1/2035	1/2034
Chem-12.0	450	3	2010UJ	2	568	47,500	26.19	11 - 34	-	9	10/2010	9/2021	7/2032
Chem-12.0	450	3	2010JK1	6	464	21,216	24.42	25 - 78	-	5	3/2011	5/2011	3/2032
Chem-12.0	450	3	2009HC	3	264	19,759	24.77	21 - 66	-	4	6/2009	8/2025	10/2025
Chem-12.0	450	3	2007YF	3	200	5,550	24.77	21 - 66	-	5	1/2008	1/2022	11/2033
Chem-12.0	450	3	1999CG9	3	168	4,150	25.24	17 - 53	-	6	3/1999	4/2011	2/2033
Chem-12.0	450	3	2006HE2	3	112	2,498	26.51	9 - 30	-	5	4/2006	4/2017	1/2028
Chem-12.0	450	3	2011AU4	2	88	1,650	25.85	13 - 40	-	6	1/2011	6/2031	1/2031
Chem-12.0	450	3	2007UY1	1	80	1,254	22.88	50 - 158	-	2	1/2009	10/2019	8/2032
Chem-12.0	450	3	2006FH36	2	104	1,111	22.92	49 - 155	-	3	6/2007	4/2019	2/2034
Chem-12.0	450	3	2005QP11	2	56	1,086	26.43	10 - 31	-	3	9/2005	5/2029	3/2029
Chem-12.0	450	3	2001CQ36	3	64	1,018	22.70	54 - 171	-	1	3/2011	3/2011	1/2031
Chem-12.0	450	3	2011AA37	2	56	569	22.78	52 - 165	-	5	3/2011	3/2011	6/2026
Chem-12.0	450	3	2001QJ142	1	64	504	23.42	39 - 123	-	6	9/2001	1/2012	10/2035
Chem-12.0	450	3	1999AO10	2	96	420	23.86	32 - 101	-	6	2/1999	12/2018	9/2025
Chem-12.0	450	3	2009CV	1	32	409	24.26	26 - 84	-	3	9/2009	11/2015	2/2029
Chem-12.0	450	3	2007WA	3	48	369	24.71	22 - 68	-	6	11/2007	9/2027	11/2027
Chem-12.0	450	3	2009YF	2	40	342	24.69	22 - 69	-	7	1/2010	1/2020	11/2027
Chem-12.0	450	3	2004MN4	2	48	323	19.70	270 - 270	30.40	0	1/2008	1/2012	5/2028
Chem-12.0	450	3	2009TP	2	56	284	23.54	37 - 117	-	6	10/2009	5/2011	8/2032
Chem-12.0	450	3	2009BF2	1	24	232	25.90	12 - 39	0.02	6	2/2009	7/2019	1/2031
Chem-12.0	450	3	2010HA	1	24	172	23.99	30 - 95	-	4	5/2010	5/2011	9/2026
Chem-12.0	450	3	2005CD69	1	24	136	24.11	28 - 89	-	7	2/2005	8/2014	2/2030
Chem-12.0	450	3	2001BA16	1	16	100	25.83	13 - 41	-	5	2/2001	2/2022	1/2032
Chem-12.0	450	3	2006BJ55	1	8	85	24.21	27 - 85	-	6	2/2006	1/2030	1/2030
Chem-12.0	450	3	2004VJ1	2	40	72	24.28	26 - 83	-	6	12/2004	9/2015	5/2025
Chem-12.0	450	3	2004JN1	1	24	64	23.46	38 - 121	-	6	6/2004	10/2011	6/2029
Chem-12.0	450	3	2009WC106	1	16	63	25.47	15 - 48	-	8	11/2009	4/2028	5/2027
Chem-12.0	450	3	2003RU11	1	32	57	25.60	14 - 45	-	3	9/2003	8/2034	10/2033
Chem-12.0	450	3	2003LN6	1	56	8	24.46	24 - 76	-	5	6/2003	5/2022	8/2025
Chem-12.0	450	3	1993HD	1	16	4	25.63	14 - 44	-	9	4/1993	10/2011	12/2029
Chem-12.0	450	3	2006QV89	1	16	3	25.26	17 - 53	-	6	9/2006	7/2019	2/2032

* Update pending

All Chemical Injection Windows

2025-2035, Size ≥ 30 m, Launches ≤ 3, Time ≤ 450 days



All Chemical

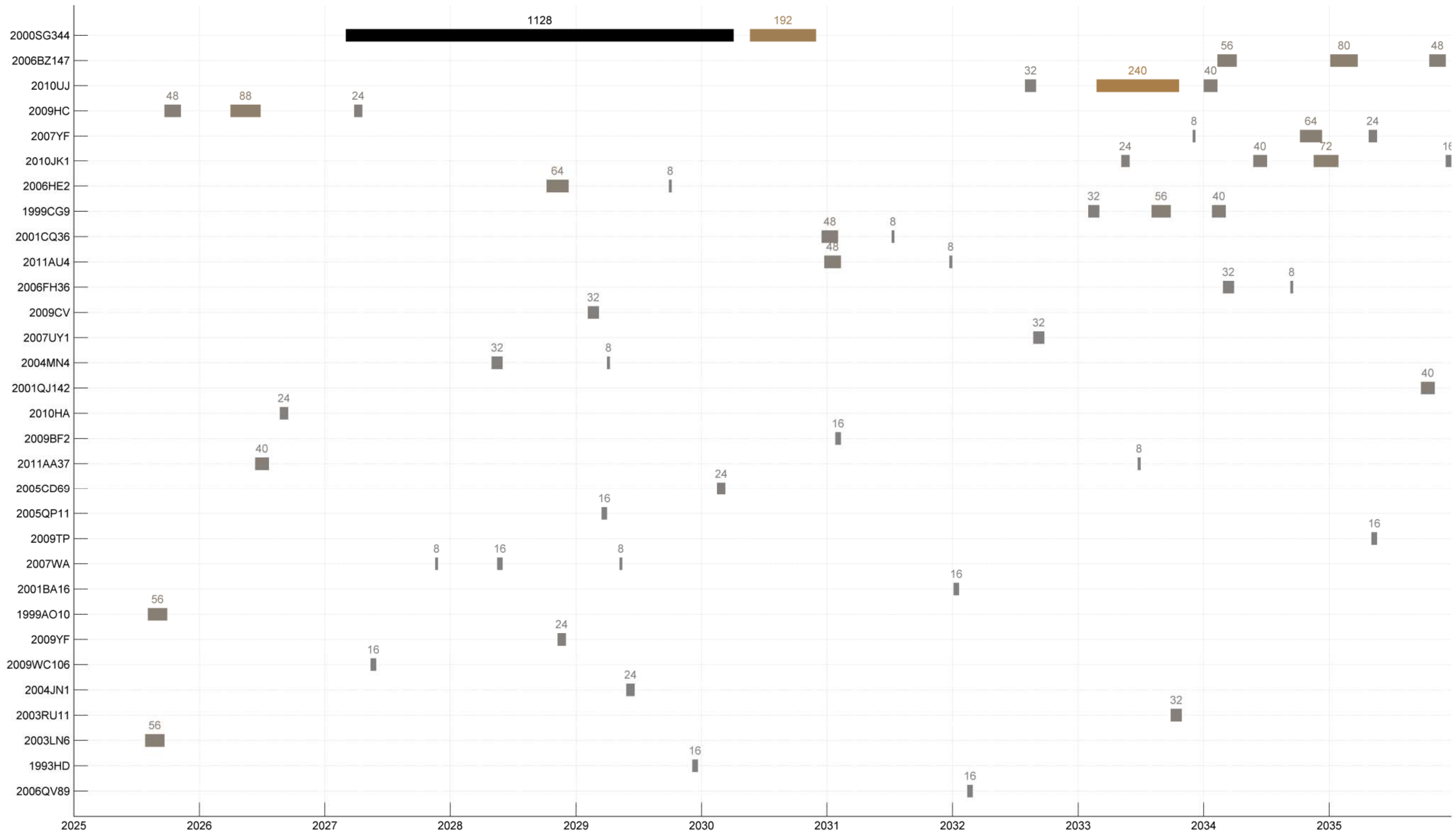
2025-2035, Size ≥ 30 m, Launches ≤ 3, Time ≤ 360 days

Case	Time of Flight < (days)	Number of Launches <	Asteroid Name	Number of Windows	Total Window Days	Total Trajectories in Windows	Hmag	Size Range (m)	Rotation Period (Hr)	OCC	Last Observed	Next Observation	Next Mission Opportunity
Chem-12.0	360	3	2000SG344	2	1320	398,277	24.79	21 - 66	-	3*	10/2000	5/2028	9/2028
Chem-12.0	360	3	2006BZ147	3	184	14,595	25.44	15 - 49	-	3	9/2007	1/2035	3/2034
Chem-12.0	360	3	2010UJ	3	312	13,201	26.19	11 - 34	-	9	10/2010	9/2021	8/2032
Chem-12.0	360	3	2009HC	3	160	7,671	24.77	21 - 66	-	4	6/2009	8/2025	10/2025
Chem-12.0	360	3	2007YF	3	96	3,110	24.77	21 - 66	-	5	1/2008	1/2022	12/2033
Chem-12.0	360	3	2010JK1	4	152	1,884	24.42	25 - 78	-	5	3/2011	5/2011	5/2033
Chem-12.0	360	3	2006HE2	2	72	1,849	26.51	9 - 30	-	5	4/2006	4/2017	11/2028
Chem-12.0	360	3	1999CG9	3	128	1,154	25.24	17 - 53	-	6	3/1999	4/2011	2/2033
Chem-12.0	360	3	2001CQ36	2	56	946	22.70	54 - 171	-	1	3/2011	3/2011	1/2031
Chem-12.0	360	3	2011AU4	2	56	862	25.85	13 - 40	-	6	1/2011	6/2031	1/2031
Chem-12.0	360	3	2006FH36	2	40	803	22.92	49 - 155	-	3	6/2007	4/2019	3/2034
Chem-12.0	360	3	2009CV	1	32	409	24.26	26 - 84	-	3	9/2009	11/2015	2/2029
Chem-12.0	360	3	2007UY1	1	32	358	22.88	50 - 158	-	2	1/2009	10/2019	9/2032
Chem-12.0	360	3	2004MN4	2	40	315	19.70	270 - 270	30.40	0	1/2008	1/2012	5/2028
Chem-12.0	360	3	2001QJ142	1	40	279	23.42	39 - 123	-	6	9/2001	1/2012	10/2035
Chem-12.0	360	3	2010HA	1	24	172	23.99	30 - 95	-	4	5/2010	5/2011	9/2026
Chem-12.0	360	3	2009BF2	1	16	161	25.90	12 - 39	0.02	6	2/2009	7/2019	2/2031
Chem-12.0	360	3	2011AA37	2	48	151	22.78	52 - 165	-	5	3/2011	3/2011	7/2026
Chem-12.0	360	3	2005CD69	1	24	131	24.11	28 - 89	-	7	2/2005	8/2014	2/2030
Chem-12.0	360	3	2005QP11	1	16	114	26.43	10 - 31	-	3	9/2005	5/2029	3/2029
Chem-12.0	360	3	2007WA	3	32	101	24.71	22 - 68	-	6	11/2007	9/2027	11/2027
Chem-12.0	360	3	2009TP	1	16	101	23.54	37 - 117	-	6	10/2009	5/2011	5/2035
Chem-12.0	360	3	2001BA16	1	16	93	25.83	13 - 41	-	5	2/2001	2/2022	1/2032
Chem-12.0	360	3	1999AO10	1	56	74	23.86	32 - 101	-	6	2/1999	12/2018	9/2025
Chem-12.0	360	3	2009YF	1	24	72	24.69	22 - 69	-	7	1/2010	1/2020	11/2028
Chem-12.0	360	3	2009WC106	1	16	63	25.47	15 - 48	-	8	11/2009	4/2028	5/2027
Chem-12.0	360	3	2004JN1	1	24	59	23.46	38 - 121	-	6	6/2004	10/2011	6/2029
Chem-12.0	360	3	2003RU11	1	32	57	25.60	14 - 45	-	3	9/2003	8/2034	10/2033
Chem-12.0	360	3	2003LN6	1	56	8	24.46	24 - 76	-	5	6/2003	5/2022	8/2025
Chem-12.0	360	3	1993HD	1	16	4	25.63	14 - 44	-	9	4/1993	10/2011	12/2029
Chem-12.0	360	3	2006QV89	1	16	3	25.26	17 - 53	-	6	9/2006	7/2019	2/2032

* Update pending

All Chemical Injection Windows

2025-2035, Size ≥ 30 m, Launches ≤ 3, Time ≤ 360 days



All Chemical

2025-2035, Size ≥ 30 m, Launches ≤ 3

TOF ≤ 270 Days (9 NEAs)

Case	Time of Flight < (days)	Number of Launches <	Asteroid Name	Number of Windows	Total Window Days	Total Trajectories in Windows	Hmag	Size Range (m)	Rotation Period (Hr)	OCC	Last Observed	Next Observation	Next Mission Opportunity
Chem-12.0	270	3	2000SG344	1	968	83,922	24.79	21 - 66	-	3*	10/2000	5/2028	11/2028
Chem-12.0	270	3	2010UJ	1	192	3,499	26.19	11 - 34	-	9	10/2010	9/2021	7/2033
Chem-12.0	270	3	2007YF	1	24	367	24.77	21 - 66	-	5	1/2008	1/2022	11/2034
Chem-12.0	270	3	1999CG9	1	40	201	25.24	17 - 53	-	6	3/1999	4/2011	8/2033
Chem-12.0	270	3	2009CV	1	24	182	24.26	26 - 84	-	3	9/2009	11/2015	2/2029
Chem-12.0	270	3	1999AO10	1	56	74	23.86	32 - 101	-	6	2/1999	12/2018	9/2025
Chem-12.0	270	3	2009YF	1	24	72	24.69	22 - 69	-	7	1/2010	1/2020	11/2028
Chem-12.0	270	3	2006BZ147	1	48	41	25.44	15 - 49	-	3	9/2007	1/2035	11/2035
Chem-12.0	270	3	2010JK1	1	8	7	24.42	25 - 78	-	5	3/2011	5/2011	6/2034

* Update pending

TOF ≤ 180 Days (5 NEAs)

Case	Time of Flight < (days)	Number of Launches <	Asteroid Name	Number of Windows	Total Window Days	Total Trajectories in Windows	Hmag	Size Range (m)	Rotation Period (Hr)	OCC	Last Observed	Next Observation	Next Mission Opportunity
Chem-12.0	180	3	2000SG344	2	480	10,366	24.79	21 - 66	-	3*	10/2000	5/2028	2/2028
Chem-12.0	180	3	2010UJ	2	128	711	26.19	11 - 34	-	9	10/2010	9/2021	5/2033
Chem-12.0	180	3	1999CG9	1	40	101	25.24	17 - 53	-	6	3/1999	4/2011	8/2033
Chem-12.0	180	3	1999AO10	1	48	59	23.86	32 - 101	-	6	2/1999	12/2018	9/2025
Chem-12.0	180	3	2006BZ147	1	8	2	25.44	15 - 49	-	3	9/2007	1/2035	12/2035

* Update pending

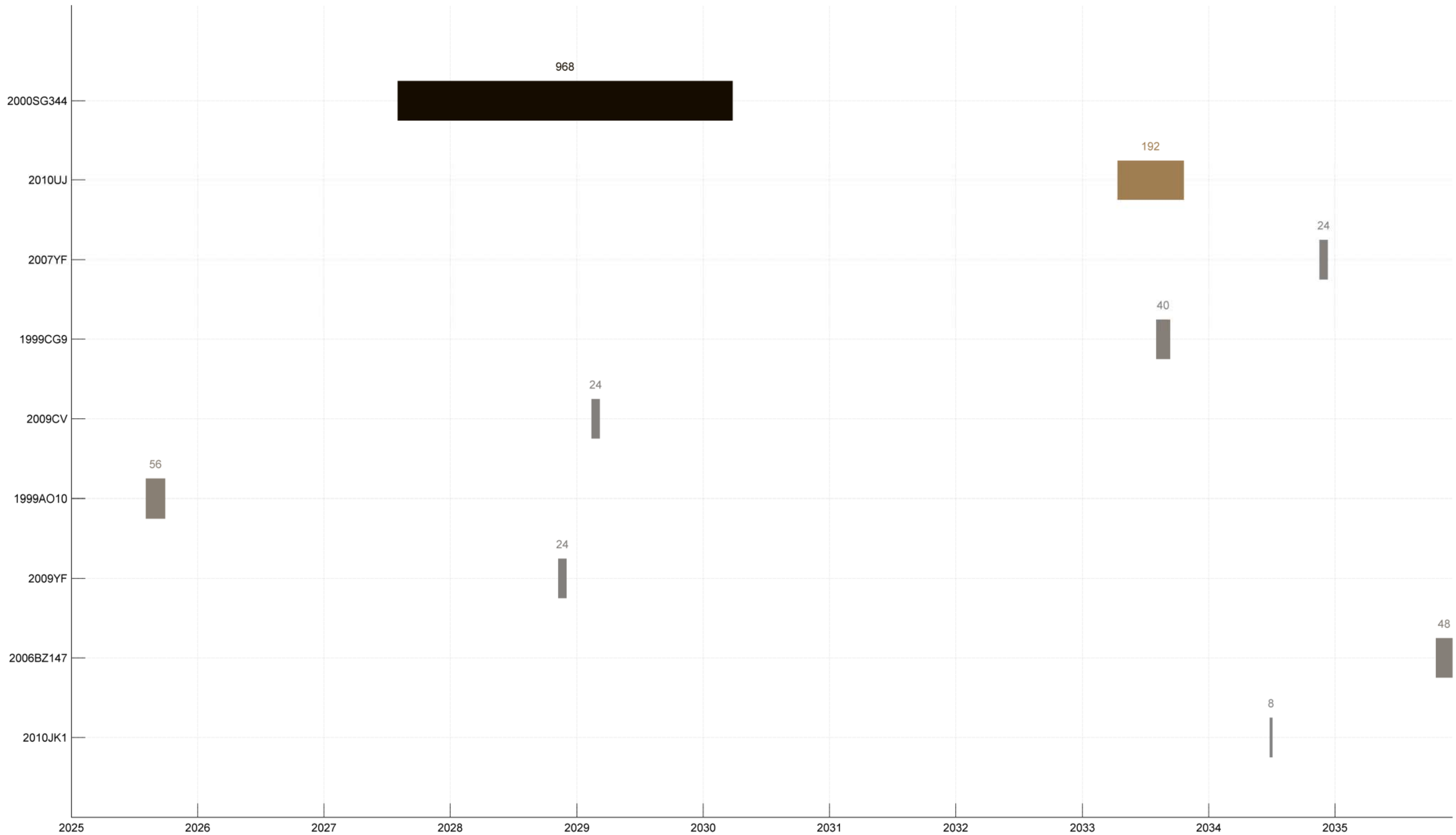
TOF ≤ 90 Days (1 NEAs)

Case	Time of Flight < (days)	Number of Launches <	Asteroid Name	Number of Windows	Total Window Days	Total Trajectories in Windows	Hmag	Size Range (m)	Rotation Period (Hr)	OCC	Last Observed	Next Observation	Next Mission Opportunity
Chem-12.0	90	3	2000SG344	2	32	6	24.79	21 - 66	-	3*	10/2000	5/2028	4/2028

* Update pending

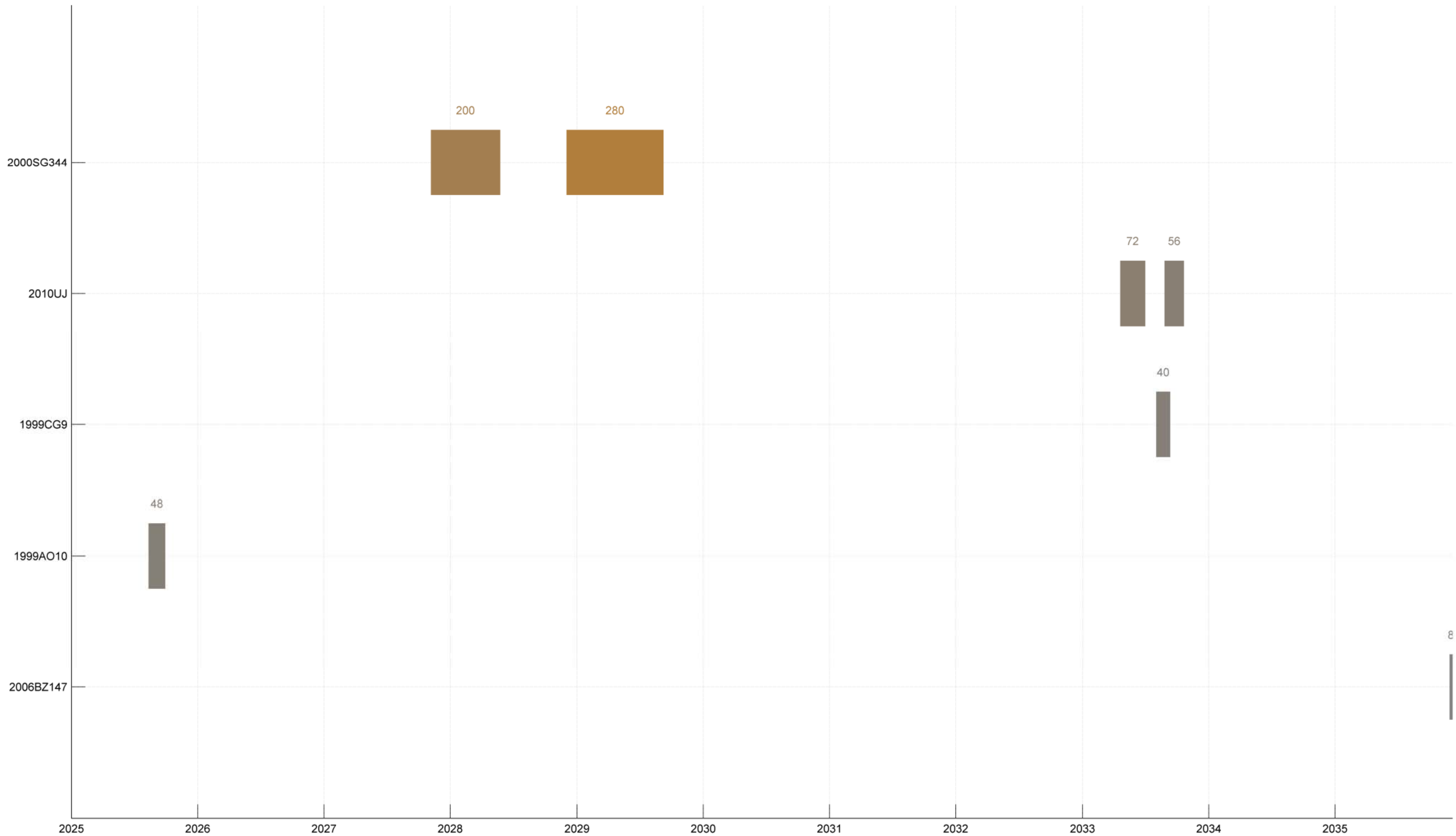
All Chemical Injection Windows

2025-2035, Size ≥ 30 m, Launches ≤ 3, Time ≤ 270 days



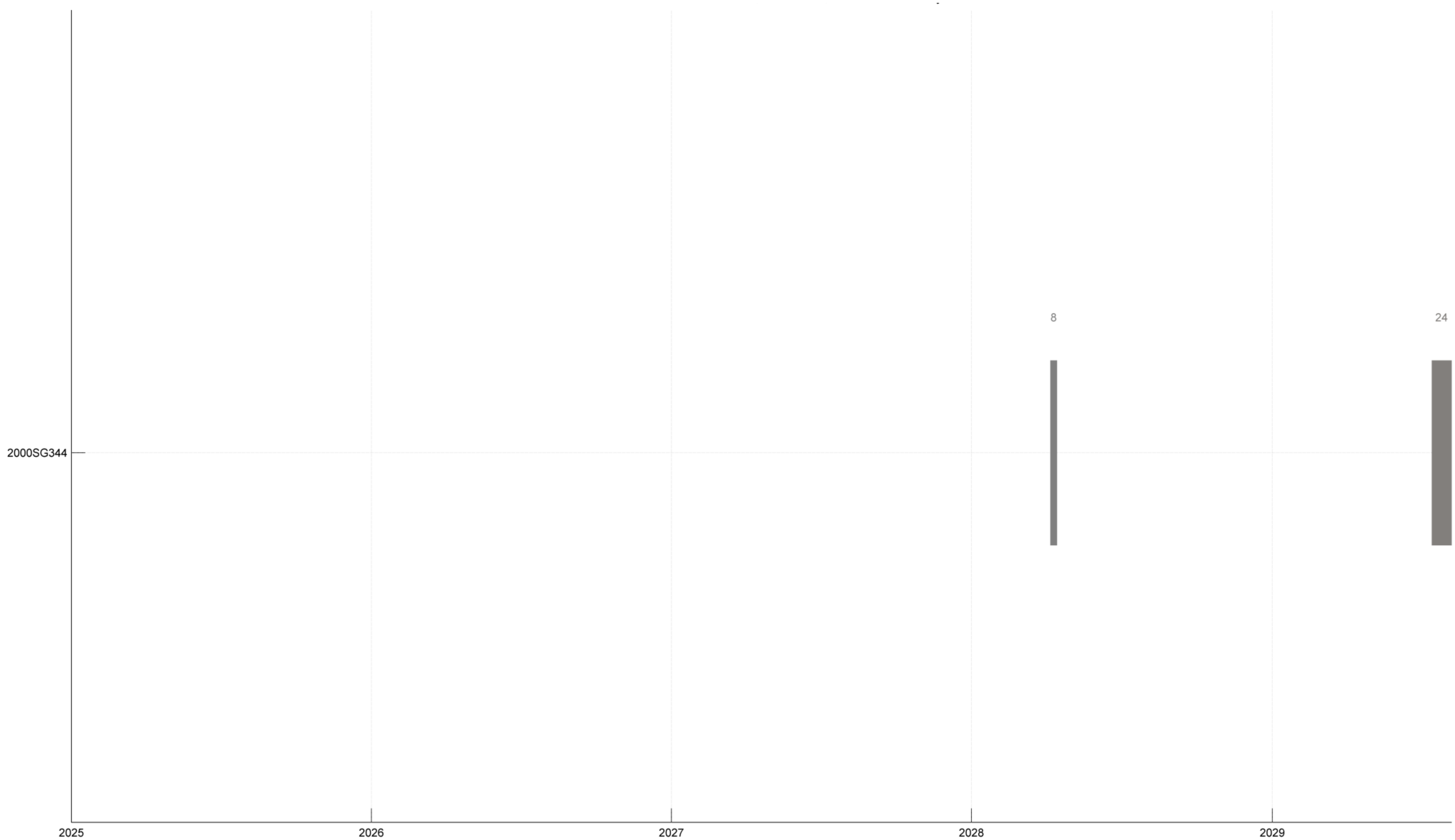
All Chemical Injection Windows

2025-2035, Size ≥ 30 m, Launches ≤ 3, Time ≤ 180 days



All Chemical Injection Windows

2025-2035, Size ≥ 30 m, Launches ≤ 3, Time ≤ 90 days



Comparison of JSC and LaRC Mass Estimation Software

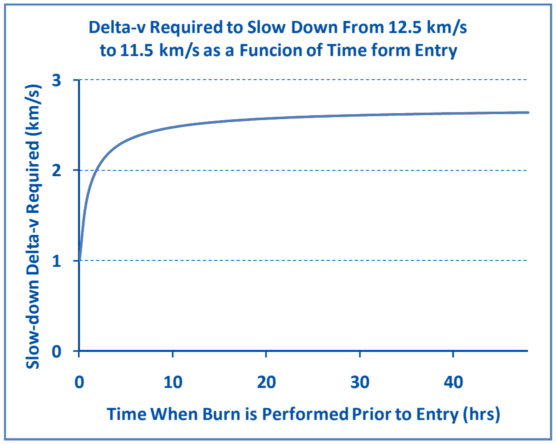
- **A limited comparison of the outputs of the JSC & LaRC mass estimation software tools was performed and is summarized in the table below:**
  - High thrust ballistic trajectories – all chemical architecture
  - Dates between 2025-2035 and size greater than 30 m
  - Elements included in estimate: CPS(s), DSH, MPCV, and SEV

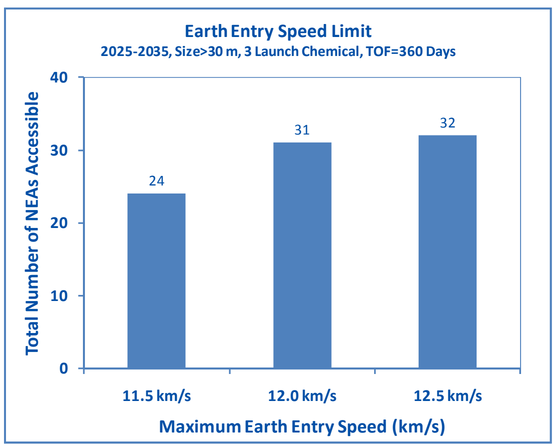
	Number of Potential NEA Targets						
	JSC - 2 Launch	LaRC - 200 t	JSC - 3 Launch	LaRC - 300 t	JSC - 4 Launch	LaRC - 400 t	JSC - 5 Launch
TOF <= 90 Days	0	0	1	0	2	1	5
TOF <= 180 days	1	1	6	4	15	11	23
TOF <= 270 days	1	1	10	9	23	22	48
TOF <= 360 days	4	3	32	28	64	57	103
TOF <= 450 days	5	4	34	32	70	73	108

- **Results of estimation tools compared well and trends were consistent**
  - Differences in the targets results are due to differences in the algorithms, mass assumptions, and methodologies for binning the targets (e.g., 87.75 t net payload per SLS launch vs. 100 t IMLEO increments)
  - LaRC IMLEO tool did not assess targets requiring above 400 t IMLEO
  - All targets with solutions below IMLEO threshold were included in count (a single NHATS trajectory point below the IMLEO threshold may not represent a viable departure window)

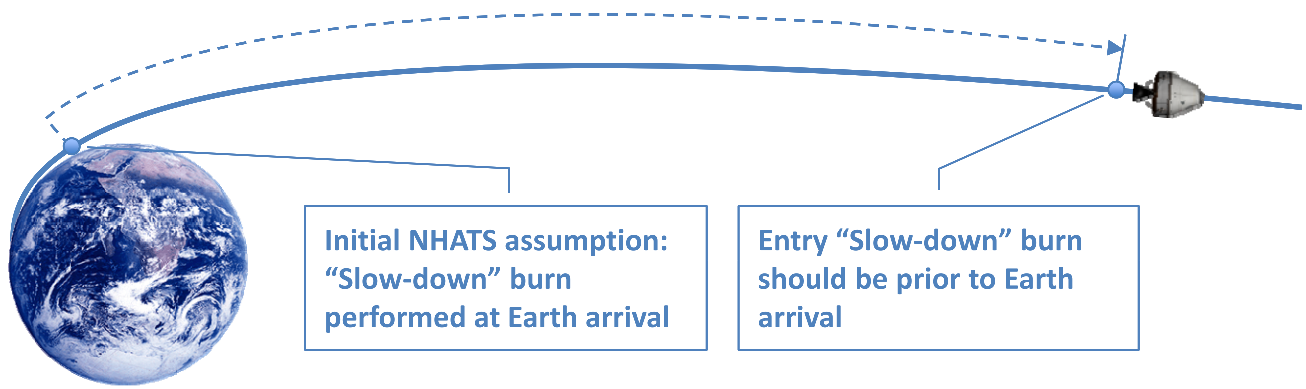
Earth Entry Speed Limit

- **NHATS Phase II trajectory scans performed with 12.0 km/s Earth entry speed limit (at Earth arrival).**
- **Over 50% of the NHATS trajectories result in Earth entry speeds in excess of 12.0 km/s**





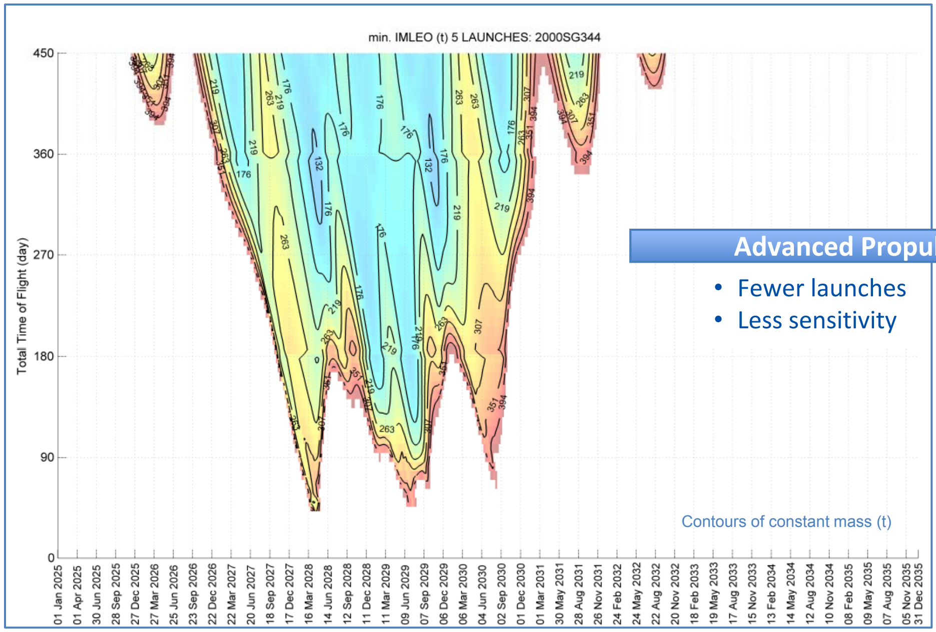
- **Quick look assessment performed to determine the sensitivity to various Earth entry speed limits (12.5 km/s, 12.0 km/s and 11.5 km/s)**
  - If trajectory meets entry speed limit, no slow-down maneuver required
  - If trajectory exceeds entry speed limit, deep space maneuver performed prior to Earth arrival



High-Thrust Injection Windows Based on Mass

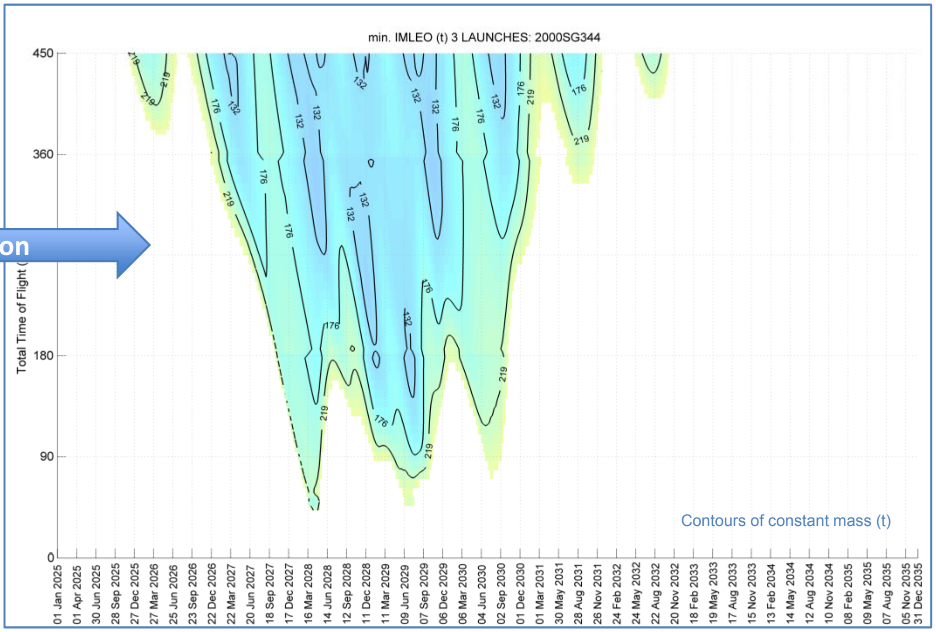
NEA: 2000SG344

All Chemical Propulsion ≤ 5 launches	All Nuclear Thermal Propulsion ≤ 3 launches



Advanced Propulsion

- Fewer launches
- Less sensitivity



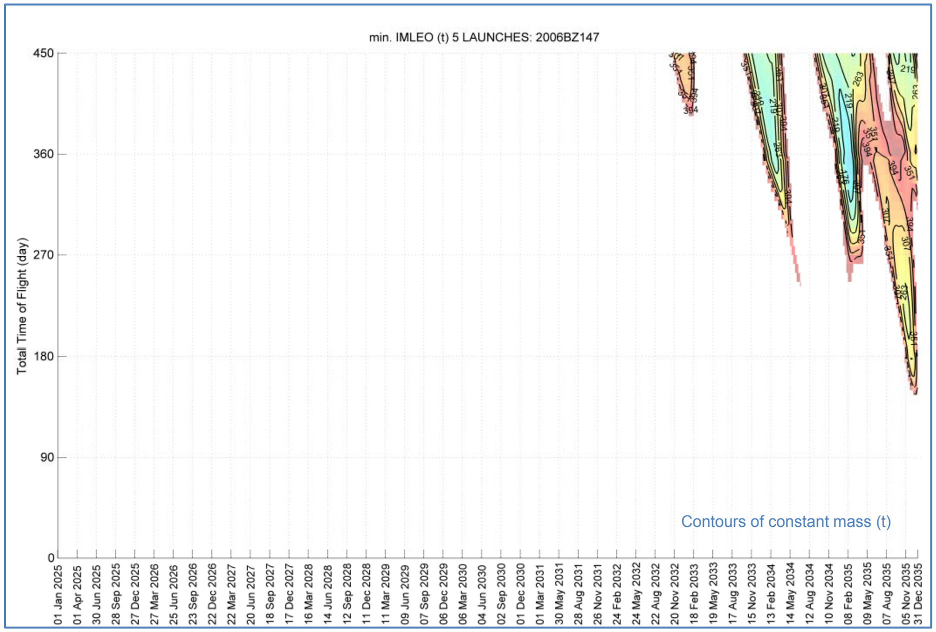
Estimated size: 21-66 m

Note: This window is atypical

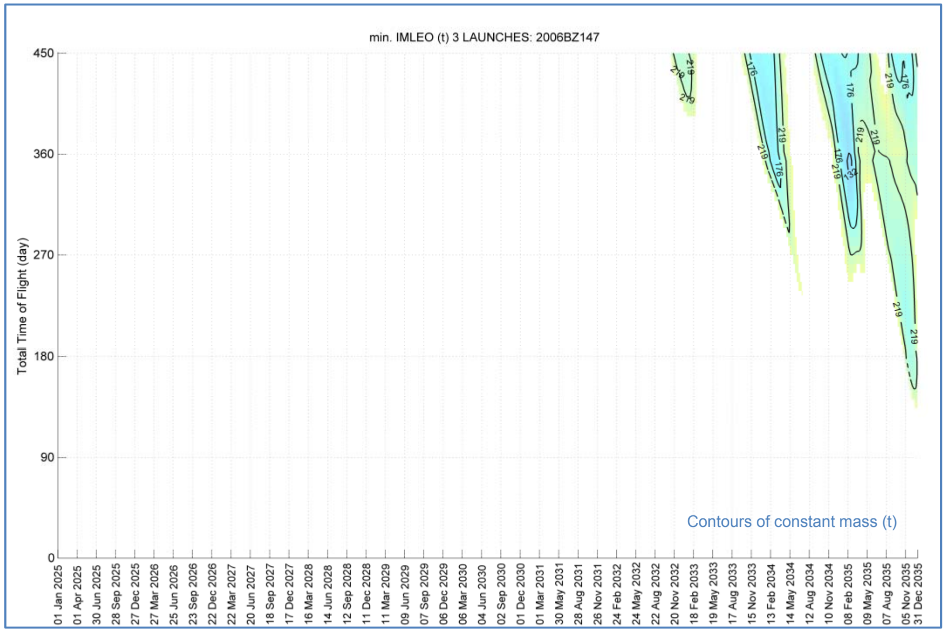
High-Thrust Injection Windows Based on Mass

NEA: 2006BZ147

All Chemical Propulsion ≤ 5 launches



All Nuclear Thermal Propulsion ≤ 3 launches

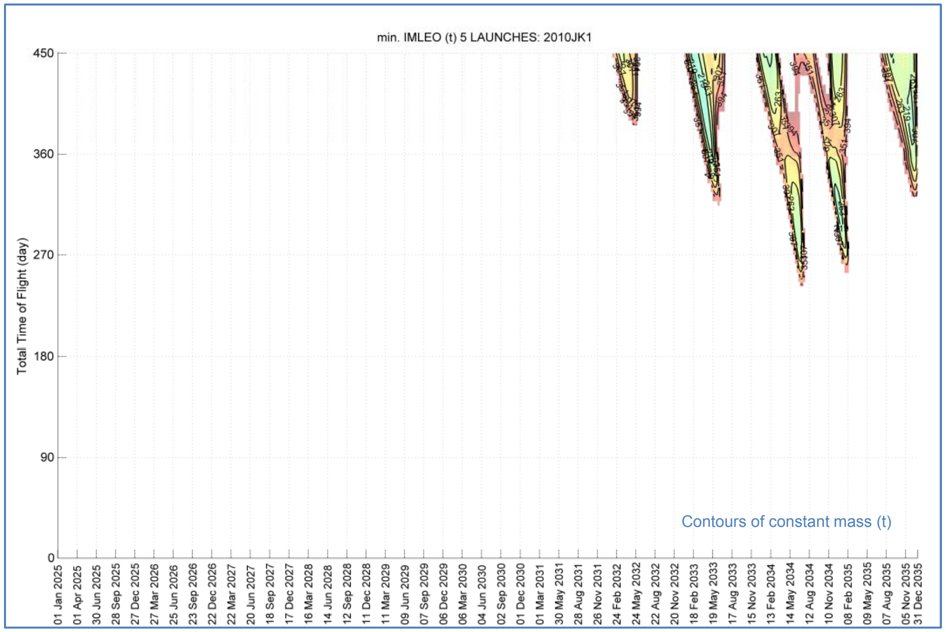


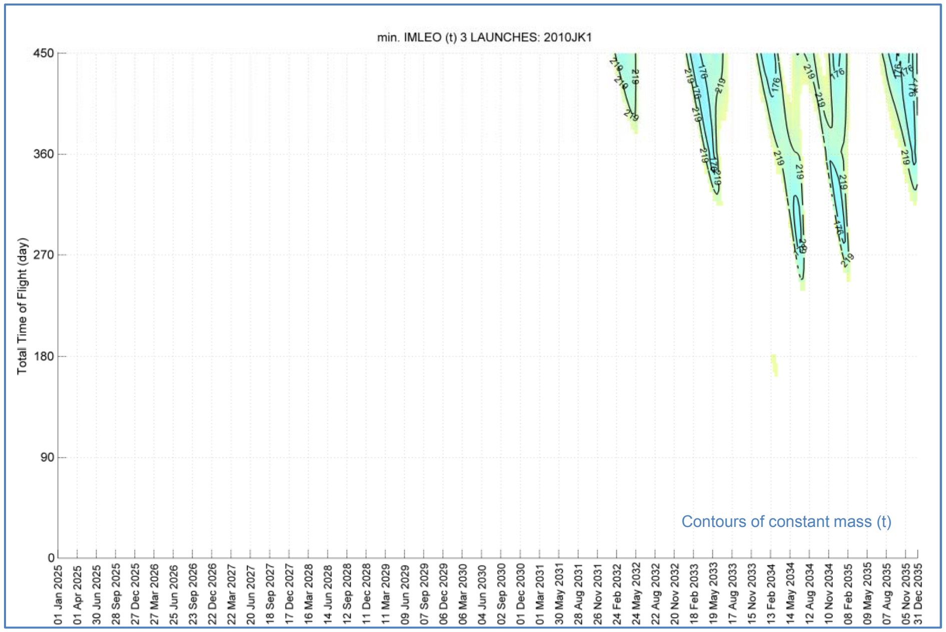
Estimated size: 15-49 m

High-Thrust Injection Windows Based on Mass

NEA: 2010JK1

All Chemical Propulsion ≤ 5 launches	All Nuclear Thermal Propulsion ≤ 3 launches



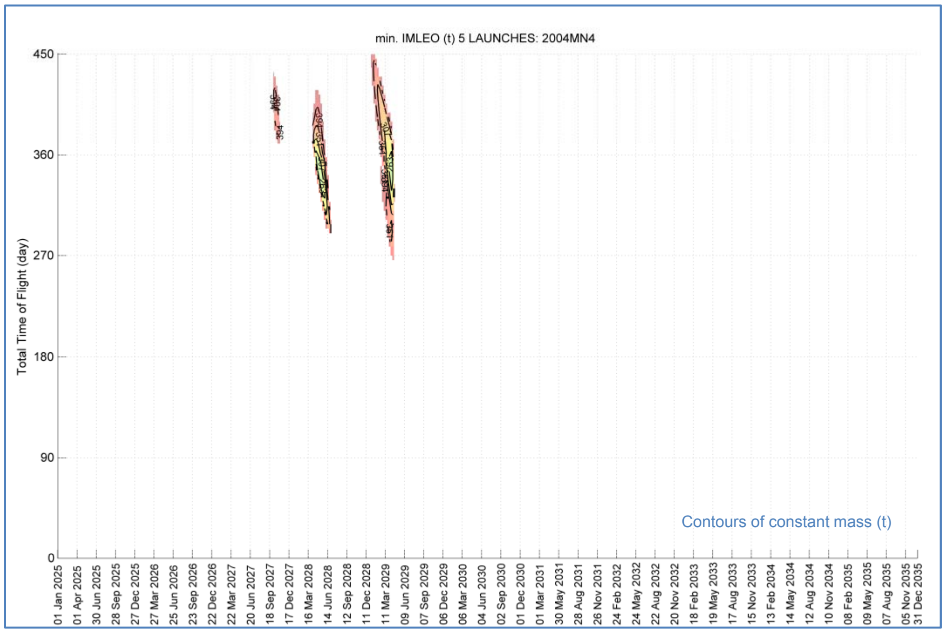


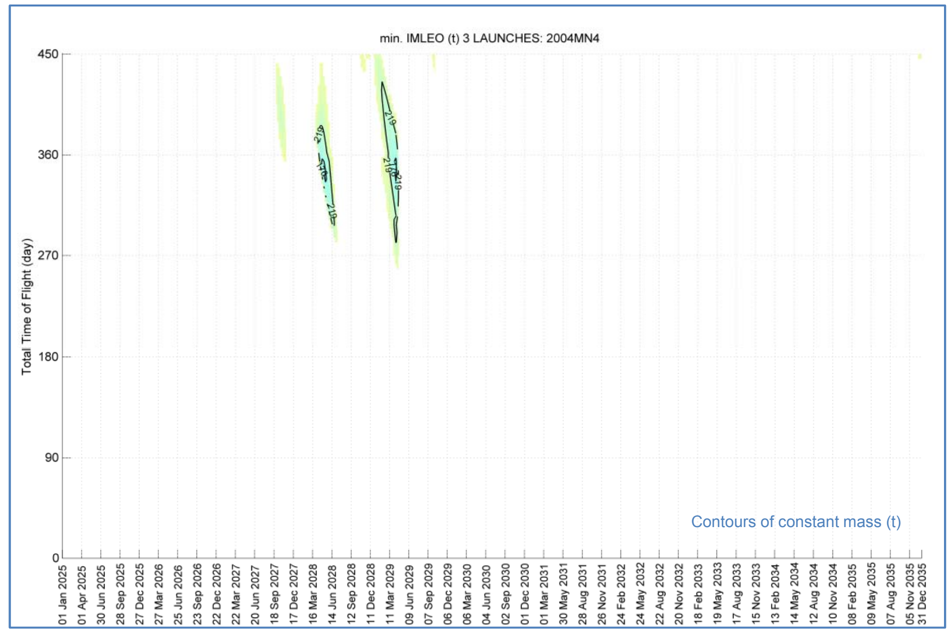
Estimated size: 25-78 m

High-Thrust Injection Windows Based on Mass

NEA: 2004MN4 (Apophis)

All Chemical Propulsion ≤ 5 launches	All Nuclear Thermal Propulsion ≤ 3 launches



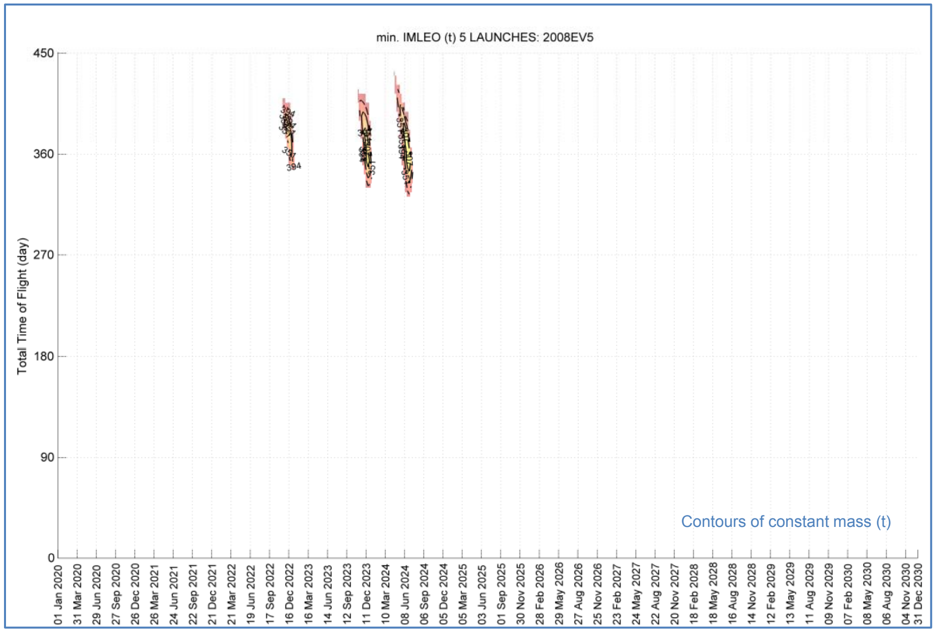


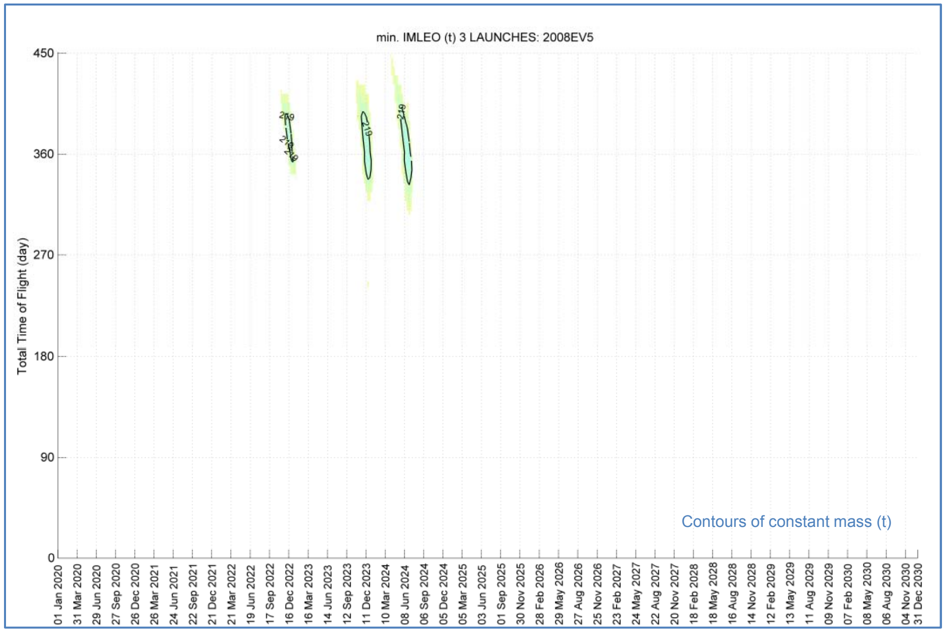
Estimated size: 270 m

High-Thrust Injection Windows Based on Mass

NEA: 2008EV5

All Chemical Propulsion ≤ 5 launches	All Nuclear Thermal Propulsion ≤ 3 launches





Estimated size: 450 m

Qualifying Factors for HSF Target Selection/Consideration

- **Orbit Condition Code (OCC)**
  - Several NEAs have significant uncertainties associated with their orbital position and some are even considered to be "lost".
  - A NEA's OCC can be improved by use of ground-base assets (optical and radar) to better determine its orbit provided there exists an appropriate viewing geometry that will enable collection of high quality data.
  - However, use of ground-base assets (optical and radar) are not able to effectively observe those NEAs that are the most accessible in terms of time of flight and mission mass (i.e., in Earth-like orbits with long synodic periods) within the time span from 2025 - 2035.
  - And, some NEAs do not have repeat apparitions that will enable further collection of data from the ground in time to plan for the human mission due to their phasing with the Earth.
- **System Type (*i.e.,* binary/ternary asteroids)**
  - Approximately 1/6 of all NEAs are binary or ternary systems. Such multiple systems would probably not be desirable for the first HSF mission due to the added complexity of spacecraft operations in and around the target NEA.
  - Confirmation of companion satellites around the NEA can be obtained by ground-based assets (radar and optical), but is not guaranteed due to signal-to-noise, system orientation, and viewing geometry limitations.
- **Spin Rate/Mode**
  - Small NEAs (< 100 m) predominantly have rotation rates < 2 hrs. The current estimates from the NEA light curve database is that ~85% have rotations < 2 hrs. Such rotation rates may preclude them from HSF consideration. Maximum acceptable NEA rotation rate for human missions is still being evaluated.
  - Larger NEAs (> 150 m) spin much slower so the percentage with rotation rates < 2 hrs drops to only 5%.
  - Some NEAs also have non-principal axis rotation (tumble). Such NEAs may not be good candidates for HSF exploration.
  - Accurate rotational characterization from ground-based assets is possible, but can be limited by low signal-to-noise and poor viewing geometries.
- **Active Surfaces (i.e., dormant/inactive comets)**
  - Approximately 5-10% of the NEA population may dormant/inactive comets. A potentially active NEA would present extreme risks to both spacecraft and crew during close proximity operations (*e.g.*, Comet Hartley 2).
  - Ground-based assets do not have the capabilities to discriminate whether a NEA could be potentially active.
  - A robotic precursor may be required to asses the NEA for potential activity at/near the surface.
- **Near-Surface Structure and Regolith Mechanical Properties**
  - Many NEAS may be rubble piles with regolith of varying particle size that is several meters deep. Depending on the near-surface structure and regolith mechanical properties, anchoring/attachment to the NEA may not be possible.
  - A robotic precursor may be required to determine the near-surface structure and regolith mechanics properties.

Observations

- **The NEA exploration strategy should provide targets with sufficiently long departure windows and adequate backup opportunities (secondary) to the primary object to be explored. Based on the current NEA data set…..**
  - There is a strong correlation of the number of currently available targets with
    - Mission duration (greatest increase at one year total duration)
    - Propulsion technology choice and/or total architecture mass
    - Desired size of the NEA
  - The number of NEAs available increases as the architectures approach capabilities similar to that of the crew portion of a Mars architecture
    - Advanced propulsion concepts (NTP and most probably SEP) decrease the sensitivity of the architecture to ΔV and injection window sensitivity. NTP can also provide improved access to NEAs with shorter mission durations.
  - The existing target list includes a few short duration missions (≤ 180 days), and even fewer very short duration missions (≤ 90 days), but they tend to be to smaller objects and require more propulsive capability
    - 2025-2030 is a "calm" period (relatively few targets); 2030-2035 provides relatively more targets
  - Further characterization is needed for factors to 'qualify' any particular NEA (see previous slide).
    - Basic NEA characterization is sparse for most of the targets on the "short list".
    - Future ground-based viewing opportunities may come too late in time to effectively plan for a human mission opportunity in the late 2020s.
    - Remote sensing assets are able to determine some basic characteristics of the target, but may not be able to given limitations in signal-to-noise and viewing geometries (i.e., NEA not observable during daytime sky). In addition, some physical properties such as surface structure, regolith mechanical properties, activity, etc. can only be determined *in situ* via a robotic spacecraft.

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Acronyms and Terms

C_3	Characteristic Energy (Square of the Hyperbolic Excess Velocity)	L1	Libration Point 1 (Earth-Moon System)
CPS	Cryogenic Propulsion Stage	LaRC	Langley Research Center
CTV	Crew Transfer Vehicle	LEO	Low Earth Orbit
Delta-v	Change in velocity	MPCV	Multi-Purpose Crew Vehicle
DRA	Design Reference Architecture	NEA	Near Earth Asteroid
DSH	Deep Space Habitat	NHATS	NEA Human Space Flight (HSF) Accessible Targets Study
EDL	Entry Descent and Landing	NOI	NEA Orbit Insertion
E-M	Earth-Moon	NTP	Nuclear Thermal Propulsion (used interchangeably with NTR)
EP	Electric Propulsion	NTR	Nuclear Thermal Rocket (used interchangeably with NTP)
GSFC	Goddard Space Flight Center	OCC	Orbit Condition Code
HEFT	Human Exploration Framework Team	PCC	Pork Chop Contour
Hmag	Absolute visual magnitude (estimate of the NEAs brightness)	SEP	Solar Electric Propulsion
HSF	Human Space Flight	SEV	Space Exploration Vehicle
IMLEO	Initial Mass in Low-Earth Orbit	SLS	Space Launch System (aka Heavy Lift)
JPL	Jet Propulsion Laboratory	SM	Service Module
JSC	Johnson Space Center	t	Metric Tons
km/s	Kilometers per second	TNI	Trans-NEA Injection